ESSA ERLTM-NSSL 47

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DEPARTMENT OF
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**PUBLICATION**

# ESSA Technical Memorandum ERLTM-NSSL 47

**U.S. DEPARTMENT OF COMMERCE**
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
Research Laboratories

# Evaluation of Roughness Lengths at the NSSL-WKY Meteorological Tower

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JUL 1971
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| (ACCESSION NUMBER) | (THRU) |
| 25 | G3 |
| (PAGES) | (CODE) |
| CR 121475 | 20 |
| (NASA CR OR TMX OR AD NUMBER) | (CATEGORY) |

FACILITY FORM 602

National
Severe Storms
Laboratory
NORMAN,
OKLAHOMA
August 1970

Sgt- 65413

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Environmental Science Services Administration
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Norman, Oklahoma
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# FOREWORD

The work reported here reflects the cooperation and assistance of WKY Television Systems, Inc., and the National Aeronautics and Space Administration. We particularly acknowledge use of WKY transmitter building to house recording equipment. NASA's financial support assisted in the purchase and installation of conduit and temperature and wind sensors on the tower, and has been a continuing substantial aid to investigations.

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# EVALUATION OF ROUGHNESS LENGTHS
# AT THE NSSL-WKY METEOROLOGICAL TOWER

Leslie D. Sanders and Allen H. Weber[1]
National Severe Storms Laboratory

## ABSTRACT

Wind and temperature sensors have been installed by NSSL to 1458 ft above ground on the transmitting tower of WKY-TV, Oklahoma City; the tower site, instrumentation, and surrounding terrain are described. Wind profiles averaged over 15 to 25 minute periods of neutral stability have been used to estimate the surface roughness length, $z_0$, whose mean values range from less than 1 to 14 cm for different wind directions. Plots of the standard deviation of horizontal wind direction, $\sigma_\alpha$, vs. $\ln(z/z_0)$ are compared with the theoretical curve derived from work of Panofsky and Prasad, with mixed results. Estimates of friction velocity derived from measurements of vertical velocity with a Gill UVW anemometer in four cases lead to estimates of $z_0$ similar to those obtained by wind profile extrapolation.

## 1. INTRODUCTION

The WKY-TV tower in Oklahoma City has been equipped by the National Severe Storms Laboratory (NSSL) with wind and temperature sensors at seven levels up to 444.6 m above ground, primarily to aid in defining mesoscale features of severe convective storms and related phenomena. Since wind data are available from few towers of this height, there is also substantial interest in application of the data to studies of low-altitude turbulence and vertical wind shear. It is thus desirable to determine the tower parameters pertinent to boundary layer theory for use in data evaluation and to provide a basis for comparing the NSSL-WKY data with those from sites having different terrain roughness characteristics. This paper presents a description of the tower facility, and estimates of roughness length calculated for conditions of neutral stability.

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[1] Prof. Weber was employed at NSSL during the summer of 1969. His present affiliation is Department of Geosciences, North Carolina State University, Raleigh, N.C.

## 2. TOWER SITE AND INSTRUMENTATION

Through the cooperation of the management of WKY Television Systems, Inc., NSSL in 1966 installed a meteorological instrumentation system on the 1602-ft WKY-TV transmitting tower in Oklahoma City (see fig. 1). Space for recording equipment is provided in the basement of the transmitter building approximately 175 ft from the tower.

The tower site at 35° 34.2'N x 97° 29.4'W is approximately 6 nautical miles north-northeast of downtown Oklahoma City and 20 nautical miles north of NSSL in Norman, Oklahoma. The area surrounding the tower is relatively undeveloped within a 3-km radius. Terrain is gently rolling, consisting of mostly open fields of crops or grazing land. Wooded areas are confined mainly to shallow gullies and surrounding drainage areas and ponds. The topography surrounding the site within 2 nautical miles (3.7 km) is shown in figure 2. Terrain elevations within 2 km vary from approximately 1075 to 1195 ft MSL, while the base of the tower is at 1148 ft MSL. Terrain, buildings, and trees in the immediate vicinity, as derived from photographs from the tower, engineer's site plans, and topographic maps are shown in figure 3.

The tower base lies in a shallow gully slightly lower than the surrounding terrain. When the instruments were originally installed, it appeared that this depression, plus the obstruction to airflow by the nearby transmitter building and connecting conduit bridge, would cause wind measurements near the ground at the tower to be unrepresentative of the ambient wind field in undisturbed areas. For this reason, surface wind observations are made on a 7.0-m (23-ft) tower at a ground elevation 5.2 m (17 ft) higher than and 250 ft NW of the base of the tall tower. An approximate terrain cross section through both the surface and the tall towers, along azimuths of 305° - 125°, is shown in figure 4. The resultant ambiguity in the effective height of wind measurement is evident.

The station transmitter building, approximately 200 ft south of the surface wind tower, lies between azimuths of 162° and 189° with respect to the surface wind sensor, and between azimuths of 242° and 258° with respect to sensors on the TV tower. The 37 x 91-ft building extends 12 to 20 ft above ground, with its highest section 10 ft lower than the surface wind sensor. The wind at the surface tower occurs within the sector occupied by the transmitter building about 25 percent of the time (see fig. 5).

Trees adjacent to the pond SSE of the TV tower (see fig. 3), and about 100 to 500 ft from the wind sensors, lie in the sector 150° to 190° (140° to 162° from the surface wind tower). The trees which are generally 15 to 25 ft high, present much larger surface roughness elements than the grasses and weeds which prevail in the other sectors. At greater distances from the tower, trees which range in coverage from scattered to solid groves extend from about 1000 ft to more than a mile from the tower in the sector 135° to 160°. The area surrounding the tower is used for grazing cattle. Of course, the height of grasses and weeds varies with rainfall amount and grazing periods, but no record has been kept of the typical height of vegetation.

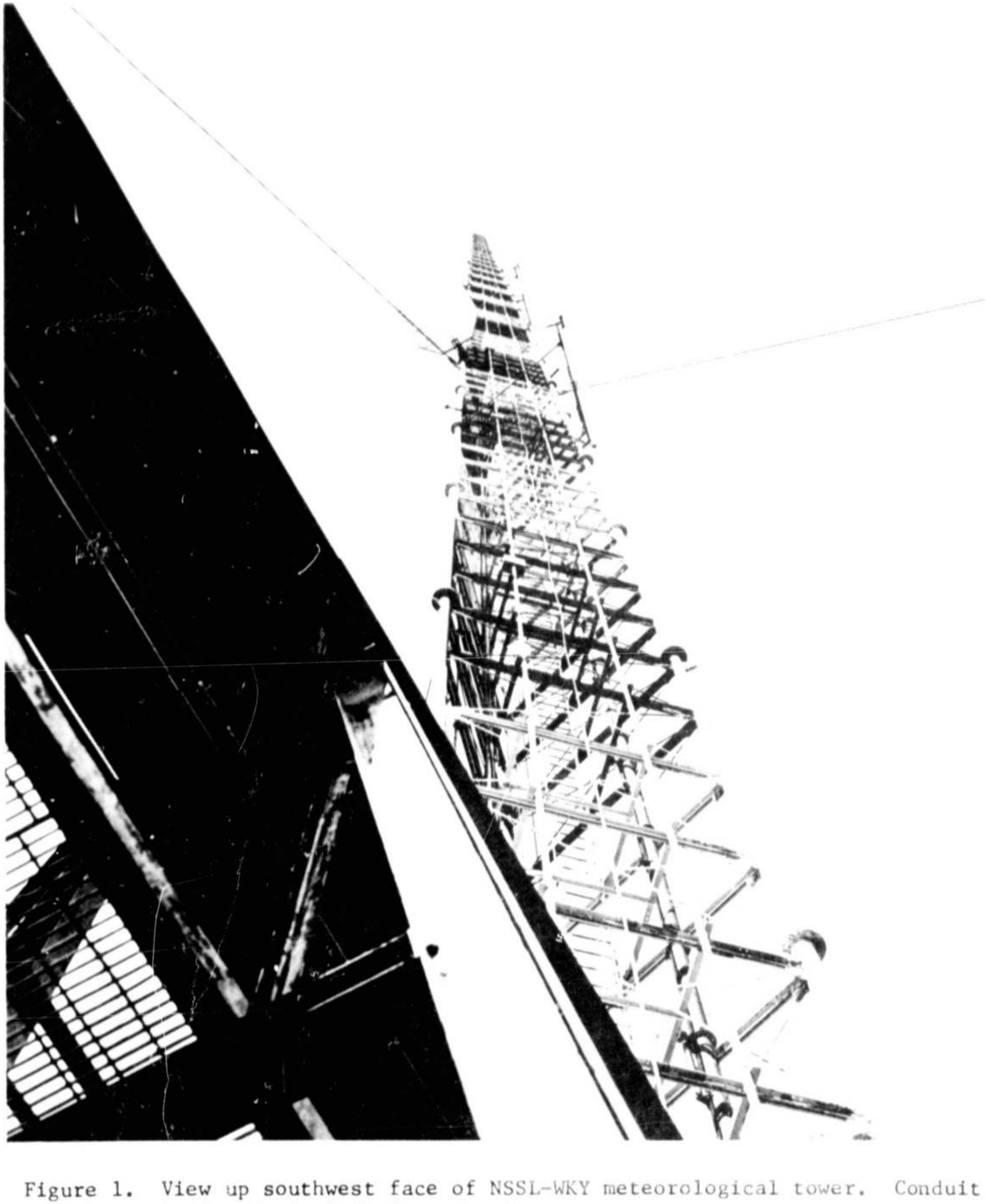

Figure 1. View up southwest face of NSSL-WKY meteorological tower. Conduit bridge is in left foreground.

