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Comparison of Low-Altitude Wind-Shear Statistics Derived From Measured and Proposed Standard Wind Profiles

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SUMMARY

In 1977 NASA Langley Research Center collected data onboard wide-body jet transports to determine the feasibility of measuring winds and wind shear during landings and takeoffs. From these data a measured set of wind profiles was determined and wind-shear statistical parameters were estimated for over 640 landings and takeoffs. Another set of wind profiles was simulated using a wind field data base proposed by the Federal Aviation Administration. Over 640 profiles were determined for ascent and descent trajectories through the proposed two-dimensional wind fields assuming a 3° glide slope on approach and a 6° climbout on takeoff. From these data sets, wind shears were calculated and grouped in 100-ft altitude bands from 100 to 1400 ft and in 0.025-knot/ft wind-shear intervals between ±0.600 knot/ft. Frequency distributions, means, and standard deviations were derived for each altitude band and compared. Also, relative and cumulative frequency distributions were derived for the total sample (all altitudes) and compared. For the measured data set no wind-shear values existed outside ±0.200 knot/ft.

Frequency distributions in each altitude band for the simulated data set were more dispersed below 800 ft and less dispersed above 900 ft than those for the measured data set. Distributions for both data sets, however, were practically symmetrical for all altitudes. Total sample frequency of occurrence for the two data sets was about equal for wind-shear values between ±0.075 knot/ft, but the simulated data set had significantly higher frequency of occurrence values for all wind shears outside these boundaries. Normal distribution fits of both data sets showed that neither data set was normally distributed. Similar results were observed from the cumulative frequency distributions.

INTRODUCTION

Safe and reliable air transportation systems are essential to the United States economy and security. For this reason, a continuous, vigorous effort is maintained to improve these systems and to understand the environments in which they operate. For example, wind shear, defined as the local variation of the wind vector or its components in a given direction and distance (ref. 1), has been identified as being especially hazardous during the landing and takeoff of aircraft, and the Federal Aviation Administration (FAA) has instituted a major programmatic effort to study this problem (ref. 2). As part of this effort, a wind profile data base is being defined for use in flight simulation studies. These studies should improve the scientific understanding of the wind-shear hazard and should aid in definition of aircraft response requirements and in the design of systems to help the pilot cope with this hazard.

Since various government agencies and industrial interests are involved, the FAA has sponsored several studies to define standard wind profiles for use in simulation studies. In reference 2, 21 profiles selected for use in piloted simulator tests are presented, and 7 of the 21 are suggested for use in simulators to demonstrate methods and systems that will enable the pilot to cope successfully with wind shear. Reference 3 presents a comprehensive set of wind profiles and associated wind-shear characteristics, which encompass many of the wind-shear environments that aircraft could potentially encounter in the terminal area. Some of these were used to formulate the models of reference 2. Reference 4 summarizes the development and testing of airborne displays, instrumentation, and procedures for aiding jet-transport pilots in coping with wind-shear effects. These tests used the seven candidate standard wind-shear profiles suggested in reference 2. Finally, in reference 5, the reference 2 data base was used in real-time aircraft simulation studies of NASA's Terminal Configured Vehicle (TCV), and potential areas for improvement in the data base were pointed out. These references indicate that the profiles suggested in reference 2 provide a reasonable data base for studying the wind-shear hazard. Generally, however, further studies, both analytical and experimental, are recommended to improve the data base.

NASA has been collecting and analyzing data on the operating environment of aircraft for many years. In reference 6, for example, wind and wind-shear data were obtained from parameters recorded onboard wide-body jet transports during landing and takeoff. This study was made to determine the feasibility of measuring winds and wind shears during normal commercial aircraft operations. These parameters were recorded over a 2-week period during a total of 641 takeoffs and landings, from which 6300 wind samples were obtained. From these wind samples, wind-shear values were calculated and grouped in 100-ft altitude bands from 100 to 1400 ft. In addition, shear values in each altitude band were grouped and plotted as histograms. From these histograms, frequency distributions, means, and standard deviations of the wind shear were calculated. Finally, probability of occurrence of wind shear of a specific magnitude for any operation and altitude was presented.

The purpose of the present study was to compute statistical parameters from wind-shear data generated using the 21 proposed standard wind profiles of reference 2 and to compare these parameters with those of reference 6. Specifically, comparisons were made of frequency distributions, means, and standard deviations of wind shear in each altitude band and of relative and cumulative frequency distributions for the total sample. It should be noted, however, that the statistical distributions from the two data sources depended on the characteristics of each data set. For example, more than half of the 21 profiles of reference 2 represented thunderstorm environments, whereas the data of reference 6 were apparently collected during more moderate weather conditions. Also, wind shear due to changes in wind direction was not considered in the estimates of the total wind-shear distributions.

DESCRIPTION OF DATA SETS

Proposed Standard Wind Profiles

Standard wind profiles and associated turbulence parameters proposed by the FAA for use in piloted simulation tests and in training and system qualification tests are discussed in reference 2. Wind profiles are identified and listed in table I. For convenience, the profiles were numbered 1 to 21 for this study as listed in the first column. The last three columns list the profile numbers assigned in reference 2 and those used in aircraft simulation studies in reference 2 to determine relative wind profile severity. These numbers are not used in this report, but are listed here for continuity.

The 21 wind profiles of reference 2 were derived from measured data and from mathematical models representing a variety of atmospheric conditions. The FAA study used these data in an analytical simulation of an airplane with three rigid-body degrees of freedom and with simplified pitch attitude and thrust control systems. These wind profiles were described as a function of altitude and range. Each profile was assigned a severity rank based on established performance criteria (see ref. 2). Profiles were compared, and potentially hazardous wind profiles were identified and designated as low, moderate, or high (see table I). As might be expected and as stated previously, 12 of the 21 wind profiles selected represent thunderstorm environments (profiles 7, 8, and 11 to 20), and the sources of wind data for 9 of these profiles were accident reconstruction reports. Wind data for the other three were obtained from tall meteorological tower measurements (profiles 7 and 8) and a mathematical model (profile 16). Accident reports were the source of profiles 5, 6, and 9, representing conditions preceding warm frontal systems. Profiles 10 and 21 represent conditions following cold fronts. (It is worth noting that in ref. 7, Goff concluded that air masses following strong cold fronts appear to rival thunderstorm outflows in terms of potential hazards to aviation.) The remaining four profiles (profiles 1 to 4) represent either neutral or stable atmospheric conditions (see ref. 2 for definitions). Profiles 1 to 16 were designed for studying the wind-shear hazard occurring during approach and landing, whereas profiles 17 to 21 were designed for takeoff and climbout.

Wind Profiles Measured During Commercial Aircraft Operations

In reference 6, information from digital flight data recorders interfaced with the aircraft integrated data system was used to derive 641 measured wind profiles. Data were collected for a 2-week period during the spring of 1977. Table II lists the location of 14 airports from which the operations were conducted and the number of profiles measured for each location. In reference 6 it was noted that the data set may be biased because 25 percent of the data were obtained during training flights at one airport and more than 60 percent of the data were obtained from operations at three airports. Also, no attempt was made to correlate the flight operations with existing meteorological conditions.

Measurement systems onboard the aircraft were activated so that a wind sample data point was obtained every 3 or 4 seconds (see ref. 6). From these measurements, plots of resultant wind velocity as a function of altitude up to 1400 ft were constructed for each operation. Wind shears were calculated from these profiles as the first derivative of resultant wind velocity with respect to altitude. A data point was obtained on the average at altitude increments of 30 to 50 ft for altitudes below 800 ft. Above 800 ft, however, vertical spacing between data points was nearly uniformly distributed between 0 to 100 ft, since for some operations the aircraft leveled off and for others it continued to climb. This created a bias in the distribution; however, Dunham (ref. 6) concluded that the data do reasonably characterize the distribution of wind shear and that this distribution was independent of altitude.

METHOD OF ANALYSIS

To compare statistical properties calculated in reference 6 with those for the data derived from the wind profiles of reference 2, ascent and descent trajectories were simulated through these wind profiles (two-dimensional wind fields). Using this technique, 645 operations (takeoffs and landings) were generated compared with 641 for the data set in reference 6. The operations are listed in table III.

The wind profiles of reference 2 were referenced to the glide-path intercept point (GPIP) of the runway coordinate system shown in figure 1. For a specific operation in this study the wind profile was determined from unpublished tables of the data used in reference 2 and from calculations of the altitude and range from

$$z = z_o + (V \sin \gamma)\ \Delta t$$

and

$$x = x_o + (V \cos \gamma)\ \Delta t$$

where the subscript o indicates initial value. The time interval Δt was selected so that the altitude increment between data points ranged from 26 ft for the slowest descent rate to 83 ft for the fastest ascent rate. Typical aircraft velocity values V of 130 and 140 knots, respectively, were assumed during descent and ascent. Also, nominal glide-path and climbout angles of $\gamma = 3°$ and $6°$, respectively, were assumed, and additional operations were obtained by varying these parameters and the GPIP as indicated in table III.

Wind profiles 1 to 6, 9, and 16 (see table I) were described as a function of altitude only. For this reason, the nominal glide-path angle was used for these simulations to produce the first eight operations listed in table III. Wind profiles 7, 8, and 10 to 15, however, were derived as functions of altitude and range, so that unique profiles could be generated by varying either the glide-path angle or GPIP. Using this method, 392 operations were generated. Similarly, 245 operations were generated for the takeoff wind fields (profiles 17 to 21 in table I). Total or resultant wind speed was calculated as the root sum square of the three wind components, whereas in reference 6 it was calculated as the root sum square of the two horizontal components. A separate study, however, showed that the statistical comparisons were unaffected by including the vertical wind component. Wind shear for both data sets was calculated as the change in total wind velocity with altitude.

Wind-shear values were calculated for each profile and sorted in altitude bands of 100 ft for altitudes between 100 and 1400 ft. For example, all shear values occurring between 100 ± 50 ft comprised the 100-ft altitude band. In addition, in each altitude band, wind-shear values were grouped in constant class intervals of 0.025 knot/ft between ±0.600 knot/ft. These groupings are shown in table IV.

The number of wind-shear values within each wind-shear interval were summed for all altitude bands. These results are listed in table V. For the 14 altitude bands and 48 wind-shear intervals there were 21 216 wind-shear values calculated. These values were used to calculate frequency distributions, means, and standard deviations for comparison with the results of reference 6.

The method of moments for grouped data was used to calculate the means and standard deviations for the two data sets. For example, the rth moment is (see ref. 8)

$$\overline{W}^r = \frac{f_1 W_1^r + f_2 W_2^r + \ldots + f_k W_k^r}{N} = \frac{1}{N} \sum_{j=1}^{k} f_j W_j^r$$

where $N = \sum_{j=1}^{k} f_j$. The first moment (r = 1) is the arithmetic mean $\bar{W}$. The rth moment about the mean is

$$m_r = \frac{\sum_{j=1}^{k} f_j\left(W_j - \bar{W}\right)^r}{N} = \overline{\left(W - \bar{W}\right)^r}$$

When $r = 1$, $m_r = 0$; and when $r = 2$, $m_2 = \sigma^2$, the variance, and $\sqrt{\sigma^2}$ is the standard deviation. For the simulated data set listed in table IV, the variable W_j represents the wind-shear value at the interval midpoint, f_j is the number of occurrences in the interval, $k = 48$, the number of wind-shear intervals, and $N = 21\ 216$, the total sample size. For the simulated data set (table V), the mean and standard deviation of the frequency distribution were 0.0004 and 0.052, and for the measured data set, they were 0.0029 and 0.033.

RESULTS AND DISCUSSION

The number of occurrences in each wind-shear interval listed in table IV are plotted as histograms in figure 2 and compared with similar data from reference 6. Each histogram represents 1 of the 14 altitude bands, and the number of data points (wind-shear values calculated) in each altitude band are given on figure 2 for both data sets. Also, the number of data points in the wind-shear class interval with the maximum number of occurrences is listed for both data sets and each distribution. No wind-shear values existed outside ±0.200 knot/ft for the measured data set.

The distributions for the 100- and 300-ft altitude bands for the simulated data show the maximum number of occurrences in the interval from +0.025 to +0.050 knot/ft. For all other altitude bands, the maximum number of occurrences was within ±0.025 knot/ft. Maximum number of occurrences for the measured data set occurred within ±0.025 knot/ft for all altitude bands. This implies that an aircraft encountering the simulated wind fields in the 100- and 300-ft altitude bands would experience larger shears, creating an apparently more hazardous environment. For wind-shear bands outside ±0.050 knot/ft, the simulated data were more broadly distributed than the measured data for altitudes from 100 to 800 ft. Above the 800-ft band this trend reversed and the wind-shear values for the measured data were more broadly distributed for all wind-shear increments; however, the number of occurrences in most wind-shear intervals had decreased to below 5 percent of the maximum.

Figure 3 shows the variation of the mean and standard deviation of wind shear with altitude for both data sets. The variation of standard deviation with altitude shows that the simulated data set had greater dispersions about the mean between 100 and 800 ft than the measured data set, but less above 900 ft. Standard deviations for the measured data set were practically constant up to an altitude of 1100 ft and decreased above 1100 ft, whereas those for the simulated data set decreased continuously with altitude. These results show that the reference 2 wind fields would provide a more hazardous environment due to wind shear below 800 ft than the measured data set. This would be expected, however, because some of the wind profiles of reference 2 were designed to represent severe wind-shear encounters which pilots would normally avoid (see table I).

