Analysis of Low-Altitude Wind Speed and Direction Shears

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Horizontal wind profile measurements recorded at the NASA 150 Meter Ground Winds Tower Facility at the Kennedy Space Center, Fla., are analyzed to evaluate wind shears known to be hazardous to the ascent and descent of conventional aircraft and the Space Shuttle. Twenty 5 s intervals of high [10<18 m/s (19<35 knots)] and gale force [18<33 m/s (35<64 knots)] surface winds provided instantaneous recordings every 0.1 s per speed, direction, and tower level from 3-150 m (10-500 ft). Mathematical (maximum, mean, standard deviation) and graphical (percentage frequency distribution) descriptions of absolute, positive, and negative speed and direction shears with altitude (six vertical layers) and along flight path (one horizontal distance) are presented as functions of the intensity categories and significant values.

Introduction

THE essence of statements frequently found in the literature is the data currently available on low-altitude wind shears are insufficient to allow valid estimations of the probabilities of occurrence or the intensity of potentially hazardous shears to aircraft operations. Hence, current models do not show how significantly wind shears can influence an aircraft during takeoff and landing. The problem is that input shears are not representative of real values for flight simulation purposes.

The meteorological mechanisms that cause strong wind shear are gust fronts formed by severe thunderstorms, fast-moving frontal zones, and low-altitude temperature inversions.[1] Wind shear generates eddies between two wind currents of differing velocities. The differences may be in wind speed, wind direction, or in both.

In the atmospheric boundary layer under normal conditions, the major wind shear tendency is vertical. Prior to 1977, practically all the literature reported only magnitudes of vertical shear with values on the order of $0.13\text{-}0.16 s^{-1}$ [4-5m/s/30 m (8-10 knots/100 ft)] considered severe.[2] Order of magnitude analysis of the equations of motion for an aircraft illustrates that low values of horizontal shear, $0.02\ s^{-1}$ [0.6 m/s/30 m (1.2 knots/100 ft)], are much more hazardous than larger values of vertical shear.[2] But very little information relative to the strength of horizontal wind shear and how it influences an aircraft is available. With the exception of Refs. 3 and 4, few precise values of the frequency and intensity of vertical and horizontal direction shears have been published.

To augment an earlier study[5] of vertical and horizontal wind speed shears, this analysis presents frequency and intensity of absolute, positive and negative shears for both speed and direction. Data used were recorded during high [≥ 10 m/s (19 knots)] wind conditions at the NASA 150 Meter Ground Winds Tower Facility at Kennedy Space Center, Florida.

Analysis Scenario

Wind shear, a wind change producing an increase or decrease in the airspeed of an aircraft, may be associated with a wind speed gradient or a direction shift at any level in the atmosphere. The turbulent atmospheric boundary layer (surface layer) extends from the ground to a height of approximately 100 m (330 ft) and is characterized by constant fluxes of momentum, temperature, and humidity.[6] The main objective of this analysis is the determination of frequency and intensity of speed and direction shears from 3-150 m (10-500 ft) during strong surface winds.

Facility Description

The NASA 150 Meter Ground Winds Tower Facility is a unique source of high resolution wind and temperature profile measurements (Fig. 1). Site characteristics and basic functional operations of the facility, located midway between pad B and the Space Shuttle runway at launch complex 39 (Fig. 2), are described by Kaufman and Keene.[7] A Kennedy Space Center report[8] details the calibration procedures, response characteristics, electronic circuitry, etc., for the facility. Traver et al.[9] summarize the design concepts and operational functions of the automatic data acquisition system (ADAS).

Data Set

In the wind profile data mode, the ADAS provides time-coincident measurements each 0.1 s and digitally records as instantaneous readings on magnetic tape. The data for this analysis consists of 20 intervals of 5 s each during high surface winds on July 3, 1973, between 1930 and 2200 GMT. This analysis adheres to the World Meteorological Organization recommended practices for aviation climatology that wind-averaging periods not exceed 10 min and that gust-averaging periods be at least 5 s.[10] Specifically, the 20 intervals (one 5 s interval every 100 during 4 approximately 10 min periods) are listed in Table 1. Table 2 presents a mathematical description (maximum, mean, standard deviation) of the wind velocity observations at eight tower levels used in the shear determinations. Descriptions of speed and direction shears for four 30 m (100 ft) layers below 150 m (500 ft) and two approximately 15 m (50 ft) layers and one distance below 30 m are presented in Tables 3 and 4.

Definitions

Vertical shearing of the horizontal wind (the change of wind speed with height) was determined by means of two anemometers mounted at different heights on a single tower.

