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RESEARCH MEMORANDUM

AN EXPERIMENTAL STUDY OF THE RELATION BETWEEN AIRPLANE AND WIND-VANE MEASUREMENTS OF ATMOSPHERIC TURBULENCE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Simultaneous measurements of horizontal-velocity fluctuations derived from the motions of wind vanes mounted on a tower and vertical-velocity fluctuations derived from the vertical accelerations of an airplane flying in the immediate vicinity of the tower have been examined for relations between the horizontal gusts measured with the vanes and the vertical gusts measured with the airplane. The measurements were made at the Brookhaven National Laboratory in clear air and on generally windy days.

The results indicate that good correlation is obtained between the horizontal gusts evaluated from the vane motions and the vertical gusts measured by the airplane provided that the gusts selected in both cases are of about the same wave length. It appears from these results that airplane measurements of turbulence can be interpreted in terms of surface measurements to extend the scope of data available to either the engineer or the meteorologist.

INTRODUCTION

Atmospheric turbulence gives rise to a number of problems in aeronautics, meteorology, and related fields. In attempts to obtain measures of the turbulence that relate most directly to the particular problem at hand, a variety of methods and instruments have been used. The airplane, as an example, has formed the basis for measuring atmospheric gusts in studies of gust loads on airplanes, while wind vanes, anemometers, balloons, and smoke have been used in meteorological work. In general, it has not been possible to use given sets of data interchangeably for different studies because of difficulties in correlating the various measurements of turbulence.

In view of the interest in correlating turbulence data from various sources, a joint investigation was carried out to explore the subject of turbulence as measured by an airplane and by wind vanes mounted on a tower. The investigation represented the cooperative effort of the National Advisory Committee for Aeronautics, Air Weather Service, Brookhaven National Laboratory, and the U. S. Weather Bureau. It was conducted at Brookhaven National Laboratory in the spring of 1950. This memorandum presents the results obtained from the airplane and tower measurements of atmospheric turbulence and correlates the two sets of measurements.

METHOD AND APPARATUS

The method used in the study was to fly a light airplane at altitudes corresponding to measuring stations on the tower in traverses across and along the mean wind and to compare statistically the gust histories obtained from airplane instruments with measurements made from the tower. For this purpose, only a certain range of the wave lengths for the records obtained from the tower is relevant and was used, as will be indicated subsequently.

Airplane and Instruments

An L-5 airplane was selected for the investigation because it could be operated safely at low altitudes and at a low speed in the immediate vicinity of the tower. The characteristics of the airplane pertinent to the present tests are given in table I. The airplane was equipped with radio for ground communication.

The following instruments were installed in the airplane for gust measurements:

NACA recording accelerometer
NACA airspeed-altitude recorder
NACA synchronous timer (1-sec interval)

The accelerometer was mounted at the center of gravity of the airplane to record the vertical accelerations. The airspeed-altitude recorder was connected to a pitot-static head installed on a boom below the wing and extending about 1 chord forward of the leading edge. The two recorders in the airplane were synchronized by the 1-second interval timer. Synchronization with ground operations was obtained by transmitting a radio pulse when flight instruments were turned on or off. The recording instruments in the airplane operated at a film speed of 1/4 inch per second.

Tower and Instrumentation

The base of the meteorological tower at the Brookhaven National Laboratory is located about 70 feet above sea level in fairly level country. The laboratory facilities are close to the tower and the surrounding areas are generally wooded with some cleared farm lands. The wind has a clear sweep from all directions with no large obstructions to modify the flow. For the present study, wind instruments on the tower (fig. 1) were mounted at elevations of 37, 150, 300, and 410 feet above the terrain.

The wind and gust measurements from the tower were obtained from Bendix-Friez Aerovanes (fig. 2). The Aerovanes were connected to Esterline-Angus Recorders which had a chart speed of 3 inches per minute. Because of the slow response of the impeller-type anemometer used on the Aerovane, the anemometer was used to obtain only the average wind speed and the motions of the directional vane were the primary source of data for deriving the horizontal gust components. In order to obtain a measure of the characteristics of the vane, studies of the response of the combination of vane and recorder under unsteady conditions were made in the Langley gust tunnel. The results obtained for the natural frequency and damping characteristics of the vane are included in table I.

SCOPE OF TESTS

Table II presents a summary of the general weather conditions at the time of each flight. The table indicates that all flights were made in clear air with only middle and high cloud types present in the majority of the cases. The wind velocities at the flight altitudes varied from 5 to about 30 feet per second. The lapse rates in table II were obtained from the temperatures at 1,000 and 100 feet above sea level. The table indicates that superadiabatic lapse rates were generally present in this layer. In one case, an early morning flight, a strong inversion was present. Below 100 feet, the lapse rates were generally superadiabatic.

On each flight the pilot made four traverses at each altitude along and across the wind as indicated by the courses shown in figure 3. The flight altitudes were approximately 150, 300, and 410 feet above terrain to correspond to the altitudes of the tower instruments. The pilot informed the tower of the start and end of each traverse on all surveys and attempted to maintain his assigned altitude with a minimum use of the controls.

Table III presents the scope of the gust records from the airplane and tower which have been included in the present analysis. The 410-foot tower level was selected for study, and as indicated in the table, the Aerovane data from this level were evaluated for all flights in which records were obtained. In order to obtain a measure of the variation of turbulence with altitude, the Aerovane records from two flights were evaluated for all tower levels. As a further check on altitude variation, the tower data for the 150-foot level were evaluated for five additional flights.

