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TURBULENCE EFFECTS UPON LASER PROPAGATION IN THE MARINE BOUNDARY LAYER

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ABSTRACT

Shipboard measurements of small scale temperature and velocity fluctuations have been accomplished to determine optical wave propagation properties of the marine boundary layer. Measurements were recorded for ocean conditions in Monterey Bay and in the confines of the Pacific Missile Range. Laser beam propagation measurements were performed in conjunction with the meteorological measurements.

INTRODUCTION

The propagation of a light beam through the atmosphere is affected by the refractive nature of the medium. This has important consequences for various optical systems applications including image resolution, optical communications, and laser radars.

In addition to the regular variation of atmospheric refractive index with altitude, there exist small inhomogeneities in the refractive index associated with fluctuations in the density and the temperature of the air. These cause random phase and amplitude distortions in propagating wave fronts and thus degrade spatial and temporal coherence therein. Hence, there is an increase in beam divergence which reduces the power density and degrades angle resolution. A non-uniformity in the illumination field is induced which impairs target detection statistics and reduces the efficiency of detection. Moreover, amplitude modulation noise is introduced, as well as alteration of the frequency distribution and polarization of the transmitted beam.

The magnitude of these effects place limitations on optical system performances and must be included in design considerations. It is desirable to have a theory sufficiently well-developed to permit derivation of propagation characteristics in real time from measurements of meteorological variables.

Descriptions of small scale fluctuations which affect laser propagations have not been as complete nor in the quantity for the overwater regime as for the overland regime. Overwater descriptions are necessary, even though considerable progress has been made in overland investigations such as from experiments by AFCRL. (Wyngaard et al., 1971). The necessity exists because of increasing evidence of the influence on atmospheric motions by oceanic waves. (Davidson, 1974). This wave influence has been observed to be significant enough to warrant re-examination of empirical expressions relating small scale properties to mean wind and temperature profiles.

It is toward this end that the research efforts of the Electro-Optics/Laser Technology Research Group at the Naval Postgraduate School have been directed in the last two years. A short review of the meteorological program of this study is now presented, together with some primary findings of the research.

THEORY

On the basis of the isotropic nature of small scale fluctuations, only one parameter is necessary to describe the intensity of the atmospheric refractive index fluctuations over many scales. (Tatarski, 1964). It is the refractive index structure function parameter, C_N^2, where

$$C_N^2 = [n'(x) - n'(x+r)]^2/r^{2/3} \tag{1}$$

Herein, $n'(x)$ and $n'(x+r)$ are refractive index fluctuations at two points on a line oriented normal to the mean wind direction separated by the distance, r. This distance, r, is less than the outer scale, L_0 - the lower end of the inertial subrange - and greater than the inner scale, ℓ_0 - the smallest scale of naturally occurring turbulence. The brackets in Eq. (1) designate an RMS evaluation of the quantities contained therein.

Fortunately, C_N^2 can be related to the temperature structure function parameter, C_T^2, in the following manner, i.e.,

$$C_N^2 = [79 \times 10^{-6}(P/T^2)]^2\, C_T^2 \tag{2}$$

where P = barometric pressure

T = atmospheric temperature.

Equally fortunately, both C_N^2 and C_T^2 are readily measurable quantities.

Since turbulence is nearly synonymous with density and temperature fluctuations, it is ultimately necessary to describe mean thermal stratification in terms of the atmospheric stability parameters, Ri (Richardson Number) and L (Monin-Obukhov Length). In this regard, concomitant measurements of both atmospheric mean profiles and flux gradients are necessary for a complete determination of atmospheric transmission behavior.

MEASUREMENTS

From optical measurements

$$C_N^2 = K\,\sigma^2\,\eta^{7/6}\,L^{11/6} \tag{3}$$

where K = constant dependent upon beam geometry

σ^2 = log intensity variance

η = laser wavelength

L = propagation pathlength

Since log intensity variance values are directly available from analog processing of phototube signals, pathline values of refractive index values are readily available.

Likewise, point measurements of C_T^2 (which ultimately lead to pointwise measurements of C_N^2) are readily accomplished. By definition,

$$C_T^2 = [T'(x) - T'(x+r)]^2/r^{2/3} \tag{4}$$

where $T'(x)$ and $T'(x+r)$ are temperature fluctuations at two points along the propagation path separated by the distance, r. Obviously, two fast response probes in conjunction with analog circuitry configured to yield RMS values of the measured temperature fluctuation differences can generate C_T^2 values directly. Systems using thin platinum wires as sensors have been developed to achieve such direct C_T^2 measurements in a band of 0-1 KHz.

