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Low-Altitude Wind Measurements From Wide-Body Jet Transports

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National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

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SUMMARY

For a 2-week period in the spring of 1977, data were collected onboard wide-body jet transports for the determination of winds and wind shear during landings and take-offs. The data represent about 640 take-offs or landings at 14 airports in Europe and the United States. Analysis of the wind-shear data indicates that shears of a given value are equally likely to occur at any altitude in the lower 1400-ft section of the atmosphere. Analysis of the data indicates that low shears (±0.033 knot/ft) have a 67-percent chance of occurrence during a landing or take-off, while higher values (±0.15 knot/ft) have a 0.5-percent chance of occurrence. A determination of the duration of a given shear was not made.

INTRODUCTION

Although the occurrence of wind shear and its effect on airplane operations have been generally understood, the 1975 crash of a commercial passenger jet (ref. 1) focused attention on the catastrophic effect of severe wind shears on airplanes at low altitudes. As a result of this accident and later accidents, several government studies were undertaken to calculate the effects of wind shear on airplanes (refs. 2 and 3) and the meteorological and topographic conditions which create wind shear hazards near airports (refs. 4 and 5). The Federal Aviation Administration investigated several means of coping with the potential hazard associated with wind shears. Means investigated included pilot/air traffic controller alerting systems, improved forecasting, and airborne sensing systems (ref. 6).

For some time, the National Aeronautics and Space Administration has been collecting data on the operating environment of airplanes (ref. 7). As a portion of these efforts, a study was undertaken to determine the feasibility of measuring winds and wind shears during normal commercial operations. These measurements appeared feasible after implementation of the Federal Aviation Administration regulation requiring that aircraft certified after 1969 be equipped with a digital flight data recorder (DFDR) to record certain parameters on a magnetic tape. The DFDR was to replace the previous requirement for a foil-type crash recorder. The new digital recorders are generally interfaced with a signal processing system (aircraft integrated data system, AIDS), which is often used to record aircraft performance measurements for maintenance purposes (ref. 8). The data recorded on some of these systems represented a potential source of in-flight data for the derivation of atmospheric winds and turbulence. This report describes the results of obtaining wind and wind-shear data from these onboard data systems.

SYMBOLS

V_{gs} airplane ground speed, knots

V_t true airspeed, knots

W_{ew} wind velocity in east/west direction (positive direction toward the east), knots

W_{ns} wind velocity in north/south direction (positive direction toward the north), knots

α angle of attack, deg

γ aircraft flight-path angle (positive for ascent), deg

ζ drift angle of airplane (angle between aircraft heading and ground-track vector; positive direction clockwise from aircraft heading), deg

θ pitch attitude of airplane (angle between local horizon and fuselage reference; positive for reference line above horizon), deg

ϕ aircraft heading (positive direction clockwise from true north), deg

DATA COLLECTION PROCEDURE

The measurement of atmospheric winds by an airplane requires knowledge of the airspeed of the airplane and its inertial speed. The wind is the difference between the airspeed and inertial speed. Under a NASA contract, a U.S. air carrier operating wide-body jets with DFDR-AIDS made a magnetic-tape copy of data recorded during landings and take-offs. The parameters recorded and their accuracies are listed in table I. As indicated in table I, several parameters were measured onboard the airplane by more than one system (i.e., true airspeed from both the pilot's and copilot's air data computers). For the purposes of these tests, the air carrier programmed the AIDS to sample and record the data at a rate of one sample every 3 to 4 seconds. The recording system was activated by the radar altimeter to record data during landings and take-offs. Data were collected for the entire contractor fleet equipped with DFDR-AIDS for a 2-week period during the spring of 1977.

DATA REDUCTION

The data tape contained over 14 000 data samples of each of the parameters listed in table I. Since occasional aircraft systems failures produced no usable data on a channel, the data were scanned to remove these invalid data. Additionally, the airspeed measurement and ground-speed measurement were known to be unreliable below 100 knots. Since the airplane flying speeds were greater than 100 knots, data were only considered for altitudes greater than 5 ft. This eliminated the erroneous values recorded during take-off roll and landing roll. For valid data at a given time sample, the average value for all the systems which measured the parameter were used. Before the averaging was done, the parameters with multiple measurements were checked to see that they agreed with each other within the accuracies described in table I.

The wind speed at each data sample was calculated by subtracting the true airspeed from the ground speed. The airspeed parallel to the ground is given by

$V_t \cos(\theta - \alpha)$. The components of wind in the north/south direction and the east/west direction are as follows:

$$W_{ns} = V_{gs} \cos(\psi + \zeta) - V_t \cos(\theta - \alpha)\cos \psi$$

$$W_{ew} = V_{gs} \sin(\psi + \zeta) - V_t \cos(\theta - \alpha)\sin \psi$$

where $\theta - \alpha = \gamma$. The total wind is the square root of the sum of the squares of the east/west and north/south components.

Because of an unknown bias in the measurement of angle of attack α and because there was no calibration for upwash effects, the angle-of-attack measurement was not usable. However, since the quantity $\theta - \alpha$ is equivalent to the aircraft flight-path angle γ, and for take-off and landings the flight-path angle is small (<5°), the term $\cos(\theta - \alpha)$ was taken to be unity.

The main data management task was to sort the raw data from the magnetic tape into individual operations, i.e., landing or take-off. Two methods were used for sorting the data. One was based on altitude change and the other on time difference. The altitude scanning of the data for blocking into landings and take-off were done by checking successive altitudes and noting whether the altitudes were decreasing (landing) or increasing. Additionally, for the same given operation, the time between data points was checked to see that time was monotonically increasing. The data were grouped into about 640 landings or take-offs, from which approximately 6300 wind measurements were obtained. The primary parameters for determining wind speed are the airspeed and the ground speed. Both of these parameters are measured by systems which have fairly low frequency response limits, and the airspeed system is generally highly damped; consequently, the determination of winds is not strongly influenced by high frequency atmospheric turbulence. The wind measurements are thought to be reasonably representative of the mean wind over the data sample period.

Figures 1 and 2 show typical wind velocity measurements as a function of altitude for the north/south and east/west components. Figure 1 data were taken during a take-off, and figure 2 data were taken during a landing. Take-off data are generally distinguished from landing data by the vertical spacing of the data points. The rate of ascent is generally greater than the rate of descent; therefore, for a constant sampling rate, the data points are more widely spaced in altitude during take-offs than landings.

Wind profiles such as figures 1 and 2 were used to calculate wind shear. Wind shear is defined as the first derivative of the wind with respect to altitude. For computational purposes, wind shear was calculated from data runs by dividing the wind change between data points by the altitude change between the points. Within the computer data reduction program, the calculated values of wind shear were assumed to apply at an altitude halfway between the data points. Wind shears were calculated for both the wind components (W_{ew} and W_{ns}) and the total wind speed (i.e., $(W_{ns})^2 + (W_{ew})^2$). Once wind shears were calculated, they were sorted into 100-ft altitude increments. It should be noted that the determination of the duration of the wind-shear values was not included in this study. Because the effect of wind shear on aircraft dynamics is dependent on the duration as well as the magnitude of the shear, this limitation of the study should be considered in applying the results presented in this report.

RESULTS AND DISCUSSION

Data Set

The data analyzed were for landings and take-offs at the 14 airports shown in table II. The airport in Atlantic City, NJ, had the highest percentage of operations. This airport is used as a training field. The other major airports where operations were recorded were in New York and London. Between these three airports (Atlantic City, London, and New York), more than 60 percent of the data were obtained. The data in this report represent a small sample of operations for a 2-week period. The data may have some bias in it, as 25 percent of the data were obtained in training flights at one airport. Typically, training flights consist of numerous approaches, landings, touch-and-go landings, go-arounds, and take-offs in a short time. Considering that in the short range the wind field in the vicinity of an airport may not change much, then 25 percent of the data represents continual sampling of the same wind field. For this report, no attempt was made to correlate the flight operation with the existing weather.

Wind Shears

Figure 3 is a bar-graph presentation of the distribution of north/south and east/west wind shears in altitude increments of 100 ft from 100 ft to 1400 ft. As previously mentioned, the data system was programmed to turn on for all radar altitudes less than 1000 ft; however, the switching logic was not absolute, so some data were obtained at altitudes greater than 1000 ft. Although wind data were obtained at altitudes up to about 1900 ft, the statistical sample size above 1400 ft is small for the type of presentation shown in figure 3. The data of figure 3 represent all the data for a 50-ft increment on either side of the indicated sample altitude. The wind shears at each altitude band were divided into increments of 0.025 knot/ft. The bar graphs of figure 3 were normalized at each altitude band with respect to the wind-shear increment having the maximum number of occurrences. This was done so that any trend in the distribution of wind shears with altitude could be easily detected. The wind-shear frequency distributions used to construct figure 3 are shown in table III. A cursory examination of figure 3 shows no dependence of the distribution of wind shear on altitude. A further examination was conducted to determine if the statistical properties of distributions shown in figure 3 varied with altitude. It was found that for all altitudes the mean wind-shear value was approximately zero. Throughout each altitude band the standard deviation was about the same, with a mean of the standard deviations of 0.033 knot/ft and a one-sigma value of the standard deviations of 0.0057 knot/ft. It appears that the statistical properties of the wind-shear distributions did not vary greatly with altitude. It is concluded, therefore, that the distribution of wind shear is independent of altitude.

As a check on the quality of the data analysis, a distribution of the wind-speed change and altitude change between successive data points were obtained as a function of the 100-ft altitude increments. The distribution of wind speeds was not dependent on altitude. The mean wind at each altitude increment was about 12 knots, and the standard deviation was about 6 knots. Although the distribution of wind speeds was not dependent on altitude, the distribution of vertical spacing of data points was not uniform with altitude. (See fig. 4.) For altitudes under 800 ft, the vertical distances between data points are mostly grouped into height changes of 30 to 50 ft. Above 800 ft, the vertical spacing between data points is nearly uniformly distributed over incremental height changes from 0 to 100 ft. It is worth noting that, for an airplane on a 3° flight-path angle at 130 knots, a 4-second sampling time is equivalent to an altitude change between data points of about 45 ft. Since aircraft are generally on a stabilized flight path below 800 ft, the spacing between the data points would be fairly uniform, as shown in figure 4. At altitudes above 800 ft, a greater variation in flight path could be expected, and this greater variation would yield a uniform dispersion between data points as shown in the higher-altitude data of figure 4. Since the distribution of vertical displacement between data points with altitude shows an expected operational bias, and the variation of wind shear (fig. 3) with altitude is uniform (unbiased by aircraft operational procedures), the wind-shear data are thought to be a reasonable characterization of the distribution of wind shear for the data sample investigated. The result of uniform distribution of wind shear with altitude is contrary to the result obtained in reference 9, in which the mean magnitude of frequency of occurrence of wind shear decreased with altitude. The data of reference 9 were obtained from instrumented meteorological towers at one geographic location for a continuous time of 2 hours 21 minutes. These tower-measured shear values were obtained from a 150-m tower at heights of 150, 120, 90, 60, 30, 18, and 3 m. The conclusion of reference 9 is in part based upon some fairly high values of shear measured at 30 m and below, but most of the aircraft data were obtained above 30 m. The airplane data agree well with the tower data at the higher altitudes in terms of mean wind shear and maximum wind shear. The aircraft data were obtained at several locations (table II) over a 2-week period and should be more representative of the mean atmospheric conditions encountered during flight operation.

The distributions of wind shear based on total wind speed (i.e., $\sqrt{(W_{ew})^2 + (W_{ns})^2}$) with altitude at 100-ft altitude increments are shown in figure 5. The data of figure 5 were normalized in the same manner as for figure 3. Figure 5 shows no variation in the distribution of wind-speed shear with altitude. This should be expected, since a similar result was noted for the east/west and north/south components in figure 3, and since the data in figure 5 are derived from the basic data of figure 3. The data samples of figure 5 are slightly smaller than the data samples of figure 3. For instance, in figure 3 the 200-ft altitude increment for the east/west wind shear was comprised of 617 data points, while in figure 5 the total wind shear is for 614 data points at the 200-ft altitude increment. This minor discrepancy is associated with the data sorting routine, in which erroneous data points were eliminated. In figure 3, the data checks were made on the wind components, while in figures 5 and 6, the data checks were made on the components and the totals. Consequently, a few additional data points were eliminated.

Wind-Shear Probability

The wind-shear data seem independent of altitude. Therefore, a histogram of frequency distribution based on total wind speed for the entire data set was constructed. (See fig. 6.) In figure 6, the frequency of occurrence of a given shear value per sample size (6277 points) is plotted. Figure 6 can be used as an indication of the probability of a given wind shear. The distribution of figure 6 has a standard deviation of 0.033 knot/ft. As indicated in the figure, low shear values (±0.033 knot/ft) have a 67-percent chance of occurrence. Higher shear values, on the order of 0.15 knot/ft, have a 0.5-percent chance of occurrence.

Figure 7 is a cumulative frequency distribution of the data in figure 6. The data points in figure 7 were plotted in the lower band edge of the wind-shear increments and represent a cumulation of the frequency of occurrence from the highest to the lowest. Interpretation of figure 7 yields the probability of encountering a wind shear of a given value or greater. For example, the data indicate that there is a 2-percent chance of encountering a wind shear of ±0.1 knot/ft or greater. For this data set, an analysis was not done to determine the maximum duration of a given shear value; consequently, the probability distribution does not relate any information with regard to duration of shear.

The analysis has shown the feasibility of determining wind variation with altitude from data generally available on wide-body transports. Based on a small data set, the probability of occurrence of a given wind-shear encounter for the lower 1400 ft of an approach or take-off was determined.

CONCLUDING REMARKS

The data illustrate the feasibility of calculating winds and wind shear from data recorded onboard commercial aircraft. The data represent about 640 landings or take-offs during a 2-week period in the spring of 1977. Wind measurements were made over the lower 1400-ft section of the atmosphere. Data were taken at 14 airports in Europe and the United States. Analysis of wind-shear data distribution indicates that wind shears of a given value are equally likely to occur at any altitude in the lower 1400-ft section of the atmosphere. Analysis of the data indicates that low shears (±0.033 knot/ft) have a 67-percent chance of occurrence during a landing or take-off, while higher values (±0.15 knot/ft) have a 0.5-percent chance of occurrence. A determination of the duration of a given shear was not made.

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September 10, 1982

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TABLE I.- DATA PARAMETERS

Parameter	Accuracy
True airspeed,[1] knots	±2.0 knots
Angle of attack, deg	±0.5°
Radio altimeter,[1] ft	±5 ft
Time, hr/min/sec	±1 sec
INS true heading,[2] deg	±0.4°
INS drift angle,[2] deg	±0.5°
INS track-angle error,[2] deg	±0.5°
INS pitch attitude,[2] deg	±0.5°
INS ground speed,[2] knots	±2.0 knots
INS latitude,[2] minutes	±0.6 n.mi./flight hr
INS longitude,[2] minutes	±0.6 n.mi./flight hr

[1]Measured by two independent systems; both values recorded.

[2]Measured by three independent systems; all values recorded.

TABLE II.- PERCENT OF TOTAL DATA TAKEN AT EACH AIRPORT

Airport location	Percent of total data
Atlantic City, New Jersey	25
New York, New York	19
London, England	17
Madrid, Spain	7.5
Paris, France	7
Boston, Massachusetts	5.5
Rome, Italy	4.3
Chicago, Illinois	4
Los Angeles, California	2.6
Barcelona, Spain	2
Philadelphia, Pennsylvania	2
Milano, Italy	1.9
Algiers	1.7
Monaco	<1

TABLE III.- FREQUENCY OF OCCURRENCE FOR WIND-SHEAR DISTRIBUTIONS SHOWN IN FIGURE 3

Direction	Altitude, ft	Frequency of occurrence of wind shear, knot/ft, from -															
		-0.20 to -0.175	-0.175 to -0.15	-0.15 to -0.125	-0.125 to -0.10	-0.10 to -0.075	-0.075 to -0.05	-0.05 to -0.025	-0.025 to 0.0	0.0 to 0.025	0.025 to 0.05	0.05 to 0.075	0.075 to 0.10	0.10 to 0.125	0.125 to 0.15	0.15 to 0.175	0.175 to 0.20
N/S	100	0	1	4	3	8	22	76	165	190	95	33	15	4	6	1	0
E/W	100	0	1	0	5	6	21	72	184	210	84	23	12	2	3	0	0
N/S	200	1	2	1	6	4	29	63	186	197	85	28	8	2	2	3	0
E/W	200	0	0	1	1	5	15	52	210	228	65	27	5	5	3	0	0
N/S	300	1	0	3	2	6	15	59	184	215	79	23	10	3	2	2	2
E/W	300	3	0	3	2	3	17	49	214	226	56	21	4	5	3	0	0
N/S	400	2	0	1	4	11	19	44	168	195	68	10	11	2	1	2	0
E/W	400	0	0	3	0	5	13	43	174	206	71	14					
N/S	500	0	1	1	4	8	25	61	206	206	47	21	3	5	3	0	1
E/W	500	4	0	2	3	6	13	54	192	227	65	14	5	2	0	1	0
N/S	600	0	1	0	2	4	16	58	194	178	57	15	7	5	1	1	1
E/W	600	0	1	1	1	6	13	44	196	207	52	14	3	1	1	0	0
N/S	700	2	1	1	1	8	22	56	197	224	60	19	6	3	0	3	1
E/W	700	4	1	3	2	3	14	57	204	243	45	15	5	4	1	3	0
N/S	800	1	1	0	1	6	12	38	198	179	49	12	5	4	2	1	0
E/W	800	1	0	2	1	5	13	40	190	180	47	21	2	4	1	2	1
N/S	900	1	0	1	1	8	11	25	169	141	25	13	6	0	4	1	3
E/W	900	0	2	2	0	1	11	34	151	169	23	7	5	1	1	0	1
N/S	1000	3	1	2	0	1	8	38	145	112	22	20	4	1	1	1	1
E/W	1000	0	0	1	3	3	8	23	131	141	32	6	5	4	3	0	3
N/S	1100	1	1	2	2	6	14	31	118	108	30	11	3	5	1	1	1
E/W	1100	1	0	0	3	11	10	25	107	132	27	11	6	1	1	0	0
N/S	1200	1	0	1	2	1	2	19	91	98	20	2	4	1	1	0	0
E/W	1200	0	0	1	1	3	6	11	99	98	20	1	3	0	0	0	1
N/S	1300	0	0	0	0	1	3	10	81	59	11	3	0	0	0	0	0
E/W	1300	0	0	0	0	0	2	14	64	73	13	1	1	0	0	0	0
N/S	1400	0	0	0	0	0	3	1	31	41	3	0	1	0	0	0	0
E/W	1400	0	0	0	0	1	0	4	37	34	4	1	1	0	0	0	0