Table VI summarizes the total sample statistics calculated for both data sets. Values for the relative frequency distributions are listed in table VI(a) and for cumulative frequency distributions in table VI(b). Number of occurrences in each wind-shear interval for the simulated data set is from table V. Simulated values of frequency of occurrence are compared with the measured values in figure 4, in which the number of occurrences in a given wind-shear interval has been divided by sample size (21 216 for the simulated data set and 6277 for the measured data set). Since the statistical properties of the distributions for each altitude band did not vary greatly with altitude for the measured data set (see ref. 6 and fig. 3), the total sample distribution in figure 4 also represents the frequency of occurrence of a given shear in each altitude band. This is not true for the simulated data set, however, because the statistical properties did vary significantly with altitude, as shown in figure 3. Total sample frequency of occurrence for the two data sets was about the same for wind-shear values between ±0.075 knot/ft, but the simulated data set had significantly larger values for all wind-shear values outside these boundaries. Calculations of normal distribution fits of both data sets showed that neither the measured nor the simulated data set was normally distributed.

Cumulative frequencies of occurrence from table VI(b) for both data sets are shown in figure 5. Similar to figure 4, this comparison shows a broader distribution for the simulated data set and generally greater probabilities for given shear values for the simulated data set. Both distributions appear to be nearly symmetrical about zero.

As mentioned previously, the measured data set did not contain wind-shear values outside ±0.200 knot/ft. The simulated data set, however, had 168 points, or about 1 percent of the total number of points, outside these boundaries. Table VII lists the distribution of these 168 points in the altitude bands and wind-shear intervals. This distribution shows that these wind-shear values are concentrated in the lower altitude bands. For example, 47 points (28 percent) occurred in the 100-ft band, 15 points (9 percent) in the 500-ft band, and only 1 point (0.6 percent) in the 1000-ft band. Similarly, the simulated wind-shear values outside ±0.200 knot/ft occurred in the lower wind-shear intervals, 143 points (85 percent) being between ±0.200 and ±0.300 knot/ft.

CONCLUDING REMARKS

Wind-shear statistics derived from wind profiles generated from proposed standard wind fields have been compared with statistics derived from data measured onboard commercial aircraft. A large sample was used for each data set to calculate wind-shear values in 100-ft altitude bands from 100 to 1400 ft. Wind-shear values were grouped in increments of 0.025 knot/ft, and frequency distributions, means, and standard deviations were compared in each 100-ft altitude band. Similarly, wind-shear values were grouped for all altitude bands, and relative and cumulative frequency distributions were compared for the total sample.

Frequency distributions in each altitude band for the simulated data set were more dispersed below 800 ft and less dispersed above 900 ft than those for the measured data set. Distributions for both data sets, however, were practically symmetrical for all altitudes. Total sample frequency of occurrence for the two data sets was about the same for wind-shear values between ±0.075 knot/ft, but the simulated data set had significantly larger values for all wind-shear values outside these boundaries. Normal distribution fits of both data sets showed that neither data set was normally distributed. Similar results were observed from the cumulative frequency distributions. It should be noted that the statistical properties as presented in this paper for both data sets may be biased by such factors as sample size, data sampling rate, methods used for calculating wind shear, and the data base from which the distributions were derived.

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TABLE I.- SUMMARY OF WIND PROFILES SUGGESTED FOR USE IN PILOTED SIMULATIONS (REF. 2)

Profile no.	Relative wind profile severity	Source of wind data	Meteorological wind type	FAA derived wind profile no.	B-727 piloted simulator tests, wind profile no.	DC-10 simulator tests, wind profile no.
Approach						
1	Low	Meteorological math model	Neutral	N2A	B1	D1
2		Meteorological math model	Stable	S1A	B2	
3		Meteorological math model	Stable	S2A	B3	
4		Tower measurements	Stable	S6A	B4	
5	Moderate	Logan accident reconstruction	Warm front	F1A	B5	D5
6		Same as 5, rotated 40°	Warm front	F2A	B6	
7		Tower measurements	Thunderstorm	T8A	B7	D7
8		Tower measurements	Thunderstorm	T9A	B8	D8
9		Tokyo accident reconstruction	Warm front	F5A		D2
10	High	Tower measurements	Cold front	F3A	B9	D9
11		Philadelphia accident reconstruction	Thunderstorm	T24A	B10	
12		Kennedy accident reconstruction	Thunderstorm	T0A	B11	
13		Kennedy accident reconstruction	Thunderstorm	T0B	B12	D6
14		Kennedy accident reconstruction	Thunderstorm	T0C		D10
15		Philadelphia accident reconstruction	Thunderstorm	T25A		D4
16		Math model	Thunderstorm	M1A		D3
Takeoff						
17	High	Kennedy accident reconstruction	Thunderstorm	T0D		D11
18		Philadelphia accident reconstruction	Thunderstorm	T23A		D12
19		Philadelphia accident reconstruction	Thunderstorm	T24B		D13
20		Philadelphia accident reconstruction	Thunderstorm	T25B		D14
21		Tower measurements	Cold front	F3B		D15

TABLE II.- AIRPORTS AND NUMBER OF WIND PROFILES MEASURED AT EACH AIRPORT

[From ref. 6]

Airport	Number of profiles	Percent of total
Atlantic City, New Jersey	160	25.0
New York, New York	122	19.0
London, England	109	17.0
Madrid, Spain	48	7.5
Paris, France	45	7.0
Boston, Massachusetts	35	5.5
Rome, Italy	28	4.3
Chicago, Illinois	26	4.0
Los Angeles, California	17	2.6
Barcelona, Spain	13	2.0
Philadelphia, Pennsylvania	13	2.0
Milano, Italy	12	1.9
Algiers	11	1.7
Monaco	2	<1.0

TABLE III.- OPERATIONS DERIVED FROM SIMULATED FLIGHTS THROUGH THE WIND PROFILES OF REFERENCE 2

Operations	Profile numbers	Flight-path angle, γ, deg	Glide-path intercept point, x_o, ft	Inertial velocity, V_o, knots
1 to 8 (approach)	1 to 6, 9, 16	3	0	130
9 to 400 (approach)	7, 8, 10 to 15	3, 3 ± 0.25, 3 ± 0.50, 3 ± 0.75	0, ± 3937, ± 7874, ± 11800	130
401 to 645 (takeoff)	17 to 21	6, 6 ± 0.25, 6 ± 0.50, 6 ± 0.75	0, ± 3937, ± 7874, ± 11800	140

TABLE IV.- SIMULATED WIND-SHEAR VALUES GROUPED IN 100-FT ALTITUDE BANDS AND WIND-SHEAR INTERVALS OF 0.025 KNOT/FT

(a) 100-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.275	0	0
-.275 to -.250	1	.32
-.250 to -.225	4	1.28
-.225 to -.200	5	1.60
-.200 to -.175	11	3.51
-.175 to -.150	10	3.19
-.150 to -.125	10	3.19
-.125 to -.100	24	7.67
-.100 to -.075	27	8.63
-.075 to -.050	41	13.10
-.050 to -.025	69	22.04
-.025 to .000	234	74.76
.000 to .025	268	85.62
.025 to .050	[a]313	100.00
.050 to .075	47	15.02
.075 to .100	74	23.64
.100 to .125	61	19.49
.125 to .150	50	15.97
.150 to .175	34	10.86
.175 to .200	20	6.39
.200 to .225	12	3.83
.225 to .250	4	1.28
.250 to .275	5	1.60
.275 to .300	1	.32
.300 to .325	2	.64
.325 to .350	0	0
.350 to .375	3	.96
.375 to .400	2	.64
.400 to .425	1	.32
.425 to .450	3	.96
.450 to .475	1	.32
.475 to .500	0	0
.500 to .525	2	.64
.525 to .550	0	0
.550 to .575	0	0
.575 to .600	1	.32
Total	1340	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(b) 200-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.575	0	0
-.575 to -.550	1	.19
-.550 to -.350	0	0
-.350 to -.325	1	.19
-.325 to -.300	2	.37
-.300 to -.275	1	.19
-.275 to -.250	2	.37
-.250 to -.225	3	.56
-.225 to -.200	7	1.31
-.200 to -.175	16	2.99
-.175 to -.150	17	3.17
-.150 to -.125	6	1.12
-.125 to -.100	21	3.92
-.100 to -.075	47	8.77
-.075 to -.050	91	16.98
-.050 to -.025	118	22.01
-.025 to .000	254	47.39
.000 to .025	[a]536	100.00
.025 to .050	138	25.75
.050 to .075	75	13.99
.075 to .100	54	10.07
.100 to .125	34	6.34
.125 to .150	14	2.61
.150 to .175	19	3.54
.175 to .200	19	3.54
.200 to .225	8	1.49
.225 to .250	3	.56
.250 to .275	1	.19
.275 to .300	2	.37
.300 to .325	1	.19
.325 to .350	3	.56
.350 to .600	0	0
Total	1494	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(c) 300-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.325	0	0
-.325 to -.300	1	.24
-.300 to -.275	1	.24
-.275 to -.250	0	0
-.250 to -.225	2	.48
-.225 to -.200	5	1.21
-.200 to -.175	17	4.12
-.175 to -.150	28	6.78
-.150 to -.125	32	7.75
-.125 to -.100	22	5.33
-.100 to -.075	35	8.47
-.075 to -.050	75	18.16
-.050 to -.025	144	34.87
-.025 to .000	253	61.26
.000 to .025	381	92.25
.025 to .050	[a]413	100.00
.050 to .075	54	13.08
.075 to .100	45	10.90
.100 to .125	29	7.02
.125 to .150	30	7.26
.150 to .175	30	7.26
.175 to .200	18	4.36
.200 to .225	7	1.69
.225 to .250	3	.73
.250 to .275	1	.24
.275 to .300	1	.24
.300 to .600	0	0
Total	1627	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(d) 400-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.275	0	0
-.275 to -.250	1	.23
-.250 to -.225	0	0
-.225 to -.200	12	2.72
-.200 to -.175	9	2.04
-.175 to -.150	22	4.99
-.150 to -.125	26	5.90
-.125 to -.100	19	4.31
-.100 to -.075	25	5.67
-.075 to -.050	49	11.11
-.050 to -.025	83	18.82
-.025 to .000	265	60.09
.000 to .025	[a]441	100.00
.025 to .050	311	70.52
.050 to .075	85	19.27
.075 to .100	50	11.34
.100 to .125	43	9.75
.125 to .150	42	9.52
.150 to .175	17	3.85
.175 to .200	7	1.59
.200 to .225	3	.68
.225 to .250	4	.91
.250 to .275	1	.23
.275 to .600	0	0
Total	1515	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(e) 500-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.225	0	0
-.225 to -.200	4	1.04
-.200 to -.175	6	1.56
-.175 to -.150	19	4.94
-.150 to -.125	21	5.45
-.125 to -.100	30	7.79
-.100 to -.075	47	12.21
-.075 to -.050	190	49.35
-.050 to -.025	166	43.12
-.025 to .000	260	67.53
.000 to .025	[a]385	100.00
.025 to .050	90	23.38
.050 to .075	58	15.06
.075 to .100	65	16.88
.100 to .125	47	12.21
.125 to .150	16	4.16
.150 to .175	8	2.08
.175 to .200	7	1.82
.200 to .225	5	1.30
.225 to .250	3	.78
.250 to .275	2	.52
.275 to .300	0	0
.300 to .325	1	.26
.325 to .600	0	0
Total	1430	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(f) 600-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.275	0	0
-.275 to -.250	1	.22
-.250 to -.225	0	0
-.225 to -.200	1	.22
-.200 to -.175	2	.44
-.175 to -.150	16	3.52
-.150 to -.125	30	6.59
-.125 to -.100	56	12.31
-.100 to -.075	96	21.10
-.075 to -.050	110	24.18
-.050 to -.025	141	30.99
-.025 to .000	408	89.67
.000 to .025	[a]455	100.00
.025 to .050	93	20.44
.050 to .075	72	15.82
.075 to .100	60	13.19
.100 to .125	25	5.49
.125 to .150	12	2.64
.150 to .175	17	3.74
.175 to .200	4	.88
.200 to .225	7	1.54
.225 to .600	0	0
Total	1606	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(g) 700-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.275	0	0
-.275 to -.250	2	.48
-.250 to -.225	2	.48
-.225 to -.200	3	.72
-.200 to -.175	5	1.19
-.175 to -.150	11	2.63
-.150 to -.125	13	3.10
-.125 to -.100	37	8.83
-.100 to -.075	127	30.31
-.075 to -.050	130	31.03
-.050 to -.025	374	89.26
-.025 to .000	236	56.32
.000 to .025	[a]419	100.00
.025 to .050	66	15.75
.050 to .075	48	11.46
.075 to .100	46	10.98
.100 to .125	10	2.39
.125 to .150	7	1.67
.150 to .175	7	1.67
.175 to .200	3	.72
.200 to .225	3	.72
.225 to .250	1	.24
.250 to .600	0	0
Total	1550	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(h) 800-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.225	0	0
-.225 to -.200	2	.48
-.200 to -.175	3	.72
-.175 to -.150	7	1.68
-.150 to -.125	6	1.44
-.125 to -.100	17	4.09
-.100 to -.075	41	9.86
-.075 to -.050	119	28.61
-.050 to -.025	270	64.90
-.025 to .000	386	92.79
.000 to .025	[a]416	100.00
.025 to .050	59	14.18
.050 to .075	50	12.02
.075 to .100	10	2.40
.100 to .125	5	1.20
.125 to .150	4	.96
.150 to .175	4	.96
.175 to .200	1	.24
.200 to .225	1	.24
.225 to .250	1	.24
.250 to .275	1	.24
.275 to .600	0	0
Total	1403	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(i) 900-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.225	0	0
-.225 to -.200	1	.13
-.200 to -.175	0	0
-.175 to -.150	2	.26
-.150 to -.125	2	.26
-.125 to -.100	7	.91
-.100 to -.075	22	2.85
-.075 to -.050	30	3.88
-.050 to -.025	67	8.67
-.025 to .000	601	77.75
.000 to .025	[a]773	100.00
.025 to .050	53	6.86
.050 to .075	14	1.81
.075 to .100	3	.39
.100 to .125	7	.91
.125 to .150	3	.39
.150 to .175	3	.39
.175 to .200	2	.26
.200 to .225	1	.13
.225 to .250	1	.13
.250 to .600	0	0
Total	1592	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(j) 1000-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.200	0	0
-.200 to -.175	2	.28
-.175 to -.150	0	0
-.150 to -.125	0	0
-.125 to -.100	2	.28
-.100 to -.075	18	2.50
-.075 to -.050	22	3.06
-.050 to -.025	77	10.71
-.025 to .000	[a]719	100.00
.000 to .025	684	95.13
.025 to .050	45	6.26
.050 to .075	4	.56
.075 to .100	4	.56
.100 to .125	0	0
.125 to .150	3	.42
.150 to .175	3	.42
.175 to .200	1	.14
.200 to .225	1	.14
.225 to .600	0	0
Total	1585	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(k) 1100-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.150	0	0
-.150 to -.125	1	.15
-.125 to -.100	1	.15
-.100 to -.075	9	1.32
-.075 to -.050	23	3.37
-.050 to -.025	58	8.50
-.025 to .000	[a]682	100.00
.000 to .025	613	89.88
.025 to .050	29	4.25
.050 to .075	3	.44
.075 to .100	0	0
.100 to .125	1	.15
.125 to .150	1	.15
.150 to .175	1	.15
.175 to .200	2	.29
.200 to .600	0	0
Total	1424	

[a]Number of occurrences of maximum.

