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Wind Time Series Analyses for WECS Applications

Jack W. Reed

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ABSTRACT

A methodology for wind power analyses of wind speed time series is described, including computation flow diagrams and a FORTRAN program listing. Examples of results are presented but complete outputs will follow in specialized reports. Primary calculation stages are (a) data homogenization for moved anemometers, (b) extrapolations to selected standardized heights, (c) distribution smoothing for observation bias, (d) power distribution function calculation, (e) turbine speed limit effects analysis, (f) time variability assessment, and (g) analysis of light wind durations.

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Introduction

After the climatology of available wind power was completed for the United States,[1,2] another needed step appeared to be a look in detail at historical records of hourly wind observations from stations located in various climatic regimes. Specific goals were (a) to more precisely define the wind speed probability density functions (PDF), providing analytic descriptions where they were found to be appropriate; (b) to generate parallel wind speed PDFs and time-series for selected heights above ground; (c) to establish the effects of WECS (wind energy conversion systems) speed limit assumptions on wind power capture from the different wind speed PDFs; and (d) to generate statistical distributions of time periods with and without sufficient wind speeds for significant power production.

To these ends, fifteen weather stations with long-term records were selected as representative of U.S. wind climate zones. A ten-year record was estimated to be sufficient for averaging any long-term oscillations, particularly quasi-biennial or sunspot eleven-year cycling.

Hourly observation records appeared desirable, and this dictated record periods prior to 1965, when archiving was reduced to the preservation of three-hourly reports. Three-hourly data do not clearly define diurnal variations where they may be important. They may be inadequate for establishing the distribution of many interesting higher wind speeds. They may also distort the "on" and "off" duration statistics for wind turbine operations. Corotis[3] has recently shown, however, that there are only two or three "independent" wind observations per day, because of the time-lag correlation between observations. Thus, for the bulk of wind power calculations that deal simply with means and standard deviations, statistics from three-hourly reports should be as good as from hourly observations.

Magnetic tape reproductions of ten-year weather observation records for 1955-1964 were obtained from the NOAA National Climatic Center (NCC), Asheville, North Carolina. The fifteen selected stations are listed in Table I. Specific selections were based on (1) wind climate, (2) record availability and quality, and (3) special WECS project interests in certain locations such as Albuquerque, Cleveland, and Enewetak.

This report describes the methodology which has been used in analyzing these data tapes. A FORTRAN program, as currently operated, is reproduced in the Appendix. Copies of this program card deck could be furnished to other agencies for use with other raw wind speed data sets, provided the input format was maintained.

TABLE I

Stations Selected for Detailed Wind Power Analyses

Station	Record Period Start	Record Period Stop	Anemometer Height (m)	Anemometer Height (ft)	Remarks	Station Selection Criteria
Corpus Christi, TX	1/1/55	12/31/60*	19.2	63	Atop control tower roof	Gulf coast winds
	1/1/61*	12/31/64	6.7	22	Near runway 13R-31L	
Albuquerque, NM	1/1/55	2/4/60	14.6	48	Atop airport adm. bldg.	Sandia VAWT Lab
	2/5/60	12/31/64	7.0	23	Near E-W runway	
Memphis, TN	1/1/55	7/22/58	16.8	55	Atop airport adm. bldg.	Southeast U.S., light winds
	7/23/58	12/31/64	6.7	22	(Near runway?)**	
Dodge City, KS	1/1/55	4/12/61	17.7	58	Atop airport adm. bldg.	High plains winds
	4/13/61	12/31/64	6.1	20	(Near runway?)**	
Nantucket Shoals, MA	4/1/57	12/4/62	61.0	200	Radio mast, top deck, Texas Tower	Atlantic offshore winds
Cleveland, OH	1/1/55	1/30/56	17.1	56	Atop mun. airport adm. bldg.	NASA Lewis Lab and turbine
	1/31/56	6/25/59	26.8	88	Atop int'l airport term. bldg.	
	6/26/59	12/31/64	6.1	20	(Near runway?)**	
Fargo, ND	1/1/55	6/26/61	26.2	86	Atop airport adm. bldg.	Northern plains winds
	6/27/61	12/31/64	6.1	20	(Near runway?)**	
Lubbock, TX	1/1/55	12/31/64	20.7	68	Atop airport term. bldg.	High plains winds, Texas Tech turbine project
Oklahoma City, OK	1/1/55	12/31/64	4.0	13	Near N-S runway	Plains winds, university turbine projects
Cheyenne, WY	1/1/55	10/2/57	22.3	73	Atop airport bldg.	Western high plains.
	10/3/57	12/31/64	10.1	33	(Near runway?)**	
Great Falls, MT	1/1/55	8/1/59	22.9	75	Atop airport adm. bldg.	Mountainous and windy
	8/2/59	12/31/64	7.0	23	(Near runway?)**	
Tatoosh Is., WA	1/1/55	12/31/64	19.5	64	Atop USWB office	Pacific coastal winds
Enewetak, Marshal Is.	1/1/60	6/30/69	----	Unkn	----	Tradewinds, ERDA site
San Nicolas Is., CA	1/1/60	6/30/63*	21.9	72	Atop control tower	Pacific coastal winds
	7/1/63*	12/31/69	4.0	13	800 ft SE of opns bldg.	
Cape Hatteras, NC	3/1/57	12/31/64	9.8	32	At USWB bldg. in Buxton	Atlantic coastal winds

*Exact date of anemometer relocation not recorded.

**Final location not specified but it probably was near a runway.

NOAA-NCC Records

Each ten-year standard station record of hourly weather observations filled one 7-track magnetic tape at 556 bpi (bits per inch). The tape code is described in a paper provided by NCC.[4] At Sandia Laboratories, computer processing equipment required a translation into local format. In this process, only wind speeds (and date-time groups) were extracted for WECS studies, since Sandia is primarily concerned with nondirectional vertical-axis wind turbine (VAWT) systems. Wind directions, as well as other meteorological variables, could be extracted from the original tapes, should need arise.

Extracted data were placed on a Sandia tape as daily records, coded as follows, NNNNNYYMMDDHHSSSHHSSS...HHSSS, where N is the weather station international index number, Y is year, M is month, D is date, H is hour, and S is wind speed in knots. Missing speeds are indicated by 999.

Records or files of seven stations can be contained on one magnetic tape, so three library tapes are required for data storage. These three tapes are also placed on permanent disc file units for immediate access, but these assignments require periodic renewal. Access to one station file is obtained by control card call for a tape and file number. From this point, data are processed by one of three Sandia CDC-6600 computers according to FORTRAN program instructions reproduced in the Appendix.

A flow diagram of major operations in the current computer program is shown in Figure 1. The remainder of this paper is an explanation of this figure. Available random-access storage does not allow input of the full ten-year file of 87,672 hourly wind speed measurements. A requested station file is placed in extended mass storage, and one-year blocks are recalled for processing.

Definitions of Statistical Operations

Wind speed reports were provided in discrete integer knot units, $u_i = i - 1$, for $1 \le i \le n$, and n is determined by the highest reported speed at each station.* Missing data were indicated by $u_{101} = 999$. Sample size corrections have been made for missing data, but derivations and notations that follow will proceed as if there were a complete set. The probability, Pr, that wind speed, U, takes the values u_i is defined by:

$$\Pr(U = u_i) = f(u_i) \quad , \quad (1 \le i \le n) \tag{1}$$

so that:

$$\sum_{i=1}^{n} f(u_i) = 1 \quad . \tag{2}$$

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*Symbols and definitions used in text equations and the FORTRAN program precede the program listing in the Appendix.