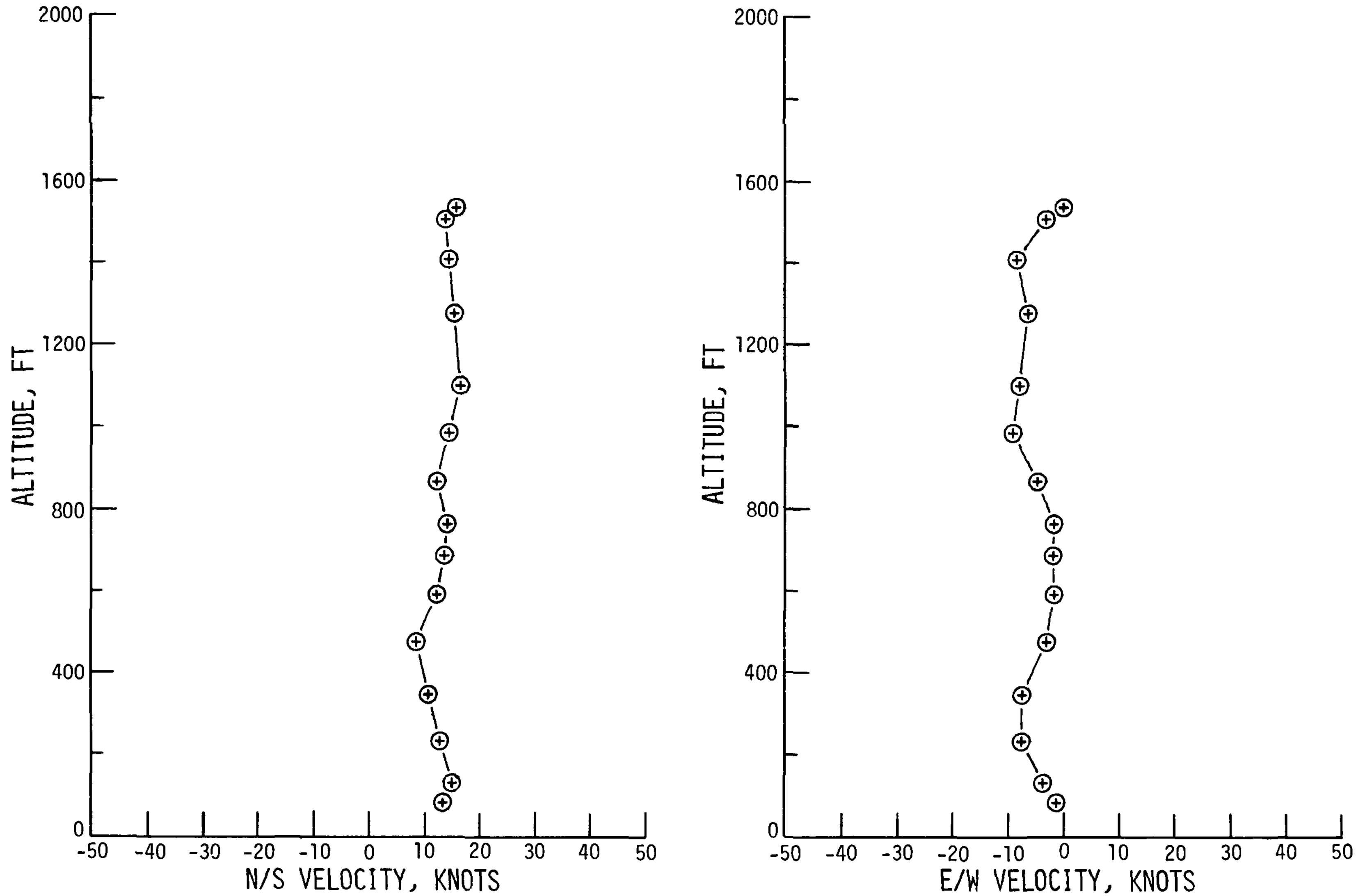


Figure 1.- Typical measurement of north/south and east/west wind components as a function of altitude for a take-off.

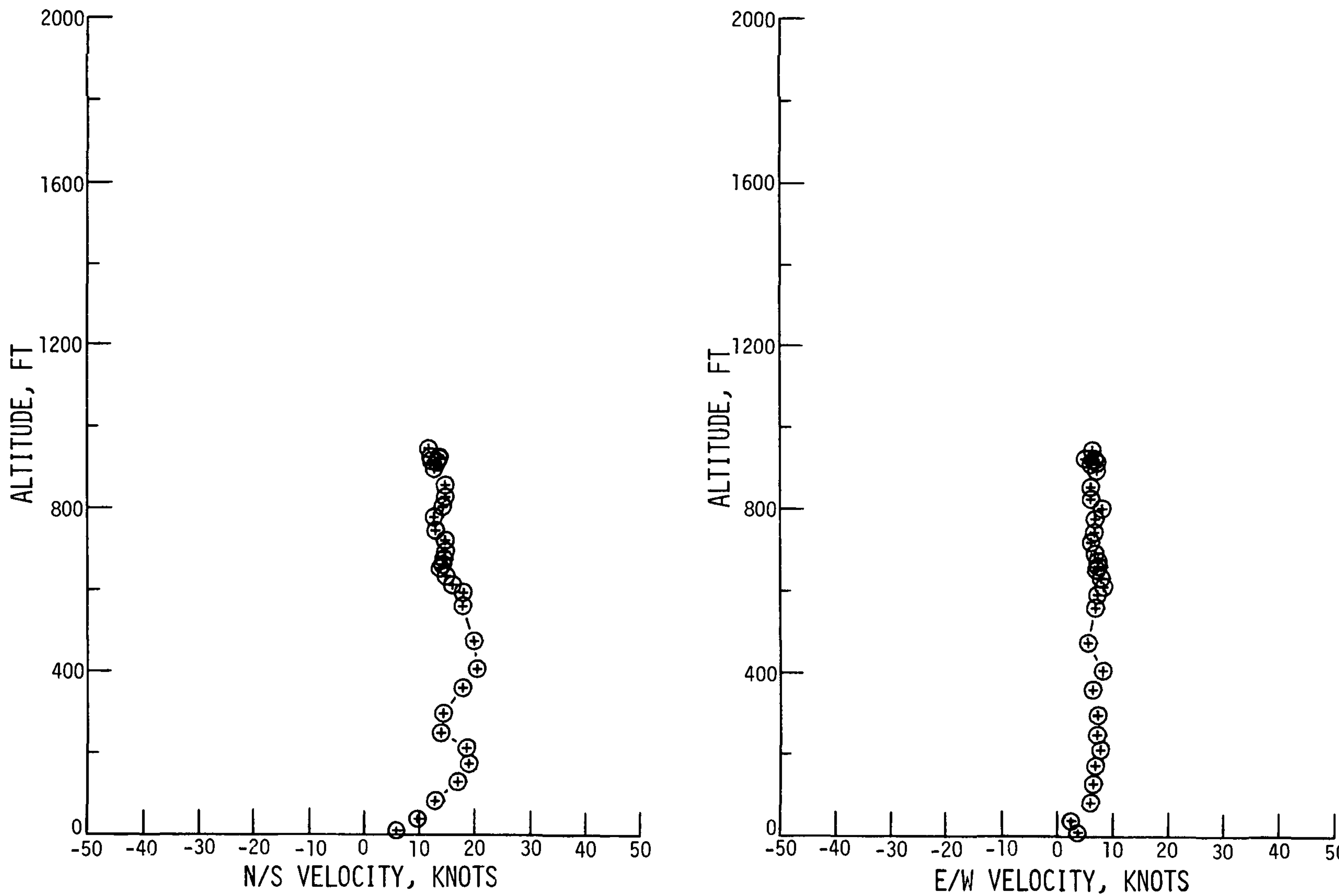
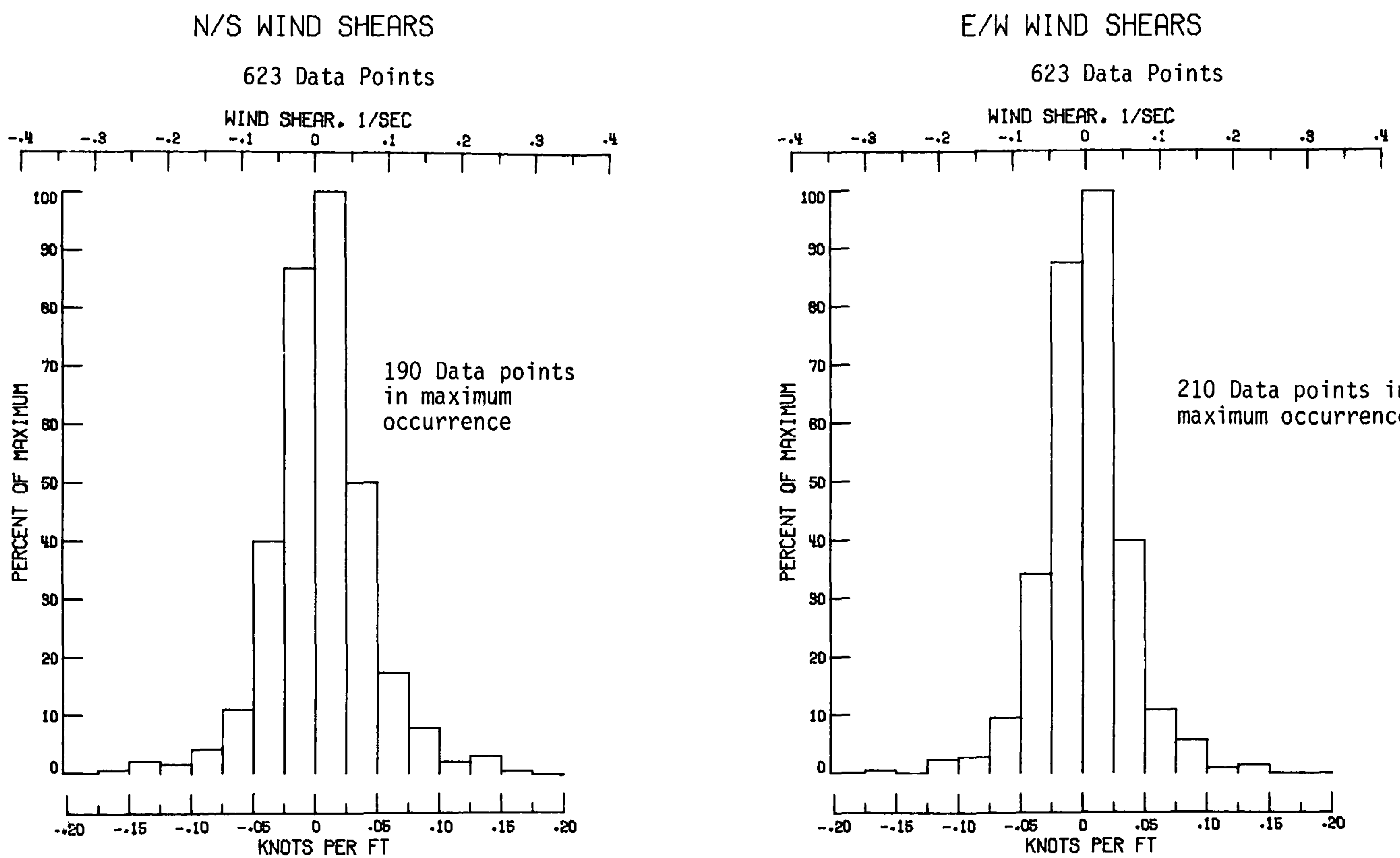
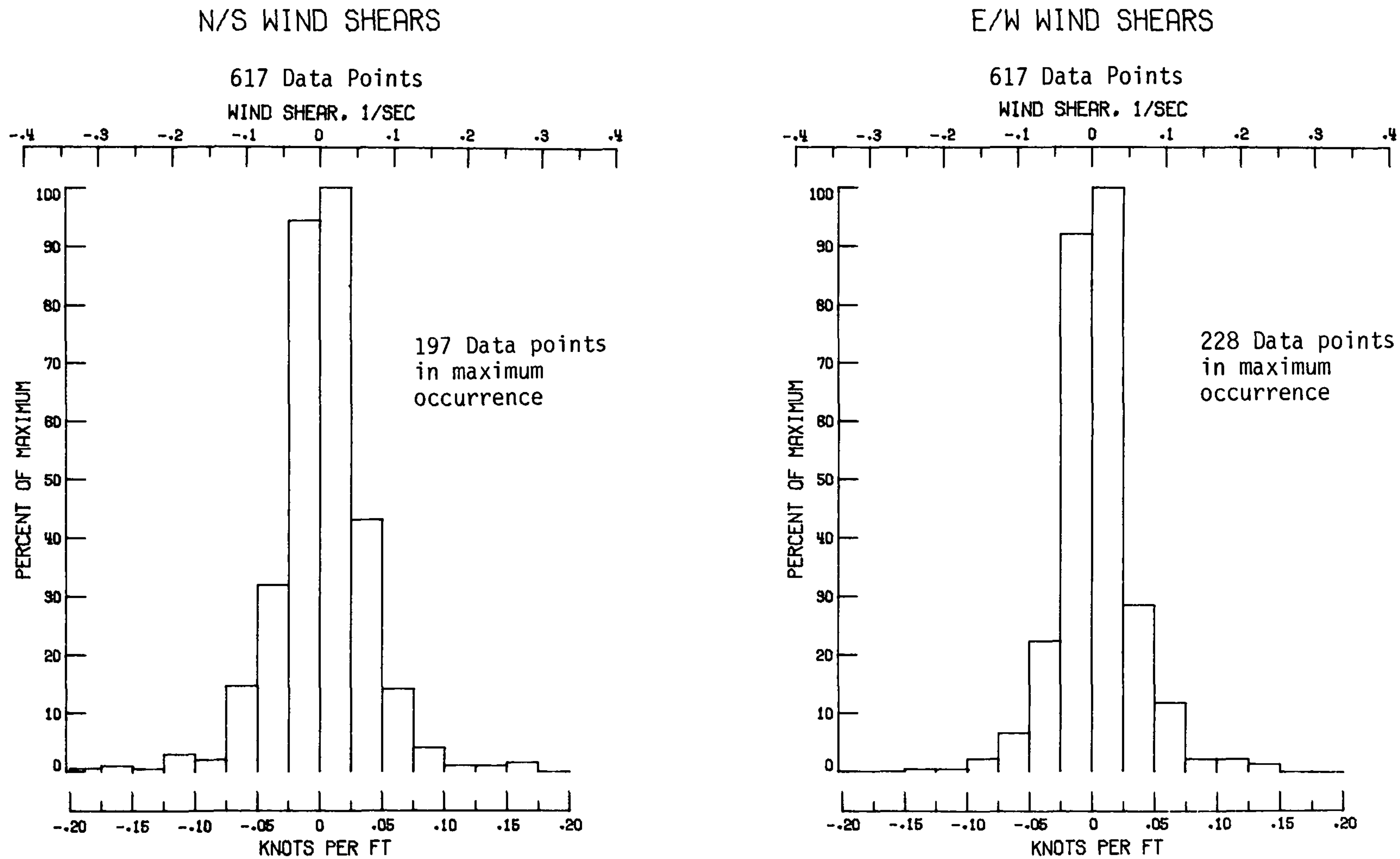


Figure 2.- Typical measurement of north/south and east/west wind components as a function of altitude for a landing.



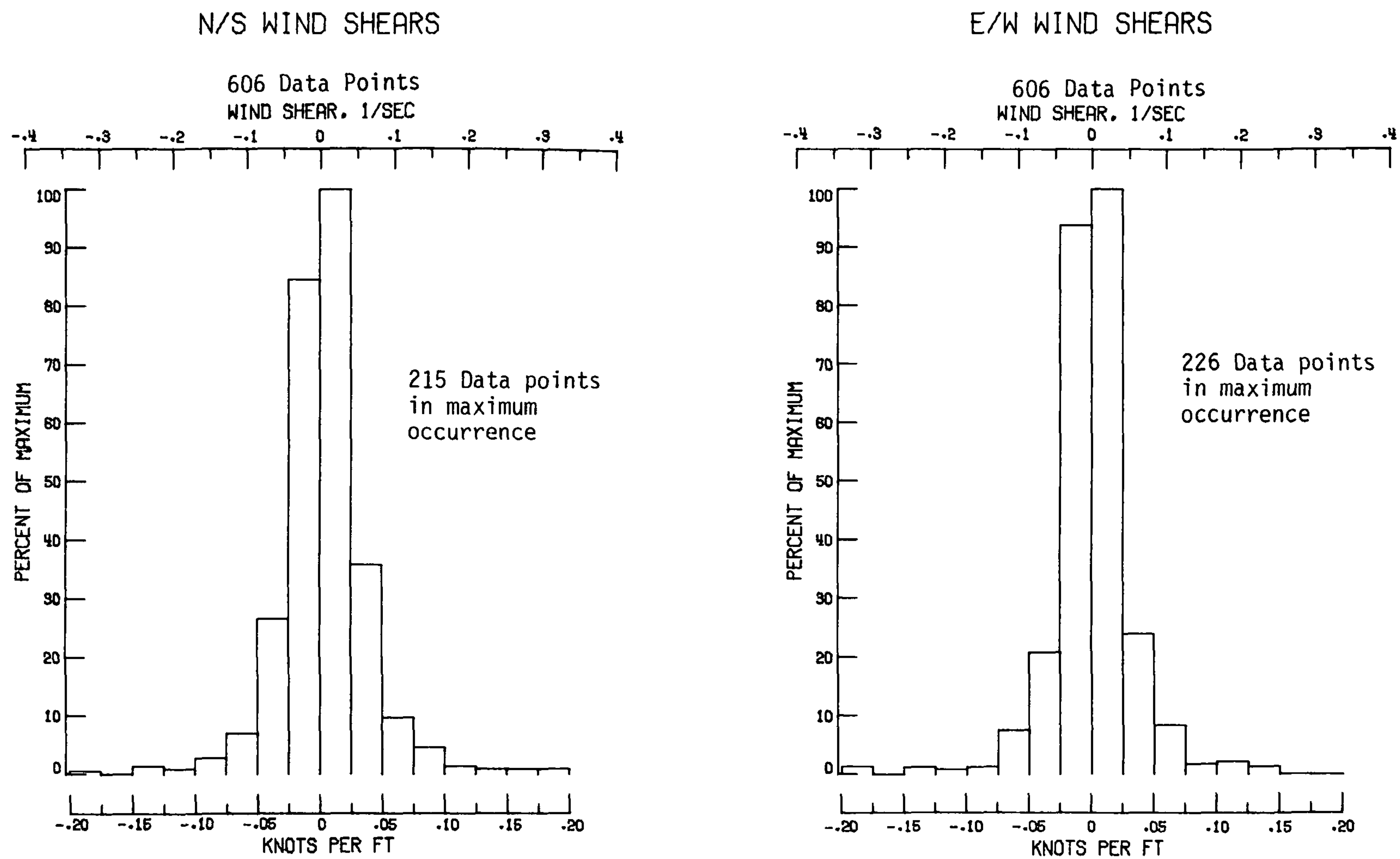
(a) 100 ft.

