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SIMULATION OF WIND SPEED TIME SERIES FOR WIND ENERGY CONVERSION ANALYSIS

By
R. B. Corotis

August 1982

Work Performed Under Contract No. AC06-76RL01830

The Johns Hopkins University
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EXECUTIVE SUMMARY

In order to investigate operating characteristics of a wind energy conversion system it is often desirable to have a sequential record of wind speeds. Sometimes a long enough actual data record is not available at the time an analysis is needed. This may be the case if, e.g., data are recorded three times a day at a candidate wind turbine site, and then the hourly performance of generated power is desired. In such cases it is often possible to use statistical characteristics of the wind speed data to calibrate a stochastic model and then generate a simulated wind speed time series. Any length of record may be simulated by this method, and desired system characteristics may be studied.

A simple wind speed simulation model, WEISIM, is developed based on the Weibull probability distribution for wind speeds with a correction based on the lag-one autocorrelation value. The model can simulate at rates from once a second to once an hour, and wind speeds can represent short-term averages (e.g. 1-sec averages) or longer-term averages (e.g. 1-min or 1-hr averages). The validity of the model is verified with PNL data, which is data collected at MOD-OA wind turbine sites, for both histogram characteristics and persistence characteristics.

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CHAPTER ONE

INTRODUCTION

This report contains the description of a versatile real-time wind speed simulation model. The model is based on modified Weibull distributions using assumptions of a Gauss-Markov sequence. Simulated wind speeds are compared to Pacific Northwest Laboratory (PNL)[a] high-frequency data and National Weather Service (NWS) data in terms of probability histograms, autocorrelation, and persistence. Emphasis is on the high-frequency data (about 1 Hz) since a previous report (Corotis 1980) compared results with NWS data. The high-frequency wind speed tapes were supplied by PNL. They contain 1-sec average wind speeds recorded once every 2 seconds from three heights on the meteorological tower at the Clayton, New Mexico, MOD-OA, 200 kW wind turbine site (height 1 = 9.1 m, height 2 = 30.0 m, and height 3 = 45.7 m) and two heights at the Amarillo, Texas, candidate site (height 1 = 9.1 m and height 2 = 45.7 m). The Clayton tape also contains wind speed from the turbine nacelle anemometer and turbine power output. This data collection program is described in more detail in Renné et al. (1982).

(a) Operated for the Department of Energy by the Battelle Memorial Institute

CHAPTER TWO

PROBABILITY DISTRIBUTION OF WIND SPEED

No probability density function (PDF) has been widely accepted to model the type of high-frequency data utilized here. It has been shown that the Rayleigh and Weibull distributions (Wentink 1976; Cliff 1977; Doran, Bates, Liddell, & Fox 1977; Justus 1978; Corotis, Sigl, & Klein 1978; Chou & Corotis 1981) can model wind speeds recorded hourly using a 1-min averaging time. In order to facilitate a comparison and analysis of the applicability of these two PDFs to high-frequency wind speed data, a summary description of the distributions follows.

The Rayleigh distribution can be derived as the magnitude of the vector sum of two orthogonal wind velocity components. The derivation assumes the two velocity components to be independent and identically distributed, zero-mean, Gaussian random variables. The PDF is given by

$$f_V(v) = \frac{\pi v}{2m^2} \exp\left[-\frac{\pi}{4}\left(\frac{v}{m}\right)^2\right] \tag{2.1}$$

in which

$$m = E[V] = \sigma\sqrt{\frac{\pi}{2}} \tag{2.2}$$

and the cumulative distribution function (CDF) is given by

$$F_V(v) = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{v}{m}\right)^2\right] \tag{2.3}$$

The variance is directly related to the mean by

$$\mathrm{Var}[V] = \left[\frac{4}{\pi} - 1\right]E^2[V] = \left[\frac{4-\pi}{2}\right]\sigma^2 \tag{2.4}$$

Thus, the coefficient of variation, V_i, is constant and is

$$V_i = \sqrt{\frac{\mathrm{Var}[V]}{E^2[V]}} = \sqrt{\frac{4}{\pi} - 1} = 0.523 \tag{2.5}$$

The Weibull PDF can be derived from the Type III asymptotic extreme value distribution for smallest values (Benjamin & Cornell 1970) where the wind velocities are assumed to have a lower limit of zero, resulting in the PDF

$$f_V(v) = \left[\frac{kv^{k-1}}{c^k}\right] \exp\left[-\left(\frac{v}{c}\right)^k\right] \tag{2.6}$$

where k and c are the shape and scale parameters, respectively. These are related to the mean and variance by

$$m_v = c\,\Gamma(1 + \frac{1}{k}) \tag{2.7}$$

$$\sigma_v^2 = c\left[\Gamma(1 + \frac{2}{k}) - \Gamma^2(1 + \frac{1}{k})\right] \tag{2.8}$$

where Γ is the gamma function.

Calculations of the Rayleigh and Weibull distributions calibrated by the method of moments were included with high-frequency data analysis in a computer program named HISTO (Corotis 1977). Selected results of the analysis are shown in Figures 2.1 through 2.4. Chi square and Kolmogorov-Smirnov (K-S) goodness-of-fit tests were also calculated and Tables 2.1 and 2.2 show the values for the hours of sampled data. The K-S test is dependent on the number of independent samples, n, which, in the case of a continuous correlated time series with decaying exponential autocorrelations, is given by (Corotis 1974)

$$n = \frac{(at)^2}{2at + e^{-at}-2} \quad \text{and } a = -\ell n \rho \tag{2.9}$$

where t is the length of the sampling time and ρ is the lag-one autocorrelation. Although this expression is not strictly applicable for the discrete case, the curve, which is shown in Figure 2.5, provides an upper bound on the number of independent samples for a given lag-one autocorrelation.

Both the Rayleigh and Weibull distributions did not pass the chi square test. The high tail regions contributed most of the value to this test and grouping the data differently would improve the numbers, but not enough to pass the test at reasonable significance levels. The Rayleigh distribution did not pass the K-S test in any instance for the 10% significance level, however, the Weibull distribution did.

Further difficulties of matching the actual distributions with the Rayleigh distribution occur when the coefficient of variation, V_i, is compared to the actual data. For these data, the range of V_i is from 0.104 to 0.190, whereas the Rayleigh has a constant V_i of 0.523. This restriction inhibits the distribution from adequately modeling the dispersion of the actual data

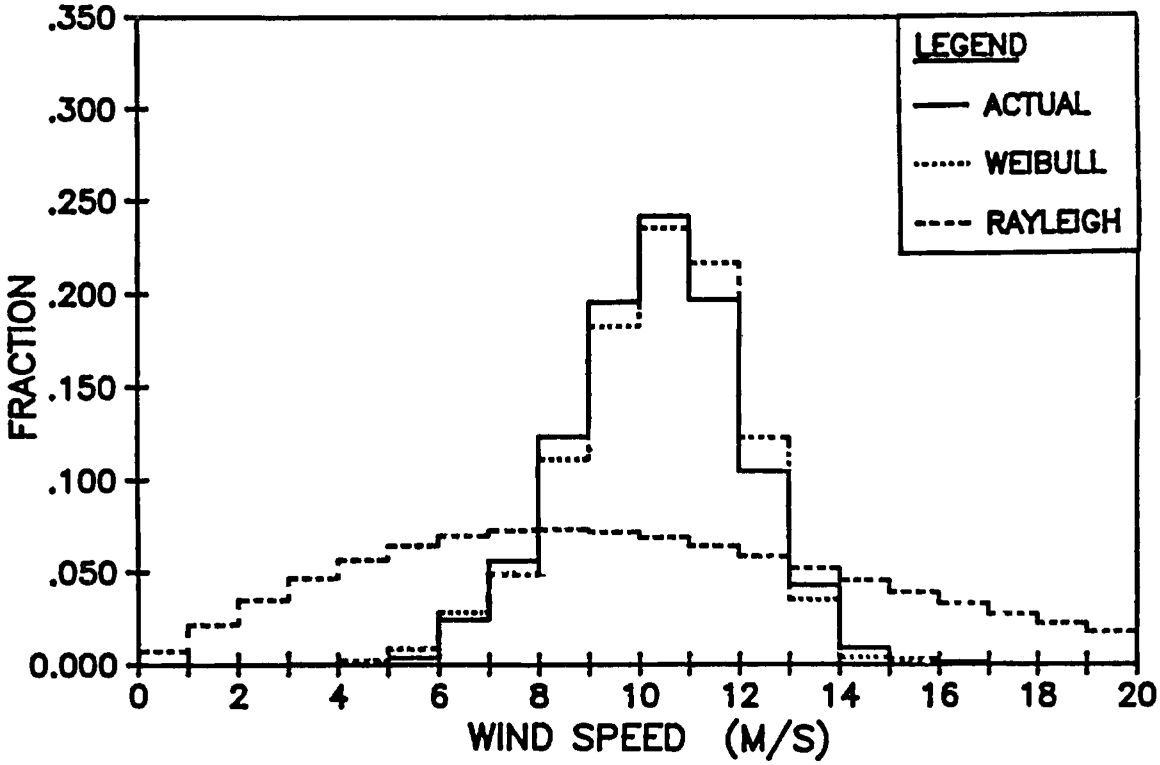

Figure 2.1 Histograms of Wind Speed Distribution for Clayton, New Mexico, 9.1 m, Hour 1

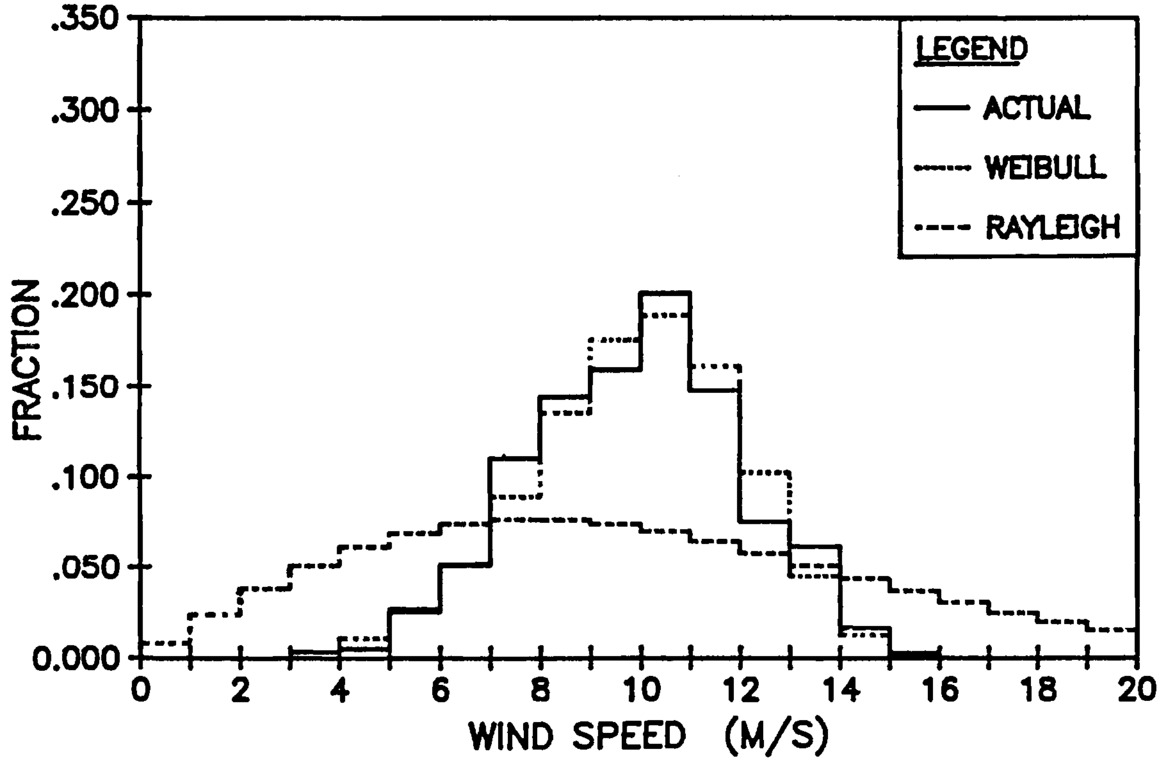

Figure 2.2 Histograms of Wind Speed Distribution for Clayton, New Mexico, Nacelle, Hour 2

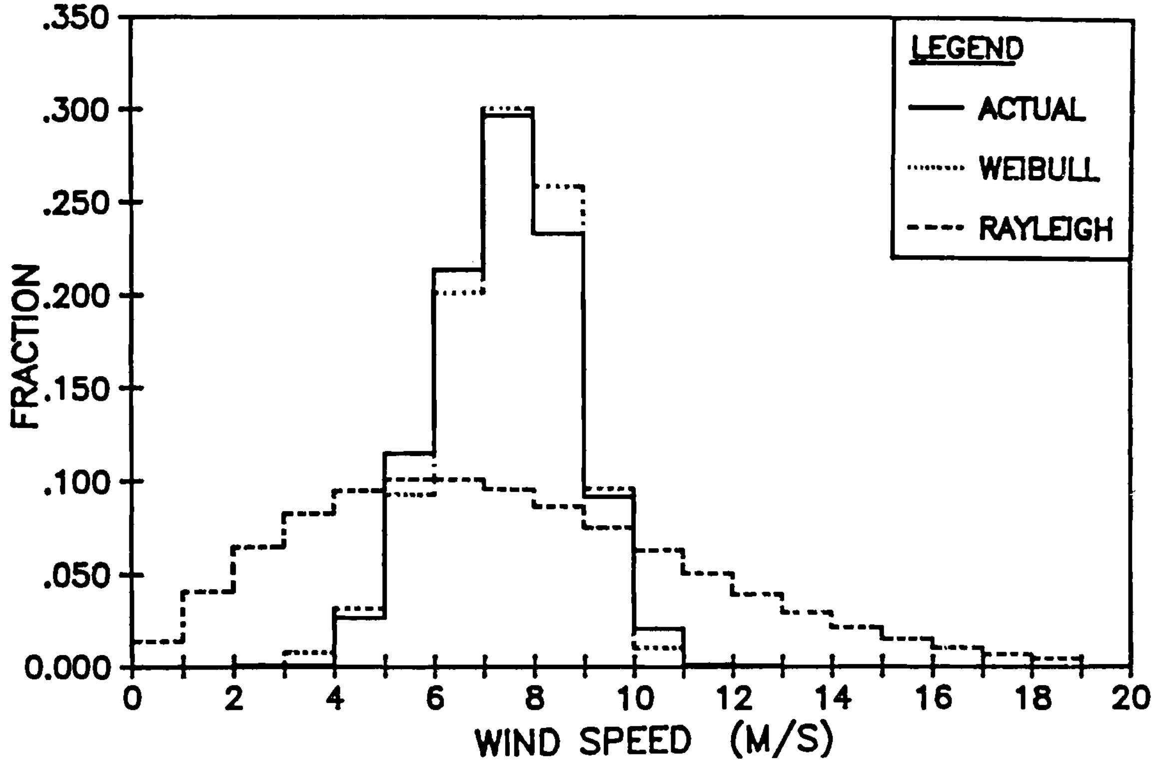

Figure 2.3 Histograms of Wind Speed Distribution for Amarillo, Texas, 9.1 m, Hour 2

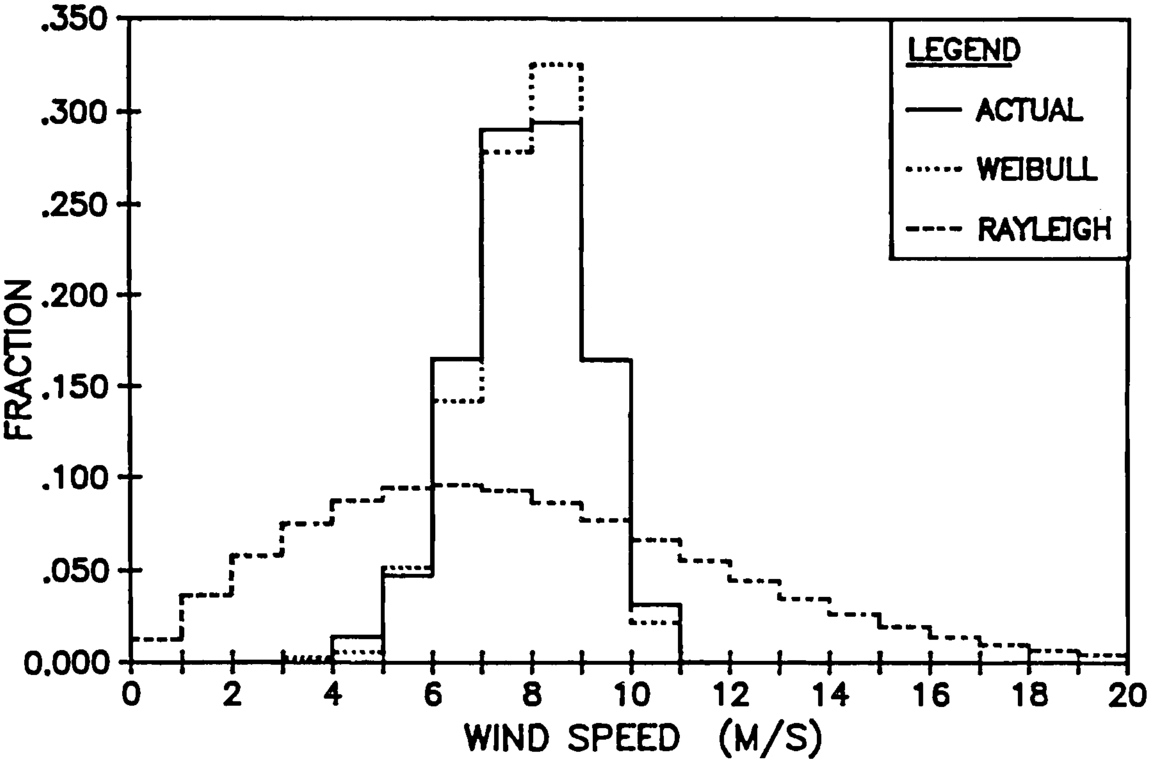

Figure 2.4 Histograms of Wind Speed Distribution for Amarillo, Texas, 45.7 m, Hour 4

TABLE 2.1. Goodness-of-Fit Values for Clayton, New Mexico

Height	Hour	Rayleigh		Weibull		10% Significance Limit	
		Chi Square	K-S	Chi Square	K-S	Chi Square	K-S
9.1 m	1	2192	.2885	520.7	.0303	14.5	0.0958
	2	1812	.2714	169.5	.0493	14.5	0.0996
	3	2368	.2921	157.6	.0210	14.5	0.0996
30.0 m	1	2967	.3271	138.1	.0512	13.5	0.1239
	2	2384	.2976	183.3	.0477	14.5	0.1171
	3	3313	.3080	35.3	.0217	13.5	0.1152
45.7 m	1	2903	.3296	480.8	.0551	13.5	0.1274
	2	2724	.3147	292.2	.0484	14.5	0.1267
	3	3733	.3317	58.0	.0282	13.5	0.1181
Nacelle	1	1828	.2781	267.7	.0581	13.5	0.1812
	2	1423	.2403	55.4	.0224	16.0	0.1632
	3	2181	.2746	34.2	.0194	13.5	0.1925

TABLE 2.2. Goodness-of-Fit Values for Amarillo, Texas

		Rayleigh		Weibull		10% Significance Limit	
Height	Hour	Chi Square	K-S	Chi Square	K-S	Chi Square	K-S
9.1 m	1	1928	0.281	70.8	0.0391	12.0	0.127
	2	1937	0.269	43.1	0.0218	9.2	0.151
	3	1625	0.253	51.5	0.0285	10.5	0.177
	4	2191	0.301	171.7	0.0476	9.2	0.105
	5	2286	0.306	684.1	0.0837	9.2	0.157
	6	2239	0.312	157.0	0.0420	7.8	0.141
	7	2897	0.345	811.9	0.1107	6.2	0.146
45.7 m	1	2690	0.319	188.9	0.0418	10.5	0.131
	2	2713	0.305	53.1	0.0302	10.5	0.171
	3	2357	0.290	24.5	0.0266	9.2	0.147
	4	2473	0.308	31.7	0.0213	9.2	0.120
	5	2442	0.323	138.5	0.0472	7.8	0.171
	6	2771	0.341	127.2	0.0458	7.8	0.168
	7	4433	0.355	76.3	0.0680	6.2	0.146

