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AN ANALYSIS OF THE ROUGHNESS LENGTH ASSOCIATED WITH THE NASA 150-METER METEOROLOGICAL TOWER

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ABSTRACT

The surface roughness length at the NASA 150-meter meteorological tower located at KSC is determined as a function of wind direction. The roughness length estimates, which were calculated with wind profile laws consistent with the Monin and Obukhov similarity hypothesis, were determined for thirty-nine wind and temperature profiles. Most of the cases were obtained during the hours of 0700 and 1600 EST, and the duration of each test ranged between one-half to one hour. The mean wind speed data were obtained at the 18- and 30-meter levels, and the mean temperature data were obtained at the 18- and 60-meter levels. For those wind directions θ in the ranges $0° \leqq \theta < 150°$, $180° \leqq \theta < 240°$, and $300° \leqq \theta < 360°$ the roughness length is 0.23m; for those wind directions in the ranges $150° \leqq \theta < 180°$ and $240° \leqq \theta < 300°$, the roughness length has the values 0.51m and 0.65m, respectively.

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LIST OF SYMBOLS

Symbol	Definition
c_p	specific heat at constant pressure
g	acceleration of gravity
H	heat flux
k	von Karman's constant
K_h	eddy viscosity coefficient
K_m	eddy heat conduction coefficient
L	Monin-Obukhov stability length
L'	$K_h L/K_m$
p_1	standard sea-level pressure
R_f	flux Richardson number
Ri	gradient Richardson number
R	specific gas constant of air
T	mean temperature
u	mean wind speed
u_*	surface friction velocity
z	height
z_o	surface roughness length
θ	mean potential temperature and wind direction
ρ	mean density
ϕ	dimensionless shear, a universal function of z/L
ϕ_1	dimensionless shear, a universal function of z/L'
ψ	wind profile defect, a universal function of z/L'

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SUMMARY

The surface roughness length at the NASA 150-meter meteorological tower located at KSC is determined as a function of wind direction. The roughness length estimates, which were calculated with wind profile laws consistent with the Monin and Obukhov similarity hypothesis, were determined for thirty-nine wind and temperature profiles. Most of the cases were obtained during the hours of 0700 and 1600 EST, and the duration of each test ranged between one-half to one hour. The mean wind speed data were obtained at the 18- and 30-meter levels, and the mean temperature data were obtained at the 18- and 60-meter levels. For those wind directions θ in the ranges $0° \leqq \theta < 150°$, $180° \leqq \theta < 240°$, and $300° \leqq \theta < 360°$ the roughness length is 0.23m; for those wind directions in the ranges $150° \leqq \theta < 180°$ and $240° \leqq \theta < 300°$, the roughness length has the values 0.51m and 0.65m, respectively.

I. 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., turbulent diffusion, aircraft operations, and 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-meter meteorological tower at the Kennedy Space Center, Florida. 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 meter levels with Climet wind sensors (Model Cl-14) and Climet aspirated thermocouples (Model 016) located at the 18, 60, 120, and 150 meter levels.

To develop turbulence models based upon the data from this tower, the surface roughness length z_0 of this site must be known. The parameter is of no great interest in itself, but rather, 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, 1967) or heuristic considerations using eddy coefficients (Blackadar, 1965). In the absence of vertical velocity fluctuation data -- this is the situation at the NASA 150-meter meteorological tower -- these profile laws permit us to calculate the surface friction velocity. The friction velocity in turn is used as a velocity scaling parameter which ultimately permits us to combine turbulence data in the form of spectra, cospectra, variances, etc., based upon similarity considerations.

II. THEORETICAL BACKGROUND

In the first 30 to 60 meters of the atmosphere, the Monin-Obukhov similarity hypothesis predicts that

$$\frac{kz}{u_*}\frac{du}{dz} = \phi(z/L), \tag{1}$$

where u is the mean[1] wind at height z, u_* is the surface friction velocity, k is von Karman's constant with numerical value equal to approximately 0.4, $\phi(z/L)$ is a universal function of z/L which is determined experimentally, and L is the Monin-Obukhov stability length given by

$$L = -\frac{u_*^3 \, c_p \, \rho T}{kg \, H}, \tag{2}$$

where c_p is the specific heat at constant pressure, ρ and T denote the mean density and Kelvin temperature, respectively, g is acceleration of gravity, and H is the vertical heat flux. The friction velocity u_* is given by

$$u_* = \sqrt{-\overline{u'w'}}, \tag{3}$$

[1] All means are time averages.

