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A Bibliography, with Abstracts and Annotations, of Publications on and Related to Underwater Acoustic Fluctuations

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A bibliography of publications on and related to underwater acoustic fluctuation phenomena is given. The bibliography is annotated with up to three items: the abstract of each publication, a list of keywords characterizing the publication's subject matter, and one or more comments describing the publication's subject matter in more detail.

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INTRODUCTION

The following bibliography on fluctuation phenomena and related research was compiled in support of the WISPR Filter Development and Evaluation Project, an exploratory development project funded by the Office of Naval Research (ONR). Abstracts and other annotations have been included in order to make the bibliography more useful to the various researchers involved in that project.

The listings and associated material that are included herein come from the open literature, most of which are readily available as widely distributed scientific journals. Only articles which were considered relevant to the WISPR Filter Development and Evaluation Project have been included. Hence, this collection of articles cannot be considered either comprehensive or exhaustive where fluctuation research is concerned.

Definitions of Annotation Keywords:

Abbreviation	Meaning
AMech:	Acoustic Mechanisms
Appl:	Applications
Atm:	Atmospheric
Exper:	Experimental
Fine:	Finestructure
Fish:	Related to fish.
GWave:	Gravity waves
HF:	High Frequency
IWav:	Internal waves
Mag:	Magnetic
Meso:	Mesoscale (Ocean Weather)
Micro:	Microscale
Mod:	Modeling
Mult:	Multipaths
Nois:	Noise
Opt:	Optical
Prop:	Propagation
Plane:	Plane Wave Approximation
RSurf:	Rough Surface Scattering
Shallow:	Shallow Water
Sphere:	Spherical Wave Approximation
Stat:	Statistics
Strong:	Strong Turbulence
Theo:	Theory
Tides:	Tides
Weak:	Weak Turbulence
Wind:	Wind noise

Ali, H.B., "Oceanographic Variability in Shallow-Water Acoustics and the Dual Role of the Sea Bottom," IEEE J. of Oceanic Engineering 18 (1) 31-41 (1993).

Abstract— Acoustic propagation in shallow water is an area of major concern to the Navy. The difficulties associated with the use of acoustics in the ocean, however, are aggravated in shallow water. Multipath propagation and extensive boundary interactions, especially with the sea bottom, conspire, along with a host of other phenomena, to produce a highly variable and often unpredictable acoustic field. The responsible mechanisms, and hence the acoustic effects, cover a wide range of temporal and spatial scales. The mechanisms are classified as either deterministic or random, although the two types often act in concert. The sea bottom plays a dual role in shallow-water acoustics. Because of extensive interactions with the sound field, the bottom can severely degrade waterborne propagation. On the other hand, the sea bottom (and subbottom) can provide a *seismic* path that not only is relatively stable, but exists even under environmental conditions that preclude an effective waterborne path. Propagation in the bottom is particularly significant at very low frequencies, often being more efficient than high-frequency waterborne propagation. The preceding aspects of shallow-water acoustics—viz., variability and the dual role of the sea bottom—are illustrated using the results of experiments conducted in diverse geographic areas by the Naval Research Laboratory/SSC and by the SACLANT Undersea Research Centre.

Keyword codes: Prop, Mult, IWav, Meso.

Ali, H.B., "Spatial and temporal variabilities in underwater acoustic transmission: An analytical review," SACLANTCEN Memorandum SM-166, 1983.

An overview of temporal and spatial variability in underwater acoustic transmission is provided, based on a literature survey of previous experimental studies. Following comments on the use of the term "fluctuations", the medium-induced degradations of a transmitted signal are described and general approaches to medium (channel) characterization are discussed. The use of the scattering-function technique and the alternative, but equivalent, wide-sense stationary uncorrelated scattering (WSSUS) channel approach are considered, using experimental results to demonstrate the utility and the limitations of these methods. Following brief remarks on the effect of acoustic fluctuations on sonar performance, examples of environmental and acoustic fluctuations are provided. In conformity with current practice, the temporal and spatial scales of ocean variability are analyzed in terms of: (1) a mean vertical profile representing local climatology, (2) a mesoscale component that is deterministic on the acoustic time scale, and (3) a statistical component representing smaller scale, random fluctuations due to internal waves and fine structure. Each component is discussed at length, using experimental results from several sources. Tidally induced fluctuations are discussed separately, followed by some comments on the significant effects due to source/receiver motions. Recommendations are given on several areas of acoustic transmission fluctuations that warrant further investigation.

Keyword codes: Mult, IWave, Micro, Fine, Meso, AMech, Prop.

Andrews, R.S., "Aperature-averaging factor for optical scintillations of plane and spherical waves in the atmosphere," J. Opt. Soc. Am. 9 (4) 597-600 (1992).

Previous analyses of aperture averaging of optical scintillations in the turbulent atmosphere have generally involved either numerical integrations or approximation formulas based on asymptotic results for large apertures. Here I develop the exact expressions for the aperture-averaging factor in the weak-turbulence regime for both plane and spherical waves. For computational ease, accurate approximation or interpolation formulas that can be applied in most cases of interest with greater accuracy than previous approximations are also developed.

Keyword codes: Atm, Opt, Theo, Weak, Plane, Spher.

Andrews, R.S. and L.F. Turner, "Amplitude fluctuation of underwater signals and its effect on the bit-error probability of underwater data-transmission systems," Proceedings of the Institution of Electrical Engineers - London 124 (2), 115-119 (1977).

Two models are proposed for the probability density function (p.d.f.) of the amplitude fluctuations that arise when short-duration sound pulses are transmitted under shallow-water conditions. The models are derived for the conditions in which the prevailing surface-wind directions are parallel and perpendicular to the line of transmission. The probability density functions obtained from the models are compared with experimentally measured p.d.f.s and are found to be in excellent agreement. The models are then used to predict the bit-error probability in a binary underwater amplitude-shift-keyed (a.s.k.) data-transmission system and the results are compared with experimentally measured error probabilities. It is found that the measured error probabilities lie between the values computed using the p.d.f. models and it is conjectured that the proposed models provide approximate upper and lower bounds to the average error probability in a.s.k. underwater data-transmission systems. Finally, the p.d.f. models are used to compute new receiver-operating-characteristic (r.o.c.) curves.

Keyword codes: Stat, Mod, Wind, Sallow, HF, Appl.

1.) Direct path statistics are Gaussian.
2.) Surface Reflected Path has Rayleigh or Rician statistics.

Andrews, R.S. and L.F. Turner, "Investigation of the amplitude fluctuations of high-frequency short-duration sound pulses propagated under short-range shallow-water conditions," J. Acoust. Soc. Am. 58, 331-335 (1975).

This paper reports on part of a general investigation that has been carried out to determine the feasibility and limits of performance of high-data-rate underwater digital data communication. Specifically, the paper deals with the amplitude fluctuations that are encountered when high-frequency 0.8-msec duration pulses are transmitted under short-range shallow-water conditions. In the paper, the results of an analysis of experimentally measured amplitude fluctuations are presented. The results, which are presented in the form of amplitude-frequency spectra, autocorrelation functions, and probability density functions, are interpreted in terms of the prevailing climatic conditions, and the results are related to existing relevant theories of fluctuations.

Keyword codes: Exper, Amec, Shallow, HF, GWav.

Andrews, R.S. and L.F. Turner, "On the Performance of Underwater Data Transmission Systems Using Amplitude-Shift-Keying Techniques," IEEE Trans. on Sonics and Ultrasonics, SU-23 (1) pp. 64-71 (1976)

Abstract—As part of a general investigation into various aspects relating to underwater data transmission, an experimental amplitude-shift-keyed (ASK) system has been developed and tested. The system is described and the results from tests carried out with the system are presented. The tests, which were carried out under shallow-water transmission conditions, were designed to provide information relating to the limits of achievable performance. The results obtained indicate that with a simple system, it is possible, when using a peak transmitted power of only 50 mWatts, to transmit data at a rate of approximately 600 bits/sec over ranges up to 650 meters, and to do so with a probability of bit-error that is consistantly of the order of 10^{-3}. The results indicate that if the probability of bit-error is to be maintained at approximately 10^{-3}, then significant improvements in system performance in the form of increases in range and data-rate should be possible provided greater transmitter power is used. However, in order to do so it would be necessary, in addition to using increased transmitter power, to employ a much more sophisticated system capable of overcoming the effects of pulse dispersion and multipath.

Exper, Prop, Shallow, HF, Mult,
1.) Experiment took place in a reservoir approximately 1500m x 600m x 15m.
2.) Errors in pulse transmission due to acoustic medium flectuations are investigated.

Axelrod, E.H., B.A. Schoomer, and W.A. Von Winkle, "Vertical Diurectionality of Ambient Noise in the Deep Ocean at a Site bnear Bermuda," J. Acoust. Soc. Am. 37 (1), 77-83 (1965).

The vertical directionality of ambient ocean noise at 2400 f (fathoms) off Bermuda has been determined experimentally, using a novel data-reduction technique. In agreement with qualitative models, the results indicate that low-frequency noise arrives primarily from the horizontal while noise of higher frequency is incident from overhead. The measured dependence of observed levels on Beaufort-scale wind force is also consistent with the presumed sources of the noise. Absolute noise levels are several decibels lower than those measured near the surface.

Exper, Wind, Nois, AMech,
1.) Experiment took place in 2400 f of water in the Atlantic Ocean near Bermuda from January to August.

Baker, M.A., S.A.Mack and H.C. Schoeberlein, "Statistical Aspects of Turbulence and Microstructure in the Ocean," Johns Hopkins APL Technical Digest, 13 (2) 342-(1992).

The ocean has a large range of length scales controlled by vastly different physical processes. Patches of small-scale fluctuations in velocity (turbulence) and temperature and salinity (microstructure) are distributed intermittently in time and space throughout the ocean. This article discusses the sources and statistics of small-scale fluctuations along with techniques to discriminate between sources of microstructure in the ocean.

Exper, Stat, Micro.
1.) Experiments were conducted in a 88cm x 56cm tank.
2.) Discrimination between turbulence induced microstructure and salt fingering is discussed.

Bannister, R.W., "Deep sound channel noise from high-latitude winds," J. Acoust. Soc. Am. 79, 41-48 (1986).

The contribution to underwater ambient noise from the persistent winds which blow at high latitude is discussed and estimated. Energy is ducted into low-loss paths in the deep sound channel by favorable horizontal sound-speed gradients. A concept of "wind-noise lanes" is developed into a simple model which is used to predict the resulting underwater ambient noise levels as a function of season and latitude. Three main oceans are considered—the Pacific, Atlantic, and Indian Oceans. In general terms, predicted omnidirectional levels at 50 Hz lie between 65 and 75 dB *re*: 1 $\mu Pa^2/Hz$ and are comparable to those generally associated with light-to-moderate ship traffic. The spectral shape of high-latitude wind noise is also similar to that associated with ships. High-latitude wind noise arrives within $\pm 15°$ of horizontal, and the predicted magnitude of this low-angle component also matches measurements well. It is concluded that the component of noise associated with high-latitude winds can be significant at low frequencies. Properties of omnidirectional noise, as well as vertical and horizontal directivity, may be dominated by this component under some conditions. It appears, however, to have been often overlooked in the interpretation of data.

AMec, Nois, Wind.

Barabanenkov, Yu.N., Yu.A. Kravtsov, S.M. Rytov, and V.I. Tamarskii, "Status of the theory of propagation of waves in a randomly inhomogeneous medium," Soviet Physics USPEKHI, a translation of Uspekhi Fizicheskikh Nauk, 13, 551-680 (1971).

CONTINUALLY more attention has been paid over the last 10—15 years to studying propagation of waves in randomly-inhomogeneous media. The heightened interest in this problem has been primarily due to the large number of pressing applied problems that arise in radio physics, acoustics, optics, plasma studies and certain other branches of physics. New phenomena pertaining to the same problem have gradually accrued to the classical objects of the theory, which are light scattering in the atmosphere and passage of radiation through the atmospheres of stars and planets. Diffuse reflection of radio waves from the ionosphere; scattering of sound and ultrasound in sea water; the so-called ultra-long-range propagation of ultrashort waves; incoherent scattering of radiowaves in the ionosphere; twinkling of extraterrestrial radio emission sources due to the ionosphere and the interplanetary plasma; and propagation of laser beams in air and in water: this is a characteristic (and of course not exhaustive) list of the problems that have arisen, not to mention the purely applied problems involving accuracy of measurement by radio methods of the coordinates of objects moving in the ionosphere or in outer space. Naturally, the abundance and variety of such problems has stimulated development and refinement of statistical methods for calculating wave fields propagating in a randomly-inhomogeneous medium or passing through a layer of such a medium.

This review is an attempt to outline the existing methods of the theory and their limits of applicability, as well as the role of the new methods for treating multiple scattering of waves that have recently developed at a heightened pace. These include the Markov approximation in the parabolic-equation method, or the application of methods that were originally developed in quantum electrodynamics for summing the series of the perturbation theory. The theory is being developed so intensively that a number of new results have not yet been reflected in the existing monographs and reviews.* Furthermore, the original papers are very numerous and scattered throughout journals concerned with the most varied topics. Therefore, it would probably be of some use to systematize them even partially from the standpoint of the theoretical methods used.

Propagation of waves in randomly-inhomogeneous

Theor, Stat, Prop.

1.) Here theory is reviewed without considering sea surface or sea bottom interactions.

Baykal, Y. and M.A. Plonus, "Frequency averaging for beam waves in weak and very strong turbulence," IEEE Trans. on Antennas and Propagation AP-30 (4), 802-805 (1982).

Abstract—The scintillation index for a temporally partially coherent beam wave source is calculated in the narrow-band approximation for weak and very strong atmospheric turbulence. It is found that frequency averaging in weak turbulence is not affective for collimated and focused beams with sizes much less than the first Fresnel zone. In the limit of very strong turbulence, frequency averaging effect on the scintillations becomes large for large source sizes.

Theor, Weak, V.Strong, Stat.
1.) The scintillation index is calculated for weak and very strong turbulence.

Belenkii, M.S., V.V. Boronoev, N.Ts. Gomboev, V.L. Mironov, and E.A. Trubacheev, "Curvature of the average phase front of a laser beam in a turbulent atmosphere: an experimental study," Opt. Spectrosc. (USSR) 49 (3), 324-327 (1980).

A theoretical basis is given for the possiblity of determining the radius of curvature of the average phase front of a laser beam propagating in a turbulent atmosphere by the well-known autocollimation method. Experimental data are obtained that verify that the average phase front of the laser beam undergoes additional bending caused by the medium.

Opt, Exper, Atm, Theo.

Beran, M.J. and R. Mazar, "Intensity fluctuations in a quadratic channel," J. Acoust. Soc. Am. 82, 588-592 (1987).

Using previously developed two-scale solutions [S. Frankenthal *et al.*, J. Acoust. Soc. Am. **71**, 1124–1130 (1982); B. J. Uscinski, Proc. R. Soc. London Ser. A **380**, 137–169 (1982); C. Macaskill, *ibid.* **386**, 461–474 (1983); S. Frankenthal *et al.*, J. Opt. Soc. Am. A **1**, 585–597 (1984); A. M. Whitman and M. J. Beran, *ibid.* **2**, 2133–2143 (1985)], the scintillation of acoustic radiation in a random medium with a vertical quadratic mean sound-speed profile is considered. It is assumed that the statistics of the random medium are sufficiently anisotropic that fluctuations in the cross horizontal direction may be neglected. A point source is used as a boundary condition. Numerical calculations are performed for Gaussian and exponential correlation functions. Results are compared to those obtained in the absence of a channel. When the focusing length of the channel is small compared to the distance at which saturation would occur in the absence of a channel, the scintillation index is dramatically affected by the presence of the channel.

Theor.
1.) The scintillation index for Gaussian and exponential correlation functions is calculated for various values of the focusing length of a 2-D model.

Beydoun, W.B. and A. Tarantola, "First Born and Rytov approximations: Modeling and inversion conditions in a canonical example," J. Acoust. Soc. Am. 83, 1045-1055 (1988).

First Born and, more recently, first Rytov approximations are widely used for solving complex forward and inverse seismic scattering problems. The exact pressure-field response from a one-dimensional velocity slab included in an infinite constant velocity medium is expressed analytically. This solution is used for testing these two approximations in modeling and in inversion. Conditions of applicability and parameter estimates lead to the following results: The first Rytov approximation is best suited for modeling and inverting the transmitted, or forward scattered, part of the wave field, whereas the first Born approximation is best suited for modeling and inverting the primary reflected, or backscattered, part of the wave field. If the long wavelength condition holds, linearization of the field with respect to slowness squared is preferable over linearization with respect to slowness, allowing for a very large velocity contrast between the slab and the reference medium. However, if the weak heterogeneity condition holds (i.e., small velocity contrast), the linearization choice is reversed. Numerical examples show and display these differences quantitatively.

Theor, Mod, Prop.

Bhattacharyya, A., "Chaotic behaviour of ionospheric turbulence from scintillation measurements," Geophys. Res. Lett. 17 (6), 733-736 (1990).

Abstract. Ionospheric amplitude and phase scintillation data have been analysed to estimate the 'information dimension' associated with the attractor of the system. For weak scintillations, both amplitude and phase data yield identical results which demonstrate that spatial fluctuations of electron density in the ionosphere may be characterized by a few degrees of freedom. Stronger scintillations are attributed to steepened density irregularities which cause 'focusing' of the incident radio wave. This results in the amplitude scintillations exhibiting higher dimensional chaos but spatial fluctuations in ionospheric density still involve low dimensional chaos.

Exper, Appl, Opt, Atm.

Bissonnette, L.R., "Modeling of laser beam propagation in atmospheric turbulence," Proceedings of the Second International Symposium on Gas Flow and Chemical Lasers, J.F. Wendt, ed. (Hemisphere, Washington, D.C., 1979), 73-94).

This paper describes a method of closing the set of second-order partial differential equations for the first- and second-order statistical moments of the complex wave amplitude defined on the geometrical phase front. The resulting equations are linear, contain only algebraic coefficients, and are uniformly valid over the complete propagation range. The hypothesis of normal probability distribution of the complex amplitude which is used to obtain the irradiance variance in terms of the complex-amplitude moments is shown to be consistent with the stochastic wave equation. The model gives the well-known perturbation results in the limit of small propagation distance. Solutions for average irradiance and irradiance variance profiles of laser beams are easily and quickly calculated by a numerical finite difference method. Predictions agree very well with experimental data over the complete propagation range.

Opt, Atm, Theor, Mod, Stat, Prop.
1.) Modeled average irradiance and standard deviation of irradiance are compared to data.
2.) Experimental data is obtained by measurements in a 1.5m x .6m x .4m tank filled with water.

Bissonnette, L.R., "Propagation model of laser beams in turbulence," J. Opt. Soc. Am. 73 (3), 262-268 (1983).

A closed set of three simultaneous partial differential equations is derived for the solution of the average irradiance and the irradiance variance of focused laser beams in turbulence. The equations are uniformly valid for arbitrary scintillation levels. Examples of solutions calculated by finite difference techniques are shown to fit typical atmospheric and laboratory data well. Analytic solutions derived for asymptotic conditions are in good agreement with the related classic perturbation results. The model also provides interesting physical insight into the phenomena of saturation and supersaturation.

Opt, Atmos, Prop, Theo, Mod, Stat, Weak, Strong.

1.) The statistic calculated is irradiance standard deviation.
2.) Beam radius and beam spread are also shown.

Bissonnette, L. R. and P.L. Wizinowich, "Probability distribution of turbulent irradiance in a saturation regime," Applied Optics 18 (10), 1590-1599 (1979).

Application of the central limit theorem to the stochastic equation of propagation suggests that the probability distribution of the complex wave amplitude defined on the geometrical phase front is approximately normal. The resulting irradiance probability density function, valid in the strong scintillation regime, is an exponential multiplied by the modified Bessel function I_0 both of argument proportional to the irradiance; it is not the Rice-Nakagami density function. Quantitative tests show that this exponential-Bessel function constitutes as good a fit as the log-normal to the irradiance probability data reported in this paper. Since the normal distribution hypothesis is consistent with the stochastic wave equation, the model proposed here should be a simple substitute to the often used but theoretically incorrect log-normal irradiance probability distribution model.

Stat, Theo, Prop, Strong.

1.) Exponential, Bessel and log-normal irradiance probability density functions are compared with data.
2.) Chi-Square and Kolmogorov tests are done to quantify the goodness of fit on probability density functions to data. The goodness of fit results are not easy to evaluate.

Boyles, C.A., L.B. Dozier and G.W. Joice, "Application of coupled mode theory acoustic scattering from a rough sea surface overlying a surface duct," Johns Hopkins APL Technical Digest 6 (3) 216-226 (1985).

The technique of local normal modes can be used to obtain an exact numerical solution of the wave equation for the case of an oceanic waveguide that can possess both vertical and horizontal sound-speed gradients as well as a time-varying, randomly rough sea surface. The solution is then applied to long-range propagation in a surface duct that is formed in the upper layer of the ocean when certain oceanographic conditions occur. When a duct forms, significant acoustic energy that can become trapped in it propagates along it by repeated refractions and surface reflections and can be carried long distances.

Theo, Mod, Prop, Mult, RoughSurf.

Brockett, P.l., M. Hinich, and G.R. Wilson,"Nonlinear and non-Gaussian ocean noise," J. Acoust. Soc. Am. 82 (4), 1386-1394 (1987).