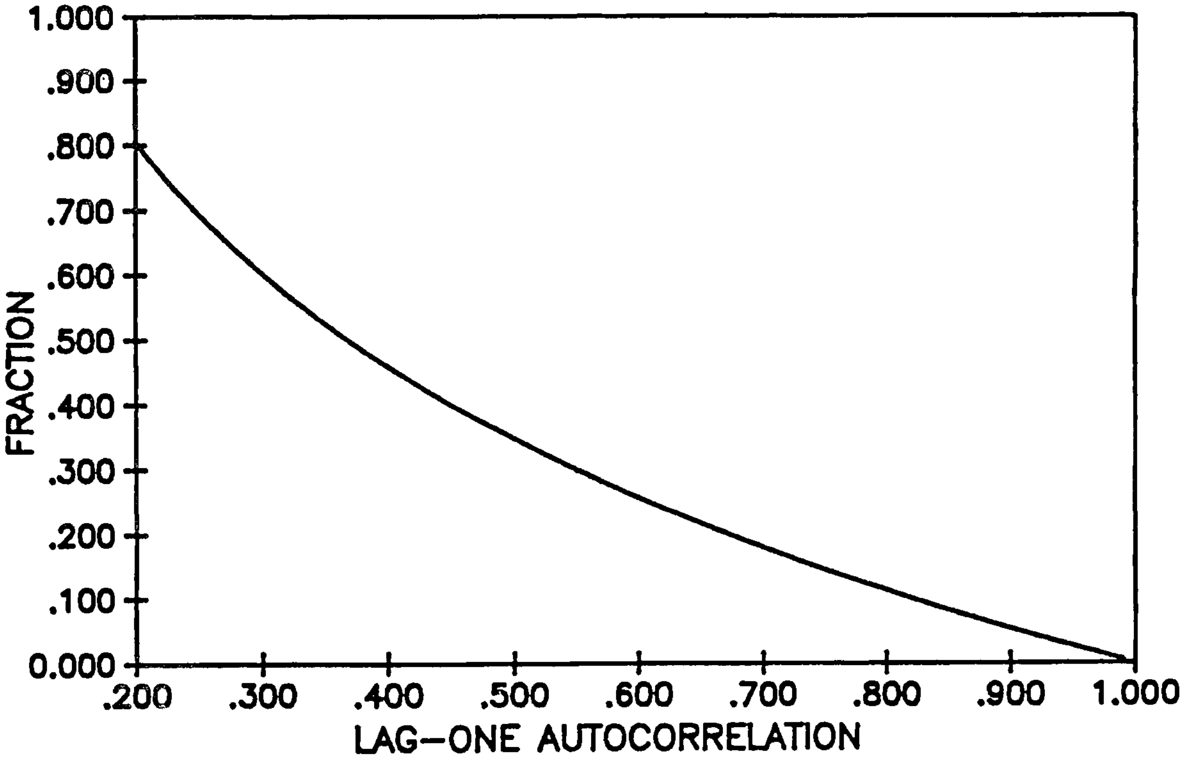

Figure 2.5 Fraction of Total Sample That Is Independent for A Lag-One Autocorrelation

so that the Rayleigh must be considered an unacceptable model for high-frequency wind speeds. This also implies that an inadequate representation would result from modeling the wind speed components as independent, Gaussian-distributed random variables.

The Weibull distribution is a two-parameter distribution which can exactly match both the mean and standard deviation of the actual data. The histograms and K-S tests indicate that the Weibull also adequately models the general shape of the data distribution. If better agreement with actual data is required, one should consider the use of a shifted Weibull (Appendix B). Although parameter calculation involves the gamma function, which is not very tractable, present high-speed digital computers greatly simplify this calculation.

CHAPTER THREE

WEISIM SIMULATION MODEL

An earlier study by Corotis, Sigl and Cohen (1977) indicates that the temporal correlation of hourly wind speed is well approximated by a decaying exponential with a superimposed sinusoid for the diurnal cycle. The actual high frequency data provided for this study do not form a long enough record to ascertain the diurnal variation, but the autocorrelations, up to a lag time of 150 sec, show reasonable agreement with a decaying exponential (Figures 3.1 and 3.2). Since the wind speeds have a nonzero autocorrelation, any realistic wind speed simulation program must condition the new values on previous values.

The WEISIM model, developed by Chou & Corotis (1981), performs the simulation of a correlated time series of hourly wind speeds based on the Weibull distribution. An alternative approach for hourly wind speed simulation was also developed by (Ramsdell et al. 1981). The simulation utilizes an approximate procedure for the Weibull distribution with a conditional mean and variance given by

$$m_{i/i-1} = E\left[V_i \middle| V_{i-1} = v_{i-1}\right] = m_i + \rho\left[\frac{v_{i-1} - m_{i-1}}{\sigma_{i-1}}\right]\sigma_i \qquad (3.1)$$

$$\sigma^2_{i|i-1} = \mathrm{Var}\left[V_i \middle| V_{i-1} = v_{i-1}\right] = (1 - \rho^2)\,\sigma_i^2 \qquad (3.2)$$

in which ρ is the autocorrelation between V_i and V_{i-1}. Equations 3.1 and 3.2 are the exact conditional expressions in the case of a Gaussian distribution. High frequency wind speeds with a Weibull distribution and an exponentially decaying autocorrelation can be approximately simulated by the WEISIM model. However, when the lag-one autocorrelation exceeds 0.75, the approximation used in WEISIM creates a tendency for the simulated variable to have too high a standard deviation, e.g., when the lag-one autocorrelation exceeds 0.9 the simulated wind speeds have a standard deviation as much as two times the input standard deviation. This results from the use of an adjusted Weibull marginal distribution in lieu of a conditional distribution. Thus, a method for correcting this discrepancy was developed which, depending on the characteristics of the simulation desired, can be used to create a good model for predicting wind speed distribution or persistence. A description of the

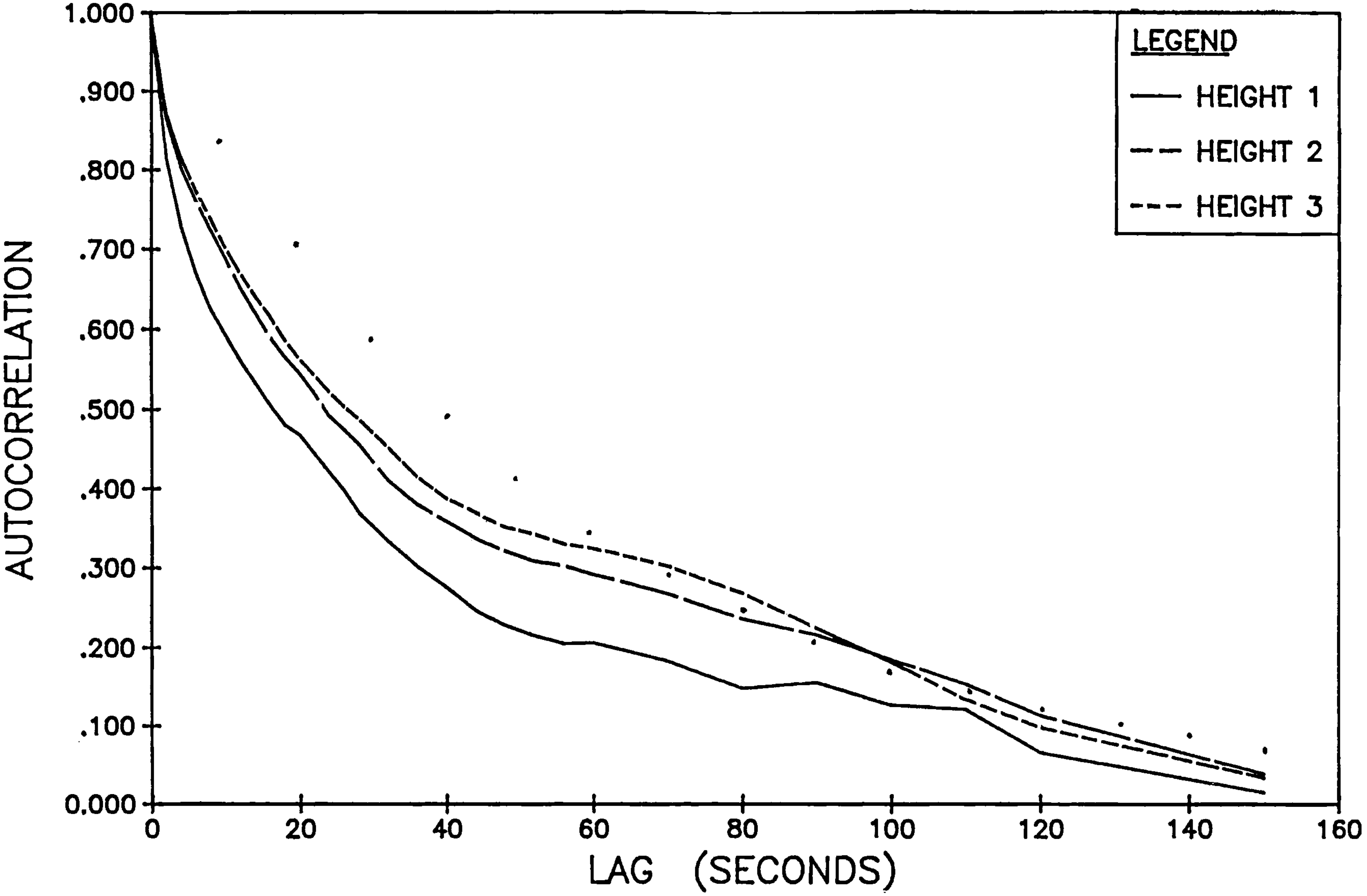

Figure 3.1 Autocorrelations for The Three Meteorological Tower Heights at Clayton, New Mexico, with Dotted Line Showing Exact Exponential

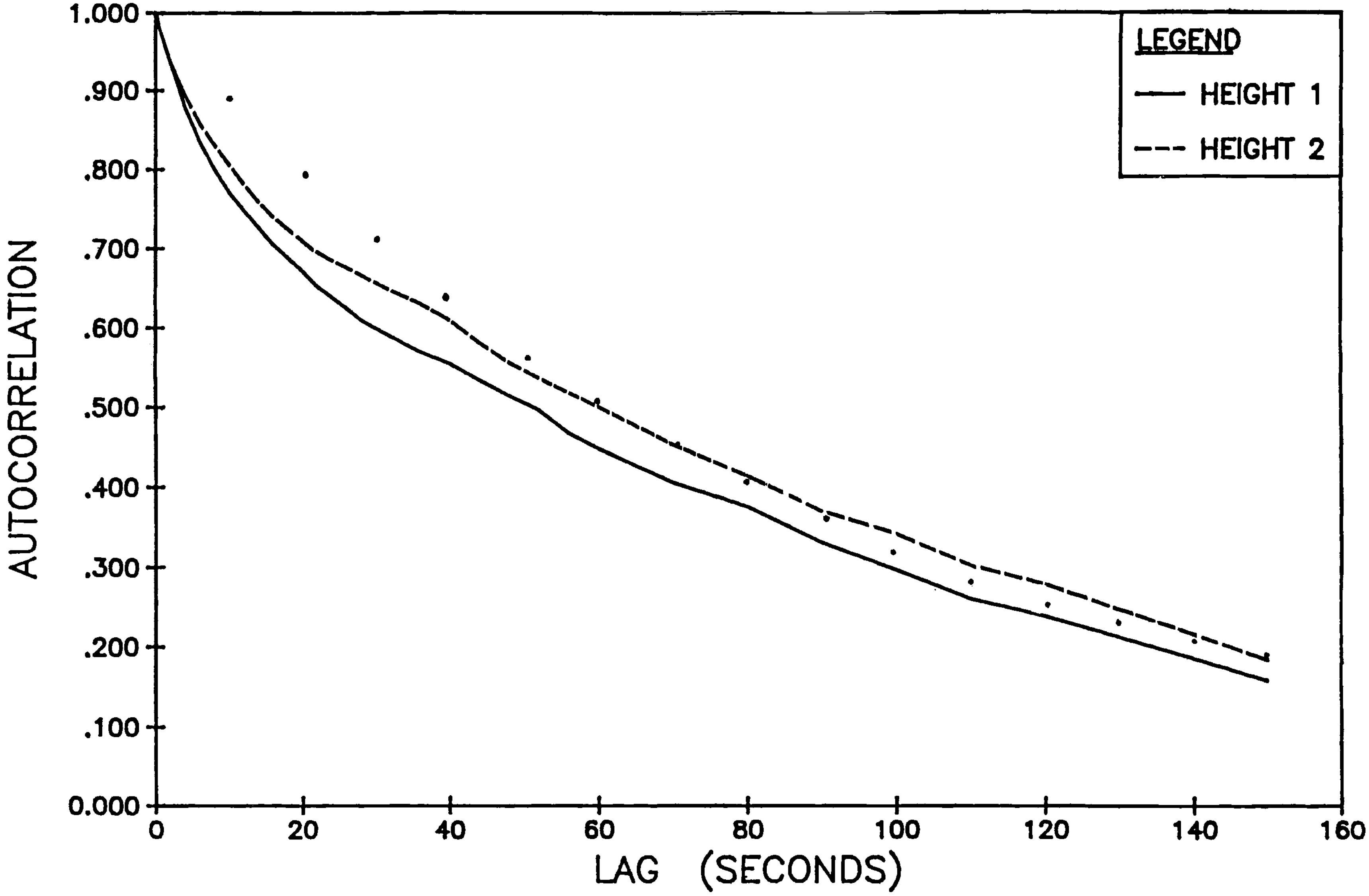

Figure 3.2 Autocorrelations for The Two Meteorological Tower Heights at Amarillo, Texas, with Dotted Line Showing Exact Exponential

program is provided in Appendix C.

The differences in simulated and actual wind speed autocorrelations can be seen in Figures 3.3 to 3.6, which show linear and semi-log plots of the actual data with two different simulations, one using the actual lag-one autocorrelation and the other using a corrected lag-one to pass through the 1/e value of the actual data. The autocorrelation of the simulated data is more exponentially distributed, due to the application of the exact Gaussian conditional (Equations 3.1 and 3.2), which assumes exponential autocorrelation.

It can be seen that the overall autocorrelation behavior is best modeled when the assumed exponential function has an effective lag-one value, ρ_e, somewhat higher than the actual lag-one autocorrelation value, ρ_a. This improves the autocorrelation of simulated data to more closely approximate that of the actual data. This equivalent autocorrelation, ρ_e, was chosen to yield persistence results that were in good agreement with actual data. Based on observed ρ_a values ranging from 0.81 to 0.95, a linear regression analysis was performed between the ρ_e thus chosen and the actual lag-one autocorrelation. The linear relationship between ρ_e and ρ_a can be reasonably used in the range of 0.75 to 0.95 for ρ_a because ρ_e approaches ρ_a when $\rho_a = 0.75$. For ρ_a values below 0.75 satisfactory results are obtained using ρ_a directly (Chou & Corotis, 1981). Thus, in WEISIM, the equivalent autocorrelation, ρ_e, used in the simulation is given by

$$\rho_e = \rho_a; \quad \text{if } \rho_a \leq 0.75 \tag{3.3}$$

and from the linear regression analysis,

$$\rho_e = 1.153\rho_a - 0.1034; \quad \text{if } 0.75 \leq \rho_a \leq 0.95 \text{ .} \tag{3.4}$$

The last relation exhibited a correlation of fit of 0.992.

Histograms of data by hour are shown in Figures 3.7 to 3.10, and the hourly statistics are presented in Tables 3.1 and 3.2. Three separate, consecutive hours of data are shown on the same graph to indicate the hourly variation in distribution. The hourly means and standard deviations are similar so that random hourly fluctuations in the histogram shape create most of the observable differences. Wind speeds were simulated for Clayton and Amarillo at the elevations where actual data were recorded. Selected results

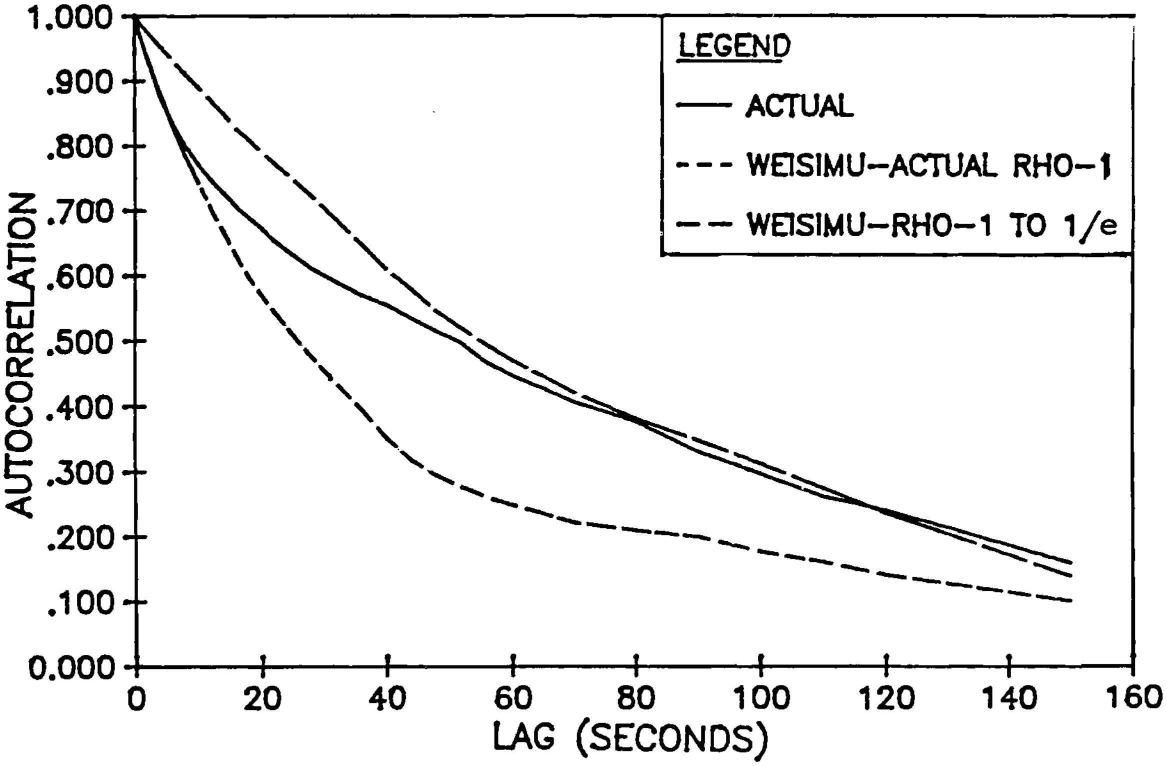

Figure 3.3 Autocorrelation Function on A Linear Scale at Amarillo, Texas, 9 .1 m

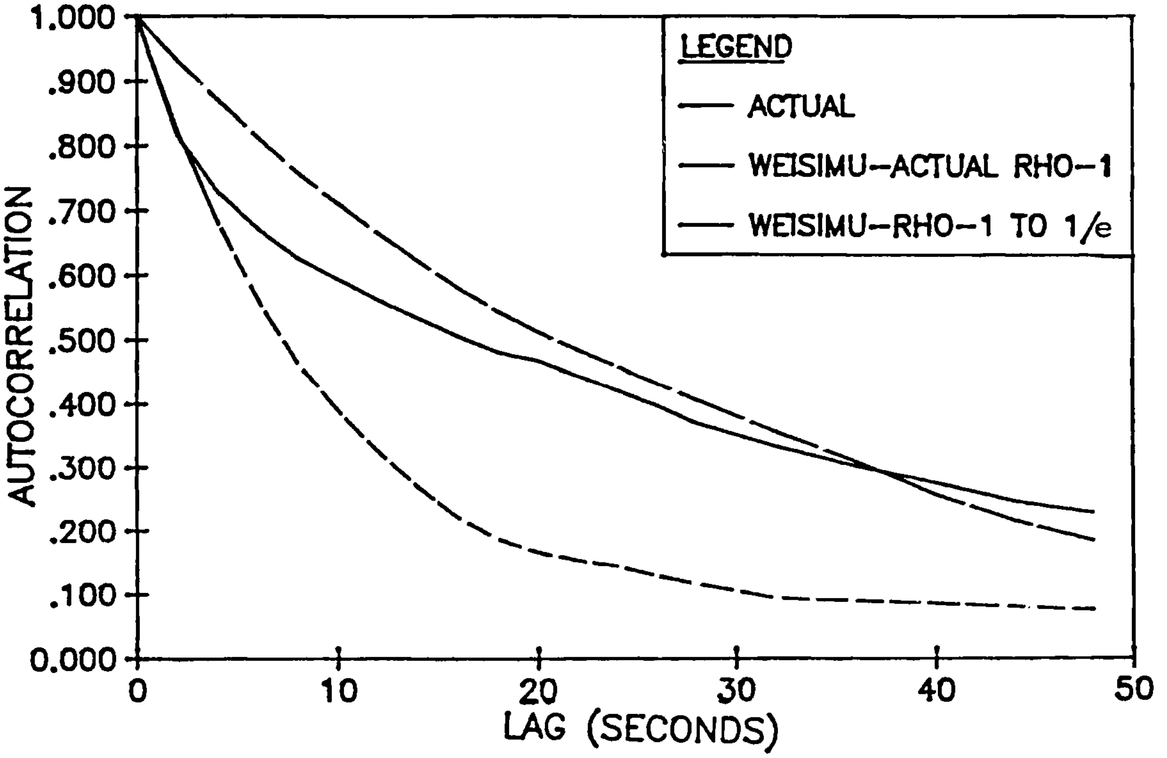

Figure 3.4 Autocorrelation Function on A Linear Scale at Clayton, New Mexico, 9.1 m