Over the inertial subrange, the relation existent between the temperature structure function parameter, C_T^2 , and the Fourier Transform of the temperature correlation function, $\phi(k)$, is

$$C_T^2 = 4\phi(k)\,k^{5/3} \tag{5}$$

where k is the temperature spectrum wavenumber. (Kolomogorov, 1941) Thus, data obtained from one fast response temperature sensor can be treated to yield C_T^2 values. Herein, implicit use is made of Taylor's Hypothesis to relate correlation distance (r) to wavenumber (k) via the mean wind velocity ($\overline{U}$). Hence, it is necessary to obtain mean velocity values in conjunction with temperature spectrum measurements to arrive at final C_T^2 values.

A third approach toward the measurement of the temperature structure function parameter involves its dependence on the dissipations of turbulent kinetic energy (ε) and temperature variance (χ). (Corsin, 1951). Dimensional arguments relate the temperature spectrum to these parameters in the following manner:

$$\phi(k) = \beta\chi\varepsilon^{-1/3}\,k^{5/3} \tag{6}$$

Hence,

$$C_T^2 = \beta\chi\varepsilon^{-1/3} \tag{7}$$

where β is an empirically derived constant. Turbulence measurements demand the incorporation of hot wire or sonic anemometer gear to record the data that results in determinations of the kinetic energy dissipation term. Likewise, temperature variance measurements require fast response thermal systems to record the data that results in determinations of the temperature dissipation factor. Again, since the Taylor Hypothesis is utilized in conjunction with these dissipation data, the presence of a mean wind record is necessary for final determinations. Such a record is, of course, available from the anemometer gear used in conjunction with turbulence measurements.

It is to be noted that these determinations for C_T^2 hold for scales greater than the atmospheric turbulence microscale, ℓ_o , the smallest scale of naturally occurring turbulence. Physically, this microscale affects seeing conditions. Now, when equilibrium exists, the atmospheric turbulence spectrum is dependent only upon the rate of dissipation of turbulent kinetic energy (ε) and the kinematic viscosity of the constituent atmosphere (ν). (Lumley and Panofsky, 1964). Dimensional analysis yields,

$$\ell_o = (\nu^3/\varepsilon)^{1/4} \tag{8}$$

Now, over the inertial subrange, i.e., the range in turbulent velocity spectrum wavenumber space between the input of energy (large scales, small wavenumbers) and the dissipation region (small scales, large wavenumbers), Kolomogorov postulated that

$$\psi(k) = \kappa\,\varepsilon^{2/3}\,k^{-5/3} \tag{9}$$

where

$\psi(k)$ = velocity spectrum

κ = empirically derived constant.

Hence, velocity spectra in the vertical subrange can be treated to yield optically relevant results, viz., values of microscale.

As can be expected, the height variations of these optical parameters are of ultimate importance. Likewise, relationships between these turbulent (small scale) quantities and the mean (large scale) meteorological variables (wind speed, temperature gradient) are equally important. This latter similarity relationship is dependent upon atmospheric stability conditions and is characterized by relationships involving the Richardson Number (Ri) and the Monin-Obukhov Length (L).

RESULTS

Shipboard observational experiments to describe the height and stability dependence of small scale properties of atmospheric turbulence are being performed in Monterey Bay and over the open ocean off the west coast by a team of NPS investigators from the Departments of Meteorology, Oceanography, Physics, and Engineering. Simultaneous laser transmission experiments are being completed in conjuction with these meteorology studies. The shipboard sensor arrangement aboard the NPS Research Vessel, ACANIA, appears in Figure 1. Instrumentation consists of hot wire anemometers, platinum resistance wire thermometers, and lyman-alpha humidiometers for turbulence measurements and cup anemometers, quartz sensor thermometers, and lithium chloride hygrometers for mean determinations. Coincident accelerometer measurements in early experiments supported other results that indicated the high frequency portion of velocity spectra can be interpreted for dissipation rates and inner scale determinations.

First results were derived from structure function measurements using separated pairs of sensors. These yielded a consistent height dependence for C_T^2 of $z^{-4/3}$ over long periods (Fig. 2) during which C_T^2 at individual levels changed by a factor of three between minimum and maximum values. Although a $z^{-4/3}$ dependence was predicted by Wyngaard, 1971, for free convection results, the overwater results were observed in only slightly unstable conditions.