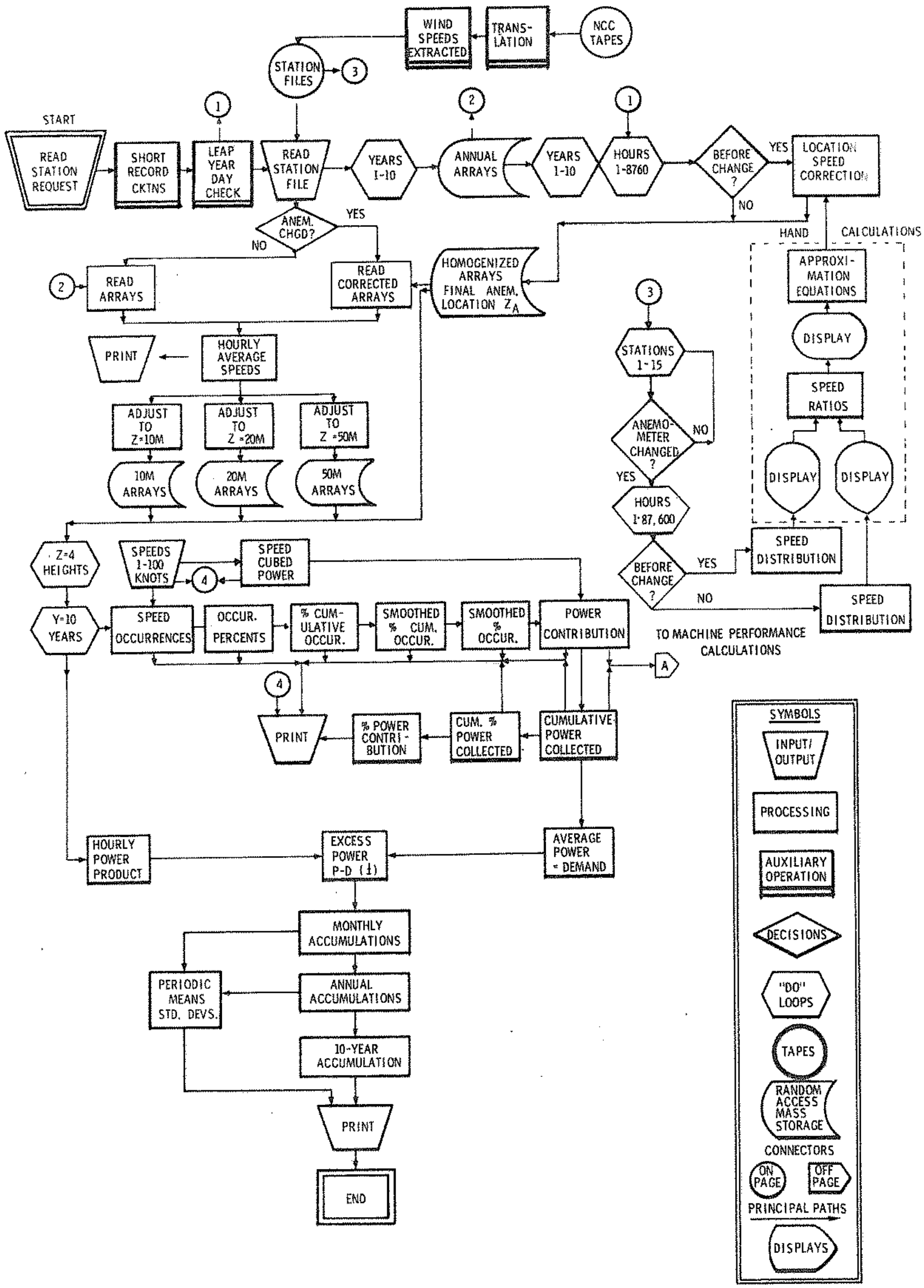

Figure 1. Wind Power Evaluation Program

Here, $f(u_i)$ is called the probability density function (PDF) of U. The cumulative probability function (CPF) is defined by:

$$F(u_m) = Pr(U \leq u_m) = \sum_{i=1}^{m} f(u_i) \, , \tag{3}$$

so that:

$$F(u_n) = 1 \, .$$

Time series for wind speeds, $s_k(j)$ were provided for $1 \leq j \leq J$. In these evaluations $J = 87672$ (including 3 leap years), except where full ten-year records were not available. Subscripts k are referenced to anemometer heights, z_k, for $1 \leq k \leq 3$ periods, obtained from weather station histories. Selected heights above ground will be taken to represent "standard" anemometer exposure at $z_4 = 10$ m, and exposures at $z_5 = 20$ m and $z_6 = 50$ m for application to wind turbine evaluations.

Anemometer Location Changes

Station histories showed that the anemometer was moved at least once during the 1955-1964 period of record at nine of the fifteen selected weather stations. Most of these anemometer changes were made to move the instrument from atop a control tower or airport terminal building to a point near an important runway and near 6 m above ground. This height was set by National Weather Service (NWS) policy to be representative of effective winds for large aircraft operations.

To obtain a homogeneous ten-year time series of speeds at one level for these stations, an intermediate data processing procedure was necessary, as described in detail in another report.[5] For anemometer changes at times $j = M$ and $j = N$ (at most there were two anemometer moves), the time series was separated into two or three sequential series, S, as required.

$$\begin{aligned} S(1) &= s_1(j) \, , \quad \big(1 \leq j \leq (M-1)\big) \, , \\ S(2) &= s_2(j) \, , \quad \big(M \leq j \leq (N-1)\big) \, , \\ S(3) &= s_3(j) \, , \quad (N \leq j \leq J) \, , \end{aligned} \tag{4}$$

and corresponding CPFs, $F_1(u_m)$, $F_2(u_m)$, and $F_3(u_m)$ were calculated. In summary, as shown by the flow diagram, data collected during each anemometry era was used to generate a separate CPF. It was necessary to assume that these CPFs only differed in result of this anemometer move, and that climatic variations between the various periods of record could be ignored. Establishing corrections for possible local climatic deviations between anemometry eras could be difficult and probably not justifiable. It was thus assumed that equal probability points on pairs of distribution curves were directly related by a scalar speed coefficient. A sketch for the procedure is shown in Figure 2, where discrete

$$x_m = F_3(u_m) , \qquad (5)$$

continuous

$$x = F_k(u) , \qquad (5a)$$

and the continuous inverse function is

$$u = F_k^{-1}(x) = G_k(x) \qquad (6)$$

It was assumed that points of discrete CDFs could be connected by a continous CDF. The scalar speed ratios, a, between CDFs at z_1 and z_2 and the final height, z_3, were calculated for each integer speed, $u_m = G_3(X)$, by

$$a_k = G_k(X)/G_3(X) , \qquad (7)$$

and graphed versus u_m in the form illustrated by Figure 3. In general, these ratios at a station were not constant but varied with wind speed, particularly at low speeds. At some stations this variation could be neglected because there is no useful power in such light winds. Where there was significant variation in the ratio, one or two linear approximations were assumed for the relationship

$$a_k(u_m) = \frac{u}{u_m} = A + Bu_m . \qquad (8)$$

Since Equation (8) shows that it is quadratic in u_m, the solution for u_m and the adjustment function for estimating speed, $\hat{u}$, at z_3 from a speed observation at z_k follows

$$\hat{u} = \frac{-A \pm \sqrt{A^2 + 4Bu}}{2B} \qquad (9)$$

This was used by the computer program to adjust observations made before the anemometer was changed. Results were rounded off to integer values to yield a time series of homogeneous data, $\hat{S}(3)$, at the final anemometer location,

