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Analysis and Specification of Slant Wind Shear

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8 November 1982

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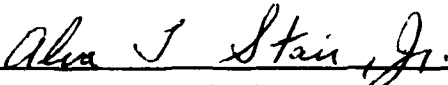
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20. Abstract (Continued)

(in this study, 60 m) and the surface separated by a horizontal distance equivalent to that which an aircraft would traverse in descending or ascending that height.

Additional study was also completed on the specification of slant wind shear along the runway through the use of an offset towersurface site system. It was found that offset towers (30 m high) located 500 m from the runway have a 75 to 77 percent Probability of Detection (POD) of differentiating between light, moderate, or greater wind shear with only a 17 to 19 percent False Alarm Rate (FAR). Fifteen-meter high offset towers located the same distance from the runway have a POD of 77 to 80 percent but a higher FAR of 25 percent. Use of a modified Critical Success Indicator (CSI), which tolerates a higher rate of false alarms in the interest of minimized failures of detection, resulted in complete equivalence between the 15 m and the 30 m tower systems. Surface wind systems alone were essentially incapable of detecting SWS events in this data base and had PODs as low as 4 percent with CSI values ranging from 5 to 0.

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Preface

The efforts of Mrs. Joan Ward and Mr. James H. Willand, Systems and Applied Sciences Corporation, in the formulation of the data editing, processing and specification programs are most gratefully acknowledged. Many other individuals aided in this program; in particular, Mr. Leo Jacobs and Mr. Ralph Hoar of AFGL and Mr. Clyde Lawrance, SASC, made a significant contribution in the maintenance, calibration, and operation of the sensors at the Otis WTF. In addition, the author is most grateful to Mr. Donald Chisholm and Dr. Stuart Muench for many valuable discussions concerning the study, and also for their helpful comments on the paper itself. The author also wishes to acknowledge the kind assistance of Mrs. Betty Blanchard in typing the manuscript.

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Analysis and Specification of Slant Wind Shear

1. INTRODUCTION

The wind distribution in the lowest layers of the atmosphere represents a practical and extremely important problem in aircraft operations. In a large percentage of aircraft takeoffs and landings, wind conditions in the vicinity of an airfield do not represent a significant hazard. In a very small percentage of the cases, however, wind conditions may exist that threaten the safety of the aircraft. Aagard¹ emphasized that the swept wing configuration of modern type jet aircraft, combined with their low speed performance characteristics, have accentuated the low-level wind-shear problem.

In another paper, Schwarz² reported that, of 6500 aircraft accidents occurring worldwide in ten years, more than twice as many accidents occurred in the terminal area as along a route. In addition, 20 percent of all accidents were weather related. In the landing phase, unfavorable winds were listed third in importance

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1. Aagard, A. (1981) International Air Transport Association, Proceedings of 1st International Conference on Aviation Weather Systems, pp. 17-19.
2. Schwarz, U. (1981) Aeronautical User Requirements for Meteorological Information, Proceedings of 1st International Conference on Aviation Weather Systems, pp. 1-5.

after low cloud base (1) and fog (2) in contributing to the accidents. In the takeoff phase, unfavorable winds led the list for general aviation and airline accidents.

In a report on Air Weather Service (AWS) support of Air Force and Army operations, Forsyth³ noted AWS concern over the low-level wind-shear problem. This concern has been formalized with AFGL through Geophysics Requirement 3-76 specifying the need for continuous forecasts that provide the probability of mission-degrading events occurring at the terminal, imminently or within a few hours, as a means of effective air control. The AWS has also, through MAC ROC 501-76, documented the need for a low-altitude wind-warning system (LAWWS) to measure the low-level wind profile on a continuous basis. Furthermore, the need for rapid dissemination of weather information has been noted through the issuance of the multi-command AFCC-ROC-801-77, the Automated Weather Distribution System (AWDS).

Wind shear, as defined in the Glossary of Meteorology,⁴ is the local variation of the wind vector, or any of its components, in a given direction. This variation can manifest itself as a change in wind speed, wind direction, or both, with distance along a vertical or horizontal axis. The vertical wind shear, usually denoted by $\frac{\Delta V}{\Delta Z}$, is the variation of the vector wind velocity with height, whereas the horizontal wind shear, $\frac{\Delta V}{\Delta X}$, is the variation over a given horizontal distance. ∇V is defined as the three-dimensional vector, $\nabla V = iu + jv + kw$. In practice, the vertical velocity field, w , is seldom measured and wind shears are computed for horizontal winds, u and v , only along a vertical and horizontal distance.

