Characteristics of Turbulence Observed at the NASA 150-m Meteorological Tower

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ABSTRACT

Recent observations of turbulence obtained at the NASA 150-m meteorological tower located at Kennedy Space Center, Fla., are presented. The wind data were obtained at the 18-, 30-, 60-, 90-, 120- and 150-m levels, while temperature data were obtained at the 3-, 18-, 60-, 120- and 150-m levels. Most of the tests were made during the daylight hours, and the duration time of each test ranged between 30-60 min.

A survey of the surface roughness length associated with the tower site is presented. Estimates of the roughness length were calculated with wind profile laws consistent with the Monin-Obukhov similarity hypothesis. In the case of those wind directions θ in the ranges $0°\leq\theta<150°$, $180°\leq\theta<240°$, and $300°\leq\theta<360°$, the roughness length is 0.23 m, while for those wind directions in the ranges $150°\leq\theta<180°$ and $240°\leq\theta<300°$, the roughness length has the values 0.51 m and 0.65 m, respectively. Longitudinal turbulence spectra calculated from recent observations are also presented. It is shown that the nondimensional frequency nz/u, associated with the peak of the logarithmic spectrum is proportional to $z^{4/5}$, where u is the wind speed at height z and n the frequency. Based upon an analysis of the logarithmic spectrum in the inertial subrange, it is implied that the local mechanical production of turbulent energy is balanced by the local viscous dissipation at the 18-m level.

1. Introduction

In recent years, low altitude winds and turbulence have been the object of extensive interest in the aerospace and meteorological community for the design of space vehicles, buildings, bridges, antennae, aircraft, etc.; for the study of turbulence diffusion; for aircraft operations; and for many other engineering and scientific problems. The National Aeronautics and Space Administration has addressed the problem of low level winds and turbulence in the context of space vehicle design. NASA personnel are now developing analytical models of launch vehicles which predict the response of these vehicles to various types of ground wind forcing functions. These forcing functions can be prescribed in terms of wind profiles, discrete gusts, gust factors, and spectral estimates of turbulent wind fluctuations.

To provide meaningful ground wind design data for these response and loading calculations, NASA has constructed a 150-m meteorological tower at the Kennedy Space Center, Fla. This tower, described by Kaufman and Keene (1965), is located in the vicinity of Launch Complex 39 and is situated in a well-exposed area free of nearby structures which could interfere with the air flow. It is instrumented at the 18-, 30-, 60-, 90-, 120- and 150-m levels with Climet wind sensors (Model C1-14), and Climet aspirated thermocouples (Model 016) located at the 18-, 60-, 120- and 150-m levels.

To develop turbulence models based upon the data from this tower, the surface roughness length z_0 of this site must be known. While the parameter is of no great interest in itself, its importance lies in the fact that it serves as a scaling length in the formulation of boundary layer wind profile laws based upon asymptotic similarity considerations (Blackadar,[1] 1967) or heuristic considerations using eddy coefficients (Blackadar *et al.*, 1965). These profile laws permit the calculation of the surface friction velocity in the absence of vertical velocity fluctuation data at the NASA 150-m meteorological tower. Based upon similarity considerations, the friction velocity in turn is used as a scaling parameter which ultimately permits the combination of turbulence data in the form of spectra, cospectra, variances, etc. Accordingly, one purpose of this paper is to establish the surface roughness length configuration for this tower site.

In many types of launch vehicle response calculations, engineers have employed Fourier transforms to solve the equations of motion which describe and predict the ultimate behavior of the launch vehicle. Thus, the input function which forces the subsequent motions of the vehicle must be described in terms of Fourier amplitudes, and it follows that the design engineer must have explicit information about the spectrum of turbulence. Motivated by this requirement, the Aerospace Environment Division at the Marshall Space Flight Center has entered upon an extensive program to define the spectral nature of the longitudinal and lateral components of turbulence at the Kennedy Space Center (KSC). To date, we have examined the longitudinal spectrum for approximately 25 cases of turbulence at KSC, most of

[1] Blackadar, A. K., 1967: External parameters of the wind flow in the barotropic boundary layer of the atmosphere. Paper presented at the Study Conf. on the Global Atmos. Res. Prog., 27 June–11 July 1967.

which are associated with unstable conditions. Thus, the second purpose of this paper is to present the results of our studies with regard to the longitudinal spectrum.