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Vertical shear magnitudes were derived by algebraically subtracting the wind speed at the lower height from the upper and dividing by the distance between heights,

$$WS_U - WS_L/d_{(U-L)} = \Delta WS/\Delta d \tag{1}$$

Horizontal shearing of the horizontal wind (the change of wind sheer with horizontal distance) was determined by two anemometers mounted at the same height on different towers. Horizontal shear magnitudes for one distance [18 m (60 ft)] between the tall and short towers at the 18 m height were derived by algebraically subtracting the wind speed at the short tower from the speed at the tall and dividing by the distance between towers,

$$WS_T = WS_S/d_{(T-S)} = \Delta WS/18 \tag{2}$$

Similarly, vertical and horizontal wind direction shearing of the horizontal wind was determined by

$$WD_U - WD_L/d_{(U-L)} = \Delta WD/\Delta d \tag{3}$$

and

$$WD_T - WD_S/d_{(T-S)} = \Delta WD/18 \tag{4}$$

Normally, wind speed increases with increasing altitude throughout the troposphere. Shear produced by this increase in speed with altitude throughout a layer is defined in this analysis as positive speed shear. But, wind speed sometimes decreases with height through a layer. Shear produced by a decrease in speed with altitude is defined as negative shear. In this analysis, positive and negative direction shears are similarly defined. The absolute value of a wind velocity shear is its numerical value with the positive or negative sign ignored. No shear (zero) exists without an increase or decrease through a vertical layer or across a horizontal distance.

Intensity Categories

In order to relate wind speed shear determinations to some scale of intensity, a summary of criteria given by Brown[11] from Badner[12] is presented in Table 5 for categories of severity of speed shear intensity in metric and customary units. The increment of height or distance is included to preserve the dimensions of a shear and to more easily relate to the other measures of wind shear of significance to aviation.

Very little information is in the literature relative to the expected intensity of wind direction shear. Hence, this analysis categorized in Table 6 severity of direction shears in order to relate the determinations to some scale of intensity.

Significant Values

For vertical wind speed shear Greene et al.,[13] designated the value 0.084 s^{-1} [2.5 m/s/30 m (5.0 knots/100 ft)] to be significant for aircraft operations. Snyder[14] showed 0.1 s^{-1} [3 m/s/30 m (6 knots/100 ft)] in the lowest 100 m (330 ft) to be dangerous, and Frost[2] reported values from the literature of 0.13-0.16 s^{-1} [4-5 m/s/30 m (8-10 knots/100 ft)] were considered serious. Greene's value, 0.084 s^{-1}, occurs in the lower

Table 1 Time intervals of surface winds

GMT, h min: s		
1931:16.0 – 20.9	1943:21.0 – 25.9	2143:47.0 – 51.9
1933:16.0 – 20.9	1945:01.0 – 05.9	2145:27.0 – 31.9
1934:56.0 – 00.9	1946:41.0 – 45.9	2147:07.0 – 11.9
1936:36.0 – 40.9	1948:21.0 – 25.9	2148:47.0 – 51.9
1938:16.0 – 20.9	1950:01.0 – 05.9	2150:32.0 – 36.9
1939:56.0 – 00.9	2000:06.0 – 10.9	2152:12.0 – 16.9
1941:41.0 – 45.9	2001:51.0 – 55.9	

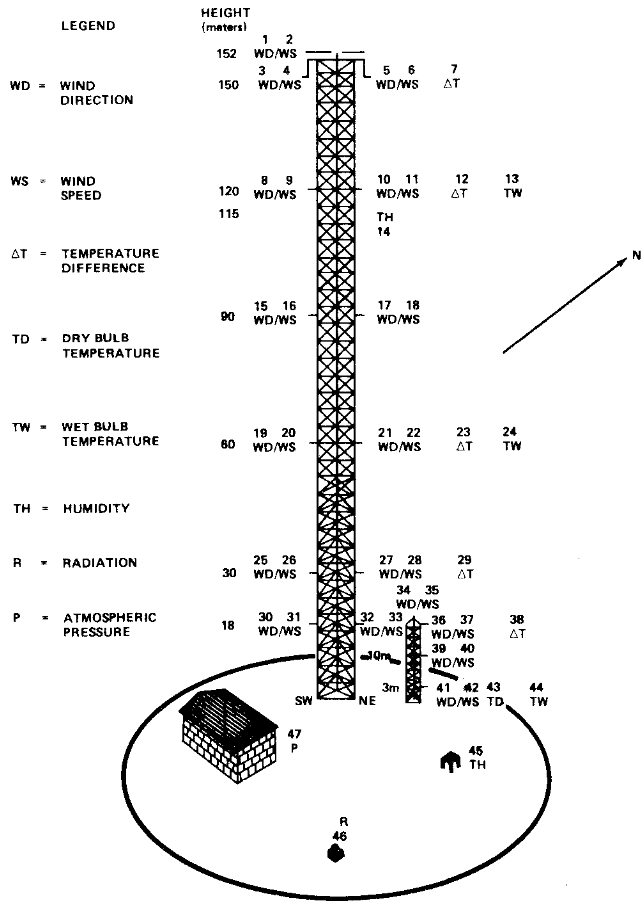

Fig. 1 NASA's 150-Meter Ground Winds Tower Facility at Kennedy Space Center, Fla.