It will be suggested in this paper that neither of these measurements represents the wind shear of most importance to the aircraft operator. On takeoffs or landings, the aircraft follows a slant trajectory and encounters winds that are separated over a considerable horizontal distance and to a somewhat lesser extent (about one order of magnitude) in the vertical. Thus, wind shears measured along a vertical axis alone, by a tower or acoustic Doppler, or along a horizontal axis, by a surface network of wind sets, may give a misleading picture of the operationally important wind-shear field. As a result, in this paper the term Slant Wind Shear (SWS) will be used to represent this concept and to denote the horizontal wind shear along an aircraft takeoff or landing trajectory.

Several methods have been used for the detection of low-level wind shear. Surface wind networks, pressure jump networks, acoustic Doppler radar, single

3. Forsyth, M.D., Jr. (1981) Air weather service support to Air Force and Army aviation - present and future, Proceedings of 1st International Conference on Aviation Weather Systems, pp. 37-39.
4. American Meteorological Society (1959) Glossary of Meteorology, Boston, Mass.

and dual Doppler radar, and individual and multiple towers have all been used, either singly or in combination.

AFGL, in response to AWS needs, developed in 1978, the concept of a modular automated airfield weather system (MAWS), (Chisholm et al⁵). This system consisted of several surface weather observing sites located near active runways together with a 30- or 45 m instrumented tower located 450 to 550 m from the center line of a runway. The distance from the runway is governed by regulation, AFR 86-14, which specifies the maximum height of obstructions in the transitional surface of an airfield. A slope formula of 7:1 holds in the zone that begins either 230 or 305 m from the center line of the runway and extends for 320 m until a maximum height of 45 m is reached.

The MAWS system was installed at Scott AFB, Illinois, in the fall of 1976 to demonstrate the feasibility of an automated observing and forecasting system using state-of-the-art microcomputers, (Chisholm et al⁶). In addition to the more common automated parameters such as wind and temperature, the system was capable of producing automated cloud height, visibility, sea level pressure, 24-hour-maximum and minimum temperatures, probability forecasts of cloud height and visibility, as well as such critical air field concerns as runway surface cross-wind components, wind chill temperature, and maximum wind gusts. Hering and Geisler⁷ demonstrated that an offset-tower surface-site combination of visibility instruments located at Otis AFB provided a probability of detection of below limit Slant Visual Range (SVR) of greater than 90 percent. Follow-on studies by Geisler⁸ developed algorithms for short-range prediction of SVR using the remote tower-surface visibility measurements. Brown^{9,10} showed the feasibility of automating the visual present weather observations using the MAWS complex, supplemented with a rain gauge, backscatter visibility meter, nephelometer, and transmissometer.

5. Chisholm, D. A., Lynch, R. H., and Weyman, J. C. (1981) A modular approach to airfield weather systems, Proceedings of 1st International Conference on Aviation Weather Systems, pp. 69-72.
6. Chisholm, D. A., Lynch, R. H., Weyman, J. C., and Geisler, E. B. (1980) A Demonstration Test of the Modular Automated Weather System (MAWS) AFGL-TR-80-0087, AD A087070.
7. Hering, W. S., and Geisler, E. B. (1978) Forward Scatter Measurements of Slant Visual Range, AFGL-TR-78-0191, AD A064429.
8. Geisler, E. B. (1979) Development and Evaluation of a Tower Slant Visual Range System, AFGL-TR-79-0209, AD A082384.
9. Brown, H. A. (1979) Preliminary Assessment of an Automated System for Detecting Present Weather, AFGL-TR-79-0137, AD A078031.
10. Brown, H. A. (1980) Automation of Visual Weather Observations, AFGL-TR-80-0097, AD A088881.

This report details the results of research into the use of the MAWS system of remote or offset tower windsets together with surface winds to specify the SWS over the approach or takeoff zone of an airfield.

2. OTIS WEATHER TEST FACILITY (WTF)

2.1 Climate and Topography

Otis AFB, Massachusetts, situated on the western edge of Cape Cod, is subject to typical Cape weather. Summers are cool with onshore winds while the winters are moderated by the relatively warm ocean temperatures. Buzzards Bay is located 8 km to the west of the base, Vineyard Sound is about 13 km to the south, and Cape Cod Bay is about 15 km to the north. Maritime or maritime-moderated air thus predominates with most of the wind regimes except for the cold Arctic outbreaks from the northwest in the winter.

The climatology of Otis AFB is thus ideal for a weather test facility and is specially suited to a study of low-level wind-shear conditions. In addition to a high frequency of maritime coastal fog, a wide variety of weather conditions can be expected to occur during the year, for example, many sea breeze incursions, 16 thunderstorm days, an annual snowfall of about 37 in., and temperatures that range from an absolute maximum of 97°F in August to an absolute minimum of -10°F in December.