EVALUATION OF DATA AND RESULTS

Airplane Data

All records of airspeed and vertical acceleration were evaluated to obtain, for each gust acceleration peak, the gust intensity and the gust-gradient distance. The procedures are described in detail in reference 1, and for the present work the following relations were used:

$$\Delta n = \frac{\rho_o a U V_i \frac{\Delta n}{\Delta n_s}}{2W/S} \tag{1}$$

and

$$H = V_t \ \Delta t \tag{2}$$

In these relations:

Δn acceleration increment of airplane, g units

ρ_o sea-level air density, slugs/cu ft

a lift-curve slope, per radian

U vertical gust velocity, ft/sec

V_i airplane indicated airspeed, ft/sec

$\frac{\Delta n}{\Delta n_s}$ correction factor to account for some of the effects of the motions of an airplane in a gust (table I)

W airplane weight, lb

S wing area, sq ft

H gust-gradient distance, ft (distance from 1g to peak acceleration)

Δt time interval from beginning to peak acceleration, sec

V_t true airspeed, ft/sec

The vertical gust velocities evaluated by means of relation (1) are average values over the airplane span which for this airplane was 33 feet. For the evaluation of the large number of gusts recorded, this procedure was followed in lieu of a more accurate method in order to permit rapid evaluation of the data. In the evaluation and subsequent analysis, the positive and negative gust velocities were treated alike regardless of sign.

The gust velocities for all traverses at a given altitude and a given flight were combined to obtain cumulative frequency distributions of the type shown in figure 4. In this figure, the cumulative frequency distribution for one altitude has been divided by the flight mileage. The results indicate the average number of gusts greater than given intensities that were encountered per mile of flight at the given altitude.

The gradient distances were evaluated from the airplane records as indicated by relation (2) by multiplying the time interval from 1g to peak acceleration increment by the true airspeed. For an assumed 1 - cosine shaped gust as currently used in evaluating airplane accelerometer records, the gradient distance represents 1/2 the wave length of the gust. A sample of the results obtained from two flights is shown in figure 5. The relative frequency distribution in this figure indicates the proportion of gusts having various gradient distances.

Tower Data

In obtaining the lateral gust velocities from the Aerovane records, it was assumed that the mean wind speed at each altitude and during each traverse was a constant. For simplicity of evaluation, it was also assumed that the wind vane followed the lateral fluctuations of the stream for the range of wave lengths represented by the airplane gradient distances. Under these assumptions, several methods of evaluating the records were examined in attempts to derive a simple and consistent measure of the gusts. These preliminary evaluations indicated that the method of reading the fluctuations from a fixed reference as applied to the airplane acceleration records could not be readily applied to the vane records because of difficulties in assigning a mean wind direction to the individual fluctuations (see fig. 6). Further work indicated that the cross-wind components of the mean flow could be most simply represented by the total changes in vane heading. No direct parallel can be drawn between this method of evaluating the vane records and the method of evaluating the airplane records; nevertheless, the results obtained from the vane are an indication of the level of turbulence intensity for comparison with the airplane data.

On the basis of this study of the records, the lateral gust velocities were evaluated from the total changes in wind direction by the relation

$$u = \bar{v} \sin \Delta\alpha \tag{3}$$

where

u lateral gust velocity, ft/sec

$\bar{v}$ mean wind speed, ft/sec

$\Delta\alpha$ total change in wind direction, deg

The evaluation of the vane records by means of relation (3) was restricted to only the gusts that had wave lengths within the same range as the wave lengths represented by the gradient distances obtained from the airplane measurements. Figure 5 indicates that the gradient distances varied from about 10 to 130 feet for the test airplane. This range of distance accordingly specified the lengths of the gusts evaluated from the vane records. As a check on the wave lengths represented by the changes in wind direction, the time for each change in vane heading Δt was multiplied by the mean wind speed to obtain a gust length. It will be noted from figure 6 that the gust lengths obtained by this procedure represent one-half the wave length of the complete oscillation of the vane. The results of the calculations for gust lengths from the Aerovane records have been plotted in figure 5 for comparison with the gradient distances from the airplane data.

The gust data evaluated from the tower by means of relation (3) were treated in the same manner as the airplane data in that cumulative frequency distributions were obtained at each altitude of interest for each flight. The distribution for each altitude was then divided by the wind mileage past the tower at the pertinent elevation. As an example, the results obtained from the tower are compared with the corresponding airplane data for one flight and for the same elevation in figure 4. It was found impractical during the evaluation of tower data, for the time being at least, to correlate short individual portions of tower data with individual portions of the airplane runs.

In order to correlate the gust data obtained from the airplane and vane records, a convenient measure of the distributions for each flight was taken. Since the turbulence intensity varied from flight to flight, two points were taken from each distribution to show the correlation.

The gust velocity that was exceeded five and ten times per mile from each curve was arbitrarily selected as a measure of the intensity of the turbulence. These gust velocities for the vane are plotted against the gust velocities for the airplane in figure 7 for the two altitudes where most data were evaluated.

For two flights, the airplane and tower data were evaluated for all altitudes as indicated in table III to determine the variation of gustiness with altitude. The results from both flights were similar, and to show the variation, the results for one flight are plotted in figure 8.

DISCUSSION

Inspection of figure 5 indicates that the frequency distributions of wave lengths as evaluated for the airplane and vane were essentially the same. It appears from the figure that the airplane data have a slight tendency toward the longer wave lengths but the bias does not appear large. It will also be noted from figure 5 that, for the majority of the cases, the gust lengths evaluated for the vane were greater than 20 feet. This range of gust length is roughly equal to or greater than the wave length of about 42 feet for the damped natural frequency of the vane (table I). Although the vane would respond accurately for the longer gust lengths evaluated, some overshoot would be expected for the shorter values. As has been indicated, however, no correction was made in this initial work for the response of the vane in the reduction of the large amount of records obtained.