$$\hat{S}(3) = \hat{s}_3(j) \ , \quad (1 \le j \le J) \ . \qquad (10)$$

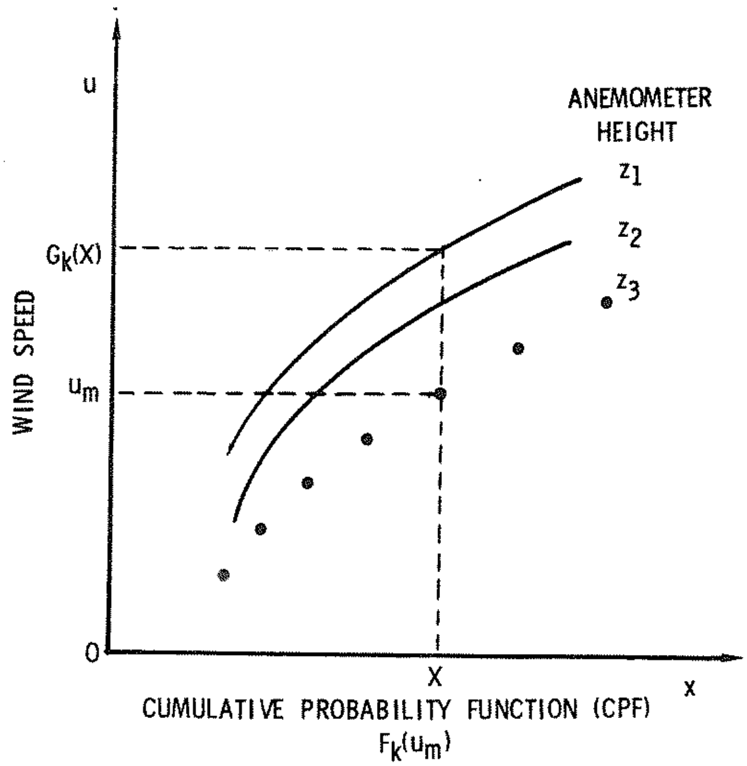

Figure 2. Typical Wind Speed Distributions for Changed Anemometer Locations

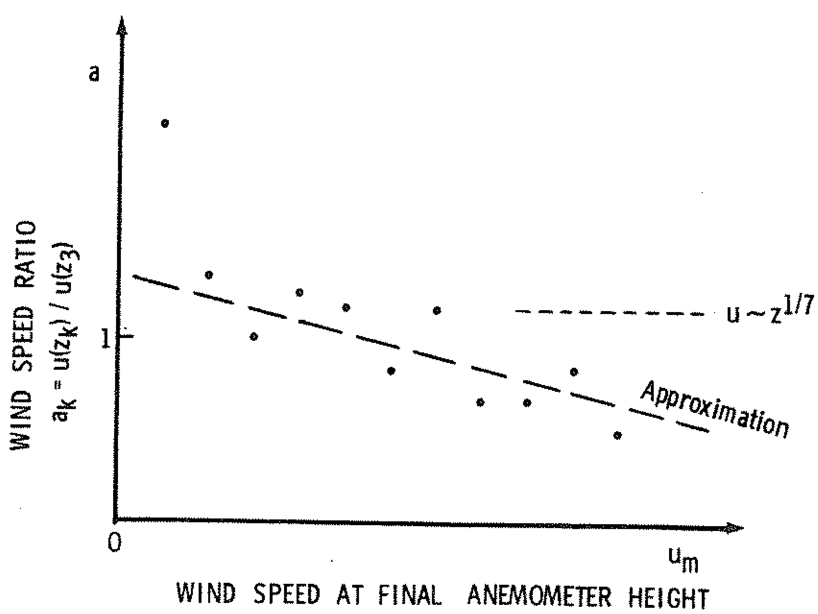

Figure 3. Typical Speed Ratios Versus Wind Speed

Extrapolations to Selected Heights

The next stage in calculation is to synthesize time series of wind speeds at 10 m, 20 m, and 50 m above level ground. For this it has been assumed that the final anemometer location was above level ground. Information in Table I generally justifies this assumption. Lubbock, Tatoosh Island, and Cape Hatteras were exceptions where the anemometer was mounted on a building, and at Enewetak no anemometer exposure was reported. Primary WECS concerns were with moderate-to-high wind speeds, and such wind speeds would cause neutral thermodynamic stability (an adiabatic temperature lapse rate with height) from ground friction turbulence. With neutral conditions, an approximation is usually valid, that wind speed increases with the one-seventh power of height above level ground in open country.[6] This relation was then used to generate speed data time-series at other heights from the time-series of anemometer-height speed observations. Results are placed in mass storage, again in one-year blocks,

$$s_4(j) = (10/z_3)^{1/7} \cdot s_3(j) \ ,$$

$$s_5(j) = (20/z_3)^{1/7} \cdot s_3(j) \ ,$$

$$s_6(j) = (50/z_3)^{1/7} \cdot s_3(j) \ . \qquad (11)$$

At this point there are 350, 688 wind speeds from a ten-year record, stored in forty blocks, ready for further analysis.

Wind Speed and Power Distribution

All subsequent calculations are made for each of four prescribed heights, z_k, $(3 \le k \le 6)$. The first step constructs a table of reported occurrences, $T(u_i)$, and cumulative occurrences,

$$C(u_m) = \sum_{i=1}^{m} T(u_i) \ , \qquad (12)$$

for each integer wind speed, $0 \le u_i \le n-1$. From this listing and the total number of observations, J, PDF and CPF tables are calculated and listed from:

$$f(u_i) = T(u_i)/J \ ,$$

$$F(u_m) = C(u_m)/J \ . \qquad (13)$$

It has been noted many times before, and confirmed by these data sets, that observers tend to report certain number digits at the expense of others. Integer multiples of five and two knots were favored in these data sets as shown by an example in Figure 4. A part of this bias is smeared by the homogenization and round-off processes of the preceding section. It was found, by trial and error, that it still required weighted smoothing over at least six knots of speed in the CPF to produce a reasonably smooth PDF curve. No attempt was made to smooth the occurrences of calms. Other smoothed CDF points, $\widetilde{F}$, were obtained by the following procedure, using simplified notation that $F(i) = F(u_i)$:

$$\widetilde{F}(2) = 1/4 \quad \big(F(1) + 2F(2) + F(3)\big)$$

$$\widetilde{F}(3) = 1/9 \quad \big(F(1) + 2F(2) + 3F(3) + 2F(4) + F(5)\big)$$

$$\widetilde{F}(i) = 1/24 \Big(F(i-3) + F(i+3) + 3\big(F(i-2) + F(i+2)\big) + \big(5\,F(i-1) + F(i+1)\big) \quad + 6F(i)\Big) \ , \ (4 \le i \le n) \ . \qquad (14)$$

There was no problem at the upper limit because $f(i) = 0$ for $(i \ge n)$. The smoothed PDFs were obtained from

$$\widetilde{f}(i) = \widetilde{F}(i) - \widetilde{F}(i-1) \ , \qquad (15)$$

and a smoothed table of occurrences, integer $J(\widetilde{f}(i))$ was calculated. Raw and smoothed occurrences are shown by example in Figure 5.

Wind power, proportional to air density, ρ, and the cube of wind speed, is next computed and multiplied by the smoothed PDF to give the wind power PDF (per unit of area normal to the wind),

$$p(u_i) = \widetilde{f}(u_i) \cdot u_i^3 \cdot \rho/2 \ . \qquad (16)$$

Standard atmosphere sea level density,[7] $1.225\ kg/m^3$, is frequently used for first order wind power estimates, so that

