AFFDL-TR-68-23

TAKE-OFF AND LANDING CRITICAL ATMOSPHERIC TURBULENCE (TOLCAT) ANALYTICAL INVESTIGATION

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The Travelers Research Center, Inc.

TECHNICAL REPORT AFFDL-TR-68-23
7235-302

APRIL 1968

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300 - June 1968 - CO455 - 37-798

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FOREWORD

This report was prepared by The Travelers Research Center, Inc. (TRC), Hartford, Connecticut, in partial fulfillment of USAF Contract Number F33615-67-C-1557 "Take-Off and Landing Critical Atmospheric Turbulence (TOLCAT)," ADP 682E. The work was administered under the direction of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with William P. Johnson (FDTE) as Project Engineer.

The work reported in this study was conducted by the Micro and Meso Meteorology Division, Environmental Sciences Department of TRC. Mr. N. E. Bowne was Principal Investigator and Mr. G. E. Anderson cooperated in the project effort. The work was carried out at TRC as Project 7235; the work was accomplished during the period from April 1967 to March 1968. The final, completed report was submitted in March 1968.

This technical report has been reviewed and is approved.

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ABSTRACT

A review and analysis of current knowledge of turbulence in the atmospheric boundary layer is presented. Particular emphasis is on identifying and analyzing the aspects of low altitude turbulence that have the greatest influence on the design and operation of V/STOL aircraft in the atmospheric boundary layer. The nature, quality, and applicability of reported turbulence measurements is discussed, and several resulting empirical descriptions of the boundary layer are compared. Deficiencies in the data are specifically identified and discussed. The foundations, assumptions, and limitations of the statistical analyses of boundary layer turbulence which are now in use are identified and discussed. The nature of atmosphere-vehicle interactions and current and potential methods of analyzing these interactions are discussed.

It was found that the most serious problem for V/STOL operations and design is the encounter of a V/STOL vehicle with large, intense individual disturbances. Some basic disturbance modes and some causal relationships are known, but few experimental studies were designed for providing this type of information. Most current analytic techniques are unsuitable for the required analysis. The nature of the flow features of interest and the data required to analyze them are indicated.

Distribution of this abstract is unlimited.

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SYMBOLS

A	constant in empirical spectral functions
a	Fourier coefficient
B	constant in empirical spectral functions
b	Fourier coefficient
C	constant in empirical spectral functions
c	constant in empirical spectral function
C_p	specific heat at constant pressure
E	energy
F	external force on fluid
f*	normalized frequency $= n\ z/U$
G	normalized spectra function $= n\ S/(\sigma)^2$
g	gravitational acceleration
H	total heat flux
h	enthalpy per unit mass
K	eddy transport coefficient
k	wave number
L	Obukhov scale length of turbulence
ℓ	Prandtl's turbulent mixing length
n	frequency
P	pressure
R	correlation coefficient
Ri	Richardson's number; $Ri = \frac{g}{T} \frac{dT}{dZ} / \left(\frac{dU}{dZ} \right)^2$
r	generalized distance measure
S(n)	spectrum expressed as function of frequency
T	Temperature
t	time
U	mean, or time-averaged velocity
u	Cartesian velocity component parallel to U
v	horizontal transverse Cartesian velocity component
w	vertical transverse Cartesian velocity component

SYMBOLS (Continued)

x	Cartesian coordinate parallel to U; also generalized coordinate
y	horizontal transverse Cartesian coordinate
z	vertical Cartesian coordinate
α	angle between wind and line of anemometers
β	parameter in Monin-Obukhov shear expression
γ	temperature lapse rate
θ	potential temperature
λ	wave length
μ	fluid viscosity
ν	kinematic viscosity
ρ	mass density
σ	variance
τ	correlation time lag; also shear stress
$\Phi(k)$	spectrum expressed as function of wave number
$\Delta(\ )$	difference notation

Subscripts

$*$	variable defined by flux, as $u_* = \sqrt{\frac{\tau}{\rho}}$ = shear stress velocity
c	concentration, as K_c = eddy mass diffusivity
h	heat, as K_h = eddy heat diffusivity
i, j	tensor indices
m	momentum, as K_m = eddy momentum diffusivity
0	reference value, as z_0 = reference height

Superscripts

$(\ )'$	indicates the fluctuating component of a variable
$\overline{(\ )}$	indicates an average

SECTION I

INTRODUCTION

The problem of operation of aircraft in a turbulent environment is becoming increasingly acute. Aircraft are designed and built for increasingly diverse operational modes and tasks in ever broader ranges of the atmosphere; the number and variety of problems of interaction with the atmosphere increase apace.

Recognition of the significance and complexity of the problem led to the organization in June 1966 of a US Air Force Program entitled, "Critical Atmospheric Turbulence (ALLCAT)." This Program was divided into individual CAT Projects according to altitude regimes of interest.

The subject of this report is Take Off and Landing Critical Air Turbulence (TOLCAT). TOLCAT is turbulence in the lowest altitude regime of those identified in the ALLCAT Program. The limits of the altitude regime of TOLCAT are somewhat flexible. The best working definition is determined, not by geometry, but by operational and phenomenological criteria. It is the region of the atmospheric boundary layer that is subject to significant shear, heat diffusion and roughness-generated turbulence. Operationally, it is the region within which rapid changes of flight mode must occur for typical aircraft (i.e., transitions from take-off and landing modes to climb or cruise modes). Since transition problems are particularly severe for V/STOL, (Vertical or Short Take-Off or Landing) aircraft, the emphasis in this program has been on the particular aspects of atmospheric turbulence that are most significant for V/STOL operations.

The approach used in this study was to survey the considerable volume of literature that has been published on the atmospheric boundary layer, turbulence, data analysis, and aircraft-turbulence interactions. The data, theories and conclusions were analyzed and sorted as to their value in modeling the present problem.

In general, it was found that only the most elementary aspects of V/STOL-turbulence interactions could be analyzed with the available theory and data. Gaping voids exist in both theory and data. Existing models of atmospheric turbulence, notably Pritchard's [38], have made the best use of the available knowledge. Further experimental data appear to be necessary to advance the analysis.

Review and analysis of previous work, led to the identification of specific deficiencies in the theory and data that limit realistic model making.

SECTION II

SUMMARY OF AVAILABLE DATA

Available data that completely describe the turbulent state of the atmosphere in even a limited volume do not exist and may never be acquired because of the complexity of the problem. However, available data are extremely deficient in even providing sufficient information for an initial realistic estimate of the three-dimensional structure of turbulence and its evolution with time. The primary reason for this state is the lack of observations of space variations. Aircraft observations obtained by Lappe, et al [24] provide a description of the Eulerian space spectrum of turbulence.

An Eulerian description is obtained from measurements at a fixed point or points. An Eulerian time measurement is exemplified by an anemometer on a mast that measures the motion of air past a point. Eulerian space measurement is obtained from simultaneous measurements at different points. An aircraft does not make simultaneous observations at different points on its flight path, but at low levels the speed of the aircraft is sufficiently greater than the speed of the air motions that measurements at short separations may be considered approximately simultaneous. Eulerian time measurements at a single point, usually on towers, are abundant, but neither aircraft nor single tower measurements provide an adequate description of air motions varying in space and time.

Aircraft measurements are deficient because they measure only the instantaneous field of turbulence as they fly through it. This measurement might be likened to a snapshot. The time changes are not obtained even by repeating the same flight path. Tower anemometer measurements provide the time history of the field of turbulence as it is advected past a point but provides no information on spatial behavior except by assuming that the Taylor hypothesis equating time and distance, $x = Ut$, is valid, a point that needs interpretation. These observations may be likened to motion pictures with a very limited depth of field. Carrying the photographic analogy to the requirements area, the data should be motion pictures made with a wide angle lens and great depth of field.

1. Flow Visualization

Perhaps naturally, one of the earliest references reviewed [42] reported attempts at turbulent flow visualization. Sherlock and Stout [42] reported a particularly ingenious yet simple technique for deriving a two-dimensional picture of the flow disturbances from measurements of a single velocity component (Fig. 1). Velocity traces from many levels of several towers were analyzed to produce an isotach map in a (t, z) or(x, z) plane. The success of the method is startling, but it is partly due to the fortunate but unusual circumstance of high wind but with low shear.

Similar "portraits" of turbulence were presented by Jones [19]. These presentations are derived from two-component velocity measurements taken at several stations across the wind at a single height. [i.e., a (t, y) or (x, y) plane] again, there is little shear in this plane.

Calculations were made at TRC under this subject contract with TRC data [16]. u, w component measurements from different levels on a single tower were used to calculate streamlines in a (t, z; x, z) plane. Shear in this plane distorted the cell portraits and they were not useful for visualizing the flow. The calculations did, however, filter the data. This revealed streamwise disturbance scales much larger than the vertical scales. The analysis is not quite clear, since sheared convection cells do tend toward the roll cell configuration (cf., [11], [18], [26]). Schlichting [41] describes a photographic technique, attributed to Nikuradse, of subtracting the mean motion at any particular station in a shear profile. In a remarkable series of pictures, he shows the turbulence at the match station to be selectively depicted. Turbulence at other stations "disappears."

2. Multiple Horizontal Anemometer Observations

Multiple anemometers have been used and the data analyzed for space correlations at three locations. Panofsky [35] has reported on the Great Plains data utilizing lines of anemometers along and across the wind at a height of two meters. Shiotani [43] has reported on a line of anemometers located along the shore of Shikoku Island at a height of 40 meters. Armendariz [1] has measured correlations between two anemometers along the direction of the wind at a height of 19 meters at White Sands Missile Range. Another set of observations reported by Frazier [12] were not

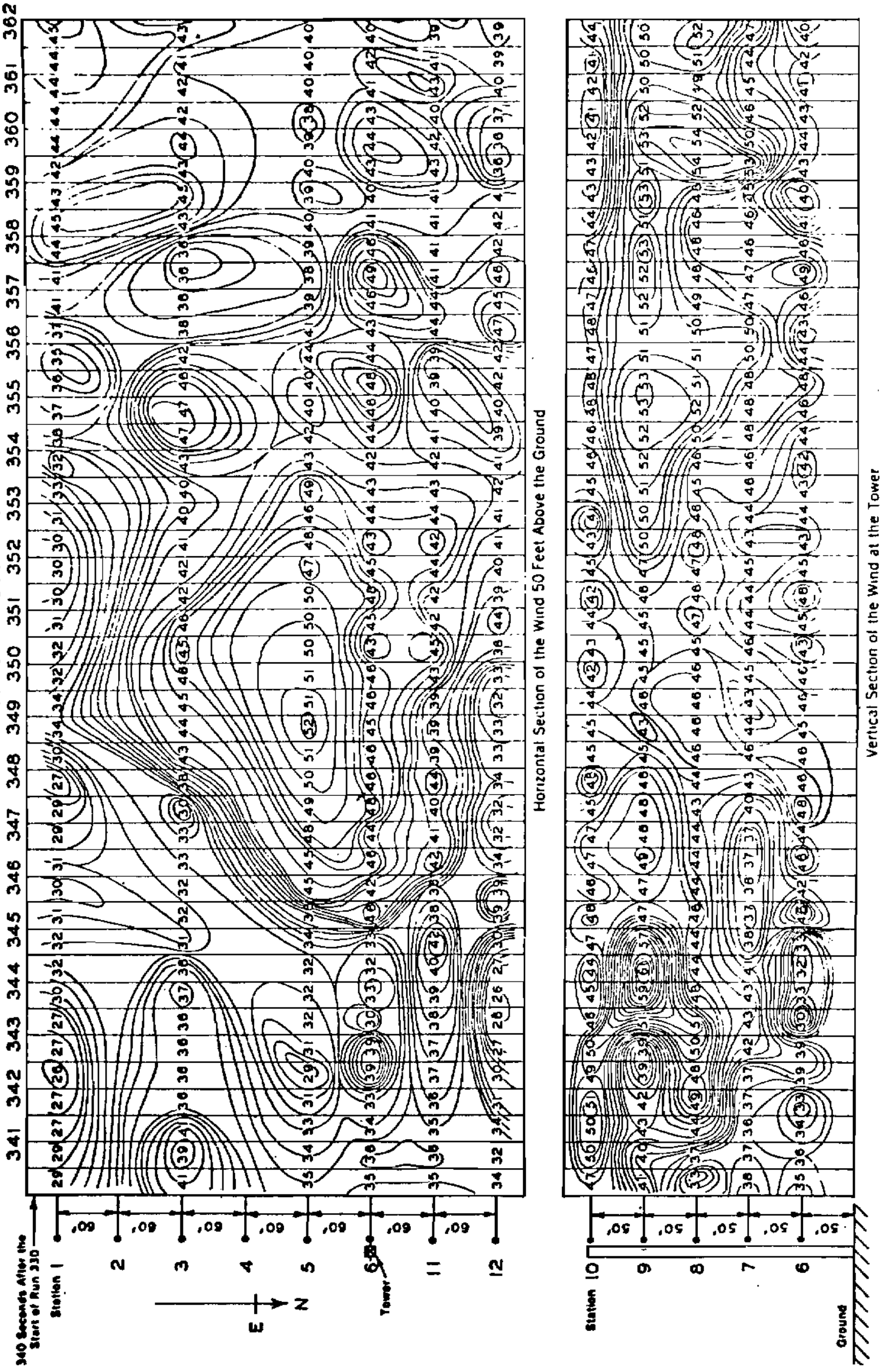


Figure 1. Wind gusts shown by isotachs. Reproduced from Sherlock and Stout [42]

considered adequate because the heights of anemometers changed to simulate a flat ballistic missile trajectory. Obukhov [32] published results for very small separations corresponding to the inertial subrange.

3. O'Neill, Nebraska Data

Panofsky [36], and Panofsky, Cramer and Rao[35] have discussed the O'Neill data taken at a height of two meters along a line of anemometers extending for 90 meters. Observations were obtained for both daytime and night periods. The level of turbulence was so low at night that only the elongation of eddy motions in the direction of the wind is of interest and attention will be concentrated in this study on the daytime observations. Figure 2 shows time lagged and space correlations for typical daytime observations at O'Neill from Panofsky, Cramer and Rao [35]. The space correlations were smoothed by eye and the lateral and longitudinal spectra were computed. A log-log plot is shown in Fig. 3 and the variance-log plot is shown in Fig. 4. Since only the correlation values were used, these are relative spectral densities, i.e., they can be assumed to have been divided by the total variance. Both components appear to obey the -5/3 slope law for wavelengths less than 30 feet. It should be pointed out that the lateral and longitudinal data were not obtained simultaneously, but were obtained in different observational periods. This helps explain the difference in high wave number energy illustrated in Fig. 4. The surface at O'Neill was very flat and grass covered so convective turbulence was important in daytime situations. These spectra are not significantly different from time spectra.

These data were also used to test Taylor's hypothesis that $x = Ut$. If the wind is along or at a small angle to the line of anemometers, and the eddies travel with the wind at the height of observation, the lag time, Δt, for maximum correlation is related to the distance, Δx, between anemometers by

$$\Delta t = \Delta x \frac{\sec \alpha}{U} \tag{1}$$

where α is the angle between the mean wind direction and the line of anemometers and U is the mean wind speed. The O'Neill daytime data generally show good agreement with the hypothesis but the maximum distance measured was 300 feet. Figure 5 shows a diagram with correlation functions lagged both in time and space with lines

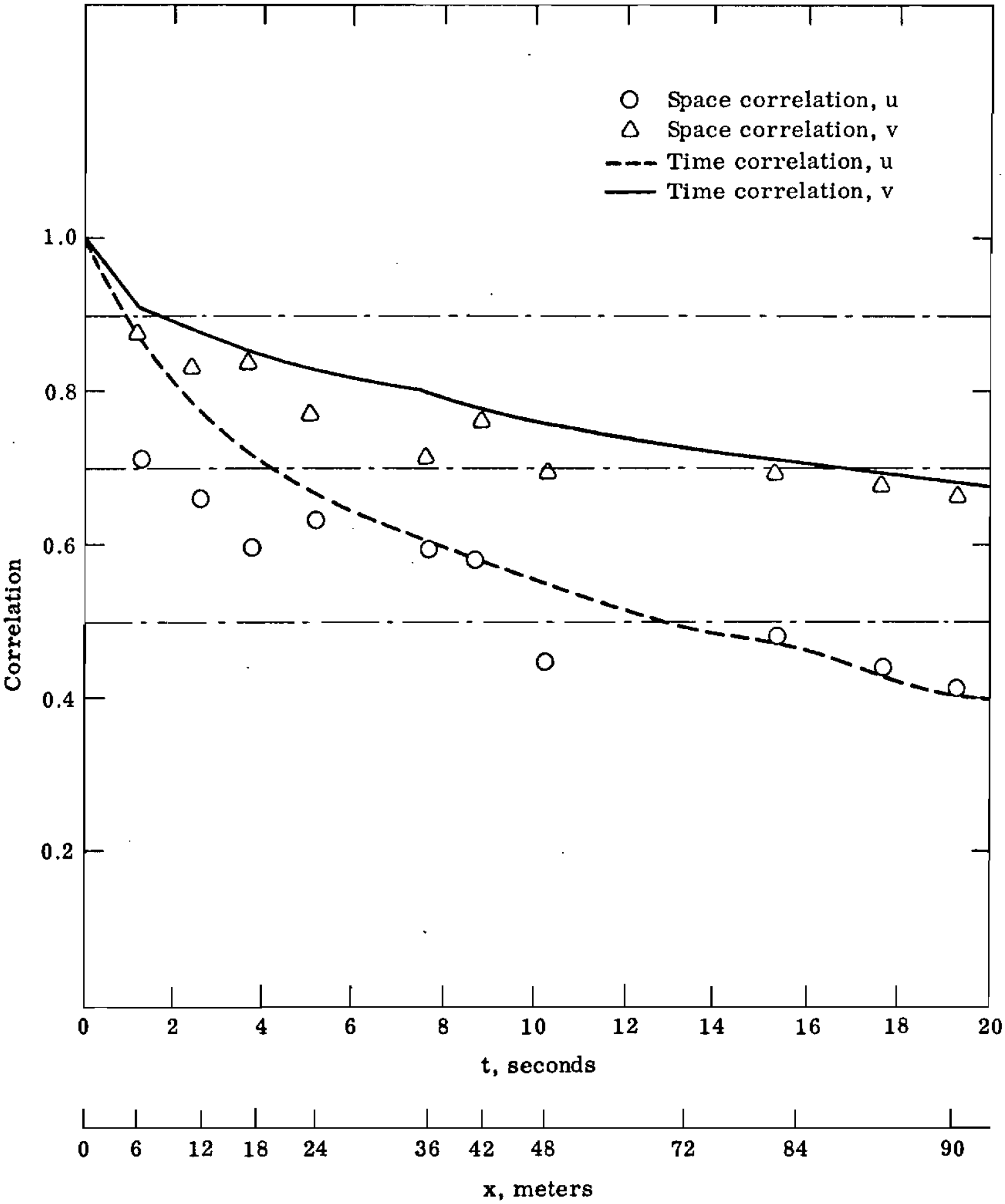


Figure 2. Various Eulerian correlation functions at 2 meters at O'Neill, Nebraska in space or in time during typical daytime observations [35]

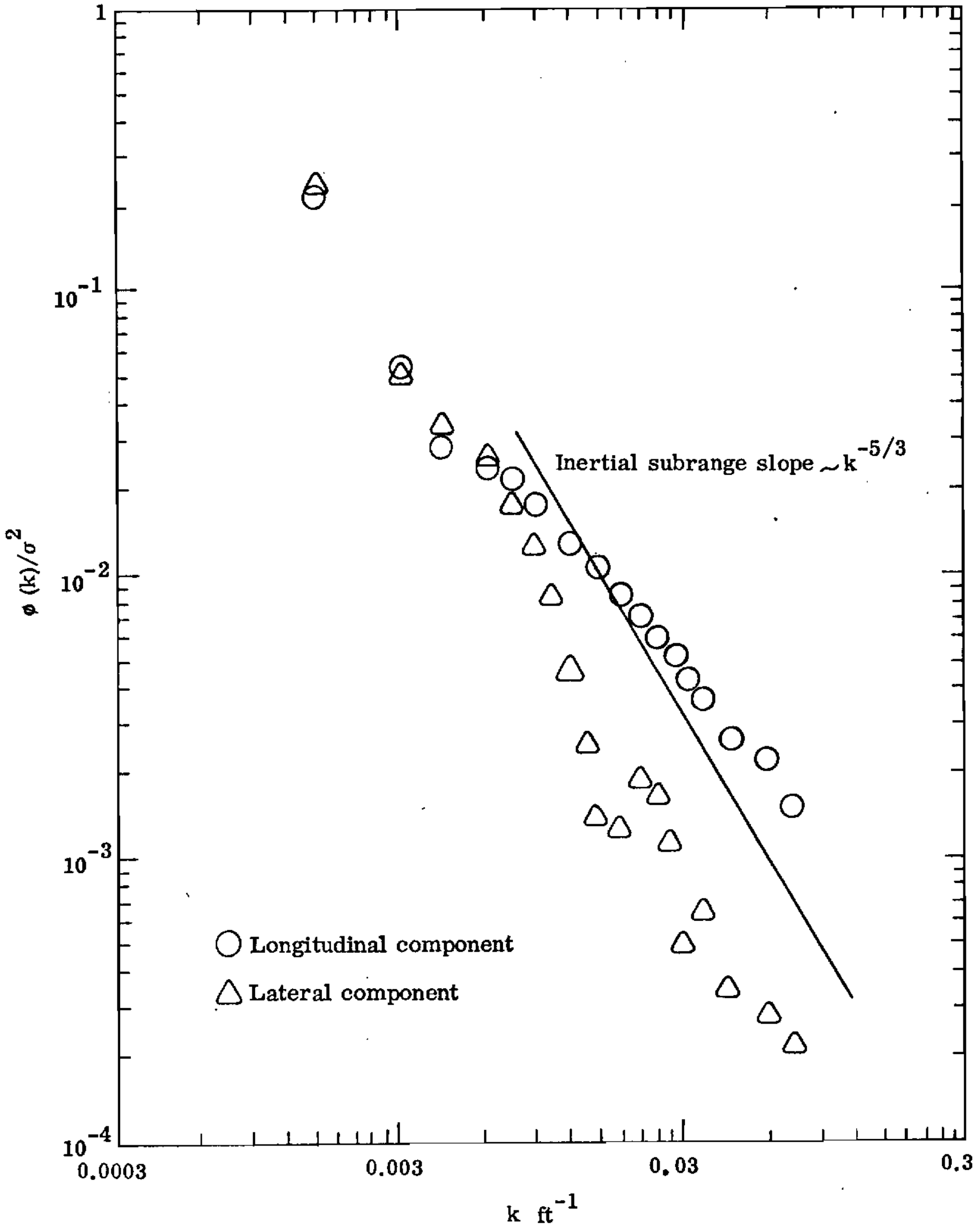


Figure 3. Relative spectral density of turbulent components at O'Neill, Nebraska from a typical daytime case illustrated in Figure 2 [35]