where u' and w' denote the longitudinal and vertical velocity fluctuations about the mean wind vector and the vertical heat flux is given by

$$H = \rho c_p \overline{w'T'}, \tag{4}$$

where T' is the temperature fluctuation about the mean temperature and the overbar denotes the time averaging operator

$$\overline{(\ )} = \frac{1}{\tau} \int_0^\tau (\ )\, dt,$$

τ being the interval of time over which the averaging process is performed. If $\phi(z/L)$ is known, it is possible to obtain the wind profile by integrating equation (1) and applying the boundary condition that u must vanish at $z = z_o$, where z_o is the surface roughness length. z_o may be interpreted as that height above the local mean level surface of the earth below which the flow has been disrupted to the extent that the flow is completely turbulent; i.e., the mean flow vanishes for $z \leq z_o$. In terms of $\phi(z/L)$, the wind profile is given by

$$u = \frac{u_*}{k} \left\{ \ln \frac{z}{z_o} - \int_{-z_o/L}^{-z/L} \frac{1 - \phi(\xi)}{\xi}\, d\xi \right\} . \tag{5}$$

There are various ways to calculate the roughness length z_o from equation (5); however, in any event, three pieces of information are required. This information can be (1) the mean wind speed measured at three levels, or (2) the mean wind speed measured at two levels and either u_* if H is unknown or H if u_* is unknown, or (3) the mean wind speed measured at one level, u_* and H. In the Monin-Obukhov theory u_* and H are height invariant, so that a calculation of these quantities at more than one level gains little, unless the theory is incorrect. In that case, the wind profile law must be reformulated ab initio. However, the theory is most applicable near the surface of the earth so that the best estimate of u_* and H is obtained at the lower levels near the surface of the earth, say below 10 m. In the first case, one would evaluate equation (5) at three levels to yield three transcendental equations in three unknowns, namely, z_o, H and u_*. These equations would be difficult to solve since it would require a trial-and-error approach on the computer in view of their complicated transcendental nature. In the case of the NASA 150-meter meteorological tower, we would have to use the mean wind speeds obtained at the 18-, 30-, and 60-meter levels; however, it is questionable to employ the 60-meter level wind speeds since the Monin-Obukhov theory tends to fail at these levels. In the second case, we would evaluate equation (5) at two levels and solve for two unknowns, namely z_o and H if u_* is known, and z_o and u_* if H is known. In the third case, we would evaluate equation (5) at one level and solve for z_o directly. However, in both cases (2) and (3), we require w' data to calculate u_* and/or H. At the present time, the NASA 150-meter meteorological tower does not possess the capability to obtain w' data; therefore, we must use technique (1) to calculate z_o or cast the theory in terms of parameters that can be measured within the capabilities of the current instrumentation at KSC in order to avoid the problem of solving a set of complicated transcendental equations. The latter alternative is the most expedient approach and it will permit a calculation of z_o with wind data obtained at the 18- and 30-meter levels, levels at which the Monin-Obukhov theory is valid.

The flux Richardson number is defined to be

$$R_f = \frac{g}{T} \frac{H}{\rho c_p u_*^2 \frac{du}{dz}} . \tag{6}$$

Combining equations (1) and (6), we find

$$\frac{z}{L} = \phi(z/L)\ R_f . \tag{7}$$

The eddy heat conduction and viscosity coefficients are given by

$$K_h = - \frac{\frac{H}{c_p \rho}}{\frac{d\theta}{dz}} \tag{8}$$

and

$$K_m = \frac{u_*^2}{\frac{du}{dz}} , \tag{9}$$

where θ is the mean potential temperature.

Upon combining equations (2), (8), and (9), we find

$$\frac{z}{L} = \frac{z}{L'} \frac{K_h}{K_m} , \tag{10}$$

where

$$L' = \frac{u_* T \frac{du}{dz}}{kg \frac{d\theta}{dz}} . \tag{11}$$

Combining (6), (8) and (9), we obtain the additional relationship

$$R_f = \frac{K_h}{K_m} Ri, \tag{12}$$

where Ri is the gradient Richardson number given by

$$Ri = \frac{\frac{g}{T} \frac{d\theta}{dz}}{(\frac{du}{dz})^2} . \tag{13}$$

Ri is called the gradient Richardson number since it is based upon the gradients of θ and u. Most investigators postulate K_h/K_m to be a function of the gradient Richardson number. If this assumption is imposed, equations (7), (10) and (12) constitute three equations in four unknowns, namely, R_f, Ri, z/L and z/L', and it is possible to express three of these unknowns in terms of the fourth one. Thus, we can solve for R_f, Ri, and z/L as functions of z/L' and conclude from equation (1) that