TABLE IV.- Continued

(l) 1200-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.125	0	0
-.125 to -.100	1	.13
-.100 to -.075	5	.66
-.075 to -.050	30	3.94
-.050 to -.025	49	6.44
-.025 to .000	[a]761	100.00
.000 to .025	751	98.69
.025 to .050	34	4.47
.050 to .075	4	.53
.075 to .100	2	.26
.100 to .125	2	.26
.125 to .150	0	0
.150 to .175	2	.26
.175 to .600	0	0
Total	1641	

[a]Number of occurrences of maximum.

TABLE IV.- Concluded

(m) 1300-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.100	0	0
-.100 to -.075	1	.13
-.075 to -.050	13	1.73
-.050 to -.025	43	5.73
-.025 to .000	676	90.01
.000 to .025	[a]751	100.00
.025 to .050	26	3.46
.050 to .075	3	.40
.075 to .100	1	.13
.100 to .125	0	0
.125 to .150	1	.13
.150 to .600	0	0
Total	1515	

[a]Number of occurrences of maximum.

(n) 1400-ft altitude band

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.100	0	0
-.100 to -.075	2	.24
-.075 to -.050	8	.97
-.050 to -.025	31	3.76
-.025 to .000	606	73.54
.000 to .025	[a]824	100.00
.025 to .050	19	2.31
.050 to .075	4	.49
.075 to .600	0	0
Total	1494	

[a]Number of occurrences of maximum.

TABLE V.- FREQUENCY DISTRIBUTION OF SIMULATED WIND-SHEAR DATA FOR ALL 14 ALTITUDE BANDS

Wind-shear interval, knot/ft	Number of occurrences	Percent of maximum
-0.600 to -0.575	0	0
-.575 to -.550	1	.005
-.550 to -.525	0	0
-.525 to -.500	0	0
-.500 to -.475	0	0
-.475 to -.450	0	0
-.450 to -.425	0	0
-.425 to -.400	0	0
-.400 to -.375	0	0
-.375 to -.350	0	0
-.350 to -.325	1	.005
-.325 to -.300	3	.014
-.300 to -.275	2	.009
-.275 to -.250	7	.033
-.250 to -.225	11	.052
-.225 to -.200	40	.189
-.200 to -.175	71	.335
-.175 to -.150	132	.622
-.150 to -.125	147	.693
-.125 to -.100	237	1.117
-.100 to -.075	502	2.366
-.075 to -.050	931	4.388
-.050 to -.025	1 690	7.966
-.025 to .000	6 341	29.882
.000 to .025	7 697	36.279
.025 to .050	1 689	7.961
.050 to .075	521	2.456
.075 to .100	414	1.951
.100 to .125	264	1.244
.125 to .150	183	.863
.150 to .175	145	.683
.175 to .200	84	.396
.200 to .225	48	.226
.225 to .250	20	.094
.250 to .275	11	.052
.275 to .300	4	.019
.300 to .325	4	.019
.325 to .350	3	.014
.350 to .375	3	.014
.375 to .400	2	.009
.400 to .425	1	.005
.425 to .450	3	.014
.450 to .475	1	.005
.475 to .500	0	0
.500 to .525	2	.009
.525 to .550	0	0
.550 to .575	0	0
.575 to .600	1	.005
Total	21 216	

TABLE VI.- SUMMARY OF THE TOTAL SAMPLE STATISTICS FOR BOTH DATA SETS

(a) Frequency distributions

Wind-shear interval, knot/ft	Interval midpoint, knot/ft	Simulated data		Frequency of occurrence[a]	
		No. of occurrences, f	$\sum f$	Simulated data	Measured data
-0.600 to -0.575	-0.5875	0	0	0	
-.575 to -.550	-.5625	1	1	.0000	
-.550 to -.525	-.5375	0	1	0	
-.525 to -.500	-.5125	0	1	0	
-.500 to -.475	-.4875	0	1	0	
-.475 to -.450	-.4625	0	1	0	
-.450 to -.425	-.4375	0	1	0	
-.425 to -.400	-.4125	0	1	0	
-.400 to -.375	-.3875	0	1	0	
-.375 to -.350	-.3625	0	1	0	
-.350 to -.325	-.3375	1	2	.0000	
-.325 to -.300	-.3125	3	5	.0001	
-.300 to -.275	-.2875	2	7	.0001	
-.275 to -.250	-.2625	7	14	.0003	
-.250 to -.225	-.2375	11	25	.0005	
-.225 to -.200	-.2125	40	65	.0019	
-.200 to -.175	-.1875	71	136	.0033	0.00112
-.175 to -.150	-.1625	132	268	.0062	.00173
-.150 to -.125	-.1375	147	415	.0069	.00301
-.125 to -.100	-.1125	237	652	.0112	.00537
-.100 to -.075	-.0875	502	1 154	.0237	.00968
-.075 to -.050	-.0625	931	2 085	.0439	.02830
-.050 to -.025	-.0375	1690	3 775	.0797	.07138
-.025 to .000	-.0125	6341	10 116	.2989	.31484
.000 to .025	.0125	7697	17 813	.3628	.38370
.025 to .050	.0375	1689	19 502	.0796	.11188
.050 to .075	.0625	521	20 023	.0246	.03741
.075 to .100	.0875	414	20 437	.0195	.01391
.100 to .125	.1125	264	20 701	.0124	.00554
.125 to .150	.1375	183	20 884	.0086	.00206
.150 to .175	.1625	145	21 029	.0068	.00190
.175 to .200	.1875	84	21 113	.0040	.00190
.200 to .225	.2125	48	21 161	.0023	
.225 to .250	.2375	20	21 181	.0009	
.250 to .275	.2625	11	21 192	.0005	
.275 to .300	.2875	4	21 196	.0002	
.300 to .325	.3125	4	21 200	.0002	
.325 to .350	.3375	3	21 203	.0001	
.350 to .375	.3625	3	21 206	.0001	
.375 to .400	.3875	2	21 208	.0001	
.400 to .425	.4125	1	21 209	.0000	
.425 to .450	.4375	3	21 212	.0001	
.450 to .475	.4625	1	21 213	.0000	
.475 to .500	.4875	0	21 213	0	
.500 to .525	.5125	2	21 215	.0001	
.525 to .550	.5375	0	21 215	0	
.550 to .575	.5625	0	21 215	0	
.575 to .600	.5875	1	21 216	.0000	

[a]Frequency of occurrence is obtained by dividing the number of occurrences in a given interval by total sample size.

TABLE VI.- Concluded

(b) Cumulative frequency distributions

Wind-shear interval, knot/ft	Interval midpoint, knot/ft	Cumulative no. of occurrences		Cumulative frequency of occurrence[a]	
		Negative wind shear	Positive wind shear	Simulated data	Measured data
-0.600 to -0.575	-0.5875	0		0	
-.575 to -.550	-.5625	1		.0000	
-.550 to -.525	-.5375	1		.0000	
-.525 to -.500	-.5125	1		.0000	
-.500 to -.475	-.4875	1		.0000	
-.475 to -.450	-.4625	1		.0000	
-.450 to -.425	-.4375	1		.0000	
-.425 to -.400	-.4125	1		.0000	
-.400 to -.375	-.3875	1		.0000	
-.375 to -.350	-.3625	1		.0000	
-.350 to -.325	-.3375	2		.0001	
-.325 to -.300	-.3125	5		.0002	
-.300 to -.275	-.2875	7		.0003	
-.275 to -.250	-.2625	14		.0007	
-.250 to -.225	-.2375	25		.0012	
-.225 to -.200	-.2125	65		.0031	
-.200 to -.175	-.1875	136		.0064	0.00112
-.175 to -.150	-.1625	268		.0126	.00285
-.150 to -.125	-.1375	415		.0196	.00585
-.125 to -.100	-.1125	652		.0307	.01123
-.100 to -.075	-.0875	1 154		.0544	.02091
-.075 to -.050	-.0625	2 085		.0983	.04921
-.050 to -.025	-.0375	3 775		.1779	.12060
-.025 to .000	-.0125	10 116		.4768	.43544
.000 to .025	.0125		11 100	.5232	.55830
.025 to .050	.0375		3 403	.1604	.17459
.050 to .075	.0625		1 714	.0808	.06271
.075 to .100	.0875		1 193	.0562	.02530
.100 to .125	.1125		779	.0367	.01139
.125 to .150	.1375		515	.0243	.00585
.150 to .175	.1625		332	.0156	.00379
.175 to .200	.1875		187	.0088	.00190
.200 to .225	.2125		103	.0049	
.225 to .250	.2375		55	.0026	
.250 to .275	.2625		35	.0016	
.275 to .300	.2875		24	.0011	
.300 to .325	.3125		20	.0009	
.325 to .350	.3375		16	.0008	
.350 to .375	.3625		13	.0006	
.375 to .400	.3875		10	.0005	
.400 to .425	.4125		8	.0004	
.425 to .450	.4375		7	.0003	
.450 to .475	.4625		4	.0002	
.475 to .500	.4875		3	.0001	
.500 to .525	.5125		3	.0001	
.525 to .550	.5375		1	.0000	
.550 to .575	.5625		1	.0000	
.575 to .600	.5875		1	.0000	

[a]Cumulative frequency of occurrence is obtained by dividing the cumulative number of occurrences in a given interval by the total sample size.

TABLE VII.- DISTRIBUTION OF WIND-SHEAR OCCURRENCES OUTSIDE
±0.200 KNOT/FT FOR SIMULATED DATA SET

Altitude band, ft	Number of occurrences in wind-shear interval, knot/ft, of -				
	±0.200 to ±0.300	±0.300 to ±0.400	±0.400 to ±0.500	±0.500 to ±0.600	Total
100	32	7	5	3	47
200	27	7	0	1	35
300	20	1		0	21
400	21	0			21
500	14	1			15
600	9	0			9
700	11				11
800	5				5
900	3				3
[a]1000	1				1
Total ...	143	16	5	4	168

[a]No wind shears outside ±0.200 knot/ft occurred above 1000 ft.