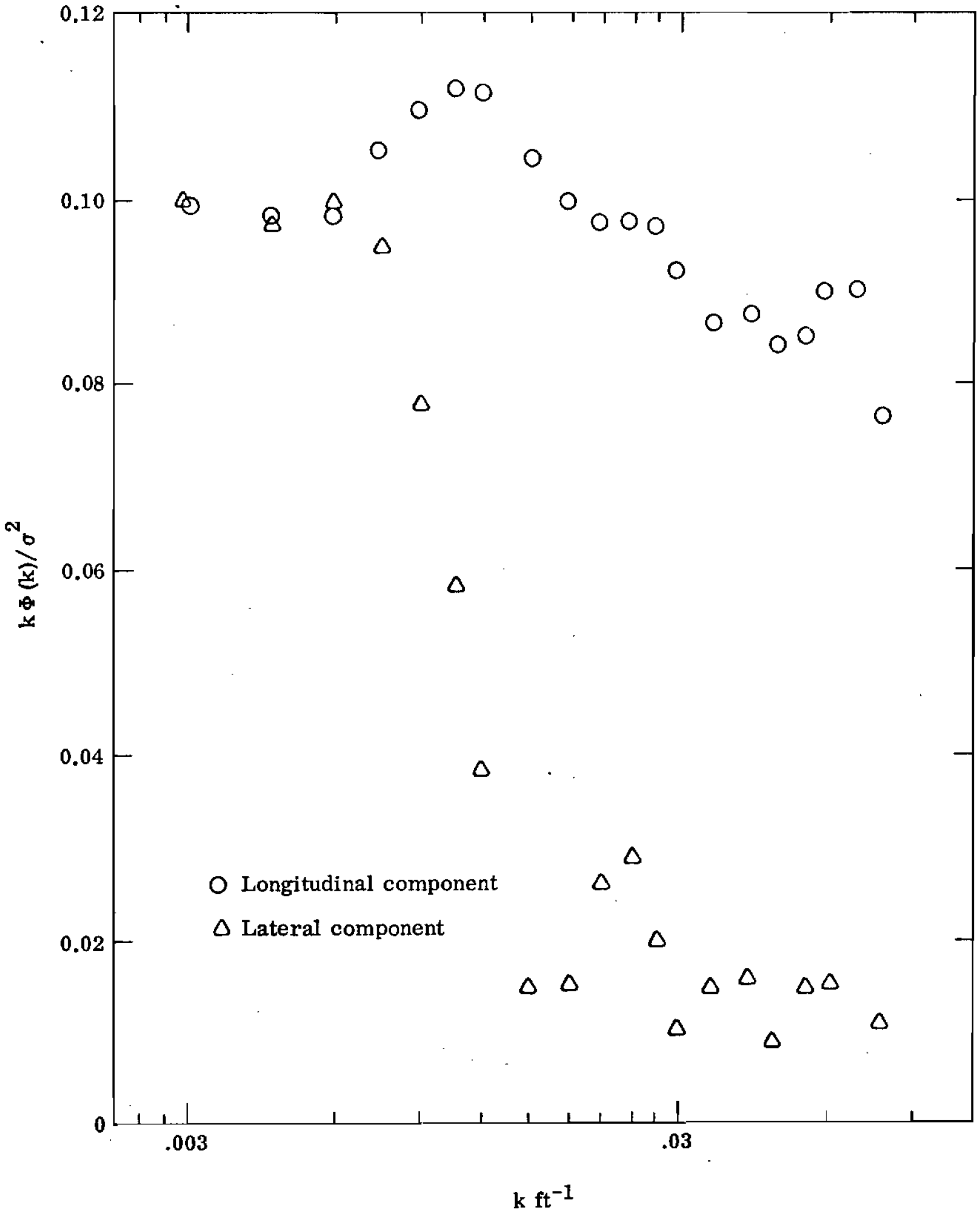


Figure 4. Space spectra from O'Neill data for daytime case. See Figures 1 and 2 [35]

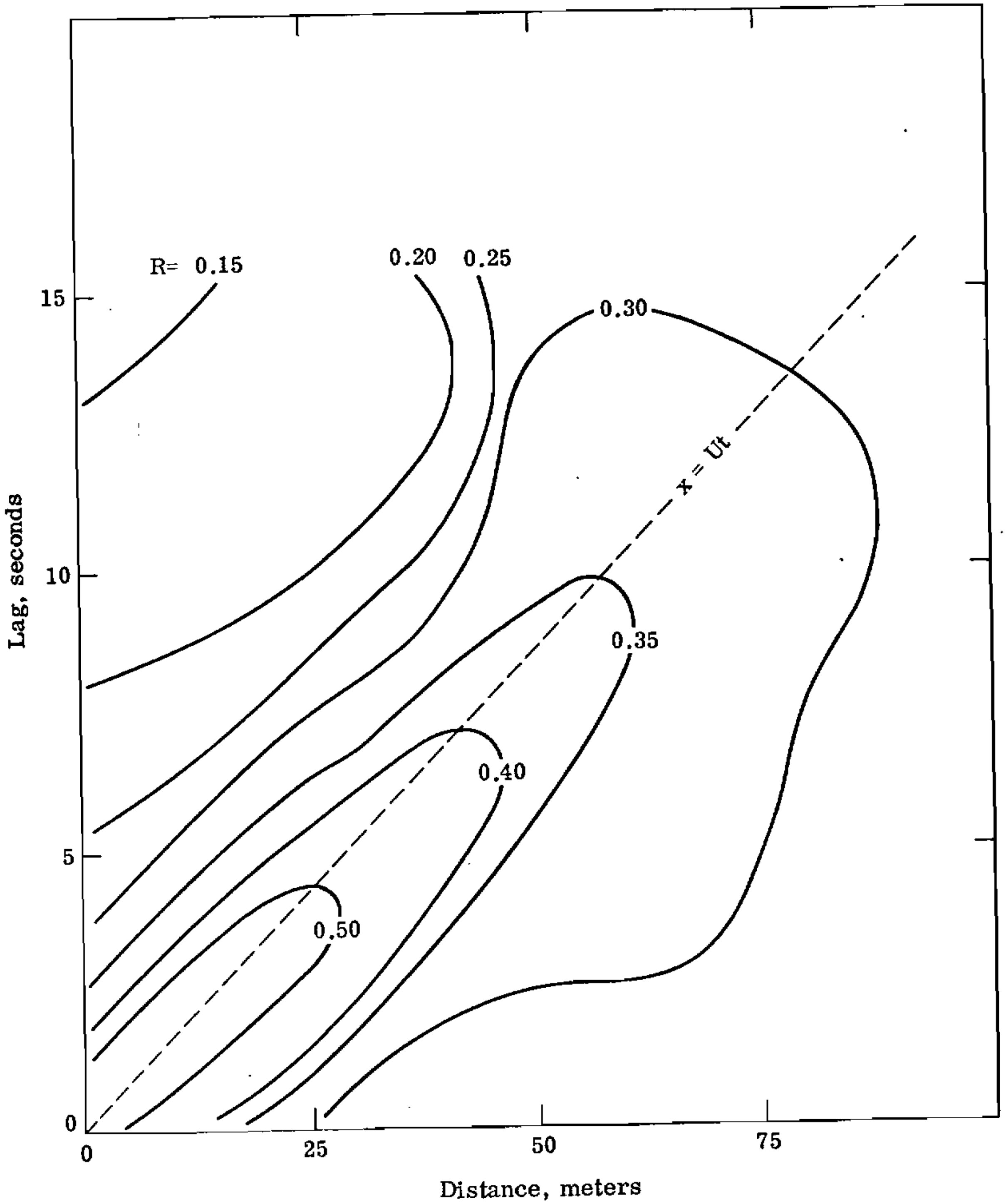


Figure 5. Isopleths of correlation functions in space time coordinates, for velocity at 2 m at O'Neill on a day when wind was lined up with anemometers [27]

of constant correlation given on it. The dashed line is drawn according to Eq. (1). The isopleths approximate ellipses with major axes along the line. Therefore the hypothesis that the eddies travel with the wind appears reasonable.

4. White Sands Data

Data have been collected at White Sands Missile Range by Mr. Armendariz from a triangular array of anemometers at 900 ft separation. Measurements were made at a height of 60 ft using data read from strip charts with a four second averaging period. The site is almost flat with various densities and heights of sagebrush. Data collected when the wind direction was aligned along one pair of anemometers (Aerovanes) is shown in Figs. 6 and 7. Direction fluctuation correlations are shown for time lags varying from 0 to 500 seconds in Fig. 6. The original data had a noticeable trend, that is the correlation coefficient became asymptotic to some value other than zero and a correction was applied according to

$$R_c = \frac{R - R_{500}}{1 - R_{500}} \tag{2}$$

When R is the correlation value at any time less than 500 seconds lag, R_{500} is the value at 500 seconds lag and R_c is the corrected value. The original value of the lag correlation between anemometers is shown in Table I.

TABLE I
ORIGINAL VALUES OF LAG CORRELATION
AT 500 SECONDS

	Direction	Speed
Neutral	0.08	0.0
Forced convection	0.10	0.21
Free convection	0.16	0.0

Peaks in the $R(\tau)$ curve for direction fluctuation occur near 20 to 30 seconds while the $R(\tau)$ curves for speed fluctuations peak in the range from 10 to 40 seconds. If the eddies moved with the mean wind speed according to Eq. (1), $R(\tau)$ should be a maximum at 40 seconds. Lack of agreement is not too surprising because the

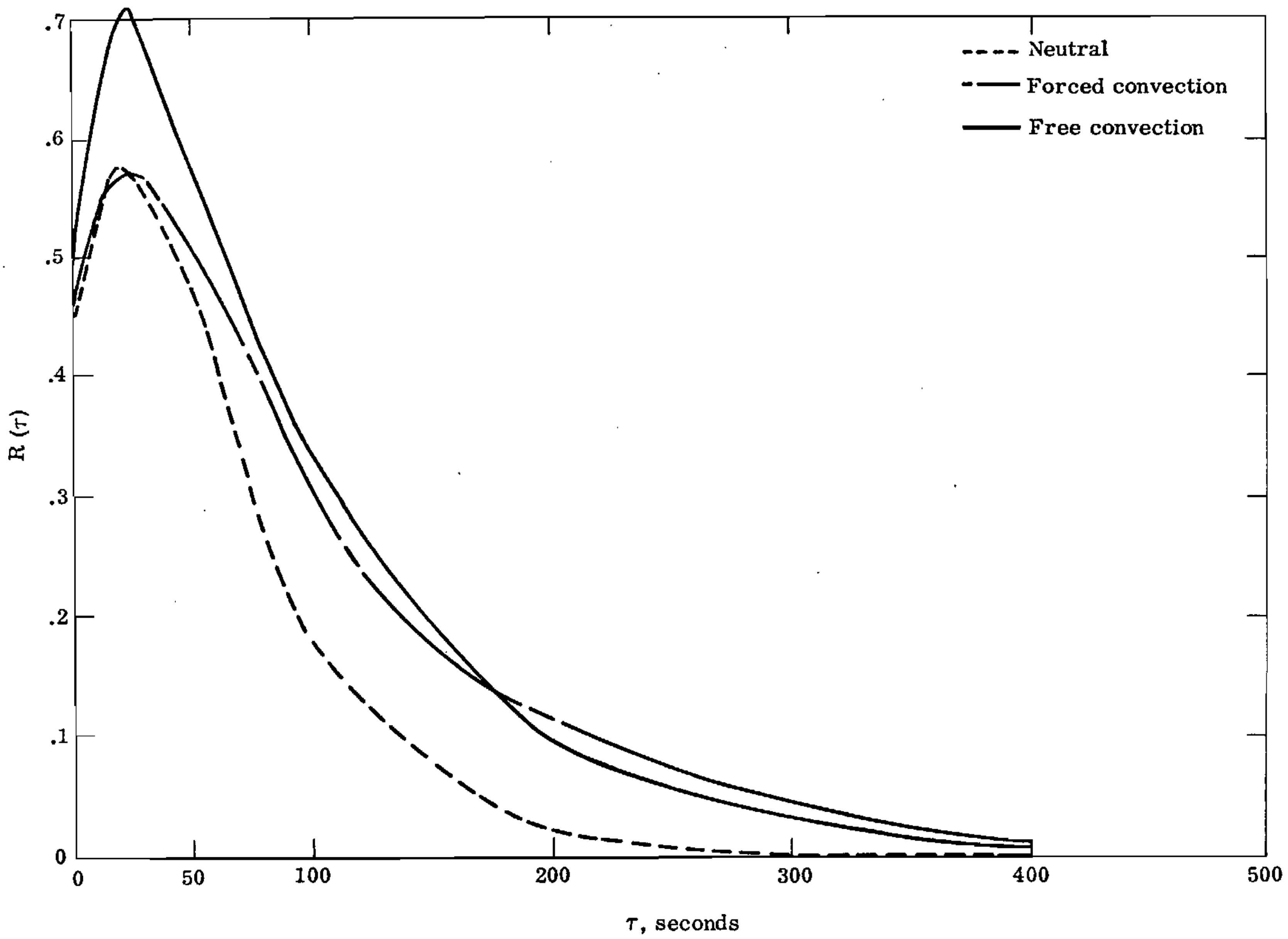


Figure 6. Direction fluctuation correlations between Aerovane anemometers at 60 ft with 900 ft separation when wind direction was along the line of anemometers [1]

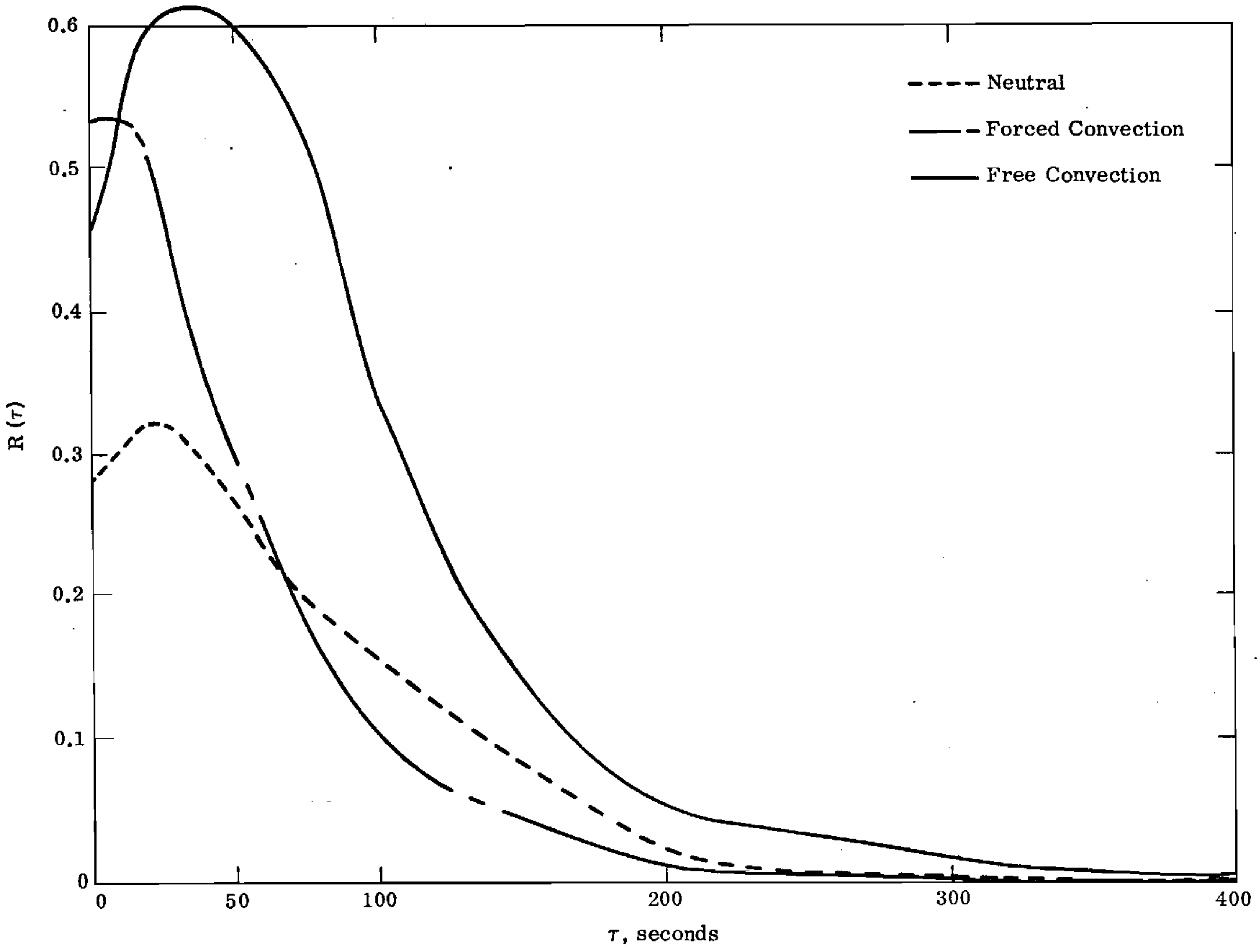


Figure 7. Lagged speed correlation between Aerovane anemometers at 60 ft with 900 ft separation when wind direction was along the line of anemometers [1]

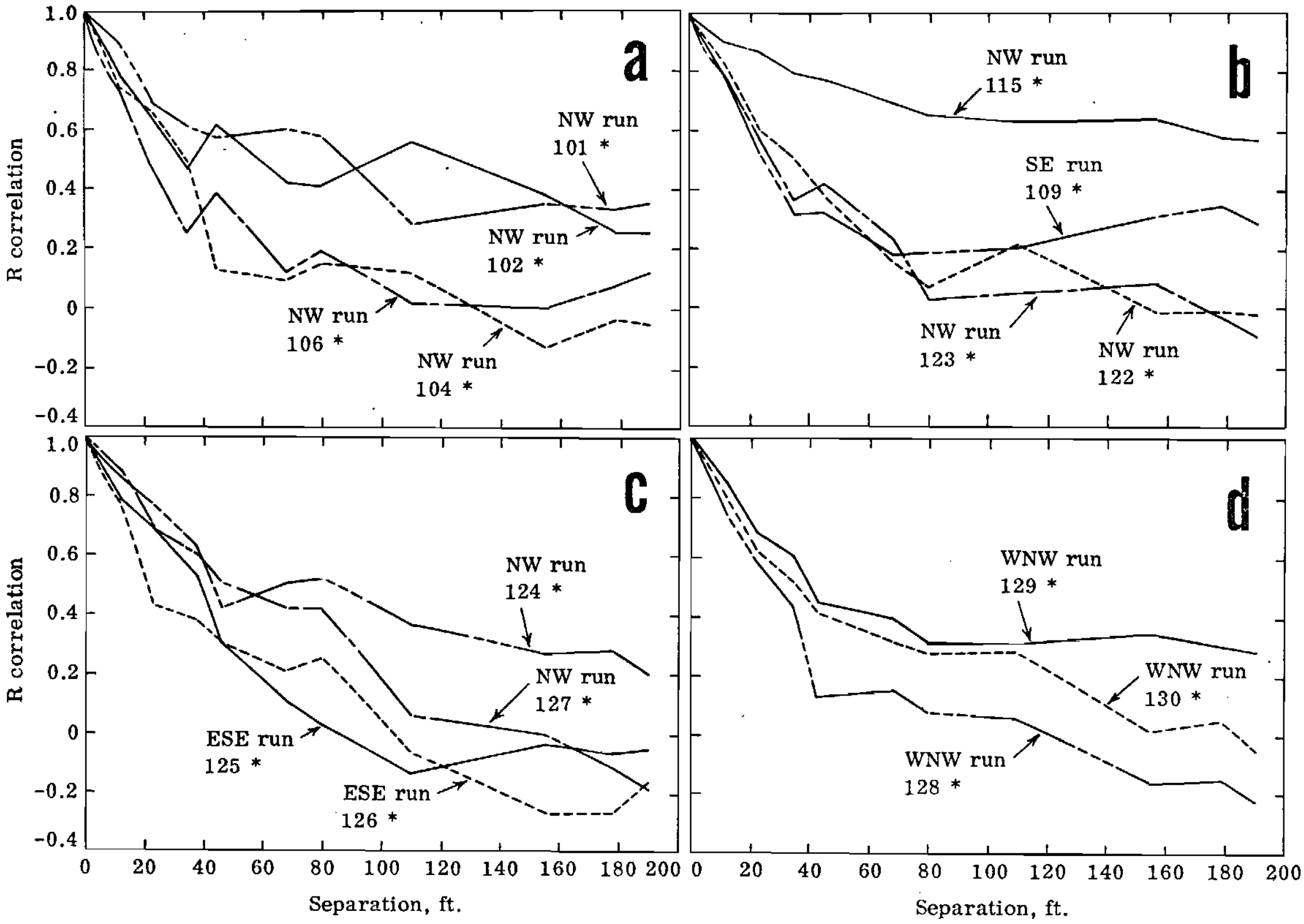
atmosphere was unstable with some convective turbulence. Therefore it is safe to assume that there was a vertical speed shear. Two anemometers yield correlation between only two points, and they yield no information of the air trajectory. If conditions were not completely homogeneous and stationary there would be little chance for perfect agreement between the direction and speed correlations. The main feature to be noted from these data is the significant correlation of velocity component fluctuations at separation distances of 900 ft.