$$\frac{kz}{u_*} \frac{du}{dz} = \phi \left(\frac{z}{L} (z/L') \right) = \phi_1 (z/L'), \tag{14}$$

where $\phi_1(z/L')$ is a universal function of z/L'. Integration of equation (14) yields a wind profile law identical in form to equation (5) with ϕ_1 and L' replacing ϕ and L, respectively, so that

$$u = \frac{u_*}{k} \left\{ \ln \frac{z}{z_o} - \psi(z/L') \right\} , \tag{15}$$

where $\psi(z/L')$ is a universal function of z/L' given by

$$\psi(z/L') = \int_{-z_o/L'}^{-z/L'} \frac{1 - \phi_1(\xi)}{\xi} \, d\xi \tag{16}$$

provided $\phi_1(z/L')$ is a known function.

The derivative $d\theta/dz$ in equation (13) can be related to the vertical temperature gradient by differentiating Poisson's law,

$$\theta = T(p_1/p)^{R/c_p} \tag{17}$$

and employing the condition for hydrostatic equilibrium,

$$\frac{dp}{dz} = - \rho g, \tag{18}$$

where p_1 is the standard sea level pressure in appropriate units and R is the specific gas constant for air. The desired result is

$$\frac{1}{\theta} \frac{d\theta}{dz} = \frac{1}{T} \left(\frac{dT}{dz} + \frac{g}{c_p} \right) . \tag{19}$$

We have used the ideal gas law

$$p = R\rho T \tag{20}$$

in deriving equation (19). Within the atmospheric boundary layer we can approximate

$$\frac{1}{T}\frac{d\theta}{dz} \quad \text{with} \quad \frac{1}{\theta}\frac{d\theta}{dz} ,$$

so that equation (13) reads

$$Ri \simeq \frac{\frac{g}{T}\left(\frac{dT}{dz} + \frac{g}{c_p}\right)}{\left(\frac{du}{dz}\right)^2} . \tag{21}$$

In practice, one usually obtains an estimate of Ri based upon the mean wind speed and temperature profiles and then calculates z/L' from an experimentally determined expression relating Ri and z/L'. Such an expression is predicted to exist according to this analysis. Ri as given by (21) is estimated with mean flow quantities that can be measured with data obtained from the NASA 150-meter meteorological tower. Upon determining z/L', one calculates ψ with another experimentally determined relationship which is obtained by experimentally determining $\phi_1(z/L')$ and then producing the integral (15) with the assumption that $z_0/L' \ll z/L'$, so that the lower limit on this integral can be approximated as $z_0/L' \simeq 0$. The functions $z/L'(Ri)$ and $\psi(z/L')$ have been determined by other investigators based upon simultaneous measurements of the wind profile, the longitudinal and vertical velocity fluctuations, and the mean temperature profile made at various tower sites around the globe. According to Lumley and Panofsky (1963),

$$\frac{z}{L'} = \frac{Ri}{(1 - 18Ri)^{1/4}} \qquad (Ri < -0.01) \tag{22}$$

$$\frac{z}{L'} = Ri \qquad (-0.01 \leq Ri \leq 0.01) \tag{23}$$

$$\frac{z}{L'} = \frac{Ri}{1 - 7Ri} \qquad (0.1 \geq Ri > 0.01). \tag{24}$$

Presumably for $Ri > 0.1$ no simple relation exists between Ri and z/L' since turbulence, if present at all, is relatively weak and the mean flow at various levels tends to be uncoupled. Those cases associated with $Ri > 0.1$ were not examined in this study. The function $\psi(z/L')$ that correspond to the expressions given by equations (23) and (24) are given by

$$\psi(z/L') = -4.5\ \frac{z}{L'} \qquad (-0.01 \leq Ri \leq 0.01) \tag{25}$$

$$\psi(z/L') = -7\ \frac{z}{L'} \qquad (0.1 \geq Ri > 0.01). \tag{26}$$

Panofsky (1963) has graphically indicated the function $\psi(z/L')$ for $Ri < -0.01$, and this author finds that the function