Bispectral analysis is a statistical tool for detecting and identifying a nonlinear stochastic signal-generating mechanism from data containing its output. Bispectral analysis can also be employed to investigate whether the observed data record is consistent with the hypothesis that the underlying stochastic process has Gaussian distribution. From estimates of bispectra of several records of ambient acoustic ocean noise, a newly developed statistical method for testing whether the noise has a Gaussian distribution, and whether it contains evidence of nonlinearity in the underlying mechanisms generating the observed noise is applied. Seven acoustic records from three environments are examined: the Atlantic south of Bermuda, the northeast Pacific, and the Indian Ocean. The collection of time series represents both ambient acoustic noise (no local shipping) and noise dominated by local shipping. The three ambient records appeared to be both linear and Gaussian processes when examined over a period on the order of a minute, but were found to be nonlinear and non-Gaussian when examined over shorter time periods on the order of a second. In each case the time series dominated by local shipping noise tested to be nonlinear and non-Gaussian over both short and long time periods.

Nois, Stat, Exper, AMec.

Brown, M.V. and J. Ricard, "Fluctuations in Surface-Reflected Pulsed cw Arrivals," J. Acoust. Soc. Am. 32 (12), 156-161 (1973).

A pulse of 168-cps sound was scattered from the ocean surface and analyzed for fluctuation as a function of the angle of incidence. A $(\cos\varphi)^{2.5}$ relation is found between the relative standard deviation of the energy and the incident angle, as measured from the normal.

Exper, Stat, GWav, RSurf, Mult.
1.) The standard deviation is calculated as a function of range, ray path length and incident angle.

Brownlee, L.R., "Rytov's method and large fluctuations," J. Acoust. Soc. Am. 53 (1), 156-161 (1973).

Rytov's method has been the subject of arguments as to whether or not it has a greater domain of applicability than the method of small perturbations. In order to be able to use the result of Rytov's method one must assume that the sizes of the patches of inhomogeneity are much larger than the wavelength of the sound; i.e., $\lambda \ll l$. Making use of this assumption, when we use the solution for Ψ' to compare the discarded term $|\nabla\Psi'|^2$ with the remaining terms, we discover that Rytov's method has the *same* domain of applicability as the method of small perturbations. Using a simple geometrical model we deduce by physical reasoning the results of Mintzer and Bergmann. This model is then used to extend the theoretical prediction for the amplitude fluctuations in the (Mintzer) range $(\lambda L)^{1/2} \gg L_0$ to cover the case where the fluctuations are large.

Theory, Mod, Strong.

Brunner, F.K., "Atmospheric turbulence: The limiting factor to geodetic precision," Aust. J. Geod. Photo. Surv. 31, 51-64 (1979).

The effects of atmospheric turbulence on geodetic measurements are investigated. The stochastic behaviour of atmospheric turbulence inhibits correcting the geodetic measurements for these effects. Therefore the fluctuating part of the geodetic refraction effect represents the fundamental limit in the ultimate precision of geodetic measurements.

The calculation of the precision of almost all geodetic measurements can be related to the refractive index structure parameter C_n^2. Estimation techniques for C_n^2 are reviewed. The main results for a plane electromagnetic wave propagating through a locally isotropic and homogeneous turbulent atmosphere are discussed.

The ultimate precision of two types of terrestrial geodetic measurements is estimated as a function of instrumental design parameters and the strength of atmospheric turbulence, expressed by C_n^2. It is further shown that the averaging process of the random signal is of vital importance for improving the precision of the geodetic measurement. An application is presented for the evaluation of the precision of geodetic levelling.

Opt, Atmos, Stat.
1.) Angle of arrival fluctuations and the refractive index structure parameter versus time of day.

Chapman, D.M.F., "A simple estimate of propagation loss fluctuations due to modal interference," J. Acoust. Soc. Am. 85 (3), 1097-1106 (1989).

A simple estimate of propagation loss fluctuations due to deterministic modal interference has been devised for use with normal mode computer codes. It is based upon the relative mode amplitudes, and is easy to compute along with the incoherent mode sum that is used to estimate average propagation loss. The estimated levels of propagation loss fluctuation compare favorably with those computed from the coherent mode sum for shallow water environments.

Mod, Stat, Theo.

Ching, P.A. and D.E. Weston, "Fast acoustic fluctuations caused by fish," J. Sound Vib. 39 (3), 287-292 (1975).

Acoustic fluctuations of sound have been studied in the shallow waters of the Bristol Channel for a number of years and several different types have been identified. One of these, occurring in the summer day-time only, is a fluctuation of about 10 dB with a period of about 80 seconds. It has been observed at transmission frequencies between 312 Hz and 4·44 kHz but was most frequently recorded between 1 and 2 kHz. Because of its timing the phenomenon is attributed to fish, and, although the mechanism has not been positively identified, it is thought to involve fish clustering round the hydrophone.

Fish, Shallow, Exper.

Chow, P.L., W.E. Kohler, G.C. Papanicolaou (eds.), Multiple Scattering and Waves in Random Media, North-Holland, New York, 1981.

Clark, J.G. and M.Kronengold, "Long-period fluctuations of CW signals in deep and shallow water," J. Acoust. Soc. Am. 56 (4), 1071-1083 (1974).

In July 1972, as part of the cooperative studies between the Miami and Michigan Project MIMI research groups, continuous fixed-system underwater sound propagation tests at 406 Hz were commenced between a sound source off Eleuthera, Bahamas, and receivers at Bermuda, a distance of 1250 km, and at positions intermediate in range with respect to the 1250-km path. Preliminary studies of long-period CW transmission fluctuations at Bermuda and at one intermediate position have been completed. The long-period phase and amplitude fluctuations are qualitatively quite similar to those observed in the Straits of Florida and in other relatively shallow water locations. Phase fluctuations associated with the ocean tides are a marked feature of the data. With averages taken over two-day time spans, significant variations in the statistical properties of transmission loss have been observed over a five-month time period. Shorter-period fluctuations in acoustic phase (time scale of a few minutes to a few hours) have similar characteristics in the deep and shallow water propagation ranges. [The research was supported by Code 412 of the Office of Naval Research.]

Exper, Prop, Shallow, Mult, Tides,
1.) The experiment, part of the MIMI project, took place in the Straits of Florida.

Clay, C.S., "Fluctuations of sound reflected from the sea surface," J. Acoust. Soc. Am. 32 (12), 1547-1551 (1960).

Experimental data on the reflection of sound from the sea surface suggest that the fluctuations of the received signals are due to the scattering of sound from the irregular sea surface. These data are compared with calculations based on the theory of Eckart. A Gaussian correlation function for the sea surface was assumed for the calculations. The scattered sound depends upon the sea surface parameters, source position, receiver position, and acoustic wavelength. The numerical calculations of scattered sound had the same dependence on the source-receiver separation as the experimental data. By using this, the correlation distance and rms wave height are estimated for the sea surface.

Stat, GWav, Theo, Appl, RSurf.
1.) Theory is compared with the experimental results of Brown and Ricard.

Clay, C.S., Y-Y Wang, and E.-C. Shang, "Sound field fluctuations in a shallow water waveguide," J. Acoust. Soc. Am. 77 (2), 424-428 (1985).

Experimental measurements of sound transmissions in a laboratory waveguide are analyzed. The transmissions were from a single source to a vertical array of receivers that operated as a mode filter. Water waves on the surface caused the sound fields to fluctuate at the receiver. We used theories of coherent mode transmission to describe the experiments. Within a mode, sound field fluctuations have three components: (1) phase fluctuations due to fluctuations of the horizontal component of the wave number, (2) fluctuations of depth-dependent eigenfunctions at source and receiver positions, and (3) mismatch of the mode filter to the local eigenfunction. Analysis showed that most of the fluctuations of the mode filtered signals were due to components (2) and (3).

Exper, Mult, HF, Shallow,
1.) Laboratory experimental data at 16 kHz is compared with mode theory predictions.

Clifford, S.F. and D.M. Farmer, "Ocean flow measurements using acoustic scintillation," J. Acoust. Soc. Am. 74, 1826-1832 (1983).

A wave propagating in a medium having random fluctuations in refractive index will suffer phase and amplitude perturbations. In the receiving plane, a random interference pattern will appear and this so-called scintillation pattern will vary in time for two reasons: (1) the decay of the refractive-index fluctuations producing the amplitude perturbation (eddy decay) and (2) advection of the eddies by the flow. In the case where eddy lifetimes are long compared with the scintillation period, we can derive estimates of flow from a statistical analysis of the scintillation pattern. In this paper, we discuss the propagation theory and report measurements of oceanic flows by analysis of the acoustic scintillation pattern produced by the density fluctuations in the ocean. By mounting a 214-kHz source and two receivers on opposite sides of a barge such that the axis of propagation is perpendicular to the direction of travel, we induce a known flow rate equal to the barge velocity. We compute the slope of the time-lagged covariance function of the logarithm of the amplitude at the two detectors. The slope is proportional to the path-averaged flow transverse to the propagation path. Simultaneous measurements with a current meter provide sea truth. We have shown that such a technique will measure flow velocity with reasonable accuracy. An interesting result of the measurements is the demonstration that sound speed fluctuations in the spatial window 15–30 cm satisfy the Kolmogorov spectral slope for an inertial subrange, at the shallow depth (2.1 m) of the observation.

Appl, HF, Exper.
1.) Experiment took place in the Saanich Inlet, British Columbia, during November 1982.

Clifford, S.F., G.R. Ochs and R.S. Lawrence, "Saturation of optical scintillation by strong turbulence," J. Opt. Soc. Am. 64 (2), 148-154 (1974).

The diffraction theory of optical scintillations has so far failed to describe the propagation of light over paths where the integrated amount of refractive-index turbulence is sufficient to cause saturation of the scintillations. We present a simple, physically based elaboration of the first-order perturbation theory and compare it with observations. Our theory reproduces in detail the observed saturation curve and the observed spatial covariance of the scintillations. In particular, we show why the fine-scale structure of scintillations persists deep into the saturation regime.

Opt, Strong, Atm, Exper, Prop, Mult.
1.) With the theory presented here measured log-amplitude variance is predicted at ranges below and beyond the range where scintillation is saturated, i.e., the range where the Rytov approximation no longer holds.
2.) Log-amplitude variance, ray paths and covariance functions are calculated and displayed.
3.) Light from a HeNe laser was recorded at 50, 310, 500 and 1000 m over a 24 h period.

Coles, W.A. and R.G. Frehlich, "Simultaneous measurements of angular scattering and intensity scintillation in the atmosphere," J. Opt. Soc. Am. 72, 1042-1048 (1982).

Simultaneous measurements of the spatial covariance of intensity and the angular spectrum of plane waves have been made for a diverging He–Ne laser beam propagating over a 1-km horizontal path. Most of the data are taken during strong scintillation. The measured angular spectrum is used to estimate the wave-structure function $D(s)$. The propagation equation for the intensity covariance depends on the medium only through the longitudinal derivative of $D(s)$. Thus, for a homogeneous medium, $D(s)$ is sufficient to calculate the intensity covariance, although such a calculation has not been done in general. The estimated $D(s)$ is used to calculate the intensity covariance by using weak scintillation theory and also by using an asymptotic theory for strong scintillation. The measured intensity covariances are then compared with these calculations. In both cases there is qualitative agreement, but the quantitative comparison is poor. It is shown that the inner scale of the turbulence is an important factor in weak scintillation, and it is argued that this inner scale is a dominant factor in strong scintillation.

Opt, Atm, Exper, Prop, Stat, Weak, Strong.
1.) "The structure function is a convenient statistic to use when a process is non-stationary (or nearly so), ... ".
2.) Intensity covariances, structure functions, and scintillation indices are shown.

Crawford, G.B., R.J. Lataitis and S.F. Clifford, "Remote sensing of ocean flows by spatial filtering of acoustic scintillations: Theory," J. Acoust. Soc. Am. 88, 442-454 (1990).

Space-time acoustic scintillation analysis has proved to be a valuable technique for probing ocean flows over short ($\lesssim 2$ km) acoustic paths. Measurements of the amplitude and phase perturbations in a distant receiving plane are used to infer the intervening fine-scale variability and transverse current. Observations made using one transmitter and two receivers yield path-integrated measurements that are almost uniformly weighted along the propagation path. Higher resolution measurements can be obtained using multiple sources and receivers. By combining the signals from each transmitter–receiver pair in different ways, a number of different path positions can be probed and profiles of the fine-scale variability and transverse current along the propagation path retrieved. A theory describing the performance characteristics of such a system is presented. The case of linear transmitting and receiving arrays of equally spaced elements is considered in detail. The theory predicts a potential path resolution of up to $L/[(N'_t + N'_r)/2]$, where $N'_t \gg 1$ and $N'_r \gg 1$ are the number of transmitters and receivers, respectively, and L is the propagation path length. The specific case of four-element transmitting and receiving arrays is also considered, and some simulations of profile retrievals are presented. A future paper [D. M. Farmer and G. B. Crawford, J. Acoust. Soc. Am. (in preparation)] will present results of an experiment to test such a system.

Theor, Appl, Fine, Mult, Weak.

1.) A simple Kolmogorov spectrum is used to describe refractive index fluctuations. This "is best suited for relatively short paths across well-mixed flows".
2.) Flow speed is estimated from the refractive index structure function.

Daigle, G.A., J.E. Piercy and T.F.W. Embleton, "Line-of-sight propagation through atmospheric turbulence near the ground," J. Acoust. Soc. Am. 74 (5) 1505-1513.

Line-of-sight measurements of the log-amplitude and phase fluctuations of pure tones between 250 and 4000 Hz propagated over distances between 2 and 300 m in the turbulent atmosphere close to the ground are compared quantitatively with simple theory using simultaneously measured meteorological variables. The theory is based on the assumption of homogeneous and isotropic turbulence and approximates the availability of eddy sizes in the source region of turbulence by a Gaussian spectrum. In particular the transverse or mutual coherence function (the coherence in a plane perpendicular to the direction of propagation) and the coherence in the direction of propagation which we call the longitudinal coherence, are also calculated and compared with the measurements. When the measured mean square phase fluctuations are compared with the theory using the meteorological measurements, good agreement is obtained. However the measured mean square log-amplitude fluctuations are in general substantially smaller than predicted and, in addition, show clear evidence of saturation. The distance to saturation is shown to correspond to the longitudinal coherence length. Because of this behavior of the amplitude fluctuations both the transverse and longitudinal coherences are essentially a function of the phase variance only.

Exper, Atm, Stat, Prop, Strong,

1.) Saturation of amplitude fluctuations is found experimentally, contrary to expectations based on theory, but similar to the findings of other researchers.
2.) Measured mean square phase fluctuations are not saturated and match theoretical expectations.

Dashen, R.F., S.M. Flatte´, W.H. Munk and F. Zachariasen, "Limits on coherent processing due to internal waves," Stanford Research Institute Technical Report JSR-76-14, Stanford Research Institute, Menlo Park, California, 1977.

We derive estimates of the effects produced by internal waves in the ocean on coherent spatial and temporal processing of acoustic signals based on the empirical Garrett-Munk GM75 internal wave spectrum. We present results for horizontal and surface limited rays, for point and array receivers, and for stationary and moving sources.

IWav, Theo, Mult.

1.) Discusses the limitations on coherent processing due to refractive index fluctuations caused by internal waves.

Dashen, R.F., and G-Y Wang, "Intensity fluctuation for waves behind a phase screen: a new asymptotic scheme," J. Opt. Soc. Am. A 10 (6) 1219- (1993).

A new asymptotic scheme is presented through the computation of $\langle I^2 \rangle$ and $\langle I_1 I_2 \rangle$ for waves behind a random phase screen with a power-law correlation. It illustrates the basic idea for an effective new expansion technique that yields a considerably faster convergent asymptotic series for intensity moments in the strong-fluctuation regime. This scheme can also be generalized to the computation of various statistical moments of intensity and log-intensity in continuous media with a power-law spectrum.

Theo, Strong.

1.) This paper deals with continuous media with a power-law spectrum.

Davidson, F. and A. Gonzalez-del-Valle, "Measurements of three-parameter log-normally distributed optical-field irradiance fluctuations in a turbulent medium," J. Opt. Soc. Am. 65 (6), 655-663 (1975).

A laser beam was passed through a turbulent mixture of hot and cold water. The optical path contained no solid scattering particles. It was, therefore, similar to an atmospheric path containing only clear-air turbulence. The field irradiance was accurately described by a truncated three-parameter log-normal probability density. The statistics of the integral of the field irradiance over an area comparable in size to one coherence area was also always characterized by a three-parameter log-normal density. This probability density, when used in the Mandel formula for the single-photon-counting probability, correctly predicted the observed results. The parameters of the irradiance density could be varied by changing the temperature of the hot- and cold-water mixture, or the position of the optical path. The observed photon-counting probabilities could not be obtained by use of a two-parameter log-normal irradiance density (more commonly called the log-normal density) in the Mandel formula.

Opt, Exper.

1.) A three parameter, log-normal distribution fits the field irradiance values measured in the laboratory.

DeFerrari, H.A., "Numerical method for computing multipath interference in a time-varying medium," J. Acoust. Soc. Am. 54, 1757-1759 (1973).

Ray-model simulations of multipath interference of CW signals require precise computation of travel times along the paths between source and receiver. The travel times for each ray path must be known with sufficient precision to resolve the phase of the arrival. The effects of time-varying sound-speed profiles can then be simulated by allowing the state of the medium to change slightly for each multipath summation. This letter is concerned with a numerical method for making such computations.

Mod, Theo, Mult.

DeFerrari, H.A., "Time-varying multipath interference of broad-band signals over a 7-NM range in the Florida Straits," J. Acoust. Soc. Am. 53, 162-180 (1973).

The frequency response function of a propagation channel is formulated by the coherent (vectorial) summation of CW signals arriving via many ray paths between source and receiver. Six months of continuous measurements of water temperature from a moored thermistor string in the Florida Straits are analyzed to determine the temporal variation of the sound speed profile. The observed average profile and its temporal variations are shown to be closely modeled by fitting the data with two layers of linear sound speed gradient. In order to investigate the effects on propagation of temporal variations of the two layers, a model of Refracted Bottom-Reflected (RBR) propagation is developed for the particular case of a bottomed source and receiver. Model computations determine the relative influence of the parameters of the two layers upon the interference of broad-band signals. The general features of multipath interference which are observed in the Florida Straits are presented and discussed. Model simulations of multipath interference are used to interpret experimental results. Some characteristics of the propagation channel (e.g., bandwidth of an interference fade) are shown to depend on average values of the model parameters, while others (e.g., CW amplitude) depend on small fluctuations about the averages and thus cannot be estimated with idealized propagation models. For typical profiles the gradient near the bottom determines the average properties of the channel frequency response function.

Exper, Mult.
1.) Source and receiver are both on the bottom.
2.) Experiment, part of project MIMI, took place in the Florida Straits at 420 Hz ±25Hz.

Desaubies, Y.J.F, "Acoustic-phase fluctuations induced by internal waves in the ocean," J. Acoust. Soc. Am. 60, 795-800 (1976).

Acoustic-phase fluctuations induced by internal waves in the ocean are calculated in the geometric approximation. The results compare favorably with available experimental data.

IWav, HF, Theory.
1.) Theory is compared with data from the Cobb experiment obtained by Ewart.

Desaubies, Y.J.F, "On the scattering of sound by internal waves in the ocean," J. Acoust. Soc. Am. 64, 1460-1469 (1978).

The parabolic approximation to the wave equation is applied to the calculation of the spectral density of amplitude and phase fluctuations of a plane sound wave propagating through a random field of internal waves in the ocean. The dependence of the predicted spectra on wave number and frequency shows that the lowest-mode internal waves dominate the phase variance, while the amplitude fluctuations are controlled by intermediate scales. The results are compared with previous theories and available data. There is a discrepancy between observed amplitude spectra and predictions based on the internal wave models. It is concluded that internal waves are not solely responsible for the scattering of sound in the ocean and that other effects must contribute.

IWav, HF, Mod.
1.) The Rytov approximation is used in the modeling.
2.) Calculations are compared to Cobb seamount data from Ewart.

DeWolf, D.A., "Are Strong Irradiance Fluctuations Log Normal or Rayleigh Distributed?," J. Opt. Soc. Am. 59 (11), 1455-1460 (1969).

Probability distributions of fluctuating irradiance data from experiments involving light propagation through turbulent air indicate log-normal behavior. Nevertheless, the dependence of the variance upon wavenumber, turbulence strength, and propagation distance is predicted reasonably well by calculations that yield a Rice distribution, but not by other calculations based on a log-normal distribution. We suggest that the discrepancy is caused by infrequent high-irradiance fluctuations, and present an approximate solution of the electric field valid only for high irradiance that extends the lower-irradiance distribution into a log-normal tail.

Stat, Atm, Opt, Theor, Prop, Strong.
1.) Irradiance cumulative probability distributions are shown for calculated Rayleigh and log-normal distributions, and for five different experimentally measured distributions.

DeWolf, D.A., "Saturation of Irradiance Fluctuations Due to a Turbulent Atmosphere," J. Opt. Soc. Am. 58 (4), 461-466 (1968).

Expressions for the variance and other probability moments of strongly fluctuating irradiance of light after propagation through turbulent atmosphere are developed from a high-frequency approximation of the solution of the scalar wave equation. These expressions imply a Rayleigh distribution of the irradiance in the limit of strong turbulence and/or long propagation paths. The theory provides a good fit to Gracheva and Gurvich's data (corrected for a processing error) and to the more dispersed recent data of Gracheva. It is argued that existing evidence for a log-normal distribution cannot reject a Rayleigh distribution whereas the assumption of log-normal distribution has implications conflicting with theory and/or experiment.

Stat, Opt, Atm, Theo, Prop, Strong.

1.) Log irradiance fluctuations for several measured data sets and several theories are shown.

DeWolf, D.A., "Strong irradiance fluctuations in turbulent air: plane waves," J. Opt. Soc. Am. 63 (2), 171-179 (1973).