2. The surface roughness length

According to Lumley and Panofsky (1964), the mean wind profile in the first 30–60 m of the atmosphere is given by

$$u=\frac{u_*}{k}\left\{\ln\left(\frac{z}{z_0}\right)-\psi(z/L')\right\}, \tag{1}$$

where u, u_*, and k denote, respectively, the mean wind at height z, the surface friction velocity, and von Kármán's constant with numerical value equal to ~ 0.4, z_0 is the surface roughness length which is to be determined, and ψ a universal function of z/L', where L', a stability length, is given by

$$L'=u_*\frac{du}{dz}T\left(kg\frac{d\theta}{dz}\right)^{-1}, \tag{2}$$

involving the acceleration of gravity g and the Kelvin and potential temperatures, T and θ, associated with the mean flow. The term z/L' is related to the Richardson number Ri through the experimentally derived relationships

$$z/L'=\mathrm{Ri}(1-18\mathrm{Ri})^{-\frac{1}{4}} \quad (\mathrm{Ri}<-0.01), \tag{3}$$

$$z/L'=\mathrm{Ri} \quad (-0.01\leqq \mathrm{Ri}<0.01), \tag{4}$$

$$z/L'=\mathrm{Ri}(1-7\mathrm{Ri})^{-1} \quad (0.1\geqq \mathrm{Ri}>0.01), \tag{5}$$

where Ri is given by

$$\mathrm{Ri}=\frac{g}{T}\frac{d\theta}{dz}\left(\frac{du}{dz}\right)^{-2}. \tag{6}$$

Eq. (3) is a form of the KEYPS (Panofsky *et al.*, 1960) equation, and Eqs. (4) and (5) were obtained by Panofsky (1963) and McVehil (1962), respectively. The functions $\psi(z/L')$ that correspond to (4) and (5) are given by

$$\psi(z/L')=-4.5\frac{z}{L'} \quad (-0.01\leqq \mathrm{Ri}\leqq 0.01) \tag{7}$$

$$\psi\left(\frac{z}{L'}\right)=-7\frac{z}{L'} \quad (0.1\geqq \mathrm{Ri}\geqq 0.01). \tag{8}$$

Panofsky (1963) has graphically indicated the function $\psi(z/L')$ for $\mathrm{Ri}<-0.01$. The following function appears to faithfully reproduce his curve:

$$\psi\left(\frac{z}{L'}\right)=0.044\left(\frac{-z/L'}{0.01}\right)^{p} \quad (\mathrm{Ri}<-0.01), \tag{9}$$

where

$$p=1.0674-0.678\ln\left(\frac{-z/L'}{0.01}\right).$$

Paulson (1967) has integrated the KEYPS equation and finds that the exact expression for $\psi(z/L')$ is given by

$$\psi\left(\frac{z}{L'}\right)=1-\phi-3\ln\phi+2\ln\left(\frac{1+\phi}{2}\right)+2\tan^{-1}\left(\phi-\frac{\pi}{2}\right)+\ln\left(\frac{1+\phi^2}{2}\right) \quad (\mathrm{Ri}\leqslant 0). \tag{10}$$

In this equation, ϕ is the dimensionless shear, i.e.,

$$\phi=\frac{kz}{u_*}\frac{du}{dz}, \tag{11}$$

and is a function of z/L'. The function $\phi(z/L')$ is an experimentally known function determined from data obtained at various tower sites (see Lumley and Panofsky, 1964). In this study we used the approximate form of $\psi(z/L')$ for $\mathrm{Ri}<-0.01$ given by Eq. (9), which differs from the exact expression [Eq. (10)] by no more than a few per cent. The author was unaware of Paulson's result and wishes to thank Dr. J. Businger for bringing this work to his attention. To obtain the wind law in terms of z/L', we must assume that the ratio of the eddy heat conduction coefficient K_H to the eddy viscosity coefficient K_M is independent of height. Current observations appear to show that K_H/K_M is a monotonically decreasing function of Ri, with a value near unity for neutral wind conditions (Paulson, 1967). However, in spite of this variation of K_H/K_M, Paulson finds that the KEYPS equation gives a good description of the wind profile. The advantage of the formulation of the wind profile in terms of z/L' is that the parameter L' can be calculated from wind and temperature profiles alone.