$$\psi(z/L') = .044 \left(\frac{-z/L'}{0.01}\right)^{1.0674-.0678\ \ln\left(\frac{-z/L'}{0.01}\right)} \qquad (Ri < -0.01) \tag{27}$$

faithfully reproduces his curve. This function is shown in figure 1. One should keep in mind that the relationships (22) through (27) have been deduced from measurements obtained at other sites. The Monin-Obukhov similarity hypothesis concerns the dependency of the gradients of θ and u upon z/L and thus z/L' in view of our assumption concerning K_h/K_m. This hypothesis is independent of the site, and it is only through the integration of equation (14) and application of the lower boundary condition ($u = 0$ at $z = z_o$) that the site enters the picture. In short, $kz\,u_*^{-1}du/dz$ does not explicitly depend upon the terrain features of the site, while u depends upon the site through z_o. Since the functional relationship between z/L' and Ri was derived directly from the Monin-Obukhov similarity hypothesis and since Ri is independent of the site, the function z/L'(Ri) is truly universal, so that it is reasonable to assume that equations (22) through (24) are also valid at KSC. Now, the function $\psi(z/L')$ is weakly dependent upon z_o through the lower limit on the integral representation of ψ, so that ψ is site-dependent. However, if we replace this lower limit with zero the contribution to ψ over the domain $0 \leq z/L' \leq z_o/L'$ is negligible, so that, although equations (25) through (27) are strictly valid for other sites, the dependence upon z_o and thus the site is small. Thus, they can be safely used in studies involving KSC data.

Upon determining the mean temperature and wind speeds at two levels, it is possible to calculate Ri with equation (21). Based upon this estimate of Ri, we can calculate z/L' with the aid of one of the equations (22) through (24). Finally, the function $\psi(z/L')$ can be evaluated with the appropriate equation from the set (25) through (27), and thus u_* and z_o can be calculated with equation (15).

III. DATA PROCESSING PROCEDURES

This analysis was based upon thirty-nine cases of turbulence at Kennedy Space Center. Most of these measurements were obtained during the hours of 0700 and 1600 EST, and the duration time of each test ranged between one-half to one hour. Mean wind speed data were obtained at the 18- and 30-meter levels, and mean temperature data were obtained at the 18- and 60-meter levels. Temperature at the 30-meter level was estimated by interpolating logarithmically between the 18- and 60-meter levels with the expression

$$T(z_2) = T(z_3) - \left\{T(z_3) - T(z_1)\right\} \frac{\ln \frac{z_3}{z_2}}{\ln \frac{z_3}{z_1}} , \tag{28}$$

where z_1, z_2, and z_3 equal 18, 30, and 60 m, respectively. An estimate of the gradient Richardson number at the 23-meter level (geometric mean height between the 18- and 30-meter 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

$$Ri(z_g) = \frac{\frac{g}{\bar{T}} \left\{\frac{T(z_2) - T(z_1)}{z_g \ln \left(\frac{z_2}{z_1}\right)} + \frac{g}{c_p}\right\}}{\left[\frac{u(z_2) - u(z_1)}{\ln (z_2/z_1)}\right]^2} z_g^2 , \tag{29}$$

where

$$z_g = \sqrt{z_1 z_2} \tag{30}$$

and

$$\bar{T} = \left\{\frac{z_2 \ln z_2 - (z_2 + 1) \ln z_1}{z_2 - z_1} - 1\right\} \left\{\frac{T(z_2) - T(z_1)}{\ln (z_1/z_1)}\right\} + T(z_1). \tag{31}$$

Then, z_g/L' was evaluated for each case by means of one of the three equations (22) through (24) 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 (25) through (27) corresponding to the appropriate Richardson number class. Equation (15) was then evaluated at the 18- and 30-meter levels to yield two equations in the two unknowns, u_* and z_o, which are given by

$$u_* = k \left\{ \frac{u(z_2) - u(z_1)}{\ln(z_2/z_1) - \psi(z_2/L') + \psi(z_1/L')} \right\} \tag{32}$$

and

$$z_o = z_2 \exp - \left\{ \frac{ku(z_2)}{u_*} + \psi(z_2/L') \right\} , \tag{33}$$

where one first evaluates equation (32) for u_* and then in turn evaluates equation (33) for z_o based upon this value of u_*.