5. Japanese Data

Shiotani [43] collected data along the east coast of Shikoku Island to study the effect of different wind loadings on suspension bridges. Anemometers were mounted on five towers at a height of 130 ft with separations between the towers of 40, 75, 148 and 360 ft for a total separation of 625 ft between the first and last tower. The towers were oriented along a line from NNE to SSW on the shore so that easterly winds had a fetch across water while westerly winds had turbulence typical of land with small hills. Space correlations at zero lag from one second readings collected over 14 minute periods were tabulated. The wind was never along the line of towers and the results presented here are for wind directions at nearly right angles to the line of anemometers. The space correlations are shown in the four sections of Fig. 8. Table II lists wind speed and direction, $\sqrt{\overline{u'^2}}$ and $\sqrt{\overline{u'^2}}/U$ for the average of all five towers. These numbers indicate the relatively high speed conditions that prevailed during the data collection periods.

Normalized lateral space spectra of the u' component obtained by Fourier transform of the correlation values are shown in Figs. 9 through 12. Onshore data are shown in Fig. 9 while Figs. 10 through 12 depict northwest winds with trajectories across the island.

In Table II note that the over water trajectories have speeds comparable to the landward cases, i.e., 28 to 50 mph. The turbulence intensity shown in the last column is only 0.06 to 0.07 as opposed to the land trajectory intensities ranging from 0.13 to 0.23. Comparing Figs. 9, 10 and 12 there is little difference in the shape of the normalized spectra. All conform to the theoretical -5/3 slope in wave number at wave lengths less than 300 ft.



* Original run identification numbers.

Figure 8. Japanese data collected by Shiotani [43] along shore of Shikoku Island: space correlations for zero lag from one second readings over a fourteen-minute period

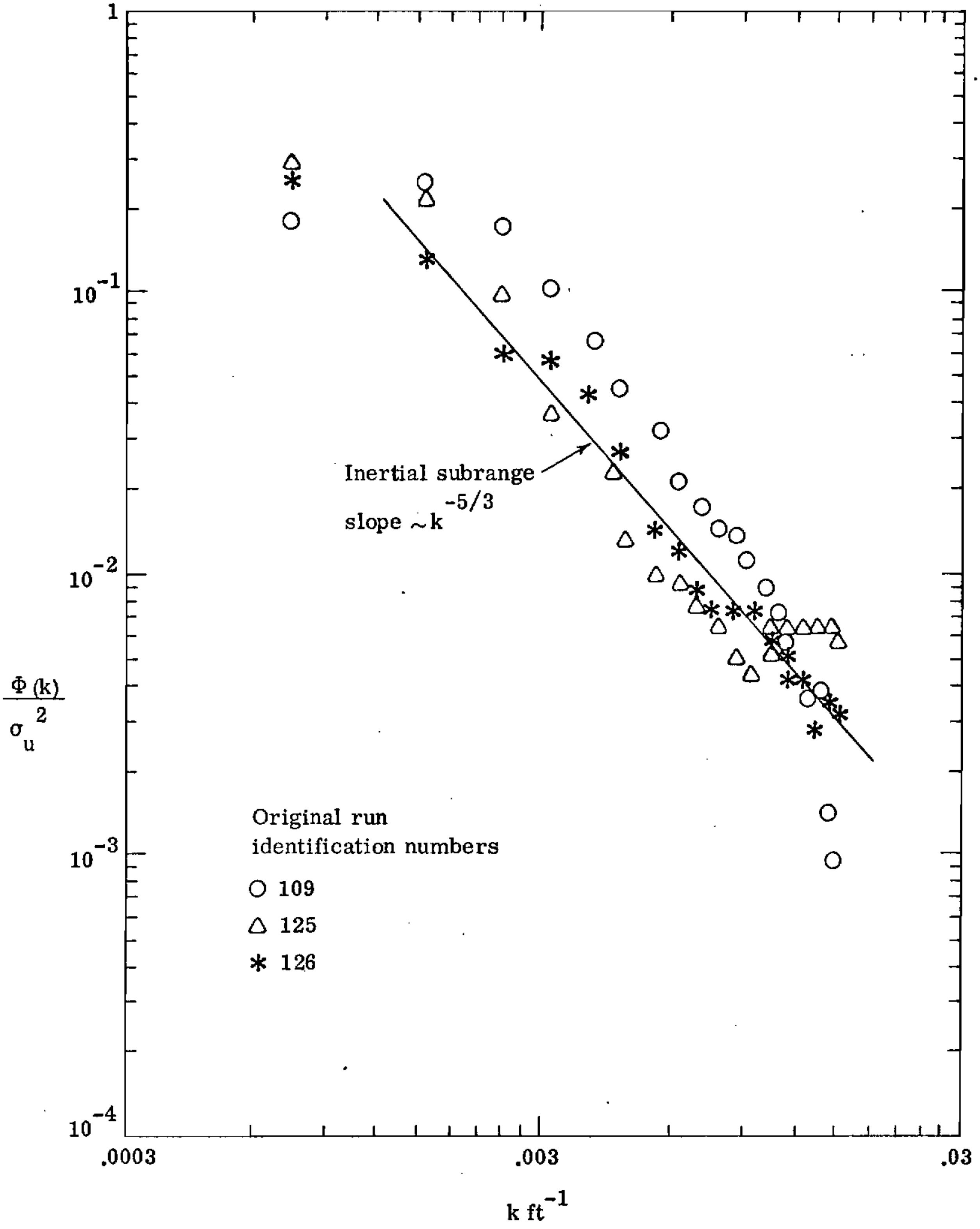


Figure 9. Japanese data collected by Shiotani [43] along shore of Shikoku Island: space spectra derived from correlation functions shown in Figure 8

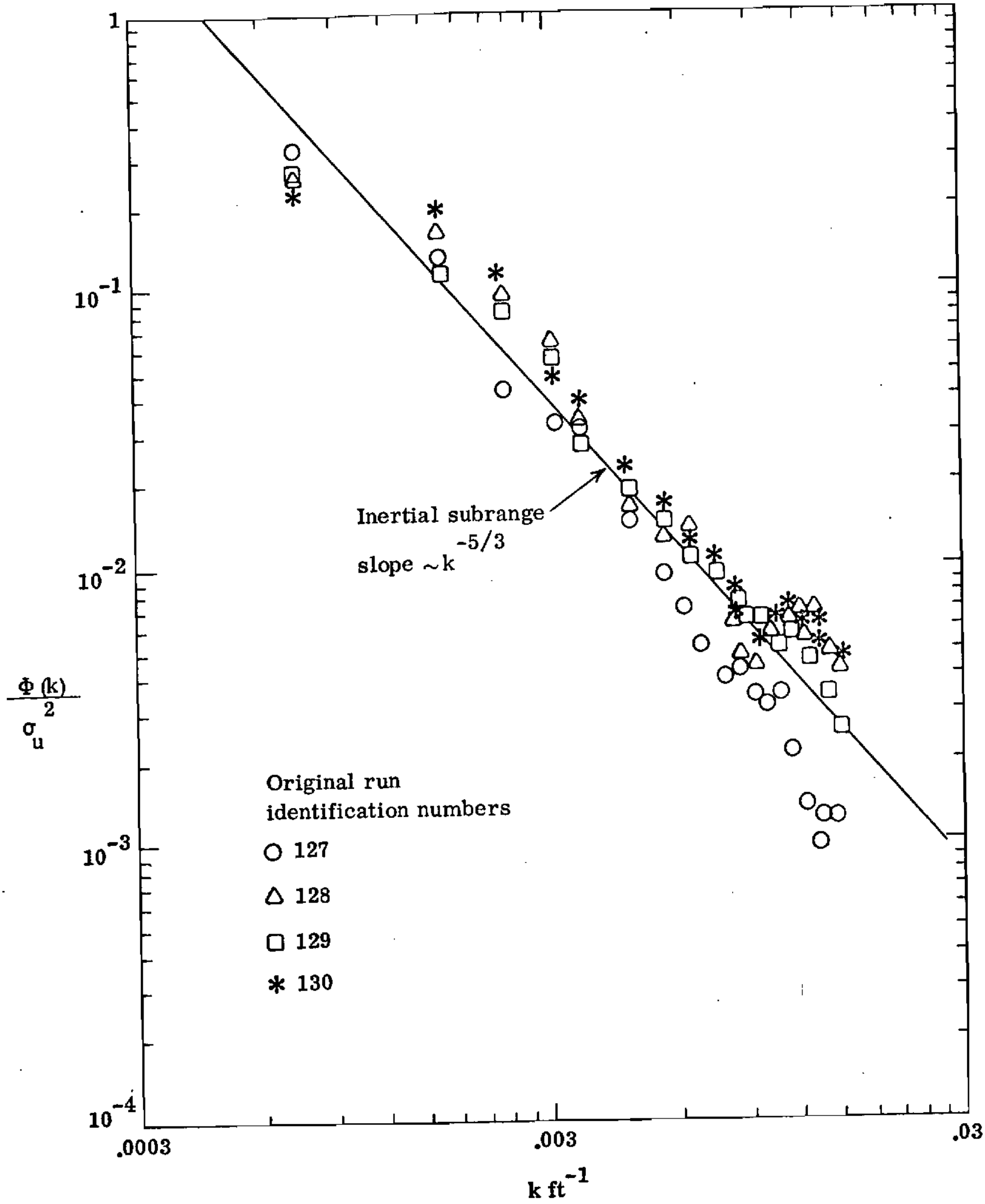


Figure 10. Japanese data collected by Shiotani [43] along shore of Shikoku Island: space spectra derived from correlation functions shown in Figure 8

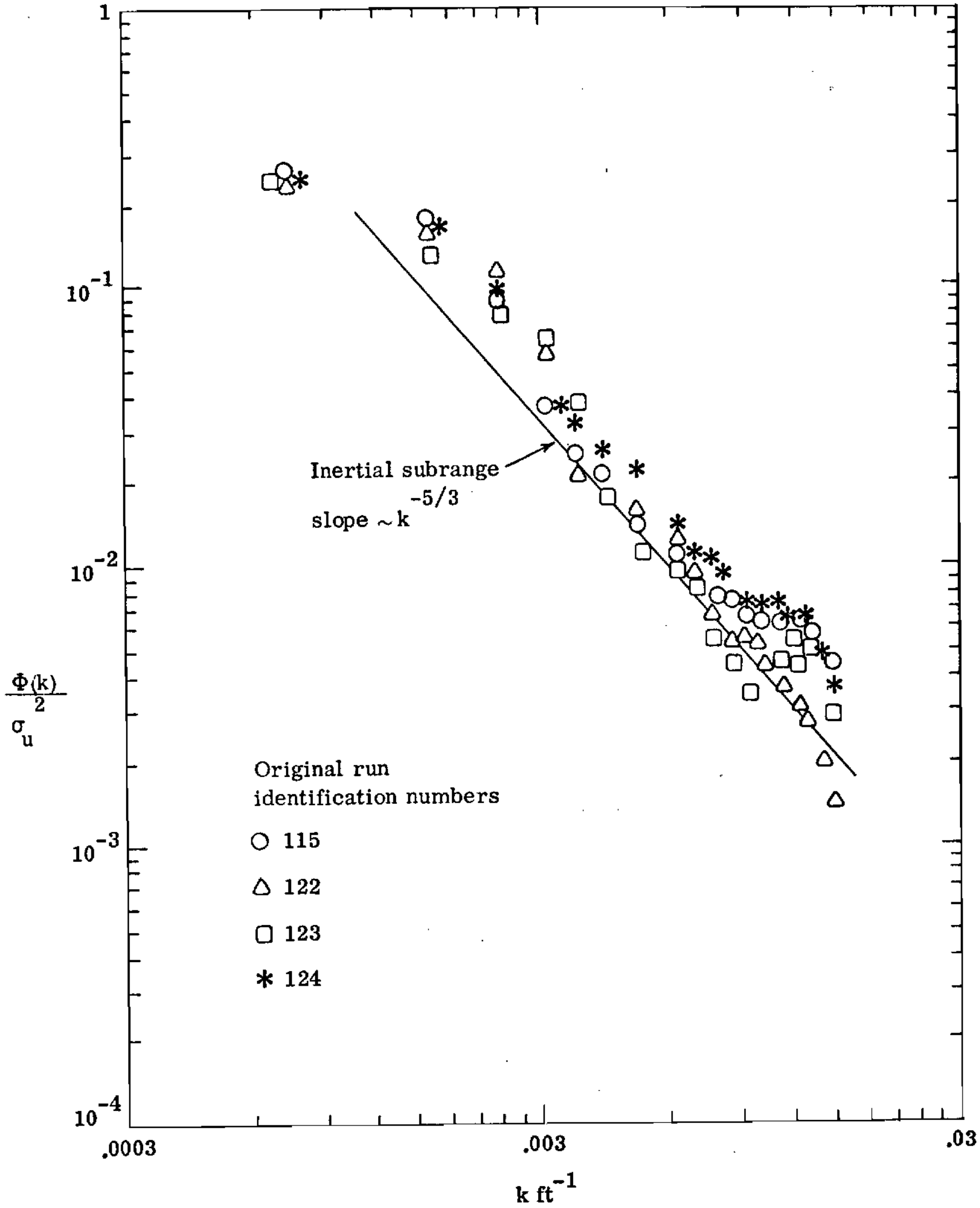


Figure 11. Japanese data collected by Shiotani [43] along shore of Shikoku Island: space spectra derived from correlation functions shown in Figure 8

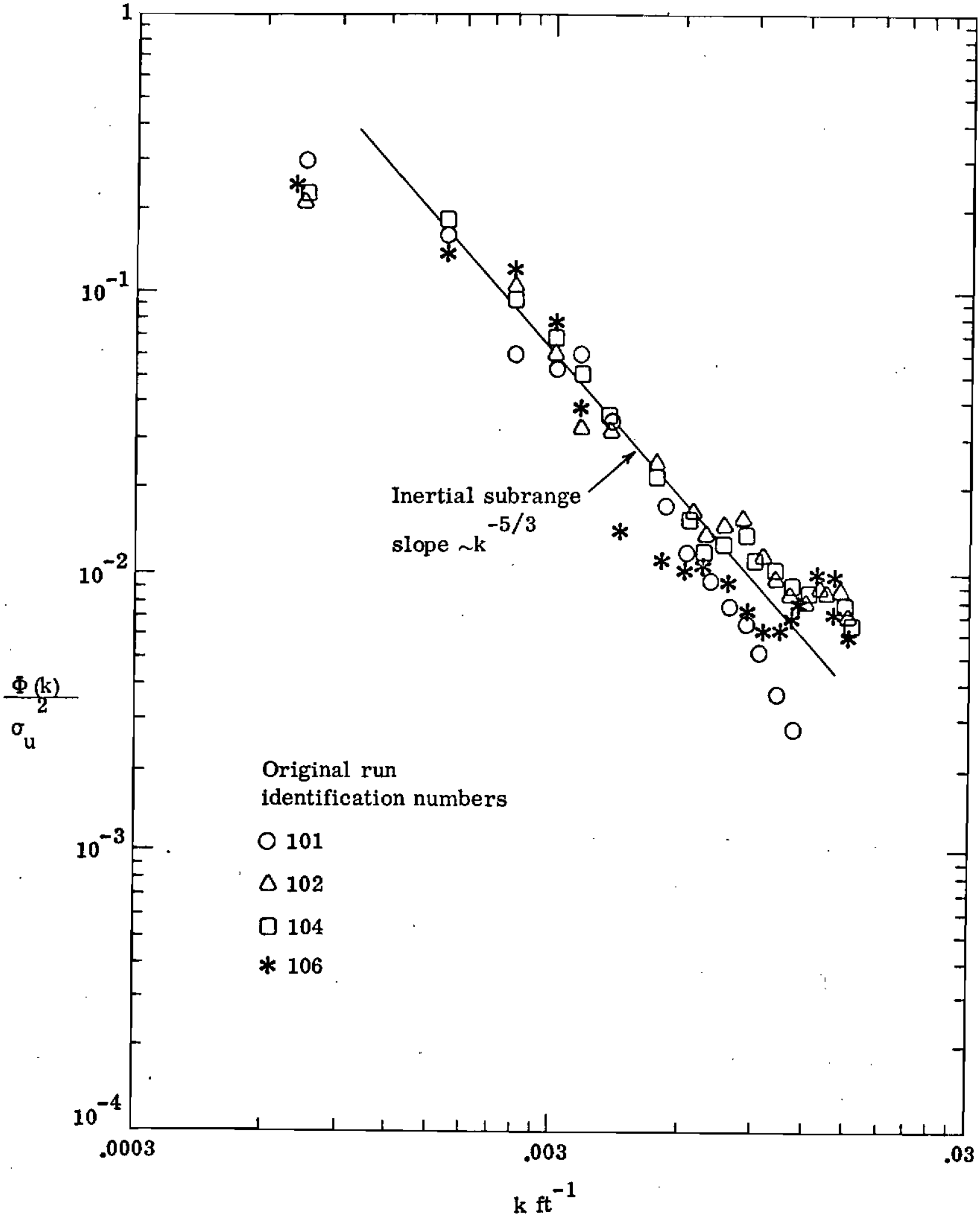


Figure 12. Japanese data collected by Shiotani [43] along shore of Shikoku Island: space spectra derived from correlation functions shown in Figure 8

TABLE II
WIND STATISTICS FOR SELECTED CASES OF SHIOTANI'S DATA

Test no.	Mean direction	Mean speed mp	$\sqrt{\overline{u'^2}}$ ft sec^{-1}	$\sqrt{\overline{u'^2}}/U$
101	NW	25	5.6	0.15
102	NW	16	4.2	0.19
104	NW	26	6.7	0.16
106	NW	32	6.9	0.15
109	SE	50	4.2	0.06
115	NW	35	12.4	0.23
122	NW	39	11.1	0.19
123	NW	43	10.2	0.16
124	NW	25	7.2	0.21
125	ESE	29	3.0	0.07
126	ESE	28	3.0	0.07
127	WNW	39	9.5	0.17
128	WNW	29	5.3	0.13
129	WNW	31	6.9	0.15
130	WNW	32	7.5	0.16

Shiotani indicated scales of turbulence, L, ranging from 100 to 300 ft when lateral correlation coefficients are approximated by an exponential function $e^{-n/L}$. L is a mixing length governing the average rate of transport of material. Realistically, the exponential approximation was valid in very few cases. A more convenient length scale may be obtained from the spectra by finding where the $k\Phi(k)$ spectral density is a maximum. Shiotani found this length to be approximately 3000 ft for his data. This length is indicative of the scale of eddies containing the largest percentage of turbulence energy. Considering all of these data to be representative of mechanical turbulence is probably valid because the wind speeds and geographic location preclude much surface convective turbulence.

6. Other Data

Multiple anemometer data have been collected to illustrate two-dimensional wind fields by Frazier [12], Sherlock and Stout [42] and Obukhov [32]. Frazier's data were at different heights which would create considerable difficulty in analysis because vertical shear would have to be accounted for in a subjective manner and results would be questionable. Sherlock and Stout show some very interesting pictures of velocity fields in the two dimensional-vertical-horizontal plane but no statistics are available from the data. Obukhov was interested in the inertial subrange and the separation distances of his anemometers was too short to be of interest here.

7. Time Spectra at a Point

The problem of wind component spectra at a point in space as a function of time has been the subject of extensive theoretical and experimental investigation. Rather accurate predictions of the spectrum of vertical velocity fluctuations are possible with decreasing accuracy for lateral, longitudinal and cross-spectra. The following sections will illustrate data from several sites to show that some characteristics of turbulence may be regarded as universal functions of simple parameters such as wind speed, surface roughness, and thermal stability. Comparisons have lead Busch and Panofsky [6] to publish the following conclusions:

- In regions over which the spectra obey -5/3 power laws, the ratio of the lateral to the longitudinal spectra shows fair agreement with the 4/3 ratio predicted by the Kolmogorov hypothesis for the inertial subrange. The vertical-longitudinal ratio has a similar tendency.

- Dissipation rates computed from the longitudinal spectra seem to be consistent with the hypothesis that dissipation is balanced by the total production of mechanical and convective energy, provided the turbulence is in equilibrium. In transition from rough to smooth terrain, dissipation exceeds the other terms.

