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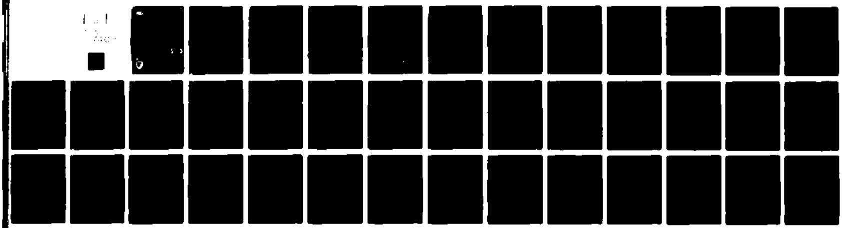

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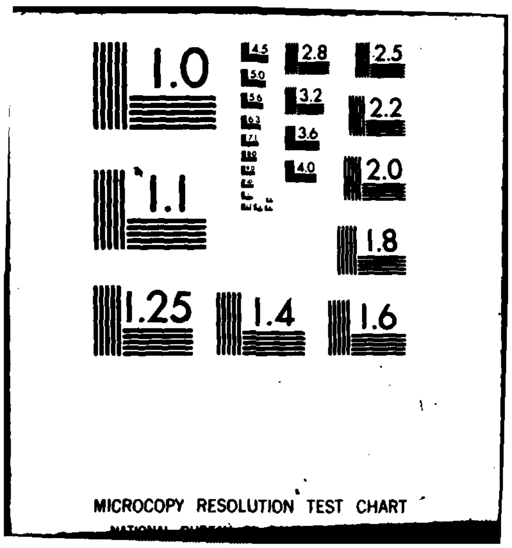

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THE ROUGHNESS LENGTHS ASSOCIATED WITH REGIONS OF HETEROGENEOUS VEGETATION AND ELEVATION

MAY 1982

By

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Under Contract DAAD07-80-D-0206

CONTRACT MONITOR: John T. Marrs

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US Army Electronics Research and Development Command
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Algorithms for calculating seasonal roughness lengths from digitized descriptions of surface vegetation and man-made objects are described. The "monthly characteristic vegetation roughness" for a one square kilometer plat is a log average of 100 roughness lengths, which correspond to the vegetation codes. Seasonal histograms for each square kilometer were also computed. The concept of a roughness length due to changes in elevation is used to derive an algorithm for its calculation. Both algorithms were used to compute roughness

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20. ABSTRACT (cont)

lengths for two regions of Central Europe. Region A contained 12,000 square kilometers of elevation and vegetation data at 100 meter intervals. Both types of roughness length were calculated for this region. Region B contained nearly 400,000 square kilometers of elevation data at a 63.5 meter interval. Region B includes region A. In region B only roughness lengths due to elevation change were calculated. The calculated vegetation and elevation roughness lengths in region A were compared. The elevation roughness lengths are generally greater than those due to vegetation in hilly country. The elevation roughness lengths of region A and region B were also compared. It is concluded that the elevation roughness algorithms are sensitive to the horizontal interval between data points.

PREFACE

This report was prepared by the University of Dayton Research Institute (UDRI) for the US Army Atmospheric Sciences Laboratory (ASL) during the period 1 October 1980 to 31 March 1981. The report describes calculations made of the aerodynamic surface roughness for a region of Central Europe. The assumptions, techniques, and mathematical algorithms used for this task are presented. Two sample calculations for a 1 km area are given.

The contract technical officer for this work was John T. Marrs of ASL. Work was performed at UDRI under the administrative supervision of Nicholas A. Engler. The technical supervisor was James K. Luers. Computer programming and data processing were done by Nancy J. Fratini, Jerry G. Jensen, Steven G. Vondrell, and Zalfa A. Abdelnour. Pamela S. Ecker edited the report and Gretchen Walther prepared the typescript. The authors wish to acknowledge the very substantial contributions of all of those mentioned above to the performance of this project.

This particular work effort was suggested by Frank V. Hansen who also supplied useful ideas on the proper approach to the problem.

CONTENTS

INTRODUCTION

The transport and diffusion of smoke and other contaminants in the atmospheric boundary layer depends in a large part upon the aerodynamic roughness of the surface. Surface roughness arises from the small scale protrusions (roughness elements) which penetrate the lowest portions of the boundary layer to exert a strong influence on the mean wind profile and the level of turbulence. Common meteorological practice [1,2] is to prescribe the roughness from the vegetation (forests, grasslands, agriculture, etc.), the man-made objects (buildings, cities), or the other surface characteristics (mud flats, sea surface, etc.) that best characterize the area under consideration. The quantitative measure of roughness is the roughness length, z_0, which is proportional to, if not a direct measure of, the vertical dimension of the individual roughness elements. Each type of surface may be assigned a value of roughness length--the values obtained primarily from field experiments. Typical values range from $z_0 \sim 10^{-5}$m for mud flats or ice to $z_0 \sim 10$m for the tall buildings in a central city.

Field studies show that a single value for roughness length prescribed in this way works well in describing the mean wind and turbulence when the terrain is reasonably flat on the large scale and of a homogeneous character. However, most practical situations involve "complex terrain" where the elevation of the land may vary considerably over relatively short distances and the surface morphology may be a complicated mixture of roughness elements that does not fall into any of the usual tidy classifications.

Transport, diffusion, and the general structure of the boundary layer in regions of complex terrain is the object of much current research. Some

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[1] Pasquill, F., Atmospheric Diffusion, (2nd Edition), Ellis Horwood Ltd., 1974.

[2] Hansen, F.V., "Engineering Estimates for the Calculation of Atmospheric Dispersion Coefficients," ASL Internal Report, U.S. Army Atmospheric Sciences Laboratory, White Sands Army Missile Range, New Mexico, September 1979.

investigators [3,4] have suggested that the general elevation changes over the scale of several kilometers or more may contribute to, or even control, the effective surface roughness in some cases. This suggests the possibility that roughness lengths can be computed from (sufficiently detailed) elevation data alone in very hilly or mountainous terrain.

This report describes two methods of computing an estimate of the surface roughness from detailed terrain descriptions of the kind that may be obtained from topographic maps. The first and more traditional method, which we call the Surface Morphology Roughness (SMR) estimation, uses descriptions of vegetation and other surface features to obtain roughness lengths without reference to the elevation field. Since seasonally changing plant growth is often the major surface feature, the SMR method includes the changes in z_0 by month of the year. The second method, Terrain Derived Roughness (TDR) estimation, uses just the elevation data--assumed to be available on a square grid--to compute a roughness length based upon changes in the surface elevation. Examples of each computation are given and a brief comparison of the two methods is included.

---

[3] Thompson, R. S., "Note on the Aerodynamic Roughness Length for Complex Terrain," J. Appl. Meteor., Vol 17, 1402-1403, (1978).

[4] Lettau, H., "Note on Aerodynamic Roughness-Parameter Estimation on the Basis of Roughness-Element Description," J. Appl. Meteor., Vol. 8, 828-832, (1969).

STATEMENT OF THE PROBLEM

The specific problem addressed here is the computation of roughness lengths for a large section of Central Europe. Two sets of data describing the region were available. The first and smaller set consisted of elevation and vegetation data supplied on a 100 meter square grid covering an area of 97 by 125 kilometers. For brevity we call this area region A. The second data set consisted of only elevation data but covered a much larger area, about 400,000 km^2. We call this region B. Data specification in region B is also on a square grid but with a spacing of 63.5 meters between points.

For region A, roughness lengths were calculated separately from the vegetation data (SMR) and from the elevation data (TDR) for each one square kilometer region or "plat". About 12,000 square kilometers were available with both elevation and vegetation data. In region B, which includes the smaller region A, the TDR was computed for each square kilometer. Additional elevation statistics were compiled for each plat in both regions A and B, including the average elevation, the standard deviation of the set of elevations in the plat, and the maximum and minimum elevations in the plat.

The grid size of one kilometer is the approximate horizontal scale for boundary layer adjustment to changes in surface roughness to occur. Smaller "patches" of distributed roughness do not completely alter the nature of the boundary layer as does a larger area of distributed roughness with a dimension of one kilometer or greater.

All results for both regions were given for each plat as identified in the Universal Transverse Mercator (UTM) system of coordinates. For region A this format presented little difficulty since the input data was supplied in the same coordinates. Region B presented more of a problem. This area was divided into 28 separate sections. The boundaries of each section are constant latitude and longitude lines, which are not coincident with lines of constant UTM coordinates. However, the elevation data points are arranged along UTM coordinate lines. In addition, the horizontal distance between adjoining elevation points, 63.5 m, does not evenly divide into 1000m (1 km). Because of this arrangement, some square kilometer plats lying on a sectional boundary may not have a full set of elevation heights. In some cases only a few data points were available; nevertheless, the TDR and elevation statistics were calculated for all square kilometers with at least three good data points. The number of plats with fewer than normal number of data points was less than one percent of the total number of plats.