Analytical results are found for irradiance statistics of a plane wave propagating through uniformly turbulent air. They result from a new error analysis of approximations made in selective summation of diagram contributions to the iterated moment equations (in integral form). The results are determined by three regimes of the parameter $k^{7/6}L^{11/6}C_n^2$ determined by its location with respect to powers of the micro- and macroscale Fresnel numbers $(\kappa_m^2 L/k)^{-1/6} \approx 0.3$ and $(kL_0^2/L) \approx 10^4$ (the numerical values are for 0.6-μm radiation and a horizontal pathlength $L \approx 1$ km). The modified-Rytov result is found in the lowest regime. Irradiance I is log-normal in the intermediate (saturation) regime and the log-amplitude variance decays asymptotically as $0.41\,(\kappa_m^{7/3}L^3C_n^2)^{-1/6}$. When $k^{7/6}L^{11/6}C_n^2$ far exceeds the macroscale Fresnel number kL_0^2/L, the irradiance tends to an exponential distribution (in agreement with previous results).

Opt, Atm, Stat, Theo, Strong, Plane.

DeWolf, D.A., "Waves in Turbulent Air: A Phenomenological Model," Proceedings of the IEEE, 62 (11) 1523-1529 (1974).

Abstract—Waves propagating through random media undergo large phase and amplitude scintillations even when the scattering at other than very small angles is insignificant. A large number of literature on the subject has been written in recent years. Nevertheless many of the more interesting effects (amplitude scintillation) are not well understood because the theory of the interaction is formulated too abstractly to give insight. The purpose of this work is to provide a phenomenological model with which we derive most of the known expressions—and some new ones—by means of back-of-the-envelope calculations. The model appears to give the needed insights.

Weak, Strong, Atm.

1.) A non-rigorous description intended to give insight without a lot of mathematics.

Di Iorio, D. and D.M. Farmer, "Path-averaged turbulent dissipation measurements using high-frequency acoustical scintillation analysis", J. Acoust. Soc. Am. 96 (2), 1056-1069 (1994).

The path-averaged turbulent kinetic energy dissipation (per unit mass) is estimated in a shallow tidal channel using acoustical scintillation analysis. The tidal current ensures that fully developed turbulence prevails. In order to make measurements of the turbulence parameters, a high-frequency (67-kHz) acoustic propagation experiment was conducted. Our acoustic data is compared to the weak scattering theory of Tatarski assuming a Kolmogorov turbulence model and compared with available oceanographic data. Analysis of log-amplitude, phase, and phase-difference spectra shows close agreement with the theory. Comparison of the acoustic data with direct measurement of temperature and salinity fluctuations using *in situ* sensors allows evaluation of the contribution of turbulent velocity fluctuations to the scintillation signal. The results show that turbulent velocity fluctuations are the dominant (~95%) component of the observed acoustic scintillation, leading to estimates of the path-averaged turbulent energy dissipation, which rises and falls with the tidal current ($\epsilon \sim 10^{-7}-10^{-5}\ m^2s^{-3}$). A confirmation of the validity of the weak scattering theory together with the Kolmogorov turbulence model in this environment is given within the context of the scattering strength–refractive index variance parameters (Γ, X).

HF, Exper, Prop.

1.) The horizontal and vertical outer scales, L_0 and L_v, are estimated from the data.

Duda, T.F., S.M. Flatte´, J.A. Colosi, B.D. Cornuelle, J.A. Hildebrand, W.S. Hodgkiss, Jr., P.F. Worcester, B.M. Howe, J.A. Mercer, and R.C. Spindel, "Measured wave-front fluctuations in 1000-km pulse propagation in the Pacific Ocean," J. Acoust. Soc. Am. 92, 939-955 (1992).

A 1000-km acoustical transmission experiment has been carried out in the North Pacific, with pulses broadcast between a moored broadband source (250-Hz center frequency) and a moored sparse vertical line of receivers. Two data records are reported: a period of 9 days at a pulse rate of one per hour, and a 21-h period on the seventh day at six per hour. Many wave-front segments were observed at each hydrophone depth, and arrival times were tracked and studied as functions of time and depth. Arrivals within the final section of the pulse are not trackable in time or space at the chosen sampling rates, however. Broadband fluctuations, which are uncorrelated over 10-min sampling and 60-m vertical spacing, are observed with about 40 $(ms)^2$ variance. The variance of all other fluctuations (denoted as low-frequency) is comparable or smaller than the broadband value; this low-frequency variance can be separated into two parts: a wave-front segment displacement (with vertical correlation length greater than 1 km) that varies substantially between rays with different ray identifiers, and a distortion (with vertical correlation length between 60 m and 1 km) of about 2 $(ms)^2$ variance. The low-frequency variance may be explained as the effect of internal waves, including internal tides. The variance of the broadband fluctuations is reduced somewhat but not eliminated if only high-intensity peaks are selected; this selection does not affect the statistics of the low-frequency fluctuations.

Exper, Mult, Stat, North Pacific, 250 Hz, IWav, Tides.

1.) Experiment, called Slice89, employed a vertical line array of receivers and a moored broadband source with a 250 Hz center frequency.

Duda, T.F., "Modeling Weak Fluctuations of Underwea Telemetry Signals," IEEE Journal of Oceanic Engineering, 16 (1), 3-11, 1991.

Abstract—Amplitude and phase fluctuations of monochromatic acoustic signals in the ocean can be predicted by calculating statistical properties of wave equation perturbation solutions. For ranges less than a few kilometers in an active mixing region, or less than 15 km in the deep ocean, weak fluctuation theory can be used to model signal fluctuations in frequency and spatial frequency. Fluctuation predictions for transmission through realistic vector wavenumber spectra of oceanic sonic refractive index fluctuations are evaluated numerically and help define the ocean regions amenable to telemetry.

Mod, HF, Prop, IWav, Fine, Micro, Sphere, Mod.

1.) Distinguishes transverse fluctuations and temporal fluctuations.

Dunphy, J.R. and J.R. Kerr, "Scintillation measurements for large integrated-path turbulence," J. Acoust. Soc. Am. 63 (8), 981-986 (1973).

Scintillation measurements are described for a very-large integrated-path turbulence. Measurements were made with simultaneous, coincident beams at 10.6 μm and 4880 Å over a 6-km uniform path. The experimental results include (i) the (log amplitude) variance at 10.6 μm showed saturation at a level comparable to that for shorter wavelengths; (ii) the variance beyond saturation at 4880 Å decreased for increasing turbulence (C_n^2), with an exponent of (−0.48) and no apparent asymptote; (iii) the covariance functions, $C_l(r)$, exhibited the emergence of two scale sizes, as manifested by a rapid initial drop vs (r), and a residual correlation out to large separations; (iv) a corresponding effect was revealed by the spectra of scintillations; (v) receiver-aperture smoothing at 4880 Å was very poor, owing to the large residual correlation sizes; and (vi) the amplitude statistics at both wavelengths approximated log-normal distributions.

Opt, Atm, Exper, Stat, Prop, Strong.

1.) Log-normal amplitude statistics are measured at large turbulence strengths, i.e., in the saturation regime, while some recent theory predicts Rayleigh amplitude statistics there.

2.) Theoretical and measured umulative probability distributions for log irradiance are shown.

Dwyer, R.F., "Use of the kurtosis statistic in the frequency domain as an aid in detecting random signals," IEEE Journal of Oceanic Engineering, OE-9, 85-92 (1984).

Abstract—Power spectral density estimation is often employed as a method for signal detection. For signals which occur randomly, a frequency domain kurtosis estimate supplements the power spectral density estimate and, in some cases, can be employed to detect their presence. This has been verified from experiments with real data of randomly occurring signals. In order to better understand the detection of randomly occurring signals, sinusoidal and narrow-band Gaussian signals are considered, which when modeled to represent a fading or multipath environment, are received as non-Gaussian in terms of a frequency domain kurtosis estimate. Several fading and multipath propagation probability density distributions of practical interest are considered, including Rayleigh and log-normal. The model is generalized to handle transient and frequency modulated signals by taking into account the probability of the signal being in a specific frequency range over the total data interval. It is shown that this model produces kurtosis values consistent with real data measurements.

The ability of the power spectral density estimate and the frequency domain kurtosis estimate to detect randomly occurring signals, generated from the model, is compared using the deflection criterion. It is shown, for the cases considered, that over a large range of conditions, the power spectral density estimate is a better statistic based on the deflection criterion. However, there is a small range of conditions over which it appears that the frequency domain kurtosis estimate has an advantage. The real data that initiated this analytical investigation are also presented.

Stat, Theo, Mult.

1.) Describes how a statistic, the frequency domain kurtosis, might be used to quantify randomly occurring signals.

Dyer, I., "Statistics of distant shipping noise," J. Acoust. Soc. Am. 53 (2), 564-570 (1973).

Distant shipping noise is modeled analytically as phase-random line components arriving from a number of independent sources. Three cases are distinguished as (a) all noise arrivals having the same intensity, (b) all having different intensity, and (c) mixtures of (a) and (b). The statistical distributions of the received noise, measured in decibels, are shown to be skewed and to be similar for all three cases, provided the number of ships is the same. Computation of the standard deviation for a location near Bermuda, based on available traffic data and for a ⅓-oct band analysis of an omnidirectional receiver, compares well with measurements by Perrone. Bandwidth and beamwidth are included implicitly in the analytical model via the number of line components, and are related through the mean frequency spacing between lines to the number of ships and their geographic locations.

Stat, Nois, Mod.

1.) Probability density of various average noise intensities caused by shipping.

Dyer, I., "Statistics of Sound Propagation in the Ocean," J. Acoust. Soc. Am. 48, 337-345 (1970).

The statistics of transmission fluctuations in the ocean are examined theoretically for both multipath and scattering processes. It is shown that, when both are present, multipath propagation dominates the fluctuations and leads to quite broad statistical distributions. In such cases, the mean and standard deviation for logarithmic measures such as transmission loss differ considerably from corresponding mean-square measures. Results for a single tone have been generalized to include multitones, as a model of ambient noise. Statistics of a signal combined with such noise have been derived; the standard deviation of the combination may be several decibels higher than the 5.6 dB of signal alone. The distributions of logarithmic quantities are generally found to be log transformations and combinations of chi-square distributions, and not log-normal distributions as commonly supposed.

Stat, Theo, Mult, Prop, Nois, RSurf.

Dyson, F., W. Munk and B. Zetler, "Interpretation of multipath scintillations Eleuthera to Bermuda in terms of internal waves and tides," J. Acoust. Soc. Am. 59 (5), 1976.

Rate-of-phase and intensity spectra due to time-varying *multipath* interference depend essentially on a single parameter ν^2 which can be interpreted as the mean-square rate-of-phase for any typical *single* path. MIMI 406-Hz phase and intensities are consistent with $\nu^{-1} = 270$ and 357 sec for Eleuthera to Bermuda and Eleuthera to midstation transmissions, respectively, compared to 192 and 286 sec from a ray-geometric calculation using an internal wave model based on oceanographic observations. Internal tides play a significant but not dominant role.

Exper, IWav, Mult, Tides,

1.) Measurements were made of propagation from Eleuthera to Bermuda.

Dyson, F., "Photon noise and atmospheric noise in active optical systems," J. Opt. Soc. Am. 65 (5), 551-558 (1975).

A general theoretical analysis is made of the performance of optical systems that are designed to give diffraction-limited images of astronomical objects by compensating effects of atmospheric seeing in real time. The heart of any such system is a feedback algorithm, which expresses the controlled displacements of mirror surfaces as functions of the output of optical sensors. The statistical behavior of the system is calculated, assuming the feedback algorithm to be linear but otherwise unrestricted. The effect of feedback in diminishing atmospheric noise while amplifying photon noise is worked out in detail, taking into account photon-photon correlations. A figure of merit for system performance, namely a statistical average of a positive quadratic function of phase errors over mirror surfaces, is arbitrarily chosen. By use of this figure of merit, the optimum feedback algorithm for any given optical system is explicitly determined. The optimum algorithm is independent of the quadratic function of phase errors that is chosen as the figure of merit. Applications of the general theory to particular optical systems are briefly discussed. In principle, systems optimized in this way should be able to give images of arbitrarily high resolution of astronomical objects brighter than about magnitude 14.

Theo, Opt, Atm, Nois,

Eckart, C., "The Scattering of Sound from the Sea Surface," J. Acoust. Soc. Am. 25 (3), 566-570 (1953).

It is assumed that the equation of the sea surface is $z = \zeta(xyt)$, and that the time average $\Phi = \langle \zeta(x'y't)\zeta(x''y''t)\rangle$ is a function only of $\xi = x''-x'$, $\eta = y''-y'$. The scattering coefficient of long-wave sound is calculated and shown to be

$$\sigma = (c^2k^2/4\pi)^2 \int\int \Phi(\xi\eta) \exp[-ik(a\xi+b\eta)]d\xi d\eta,$$

where $2\pi/k$ is the wavelength of the sound, and a, b, c are, respectively, the sum of the x, y, z direction cosines of the incident and scattered rays. For short-wave sound, the formula is more complicated, but independent of the wavelength of the sound, as it should be. However, it is shown that experiments with short waves yield much less information about the sea surface than do those with long waves. This is unfortunate, since the latter experiments are much more difficult than the former.

Theo, GWav,

1.) Concludes that " short-wave radiation will give much less information about the sea surface than long-wave radiation". This is analogous to the x-ray study of the rms thermal displacement of molecules in crystals.

Ewart, T.E., "A model of the intensity probability distribution for wave propagation in random media," J. Acoust. Soc. Am. 86 (4), 1490-1498 (1989).

Ewart and Percival [J. Acoust. Soc. Am. 80, 1745 (1986)] have shown that the generalized gamma distribution effectively models intensity probability distributions of temporal fluctuations observed in a field experiment and transverse spatial fluctuations simulated in numerical experiments. In both cases the fluctuations are due to wave propagation through a medium with a random index of refraction. Here, the transverse spatial intensity fluctuations of a wave propagating through a medium with a power-law autocorrelation function of wave speed are modeled over a regime that spans 10^8 in scattering strength and 10^6 in scaled range (range divided by the Fresnel length). This scattering parameter regime transforms to ranges between 100 m and 100 km and to frequencies between 100 Hz and 100 kHz when normalizations typical of observed ocean internal wave fluctuations are used. Contour plots of the variance, skewness, and kurtosis of the intensity distribution are presented for the range/frequency plane. It is shown that the region of saturation, i.e., exponential intensity distribution, cannot be attained except for very large source strengths. Also, the lognormal intensity distribution, which is assumed for scintillation indices near zero, can be applied only in the region of vanishingly small intensity fluctuations. This work, while based on plane-wave propagation and a fourth-order power-law transverse spectrum of the medium, retains the essential character of the intensity fluctuations and provides a prescription for modeling the intensity distribution for any medium where the random index of refraction process can be assumed stationary.

Mod, Stat, Prop, IWav, HF.

1.) The intensity probability density function, pdf, is modeled for a medium with a particular transverse correlation function. The medium is represented as a series of phase screens, a la Uscinski, J. Opt. Soc. Am. 2(12), 2077 (1985). Model results are compared with data (MATE, AATE, AFAR, San Diego) and with theory (Spival & Uscinski, J. Mod. Opt. 35(11), 1741 (1988)).

Ewart, T.E., "A numerical simulation of the effects of oceanic finestructure on acoustic transmission," J. Acoust. Soc. Am. 67, 496-503 (1980).

A simple numerical simulation model is presented which includes the effects of oceanic finestructure together with previously developed theoretical treatments of the effects of internal waves on acoustic transmission. The wave equation solution to particular layer geometries developed by Brekhovskikh [*Waves in Layered Media* (Academic, New York, 1960)] is combined with the theoretical model of acoustic scattering based on internal waves developed by Desaubies [J. Acoust. Soc. Am. 64, 1460–1469 (1978)]. In this treatment it is assumed that a single finestructure layer is passively advected by internal waves. The layer modulates the effects of internal waves. Experiments carried out at Cobb Seamount over a fixed, horizontal, wholly refracted path indicate that the power spectrum of the phase fluctuations is fit almost exactly by models based on internal waves only, while the power spectrum of the log amplitude fluctuations is not. In the present treatment the predictions of the phase fluctuations remain unaffected by the presence of finestructure, and the predicted power spectrum of the log amplitude is in considerably better agreement with observation.

Mod, IWave, Fine.

1.) A internal wave field specified by the Desaubies model, Desaubies, J. Acous. Soc. Am. 64, 1460-1469 (1978), is used and finestructure is included to better match the power spectrum of log-amplitude as a function of fluctuation frequency (cf. Figures 4 and16) than does the Desaubies internal wave field alone.

Ehrenberg, J.E., T.E. Ewart and R.D. Morris, "Signal-processing techniques for resolving individual pulses in multipath signal," J. Acoust. Soc. Am. 63 (6), 1861-1865 (1978).

A maximum-likelihood procedure for estimating the amplitudes and arrival times of individual pulses in a multipath signal is derived. Computer simulation results are presented that compare this procedure with the more traditional matched-filter and inverse-filter techniques. The maximum-likelihood technique is shown to be significantly more accurate than either the matched or inverse filter. A computer algorithm for implementing the maximum-likelihood estimation procedure is described.

Mult, Mod.
1.) Presents techniques used in the analysis of the Cobb seamount acoustic fluctuations data.

Ewart, T.E., "Acoustic fluctuations in the open ocean --A measurement using a fixed refracted path," J. Acoust. Soc. Am. 60, 46-59 (1976).

Amplitude and phase (transit time) fluctuations in pulses sent between a fixed transmitter and a fixed receiver over a wholly refracted 17.2-km path were recorded for 144.5 h. The sites were the southwest flank of Cobb Seamount and a lesser peak 17.2 km away, both at 1000 m depth. Eight-cycle pulses at 4166 Hz and 16-cycle pulses at 8333 Hz were sent alternately every 15.7 sec and received at three receivers located at 0, 5, and 15 m along a horizontal arm located perpendicular to the transmission path. Power spectra have been computed from the time series of phase and amplitude at a single receiver and the phase difference between two receivers. Extreme care was used in the analysis of the data to ensure that the time series obtained represented a single path. The power spectra of the phase data exhibit dominant tidal peaks at 24, 12.4, and 6.2 h; the power spectra of the amplitudes show less evidence of the tides. Between the inertial frequency and the Väisälä frequency, the power spectra of the phase, amplitude and phase difference fall off at approximately ω^{-3}, ω^{-1}, and $\omega^{-1/2}$, respectively. The power spectra of the phase differences for the 15-, 10-, and 5-m spacings scale according to a plane wave arrival. The phase-difference variance is below theoretical predictions, and the amplitude variance is above theoretical predictions. The high-amplitude variance is tentatively identified as "micro" multipath interference. Evidence is presented to show that the oceanographic regime of the Cobb Seamount area is typical of the open ocean environment.

Exper, HF, Prop, Stats, Tides.
1.) Phase spectra, amplitude spectra and phase difference spectra are presented.
2.) From the Cobb experiment: environmental data was good, some temperature data is shown.

Ewart, T.E., C. Macaskill, and B.J. Uscinski, "Intensity fluctuations. Part II: Comparison with the Cobb Experiment," J. Acoust. Soc. Am. 74, 1484-1499 (1983).

The intensity fluctuations measured at 4 and 8 kHz in the Cobb Experiment have been available for nearly 10 years and in that time have not successfully been predicted theoretically. We show that multiple scatter effects must be considered, and that neither the Born nor the Rytov approximation to the scattering formulation is appropriate. A companion paper [J. Acoust. Soc. Am. 74, 1474–1483 (1983)] provides the theoretical background for this work by presenting a general form of the analytical solution to the fourth-moment equation in two dimensions for a point source transmission. We use the parameters of the Garrett–Munk model of the internal wave field appropriate to the Cobb Experiment oceanographic regime to obtain the correlation functions of the acoustic refractive index field, and then predict the intensity fluctuations. We discuss corrections to the predicted spectrum that are due to finestructure effects and tidal motions. We include a discussion of the scattering parameters Γ and X, which are the scattering and range scaling parameters of the moment equation formulation, and the parameters of the path integral formulation, Γ and Φ. We present a discussion of the measured correlation functions taken during a more recent experiment at Cobb Seamount and indicate the directions we need to take to bring the scattering predictions based on internal waves and finestructure into closer agreement with experiment.

Mod, Stat, Mult, IWav, Fine, Tides, HF.

Ewart, T.E. and D.B. Percival, "Forward scattered waves in random media--The probability distribution of intensity," J. Acoust. Soc. Am. 80. 1745-1753 (1986).

An acoustic wave propagating in a medium with an index of refraction that is random in space and time acquires intensity modulations that can be modeled in terms of a space–time autocorrelation function, a scattering strength parameter γ, and a scaled range X. Over a wide range of γ, X, and medium autocorrelation functions, the probability distributions of intensity vary from lognormal at small X to exponential at large X. The generalized gamma distribution [E. W. Stacy, Ann. Math. Stat. 33, 1187–1192 (1962)] is characterized by three parameters, and reduces to many well-known distributions. It varies smoothly from lognormal to exponential as the parameters change. It is proposed that this distribution is a general analytic form that represents the probability distribution of intensity as a function of range, depth, and time in forward scattering. This proposition is tested with the measured temporal intensity fluctuations from the Mid-Ocean Acoustic Transmission Experiment, MATE. It is also tested with depth-range results from Monte Carlo simulations of wave propagation in a random medium with a power law autocorrelation function. The fitted generalized gamma distributions for the data sets chosen lie within the 95% Kolmogorov confidence bands for the true unknown probability distributions. In past treatments of this subject, the intensity moments have been used almost exclusively in modeling the probability distributions. The benefits of using distribution modeling rather than moment methods are described. Also discussed are the anomalies encountered for a medium with Gaussian autocorrelation.