- Vertical-velocity spectra obey Monin-Obukhov similarity theory up to an altitude of about 150 ft. Their shapes are reasonably uniform, the major change with stability being a change of scale of the wave number axis, i.e., any characteristic nondimensional wave number is a function of z/ℓ only. This function appears to be the same as the relation between the normalized dissipation and z/ℓ. These results are consistent with previously measured Kolmogorov constants and with measured ratios of standard deviation of vertical velocity to function velocity. Up to about 150 ft the wavelength of maximum logarithmic spectra increase linearly with height and more slowly thereafter, up to 1500 ft.

- Longitudinal spectra do not obey similarity theory in a number of ways. The wavelengths do not scale with height, and there may be differences between sites when the spectra are plotted in similarity coordinates.
- Spectra over the sea seem to have relatively more energy at low frequencies than those over land.

8. Vertical-velocity Spectra

The closer to the ground the observations are taken, the more severely the energy in low wave numbers of the vertical-velocity spectrum is limited. Therefore, it might be expected that the scale of vertical velocities would increase with height. This leads to a scaled nondimensional frequency $f^* = nz/U$, where n is the original frequency in cycles per second, z is the height above the surface, and U is the average wind speed at height z. Figures 13a through 13d provide ample evidence from a variety of sites that the smoothed and averaged spectra of the vertical velocity do scale with height when plotted in similarity coordinates and also that the peak of the curves is a function of stability. Stability is indicated by both z/ℓ and Richardson number (Ri) but at least for unstable conditions they have been shown to be equivalent by Pandolfo [33]. A comparison of the spectra from different sites is shown in Fig. 14 for unstable conditions. There is considerable similarity among the shapes of all the spectra. Also, the maximum ordinate of the logarithmic spectra in similarity coordinates is about the same in all cases, namely $f^* = 0.4$ to 0.6. The value of f* at the maximum and the high frequency portion of the spectrum does not change significantly from neutral to unstable cases. There is a definite shift of the whole spectrum toward higher frequencies as the atmosphere goes from neutral to stable thermal equilibrium with no change of spectral shape. It is convenient to break the spectrum into a product of two factors, the variance and the normalized spectrum, yielding

$$n\, S_w(n) = \sigma_w^2\, G(f^*, Ri) \qquad (3)$$

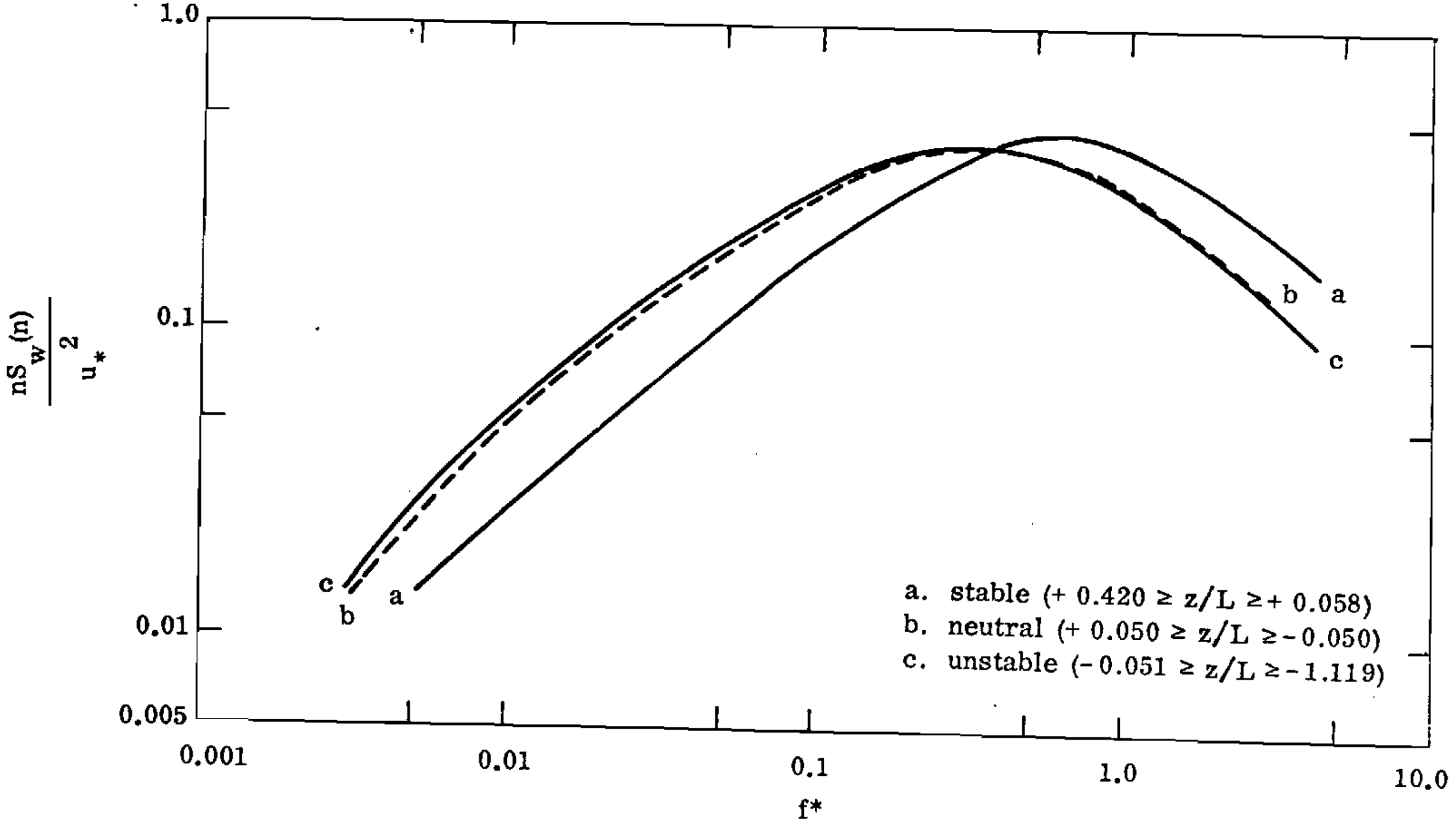


Figure 13a. Smoothed and averaged spectra of vertical velocity at heights 15 to 91 m, Round Hill

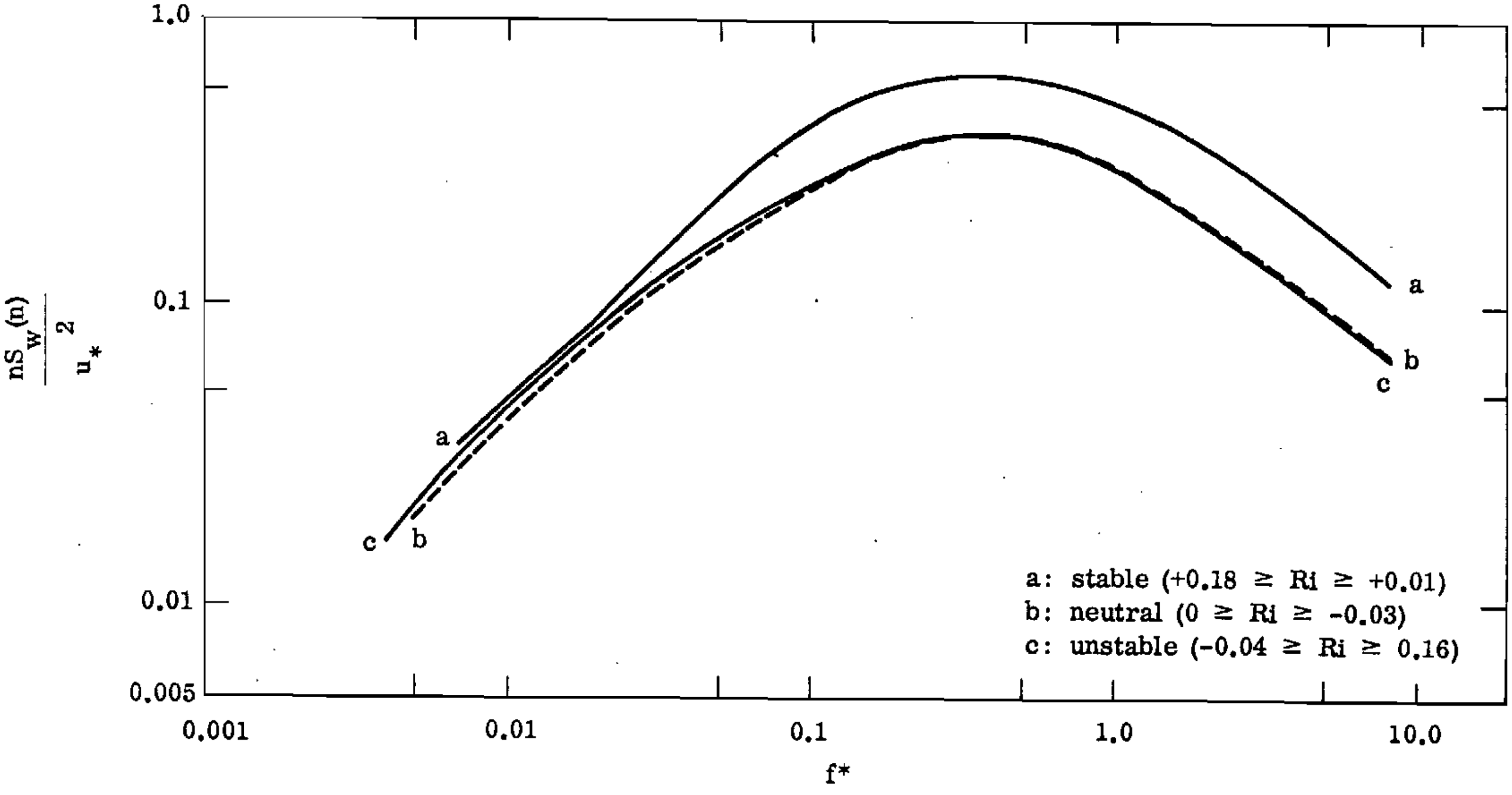


Figure 13b. Smoothed and averaged spectra of vertical velocity at heights 3 and 6.1 m, Hanford [54]

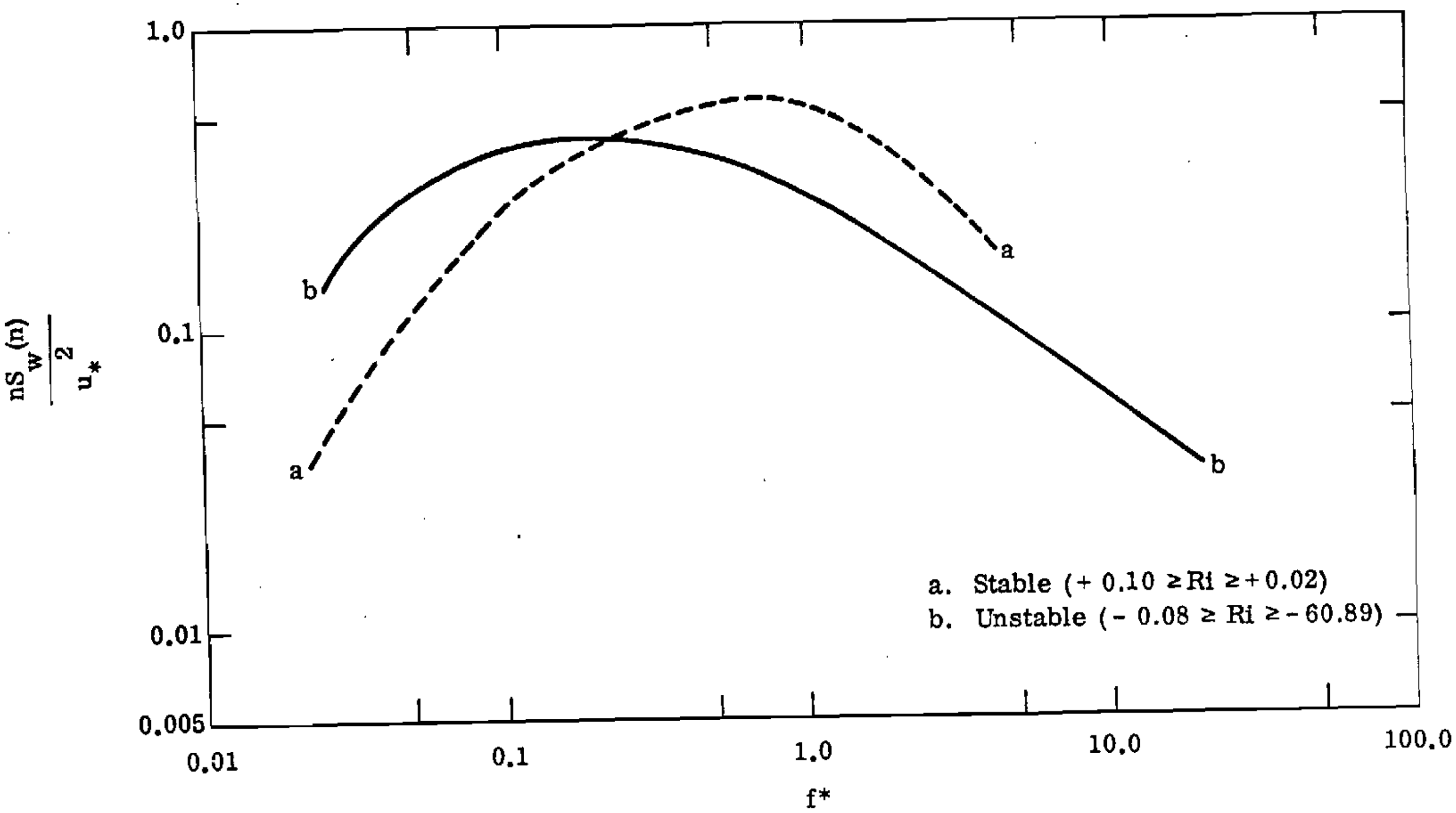


Figure 13c. Smoothed and averaged spectra of vertical velocity at height 46 m, Cedar Hill

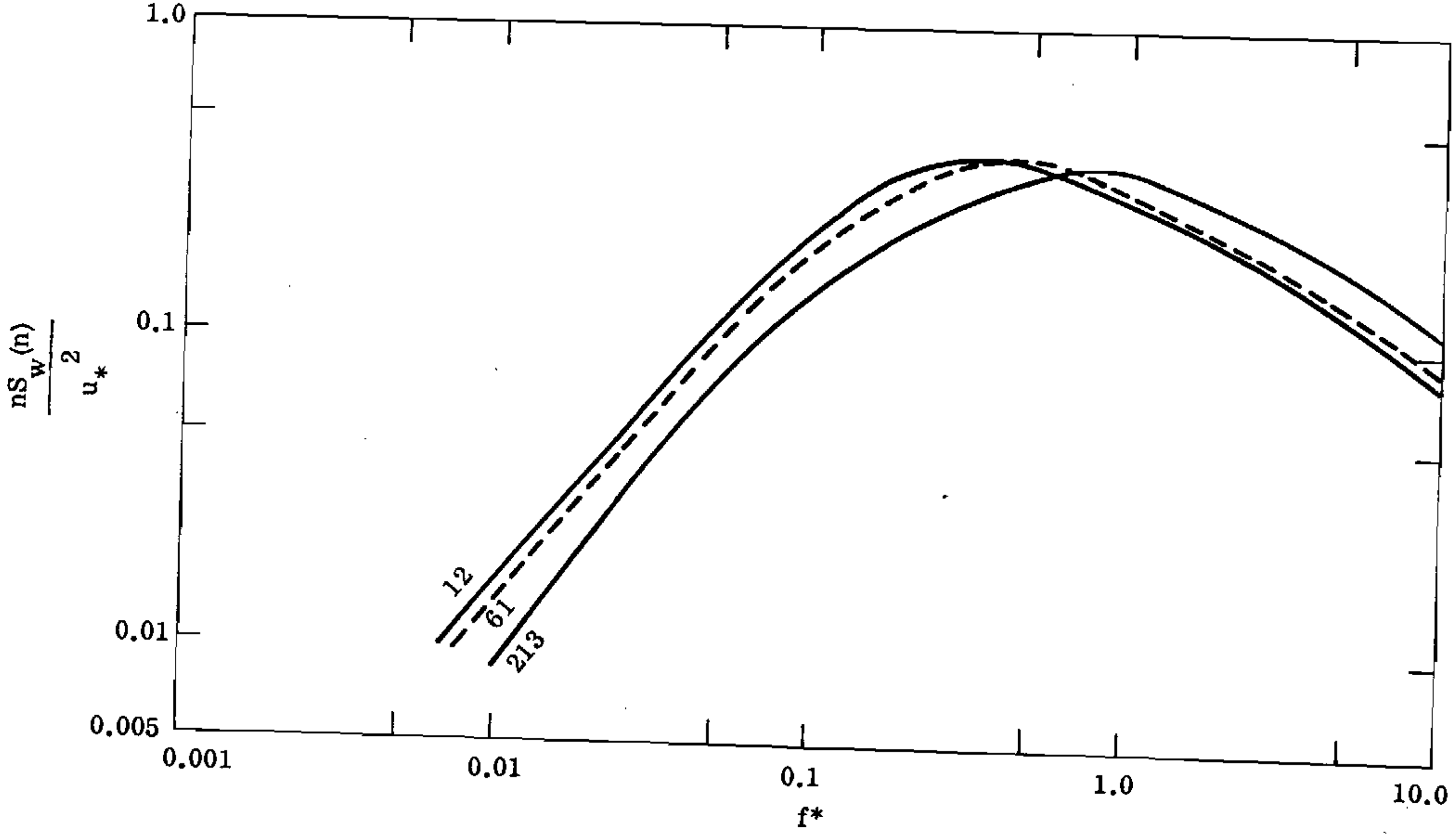


Figure 13d. Smoothed and averaged spectra of vertical velocity heights of 12, 61 and 213 meters, Fort Wayne, Indiana, $-0.005 < Ri$ (61 meters) < 0.01 [16]

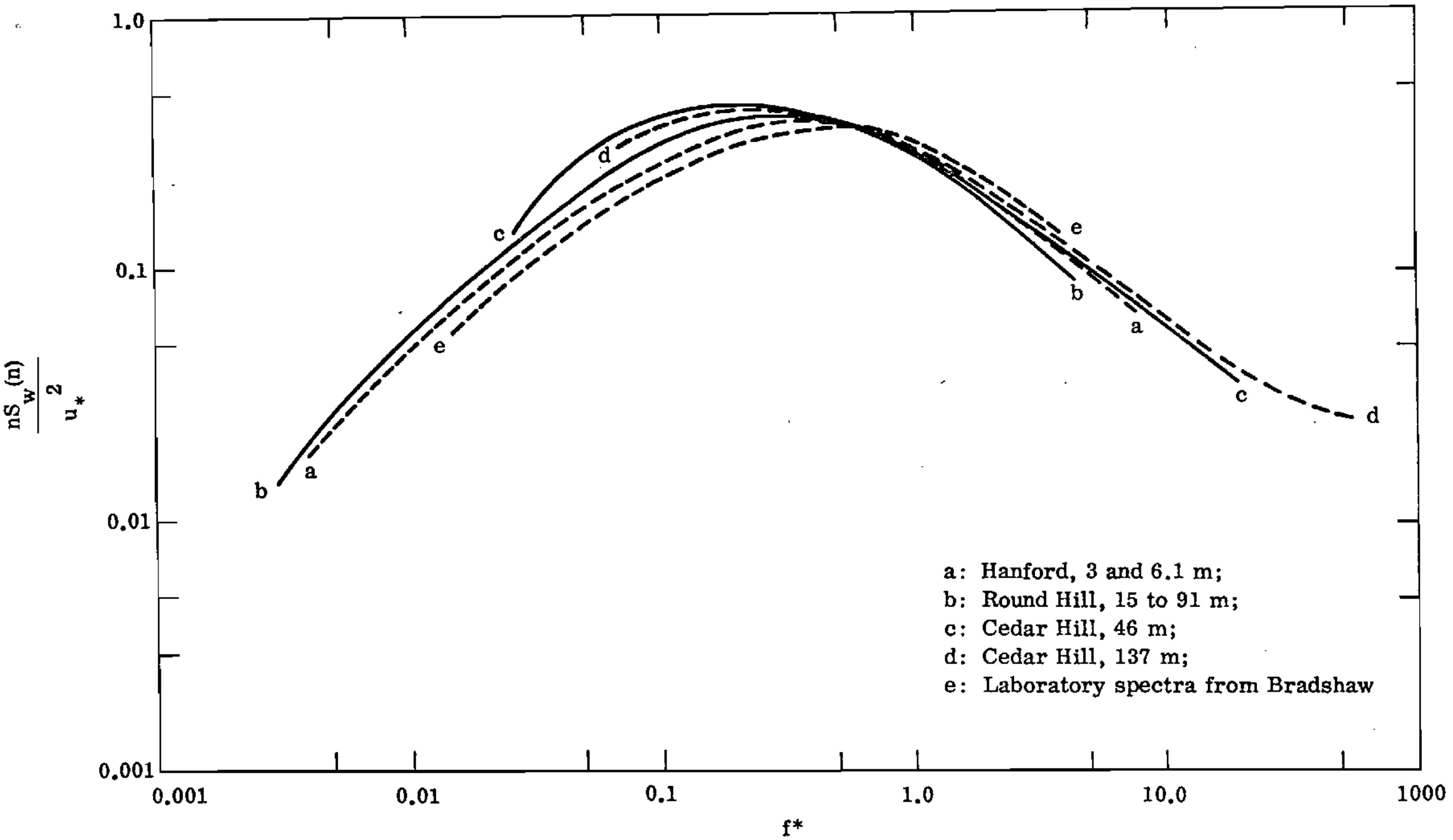


Figure 14. Comparison of vertical-velocity spectra in unstable air

where

$$\int_0^\infty G \, d(\ln n) = 1.$$

A number of forms for G(n) have been proposed. Pritchard, et al. [38] have discussed the models of Panofsky, Dryden, von Karman, and Zbrozek, while Lumley and Panofsky [27] have discussed Inoue and Henry's models. These forms, converted to wave number k, in cycles/ft, and written in the usual form, become:

Panofsky
$$\phi(k) = \sigma_u^2 \frac{c}{(1 + ck)^2} \tag{4}$$

Pritchard et al.
$$\phi(k) = \sigma_w^2 \frac{A\ell}{(1 + A\ell k)^2} \tag{5}$$

Dryden
$$\phi(k) = 2\sigma_w^2 L \frac{1 + 118.4 (Lk)^2}{[1 + 39.5 (Lk)^2]^2} \tag{6}$$

Inoue
$$\phi(k) = \sigma_u^2 \frac{C^2 k}{[1 + (Ck)^2]^{4/3}} \tag{7}$$

von Karman
$$\phi(k) = 2\sigma_w^2 L \frac{1 + 188.4 (Lk)^2}{[1 + 70.7 (Lk)^2]^{11/6}} \tag{8}$$

Zbrozek
$$\phi(k) = \sigma_u^2 \frac{42}{1 + (2\pi L k)^2} \tag{9}$$

Henry
$$\phi(k) = 0.0049 \frac{\gamma}{\gamma_d} z^{-2/3} k^{-5/3} U \tanh\left(\frac{15.2 kz}{U}\right) \tag{10}$$

These equations were plotted in Fig. 15 using the constants $\sigma_w^2 = 3.0$ ft^2/sec^2, $c = 833.3$, $A = 2.78$, $\ell = 300$ ft, $L = 500$ ft, $C = 476.2$ $\frac{\gamma}{\gamma_d} = 1$, $z = 300$ ft, $U = 19$ ft/sec. The constants selected are representative of slightly stable conditions at a height of about 300 ft above smooth terrain. The purpose of the illustration is to depict the differences in the models proposed by various writers.