The calculation of z_0 was based upon 39 wind speed and temperature profiles measured at Kennedy Space Center and the boundary layer theory presented above. Most of the measurements were obtained between the hours of 0700 and 1600 EST, and the duration time of each test ranged between 30–60 min. Mean wind speed and temperature data were obtained at the 18- and 30-m levels, and the mean temperature data were obtained at the 18- and 60-m levels. Temperatures at the 30-m level were estimated by logarithmically interpolating between the 18- and 30-m levels. An estimate of the gradient Richardson number [Eq. (6)] at the 23-m level (geometric mean height between the 18- and 30-m levels) was determined by assuming logarithmic distributions for the mean wind and temperature between these levels. The gradient Richardson number estimated in this manner is given by

$$\mathrm{Ri}(z_g)=\frac{g}{T(z_g)}\left\{\frac{T(z_2)-T(z_1)}{z_g\ln(z_2/z_1)}+\frac{g}{c_p}\right\}\times\left\{\frac{u(z_2)-u(z_1)}{\ln(z_2/z_1)}\right\}^{-2}z_g^2, \quad (12)$$

where $z_g=(z_1z_2)^{\frac{1}{2}}$, z_1 and z_2 denote 18 and 30 m, respectively, $T(z_g)$ is the Kelvin temperature at z_g estimated by logarithmic interpolation, and c_p the specific heat at constant pressure. In deriving Eq. (12), we used the approximation that

$$\frac{1}{T}\frac{d\theta}{dz}\approx\frac{1}{\theta}\frac{d\theta}{dz}=\frac{1}{T}\left(\frac{dT}{dz}+\frac{g}{c_p}\right). \quad (13)$$

The term z_g/L' was evaluated for each case by means of one of the three equations given by (3)–(5) corresponding to the appropriate Richardson number; L' was then assumed to be invariant with height; and $\psi(18/L')$ and $\psi(30/L')$ were estimated with one of the equations given by (7)–(9) corresponding to the appropriate Richardson number class. Eq. (1) was then evaluated at the 18- and 30-m levels to yield two equations, which were solved simultaneously for u_* and z_0.

The surface roughness length as a function of wind direction is shown in Fig. 1. To determine if there were any directional variations in z_0, the data in Fig. 1 were averaged over 30° sectors beginning with 0° reckoned clockwise from north (see Fig. 2). In Fig. 2 the broken-line portion of the graph associated with wind directions between 240° and 270° was obtained by linearly interpolating between the results of sectors 210°–240° and 270°–300°. This diagram shows, in the sectors 150°–180° and 240°–300°, that the roughness length is significantly higher than that associated with the other sectors. The high values of roughness length in these sectors can be attributed to the presence of trees upstream from the tower. The results did not appear to show any dependence of z_0 upon Ri. The NASA 150-m meteorological tower at KSC and the surrounding vegetation are discussed in a report by Kaufman and Keene (1965).

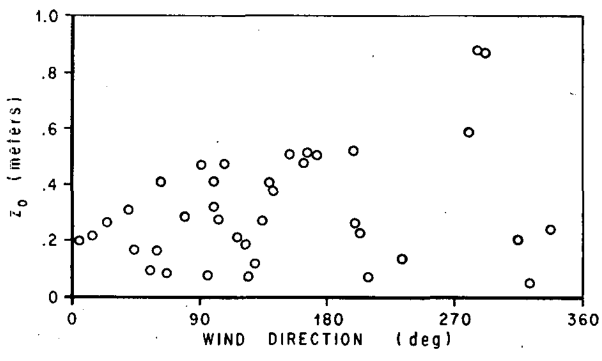

FIG. 1. Roughness length z_0 as a function of wind direction.

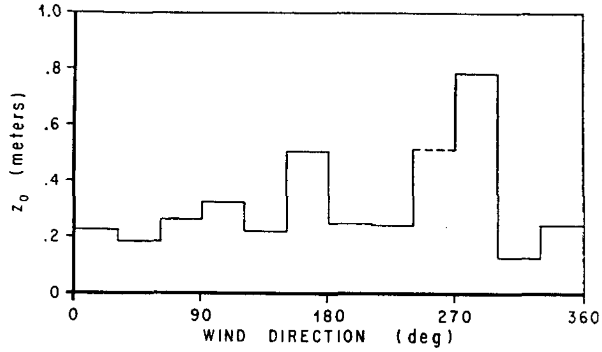

FIG. 2. Average values of z_0 as a function of wind direction.