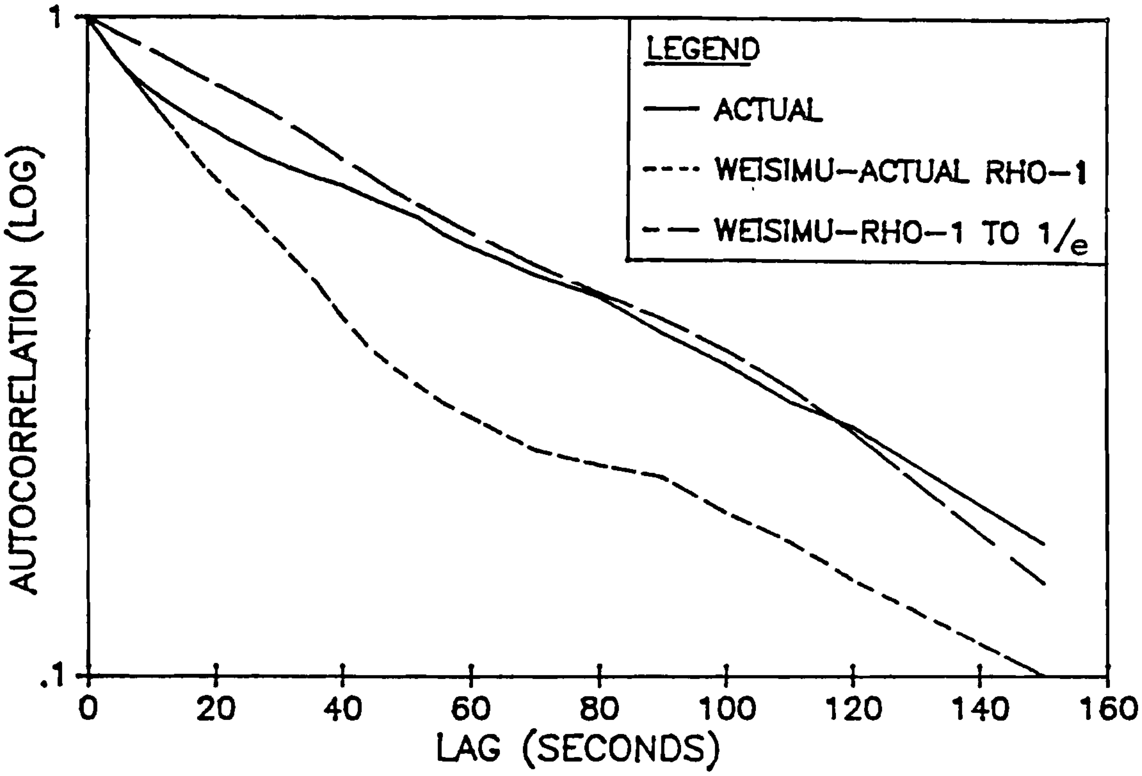

Figure 3.5 Autocorrelation Function on A Semi-Log Scale at Amarillo, Texas, 9.1 m

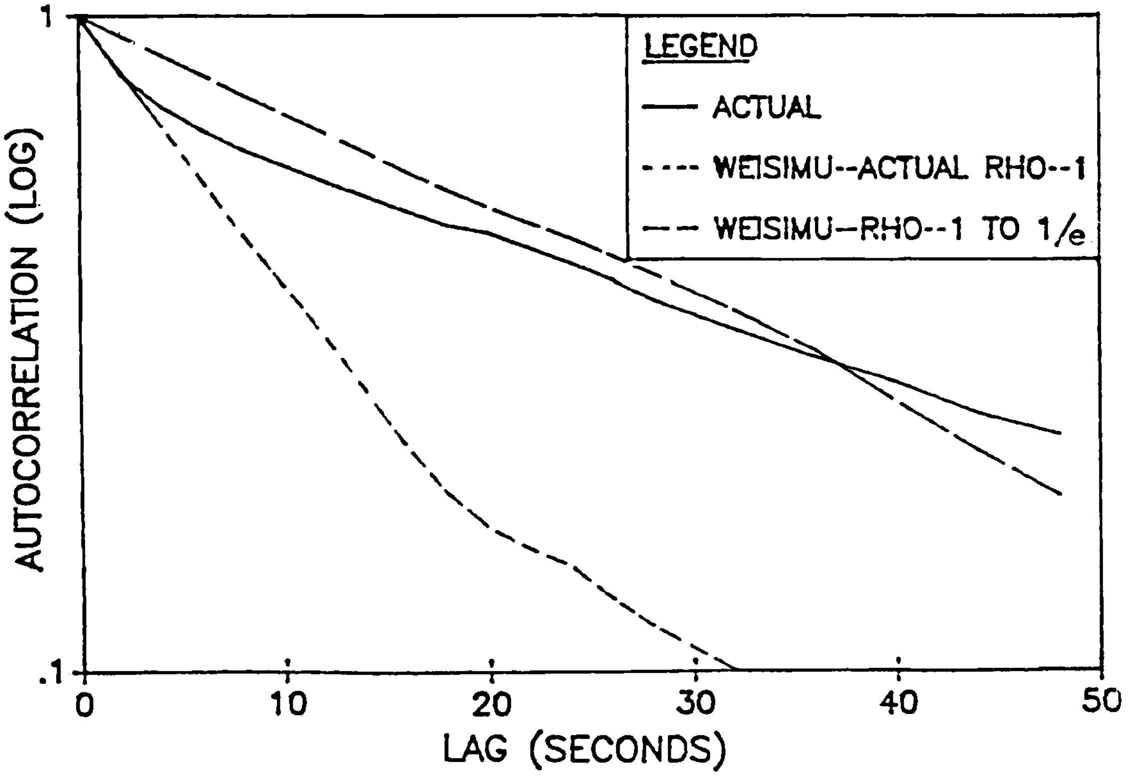

Figure 3.6 Autocorrelation Function on A Semi-Log Scale at Clayton, New Mexico, 9.1 m

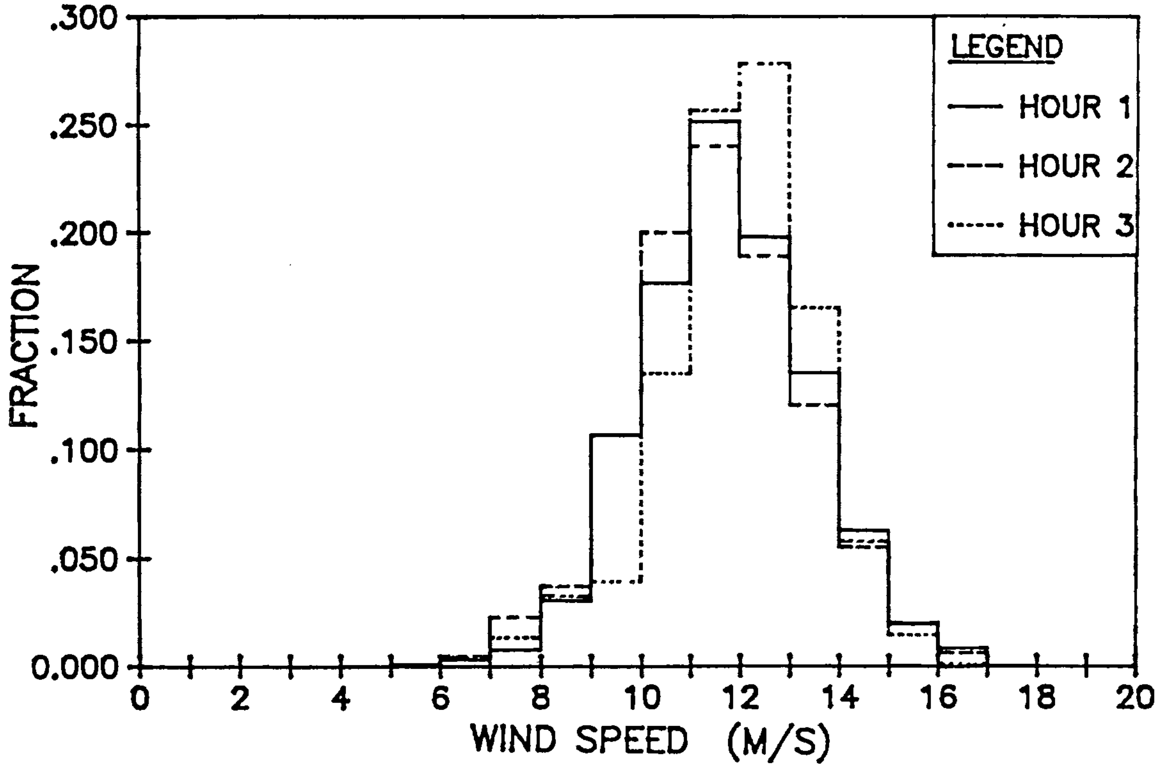

Figure 3.7 Histograms of Wind Speed Distribution for Three Hours at Clayton, New Mexico, 45.7 m

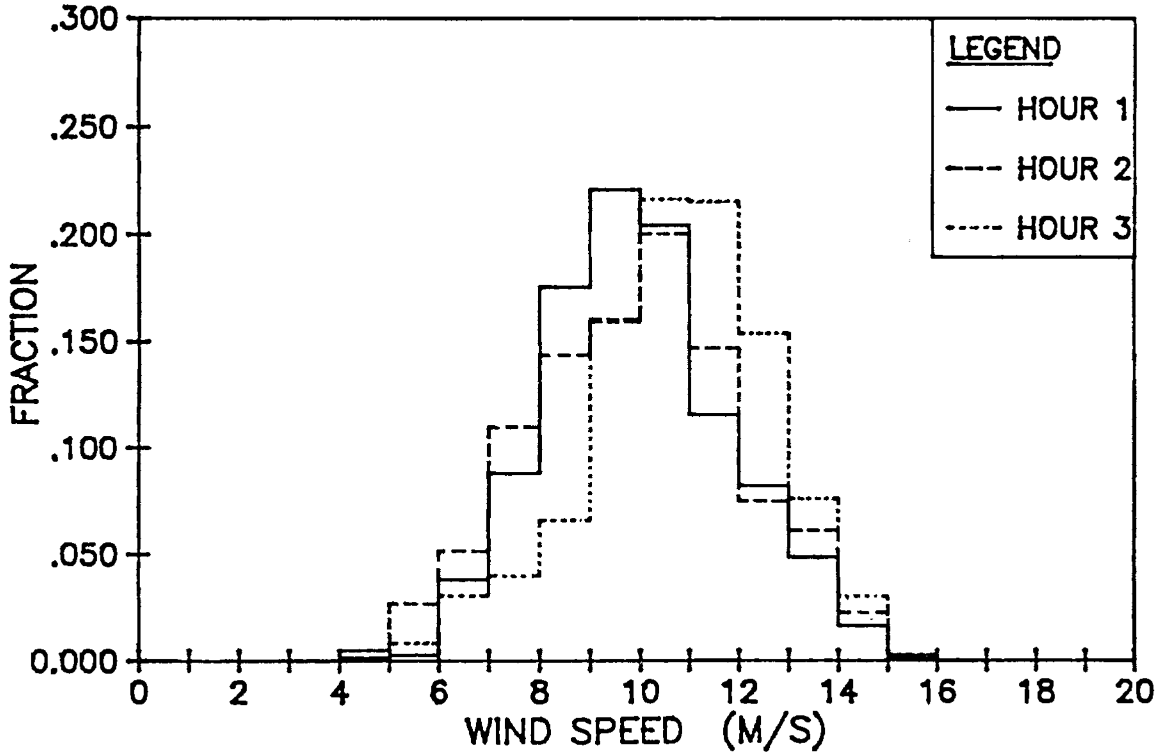

Figure 3.8 Histograms of Wind Speed Distribution for Three Hours at Clayton, New Mexico, Nacelle

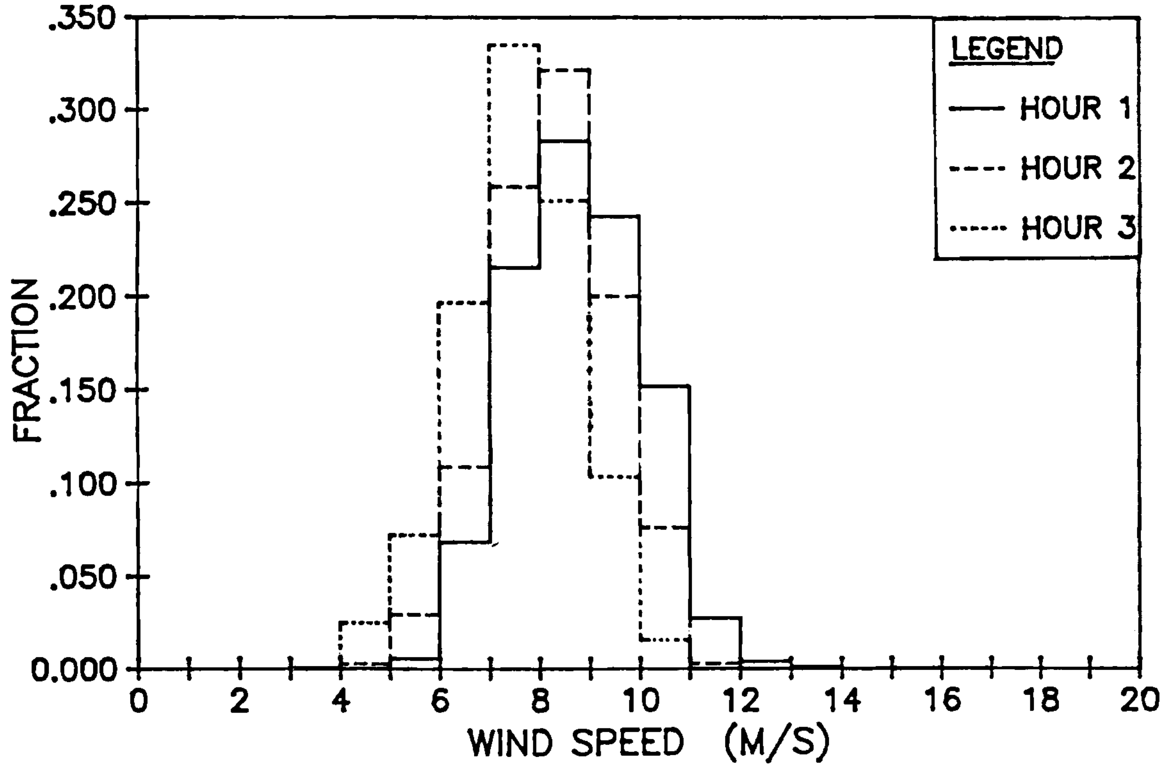

Figure 3.9 Histograms of Wind Speed Distribution for Three Hours at Amarillo, Texas, 45.7 m

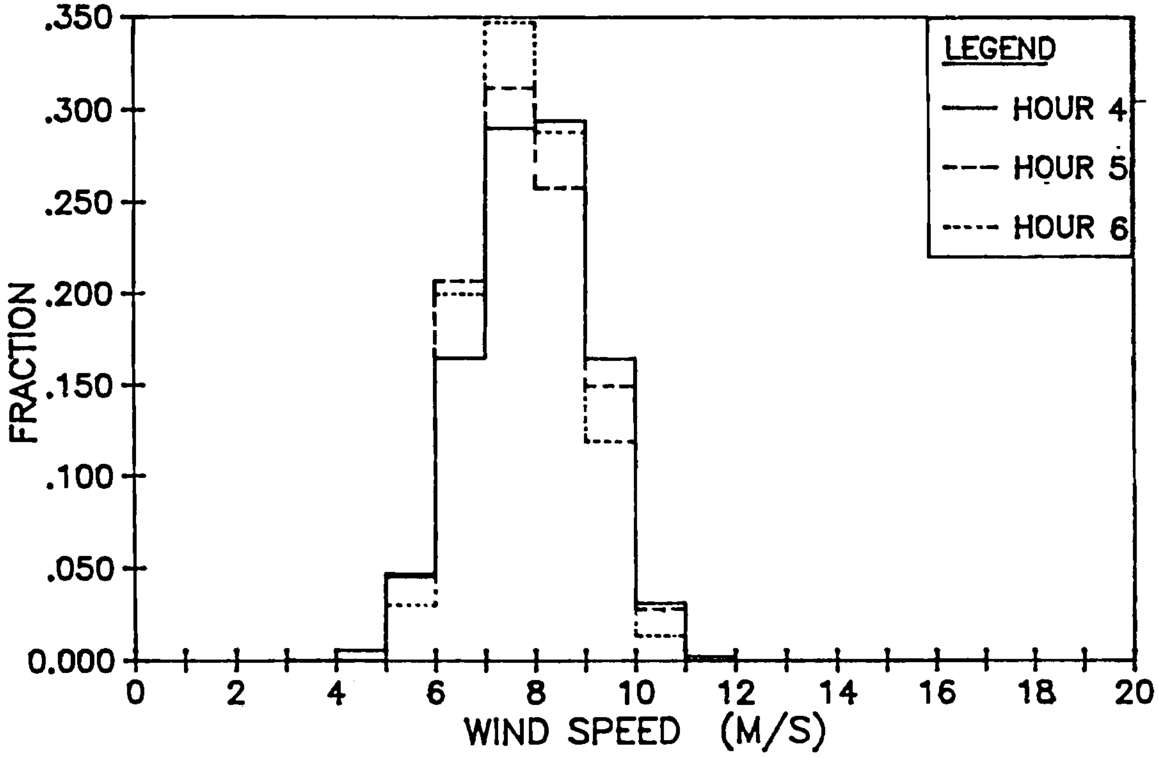

Figure 3.10 Histograms of Wind Speed Distribution for Three Hours at Amarillo, Texas, 45.7 m

TABLE 3.1. Hourly Statistics for Clayton, New Mexico

Height	Hour	Mean	Standard Deviation	Vi	Lag-One Autocorrelation
9.1 m	1	10.26	1.707	0.166	.8356
	2	10.04	1.852	0.184	.8468
	3	10.34	1.689	0.163	.8090
30.0 m	1	11.33	1.597	0.141	.8984
	2	11.23	1.800	0.160	.8868
	3	11.55	1.634	0.141	.8834
45.7 m	1	11.75	1.674	0.142	.9036
	2	11.57	1.728	0.149	.9026
	3	11.95	1.556	0.130	.8886
Nacelle	1	10.00	1.835	0.184	.9514
	2	9.92	2.091	0.211	.9403
	3	10.79	1.848	0.170	.9569

TABLE 3.2. Hourly Statistics for Amarillo, Texas

Height	Hour	Mean	Standard Deviation	Vi	Lag-One Autocorrelation
9.1 m	1	8.331	1.484	0.178	0.9032
	2	7.461	1.291	0.173	0.9307
	3	7.002	1.333	0.190	0.9491
	4	7.216	1.175	0.163	0.8610
	5	7.169	1.187	0.166	0.9356
	6	6.810	1.029	0.151	0.9211
	7	6.121	0.885	0.146	0.9257
45.7 m	1	8.779	1.257	0.143	0.9085
	2	8.285	1.190	0.144	0.9457
	3	7.583	1.214	0.160	0.9267
	4	7.920	1.201	0.152	0.8919
	5	7.839	1.134	0.145	0.9453
	6	7.812	1.038	0.133	0.9434
	7	7.667	0.796	0.104	0.9259

from the histogram analysis are presented in Figures 3.11 to 3.14. As can be seen, good agreement is found, with only minor discrepancies; these differences are no more than seen from hour to hour with the actual data. The Kolmogorov-Smirnov two-population goodness-of-fit test is applicable to these histograms, and for all cases the null hypothesis that the two histograms came from the same parent population could not be rejected for significance levels up to 10%. These results indicate the WEISIM program closely models the actual wind speed distribution.