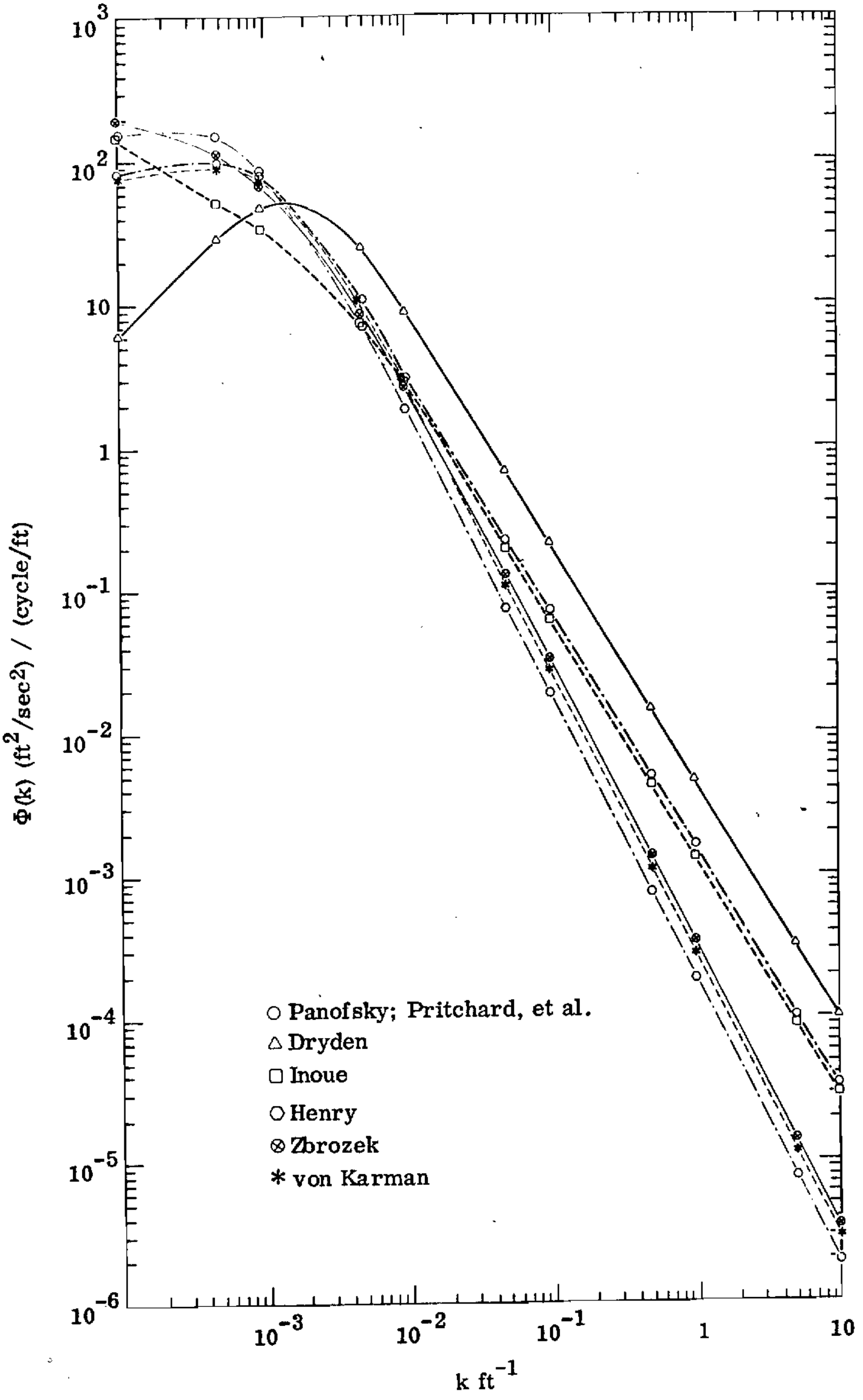


Figure 15. Plots of spectral models

The model by Inoue should be discarded because it goes to zero at low wave numbers. Henry's and von Karman's models are similar at high wave numbers but the latter's provides a better description and more useful functional form. Curves illustrating the models of Panofsky, Dryden, and Zbrozek are also quite similar at high wave numbers. The slopes of these in the area where the inertial subrange should exist are -2 rather than -5/3. The von Karman model is probably the most satisfying of the group since it captures the features of scale length, total variance, and approaches the theoretically determined slope. The major disadvantage is the lack of a stability factor.

Busch and Panofsky [6] have recently proposed a model for the vertical velocity spectra that has the form:

$$\phi(k) = \sigma_w^2 \frac{A}{1 + (Bk)^{5/3}} \qquad (11)$$

A and B are constants depending on height above ground and stability. It is basically the same as Eqs. (4) or (5) except the slope at high wave numbers is now -5/3 rather than -2 as previously.

The scatter of observed spectra is such that most of these models could be applied to problems requiring a spectral function. Those based on the most recent and abundant information are von Karman's and the Busch-Panofsky model. An example of the scatter and stability dependence is shown in Fig. 16. This is based on 265 spectra of the vertical-velocity component at 230 ft above the ground. The center dot indicates the average value at some wave number while the length of the vertical line indicates the extent of the mean square deviations about the average. Note that all values were normalized on the spectral density at 3×10^{-2} cycles/ft. This eliminates the effects of σ_w^2 and tends to illustrate the effect of stability on scale. The more stable the atmosphere the higher the value of k where the spectrum departs from the straight line power law indicating a shorter turbulent scale length, or smaller eddy size. Min-Yui [29] also found that longer samples were required to obtain stable statistics as Ri became increasingly negative. The period varied from 25 minutes for Ri = 0.172 to 40 minutes at Ri = 2.143. Also it should be noted that more than 30 per cent of the cases would lie outside the ranges indicated.

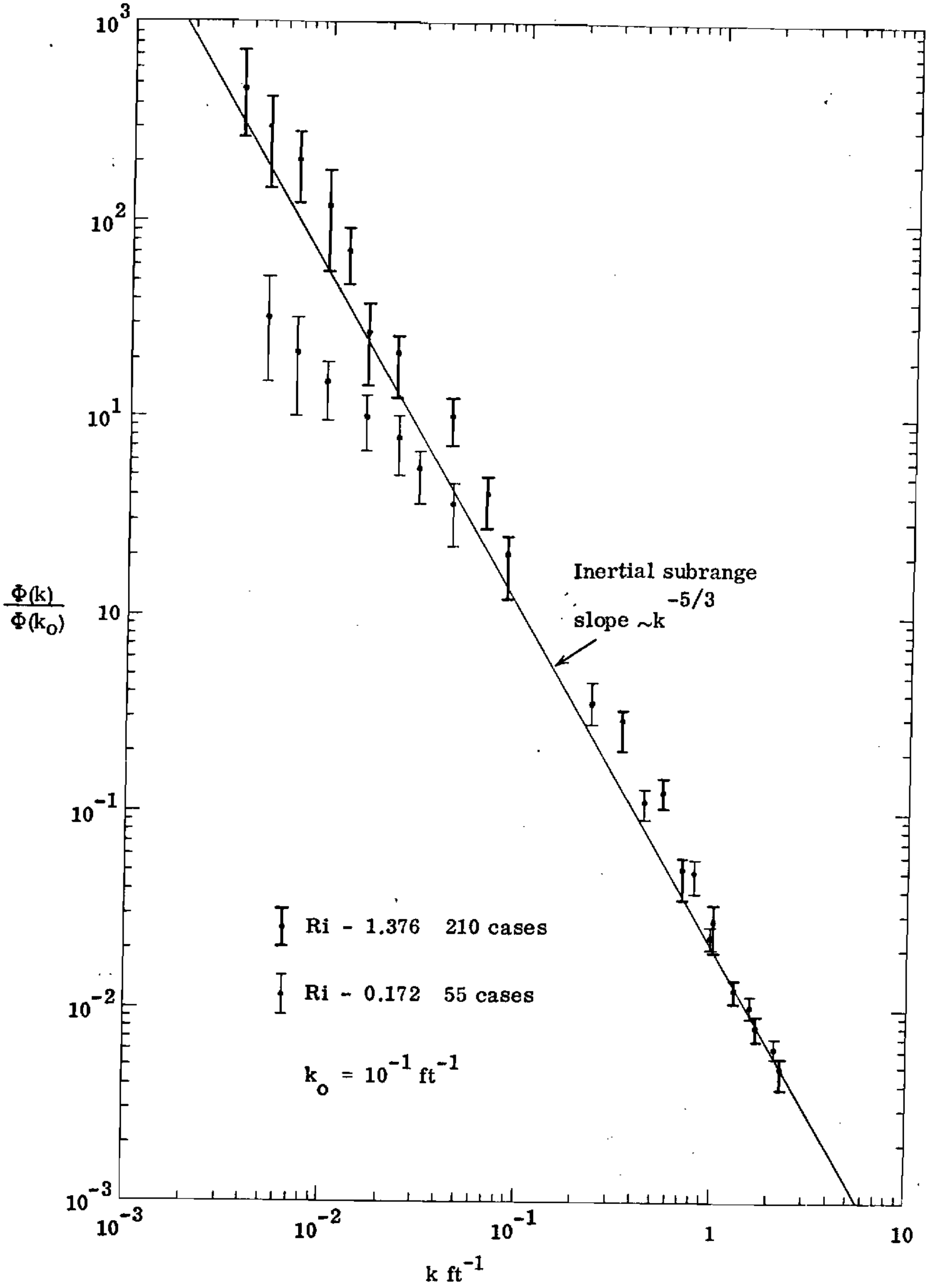


Figure 16. Averaged spatial spectra of w' for 70 m level and mean square deviations from the average ($\sigma_m 2$), from Min-Yuri [29]

In summary, the spectra of the vertical-velocity component at a point is dependent on height above the ground and thermal stability of the atmosphere, as well as the overall variance of the fluctuations. Equations (8) and (11) with appropriate constants represent the spectra adequately. In Eq. (8), L is the length about 1.67 times the height in neutral conditions, somewhat smaller in stable conditions and larger in unstable conditions. If Eq. (11) is used in the more general nondimensional frequency form

$$S_w(n) = \sigma_w^2 \frac{0.63}{1 + 1.5\left(\frac{f^*}{f_m^*}\right)^{5/3}} \qquad (12)$$

then f_m^* is near 0.32 for all conditions below 150 ft and may vary with height and stability. Existing observations are not sufficient to specify the change with very much reliability.

9. Horizontal Component Spectra

The lateral component of turbulence is frequently represented by a model of the vertical component form with appropriate substitution of the lateral variance and scale. If the turbulence is isotropic, these will be the same. The longitudinal, or along-wind spectra are represented by similar functions, two of which are listed below,

Dryden $$\varphi_u(k) = \frac{\sigma_u^2 L}{1 + 39.5 (k L)^2} \qquad (13)$$

von Karman $$\varphi_u(k) = \frac{\sigma_u^2 L}{[1 + 70.7 (Lk)^2]^{5/6}} \qquad (14)$$

Unlike the spectrum of vertical velocity, that of the lateral component does not obey similarity theory. Height is a very minor factor, in fact the scale of fluctuation in wind direction in neutral and unstable conditions is virtually independent of height above the ground. The major variation in the spectrum of the lateral component is produced by thermal stability. Panofsky [37] sums up the observations of several investigators by pointing out that increasing instability greatly increases the low frequency portion of the spectra but leaves the high frequency portions relatively unaffected. Since the lateral variance is proportional to wind speed, then given a certain wind speed, the effect of increasing lapse rate is to superimpose long-period variability on top of the shorter-period mechanical turbulence. These effects can be taken into account in turbulence models by increasing the appropriate length scales in the spectral equations. However, our only knowledge of the spectra of lateral velocity is based on time series data. Conversion to length scales via the Taylor hypothesis may be questionable. Therefore, it is more realistic to discuss spectral variability in terms of frequency.

The spectrum of the longitudinal component falls between that of vertical and lateral velocities. Low frequencies are affected by changes in stability somewhat more than high frequencies but are not affected as much as the lateral component. Under all conditions, the longitudinal spectrum contains considerable energy at low frequencies so that in stable and neutral air, when this energy is less than in unstable air, it is still considerably greater than the other two components. Thus the larger eddies in stable air are elongated in the wind direction.

Some features of these horizontal spectra become apparent when compared to the vertical. Plots for the three components obtained from a data collection at Fort Wayne, Indiana described by Hilst and Bowne [16] are shown in Figs. 17 to 19. The observations were obtained at night with an average wind speed of 9 mph at 40 ft and a lapse rate very close to dry adiabatic up to 300 ft but becoming slightly more stable above, the lapse rate at 700 ft was about half the adiabatic. The vertical component in Fig. 17 illustrates the features pointed out in Section 8, [16]. f* maximum is about 0.2 for the lower levels and about 0.5 at the 700 ft level. The upper level is beyond the altitude where similarity might be expected to hold, therefore, the significance of the separation is not great. The lateral component here is well-balanced because the turbulence is almost purely mechanical. The peaks move toward increasing f* with height, but the decrease in relative magnitude indicates more energy at lower frequencies at 200 and 700 ft than at 40 ft. In Fig. 19 there is further evidence that the longitudinal spectra are intermediate between the lateral and vertical. There appears to be a peak in relative energy at $f^* \simeq 0.1$ at all levels with some increase in high frequency content at the lowest level; however, in general, most of the

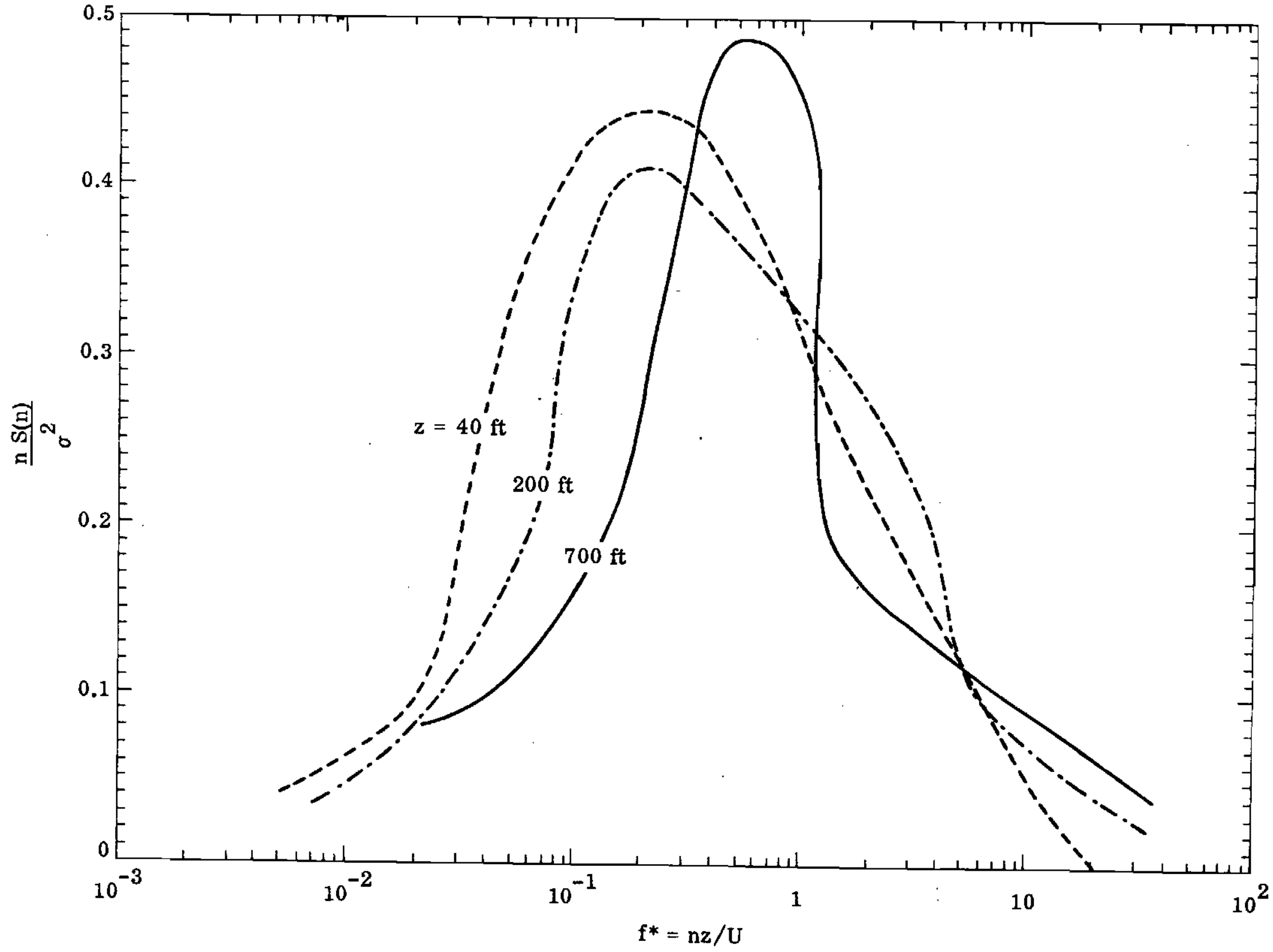


Figure 17. Normalized w component spectra, WANE Tower data-test No. 65-09, Fort Wayne, Indiana

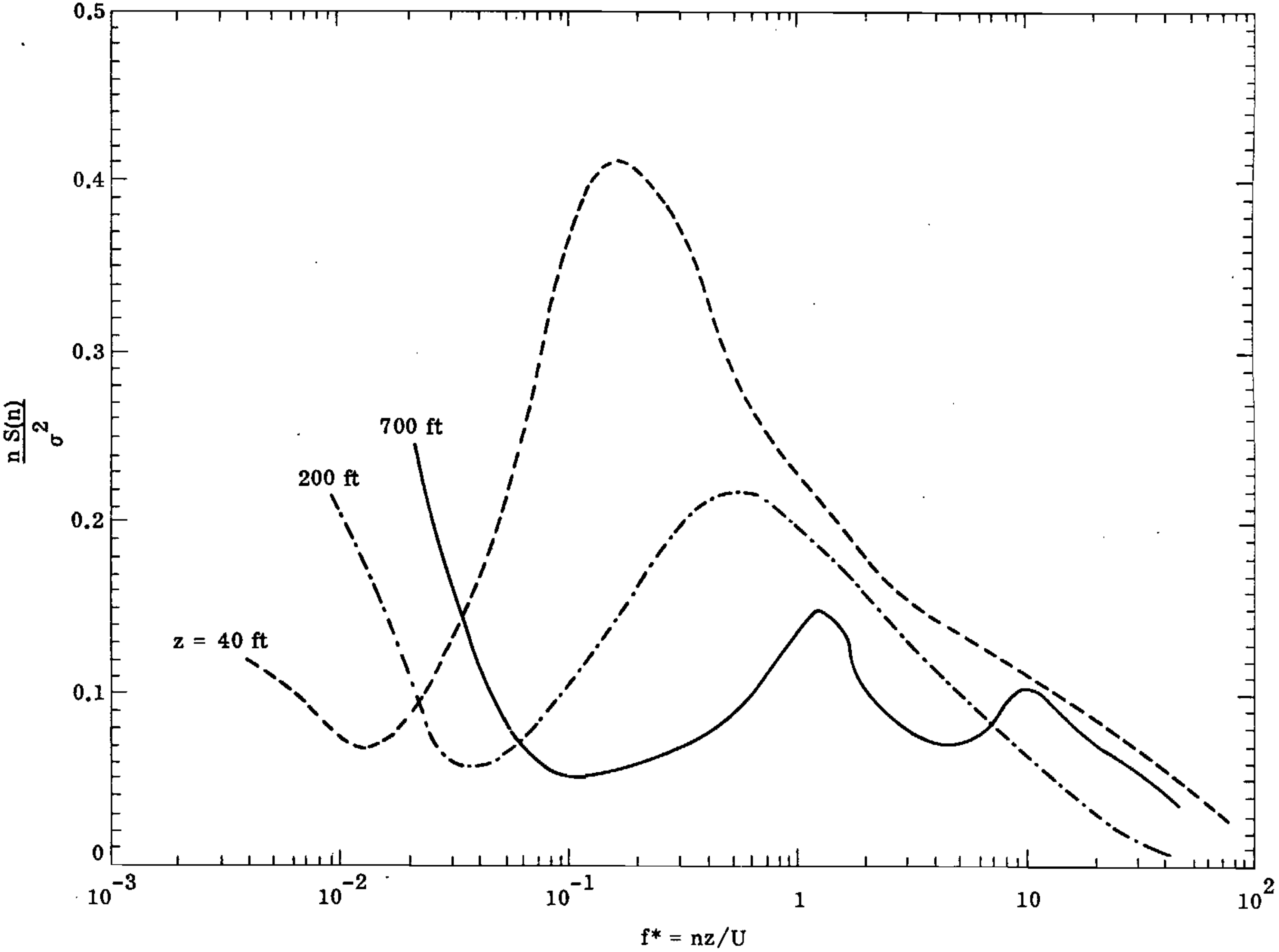


Figure 18. Normalized v component spectra, WANE Tower data-test No. 65-09, Fort Wayne, Indiana