Table 1 shows the values of roughness length and the associated wind direction ranges appropriate for analyzing wind profiles measured at the 150-m tower. The values of z_0 in this table are based upon a sector average and the results shown in Fig. 2. The statistical error for the roughness length in sectors 1, 3, and 5 is 0.14 m and is based upon 32 observations. Because of the insufficient number of observations in the other sectors, it was not possible to obtain a reliable estimate of the statistical error in these sectors.

3. The longitudinal spectrum

Nineteen cases of turbulence were selected to define the longitudinal spectrum of turbulence for unstable conditions. The duration time for each test ranged between 30–60 min. The procedure used to calculate the longitudinal components of turbulence consisted of 1) converting the digitized wind speeds and directions (10 data points per second) into the associated north-south and east-west components and averaging these components over the duration of each test; 2) calculating the mean wind speed and direction, based upon these averaged components; and 3) projecting the original digitized data on this mean wind vector and subtracting the mean wind speed to yield the longitudinal components of turbulence. Trends contained within the data were removed by fitting the longitudinal components to a second-order polynomial and in turn subtracting this polynomial from the longitudinal turbulence component time history. In order to reduce computation time, the resulting data, with trend removed, were block averaged over 0.5-sec intervals. The spectra were calculated from these processed data by

TABLE 1. Values of z_0 for various sectors.

Sector	Wind direction θ (deg)	z_0 (m)
1	$0°\leqq\theta<150°$	0.23
2	$150°\leqq\theta<180°$	0.51
3	$180°\leqq\theta<240°$	0.23
4	$240°\leqq\theta<300°$	0.65
5	$300°\leqq\theta<360°$	0.23

employing the standard correlation-Fourier transform methods outlined in the book of Blackman and Tukey (1958). These spectra were corrected for the 0.5-sec block-averaging operation, as well as for the response properties of the wind sensor.

If we apply the similarity theory of Monin (1959) to the longitudinal velocity spectrum, then we might expect that

$$\frac{nS(n)}{u_*^2}=F(f,\,\mathrm{Ri}), \tag{14}$$

where $nS(n)$ is the longitudinal logarithmic spectral density associated with the frequency n[cps], and

$$f=nz/u(z). \tag{15}$$

The scaling velocity u_* was obtained from the wind and temperature profile data and the boundary layer theory outlined in Section 2. The spectral estimates were plotted in similarity coordinates, and a curve was drawn by eye. Of course, the data points scattered about this line. These curves are shown in Figs. 3–8, and they represent average spectra at each level over the intervals of Richardson numbers given in Table 2.

Figs. 3–8 show a maximum in the logarithmic spectrum at low frequencies, and the position of the maximum shifts toward higher values of f as the height increases. This means that $F(f,\,\mathrm{Ri})$ is not a universal function and that additional parameters need to be considered in the dimensional analysis. This should not be surprising in view of the fact that the Monin-Obukhov similarity hypothesis fails above approximately 30 m, since the eddy stress and/or the heat flux are not invariant with height above this level, and Coriolis forces tend to become important. One might wish to include in a dimensional analysis all those parameters that occur in the wind profile law, since the wind profile "drives" the turbulent portion of the flow. Of course, the turbulence influences the wind profile through the eddy stress and the eddy heat flux terms