This close approximation was achieved with an empirically derived correction for the tendency toward increased dispersion in simulated data for those cases in which the lag-one autocorrelation was greater than 0.75. The simulated output values, v_{sim}, were adjusted to the final values, v_{out}, by the expression

$$v_{out} = m_i + F(v_{sim} - m_i) \tag{3.5}$$

where m_i is the initial mean, and F is the correction factor, empirically found to be

$$F = -2.75\rho_a + 3.085; \quad 0.75 \leq \rho_a \leq 0.95 \tag{3.6}$$

where ρ_a is the input lag-one autocorrelation ($F = 1$ for $\rho_a < 0.75$). This procedure effectively reduces the simulated standard deviations so that they agree closely with the initial standard deviation. There is no effect on the simulated mean since the input mean is used as the midpoint for correction. Output means and autocorrelation are unaffected by the correction, although the simulation program does in general tend to create data with 1% to 2% higher lag-one autocorrelation than the actual data. This was felt to be insignificant.

The ability to model persistence of wind speed is useful in determining the temporal characteristics of the power available in the wind at a given location and the on-off cycling of a wind turbine.

Probability histograms of the duration of runs above and below fixed run levels for hourly data were found to be approximately exponential (Corotis 1976). This tendency also exists in high-frequency data, as shown in Figures 3.15 to 3.18, where some representative results are presented. Also shown are curves for simulated wind speeds, which show close agreement with the actual run-duration histograms. The tendency of the simulated data to have more variance in the persistence of runs is corrected in a similar manner to wind

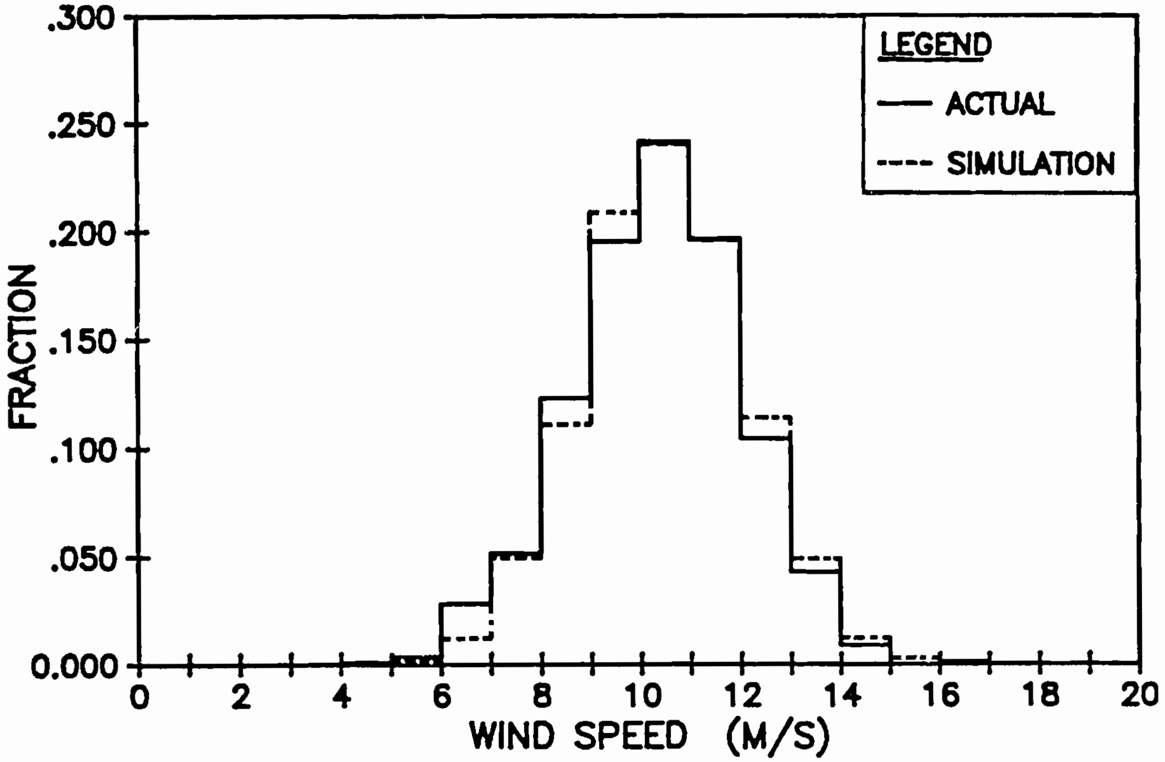

Figure 3.11 Histograms of Wind Speed Distribution for Hour 3, Clayton, New Mexico, 9.1 m

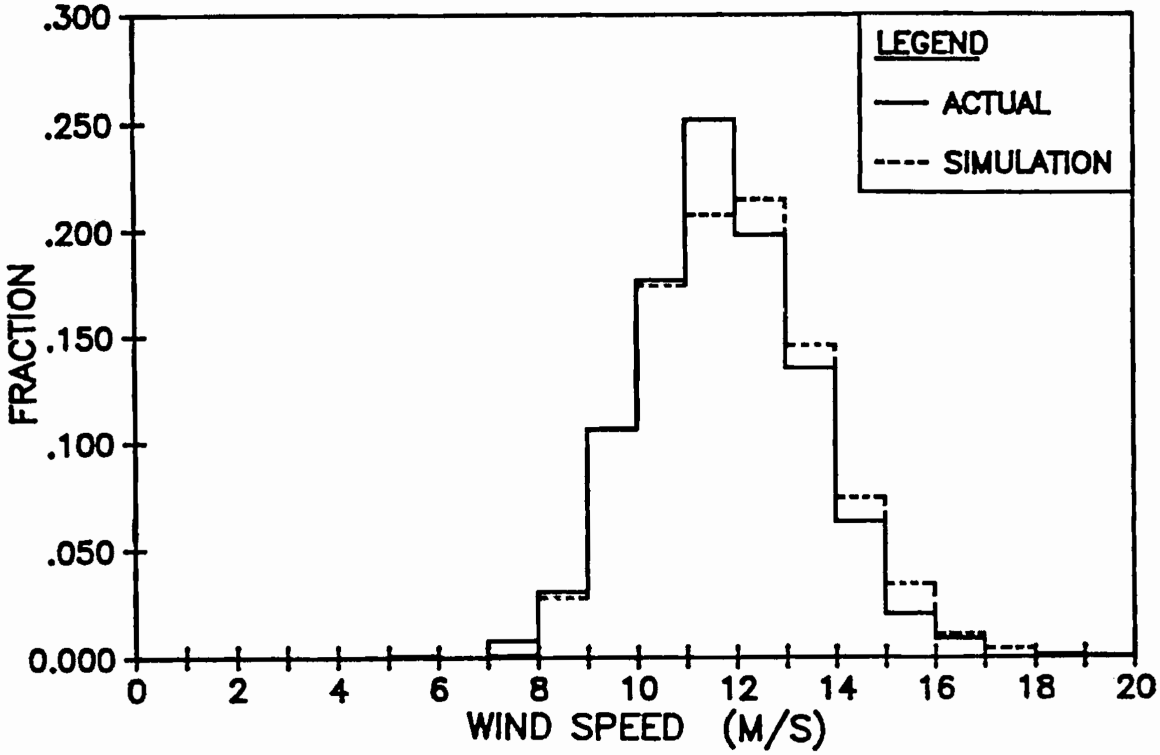

Figure 3.12 Histograms of Wind Speed Distribution for Hour 1, Clayton, New Mexico, 45.7 m

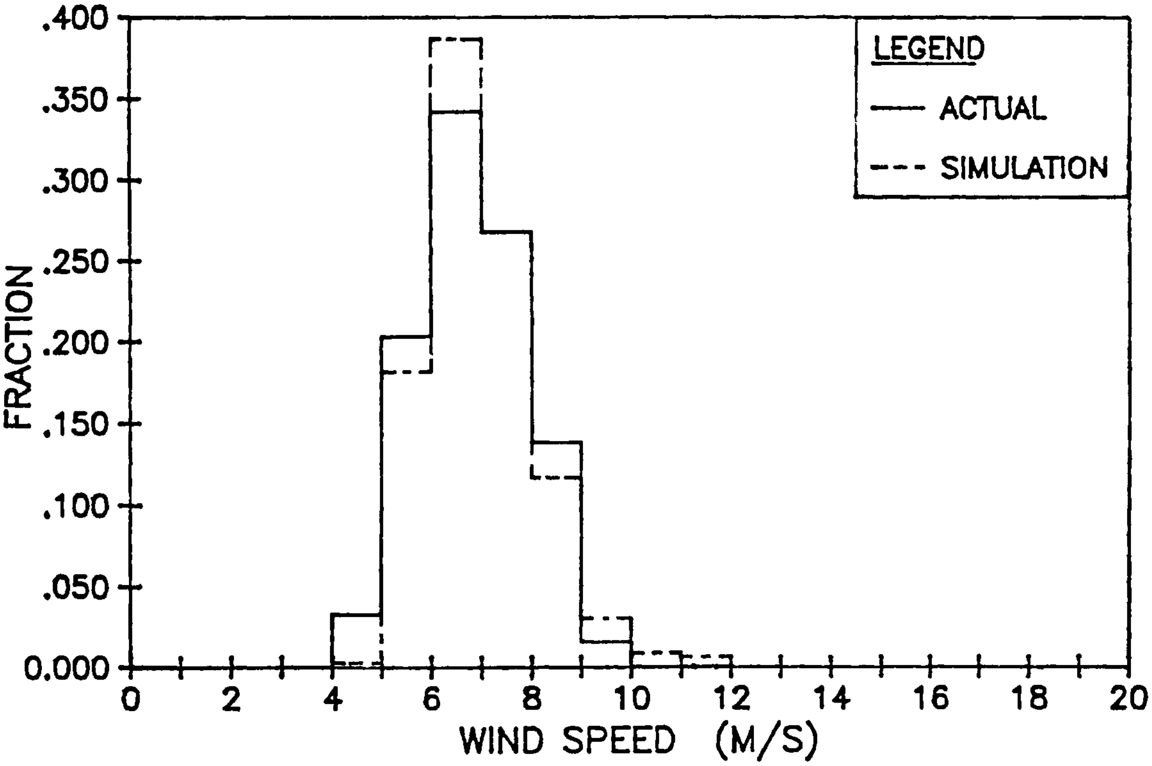

Figure 3.13 Histograms of Wind Speed Distribution for Hour 6, Amarillo, Texas, 9.1 m

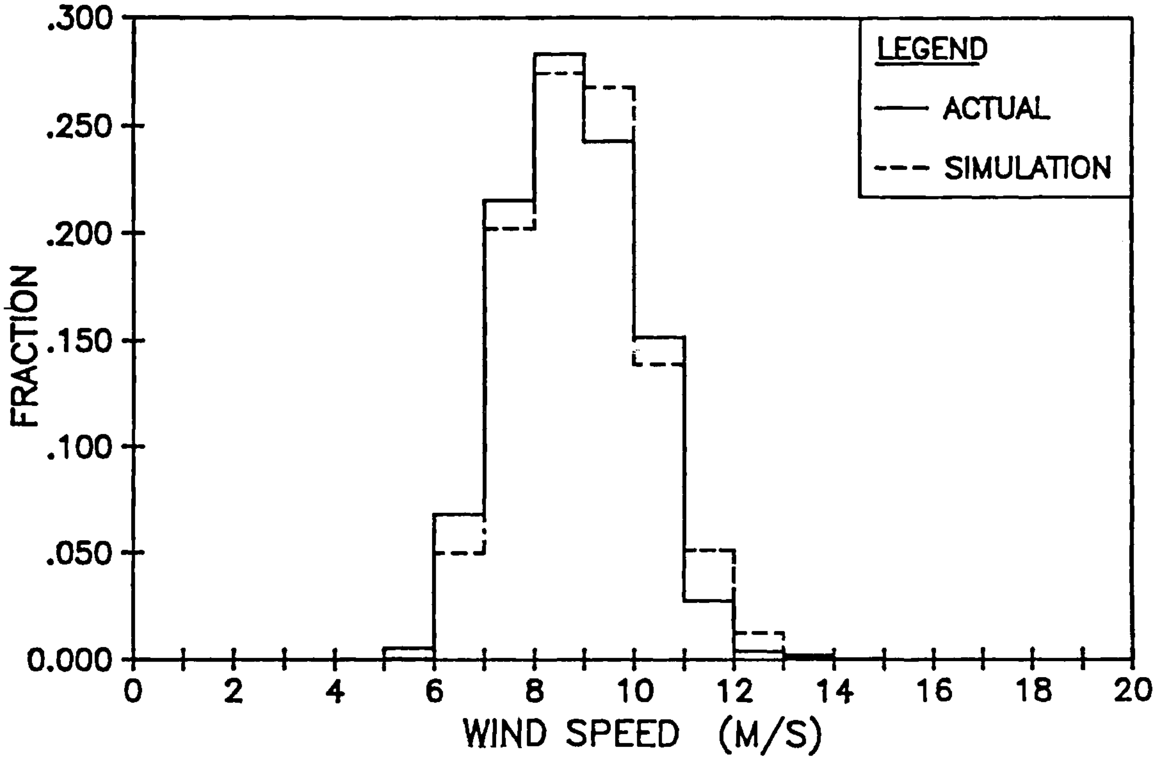

Figure 3.14 Histograms of Wind Speed Distribution for Hour 1, Amarillo, Texas, 45.7 m

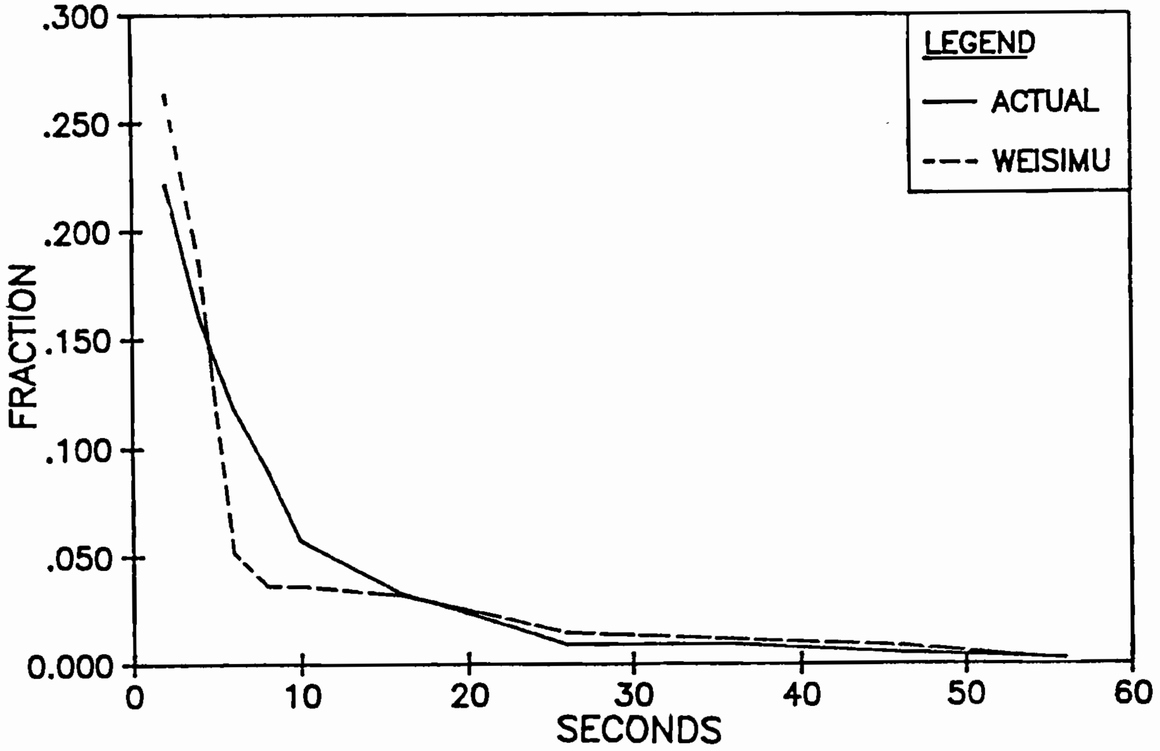

Figure 3.15 Fraction of Run Lengths Above 10 Meters Per Second at Clayton, New Mexico, Nacelle

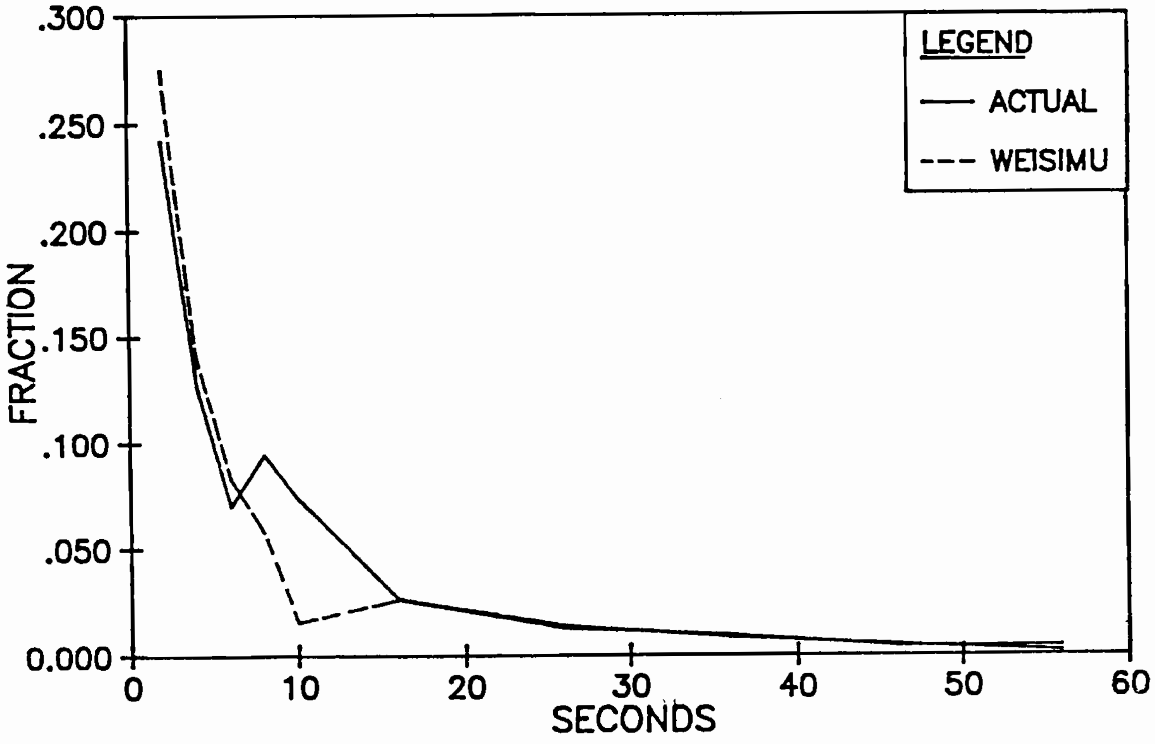

Figure 3.16 Fraction of Run Lengths Below 10 Meters Per Second at Clayton, New Mexico, Nacelle