Because of the horizontal distance between elevation points, 63.5 m, square kilometers are intersected by either 15 or 16 North-South lines of data and by either 15 or 16 East-West lines of data. Thus some square kilometers have 225 points, some 240 points, while most have 256 points. The number of data points used for calculating the parameters of each 1 square kilometer was always reported for each plat.

The concept of a terrain derived roughness is discussed in a following section. Although a variety of vegetation based roughness measurements have been made, there is no complete set of roughness lengths that corresponds to many commonly encountered types of vegetation. It is sometimes possible to categorize a specific vegetation form or type for which no roughness measurements have been made by using a combination of similar vegetation forms or types for which roughness measurements have been made. This procedure is described in the following section.

SURFACE MORPHOLOGY

The smaller area data base, region A, has 31 codes to indicate the vegetation type representative of each grid point. The roughness lengths associated with each .egetation code were obtained, as far as possible, from published data and assembled in a table of roughness lengths by vegetation code. Published values of the roughness length of vegetation that matched a particular vegetation code were used; many of the values are listed in the ESDU compilation [5]. Several vegetation codes had no corresponding published value for roughness length. In those cases the appropriate roughness length was estimated by combining roughnesses from similar vegetation and taking an average.

Agricultural crops were listed with a roughness length of 4.5×10^{-2} m. This was taken to represent the summer value. For a snow covered surface in the winter the value was 2×10^{-3} m. In the event that the surface was not snow covered (based on climatology) then the roughness was 7.5×10^{-3} m. Uncut grass, $z_0 = 2\times10^{-2}$ m, was selected as representative of grassland, pasture, and meadows. In the winter with snow cover the z_0 was 2×10^{-3} m and without snow cover it was 7.5×10^{-3} m.

Six estimates from the literature of roughness length for coniferous forest were averaged to arrive at 1.1 m. Deciduous forest was estimated at 1 m for the summer. The ratio of summer to winter roughnesses of "few trees" (5.5 to 1) was used to estimate the winter roughness length of a deciduous forest as 0.18 m. Mixed forest was assumed to be 50 percent deciduous and 50 percent coniferous and their values were averaged by season. Forest clearings and cutover areas were assumed to be 50 percent mixed forest and 50 percent isolated trees. The seasonal values are simply the average of the two.

Orchards were considered to be the average of "few trees" and "many trees" or 1.3×10^{-1} m in summer and 1.4×10^{-2} m in the winter. The value for "many hedges" was used to estimate the roughness length for vineyards and hop-gardens. Brushland and scrubgrowth (dense) were considered to be the

[5] ESDU 7206, 1972, "Characteristics of Wind Speed in the Lowest Layers of the Atmosphere near the Ground: Strong Winds," Eng. Sci. Data Unit, Ltd., 251 Regent St., London, WIR7AD.

een "many trees and hedges" and "many hedges" or 1.4×10^{-1} m in 1/5.5) of this value in winter (2.5×10^{-2} m). "Open brushland" was e 50 percent brush and 50 percent grass. The resulting seasonal average of the two. "Wetlands" consisted of an average of a "few arge expanses of water or ice. Values for the description "nearly closely spaced low growing vegetation" (9.5×10^{-3} m) were estimated between "grassland/pasture/meadows" and "widely spaced low growing . "Abandoned agriculture" was assumed in summer to be long grass and in winter to be cut grass (7.5×10^{-3} m). "Peat cuttings" were e the same as "grass/pasture" (2×10^{-2} m). Default values for "no set to 10^{-2} m. The roughness table summarizes lengths by vegeta- r each month (Table 1). In transitional seasons (April-June and e values were linearly interpolated between respectively March and or October and December values. This procedure was used for all lants and trees.

egion A, an average snow cover was not expected, because the region ry mean tempeature of 0°C or above [6], which does not permit snow y long on the ground.

al values were derived from the vegetation code data. We calcu- nthly characteristic vegetation roughnesses for each square The procedure was to first use the vegetation roughness lengths to z_0 to each of the 100 points (region A) and then find the average $\ell n\ z_0$'s, called L_{AV}. The "monthly characteristic vegetation $\bar{z}_0$, was then computed as

$$\bar{z}_0 = \exp(L_{AV}) \quad .$$

se of the log average was based on the recommendation by Kung [7] an average z_0 for a region of mixed roughness elements.

ological Office, "Tables of Temperature, Relative Humidity, itation and Sunshine for the World," Part III, Europe and the , London, Her Majesty's Stationary Office.

E. C., 1963, "Climatology of Aerodynamic Roughness Parameters and Dissipation in the Planetary Boundary Layer of the Northern here, Annual Report, Dept. of Meteorology, University of Wisconsin, 039-AMC-000878, 37-96.

TABLE 1

ROUGHNESS LENGTHS, $\bar{z}_0$
(meters)

JAN	FEB	MAR	APR	MAY	JUNE
7.5×10^{-3}	7.5×10^{-3}	7.5×10^{-3}	7.5×10^{-3}	2.0×10^{-2}	3.25×10^{-2}
7.5×10^{-3}	7.5×10^{-3}	7.5×10^{-3}	7.5×10^{-3}	1.15×10^{-2}	1.6×10^{-2}
1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-3}	2.5×10^{-2}	4.0×10^{-2}
1.1	-	-	-	-	-
0.18	0.18	0.18	0.18	0.45	0.72
0.64	0.64	0.64	0.64	0.78	0.91
0.32	0.32	0.32	.32	0.40	0.48
2.4×10^{-2}	2.4×10^{-2}	2.4×10^{-2}	2.4×10^{-2}	5.8×10^{-2}	9.5×10^{-2}
1.45×10^{-2}	1.45×10^{-2}	1.45×10^{-2}	1.45×10^{-2}	3.6×10^{-2}	5.8×10^{-2}
2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	6.3×10^{-2}	10.2×10^{-2}
1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	4.0×10^{-2}	6.4×10^{-2}
0.5×10^{-2}	0.5×10^{-2}	0.5×10^{-2}	0.5×10^{-2}	1.25×10^{-2}	2.00×10^{-2}
2.0×10^{-2}	-	-	-	-	-
1.8×10^{-4}	1.8×10^{-4}	1.8×10^{-4}	1.8×10^{-4}	4.5×10^{-4}	7.2×10^{-4}
1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	4.3×10^{-3}	6.9×10^{-3}
7.5×10^{-3}	7.5×10^{-3}	7.5×10^{-3}	7.5×10^{-3}	2.15×10^{-2}	3.6×10^{-2}
5.0×10^{-4}	-	-	-	-	-
4.0×10^{-1}	-	-	-	-	-
5.0×10^{-4}	-	-	-	-	-
4.0×10^{-1}	-	-	-	-	-
5.5×10^{-1}	-	-	-	-	-
8.5×10^{-1}	-	-	-	-	-
10^{-2}	-	-	-	-	-

TABLE 1 (Continued)

ROUGHNESS LENGTHS, $\bar{z}_0$
(meters)

Vegetation Code	JUL	AUG	SEP	OCT	NOV	DEC
1	4.5×10^{-2}	4.5×10^{-2}	4.5×10^{-2}	4.5×10^{-2}	2.6×10^{-2}	7.5×10^{-3}
2	2.0×10^{-2}	2.0×10^{-2}	2.0×10^{-2}	2.0×10^{-2}	1.4×10^{-2}	7.5×10^{-3}
3	5.5×10^{-2}	5.5×10^{-2}	5.5×10^{-2}	5.5×10^{-2}	3.25×10^{-2}	1.0×10^{-2}
4	1.1	-	-	-	-	-
5	1.0	1.0	1.0	1.0	0.59	0.18
6	1.05	1.05	1.05	1.05	0.85	0.64
7	0.55	0.55	0.55	0.55	0.44	0.32
8	1.3×10^{-1}	1.3×10^{-1}	1.3×10^{-1}	1.3×10^{-1}	8.7×10^{-2}	2.4×10^{-2}
9	8.0×10^{-2}	8.0×10^{-2}	8.0×10^{-2}	8.0×10^{-2}	4.8×10^{-2}	1.45×10^{-2}
10	1.4×10^{-1}	1.4×10^{-1}	1.4×10^{-1}	1.4×10^{-1}	8.2×10^{-2}	2.5×10^{-2}
11	8.0×10^{-2}	8.0×10^{-2}	8.0×10^{-2}	8.0×10^{-2}	4.8×10^{-2}	1.6×10^{-2}
12	2.75×10^{-2}	2.75×10^{-2}	2.75×10^{-2}	2.75×10^{-2}	1.6×10^{-2}	0.5×10^{-2}
13	2.0×10^{-2}	-	-	-	-	-
14	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	5.9×10^{-4}	1.8×10^{-4}
15	9.5×10^{-3}	9.5×10^{-3}	9.5×10^{-3}	9.5×10^{-3}	5.6×10^{-3}	1.7×10^{-3}
16	5.00×10^{-2}	5.00×10^{-2}	5.00×10^{-2}	5.00×10^{-2}	2.9×10^{-2}	7.5×10^{-3}
17	5.0×10^{-4}	-	-	-	-	-
27	4.0×10^{-1}	-	-	-	-	-
28	5.0×10^{-4}	-	-	-	-	-
29	4.0×10^{-1}	-	-	-	-	-
30	5.5×10^{-1}	-	-	-	-	-
31	8.5×10^{-1}	-	-	-	-	-
0	10^{-2}	-	-	-	-	-