IV. RESULTS

The data used in the calculations in section III are shown in table I, and the surface roughness length as a function of wind direction is shown in figure 2. To determine if there were any directional variations in z_o, the data in figure 2 were averaged over 30° sectors beginning with 0° reckoned clockwise from north (see figure 3). The broken-line portion of this graph associated with wind directions between 240° and 270° was obtained by linearly interpolating between the results of sectors 210° through 240° and 270° through 300°. This diagram shows that in the sectors 150° through 180° and 240° through 300° the roughness length is significantly higher than the roughness length associated with the other sectors. These high values of roughness length in these sectors can be attributed to the presence of trees upstream from the tower. The NASA 150-meter meteorological tower at KSC and the surrounding vegetation are discussed in a report by Kaufman and Keene (1965).

Based upon a sector average and the results shown in figure 3, table II shows the values of roughness length and the associated wind direction ranges appropriate for analyzing wind profiles from the NASA 150-meter meteorological tower. The statistical error for the roughness length in sectors 1, 3, and 5 is .14m and is based upon 32 observations. Since the observations in the other sectors were not sufficiently numerous to obtain a reliable estimate of the statistical error, the result must be considered tentative.

TABLE II

Sector	Wind Direction (θ) (degrees)	z_o (meters)
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

TABLE I

Date	Time EST	18m Wind Speed (m/sec^{-1})	18m Wind Direction (0 from N)	T(18) - T(3) (°F)	30m Wind Speed (m/sec^{-1})	30 m Wind Direction (0 from N)	T(60) - T(3) (°F)	Ri(23)	z_o (m)	T(3) (°F)
3/16/67	0933-1055	12.178	8	-1.71	13.392	12	-3.14	-0.06	.219	67.5
3/24/67	1052-1121	4.404	315	-2.08	4.682	324	-3.69	-1.334	.211	76.0
3/31/67	0834-0934	9.022	66	-1.4	9.655	74	-2.72	- .192	.086	72.5
4/13/67	0850-0940	8.176	103	-1.71	8.923	109	-3.39	- .196	.277	76.5
4/20/67	1300-1341	7.278	54	-3.13	7.722	59	-4.74	- .522	.099	76.5
4/21/67	1215-1300	6.468	129	-2.26	6.873	135	-3.79	-5.82	.121	77.5
4/25/67	1009-1030	4.710	39	-2.64	5.075	46	-4.20	- .736	.314	79.1
4/25/67	1107-1140	5.538	154	-2.43	6.104	154	-4.05	- .322	.515	81.0
4/27/67	1352-1422	6.017	286	-1.61	6.882	281	-2.79	- .083	.884	88.0
4/28/67	1435-1505	6.600	291	-2.07	7.512	287	-3.63	- .120	.875	69.4
4/28/67	1039-1108	8.581	5	-2.37	9.311	10	-3.91	- .183	.200	71.5
5/08/67	1242-1342	5.564	280	-1.70	6.162	273	-3.43	- .312	.591	89.1
5/11/67	1130-1230	6.918	164	-2.84	7.627	162	-4.83	- .270	.482	84.5
5/17/67	1215-1305	5.936	24	-3.36	6.408	29	-4.96	- .457	.265	78.1
5/22/67	1210-1308	6.884	173	-2.52	7.643	173	-4.16	- .181	.513	84.6
5/24/67	1115-1145	6.154	323	-1.51	6.490	334	-2.62	- .511	.057	69.3
6/1/67	1236-1306	4.435	90	-1.17	4.863	95	-2.47	- .401	.474	84.1
6/19/67	0749-0848	3.828	338	-2.90	4.079	331	-4.37	-1.423	.247	79.3
6/20/67	0916-0940	2.896	59	-1.89	3.057	57	-3.11	-2.549	.170	83.2
6/21/67	0942-1053	3.930	134	-1.42	4.224	128	-2.60	- .721	.278	83.7
7/6/67	0739-0844	4.337	142	- .97	4.790	137	-1.77	- .137	.381	82.0
7/10/67	1035-1143	3.697	166	-1.56	4.039	165	-2.92	- .672	.519	86.7
7/11/67	1107-1214	3.602	95	-1.80	3.765	93	-3.13	-2.852	.080	86.5
7/11/67	1230-1340	3.778	139	-1.42	4.090	133	-3.36	- .850	.412	87.0
7/12/67	1130-1240	3.634	43	-2.41	3.839	40	-3.81	-1.952	.166	86.9
7/12/67	2038-2138	3.992	210	+0.18	4.708	214	+0.13	+ .079	.077	79.1
7/17/67	1145-1245	4.451	125	-1.58	4.666	125	-2.78	-1.389	.075	84.8
7/17/67	1309-1340	5.471	125	-1.67	5.751	127	-3.06	-1.037	.079	86.1
7/20/67	0815-0845	2.501	90	-1.17	2.677	92	-2.22	-1.637	.324	81.9
7/25/67	1130-1200	3.231	203	-1.29	3.436	175	-2.56	-1.675	.235	86.2
7/26/67	0940-1009	3.25	233	-1.32	3.424	231	-2.53	-2.149	.142	85.3
7/28/67	1136-1237	3.770	199	-1.38	4.139	172	-2.57	- .461	.526	89.5
8/01/67	1135-1235	3.474	100	-1.58	3.766	117	-2.79	- .767	.415	82.5
8/03/67	0930-1030	5.242	107	-0.96	5.795	92	-2.25	- .249	.476	80.2
8/09/67	1419-1449	4.508	122	-1.67	4.791	115	-3.20	-1.174	.194	85.5
8/10/67	0916-0946	3.761	200	-1.32	4.011	199	-2.89	-1.564	.267	84.9
8/17/67	0815-0915	2.693	116	-0.78	2.854	117	-1.92	-2.273	.211	83.6
8/24/67	1129-1229	4.925	79	-2.58	5.306	77	-4.12	- .655	.293	86.5
8/25/67	0739-0839	4.026	62	-1.07	4.379	59	-2.33	- .561	.411	82.5