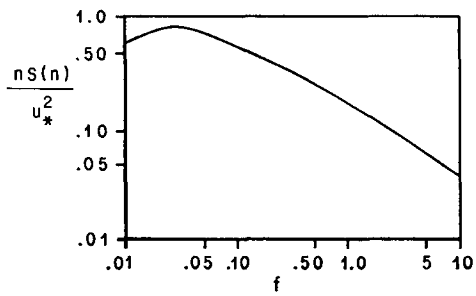

Fig. 3

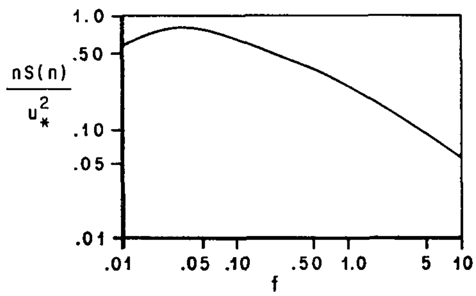

Fig. 4

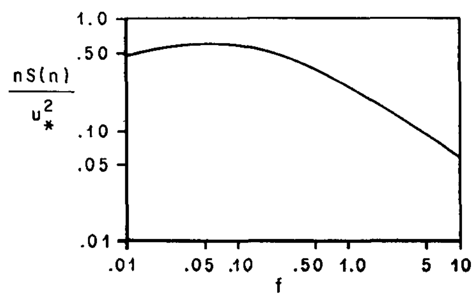

Fig. 5

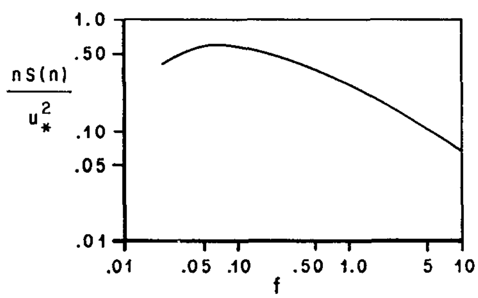

Fig. 6

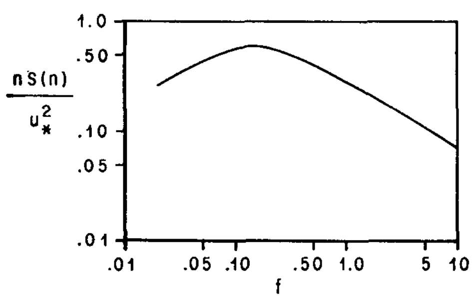

Fig. 7

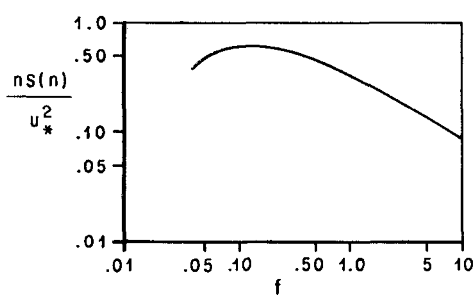

Fig. 8

Fig. 3–8. Average unstable longitudinal spectra at 18, 30, 60, 90, 120 and 150 m.

TABLE 2. Peak logarithmic spectrum values at various levels.

Height (m)	Richardson interval	$\left(\frac{nS(n)}{u_*^2}\right)_{\text{peak}}$
18	$-0.85 \leq \text{Ri} \leq -0.04$	0.85
30	$-13.0 \leq \text{Ri} \leq -0.068$	0.76
60	$-4.5 \leq \text{Ri} \leq -0.13$	0.60
90	$-6.2 \leq \text{Ri} \leq -0.075$	0.60
120	$-8.0 \leq \text{Ri} \leq -0.2$	0.59
150	$-20.0 \leq \text{Ri} \leq -0.11$	0.65

in the mean equations of motion. Thus, among the variables that $nS(n)/u_*^2$ could depend upon, one might include the Coriolis parameter and the geostrophic wind, perhaps through a surface Rossby number.

Figs. 3–8 also show a decrease in the peak value of the logarithmic spectrum between 18 and 60 m, while above 60 m, the peak value appears to be a constant. These results are indicated in Table 2. Busch and Panofsky (Panofsky *et al.*, 1967) have reported values of the peak of the logarithmic longitudinal spectrum on the order of 1.3 and 1 at 16 m from sites A and B, respectively, located at Round Hill in South Dartmouth, Mass., while these authors also find the peak of the logarithmic spectrum is on the order of 1 at 40 m at site A and 0.9 at 46 m at site B. A discussion of these sites can be found in their report. However, site B is similar to the KSC site, and the values of the peak of the logarithmic spectrum from the KSC site are 15% less than those associated with site B at Round Hill. These differences are within the confidence bands of the spectral estimates.