Stat, Theory, Prop.

1.) A generalized γ distribution of intensity (Stacy, Ann. Math. Stat. 33 1187-1192 (1962)) having the lognormal, exponential and chi-square distributions among its special cases, is generated from MATE data and from Monte Carlo simulated data by a maximum likelihood solution for the three parameters defining the generalized γ distribution.
2.) It is suggested that the intensity probability distributions be modeled rather than the intensity moments.

Ewart, T.E. and S.A. Reynolds, "Experimental ocean acoustic field moments versus predictions," in J. Potter and A. Warn-Varnas (eds.), Ocean Variability and Acoustic Propagation, pp. 23-40, Klewer, Netherlands, 1991.

ABSTRACT. Results for various moments of a propagating ocean acoustic complex wavefield will be presented from field and numerical experiments. They will be compared with theoretical predictions. It will be shown that the ocean environment must be well understood to achieve substantive agreement between theory and measurement. The comparisons will include complex field correlations, intensity correlations, phase correlations and intensity probability distributions. An attempt will be made to summarize the significance of these results within our current understanding, and to identify areas of research that will extend our understanding of volume scattering.

Exper, Mod, Stat, HF, Prop.
1.) Deals with Fermat paths where definitions of phase and amplitude are unambiguous.
2.) Two point statistics are not adequate to describe intensity fluctuations because the process is not Gaussian.

Ewart, T.E. and S.A. Reynolds, "The Mid-Ocean Acoustic Transmission Experiment, MATE," J. Acoust. Soc. Am. 75 (3), 785-802, 1984.

An experiment to measure phase (travel time) and intensity fluctuations in sound pulses transmitted at 2, 4, 8, and 13 kHz over an 18.1 km wholly refracted Fermat path is discussed. Simultaneously with the acoustic monitoring the index of refraction fluctuations were measured in space and time with sufficient resolution to determine the correlation function of the medium. The site was the Cobb Seamount in the northeast Pacific (46°46′N, 130°47′ W), and the time period was 30 days in June–July, 1977. In terms of both the quality and quantity of acoustic and oceanographic measurements, this experiment represents a significant improvement over an earlier experiment in the same location [J. Acoust. Soc. Am. 60, 46–59 (1976)]. The acoustic measurements cover a wider range of acoustic frequencies and more closely represent measurements from a single Fermat path. Approximately 25% of the acoustic data are discussed here; the representations of the correlation function of the index of refraction are based on all of the oceanographic data. The physical processes responsible for the fluctuations in the index of refraction are those due to the tides, internal waves, and finestructure. The effects of internal waves are treated in detail. The moments of the observed intensity fluctuations are discussed, as are the spectral distributions of the second moments of phase and intensity. The observations are compared with theoretical predictions based on the Rytov approximation and on a multiple scatter formulation (approximate solution to the fourth moment equation).

Exper, Iwave, HF, Mod, Stat, Mult.
1.) A single, wholly refracted Fermat path between source and receiver was isolated and fluctuations in intensity and travel time (phase) over this path were measured. A transverse autocorrelation function was calculated based on internal wave models alone. Use of the Rytov approximation, including advected finestructure was used to model phase and intensity model phase and intensity distributions. Use of multiple scattering with an arbitrary autocorrelation function was also used to model the phase and intensity distributions. The Rytov approximation model achieved much better results.

Fante, R.L., "Irradiance scintillations: Comparison of theory with experiment," J. Acoust. Soc. Am. 65 (5) 548-550 (1975).

A new theory is used to calculate the covariance of irradiance scintillations of an optical wave in a turbulent medium. These agree well with recent experimental data.

Theo.

Fante, R.L., "Some physical insights into beam propagation in strong turbulence," Radio Science 15 (4), 757-762 (1980).

In this paper we examine some of the physical implications of using the extended Huygens-Fresnel principle to calculate laser beam properties in strong turbulence. We shall demonstrate the roles played by the log-amplitude and phase fluctuations and will show that quadratic phase structure functions lead to results incompatible with experimental data. We shall also prove that the Huygens-Fresnel principle automatically predicts a normalized irradiance variance of unity and Gaussian field statistics in strong turbulence provided that certain conditions on the turbulence strength and spectrum are satisfied.

Opt, Theo, Strong.

Fante, R.L., "Two-position, two-frequency mutual-coherence function in turbulence," J. Opt. Soc. Am. 71 (12), 1446-1451 (1981).

By using the extended Huygens–Fresnel principle, an expression has been obtained for the generalized two-position, two-frequency mutual-coherence function of an electromagnetic beam in a turbulent medium. That result has been examined for different states of source coherence and for different turbulence conditions.

Opt, Theo.

1.) The mutual coherence function obtained gives a complete description of the second moment of the field, according to the author.

Farmer, D.M. and S.F. Clifford, "Space-Time Acoustic Scintillation Analysis: A New Technique for Probing Ocean Flows." IEEE Journal of Oceanic Engineering, OE-11 (1), 42-50 (1986).

Abstract—We present a new approach to the measurement of ocean flows. The technique exploits the coherence of the fine structure in the ocean under the influence of advection. Sound passing through this fine structure is modulated in space and time, so that the evolution and motion of the resulting pattern at a distant receiving plane contains information about the intervening flow field. The details of the fine-scale structure itself may also be recovered, to an extent determined by the complexity of the transmitter and receiver array. Two special cases of oceanographic interest are considered. First, a fully developed turbulent flow, such as that encountered in tidal channels, for which the scale of fine structure contributing to the scintillation field lies within the inertial subrange, and second, the internal wave field more generally applicable to the open ocean. We describe an experimental test of the concept. Sound traveling across a 0.66-km path in Cordova Channel, British Columbia, Canada, is detected by two closely spaced receivers. The flow speed is derived using three separate estimators and the results compared with current measurements obtained from a moored current meter. Agreement between the two types of measurement is excellent.

Appl, Theo, Exper, HF.

1.) The experiment was carried out in the Cordova Channel, B.C. at 86 kHz.

Farmer, D.M., S.F. Clifford and J.A. Verral, "Scintillation Structure of a Turbulent Tidal Flow," J. Geophys. Res. 92 (C5) 5369-5382 (1987).

We describe observations of fine structure in a turbulent tidal channel on the British Columbia coast obtained with towed and vertical conductivity, temperature, and depth profiles and a novel acoustic technique. The acoustic scheme involves the detection of the scattering of sound waves by fine structure moving through a pair of acoustic paths that traverse the channel. The larger scale flow and also the fine structure can be observed in this way, providing a time series measurement of the flow properties as the tidal current changes. The channel is characterized by periods of intense mixing through most of the tidal cycle. Near slack water it becomes stratified, and although it remains active, the outer scale of the turbulence decreases to 2-3 m. The fine-scale variability is a sensitive function of flow speed and stratification.

Exper, HF, Appl.

1.) The refractive index structure parameter, C_n^2, a measure of turbulence strength, is calculated from a measured acoustic log amplitude variance and the wave structure function of the received acoustic field.

Farmer, D.M. and G.B. Crawford, "Remote sensing of ocean flows by spatial filtering of acoustic scintillations: Observations," J. Acoust. Soc. Am. 90 (3), 1582-1591 (1991).

The concept of spatial aperture filtering is tested with a linear array of four sources and four hydrophones on opposite sides of a tidal channel. The system is used to develop time series of the spatially filtered signal at different locations in the channel, from which flow speed may be derived. Results are in reasonable accord with independent current measurements, and reproduce the observed time-dependent horizontal shear of the flow. A concept of synthetic spatial aperture filtering is introduced whereby additional transmitter-receiver paths are synthesized through appropriate time delays so as to derive new information on the flow field.

Exper, Appl, HF, Shallow.

1.) Measured current speed in a shallow water (<30m) ocean channel using four acoustic projectors and four hydrophone receivers.

Farmer, D.M. and S. Vagle, "Waveguide propagation of ambient sound in the ocean-surface bubble layer," J. Acoust. Soc. Am. 86, 1897-1908 (1989).

Measurements of the ambient sound generated by breaking waves over the range 40–20 000 Hz reveal well-defined spectral peaks, the frequency of which may remain generally consistent from one breaking event to the next, but which can change significantly over the course of a storm, or from one storm to another. A theory is proposed, based on the concept of trapping of a portion of the sound in the waveguide formed by the ocean-surface bubble layer. Simultaneous measurements of the bubble population and size distribution as a function of depth and time were obtained with a multifrequency inverted echo sounder, allowing calculation of the resulting (dispersive) sound-speed anomaly profile. Theoretical predictions of the spectral peaks, which are associated with modal cutoff frequencies, are in good agreement with the observations. It is suggested that this result might have application to the remote determination of ocean-surface bubble fields relevant to the study of wave breaking, turbulence, and the air–sea gas flux.

Nois, HF.

Ferguson, B.G. and D.V. Wyllie, "Comparison of observed and theoretical responses of a horizontal line array to wind-induced noise in the deep ocean," J. Acoust. Soc. Am. 82, 601-605 (1987).

Various noise models consisting of distributions of surface or volume sources with different directional properties have been proposed to describe the ambient noise in the ocean. The theoretical response of a conventional beamformer steered towards broadside, and then towards endfire, is calculated for a number of these mathematical models. The predicted response for each model is then compared with the observed response for data recorded under conditions in which the ambient noise consisted only of noise generated by the action of wind and waves at the ocean surface. Good agreement between theory and experiment is obtained by using the surface model of Cron and Sherman [J. Acoust. Soc. Am. 34, 1732–1736 (1962)] with the directionality index m set to unity. This provides strong support for modeling wind-induced noise as a uniform distribution of independent vertical dipole sources extending over the surface of the ocean, with each source having an amplitude directionality function given by $\cos \alpha$, where α is the angle measured from the downward-pointing vertical axis. The surface model of Cox [J. Acoust. Soc. Am. 54, 1289–1301 (1973)] is also found to provide good agreement with the experimental results, but other models—two- and three-dimensional isotropic noise models, Cron and Sherman's model with increased directionality ($m = 2,3$), and Cox's traffic noise model—are shown to be inappropriate in reproducing the observed response.

Exper, Nois, Wind, Mod.

1.) The experiment was conducted at 340 Hz in the Tasman Sea.

Flatte´, S.M., R. Leung and S.Y., Lee, "Frequency spectra of acoustic fluctuations caused by oceanic internal waves and other finestructure," J. Acoust. Soc. Am. 68 (6), 1773-1779 (1980).

The frequency spectrum of log-amplitude fluctuations is substantially modified (flattened) by a previously neglected effect: the vertical advection of short internal waves by the more energetic internal waves with large vertical wavelength. The log-amplitude spectrum is sensitive to this vertical advection and to curvature of the equilibrium sound ray, whereas the phase spectrum is not. Noninternal-wave "frozen" finestructure contributes to the log-amplitude frequency spectrum through vertical advection, but not to the phase spectrum. The Cobb Seamount experiment is treated as an example; the spectrum of the modified theory agrees well with observations except at high frequency (near the buoyancy frequency).

IWav, Fine.

1.) Discusses the Cobb seamount experiment and points out an error in Ewart, J. Acoust. Soc. Am. 67, 496-503 (1980).

Flatte´, S.M., S.A. Reynolds, and R. Dashen, "Path-integral treatment of intensity behavior for rays in a sound channel," J. Acoust. Soc. Am. 82, 967-972 (1987).

The intensity coherence function (ICF) of the acoustic wavefunction from a point source is derived by the path-integral technique for transmission through internal waves in the presence of a sound channel. Separations in time are emphasized, although separations in transverse horizontal position, vertical position, and acoustic frequency are discussed. Approximate intensity coherence times, lengths, and bandwidths due to internal-wave fluctuations are derived. Analytic approximations suitable for computer coding are presented for the micropath focusing parameter γ, which controls the deviation of higher intensity moments from the Rayleigh-distribution values.

Theo.

Flatte´, S.M., S.A. Reynolds, R. Dashen, B. Buehler and P. Maciejewski, " AFAR measurements of intensity and intensity moments," J. Acoust. Soc. Am. 82, 973-980 (1987).

In an acoustic-oceanographic experiment (AFAR) performed near the Azores in 1975, frequencies from 400–4670 Hz were transmitted over a 35-km wholly refracted path. In addition, a separate data set was gathered over a 3-km path in 1973. Measurements of the intensity coherence function of time and frequency, intensity moments, and the probability distribution of intensity are presented and compared with predictions of fluctuations due to internal waves.

Exper, IWav.

Fortuin, L., "Survey of literature on reflection and scattering of sound waves at the sea surface," J. Acoust. Soc. Am. 47 (5), 1209-1228 (1970).

The problem of diffraction of waves at uneven surfaces has received increasing attention in the past 15–20 years. This has resulted in a large number of reports and papers in the open literature. In this review article most of the publications dealing with sound waves and pressure release surfaces (both theoretical and experimental) that appeared up to the beginning of 1969 are mentioned as references. They are classified by subject, and the main currents in the literature (Rayleigh and Uretsky method for sinusoidal boundaries, Eckart theory with Kirchhoff approximation for random surfaces, experiments at sea) are analyzed and discussed. General trends, relations between studies, agreements, and contradictions are mentioned. It is found that nearly all of the publications cover only part of the problem: although the wave diffraction at rough surfaces is a function of three basic quantities simultaneously (i.e. time, frequency of incident wave, and geometry), most of the papers deal with only one or another of these three variables. Possible directions of future research are indicated.

GWav, RSurf.
1.) Section V-A contains a discussion of phase and amplitude fluctuations.

Fried, D.L., "Propagation of a spherical wave in a turbulent medium," J. Opt. Soc. Am. 57 (2), 175-180 (1967).

The log-amplitude covariance and the phase-structure function, associated with the statistics of propagation of a spherical wave in a turbulent medium, are derived for a propagation path over which the statistics of turbulence are constant. Analytic and graphical representation of the results are presented. The theoretical prediction of the zero crossing of the log-amplitude covariance for a spherical wave is found to be in much better agreement with Tatarski's experimental results than were the results of the infinite-plane wave analysis—as might have been expected, in retrospect, from consideration of the details of Tatarski's experiment.

Theo, Prop.

Goland, V.I., "Influence of the model of a random medium on the interference structure of a sound field in an acoustic waveguide," Sov. Phys. Acoust. 37 (1), 33-37 (1991).

The Sturm–Liouville problem is solved by numerical simulation and analytically by perturbation methods for an underwater sound channel with a random sound velocity profile. It is shown that allowance for the finite correlation radius of the refractive index is of fundamental importance for high-order normal modes. In particular, the intermodal correlation coefficient tends to unity as the correlation radius or the mode order increases. Moreover, the deviation of the regular sound velocity profile from a constant imparts a turning point to the lowest modes and creates a group of modes whose interference periods are smaller than the unperturbed periods on the average. This difference can become of the order of 1 km at a frequency of 100 kHz and increases as the frequency increases. the mode orders in this group are determined by the depth dependence of the sound velocity fluctuation intensity.

Theo.

Goodman, R.R., "Propagation in Fluctuating Media," New Directions in Physical Acoustics, Proceedings of the International School of Physics "Enrico Fermi", Course LXIII, edited by D. Sette, 337-368 (1976).

Theo, Gwav, IWav, Prop.
1.) Equations are derived for a fluctuating ocean and for acoustic propagation in that ocean.

Haugstad, B.S., "Turbulence in planetary occultations: A strong scattering formulation including an inhomogeneous background," Radio Science 17 (3), 565-573 (1982).

> We show, from a Huygens-Fresnel integral formulation of the scattered electromagnetic field, that the wave equation for a thin turbulent medium with nonconstant mean characteristics can be reformulated as a problem involving turbulence on a constant background. This is accomplished by a set of simultaneous transformations, which, when reversed and applied to known solutions of the simpler problem involving a constant background, yield results that correctly account for the inhomogeneous ambient atmosphere upon which the turbulence is superimposed. When applied to the mutual coherence function it is found that this quantity is unaltered if the separation of the two field points in the plane of the receiver is replaced by the corresponding separation obtained by projecting these points along the average refracted rays back to the ray periapsis. For the associated spectral broadening function this implies that spectra corresponding to different occultation depths and geometries may be obtained by simple translation of a shape-invariant spectrum along the frequency axis. We also find that the scintillation index approaches asymptotically unity in strong scattering in precisely the same way as if the ambient background were strictly homogeneous, consistent with recent numerical simulations of a one-dimensional scattering model.

Opt, Theo, Atm, Prop, Strong.

Hewish, A., "Quasi-periodic scintillation patterns," in Wave Propagation and Scattering, B.J. Uscinski, ed., (Clarendon, Oxford, 1986), 203-213.

> The dynamic spectra of naturally occurring scintillation patterns sometimes display significant quasi-periodic variations. The nature of this phenomenon is discussed and it is shown how these patterns may be used to investigate the power spectrum of the irregularities in the random medium which causes scintillation. Application of the method to pulsar scintillation indicates that Kolmogorov turbulence is often a poor representation of the interstellar plasma.

Stat.
1.) The widely accepted ensemble averaging method is called into question here.

Hill, R.J., "Theory of saturation of optical scintillation by strong turbulence: plane-wave variance and covariance and spherical-wave covariance," J. Opt. Soc. Am. 72 (2), 212-222 (1982).

The heuristic theory of covariance of log amplitude for saturation of scintillation, which was originally developed for spherical waves, is extended to the plane-wave case. Comparison of calculated log-amplitude variance of plane waves with observation is good, but measurements of this specific quantity are scarce. For strong refractive turbulence, the log-amplitude variance tends to increase as the inner scale of turbulence increases relative to the Fresnel-zone size; for spherical waves this behavior is in quantitative agreement with data. In strong turbulence the path-weighting functions of the log-amplitude variance tend to be uniform with localized peaks near the transmitter and receiver for spherical waves but only one localized peak near the receiver for plane waves. The dependence of the log-amplitude covariance on a minimum number of nondimensional parameters is found (similarity relationships), and this set of parameters is shown to be nonunique. The specialization of this parameter set to the case of strong refractive turbulence reveals important differences between cases in which the coherence length ρ_0 is larger as opposed to smaller than the inner scale l_0. In strong refractive turbulence the covariance function has three distinct ranges: at sufficiently large separations it has the same form as in the weak refractive-turbulence limit, at intermediate separations it is nearly independent of the separation, and at small separations r it rises sharply. For $\rho_0 \gg l_0$, the conventional strong-turbulence result of covariance depending only on r/ρ_0 is obtained, but for $\rho_0 \ll l_0$ the covariance depends on both r/ρ_0 and ρ_0/l_0. The lack of scaling of measured intensity covariance with r/ρ_0 corresponds to the case $\rho_0 \ll l_0$. There is no reason to prefer the transverse scale $(k^3C_n{}^2)^{-3/11}$ to ρ_0 for $\rho_0 \gg l_0$, and there is no reason for using this transverse scale for $\rho_0 \ll l_0$ because of the strong inner-scale effect on the covariance.

Stat, Theo, Opt, Atm, Strong.
1.) The inner scale of the turbulence, l_0, is discussed.

Hillion, P., and S. Quinnez, "Plane wave diffraction for light in a weakly turbulent medium," J. Optics (Paris) 13 (1), 41-48 (1982).

SUMMARY: This paper brings a complement to a previous work [1] on a new diffraction theory. For the propagation of a light beam in a weakly turbulent medium we prove that provided the diffracted intensity has a log-normal distribution, this theory gives for the variance $\sigma^2_{Log\,I}$ the same expression as Tatarskii's [3].

Opt, Stat, Theo.
1.) Assumes a gaussian random field with a lognormally distributed diffracted intensity.

Horton, C.W., "A review of reverberation, scattering, and echo structure," J. Acoust. Soc. Am. 51, 1049-1061 (1971).

The last 20 years have seen a tremendous amount of work in the area of reverberation and scattering. An effort is made to summarize with graphs and charts the amount and nature of this work. Comparisons are made between the results of measurements at sea, measurements with models, and theoretical calculations. Since theoretical solutions of scattering from randomly rough surfaces involve numerous approximations, these different solutions are classified with the aid of tree diagrams so that one can chart a path through the various approximations. Most of the unclassified work on echo structure has been devoted to intensive analyses for targets of relatively simple geometric shape. For example, the sphere and the cylinder (with and without internal structure) still present interesting problems.

HF, RSurf.
1.) Concerns Scattering/Echoes/Reverberation from rough surfaces and Scattering/Echoes from submerged cylinders and spheres.

Hughes, S.J., D.D. Ellis, D.M.F. Chapman, and P.R. Stall, "Low-Frequency acoustic propagation loss in shallow w.ater over hard-rock seabeds covered by a thin layer of elastic-solid sediment," J. Acoust. Soc. Am. 88, 283-297 (1990).

Shallow-water seabeds are often varied and complex, and are known to have a strong effect on acoustic propagation. Some of these seabeds can be modeled successfully as fluid or solid half-spaces. However, unexpectedly high propagation loss with respect to these models has been measured in several regions with rough, partially exposed, hard-rock seabeds. It is shown that the high propagation loss in these areas can be modeled successfully by introducing a thin layer of elastic–solid sediment over the hard-rock substrate. Propagation loss predictions using the SAFARI fast-field program exhibit bands of high loss at regularly spaced frequencies. Normal-mode calculations show resonance phenomena, with large peaks in the modal attenuation coefficients at these same frequencies, and with rapid changes in the mode wavenumbers. Bottom reflection loss calculations indicate that the high propagation loss is due to absorption of shear waves in the sediment layer.

Shall.

Ishimaru, A., "Difference between Ishimaru's and Furutsu's theories on pulse propagation in discrete random media," J. Opt. Soc. Am. A 1 (5), 506-509 (1984).