The television tower is of triangular cross section, 10 ft on a side, from its base to 1515 ft above ground (fig. 1). Two legs of the tower lie due north and south, the third leg to the west. Wind transmitters are mounted 10 ft (one tower diameter) south of the west leg on retractable instrument booms (fig. 6). The tower "shadow" thus lies between 360° and 060°. Wind directions occur in this sector approximately 12 percent of the time (fig. 5). The tower effect on wind measurements may be significant over a substantially larger sector, depending on the observational precision required. Tower effects on wind speed measurements as determined by Gill, Olsson, and Suda (1966 and 1967) from wind tunnel tests on a model tower of similar cross section are depicted in figure 7.

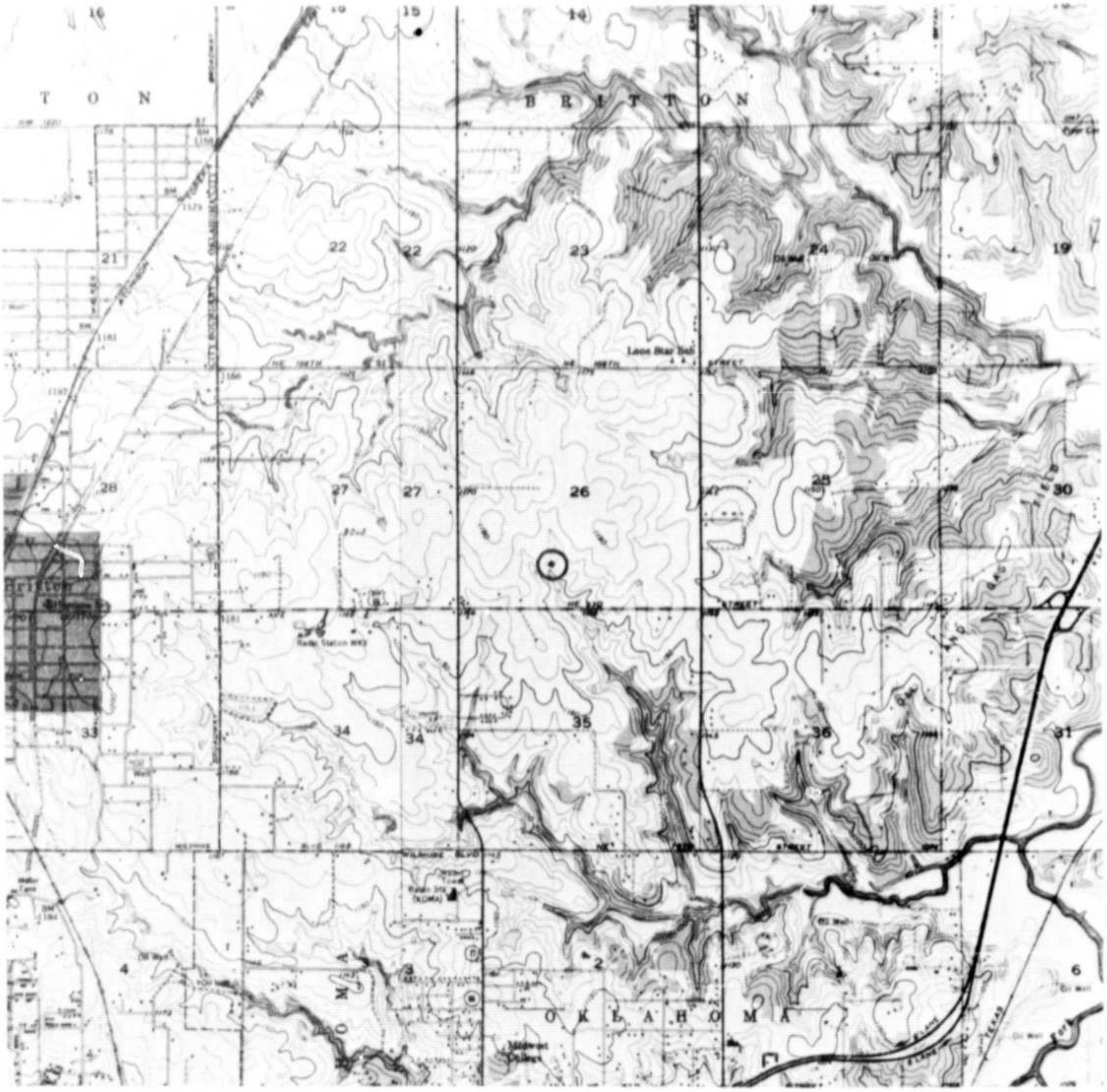

Figure 2. USGS quadrangle map showing topography within 2 nautical miles of tower (circled). Contours are at 10-ft intervals. (Section-line roads are 1 statute mile apart.)

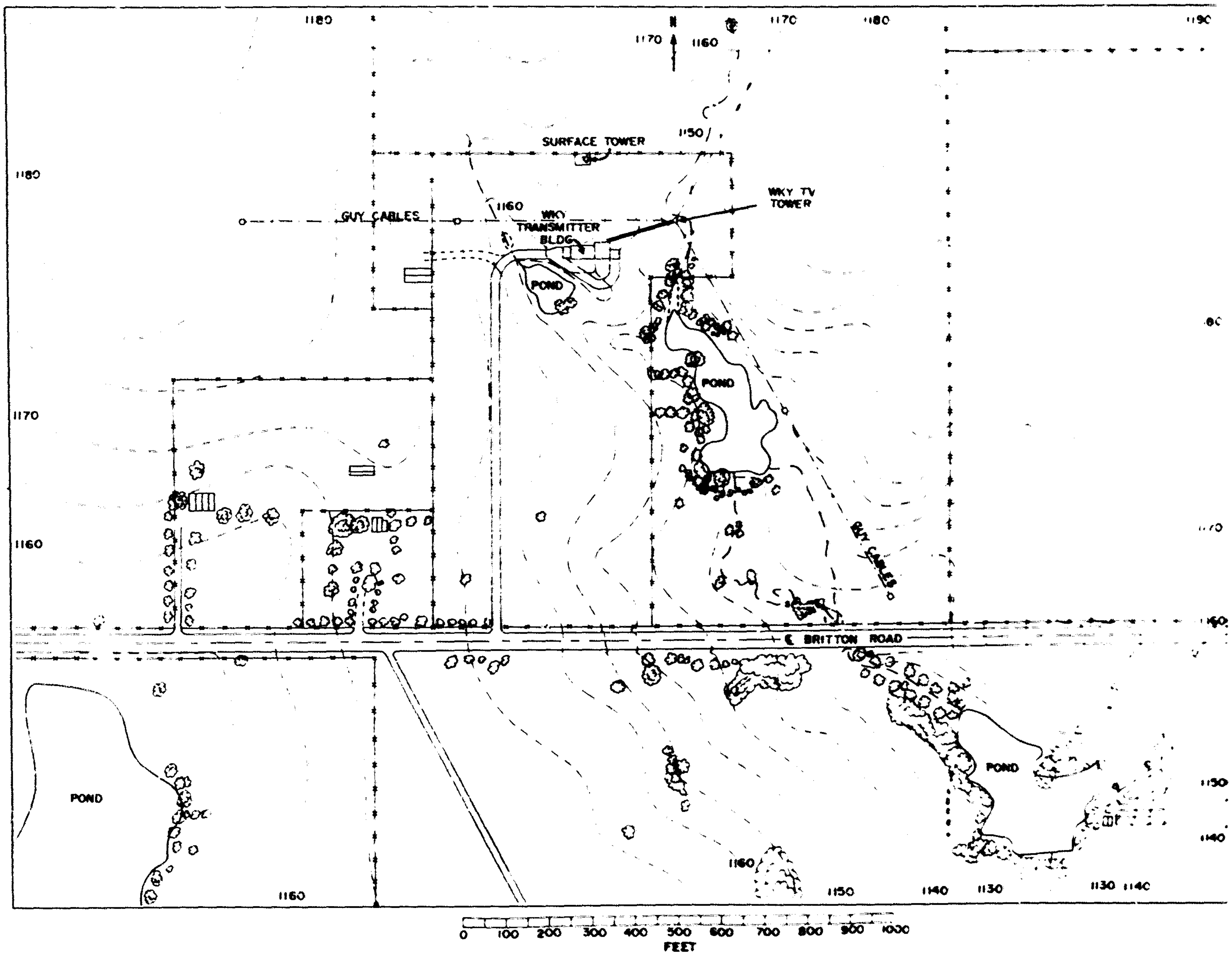

Figure 3. Plan of immediate tower vicinity with trees, buildings and approximate topography (5-ft contours).

Heights above ground of the wind and temperature sensors for the six tower levels and the surface site are given in table 1.

Table 1. Height Above Ground of Wind and Temperature Sensors on WKY-TV Tower

| Level No. | Height of Wind Sensor* Feet | Height of Wind Sensor* Meters | Height of Temperature Sensor Feet | Height of Temperature Sensor Meters |
|---|---|---|---|---|
| (Sfc.) | (23.0) | ( 7.0) | ( 6.6) | ( 2.0) |
| 1 | 146.0 | 44.5 | 143.5 | 43.7 |
| 2 | 296.0 | 90.2 | 293.5 | 89.5 |
| 3 | 581.0 | 177.1 | 578.5 | 176.3 |
| 4 | 873.5 | 266.2 | 871.0 | 265.5 |
| 5 | 1166.0 | 355.4 | 1163.5 | 354.6 |
| 6 | 1458.5 | 444.6 | 1456.0 | 443.8 |

* Heights refer to horizontal axis through center of aerovane propeller.

( ) Surface sensors are 250 ft at 305° from TV tower, at 17 ft (5.2 m) higher ground elevation.