Table 2 Mathematical description of surface winds

Height m	Height ft	Speed, m/s (knots) Max		Mean		Std. dev.		Direction, deg Max	Mean	Std. dev.
150	500	27.4	53.3	16.63	32.33	0.567	1.102	238	145	2.040
120	400	26.4	51.3	16.16	31.42	0.543	1.056	228	141	2.206
90	300	26.0	50.5	15.20	29.55	0.549	1.067	250	161	2.687
60	200	24.6	47.8	13.96	27.14	0.791	1.538	221	093	3.387
30	100	21.5	41.8	11.37	22.10	1.197	2.327	265	099	6.503
18T[a]	60	20.7	40.2	10.26	19.95	1.257	2.444	259	150	7.307
18S[a]	60	17.6	34.2	10.28	19.98	1.052	2.045	264	152	7.160
3	10	13.5	26.2	6.96	13.53	1.079	2.098	250	132	10.229

[a] 18T and 18S denote the 18 m (60 ft) levels on the tall and short towers, respectively.

Table 3 Mathematical description of wind speed shears

Layer/distance		Absolute						Positive						Negative					
		Max		Mean		Std. dev.		Max		Mean		Std dev.		Max		Mean		Std. dev.	
m	ft	s^{-1}	knots ft^{-1}	s^{-1}	knots ft^{-1}	s^{-1}	knots ft^{-1}	s^{-1}	knots ft^{-1}	s^{-1}	knots ft^{-1}	s^{-1}	knots ft^{-1}	s^{-1}	knots ft^{-1}	s^{-1}	knots ft^{-1}	s^{-1}	knots ft^{-1}
150-120	500-400	0.160	0.093	0.030	0.017	0.018	0.010	0.160	0.093	0.031	0.018	0.017	0.010	0.103	0.060	0.019	0.011	0.010	0.006
120-90	400-300	0.173	0.101	0.040	0.023	0.022	0.013	0.173	0.101	0.042	0.024	0.021	0.012	0.123	0.072	0.016	0.009	0.011	0.006
90-60	300-200	0.327	0.191	0.051	0.030	0.026	0.015	0.327	0.191	0.052	0.030	0.024	0.014	0.117	0.068	0.019	0.011	0.013	0.008
60-30	200-100	0.387	0.226	0.096	0.056	0.040	0.023	0.387	0.226	0.098	0.057	0.038	0.022	0.200	0.117	0.025	0.015	0.015	0.009
30-18T	100-60T	0.792	0.462	0.138	0.080	0.091	0.053	0.792	0.462	0.149	0.087	0.090	0.052	0.408	0.238	0.068	0.040	0.042	0.024
18S-3	60S-10	0.713	0.416	0.227	0.132	0.089	0.052	0.713	0.416	0.235	0.137	0.087	0.051	0.087	0.051	0.037	0.022	0.019	0.011
18T-18S	60T-60S	0.678	0.395	0.132	0.077	0.070	0.041	0.678	0.394	0.099	0.058	0.048	0.028	0.422	0.246	0.105	0.067	0.050	0.029

Table 4 Mathematical description of wind direction shears

Layer/distance		Absolute						Positive						Negative					
		Max		Mean		Std. dev.		Max		Mean		Std dev.		Max		Mean		Std. dev.	
m	ft	deg/m	ft	m	ft	m	ft	deg/m	ft	m	ft	m	ft	deg/m	ft	m	ft	m	ft
150-120	500-400	0.633	0.190	0.166	0.050	0.089	0.027	0.633	0.190	0.174	0.052	0.094	0.028	0.533	0.160	0.121	0.036	0.034	0.010
120-90	400-300	1.200	0.360	0.677	0.203	0.139	0.042	0.800	0.240	0.800	0.240	0.000	0.000	1.200	0.360	0.672	0.202	0.115	0.035
90-60	300-200	3.167	0.950	2.262	0.679	0.141	0.042	3.167	0.950	2.262	0.679	0.141	0.042	0.533	0.160	0.533	0.160	0.000	0.000
60-30	200-100	1.933	0.580	0.457	0.137	0.218	0.065	1.200	0.360	0.237	0.071	0.131	0.039	1.933	0.580	0.419	0.126	0.169	0.051
30-18T	100-60T	9.583	2.875	4.903	1.471	0.731	0.219	4.000	1.200	1.453	0.436	0.748	0.224	9.583	2.875	4.724	1.417	0.626	0.188
18S-3	60S-10	5.733	1.720	1.445	0.434	0.754	0.226	5.733	1.720	1.495	0.449	0.753	0.226	2.400	0.720	0.523	0.157	0.329	0.099
18T-18S	60T-60S	3.111	0.933	0.571	0.171	0.373	0.112	3.111	0.933	0.506	0.152	0.352	0.106	2.611	0.783	0.566	0.170	0.328	0.098