The comparison in figure 7 of the gust intensities measured by the airplane and the vane indicates good correlation, with both measurements reflecting the same levels of turbulence. For the gust velocities that were exceeded both five and ten times per mile, the data points in the figure lie along the 1-to-1 relation indicated by the straight lines and have a maximum scatter of about 30 percent. Although this close agreement in gust intensity was not necessarily expected, figure 7 indicates that the gust velocities obtained from both this airplane and the vane records are of about equal magnitudes for the present evaluation procedures.

The scatter in figure 7 is partially due to the small samples involved (about 15 miles, see table III) and possibly to minor deviations from isotropy. Characteristics of the gustiness in regard to isotropy were checked by comparing measurements from a horizontal and a vertical vane which was mounted at an elevation of 355 feet on the tower. The results indicated only small differences in the velocities and wave lengths of the gusts in either direction. It may also be noted from figure 7 that the correlation for the data at 150 feet is about the same as the data at 410 feet, thereby suggesting little deviation from isotropy.

The sample of the variation of gust velocity with altitude given in figure 8 indicates that the tower and airplane data are essentially in agreement throughout the altitude range of the tests. As has been indicated, the results for a second flight gave the same agreement between the airplane and vane measurements as shown in the figure. In general, a decrease in gust velocities with increasing altitude similar to that shown in figure 8 was noted from an inspection of the vane records for the balance of the flights.

Of interest in regard to spatial distributions of turbulence, brief studies of some of the airplane records indicated little or no variations with local terrain. These results indicated that for the present tests the turbulence was fairly homogeneous within the area of the tower. It might be expected, however, that local effects would cause some variations in the turbulence for unstable lapse rates and low wind velocities where mixing is not complete.

In view of the good correlation between the airplane and vane measurements of gust velocities in figure 7, it appears that within the restrictions of the present tests, vane measurements of turbulence can be interpreted in terms of airplane measurements. This result gives promise that information from flight and surface measurements of turbulence may be interchanged to extend the scope of data available to either the engineer or the meteorologist.

CONCLUDING REMARKS

A study of preliminary measurements of atmospheric turbulence taken by an airplane in the immediate vicinity of wind vanes mounted on a tower indicates that, when the two sets of gust data represent the same wave lengths, good correlation is obtained between the vertical gusts measured by an airplane and the horizontal gusts evaluated from the vane motions. Although further work on this subject is obviously needed, the present results give promise that airplane measurements of turbulence can be interpreted in terms of wind-vane measurements, and conversely, wind-vane measurements of turbulence can be interpreted to obtain what might be measured with an airplane.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., December 23, 1952.

REFERENCE

1. Donely, Philip: Summary of Information Relating to Gust Loads on Airplanes. NACA Rep. 997, 1950. (Supersedes NACA TN 1976.)

TABLE I.- SUMMARY OF AIRPLANE AND AEROVANE CHARACTERISTICS

PERTINENT TO GUST MEASUREMENTS

Airplane:	
Mean aerodynamic chord, ft	4.75
Slope of the lift curve, per radian	4.8
Wing area, sq ft	155
Average test weight, lb	2200
Average test airspeed, fps	135
Acceleration ratio (for 1 - cosine shaped gust and a gradient distance of 12.5 chords)	0.66
Aerovane:	
Percent critical damping	27
Wave length of damped natural frequency, ft	41.9
Damped natural frequency, cps	0.024 × wind velocity in feet per second

TABLE II.- SUMMARY OF WEATHER CONDITIONS

Date	Time e. s. t.	Visibility, miles	Clouds			Lapse rate, °C/1,000 ft	Average wind direction, deg, and velocity, fps, for tower elevation of -			
			Low	Middle	High		37 ft	150 ft	300 ft	410 ft
Apr. 17, 1950	1126 to 1225	8	0	2 Ac	6 Cs	-5.0	210-20.6	209-27.1	210-28.4	209-29.7
Apr. 21, 1950	1034 to 1122	7	E 6000 3 Sc	7 Ac As		-4.8	324-18.7	322-24.1	320-24.4	313-25.7
Apr. 28, 1950	1404 to 1449	3	E 1500 10 Sc			----	012-8.8	--------	012-8.6	--------
May 9, 1950	0915 to 1004	15	0	0	1 Cs	-4.0	351-6.3	336-5.8	355-6.2	348-6.6
May 11, 1950	1235 to 1321	15	0	1 Ac	0	-4.4	308-16.9	309-19.9	311-20.9	307-22.5
May 22, 1950	1157 to 1242	15	0	0	0	-5.3	137-20.8	140-23.0	137-24.7	137-25.9
May 22, 1950	1430 to 1512	15	0	0	3 Ci	-5.3	130-20.6	133-22.4	135-23.8	135-17.8
June 2, 1950	0835 to 0921	8	0	0	0	-2.3	284-13.1	282-14.9	282-15.4	277-16.9
June 5, 1950	1300 to 1347	15	E 4000 1 Sc	0	0	-2.6	200-16.3	200-18.9	201-20.2	197-22.0
June 6, 1950	0403 to 0452	8	0	0	0	12.8	Calm	233-11.8	245-21.2	257-21.3
June 7, 1950	1306 to 1354	8	E 6500 1 Cu	2 Ac	0	-3.9	200-15.1	199-17.8	199-17.8	198-19.7
June 7, 1950	1744 to 1830	10	0	4 Ac	6 Ci	1.1	204-10.6	206-15.8	210-21.2	208-27.5
June 8, 1950	1457 to 1543	7	6000 1 Cu	2 Ac	0	-1.7	206-17.7	206-22.9	206-24.4	209-27.5
June 12, 1950	1348 to 1446	15	0	0	0	-5.0	190-15.7	188-18.0	187-19.7	185-21.4
June 13, 1950	0844 to 0933	15	0	0	7 Ci	-4.5	216-15.9	215-19.9	216-21.3	213-22.6