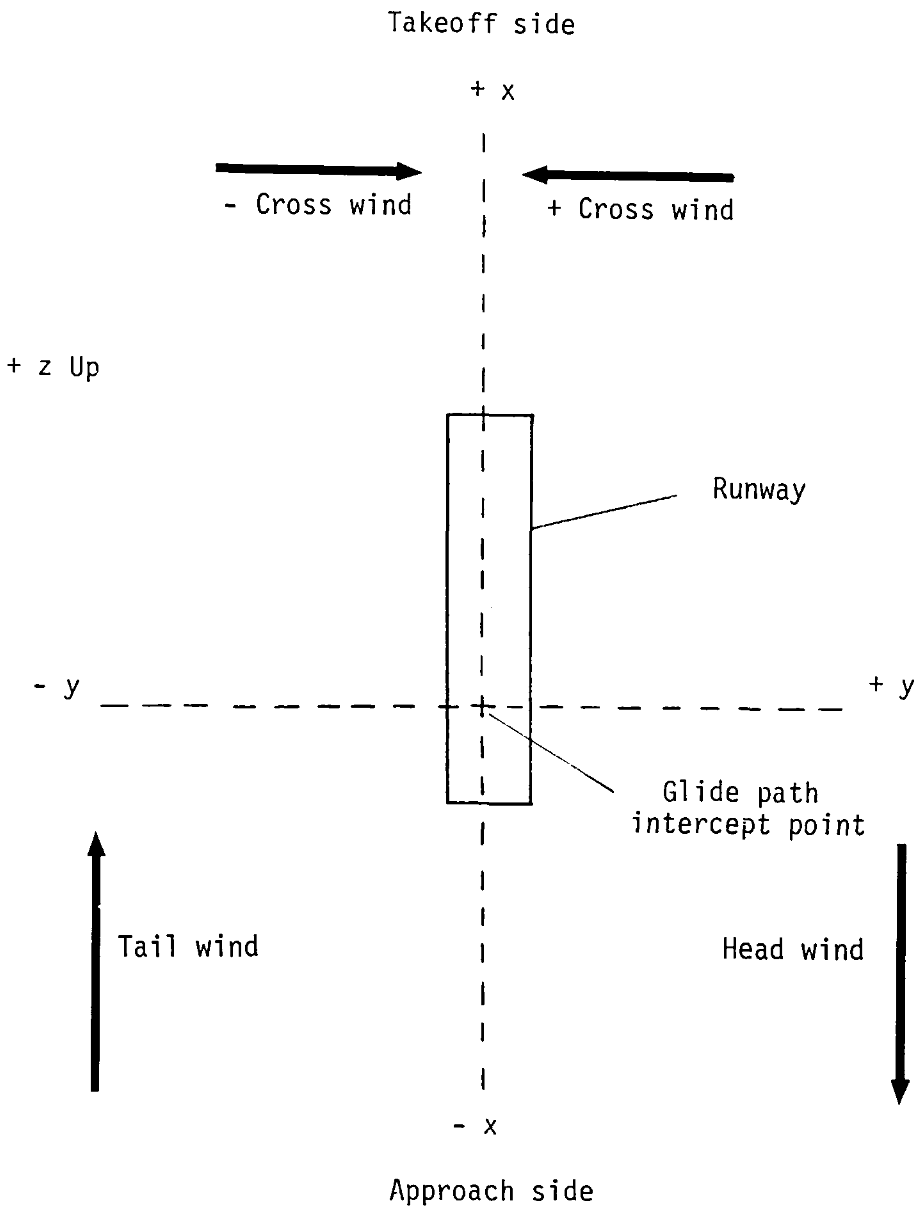
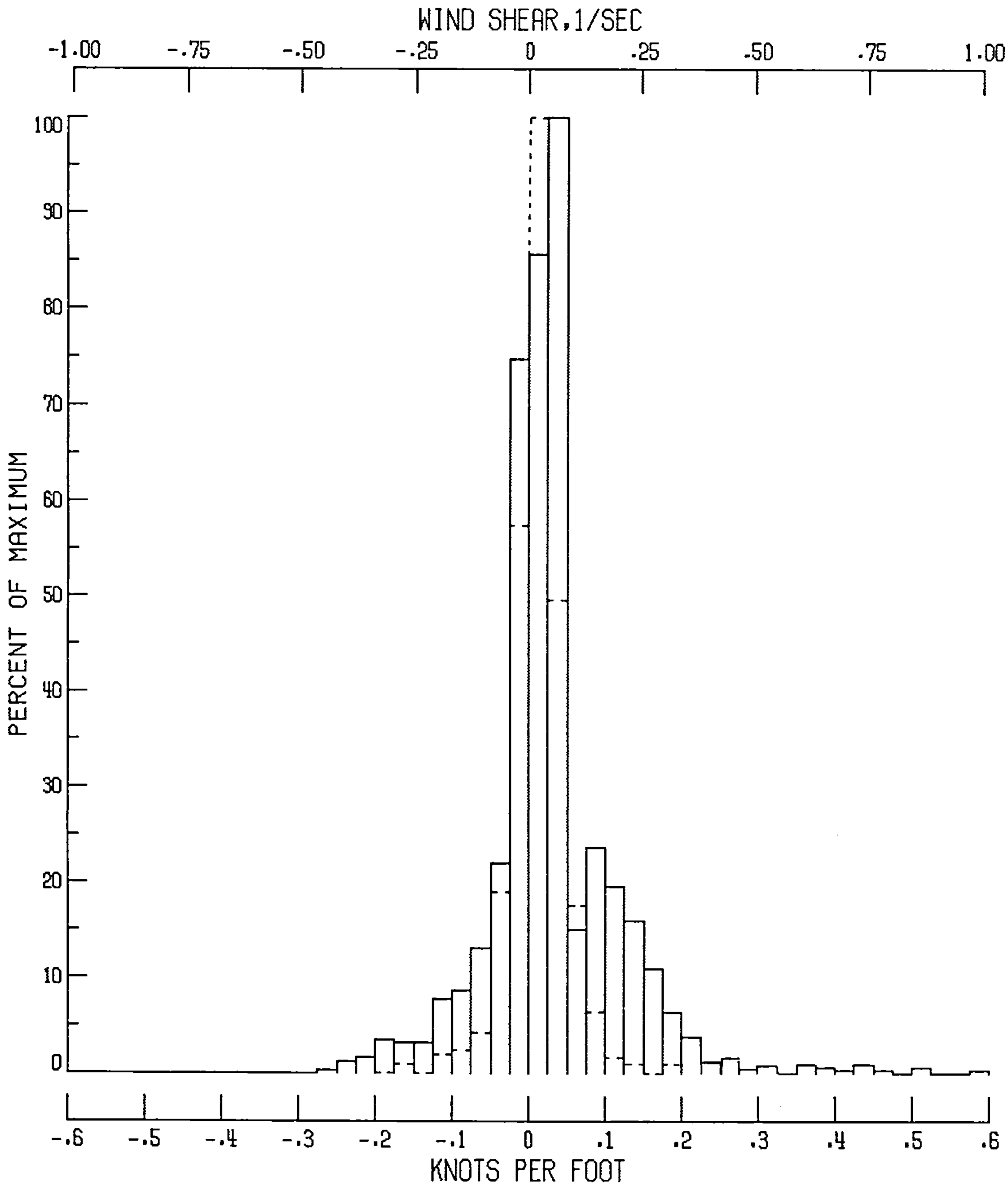


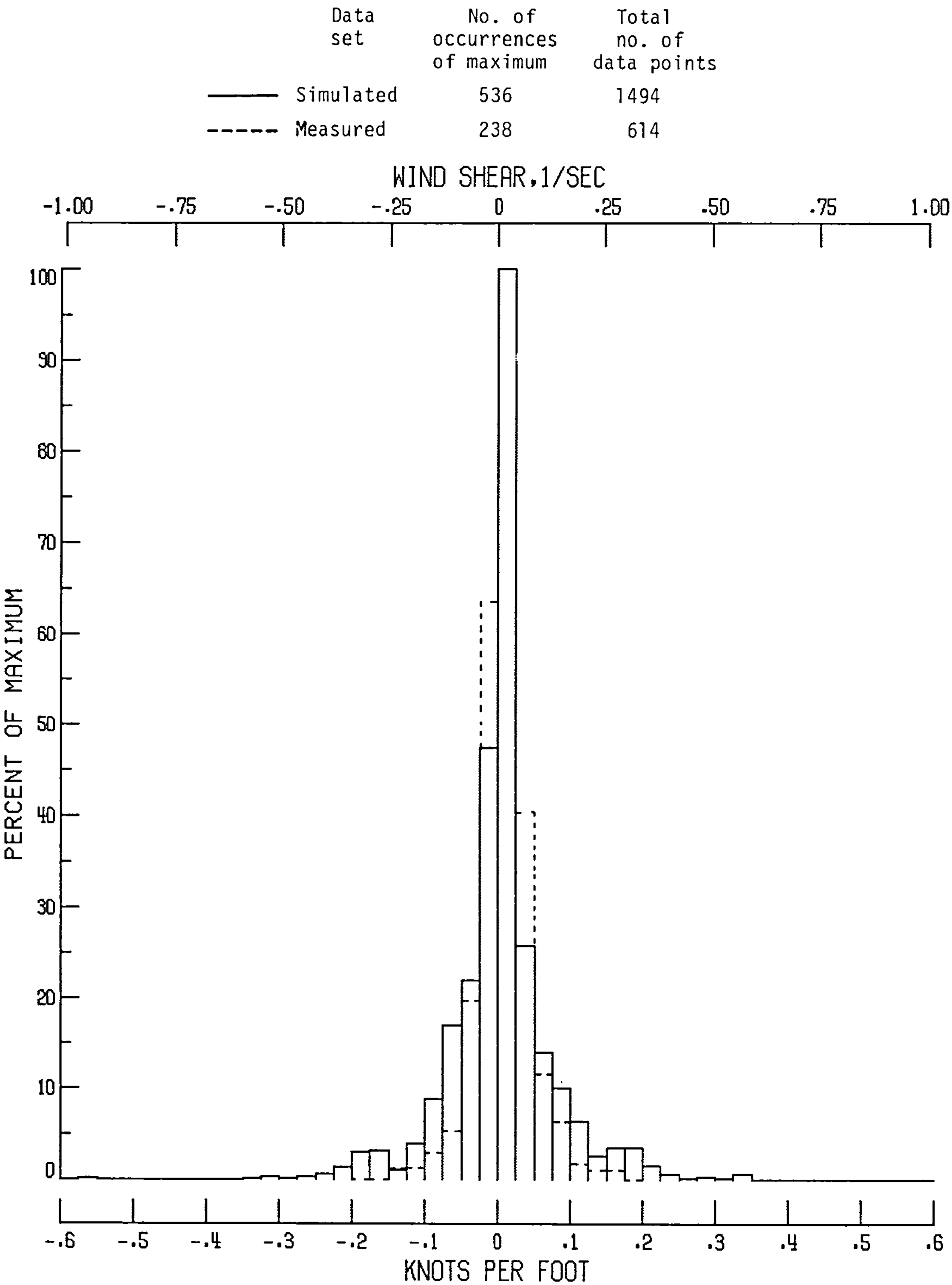
Figure 1.- Runway coordinate system and sign convention.

	Data set	No. of occurrences of maximum	Total no. of data points
———	Simulated	313	1340
-----	Measured	235	623



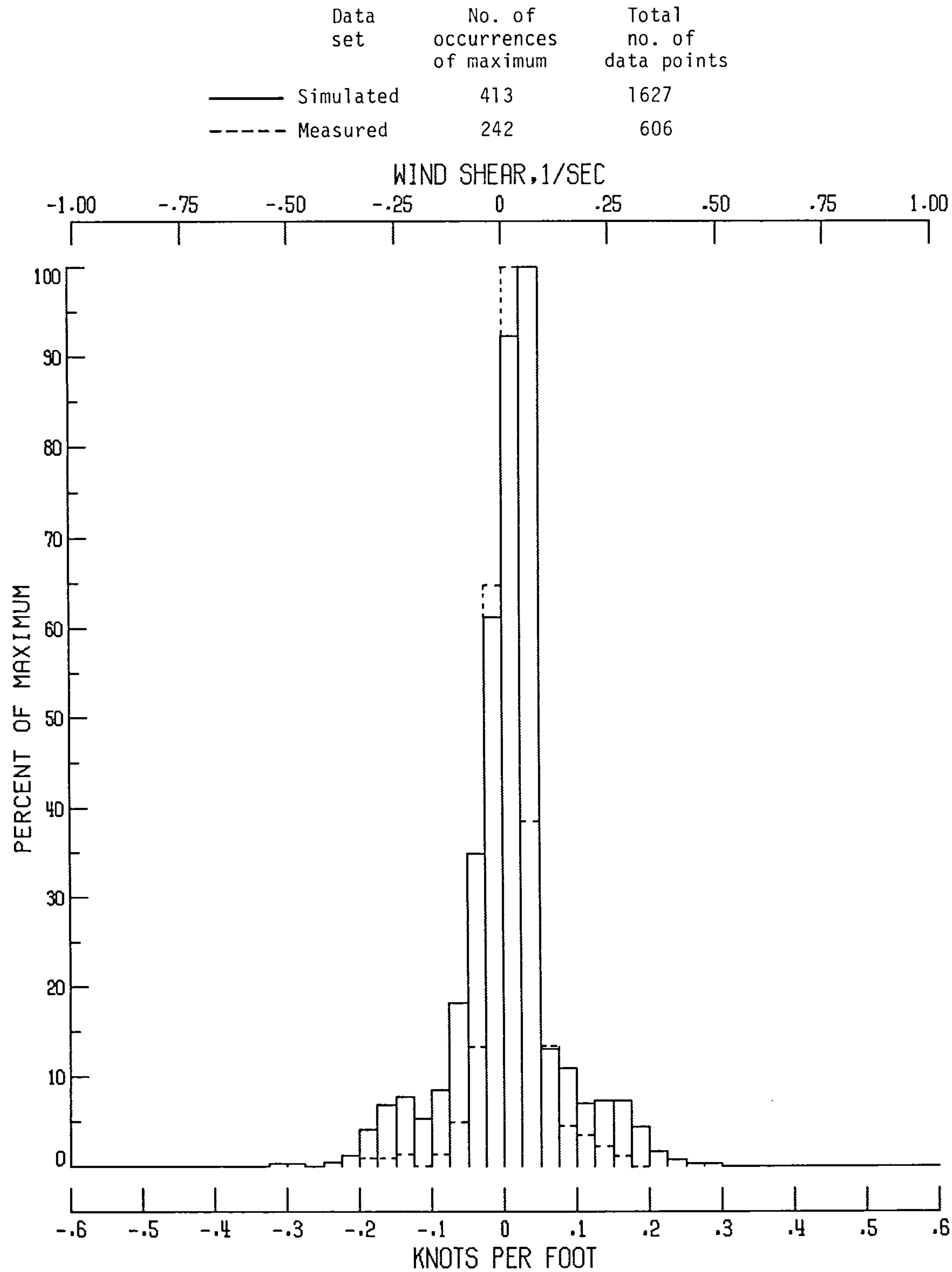
(a) 100-ft altitude band.

Figure 2.- Distribution of wind shears in 100-ft altitude bands.