Table 5 Wind speed shear intensity categories

	Metric			U. S. Customary		
Category	ms^{-1}/m	$ms^{-1}/15$ m	$ms^{-1}/30$ m	knots/ft	knots/50 ft	knots/100 ft
Light	0.000 < 0.067	0.0 < 1.0	0.0 < 2.0	0.000 < 0.040	0.0 < 2.0	0.0 < 4.0
Moderate	0.067 < 0.133	1.0 < 2.0	2.0 < 4.0	0.040 < 0.080	2.0 < 4.0	4.0 < 8.0
Strong	0.133 < 0.200	2.0 < 3.0	4.0 < 6.0	0.080 < 0.120	4.0 < 6.0	8.0 < 12.0
Severe	≥ 0.200	≥ 3.0	≥ 6.0	≥ 0.120	≥ 6.0	≥ 12.0

Table 6 Wind direction shear intensity categories

	Metric			U. S. Customary		
Category	deg/m	deg/15 m	deg/30 m	deg/ft	deg/50 ft	deg/100 ft
Light	0.000 < 0.533	0.0 < 8.0	0.0 < 16.0	0.000 < 0.160	0.0 < 8.0	0.0 < 16.0
Moderate	0.533 < 1.067	8.0 < 16.0	16.0 < 32.0	0.160 < 0.320	8.0 < 16.0	16.0 < 32.0
Strong	1.067 < 1.600	16.0 < 24.0	32.0 < 48.0	0.320 < 0.480	16.0 < 24.0	32.0 < 48.0
Severe	≥ 1.600	≥ 24.0	≥ 48.0	≥ 0.480	≥ 24.0	≥ 48.0

part of the moderate intensity category (Table 5), Snyder's, 0.1 s^{-1}, in the upper part of that category, and Frost's, 0.13-0.16 s^{-1}, in the lower half of the strong category.

Order of magnitude analyses by Frost[2] of the equations of motion for an aircraft illustrate that low values of horizontal (along the flight path) wind speed shear, 0.02 s^{-1} [0.36 m/s/18 m (1 knot/60 ft)] are much more hazardous than larger values of vertical shear. This value, 0.02 s^{-1}, occurs in the lower third of the light category.

For wind direction shear, Alexander and Camp[3] designated changes of 30 deg to be significant. This shear, 1.0 deg m^{-1}, [30 deg/30 m (30 deg/100 ft)] is almost the upper limit of the moderate intensity category (Table 6). Kalafus[15] considered large changes (>40 deg in wind direction hazardous to aircraft. This shear value, 1.3 deg m^{-1} [40 deg/30 m (40 deg/100 ft)], occurs midway in the strong category.

To generalize prior works and this analysis, a single value was designated as significant for wind speed shear, 0.1 s^{-1} or 0.06 knot ft^{-1} [3 m/s/30 m (6 knots/100 ft)], and for direction shear, 1.0 deg m^{-1} or 0.3 deg ft^{-1} [30 deg/30 m (30 deg/100 ft)]. These significant values and the intensity categories are highlighted in the frequency distributions discussed in the next section.

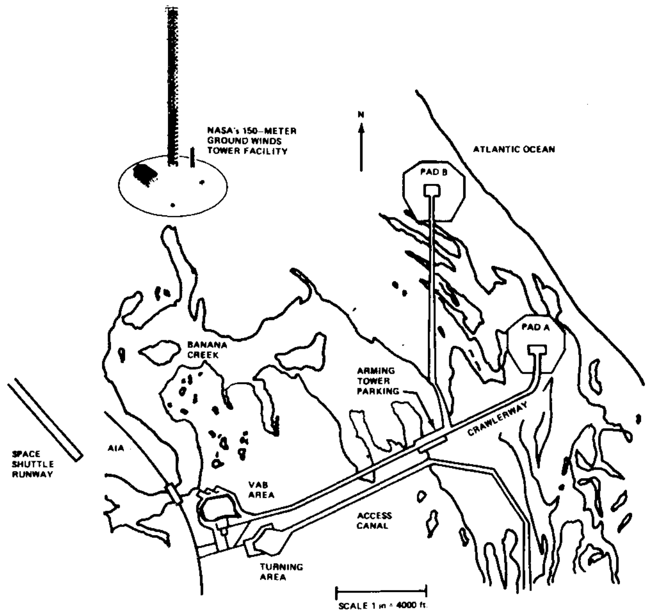

Fig. 2 NASA's 150-Meter Ground Winds Tower Facility at launch complex 39, Kennedy Space Center, Fla.