Seasonal roughness histograms for each square kilometer were also generated for seasons defined as: Winter--December, January, February; Spring--March, April, May; Summer--June, July, August; and Fall--September, October, November. The range of z_0 values, which comprise six orders of magnitude, were divided into 12 bands. For each season the total number of data points whose vegetation code represented a roughness length within each of the twelve roughness length bands was determined. A histogram was then generated of roughness length band versus number of occurrences at data points within the one square kilometer for a three month period. The 12 bands for each histogram are listed in Table 2, and Table 3 links the vegetation code numbers with vegetation description.

As an example, the January and July vegetation roughness calculations for a typical square kilometer are given below. The vegetation codes for this square kilometer appear below just as they do on the data tape.

2	2	2	2	2	2	2	2	2	11
2	2	2	2	2	2	2	11	11	11
2	2	2	2	2	2	11	11	11	11
2	2	2	11	11	11	11	11	11	11
2	11	11	11	11	11	11	11	11	11
2	11	11	11	11	11	11	11	11	11
2	2	11	11	11	11	11	11	11	11
2	2	11	11	11	11	11	11	11	11
2	11	11	11	11	11	11	11	11	11
2	2	2	2	11	11	11	11	11	11

The vegetation consists of grassland (code 2) for which $z_0 = 7.5\times10^{-3}$ m in winter and $z_0 = 2\times10^{-2}$ m in summer and open brushland (code 11) for which $z_0 = 1.6\times10^{-2}$ m in winter and $z_0 = 8.0\times10^{-2}$ m in summer. Following the procedures described perviously, $\ell n\ z_0$'s are assigned to each of the 100 points. There are 36 code 2 points ($\ell n\ z_0 = -4.89$ winter, $\ell n\ z_0 = -3.91$ summer) and 64 code 11 points ($\ell n\ z_0 = -4.13$ winter, $\ell n\ z_0 = -2.53$ summer). Collectively the average $\ell n\ z_0$ is derived for both January and July by adding the 100 separate $\ell n\ z_0$ and dividing by 100.

The "monthly characteristic vegetation roughness", $\bar{z}_0$, is then determined to be .01218 m in January and .04857 m in July.

TABLE 2

VEGETATION ROUGHNESS BANDS

Band	Min z_o	Max z_o	Min ($\ell n\ z_o$)	Max $\ell n\ z_o$)	Typical Features
1	10^{-5}m	5×10^{-5}m	-11.5	-9.90	Ice, Mud Flats
2	5×10^{-5}m	10^{-4}m	- 9.90	-9.21	
3	10^{-4}m	5×10^{-4}m	- 9.21	-7.60	Calm Sea
4	5×10^{-4}m	10^{-3}m	- 7.60	-6.91	
5	10^{-3}m	5×10^{-3}m	- 6.91	-5.30	Snow Surface
6	5×10^{-3}m	10^{-2}m	- 5.30	-4.61	
7	10^{-2}m	5×10^{-2}m	- 4.61	-3.00	
8	5×10^{-2}m	10^{-1}m	- 3.00	-2.30	Grass Crops
9	10^{-1}m	5×10^{-1}m	- 2.30	-0.693	Crops
10	5×10^{-1}m	1 m	- 0.693	0	Forest
11	1 m	5 m	0	1.61	
12	5 m	10 m	1.61	2.30	

TABLE 3

VEGETATION DESCRIPTION BY CODE

Description	Code
No data	0
Agriculture, cropland	1
Grassland, pasture, meadows	2
Grassland, scattered trees	3
Coniferous forest	4
Deciduous forest	5
Mixed forest	6
Forest clearings, cutover areas	7
Orchards	8
Vineyards, hop-gardens	9
Brushland, scrub growth (dense)	10
Brushland, scrub growth (open)	11
Wetlands	12
Peat cuttings	13
Nearly barren w/widely spaced low growing vegetation	14
Nearly barren w/closely spaced low growing vegetation	15
Abandoned agriculture	16
Bare ground, sand dunes	17
Undefined	18
Undefined	19
Undefined	20
Undefined	21
Undefined	22
Undefined	23
Undefined	24
Undefined	25
Undefined	26
Surface mines	27
Open water	28
Villages	29
Towns	30
Cities	31

TERRAIN DERIVED ROUGHNESS

The computation of roughness lengths from elevation data is based upon a formula given by Lettau [4] for estimating the roughness for distributions of more-or-less identical elements. The relationship is

(1) $$z_o = 0.5h\ S/A$$

where

h is the average vertical extent (height) of an element (m),

S is the average projected area of an element perpendicular to the wind (m^2), and

A is the average horizontal ("lot") area (m^2) occupied by an element.

As Lettau points out, equation (1) incorporates not only the height of the elements but also a measure of their presented area and their spacing density. This formula should then be preferred over the exponential relationships (e.g. $z_o = ah^b$) given by Kung [7] and others which involve only the element height.

In our adaptation of Lettau's formula the elevation data is first processed to obtain estimates of h, S, and A over a specified area. The data is supplied as elevations in meters above sea level given on a square grid. The spacing between grid points is ℓ meters and the lines formed by the rows of points run generally North-South and East-West. Calculations to compute a z_o are performed on each row (South to North traverse) and then on each column (West to East traverse) of the elevation data. The 20 to 32 values (the exact number depends on the grid interval) are averaged to produce the "typical" z_o for the square kilometer. This cross pattern is adopted in order to produce an average estimate that is independent, as much as possible, of wind direction. The expressions below which apply to a single traverse are not dependent upon which direction, e.g. South to North or North to South, the traverse is made.

To estimate h we first compute the number of "peaks and valleys", N, encountered in a traverse. The first elevation in a traverse is considered a peak if the second elevation is lower and a valley if the second is higher. For the second, third, fourth, etc. points in a traverse, a peak is counted when both the preceding and following points around a given point are lower in elevation. A valley is counted when both neighboring points are higher. In any other situation no increase is made in N. The final point in a traverse is treated in the same way as the first point, it is a peak if it is higher than the next to last point and a valley if it is lower. As the value of N is computed for each traverse a running sum of the total vertical excursion, E, is kept. E is the total upward and downward distance in meters covered in moving along the row of elevation points. The estimate of h is then computed as

$$(2) \qquad h = \frac{E}{2(N-1)} \quad .$$

When N is one or zero we have a flat traverse and a default value of 1×10^{-2}m is set for z_0, the remaining computations for the traverse being ignored.

For the average projected area of the terrain "bumps" we multiply E/2 by the width of the grid spacing, ℓ, and divide by N-1.

$$(3) \qquad S = \frac{E}{2} \cdot \frac{\ell}{(N-1)}$$

We are thus assuming the bumps to be two-dimensional "washboard". The lot area per bump is the traverse horizontal area divided by (N-1), or

$$(4) \qquad A = (\ell \cdot 1\text{km})/(N-1)$$

Combining the three numbers in Lettau's formula, eq (1), we obtain the TDR for the traverse in meters

$$(5) \qquad z_0 = E^2/[8000(N-1)] \ .$$

For a square kilometer the reported TDR is the average z_0 for the M (20 to 32) traverses,
or

$$(6) \qquad z_0 = \frac{1}{M}\sum_{i=1}^{M} (z_0)_i \quad .$$

As a further indication of the roughness of the terrain we compute the average number of peaks and valleys, N, from the values for each traverse

(7) $$N = \frac{1}{M}\sum_{i=1}^{M} (N)_i \quad .$$

This value was included with each calculation of the TDR.