Fig. 9 is a plot of the frequency f_m associated with the maximum of the logarithmic spectrum for KSC. A least-square fit of the KSC data revealed that

$$f_m = 0.00261 z^{4/5}, \tag{16}$$

where z has the units of meters and the curve associated with this function is indicated in Fig. 9. In this figure

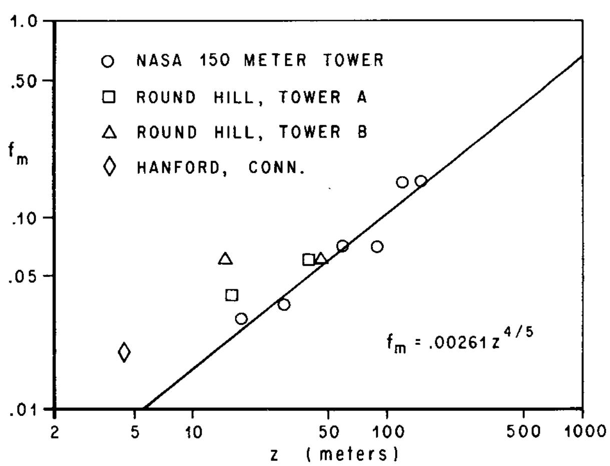

FIG. 9. Frequency f_m associated with the maximum of the logarithmic spectrum at KSC as a function of z.

we have included data points from the tower sites located at Round Hill in South Dartmouth, Mass., and Hanford, Conn. A discussion of these sites can be found in a recent report by Panofsky and his collaborators (1967). The data points from these sites, in addition to those obtained at KSC, below 60 m, imply that $f_m \sim z^{3/5}$. Berman and Panofsky (Blackadar *et al.*, 1965) find in the case of neutral stability conditions that $f_m \sim z^{3/4}$.

If we assume that the correlation function associated with the unstable spectrum is given by

$$R(\xi,z) = e^{-\xi/L(z)}, \tag{17}$$

where $L(z)$ is the integral scale of turbulence and ξ the longitudinal space lag which is related to the time lag τ through Taylor's hypothesis, so that

$$\xi = u(z)\tau, \tag{18}$$

then upon Fourier transforming (17) and calculating the frequency associated with the peak of the logarithmic spectrum, we find

$$L(z) = \frac{z}{2\pi f_m}. \tag{19}$$

Eqs. (16) and (19) imply that the integral scale of turbulence is proportional to $z^{1/5}$, while if $f_m \sim z^{3/5}$, which is implied by the data in Fig. 9 for $z \leq 60$ m, then $L(z) \sim z^{2/5}$.

4. Energy budget considerations

In the case of homogeneous terrain, the budget of turbulent energy is given by

$$\frac{d\bar{E}}{dt} = u_*^2 \frac{du}{dz} + \frac{H}{c_p \rho} \frac{g}{T} - \epsilon - \frac{d}{dz}\left(\frac{\overline{p'w'}}{\rho} + \overline{w'E}\right), \tag{20}$$

where H is the eddy heat flux, ρ the mean density, E the turbulent kinetic energy per unit mass, p' and w' denote, respectively, the turbulent fluctuations of pressure and vertical velocity, ϵ is the viscous dissipation, and the overbar denotes the time-averaging operator. It is possible to write (20) in a dimensionless form by multiplying each term by kz/u_*^3 (Busch and Panofsky, 1968), so that

$$\frac{kz}{u_*^3} \frac{d\bar{E}}{dt} = \phi - \frac{z}{L} - \phi_\epsilon - \phi_D. \tag{21}$$

The terms in this expression are in one-to-one correspondence with those in Eq. (20) and L is the Monin-Obukhov stability length,

$$L = -\frac{u_*^3 c_p \rho T}{kgH}.$$

Near the ground a majority of meteorological conditions are characterized, at least approximately, by horizontal homogeneity, steady mean wind with no change of wind direction with height, and steady heating from below. It is reasonable to make these assumptions with regard to the KSC site, so that $d\bar{E}/dt=0$.

It is easily shown that the longitudinal spectrum in the inertial subrange can be expressed by the form

$$\frac{nS(n)}{u_*^2}=\alpha k^{-\frac{2}{3}}\phi_\epsilon^{\frac{2}{3}}f^{-\frac{2}{3}}, \qquad (22)$$

where α is Kolmogorov's constant, with numerical value equal to 0.146 according to Record and Cramer (1966). This equation serves as a basis for examining how the turbulence energy budget is balanced in the atmospheric boundary layer. Thus, by assuming various balancing schemes for Eq. (21), we can infer a value of ϕ_ϵ. Based upon this estimate of ϕ_ϵ and the spectral estimates in the inertial subrange, we can calculate a value of α which will serve as a measure of the validity of the particular balancing scheme in question. Based upon data obtained at Brookhaven, Lumley and Panofsky (1964) suggest that over homogeneous terrain the local mechanical energy production is balanced by the local viscous dissipation, so that