There are significant differences between Ishimaru's theory [J. Opt. Soc. Am. 68, 1045 (1978)] and Furutsu's theory [J. Opt. Soc. Am. 70, 360 (1980)] on pulse propagation in discrete random media, although both deal with the same physical problem. In this paper we attempt to clarify the confusion created by the two theories. A simple numerical example is shown to illustrate the difference and the range of validity of the theory. It is shown that if a delta-function pulse is initiated at $r = 0$ and $t = 0$ in a discrete random medium, Furutsu's diffusion theory predicts that the pulse diffuses instantly and arrives at all points with infinite speed for $t > 0$; therefore its range of validity is limited to the time interval $t \gg L/C$, where L is the propagation distance and C is the velocity of light. Ishimaru's theory gives a delta-function pulse propagating out at a finite velocity of $c/\sqrt{3}$ followed by a diffusing tail. Therefore Ishimaru's is not a usual diffusion theory, but it includes both propagation and diffusion, and its range of validity is different from that of the pure diffusion theory. The limitations of both theories are also discussed.

Theo, Prop, Opt, Atm.
1.) Techniques presented in two papers on pulse propagation in discrete scatterers, Furutso (1980) and Ishimaru (1978) are compared.

Ishimaru, A., "Theory of optical propagation in the atmosphere," Optical Engineering 20 (1), 063-070 (1981).

Abstract. For the past few decades, numerous investigations have been reported on optical propagation in the turbulent atmosphere. In recent years, however, the theoretical study of optical propagation in fog, clouds, and other particulate matter has attracted considerable attention. Though much progress has been reported in the theoretical study of these phenomena, there are several areas where the theory is still not conclusive and further investigations are needed. This paper presents a review of the present state-of-the-art in the theory of optical propagation in the atmosphere and some discussions on the future directions of investigations in this area. Both cw and pulse propagations are considered and the quantitative discussions are given on angular broadening, pulse broadening, and coherence bandwidth of the optical wave in the turbulence and the particulate matter. It is noted that the forward scatter approximations are valid for the turbulence case, but for the case of particulate matter, it is convenient to consider three regions: first-order scattering, forward scatter, and diffusion; and it is important to take into account the effects of transmitter and receiver characteristics.

Theo, Prop, Opt, Atm.

Ishimaru, A., Wave Propagation and Scattering in Random Media, Volumes I and II (Academic Press, New York, 1978).

Theo, Prop, RSurf, Plane, Sphere, Strong, Weak, IWave, Fine, Micro.

Ishimaru, A., " Wave Propagation and Scattering in Random Media and Rough Surfaces," Proceedings of the IEEE 79 (10), 1359-1366 (1991).

Many natural and man-made media such as the atmosphere, oceans, geophysical media, biological media, and composite and powdered materials have random spatial inhomogeneities and vary randomly in time, and these media are called "random media." Microwaves, optical waves, and acoustic waves propagating in these media experience random fluctuations in space and time, and these fluctuations affect a broad range of practical problems such as communications, remote-sensing, imaging, and object identification. In addition, waves in random media present some of the most challenging problems to theoreticians. This paper reviews the historical development, basic theories, and some recent new developments and discoveries, including backscattering enhancement.

Theo, Prop, Mult, RSurf.

Keller, J.B., "A survey of the theory of wave propagation in continuous random media," Proceedings of the Symposium on Turbulence of Fluids and Plasmas, MRI Symposium Proceedings, XVIII (Brooklyn, N.Y.: Polytechnic Press of the Polytechnic Institute of Brooklyn, 1968).

Problems of wave propagation in continuous random media can be formulated in terms of partial differential equations with random coefficients. The statistical properties of the solutions can be obtained by perturbation methods, in which it is assumed that the random portions of the coefficients are small corrections to the non-random parts. These perturbation methods usually lead to secular terms which limit their validity to very short propagation paths. Methods of modifying the perturbation theories to eliminate these secular terms have been developed and will be described. Some of these methods are systematic ("honest") and others are unsystematic ("dishonest"). Examples of these methods will be presented and their results will be described. Then an equation for the second moment or correlation function of the solution will be given. Finally the results will be used to derive a theory of turbulence.

Theo.
1.) The Born approximation is used.

Kennedy, R.M., "Phase and Amplitude Fluctuations in Propagating through a Layered Ocean," J. Acoust. Soc. Am. 86, 737-745 (1969).

A propagation experiment was conducted over a 25-mile wholly refracted (RRR) path for 48 h in October 1967. The data recorded during the experiment consisted of both the arrival time and the amplitude of acoustic pulses at 11 vertically spaced hydrophones. The source and the receivers were fixed, and the medium was sampled every tenth of an hour with a 10-msec pulse at 800 Hz. The propagation path between source and receiver was purely refractive and amounted to a complete cycle of RRR type of propagation. The means, variances, autocorrelation, autospectral density, cross correlation, and coherence function were estimated for both the amplitude and phase data. The probability distribution function for both amplitude and phase is demonstrated to be nearly Gaussian. An interrelationship between the time and space characteristics of the random inhomogeneities of the medium is illustrated. Wherever possible, the measured results are compared with the theoretical values of Chernov (1960). A comparison of the theory, which is based on a statistically homogeneous medium, with the measured values, obtained in a layered medium, is discussed.

Exper, Prop, Stat.

Kennedy, R.M. and T.K. Szlyk, "A multipath calculation of surface-generated underwater acoustic ambient vertical directivity," J. Acoust. Soc. Am. 86, 1920-1927 (1989).

A general calculation of the spatial correlation function due to a distributed acoustic source near the water surface has been done by others using normal-mode theory. In this article, a multiple-ray-path analysis is used to calculate the acoustic ambient vertical directivity function. Multipath propagation and ambient directional functions are physically intuitive concepts in underwater acoustic theory, and direct application of these notions has advantages in the interpretation of data. Existing procedures and computer codes are used to expand the received pressure field, from a distributed source, into a sum of terms interpreted as multiple propagation paths. Standard forms for the source function and a geometric transformation are used to convert the pressure field to a solid-angle density function. Surface roughness, bottom geoacoustic parameters, and sound velocity-depth profiles measured in the Tongue of the Ocean in the Bahamas are used in the calculations to predict hydrophone array performance in that area. Directivity function versus elevation angle and frequency are displayed for observers above and below a seasonal thermocline. A path-by-path contribution to the vertical distribution of energy is discussed.

Mult, Theo.

Kewley, D.J., D.G. Browning and W.M. Carey, "Low-frequency wind-generated ambient noise source levels," J. Acoust. Soc. Am. 88, 1894-1902 (1990).

Measurements of ambient noise (30–800 Hz) useful in characterizing the wind-generated component have been obtained in the low ship density Southern Hemisphere. Source levels that characterize the frequency and wind speed dependence of this noise have been obtained by Burgess and Kewley using vertical noise directionality data and had been implemented in a diagnostic computerized noise model. Northern Hemisphere vertical noise directionality data have been examined, processed for source level, and compared to these results. These data and other data summaries, when taking a two-mechanism viewpoint, are found to be consistent with respect to wind speed and frequency dependence. When a dipole source model, based on the possible physical mechanism of sound production, is used, a set of consistent source levels for wind-dependent noise is realized from the several data sets examined.

Wind, Nois.

Kibblewhite, A.C., A.L. Anderson, and G.E. Ellis, "Factors controlling the Ambient noise field below the Deep Sound channel (U)," Applied Research Laboratories, The University of Texas at Austin Technical Report 77-54, September 1977.

(U). In a recent experiment, a number of hydrophone systems were deployed at various positions in the Northeast Pacific Ocean. The ambient sea noise was recorded at different depths throughout the water column and the signals analyzed to establish the spectral properties of the noise field at each receiving site. The general features of the noise field were described in a recent paper (JUA(USN), April 1977) in which the main components of the field were identified as distant shipping and local wind effects. A second paper (J. Acoust. Soc. Am., in press) examined the implications of certain specific properties of the noise field above critical depth to the anomalously high values of attenuation often reported at frequencies below 100 Hz. This paper examines other characteristics of the deep-water noise field and discusses their relevance to boundary effects and the leakage of energy from the Deep Sound Channel.

Nois, Prop.

Lawrence, R.S., G.R. Ochs and S.F. Clifford, "Measurements of Atmospheric Turbulence Relevant to Optical Propagation," J. Opt. Soc. Am. 60, 826-830 (1970).

The aspect of atmospheric turbulence of interest to optical-propagation studies is the variation of refractive index. We demonstrate the application of high-speed temperature sensors to the direct measurement of this variation at optically important scale sizes, as small as a few millimeters. The thermometers, used in pairs with spacings ranging from 3 mm to 1 m, disclose that the turbulence near the ground frequently differs substantially from the Kolmogoroff model, and that the temperature difference does not follow the gaussian probability-distribution function. A model of the turbulent atmosphere containing sharply bounded regions with stronger than average turbulence agrees well with our observations. We also demonstrate the use of a single sensor mounted on an airplane to observe refractive-index variations at heights up to 3 km.

Opt, Atm, Exper.

1.) Shown are variations of the turbulence structure parameter, C_n^2, with height from 0 to 3 km high over a 30 minute period, and with time, for 24 hours at at height of 1.5m or 2.0m.

Lawson, L.M. and D.R. Palmer, "Acoustic ray-path fluctuations induced by El NINO," National Oceanic and Atmospheric Administration Technical Memorandum ERL AOML-56, January 1984.

This report represents a first step in determining the degree to which an El Niño event can be monitored using acoustic tomographic techniques. In tropical waters an acoustic ray entering the near-surface region from below usually is strongly refracted because of the steep gradient in the sound speed and therefore turns over very rapidly. Since the temperature perturbation associated with an El Niño event is restricted to this near-surface region, there has been some concern that ray path travel-time fluctuations would be too small to be easily detected. In this report we address this concern using data measured during the 1982-1983 event. We conclude that the travel-time fluctuations are large enough to be easily measured for almost all ray-path configurations of interest. We also discuss the direction future efforts might take.

Appl, Theor.

Leader, J.C., "Similarities and distinctions between coherence theory relations and laser scattering phenomena," Optical Engineering 19 (4), 593-601 (1980).

Abstract. Similar field-variables are studied in coherence theory and various laser scattering phenomena. However, a time average replaces the ensemble average in most analyses of coherence. It is demonstrated that when the phase deviation resulting from laser scattering is greater than 2π radians and the average scattered field-intensity is a slowly varying spatial variable, coherence relations can be applied to scattering phenomena by replacing the time average with a spatial average. A gedanken experiment is employed to demonstrate the correspondence of results obtained via coherence theory and scattering analyses. The reduction in observed intensity fluctuations by temporal and spatial averaging is also explicated. The implications of coherence theory results in laser scattering phenomena are discussed as well as the converse.

Opt, Theo.

Leeman, S., M.A. Fiddy and L. Zapalowski, "Born vs. Rytov: is the debate over?," SPIE 558, Inverse Optics II, 11-14 (1985).

The Born and Rytov approximations are re-examined, and several necessary conditions for he ir validity are derived without recourse to extensive.numerical computations for simple bjects of specific geometries. Some published statements as to the relative merits of the wo approximations, as well as the identity of their validity domains, are suggested to be n error.

Theo.
1.) The Born and Rytov approximations are used to obtain methods for inverting the scattered wave field for imaging purposes.

Levine, M.D., "Internal Waves Under the Arctic Pack Ice During the Arctic Internal Wave Experiment: The Coherence Structure," J. Geophys. Res. 95 (C5), 7347-7357 (1990).

The spectral composition of internal gravity waves under the Arctic pack ice during the Arctic Internal Wave Experiment (AIWEX) was found to be strikingly different from observations at lower latitudes. Time series of vertical displacement were inferred from horizontal and vertical arrays of temperature and conductivity sensors. Frequency spectra indicate a whiter spectrum (spectral slope near -1) and a less energetic wave field (by a factor of 0.02) than observations at lower latitude. The analysis of vertical and horizontal coherences revealed a horizontally isotropic wave field that is consistent with assumptions of a random field of linear internal waves. The wavenumber bandwidth of the wave field is about a factor of 10 wider than found at lower latitude.

IWav, Theo, Exper.

Levine, M.D., J. D. Irish, T.E. Ewart and S.A. Reynolds, "Simultaneous Spatial and Temporal Measurements of the Internal Wave Field During MATE," J. Geophys. Res. 91 (C8), 9709-9719 (1986).

A statistical description of the deep ocean internal wave field is presented using measurements from the Midocean Acoustic Transmission Experiment, conducted near Cobb Seamount in the NE Pacific (46°46'N, 130°47'W) during June–July 1977. The unique feature of this experiment is the variety of data obtained simultaneously from the same location: time series of temperature and velocity, and vertical and horizontal profiles of temperature. A generalized form of the Garrett-Munk (GM) internal wave spectrum is developed and used to interpret the data. This spectral model is specified by three parameters, $\bar{E}$, t, and p (energy level, wave number bandwidth, and frequency spectral slope, respectively). The variety of measurement types permit these three model parameters to be estimated from more than one measurement. The overall best fit values to the MATE data were $p = 2.7$ (GM use $p = 3$), $t = 3.1$ m^{-1} s (equivalent to $j_* = 6$, twice the GM value), and $\bar{E} = 8 \times 10^{-4}$ J/kg (within 20% of the GM level). Although significant differences were found in the values of the bandwidth (t) and spectral slope (p) from those specified by Garrett-Munk, the deviations are consistent with the behavior expected in a random internal wave field.

IWave, Exper.

Longuet-Higgins, M.S., "A stochastic model of sea-surface roughness. II," Proc. R. Soc. Lond. A (1991) 435, 405-422.

A two-scale model of a wind-ruffled surface is developed which includes (1) modulation of the short waves by orbital straining in the long waves, (2) dissipation of short-wave energy by breaking, and (3) regeneration of the short-wave energy by the wind. For simplicity the long waves are at first assumed to be uniform. It is shown that the character of the surface is governed by the parameter $\Omega = \beta/(\sigma\gamma KA)$, where β is the proportional rate of short-wave growth due to the wind, σ, K and A are the long-wave frequency wavenumber and amplitude, and $\gamma = 2.08$. When $\Omega < 1$ the short waves break over only part of the long-wave surface. When $\Omega \geqslant 1$ they break everywhere.

The mean-square steepness $\overline{s^2}$ of the short waves is an increasing function of β/σ, but a decreasing function of the long-wave steepness AK. The phase angle between $\overline{s^2}$ and the long-wave elevation η is an increasing function of Ω. The correlation between $\overline{s^2}$ and η is largest when $\Omega \ll 1$, but tends to 0 as $\Omega \rightarrow 1$.

The simple model is extended to the case when the long-wave amplitude A has a Rayleigh probability density. To take account of the 'sheltering' effect of high waves we compute the case when any two successive waves have a bivariate Rayleigh density.

The application of the model to laboratory and field data is discussed.

RSurf, Wind.

Macaskill, C. and T.E. Ewart, "The probability distribution of intensity for acoustic propagation in a randomly varying ocean," J. Acoust. Soc. Am. 76 (5), 1466-1473 (1984).

Probability distributions of intensity fluctuations from the MATE, AFAR, and S. W. Bermuda underwater acoustics experiments are compared with recently derived theoretical expressions. The limitations and strengths of these expressions are discussed. In particular, it is found that the work of Furutsu [J. Math. Phys. 17, 1252–1263 (1976)] gives a good description of the probability distribution function of intensity or log intensity, requiring only a knowledge of the second- and third-order intensity moments. Furutsu's description is not asymptotically correct at large range, so a modified form is proposed for the moments of intensity that reduce analytically to the log-normal distribution at short range and to the exponential distribution at large range. This new form also predicts the higher moments well but cannot be inverted analytically. A numerical inversion is used, and the ensuing distribution agrees well with the analytical result of Furutsu. It is expected that the new expression will be applicable at all ranges.

Stat, Exper, Theor, Mod.
1.)The exponential probability distribution does not match the MATE data at intermediate intensities.

Macaskill, C.C. and B.J. Uscinski, "Propagation in waveguides containing random irregularities: the second moment equation," Proc. R. Soc. Lond. A 377, 73-98 (1981).

The parabolic moment equations can be used to describe wave propagation in a waveguide, with an arbitrary refractive index profile, that contains weakly scattering irregularities. These equations remain valid even in the case of multiple scatter. An exact solution can be given if the guide has a parabolic profile, when the intensity on the axis of the guide exhibits periodic foci which are rapidly blurred as scattering increases. Exact solutions cannot be obtained when the profile is non-parabolic. The paper presents an approximate method of solving the second moment equation for an arbitrary profile. A simplified form of the solution useful in practice is given, and the method is illustrated for a waveguide with a cubic profile. The physical significance of the solution is discussed.

Stat, Theo, Prop.

Mackenzie, K.V., "Long-Range shallow-water signal-level fluctuations and frequency spreading," J. Acoust. Soc. Am. 34, 67-75 (1962).

The fluctuation of the received sound for frequencies of 350, 700, 1200, and 2400 cps was studied for transmission over flat 60-fathom sand and 50-fathom sandstone bottoms out to ranges of 15 miles. The received sound fluctuated over a range of 50 db. In general, the amplitude distribution was neither Gaussian nor Rayleigh. No significant correlation was found between the outputs of the receiving hydrophones which were separated vertically by 90 or more feet. The frequency was spread due to transmission and the relative power P is related to the half-width of the spectra $|f-f_0|$ from 350 to 2400 cps by

$$P=bf_0|f-f_0|^{-2},$$

where $b=(7.7\pm0.8)\times10^{-4}$ (cps)^2 for the sand bottom and $(3.9\pm2.7)\times10^{-4}$ (cps)^2 for the sandstone bottom. Special measurements indicated no significant asymmetry between the spectra above f_0 from that below f_0.

Exper, Prop, Shallow.

Mahajan, V.N. and B.K.C. Lum, "Imaging through atmospheric turbulence with annular pupils," Applied Optics 20 (18), 3233-3237 (1981).

The image degradation due to Kolmogorov atmospheric turbulence is considered in terms of the time-averaged optical transfer function, point spread function, Strehl ratio, and encircled energy for imaging systems with annular pupils. The applications include imaging with mirror telescopes and propagation of obscured laser beams through turbulence. Numerical results are given for obscuration ratios of 0, 0.25, 0.50, and 0.75.

Opt, Atm, Theo.

Mazar, R. and L.B. Felsen, "High-frequency coherence functions propagated along ray paths in the inhomogeneous background of a weakly random medium: I -- Formulation and evaluation of the second moment," J. Acoust. Soc. Am. 81, 925-937 (1987).

Ray trajectories have previously been shown to play an important role in determining the transport properties of high-frequency coherence functions constructed from parabolically approximated wave fields. In a weakly fluctuating medium with inhomogeneous refracting background, the parabolic approximation has conventionally been made around a straight propagation direction, thereby restricting its validity to a narrow angular domain with respect to this direction. This limitation is now removed by implementing the parabolic approximation in local coordinates around the curved ray paths connecting a source with an arbitrarily located observer in the background medium. The corresponding partial differential equation for the two-point coherence function is solved by a multiscale expansion method. Solution strategies are distinguished according to whether the observer is reached by a single ray, by two or more rays with vastly differing trajectories, or by two or more closely adjacent rays. In the first instance and also in the second (because the fluctuations decorrelate the separate ray fields), the coherence function can be synthesized by contributions from each individual path. In the third instance, which represents observations near caustics or foci, the adjacent ray fields must be treated collectively. The resulting integral expressions for the intensities can be simplified when the excitation is due to a line source and fluctuations are omitted. The reduced explicit forms are found to agree with the ray acoustically computed deterministic intensities at regular observation points and near simple caustics, thereby lending confidence in the validity of our approach and the quality of our approximations. These asymptotic ray acoustic studies of coherence functions have also been extended to phenomena involving reflection, refraction, and diffraction at interfaces and boundaries.

Theo, Weak, Mult.

Mazar, R. and L.B. Felsen, "High-frequency coherence functions propagated along ray paths in the inhomogeneous background of a weakly random medium: II -- Higher moments," J. Acoust. Soc. Am. 82, 593-600 (1987).

In a previous article [R. Mazar and L. B. Felsen, J. Acoust. Soc. Am. 81, 925–937 (1987)], it has been shown how the ray trajectories in the refracting background of a weakly fluctuating medium with large scale inhomogeneities can form the basis for propagating and evaluating the high-frequency two-point coherence function. Approximate results there, derived by a multiscale expansion technique, account for multiple isolated ray arrivals at observation points far from caustics, and blend smoothly into the transitional behavior due to closely adjacent rays near caustics. In the absence of fluctuations, this assertion has been verified by recovery of the isolated ordinary and uniform deterministic ray theory intensities, respectively, and it is therefore believed that our spectral construction properly describes the high-frequency two-point coherence function when randomness is included. The ray-based approach is now extended to multifrequency higher-order coherence functions. The new results are shown to recover the predictions from nonuniform and uniform ray theory when the fluctuations are removed, and they are also shown to yield previously obtained results for the special case of the two-frequency fourth moment in a homogeneous background. These checks lend confidence in the validity of the extended theory presented here.

Theo, Weak, HF, Mult.

McDaniel, S.T., "Vertical Spatial Coherence of Backscatter from Bubbles," IEEE J. of OCeanic Engineering, OE-12 (2) 349-356 (1987).