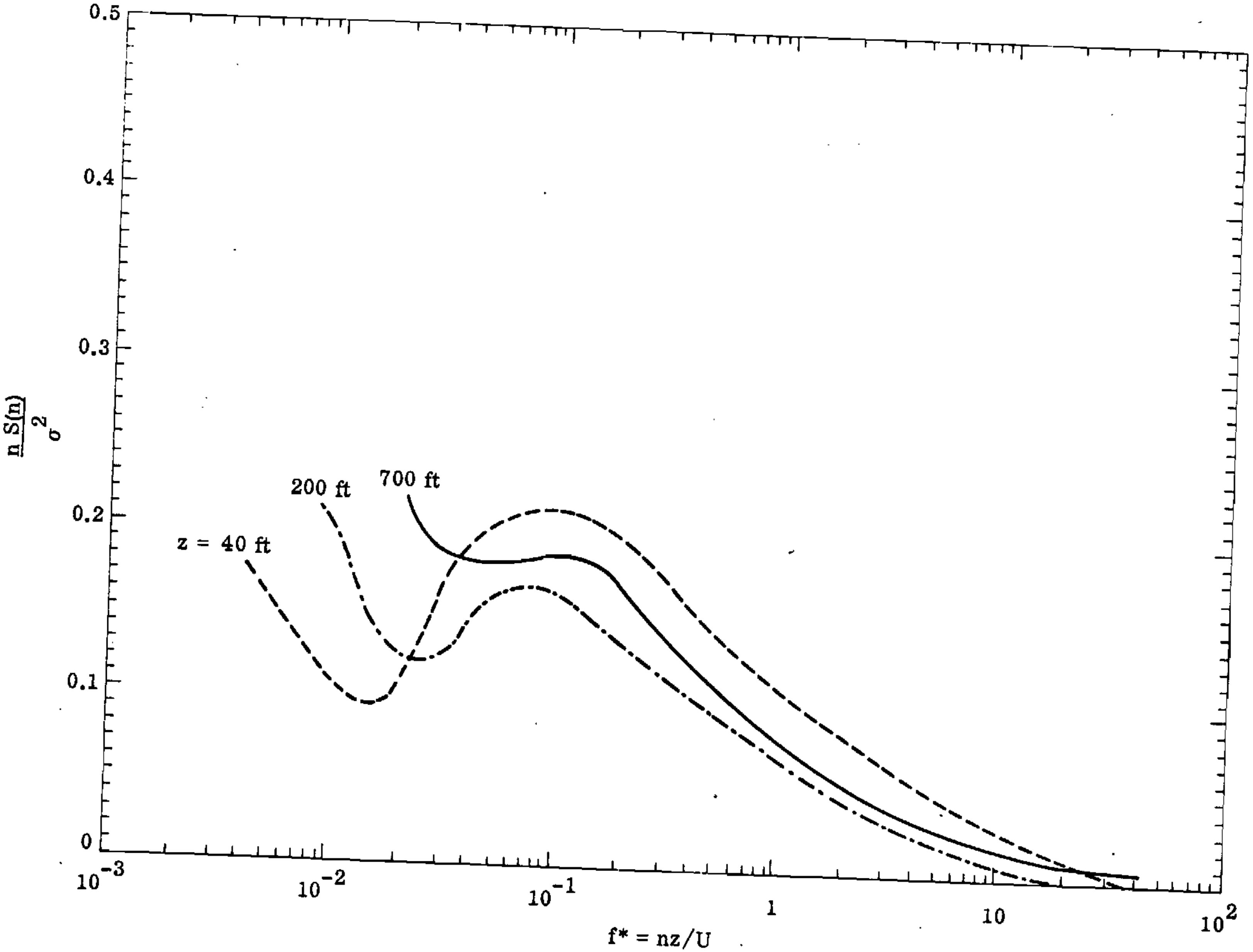


Figure 19. Normalized u component spectra, WANE Tower data-test No. 65-09, Fort Wayne, Indiana

energy appears to be contained at frequencies low compared to the other components. The scales of turbulence indicated by the peaks of the spectra are shown in Table III for this one case. These figures are valuable as guides to the order of magnitude but not for general use.

TABLE III
LENGTH SCALES OF TURBULENCE FOR
FORT WAYNE WIND DATA

Component	Observation Height		
	40 ft	200 ft	700 ft
w	200 ft	1000 ft	1400 ft
v	220 ft	400 ft	700 ft
u	400 ft	2000 ft	7000 ft

The scale for the vertical component is 5 times the height, a reasonable approximation to the overall average of 3 times the height found by Panofsky [34] for the first 150 ft. The scale indicates the eddy sizes containing the most energy or, looked at in another way, the most predominant eddy size. The lateral spectral peaks are significant by statistical tests and provide a measure of the mechanical turbulence because the nocturnal test period precludes thermal activity at this rural location. The increase in spectral energy at lower frequencies is indicated by the upward trends of the graphs, but the period of observation was too short to identify another spectral peak. The same observation is even more true for the longitudinal component, but here the peak is not significant at the upper levels and may indicate a trend in the wind speed data that was not removed, although a trend is not apparent on casual inspection.

10. Magnitude of the Turbulent Fluctuations

A factor that has appeared with regularity in the preceding sections in the spectral models is the variance of the turbulent component under investigation.

The factor σ_w^2, σ_v^2 or σ_u^2 determines the overall level of the turbulence and is directly related to the wind speed and surface roughness in the boundary layer. Empirical evidence is available to show that a relatively constant ratio exists between the turbulent fluctuations and the boundary layer friction velocity u_*. These ratios are:

$$\frac{\sigma_w}{u_*} = 1.29; \qquad \frac{\sigma_v}{u_*} = 2.0 \qquad \frac{\sigma_u}{u_*} = 2.5.$$

These values are for levels within the first 50 feet above the ground but hold for a wide range of stabilities. The σ_w ratio is more stable than σ_v or σ_u which show about 20% variation from one location to another. When height effects are taken into account, the profile laws of wind speed, discussed in the next section, may be used to obtain

$$\sigma_w = \frac{0.52\,U}{\ln\left(\frac{z}{z_0}\right)} \tag{15}$$

$$\sigma_v = \frac{0.80\,U}{\ln\left(\frac{z}{z_0}\right)} \tag{16}$$

$$\sigma_u = \frac{U}{\ln\left(\frac{z}{z_0}\right)} \tag{17}$$

At heights above 300 ft these equations become indicators of magnitude rather than solid engineering estimates because there have been insufficient data collected to verify the concepts. The concepts of the turbulent boundary layer and the theories for representing some of the characteristics such as velocity profiles are discussed in the next section.

The magnitudes of shear discontinuities in boundary layer velocity profiles arising from surface roughness discontinuities have been measured and reported by Hansen [15] and Panofsky [37].

11. Summary

A total of 45 documents and reports containing data from 14 separate facilities were reviewed. Twenty-four documents were considered to contain sufficient significant data for inclusion in the list of references and discussion in this report. Two types of data collection activities were reviewed.

Multiple anemometer data were discussed in Sections 3, 4, and 5 above. These data provided information from five locations, only these were significant for lateral or longitudinal correlations and space spectra. These data provide the only information available for comparing space and time scales of trubulence but provide a measure of only one component of the turbulent wind field at any one time. Other deficiencies included single height measurements and general lack of applicability to TOLCAT problems because of the purpose of the measuring program was limited to a specific interest.

Other sites with multiple anemometer arrays are Dugway Proving Ground, Utah; National Reactor Testing Station, Idaho; Nevada Test Site, Nevada; Kennedy Space Center, Florida; Battelle Northwest, Washington; Vandenberg AFB, and Edwards AFB, California; and the test sites used in numerous diffusion and air pollution field programs. These data were not judged to be appropriate to the TOLCAT problem because of the separation distance between anemometers and methods of data recording which were more closely allied with trajectory information than turbulence data.

Time series information from single tower data were compared for Round Hill, Massachusetts; Brookhaven, New York; Fort Wayne, Indiana; Battelle Northwest, Washington; Cedar Hill, Texas; O'Neill, Nebraska and Sublette, Kansas. Vertical velocity spectra can be specified quite well and comparisons between sites are possible through dynamic similarity reasoning. Lateral and longitudinal spectra are not well behaved and depend on gross atmospheric conditions as well as local site characteristics. Data from all of these sites are of good quality but provide time history information and no horizontal definition.

SECTION III

DESCRIPTION OF THE ATMOSPHERIC BOUNDARY LAYER AND TURBULENCE REGIME

1. Definition of Boundary Layer

a. Prandtl's Viscous Boundary Layer

The concept of a boundary layer in a fluid flow was the sword Prandtl used to slice the Gordian knot of the Navier-Stokes equations (see Lamb [23]). It had long been recognized that for many fluid flows of interest the viscosity and scales were such that shear stress terms of the Navier-Stokes equations would be of negligibly small magnitude. This observation led to attempts to find solutions to equations truncated by the elimination of the shear stress terms. Solutions thus obtained, however, often seemed at odds with observations of real flows. In particular, the solutions could not satisfy all physical boundary conditions because the neglected shear stress terms were of second order (i.e., they depend on second derivatives of velocity), whereas the terms remaining in the truncated equations were of first order (i.e., they depend on first derivatives of velocity).

Attempts were made to obtain solutions for small, not zero, shear stress by expanding about irrotational solutions. The basic problem of meeting all physical boundary conditions could not be met by this technique however. Prandtl recognized that the offending boundary condition—no slip of the fluid at any solid interface, required that shear stress effects be not only finite but actually large in some region near the interface, however small the region might be. The smallness of the region of viscous influence allowed other first order terms of the equations to be eliminated leaving Prandtl with much simplified second order equations which could be solved in many cases. Outside the region of viscous influence (the boundary layer) first order equations adequately describe the flow. At the interface between regions, mutual boundary conditions may be met.

b. The Atmospheric Boundary Layer

The success of this concept has led to a technique of analyzing the order of magnitude of terms in difference equations. For many atmospheric flows of interest, the viscous shear stress contributes little to the force balance on the fluid. Indeed the scales of atmospheric flows are so large that the viscous boundary layer is usually of little interest. Small scale motions of the atmosphere caused by local surface disturbances (e.g., roughness, topography, thermal conditions) do convect momentum at a rate sufficient to shear the atmosphere. Although these motions exist on many scales and even contribute to the synoptic scale flow patterns (i.e., patterns large enough to appear on weather maps), the intensity of the shear stress is a maximum near the earth's surface. The region of significant shear stress is small enough that it may be described as a boundary layer.

c. Reynolds Equation

The specific definition of the boundary layer is rather arbitrary, since the shear stress terms appear explicitly in the momentum equations (the Reynolds form of the Navier-Stokes equations) through rather arbitrary distinctions between mean and fluctuating components of the velocity field.

Reynolds'(see Hinze [17]) definition of the velocity of a turbulent flow is:

$$u = U + u' \tag{18}$$

where

u is the velocity; $u = u(x_i, t)$; U is the time mean velocity;

$$U = \frac{1}{\Delta t} \int_0^{\Delta t} u \, dt = U(x_i)$$

and u' is the deviation from the mean; i.e., $u' = u'(x_i, t)$ defined by Eq. (18). If Eq. (18) is substituted into the Navier-Stokes equations, it may be shown [17] that the equations for the mean motion are unchanged except for the addition of "Reynolds stress" terms which are functions of the velocity fluctuations, i.e., in an inertial reference frame,

$$\rho\left(\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j}\right) + \frac{\partial P}{\partial x_i} - F_i = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x} - \rho \overline{u_i' u_j'}\right) \tag{19}$$

If the turbulent stresses are much stronger than the viscous stresses, the equations become

$$\rho\left(\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j}\right) + \frac{\partial P}{\partial x_i} - F_i = - \frac{\partial}{\partial x_j}\left(\rho \overline{u_i' u_j'}\right) \tag{19a}$$

An inconsistency immediately appears. If $U_i \neq U_i(t)$, then $\frac{\partial U_i}{\partial t} = 0$. It is desired, however, to use the equations to compute time variations in the mean state of the flow.

The system is quasi-rational if the time scale of the motions described by u′ is small compared with the relevant time scale associated with changes of U. The time scales are suitably separated if there is a "gap" in the spectrum of disturbances. There is some controversy over the existence, ubiquity, and/or nature of such a gap in the spectrum of atmospheric motions ([48], [14], [22], see also Fig. 21). Investigators are continually finding contamination of measured "turbulence" spectra by "trends" in the mean flow (e.g., [31], [13]). In the face of trends, it is sometimes proposed that the spectra be measured to some lower frequency, thus redefining the trends as fluctuations and narrowing the definition of the mean state. Since the Reynolds formulation was arbitrary at the outset, this redefinition is valid, but two major problems remain:

- The problem of trends is merely a shifted to a new frequency unless a significant spectral gap exists at <u>some</u> wavelengths.
- The relegation of real fluid motions to elements of a stress state is the effective replacement of a complete description of the flow by some integral properties of the flow, i.e., a stress tensor description of a turbulent field is a table of the mean properties of a flow which is considered to be too complex to be described fully.

Some implications of these problems will be discussed in Section IV. It is sufficient to say here that the definition of a Reynolds stress state is often useful and valid.

2. Turbulent Boundary Layer Analysis

a. Determinacy

Equation (19a) is indeterminate since it forms a set of three vector equations and there are three mean velocities, three fluctuating velocities, pressure, density, and the external forces to solve for. In addition to Eq. (19a), other available equations are continuity of mass, the equation of state of the fluid, and the equation of the external force field (gravity, for the atmosphere). These equations may be used to reduce the problem to three momentum equations with three mean and three fluctuating velocities as unknowns. This system is still indeterminate.

b. Empirical Formulation of Stresses

The typical approach to the solution of the problem is to determine, by analysis or experiment, the dependence of the stress terms upon the mean flow. Since the Reynolds formulation is only used when the flow is too complex to analyze in detail, the dependence of the stress terms upon the mean flow can, at most, only be made consistent with boundary conditions or "models" of the flow field or of the turbulent processes involved.

Of particular interest for the atmospheric boundary layer is the case where the Reynolds stress terms are the only significant terms in the equation. For flow over a reasonably uniform surface of large extent this is appropriate. There is a large disparity between the vertical and horizontal scales (i.e., the boundary layer thickness is small compared to the wind fetch). Therefore the mean vertical accelerations will be negligible. The surface uniformity assures that mean horizontal accelerations will be negligible. Equations (19) and (19a) then reduce to the simple condition that the Reynolds stress is constant. Equation (19a) becomes

$$\frac{\partial}{\partial z} \rho \overline{u_i' u_j'} = 0 \tag{20}$$

for a constant density fluid or $\overline{u_i' u_j'} = u_*^2$.

To relate u_* (called the shear stress velocity) to the mean profile, physical insight and experience must be called on to provide an empirical relationship, One of Prandtl's major contributions (discussed by Schlichting [41]) to turbulence analysis was a physical model for the correlation of streamwise and transverse velocity fluctuations. Since the mean product of independent (uncorrelated) random fluctuations is zero, u_*^2 is a measure of the dependence of u_j' on u_i'.

Let $u_i' = u'$, $u_j' = w'$ and $\partial U_i/\partial x_j = \partial U/\partial z$.

Then any eddy superimposed on the mean flow will probably have a strength proportional to the difference in mean velocity across it. If a typical eddy dimension is ℓ, the magnitudes of u' and v' should be proportional to $\ell \ \partial U/\partial z$. In addition, the signs of u and v should be negatively correlated, since the sign of $\partial U/\partial z$ should determine the probability of the sign of the streamwise momentum perturbation convected by any transverse motion. Prandtl thus obtained

$$\overline{u'w'} = -\ell \left| \frac{\partial U}{\partial z} \right| \frac{\partial U}{\partial z} \tag{21}$$

For the usual boundary layer case of positive shear and constant Reynolds stress

$$\overline{u'w'} = -\left(\ell \frac{\partial U}{\partial z} \right)^2 = u_*^2 \tag{21a}$$

or

$$\partial U/\partial z = u_*/\ell \, .$$

It must be emphasized that implicit in this formulation is the physical concept of the interchange of "parcels" of fluid between layers of the mean flow. Each parcel is supposed to have a thermodynamic identity (mass composition, momentum and energy) established in the layer of its origin. It carries this identity, or some constant fraction of it, to its destination where it is out of equilibrium by the difference in mean states between the origin and destination.

c. Adequacy of Model

Prandtl's "mixing length" formulation, however weak theoretically, has proved invaluable in analyzing a great array of physical problems. It has formed the basis of almost all the engineering analysis of turbulent flows, as well as proving useful in scientifically analyzing problems.

Despite its widespread use, "mixing length" theory is not an unqualified success. Questions have arisen as to the accuracy of the eddy model dynamics. G. I. Taylor [46] early expressed concern that an eddy—the complete flow field implied by interchanging fluid parcels—cannot simply pick up momentum on one side, and, like a waterwheel, dump it at the other. Taylor hypothesized that the eddy conserves vorticity rather than momentum. Results derived from this hypothesis are more accurate in some respects and less in others. Physically it appears likely that the eddy conserves neither momentum nor vorticity nor does it gain or lose either by any simple rule. Since the eddy is a complete motion, often unstable, often dissipative and always interacting with its surroundings, no simple transport models could be expected to be completely accurate.

The question raised previously (Section III-1c) as to the adequacy of the turbulent representation should be particularly pertinent in regions where the turbulence or the mean flow is time dependent. This situation does exist at the limits of a turbulent region (e.g., the outer edge of the boundary layer). A recent paper by Yen [50] suggests that the intermittency of turbulence observed in the outer regions of free shear zones is responsible for much of the inadequacy of and discrepancies between the Prandtl and Taylor turbulence models. Taking this factor into account is shown to give much more consistent results. One particular problem apparently resolved is the discrepancy in values obtained for the ratio of the turbulent diffusion coefficients for momentum and for scalar quantities (mass and energy).

d. Turbulent Transport Processes

The identification of dynamic quantities that may be conserved during eddy motions suggests that scalar quantities such as mass and energy might be transported in an analogous fashion. If the molecular diffusive properties of the fluid are all of the same order, which is indeed nearly the case for common gases, then whatever relation exists between the actual eddy size and l, the integral property for momentum transfer, should exist also for the scalar transports. Evidence on this point is somewhat conflicting [50], [49], [9], but it appears valid at least to much less than an order of magnitude.

In liquids and perhaps in dense plasmas, this is not the case. In these media molecular heat diffusivity is much greater than momentum diffusivity which, in turn, is much greater than mass diffusivity.

The Boussinesq [17] theory of turbulent diffusion, much older than the mixing length theory, is perhaps more applicable to transport phenomena.

Boussinesq's theory is analogous to Newton's relationship for a continuum; that the stress is proportion to the strain.

For molecular properties

$$\tau = \rho \nu \nabla u \tag{22}$$

For turbulent properties

$$\tau = \rho u_*^2 = \rho K_m \nabla U \tag{23}$$

Similarly, Fickian turbulent mass diffusion gives

$$m = - \rho \overline{c'w'} = \rho K_c \nabla c \tag{24}$$

and Fourier turbulent heat diffusion gives

$$q = - \rho \overline{h'w'} = \rho K_h \nabla h \tag{25}$$

The formal neatness of Eqs. (23), (24), and (25) represents some sacrifice of information.