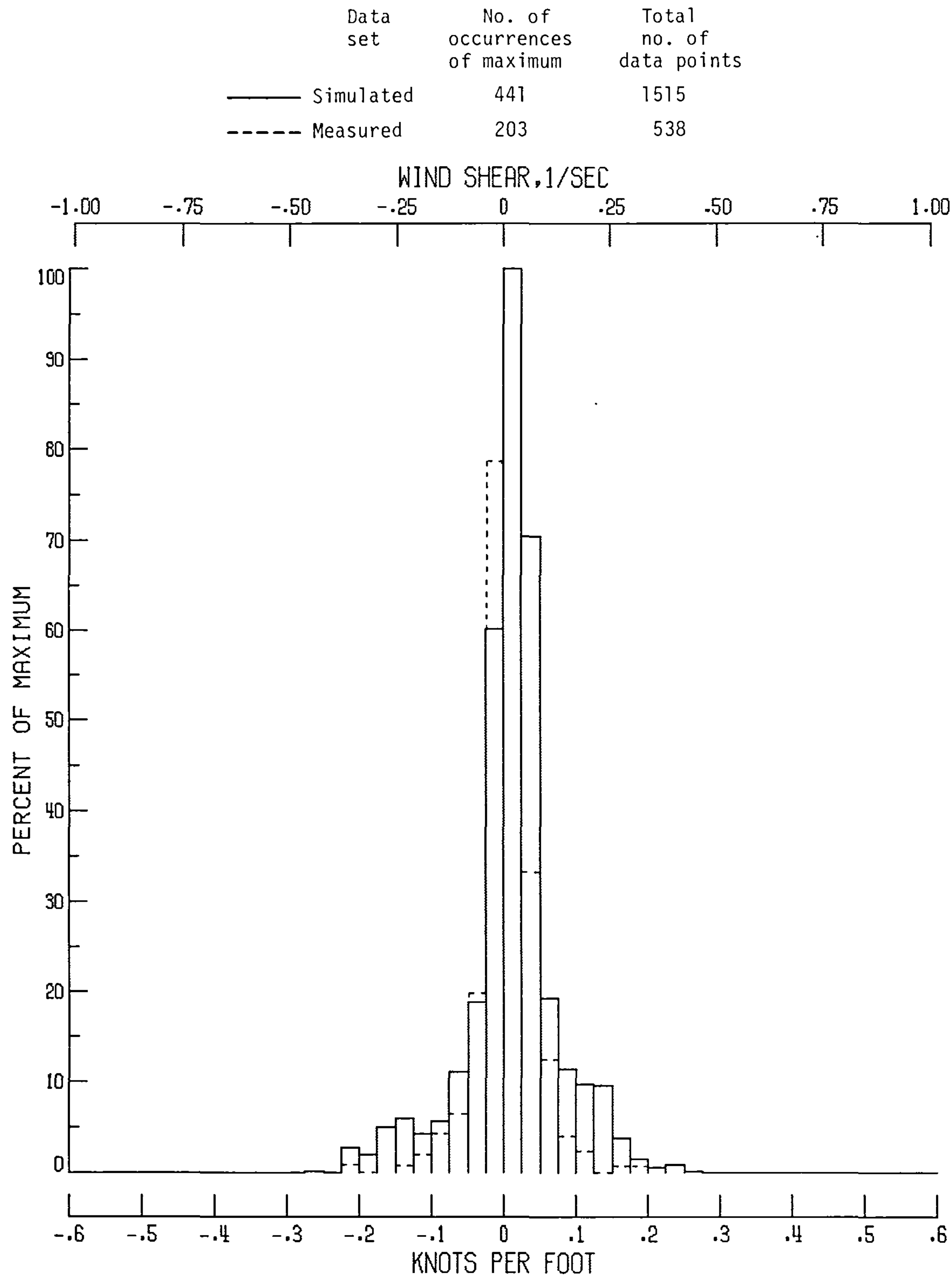
(b) 200-ft altitude band.

Figure 2.- Continued.



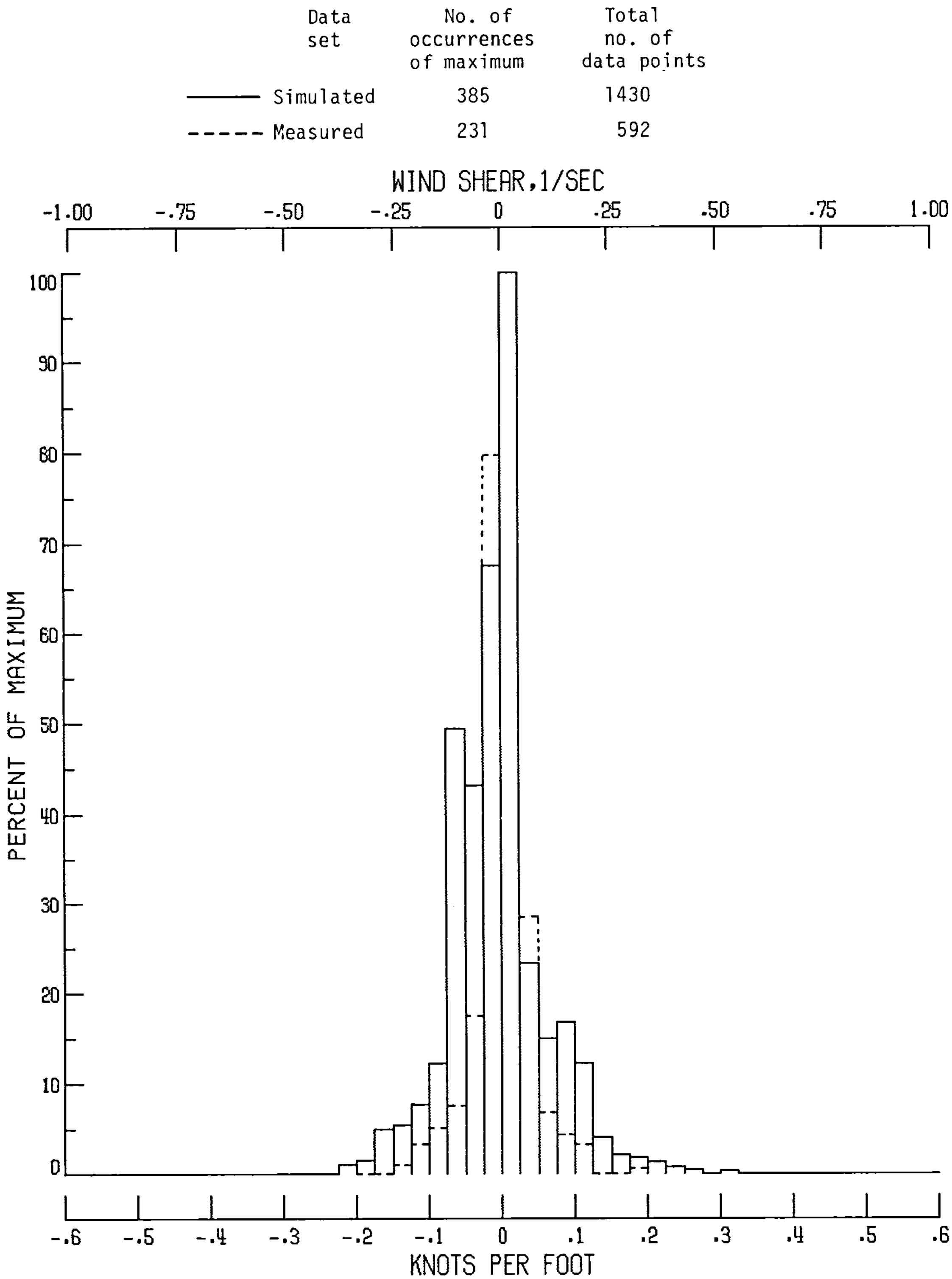
(c) 300-ft altitude band.

Figure 2.- Continued.



(d) 400-ft altitude band.

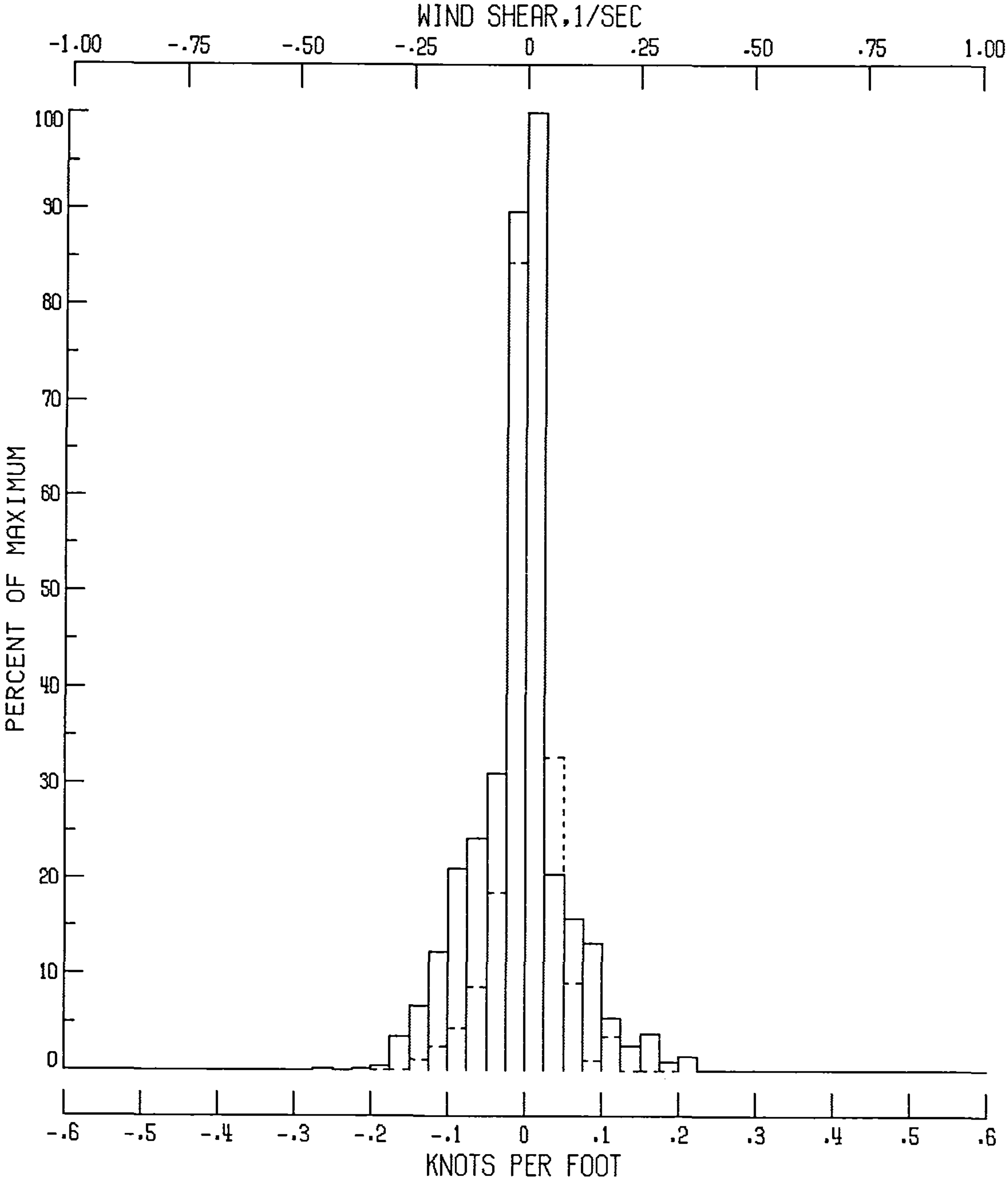
Figure 2.- Continued.



(e) 500-ft altitude band.

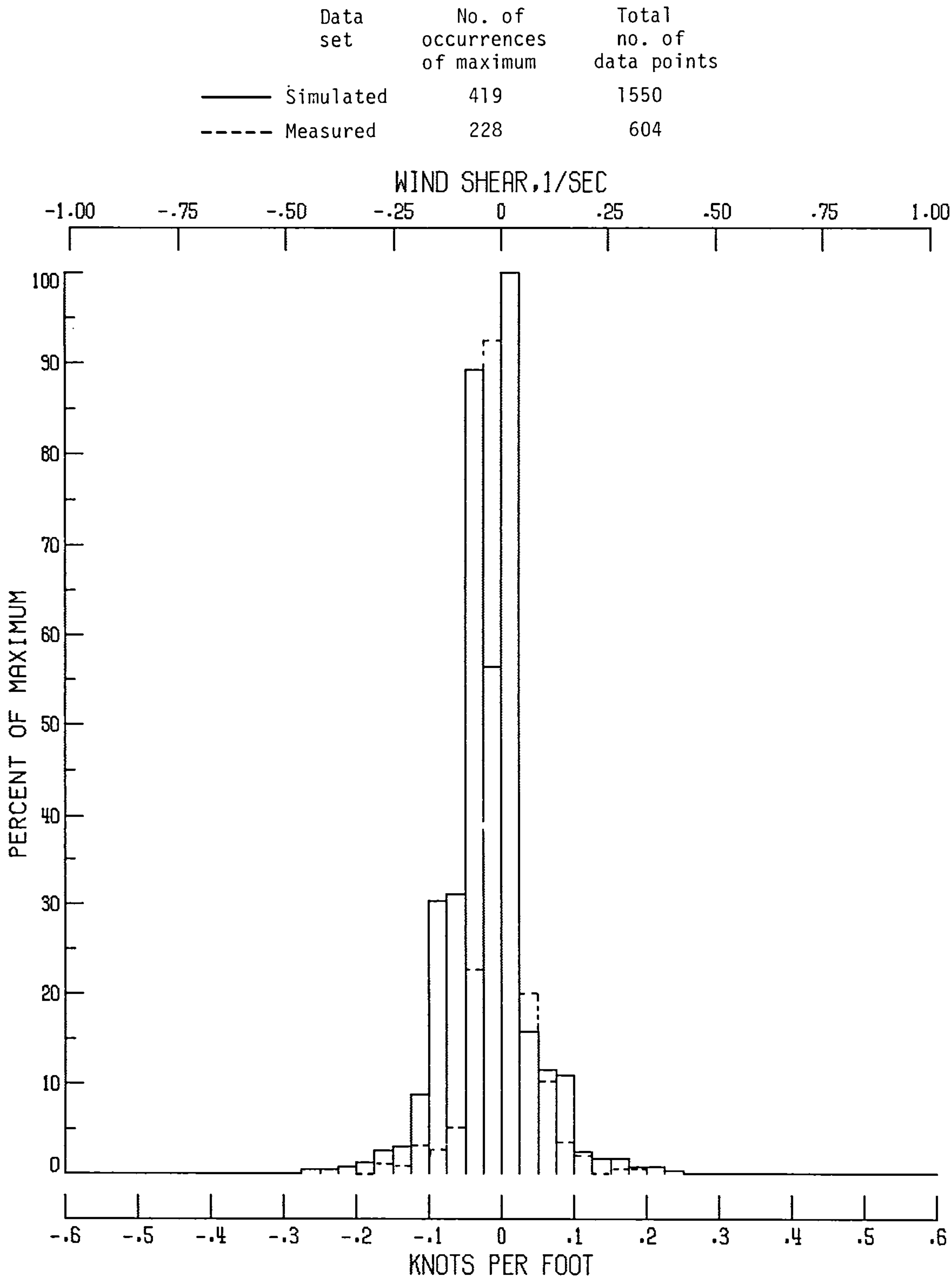
Figure 2.- Continued.