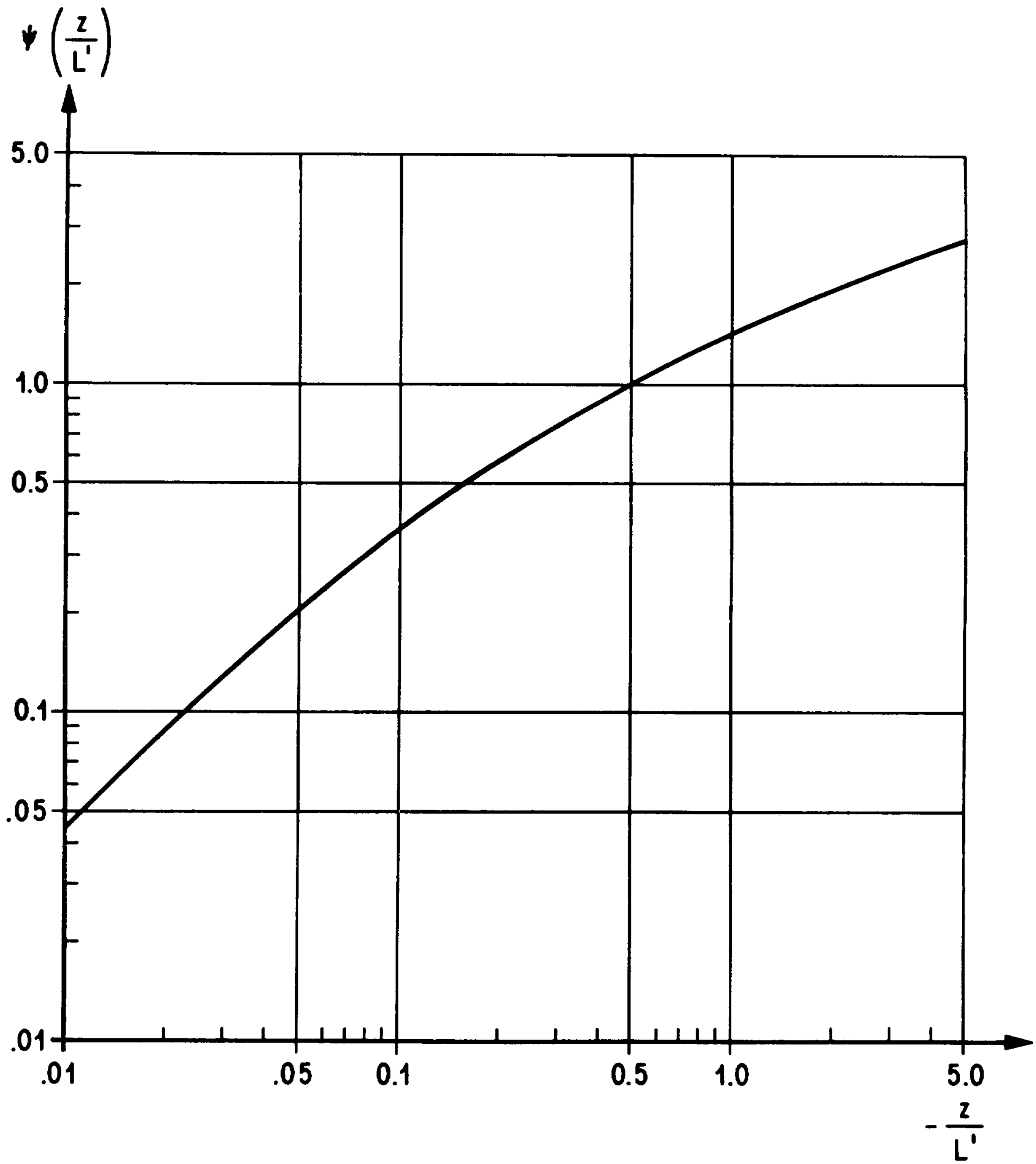

FIG. 1. PANOFSKY'S ψ FOR Ri <-0.01

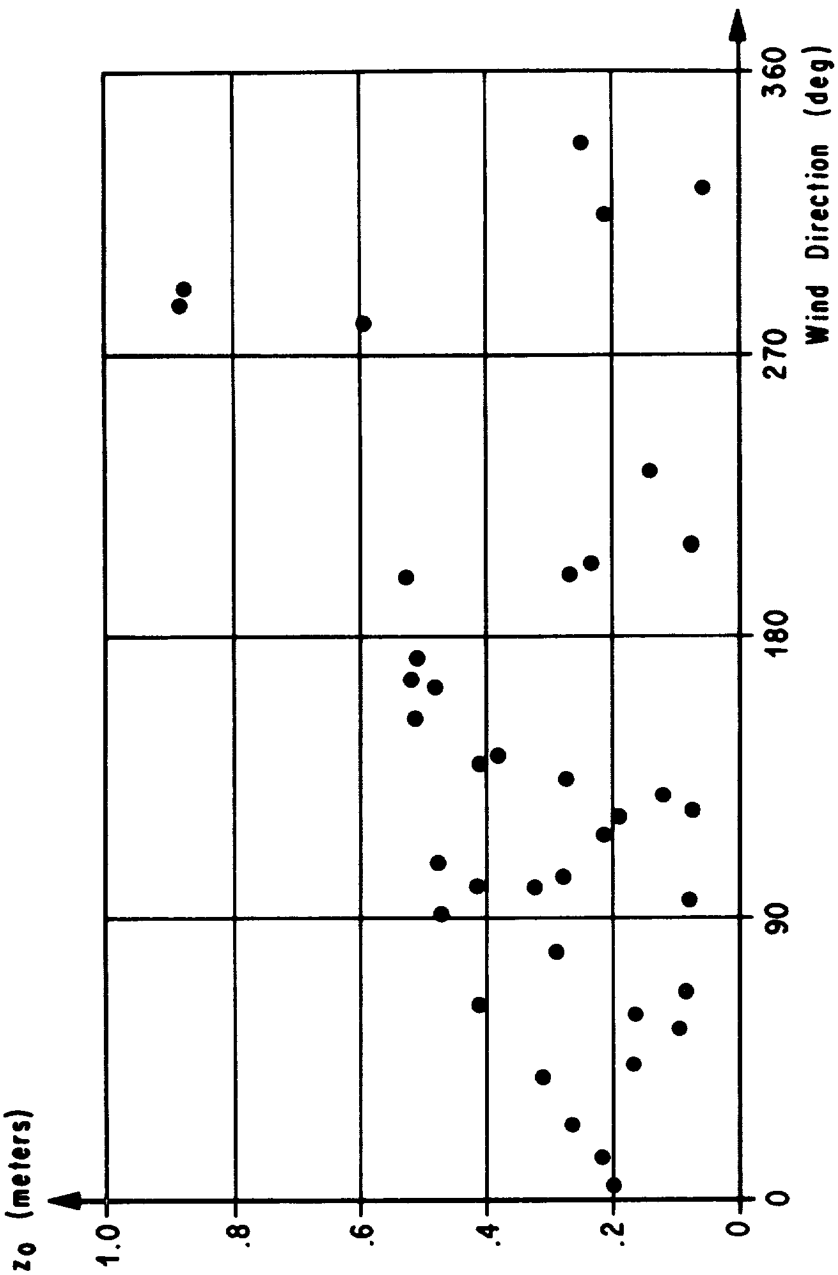

FIG. 2. CALCULATED ROUGHNESS LENGTHS VS WIND DIRECTION