$$p = 0.6125\ u^3\ W/m^2, \text{ for u in m/s,}$$

$$= 0.05472\ u^3\ W/m^2, \text{ for u in mph,}$$

$$= 0.08355\ u^3\ W/m^2, \text{ for u in knots.} \qquad (17)$$

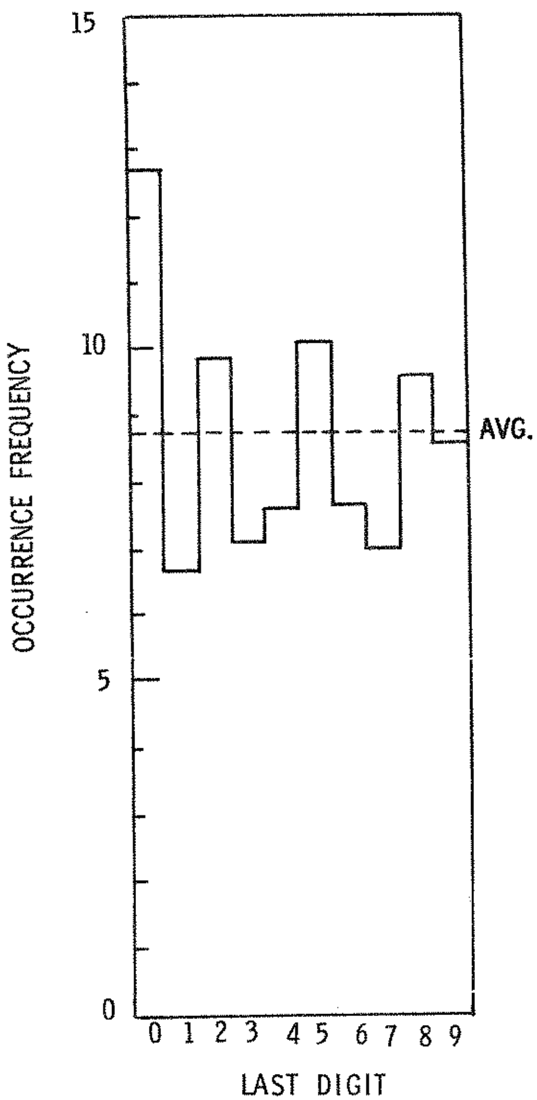

Figure 4. Last Digit Usage in Wind Speed Observations

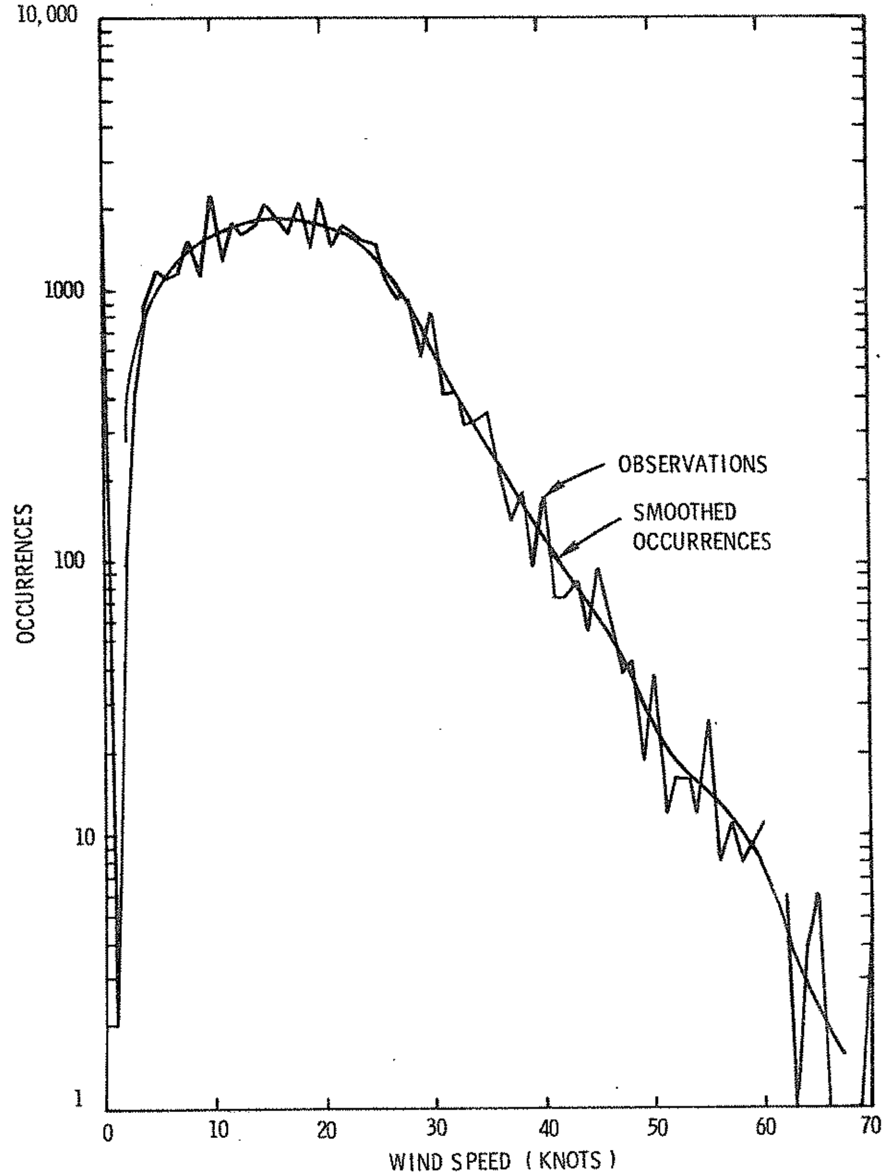

Figure 5. Wind Speed Occurrence Distribution Nantucket Shoals, MA

Where pressure and temperature are known, the coefficient should be multiplied by $2.696\ \Phi/T$, for atmospheric pressure, Φ, in kPa, and air temperature, T, in K. If only the altitude, z, is known, a multiplier, exp(kz), may be used to correct for standard atmosphere pressure-altitude. In this exponential term, $k = 0.1206$ for z in km above MSL (mean sea level), or $k = 3.676 \times 10^{-5}$ for z in ft MSL.

Accumulation over the range of observed speeds gives total available power, as a ten-year average of hourly values,

$$P(u_n) = \sum_{i=1}^{n} p(u_i) \quad . \tag{18}$$

Comparison calculations have shown that the arithmetic smoothing increased average wind power estimates by 2 to 3 percent, as could be expected. Because wind speed is cubed, each speed observation that is increased by smoothing adds more power than is removed by an equal speed decrease. The percent of this total, q(i), contributed by each speed is next calculated from

$$q(i) = 100p(u_i)/P(u_n) \quad , \tag{19}$$

along with a cumulative percentage

$$Q(m) = \sum_{i=1}^{m} q(i) \quad . \tag{20}$$

The power duration curve, D(m), as frequently drawn, is simply a scalar conversion of the cumulative percentage multiplied by the annual average power,

$$D(m) = 0.0876\ Q(m)\ P(u_n) \quad , \tag{21}$$

for kilowatt hours per year. At this point, results versus wind speed are tabulated for each of the four heights above ground. Typical results for a wind power PDF are shown in Figure 6. A wind power duration curve is shown in Figure 7.