Data set	No. of occurrences of maximum	Total no. of data points
——— Simulated	455	1606
- - - - - Measured	205	536



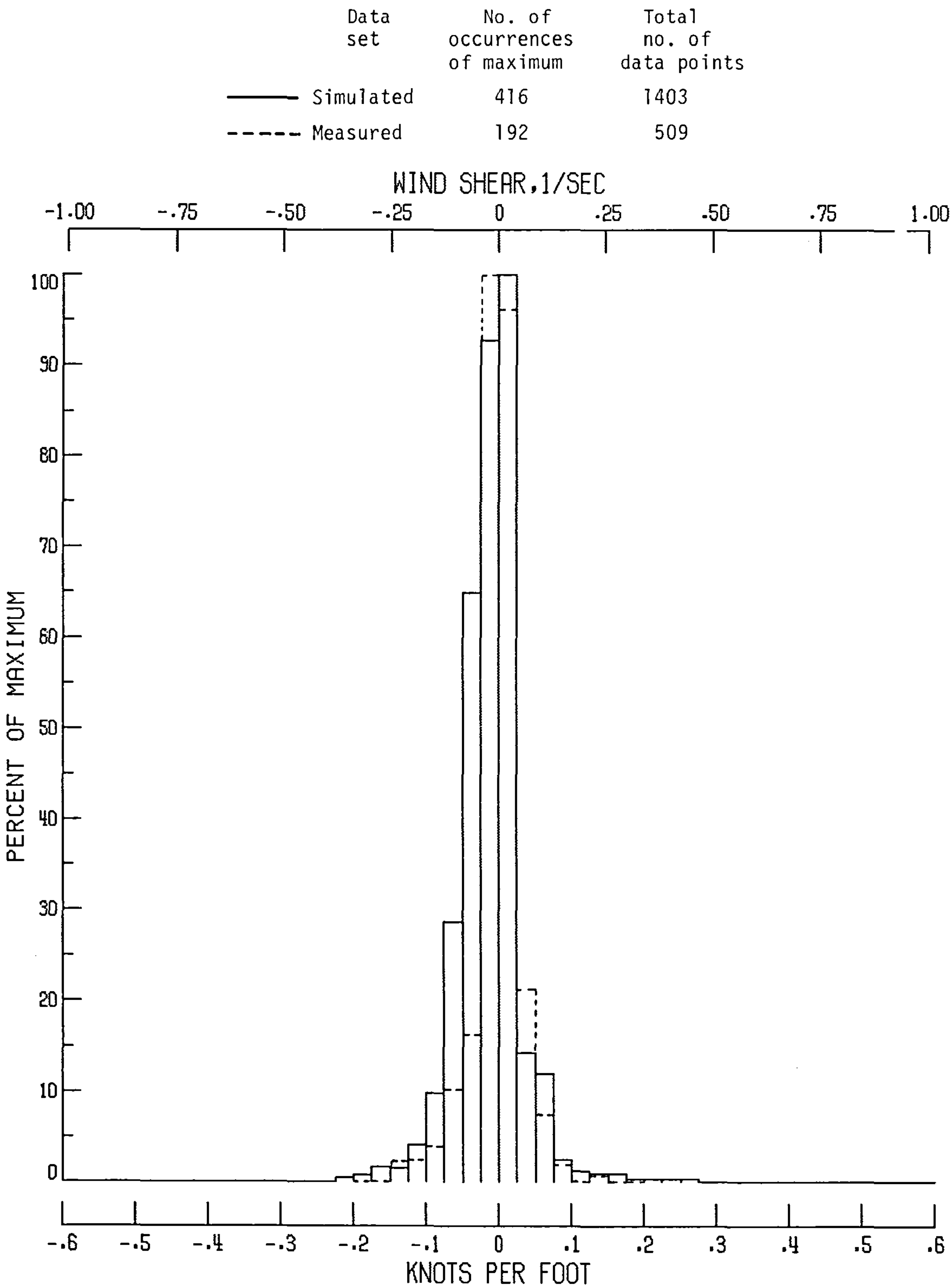
(f) 600-ft altitude band.

Figure 2.- Continued.



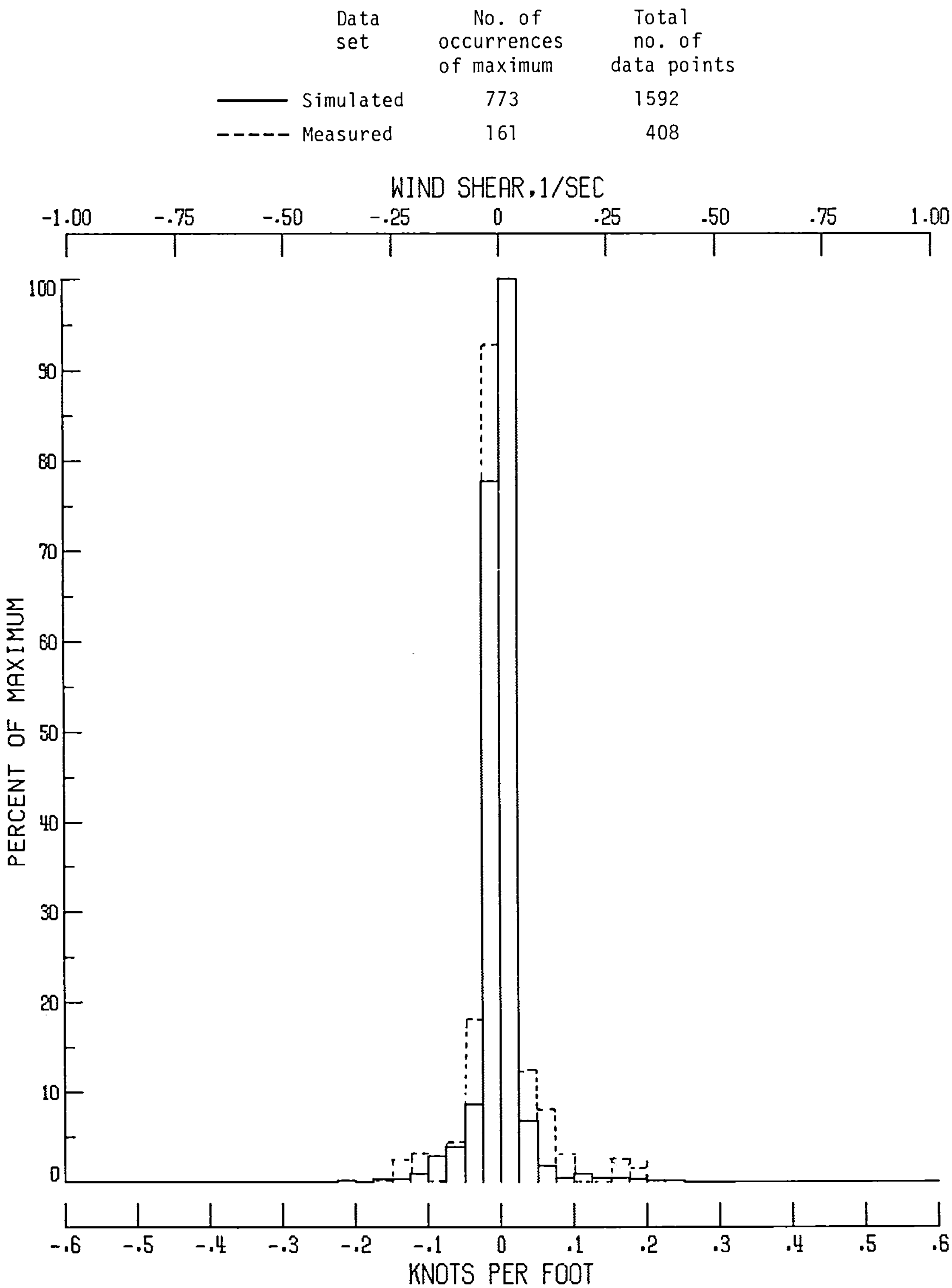
(g) 700-ft altitude band.

Figure 2.- Continued.



(h) 800-ft altitude band.

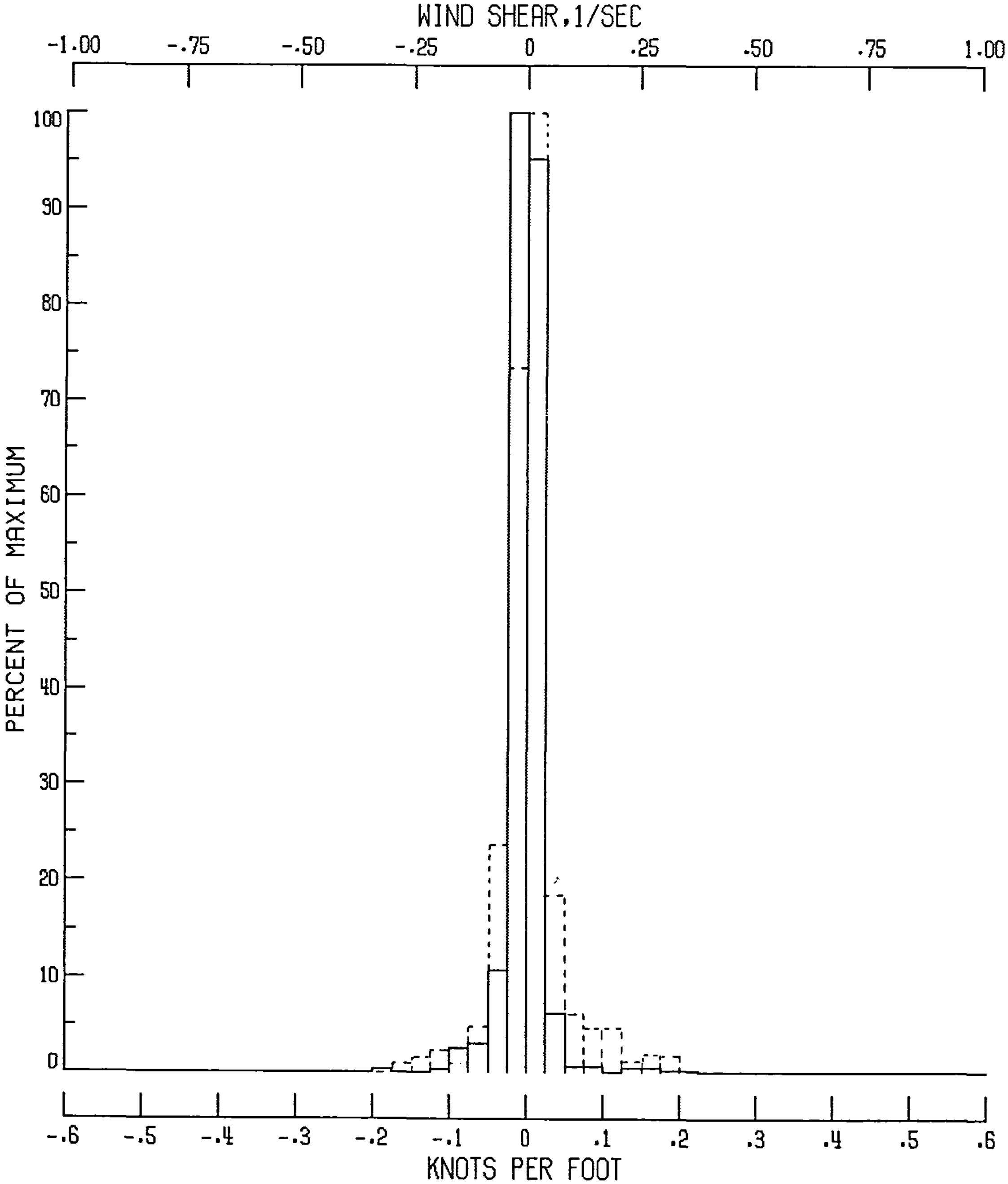
Figure 2.- Continued.



(i) 900-ft altitude band.