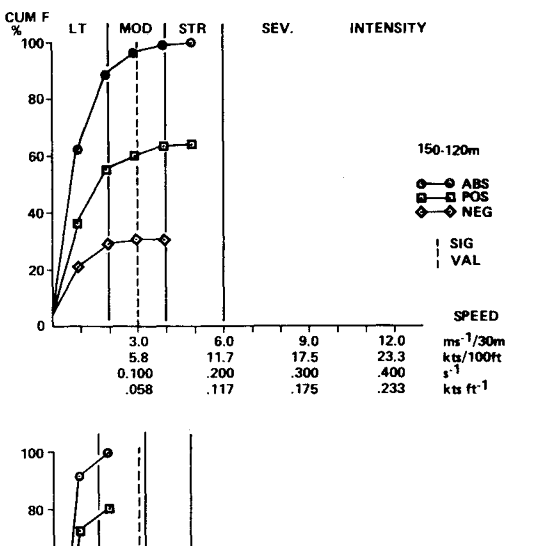

Fig. 3 Vertical wind speed and direction shears at the 150-120 m (500-400 ft) layer.

Analytical Results

To help characterize wind shear, the short-lived dynamic meteorological hazard to conventional aircraft and the Space Shuttle, mathematical (maximum, mean, standard deviation) and graphical (percentage frequency distribution) descriptions of vertical and horizontal, absolute and signed, speed and direction shears were determined for periods of strong surface winds.

Tables 7 and 8 present percentage of occurrence of speed and direction shear intensity categories by vertical layers and horizontal distance and by absolute, zero, positive and negative sign. Tables 9 and 10 present the percentage of occurrence of the significant values. Figures 3-9 present cumulative percentage frequencies of absolute, positive and negative speed and direction shears as functions of vertical layers and horizontal distance, intensity category, and significant value.

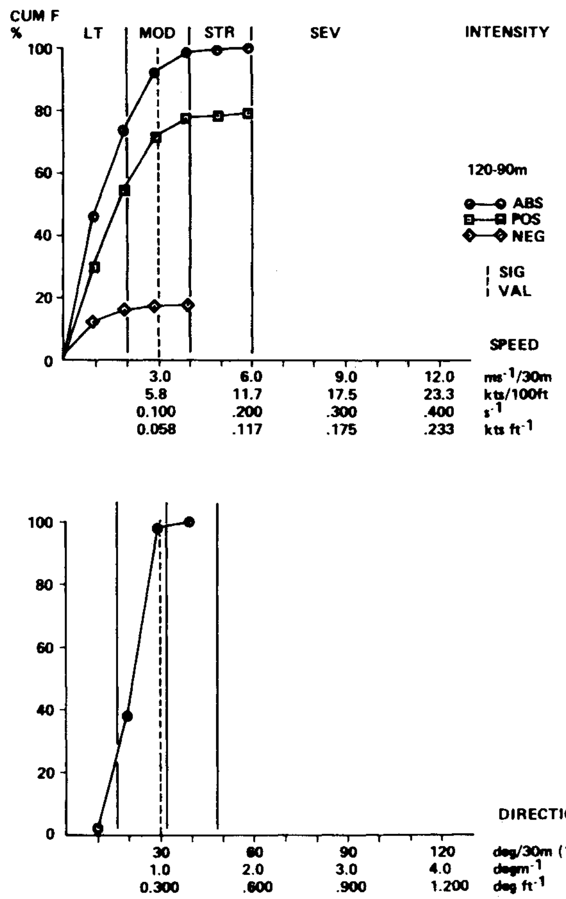

Fig. 4 Vertical wind speed and direction shears at the 120-90 m (400-300 ft) layer.

Table 7 Wind speed shear intensity percentages

Layer/distance		Light 0.000<0.067 m s^{-1}/m 0.000<0.040 knots/ft				Moderate 0.067<0.133 0.040<0.080			Strong 0.133<0.200 0.080<0.120			Severe ≥0.200 m s^{-1}/m ≥0.120 knots/ft		
m	ft	Abs	Pos	Zero	Neg	Abs	Pos	Neg	Abs	Pos	Neg	Abs	Pos	Neg
150-120	500-400	89.00	55.10	4.80	29.10	10.50	8.70	1.80	0.50	0.50	0	0	0	0
120-90	400-300	73.80	54.20	3.40	16.20	25.00	23.60	1.40	1.20	1.20	0	0	0	0
90-60	300-200	71.30	50.80	3.10	17.40	21.10	19.90	1.30	5.90	5.90	0	1.60	1.60	0
60-30	200-100	42.50	26.70	1.50	14.30	27.80	27.20	0.60	20.70	20.20	0.50	9.00	8.90	0.10
30-18T	100-60T	36.00	20.00	4.00	12.00	24.00	17.00	7.00	16.00	12.00	4.00	24.00	20.00	4.00
18T-18S	60T-60S	35.00	20.00	1.50	13.50	27.00	15.00	12.00	19.00	10.00	9.00	19.00	12.00	7.00
18S-3	60S-10	15.00	9.00	1.30	4.70	14.00	13.00	1.00	11.00	11.00	0	60.00	60.00	0