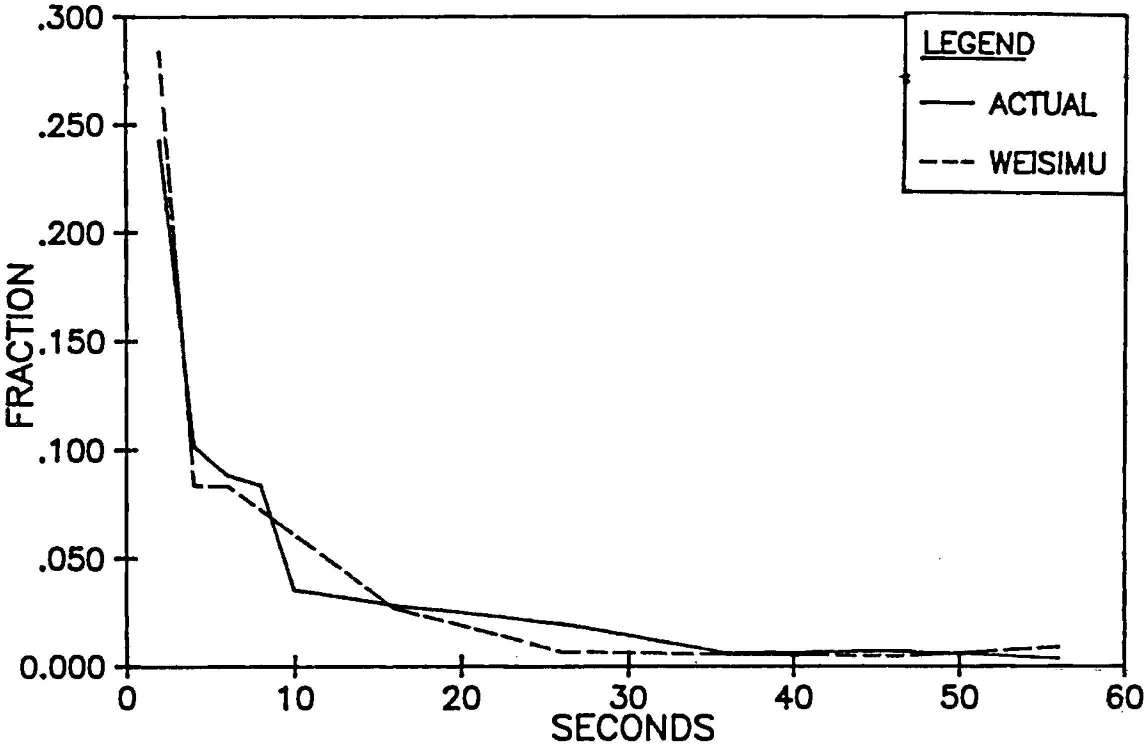

Figure 3.17 Function of Run Lengths Above 8 Meters Per Second at Amarillo, Texas, 9.1 m

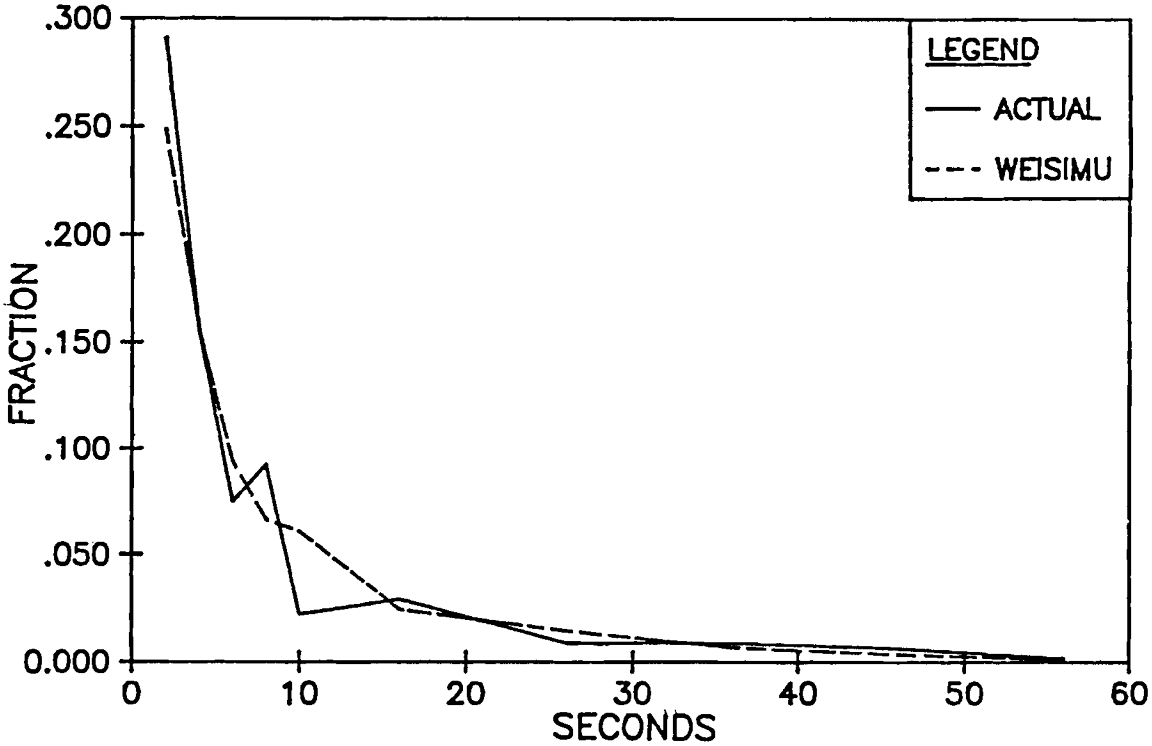

Figure 3.18 Fraction of Run Lengths Below 8 Meters Per Second at Amarillo, Texas, 9.1 m

speed distribution. In this case, the correction factor, F' is found to be

$$F' = -1.469\, \rho_e + 2.047; \quad 0.75 \leq \rho_e \leq 0.99 \tag{3.7}$$

where ρ_e is related to ρ_a by Equations 3.3 and 3.4, and $F' = 1$ for $\rho_e < 0.75$. Simulated velocities are modified by

$$V_{out} = m_i + F'(V_{sim} - m_i) \tag{3.8}$$

Good modeling of persistence is achieved as shown in Figures 3.19 to 3.22, which compare means and standard deviations of run lengths between the simulated and actual wind speeds.

Another simulation model proposed by McWilliams and Sprevak (1982) was also studied here. This model simulates the wind velocity components individually. The simulation is based on the assumption that the components are independent and normally distributed. Thus, the conditional mean and variance given by Equations 3.1 and 3.2 for each component will be exact. That is,

$$m_{V^*_i | V^*_{i-1}} = m_{V^*_i} + \rho \left| \frac{V^*_{i-1} - m_{V^*_{i-1}}}{V^*_{i-1}} \right| \tag{3.9}$$

$$\sigma^2_{V^*_i | V^*_{i-1}} = (1 - \rho^2)\sigma^2_{V^*_i} \tag{3.10}$$

where * represents either X or Y component.

A computer program, NORCOM, was written to simulate the wind velocity components and compute the wind speed by

$$V_{V_t} = \sqrt{V^2_{X_i} + V^2_{Y_i}} \tag{3.11}$$

A comparison among the actual and two simulated wind speeds is shown in Figures 3.23 to 3.26. In general, both simulation models show good agreement with the actual data. However, WEISIM appears to yield a better autocorrelation agreement with the actual data than NORCOM. The difference in autocorrelation between WEISIM and NORCOM can be due to the sensitivity of direction of the wind velocity in NORCOM. Although the wind velocity components may be nearly independent at any instant, the time-lagged cross correlation between components may be significant. Since WEISIM simulates wind speeds rather than components, it implicitly includes this effect.

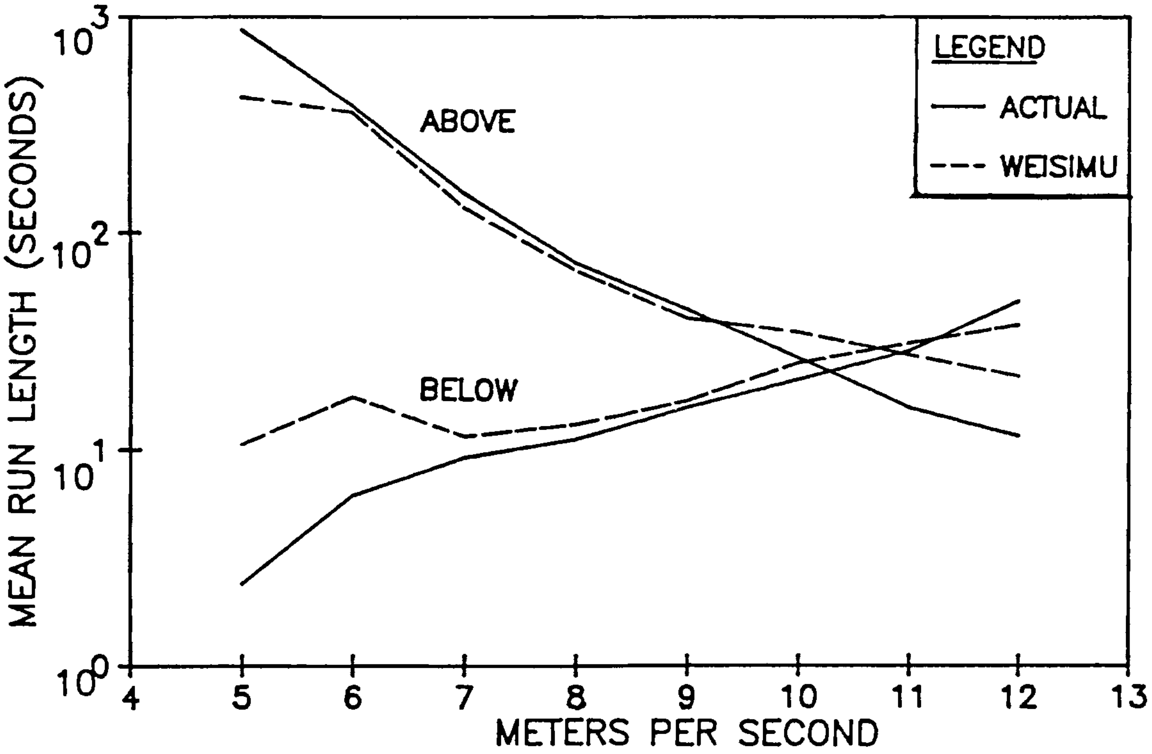

Figure 3.19 Mean Run Lengths Above And Below Fixed Run Levels at Clayton, New Mexico, Nacelle

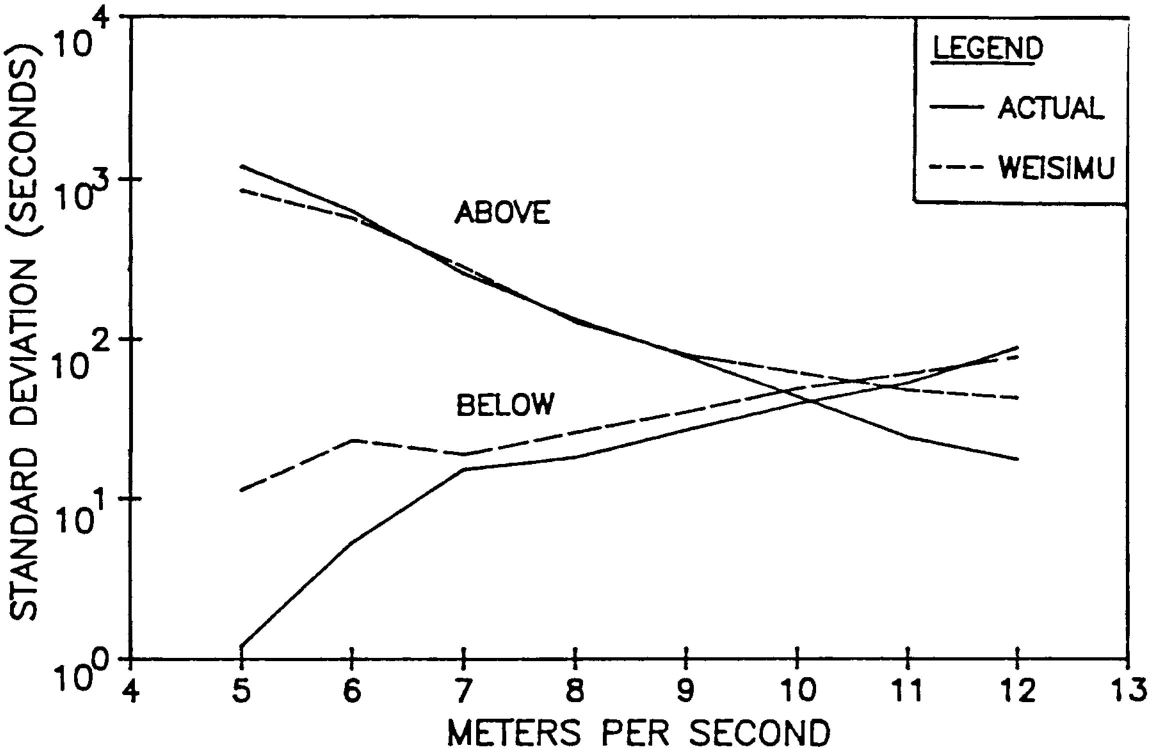

Figure 3.20 Standard Deviation Above And Below Fixed Run Levels at Clayton, New Mexico, Nacelle

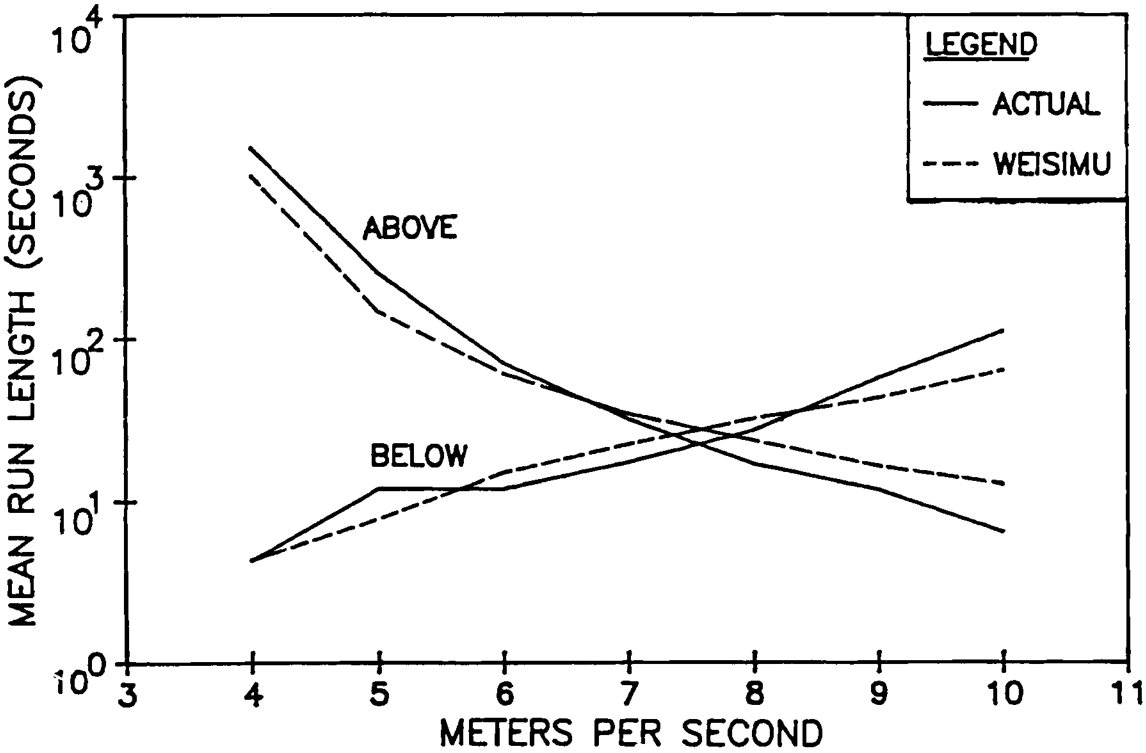

Figure 3.21 Mean Run Lengths Above And Below Fixed Run Levels at Amarillo, Texas, 9.1 m

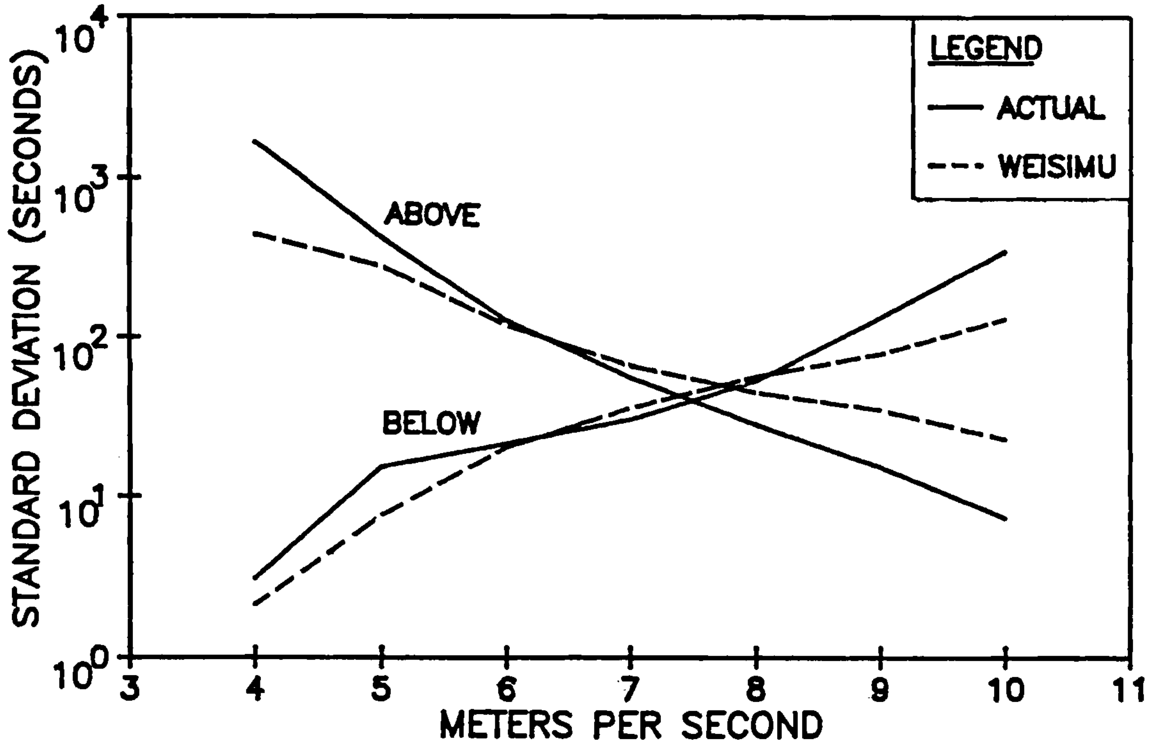

Figure 3.22 Standard Deviation Above And Below Fixed Run Levels at Amarillo, Texas, 9.1 m

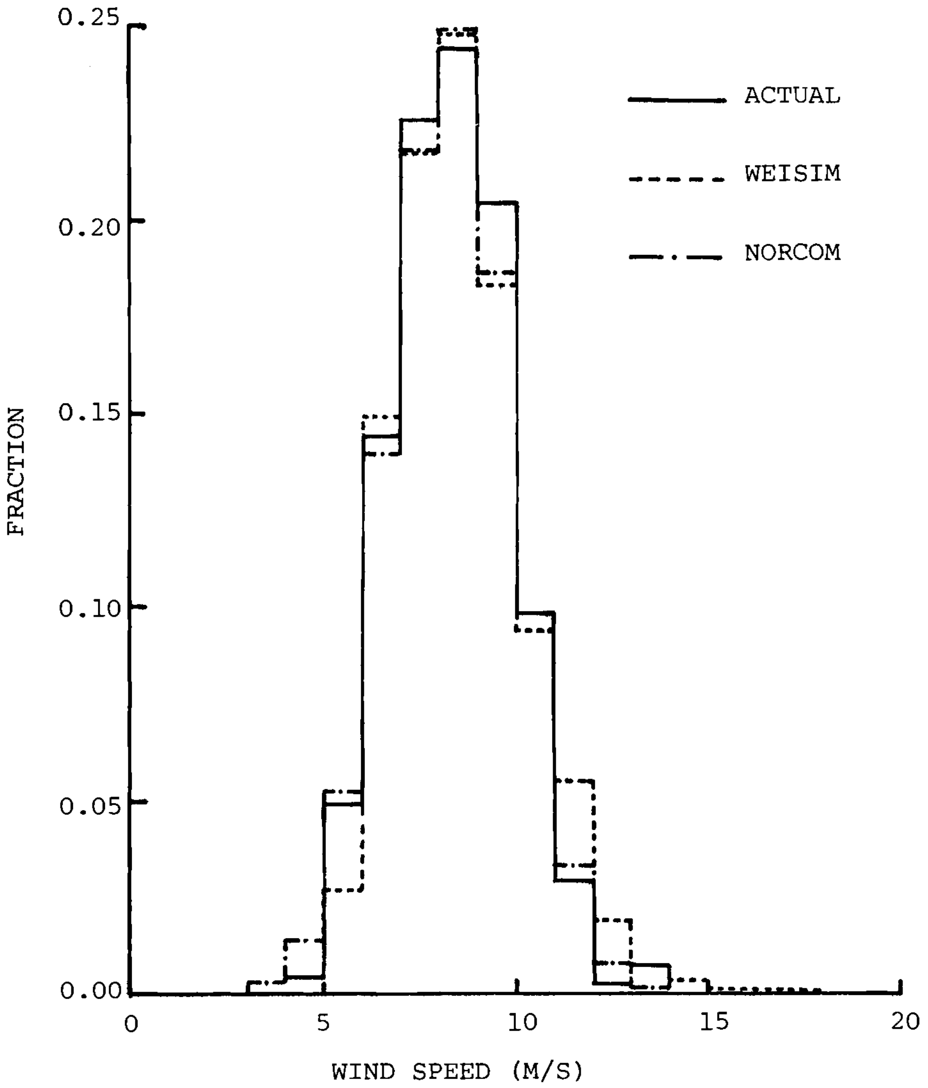

FIGURE 3.23 Observed and Simulated Wind Speed Histograms for Amarillo, Texas, 9.1 m, Hour 1.