Figure 3.- Distribution of north/south and east/west wind shears at various altitudes.



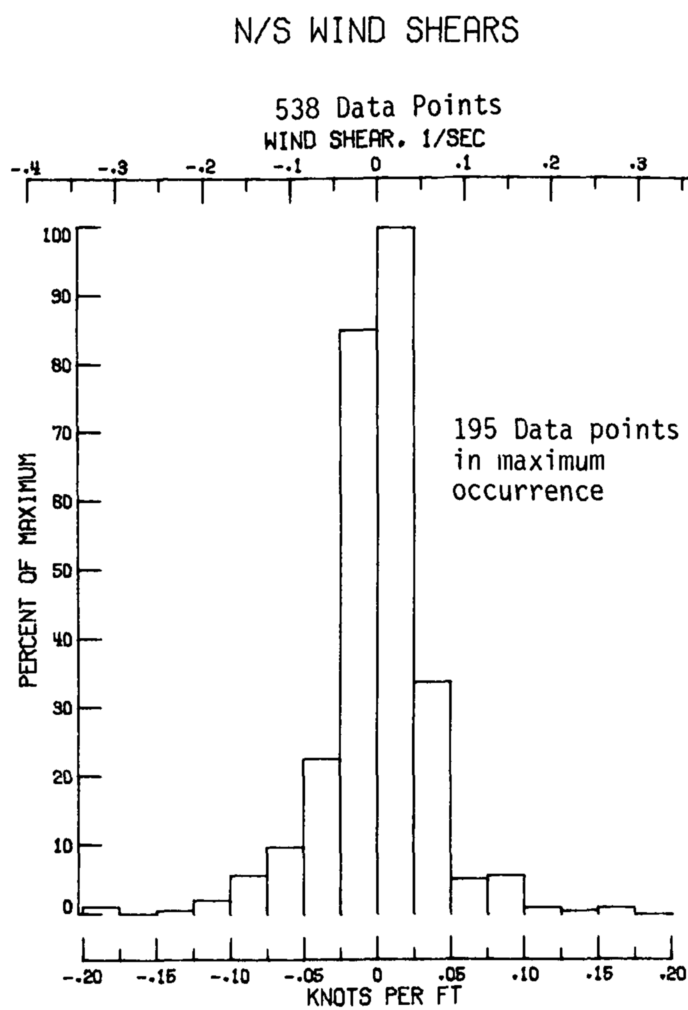
(b) 200 ft.

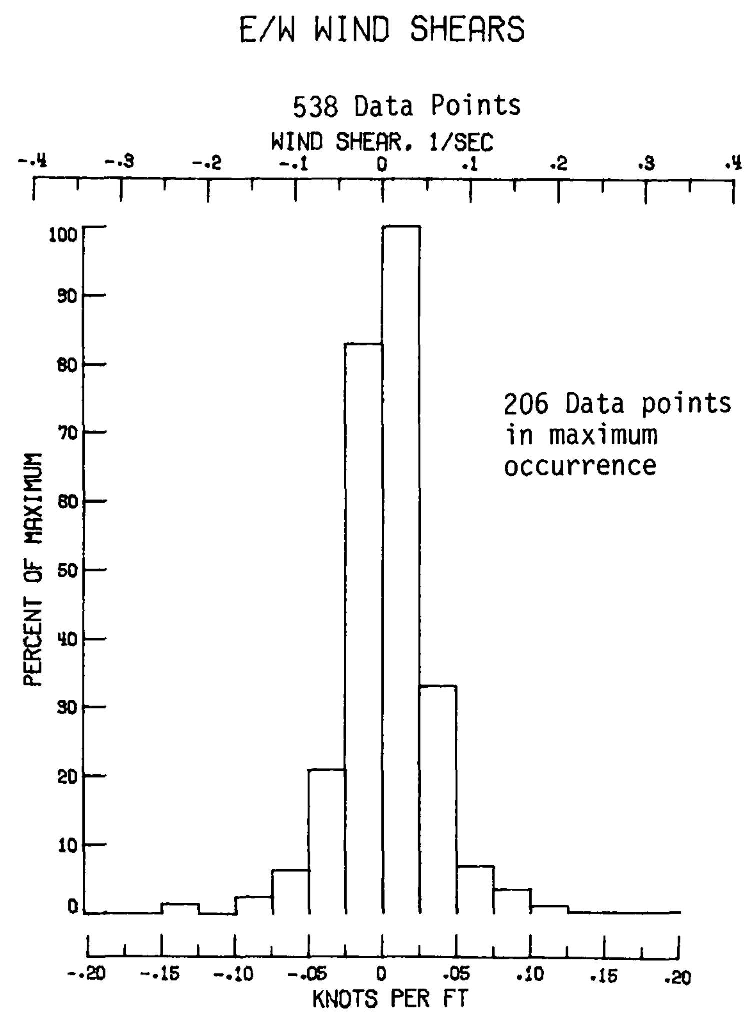
Figure 3.- Continued.



(c) 300 ft.

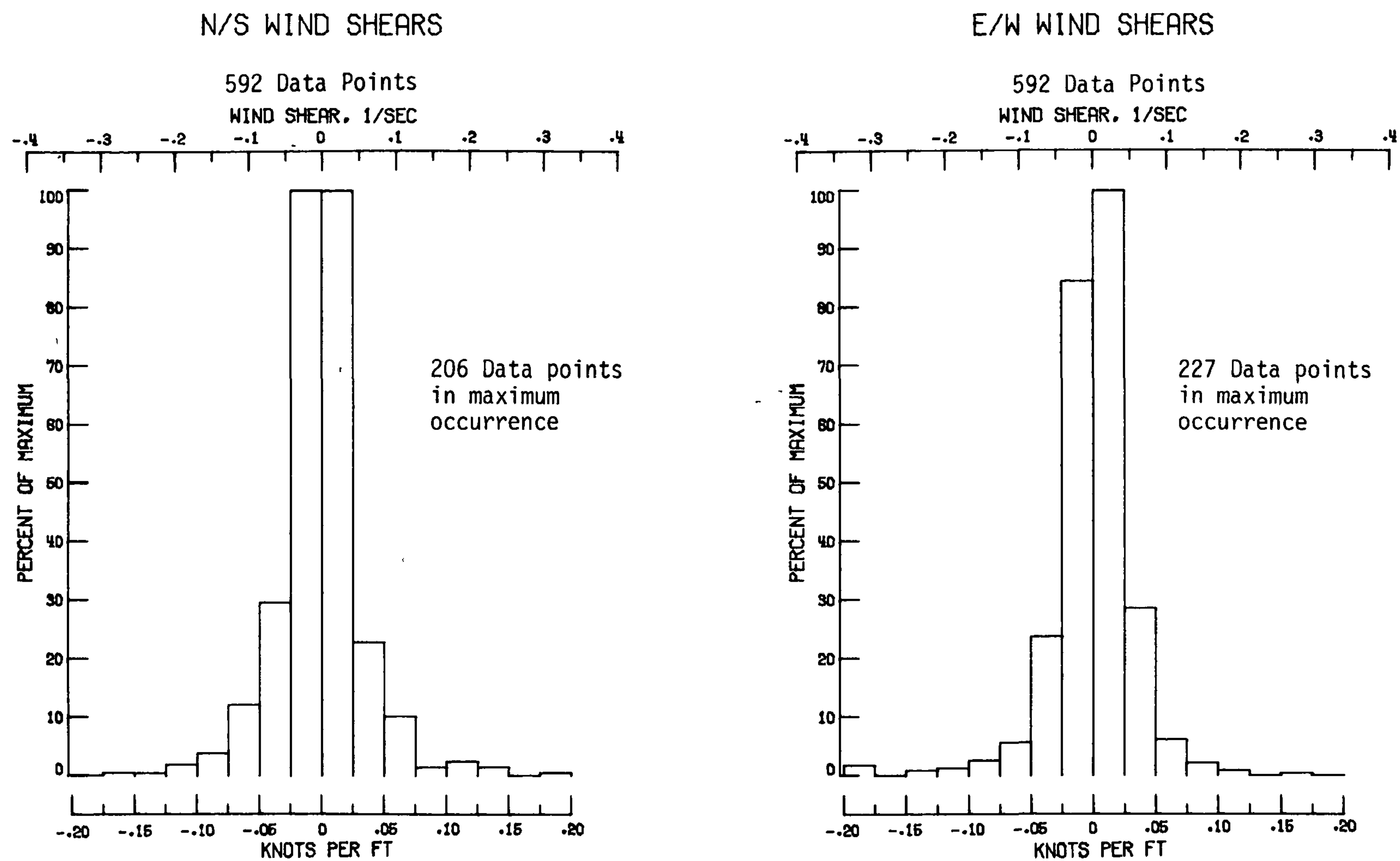
Figure 3.- Continued.





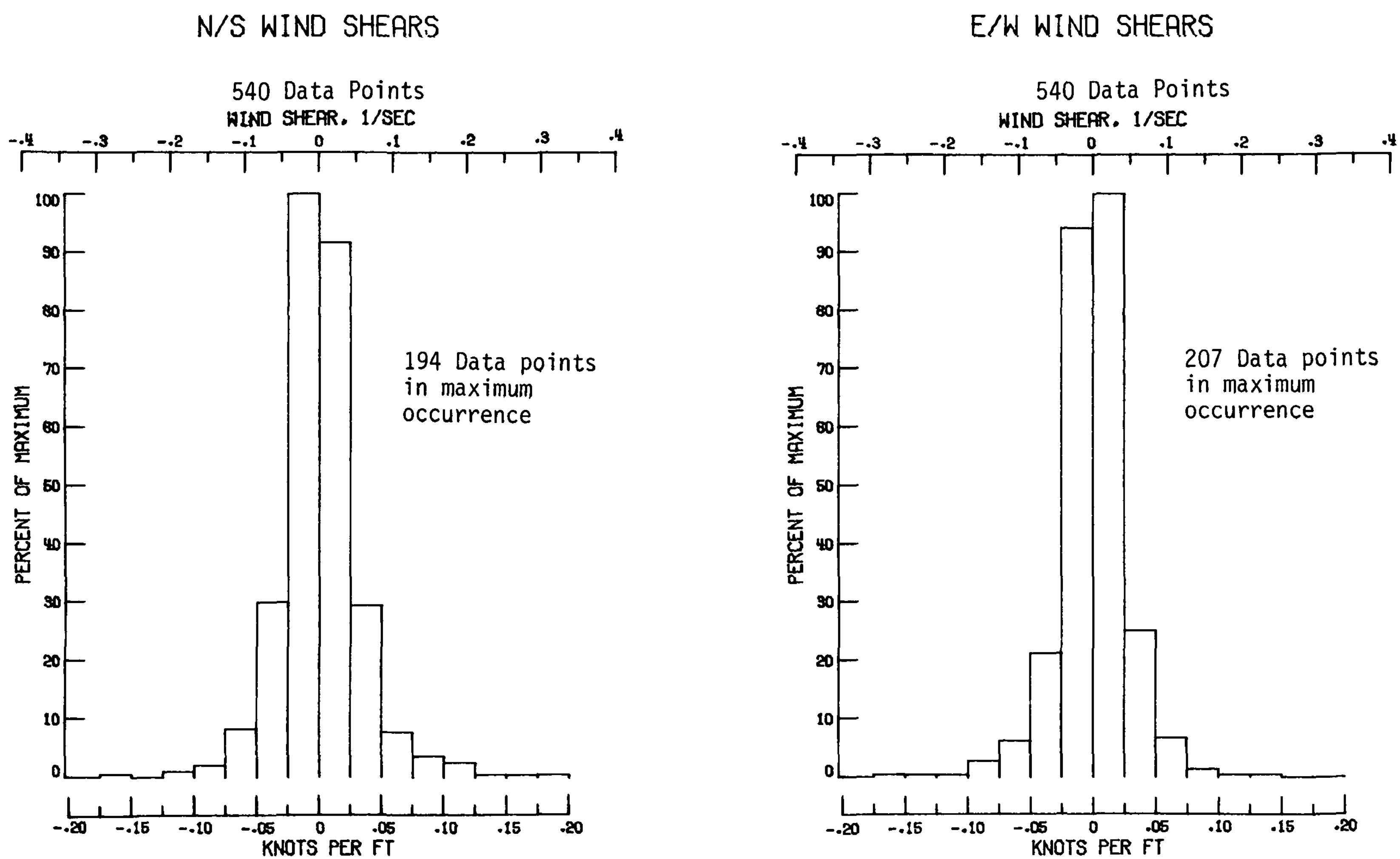
(d) 400 ft.

Figure 3.- Continued.



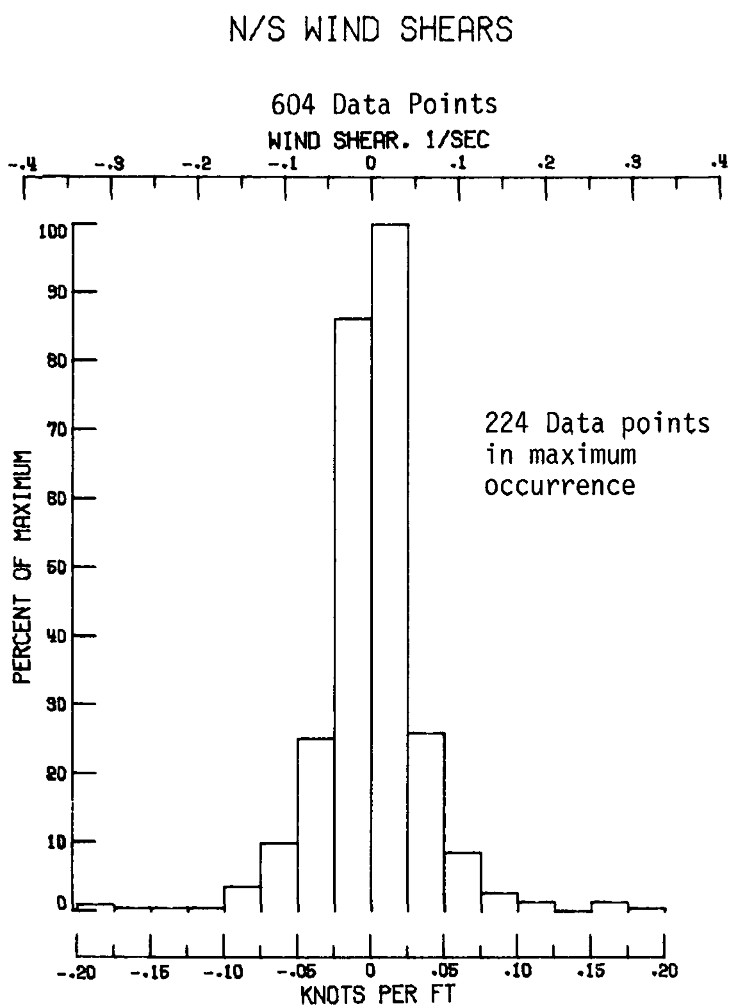
(e) 500 ft.

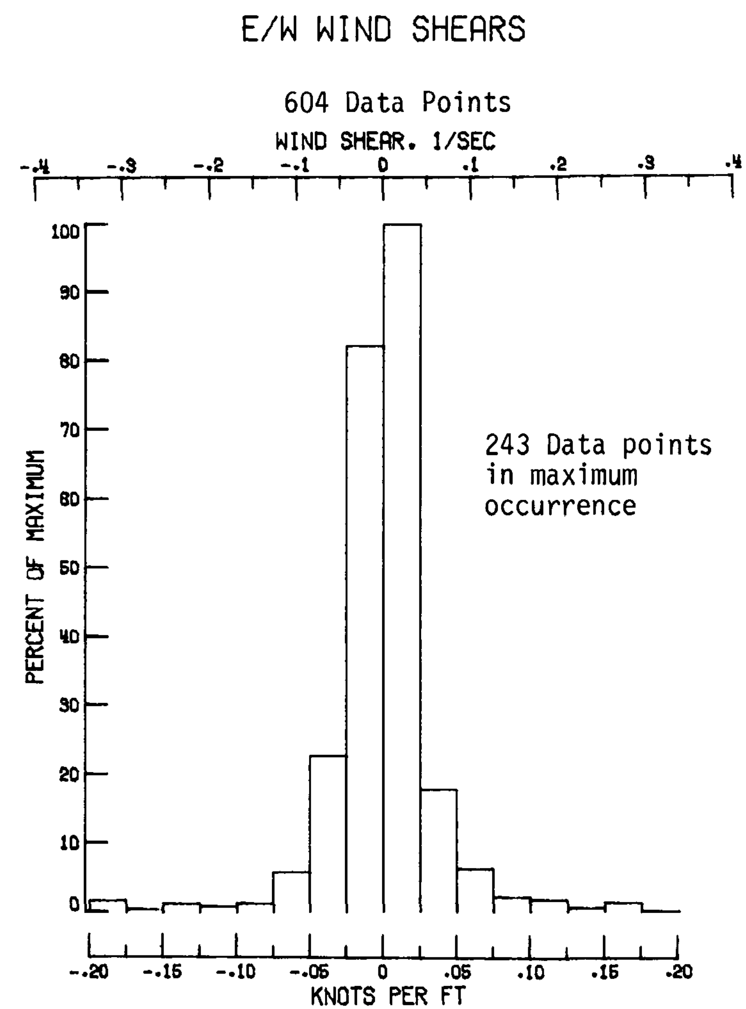
Figure 3.- Continued.



(f) 600 ft.