Several observational periods with near neutral stratification resulted in small temperature differences between the paired wires. This led to the use of temperature variance spectra using single sensors for estimating C_T^2. Preliminary spectral results obtained at four levels reveal differences from the $z^{-4/3}$ relationship depending on thermal stratification.

The observational experiments required to evaluate existing predictions with regard to the overwater regime emphasized the height dependence of both the temperature structure function parameter (C_T^2) and the turbulent kinetic energy dissipation factor (ϵ) that enters directly into microscale calculations (Eq. 8).

A typical plot of the height variation of C_T^2 for neutral atmospheric conditions is shown in Figure 3 (Lund, 1975). Herein, experimental agreement with the predicted -3/2 relationship is evident. A similarly typical plot of the height variation for ϵ, again for neutral atmospheric conditions, is shown in Figure 4. Again, a close agreement with the -1 relationship determined from overland analyses is portrayed.

Typical results for temperature structure function data recorded in unstable atmospheric conditions (i.e., ocean water temperature greater than ambient air temperature) are shown in Figure 5 (Bone, 1974). The general slope of this plot agrees very well with the -4/3 predictions from overland analyses. One might expect slightly greater negative slopes for greater instability situations. However, -4/3 should be the limiting slope if overland results are valid overwater. Since C_T^2 is a function of both ϵ and χ (Eq. 7), it is possible that wind-wave coupling effects upon ϵ values would influence C_T^2 values.

Results on ϵ height variations (again, for unstable atmospheric conditions) are shown in Figure 6. Negative slopes greater than -1 are noted herein. This is in agreement with present boundary layer theory for overland results.

This deviation of the slope from -1 was examined to determine if perhaps it could be accounted for by the influence of unstable stratifications. A slight shift toward a -1 slope was observed. However, complete adjustment to a -1 slope could not be accomplished. The fact that stability corrections did not completely restore the -1 slope leads to the speculation that wind-wave coupling effects are present (Johnston, 1974).

CONCLUSION

In general, the preliminary height variations of C_T^2 and ϵ observed in this study agree well with the overland expressions. This agreement buttresses the constant flux assumption which is the cornerstone of the developed predictive analyses. However, the possible existence of wind-wave coupling effects will remain a matter of speculation until a sufficient data base is recorded to adequately explain the discrepancies evident in "corrected" unstable atmospheric results.

In general, the present shipboard system is providing results which provide useful description of those small scale turbulent properties which are important for optical transmissions in the marine environment.

Future work in this regard will include determinations of C_T^2 utilizing the Corsin relation (Eq. 7) which in practice involves operations with differentiated velocity and temperature fluctuation signals. Furthermore, analysis of the spectra of these differentiated velocity signals will provide a second method for estimating ϵ by allowing the upper limit of the inertial subrange of the velocity spectrum to be defined. Since the microscale is directly related to the dissipation wavenumber (via the Taylor Hypothesis), the turbulent kinetic energy dissipation factor will be obtained in conjunction with simultaneous laser transmissions involving several wavelength and propagation distances.

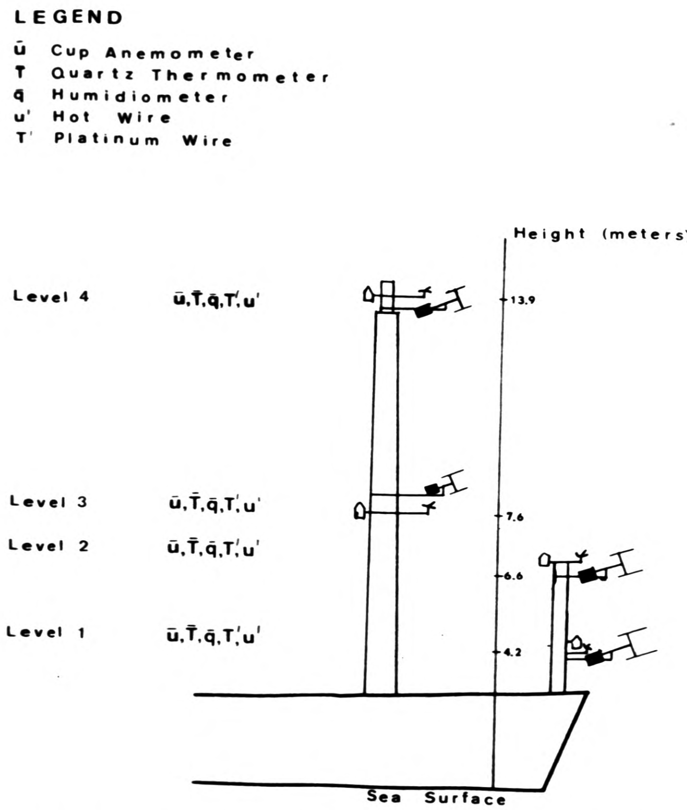

FIG. 1 SENSOR MOUNTING ARRANGEMENT ON R/V ACANIA.