Table 8 Wind direction shear intensity percentages

Layer/distance		Light 0.000<0.533 deg/m 0.000<0.160 deg/ft				Moderate 0.533<1.067 0.160<0.320			Strong 1.067<1.600 0.320<0.480			Severe ≥1.600 deg/m ≥0.480 deg/ft		
m	ft	Abs	Pos	Zero	Neg	Abs	Pos	Neg	Abs	Pos	Neg	Abs	Pos	Neg
150-120	500-400	97.00	77.50	2.30	17.20	3.00	2.50	0.50	0	0	0	0	0	0
120-90	400-300	26.50	26.50	0	0	72.00	72.00	0	1.50	1.50	0	0	0	0
90-60	300-200	1.00	1.00	0	0	14.00	14.00	0	14.50	14.50	0	70.50	70.50	0
60-30	200-100	61.20	33.00	1.20	27.00	25.50	7.50	18.00	11.30	0.30	11.00	2.00	0	2.00
30-18T	100-60T	6.00	3.00	0.30	2.70	6.00	5.00	1.00	7.00	6.50	0.50	81.00	11.00	70.00
18T-18S	60T-60S	61.00	25.00	1.30	34.70	29.00	12.00	17.00	8.00	1.50	6.50	2.00	1.50	0.50
18S-3	60S-10	18.00	14.00	0.20	3.80	21.00	18.00	3.00	21.00	20.00	1.00	40.00	39.00	1.00

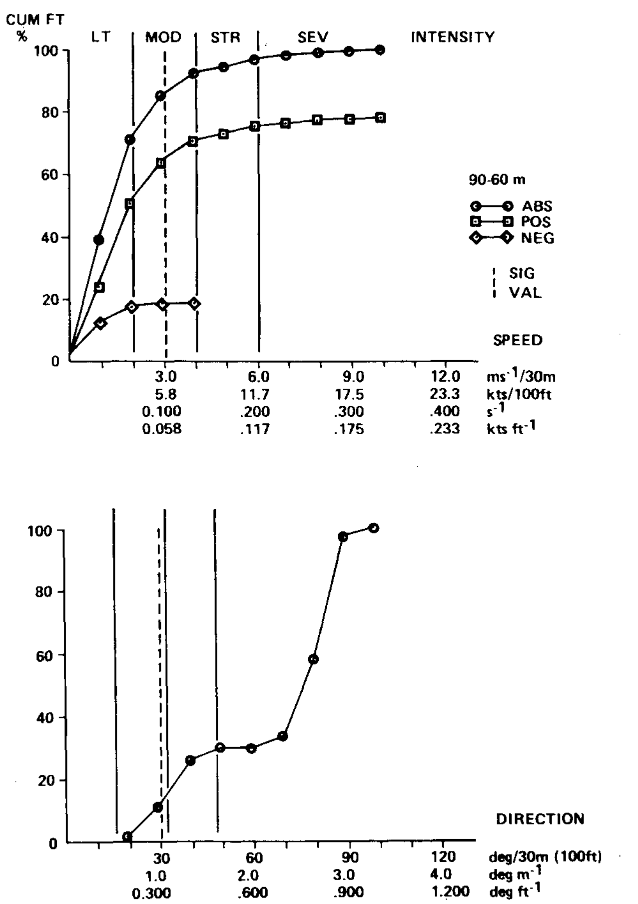

Fig. 5 Vertical wind speed and direction shears at the 90-60 m (300-200 ft) layer.

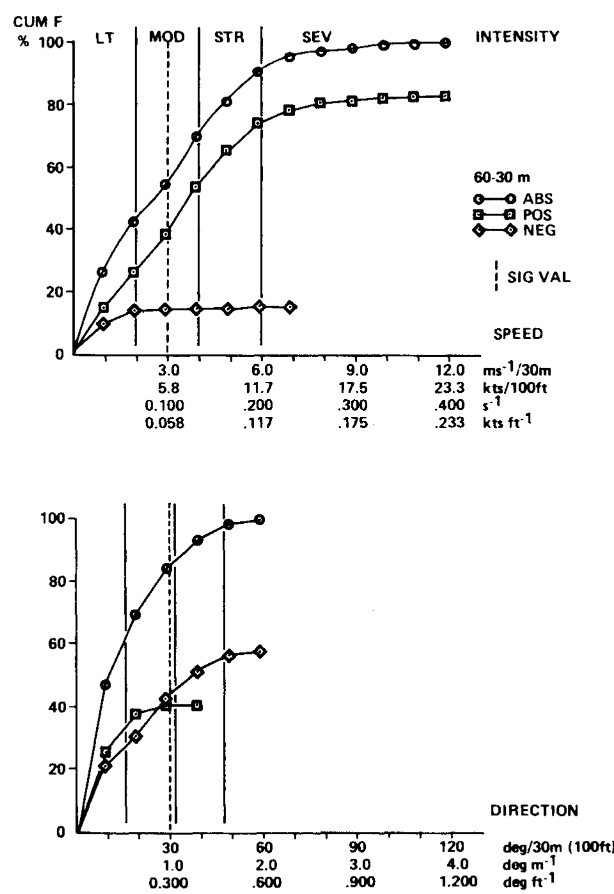

Fig. 6 Vertical wind speed and direction shears at the 60-30 m (200-100 ft) layer.