As an example of the above procedure consider the following 100 elevations from a typical one square kilometer plat:

160	153	147	146	151	141	139	140	139	150
151	148	142	140	145	139	136	138	143	150
140	140	136	134	135	135	139	142	143	149
134	134	133	134	135	141	142	149	156	165
133	135	135	138	150	161	152	167	180	183
138	138	140	150	177	180	170	181	184	184
149	143	148	154	180	181	184	184	184	180
155	150	155	159	171	178	183	184	181	169
160	162	163	168	168	175	182	184	180	162
160	166	171	175	178	180	185	182	169	158

In this case there are 20 traverses, 10 South-North and 10 East-West. If we number the traverses from the left for South-North and from the bottom for East-West, the values of N, E, and z_0 computed by equations (2) through (5) are

Traverse	N	E (meters)	z_0 (meters)
(S-N)			
1	2	54	.3645
2	3	51	.1626
3	3	52	.1690
4	2	53	.3511
5	4	83	.2870
6	5	65	.1320
7	5	56	.0980
8	3	48	.1440
9	2	60	.4500
10	3	62	.2403

(E-W)

1	3	52	.1690
2	3	46	.1323
3	4	61	.1550
4	3	51	.1626
5	2	66	.5445
6	4	68	.1927
7	2	33	.1361
8	2	21	.0551
9	5	39	.0475
10	7	42	.0268

Finally the characteristic roughness length for this plat is the mean of these 20 values

$$z_0 = .2015 \text{ meters},$$

and the average number of peaks and valleys is

$$N = 3.35 \quad .$$

The additional statistics for this plat are: mean elevation is 156.9 meters, the standard deviation is 17.53 meters, and the maximum and minimum elevations are 185 and 133 meters respectively.

DISCUSSION

Calculations of Surface Morphology Roughnesses (SMR) are consistent with expectation. Without regard to season or location, SMR lengths range predominately between .01 and 1 meters with few exceptions. They are greatest in summer months for cities and forest areas and least in winter months for grass covered plats.

Terrain derived roughnesses (TDR) are also consistent with expectations. They are greatest for hilly country and least for flat areas. Their range is from .01 meter to above 1 meter. It is interesting to compare the TDR's to the more traditional SMR's especially in hilly country. The TDR's are considerably larger. It is reasonable to expect that the vegetative roughness in hilly country is of secondary importance.

TDR's for region A with a granularity of 100 meters are generally larger than those calculated for identical square kilometer areas using region B data whose granularity is 63.5 m. In addition, the standard deviations of elevation height using 100 meter data is also larger than that calculated using 63.5 meter data. This comparison suggests that both the TDR and elevation standard deviation are sensitive to the interval between data points. Further study of this sensitivity to granularity is required.