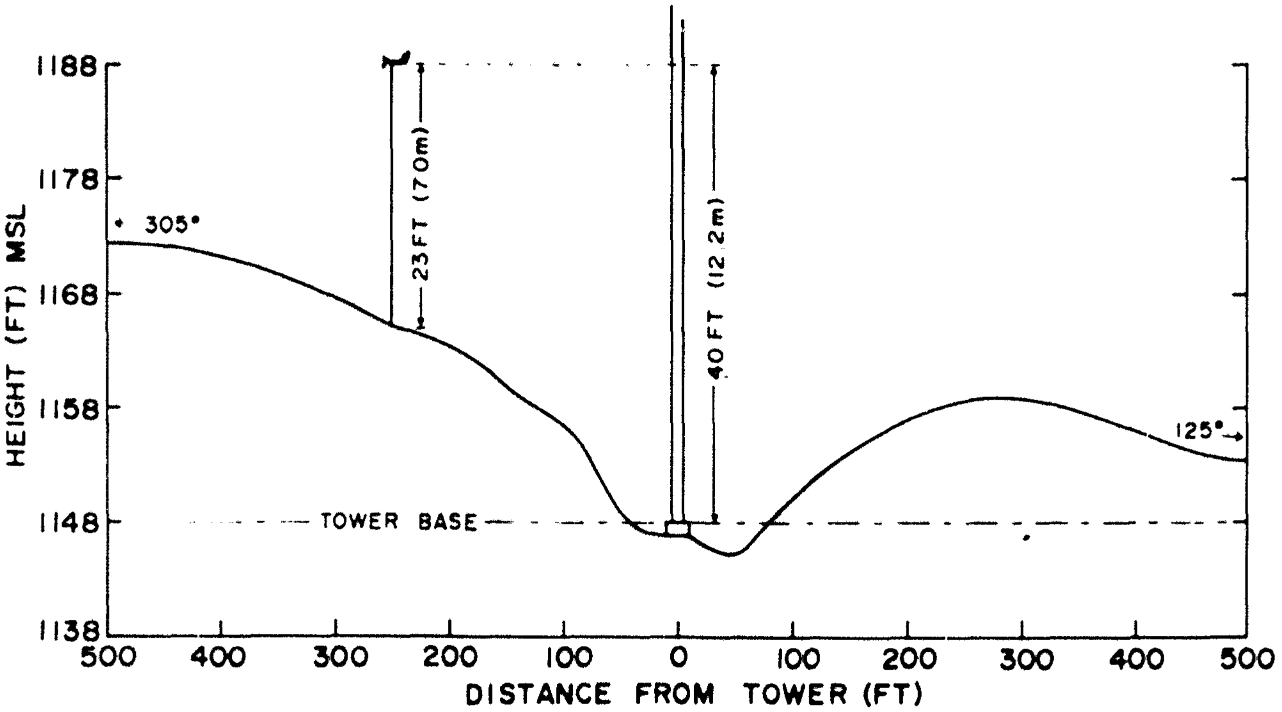

Figure 4. Approximate terrain profile through 7-m and 445-m towers along azimuths 305°-125°.

Wind sensors installed at all tower levels and at the surface station are Bendix-Friez aerovane wind transmitters with three-bladed propellers. Continuous analog wind records at a chart speed of 6 in./hour have been obtained from the seven transmitters from May 18, 1966, through January 1, 1968, from April 1 through May 31, 1968, and from April 8 through July 18, 1969. Wind speeds are recorded in knots on a 0-120 knot range.

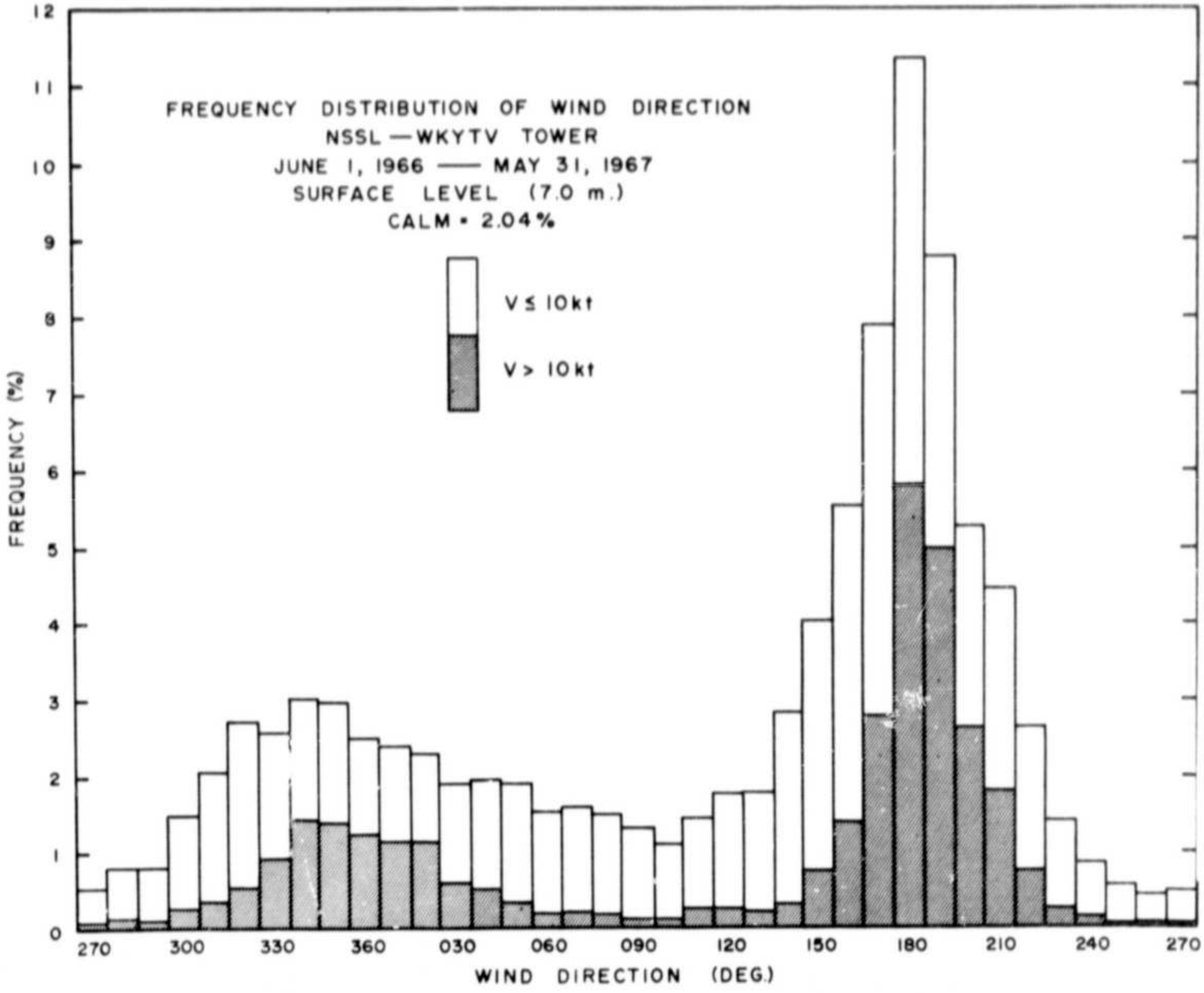

Figure 5. Frequency distribution of wind direction at 7 m at NSSL-WKY tower, June 1, 1966, to May 31, 1967.

Figure 6. Aerovane wind transmitter and Climet aspirated radiation shield containing thermistor temperature sensor, mounted on tower instrument boom. View to southwest.

Temperature sensors at all locations are linearized thermistor composites manufactured by Yellow Springs Instrument Company. As mounted in Climet aspirated radiation shields the thermistors have a response time of 30 ±5 sec. Temperature measurements are made 2 m above ground on the surface tower. On the tall tower, temperature sensors are mounted 2.5 ft (0.76m) below the wind propeller axis at each level. Ambient temperatures are measured at the surface (2.0 m) and sixth levels, and temperature differences referenced to the sixth level ($\Delta t_i = t_i - t_6$) are measured on the surface tower and at levels 1 through 5 on the tall tower. Ambient temperatures are recorded on an L & N Speedomax W multipoint recorder at a 3-sec print cycle. Temperature differences are recorded on an identical recorder at a 1.2-sec print cycle. Continuous analog temperature records at a chart speed of 6 in./hour or 12 in./hour have been obtained from December 9, 1966, through January 1, 1968, from April 1 through May 31, 1968, and from April 8 through July 18, 1969.[2] Temperatures are recorded in °C with optional ranges of -25°C to +25°C and -5°C to +45°C for ambient, and ±10°C and ±25°C for Δt's.

During late spring and summer 1969, a Gill UVW anemometer was installed 7 m above ground at the surface wind transmitter site. This system was installed with the cooperation of Dr. Y. Sasaki, Department of Meteorology, University of Oklahoma, with support from NSSL. Observations with this instrument during June and July 1969 were used to compute friction velocity during conditions of near-neutral stability.