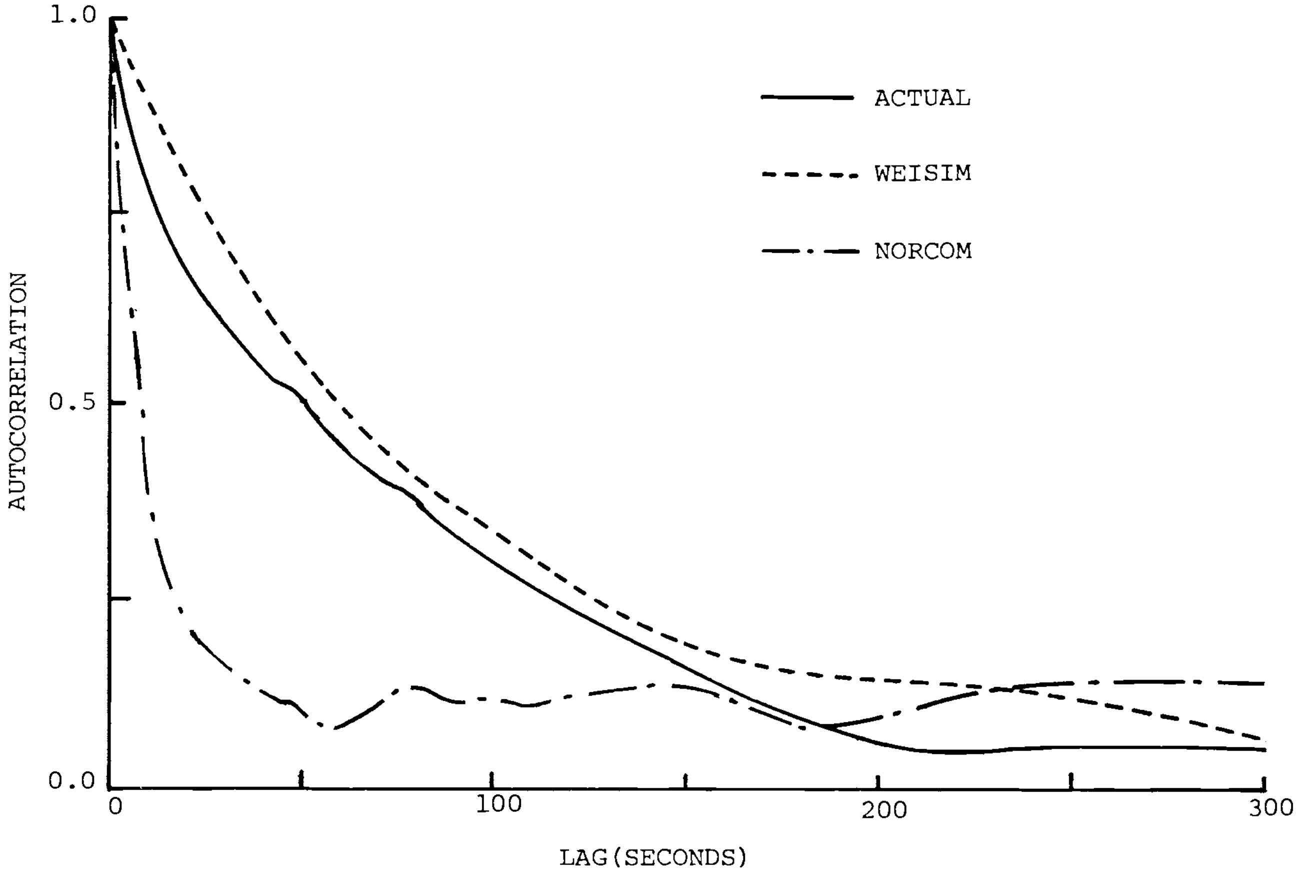

Figure 3.24. Observed and Simulated Wind Speed Autocorrelation for Amarillo, Texas, 9.1 m, First 3 Hours.

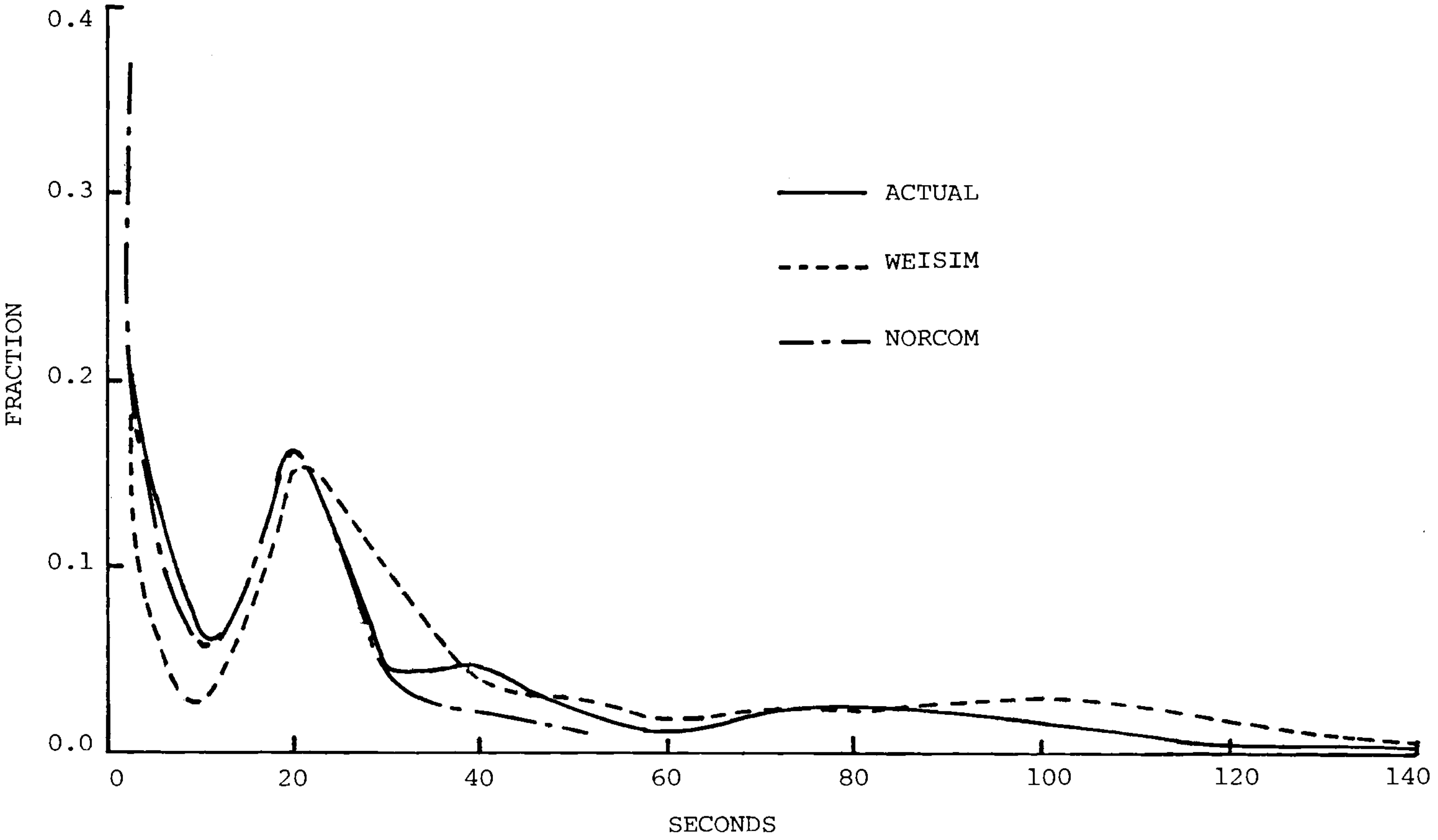

Figure 3.25 Observed and Simulated Wind Speed Persistence Above 8 M/S for Amarillo, Texas, 9.1 m, First 3 Hours

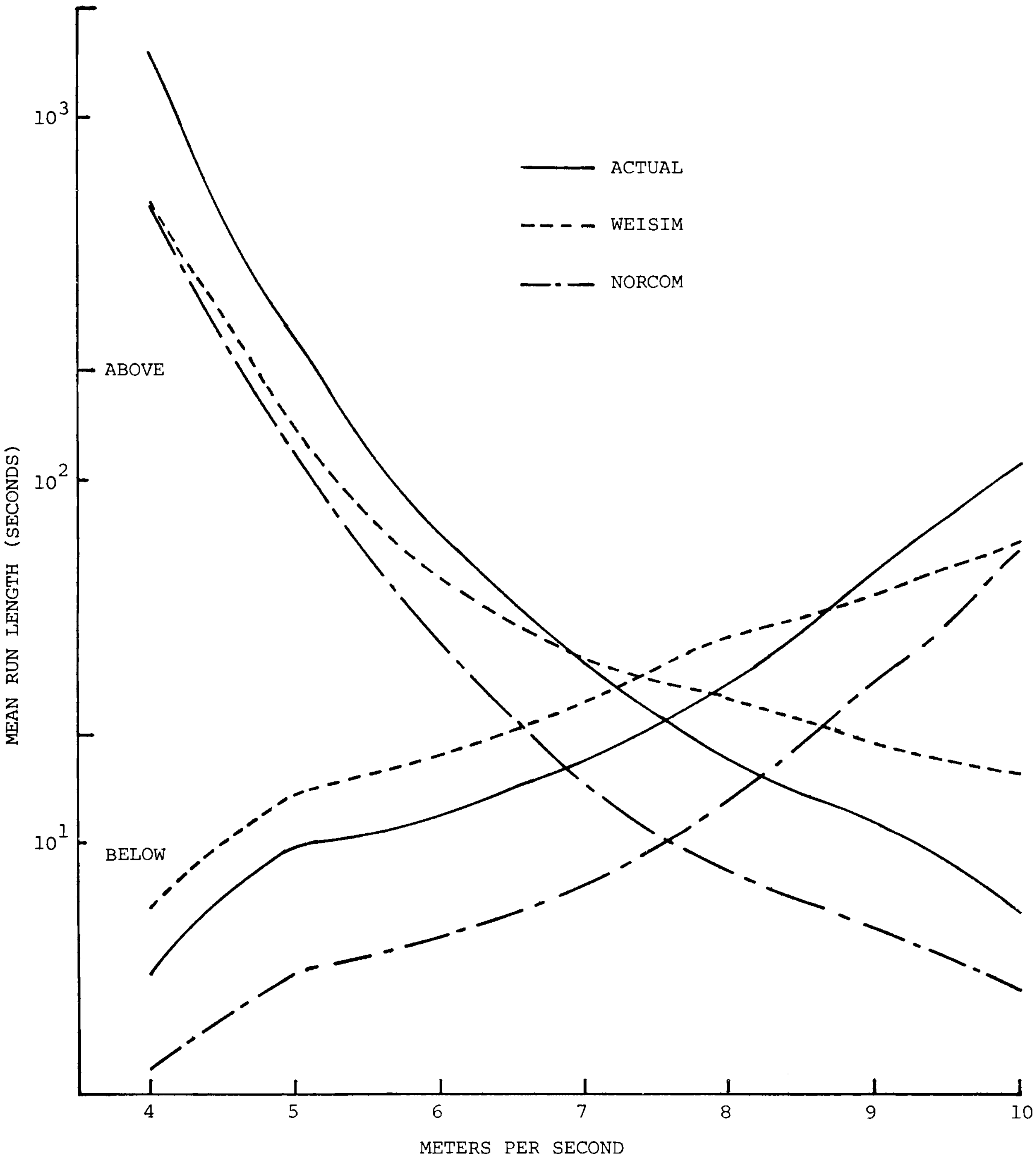

Figure 3.26 Observed and Simulated Persistence Mean Run Lengths Above and Below Fixed Wind Speed Levels for Amarillo, Texas, 9.1 m, First 3 Hours.

CHAPTER FOUR

THE DECIDE PROGRAM

Run lengths measured with respect to the cut-in speed of the wind turbine generator are important in determining the operating policy that maximizes output and minimizes blade and mechanical stress caused by starting or stopping the turbine. A program, DECIDE (Appendix D), has been written to analyze the effect of different operating policies for a given turbine and wind regime.

Every wind turbine generates power as a function of wind speed. The power generated by a particular wind turbine is a function of the rated power, cut-in speed, rated speed, and cut-out speed. As wind speed increases from cut-in speed to rated speed, power generated may be related to wind speed in an approximately parabolic manner (Justus 1978). For wind speeds between rated speed and cut-out speed, rated power is produced. A wind speed record can be used to determine the power-generating potential for a given wind turbine. This procedure is complicated by the operating policy, which attempts to maximize power generation and minimize blade and mechanical stress.

The DECIDE program reduces the high-frequency wind speed data record to a sequential set of time-averaged values. The user of the program specifies an operating policy in terms of the number of consecutive averages that must be above or below the cut-in speed of the turbine to cycle it on or off. The number of on-off cycles and amount of energy produced are recorded by the program and compared. This procedure assumes the wind speed record represents average speed over the swept area of the turbine and there is no lag in turbine response. The effect of different wind speed records and different operating policies can be quickly ascertained. For areas where incomplete or insufficient wind data are available, the WEISIM program can be used to simulate wind speed data to provide supplemental records. As more data are collected, better estimates of power available and the optimum operating policy can be made.

Table 4.1 shows the power computed as described above that would be produced by a MOD-1 turbine for a wind speed data record at Amarillo, Texas, and compares the results with a simulation for the same length of time. It can be seen that reasonable agreement exists between actual and simulated data and that using longer averaging times significantly decreases the number

TABLE 4.1. Statistics from DECIDE Program for Amarillo, Texas, 9.1 m

Averaging Time (seconds)	Number of Averages	Number of On-Off Cycles		Energy (kW)	
		Actual	WEISIMU	Actual	WEISIMU
8	1	28	28	4159	4682
8	2	7	15	4156	4679
8	3	5	5	4151	4676
8	4	3	2	4147	4673
4	1	61	44	4160	4684
4	2	24	24	4158	4682
4	4	7	10	4153	4679
4	6	5	4	4147	4676
4	8	3	2	4144	4672

of on-off cycles, but has only minor effects on the total energy produced. The effect of using, e.g., one 8-sec average or two 4-sec averages on the number of on-off cycles or energy produced is also minor. The small number of runs below cut-in speed for either method of averaging data results in consistent levels of energy produced. While the results for the number of on-off cycles are reliable, the reader is cautioned that the energy results do not take into account the lag in turbine response.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that the high-frequency wind speeds can be modeled by the two-parameter Weibull distribution. The single-parameter Rayleigh distribution, which is a good model for National Weather Service wind speed data, fails to represent high-frequency wind speeds for a data record on the order of an hour. This is due to lower coefficients of variation when a record is only an hour in duration because of the lack of inter-hour and inter-day variation.

A versatile real-time wind speed simulation model, WEISIM, has been developed and verified with actual data. The simulation is based on a modified conditional Weibull distribution for wind speed. The model is simple to use and can be employed with a minimum of input information (mean and variance of wind speed and a single autocorrelation value), or can include more complete diurnal cycle information. The program can simulate wind speed data corresponding to averaging times from 1 sec to 1 hr, and it can perform anywhere from one simulation an hour to 3600 simulations an hour. The program has been checked with actual data for an averaging time of 1 sec and simulation rate of 2 sec, (corresponding to DOE/PNL candidate site data), and for an averaging time of 1 min and simulation rate of 1 hr (corresponding to NWS data).

The simulated wind speeds provide good agreement to actual data means, variances, histograms, autocorrelations, persistence mean durations, and persistence duration variances. When lag-one autocorrelation values exceed 0.75, one correction factor must be applied to achieve realistic variances and histograms, and another factor to achieve realistic persistence results.

The NORCOM model, which is based on the Gaussian distribution on the wind velocity components, shows good agreement with the actual data in the statistical analysis used in this study except for autocorrelation, which can be due to the model's sensitivity to wind direction.

Wind speed persistence is used in program DECIDE, which was written to determine the number of on-off cycles for various wind turbine operating policies. The program tracks on-off cycles and energy produced, the latter quantity in a crude way neglecting turbine inertia effects. The preliminary study shows that the averaging time has a significant effect on the number of on-off cycles for short averaging times. For longer averaging times, the effect is less pronounced.

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APPENDIX A

SHIFTED WEIBULL DISTRIBUTION

APPENDIX A

SHIFTED WEIBULL DISTRIBUTION

The basic formulation of the Weibull distribution derives from the Type III extreme value distribution where e is zero. The cumulative distribution function and probability density function (Benjamin and Cornell, 1970) are given by Eqs. B-1 and B-2, respectively:

$$F_z(z) = 1 - \exp\left[-\left(\frac{z-e}{c-e}\right)^k\right] \quad ; \quad z \geq e \qquad \text{(B-1)}$$

$$f_z(z) = \frac{k}{c+e}\left(\frac{z-e}{c-e}\right)^{k-1} \exp\left[-\left(\frac{z-e}{c-e}\right)^k\right] \quad ; \quad z \geq e \qquad \text{(B-2)}$$

with moments:

$$m_z = e + (c-e)\ \Gamma\left(1+\frac{1}{k}\right) \qquad \text{(B-3)}$$

$$\sigma_z^2 = (c-e)^2\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right] \qquad \text{(B-4)}$$

$$E\left[(z-e)^n\right] = (c-e)^n\ \Gamma\left(1+\frac{n}{k}\right) \qquad \text{(B-5)}$$

where Γ is the gamma function.

A better fit to the actual wind speed distribution may be found by considering a shift e from zero. A third statistic must be obtained from the data in order to calculate e. This can be done expanding Eq. B-5 with n = 3.

$$E\left[(z-e)^3\right] = E\left[z^3\right] - 3e\,(m_z^2 + \sigma_z^2) + 3e^2 m_z - e^3 \qquad \text{(B-6)}$$

Substituting into Eq. B-5

$$E\left[z^3\right] = (c-e)^3 \Gamma\left(1+\frac{3}{k}\right) + 3e(m_z^2 + \sigma_z^2) - 3e^2 m_z - e^3 \qquad \text{(B-7)}$$

With these three equations and three unknowns a solution for c, k, and e can be made from the data statistics.

From Eq. B-4, expanding the quadratic term yields:

$$e^2 - 2ce + c^2 = \frac{\sigma_z^2}{\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)} = R_1 \qquad \text{(B-8)}$$

Solving for e:

$$e = \frac{2c \pm \sqrt{4c^2 - 4(c^2 + R_1)}}{2}$$

$$= c \pm \sqrt{R_1} \qquad \text{(B-9)}$$

Since all $z \geq e$ and c is a moment of the data, then $c > e$. Also, in Eq. B-5 for n = 3, $E\left[(z-e)^3\right] > 0$, $\Gamma\left(1+\frac{3}{k}\right) > 0$ which implies $(c-e)^3 > 0$ and $c > e$. Therefore, the negative sign is the correct root. From Eq. B-3

$$m_z = e\left[1 - \Gamma\left(1+\frac{1}{k}\right)\right] + c\Gamma\left(1+\frac{1}{k}\right) \tag{B-10}$$

$$e = \frac{m_z - c\Gamma\left(1+\frac{1}{k}\right)}{1 - \Gamma\left(1+\frac{1}{k}\right)} = R_3 - cR_2 \tag{B-11}$$

in which

$$R_2 = \frac{\Gamma\left(1+\frac{1}{k}\right)}{1 - \Gamma\left(1+\frac{1}{k}\right)} \tag{B-12}$$

and

$$R_3 = \frac{m_z}{1 - \Gamma\left(1+\frac{1}{k}\right)} \tag{B-13}$$

Combining Eqs. B-9 and B-10 to solve for c:

$$c = \frac{R_3 + \sqrt{R_1}}{1 + R_2} \tag{B-14}$$

In a similar manner from Eq. B-3

$$c = \frac{m_z - e\left[1 - \Gamma\left(1+\frac{1}{k}\right)\right]}{\Gamma\left(1+\frac{1}{k}\right)} = R_4 - \frac{e}{R_2} \tag{B-15}$$

in which

$$R_4 = \frac{m_z}{\Gamma\left(1+\frac{1}{k}\right)} \qquad \text{(B-16)}$$

Combining Eqs. B-15 and B-9 to solve for e:

$$e = \frac{R_4 - \sqrt{R_1}}{1 + \frac{1}{R_2}} \qquad \text{(B-17)}$$

Equations B-17 and B-14 can now be substituted into Eq.B-7 and an iterative solution for k can be performed in a manner similar to the method used in the WEISM program. For present high speed computers, the computation is handled quickly.