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APPENDIX

COMPUTER PROGRAM LISTINGS

This appendix contains the FORTRAN listings of the computer programs used to compute the roughness lengths and other terrain data. Program VEGRUF was used for region A which contained both elevation and surface type data. Program TDRUFF was used for region B which contained only elevations. Both programs were developed and executed on a Digital Equipment Company VAX/11-780 computer using the VAX/VMS Version 2 operating system and VAX FORTRAN-IV PLUS.

```
      PROGRAM VEGRUF
C
C     VEGRUF COMPUTES VALUES OF SURFACE MORPHOLOGY
C     ROUGHNESS, TERRAIN DERIVED ROUGHNESS, AND TERRAIN
C     STATISTICS FOR ELEVATION AND SURFACE CHARACTERISTICS
C     DATA SUPPLIED ON A SQUARE GRID
C
C     VEGRUF WAS CREATED FOR THE US ARMY ATMOSPHERIC
C     SCIENCES LABORATORY BY THE UNIVERSITY OF DAYTON
C     RESEARCH INSTITUTE   31 MARCH 1981
C
C     NOTE: SOME PARTS OF THIS CODE MAY BE SPECIFIC TO
C     DEC VAX/VMS FORTRAN.
C
C     INPUT:
C
C     UNIT 1:  RAW DATA TAPE WITH DATA SPACED AT 100 METER
C               GRANULARITY
C              DATA IS TO BE SUPPLIED AS 97 KM LONG SCAN LINES
C               ONE LINE PER RECORD
C     UNIT 5:  USER IDENTIFICATION OF RUN
C       RECORD 1:
C         IUTMX=UTM X COORDINATE OF THE SOUTHWEST CORNER OF THE DATA AREA
C         IUTMY=UTM Y COORDINATE OF THE SOUTHWEST CORNER OF THE DATA AREA
C
C     OUTPUT:
C
C     UNIT 2:  ROUGHNESS DATA OUTPUT FOR EACH SQUARE KM.
C     UNIT 6:  ECHO OF USER IDENTIFICATION ABOVE
C
C
      COMMON/COLUMN/GRID(970,10,2),NPTINC,NRCINC,NPTKM,NRCKM,XNTOT
      COMMON/HOUT/HMEAN(97),HSIGMA(97),HMAX(97),HMIN(97),HZERO(97),
     1            HNPV(97)
      COMMON/RUFOUT/IVC(97),NU(97),ZHAT(12,97),IHISTO(12,4,97)
      DIMENSION MEAN(97),ISIGMA(97),IHMAX(97),IHMIN(97),IHZERO(97),
     1          IZHAT(12,97),IHNPV(97)
      INTEGER*2 GRID
      EQUIVALENCE (HMEAN,MEAN),(HSIGMA,ISIGMA),(HMAX,IHMAX),
     1            (HMIN,IHMIN),(HZERO,IHZERO),(ZHAT,IZHAT),
     2            (HNPV,IHNPV)
      IFILER=1
      NPTINC=1
      NRCINC=1
      NPTKM=10/NPTINC
      NRCKM=10/NRCINC
      XNTOT=FLOAT(NPTKM*NRCKM)
      OPEN(UNIT=2,BLOCKSIZE=20400,RECORDSIZE=20400,RECORDTYPE='FIXED
     1   CARRIAGECONTROL='NONE',STATUS='NEW')
C
C     READ IN UTM COORDINATES OF THE SOUTHWEST CORNER AND
C     ECHO ON OUTPUT.
C
      READ(5,10)IUTMX,IUTMY
   10 FORMAT(2I10)
      WRITE(6,20)IUTMX,IUTMY
   20 FORMAT(1H1,'SW UTM COORDINATES = (',I10,',',I10,')')
      WRITE(2,1100)(IUTMX,IUTMY,I=1,1020)
C
C     READ IN AND COMPUTE THE MEAN HEIGHT, AND ROUGHNESS HEIGHT FOR
C     EACH SQUARE KM OF 125 97KM COLUMNS.
```

```
      DO 1000 I=1,126
C
C     SUBR GETCOL ARRANGES THE SCAN LINES INTO A 1 KM WIDE (E-W) COLUMN
C     OF DATA 97 KM HIGH (N-S). DATA IS STORED IN ARRAY 'GRID'
C
      CALL GETCOL
      IF(I .LT. 120)GO TO 1000
C
C     SUBR HCOMP COMPUTES THE OUTPUT DATA OBTAINED FROM THE
C     ELEVATION DATA, I.E. THE TDR AND TERRAIN STATISTICS.
C
      CALL HCOMP
      WRITE(6,40)HMEAN,HSIGMA,HMAX,HMIN,HZERO,HNPV
      FORMAT(1X,10F11.4)
C
C     SUBR GETRUF COMPUTES THE OUTPUT DATA OBTAINED  FROM
C     THE SURFACE TYPE CODES, I.E. THE SMR
C
      CALL GETRUF
      WRITE(6,50)IVC,NU,ZHAT,IHISTO
      FORMAT(19(1X,10I10/),(1X,4I10/),97(12F11.4/),(1X,12I10/))
C
C     SCALE THE OUTPUT VARIABLE AND CONVERT TO INTEGER
C     THIS IS A SPACE SAVING PROCEDURE FOR THE OUTPUT TAPE
C
      DO 150 J=1,97
      MEAN(J)=IFIX(HMEAN(J)*10.+.5)
      ISIGMA(J)=IFIX(HSIGMA(J)*100.+.5)
      IHMAX(J)=IFIX(HMAX(J)+.1)
      IHMIN(J)=IFIX(HMIN(J)+.1)
      IHNPV(J)=IFIX(HNPV(J)*100.+.5)
      IHZERO(J)=IFIX(HZERO(J)*1.E6+.5)
      DO 140 K=1,12
      IZHAT(K,J)=IFIX(ZHAT(K,J)*1.E6+.5)
 140  CONTINUE
 150  CONTINUE
      NSTART=-29
      NEND=0
      DO 160 M=1,3
      NSTART=NSTART+30
      NEND=NEND+30
      WRITE(2,1100)((MEAN(J),ISIGMA(J),IHMAX(J),IHMIN(J),IHNPV(J),
     1              IHZERO(J),IVC(J),NU(J),(IZHAT(K,J),K=1,12),
     2              ((IHISTO(K,L,J),K=1,12),L=1,4)),J=NSTART,NEND)
 160  CONTINUE
      WRITE(2,1100)((MEAN(J),ISIGMA(J),IHMAX(J),IHMIN(J),IHNPV(J),
     1              IHZERO(J),IVC(J),NU(J),(IZHAT(K,J),K=1,12),
     2              ((IHISTO(K,L,J),K=1,12),L=1,4)),J=91,97),
     3              (IFILER,N=1,1564)
 1000 CONTINUE
 1100 FORMAT(2040I10)
      STOP
      END
```

```
      SUBROUTINE GETCOL
C
C     THIS SUROUTINE FILLS THE ARRAY GRID WITH THE HEIGHT AND
C     ROUGHNESS TYPE FOR EACH DESIRED DATA PT.  IN A COLUMN OF 97 SQUARE KMS
C
C     INPUT AND OUTPUT INCLUDED IN COMMON/COLUMN/
C
C     INPUT:
C       NPTINC=THE INCREMENT ADDED TO THE POINT COUNTER TO DETERMINE
C              WHICH POINTS WITHIN A RECORD WILL BE USED.
C       NRCINC=THE INCREMENT ADDED TO THE RECORD COUNTER TO DETERMINE
C              WHICH RECORDS WILL BE USED.
C       NPTKM =THE RESULTANT NUMBER OF POINTS TO BE EXTRACTED PER KM
C              FROM A RECORD.
C
C     OUTPUT:
C       GRID()=
C         THE FIRST SUBSCRIPT VARIES FROM 1 TO NPTKM*97 AND INDEXES
C            THE POINTS OF A 97 KM SPAN IN THE N-S DIRECTION.
C         THE SECOND SUBSCRIPT VARIES FROM 1 TO 10/NRCINC AND INDEXES
C            THE RECORDS WITHIN A KM SPAN IN THE E-W DIRECTION.
C         THE THIRD SUBSCRIPT DENOTES THE TYPE OF DATA STORED IN GRID.
C            1 IMPLIES ELEVATION IN METERS ABOVE MEAN SEA LEVEL.
C            2 IMPLIES SURFACE TYPE.
C
      COMMON/COLUMN/GRID(970,10,2),NPTINC,NRCINC,NPTKM,NRCKM,XNTOT
      INTEGER*2 IBUF(1942)
      BYTE BUFFER(3884)
      BYTE IELBYT(2),ISURBY(2)
      EQUIVALENCE(IBUF(1),BUFFER(1)),(IELBYT(1),IELEV),(ISURBY(1),ISURF)
      INTEGER*2 IELEV,ISURF,GRID
      PARAMETER IO$_READLBLK = '21'X
      PARAMETER EOF='870'X
      PARAMETER BUFSIZE=3884
      INTEGER*2 CHANNEL,IOSB(4)
      INTEGER*4 SYS$ASSIGN,SYS$QIOW
      LOGICAL L$ASSIGN
      DATA L$ASSIGN/.TRUE./,NRECS/0/,NXTREC/1/
      IF(L$ASSIGN)THEN
         L$ASSIGN=.FALSE.
         IRET=SYS$ASSIGN('FOR001',CHANNEL,,)
         IF(IRET.NE.1) THEN
            WRITE(6,5)IRET
    5       FORMAT(' SYS$ASSIGN ERROR',Z8)
            STOP
            ENDIF
         ENDIF
      J=0
      DO 100 I=1,10
C
C     READ INPUT RECORD. (THERE ARE 10 PER KM)
C
   10 IRET=SYS$QIOW(,%VAL(CHANNEL),%VAL(IO$_READLBLK),IOSB,,,
     1   %REF(BUFFER),%VAL(BUFSIZE),,,,)
      IF(IRET.NE.1)THEN
         WRITE(6,15)IRET
   15    FORMAT(' READ QIOW ERROR',Z8)
         STOP
         ENDIF
      IF(IOSB(1).EQ.EOF.OR.IOSB(2).EQ.0)THEN
         CLOSE(UNIT=1)
```

```
          WRITE(6,*)NRECS,  RECORDS READ
          STOP
          ENDIF
      NRECS=NRECS+1
      IF(NXTREC.NE.NRECS)GO TO 100
      NXTREC=NXTREC+NRCINC
      IF(NRECS .LE. 1190)GO TO 100
      J=J+1
      INDEX=0
C     LOOP OVER 97 KMS WITHIN RECORD
      DO 50 K=1,97
C     (10 PTS PER KM*4 BYTES PER PT)=40 BYTES PER KM
      DO 40 L=1,40,NPTINC*4
      NXTPNT=(K-1)*40+L