TABLE III.- SUMMARY OF TEST RECORDS

Date	Time	Airplane						Aerovane							
		Number of traverses and miles flown at altitude of -						Average wind velocity and wind mileage past tower during tests at altitudes of -							
		150 ft		300 ft		410 ft		37 ft		150 ft		300 ft		410 ft	
		Traverses	Miles	Traverses	Miles	Traverses	Miles	$\bar{V}$, fps	Miles	$\bar{V}$, fps	Miles	$\bar{V}$, fps	Miles	$\bar{V}$, fps	Miles
Apr. 17	1126 to 1225	4	14.6	4	15.5	4	15.6	20.6	12.2	27.1	16.3	28.4	16.8	29.7	18.6
Apr. 21	1034 to 1122	4	16.0	4	15.6	4	15.5							25.7	15.2
Apr. 28	1404 to 1449	2	7.7	6	23.2	4	15.4							----	----
May 9	0915 to 1004	4	16.0	4	15.5	4	15.5							6.6	3.7
May 11	1235 to 1321	4	16.1	4	15.5	4	15.5							22.5	12.5
May 22	1157 to 1242	4	15.9	4	15.7	4	15.7							25.9	13.2
May 22	1430 to 1512	1	2.8	2	7.8	2	7.8			22.4	3.3			17.8	10.8
June 2	0835 to 0921	4	15.9	4	15.7	4	15.8			14.9	2.5			16.9	8.3
June 5	1300 to 1347	4	15.6	4	15.8	4	15.6							22.0	11.3
June 6	0403 to 0452	(a)	(a)	(a)	(a)	(a)	(a)							(a)	(a)
June 7	1306 to 1354	4	15.7	4	15.7	4	15.6			17.8	3.8			19.7	9.6
June 7	1744 to 1830	4	15.8	4	15.6	4	15.6			15.8	5.4			27.5	14.1
June 8	1457 to 1543	4	16.0	4	15.8	4	15.9							27.5	13.1
June 12	1348 to 1446	2	7.8	2	7.8	2	7.8	15.7	8.7	18.0	10.0	19.7	10.3	21.4	10.9
June 13	0844 to 0933	4	15.7	4	15.7	4	15.6			19.9	3.4			22.6	11.3

[a]Smooth flight, no gusts.

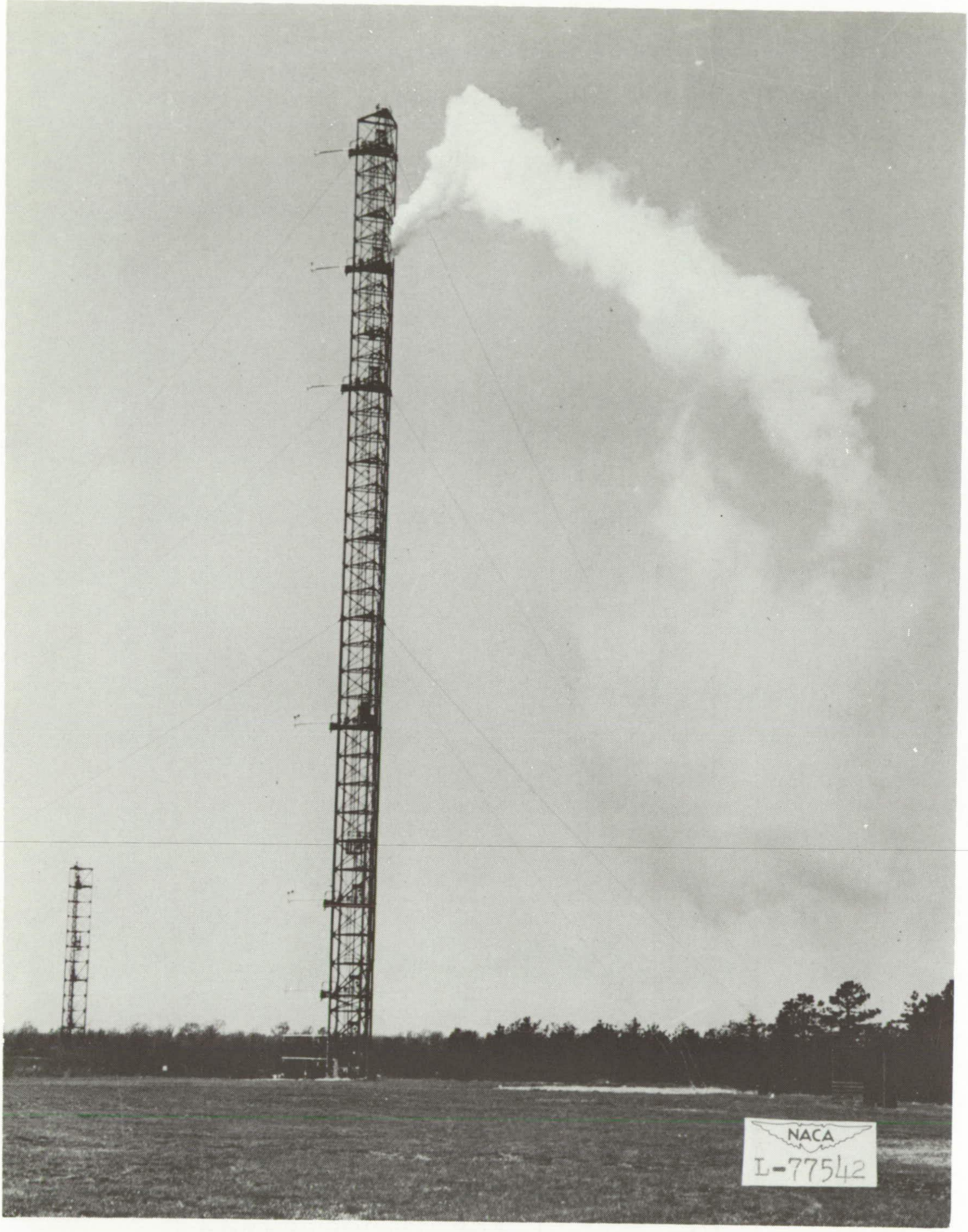


Figure 1.- Meteorological tower at Brookhaven National Laboratory.