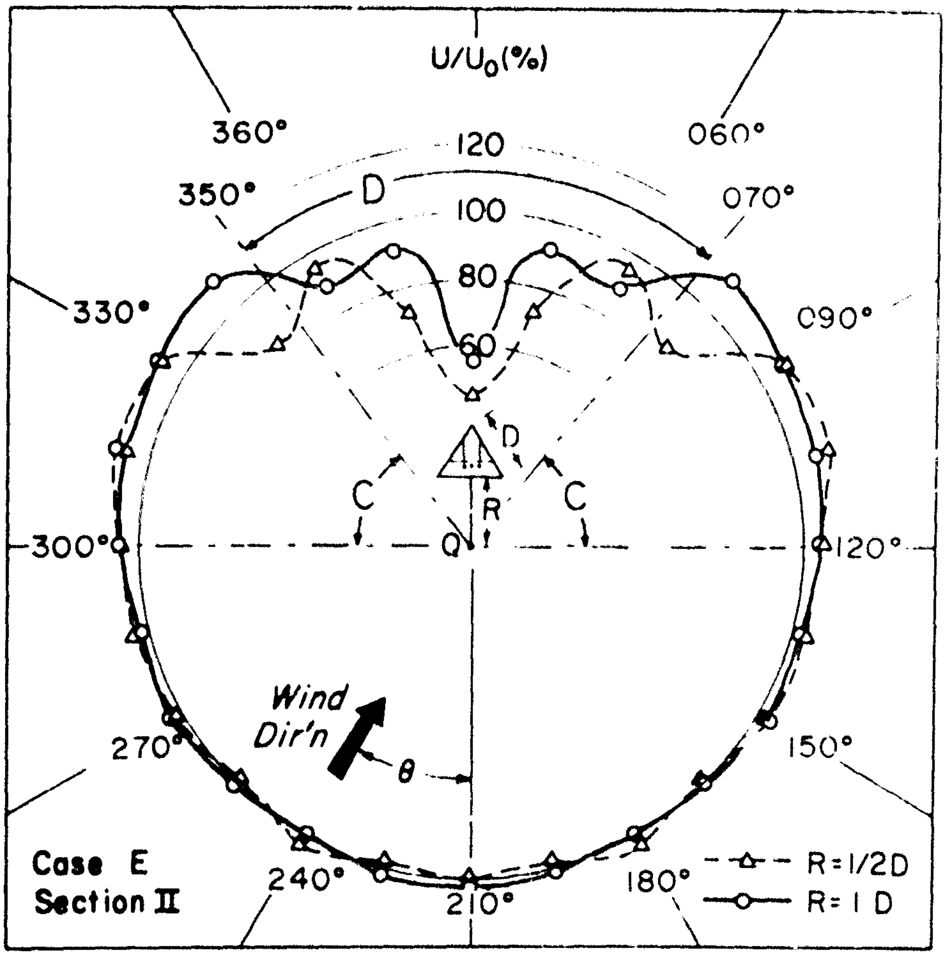

Figure 7. Ratio of sensed wind velocity, U, to ambient wind velocity, $U_0$, as a function of wind direction at sensor, O, located a distance, R, from open tower structure (from Gill, Olsson and Suda, 1966). NSSL wind sensors are exposed at R=1D.

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[2] A digital recording system was installed during 1969 and is the subject of a forthcoming paper.

# 3. ESTIMATION OF ROUGHNESS LENGTH, $z_o$

## 3.1 Introduction

Several methods are available for estimating the roughness length parameter. Perhaps the most commonly used method involves the linear extrapolation to $\bar{u} = 0$ of logarithmic wind profiles obtained during neutral stability. Other methods make use of (1) the diabatic wind profile which is based on similarity theory, (2) the diabatic wind profile with provision also for the decrease of friction velocity (or stress) with height on tall towers, and (3) a method based on the eddy energy equation which involves spectral analysis of wind observations (see Blackadar, Dutton, Panofsky and Chaplin, 1969).

Because of the vertical and horizontal spacing of wind and temperature sensors near the surface, it was believed that the stability (Richardson number) could not be defined with sufficient precision to permit using the diabatic wind profile equation (No. 1, above). For this reason, and because of its simplicity, the logarithmic profile extrapolation method for neutral stability was chosen as the best method for estimating roughness lengths at the NSSL-WKY tower.

The velocity profile in the surface boundary layer during conditions of neutral stability is given by

$$\bar{u} = \frac{u_*}{k} \ln \frac{z - D}{z_o} \cong \frac{u_*}{k} \ln \frac{z}{z_o} \quad (\text{for } z \gg D), \qquad (1)$$

where

$\bar{u}$ = mean horizontal wind speed,

$u_*$ = friction velocity $= \sqrt{\tau/\rho} = \sqrt{\overline{-u'w'}}$ ,

($\tau$ = shearing stress, $\rho$ = air density, $u' = u - \bar{u}$,

and $w' = w - \bar{w}$),

$k$ = von Karman constant, assumed = 0.4,

$z$ = height,

$D = d - z_o$ = zero point displacement parameter (Lettau, 1957)

and

$z_o$ = aerodynamic roughness parameter, or "roughness length."

This equation defines the vertical wind profile in the surface boundary layer if $u_*$, $z_o$, and D are known. Alternatively, $u_*$, $z_o$, and D can be determined from mean wind profiles observed during neutral stability. Thus $z_o$ is a fundamental parameter that serves as a scaling length in boundary layer wind profile laws.

The zero point displacement parameter is distinguished from the roughness length in that the latter parameter (on a given day) is a fixed surface characteristic of the site, while the former is the corrective height increment between the mathematically defined zero level of a numerical model of the wind profile and the arbitrary datum level from which the observer has measured anemometer heights.

After considering the anemometer heights on the tower, the difference in terrain height and roughness for the tall tower and the 7 m surface tower, and other factors, we decided not to include determinations of the zero point displacement parameter, D, in this report. It appeared that its inclusion would needlessly complicate the calculations without significantly improving the estimates of $z_o$.

The roughness length is determined by the characteristic dimensions and areal density of the surface roughness elements upwind from an observational site. Several investigators have given typical values of roughness length over smooth terrain for various types of surfaces. Table 2 presents values of $z_o$ given by Deacon (1953), where R is the ratio of the wind speeds at 2- and 1-m height, and $u_2$ is the mean wind velocity at 2 m.

Table 2. Roughness Parameters of Various Surfaces

| Type of Surface | | R | $z_o$ (cm) |
|---|---|---|---|
| Smooth mud flats | | 1.06 | 0.001 |
| Smooth snow on short grass | | 1.07 | 0.005 |
| Desert (Pakistan) | | 1.085 | 0.03 |
| Snow surface, natural prairie | | 1.10 | 0.10 |
| Mown grass: | | | |
| 1.5 cm | | 1.11 | 0.2 |
| 3.0 cm | | 1.14 | 0.7 |
| 4.5 cm | $u_2 = 2$ m sec$^{-1}$ | 1.185 | 2.4 |
| | $u_2 = 6$-$8$ m sec$^{-1}$ | 1.15 | 1.7 |
| Long grass, 60-70 cm | $u_2 = 1.5$ m sec$^{-1}$ | 1.275 | 9.0 |
| | $u_2 = 3.5$ m sec$^{-1}$ | 1.25 | 6.1 |
| | $u_2 = 6.2$ m sec$^{-1}$ | 1.21 | 3.7 |

Lettau (1969) has presented a technique for estimating the roughness length based on the effective obstacle height h*, the average silhouette area, and the specific area (or areal density) of the roughness elements. His "oversimplified estimates" of roughness length $z_o$ for a systematic variation of h* are shown in table 3.

Table 3. Oversimplified Estimates of Roughness Length $z_o$.

| h* (cm) | Obstacle type | $z_o$ (cm) |
|---|---|---|
| 1000 | Forest trees, houses | 214 |
| 100 | Field crops, tall grasses | 13.8 |
| 10 | Lower grasses, weeds | 0.80 |
| 1 | Bare soils | 0.058 |
| 0.1 | Sand flats | 0.0036 |

Fichtl (1968 a, b) evaluated the roughness length associated with the NASA 150-m meteorological tower at Cape Kennedy by using wind profile laws consistent with the Monin-Obukhov (1954) similarity hypothesis. The Cape Kennedy tower is surrounded by level terrain with vegetation of different kinds; detailed description of the site has been given by Kaufman and Keene (1965). Fichtl's values were categorized on the basis of wind direction, and he found average roughness lengths of 0.23 m, 0.51 m, and 0.65 m for different sectors from the tower base.

Slade (1969) addressed the difficult problem of finding $z_o$ from wind profiles on a tall tower in rough and inhomogeneous terrain near Philadelphia. He found that by combining a large number of wind profiles for a given direction class, the average profile obtained was nearly linear on a semi-logarithmic scale. The wind profiles represented averages during times of near-neutral stability, i.e., during the 1-hour period ending 1/2 hour before sunset. The linearity of the logarithmic profiles combined with other evidence led Slade to conclude that the zero intercepts of these plots were a fair representation of the roughness lengths around the Philadelphia tower site. Slade's values are given in table 4.

Table 4. Values of $z_o$ for Philadelphia Tower Neutral Wind Profiles

| Profile Segment (m) | $z_o$, Northerly 1965 Data (m) | $z_o$, Northerly 1967 Data (m) | $z_o$, Southerly 1965 Data (m) | $z_o$, Southerly 1967 Data (m) |
|---|---|---|---|---|
| 12.2- 30.5 | - | 2.6 | - | 0.52 |
| 12.2- 61.0 | - | 2.5 | - | - |
| 30.5- 61.0 | 2.8 | 2.2 | 0.24 | 0.22 |
| 30.5-107.0 | 3.1 | 2.2 | - | - |
| 30.5-175.0 | 3.1 | 2.5 | - | - |

### 3.2 Data Selection and Evaluation

For the present study, the analog chart records were searched for cases of near-neutral stability. (Cases involving low wind speeds were discarded.) A plastic scale marked with temperature differences between levels corresponding to the dry adiabatic lapse rate (0.41°C, 0.45°C, 0.85°C, 0.87°C, 0.87°C, 0.87°C) was used to scan the analog records of $\Delta t$ for the months of April, May, June and July 1967, and July 1969.