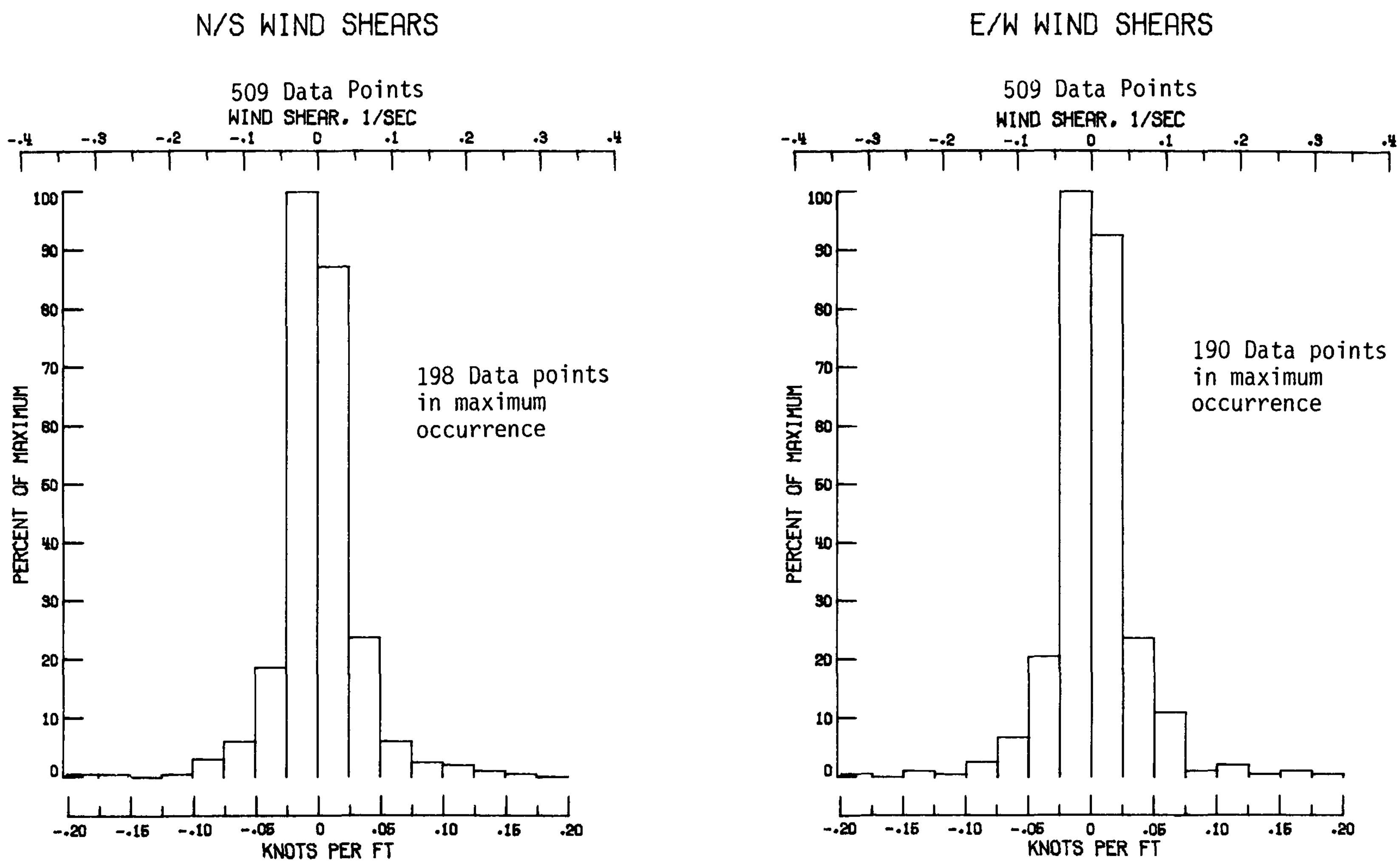
Figure 3.- Continued.





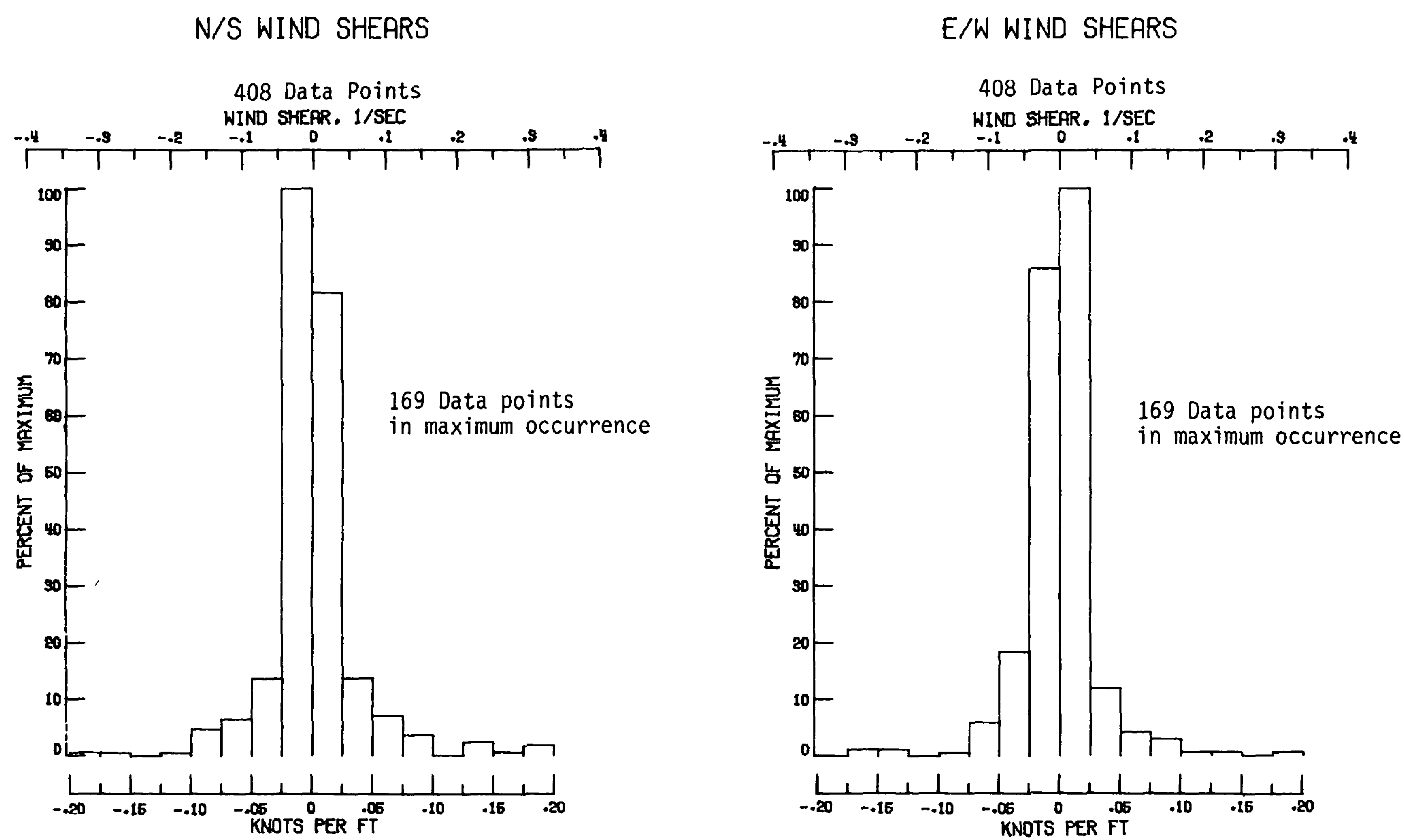
(g) 700 ft.

Figure 3.- Continued.



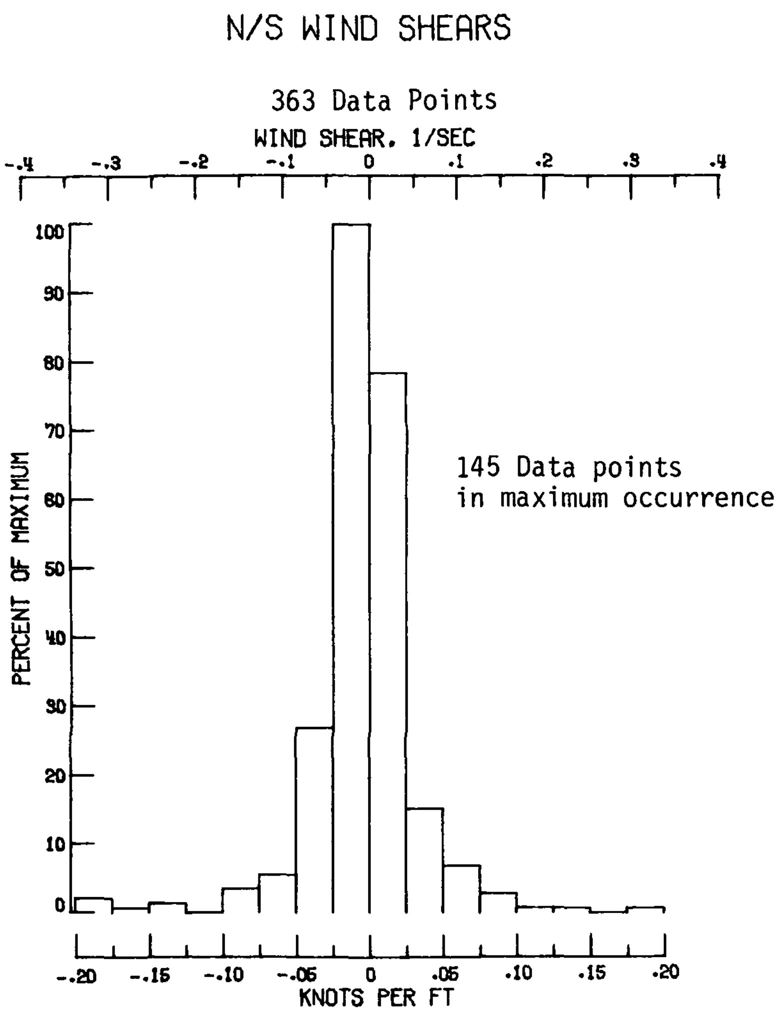
(h) 800 ft.

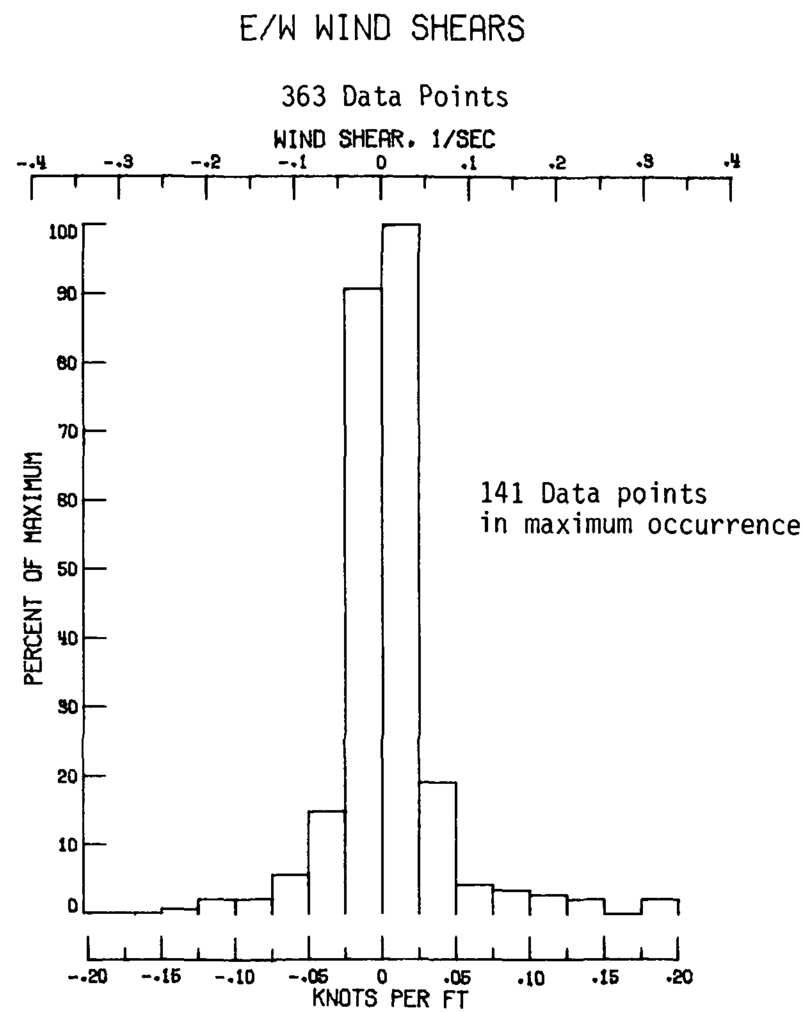
Figure 3.- Continued.



(i) 900 ft.

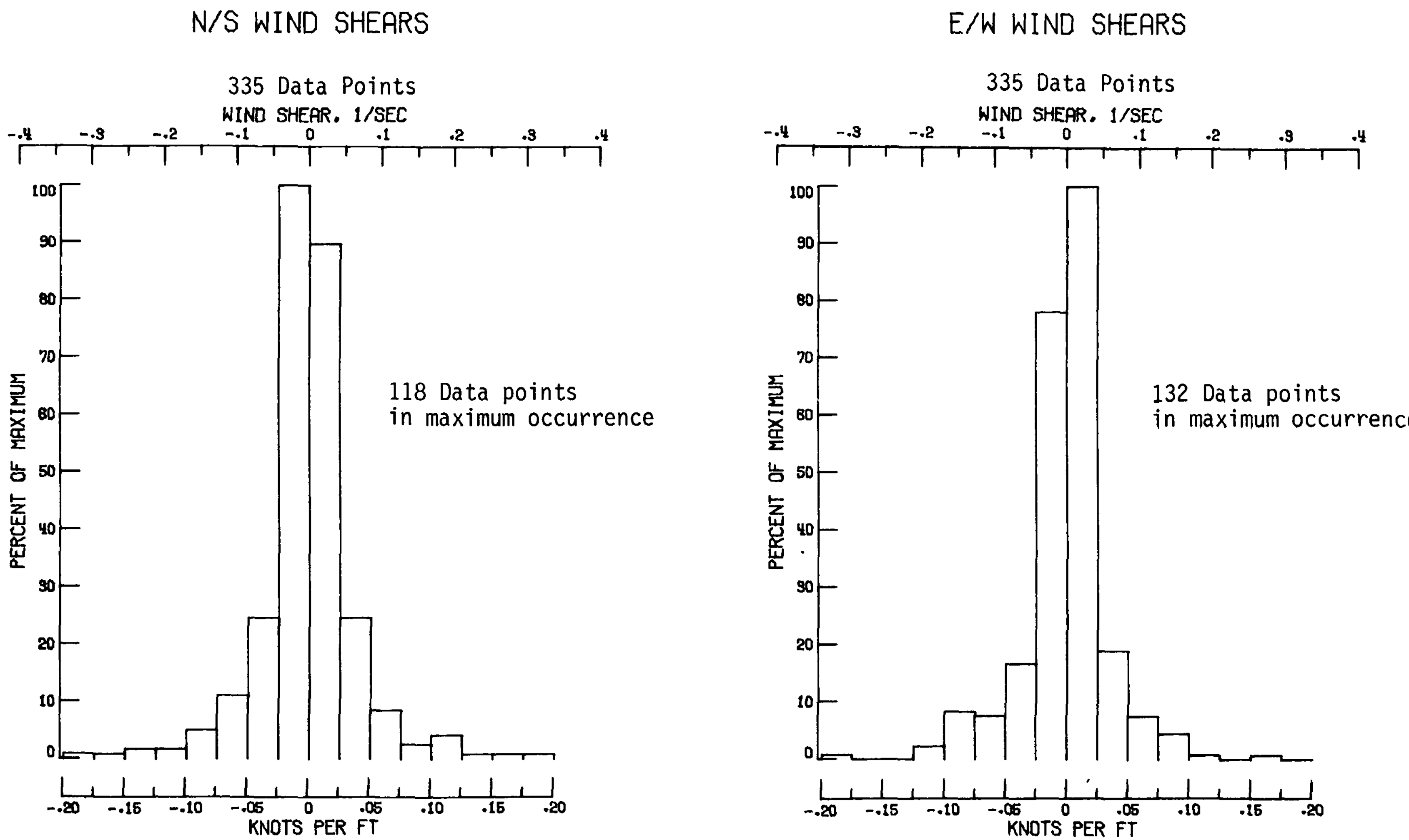
Figure 3.- Continued.





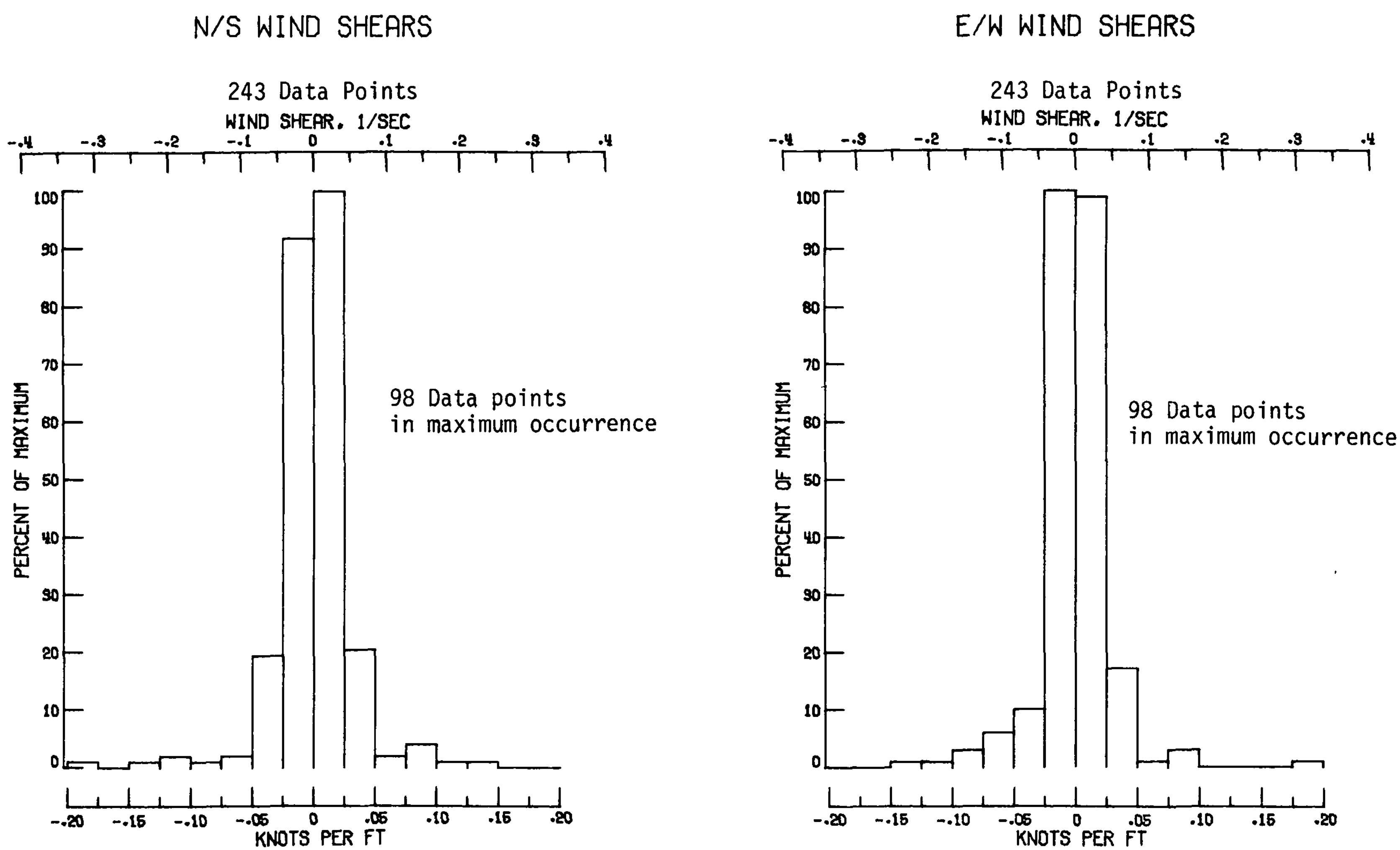
(j) 1000 ft.