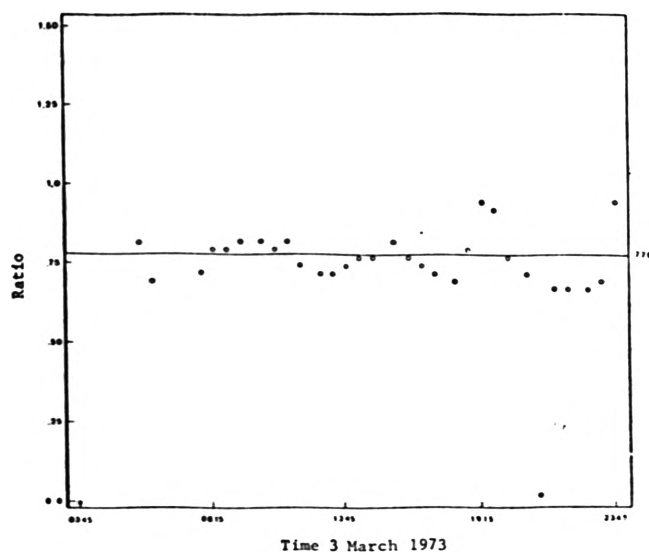

FIG. 2 OBSERVED VALUES OF RATIO, C_T(38 FEET)/ C_T(26 FEET) VERSUS TIME IN UNSTABLE CONDITIONS. THE .776 VALUE CORRESPONDS TO A $Z^{-4/3}$ RELATIONSHIP.

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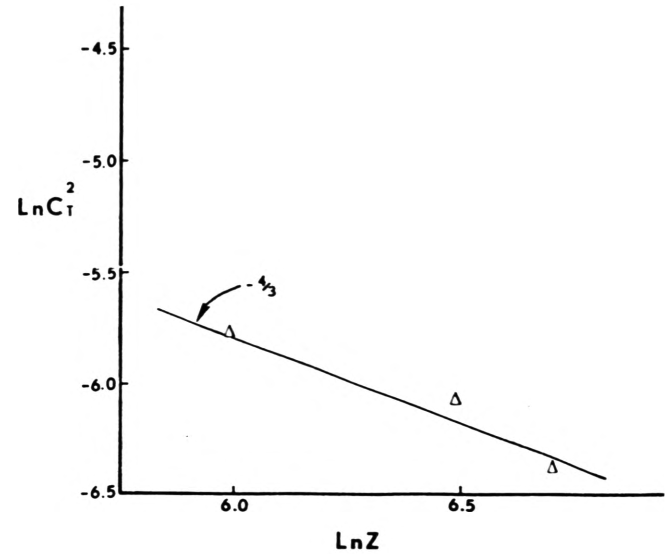

FIG. 5 C_T^2 VERSUS HEIGHT, OBSERVED DURING UNSTABLE CONDITIONS.

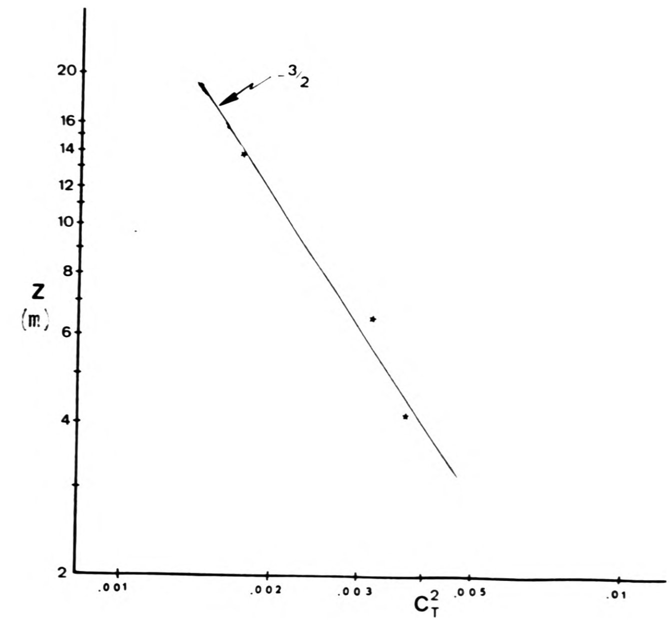

FIG. 3 C_T^2 VERSUS HEIGHT, OBSERVED DURING NEUTRAL CONDITIONS.