The occasions of neutral stability over the entire height of the WKY tower are usually of brief duration. During clear days in the spring one can generally find a nearly neutral period of about 15 to 30 minutes, one to three hours before sunset. Before then, the layer between the surface station and the first tower level usually has a super-adiabatic lapse rate; afterward the lapse rate is stable. Neutral stability throughout the height of the tower is even rarer following sunrise than before sunset. The inversion that usually forms overnight often breaks down rather abruptly and erratically from the surface upward. Sometimes the record shows a quasi-periodic behavior of the temperature during the breakdown of the inversion, and large excursions of temperature that make it difficult to identify neutral stability. Overcast days with moderate or strong surface winds sometimes have long periods of neutral stability. On these occasions, however, layers above the surface may depart from the dry adiabatic lapse rate. A substantial number of windy overcast days with long periods of neutral stability occur with northerly winds and are therefore unusable owing to the tower effect of the wind sensors.

Since wind profiles at the tower are affected by the dimensions of upwind surface roughness elements, the profile varies with wind direction when the terrain is horizontally inhomogeneous. We therefore attempted to estimate roughness length for various wind directions, but because of the distinctive bimodal climatological frequency of wind direction (see fig. 5) a significant sample was not obtained for certain wind directions.

During the period April 10 to July 27, 1967 and July 1-7, 1969, near neutral stability ($\Delta t$'s throughout height of tower within 0.1°C of dry adiabatic values) was found on 76 days, and provided 184 sample periods of 15 to 25 minutes duration. These yielded 128 usable cases of 17-minute average duration. The remaining 56 cases were made unusable by tower effects on wind speed measurements. The periods of neutral stability varied from about 15 minutes up to 3 1/2 hours duration, with a mode of about 30 minutes. Five-minute average values of wind speed, direction, and direction range were read from the analog charts. The successive 5-minute averages were combined to obtain the 128 average profiles for periods of 15-25 minutes when the average wind direction was nearly constant. Sample profiles are shown in figure 8(a). In numerous cases, the surface (7 m level) wind speed was the most difficult to fit to a logarithmic profile.

Wind profiles for the selected cases were categorized in four classes of direction in terms of their expected quality and the surface roughness. Relatively uniform surface conditions of essentially smooth, grass-covered

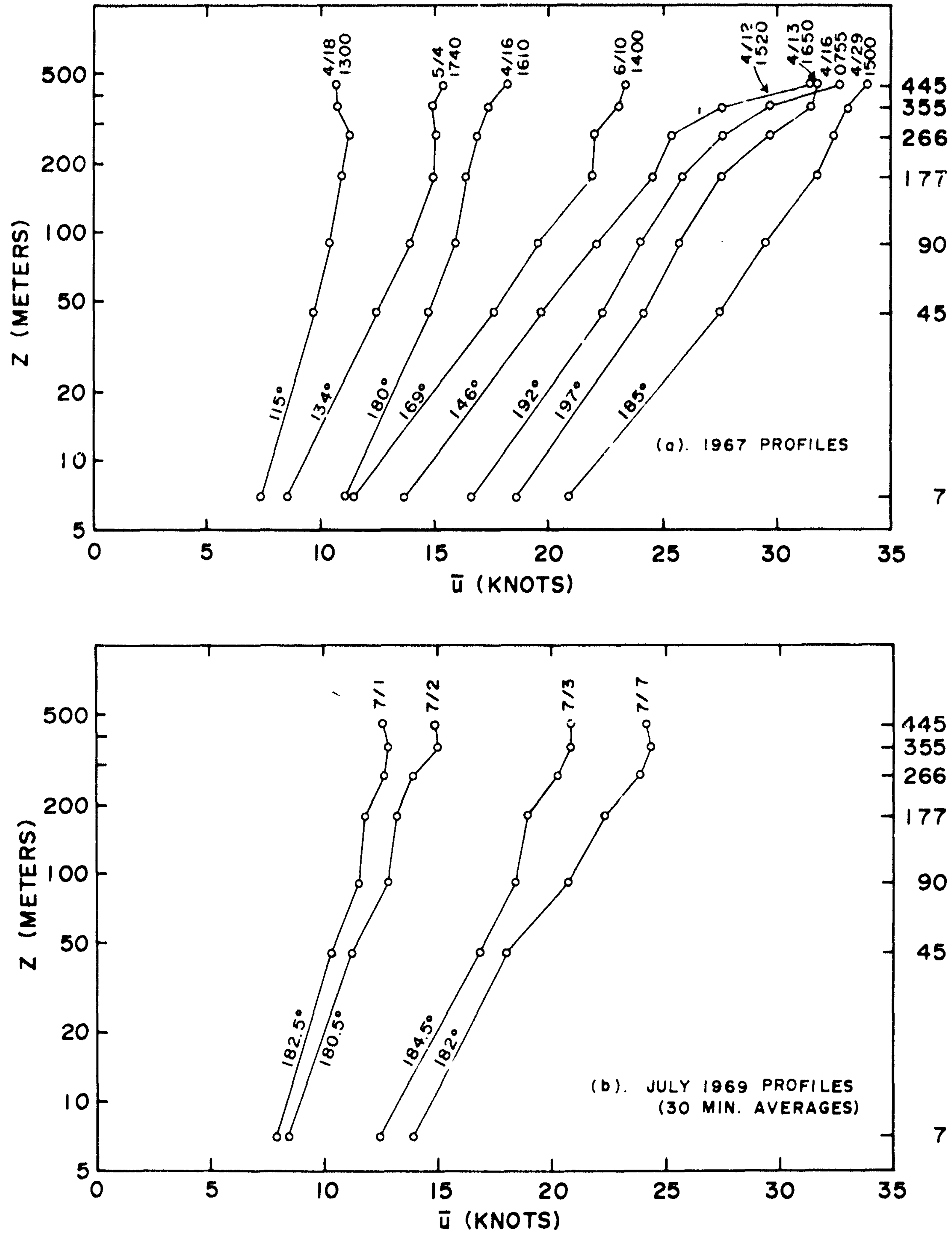


Figure 8. (a) Sample 15-min average wind velocity profiles; (b) Thirty-min average wind velocity profiles for July 1, 2, 3, and 7, 1969.

terrain exist through all directions except for the sector from 150° to 190° at the tall tower (140° to 165° at the 7-m surface tower) in which there is increased roughness due to trees. The average terrain height in this sector is lower than the tower base. The transmitter building lies in this same sector with respect to the surface wind tower. These considerations, and the tower effects on wind speed measurements as shown in figure 7, led us to characterize the data as shown in table 5.

Table 5. Wind Direction Categories

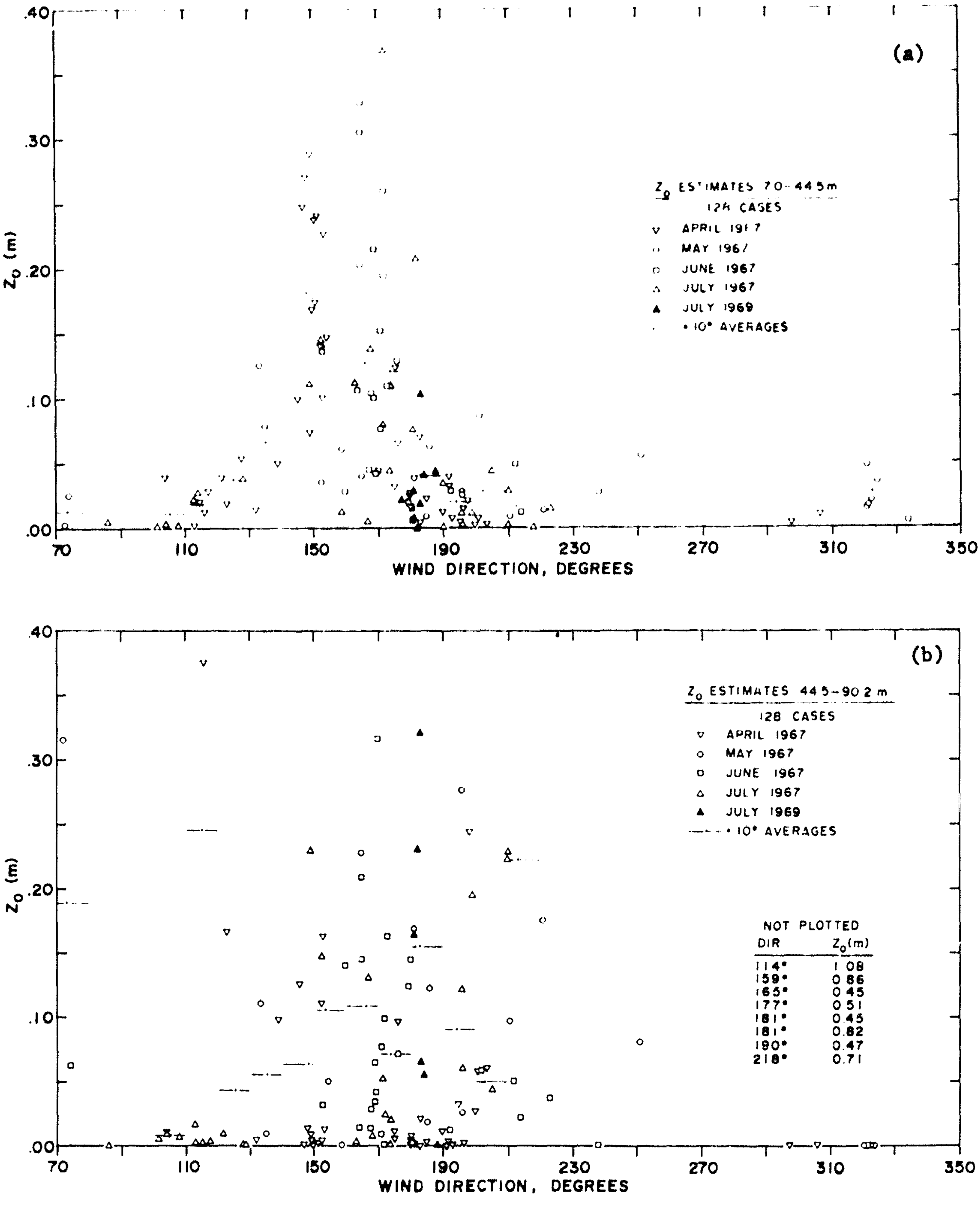
| Category | Direction Intervals | No. of Wind Profiles |
|---|---|---|
| A | 120° to 140° and 180° to 300° | 60 |
| B | 140° to 180° | 48 |
| C | 070° to 120° and 300° to 350° | 20 |
| D | 350° to 070° | 56 |

A = essentially smooth grass-covered terrain.
B = increased surface roughness (trees and building); average terrain height lower than tower base.
C = essentially smooth terrain; tower effect causes proportional over-read.
D = major tower effect (under-read), data unusable.