Figure 3.- Continued.



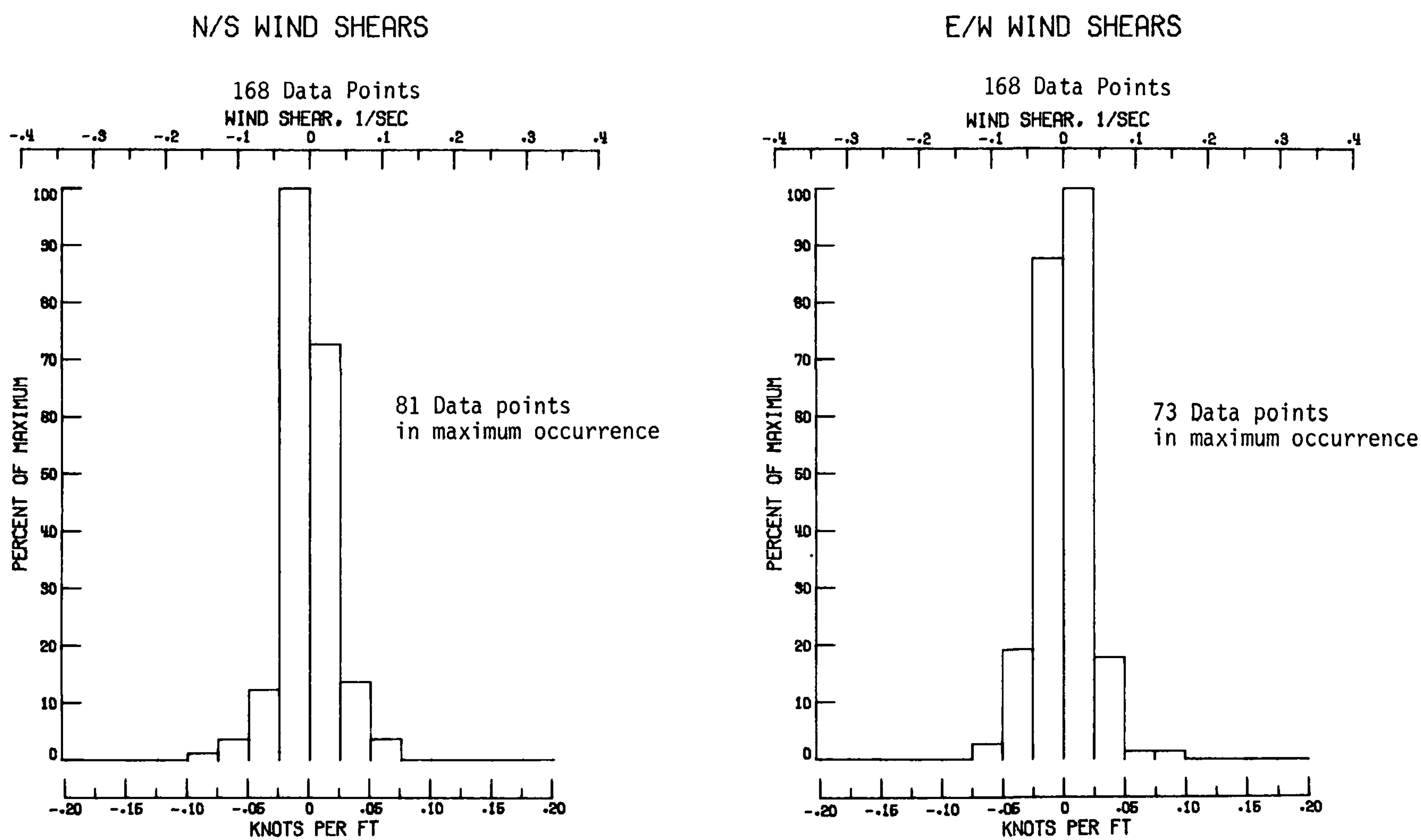
(k) 1100 ft.

Figure 3.- Continued.



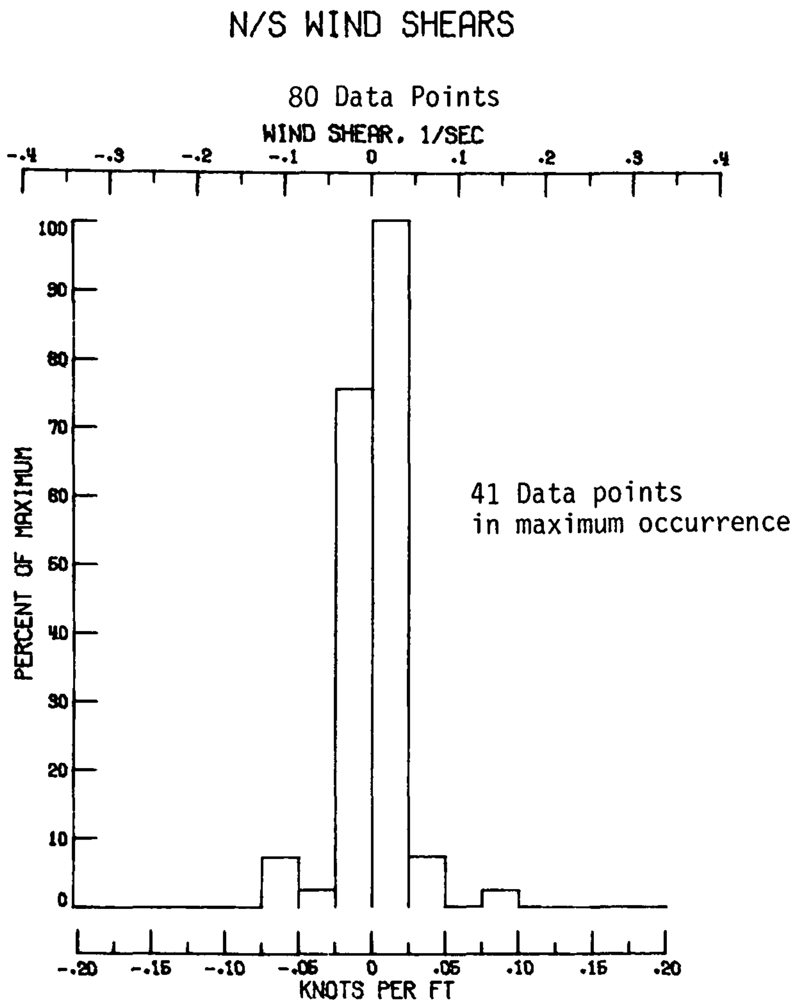
(l) 1200 ft.

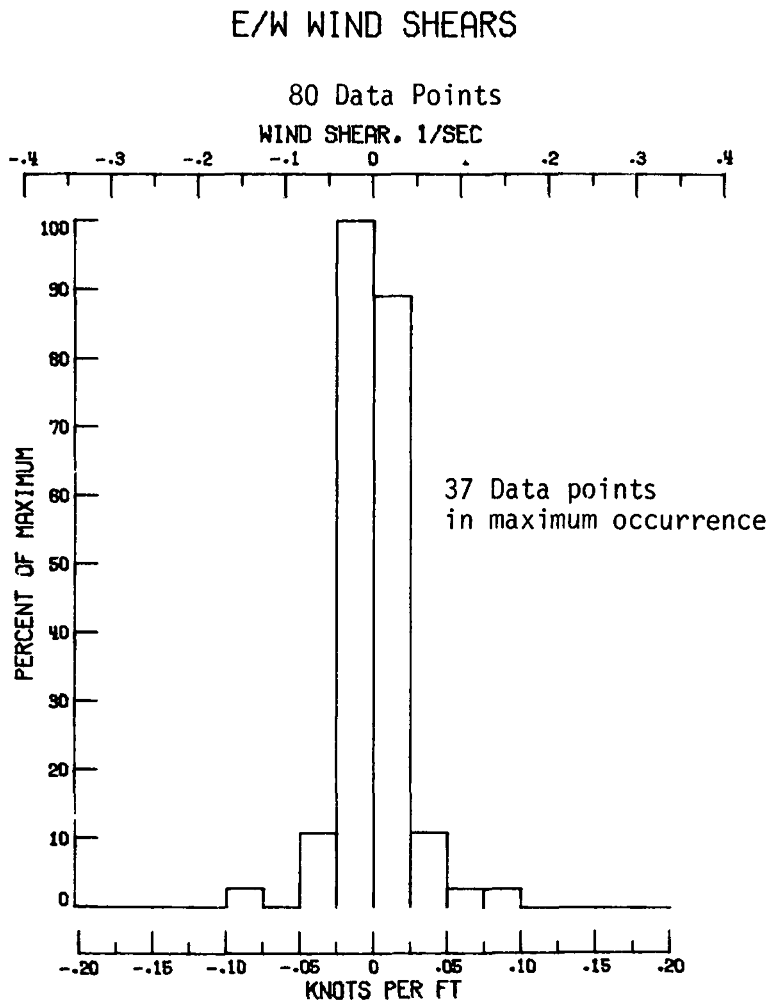
Figure 3.- Continued.



(m) 1300 ft.

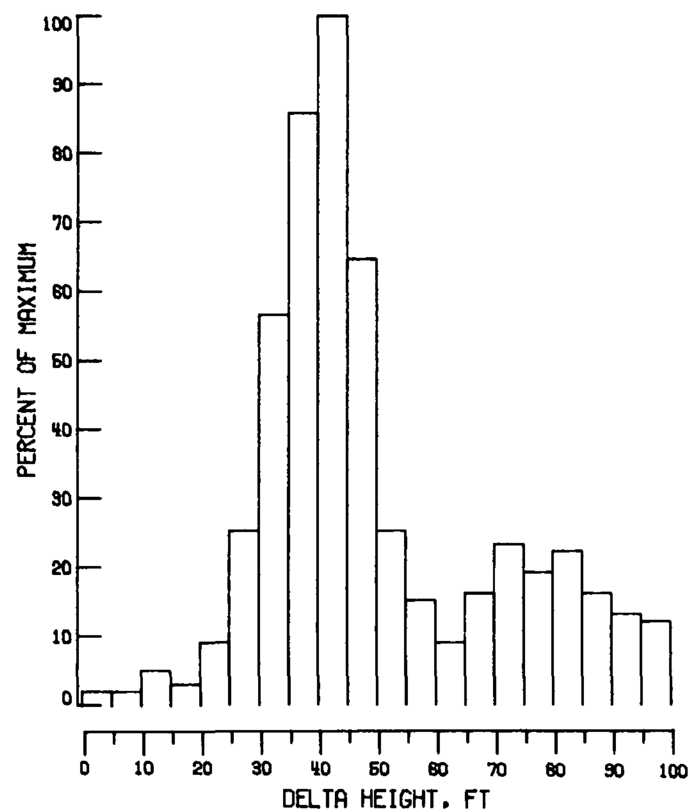
Figure 3.- Continued.



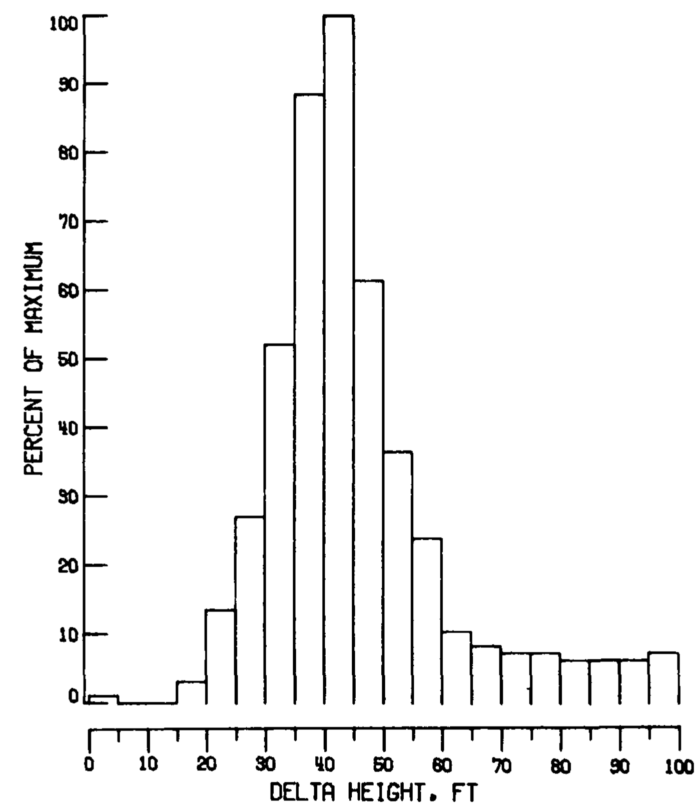


(n) 1400 ft.

Figure 3.- Concluded.

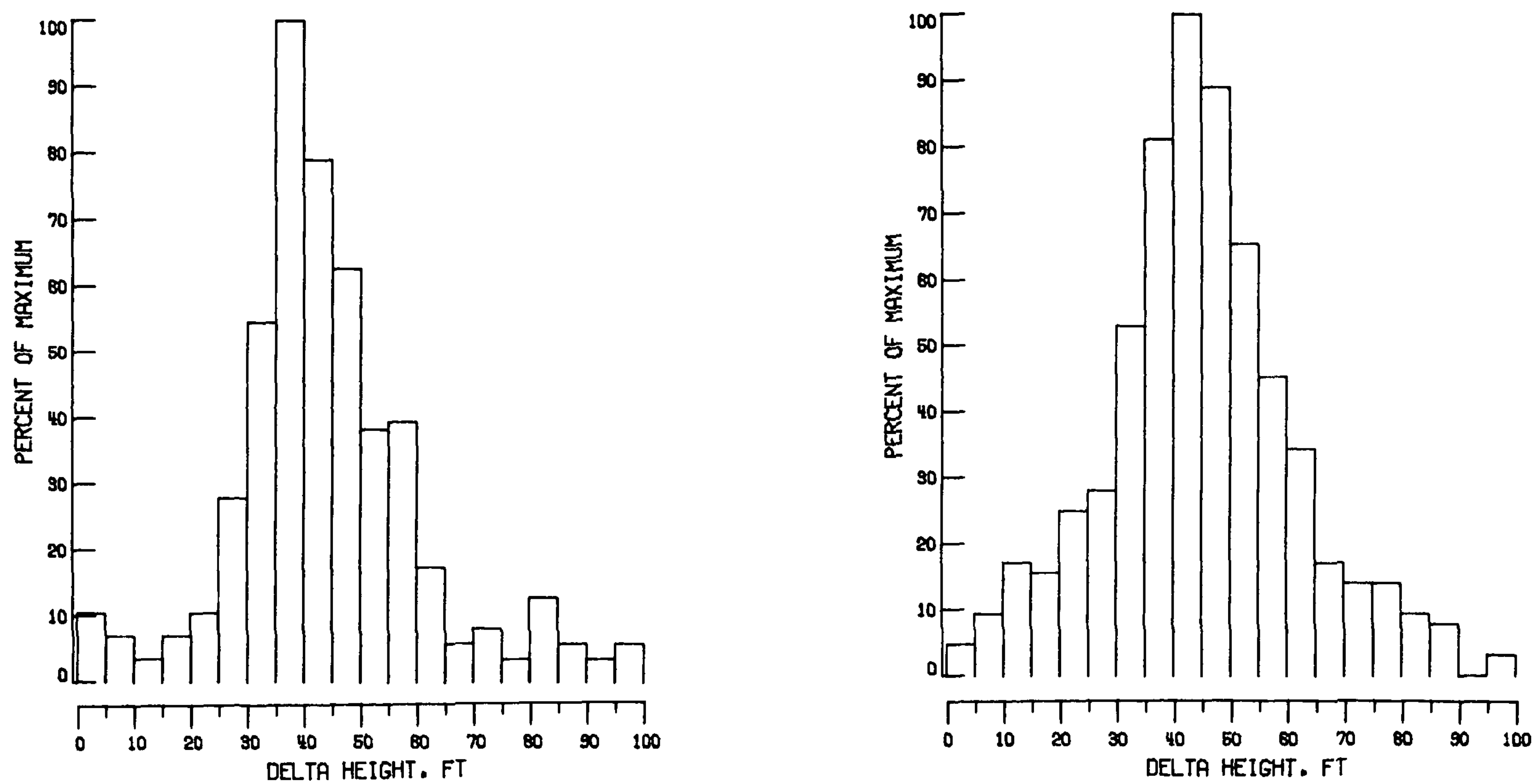


(a) 100 ft.



(b) 200 ft.

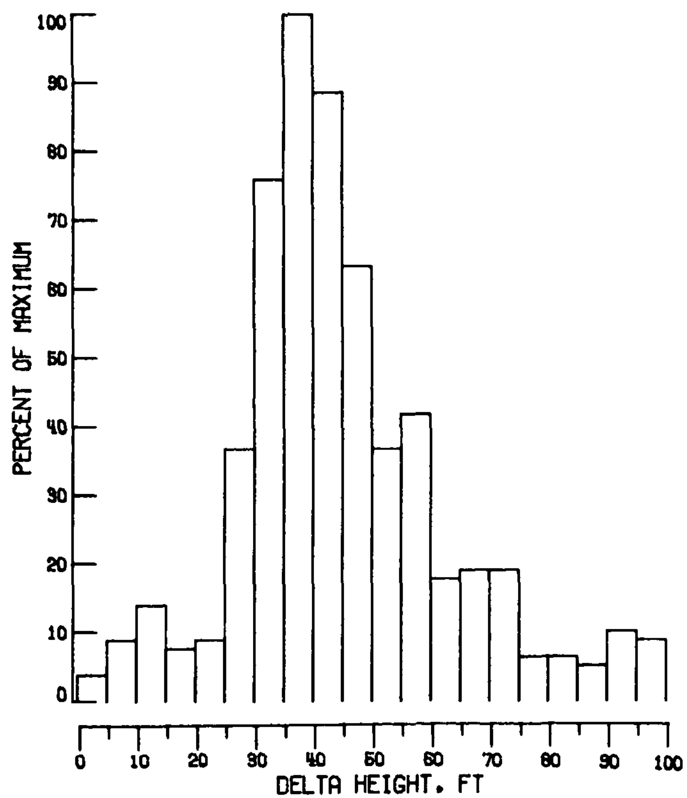
Figure 4.- Distribution of vertical distance between data points at various altitudes.