Figure 2.- Typical Aerovane installation on tower at Brookhaven National Laboratory.

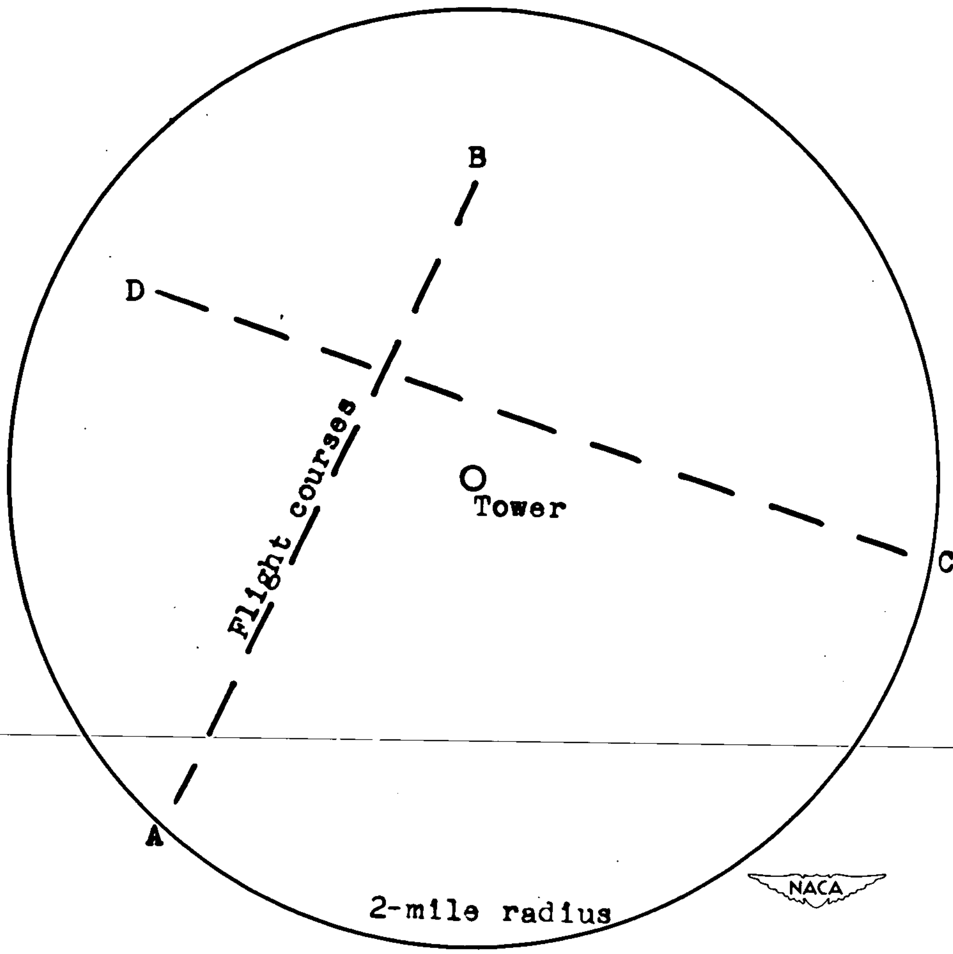


Figure 3.- Airplane flight courses relative to tower.