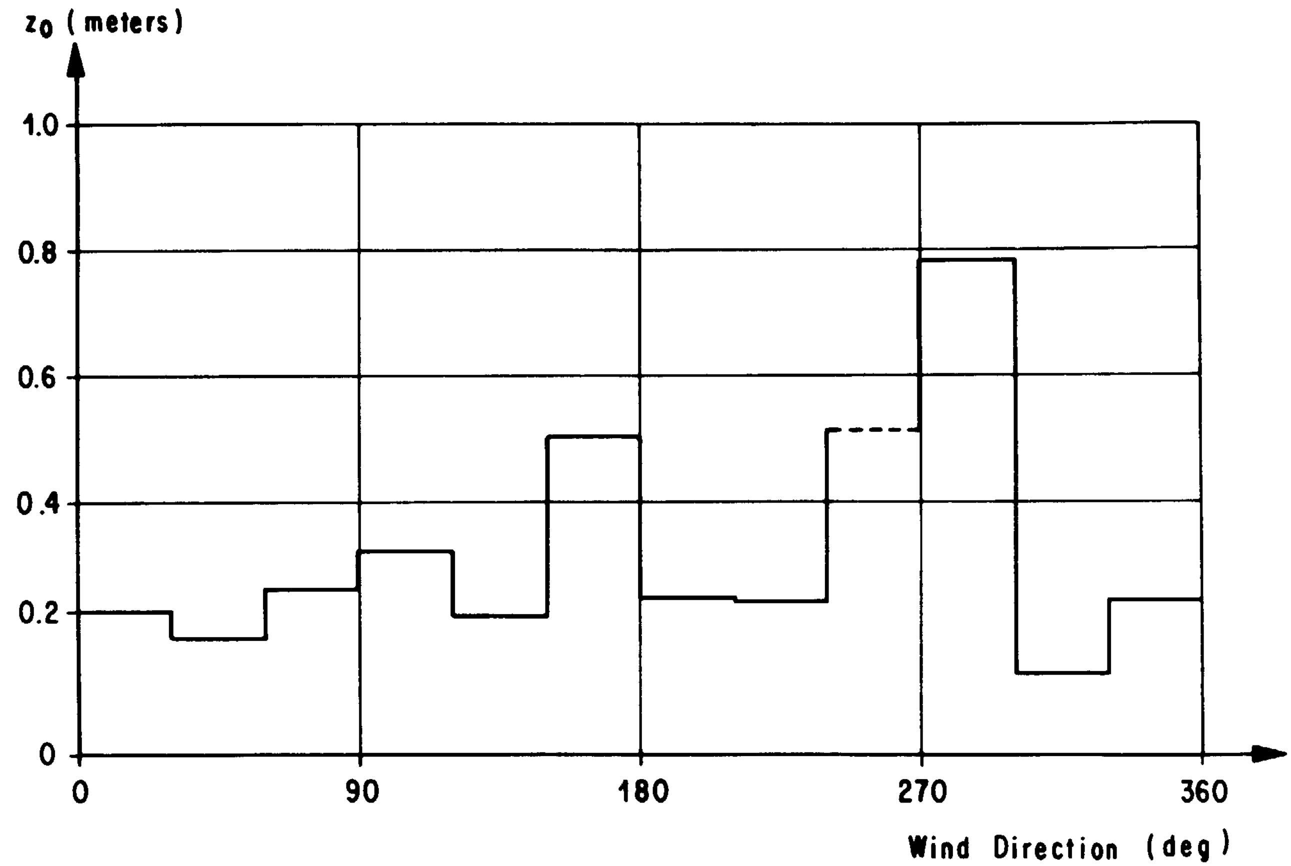

FIG. 3. AVERAGE ROUGHNESS LENGTH VERSUS WIND DIRECTION

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AN ANALYSIS OF THE ROUGHNESS LENGTH ASSOCIATED WITH
THE NASA 150-METER METEOROLOGICAL TOWER

by George H. Fichtl

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