The diffusivities are defined without relation to the dynamics of the turbulent motions. Comparison of Eqs. (21) and (22) suggests that the diffusivity, K_m, should be proportional to the mean shear, rather than independent of it as ℓ is assumed to be.

e. Velocity Profiles

Equation (21) provides a direct means of obtaining the velocity profile, U(z), of the atmospheric boundary layer if ℓ is known as a function of z. It has often been observed [46], [51] that the scales of eddies in the atmospheric boundary increase with altitude. Lumley [27], says that since z is the only relevant length ℓ must be z (or at least linearly related). Schlichting [41], states that the presence of the solid boundary "damps out" the eddies and thus eddies larger than their altitude cannot exist. A physical explanation proposed here is that eddies, i.e., closed circulation cells of whatever geometry, must be edge-alined at a solid boundary, as in Fig. 20. They may be of any size; they may be superimposed; they may be of any geometry (circles are shown for simplicity). Now each eddy is most effective at vertical transport along its horizontal diameter where its vertical velocity is greatest. Each eddy is effective at absorbing or releasing some transferable quantity at its vertical extremities where its vertical velocity is zero. Thus, diffusion at any level near the ground is most probably related to eddies which "fit" between that level and the ground.

The analyst is therefore led to linearly relating ℓ and z. A direct proportionality is unacceptable since surface inhomogeneities and/or viscous shear assures finite eddy cell sizes and/or finite shear near the ground. A more general linear relationship cannot meet any specific boundary condition at the ground, but can be empirically fit to any given eddy cell size near the ground. A common, simple relationship given by Lumley [27] is

$$\ell = k\,(z + z_0) \qquad (26)$$

where z_0—the (negative) altitude at which the velocity profile is fit, is commonly called the "roughness length" since the smallest significant cell size may be closely related to the size of typical surface roughness elements. The velocity profile thus obtained is

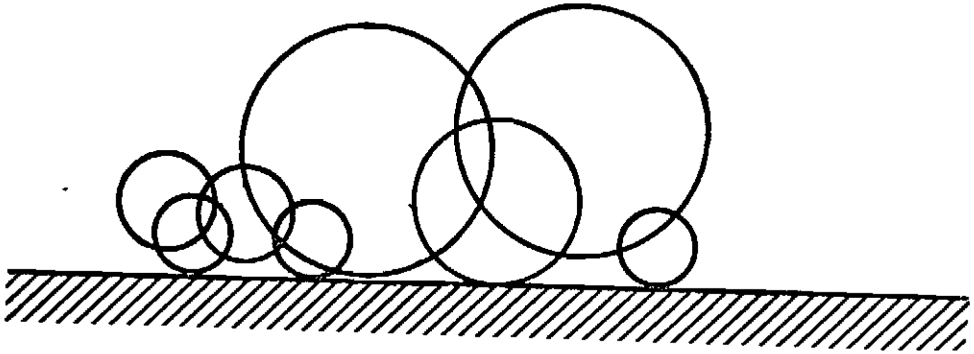


Figure 20. Turbulent eddies edge-alined at ground plane

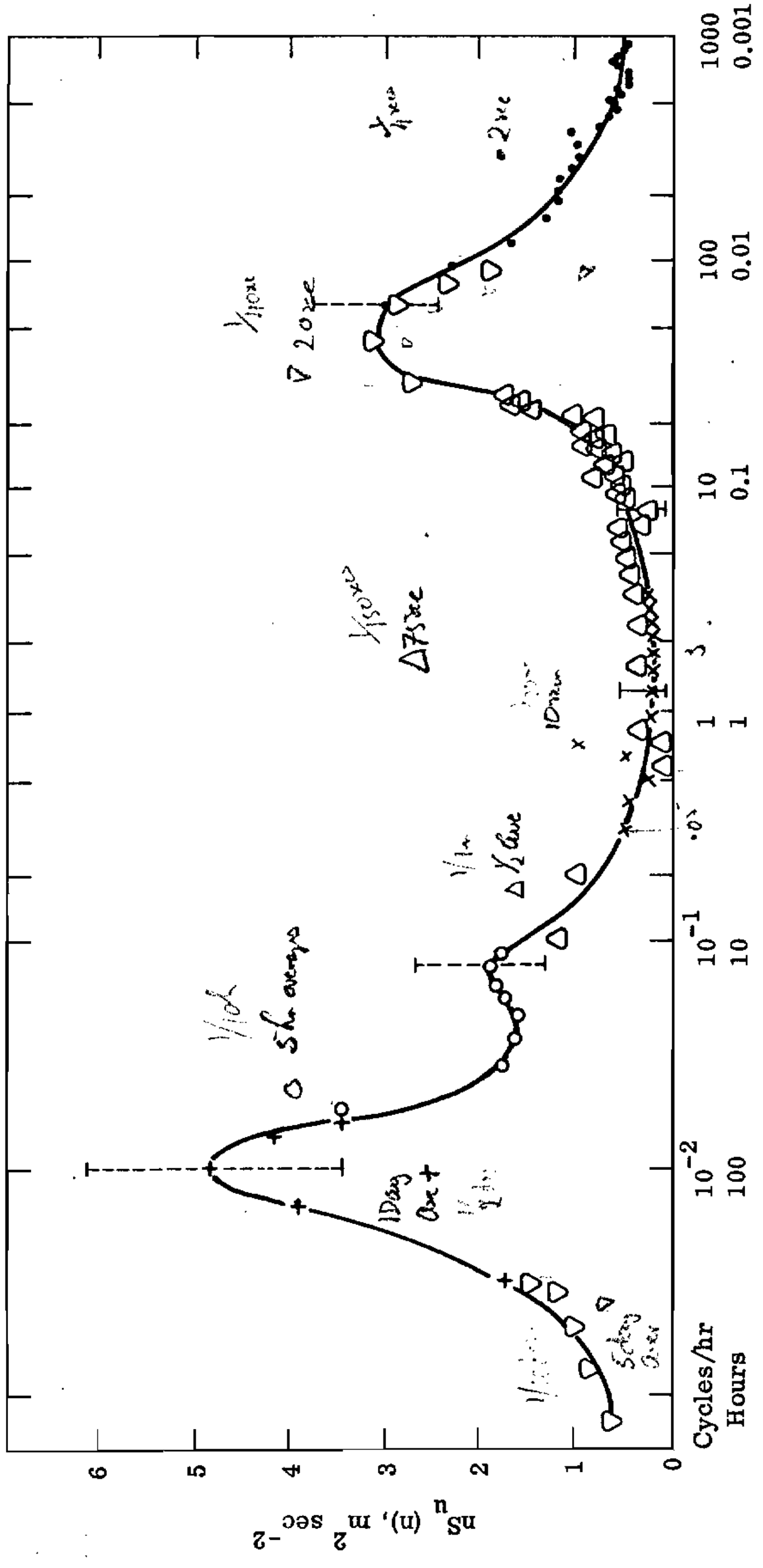


Figure 21. Schematic spectrum of wind speed near the ground estimated from a study of Van der Hoven [48]

$$U = u_*/k \ \ell n \ \frac{z + z_0}{z_0} \quad \text{or simply } U = \frac{U_*}{k} \ \ell n \ \frac{z}{z_0} \tag{27}$$

$$\text{for } z >> z_0$$

The physical arguments leading to Eqs. (26) and (27) lose force if z is much larger than some typical cell size. This would be the case if some upper limit to the eddy size existed or if some limited cell size were most representative for determing the Reynolds stress. The true dependence of representative cell sizes on the mean flow is quite complex, but Monin and Obukhov [30] have suggested by dimensional arguments that a scale length can be determined from the remaining dimensional constants in the problem. On a scale larger than simple shear-generated turbulence, heat transfer and buoyancy effects are important.

The heat transfer equation is directly analogous to the streamwise momentum equation. It is simply a statement of constant vertical heat diffusion in the absence of sources or sinks, i.e.,

$$\frac{\partial}{\partial z} \ \rho \, C_p \ \overline{T'w'} = 0 = \frac{\partial H}{\partial z} \quad \text{or} \quad \overline{T'w'} = u_* T_* \tag{28}$$

Buoyancy terms appear in the vertical momentum equation. If the Boussinesq approximation is used whereby density fluctuations are neglected everywhere but in the buoyancy term, the equation is

$$\frac{\partial}{\partial z} \ \overline{w'^2} = \frac{\lfloor T' \rfloor}{T} \ g \quad \text{or} \quad \left(\frac{u_*^2 \, T}{gLT_*} \right) \frac{\partial w_*^2}{\partial z^*} = \tau = \frac{\lfloor T' \rfloor}{T} \tag{29}$$

The bracketed form in Eq. (29) is a dimensionless constant of the problem. Since Eqs. (21a) and (28) show that u_* and T_* are independently constant and g and T are constant by definition, then L must be constant also.

An interpretation of Eq. (29) is that over some scale, L, the shear stress and heat flux are reasonably constant yet temperature fluctuations are causing an increase of the intensity of the turbulence. Over such a scale then, the <u>mean</u> (dimensionless) profiles should be a function of z^*. ($z^* = z/L$) only, since z^* is the only independent variable in any of the relevant equations.

This observation should be most valid for z << L. Monin and Obukhov [30] therefore set the dimensionless shear equal to a series expansion in z^* about the value of shear for small z*. We have suggested already in Eq. (21a) that the shear is unity for small z. Therefore, the initial terms of a series expansion give:

$$\frac{kz^*}{u_*}\;\frac{\partial U}{\partial z} = 1 + \beta z^* \tag{30}$$

Which may be integrated to give

$$U = \frac{u_*}{k}\left[\ell n\; z^*/z_0^* + \beta\,(z^* - z_0^*)\right] \tag{31}$$

Similarly the temperature distribution is given by

$$\theta - \theta_0 = T^*\left[\ell n\; z^*/z_0^* + \beta\,(z^* - z_0^*)\right] \tag{32}$$

The assumptions made to obtain these profile forms are:

- The eddy cell size is nearly linearly related to the altitude; i.e., the β term in Eq. (32) is small and buoyancy is small.
- The mean flow is spatially and temporally uniform; $\frac{dU}{dt} = 0$); i.e., the boundary layer is neither growing nor decaying.
- The mean flow is parallel to the ground plane.
- There is no dissipation of momentum or heat; i.e., molecular transport terms are negligible.
- There are no sources or sinks of horizontal momentum or heat over the altitude range analyzed; i.e., u_* and T_* are constant.
- The eddy cell size depends primarily on thermals generated by vertical forces; i.e., the gravitational force term is important.

Other authors [7], [10], [30], [45], give alternative expressions for Eq. (30). These define $\frac{z^*}{u_*}\;\frac{\partial U}{\partial z}$, the dimensionless shear, as empirical functions of z and of mean flow parameters. Each has its merits in particular cases and there is little hope for reduction in the empiricism since the problem is basically indeterminate as long as it is expressed by the turbulence equations. The question of determinacy here is different from that discussed in Section III (2a). The mean profiles are indeterminate because all terms involving the mean variables are neglected in the equations. Physically the problem is indeterminate because the mean flow is not accelerating in either space or time. This equilibrium state must be a function of the turbulence but this dependence is not expressed by the equations of motion, nor is it known physically.

3. Structure of Turbulence

a. Turbulent Spectrum

One compromise between the aesthetic desire to know the continuum flow field in full detail and the pragmatic wish to consider only integral properties of the turbulent perturbations is to treat the turbulence as a collection of independent modes of motion. The mode characteristic is typically the physical size of a region of reasonably coherent motion. The notion is quite natural. The flow can be conceived of as consisting of a basic macro-scale flow perturbed by the superposition of a variety of simple motions such as vortices or compression waves each having a distinct micro-scale.

The notion is also consistent with a Fourier or other linear decomposition of a random signal. The Fourier wave lengths correspond to the physical sizes of

$$U(r) = \sum_i \left[a_i \cos \frac{2\pi r}{\lambda_i} + b_i \sin \frac{2\pi r}{\lambda_i} \right] \tag{33}$$

the eddies or waves. The Fourier amplitudes are taken as the proportion of the signal due to disturbances of scale λ_i in the field. For unbounded fields, large with respect to the λ's, the summation may be replaced by an integral.

If the motion field (or analogously the temperature or other related field) is so decomposed, then the perturbation energy associated with each mode may be identified from Eq. (33), the energy is

$$\Phi(\lambda) = a_\lambda^2 + b_\lambda^2 \tag{34}$$

An analogous result is obtained from the integral form. Since the total turbulent field is the sum of the mode contributions, the mode contributions are derivatives of the total field with respect to the mode characteristic. For example, $\Phi(\lambda)$ the energy of disturbances of size λ is just $\frac{\partial E}{\partial \lambda}$ where E is the total turbulent energy.

b. Spectral Dynamics

If $\Phi(\lambda)$ exists, the differential equations for the total turbulent energy may be differentiated term by term with respect to λ. The results constitute equations of spectral dynamics. They show that the energy of any turbulent mode may be convected or may be transferred from mode to mode or may be generated from or released to the mean flow. This gives a powerful means of analyzing turbulence generation or suppression. It also provides a mean of determining the form of the energy spectra for particular cases. An example is Kolmogorov's [3] derivation of the equilibrium inertial subrange.

For these equations to be meaningful, there must be some dynamic likeness between disturbances of the same scale; that is, eddies of the same scale must act alike; their interaction with other eddies and the mean flow must be determined by their size. The only characteristic of eddies of a given size specified by power spectral density measurements is the mean energy. It is certainly possible to conceive spectral systems based on other variables. For example a spectrum of the number of eddies of a given vorticity could be defined. As a matter of fact an energy spectrum could be defined on the basis of the number of fluctuations of a given energy (which might be of differenct sizes). Conventional power spectral density analyses, therefore, involves the assumption that a turbulent flow field with a random array of disturbances may be approximated by a field in which all disturbances of the same physical size have the same energy.

The choice of dependent and independent variables for a spectrum is arbitrary, but the validity of linear superposition of the spectral components does depend on this choice. For example, two sets of turbulence elements could be constructed each with the same energy spectrum but with different vorticity distributions. They might, however, have different effects on the mean flow. The validity of any particular spectral assumption must depend on the flow field within the individual eddies, the nature of transport mechanisms between an eddy and its surroundings, and the intensity of each eddy.

In atmospheric boundary layers, many types of disturbance flow fields have been identified or hypothesized (see Section V). Very little has been done in analyzing transport characteristics of individual eddies. Prandtl and Taylor proposed different concepts of eddy transport characteristics (see Section III.2.c) which give somewhat inconsistent results. Increasingly sophisticated experimental and theoretical analyses of thermal convection cells have been carried out ([2], [26], [47]), and certain kinematic aspects of vortex interactions have been studied. Kraichnan (cf. [5]) has developed a whole new formalism of turbulence in which many moments of the fields (higher order correlation coefficients) are used to specify eddy interactions. Perhaps the most serious question of the validity of spectral analyses of atmospheric boundary layers is the effect of the intensity of the fluctuations on the linearization implicit in the Reynolds equations of turbulence themselves. The intensity of turbulence (the rms fluctuation divided by the mean value of a variable) for laboratory turbulence studies seldom exceeds 10%, but the intensity of turbulence in the atmospheric boundary layer is often as high as 30% and individual fluctuations often exceed 100%.

In spite of lingering doubts, spectral analysis has certainly demonstrated that it can yield significant information about atmospheric boundary layers. Care must be taken, however, to avoid attributing omnipotence to the formalism.

c. Spectral Ranges

The significant characteristics of a spectrum $E(\lambda)$ are its shape and its magnitude. Each contributes significant knowledge of the turbulent flow field. The magnitude of E at any λ is a measure of the intensity of the turbulence at that scale. The shape of E vs. λ not only gives the intensity at all λ but also gives clues to the interaction of eddies of different sizes. Conversely, notions of the physics of the turbulence give clues to the shape of the spectrum.

The second law of thermodynamics states that a system will spontaneously tend toward a higher degree of disorder unless it is "pumped up" through the expenditure of energy. The application of this law to turbulence is difficult since the boundaries of any system are nebulous, and the sources of energy for a single mode are difficult to define. Nevertheless, it is apparent that turbulence at any scale tends to break down into smaller scales or dissipate into molecular disorder. Another way of viewing the matter is that turbulence arises from some perturbations growing in an unstable mean flow. The local flow field in the perturbed zone may also be unstable and break down. Thus smaller scale perturbations will be formed, and the process may be repeated. This cascade of energy was charmingly described in L. F. Richardson's [40] couplet, "Big whirls have little whirls that feed on their velocity, little whirls have smaller whirls and so on to viscosity..."

The process is irreversible, since mechanisms generally do not exist to re-form the mean flow from the perturbed. This does not necessarily preclude large scale motions resulting from small. The "beating" of harmonic disturbances and the generation of subharmonics are examples of linear mechanisms that increase length scales in a system. Recent analytical and experimental work ([39], [21]) indicate non-linear processes can also account for energy transfers to larger scales.

The common circumstance of energy transfer to smaller scales allows equilibrium spectra to develop. Energy source and sink terms can be identified in the equations, and corresponding phenomena can be identified in the atmosphere. The relative magnitude of the effects is a function of scale. For example, buoyant generation or dissipation of turbulent energy is most effective at scales much larger than those at which viscosity dissipates turbulent energy. Ranges of the spectrum may be identified where the spectral energy balance depends on only one or two terms. In Section III.2.e, it was suggested that eddies of a scale comparable to their separation from the ground would have their geometry affected by the ground plane. Conversely, motions of a scale much smaller than this should not "feel" the ground. It would be expected that they would tend to be three-dimensional, with random asymmetries. The spectra in this case would be independent of direction. Negative (stable) buoyancy effects tend to limit turbulence from above, thus Panofsky [27]) shows that the limit of isotropic scales is a function of stability as well as height for inversion cases.

The range of scales in which buoyancy generates turbulence ought to be related to the Obukhov scale length [Eq. (29)]. This length was defined as a length over which turbulent momentum and heat fluxes were nearly constant. It might, therefore, be the lower limit of scales over which such fluxes vary; ergo, a minimum scale for thermally driven cells.

By reasoning such as this many spectral ranges may be described. The contribution of various terms may be depicted as in Figure 22 (from [27]).

d. Correlations

It was shown in Section III.1.c that the stress state of the atmosphere depended upon gradients of a tensor whose components were mean products of perturbation variables. The mean of any random variable is zero by definition. The mean square value of any random variable is always finite. The mean product of any two random variables is finite if the variables are in some way dependent on each other, i.e., they are "correlated." If such a correlation exists, and is linear, one variable may be expressed in terms of the other, and their mean product is proportional to the mean

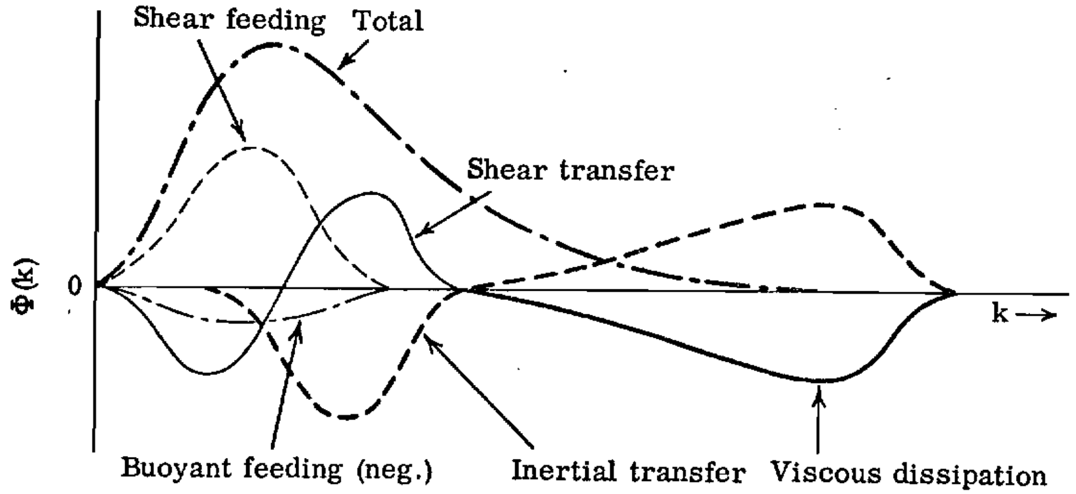


Figure 22. A schematic drawing of spectral energy transfer in a homogeneous shear flow at moderate Reynolds number, small positive Richardson number [27]

square (or autocorrelation) i.e., given

$$\left[x_1, x_2(x_1)\right] = \left[x_1, ax_1\right]$$

then $$\overline{x_1 x_2} = \overline{a x_1 \cdot x_1} = a\,\overline{x_1^2}$$

As applied to the stress state, the physical meaning is that gradients of the mean flow provide a mechanism through which a perturbation of one variable produces (is correlated with) a particular fluctuation of another. In flow where the mean field is constant, fluctuations are not so correlated and the Reynolds stresses are zero. This situation does occur far from physical boundaries. Turbulence, once generated, is left floating in an unstressed field. The perturbations are randomly oriented and uncorrelated. Turbulence of this sort is called "free turbulence." Although finite correlations are consistent with gradients of the mean variables, Eq. (19) shows that gradients of the stress tensor will exist if the mean flow field changes in space or time; i.e., correlations yield a boundary layer velocity profile; growth or decay of the profile requires gradients of the correlation tensor. Note that the same reasoning applies to the mean time and space variations of the turbulent field. Formally, variations of the stress correlation tensor may be expressed [17] as expanded tensors, the elements of which are triple correlations (i.e., $\overline{x_1 \cdot x_2 \cdot x_3}$). The equations are indeterminate; there are more variables than equations. The resolution of the indeterminacy requires additional equations, perhaps of the nature of those discussed in Sections III.2.d and III.2.e, or experimental data, which effectively reduces the number of unknowns. The required data consists of synchronized measurements of all the fluctuating variables at a three-dimensional array of stations sufficiently large to encompass a reasonably homogeneous region of the turbulent field and sufficiently dense to resolve the smallest motions of interest.