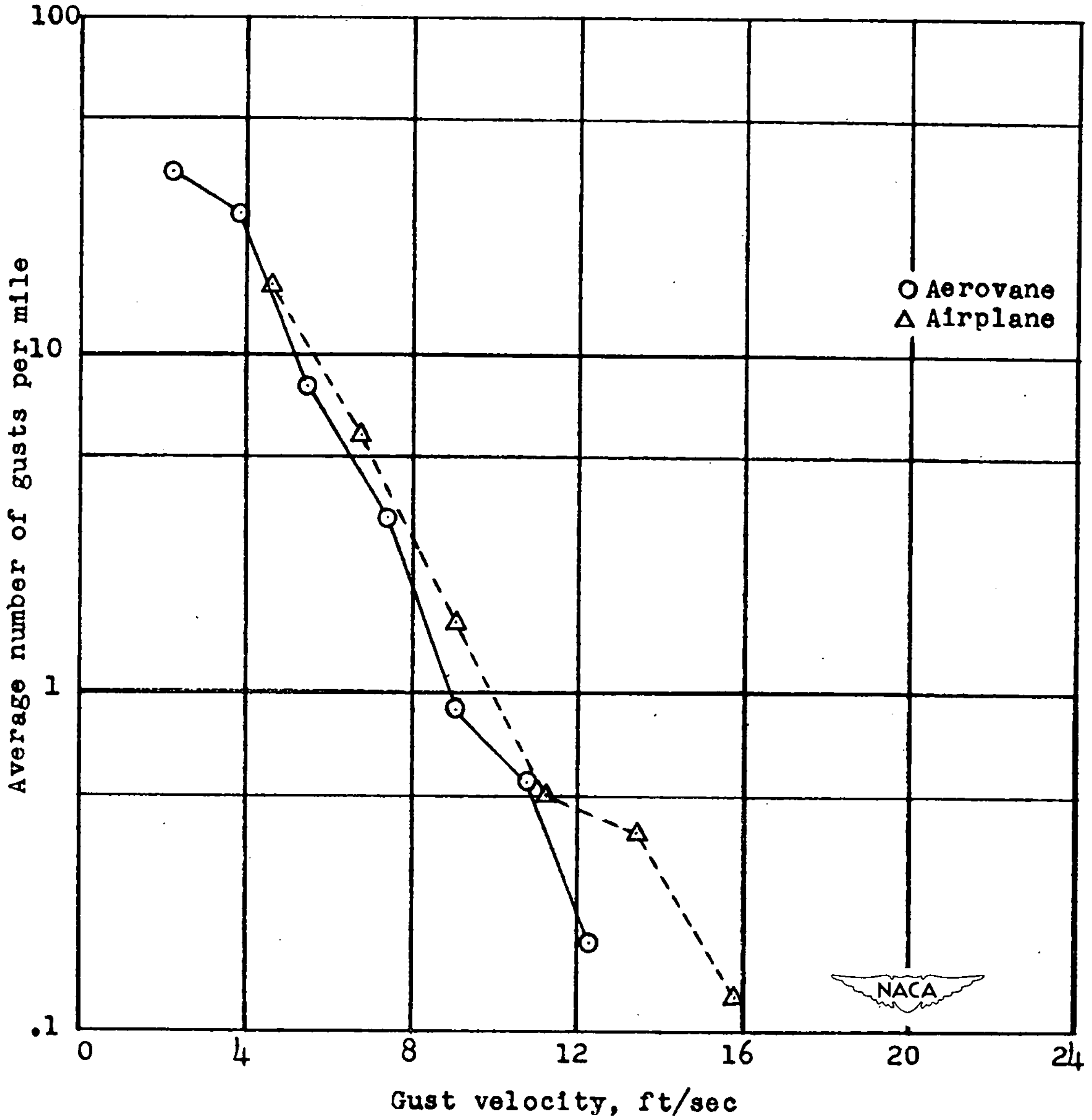


Figure 4.- Average number of gusts per mile which exceeded given gust velocities for one flight (410-foot elevation).

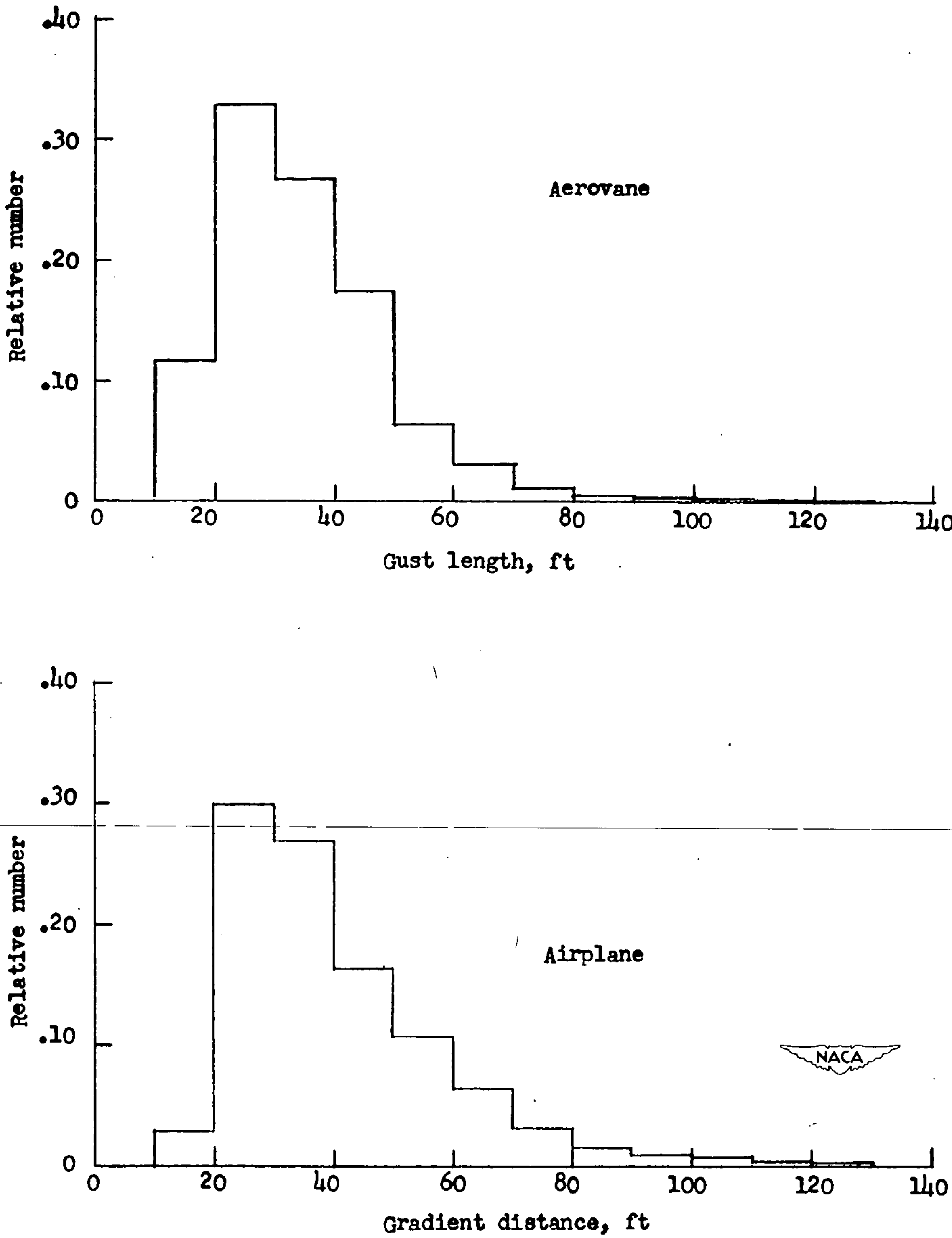


Figure 5.- Relative frequency distributions of gust length and gradient distance for Aerovane and airplane measurements.