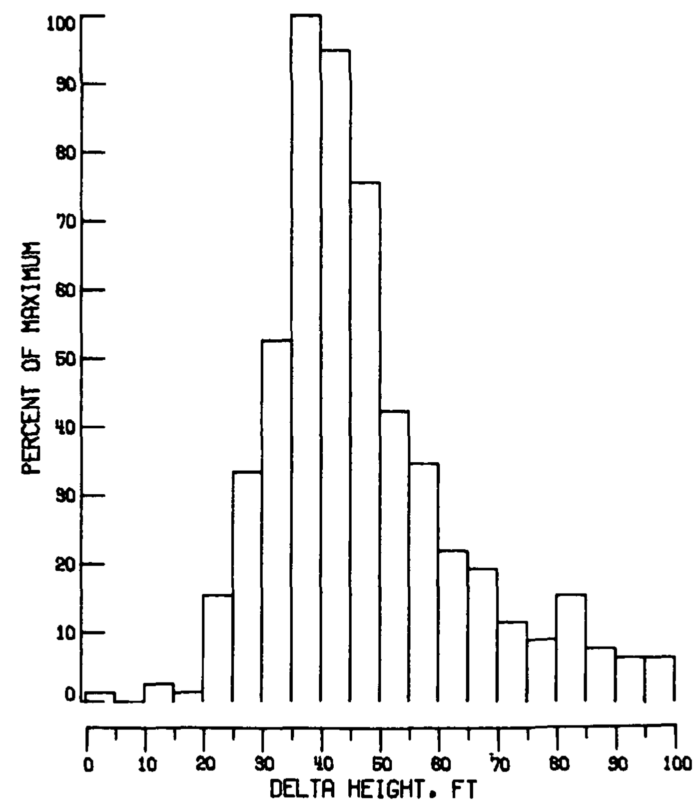
(c) 300 ft.

(d) 400 ft.

Figure 4.- Continued.

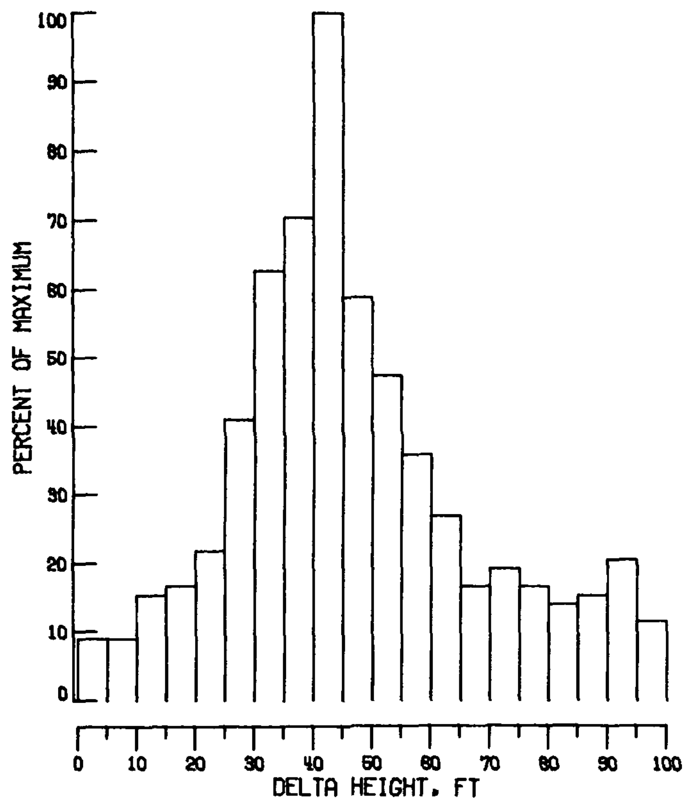


(e) 500 ft.

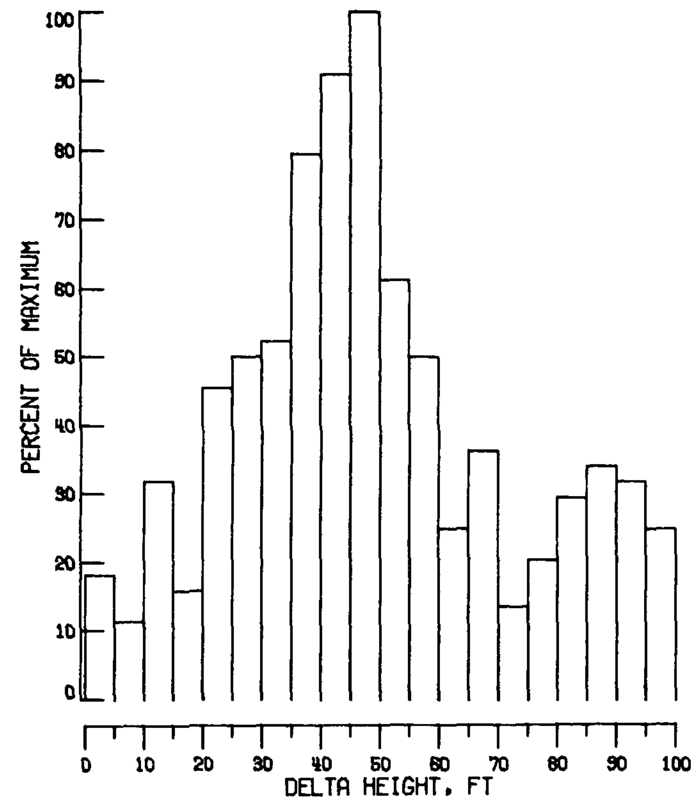


(f) 600 ft.

Figure 4.- Continued.

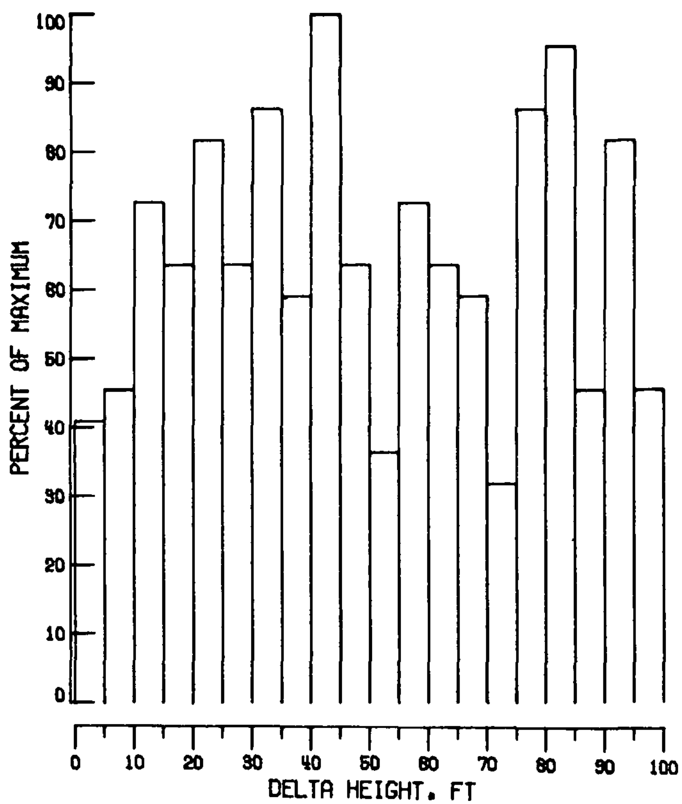


(g) 700 ft.

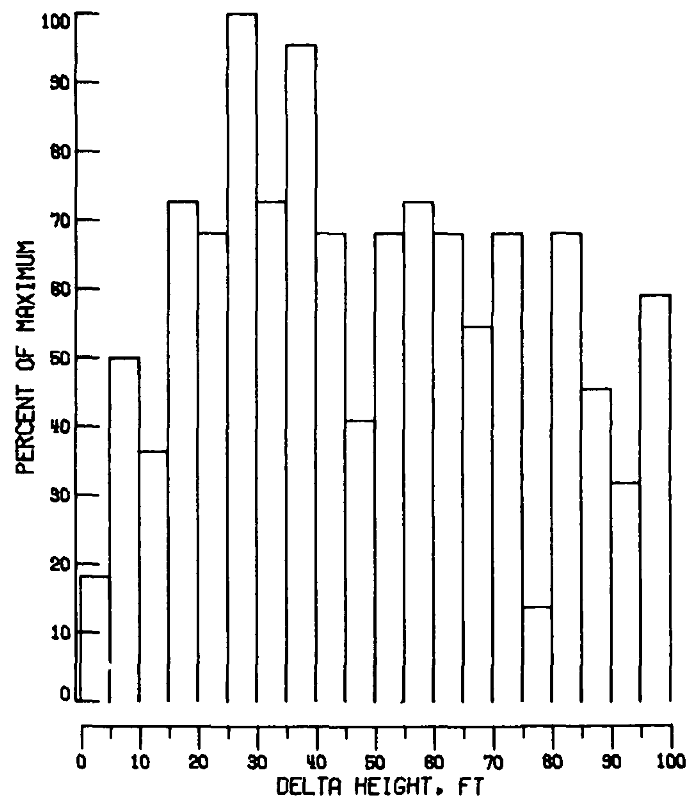


(h) 800 ft.

Figure 4.- Continued.

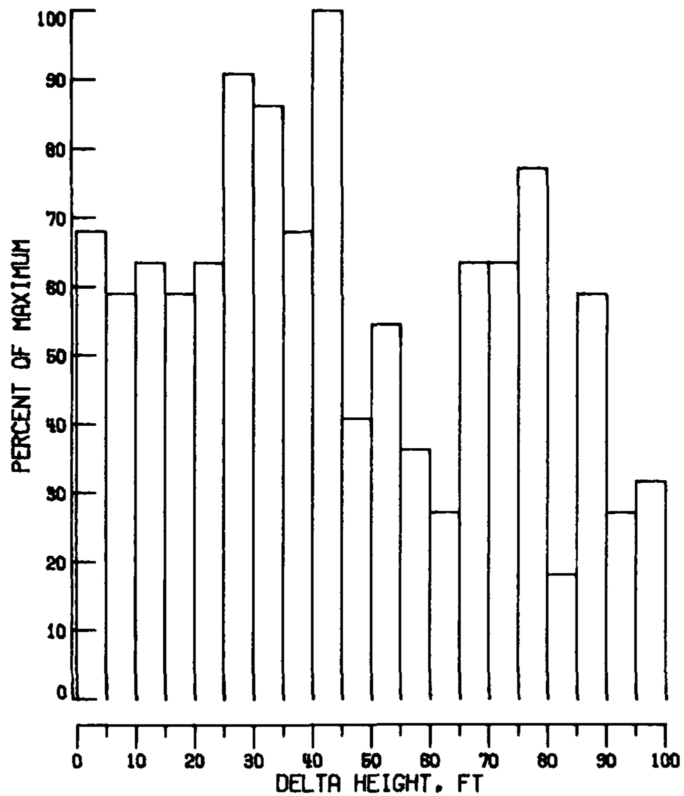


(i) 900 ft.

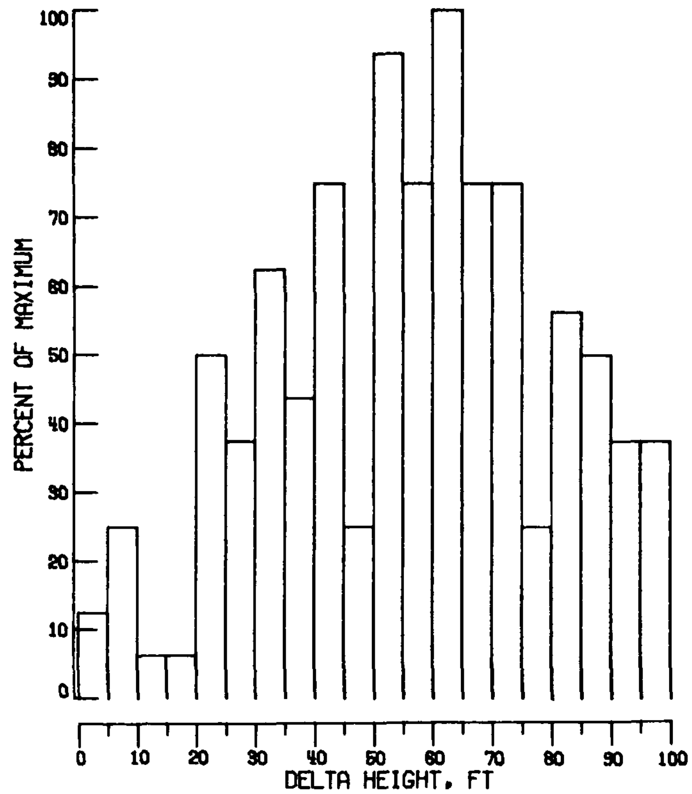


(j) 1000 ft.

Figure 4.- Continued.

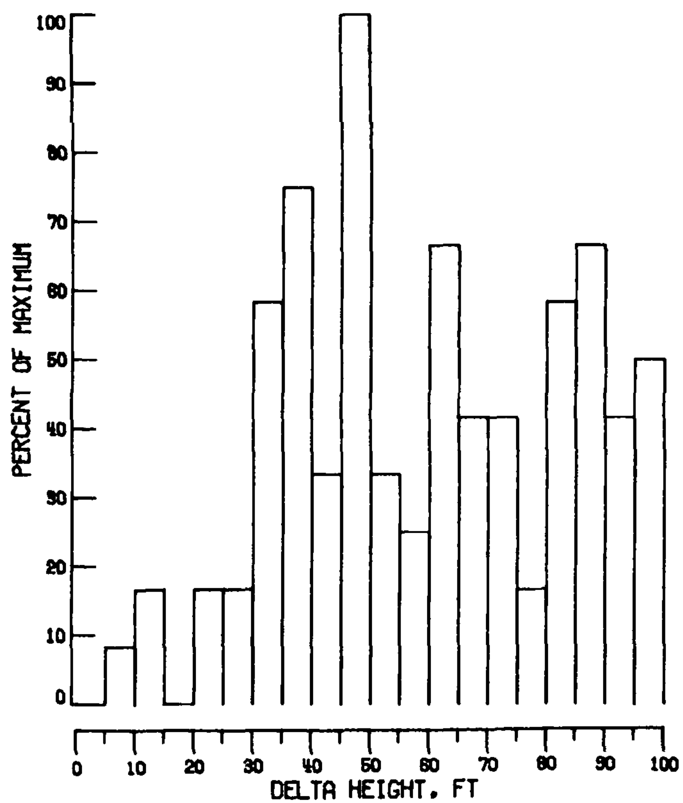


(k) 1100 ft.

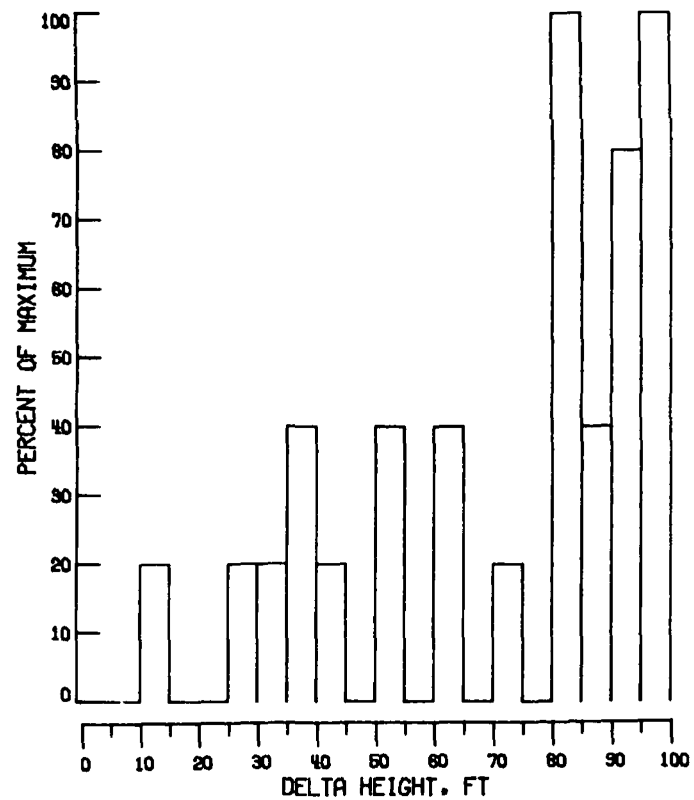


(l) 1200 ft.

Figure 4.- Continued.

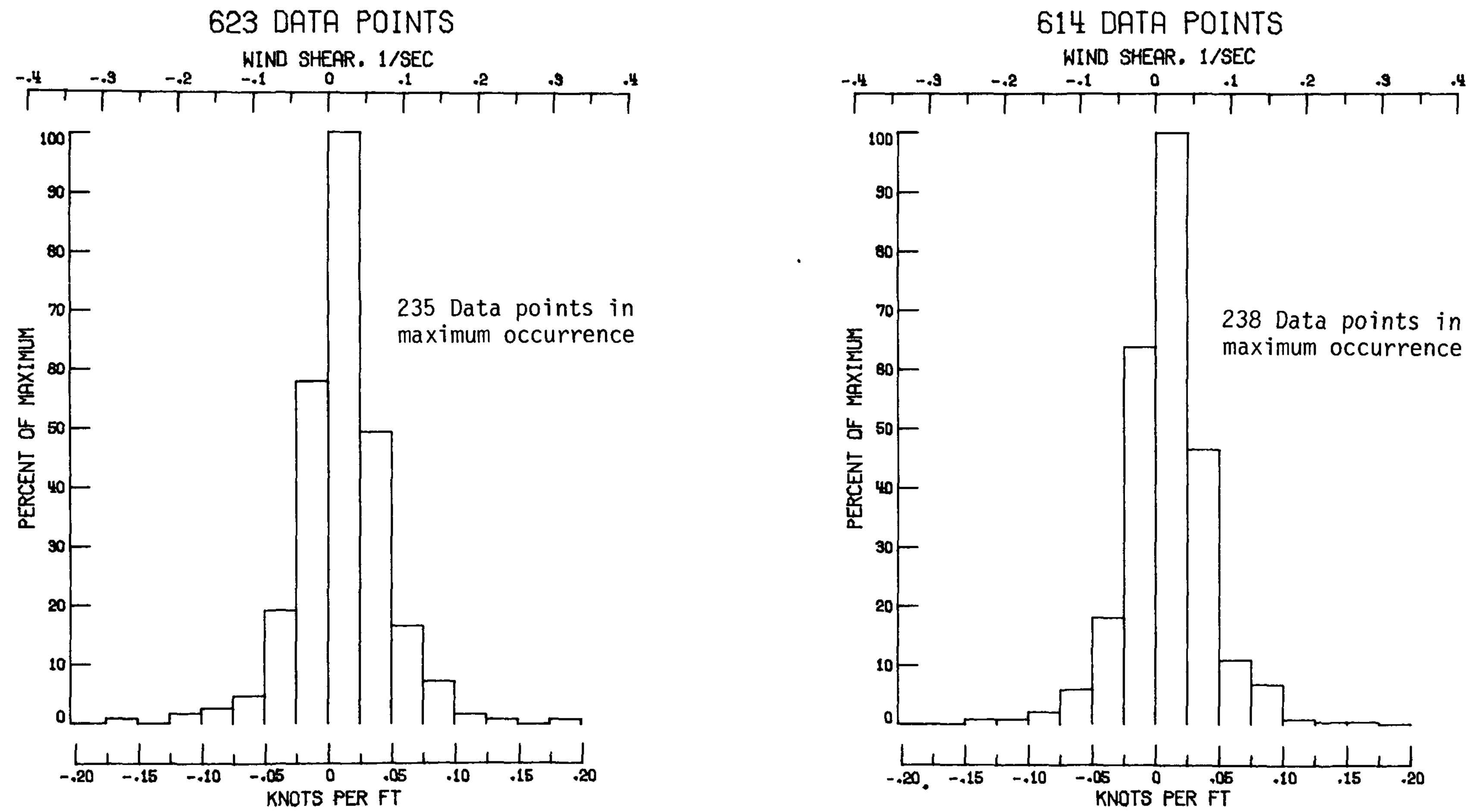


(m) 1300 ft.