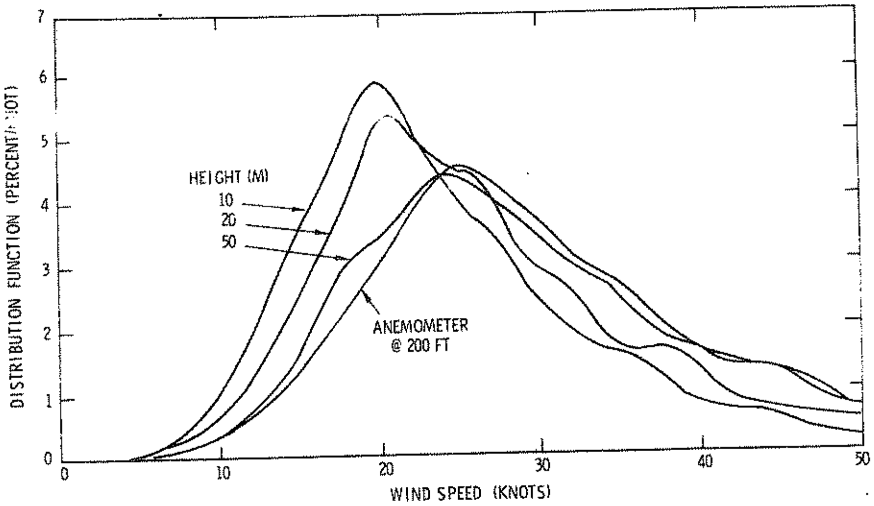

Figure 6. Wind Power Occurrence Distribution Function, Nantucket Shoals, MA

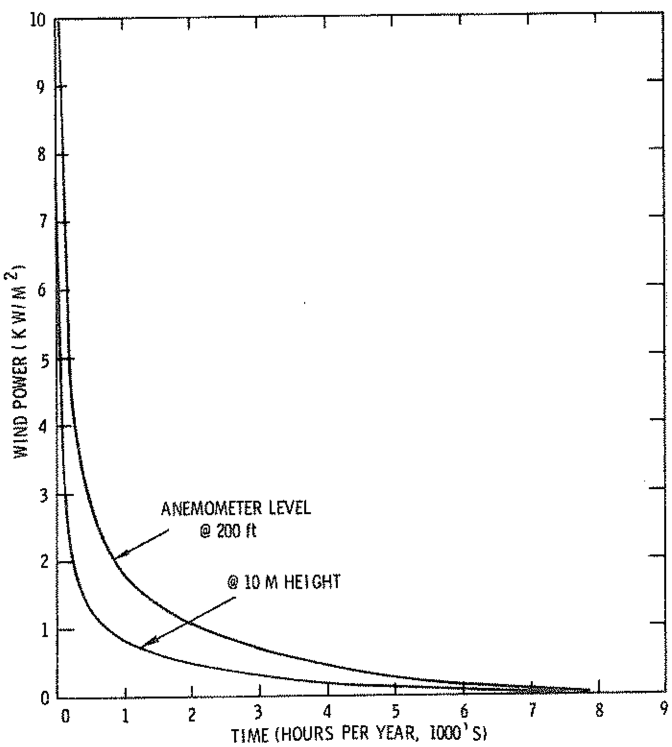

Figure 7. Average Wind Power Duration Curves, Nantucket Shoals, MA

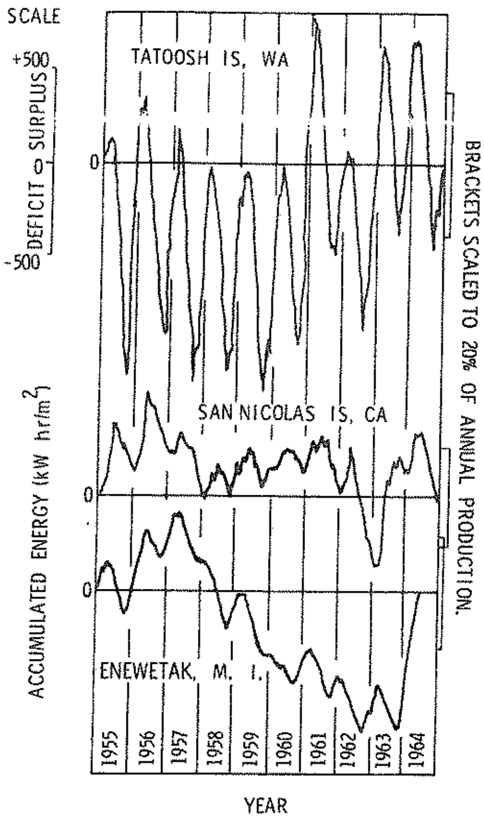

Figure 10

Cumulative Total Production Minus Constant Demand (Average Production) Pacific Locations.

One application of these analyses is to show that the yearly returns from a wind turbine are relatively uncertain. Good and bad years eventually average out but they may come in series. The situation is similar to that regularly faced by farmers (who are also dependent on the variability of the climate).

Another point to be stressed is that the oscillatory nature of wind power time series cannot be overcome by simple scaling, or underrating the collector system. When the wind is calm, output from a 200-watt Wincharger is identically equal to the output of a multigigawatt future fan. Smoothed output can only be statistically approached by a network of connected systems sufficiently spaced to have near-zero correlations between their wind occurrences.[3, 9]

Wind Variability Analysis - Periodic*

Another calculation is a statistical analysis of the periodic variability in available wind power. Monthly and seasonal average available wind powers are computed for comparison with the annual average. Average diurnal cycles are prepared for each month and season (if appropriate). Time

*Programming has not been completed for the calculations that follow, so they are not shown in the FORTRAN listing in the Appendix.

speed time series for a selected height, $s(j)$, is used to obtain a time series of wind power available

$$\Phi(j) = \rho s^3(j)/2 \ , \quad (1 \le j \le J) \ . \tag{24}$$

This hourly available wind power is used to either serve demand or add to reserves. The hourly excess (or deficit) series

$$\delta(j) = \Phi(j) - P(u_n) \tag{25}$$

is summed to give the cumulative excess series

$$L(t) = \sum_{j=1}^{t} \delta(j) \ , \quad (1 \le t \le J) \ , \tag{26}$$

where $L(J) = 0$ with some examples of results shown in Figure 10. This calculation has made no assumption about losses that could accrue from finite storage capacity, input-output cycling, or input-output rate limitations. It has pointed out the fact that the range between maximum and minimum reserve levels in ten years may extend from about 35 to 95 percent of a one-year average production, depending on local wind climate patterns. The extreme range came from a four-year sequence with average wind speeds about 9 percent below the ten-year average. At that station the anemometer change appeared to cause an 18 percent reduction in speed. Thus, the maximum climatic deviation appears to be much smaller than the shift caused by anemometer height change. Therefore, the neglect of possible climate change in record adjustment appears to have been justified.

Note particularly here that the assumed equality of demand with average production was not completely arbitrary, but was used to assure that $L(J) = 0$. Any other assumption would yield a linearly time-dependent baseline, so that at the end of a ten-year sequential calculation, energy reserves would be above or below zero by an amount equal to 87,672 hours multiplied by the amount of the assumed difference between average demand and supply.

Experimental calculations have been made with time-varying demand functions, but again these had to be carefully normalized to match the annual average demand with annual average available power. A national average demand function, including annual, seasonal, and diurnal oscillations, was obtained,[8] but more specific localized functions for our selected wind sites have not yet been made available. An interesting conclusion was reached, however, that a reasonable varying demand made very little difference in the amplitude of oscillating year-to-year reserve levels.

Response of some turbine systems, such as the VAWT, is more complicated, usually represented by a power coefficient curve; an appropriate subroutine can be added for use with VAWT response data. After integration for total collected power, under the constraints of speed limits and an output curve, the result is compared to the total power available in the wind distribution and a percent recovery factor, r, is obtained and printed, from

$$r = 100P'/P(u_n) \quad . \tag{23}$$

Preliminary calculations have shown that recovery percentages are not particularly sensitive to cut-off speeds, within "reasonable" ranges, as shown by Figure 9. Cut-in speed has moderate influence, but rated speed has the largest influence on recovery. Thus, an important output result is this array of recovery percentage versus rated speed in a given climatological wind speed PDF. It may be used by turbine designers for selecting rated speed to minimize cost, since there may be a significant cost increase for increased generator capacity to serve with an increased rated speed.

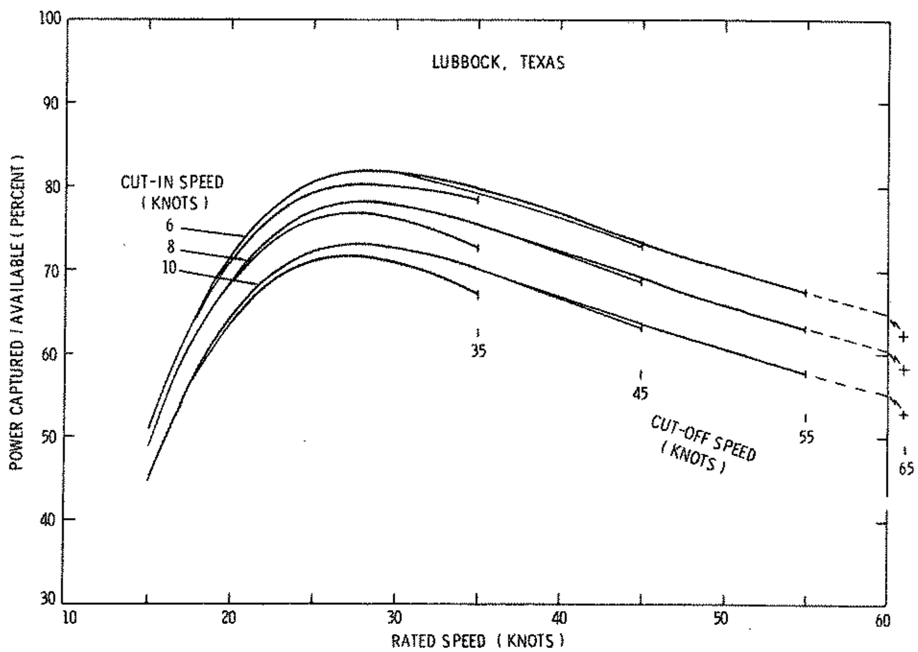

Figure 9. Wind Power Capture Versus Wind Speed Parameters

Wind Variability Analyses - Long Term

The second auxiliary calculation, which was included in the flow diagram (Figure 1), obtains cumulative statistics for the varying available wind power. This requires an assumed demand, which has been set equal to the average production, $P(u_n)$ for preliminary estimates. The wind