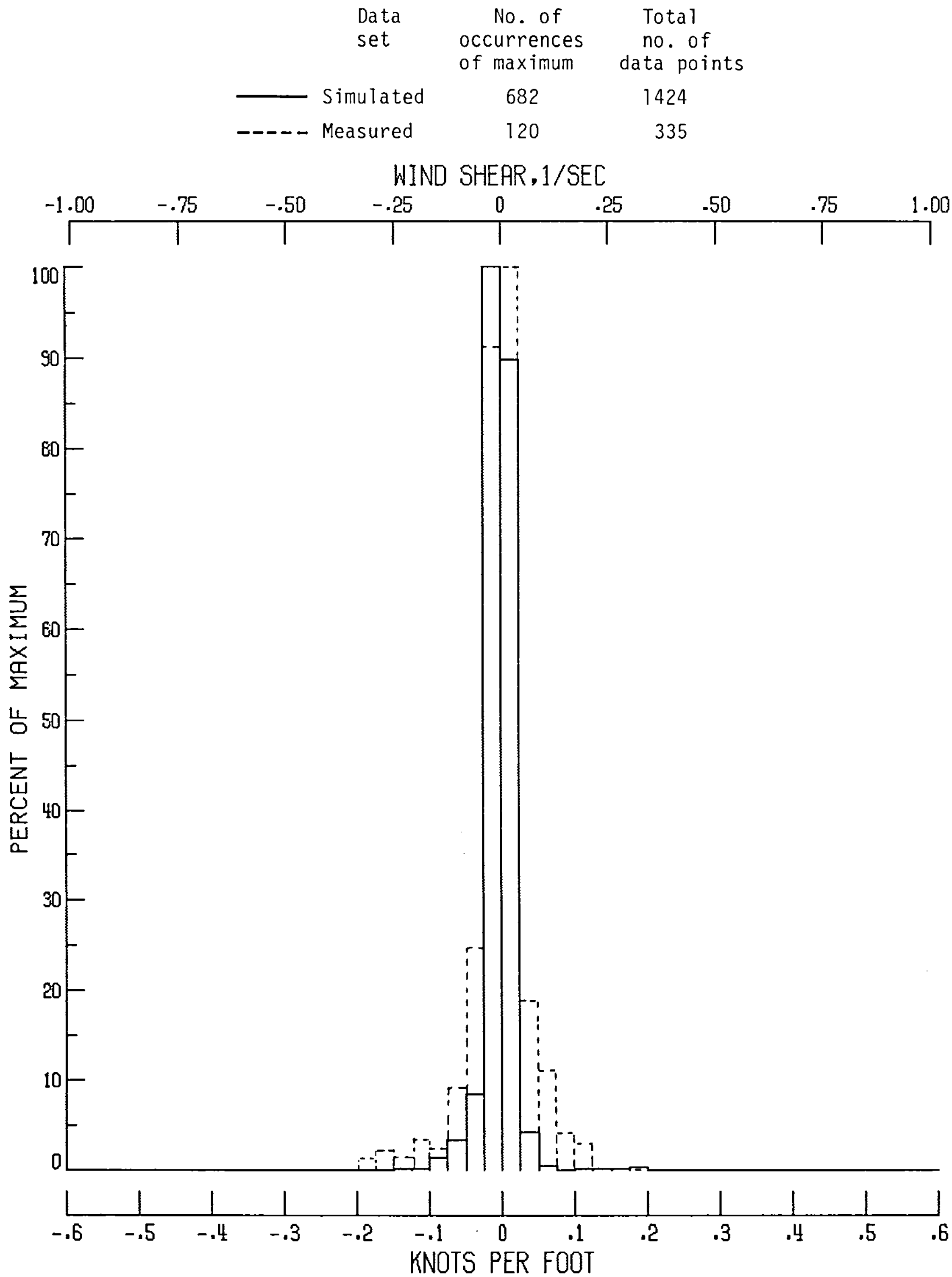
Figure 2.- Continued.

	Data set	No. of occurrences of maximum	Total no. of data points
———	Simulated	719	1585
-----	Measured	149	361



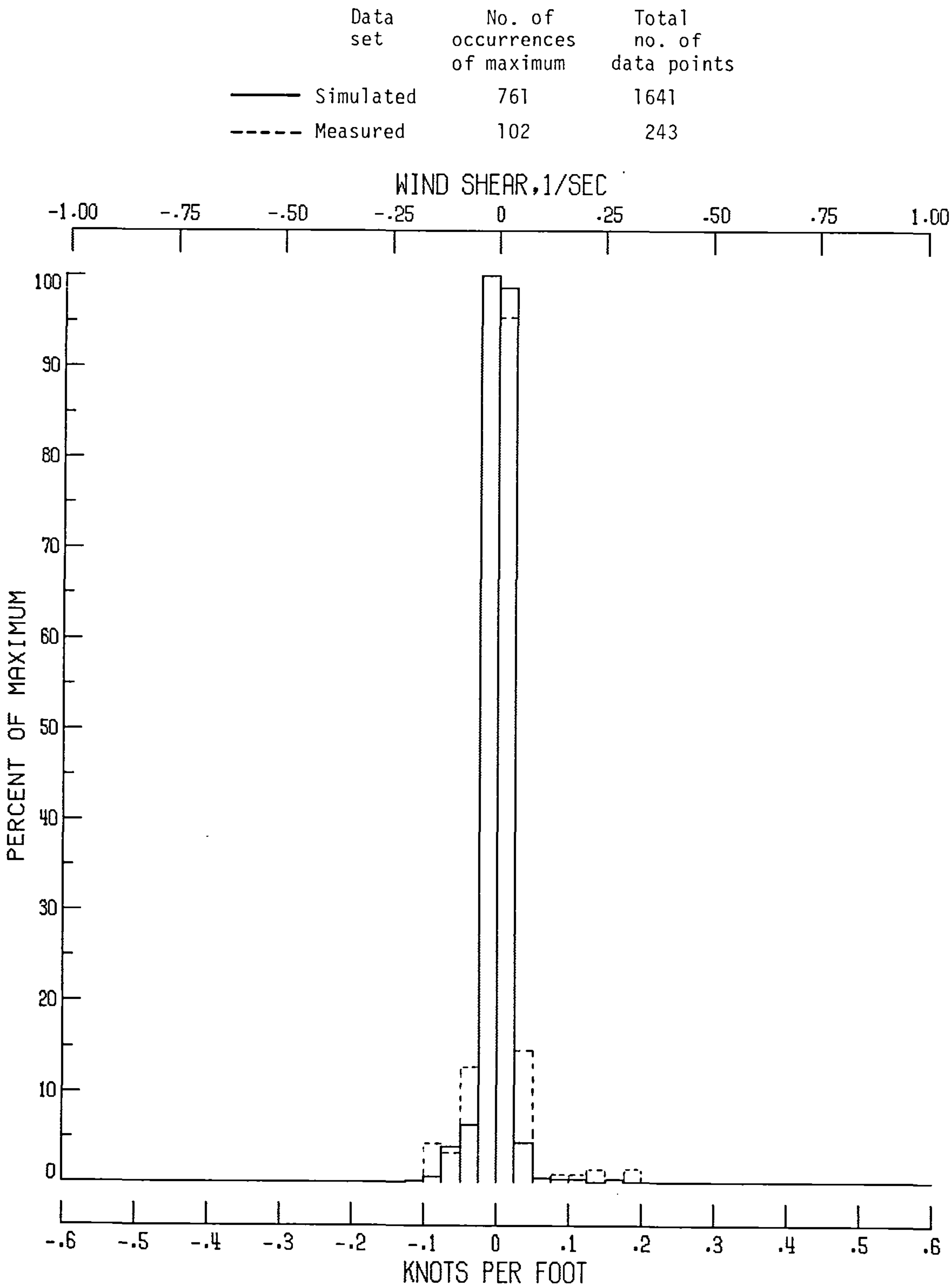
(j) 1000-ft altitude band.

Figure 2.- Continued.



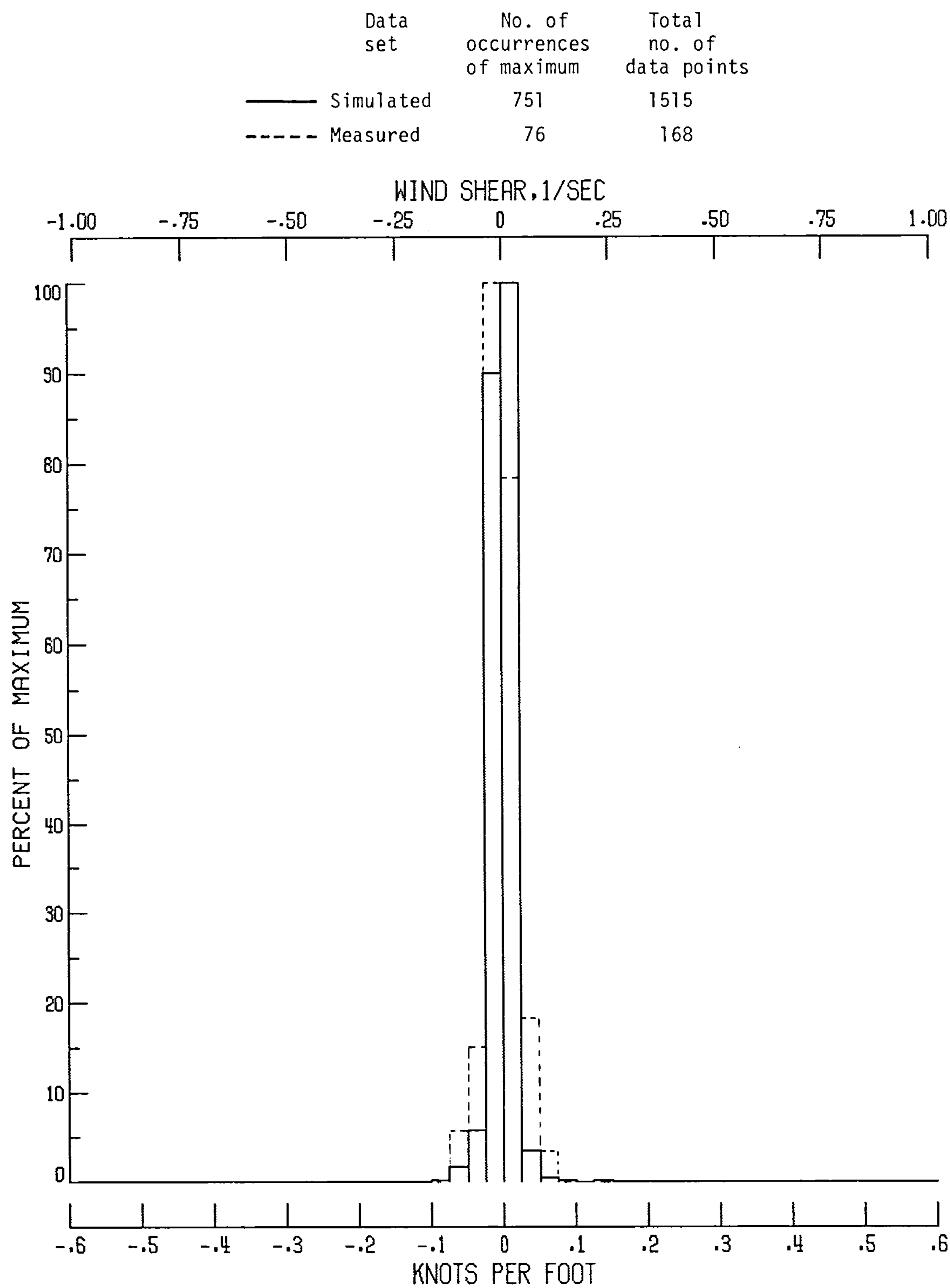
(k) 1100-ft altitude band.

Figure 2.- Continued.



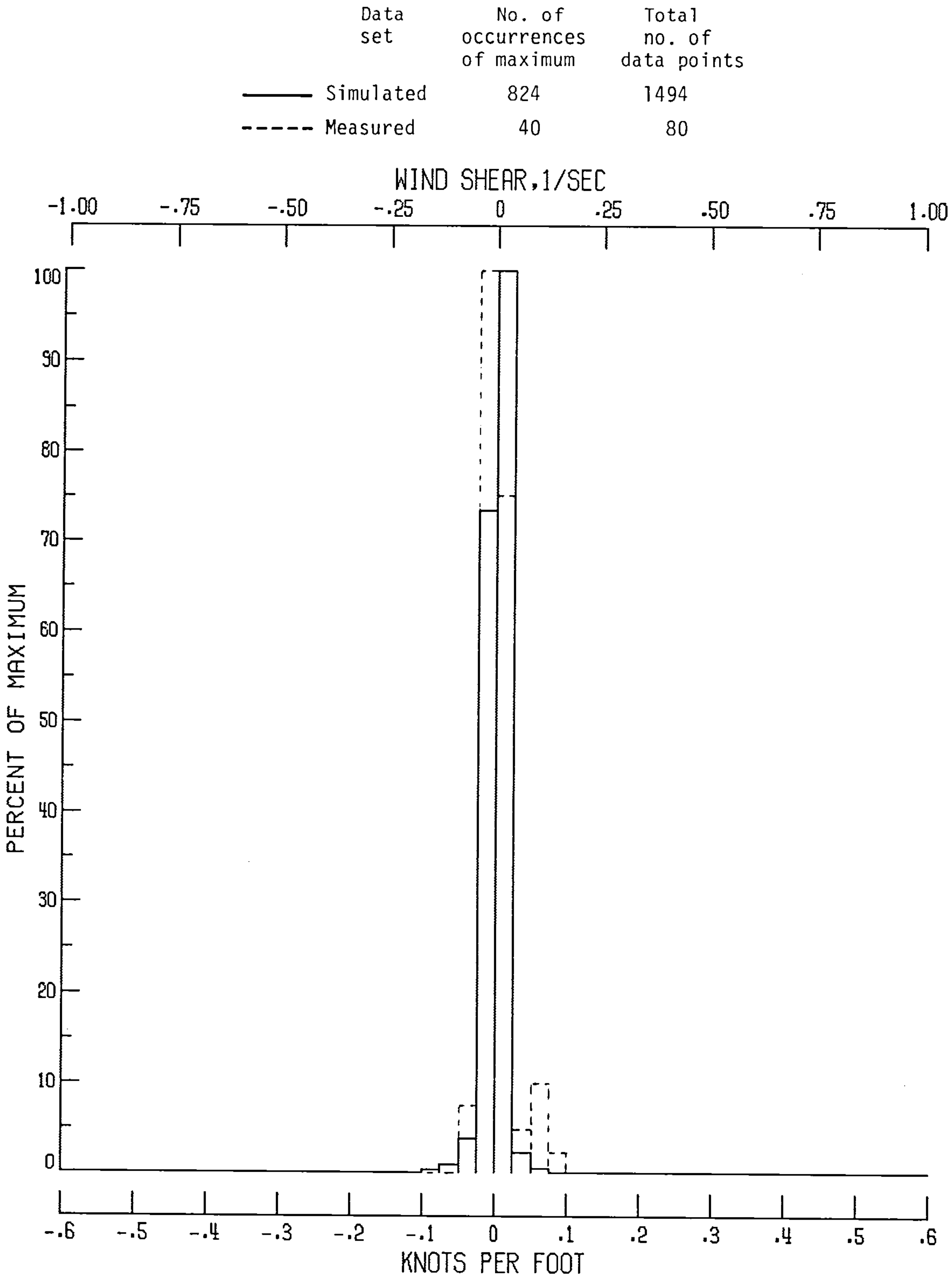
(l) 1200-ft altitude band.