(n) 1400 ft.

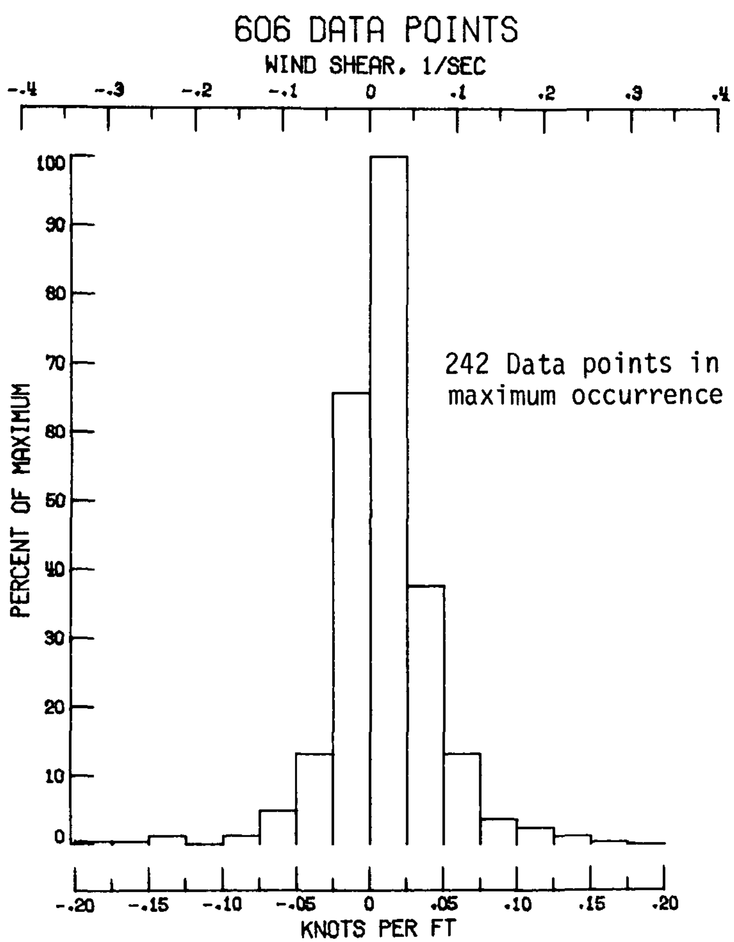
Figure 4.- Concluded.



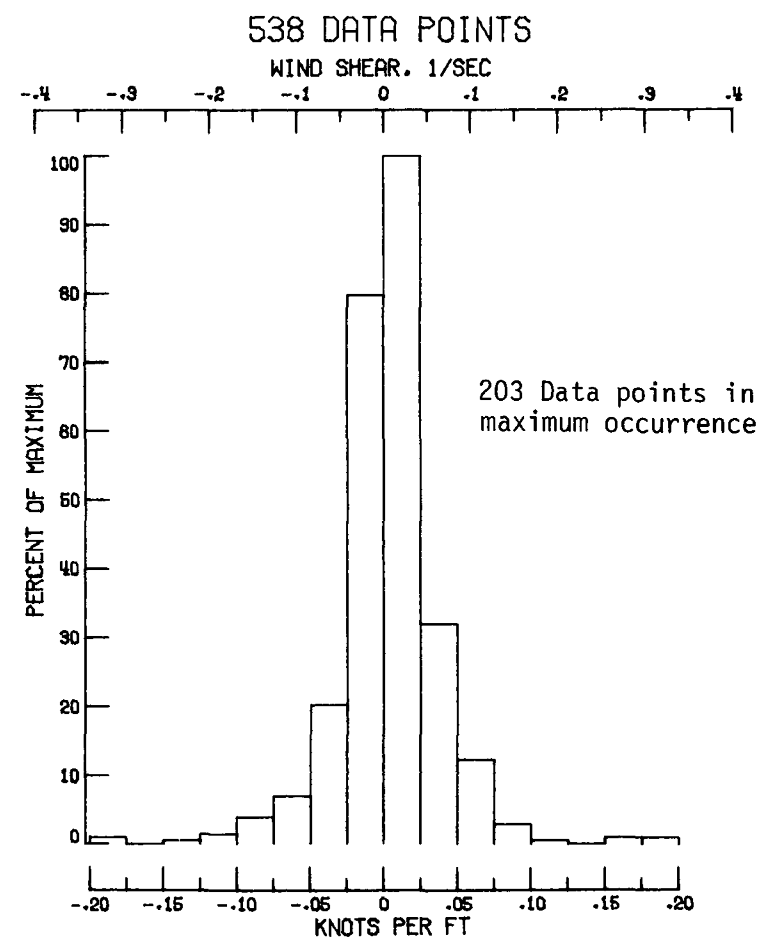
(a) 100 ft.

(b) 200 ft.

Figure 5.- Distribution of wind shear based on total wind speed at various altitudes.

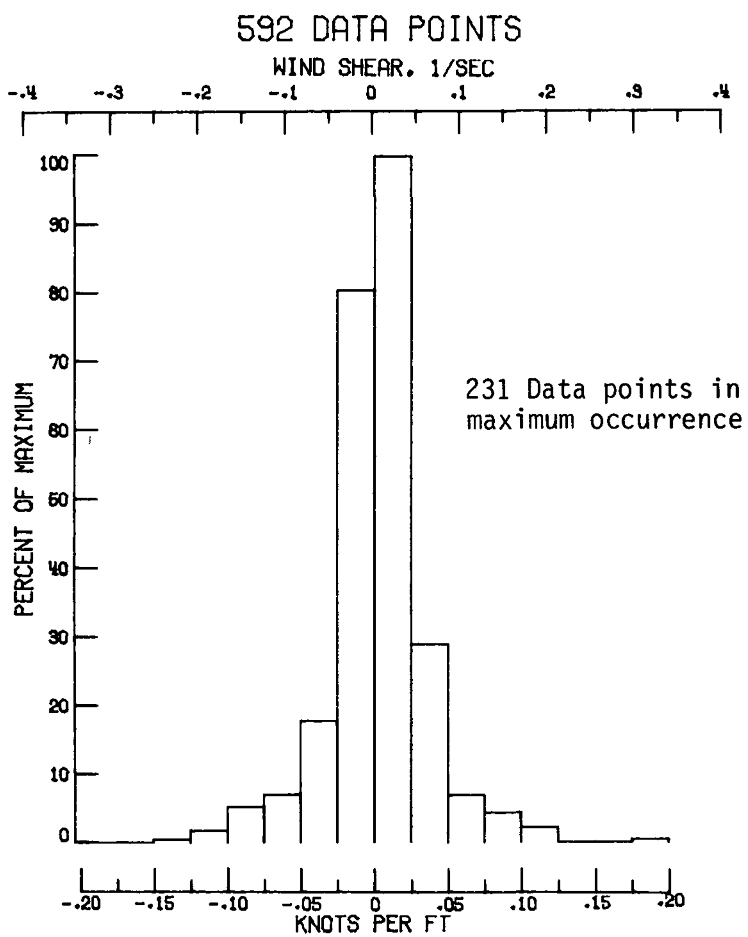


(c) 300 ft.

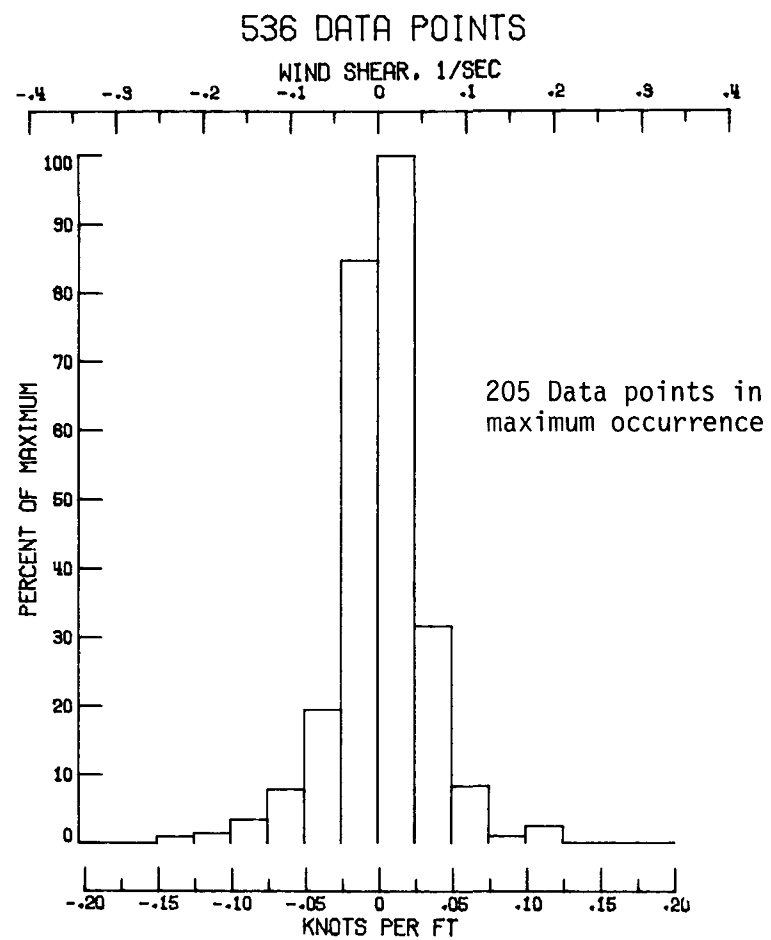


(d) 400 ft.

Figure 5.- Continued.

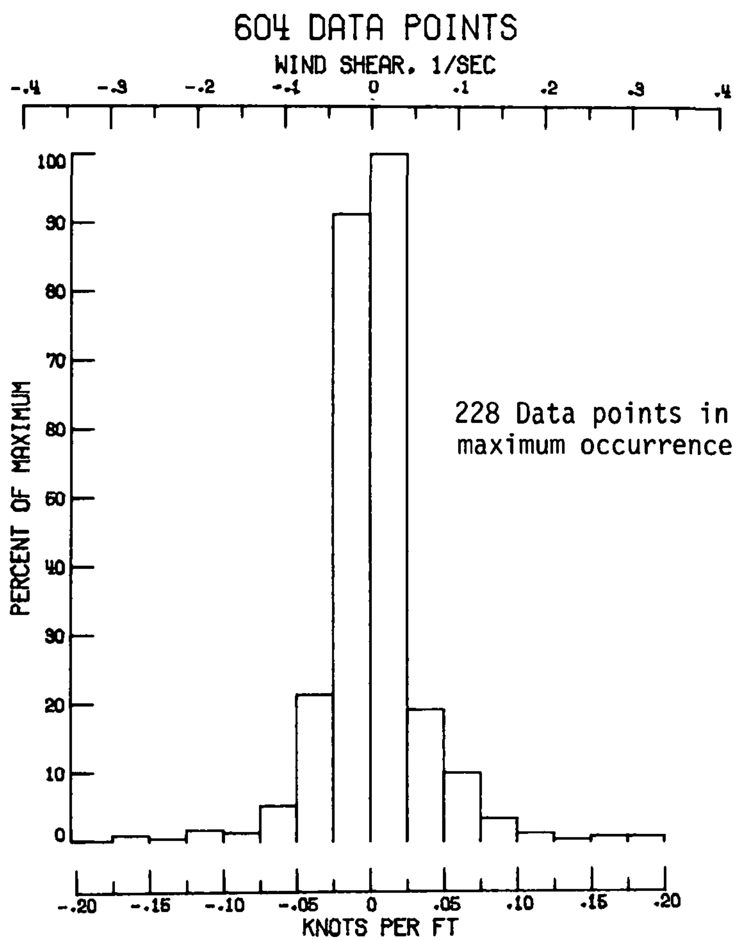


(e) 500 ft.

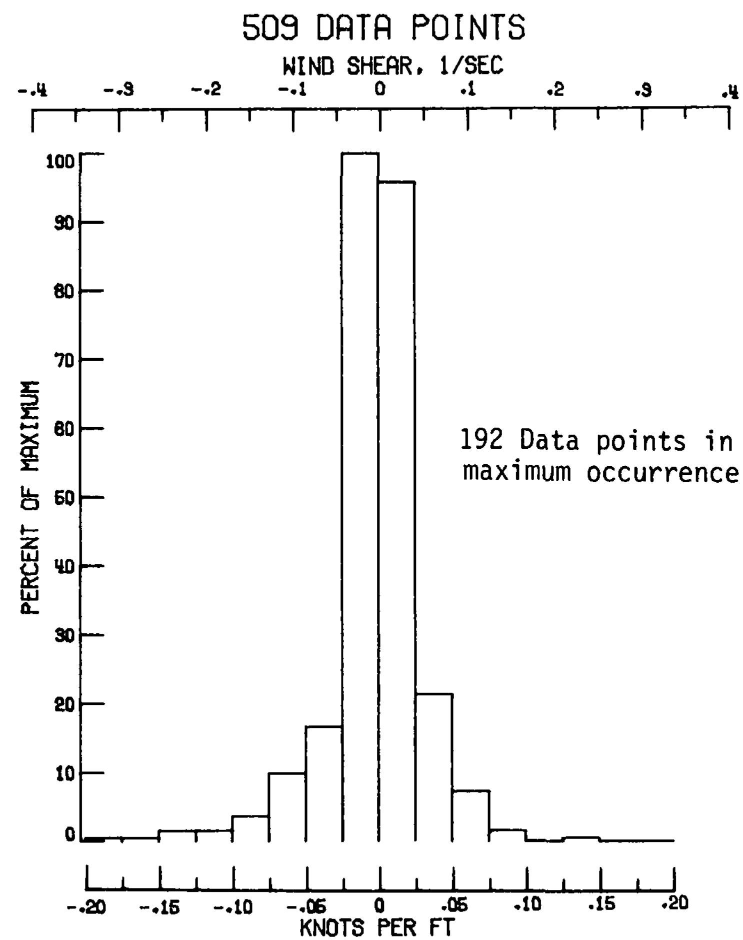


(f) 600 ft.

Figure 5.- Continued.

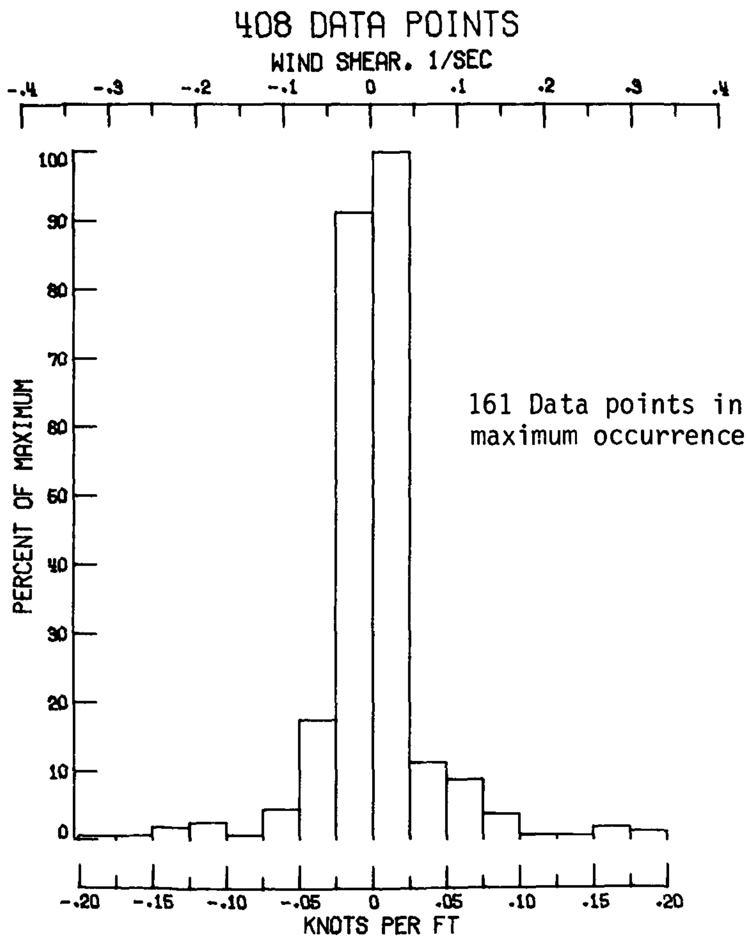


(g) 700 ft.

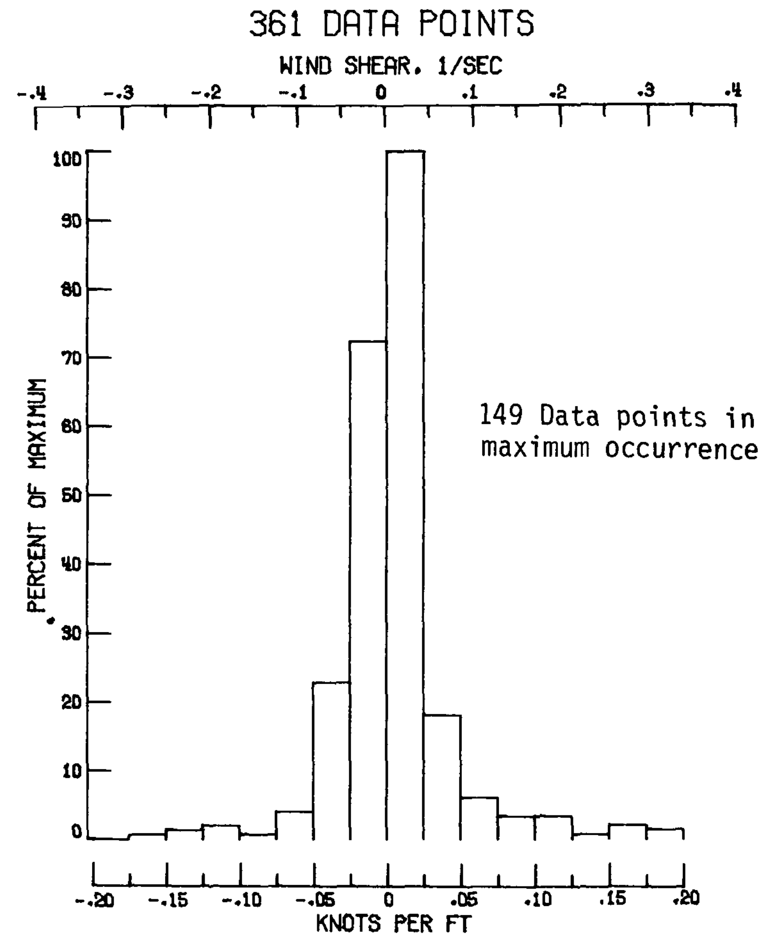


(h) 800 ft.