Abstract—A basic formalism is developed to treat the vertical spatial coherence of backscatter from wind-generated microbubbles beneath the ocean surface. This formalism treats signals multiply scattered by the sea surface and the subsurface scatterers, as well as absorption in the bubble layer. Approximate solutions are obtained for the case of narrow beamwidth sources and are applied to study the influence of measurement system and environmental parameters on coherence. Using bubble densities derived from acoustic backscatter data, the coherence is found to depend strongly on source frequency and beam pattern. The primary environmental effect is due to the increase in both bubble density and penetration depth below the surface that occurs with increasing wind-speed. At high wind speeds, the vertical coherence is sufficiently dependent on the scatterer depth distribution to provide a viable means of studying this phenomenon.

Appl, Theor, HF.

1.) Using spatial coherence as a measure bubble density versus depth below the water surface is obtained. From a vertical acoustic line array acoustic backscatter is recorded.

Mellberg, L.E. and O.M. Johannessen, "Layered oceanic microstructure -- its effect on sound propagation," J. Acoust. Soc. Am. 53, 571-580 (1973).

It has recently been established that the vertical profiles of oceanographic parameters in the seasonal and permanent thermocline regions are not the smooth curves observed by older techniques. Rather they indicate a large number of nearly homogeneous layers, with typical thicknesses of meters or less, separated by interfacial regions where strong gradients exist. Examples of typical layered microstructure profiles from different ocean areas are presented. The effects of such microstructure on sound propagation are examined qualitatively using ray tracing techniques. It was found that the layered microstructure had a significant effect only when rays vertex within the layers, in which case the isointensity loss contours degenerate into a broad scatter of points.

Exper, Mult, Micro.

Middleton, D., "Acoustic Scattering from Composite Wind-Wave Surfaces in 'Bubble-Free' Regimes," IEEE J. of Ocean. Eng. OE-14 (1), 17-75 (1989).

Abstract—The present paper examines the problem of underwater acoustic scattering from truly composite wind-wave surfaces under zero-gradient conditions ($\nabla c = 0$). Here the dominant small-scale component is postulated to be a soliton surface ensemble [49]-[54], produced by the nonlinear wind-wave interactions and associated with the wind-drift surface layer riding on the underlying, mostly large-scale gravity-capillary component of the composite surface. A general bistatic analysis, based on the Kirchhoff approximation, is presented, which includes arbitrary geometries, beam patterns, and general signals. Both "low" O(0.2-1 kHz) and "high" O(≥3 kHz) frequency signals are considered, and far-field (Fraunhofer) geometries are assumed. Surface Doppler, including Doppler spread and the modulation effects of the large-scale component, are examined. Both forward- and back-scatter régimes are considered in the determination of the scattered field and received wave intensities, scattering cross sections, and coherency measures of surface scatter.

Particular attention is given here to the high-frequency cases, with small grazing angles, moderate-to-strong mean surface winds, and essentially bubble-free régimes. Recent empirical data [6], [49], [50], [53] appropriate to these conditions are included which support the soliton conjecture and illustrate the general results. Both coherent and incoherent scattering are examined, along with relevant surface Doppler data. Part I presents the general analysis; Part II describes the results, along with the important high-frequency, small-angle cases and associated empirical data, while Part III is devoted to various supporting analyses and special results, along with a comprehensive account of the approximations and assumptions involved.

Theo, Mod, GWav, HF, RSurf, Wind.

1.) A theoretical surface scattering model, employing the author's recently postulated wind-generated soliton ensemble, is presented.

Middleton, D., "Canonical Non-Gaussian Noise Models: Their Implications for Measurement and for Prediction of Receiver Performance," IEEE Trans. on Electromag. Compat., EMC-21 (3), 209-233 (1979).

Abstract—The chief aim of this paper is to provide a short technical summary of the principal noise-model results [1]-[11], developed by the author to date, and to consider their major implications for 1) measurement, and 2) performance prediction and evaluation. The discussion is illustrated by a concise review of model statistics, methods of estimating the model parameters, including the effects on accuracy of finite data samples. A variety of signal detection problems are similarly used to illustrate the very large potential improvement possible when optimum algorithms are employed, *vis-à-vis* most of the currently used systems, which are conventionally optimized for Gaussian interference. Conditions for realizing such gains are also given, and the principal key properties of these new, general models are discussed. These models make possible, for the first time, a systematic treatment of real-world EMI environments, both for measurement and assessment, and for receiver performance therein.

Theo, Nois, Mod.

Middleton, D., "Channel Modeling and Threshold Signal Processing in Underwater Acoustics: An Analytical Overview," IEEE J. of Ocean. Eng. OE-12 (1), 4-28 (1987).

Abstract—An overview of underwater acoustic channel modeling and threshold signal processing is presented, which emphasizes the inhomogeneous, random, and non-Gaussian nature of the generalized channel, combined with appropriate weak-signal detection and estimation. Principal attention is given to the formal structuring of the scattered and ambient acoustic noise fields, as well as that of the desired signal, including both fading and Doppler "smear" phenomena. The role of general receiving arrays is noted, as well as their impact on spatial and temporal signal processing and beam forming, as indicated by various performance measures in detection and estimation. The emphasis here is on limiting optimum threshold systems, with some attention to suboptimum cases.

Specific first-order probability density functions (pdf's) for the non-Gaussian components of typical underwater acoustic noise environments are included along with their field covariances. Several examples incorporating these pdf's are given, to illustrate the applications and general methods involved. The fundamental role of the detector structure in determining the associated optimum estimators is noted: the estimators are specific linear or nonlinear functionals of the original optimum detector algorithm, depending on the criterion (i.e., minimization of the chosen error or cost function) selected. Results for both coherent and incoherent modes of reception are presented, reflecting the fact that frequently signal epoch is not known initially at the receiver.

To supplement the general discussion, a selected list of references is included, to provide direct access to specific detailed problems, techniques, and results, for which the present paper is only a guide.

Theo, Stat, AMech, Nois.

1.) This paper includes applicatons to non-Gaussian noise.

Middleton, D., "A Statistical Theory of Reverberation and Similar First-Order Scattered Fields, Part I: Waveforms and the General Process," IEEE Trans. on Inf. Theor. IT-12 (3), 372-392 (1967).

Abstract—A theory of reverberation and related first-order scattered fields is developed, based on the assumption of weak inhomogeneities (i.e., primary scattering only), and a consequent representation in terms of Poisson point processes in space and time. Both surface and volume reverberation are included, separately and together, for general geometries, source and receiver at the same and different locations, and arbitrary transmitting and receiving apertures. A combination of field- and ray-theory is employed to obtain a characteristic scattered waveform, where the inhomogeneous medium is replaced by a homogeneous and isotropic one in which a spatially and temporally random ensemble of point scatterers is embedded. The effects of the scattering mechanism are described generally by a linear, time-varying filter response. The medium itself is seen to be dispersive and is represented by a set of linear (statistical) space-time operators, by which the signal source and the receiver are coupled to one another, as well as to the point scatterers.

Broadband as well as narrowband signals and reverberation are included in the model, which is capable of handling general apertures, illuminating signals, doppler of the scatterers, multiple sources and receivers (overlapping beams), and a characteristic time-varying scatter mechanism, that reveals in detail the inherent nonstationarity of the reverberation. Shadowing effects of "rough" surfaces are included, and a variety of important special results, such as the case of narrowband excitation, and simple (time- and frequency-independent) scattering, are also described. The emphasis is on broadband (frequency-dependent) structures, and their associated space-time operators, by which the system as a whole is represented, and with the help of which one can apply the general methods of statistical communication theory to the central problems of signal processing for detection, communication, and classification, in an environment dominated by reverberation or clutter and analogous signal-dependent noise processes.

Theo, Stat, Mod.

Middleton, D., "A Statistical Theory of Reverberation and Similar First-Order Scattered Fields, Part II: Moments, Spectra, and Special Distributions," IEEE Trans. on Inf. Theor. IT-13 (3), 393-414 (1967).

Abstract—In Part I a general, first-order scattering model for reverberation has been constructed, from which the characteristic aperture and medium operators have been obtained for general geometries, signals, and arrays. Here, in Part II, the second-order statistics (intensities, covariances, and spectra) of such reverberation processes are determined in detail. In addition to the fluctuation, or purely random component of the received scatter process, an average or purely deterministic component often exists and may be significant, particularly for scattering from surfaces. Since the medium is dispersive (and time varying), reverberation is a nonstationary process (as is well known). Except for purely sinusoidal signals, these processes are (approximately) stationary only for signals of short duration (i.e., at fixed ranges), and only then can be said to possess an intensity spectrum in the usual sense. In this latter instance the familiar reverberation laws (intensity $\sim$ input signal, and $\sim$ range^{-3} or range^{-2}, respectively, for surface or volume scatter) hold for the fluctuation component, while different laws (intensity $\sim$ range^{-2}, or range^{0}) govern the deterministic components. With the composite process no such simple behavior usually appears, unless the geometry insures the dominance of a surface or volume effect. Moreover, in the general case these laws are only approximations, which may often be poor ones.

Particular attention is also given to narrowband signals. A variety of expressions for the covariances of the slowly-varying components of the received reverberation is developed in detail, for both surface and volume scatter. These results are very simply combined (additively in the means, variances, etc.) to yield analogous results for the complete, or composite reverberation process. Conditions for normality are given and a number of new results for the probability densities of such nonstationary, narrowband Gaussian processes are obtained. The first-order statistics of the envelope and phase of the received scattered return are also derived, for general narrowband signals, extending the earlier work of Rayleigh, Rice, Hoyt, Nakagami, Middleton, and Beckmann.

Many special cases for arbitrary illuminating signals are considered, including an approach to complex (distributed) targets, uniform beams, multiple receivers, transmitter and receiver at the same location, large and small doppler, etc., where the general formulation (as in Part I) is broadband, given in terms of frequency-selective apertures, time-varying dynamic cross sections, and arbitrary input signal waveforms.

A number of second-order statistical properties of the medium response is defined and evaluated, which are needed for the combined theoretical and experimental exploration of the medium itself. It is found that the present model of the dispersive reverberation channel cannot be fully described by the statistical structures postulated earlier (and successfully) in radar astronomy: a considerably more involved second-order statistic is required (and obtained) here. To what extent it may provide an adequate description of reality remains to be studied. Part II concludes with a short summary of the principal results and assumptions.

Theo, Stat, Mod.

Middleton, D., "The Underwater Medium as a Generalized Communication Channel," in L. Bjorno, ed. Underwater Acoustics and Signal Processing, 589-612 (D. Reidel, 1981).

The purpose of this paper is twofold: (1), to provide (in necessarily summary form) canonical representations of inhomogeneous random media - in particular here, the underwater acoustic medium - as generalized communication channels; and, (2), to indicate a new conceptual and analytical framework for solving specific problems in complex, realistic situations. The notion of "channel" here includes not only the medium as vehicle for the usual purposes of signal detection and extraction, but also for communication and remote sensing. The canonical operator character of the new approach permits explicit treatment in statistical-physical terms, of all types of media, local and distributed inhomogeneities, and geometries, as well as general signals, apertures, and doppler effects. (The sole restriction is that the media be linear.)

Channel characterization (mainly second-order statistics here) is based on recent new results, which include strong as well as weak scatter conditions, intermodal interactions, deterministic inhomogeneities (including boundaries), and an essentially complete statistical structure of the various (re-) radiation interactions involved. The new approach is briefly illustrated by (1), a typical volume scatter régime; and (2), an overview of the "exact" (ocean) surface scatter channel, which includes phenomena not given explicitly by earlier theories. Details of concept, method, and application are cited in the references.

Theo, Stat, Prop.

Mikhalevsky, P.N. and I. Dyer, "Approximations to distant shipping noise statistics," J. Acoust. Soc. Am. 25, 732-738 (1978).

Distant shipping noise modeled by multiple phase-random line components has a probability density and statistics easy to state in generality but difficult to compute in particular. To obtain numerical results with reasonable effort, previous computations have been based on Gaussian approximations to the densities. Here we show that an Edgeworth-series approximation to the density greatly improves the quality of the result, without adding much to the computational effort. Also, to justify adoption of the Edgeworth series, and to further develop the theoretical framework for distant shipping noise, exact analytical results are presented for several new cases of multiple line components.

Stat, Mod, Theo, Nois.
1.) Short time average of mean-square pressure is shown.

Mintzer, D., "Wave Propagation in a Randomly Inhomogeneous Medium. I," J. Acoust. Soc. Am. 25, 922-927 (1953).

The propagation of sound pulses from a point source in a medium where the index of refraction varies randomly is studied by means of the Born approximation to the wave equation. The coefficient of variation (standard deviation of the amplitude of a series of pulses, expressed as a percentage of the mean amplitude of the series) is evaluated for pulse lengths short compared with the time in which the refractive index varies significantly, and for ranges large compared with the wavelength of the sound. The results are in agreement with the experiments of Sheehy.

Theo, Prop, Stat.
1.) The Born approximation to the wave equation is used.

de Moustier, C., "Beyond bathymetry: Mapping acoustic backscattering from the deep seafloor with Sea Beam," J. Acoust. Soc. Am. 79, 316-331 (1986).

In its standard mode of operation, the multibeam echo sounder Sea Beam produces high resolution bathymetric contour charts of the seafloor surveyed. However, additional information about the nature of the seafloor can be extracted from the structure of the echo signals received by the system. Such signals have been recorded digitally over a variety of seafloor environments for which independent observations from bottom photographs or sidescan sonars were available. An attempt is made to relate the statistical properties of the bottom-backscattered sound field to the independently observed geological characteristics of the seafloor surveyed. Acoustic boundary mapping over flat areas is achieved by following trend changes in the acoustic data both along and across track. Such changes in the acoustics are found to correlate with changes in bottom type or roughness structure. The overall energy level of a partial angular-dependence function of backscattering appears to depend strongly on bottom type, whereas the shape of the function does not. Clues to the roughness structure of the bottom are obtained by relating the shape of the probability density function of normal-incidence echo envelopes to the degree of coherence in the backscattered acoustic field.

Appl, Exper, HF, Stat.

1.) Sea Beam data, normally used for bathymetry alone, is analyzed to find the backscatter signatures of various bottom types, e.g., mud and mud with manganese nodules.

Munk, W.H. and F. Zachariasen, "Sound propagation through a fluctuating stratified ocean: Theory and observation," J. Acoust. Soc. Am. 59, 818-838 (1976).

We have derived expressions for the mean-square phase and intensity fluctuations and their spectra for cw sound propagating through a channeled fluctuating ocean. The "supereikonal" approximation reduces to the geometric optics (eikonal) limit for short acoustic wavelengths: $\lambda < 2\pi$ [illegible] and $\lambda < L_V^2/(R \tan^2\theta)$, where L_H and L_V are horizontal and vertical correlation lengths of the fluctuations, R is range, and $\tan\theta$ is the ray slope, replacing the traditional (and much more severe) Fresnel condition $\lambda < 2\pi L^2/R$ for a homogeneous isotropic ocean. The results can be expressed in closed form for an exponentially stratified ocean model and associated "canonical sound channel," with superimposed fluctuations from an internal wave model spectrum based on oceanographic observations. The parameters are the stratification scale B, the inertial and buoyancy frequencies ω_{i} and $n(z)$, the scale j_* of internal wave mode numbers, and the internal wave energy per unit area. The results are in reasonable agreement with numerical experiments based on the parabolic wave equation. For the "singlepath" 4-kHz transmission over Cobb Seamount the observed and computed rms fluctuations in phase are 1.6 and 2.5 cycles, respectively; in intensity these are 5.5 and 2.2 dB, respectively, with anomalous intensities measured at high frequencies ("sporadic" multipathing?). For the multipath 406-Hz MIMI transmission, we obtain 4×10^{-3} and 5×10^{-3} sec^{-1}, respectively, for the experimentally determined and the computed rms phase rates.

Theo, Mod, Exper, Mult, IWave.

1.) Calculation results are compared with Cobb results and MIMI results.

National Defense Research Council, Physics of Sound in the Sea, Part I: Transmission, Chapter 7. Originally published as Division 6, Volume 8 NDRC Summary Technical Reports by the Committee on Undersea Warfare National Research Council.

Exper, Stat, Theo.

1.) The first moment is shown.

2.) The Rayleigh probability distribution is compared with a measured probability distribution.

Nichols, R.H., "Notes on infrasonic ambient ocean noise: Temporal autocorrelation and diurnal variation," J. Acoust. Soc. Am. 86, 306-310 (1989).

Measurements of ambient ocean noise spectrum levels were made every 6 h at frequencies of 2.5–20 Hz at three deep-bottomed sites in the northeast Pacific over a 40-day period. Autocorrelation times to $1/e$ at these frequencies were found to range from 8.9–19.9 h over the frequency range and the three sites. Autocorrelation times to the first zero-axis crossing ranged from 25.2–118 h. Forty-day average noise spectrum levels at each of the four daily sampling times were compared with one another; maximum diurnal differences among them at a given frequency and site ranged from 0.2–1.9 dB. Standard deviations of the noise spectrum levels peaked at 10 Hz. Autocorrelation times were much longer than those reported by Perrone and King [J. Acoust. Soc. Am. 58, 1186–1189 (1975)] which, in turn, were longer than those reported by Co:aras *et al.* [J. Acoust. Soc. Am. 83, 1345–1359 (1988)].

Exper, Nois, Stat.
1.) Measurements were made in the Northeast Pacific from 1 to 20 Hz.

Nichols, R.H. and H.J. Young, "Fluctuations in low-frequency acoustic propagation in the ocean," J. Acoust. Soc. Am. 43, 716-722 (1968).

An experimental study has been made of the variability of acoustic transmission in the ocean at frequencies around 270 cps between a fixed bottomed source and fixed bottomed receivers. Transmitted signal level was observed at two distances: 2 and 700 NM (nautical miles), over periods ranging from 1 to 22 h. Simultaneous measurements were made at several hydrophones at each location to investigate correlation of fluctuations at various pair spacings. Two types of variation were noted. At the 2-mile range, quasiperiodic variations in level occurred with a predominant frequency of 0.12 cps, similar to that of surface waves. These are believed to be due to multipath interference of signals reflected one or more times from the moving surface. At the 700-NM range, such variations were also observed; in addition, large slower fluctuations were observed, with periods of a few minutes to several hours. These are believed to be due to changing multipath interferences among signals passing through moving or changing water masses of different refractive indices (e.g., internal waves). Cross-correlation coefficients of either type of fluctuation were small: 0.1–0.2 at pairs of hydrophones with spacings of 25–1815 ft.

Exper, Mult, IWave.

Ochs, G.R., R.R. Bergman, and J.R. Snyder, "Laser-Beam Scintillation over Horizontal Paths from 5.5 to 145 Kilometers," J. Opt. Soc. Am. 59, 231-234 (1969).

Opt, Atm, Exper.

Parry, G., "Measurement of atmospheric turbulence induced intensity fluctuations in a laser beam," Optica Acta 28 (5), 715-728 (1981).

Abstract. We report measurements of the statistical properties of the intensity fluctuations in a He/Ne laser beam which had propagated 1·125 km through the earth's atmosphere. The beam size was such that the beam propagated as a spherical wave, and atmospheric conditions such that most measurements were made in the 'saturation' region ($\beta_0 \sim 1$–4). We found (1) that the variance of the intensity was considerably larger than that previously reported for plane wave propagation, and (2) that the probability distribution of the intensity and the derived moments were close to the *K*-distribution and its moments. The origin and significance of the *K*-distribution in atmospheric propagation is considered. Photon counting techniques were used for all measurements.

Atm, Exper, Opt, Stat, Sphere.
1.) The K-distribution were found to match the 2nd through 5th moments of the data pretty well compared to the log-normal distribution.

Parry, G. and P.N. Pusey, "K distributions in atmospheric propagation of laser light," J. Opt. Soc. Am. 69, 796-798 (1979).

> Experimental results are presented which suggest that the probability distribution of fluctuations in the intensity of laser light propagating through atmospheric turbulence are reasonably well described by K distributions in the intermediate range of propagation path lengths, $L \simeq 600$ m, $\beta_0 \simeq 1$-2, where the mean square fluctuation $\langle I^2 \rangle / \langle I \rangle^2$ can be as high as five.

Opt, Atm, Exper, Stat.

1.) K-distribution found to match the 3rd through 5th moments of the data for large fluctuations, however, the log-normal distribution matched the 3rd through 5th moments of the data for smaller fluctuations.

Perkins, J.S., W.A. Kuperman, F. Ingenito, L.T. Fialkowski and J. Glattetre, "Modeling ambient noise in three-dimensional ocean environments" J. Acoust. Soc. Am. 93, 739-752 (1993).

> A model is developed for the calculation of the spatial properties of the surface-generated noise in a three-dimensional ocean. This is an extension of the work of Kuperman and Ingenito [J. Acoust. Soc. Am. 67, 1988–1996 (1980)], which used a normal-mode representation of the noise field in a stratified ocean. Noise fields are simulated for both point receivers and vertical line receivers. These examples show how the spatial and directional characteristics of the noise field are affected by the ocean environment. For example, as is apparent in ambient noise data, surface noise propagating at high angles over a sloping ocean bottom is deflected into shallower angles. Also, matched-field processing simulations in three-dimensional ocean environments can be done in a consistent manner: signals and surface-generated noise are modeled by propagating through the same environment with the same theory.

Mod, Theo, Nois, Wind, Appl.

1.) The spatial properties of the noise are calculated, not the temporal variations.

Phillips, R.L. and L.C. Andrews, "Measured statistics of laser-light scattering in atmospheric turbulence," J. Opt. Soc. Am. 71, 1440-1445 (1981).