APPENDIX B

PROGRAM WEISIM

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PROGRAM WEISIM

The WEISIM program simulates a time series of wind speed at a site. The time interval of simulation may be set at any integer from one second to one hour, provided there are an integer number of simulated values per hour. The simulation utilizes an approximate procedure whereby the Weibull mean and variance are replaced each time step by a conditional mean and variance with a correction that would be theoretically exact in the case of a Gaussian distribution. The program also has two subroutines, PARA and POLY, which compute the parameters k and c of the Weibull distribution in terms of the mean and variance. The program can simulate a minimum of one hour, and there is no upper limit on simulation duration. However, there are certain restrictions on simulation duration. If the duration is one year or more, then an integer number of years must be simulated. If the duration is one month or more but less than a year, then an integer number of months must be simulated and the user specifies the starting month of simulation (all simulated months must be in one calendar year). If the duration is less than a month but one day or more, then an integer number of days must be simulated and the month of simulation is specified (all simulated days must be in one calendar month). Finally, if the duration is less than one day, an integer number of hours must be simulated and the user specifies the starting hour of simulation and the month of simulation (all simulated hours must be in one calendar day). The program is capable of doing more than one set of simulations at a time.

The input for the WEISIM program is on cards in the following order and format:

Card No.	Col. No.	Format	Variable	Data
1	7 - 10	I4	NUMSEC	Simulation interval in integer seconds; must divide into 3600 integrally
	16 - 20	I5	NYEAR	Number of years to be simulated; integer or blank (except negative to signify end of data)
	29 - 30	I2	NMONTH	Number of months to be simulated; integer(1-11)or blank
	39 - 40	I2	NMA	Starting month of simulation; integer between 1 and 12, used when number of years to be simulated is blank
	49 - 50	I2	NUMDAY	Number of days to be simulated; integer (less than days in month) or blank
	59 - 60	I2	NHOUR	Number of hours to be simulated; integer (1-23) or blank
	69 - 70	I2	NHA	Starting hour of simulation; integer between 1 and 24, used when preceding variable is not blank
	71 75	F5.0	G	1.0 for Wind Speed Distribution -1.0 for Wind Speed Persistence
2	1 - 80	8A10	TITLE	Title for the simulation
3 - 14	1 - 10	F10.4	SIGMA	Monthly standard deviation of wind speed, in m/s
	11 - 20	F10.4	RHO	Lag one autocorrelation of wind speed by month
15 - 26	1 - 8	F8.4	VM	Monthly mean wind speed, in m/s
	9 - 80	24F3.2	DC	Diurnal cycle effect multiplier factor, one value for each hour of the day (all blank if no diurnal cycle)

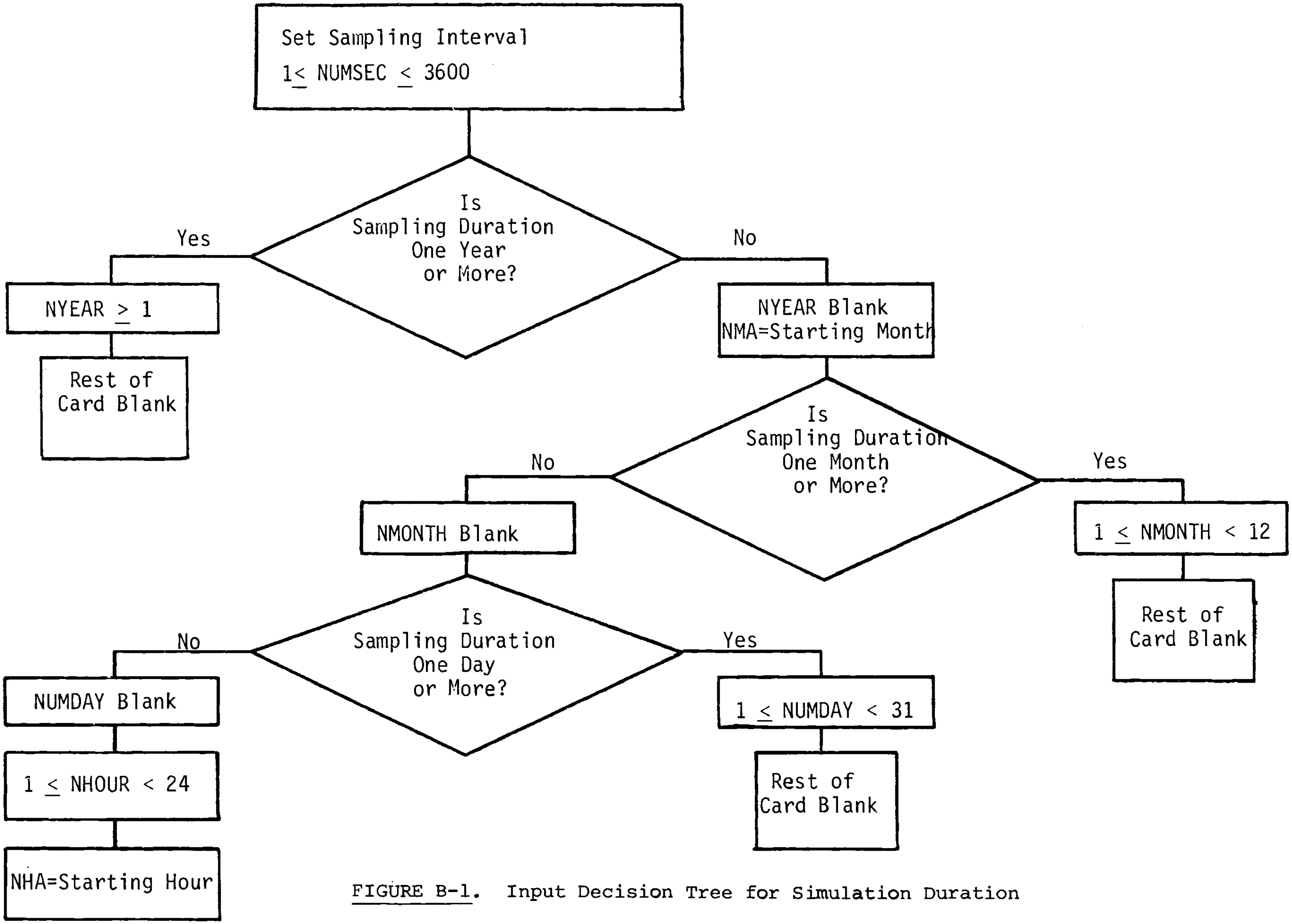

FIGURE B-1. Input Decision Tree for Simulation Duration

The output of the WEISIM program consists of a line printer table of mean wind speeds and standard deviations (including the duirnal cycle effect) by month and hour of the day. The simulated hourly wind speed is written on tape in the integer format

YYMMDDHHSSSSVVVVV

where YY = year; 1- (col. 1-2)
MM = month; 1-12 (col. 3-4)
DD = Day; 1-31 (col. 5-6)
HH = Hour; 1-24 (col. 7-8)
SSSS = Sequence; 1 - number of simulations per hour (≤ 3600)
VVVVV = Wind speed; integer centimeters per second (col. 13-17)

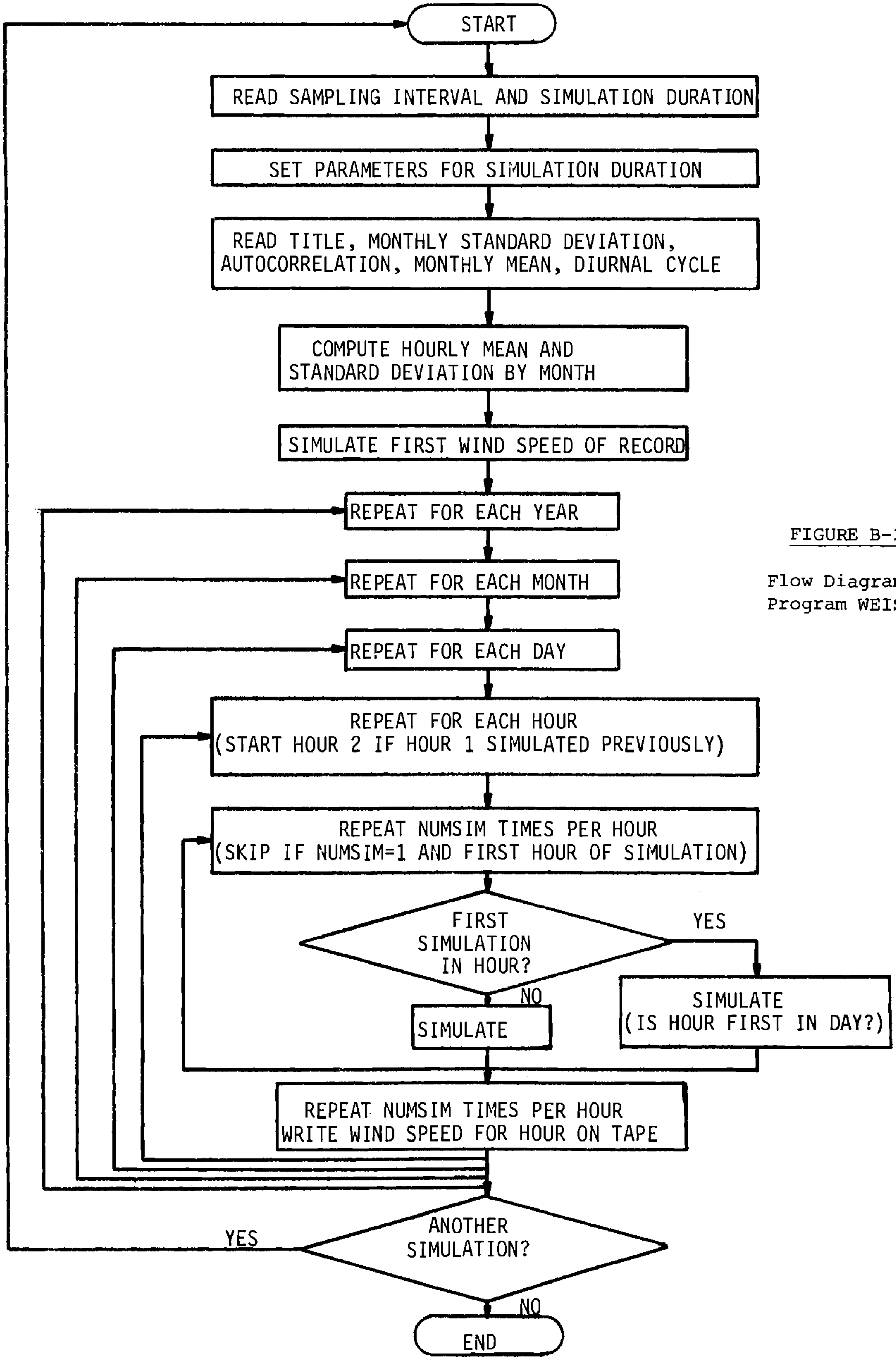

FIGURE B-2.