The relatively large number of cases in category D reflects the occurrence of longer periods of neutral conditions on overcast days with northerly and northeasterly winds.

The evaluation of the roughness length is somewhat uncertain because the average profiles are seldom perfectly straight lines in semi-logarithmic coordinates. Another complicating factor arises from the different locations of the surface and tall towers. The fact that the surface wind transmitter is 7.0 m above ground, yet is 12.2 m higher than the base of the tall tower, leaves a question as to the appropriate heights at which to plot the data. By extrapolation of the profile linearly downward from the 44.5 m and 90.2 m levels to the surface velocity, the mean effective height of the surface data was estimated to be about 8 m, compared with the actual height of 7 m above ground. There was considerable variance about this mean value. The results presented below have been derived from profiles in which the surface data were plotted at 7.0 m and the other levels at their true height above the tower base.

The analysis of roughness length was confined to the profile defined by the three levels of wind data, 7.0, 44.5, and 90.2 m. Because of the surface-level ambiguity, we initially thought that tower levels 1 and 2 would give the best estimates of $z_o$. Experience showed, however, that these two



| DIR | $Z_o$(m) |
|---|---|
| 114° | 1.08 |
| 159° | 0.86 |
| 165° | 0.45 |
| 177° | 0.51 |
| 181° | 0.45 |
| 181° | 0.82 |
| 190° | 0.47 |
| 218° | 0.71 |

Figure 9. Roughness length estimates vs. wind direction: (a) from 7.0 and 44.5 m points; (b) from 44.5 and 90.2 m points; (c) from regression line through 7.0, 44.5, and 90.2 m points.

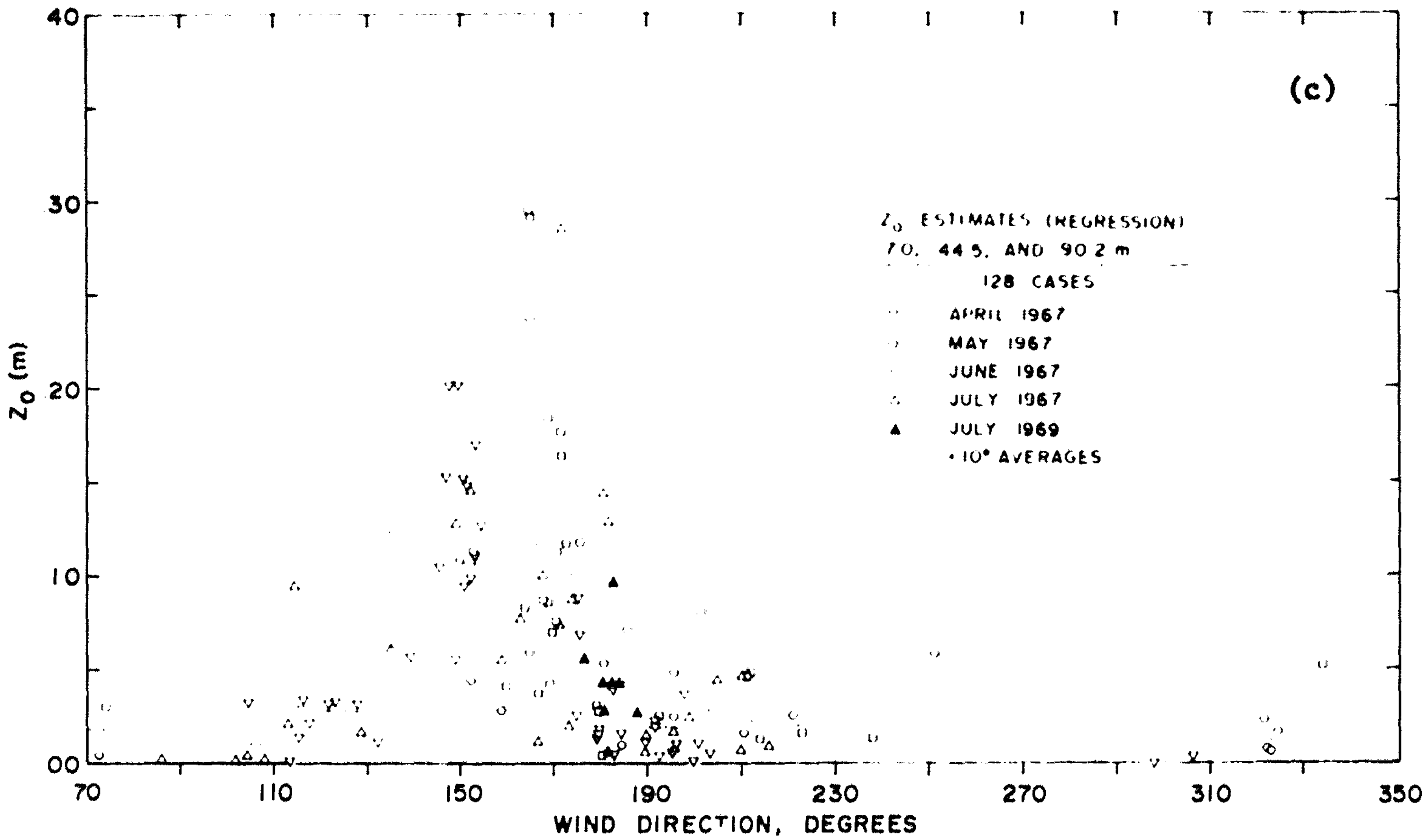


Figure 9. (Cont'd)

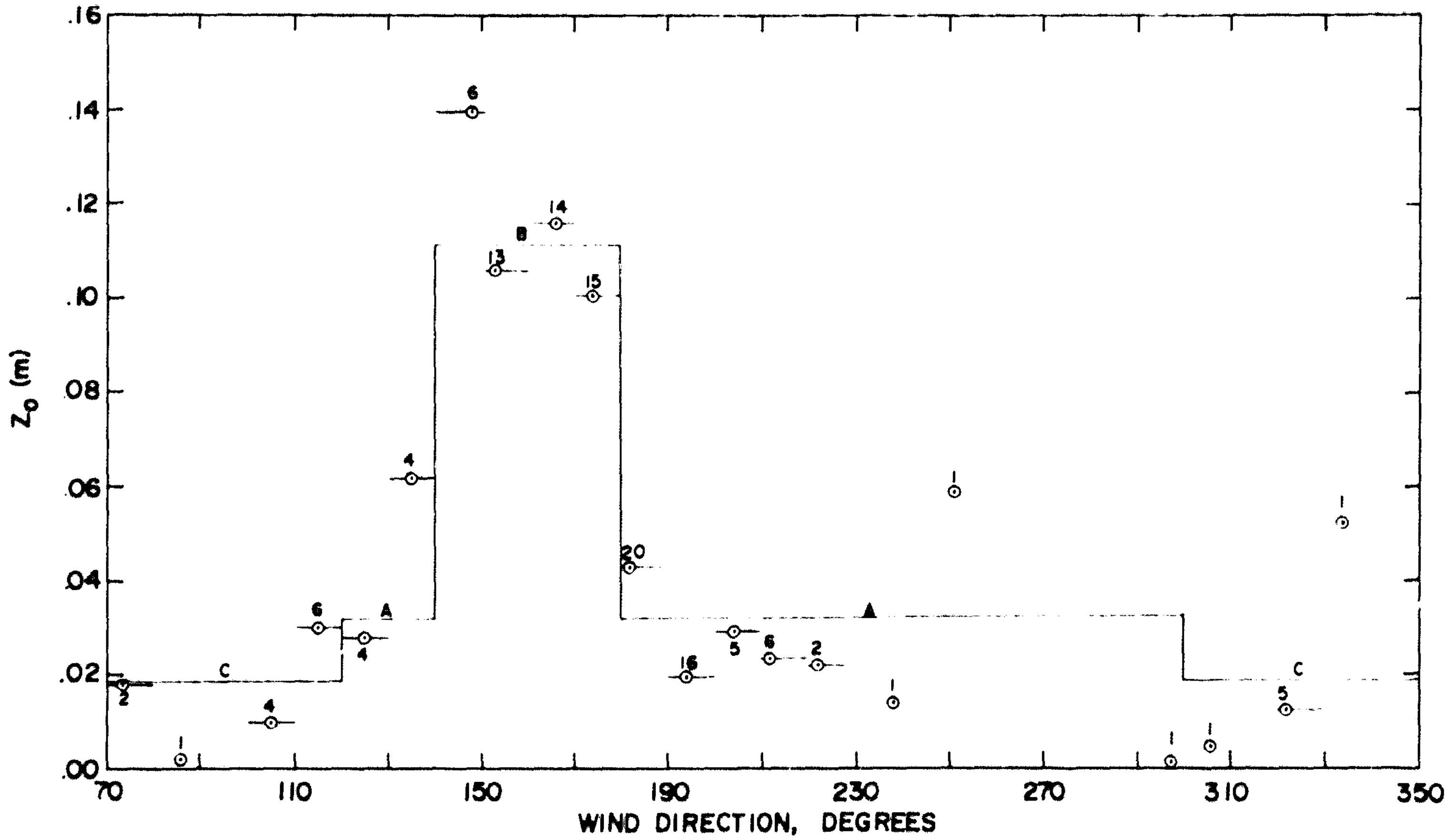


Figure 10. Mean $z_0$ for azimuth sectors 070° to 350°, and for direction categories A, B and C.