> The statistical properties associated with the intensity fluctuations of a He–Ne laser beam propagating through extended clear-air turbulence over a homogeneous range were measured and compared with existing theoretical models. The statistics were determined by measuring the first five normalized moments of the beam intensity over varying distances from 183 m to 3 km. The beam geometry was approximately that of a spherical wave. Calculated values of the refractive-index-structure parameter C_n^2 varied from a low of approximately 10^{-14} $m^{-2/3}$ to a high value of the order of 10^{-10} $m^{-2/3}$. Thus the data obtained correspond to many conditions of turbulence from weak to strong turbulence in the saturation regime. We found that the data generally support the lognormal model under conditions of weak turbulence and the negative-exponential distribution in the superstrong-turbulence regime. The K distribution fits some of, but not all, the data in the saturation regime. For conditions of strong turbulence before the superstrong regime, none of the above statistical models fits the data well. This is due primarily to the fact that a looping effect appeared in the data whereby the third- and higher-order normalized moments appear to follow a looped curve in the vicinity of their maximum values when they are plotted as functions of the second normalized moment. None of the theoretical curves for the normalized moments of the above-named distributions exhibits this looping effect (since they are essentially one-parameter distributions), and therefore they have limited applicability with respect to our data.

Opt, Atm, Stat, Exper.

1.) The measured values of the 3rd to 5th moments are found to be log-normal in weak turbulence, negative exponential in super-strong turbulence and K-distributed in some saturation regimes.

Phillips, R.L. and L.C. Andrews, "Universal statistical model for irradiance fluctuations in a turbulent medium," J. Opt. Soc. Am. 72 (7), 864-870 (1982).

A universal model is proposed for the irradiance fluctuations of an optical beam propagating through atmospheric turbulence. When this model was compared with existing measured data, we found good qualitative and quantitative agreement, which suggests that this new theoretical model is applicable under all known conditions of turbulence. In the regime of weak scattering, the normalized moments of the distribution are essentially the same as those predicted by the lognormal model, although they show large deviations from lognormal statistics in the saturation regime. The limiting form of the universal model for conditions of super-strong turbulence is that of the negative-exponential distribution, but, for more moderate conditions of turbulence, the form is that of an exponential times an infinite series of Laguerre polynomials. The new distribution was derived under the assumption that the field irradiance consists of two principal components, each of which has an amplitude that is *m* distributed.

Opt, Atm, Mod, Stat.

1.) During weak scattering the probability distribution of beam-intensity is similar to the lognormal distribution.
2.) In super strong turbulence the probability distribution of the beam-intensity can be predicted with a negative exponential distribution.

Prokhorov, F.V., F.V. Bunkin, K.S. Gochelashvily, and V.I. Shishov, "Laser Irradiance Propagation in Turbulent Media," Prodceedings of the IEEE 63, 790-811 (1975).

Abstract—The results obtained in recent years on laser irradiance propagation in random weakly inhomogeneous media with large scale index of refraction fluctuations are reviewed. Of particular concern are the problems of the correlation theory of fluctuations of irradiance propagating over large distances, where the effects of multiple scattering are greatly pronounced. Much attention is paid to the results on laser beams spread and phase fluctuations. Consideration is given to problem of the study of spatial spikes of irradiance that had passed through a turbulent media; which is comparatively new but important for practical applications. Systematic comparison of the theory with experiment is given where appropriate. The methods of analyses reviewed in this paper are applicable to a class of stochastic and dynamic partial differential equations and thus may be of interest in other areas of engineering research.

Opt, Mult, Weak, Strong, Plane, Sphere.

Puckette, P.T., "Fluctuations in the frequency and amplitude of a CW signal over short time periods in the open ocean," M.S., Applied Marine Physics, University of Miami (December, 1991).

Several six minute time series of 150 Hz and 250 Hz CW (continuous wave) signals that had been transmitted over ranges of 16 to 23 km in the open ocean are analyzed for short term fluctuations in frequency and amplitude. The data had been broadband beamformed making it possible to estimate the vertical arrival structure of the signal. Each time series containing the signal was processed first to investigate short term fluctuations in the signal and then to examine the frequency structure of the signal over time.

The power spectrum of the time series revealed that the signal had in almost every case distinctive sidebands present around the carrier frequency of the signal that were produced by propagation effects. A frequency ratio defined as the ratio of the amplitude of the carrier frequency to that of the sideband frequency was calculated over the time series. A strong correspondence was observed between the running average of the time series and the frequency ratio, as well as between the standard deviation and the inverse of the frequency ratio. The similarity between the standard deviation and the inverse of the frequency ratio suggest that for those periods of the time series during which the amplitude of the sidebands and the carrier are comparable there is an increase in the interference between the different frequency components of the signal resulting in an increase in the fluctuations of the signal.

The spacing in Hertz of the sidebands around the carrier was similar to that expected from surface scattering of the signal. To investigate this possibility a simple model of underwater sound propagation was developed using ray tracing and a theory of surface scattering. This model was used to make predictions of the vertical arrival structure of the signal and to determine if the variations in the frequency structure of the measured signal could be reasonably attributed to surface scattering.

Due to a large discrepancy between the measured vertical arrival structure and the predicted vertical arrival structure, the comparison of the modelled results and the measured results was difficult and qualitative at best. However, with judicious adjustments to the source-receiver geometry, the results indicated that surface scattering did appear to be the source of the frequency sidebands in the signal.

Exper, Mod.

Ramsdale, D.J., "Acoustic sidebands from cw sources towed at long ranges in the deep ocean," J. Acoust. Soc. Am. 63, 391-395 (1978).

Three cw sources (9.8, 110, and 262 Hz) were towed at approximately 7 knots along a great circle track from Antigua, WI, to the Grand Banks of Newfoundland. Acoustic data from each were recorded on a bottom-mounted hydrophone near Antigua, providing source-to-receiver distances of from 100 to 2800 km. High-resolution spectral analysis centered at each frequency showed that while no acoustic sidebands were discernible at 9.8 Hz, they were observable over the entire track for both the higher frequencies. Except for expected statistical fluctuations, the upper and lower sidebands were of equal amplitude and symmetrically placed about the carrier frequency. In regions of strong convergence zone activity the sideband level displayed the similar peak-to-null variations on the carrier, although the peak-to-null ratio was smaller than for the carrier. Detailed environmental data were available only near the sources. A high degree of correlation was observed between the sideband levels and the wave and swell heights when the sources were towed through a storm which occurred some 2000 km from the receiver. Sideband levels computed from the single bounce sinusoidal surface theory of Roderick and Cron [J. Acoust. Soc. Am. 48, 759–766 (1970)] using swell amplitude data at the sources agreed well with the measured levels for both frequencies during the stormy period. The separation of the sidebands in frequency from the carrier was the same for both source frequencies, was not affected by the convergence zone behavior of the sideband levels, and decreased as the sources approached and transited the stormy area.

Exper, GWav, Prop.
1.) The experiment was in the Atlantic, from Antigua, W.I. to the Grand Banks of Newfoundland.

Robertson, G.H., "Frequency stability of a cw signal transmitted over a long underwater path," J. Acoust. Soc. Am. 69 (3), 672-675 (1981).

A cw signal of 270 Hz derived from a very stable crystal oscillator was transmitted from a fixed projector at Eleuthera through 700 nautical miles (nmi) of deep water to fixed receivers at Bermuda. Samples of the received signal 40 s long were cross correlated with an equally stable reference signal of the same frequency for delay times of 0 to 18 s. Increased sensitivity of measurement was obtained by means of a heterodyning process in the correlation operation. The standard deviation of the frequency difference was calculated from data gathered over several days. In spite of multipath fading, the deviation was found to be only of the order of 0.001 Hz. For less than 5% of the time, the cross-correlation pattern could not be easily distinguished. The relationship between these results and previous measurements of signal coherence over the same path is discussed.

Exper, Stat, Mult.
1.) The experiment was between Eleuthera and Bermuda.

Ross, W.S., W.P. Jaeger, J. Nakai, T.T. Nguyen and J.H. Shapiro, "Atmospheric optical propagation -- an integrated approach," Optical Engineering 21 (4), 775-785 (1982).

Abstract. The task of characterizing optical wave propagation through the earth's atmosphere under low-visibility weather conditions is extremely difficult; it requires, in essence, solution of the general multiple-scattering problem. This paper describes results from an integrated approach to propagation through the turbid atmosphere in which experiments are used to establish the magnitude of the propagation effects and to supply empirical relationships which permit simplifying approximations in the theory. In particular, line-of-sight laser measurements of multipath spread, angular spread, beam spread, and incoherent source measurements of angular spread and power transmission versus range are reported. From the behavior of these data two approximate propagation theories, viz., multiple forward scatter and strong multiple scatter, are developed.

Atm, Opt, Exper, Mult, Prop.
1.) Paper deals with propagation through turbidity.

Scorer, R.S., "A vivid mechanical picture of turbulence," in Turbulence and Diffusion in Stable Environments, J.C.R. Hunt, ed., The Institute of Mathematics and its Applications Conference Series, New Series, Clarendon Press, Oxford (1985).

Theo.

Scrimger, J.A., "Signal Amplitude and Phase Fluctuations Induced by Surface Waves in Ducted Sound Propagation," J. Acoust. Soc. Am. 33 (2), 239-247 (1961).

The effects of surface waves on sound propagated from a continuous wave source over a range of 300 ft in water of depth 10 ft have been examined. It is found that the surface waves induce regular amplitude and phase fluctuations in the received signal. The dependence of the amount of amplitude and phase fluctuation on crest to trough height of the surface waves has been obtained for acoustic frequencies in the range 1 to 10 kc. Frequency spectra of the fluctuations, for values of the ratio of sound wavelength (λ) to wave height (A) above 18, are the same as the surface wave spectra. For values of λ/A less than 18 the fluctuation spectra are broader and show well-defined second and sometimes third harmonic components. Wave packet experiments in which the bow wave of a small boat is propagated across the length of the otherwise calm duct surface show that in the case of the uniformly rough surface the fluctuations are produced only by surface waves near the source and near the receiver.

Exper, GWav, RSurf, HF, Shallow, Mult.
1.) Experiment took place in the Esquimalt Lagoon near the Pacific Naval Laboratory.

Shapiro, J.H. and S.T. Lau, "Turbulence effects on coherent laser radar target statistics," Applied Opt. 21, 2395-2398 (1982).

This paper reports theoretical probability density and cumulative distribution functions for glint and speckle target returns in a compact coherent laser radar. Calculator programs are given to facilitate use of these results.

Opt, Stat, Theo, Atm.

Shi, X. and R.K. Ward, "Restoration of images degraded by atmospheric turbulence and detection noise," J. Opt. Soc. Am. 9 (3), 364-370 (1992).

The restoration of images blurred by atmospheric turbulence and contaminated by additive-signal-independent noise is investigated. A series of noisy short-exposure images and the *a priori* knowledge of the time-averaged autocorrelation function of the optical transfer function are assumed to be known. Three kinds of filter are discussed. These are based on the speckle interferometry technique, the Wiener criterion, and an *ad hoc* scheme. The Wiener estimates have the advantage that all the observations are considered simultaneously, but unfortunately the estimates require more knowledge about the optical transfer function than is available. Thus the *ad hoc* scheme is developed so that the least-squares estimate for each observation is first obtained. Then the Fourier modulus of the unknown is obtained by time averaging a function of these estimates. The experimental results verify the theoretical expectation that this *ad hoc* filter should outperform that based on the speckle interferometry technique in that the additive-noise effects are suppressed and the image quality is improved significantly.

Opt, Atm, Theo, Nois.

Simanin, A.A., "Possiblity of classifying water and surface rays by amplitude fluctuations of the received signal," Sov. Phys. Acoust. 36 (6), 622-624 (1990).

The statistical approach to the solution of the identification problem in underwater acoustics is thwarted by a number of obstacles; one of the main difficulties is the meager investigation of probabilistic models of currently used classification criteria. Problems associated with the statistical characteristics of single-path signals propagating in a fluctuating ocean and of like signals reflected from the rough surface or the irregular bottom of the ocean have been adequately studied from the experimental and theoretical points of view.[1-4] In the present note we synthesize a statistical algorithm for the classification of rays as water or surface rays, based on probabilistic models for the amplitude fluctuations of water [1-3] and surface[4] signals.

1.) log normal prob. dist. due to unsaturated fluctuations.
2.) K prob. dist. due to intermediate fluctuations.
3.) Rayleigh prob. dist. due to saturated fluctuations.

Stat, Appl.
1.) Found the following: log-normal distribution for unsaturated fluctuations.
K- distribution for intermediate fluctuations.
Rayleigh distribution for saturated fluctuations.

Smith, P.W., Jr., "Spatial coherence in multipath or multimodal channels," J. Acoust. Soc. Am. 60, 305-310 (1976).

An integral expression for the spatial coherence function of pure-tone sound fields is formulated under hypotheses that the component fields of individual paths or modes are locally plane waves and mutually incoherent in the average. The total field is not assumed to be a Gaussian random variable. The resulting coherence is quasi or locally homogeneous, varying slowly with average position as the strength of the component fields change. Statistical estimates for the contributions of these components are taken from existing literature on average transmission loss. The expression for coherence has an explicit dependence on the environmental parameters, the range, and the depths of source and receivers. Numerical results and approximate expressions are developed for channels characteristic of shallow and deep water.

Mult, Theo, Plane.
1.) A statistical estimate of the transmission loss is used.

Spiesberger, J.L., R.C. Spindel, and K. Metzger, "Stability and identification of ocean acoustic multipaths," J. Acoust. Soc. Am. 67, 2011-2017 (1980).

A phase-coded signal with 64-ms resolution was transmitted at 10-min intervals for a 48-day period between an acoustic source moored at 2000-m depth and a bottom mounted receiver at ~3000-m depth and at ~900-km range. About 16 multipaths were resolved. They were stable in the presence of ocean fluctuations and could be identified (with some exceptions) from ray theory. The precision to which daily travel-time fluctuations along multipaths could be measured was better than 10 ms. The resolution, stability, identification, and precision is adequate for acoustic monitoring of mesoscale ocean variability by measuring travel-time variations along ray paths.

Exper, Prop, Mult, Appl.

Spiesberger, J.L. and P.F. Worcester, "Fluctuations of resolved acoustic multipaths at long range in the ocean," J. Acoust. Soc. Am. 70, 565-576 (1981).

A phase-coded signal centered at 220 Hz with 64-ms resolution was transmitted at 10-min intervals between an acoustic source moored at 2-km depth and a bottom-mounted receiver at ~3-km depth and at ~900-km range. A variety of fluctuation statistics (pulse and cw) are computed for three resolved multipaths from a 32-day record. The fluctuations are compared with theoretical predictions based on internal wave scattering. Some measurements agree with theory; measurements that disagree differ by amounts that are statistically significant but not large. Uncertainty of the internal wave energy level could account for some discrepancies. Some theoretical results are very sensitive to small changes of the second derivative of the mean sound-speed profile. There are substantial fluctuations at frequencies below those that can be accounted for by internal waves.

Exper, Stat, Mult, Strong.

1.) Observed and theoretical values of the first through fifth moments are given for the stationary and nonstationary record.

Stanford, G.E., "Low frequency fluctuations of a CW signal in the ocean," J. Acoust. Soc. Am. 55, 968-977 (1974).

Amplitude and phase fluctuations of underwater acoustic signals measured during a series of CW experiments have been statistically analyzed in order to obtain a better understanding of long-range acoustic propagation. The signals were transmitted along a 1318-km path from Eleuthera to Bermuda that utilized a stationary projector and two stationary receivers. The analysis extends previous long-range propagation studies by examining phase fluctuations as well as amplitude fluctuations. The amplitude fluctuations were almost Gaussian in distribution and exhibited a coefficient of variation that ranged from 42% to 65%. Power spectrum levels for these fluctuations underwent their greatest change when the frequency f was between 5 and 20 cycle/h, where the spectrum level was proportionately varied between $(1/f)^2$ and $(1/f)^4$. In the region between 20 and 120 cycle/h, the spectra exhibited seasonal effects, showing a 9-dB difference in spectrum level between March and July. Correlation time for the phase fluctuations varied from 35 to 46 min, exceeding the amplitude fluctuation correlation time by a factor of seven. Power spectrum levels for the phase fluctuations decreased monotonically from 0.3 to 120 cycle/h and were approximately proportional to $(1/f)^{5/2}$.

Exper, Stat, IWave, GWave, Mult.

1.) The experiment measured acoustic propagation between Eleuthera, Bahamas and Bermuda.

Strohbehn, J.W. and S.F. Clifford, "Polarization and angle-of-arrival fluctuations for a plane wave propagated through a turbulent medium," IEEE Trans. on Antennas and Propagation AP-15, 416-421 (1967).

Abstract—The correlation function of the fluctuations of the depolarized component of a plane wave as a function of the distance between two parallel line-of-sight paths is derived in terms of the index of refraction variations. A first-order solution to the wave equation is found using spectral analysis techniques. The mean square polarization fluctuation is predicted to have a λ^2 dependence, in contrast to the work of another author which showed no wavelength dependence. Some numerical values are calculated and the restrictions on the solutions are discussed. At optical wavelengths the depolarized component is extremely small. From the point of view of minimizing the noise introduced by a turbulent atmosphere, polarization modulation seems attractive compared to amplitude or angle modulation.

The problem of determining the angle-of-arrival fluctuations when using a wave optics formulation is discussed. If one accepts the statement that the angle-of-arrival is the normal to the wave front at any point, then the correlation function of the angle-of-arrival is simply related to the correlation function of the phase fluctuations and agrees with the ray optics results.

Theo, Opt, Prop.

Sussman, B. and W.G. Kanabis, "Time-smear and frequency-smear studies on the BIFI range," J. Acoust. Soc. Am. 50, 1038-1042 (1971).

The BIFI range is a shallow-water acoustic range in Long Island Sound, about 19 miles long and 110 ft deep. Results of time-smear and frequency-smear studies made on this range are presented. It is shown how these results may be used to predict signal fluctuation. In time-smear studies, the received signal is divided into a front, a main arrival, and a tail. The relative energies of the three sections of the signal are computed, and these results are used to predict the range of signal fluctuations. The above analysis and computation are easily carried out on a digital computer using, as input, data automatically punched on cards. Frequency smear is the Doppler shift undergone by a signal as a result of being reflected from a moving surface. Many frequency-smear spectra were obtained for varying sea states, and, from these, dispersion as a function of sea state was calculated. The dispersion increased with sea state, in agreement with theory.

Exper, Shallow, Prop, Mult.
1.) The experiment was conducted in the Long Island Sound.

Talham, R.J., "Ambient-Sea-Noise Model," J. Acoust. Soc. Am. 36, 1541-1544 (1964).

A model of ambient sea noise is developed under the assumption of a surface distribution of noise sources. Volume absorption and the effects of refraction and reflection over long-range paths are included. The derived directional noise field is expressed as a function of vertical arrival angle, with the parameters being velocity profile, surface distribution, bottom-reflection coefficient, surface-reflection coefficient, and frequency. Several forms of surface source directionality are considered. In an example representative of deep-water and low-sea-state conditions, the model predicts that most of the low-frequency acoustic energy at the ocean bottom should arrive over nearly horizontal paths. This is in agreement with reported measurements. Methods of incorporating the effects of sea state into the model are discussed.

Nois, Mod, RSurf.

Tarng, J.H., C.C. Yang, and S.T. McDaniel, "Acoustic beam propagation in a turbulent ocean," J. Acoust. Soc. Am. 84, 1808-1812 (1988).

Effects of random fluctuations of sound speed in the ocean on acoustic beam propagation are investigated. These effects are especially interesting because of the existence of the vertical sound-speed profile and hence the occurence of multiple-path propagation. The path integral technique is utilized to compute the average intensity. By examining the variations of the average intensity, the following conclusions are drawn: Random fluctuations not only smooth the oscillations of the intensity, which are due to the interference among multiple paths, but also broaden the beam. It is found that this broadening is asymmetric and the energy in the beam moves toward the deeper side of the beam. This phenomenon is attributed to the effect of the vertical sound-speed profile.

Theo, HF, Mult, Mod, Prop.

Tatarski, V.I., Wave Propagation in a Turbulent Medium, McGraw-Hill, New York (1961).

Theo, Stat, Prop.

Tateiba, M., "Multiple scattering analysis of optical wave propagation through inhomogeneous random media," Radio Science 17 (1), 205-210 (1982).

A moment equation is obtained in the small angle approximation for optical waves propagated through such a random medium that the material parameter fluctuates inhomogeneously in the direction of propagation and homogeneously in the direction transverse to the propagation path. The equation is an extension of the conventional moment equation and is derived by the same method as used in a homogeneous random medium. The limit of applicability of the equation is clear, and the equation can be applied to most of the practical cases of optical propagation through inhomogeneous random media. The inhomogeneous randomness is contained merely within the coefficient of the equation. Some effects of the inhomogeneous randomness are precisely given by solving the moment equation. A multifrequency moment equation can also be given.

Theo, Prop, Opt, Atm.

Twersky, V., "Scattering by discrete random media," Proceedings of the Symposium on Turbulence of Fluids and Plasmas, MRI Symposium Proceedings, XVIII (Brooklyn, N.Y.: Polytechnic Press of the Polytechnic Institute of Brooklyn, 1968).

Several representations for the scattering of waves by statistical distributions of discrete obstacles are discussed and applied, and resulting explicit approximations for ensemble-averaged functions are compared. For practical purposes, simplified forms are given for the coherent phase shift, the coherent intensity, the incoherent intensity, and the covariant magnitude and phase; the last three functions also provide the variances and covariance of phase-quadrature components of the field. The simplified forms are designed for diagnostic applications, i.e., for inverting data to help isolate some of the fundamental parameters of the components and of their distribution via scattering measurements.

Theo.

1.) Equations are formulated for wave propagation past a single scatterer, and through sparse and dense distributions of scatterers.

Unni, S. and C. Kaufman, "Acoustic fluctuations due to the temperature fine structure of the ocean," J. Acoust. Soc. Am. 69, 676-680 (1981).