Figure 2.- Continued.



(m) 1300-ft altitude band.

Figure 2.- Continued.



(n) 1400-ft altitude band.

Figure 2.- Concluded.

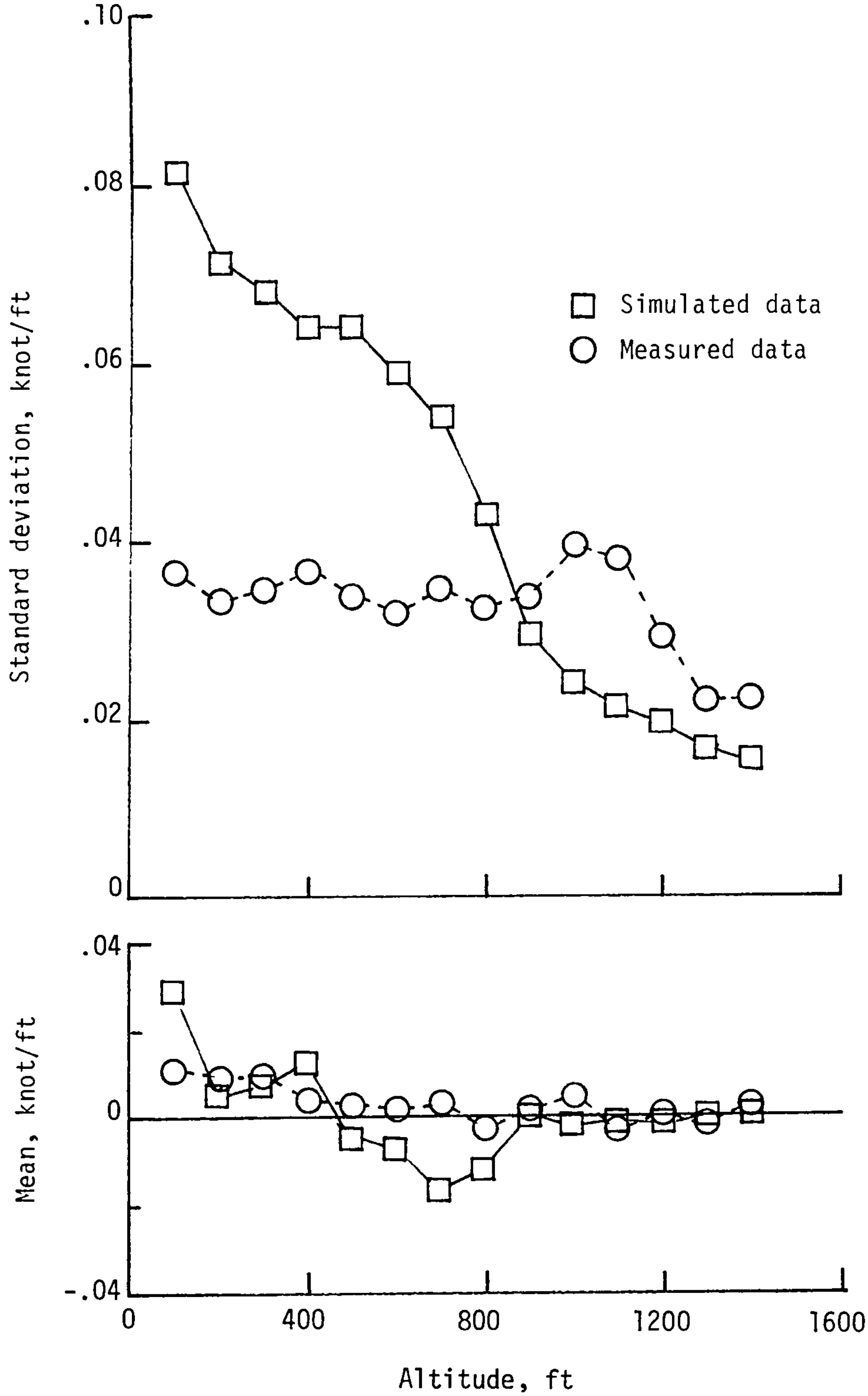


Figure 3.- Variation of mean and standard deviation with altitude.

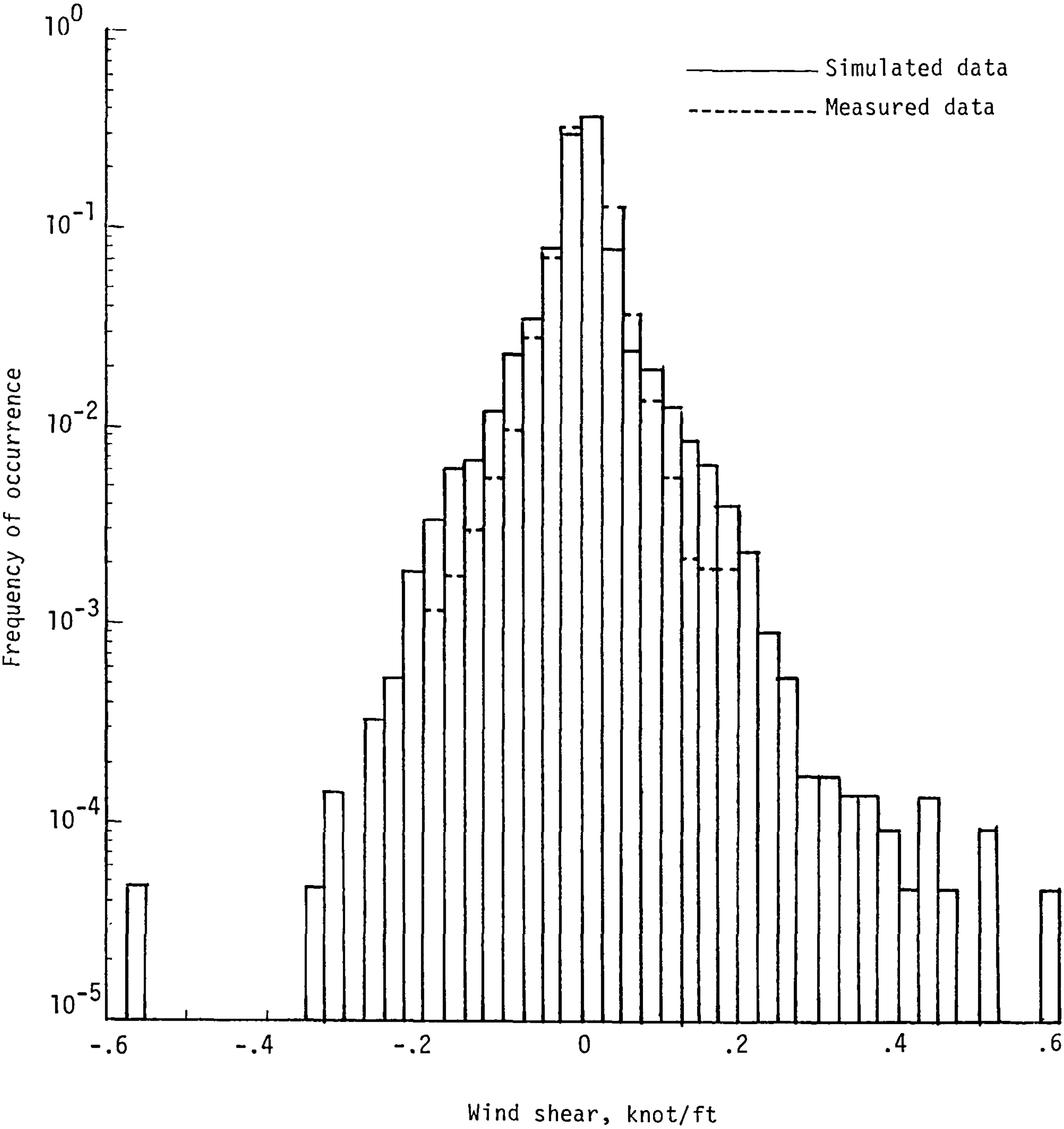


Figure 4.- Frequency of occurrence of wind shear (table VI(a)) based on total sample size.

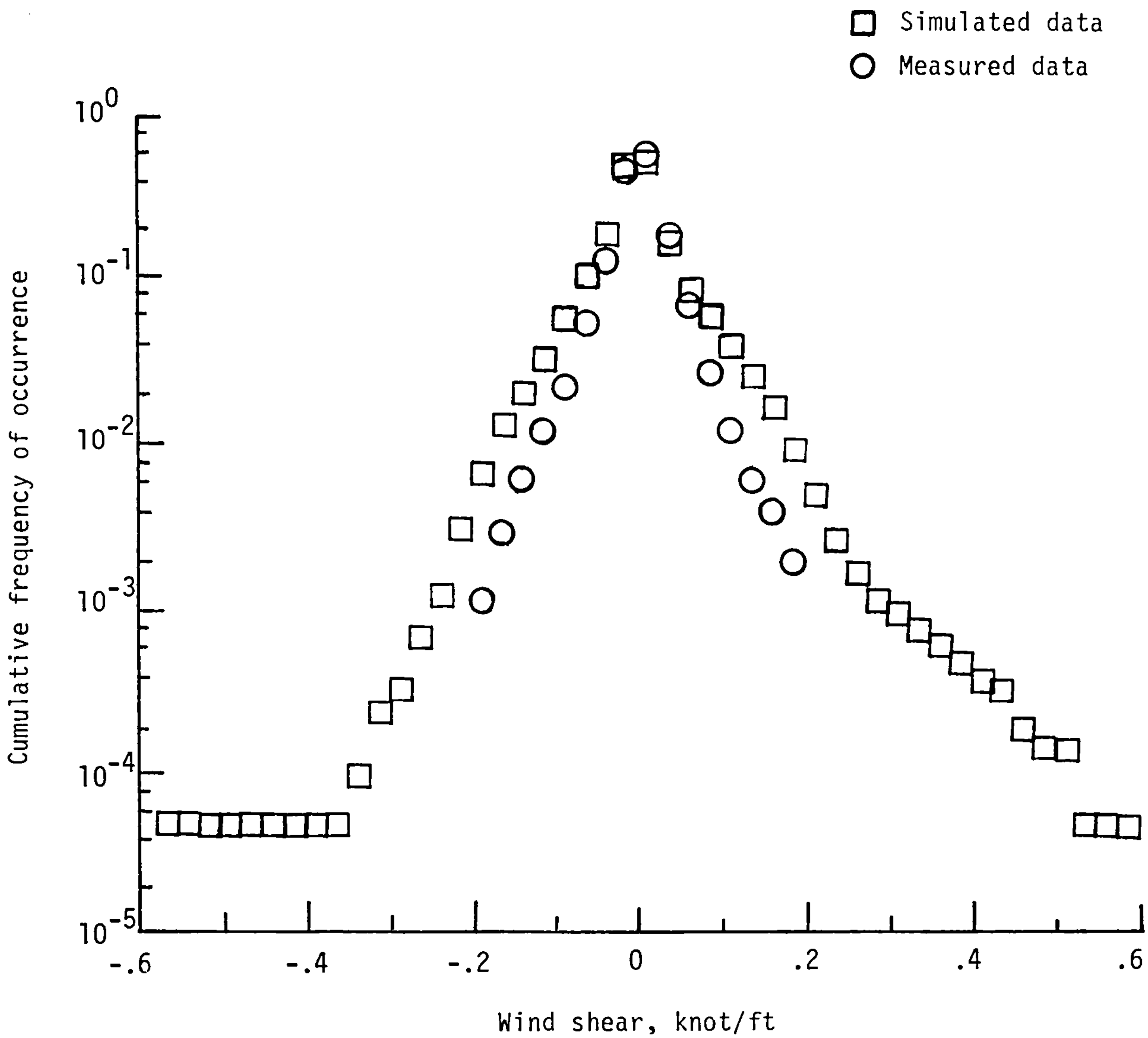


Figure 5.- Cumulative frequency of occurrence of wind shear (table VI(b)).

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15. Supplementary Notes

16. Abstract

Wind-shear statistics were calculated for a simulated set of wind profiles based on a proposed standard wind field data base. These statistics were compared with statistics derived from wind profiles measured by NASA. Wind shears were grouped in altitude bands of 100 ft between 100 and 1400 ft and in wind-shear increments of 0.025 knot/ft. The wind-shear limits were ±0.600 knot/ft for the simulated data set and ±0.200 knot/ft for the measured data set. Frequency distributions, means, and standard deviations for each altitude band were derived for both data sets and compared. Relative and cumulative frequency distributions for the total sample were derived for both sets and compared. Frequency distributions in each altitude band for the simulated data set were more dispersed below 800 ft and less dispersed above 900 ft than those for the measured data set. Distributions for both data sets were practically symmetrical for all altitudes. Total sample frequency of occurrence for the two data sets was about equal for wind-shear values between ±0.075 knot/ft, but the simulated data set had significantly larger values for all wind shears outside these boundaries. Normal distribution fits of both data sets showed that neither data set was normally distributed. Similar results were observed from the cumulative frequency distributions.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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