Table 6. Roughness Length Estimates - NSSL-WKY Tower

| Azimuth Sector | Mean/Median $z_o$(m) for Different Profile Segments | | | | |
|---|---|---|---|---|---|
| | 7.0+44.5m | 44.5+90.2m | 7.0+90.2m | Best Fit 7.0 to 90.2m | No. of Samples |
| 070°-080° | 0.013/- | 0.189/- | 0.018/- | 0.018/- | 2 |
| 080°-090° | .005/- | .000/- | .002/- | .002/- | 1 |
| 090°-100° | | | | | 0 |
| 100°-110° | .011/.002 | .008/.008 | .009/.003 | .010/.003 | 4 |
| 110°-120° | .018/.021 | .246/.009 | .030/.020 | .031/.021 | 6 |
| 120°-130° | .037/.038 | .044/.004 | .025/.028 | .028/.031 | 4 |
| 130°-140° | .067/.064 | .055/.053 | .062/.056 | .062/.058 | 4 |
| 140°-150° | .181/.179 | .063/.010 | .127/.123 | .140/.139 | 6 |
| 150°-160° | .140/.145 | .106/.012 | .095/.108 | .107/.109 | 13 |
| 160°-170° | .126/.105 | .108/.053 | .114/.080 | .116/.084 | 14 |
| 170°-180° | .120/.109 | .071/.052 | .095/.080 | .101/.087 | 15 |
| 180°-190° | .040/.023 | .155/.060 | .041/.030 | .043/.034 | 20 |
| 190°-200° | .019/.017 | .091/.018 | .018/.016 | .019/.019 | 16 |
| 200°-210° | .028/.006 | .049/.058 | .029/.012 | .029/.011 | 5 |
| 210°-220° | .016/.010 | .222/.159 | .023/.015 | .024/.015 | 6 |
| 220°-230° | .014/- | .106/- | .023/- | .022/- | 2 |
| 230°-240° | .027/- | .000/- | .011/- | .014/- | 1 |
| 240°-250° | | | | | 0 |
| 250°-260° | .055/- | .080/- | .060/- | .059/- | 1 |
| 260°-290° | | | | | 0 |
| 290°-300° | .003/- | .000/- | .001/- | .002/- | 1 |
| 300°-310° | .010/- | .000/- | .004/- | .005/- | 1 |
| 310°-320° | | | | | 0 |
| 320°-330° | .027/.021 | .000/.000 | .009/.007 | .013/.009 | 5 |
| 330°-340° | .006/- | 1.020/- | .045/- | .053/- | 1 |
| 340°-350° | | | | | 0 |
| | | | | Total = | 128 |
| A: 120°-140°<br>180°-300° | .031/.022 | .114/.042 | .031/.022 | .032/.024 | 60 |
| B: 140°-180° | .135/.111 | .090/.032 | .104/.088 | .112/.099 | 48 |
| C: 070°-120°<br>300°-350° | .017/.015 | .145/.004 | .017/.011 | .019/.011 | 20 |
| D: 350°-070° | Unusable due to tower effect | | | | (56) |

levels often gave unrealistically large $z_o$'s, and we concluded that a regression line giving a least squares fit to all three points best defined the lower portion of the profile.

Mean and median values of the estimates of $z_o$ determined from profile segments 7.0 m to 44.5 m, 44.5 m to 90.2 m, 7.0 m to 90.2 m and for the best fit profile are shown in table 6. To avoid inaccuracies in the graphical determination of $z_o$, the roughness lengths in this table were computed from the formula

$$\log z_o = \frac{\overline{u}_{n+1} \log z_n - \overline{u}_n \log z_{n+1}}{\overline{u}_{n+1} - \overline{u}_n} . \qquad (2)$$

The resulting values of the roughness length in relation to wind direction are shown in figure 9. Smoothed values of $z_o$ determined from the best fit solutions for 10° direction intervals and for the direction categories A, B, and C are shown in figure 10.

## 4. STANDARD DEVIATION OF HORIZONTAL WIND DIRECTION

Panofsky and Prasad (1965) found that the value of the standard deviation of the horizontal wind direction, $\sigma_\alpha$, can be specified as a function of $\ln(z/z_o)$ and stability. Using a method to estimate $\sigma_\alpha$ suggested by Markee (1963), Slade (1969) found that his plot of $\sigma_\alpha$ vs. $\ln(z/z_o)$ was in reasonable agreement with the Panofsky-Prasad predictions for neutral stability. Slade's data were taken from the tower near Philadelphia, which lies in rough and inhomogeneous terrain.

We decided to compare measurements from the NSSL-WKY tower with the Panofsky-Prasad predictions, and to use the quality of agreement as an indirect measure of the reliability of our $z_o$ estimates. Under conditions of steady southerly flow during July 1-7, 1969, four data samples were taken between 1640-1715 CST when neutral stability existed through the entire height of the tall tower. Wind profiles for these cases are shown in figure 8(b). As in Slade's analysis (1969), the values of $\sigma_\alpha$ were determined from the direction range values divided by 6.0. According to Markee's results the sample length is not critical since the value of $\sigma_\alpha$ generally increases with increasing sample length, as does the range.

Analysis of the wind profiles for July 1-7, 1969, and computation of roughness length from different pairs of tower levels, and also from the least squares regression of log z on $\overline{u}$ for the 7.0-, 44.5-, and 90.2-m levels, gave three estimates of $z_o$: 2.3 cm for 7.0 and 44.5 m; 15.5 cm for 44.5 and 90.2 m; and 3.6 cm for the regression line. These three estimates of $z_o$ were used to plot $\sigma_\alpha$ vs. $\ln(z/z_o)$ for July 1 and 2 combined and for July 3 and 7 combined, in order to determine which estimate of $z_o$ would give the best fit to the theoretical curve representing the Panofsky-Prasad predictions. Results are shown in figure 11.

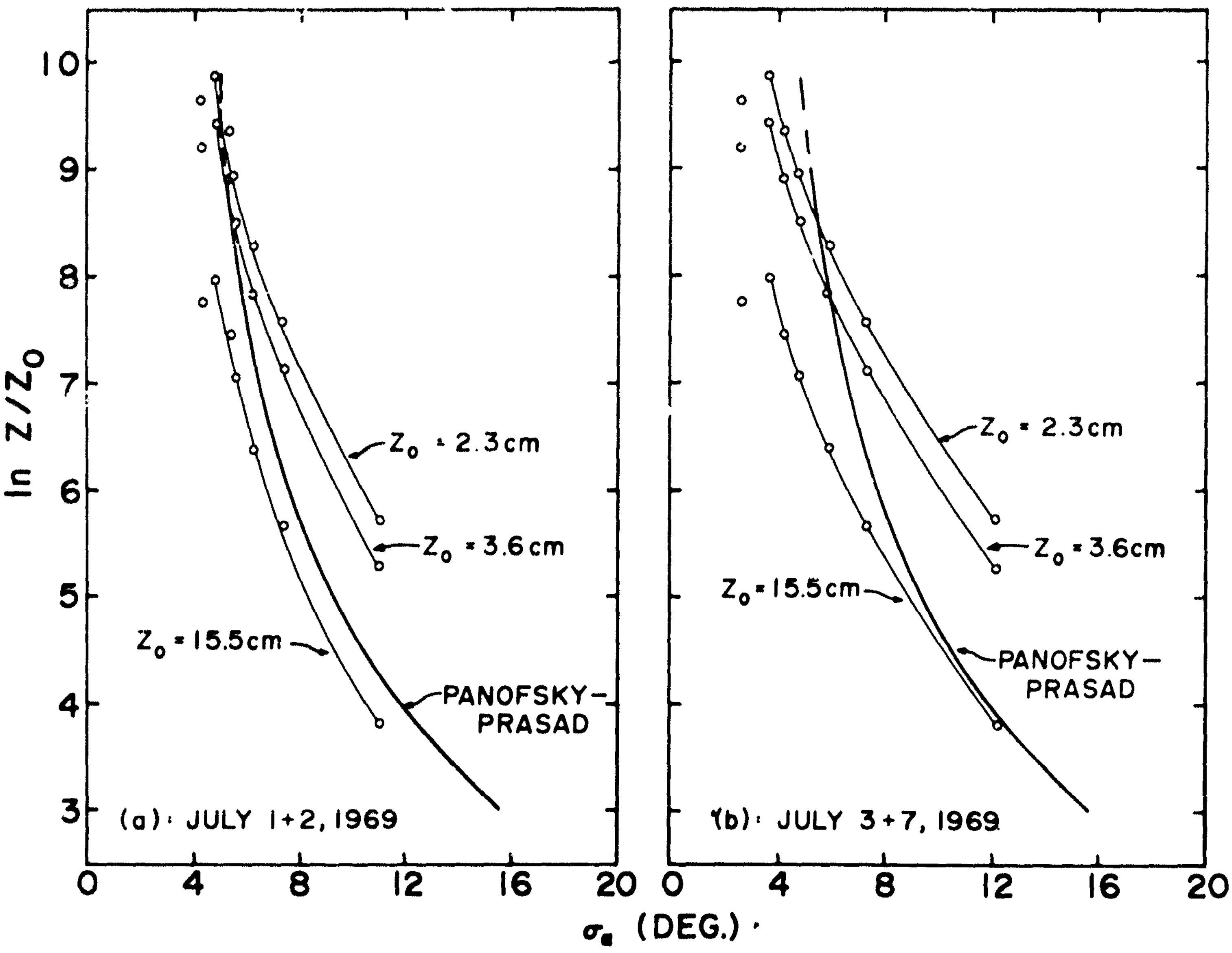


Figure 11. Plot of standard deviation of horizontal wind direction, $\sigma_\alpha$ , vs. $\ln(z/z_0)$ for alternate estimates of $z_0$. Heavy solid curve was interpolated from Panofsky and Prasad for neutral stability. (a) 60-min average profiles for July 1 and 2, 1969. (b) 60-min average profiles for July 3 and 7, 1969.