The effect of oceanic temperature fine structure on sound transmission is investigated. The model used assumes that the layered fine structure is advected horizontally and vertically by the internal waves. Taylor's frozen turbulence hypothesis is then used to determine the space–time variations in sound speed. We compare our results to those of Ewart's Cobb Seamount experiment [J. Acoust. Soc. Am. 60, 46 (1976)]. The agreement between the calculated spectrum of the log-intensity fluctuations and the experiment is excellent except at low frequencies ($\omega \lesssim 0.3$ cph) and extends, at high frequencies, even beyond the internal wave frequency range. Previous calculations based on the internal wave model of turbulence have consistently underestimated these fluctuations in this frequency range. The agreement between the observed and the previously calculated phase fluctuations is not affected; that is, the fine structure adds little to the phase fluctuations.

Fine, Mod, Exper, IWave, HF.

1.) "Considering the fine structure effects separately (from the internal wave effects), we find over a considerable range of frequencies, the log-intensity fluctuations are almost entirely due to the fine structure."

Urick, R.J., "Models for the amplitude fluctuations of narrow-band signals and noise in the sea," J. Acoust. Soc. Am. 62, 878-887 (1977).

The sound from a steady distant sinusoidal source in the sea fluctuates in amplitude because of multipath interferences, surface motion, internal waves, microstructure, and other propagation effects. Such fluctuations are found to follow a Rician or modified-Rayleigh distribution having as a parameter the fraction of random power in the received signal. At the output of conventional sonar processor—namely, a narrow-band filter, a squarer, and an integrator—the fluctuation statistics are determined by the propagation processes occurring in the sea between source and receiver. On the other hand, ambient sea noise is found, from analyses of field recordings, to have fluctuation statistics determined by the processor itself; ambient noise samples at the processor output obey a chi-square distribution having a number of degrees of freedom equal to twice the bandwidth-time product of the processor, as would be expected from a Gaussian input. The two distributions—Rician power for signals and chi-square for noise—while formally different, have remarkable similarities in the limits. In short, the output fluctuation statistics of narrow-band signals and Gaussian ambient noise can apparently be predicted from estimates of the degree of randomness introduced by the prevailing propagation conditions, and from a knowledge of the processor, respectively, provided these statistics remain stationary during the analysis period.

Mod, Stat, Nois, Mult.

Uscinski, B.J., "Analytical solution of the fourth-moment equation and interpretation as a set of phase screens," J. Opt. Soc. Am. A 2 (12), 2077-2091 (1985).

An approximate solution for the parabolic fourth-moment equation is found in the form of a multiple convolution over spatial frequencies that is extremely accurate in the case of multiple scatter. The physical significance of this solution is that it represents the extended medium as a large number of equally spaced weak phase-modulated screens. The multiple convolution can be evaluated approximately in closed form as a single integral referred to as the fundamental solution, which is useful for investigating the general behavior of the intensity-fluctuation spectra. It also allows more exact estimates to be made of the multiple convolution. These theoretical results are also compared with numerical simulations of the corresponding propagation experiment.

Theo, Stat, Plane, Prop.

Uscinski, B.J., "Intensity fluctuations in a multiple scattering medium. Solution of the fourth moment equation," Proc. R. Soc. Lond. A 380, 137-169 (1982).

The intensity fluctuations arising when a wave propagates through a medium containing weak random inhomogeneities of refractive index are described by a parabolic equation for the fourth moment of the wave field. The present paper obtains an analytical solution for this equation when an initially plane wave is normally incident on a half-space containing such a medium. The solution is in the form of a multiple convolution and is valid even for multiple scatter. The multiple convolution is evaluated to yield an expression for the spatial frequency spectrum of intensity fluctuations. This spectrum is valid for any autocorrelation function of refractive index irregularities. Media with a Gaussian autocorrelation function and a Kolmogorov-type autocorrelation function of refractive index irregularities are treated as examples. Finally the spatial frequency spectra of intensity fluctuations are integrated to give the scintillation index curves as functions of distance of propagation in the medium. The regions of validity of the different approximations are discussed and the limits of error associated with the solutions are given.

Theo, Stat, Prop.

Uscinski, B.J., "Intensity fluctuation spectra in a multiply scattering medium," Physics of the Earth and Planetary Interiors, 21, 134-147 (1980).

Large intensity fluctuations arising in a wave which propagates through a medium containing weak random inhomogeneities of refractive index are studied. Physical arguments are used to show how and why these large fluctuations are produced, and also to derive expressions for the spectrum of spatial frequencies present in the intensity fluctuations. Their dispersion, i.e. the scintillation index, is also derived. It is shown that there are three distinct regions of intensity fluctuations: that of small intensity fluctuations but where the phase fluctuations can be large: a focusing region where the scintillation index has peaks greater than unity; and finally a far-field region where the scintillation index saturates to unity. These results and the accompanying expressions agree with certain analytical solutions of the fourth-moment parabolic equation. The same methods are then used to obtain the spectra of time-frequencies in the different regions when the medium fluctuates in time but does not drift. The behaviour of the spectrum is investigated and it is shown that in the focusing region it behaves like ω^{-1} over a large range of frequencies. In the far-field region it becomes a Gaussian spectrum.

Theo, Prop.

Uscinski, B.J., "Parabolic moment equations and acoustic propagation through internal waves," Proc. R. Soc. Lond. A 372, 117-148 (1980).

Internal waves present in the ocean modulate its acoustic refractive index so that it behaves like a random weakly irregular medium with respect to an acoustic signal. The parabolic equations for the propagation of the moments of an acoustic wave are applied to this case to describe the random fluctuations of a sound wave in the ocean. A form of the Garrett–Munk spectrum with a continuous range of vertical wavenumbers instead of a discrete set of mode numbers is used to describe the irregularities of refractive index due to internal waves and to obtain the transverse autocorrelation function that appears in the moment equations. This transverse autocorrelation function differs in several important aspects from that of a turbulent medium with 'frozen' irregularities advected with the medium. Some analytical solutions for the fourth and second moments are given. The solution of the fourth-moment equation is extended to give a new result: the temporal frequency spectrum of the intensity fluctuations This spectrum, which behaves like ω^{-1} in the region where the fluctuations. are large but not saturated, describes a feature common, under certain conditions, to optical and radio-wave scatter as well as to the acoustic case. The theory is compared with some experimental observations of acoustic scattering by internal waves where a frequency spectrum of this type first seems to have been observed.

Theo, Prop, Stat, IWave.

1.) The Born approximation is used to calculate the scattering of acoustic waves by internal waves.

Uscinski, B.J., The Elements of Wave Propagation in Random Media (McGraw-Hill, New York, 1977).

Theo, Stat, Prop.

Uscinski, B.J., "Successes and failures of multiple-scatter theory," in Fluctuation Phenomena in Underwater Acoustics: an Underwater Acoustics Group Conference held at Weymouth, England 9th/10th December 1986, Proceedings of the Institute of Acoustics, Volume 8 Pt. 5, Institute of Acoustics, Edinburgh (1986).

During the last five years there have been a number of important advances in multiple scatter theory. As a result encouraging agreement was obtained between the new theory and previously unexplained experimental data. In particular, the time spectra of acoustic intensity fluctuations caused by ocean internal waves [1], which failed to agree with the results of Rytov theory and its modifications, now fitted the predictions of the new theory well [2], [3], [4].

These initial successes have led to many papers aimed at extending and refining the theory. Much effort has also been devoted to investigating the accuracy of the theoretical expressions. In this context numerical simulations of random propagation have been particularly useful. Not only have they provided a check on theoretical results but have also given us much insight into properties of the wave-field fluctuations that cannot be obtained from ensemble average expressions.

In what follows we shall outline the new developments in theory and also describe the accompanying advances in numerical simulations. However, there are some important areas where theory still remains inadequate. For example, the cross-correlation of intensity fluctuations at different wave-frequencies cannot be satisfactorily described, nor can the probability distribution of the intensity fluctuations be derived theoretically.

Theo, Mod, Prop, IWave.

Uscinski, B.J., C. Macaskill, and T.E. Ewart, "Intensity fluctuations. Part I: Theory," J. Acoust. Soc. Am. 74, 1474-1483 (1983).

This paper deals with the problem of the intensity fluctuations arising in a wave when it propagates through a medium that is randomly inhomogeneous in space and time. It is assumed that multiple scattering can occur and that the intensity fluctuations can become large. The parabolic moment equation for the fourth moment of the wave field is solved for a monochromatic point source immersed in the medium. Approximate expressions are obtained for the space–time spectrum of intensity fluctuations at any distance in the medium. The solution of the fourth moment equation is compared with results of the Rytov method of smooth perturbations, and the limitations of the latter are discussed.

Theo, Stat, Prop.

Uscinski, B.J. and D.E. Reeve, "The effect of ocean inhomogeneities on array output," J. Acoust. Soc. Am. 87, 2527-2534 (1990).

The performance of line arrays is significantly affected by the irregular spatial variations that develop in acoustic waves when they propagate in the ocean. A numerical technique that has been successful in simulating the spatial variations observed in ocean acoustic experiments has been used to study their effect on array performance. Analytical expressions, helpful for describing the output of an array in such a spatially varying sound field, have been derived on the basis of the parabolic second- and fourth-moment equations. The present paper is confined to treating vertically deployed arrays.

Mod, Plane, IWave, Theo.

Wagar, J.L., "Concurrent underwater acoustic wave front fluctuations at two frequencies over a 75-nmi path," J. Acoust. Soc. Am. 74, 226-231 (1983).

An experiment was performed to investigate the fluctuations in wave front shape of signals transmitted over a distance of about 75 nmi from a ship-suspended sound source to a bottomed set of receivers. An experimental set of eight receivers, spanning a distance of about 2300 ft in both the downslope and cross-slope directions, was laid on a 26° slope southwest of Bermuda at about 5000-ft depth. Pulses of 200- and 400-Hz signals were transmitted alternately from the projector, by the second-order RSR mode; these were recorded on an oscillograph, and delays in arrival time at each receiver were measured. Plane wave fronts were fitted to the delay data, and the azimuth and elevation angles for the wave fronts were calculated. The effect of ship motion and stationary effects were removed from the raw delays. Plane wave front fits to the adjusted data were made, and deviations from these wave fronts were found for each receiver. The wave fronts are characterized by two actions: (1) gross wave front rocking and tilting, and (2) crinkling of the wave front (short-scale effects, a dimension smaller than the maximum receiver spacing).

Exper, Mult, Plane.

Wang, T. and J.W. Strohbehn, "Perturbed log-normal distribution of irradiance fluctuations," J. Opt. Soc. Am. 64, 994-999 (1974).

In this paper, we try to clarify some of the issues involved in the log-normal paradox for irradiance scintillations of an optical wave propagating through the turbulent atmosphere. Quite arbitrarily, a perturbation has been introduced in the log-normal distribution of the irradiance fluctuations. The results show that the log-irradiance variance and covariance functions are extremely sensitive to the log-normal assumption. We find that the deviation from the log-normal distribution, in the saturation region, may be detectable experimentally. This appears to be confirmed by recent Russian experimental results. We also show that our results lend insight into other distributions as well. In particular, there are certain regions where the Rice–Nakagami probability distribution cannot exist.

Opt, Atm, Prop, Stat.

Weston, D.E., "Singing in shallow-water ambient noise" J. Acoust. Soc. Am. 88, 1020-1031 (1990).

The spectrum of the ambient noise has been observed for two sites about 40 m deep in the Bristol Channel. For winds above 5 kn (2.6 m/s), there is a series of characteristic peaks, e.g., at 10, 28, 47 Hz, etc. Up to six peaks have been seen, the frequency of each varying inversely with the water depth as the latter changes through the tidal cycle. The peaks are due to a combination of resonance effects, associated with angles near the vertical and angles near the steep critical angle for the underlying rock. It is shown how information may be deduced on sediment depth and on the presence or otherwise of seabed gas. A similar effect has been seen for water 595 m deep in the Norwegian Sea, with a peak at 1.7 Hz. The significance is discussed for theories of ambient noise and acoustic transmission. An account of the depth dependence of shallow-water ambient noise at higher frequencies is appended.

Exper, Shallow, Nois, Theo, Prop, Mult, Tides, IWave.
1.) An experiment was conducted to the SW of England at the edge of the Bristol channel area.

Weston, D.E., "Sound Focusing and Beaming in the Interference Field Due to Several Shallow-Water Modes," J. Acoust. Soc. Am. 44, 1706-1712 (1968).

The formation of sharp rays or beams in Wood's model shallow-water propagation experiments [V. M. Albers, Ed., *Underwater Acoustics* (Plenum Press, Inc., New York 1963), pp. 159–192] is due to an angular selection, and the resulting interference between neighboring high-order modes. Details of the interference mechanism are considered. A given beam should vanish and then re-form with a calculable characteristic distance. The distance is about 4 m in Wood's experiments, and the focusing is clearly visible in his results. These ideas are also applied to a moiré fringe analog, to shallow-water propagation, deep-water propagation, and to transmission of images in fiber optics.

Shallow, Mult.

Weston, D.E. and H.W. Andrews, "Acoustic fluctuations due to shallow-water internal waves," J. of Sound and Vib. 31, 357-367 (1973).

Oscillations of up to 20 dB in level with total duration of about 1½ hours have been extensively seen in acoustic propagation experiments, and are due to internal waves. The transmission distances varied from 2 to 23 km in water 35 m deep, with frequency typically about 2 kHz. The internal waves and their acoustic effects were virtually switched on and off through the tidal cycle. This is due to the delicate and varying balance between the vertical density gradient and the shear gradient which together determine the Richardson number. The oceanographic structure was complicated, and included strong horizontal temperature gradients. For 1964 and 1965 experiments in the eastern part of the working area the effects tended to occur near slack water (+2 h relative to local high water) with periods of about 5 min and wavelengths apparently about 50 m. For 1967–1969 experiments in the western part the effects tended to occur near times of maximum flow (−1 and +5 h) with periods of about 20 min and wavelengths apparently about 500 m. Measurements from five other indicators of internal waves are included.

IWav, Exper, Shallow, Tides, Prop.

1.) The effect of shallow water internal waves on acoustic propagation at high and low tide is ascertained.

Weston, D.E. and P.B. Rowlands, "Guided acoustic waves in the ocean," Rep. Prog. Phys. 42, 347-387 (1979).

Progress is reported in this review on theory and experiment for deep and shallow water, especially since 1963—so the discussion is somewhat thinly spread. Theoretical approaches use rays, modes and a wide variety of other concepts. The classic case has a constant depth profile of sound velocity, but for long ranges one must allow for profiles varying both with range and with the transverse direction. Experimentally the transmission in deep water can be very good, especially for low frequencies in the SOFAR channel, where what little attenuation there is has recently been demonstrated to arise from a boron relaxation process. For shallow water the largest uncertainties at low frequencies can come from the unknown nature of the bottom structure. The study of variability has been helped by the existence of fixed sites, showing the occurrence of fluctuations with a great variety of mechanisms and time scales. For most of these the key is multipath interference, e.g. this comes into the recently emphasised acoustic effects of internal waves in the deep sea, and also into the spatial variability in deep channels.

Exper, IWave, Tides, Prop,

1.) A summary of temporal and spatial fluctuations research is given on pages 374-379 under the heading, "Variability".

Weston, D.E. and K.J. Stevens, "Interference of Wide-Band Sound in Shallow Water," J. Sound Vib. 21, 57-64 (1972).

Propagation experiments are described covering ranges of several km and frequencies between 0·1 and 1·2 kHz. The interference pattern for a source towed past a hydrophone demonstrates a focusing effect predicted theoretically. The interference pattern for a fixed source shows tidal changes of a magnitude agreeing with theory. From the results of both experiments the number of modes effective is found to vary as (frequency) × $(\text{range})^{-1/2}$, which has important implications. The mean frequency spacing of the interference peaks and the time dispersion of pulses are reciprocally related, and for isovelocity water both are almost independent of range and frequency.

Exper, Shallow, Tides.

Wilson and F.D. Tappert, "Acoustic propagation in random oceans using the radiation transport equation," J. Acoust. Soc. Am. 66, 256-274 (1979).

A new theoretical approach to the modeling of acoustic propagation in randomly fluctuating oceans has been developed based on radiation transport equations which describe the evolution of the mutual coherence function of the acoustic pressure field. A general computer program has been developed to implement this theory for a large class of scattering models, including volume scattering by random internal waves and rough surface scattering by fully developed seas or long wavelength ocean swells. The radiation transport code at present deals with CW signals in two spatial dimensions and is used to calculate transmission loss. It has been applied to the problem of surface duct propagation with special emphasis on modeling the scattering out of the duct by random fluctuations and below-duct ensonification. Comparisons have been made to a set of experimental data reported by Pedersen and Gordon [J. Acoust. Soc. Am. 37, 105–118 (1965)], with generally excellent results.

Theo, Mod, IWav, GWav, Prop, RSurf, Mult.
1.) The radiation transport equation is used to model acoustic propagation in a random ocean.

Winick, K.A., "Atmospheric turbulence-induced signal fades on optical heterodyne communication links," Applied Optics 25 (11), 1817-1825 (1986).

The three basic atmospheric propagation effects, absorption, scattering, and turbulence, are reviewed. A simulation approach is then developed to determine signal fade probability distributions on heterodyne-detected satellite links which operate through naturally occurring atmospheric turbulence. The calculations are performed on both angle-tracked and nonangle-tracked downlinks, and on uplinks, with and without adaptive optics. Turbulence-induced degradations in communication performance are determined using signal fade probability distributions, and it is shown that the average signal fade can be a poor measure of the performance degradation.

Atm, Opt, Stat.

Worcester, P.F., "Reciprocal acoustic transmission in a midocean environment: Fluctuations," J. Acoust. Soc. Am. 66, 1173-1181 (1979).

The fluctuations in acoustic receptions from simultaneous transmission of broadband pulses in opposite directions between two points in midocean have been examined. A variety of measures of the observed fluctuations (pulse and CW) for two well-resolved paths are somewhat ambiguous due to the short time series analyzed, but in most cases are not inconsistent with the theoretical predictions based only on sound-speed perturbations due to vertical displacements. Particle velocities are found to have significant effects when *differences* between reciprocal transmissions are examined.

Exper, Mult, Prop.

Worcester, P.F., G.O. Williams, and S.M. Flatte´, "Fluctuations of resolved acoustic multipaths at short range in the ocean," J. Acoust. Soc. Am. 70, 825-840 (1981).

The fluctuations in acoustic transmission between a broadband source and an autonomous receiver moored somewhat below the sound channel axis at 23-km range have been examined. The transmitted signal was centered at 2273 Hz. A variety of measures of the observed fluctuations (pulse and cw) for three well-resolved paths computed from 72 h of data are compared with theoretical predictions based on sound-speed perturbations due to internal wave vertical displacements. Measurement and theory are found to be consistent for some statistics and inconsistent for others. The theoretical predictions depend sensitively on the mean sound-speed profile.

Exper, Stat, IWav, Mult, Fine.
1.) The experiment was conducted in San Clemente Basin, 90 km west of San Diego.
2.) Fluctuations in arrivals along individual ray paths are studied

Yang, C.C. and S.T. McDaniel, "Fourth moments of acoustic waves forward scattered by a rough ocean surface," Waves in Random Media 1, 419-439 (1991).

Abstract. Three types of statistical fourth moments of acoustic waves forward scattered by a randomly rough ocean surface are derived and numerically evaluated. The first one is related to the scintillation index which characterizes intensity fluctuations. The second one is the two-position intensity correlation function which describes the spatial correlation of wave intensity. The third is the fourth-moment two-position coherence function which carries information on the phase fluctuations of the scattered wave. In the range of weak scattering, the ratio of the absolute value of the fourth-moment two-position coherence function over the two-position intensity correlation exactly describes the mean-square fluctuation of the relative phase between the two positions. The acoustic frequency is high so that the Kirchhoff approximation can be used. Two types of spectral functions for surface-height fluctuations are considered: a Gaussian spectrum and the Donelan–Pierson spectrum. The latter is obtained from a model for the fluctuations of the ocean surface height which are controlled by the wind speed at the ocean surface.

Theo, GWav, Stat, RSurf.
1.) The moment equations are used.

Zakarauskas, P., D.M.F. Chapman, and P.R. Stall, "Underwater acoustic ambient noise levels on the eastern Canadian continental shelf," J. Acoust. Soc. Am. 87, 2064-2071 (1990).

This paper reports the analysis of shallow-water ambient noise levels collected by Defence Research Establishment Atlantic during 14 cruises over the period 1972 to 1985. A weighted average is formed to de-bias the samples, with the aim of answering the question: "If one were to pick a site randomly on the eastern Canadian continental shelf at a random time, and perform an ambient noise measurement, what would be the expected noise level?" The samples are also grouped according to whether they were taken on the Scotian Shelf, the Grand Banks, or the Flemish Cap, and according to season. The frequency range covered is 30 to 900 Hz. The weighted mean and standard deviation of the noise levels are presented, as well as the correlation coefficient between the noise levels and wind speed. The results show that the eastern Canadian continental shelf as a whole presents levels that are characteristic of areas with high shipping density and good acoustic propagation, with the Scotian Shelf showing generally higher ambient noise levels. Finally, a comparison with Piggott's ambient noise measurements [C. L. Piggott, "Ambient sea noise at low frequency in shallow water of the Scotian Shelf," J. Acoust. Soc. Am. 36, 2152–2163 (1964)] on the Scotian Shelf is made, and an explanation for the observed difference is suggested.

Exper, Nois, Shallow, Wind.
1.) Results at several wind speeds are shown.
2.) Experiment were conducted in the following waters: the Scotian Shelf, the Grand Banks, the Flemish Cap and the Laurentian Channel.

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