      IELBYT(2)=BUFFER(NXTPNT)
      IELBYT(1)=BUFFER(NXTPNT+1)
      ISURBY(2)=BUFFER(NXTPNT+2)
      ISURBY(1)=BUFFER(NXTPNT+3)
      INDEX=INDEX+1
      GRID(INDEX,J,1)=IELEV
      GRID(INDEX,J,2)=ISHFT(ISURF,-11)
   40 CONTINUE
   50 CONTINUE
  100 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE HCOMP
C
C     THIS SUBROUTINE COMPUTES THE OUTPUT VARIABLES DERIVED FROM THE
C     RAW ELEVATION DATA FOR EACH OF THE 97 SQUARE KMS CONTAINED IN
C     ARRAY GRID.
C
C     INPUT:
C
C     NPTKM=THE NUMBER OF POINTS IN THE N-S DIRECTION PER KM
C     NRCKM=THE NUMBER OF POINTS IN THE E-W DIRECTION PER KM
C     XNTOT=THE TOTAL NUMBER OF POINTS PER KM
C     GRID()=
C       THE FIRST SUBSCRIPT VARIES FROM 1 TO NPTKM*97 AND INDEXES
C          THE POINTS OF A 97 KM SPAN IN THE N-S DIRECTION.
C       THE SECOND SUBSCRIPT VARIES FROM 1 TO 10/NRCINC AND INDEXES
C          THE RECORDS WITHIN A KM SPAN IN THE E-W DIRECTION.
C       THE THIRD SUBSCRIPT DENOTES THE TYPE OF DATA STORED IN GRID.
C          1 IMPLIES ELEVATION IN METERS ABOVE MEAN SEA LEVEL.
C          2 IMPLIES SURFACE TYPE.  (NOT USED IN THIS SUBROUTINE)
C
C     OUTPUT:
C
C     N.B.  THE LAST SUBSCRIPT OF EACH OF THE OUTPUT ARRAYS VARIES
C        FROM 1 TO 97 WITH ONE VALUE FOR EACH OF THE 97 SQUARE KMS
C        FROM SOUTH TO NORTH RESPECTIVELY.
C
C     HMEAN(97)=THE MEAN ELEVATION (METERS)
C     HSIGMA(97)=THE ELEVATION STANDARD DEVIATION (METERS)
C     HMAX(97)=THE MAXIMUM ELEVATION (METERS)
C     HMIN(97)=THE MINIMUM ELEVATION (METERS)
C     HZERO(97)=THE TERRAIN ROUGHNESS PARAMETER (METERS)
C     HNPV(97)=THE AVERAGE NUMBER OF PEAKS AND VALLEYS/SQ.KM
C
      COMMON/COLUMN/GRID(970,10,2),NPTINC,NRCINC,NPTKM,NRCKM,XNTOT
      COMMON/HOUT/HMEAN(97),HSIGMA(97),HMAX(97),HMIN(97),HZERO(97),
     1            HNPV(97)
      INTEGER*2 GRID
      DIMENSION HTRAV(20)
      DO 1000 J=1,97
      HMEAN(J)=0.0
      HSIGMA(J)=0.0
      HZERO(J)=0.0
      NPVDIR=0
      HMAX(J)=FLOAT(GRID((J-1)*NPTKM+1,1,1))
      HMIN(J)=HMAX(J)
      DO 90 L=1,NRCKM
      DTOTAL=0.0
      NPNV=0
      HNEXT=FLOAT(GRID((J-1)*NPTKM+1,L,1))
      DO 80 K=1,NPTKM
      H=HNEXT
      HMEAN(J)=HMEAN(J)+H
      HSIGMA(J)=HSIGMA(J)+H**2
      IF(H.GT.HMAX(J))HMAX(J)=H
      IF(H.LT.HMIN(J)) HMIN(J)=H
      IF(K.EQ.1) THEN
           HNEXT=FLOAT(GRID((J-1)*NPTKM+K+1,L,1))
           DIFF=HNEXT-H
           IF(DIFF.NE.0.0)THEN
                NPNV=NPNV+1
                DTOTAL=DTOTAL+ABS(DIFF)
```

```
                        ENDIF
                  HPREV=H
            ELSE IF(K.LT.NPTKM) THEN
                  HNEXT=FLOAT(GRID((J-1)*NPTKM+K+1,L,1))
                  IF((H.GT.HPREV.AND.H.GT.HNEXT).OR.
     1               (H.LT.HPREV.AND.H.LT.HNEXT)) NPNV=NPNV+1
                  DIFF=HNEXT-H
                  DTOTAL=DTOTAL+ABS(DIFF)
                  HPREV=H
            ELSE
                  DIFF=H-HPREV
                  IF(DIFF.NE.0.0)NPNV=NPNV+1
            ENDIF
 80         CONTINUE
            IF(NPNV.EQ.0.OR.NPNV.EQ.1) THEN
                  HTRAV(L)=1.0E-2
            ELSE
                  HTRAV(L)=DTOTAL**2/((NPNV-1)*8000.)
            ENDIF
            NPVDIR=NPVDIR+NPNV
            IF(HTRAV(L).EQ.0.0)HTRAV(L)=1.0E-2
 90         CONTINUE
            HSIGMA(J)=SQRT((HSIGMA(J)-(HMEAN(J)**2/XNTOT))/(XNTOT-1.0))
            HMEAN(J)=HMEAN(J)/XNTOT
            DO 190 K=1,NPTKM
            DTOTAL=0.0
            NPNV=0
            HNEXT=FLOAT(GRID((J-1)*NPTKM+K,1,1))
            DO 180 L=1,NRCKM
            H=HNEXT
            IF(L.EQ.1) THEN
                  HNEXT=FLOAT(GRID((J-1)*NPTKM+K,L+1,1))
                  DIFF=HNEXT-H
                  IF(DIFF.NE.0.0)THEN
                        NPNV=NPNV+1
                        DTOTAL=DTOTAL+ABS(DIFF)
                        ENDIF
                  HPREV=H
            ELSE IF(L.LT.NRCKM) THEN
                  HNEXT=FLOAT(GRID((J-1)*NPTKM+K,L+1,1))
                  IF((H.GT.HPREV.AND.H.GT.HNEXT).OR.
     1               (H.LT.HPREV.AND.H.LT.HNEXT)) NPNV=NPNV+1
                  DIFF=HNEXT-H
                  DTOTAL=DTOTAL+ABS(DIFF)
                  HPREV=H
            ELSE
                  DIFF=H-HPREV
                  IF(DIFF.NE.0.0) NPNV=NPNV+1
            ENDIF
 180        CONTINUE
            IF(NPNV.EQ.0.OR.NPNV.EQ.1) THEN
                  HTRAV(NRCKM+K)=1.0E-2
            ELSE
                  HTRAV(NRCKM+K)=DTOTAL**2/((NPNV-1)*8000.)
            ENDIF
            NPVDIR=NPVDIR+NPNV
            IF(HTRAV(NRCKM+K).EQ.0.0)HTRAV(NRCKM+K)=1.0E-2
 190        CONTINUE
            DO 300 K=1,NRCKM+NPTKM
            HZERO(J)=HZERO(J)+HTRAV(K)
 300        CONTINUE
```

```
      HZERO(J)=HZERO(J)/(NRCKM+NPTKM)
      HNPV(J)=FLOAT(NPVDIR)/FLOAT(NRCKM+NPTKM)
1000  CONTINUE
      RETURN
      END
```

```
      SUBROUTINE GETRUF
C
C        THIS SUBROUTINE COMPUTES THE OUTPUT VARIABLES DERIVED FROM THE
C        SURFACE TYPE DATA FOR EACH OF THE 97 SQUARE KMS CONTAINED
C        IN ARRAY GRID.
C
C        INPUT:
C
C        NPTKM=THE NUMBER OF POINTS IN THE N-S DIRECTION PER KM
C        NRCKM=THE NUMBER OF POINTS IN THE E-W DIRECTION PER KM
C        GRID()=
C          THE FIRST SUBSCRIPT VARIES FROM 1 TO NPTKM*97 AND INDEXES
C             THE POINTS OF A 97 KM SPAN IN THE N-S DIRECTION.
C          THE SECOND SUBSCRIPT VARIES FROM 1 TO 10/NRCINC AND INDEXES
C             THE RECORDS WITHIN A KM SPAN IN THE E-W DIRECTION.
C          THE THIRD SUBSCRIPT DENOTES THE TYPE OF DATA STORED IN GRID.
C             1 IMPLIES ELEVATION IN METERS ABOVE MEAN SEA LEVEL.
C                         (NOT USED IN THIS SUBROUTINE)
C             2 IMPLIES SURFACE TYPE.
C
C        OUTPUT:
C
C        N.B.  THE LAST SUBSCRIPT OF EACH OF THE OUTPUT ARRAYS VARIES
C           FROM 1 TO 97 WITH ONE VALUE FOR EACH OF THE 97 SQUARE KMS
C           FROM SOUTH TO NORTH RESPECTIVELY.
C
C        IVC(97)=THE CHARACTERISTIC SURFACE TYPE.  (MOST COMMON)
C        NU(97)=THE NUMBER OF UNDEFINED SURVACE TYPE CODES.
C        ZHAT(12,97)=THE SET OF MONTHLY CHARACTERISTIC SURFACE
C                    ROUGHNESS VALUES. (ONE FOR EACH MONTH,
C                     JAN.-DEC.)
C        IHISTO(12,4,97)=HISTOGRAM VALUES
C           THE FIRST SUBSCRIPT VARIES FROM 1 TO 12 AND INDEXES THE
C              BAND FOR EACH HISTOGRAM.
C           THE SECOND SUBSCRIPT INDEXES THE SEASON OF THAT HISTOGRAM
C              1 IMPLIES WINTER (DJF)
C              2 IMPLIES SPRING (MAM)
C              3 IMPLIES SUMMER (JJA)
C              4 IMPLIES FALL   (SON)
C           THE THIRD SUBSCRIPT DENOTES WHICH SQUARE KM AS NOTED
C              ABOVE
      COMMON/COLUMN/GRID(970,10,2),NPTINC,NRCINC,NPTKM,NRCKM,XNTOT
      COMMON/RUFOUT/IVC(97),NU(97),ZHAT(12,97),IHISTO(12,4,97)
      INTEGER*2 GRID
      DIMENSION ICOUNT(32),ZZERO(12,32),XMEAN(12),NPT(12),BNDLMT(13)
      PARAMETER DUMMY=1.E-2
      DATA BNDLMT/10.E-5,5.E-5,1.E-4,5.E-4,1.E-3,5.E-3,1.E-2,5.E-2,