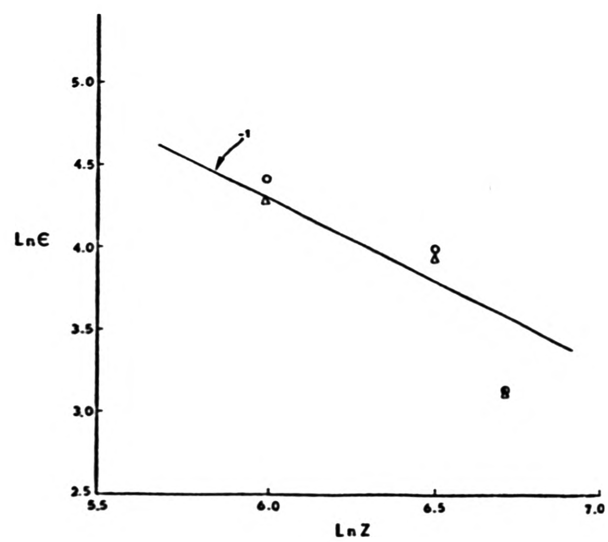

FIG. 6 ε VERSUS HEIGHT, OBSERVED DURING UNSTABLE CONDITIONS.

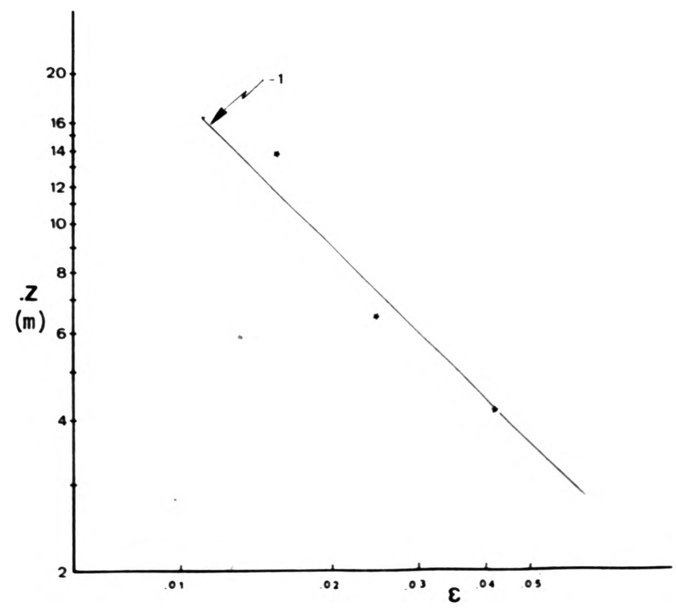

FIG. 4 ε VERSUS HEIGHT, OBSERVED DURING NEUTRAL CONDITIONS.

DISCUSSION

R. S. Brodkey, Ohio State University: What is the effect of the vertical stability of your ship? That is what happens when the boundary layer moves up and down due to wave or ship motion?

Davidson: Because the gradient of the measured quantities is not constant with respect to height, a bias is expected in our representation due to the ship vertical motion. However, our measurements are not expected to be sensitive enough to detect this bias.

J. M. Delhaye, Centre d' Etudes Nucleaires de Grenoble: I notice in your paper that you are measuring the fluctuating component of the humidity. Could you give some information on the lyman alpha humidometer? What accuracy can you expect with his technique?

Davidson: The Lyman-alpha sensor measures humidity as a function of the absorption of ultraviolet light by the 1215°A° Lyman-alpha transition of hydrogen in water vapor. It consists simply of a UV source tube and detector, separated by an absorbing air gap (1 cm) representing the ambient medium. Because water soluble windows (LiF or MgF_2) are required for transmission in the ultraviolet, the reference (dry air) voltage is highly variable. However, the signal versus vapor pressure curve has been found to be more stable, enough to obtain satisfactory calibration for fluctuation statistics. We believe the variance spectral estimates of specific humidity in the 1 to 20 Hz band can be defined within 30%, which we assign to estimates of the humidity structure function parameter, C_q^2.