Figure 5.- Continued.

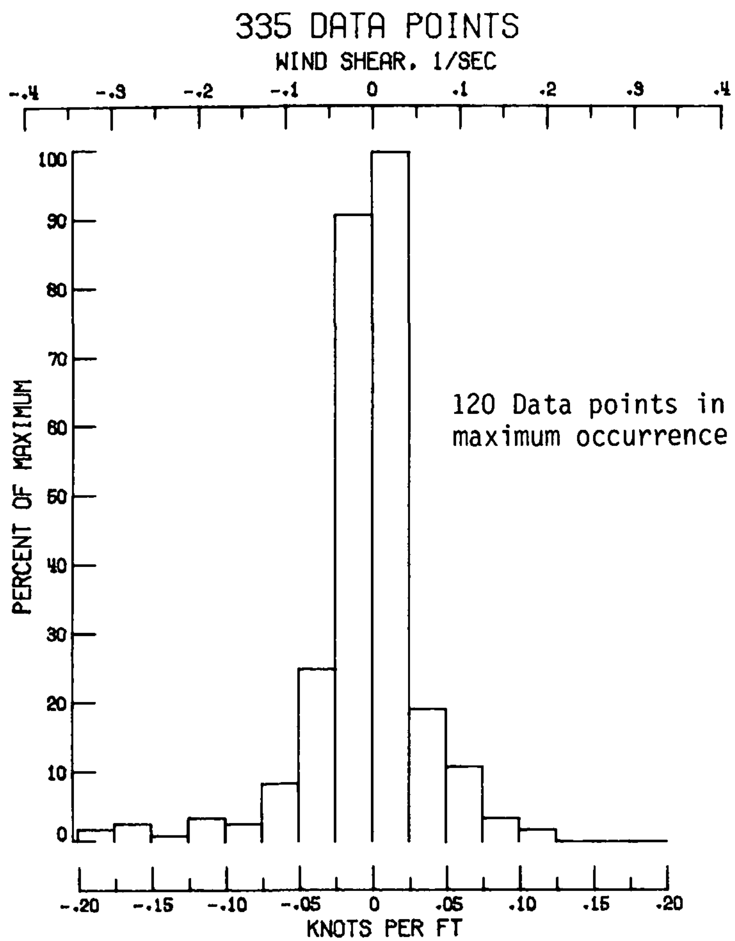


(i) 900 ft.

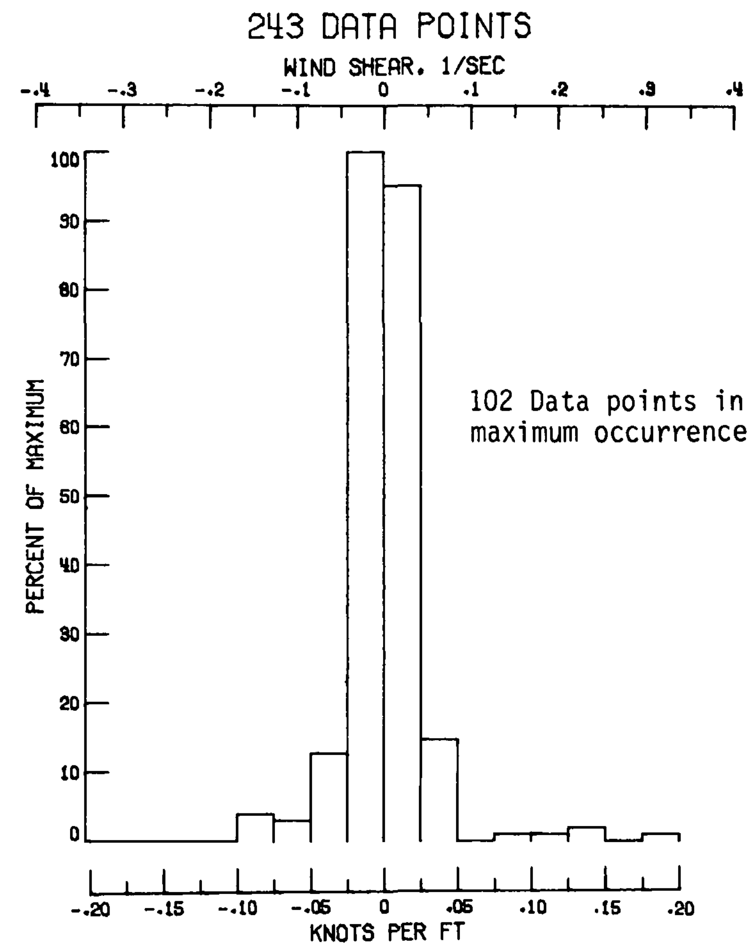


(j) 1000 ft.

Figure 5.- Continued.

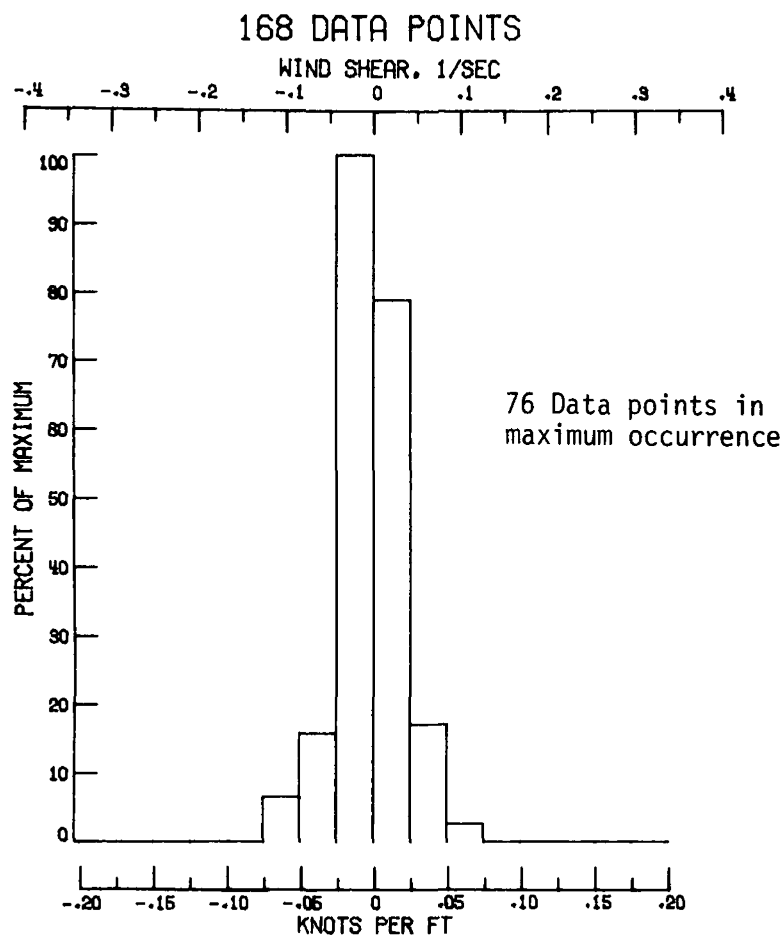


(k) 1100 ft.

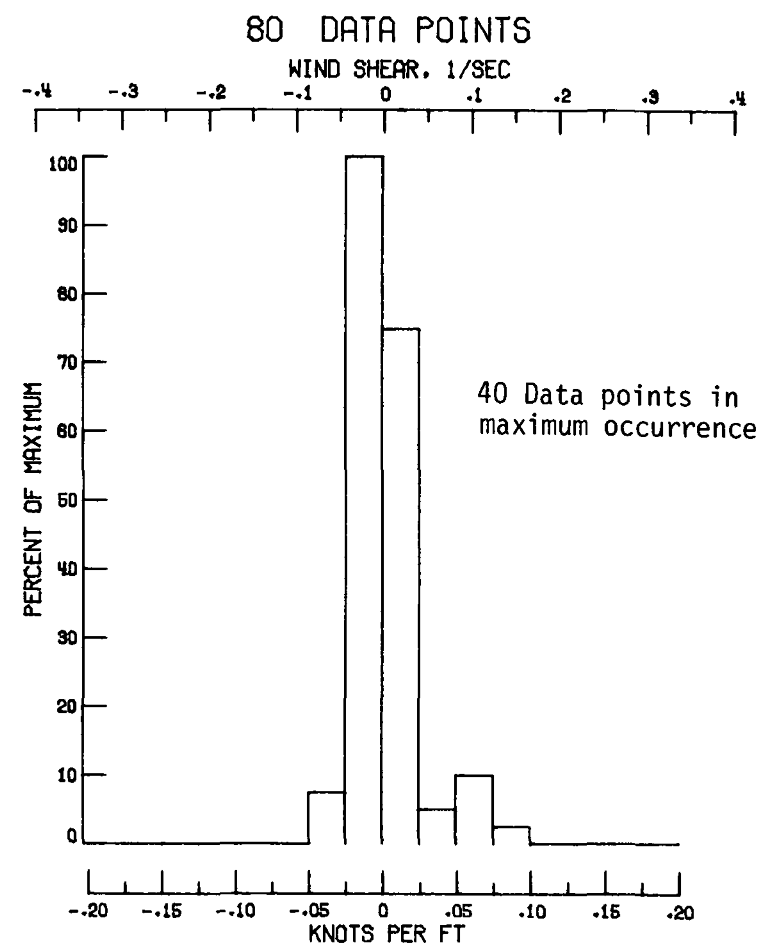


(l) 1200 ft.

Figure 5.- Continued.



(m) 1300 ft.



(n) 1400 ft.

Figure 5.- Concluded.

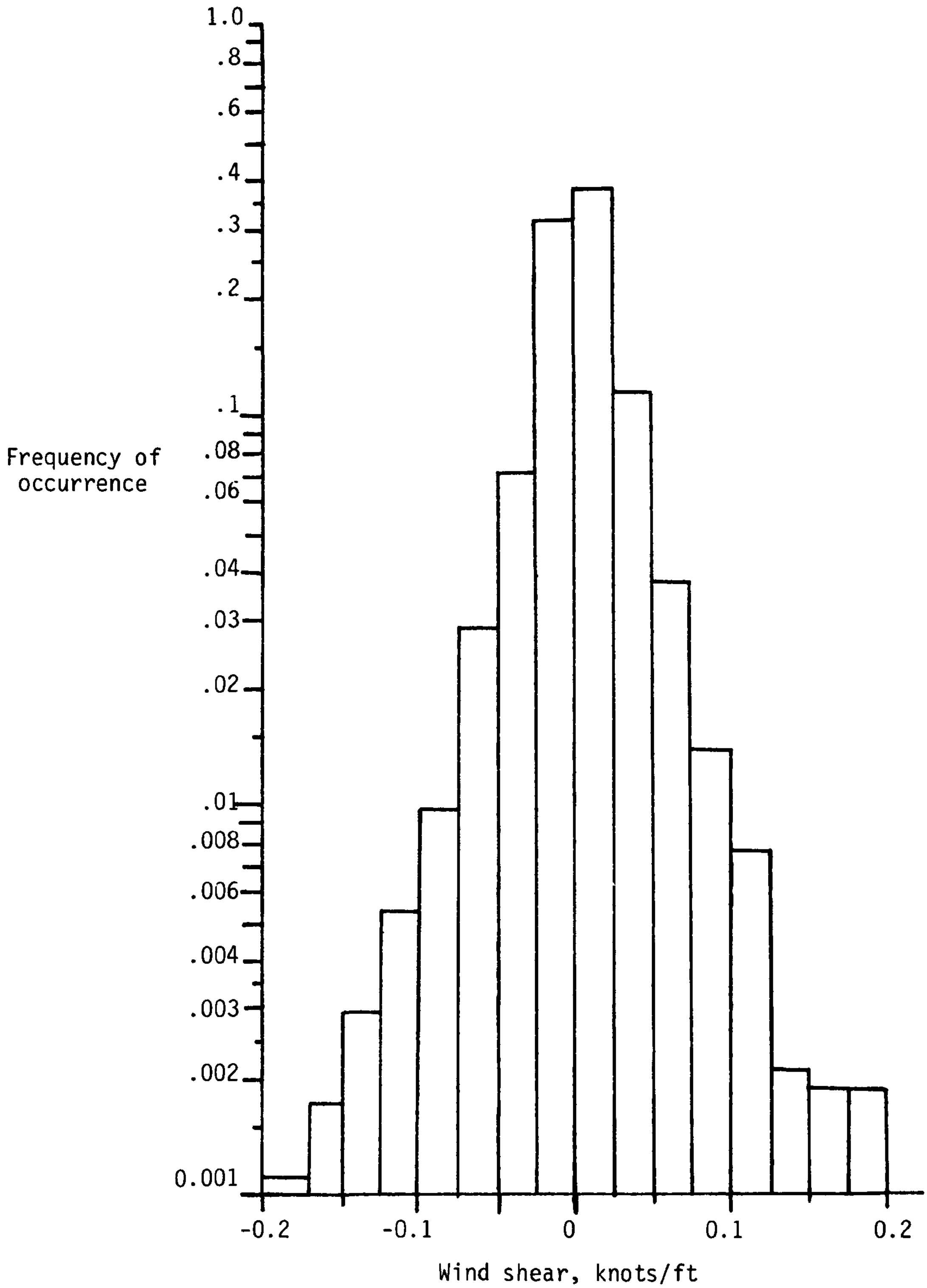


Figure 6.- Frequency of occurrence for total sample size based on shear value from total wind speed.

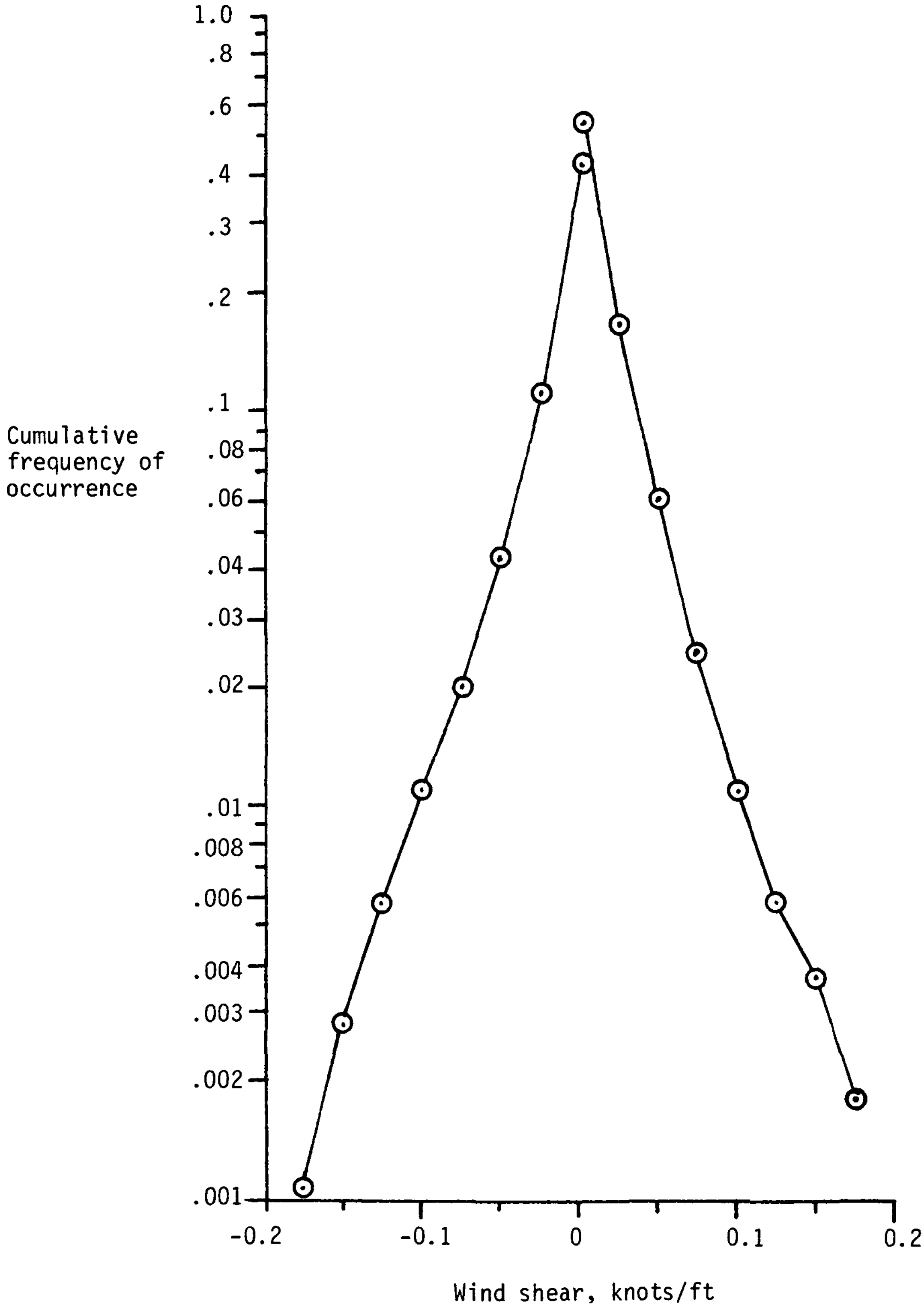


Figure 7.- Cumulative frequency of occurrence for total sample size based on shear value from total wind speed.

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16 Abstract

For a 2-week period, data were collected onboard wide-body jet transports for the determination of winds and wind shear during landings and take-offs. The data represent over 640 take-offs or landings at 14 airports. The inertial navigation system ground-speed measurements and the airspeed and altitude were used to calculate the wind profile in the lower 1400 ft of flight. The wind profiles were used to determine the wind shears (change in wind with altitude) encountered. These limited data were used to determine a probability of encounter for various wind shears.

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