Table 9 Wind speed shear significant value percentages

Layer/distance		3 ms^{-1}/30 m, 6 knots/100 ft						
		0.1 s^{-1} ≤0.06 knots ft^{-1}				0.1 s^{-1} >0.06 knots ft^{-1}		
m	ft	Abs	Pos	Zero	Neg	Abs	Pos	Neg
150-120	500-400	96.10	60.60	4.80	30.70	3.90	3.70	0.20
120-90	400-300	92.40	71.60	3.40	17.40	7.60	7.40	0.20
90-60	300-200	85.50	63.90	3.10	18.50	14.50	14.30	0.20
60-30	200-100	54.60	38.60	1.50	14.50	45.40	44.40	1.00
30-18T	100-60T	50.00	28.00	4.00	17.00	51.00	41.50	9.50
18T-18S	60T-60S	49.50	28.00	1.50	20.00	50.50	29.00	21.50
18S-3	60S-10	21.30	15.00	1.30	5.00	78.70	77.50	1.20

Table 10 Wind direction shear significant value percentages

Layer/distance		30 deg/30 m, 30 deg/100 ft						
		≤1.0 deg m^{-1} 0.3 deg ft^{-1}				≤1.0 deg m^{-1} 0.3 deg ft^{-1}		
m	ft	Abs	Pos	Zero	Neg	Abs	Pos	Neg
150-120	500-400	100.00	-	2.30	-	0	-	-
120-90	400-300	98.00	0.10	0	97.90	2.00	2.00	0
90-60	300-200	11.10	11.00	0	0.10	88.90	88.90	0
60-30	200-100	84.70	40.70	1.20	42.80	15.30	0.10	15.20
30-18T	100-60T	11.30	8.00	0.30	3.00	88.70	17.70	71.00
18T-18S	60T-60S	85.30	35.00	1.30	49.00	14.70	5.00	9.70
18S-3	60S-10	36.20	30.00	0.20	6.00	63.80	61.50	2.30

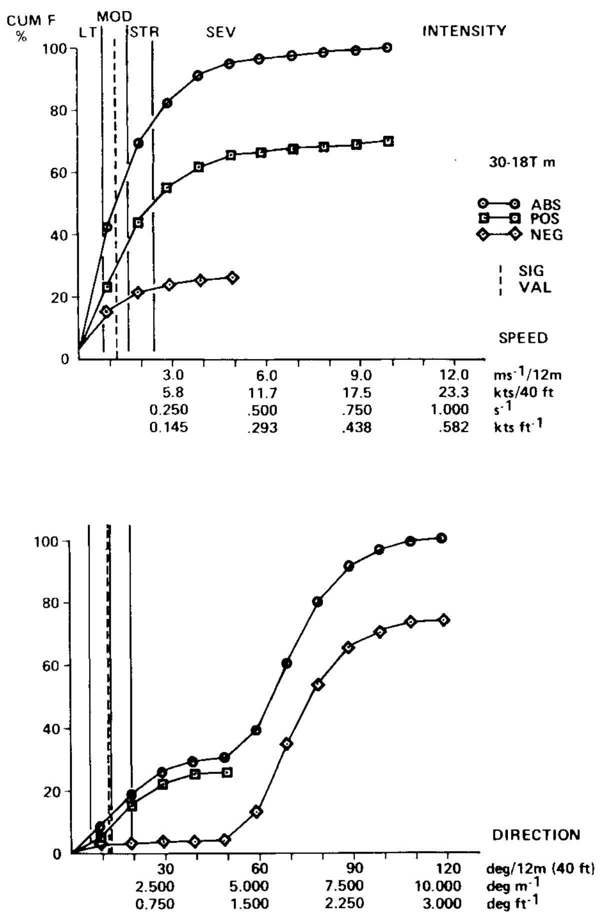

Fig. 7 Vertical wind speed and direction shears at the 30-18T m (100-60 ft) layer.