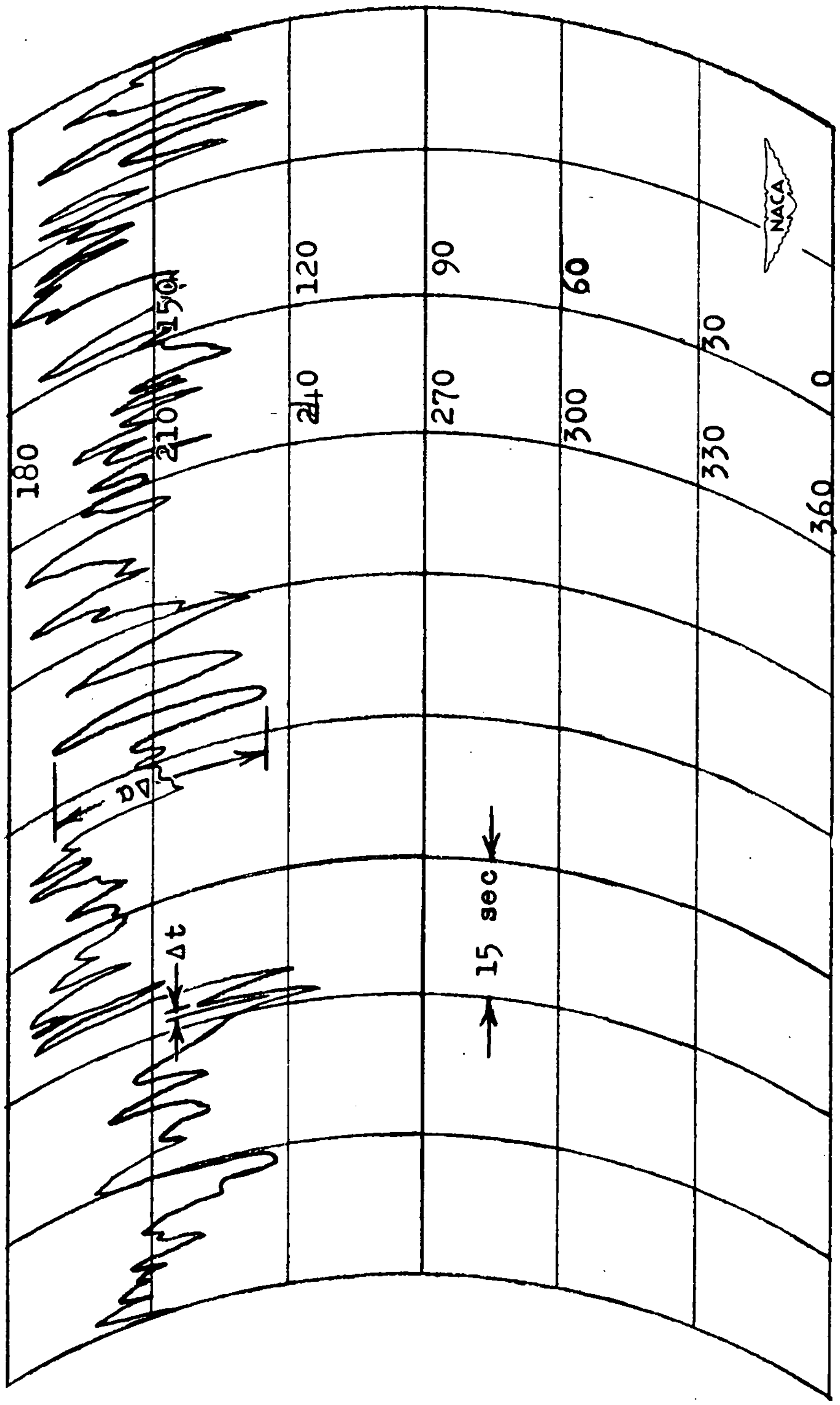
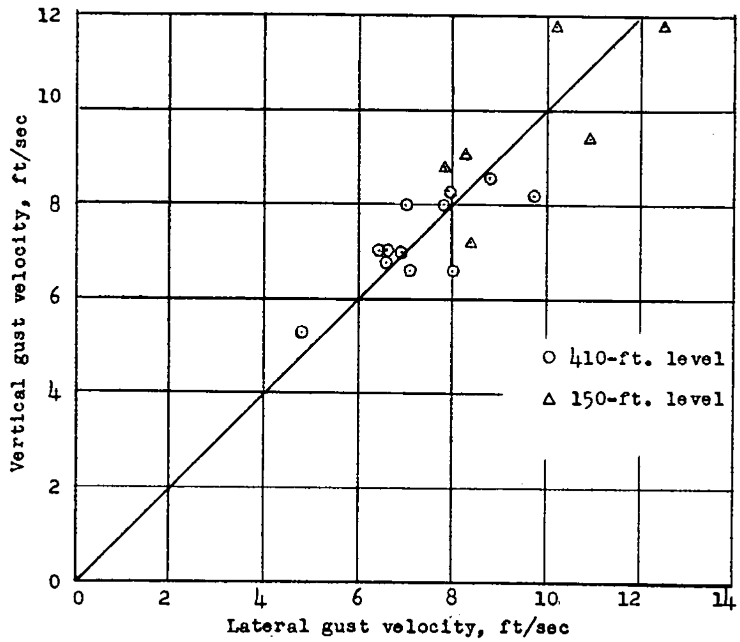
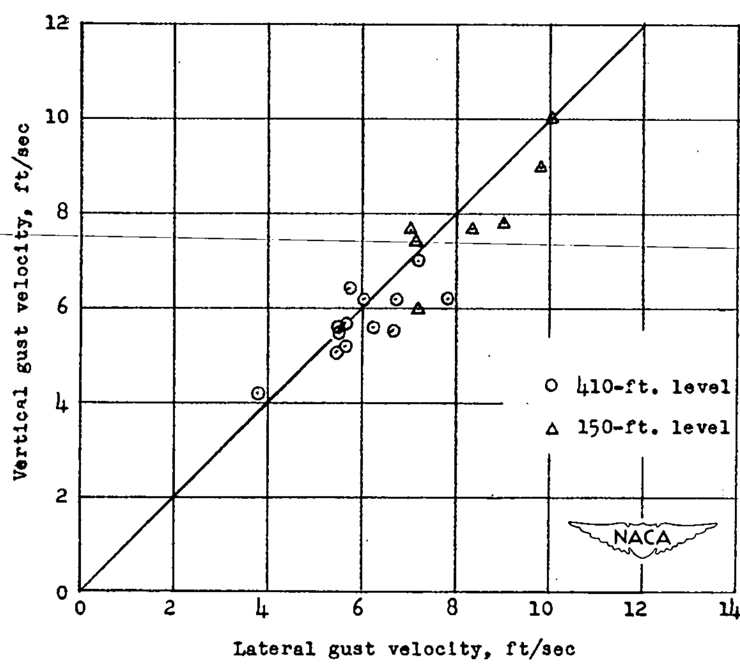