Results may also be used as input to two further calculation routines. First, power PDFs are used with speed limit sets and an assumed curve for turbine output versus wind speed, $\epsilon(u)$, to obtain an integrated power capture, P', as a function of the variable turbine parameters. This is shown by the flow diagram in Figure 8. In general,

$$P' = \sum_{i=1}^{n} \epsilon(u_i) \cdot p(u_i) \tag{22}$$

where $\epsilon(u_i) = 0$ for speeds below cut-in and above cut-off. For speed-controlled turbines $p(u_i) = p(u_r)$ for speeds above rated speed, u_r. Available power in the wind at speeds below cut-in or above cut-off is lost. There is also power lost as turbine collection efficiency varies with wind speed, and still more is lost in higher winds if the turbine is governed at rated power. In routine calculation, a parabolic function is applied as the turbine output curve varies from zero at cut-in to rated power at rated speed. Other specified performance curves, from VAWT systems, for example, may be substituted at this stage of calculation. No assumption is made about actual conversion efficiency at the rated speed; this conversion includes the limiting Betz coefficient as well as internal turbine system losses that would be system specific.

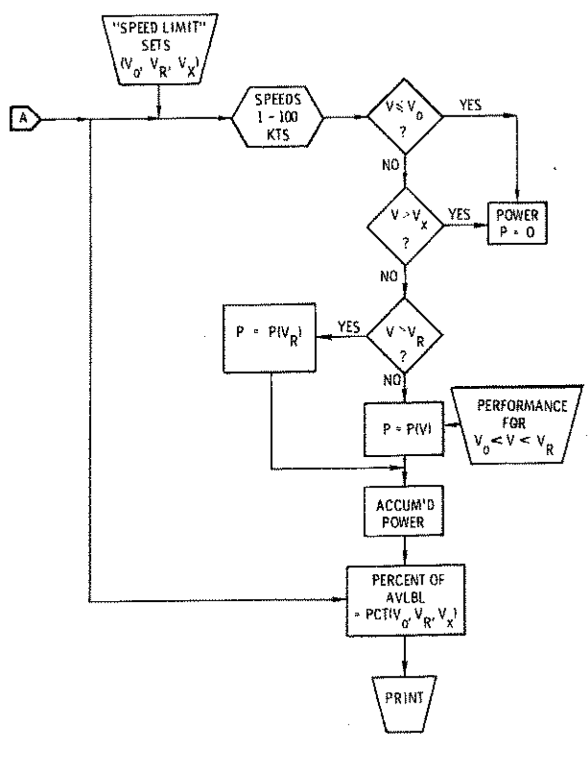

Figure 8. Turbine Speed Limits Analysis Flow Diagram

lag correlation coefficients, $R(\Delta t)$, are calculated for various time intervals Δt, from

$$R(\Delta t) = \frac{1}{\sigma^2(\Phi)} \left[\frac{1}{J} \sum_{j=1}^{J} \Phi(j) \cdot \Phi(j + \Delta t) - P^2(u_n) \right] , \tag{27}$$

where

$$\sigma^2(\Phi) = \frac{1}{J} \sum_{j=1}^{J} \Phi^2(j) - P^2(u_n) . \tag{28}$$

Similar lag correlations are calculated for week-to-week, month-to-month, and year-to-year variations in periodically averaged powers. These statistics should help to define the climatological component of the dependability of wind power extraction systems.

Durations of Light Winds

In this calculation, time series of wind speeds are scanned, logging the duration of occasions with speeds below a prescribed value. In a preliminary run, with Albuquerque data, the extreme lulls in ten years lasted 179 hours at 20 m and 129 hours at 50 m. In an "average" year lulls of 119, 111, and 107 hours should be expected, along with a collection of shorter low-speed intervals. At windier locations, these lulls will probably be of generally shorter duration, but several days of below cut-in speeds can probably be expected each year, even at good sites.

It is not yet clear how these lull statistics can be used by wind turbine planners, but they are frequently requested. It is hoped that a useful format can be generated for presenting these results.

Summary

A procedure has been developed for analyzing time series of wind speed observations for various wind power evaluations. A computer program has been produced to yield wind speed and available wind power PDF and CPF at anemometer level and at selected heights of 10, 20, and 50 meters above flat terrain. Various integrations are performed for total available wind power and for extracted power under assumed models for operating speed limits and turbine response. Wind speed time series are also transformed to wind power time series, which are used to generate time-dependent variability statistics and wind-reliability estimates.

Input wind data, as obtained from NCC archives, frequently required adjustment because the anemometer was moved during the period of record used in time series calculations. A homogeneous record, at one height, is needed for detailed evaluation. A procedure was developed for comparing CPFs for the various anemometer locations and producing appropriate station-specific adjustment functions for generating homogeneous data series. Considerable smoothing of CPFs was found necessary to overcome observer bias in speed recording.