     1  1.E-1,5.E-1,1.0,5.0,10.0/
      DATA (ZZERO(I,1),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,2),I=1,12)/4*7.5E-3,2.0E-2,3.25E-2,4*4.5E-2,
     1                             2.6E-2,7.5E-3/
      DATA (ZZERO(I,3),I=1,12)/4*7.5E-3,1.15E-2,1.6E-2,4*2.0E-2,
     1                             1.4E-2,7.5E-3/
      DATA (ZZERO(I,4),I=1,12)/4*1.0E-2,2.5E-2,4.0E-2,4*5.5E-2,3.25E-2,
     1                             1.0E-2/
      DATA (ZZERO(I,5),I=1,12)/12*1.1/
      DATA (ZZERO(I,6),I=1,12)/4*.18,.45,.72,4*1.0,.59,.18/
      DATA (ZZERO(I,7),I=1,12)/4*.64,.78,.91,4*1.05,.85,.64/
      DATA (ZZERO(I,8),I=1,12)/4*.32,.40,.48,4*.55,.44,.32/
      DATA (ZZERO(I,9),I=1,12)/4*2.4E-2,5.8E-2,9.5E-2,4*1.3E-1,8.7E-2,
     1                             2.4E-2/
```

```
      DATA (ZZERO(I,10),I=1,12)/4*1.45E-2,3.6E-2,5.8E-2,4*8.0E-2,4.8E-2,
     1                              1.45E-2/
      DATA (ZZERO(I,11),I=1,12)/4*2.5E-2,6.3E-2,10.2E-2,4*1.4E-1,8.2E-2,
     1                              2.5E-2/
      DATA (ZZERO(I,12),I=1,12)/4*1.6E-2,4.0E-2,6.4E-2,4*8.0E-2,4.8E-2,
     1                              1.6E-2/
      DATA (ZZERO(I,13),I=1,12)/4*.5E-2,1.25E-2,2.0E-2,4*2.75E-2,1.6E-2.
     1                              .5E-2/
      DATA (ZZERO(I,14),I=1,12)/12*E-2/
      DATA (ZZERO(I,15),I=1,12)/4*1.8E-4,4.5E-4,7.2E-4,4*1.0E-3,5.9E-4,
     1                              1.8E-4/
      DATA (ZZERO(I,16),I=1,12)/4*1.7E-3,4.3E-3,6.9E-3,4*9.5E-3,5.6E-3,
     1                              1.7E-3/
      DATA (ZZERO(I,17),I=1,12)/4*7.5E-3,2.15E-2,3.6E-2,
     1                              4*5.0E-2,2.9E-2,7.5E-3/
      DATA (ZZERO(I,18),I=1,12)/12*5.0E-4/
      DATA (ZZERO(I,19),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,20),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,21),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,22),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,23),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,24),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,25),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,26),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,27),I=1,12)/12*DUMMY/
      DATA (ZZERO(I,28),I=1,12)/12*4.0E-1/
      DATA (ZZERO(I,29),I=1,12)/12*5.0E-4/
      DATA (ZZERO(I,30),I=1,12)/12*4.0E-1/
      DATA (ZZERO(I,31),I=1,12)/12*5.5E-1/
      DATA (ZZERO(I,32),I=1,12)/12*8.5E-1/
      DO 1000 J=1,97
      NU(J)=0
      IMAX=0
      DO 10 I=1,32
      ICOUNT(I)=0
10    CONTINUE
      DO 20 L=1,4
      DO 20 K=1,12
      IHISTO(K,L,J)=0
20    CONTINUE
      DO 30 I=1,12
      XMEAN(I)=0.0
      NPT(I)=0
30    CONTINUE
      DO 90 L=1,NRCKM
      DO 80 K=1,NPTKM
C     EXTRACT SURFACE TYPE, INCREMENT PROPER COUNTER
      ISURF=GRID((J-1)*NPTKM+K,L,2)
      INDEX=ISURF+1
      ICOUNT(INDEX)=ICOUNT(INDEX)+1
      DO 50 I=1,12
C     IF UNDEFINED CODE DO NOT PROCESS
      IF(ISURF.EQ.0.OR.(ISURF.GE.18.AND.ISURF.LE.26))GO TO 50
      HEIGHT=ZZERO(I,INDEX)
C     COMPUTE AVERAGE AND FILL HISTOGRAM
      XMEAN(I)=XMEAN(I)+LOG(HEIGHT)
      NPT(I)=NPT(I)+1
C     GET SEASON INDEX
      IF(I.EQ.12) THEN
          ISEASN=1
      ELSE
```

```
            ISEASN=I/3+1
      ENDIF
C     GET BAND INDEX
      DO 40 M=1,12
      IF(HEIGHT.GE.BNDLMT(M).AND.HEIGHT.LT.BNDLMT(M+1)) THEN
            IBAND=M
            GO TO 45
            ENDIF
40    CONTINUE
      STOP 'GETRUF'
45     IHISTO(IBAND,ISEASN,J)=IHISTO(IBAND,ISEASN,J)+1
50    CONTINUE
80    CONTINUE
90    CONTINUE
      DO 100 I=1,12
      XMEAN(I)=XMEAN(I)/FLOAT(NPT(I))
      ZHAT(I,J)=EXP(XMEAN(I))
100   CONTINUE
      DO 110 I=1,32
      IF(I.EQ.1) THEN
            NU(J)=NU(J)+ICOUNT(I)
      ELSE IF(I.GE.2.AND.I.LE.18) THEN
            IF(ICOUNT(I).GT.IMAX) THEN
                  IVC(J)=I-1
                  IMAX=ICOUNT(I)
                  ENDIF
      ELSE IF(I.GE.19.AND.I.LE.27) THEN
            NU(J)=NU(J)+ICOUNT(I)
      ELSE
            IF(ICOUNT(I).GT.IMAX) THEN
                  IVC(J)=I-1
                  IMAX=ICOUNT(I)
                  ENDIF
      ENDIF
110   CONTINUE
1000  CONTINUE
      RETURN
      END
```

```
      PROGRAM TDRUFF
C-----------------------------------------------------------------------
C- THIS PROGRAM COMPUTES VALUES OF TERRAIN-DERIVED AERODYNAMIC ROUGHNESS
C-  AND TERRAIN STATISTICS FOR ELEVATION DATA SUPPLIED ON A SQUARE GRID.
C-
C- TDRUFF WAS CREATED FOR THE US ARMY ATMOSPHERIC SCIENCES LABORATORY BY
C-  THE UNIVERSITY OF DAYTON RESEARCH INSTITUTE 31 MARCH 1981.
C-
C- NOTE: SOME PARTS OF THIS CODE MAY BE SPECIFIC TO DEC VAX/VMS FORTRAN
C-----------------------------------------------------------------------
C-
      INTEGER*2 IDATA(2500,25),IWORK(25,25)
      DATA IDATA/62500 * -1000/
      DATA IWORK/625*-1000/
C-
C- READ IN SCAN LINES TO FORM A COLUMN OF 1KM WIDE DATA
C-
      OPEN(UNIT=2,RECORDTYPE='VARIABLE',STATUS='OLD',
     X        FORM='UNFORMATTED',RECORDSIZE=7500)
C-
C- READ PAST THE TWO HEADER RECORDS AT THE BEGINNING OF THE TAPE.
C-
      READ(2)
      READ(2)
      IEOF = 0
      IX = 0
      ICOL = 1
      IREC = 0
      READ *,BASEN,BASEE,NPPCOL,DELTA
      STARTE = FLOAT(IFIX(BASEE) / 1000) * 1000.
      STARTN = FLOAT(IFIX(BASEN)/1000) * 1000.
      ENDNOR = STARTN + 1000.
      ENDEAS = STARTE + 1000.
      ELAST = BASEE - DELTA
      ENEXT = ELAST + DELTA
      PRINT *, 'BASEN,BASEE,NPPCOL,DELTA: ',BASEN,BASEE,NPPCOL,DELTA
C-
C- NPPCOL = # OF POINTS PER SCAN LINE(COLUMN)
C-
50    CONTINUE
      IF(ENEXT.LT.ENDEAS) THEN
              READ(2,END=52) (IDATA(IROW,ICOL),IROW=1,NPPCOL)
              GO TO 54
52            IEOF = 1
      GO TO 53
54            CONTINUE
              ELAST = ENEXT
              ENEXT = ENEXT + DELTA
              IREC = IREC + 1
              ICOL = ICOL + 1
              GO TO 50
              ENDIF
C-
C- A 1 KM WIDE COLUMN HAS BEEN READ IN. NOW DIVIDE IT INTO
C- 1KM TALL SECTORS (1KM BY 1KM) FOR FURTHER PROCESSING
C-
53    ICOL = ICOL - 1
C-
C- ICOL=0 OCCURS WHEN THE PROGRAM ENCOUNTERS AN END OF FILE WHEN READING
C-  THE FIRST RECORD OF  THE NEXT COLUMN OF SQUARE KILOMETERS.
C-
```

```
            IF(ICOL.EQ.0) GO TO 100
            IROWABS = 1
            TOPNOR = FLOAT(IFIX(BASEN+FLOAT(NPPCOL)*DELTA)/1000 * 1000) +
     X           1000.
            STARTN = FLOAT(IFIX(BASEN)/1000 * 1000)
            ENDNOR = STARTN + 1000
            IROW = 1
            ROWLAST = BASEN - DELTA
 70         ROWNEXT = ROWLAST + DELTA
 73         CONTINUE
            IF(ROWNEXT.LT.ENDNOR) THEN
                    DO 75 IC = 1,ICOL
 75                         IWORK(IROW,IC) = IDATA(IROWABS,IC)
                    IROW = IROW + 1
                    IROWABS = IROWABS + 1
                    ROWLAST = ROWNEXT
                    GO TO 70
                    ENDIF
C-
C- DONE FILLING THE IWORK ARRAY(THIS ARRAY REPRESENTS
C- A 1KM BY 1KM AREA).  ARRAY HAS DIMENSIONS IROW-1,ICOL