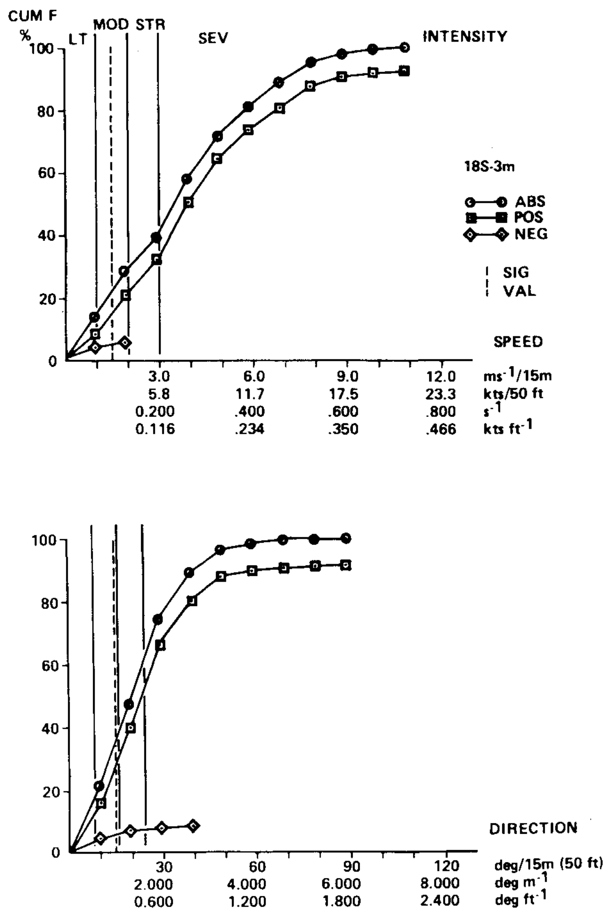

Fig. 8 Vertical wind speed and direction shears at the 18S-3 m (60-10 ft) layer.

Table 11 Low-altitude wind shear determinations

Layer/distance m	Layer/distance ft	Intensity Light	Intensity Moderate	Intensity Strong	Intensity Severe	Significant value >0.1 s^{-1} (0.06 knot ft^{-1}
		1) Vertical wind speed shear percentage (Table 5)				
150-120	500-400	89	10	1	0	4
120-90	400-300	74	25	1	0	8
90-60	300-200	71	21	6	2	15
60-30	200-100	42	28	21	9	45
30-18T[a]	100-60T	36	24	16	24	48
18S-3	60S-10	15	14	11	60	78
		2) Horizontal wind speed shear percentage (Table 5)				
18T-18S[a]	60T-60S	35	27	19	19	53
		3) Vertical wind direction shear percentage (Table 6)				
						>1.0 deg m^{-1} (0.3 deg ft^{-1})
150-120	500-400	97	3	0	0	0
120-90	400-300	26	72	2	0	2
90-60	300-200	1	14	15	70	89
60-30	200-100	61	26	11	2	15
30-18T[a]	100-60T	6	6	7	81	89
18S-3	60S-10	18	21	21	40	64
		4) Horizontal wind direction shear percentage (Tabel 6)				
18T-18S[a]	60T-60S	61	29	8	2	13

[a] 18T and 18S denote the 18 m (60 ft) level on the tall and short towers, respectively.

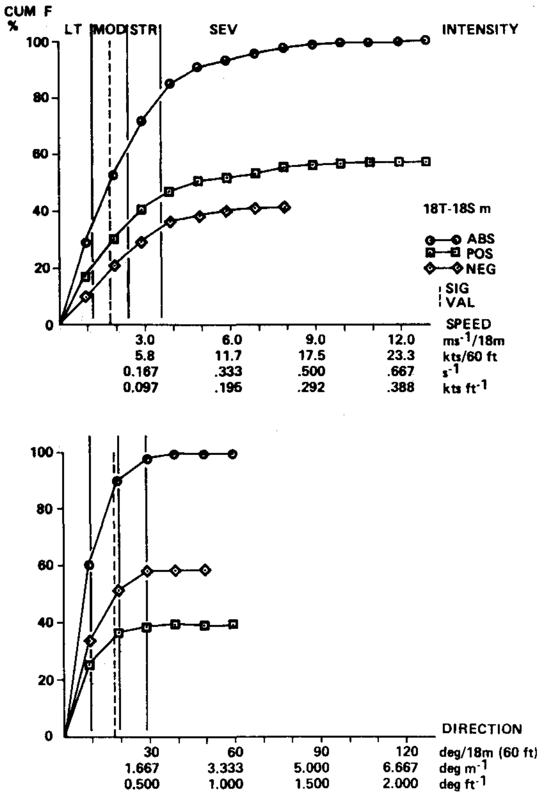

Fig. 9 Horizontal wind speed and direction shears at the 18T-18S m (60T-60S ft) distance.

Conclusions

Because low wind speeds and subsequent light shears present fewer problems in terminal areas, interest is naturally greatest in high winds and strong shears. This analysis presents temporal and spatial, vertical and horizontal, speed and direction wind shear information during strong surface winds near a runway. Based on shear definitions, intensity categories and significant values discussed in previous sections, percentages for low-altitude wind shear determinations from tower measurements of wind velocity at launch complex 39, Kennedy Space Center, Fla., are shown in Table 11.

This study substantiates the belief that for aircraft takeoff and landing operations, the need for wind shear information is most important over the lowest 100 m (330 ft) of the atmospheric boundary layer. It is also realized that magnitude and frequency of shear determinations would be of greater value for probability estimations, model development, and flight simulation if the duration of wind shears and the effect of wind speed and direction changes with position along the flight path were included. Hence, the duration of shears determined in this data set and the effect of wind change with position along the flight path will be addressed in another analysis.

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