Figure 6.- Sample record of vane indications of wind direction. Average wind velocity, 10 miles per hour at 210°



(a) Gust velocity exceeded 5 times per mile.



(b) Gust velocity exceeded 10 times per mile.

Figure 7.- Comparison of the intensity of vertical and lateral gust velocities exceeded 5 and 10 times per mile for individual flights. Vertical velocities from airplane measurements; horizontal velocities from Aerovane measurements.

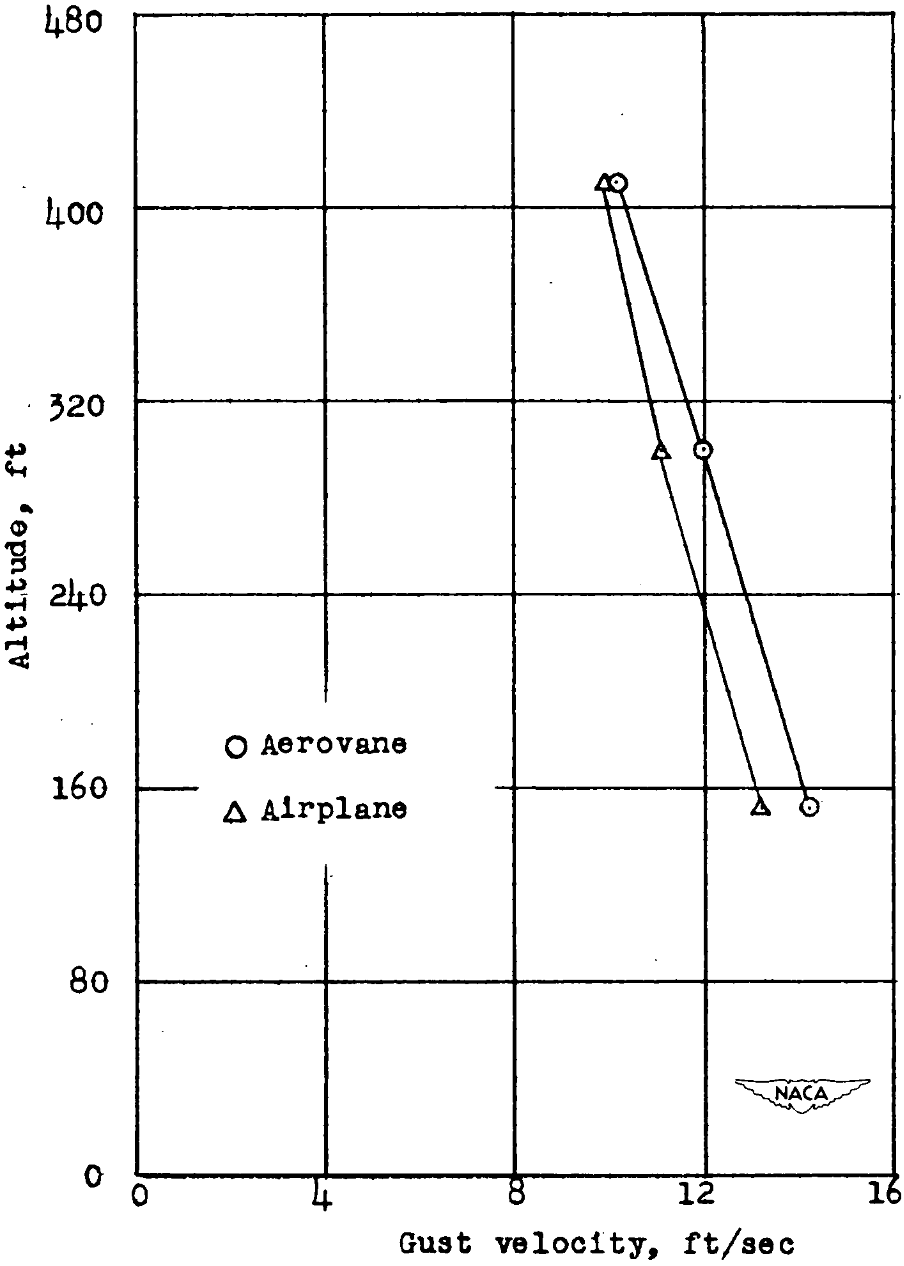


Figure 8.- Variation with altitude of the gust velocity exceeded once per mile for a typical flight.