C-
            IROW = IROW - 1
            IN = IFIX(STARTN)
            IE = IFIX(STARTE)
C-
C- SUBROUTINE CALC COMPUTES THE VARIOUS VALUES FOR THE SQUARE KILOMETER
C-  REPRESENTED IN THE ARRAY IWORK.
C- IN IS THE NORTHING OF THE LOWER LEFT CORNER OF THE SQUARE
C- IE IS THE EASTING OF THE LOWER LEFT CORNER OF THE SQUARE.
C-
            CALL CALC(IWORK,ICOL,IROW,IN,IE)
C-
C- SUBROUTINE COMDAT SIMPLY RE-INITIALIZES THE IWORK ARRAY TO NO-DATA
C-  (-1000 VALUES).
C-
            CALL COMDAT(IWORK,IROW,ICOL,STARTN,STARTE)
            STARTN = FLOAT(IFIX(ENDNOR+1)/1000*1000)
            ENDNOR = STARTN + 1000
            IROW = 1
            IF(STARTN.LT.TOPNOR) GO TO 73
C-
C- THIS ENDS THE DATA COLUMN PROCESSING SECTION
C- COMPUTE PARAMETERS TO READ IN ANOTHER 1KM WIDE
C- COLUMN OF DATA
C-
C-
C- TEST FOR END OF FILE.
C-
            IF(IEOF.EQ.1) GO TO 100
            STARTE = ENDEAS
            ENDEAS = ENDEAS + 1001
            ENDEAS = FLOAT((IFIX(ENDEAS)+1)/1000*1000)
            ICOL = 1
            DO 80 I=1,2500
            DO 80 J = 1,25
 80                 IDATA(I,J) = -1000
            GO TO 50
C-
C- END OF FILE SECTION
C-
```

```
100    WRITE(6,110) IREC
110    FORMAT(' RECORDS READ = ',I10)
       STOP 'END OF JOB'
       END
```

```
       SUBROUTINE COMDAT(IWORK,IRDIM,ICDIM,STARTN,STARTE)
       INTEGER*2 IWORK(25,25)

C-
C- RE-INITIALIZE THE IWORK ARRAY TO NO-DATA VALUES
C-   AREA REPRESENTED IN THE IWORK ARRAY.
C-
       DO 30 I = 1,25
       DO 30 J = 1,25
30            IWORK(I,J) = -1000
       RETURN
       END
```

```
      SUBROUTINE CALC(IDATA, IXDIM, IYDIM, NORTH, IEAST)
C-
C----------------------------------------------------------------------
C- THIS SUBROUTINE COMPUTES THE OUTPUT VARIABLES FROM THE ELEVATION
C-  DATA FOR EACH OF THE SQUARE KILOMETERS CONTAINED IN AN ARRAY GRID
C-  IT ALSO CALLS ROUTINE PEAKS TO COUNT THE NUMBER OF PEAKS AND VALLEY
C-  IN A SCAN LINE ACROSS 1 KM SQUARE.
C-
C- INPUT:
C- -----
C- IXDIM = THE NUMBER OF POINTS IN THE N-S DIRECTION PER KM.
C- IYDIM = THE NUMBER OF POINTS IN THE E-W DIRECTION PER KM.
C- NORTH = NORTHING OF S-W CORNER POINT.
C- IEAST = EASTING  OF S-W CORNER POINT.
C- IDATA( ) = THE FIRST  SUBSCRIPT VARIES FROM 1 TO 16 AND INDEXES THE
C-            POINTS OF 1 SQUARE KM IN THE N-S DIRECTION.
C-            THE SECOND SUBSCRIPT VARIES FROM 1 TO 16 AND INDEXES THE
C-            POINTS OF 1 SQUARE KM IN THE E-W DIRECTION.
C-
C- OUTPUT:
C- ------
C- NORTH  = NORTHING OF S-W CORNER POINT.
C- IEAST  = EASTING  OF S-W CORNER POINT.
C- HBAR   = THE MEAN ELEVATION (METERS).
C- SIGMA  = THE ELEVATION STANDARD DEVIATION (METERS).
C- HOBAR  = THE TERRAIN ROUGHNESS  PARAMETER (METERS).
C- ICOUNT = NUMBER OF ELEVATION DATA POINTS IN A SQUARE KM.
C- IMIN   = THE MINIMUM ELEVATION (METERS).
C- IMAX   = THE MAXIMUM ELEVATION (METERS).
C----------------------------------------------------------------------
C-
      INTEGER*2 IDATA(25,25), IARAY(30)
      SUM = 0.
      ISCANS = 0
      SUMSQ = 0.
      IMAX = 0
      IMIN = 30000
      NPV = 0
      HOBAR = 0.
      ICOUNT = 0
      DO 50 IROW = 1, IYDIM
      DO 50 ICOL = 1, IXDIM
              IF(IDATA(IROW, ICOL).EQ.-1000) GO TO 50
              ICOUNT = ICOUNT + 1
              DATA = FLOAT(IDATA(IROW, ICOL))
              SUM = SUM + DATA
              SUMSQ = SUMSQ + (DATA*DATA)
              IF(IDATA(IROW, ICOL).LT.IMIN) IMIN = IDATA(IROW, ICOL)
              IF(IDATA(IROW, ICOL).GT.IMAX) IMAX = IDATA(IROW, ICOL)
 50           CONTINUE
      IF(ICOUNT.EQ.0) RETURN
      HBAR = SUM / FLOAT(ICOUNT)
      IF(ICOUNT.EQ.1) THEN
              SIGMA = 0.
              HOBAR = 0.
              GO TO 300
              ENDIF
      A = SUMSQ - (SUM*SUM/FLOAT(ICOUNT))
      IF( A.LT.0. ) THEN
              SIGMA = 0.
      ELSE
```

```
                 SIGMA = SQRT(A / FLOAT(ICOUNT-1))
         ENDIF
C-
C- FOR EACH ROW ,BUILD AN ARRAY OF DATA VALUES
C-
         DO 100 IROW = 1,IYDIM
                 IC = 0
                 DO 90 ICOL = 1,IXDIM
                         IF(IDATA(IROW,ICOL) EQ.-1000) GO TO 90
                         IC = IC + 1
                         IARAY(IC) = IDATA(IROW,ICOL)
90                       CONTINUE
C-
C- COMPUTE THE NUMBER OF PEAKS AND VALLEYS FOR THIS ROW.
C-
                 CALL PEAKS(IARAY,IC,HO,NPNV,ISCANS,ISCANS)
                 HOBAR = HOBAR + HO
100              NPV = NPV + NPNV
C-
C- FOR EACH COLUMN BUILD AN ARRAY OF DATA VALUES
C-
         DO 200 ICOL = 1,IXDIM
                 IC = 0
                 DO 190 IROW = 1,IYDIM
                         IF(IDATA(IROW,ICOL).EQ.-1000) GO TO 190
                         IC = IC + 1
                         IARAY(IC) = IDATA(IROW,ICOL)
190                      CONTINUE
C-
C- COMPUTE THE NUMBER OF PEAKS AND VALLEYS FOR THIS COLUMN.
C-
                 CALL PEAKS(IARAY,IC,HO,NPNV,ISCANS)
                 HOBAR = HOBAR + HO
200              NPV = NPV + NPNV
C-
C- COMPUTE FINAL VALUES AND OUTPUT THEM
C-
300      IF(ISCANS.EQ.0) THEN
                 HOBAR = 0
         ELSE
                 HOBAR = HOBAR / FLOAT(ISCANS)
         ENDIF
C-
C- WRITE THE OUTPUT RECORD FOR THIS KILOMETER SQUARE.
C-
         WRITE(7,1000) NORTH,IEAST,HBAR,SIGMA,HOBAR,ICOUNT,IMIN,IMAX
1000     FORMAT(2I8,3E14.7,3I8)
         RETURN
         END
```

```
      SUBROUTINE PEAKS(IARAY, IC, HO, NPNV, ISCANS)
      INTEGER*2 IARAY(30)
-
- THIS ROUTINE DETERMINES THE NUMBER OF PEAKS AND VALLEYS IN A  SCAN
- LINE ACROSS A 1 KM SQUARE AND THE TDR (HO) FOR THE SCAN  LINE
- (TRAVERSE).  THIS SCAN LINE IS STORED IN IARAY.
-
      NPNV = 0
      NPEAKS = 0
      NVALLS = 0
-
- HERE IS THE DEFAULT SETTING FOR HO
-
      HO = 1.E-2
      IF(IC.LE.2) RETURN
      ISCANS = ISCANS + 1
      DTOTAL = 0.
      IF(IARAY(1).GT.IARAY(2)) THEN
              NPEAKS = NPEAKS + 1
      ELSE
              IF(IARAY(1).LT.IARAY(2)) THEN
                      NVALLS = NVALLS + 1
              ENDIF
      ENDIF
      ICM1 = IC - 1
      DO 30 I = 2, ICM1
              IF((IARAY(I).GT.IARAY(I-1)).AND.(IARAY(I).GT.
     X           IARAY(I+1))) THEN
                      NPEAKS = NPEAKS + 1
              ELSE
                      IF((IARAY(I).LT.IARAY(I-1)).AND.(IARAY(I).LT.
     X                   IARAY(I+1))) THEN
                              NVALLS = NVALLS + 1
                      ENDIF
              ENDIF
30            DTOTAL = DTOTAL + ABS(FLOAT(IARAY(I)-IARAY(I-1)))
-
-
      IF(IARAY(IC).GT.IARAY(IC-1)) THEN
              NPEAKS = NPEAKS + 1
      ENDIF
      IF(IARAY(IC).LT.IARAY(IC-1)) THEN
              NVALLS = NVALLS + 1
      ENDIF
      DTOTAL = DTOTAL + ABS(FLOAT(IARAY(IC) - IARAY(IC-1)))
      NPNV = NPEAKS + NVALLS
      IF(NPNV.LE.1) THEN
              DTOTAL = 0.
              HO = 1.E-2
      ELSE
              HO = (DTOTAL * DTOTAL) / (8000. * (NPNV-1))
      ENDIF
      RETURN
      END
```