Flow Diagram for Program WEISIM

```
      PROGRAM WEISIM (INPUT,OUTPUT,TAPE5)
      DIMENSION TITLE(8),CO(5),SIGMA(12),RHO(12),
     1NDAY(12),VM(12),DC(12,24),VMEAN(12,24),STD(12,24),ISPEED(3600),
     2VEL(3600),F(12),HEAD(2),RHOM(12)
      REAL MODM,MODS
      DATA HEAD /7H HISTO ,7HPERSIST/
      DATA NDAY/31,28,31,30,31,30,31,31,30,31,30,31/
C     THIS PROGRAM SIMULATES ONE WIND SPEED EVERY NUMSEC
C     SECONDS (NUMSEC VARIES FROM 1 TO 3600) AT A SITE
C      THE SIMULATION IS BASED ON THE WEIBULL DISTRIBUTION
C     AND THE PROGRAM SIMULATES A MINIMUM OF ONE HOUR
C     READ IN SAMPLING INTERVAL, NUMBER OF YEARS OR NUMBER OF MONTHS
C     (AND STARTING MONTH) OR NUMBER OF DAYS OR NUMBER OF HOURS
C     (AND STARTING HOUR) TO BE SIMULATED
C     G IS A FLAG, IF (G .GT. 0), A SIMULATION FOR WIND SPEED
C     DISTRIBUTION IS DESIRED; IF (G LT. 0),A SIMULATION
C     FOR PERSISTENCE IS DESIRED
    1 READ 1001,NUMSEC,NYEAR,NMONTH,NMA,NUMDAY,NHOUR,NHA,G
      II=3
      IHB=25
      IMA=1
      IMB=12
      IHA=1
      IF(NYEAR)999,82,85
   82 IMA=NMA
      IMB=NMA+NMONTH-1
      IF(IMB.GT.12)GO TO 93
      IF(NMONTH)83,83,85
     83 TNDAY=NDAY(NMA)
      NDAY(NMA)=NUMDAY
      IF(NUMDAY.GT.31)GO TO 93
      IF(NUMDAY)84,84,85
   84 II=NHA+2
      IHB=NHA+NHOUR
      IHA=NHA
      IF(IHB.GT.25)GO TO 93
   85 NUMSIM=3600/NUMSEC
      GO TO 94
   93 PRINT 2008
      GO TO 1
   94 CONTINUE
    2 READ 1002,(TITLE(K),K=1,8)
C       COEFFICIENTS FOR COMPUTING THE PARAMETERS
C       K AND C OF THE CDF OF THE WEIBUL DISTRIBUTION
      CO(1)=-0.57486
      CO(2)=0.95124
      CO(3)=-0.69986
      CO(4)=0.42455
      CO(5)=-0.10107
C       READ IN STANDARD DEVIATION AND LAG 1 AUTOCORRELATION
C       FOR EACH MONTH
      DO 10 I=1,12
      READ 1003, SIGMA(I),RHOM(I)
     10 CONTINUE
      DO 311 J = 1,12
      IF (RHOM(J) .LE. 0.75) GO TO 200
```

```
        IF (RHOM(J) .GT. 0.95) GO TO 201
        RHO(J) = 1.153*RHOM(J)-0.1034
        GO TO 311
    200 RHO(J) = RHOM(J)
        GO TO 311
    201 RHO(J) = 1.0
    311 CONTINUE
        IF (G .LT. 0) GO TO 203
        IG = 1
        DO 312 J = 1,12
        IF (RHOM(J) .LE. 0.75) GO TO 204
        F(J) = -2.75024*RHOM(J)+3.08465
        GO TO 312
    204 F(J) = 1.0
    312 CONTINUE
        GO TO 15
    203 IG = 2
        DO 313 J = 1,12
        IF (RHO(J) .LE. 0.75) GO TO 205
        F(J) = -1.469*RHO(J)+2.047
        GO TO 313
    205 F(J) = 1.0
    313 CONTINUE
C  READ IN MEAN WIND SPEED AND DIURNAL CYCLE FOR EACH MONTH. A BLANK
C  FOR DIURNAL CYCLE MEANS NO CYCLE EFFECT
     15 DO 11 I=1,12
        READ 1004, VM(I),(DC(I,J),J=1,24)
        IF(DC(I,1).GE. 0.0001) GO TO 3
        DO 12 J=1,24
        VMEAN(I,J)=VM(I)
        STD(I,J)=SIGMA(I)
     12 CONTINUE
        GO TO 11
      3 DO 13 J=1,24
        VMEAN(I,J)=VM(I)*DC(I,J)
        STD(I,J)=SIGMA(I)*DC(I,J)
     13 CONTINUE
     11 CONTINUE
        PRINT 2001,(TITLE(K),K=1,8)
        PRINT 2002, NUMSEC
        PRINT 2007,NYEAR,NMONTH,IMA,NUMDAY,NHOUR,IHA
        PRINT 2003
        PRINT 2004
        DO 14 J=1,24
        PRINT 2005, J, (VMEAN(I,J),I=1,12)
        PRINT 2006,(STD(I,J),I=1,12)
     14 CONTINUE
        PRINT 2100, HEAD(IG)
        PRINT 2101, (RHO(I),I=1,12)
C       SIMULATE THE FIRST WIND SPEED OF THE RECORD
        ICOUNT=1
        MODM=VMEAN(IMA,IHA)
        COV=STD(IMA,IHA)/MODM
        CALL PARA(P,C,1,COV,MODM,CO)
        VEL(1)=WEIBUL(P,C)
        XVEL = VMEAN(IMA,IHA)+F(IMA)*(VEL(1)-VMEAN(IMA,IHA))
        ISPEED(1)=XVEL*100.
        IF(NUMSIM-1) 95,95,97
     95 IF(NHOUR-1) 96,97,96
     96 PRINT 3010,ICOUNT,IMA,ICOUNT,IHA,ICOUNT,ISPEED(ICOUNT)
```

```
   97 CONTINUE
      DO 19 NY=1,NYEAR
      IF (NYEAR-3)34,34,86
C     ADJUSTING FEBRUARY FOR A LEAP YEAR
 86   INY=NY/4
      XNY=INY
      YNY=NY
      YNY=YNY/4.
      ZNY=YNY-XNY
      IF(ZNY-0.001)32,32,33
   32 NDAY(2)=29
      GO TO 34
   33 NDAY(2)=28
   34 CONTINUE
      DO 20 IM=IMA,IMB
      NDY=NDAY(IM)
      DO 21 ID=1,NDY
      IF(NY.NE.1) GO TO 40
      IF(IM.NE.IMA) GO TO 40
      IF(ID.NE.1) GO TO 40
      IF(NUMSIM.GT.1) GO TO 91
      IF(NHOUR.EQ.1)II=IHB
      GO TO 41
  91  ICOUNT=2
  40  II=IHA+1
  41  DO 22 IJ=II,IHB
      IH=IJ-1
      MODS=STD(IM,IH)*SQRT(1.-RHO(IM)*RHO(IM))
      IHP=IJ-2
      DO 89 IL=ICOUNT,NUMSIM
      IF(NUMSIM-1) 99,98,99
   98 IF(NHOUR-1) 99,89,99
   99 CONTINUE
      IF(IL.NE.1) GO TO 87
      IF(IJ.NE.2) GO TO 71
      IF(ID.NE.1) GO TO 72
      GO TO 90
C     FOLLOWING PARTS ARE FOR FIRST SIMULATION
C     IN AN HOUR(IL=1)
C     THIS PART IF IT IS NOT FIRST HOUR OF THE DAY
  71  MODM=VMEAN(IM,IH)+RHO(IM)*
     1(VEL(NUMSIM)-VMEAN(IM,IHP))*STD(IM,IH)/STD(IM,IHP)
      GO TO 73
C THIS PART IF IT IS FIRST HOUR OF THE DAY AND THE DAY IS THE FIRST OF
C     THE MONTH
  90  JM=IM-1
      IF(IM.EQ.1)JM=12
      MODM=VMEAN(IM,IH)+RHO(IM)*(VEL(NUMSIM)-VMEAN(JM,24))*STD(IM,IH)
     1/STD(JM,24)
      GO TO 73
C     THIS PART IF IT IS FIRST HOUR OF THE DAY AND THE DAY IS NOT THE
C     FIRST OF THE MONTH
  72  MODM=VMEAN(IM,IH)+RHO(IM)*(VEL(NUMSIM)-VMEAN(IM,24))*STD
     1(IM,IH)/STD(IM,24)
  73  COV=MODS/MODM
      CALL PARA(P,C,1,COV,MODM,CO)
      VEL(1)=WEIBUL(P,C)
      XVEL = VMEAN(IM,IH)+F(IM)*(VEL(1)-VMEAN(IM,IH))
```

```
      ISPEED(1)=XVEL*100.
      GO TO 89
   87 ILA=IL-1
      MODM=VMEAN(IM,IH)+RHO(IM)*(VEL(ILA)-VMEAN(IM,IH))
      COV=MODS/MODM
      CALL PARA(P,C,IL,COV,MODM,CO)
      VEL(IL)=WEIBUL(P,C)
      XVEL = VMEAN(IM,IH)+F(IM)*(VEL(IL)-VMEAN(IM,IH))
      ISPEED(IL)=XVEL*100.
   89 CONTINUE
      DO 92 IL=1,NUMSIM
   92 WRITE (5,3010) NY,IM,ID,IH,IL,ISPEED(IL)
   22 ICOUNT=1
   21 CONTINUE
   20 CONTINUE
   19 CONTINUE
      IF(NYEAR) 999,101,103
  101 IF(NMONTH) 102,102,103
  102 NDAY(NMA)=TNDAY
  103 GO TO 1
 1001 FORMAT (6X,I4,5X,I5,8X,I2,8X,I2,8X,I2,8X,I2,8X,I2,F5.0)
 1002 FORMAT(8A10)
 1003 FORMAT(2F10.4)
 1004 FORMAT(F8.4,24F3.2)
 2001 FORMAT(1H1,/,30X,8A10)
 2002 FORMAT(//,35H ONE WIND SPEED IS SIMULATED EVERY ,I4,8H SECONDS,/)
 2003 FORMAT(10X,79H MEAN WIND SPEEDS AND STANDARD DEVIATIONS (IN M/S) B
     1Y MONTH AND HOUR OF THE DAY,//)
 2004 FORMAT(137H HOUR     JANUARY    FEBRUARY      MARCH      APRIL
     1 MAY       JUNE       JULY      AUGUST   SEPTEMBER    OCTOBER   NO
     2VEMBER  DECEMBER,/)
 2005 FORMAT(1X,I2,2X,12F11.4)
 2006 FORMAT(5X,12F11.4)
 2007 FORMAT(1X,22HSIMULATION IS SET FOR ,I5,8H YEARS, ,I2,25H MONTHS (I
     1NITIAL MONTH = ,I2,3H), ,I2,9H DAYS, OR,I2,23H HOURS (INITIAL HOUR
     2 = ,I2,2H).,//)
 2008 FORMAT(71H FINAL SIMULATION MONTH EXCEEDS 12 OR DAY EXCEEDS 31 OR
     1HOUR EXCEEDS 24)
 2100 FORMAT (1H1,///30X,'FOR ',A7,' SIMULATION, THE EFFECTIVE
     2         'CORRELATION RHO ARE : ',/)
 2101 FORMAT (5X,12F10.4,//)
 3010 FORMAT (4I2,I4,I5)
 999  CONTINUE
      STOP
      END
```

```
      SUBROUTINE PARA(P,CK,K,VV,AVEV,CO)
      DIMENSION CO(5)
      Q=1.
      P=1.
      T=1.
      R=2.
      PP=2.
      A=1.+VV**2
    5 C = (1. + CO(1) *(2./PP) + CO(2) *(2./PP)**2 + CO(3) *(2./PP)**3 +
     1 CO(4) *(2./PP)**4 + CO(5) *(2./PP) **5) * R
      D = (1. + CO(1) *(1./Q) + CO(2) *(1./Q)**2 + CO(3) *(1./Q)**3 +
     2CO(4) *(1./Q)**4 + CO(5) *(1./Q)**5 ) * T
      B = C / D**2
      E = B-A
      IF (E) 200,202,250
200   P=P-0.1
      Q=P
      PP=P
      T=1.
5000 IF(2./P-1.)57,57,11
  11 CALL POLY (R,T,PP,Q)
      GO TO 570
  57 R = 1.
 570 C = (1. + CO(1) *(2./PP) + CO(2) *(2./PP)**2 + CO(3) *(2./PP)**3 +
     1 CO(4) *(2./PP)**4 + CO(5) *(2./PP) **5) * R
      D = (1. + CO(1) *(1./Q) + CO(2) *(1./Q)**2 + CO(3) *(1./Q)**3 +
     2CO(4) *(1./Q)**4 + CO(5) *(1./Q)**5 ) * T
      B = C / D**2
      EM = B-A
      IF (EM*E) 30,202,35
35    P=P-0.1
      Q=P
      PP=P
      GO TO 5000
30    P=P+0.01
      T=1.
6000 IF(2./P-1.)58,58,12
  12 CALL POLY (R,T,PP,Q)
      GO TO 580
  58 R = 1.
 580 C = (1. + CO(1) *(2./PP) + CO(2) *(2./PP)**2 + CO(3) *(2./PP)**3 +
     1 CO(4) *(2./PP)**4 + CO(5) *(2./PP) **5) * R
      D = (1. + CO(1) *(1./Q) + CO(2) *(1./Q)**2 + CO(3) *(1./Q)**3 +
     2CO(4) *(1./Q)**4 + CO(5) *(1./Q)**5 ) * T
      B = C / D**2
      EEM = B-A
      IF (EM * EEM) 40,202,45
  45 GO TO 30
40    P=P-0.001
      Q=P
      PP=P
      T=1.
7000 IF(2./P-1.)59,59,13
  13 CALL POLY (R,T,PP,Q)
      GO TO 590
  59 R = 1.
 590 C = (1. + CO(1) *(2./PP) + CO(2) *(2./PP)**2 + CO(3) *(2./PP)**3 +
     1 CO(4) *(2./PP)**4 + CO(5) *(2./PP) **5) * R
```

```
      D = (1. + CO(1) *(1./Q) + CO(2) *(1./Q)**2 + CO(3) *(1./Q)**3 +
     2CO(4) *(1./Q)**4 + CO(5) *(1./Q)**5 ) * T
      B = C / D**2
      EEEM = B-A
      IF  (EEM * EEEM) 50,202,55
   55 GO TO 40
   50 GO TO 150
  250 R = 1.
      T = 1.
251   P=P+1.
      Q=P
      PP=P
      IF(P-11.)111,211,211
  111 C = (1. + CO(1) *(2./PP) + CO(2) *(2./PP)**2 + CO(3) *(2./PP)**3 +
     1 CO(4) *(2./PP)**4 + CO(5) *(2./PP) **5) * R
      D = (1. + CO(1) *(1./Q) + CO(2) *(1./Q)**2 + CO(3) *(1./Q)**3 +
     2CO(4) *(1./Q)**4 + CO(5) *(1./Q)**5 ) * T
      B = C / D**2
      EP = B-A
      IF (EP * E) 130,202,135
  135 GO TO 251
130   P=P-0.1
      Q=P
      PP=P
      T=1.
      IF(2./P-1.)61,61,16
   16 CALL POLY (R,T,PP,Q)
      GO TO 610
   61 R = 1.
  610 C = (1. + CO(1) *(2./PP) + CO(2) *(2./PP)**2 + CO(3) *(2./PP)**3 +
     1 CO(4) *(2./PP)**4 + CO(5) *(2./PP) **5) * R
      D = (1. + CO(1) *(1./Q) + CO(2) *(1./Q)**2 + CO(3) *(1./Q)**3 +
     2CO(4) *(1./Q)**4 + CO(5) *(1./Q)**5 ) * T
      B = C / D**2
      EEP = B-A
      IF (EP * EEP) 140,202,145
  145 GO TO 130
140   P=P+0.01
      Q=P
      PP=P
      T=1.
      IF(2./P-1.)62,62,17
   17 CALL POLY(R,T,PP,Q)
      GO TO 620
   62 R = 1.
  620 C = (1. + CO(1) *(2./PP) + CO(2) *(2./PP)**2 + CO(3) *(2./PP)**3 +
     1 CO(4) *(2./PP)**4 + CO(5) *(2./PP) **5) * R
      D = (1. + CO(1) *(1./Q) + CO(2) *(1./Q)**2 + CO(3) *(1./Q)**3 +
     2CO(4) *(1./Q)**4 + CO(5) *(1./Q)**5 ) * T
      B = C / D**2
      EEEP = B-A
      IF (EEEP * EEP) 160,202,165
  165 GO TO 140
160   P=P-0.001
      Q=P
      PP=P
      T=1.
      IF(2./P-1.)63,63,18
```

```
   18 CALL POLY (R,T,PP,Q)
      GO TO 630
   63 R = 1.
  630 C= (1. + CO(1) * (2./PP) + CO(2) * (2./PP)**2 + CO(3) * (2./PP)**3
     1+ CO(4) * (2./PP)**4 + CO(5) * (2./PP)**5) * R
      D = (1. + CO(1) *(1./Q) + CO(2) *(1./Q)**2 + CO(3) *(1./Q)**3 +
     2CO(4) *(1./Q)**4 + CO(5) *(1./Q)**5 ) * T
      B = C / D**2
      EEEEP = B-A
      IF (EEEEP * EEEP)  150,202,155
  155 GO TO 160
  202 CONTINUE
  150 CONTINUE
  211 CONTINUE
   69 CONTINUE
      CK=AVEV/D
      RETURN
      END
```

```
      SUBROUTINE POLY (R,T,P,Q)
      DIMENSION S(100), U(100)
      R = 2./P
      I=1
      S(I) = 2./P - 1.
    2 IF (S(I) - 1.) 15,15,3
    3 R = R * S(I)
      I = I + 1
      S(I) = (S(I-1) - 1.)
      GO TO 2
   15 J=1
      U(J) = 1./Q
      T = 1./Q
      IF (T.LT. 1) T=1.
    6 IF (U(J) - 1.) 5,5,8
    8 IF (J.EQ.1) GO TO 50
    7 T = T * (U(J))
      J = J+1
      U(J) = (U(J-1) - 1.)
      GO TO 6
    5 Q = 1./U(J)
      P = 2./S(I)
      GO TO 69
   50 IF (T.GT.1) T=1.
      GO TO 7
   69 RETURN
      END
```

APPENDIX C

PROGRAM DECIDE

APPENDIX C

PROGRAM DECIDE

The DECIDE program analyses high frequency wind data as it would operate a given wind turbine. The number of on-off cycles for a specific data record and operating policy can be computed. The program reduces the high frequency wind data record to a sequential set of averaged values. Each operating policy specifies the number of consecutive averages that must be above or below the cut-in speed of the turbine to cycle it on or off. The number of on-off cycles and amount of energy produced are recorded and compared.

The input for the DECIDE program is both on cards and on magnetic tape. The card input is in the following order and format:

Card No.	Col.No.	Format	Variable	Data
1	1-80	8A10	Title	Title of the analysis
2	1-5	I5	MAXTIM	Maximum length of run
	6-10	I5	MAXLVL	Maximum wind speed in the record.
3	1-4	I4	PRTBY1	Number of output duration ranges that have a duration of one reading.
	5-52	12I4	PRTLIM	Six pairs of input information with the first input of each pair being the number of data per range (duration); and the second input of the pair being the number of ranges that has the duration specified by the first input.
4	1-10	F10-4	CUTIN	The cut-in speed of the wind turbine

Card No.	Col. No.	Format	Variable	Data
	11-12	I2	KK	Number of readings(data) to be grouped for each average.
	13-17	I5	NDATA	Number of data to be analyzed.
	18-19	I2	M	Maximum number of consecutive groups that must be above or below cut-in speed to turn the turbine on or off.

The magnetic tape input are the wind speeds written in binary on TAPE 1.

The output of the program consists of a line print of a histogram for each run level (both above and below the level).

```
      PROGRAM DECIDE (INPUT,OUTPUT,TAPE1)
C
      COMMON /RPARMS/ CUMA,CUMB,TOTALA,TOTALB,CNTA,CNTB
      DIMENSION TITLE(8)
      DIMENSION SPEED(12600)
      REAL LVL
      INTEGER TIME,RUNLEN,BELOW,ABOVE
      INTEGER CNTA,CNTB
      INTEGER RUNABV(12600),RUNBEL(12600)
      INTEGER PRTBY1,PRTLIM(16),PLIMIT
C
C  INITIALIZE WIND STAT VARIABLES
C
      NOBS=0
C
C  READ...
C         CARD  1   TITLE
C         CARD  2   MAX LENGTH OF A RUN AND MAX NBR OF LEVELS (2I4)
C         CARD  3   OUTPUT PARAMETERS (13I4)
C
      READ 901,TITLE,MAXTIM,MAXLVL,PRTBY1,PRTLIM
  901 FORMAT (8A10,/,2I5,/,17I4)
C  CUTIN=CUTIN SPEED OF TURBINE(F10.4),KK=NUMBER OF 1 SECOND AVERAGES
C   EVERY 2 SECONDS TO BE GROUPED(I2),NDATA=NUMBER OF WIND SPEEDS TO BE
C   READ IN(I5), AND M IS THE NUMBER OF GROUPS THAT MUST BE CONSECUTIVELY
C   ABOVE OR BELOW CUTIN TO TURN ON OR OFF THE TURBINE(I2)
      READ  150,CUTIN,KK,NDATA,M
  150 FORMAT(F10.4,I2,I5,I2)
C
C  DETERMINE NBR OF OUTPUT INTERVALS ABOVE THE 1 BY 1 STANDARD
C
      PLIMIT=0
      DO 50 I=1,16,2
      IF(PRTLIM(I) .EQ. 0) GOTO 75
      PLIMIT=PLIMIT+2
   50 CONTINUE
   75 CONTINUE
C
      RNB=KK
      ISUB=NDATA/KK
      DO 151 II=1,ISUB
      SUM=0
      DO 152 I=1,KK
      READ(1) V
  152 SUM=SUM+V
      SUM=SUM/RNB
      SPEED(II)=SUM
  151 CONTINUE
```

```
C
C
C     TAPE1 IS THE DATA TAPE
C     SET INITIAL LEVEL
C
      DO 500 LL=1,M
      LLL=LL-1
      CALL PRESET (0,RUNABV,12600)
      CALL PRESET (0,RUNBEL,12600)
      RUNLEN=0
      LVL=CUTIN
      MM=M+1
      RM=LL
      AVE=0
      DO 30 III=1,LL
   30 AVE=AVE+SPEED(III)
      AVE=AVE/RM
      LSTIME=0
      TIME=1
      IF (AVE .GT. LVL) NN=1
      IF (AVE .LT. LVL) NN=2
      DO 10 JJ=MM,ISUB
      TIME =TIME+1
      IF (SPEED(JJ) .GT. LVL ) GO TO 40
      IF (NN .EQ. 2) GO TO 10
      IF (LL .EQ. 1) GO TO 70
      DO 20 I=1,LLL
   20 IF (SPEED(JJ-I) .GT. LVL) GO TC 10
      GO TO 70
   40 IF (NN .EQ. 1) GO TO 10
      IF (LL .EQ. 1) GO TO 60
```

```
      DO 80 I=1,LLL
   80 IF (SPEED(JJ-I) .LT. LVL) GO TO 10
   60 RUNLEN=TIME-LSTIME
      RUNBEL(RUNLEN)=RUNBEL(RUNLEN)+1
      NN=1
      LSTIME=TIME
      GO TO 10
   70 RUNLEN=TIME-LSTIME
      RUNABV(RUNLEN)=RUNABV(RUNLEN)+1
      NN=2
      LSTIME=TIME
   10 CONTINUE
C
C
C
C************************************************************************
C
C  CALCULATE AND PRINT BOTH WIND STATS AND RUN DURATION STATS
C
C************************************************************************
C
C
C  FIRST WIND STATS
C
  300 CONTINUE
C
C  FOR EACH LEVEL PRINT A REPORT
C
C
C
      CNTA=0
      CNTB=0
      AVGA=0
      VARA=0
      AVGB=0
      VARB=0
C
C  THE SECTION THRU 400 COMPUTES RUN STATS AND SAVES THE HISTOGRAMS
C
C
```

```
      DO 350 INT=1,MAXTIM
      INT2=INT*INT
      NRUNA=RUNABV(INT)
      CNTA=CNTA+NRUNA
      AVGA=AVGA+INT*NRUNA
      VARA=VARA+NRUNA*INT2
      NRUNB=RUNBEL(INT)
      CNTB=CNTB+NRUNB
      AVGB=AVGB+NRUNB*INT
      VARB=VARB+NRUNB*INT2
  350 CONTINUE
C
      IF(CNTA .EQ. 0) GOTO 375
      AVGA=AVGA/CNTA
      VARA=VARA/CNTA-AVGA*AVGA
C
  375 IF(CNTB .EQ. 0) GOTO 400
      AVGB=AVGB/CNTB
      VARB=VARB/CNTB-AVGB*AVGB
C
  400 CONTINUE
C
      PRINT 902, TITLE
  902 FORMAT(*1*,1X,8A10,/)
      PRINT 915,LVL,LL
  915 FORMAT (5X,'RUN DISTRIBUTION FOR CUTIN ',F6.2,' METERS PER SECOND,
     2 AND',I3,' GROUPS OF RUNS')
      PRINT 907,CNTA,AVGA,VARA
  907 FORMAT( /,5X,*COUNT ABV = *,I4,*  MEAN ABV = *,F15.5,
     1*  VAR ABV = *,F15.5)
      PRINT 908,CNTB,AVGB,VARB
  908 FORMAT (5X,'COUNT BEL = ',I4,'  MEAN BEL = ',F15.5,'  VAR BEL = ',
     2F15.5)
      PRINT 909
  909 FORMAT (1H0,15X,'DURATION',5X,'ABOVE',5X,'FRACTION',5X,'CUMULATIVE
     2',10X,'BELOW',5X,'FRACTION',5X,'CUMULATIVE',/)
C
      CUMA=0
      CUMB=0
```

```
      TOTALA=0
      TOTALB=0
C
      DO 420 LEN=1,PRTBY1
      FRACTA=0
      FRACTB=0
      RUNSA=RUNABV(LEN)
      RUNSB=RUNBEL(LEN)
      TOTALA=TOTALA+RUNSA
      TOTALB=TOTALB+RUNSB
      IF(CNTA .EQ. 0) GOTO 405
      FRACTA=RUNSA/CNTA
      CUMA=TOTALA/CNTA
  405 IF(CNTB .EQ. 0) GOTO 410
      FRACTB=RUNSB/CNTB
      CUMB=TOTALB/CNTB
      NRUNA=RUNSA
      NRUNB=RUNSB
  410 PRINT 920, LEN,NRUNA,FRACTA,CUMA,NRUNB,FRACTB,CUMB
  920 FORMAT(19X,I4,5X,I5,5X,F8.5,7X,F8.5,10X,I5,5X,F8.5,7X,F8.5)
  420 CONTINUE
C
      IF(PLIMIT .EQ. 0) GOTO 500
      ISTART=PRTBY1
      DO 450 I=1,PLIMIT,2
      CALL PRTHTG(ISTART,PRTLIM(I),PRTLIM(I+1),RUNABV,RUNBEL,LVL)
  450 CONTINUE
C
      REWIND 1
  500 CONTINUE
C
      STOP
      END
```

```
      SUBROUTINE PRTHTG(ISTART,LIMIT1,LIMIT2,RUNABV,RUNBEL,LVL)
      COMMON /RPARMS/ CUMA,CUMB,TOTALA,TOTALB,CNTA,CNTB
      DIMENSION RUNABV(1),RUNBEL(1)
      INTEGER RUNABV,RUNBEL,CNTA,CNTB
C
      LONE=ISTART
      LTWO=ISTART
      IPTR=ISTART
C
      DO 200 IGRPA=1,LIMIT2
C
      FRACTA=0
      FRACTB=0
      RUNSA=0
      RUNSB=0
C
      DO 100 IGRPB=1,LIMIT1
C
      IPTR=IPTR+1
      INRA=RUNABV(IPTR)
      INRB=RUNBEL(IPTR)
      RUNSA=RUNSA+INRA
      RUNSB=RUNSB+INRB
C
  100 CONTINUE
C
      TOTALA=TOTALA+RUNSA
      TOTALB=TOTALB+RUNSB
C
      IF(CNTA .EQ. 0) GOTO 125
      FRACTA=RUNSA/CNTA
      CUMA=TOTALA/CNTA
C
  125 IF(CNTB .EQ. 0) GOTO 150
      FRACTB=RUNSB/CNTB
      CUMB=TOTALB/CNTB
C
  150 LONE=LONE+1
      LTWO=LTWO+LIMIT1
C
      NRA=RUNSA
      NRB=RUNSB
      PRINT 175, LONE,LTWO,NRA,FRACTA,CUMA,NRB,FRACTB,CUMB
  175 FORMAT(12X,I4,* - *,I4,5X,I5,5X,F8.5,7X,F8.5,10X,I5,5X,F8.5,
     1         7X,F8.5)
C
      LONE=LTWO
C
  200 CONTINUE
C
C
      ISTART=LTWO
C
      RETURN
      END
```

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