Correlation coefficients and power spectra are related through Fourier analysis. The standard approach to statistical analysis is to first compute correlation coefficients from the fluctuating time signals; the magnitude of the power spectrum at any scale, λ, is then determined as the cross correlation of the correlation coefficient with the Fourier cosine function of wavelength λ. The linear relationship thus implied between the power spectrum, the correlation coefficient and the periodic Fourier components allows determination of the correlation coefficient also as the correlation of the spectral function and the continuum of Fourier components.

These reciprocal relations are set out in many standard texts (cf. [4]).

e. Probability Analysis

Probability analysis is often used to supplement or supplant deterministic analyses when (1) the physics are not understood so that deterministic formalisms are not available; (2) there are theoretical doubts as to the validity of deterministic analyses; or (3) there are pragmatic problems of carrying out a complex deterministic analysis.

Probability analyses accept guidance only, but not direction from the physics of the problem. Characteristic variables of the problem are identified. These variables may be examined individually, jointly, or in functional combinations. The probability of occurrence of specific values of these variables (or unions, or functions of them) is measured. The probability of various unions of the sets of variables can then be interpreted as indicating the degree of dependence of one variable on the others. Another interpretation is that such unions are variables in themselves. If a physical phenomena must be described by several characteristics, then specifying values for all these characteristics jointly describes the phenomena; the joint probability of all those values occurring is the probability of the physical event itself occurring. There can be little question of the validity of probability analysis itself, but the utility of it depends on the physical insight used in selecting the characteristic variables of the problem.

4. TOLCAT Problems

a. State-of-the-Art

The state of turbulence in the atmospheric boundary layer is important in many technological fields. It is important in determining the fluxes of mass, momentum, and energy to the atmosphere; it is important in determining the diffusion of many products of technology; it is important in determining loads on earth-bound structures; and it is important as the environment in which aerospace vehicles must operate.

Each of these applications requires somewhat different analytical techniques and therefore somewhat different collections of data. Even different vehicle operation problems require different views. They have a common aspect however, that of the interaction of the atmosphere, the vehicle and its control system. It is particularly difficult to find a mode of analysis appropriate to such complex interactions. There is little in common between the physical characteristics describing the turbulent state of the atmosphere, the dynamics of the aircraft elements, and the logic of the control system (including the pilot). Early studies of aircraft gust response were, almost exclusively quasi-steady analyses of the motion of, and forces on, a vehicle during its transit of a single, hypothetical gust. The vehicle was allowed to respond to the steady-state force coefficients generated by the gust. No control response was accounted for. The next degree of sophistication of the analysis attempted to account for variations of the force coefficients due to system accelerations. Further development of the theory took into account the possibility of the vehicle structure storing energy in conservative (e.g., elastic) modes. The dynamic state of the vehicle thus would depend on resonances as well as force coefficients. This concept led to concern for the frequency of excitation by the atmosphere as well as concern for the instantaneous flow field. Frequency considerations were also found to be important for determining the fatigue life of the structure. Power spectral analysis proved convenient for resolving the excitation properties of the flow and the dynamic response of the vehicle in a single framework. The major assumption of its use is that the interactions of the atmosphere and the vehicle are most significantly characterized by energy and frequency. This assumption is certainly natural in view of the applications discussed above. The success of the approach in solving these problems is a measure of the validity of the assumption. The main assets of the power spectral approach are [52],

- It allows a. . .realistic representation of the continuous nature of atmospheric turbulence.
- It allows airplane configurations and response characteristics to be taken into account in a rational manner.
- It allows. . .rational consideration of design and operational variations such as configuration changes, mission changes, and airplane degrees of freedom.

The third element of the problem of flight in turbulence is the control logic system. Energy and frequency aspects of the control system have been and are being studied (cf. [28]). Resonance is certainly an element of many control problems. Feedback in closed-loop control systems assures that even the inclusion of such a non-linear element as a human pilot will not eliminate resonance. Conventional power spectral analysis, however, is a linear analysis.

Computer simulations of V/STOL piloting tasks have been made [28], [44]. Typically, a hybrid computer uses aircraft response equations and statistically generated models of atmospheric turbulence to provide electro-mechanical inputs to sensory displays (CRT displays, flight instruments, shakes and tilts, etc.) and, through synchros, to a set of pilot controls. A human pilot manipulates the controls in response to the stimuli and his control decisions are fed back to the computer as input data via the control synchros. Such simulations are used to study the variation of vehicle parameters, and to analyze the pilot control task. It has been noted that "Results are extremely sensitive to the turbulence model used. Much dissatisfaction exists concerning the adequacy of the current turbulence inputs for pilot opinion work. Spectral methods have reproduced the averages, but seem to have lost the character of surprise of actual turbulence." [20]

b. State-of-the-Atmosphere

The marginal success of turbulence simulation for the study of catastrophic events is unfortunate, but is not inconsistent with the state-of-the-analysis discussed in the preceding sections. The main V/STOL operational concern is for the unusual events, but these are the low-probability events that are most difficult for probability analysis to recognize. Indeed, there is no a priori reason to believe that these events are simply elements of a random set possessing well ordered statistical properties. No analytical reasons have been proposed either. Events which occur a large proportion of the time are likely to be physically related to each other, while events which seldom occur probably do so because they are functionally independent or at least linearly independent.

As an example, it is easy to conceive of airplane receiving a train of impulses which excites a resonance which tears a wing off. The nature of the eddies producing the impulses is of relatively little importance. The more serious V/STOL problem is being upset while in a critical attitude. Upset problems can be the result of resonance (e.g., the pitching mode oscillation called "porpoising"), but a less understood danger is an unstable flight condition met during a traverse of a single or a few very intense atmospheric eddies. This sort of interaction cannot be analyzed as an impulse and does not seem to be characterized by energy and frequency.

The existence of intense eddies might be portrayed by spectral or probability analysis, but their incidence might be unrealistically estimated because,

- There is no discrimination of disturbance flow pattern. Disturbance could be a wave, a two-dimensional or three-dimensional cell of some special geometry, or a boundary layer discontinuity (e.g., a free-shear zone arising from a discontinuity of boundary conditions).
- Each of these flow patterns have distinct statistics; the velocity distributions have distinct higher moments (skewness etc.) and velocity maxima are not simply related to the mean energies.
- Decomposition into Fourier components may replace complex but coherent periodic waves shapes by a spectrum of incoherent harmonic waves. It is true that if phase information is retained the original waveform can be reconstructed. In practise, this is all but impossible.

SECTION IV

DEFICIENCIES IN EXISTING DATA AND TURBULENCE MODELS

1. The State of the Art

Nearly all analytical and experimental work on the atmospheric boundary layer has been directed toward understanding the transport of mass, momentum, and energy. The most elementary results have been obtained relating turbulent diffusivities to turbulence models. Self consistent semiempirical velocity and scalar profiles have been related to scales of turbulence as well as to mean atmospheric parameters such as thermal stability. It is felt that while refinements of these aspects of atmospheric turbulence are theoretically important, they would probably not be critical for V/STOL design or operation.

Spectra of one or more components of velocity and a very few cospectra have been measured. Despite inconsistencies these data appear to define spectra adequately for application to aircraft problems. The difference between -2 and -5/3 spectral slopes should not seriously affect V/STOL analyses. The spectrum is not defined at frequencies below the inertial subrange, nor is it clear that the spectrum is defineable simply in this critically important range. Indeed, many V/STOL computer simulations use white noise spectra [28] over this range and are little concerned over the inertial subrange. Co-spectra, however are not adequately defined, and knowledge of co-spectra is important in determining turbulence structure.

Only mean, stationary boundary layer profiles are adequately described at the present time, and specific profiles can have an effect on V/STOL piloting and control tasks that is perhaps as serious as turbulence itself. Indeed,departures of the mean profiles from analytic forms can be considered as turbulence that involves disturbances in space but not in time. While this deficiencey is serious, it is not clear what progress in the analysis of such disturbances could be expected. The variety of possible states of the boundary layer is very great. Only the case of internal shear discontinuities arising from surface roughness discontinuities has received any significant attention. Other effects such as surface pressure gradients, advection of heat and growing and dissipating turbulence, appear to have received very little attention.

The randomness often found in boundary layer profiles would seem to suggest that extensions and improvements of equilibrium descriptions such as were discussed in Section II would be of little value to a V/STOL designer or pilot. They will seldom be concerned with flight in "standard" boundary layers.

Four rather major problem areas remain, if not untouched, at least with significant unanswered questions. They are:

- The stability problem-specifically how does the onset of turbulence depend on the mean atmospheric parameters?
- The problem of the structure of turbulence—how do the statistical properties of turbulence vary in time and space (position and direction)? How do these properties depend on the mean atmospheric parameters?
- The problem of the time and space dependence of the mean turbulent flow—how may solutions to the Reynolds equations be obtained for growing or decaying boundary layers?
- The problem of the structure of turbulence elements—what typical turbulence elements exist? How do their characteristics vary with the mean flow parameters?

2. Atmospheric Boundary Layer Stability

Generally, stability considerations are of great concern in turbulence analysis, particularly when the concern is for large scale, intense disturbances. This is the case for V/STOL analyses. Because of the cascade of turbulence interactions from scale to scale, the large, intense disturbances are most closely related to the structure of the mean flow itself. They are the disturbances most likely to be generated by instabilities of the mean flow.

Stability is a very difficult subject, and there are very few satisfactory stability analyses in any area of fluid mechanics. The stability problem of the atmospheric boundary layer is fully as complex as any that have been analyzed. Disturbances are known to depend on bouyant and shear effects and surface pressure distributions (i.e., roughness, or mechanical turbulence). All of these effects can be present in the atmospheric boundary layer. Indeed, more factors that affect stability may be present. The atmospheric boundary layer is so consistently turbulent, however, that it is seldom observed in transition from steady to turbulent flow. The atmosphere is even less likely to be in a state of critical stability, since fluid flows usually must be quite unstable to exhibit turbulence. Nevertheless, conditions that make a steady flow unstable are likely to determine the scale and mode of the largest disturbances. From studies of the literature, it seems that significant results of stability studies are not now available.

3. The Structure of Turbulence

Careful analysis of the structure of turbulence should be of great importance for TOLCAT since the unusual events deemed to be of great significance are probably unusual only in their intensity. Their structure should be typical of the structure of other more common disturbance elements and should be reflected in the structure of the total turbulent field.

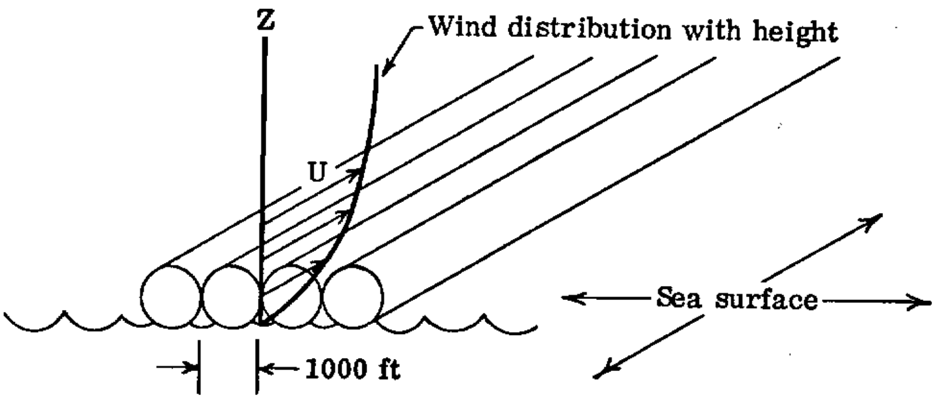
Almost none of this field structure has been examined. As discussed in Section II, certain comparisons of scale anisotropies have been made, but the experimental programs have not used sufficiently complex sensor arrays to adequately resolve the structure. It is also apparent that measurements have not been made in sufficiently varied or well selected mean atmospheric states to determine the dependence of the structure on the mode of generation of the turbulence.

4. Mean Flow Dynamics

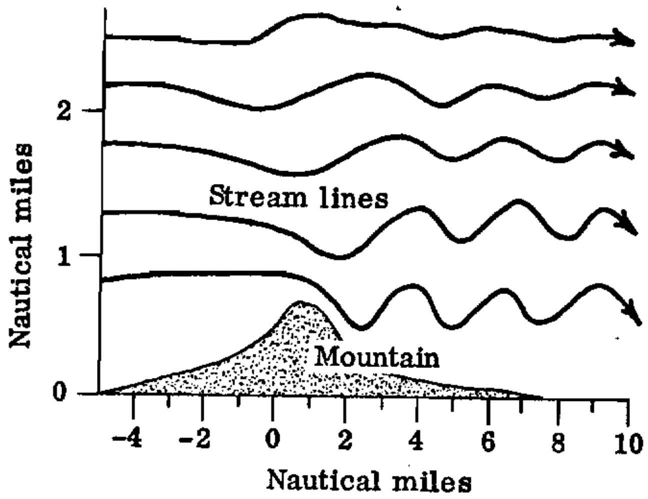
Solutions of the Reynolds equations for growing or decaying atmospheric boundary layers are of great interest for TOLCAT since this type of analysis allows estimates of the time and space scales in which an aircraft can encounter significant changes in turbulence characteristics. The undefined terms in the Reynolds equations are the gradients of the turbulence stress tensor. Further, it is the data on the structure of the turbulent field discussed in Section IV.3 which defines the stress tensor. Sparsity of these data was commented on in Section IV.3.

5. Structure of Turbulence Elements

Perhaps the most important of all aspects for TOLCAT is the determination of the detailed characteristics of each type of disturbance to be found in the turbulent field. Schematic sketches of some such flows are shown in Fig. 23. Although many modes of disturbance have been identified in the atmosphere, and the state of the mean

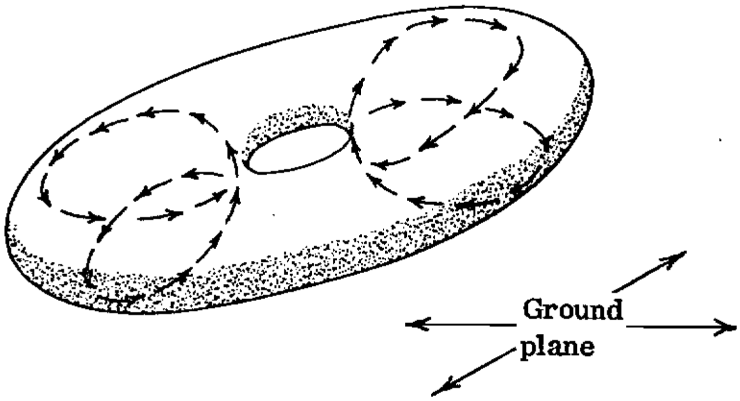


(a) Langmuir cells formed by cold air blowing over warm sea (can form over land also)



NOTE:
Lee waves extend to infinity downstream
Lee waves decrease in amplitude with height

(b) Calculated mountain wave patterns



(c) Typical toroidal "thermal" cell with no wind

Figure 23. Simple modes of atmospheric disturbances

atmosphere favoring each mode has been identified, the mode identification is quite gross. For example, almost no experimental data exists which could be used to describe three-dimensional distributions of velocity in a thermal convection cell. Some analytical solutions have been obtained, but the simplifying assumptions required leave some doubt as to the validity of the solutions. Compounding the doubt is the difference in detail between the various solutions. Indications of the existence of similar disturbances in the atmosphere appear in References [15], [18], [26].

Very limited experimental data has been found detailing discontinuities in the velocity profiles such as might arise from discontinuities in the boundary conditions (e.g., the sheet separating the zone of the boundary layer affected by an abrupt change in surface roughness from the zone not yet affected). This is certainly not turbulence, yet the transit through such a zone by an aircraft could provide the same excitation as a single gust.

These distinctive events are often hidden in random turbulence. Thus, the flow field may appear quite random, but the coherence of the motion may be significant at the scales of concern. Mollo-Christiansen [53] has shown experimentally the existence of intense von Karman vortices hidden in the turbulence of very high Reynolds number wakes of cylinders. It had been assumed that these vortices were broken up when the wake became turbulent.

Many mechanisms are known to produce turbulence, and the characteristics of individual turbulence elements are known to depend often on the mode of generation. Thus three-dimensional toroidal cells are favored in pure thermal convection, roll cells occur when thermal convection cells are subjected to shear, etc. Evidence of the details of such basic patterns and their dependence on their surroundings is, however, weak.

6. Space-Time Resolution

The space-time resolution of the data seems most critical in defining the details of the fluid flow field, therefore the most reliable data would seem to be that obtained by sensors at fixed points. The use of aircraft, balloons and other moving sensor platforms is appropriate for many studies of mean turbulence statistics, but seems unsuitable here.

The concern expressed in many references (cf. [7], [25], [35]) over Taylor's hypothesis (that turbulence statistics taken in moving and stationary coordinates are simply related) is not felt to be a serious deficiency for the present problem. If the statistics of the turbulence are invariant with space and time, then, of course, it doesn't matter much how you move your sensor about to measure those statistics. If, however, the statistics are functions of space and/or time one has difficulty in interpreting data collected by a single sensor in any coordinate system. A very large, dense array of sensors measures the total state of the flow field at all times, thus obviating the need for any hypothesis. The mass of data is apt to be unmanageable, however. Considering the variability of the atmosphere, it is perhaps more appropriate to discover the length and time scales and the causes of the variations in the statistical measures of the turbulence rather than worry about the validity of Taylor's hypothesis (Note: this could be interpreted as indicating the need of better mesoscale definition of the turbulence spectrum.)

The vertical scale of any of these motions can be as great as the layer thickness. Horizontal scales of two-dimensional motions can be unlimited, while there should be less than an order of magnitude disparity between vertical and horizontal scales of three dimensional fields. Minimum scales of interest are determined by typical physical scales of vehicles, i.e., linear or non-linear disturbances much smaller than the vehicle simply average out their effects over its surface. Very limited information is available for more precise definition of these spatial relationships.

SECTION V

CONCLUSIONS

A survey of the literature of analytic and experimental studies of turbulent atmospheric boundary layers has been made. From this survey and from the background available at TRC, analyses were made of the development of turbulence theory in general and atmospheric boundary layer theory in particular. Various theoretical and empirical formulations of atmospheric turbulence problems were examined and the assumptions necessary for each were noted. Estimates were made of the ranges of validity of these formulations.

An analysis was made of the significance of various aspects of atmospheric boundary layer theory for the design and operation of aircraft, particularly V/STOL aircraft. Deficiencies in presently available data and theories were identified.

Major conclusions of this study are:

- Current V/STOL computer simulations do not reproduce the surprises found in actual flights. However, the normal piloting task has been found to be not very sensitive to the statistics of turbulence, and is reasonably well simulated.
- The most serious V/STOL turbulence problem is the stability and control problem of an encounter with one or a few intense, unexpected disturbances. These encounters provide both the surprise and the intensity to make them dangerous.
- Presently available work defines mean boundary layer profiles, turbulent transport properties, and elementary turbulence spectra. Advances in theory and experiment in these particular areas should not substantially affect TOLCAT considerations of V/STOL design and operation.
- Theory and data are inadequate in the areas of turbulent boundary layer analysis of most direct concern to TOLCAT. These areas are flow stability, structure of the turbulent field and of turbulence elements, and analysis of nonequilibrium boundary layers. Potential advances for TOLCAT and other applications require new formalisms, since present analyses appear to be reaching linearization limits.

- Experimental data is required to improve TOLCAT analyses. These data include more complete measurement of the velocity cross correlation tensor (to yield the stress tensor), anisotropies of the three-dimensional spectrum, the spectra of temperature and cross spectra for heat flux, higher order correlations, co-, quad- and bi-spectra, and determination of the details of individual disturbance elements.

- Well-known physical concepts of the generation of fluctuations in a flow field provide a set of simple types of motion which must exist in some degree of order in a turbulent flow field. Many observations of well controlled laboratory experiments as well as of the atmosphere itself have confirmed the existence of roll and toroidal type thermal cells, vortices shed by obstacles, wave type disturbances and other specific, relatively simple motions. These motions exist, either by themselves, or hidden to varying degrees within random turbulence.

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* The Travelers Research Center 250 Constitution Plaza Hartford, Connecticut 06103	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE
Take-Off and Landing Critical Atmospheric Turbulence (TOLCAT) Analytical Investigation

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report/April 1967 to March 1968

5. AUTHOR(S) *(Last name, first name, initial)*
Bowne, Norman E.; Anderson, Gerald E.

6. REPORT DATE March 1968	7a. TOTAL NO. OF PAGES 79	7b. NO. OF REFS 53
8a. CONTRACT OR GRANT NO. F33615-67-C-1557 b. PROJECT NO. c. ADP 682E d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AFFDL-TR-68-23	

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13. ABSTRACT

A review and analysis of current knowledge of turbulence in the atmospheric boundary layer is presented. Particular emphasis is on identifying and analyzing the aspects of low altitude turbulence that have the greatest influence on the design and operation of V/STOL aircraft in the atmospheric boundary layer. The nature, quality and applicability of reported turbulence measurements is discussed, and several resulting empirical descriptions of the boundary layer are compared. Deficiencies in the data are specifically identified and discussed. The foundations, assumptions, and limitations of the statistical analyses of boundary layer turbulence which are now in use are identified and discussed. The nature of atmosphere-vehicle interactions and current and potential methods of analyzing these interactions are discussed.

It was found that the most serious problem for V/STOL operations and design is the encounter of a V/STOL vehicle with large, intense individual disturbances. Some basic disturbance modes and some casual relationships are known, but few experimental studies were designed for providing this type of information. Most current analytic techniques are unsuitable for the required analysis. The nature of the flow features of interest and the data required to analyze them are indicated.

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