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APPENDIX

Computer Analysis Program

Program Symbols	Definitions or Descriptors	Text Symbols	Text Equations
NBEG(I), I = 1, 4	Start month, day, year, anemometer height	z_1	(4)
5, 8	2d month, day, year, anemometer height	z_2, M	
9, 12	3d month, day, year, anemometer height	z_3, N	
NSTA, ISTA	International Station Index Number		
DAYCK(I, J, K)	Ith year, J days, K hours (leap year corrections)		
NYR	Year in series		
NDAYS	Days in year		
NMS	Hours in year		
SPED(I)	Hourly wind speed (knots)		
IVTAP(I, J)	Wind speed array (hour, day)	$s_k(j)$	
VBAR(I)	Hourly average wind speed		
BZ(I)	Heights above ground (feet)	z	
PK	Coefficient for W/m^2 wind power (knot speeds)	$1/2\rho$	
AZ(I)	Wind speed-height adjustment factors		(11)
PWR(I, J)	Distribution array for wind speed, J		
I = 1	Wind speed, knots	u_i	
2	Occurrences	$T(u_i)$	(12)
3	Percent occurrences (PDF)	$f(u_i)$	(1), (13)
4	Cumulative percent occurrences (CPF)	$F(u_m)$	(3), (13)
5	Smoothed occurrences	$\widetilde{T}(u_i)$	
6	Smoothed PDF	$\widetilde{f}(i)$	(15)
7	Smoothed CPF	$\widetilde{F}(i)$	(14)
8	Wind power potential, W/m^2	$1/2\rho u_i^3$	(16)
9	Wind power contribution, W/m^2	$p(u_i)$	(16)
10	Cumulative power contribution, W/m^2	$P(u_n)$	(17)
11	Percent power contribution (PDF)	$q(i)$	(18)
12	Cumulative percent contribution (CDF)	$Q(m)$	(19)
CUM(I, J, K)	Percent power accumulated with Ith cut-in speed, Jth cut-off speed, Kth rated speed	r	(22)
DEM	Electric demand	$P(u_n)$	
WP	Power production	$\Phi(j)$	(23)
XCS	Excess power produced	$\delta(j)$	(24)

```
C          SPECIAL STATION CORRECTION HERE.
C
C          CORRECTION FOR NANTUCKET, SHORT RECORD,
      IF(NSTA.NE.14658) GO TO 95
      DO 325 NTR=1,3
      NYR=NTR
      IF(NTR.NE.1.AND.NTR.NE.2) NYR=10
      CALL DAYCK(NYR,NDAYS,NMS)
      DO 326 I=1,24
      DO 327 J=1,NDAYS
      IVTAP(I,J)=999
  327 CONTINUE
  326 CONTINUE
 1011 FORMAT(1H ,*HERE I AM, NYR=*,I4)
      WRITE (6,1011) NYR
   64 FORMAT(1H0)
      WRITE (6,64)
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
  325 CONTINUE
      NYR=3
      GO TO 431
C
C          CKTN FOR ENIWETOK, ASSUME 33 FT ANEMOMETER HEIGHT.
   95 CONTINUE
      IF(NSTA.NE.41601) GO TO 96
      BZ(1)=33.
   96 CONTINUE
      NYR=1
  431 CONTINUE
      DO 201 I=1,24
      DO 200 J=1,366
      IVTAP(I,J)=999
  200 CONTINUE
  201 CONTINUE
C          CHECK FOR LEAP YEARS, 1956,1960, 1964.
      CALL DAYCK(NYR,NDAYS,NMS)
C
C          READ ONE DAY OF OBSERVATIONS FROM TAPE.
C
      DO 405 JDAY=1,NDAYS
      READ(10) ISTA,IY,IM,ID,(IH(I), SPED(I),I=1,24)
      IF(EOF(10)) 203,204
  204 CONTINUE
      IF(JDAY.EQ.1.AND.ISTA.NE.NSTA) GO TO 193
C          ERROR IN FILE RECALL, GO TO END.
      DO 207 I=1,24
      IVTAP(I,JDAY)=INT(SPED(I))
  207 CONTINUE
  405 CONTINUE
      GO TO 205
  203 CONTINUE
      IF(NSTA.NE.14658) GO TO 202
      GO TO 205
  202 CONTINUE
      PRINT 1010
 1010 FORMAT(1H ,*EOF FOUND*)
  205 CONTINUE
C
C          ENTER ONE YEAR OF UNCKTD DATA IN MASS STORAGE.
C
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
      WRITE(6,1011) NYR
C          DATA CHECK READOUT
   12 FORMAT(1H ,24I5)
      WRITE (6,12) (IVTAP(I,001),I=1,24)
      WRITE (6,12) (IVTAP(I,150),I=1,24)
      IF(NSTA.NE.14658) GO TO 199
      IF(NYR.GT.8) GO TO 210
      NYR=NYR+1
      GO TO 431
  199 CONTINUE
```

```
      NYR=NYR+1
      IF(NYR.GT.10). GO TO 210
      GO TO 431
C
C            TOTAL UNCKTD RECORD IS IN MASS STORAGE IN ONE YEAR BLOCKS.
C
  210 CONTINUE
C            SHORT CIRCUIT CHECK OF UNCKTD DATA.
      CHECK=0.
   13 FORMAT(1H0,≠AVERAGE HOURLY SPEEDS,RAW AND HEIGHT CORRECTED DATA≠)
      WRITE(6,13)
      GO TO 699
 1012 CONTINUE
      CHECK=1.
C
C
C            THIS SECTION CORRECTS ALL DATA TO THE LATEST RUNWAY
C                ANEMOMETER HEIGHT WHEN NECESSARY.
C
C
      IF(ISTA.EQ.12926) GO TO 600
      IF(ISTA.EQ.23050) GO TO 610
      IF(ISTA.EQ.13893) GO TO 620
      IF(ISTA.EQ.13985) GO TO 630
      IF(ISTA.EQ.14914) GO TO 640
      IF(ISTA.EQ.24143) GO TO 650
      IF(ISTA.EQ.93116) GO TO 660
      IF(ISTA.EQ.24018) GO TO 670
C
C            NO CORRECTION FOR HEIGHT NEEDED AT OTHER STATIONS.
C
      GO TO 699
  600 CONTINUE
C
C            HOMOGENIZATION OF CORPUS CHRISTI RECORD HEIGHTS TO
C            22FT.
      DO 601 NYR=1,6
      CALL DAYCK(NYR,NDAYS,NMS)
      CALL READMS(11,IVTAP(1,1),NMS,NYR)
      DO 602 ND=1,NDAYS
      DO 603 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6000
      IF(X.LE.10.) GO TO 604
      IF(X.LE.23.) GO TO 605
      Y=X/1.163
      GO TO 609
  604 Y=10.959*(1.-SQRT(1.-.09125*X))
      GO TO 609
  605 Y=75.112*(1.-SQRT(1.-.01987*X))
  609 CONTINUE
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6000 CONTINUE
  603 CONTINUE
  602 CONTINUE
C            DATA IN IVTAP CORRECTED TO 22 FT.
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
  601 CONTINUE
      DO 606 NYR=7,10
      CALL DAYCK(NYR,NDAYS,NMS)
      CALL READMS(11,IVTAP(1,1),NMS,NYR)
      DO 607 ND=1,NDAYS
      DO 608 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6001
      IF(              X.LE.20.) GO TO 608
      Y=X*(1.256-.0128*X)
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6001 CONTINUE
  608 CONTINUE
  607 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
  606 CONTINUE
      GO TO 699
```

```
  610 CONTINUE
C
C         HOMOGENIZATION OF ALBUQUERQUE    RECORDS TO   23  FT.
      DO 611 NYR=1,5
      CALL DAYCK(NYR,NDAYS,NMS)
      CALL READMS(11,IVTAP(1,1),NMS,NYR)
      DO 612 ND=1,NDAYS
      DO 613 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6010
      Y=X/1.063
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6010 CONTINUE
  613 CONTINUE
  612 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
  611 CONTINUE
      CALL READMS(11,IVTAP(1,1),NMS,6)
      DO 614 ND=1,35
      DO 615 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6011
      Y=X/1.063
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6011 CONTINUE
  615 CONTINUE
  614 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
      GO TO 699
  620 CONTINUE
C
C         HOMOGENIZATION OF MEMPHIS       RECORDS TO  22FT.
      DO 621 NYR=1,3
      CALL DAYCK(NYR,NDAYS,NMS)
      CALL READMS(11,IVTAP(1,1),NMS,NYR)
      DO 622 ND=1,NDAYS
      DO 623 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6020
      Y=77.19*(1.-SQRT(1.-.02042*X))
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6020 CONTINUE
  623 CONTINUE
  622 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
  621 CONTINUE
      CALL READMS(11,IVTAP(1,1),NMS,4)
      DO 624 ND=1,203