We found that none of the three estimates of $z_0$ gave a very close fit to the theoretical curve, and it appeared that a $z_0$ of 7 to 10 cm would give the best fit. When $z_0$ = 8.5 cm is used, the actual curves intersect the theoretical curve at approximately z = 40 m and appear to give a reasonable fit as shown in figure 12.

The wind direction for the eight 15-minute samples for July 1-7 varied between 177° and 188°, while the mean directions for July 1 and 2, and for July 3 and 7 were 181.5° and 183.3°, respectively. Smoothed values of $z_0$ (fig. 10) show an abrupt change from 10.1 cm (170° to 180°) to 4.3 cm (180° to 190°). It is conceivable, considering the range of direction of fluctuations (approximately 70° at 7.0 m and 45° at 44.5 m), that the resultant $\sigma_\alpha$ is more representative of the rougher surface. (When wind directions fluctuate across a zone of abrupt change of $z_o$, the range of direction, $R_\alpha$, resulting from the rougher surface would exceed that from the smoother surface and determine the magnitude of $R_\alpha$ from which $\sigma_\alpha$ was estimated. This may cast doubt on the validity of the assumption $\sigma_\alpha = R_\alpha/6$ for such a situation, and may very well account for our estimates of $\sigma_\alpha$ for July 1-7 data being too large as compared with the Panofsky-Prasad curve.)

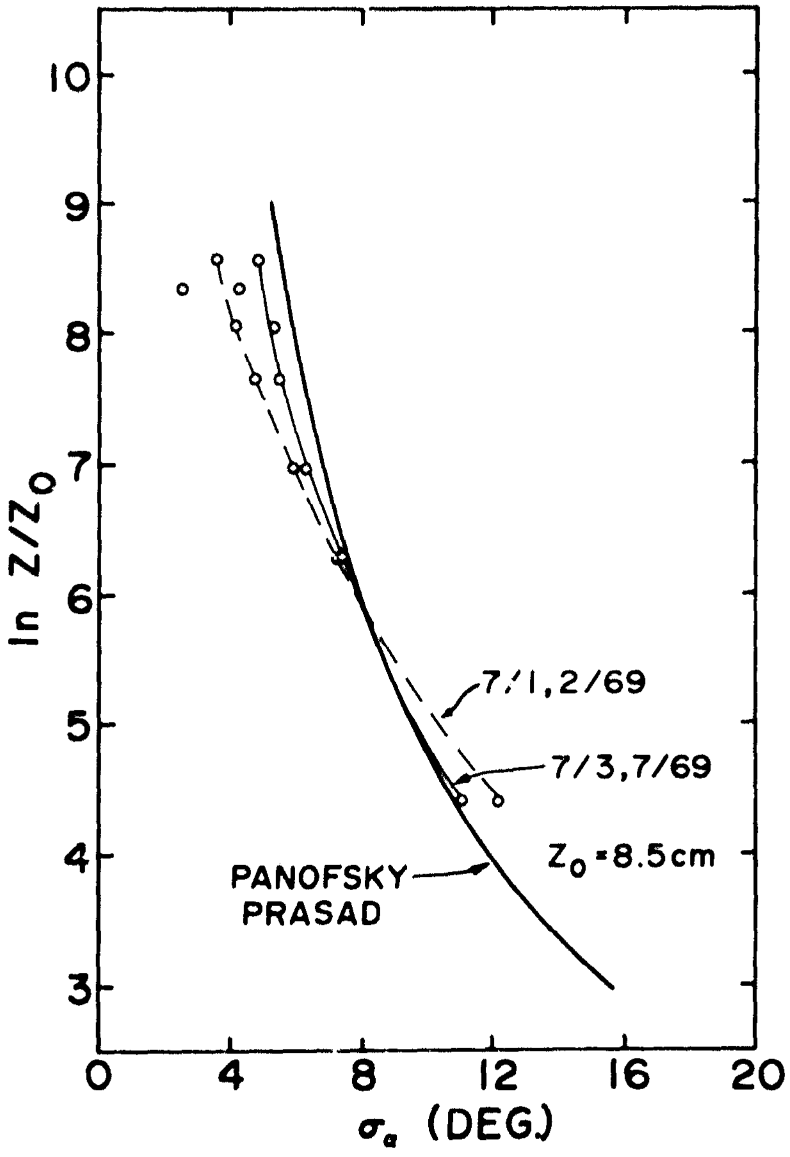


Figure 12. Same as figure 11 for $z_o$ = 8.5 cm.

## 5. ESTIMATION OF $z_o$ FROM FRICTION VELOCITY

An independent method for evaluating $z_o$ made use of measurements with a Gill UVW anemometer to estimate the surface friction velocity, $u_*$, and to compute $z_o$ from the equation $\ln z_o = \ln z - k\bar{u}/u_*$, where $\bar{u}$ was derived from Aerovane records. The Gill anemometer was mounted 7.0 m above ground adjacent to the surface Aerovane. The vertical velocity, w, was tape recorded during four 30-minute periods of neutral stability on July 1, 2, 3 and 7, 1969. Recorded data were processed on an analog computer to determine the standard deviation, $\sigma_w$, and estimates of $u_*$ were derived from the expression $u_* = \sigma_w/1.3$ as given by Busch and Panofsky (1968).

Resultant values of $z_o$ derived for the 7.0, 44.5, and 90.2 m levels, with $u_*$ assumed constant throughout this layer, are presented in table 7. Mean values of $z_o$ of 3.7, 8.1, 2.1, and 3.9 cm for the four respective days compare with estimates of 2.8, 4.8, 3.3, and 3.4 cm, respectively, obtained by extrapolation of the regression line fitting these three levels of the velocity profile. The agreement between the two independent results appears quite good and supports the validity of the results obtained by profile extrapolation.

Table 7. Roughness Length Estimates, $z_o$, Derived from Friction Velocity, $u_*$

| Date | July 1 | July 2 | July 3 | July 7 |
|---|---|---|---|---|
| $u_*$(m/s) | 0.304 | 0.376 | 0.452 | 0.543 |
| $\theta_o$* | 182.5° | 180.5° | 184.5° | 182° |
| **z(m)** | **$z_o$(m)** | **$z_o$(m)** | **$z_o$(m)** | **$z_o$(m)** |
| 7.0 | 0.034 | 0.069 | 0.024 | 0.034 |
| 44.5 | .042 | .092 | .020 | .047 |
| 90.2 | .036 | .082 | .020 | .035 |
| Mean | 0.037 | 0.081 | 0.021 | 0.039 |

* $\theta_o$ = 30-min. average wind direction at 7.0 m.

## 6. SUMMARY AND CONCLUSIONS

Estimates of the roughness length, $z_o$, derived from 15- to 25-minute average wind velocity profiles during times of neutral stability and averaged over 10° azimuth sectors range from less than 1 to 14 cm (fig. 10). The sector 140° to 180° in which 37.5 percent of the cases fall, has mean values of $z_o$ from 10 to 14 cm, corresponding to the sparse growth of trees and brush in this sector. In several of the other azimuth sectors, representing the smoother grass-covered surface, the sample is too small to give a high degree of confidence to the mean values; however, typical mean values of about 2 to 6 cm are close to values for similar surface conditions in tables 2 and 3.

The results pertain only to wind velocity profiles obtained during April, May, June and July. Seasonal variation of $z_o$ should be expected as a result of changes in height and character of surface vegetation. The displacement of the surface wind sensor from the tall tower causes ambiguity regarding the effective height to which wind observations pertain and sometimes results in simultaneous records of wind at the surface and tall towers which reflect traversal of dissimilar surface roughness characteristics.

One of the more serious limitations of the method used to estimate $z_o$ is the assumption of steady state conditions with no vertical heat flux. The occurrence of neutral stability shortly before sunset or after sunrise is transitory in most instances and perhaps of insufficient duration to permit steady state conditions to be attained.

The usefulness of this instrumental facility for boundary layer analyses could be enhanced by installation of a wind sensor near the surface on the tall tower, and by the addition of a wind sensor at or near the geometric mean height between the surface and 44.5-m levels. This would eliminate ambiguities and make it possible to better define the critical lower portion of the wind profile.

Further studies might consider evaluation of the zero point displacement parameter and seasonal variations of roughness length with changes in vegetation.

## 7. ACKNOWLEDGEMENTS

The authors are indebted to Dr. Y. Sasaki, Department of Meteorology, University of Oklahoma, for the use of the Gill UVW anemometer. Mr. John Carter and Mr. Leonard Johnson of NSSL, provided technical assistance with the installation, calibration, and operation of the instrumental system. Dr. Gene Walker, NSSL, assisted several aspects of the program, particularly the calibration of recording equipment. Dr. David Todd, School of Electrical Engineering, University of Oklahoma, designed the analog computer programs and assisted with processing the data from the Gill UVW anemometer on the OU analog computer.

We are also grateful to Dr. Steven R. Hanna for his suggestions regarding roughness length evaluation, and the engineers of WKY Television System, Inc., have our special thanks for their outstanding cooperation and interest.

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