$$\phi_\epsilon=\phi, \qquad (23)$$

while data obtained at site B at Round Hill (Panofsky *et al.*, 1967) appear to imply that over more or less homogeneous terrain the local mechanical and buoyant energy production is balanced by the local viscous dissipation, so that

$$\phi_\epsilon=\phi-\frac{z}{L}. \qquad (24)$$

The hypotheses given by Eqs. (23) and (24) will be termed hypotheses A and B, respectively. It can be shown that ϕ is a universal function of z/L' within the framework of the Monin-Obukhov similarity hypothesis. Panofsky *et al.* (1960) have determined this function based upon experimental data obtained at various tower sites around the globe. Based upon their results, it appears that ϕ is of order 1 in the case of hypothesis B, while ϕ_ϵ is a monotonically decreasing function of $-z/L'$ with $\phi(0)=1$ (neutral stratification). The term z/L' can be calculated with Eq. (3), and with this value of z/L', we can estimate $\phi(z/L')$ from Panofsky's curve.

Fourteen cases of turbulence at the 18-m level which definitely possessed an inertial subrange were selected for analysis. In each case, α was calculated using the spectral estimates calculated from the 18-m level data and ϕ_ϵ determined from Panofsky's curve of ϕ as a function of z/L' for hypothesis A and $\phi_\epsilon=1$ in the case of hypothesis B. Fig. 10 shows the results of these calculations. The line in this figure represents Record and Cramer's value of $\alpha=0.146$. The average value of

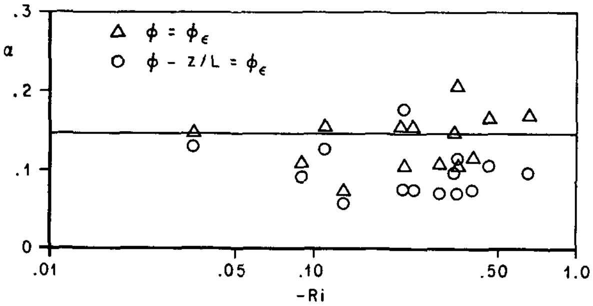

Fig. 10. Kolmogorov's α as a function of Ri. The line represents Record and Cramer's value, 0.146.

α calculated according to hypotheses A and B are 0.147 and 0.108, respectively. It would thus appear that the balancing scheme of the energy budget implied by hypothesis A is operative at Kennedy Space Center at the 18-m level. This also implies that at the 18-m level mechanically produced energy, created locally, is dissipated locally; and if $d\bar{E}/dt=0$, then energy produced locally by buoyancy forces is balanced by the vertical energy flux divergence ϕ_D.

5. Concluding remarks

This investigation shows that the roughness configuration at the NASA 150-m meteorological tower is characterized by $z_0=0.23$ m except for those wind directions θ in the interval $150°\leq\theta\leq180°$ and $240°\leq\theta<300°$ in which it is 0.51 and 0.68 m, respectively. Average unstable longitudinal logarithmic spectra from KSC imply that the frequency f_m associated with the peak of the spectra is proportional to $z^{4/5}$, while the integral scale of turbulence appears to be proportional to $z^{1/5}$. However, data from Round Hill, Mass., Hanford, Conn., and Kennedy Space Center, Fla., imply that f_m is proportional to $z^{3/5}$, while the associated scale of turbulence is proportional to $z^{2/5}$ below 60 m. It may also be concluded that longitudinal spectra are not universal with respect to Monin coordinates $[nS(n)/u_*^2, f]$, even at 18 and 30 m, where one should expect the theory to be most applicable. This means that other factors will have to be taken into account. Among these factors, one could include, for example, mesoscale flow features, the topography of the site, and the variation of eddy stress and heat flux in the vertical.

Finally, energy budget considerations at 18 m imply that the local mechanical production of energy is balanced by the local viscous dissipation, and if $d\bar{E}/dt=0$, then it may also be concluded that the local buoyant production of energy is balanced by the energy flux divergence.

Dr. Panofsky and collaborators of the Pennsylvania State University are now performing an investigation of turbulence at KSC under NASA contract NAS8-21140. In their analysis they will examine the data that were used in this study, as well as other cases. Accordingly, the results presented in this paper should be considered tentative.

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