      DO 625 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6021
      Y=77.19*(1.-SQRT(1.-.02042*X))
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6021 CONTINUE
  625 CONTINUE
  624 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,4)
      GO TO 699
  630 CONTINUE
C
C         HOMOGENIZATION OF DODGE CITY    RECORDS TO  20FT.
      DO 631 NYR=1,6
      CALL DAYCK(NYR,NDAYS,NMS)
      CALL READMS(11,IVTAP(1,1),NMS,NYR)
      DO 632 ND=1,NDAYS
      DO 633 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6030
      IF(X.GE.18.) GO TO 636
      Y=40.278*(1.-SQRT(1.-.03424*X))
      GO TO 637
```

```
  636 CONTINUE
      Y=X/1.164
  637 CONTINUE
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6030 CONTINUE
  633 CONTINUE
  632 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
  631 CONTINUE
      CALL READMS(11,IVTAP(1,1),NMS,7)
      DO 634 ND=1,102
      DO 635 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6031
      IF(X.GE.18.) GO TO 638
      Y=40.278*(1.-SQRT(1.-.03424*X))
      GO TO 639
  638 CONTINUE
      Y=X/1.164
  639 CONTINUE
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6031 CONTINUE
  635 CONTINUE
  634 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,7)
      GO TO 699
  640 CONTINUE
C
C          HOMOGENIZATION OF FARGO          RECORDS TO 20 FT.
      DO 641 NYR=1,6
      CALL DAYCK(NYR,NDAYS,NMS)
      CALL READMS(11,IVTAP(1,1),NMS,NYR)
      DO 642 ND=1,NDAYS
      DO 643 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6040
      Y=79.3699*(1.-SQRT(1.-.01659*X))
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6040 CONTINUE
  643 CONTINUE
  642 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
  641 CONTINUE
      CALL READMS(11,IVTAP(1,1),NMS,7)
      DO 644 ND=1,177
      DO 645 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6041
      Y=79.3699*(1.-SQRT(1.-.01659*X))
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6041 CONTINUE
  645 CONTINUE
  644 CONTINUE
      CALL WRITMS(11,IVTAP(1,1),NMS,7)
      GO TO 699
  650 CONTINUE
C
C          HOMOGENIZATION OF GREAT FALLS    RECORDS TO   23  FT.
      DO 651 NYR=1,4
      CALL DAYCK(NYR,NDAYS,NMS)
      CALL READMS(11,IVTAP(1,1),NMS,NYR)
      DO 652 ND=1,NDAYS
      DO 653 IHR=1,24
      X=FLOAT(IVTAP(IHR,ND))
      IF(X.EQ.999.) GO TO 6050
      Y=X/1.184
      CALL RNDOF(Y ,IVTAP(IHR,ND))
 6050 CONTINUE
  653 CONTINUE
  652 CONTINUE
```

```
6813 CONTINUE
     X= 36.604*(1.-SQRT(1.-.03877*FLOAT(IVTAP(IHR,ND))))
6812 CONTINUE
     CALL RNDOF(X,IVTAP(IHR,ND))
6810 CONTINUE
 647 CONTINUE
 686 CONTINUE
     CALL WRITMS(11,IVTAP(1,1),NMS,NYR)
 685 CONTINUE
     GO TO 699
C
C         INSERT OTHER STATION CKTN ROUTINES HERE.
C
 699 CONTINUE
C
C
C         DATA IN MASS STORAGE NORMALIZED TO FINAL ANEMOMETER HEIGHT.
C
C
C         TEST PROBLEM, HOURLY AVERAGE WINDS SPEEDS.
     DO 440 NYR=1,10
     CALL DAYCK(NYR,NDAYS,NMS)
     CALL READMS(11,IVTAP(1,1),NMS,NYR)
     DO 302 IHR=1,24
     ISUM=0
     DO 301 JDAY=1,NDAYS
      IF(IVTAP(IHR,JDAY).EQ.999) GO TO 4000
     ISUM=ISUM+IVTAP(IHR,JDAY)
     GO TO 301
4000 CONTINUE
     IMSG(IHR)=IMSG(IHR)+1
 301 CONTINUE
     VRAR(IHR)=VRAR(IHR)+FLOAT(ISUM)
 302 CONTINUE
 440 CONTINUE
     DO 450 IHR=1,24
     VRAR(IHR)-VRAR(IHR)/(3653.-FLOAT(IMSG(IHR)))
 450 CONTINUE
  10 FORMAT(1H ,24F5.2)
     WRITE(6,10) VRAR
     WRITE(6,12) IMSG
     DO 4501 I=1,24
     VRAR(I)=0.
     IMSG(I)=0
4501 CONTINUE
     IF(CHECK.EQ.0.) GO TO 1012
     WRITE(6,64)
C
C         PREPARE SPEED SERIES AT 10, 20, AND 50 METER HEIGHTS.
C
     DO 451 MA=1,3
     MB=MA+1
     AZ(MA)=(BZ(MB)/BZ(1))**(1./7.)
 451 CONTINUE
     DO 710 IZ=1,3
     NYR=1
     NYS=10*IZ+1
     NYT=NYS+9
     DO 799 NYR=NYS,NYT
     CALL DAYCK(NYR,NDAYS,NMS)
     CALL READMS(11,IVTAP(1,1),NMS,NYR)
     DO 700 ND=1,NDAYS
     DO 701 IHR=1,24
     X=FLOAT(IVTAP(IHR,ND))
     IF(X.EQ.999.) GO TO 701
     IF(X.EQ.  0.) GO TO 701
     Y=AZ(IZ)*X
     CALL RNDOF(Y ,IVTAP(IHR,ND))
 701 CONTINUE
 700 CONTINUE
```

```
      CALL WRITMS(11,IVTAP(1,1),NMS,NYQ)
      NYR=NYR+1
  700 CONTINUE
  710 CONTINUE
C
C          FOUR HEIGHT SERIES IN MASS STORAGE.
C
C
C          WIND SPEED COLUMN
C
      DO 110 J=1,101
      IPWR(1,J)=J-1
  110 CONTINUE
      IPWR(1,102)=999
      DO 120 IZ=1,4
C
C          CLEAR PWR ARRAY.
C
      PC(IZ)=0.
      DO 109 J=1,102
      DO 108 I=2,13
      IPWR(I,J)=0
      PWR(I,J)=0.
  108 CONTINUE
  109 CONTINUE
      ISUMP=0
      NYR=1
      NYT=10*IZ
      NYS=NYT-9
C
C          CALCULATE PWR-ARRAY ONE YEAR AT A TIME.
C
      DO 121 NYQ=NYS,NYT
      CALL DAYCK(NYR,NDAYS,NMS)
      CALL READMS(11,IVTAP(1,1),NMS,NYQ)
      DO 122 ND=1,NDAYS
      DO 123 IHR=1,24
      IX=IVTAP(IHR,ND)
      IF(IX.EQ.999) GO TO 124
      IF(IX.GE.100) GO TO 125
      GO TO 126
  124 CONTINUE
      ISPD=102
      GO TO 127
  125 CONTINUE
      ISPD=101
      ISUMP=ISUMP+1
      GO TO 127
  126 CONTINUE
      ISPD=IX+1
      ISUMP=ISUMP+1
  127 CONTINUE
C
C          ACCUMULATE SPEED OCCURRENCES.
C
      IPWR(2,ISPD)=IPWR(2,ISPD)+1
  123 CONTINUE
  122 CONTINUE
      NYR=NYR+1
  121 CONTINUE
      SUMP=ISUMP
C
C          OCCURRENCES TABBED, CALCULATE PCT OCC FREQ AND CUM PCT FRQ.
C
      DO 128 ISPD=1,101
      PWR(3,ISPD)=100.*(FLOAT(IPWR(2,ISPD))/SUMP)
      IF(ISPD .EQ.1) GO TO 129
      IN=ISPD-1
      PWR(4,ISPD)=PWR(4,IN)+PWR(3,ISPD)
      GO TO 128
  129 CONTINUE
      PWR(4,1)=PWR(3,1)
  128 CONTINUE
C
```

```
C          MONTHLY SUMMARIES  PRINT HERE.
C
   15 FORMAT (1H ,I2,12F10.3)
   16 FORMAT (1H0,≠MO.     ≠,10(I2,8X),≠AVG.      S.D.≠)
   17 FORMAT (1H0, 52X,≠YEAR≠)
   18 FORMAT (1H0,≠MONTHLY PRODUCTION SUMMARIES≠)
      WRITE (6,18)
      WRITE (6,14) PZ(IZ)
      WRITE (6,17)
      WRITE (6,16) (L,L=1,10)
      DO 540 LM=1,12
      WRITE (6,15) LM,(WPY(NYR,LM,3),NYR=1,10),(WPAVG(LM,L),L=1,2)
  540 CONTINUE
  500 CONTINUE
      GO TO 194
   26 FORMAT (1H0,≠WRONG STATION SELECTION≠)
  193 WRITE (6,26)
  194 CONTINUE
      STOP
      END
      SUBROUTINE DAYCK(NYR,NDAYS,NMS)
C
C          NUMBER OF DAYS DETERMINED FOR REGULAR OR LEAP YEAR.
C
      NDAYS=365
      NMS=8760
      IF(NYR.NE.2.OR.NYR.NE.6.OR.NYR.NE.10) GO TO 420
      NDAYS=366
      NMS=8784
  420 CONTINUE
      RETURN
      END
      SUBROUTINE RNDOF(ARG,IARG)
C
C          FLOATING POINT ENTRIES ROUNDED OFF AND OUTPUT AS INTEGER.
C
      DARG=FLOAT(INT(ARG))
      D=ARG-DARG
      IF(D.LT.0.5) GO TO 1200
      ARG=1.+DARG
      GO TO 1201
 1200 CONTINUE
      IARG=INT(DARG)
      GO TO 1202
 1201 CONTINUE
      IARG=INT(ARG)
 1202 CONTINUE
      RETURN
      END
```

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