Otis AFB is located on a relatively flat ridge (40 m MSL) that is oriented southwest-northeast. The base and its surroundings are characterized by low scrub-oak and -pine forests. The WTF itself, however, occupies a one-mile square area that is quite flat and almost treeless.

2.2 Tower Sites

The weather test facility (WTF), Figure 1, consists of a central complex of towers (A, B, and C), which range in height from 60 m to 30 m to 3 m. They are oriented southwest-northeast and are positioned to simulate an aircraft take-off or landing zone. At the hypothetical takeoff or touchdown point (X), a complex of weather instruments have been installed. The distance from A to X is about 300 m, which gives a slope (11°) greater than customary for an aircraft approach. Thus, any shear computed from the A60 to the X sensor may be underestimate as part of the shear may be due to horizontal separation. Two 30-m towers (P and Q) are located approximately 500 m to the left and right of the A tower. This distance was chosen to conform to AFR 86-14, which specifies the distance an obstruction must be from the runway to avoid violating air space requirements.

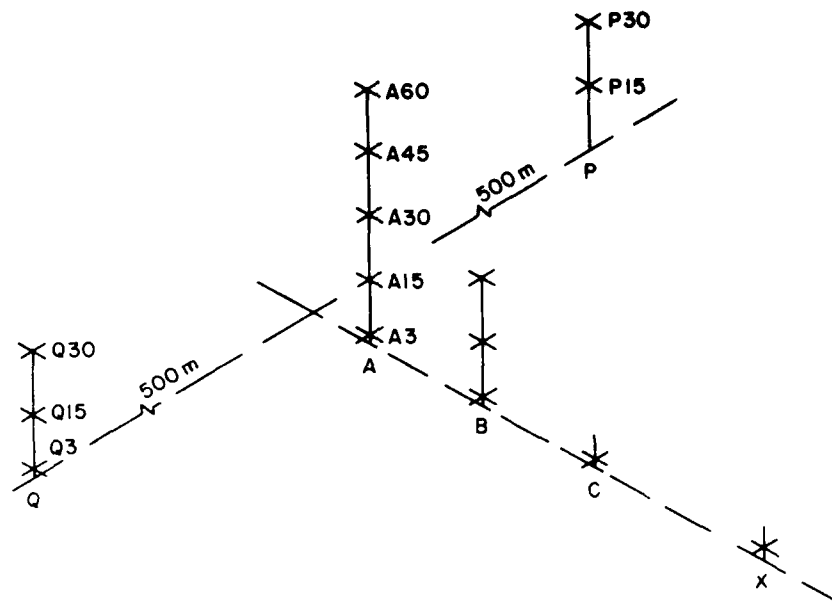


Figure 1. Configuration of Instrumented Towers and Ground Site at the AFGL Weather Test Facility, Otis AFB

2.3 Instrumentation

Towers A, P, Q, and site X were selected for the study of wind shear. The towers were equipped to measure profiles of temperature (A only), and wind speed and direction. The A tower was instrumented at five levels: 3, 15, 30, 45, and 60 m. P and Q were instrumented at approximately 15 and 30 m with wind direction and speed, (Q also had a wind set at 3 m) while site X contained a wind set and temperature sensor mounted at 3 m. All of the tower sensors were mounted on the southwest sides of the towers to give an unobstructed measurement of the predominant southwesterly winds.

Temperature was measured with E. G. & G. Model 110-S-M Temperature-Dewpoint sensors. The air temperature in this system is determined by a platinum-resistance thermometer that is thermally shielded and aspirated and whose response matches that of a standard mercury-in-glass thermometer. The temperature range is from -50°C to $+50^{\circ}\text{C}$ with accuracies over the range of interest of $\pm 0.28^{\circ}\text{C}$.

Wind speed and direction on towers A, P, Q, and site X were measured using Climatronics Wind Mark I sensors. This set is characterized by a non-contacting wind direction transducer, a solid-state light source for speed determination, and light weight cups and vane. It has a low activation threshold (0.22 m sec^{-1}), is fast responding and is also accurate, ± 1 percent or $\pm 0.07 \text{ m sec}$, whichever is greater and with stainless-steel cups has a distance constant of 2.4 m maximum. The AFGL instruments were equipped with a 0 to 540° wind direction range and have been modified with heating elements to avoid freezing problems.

At the 60-m level of tower A, another wind set was installed, the R. M. Young Propvane 8002, to serve as an independent wind measurement and as a backup for the Climatronics set at this level. The Propvane is a rugged, light-weight set equipped with an aluminum fin and thermoplastic propeller. Response characteristics are similar to the Climatronics. Its start threshold is less than 0.4 m/sec and its distance constant of the propeller is 2.4 m. The wind direction is determined by a potentiometer, while a tachometer specifies the wind speed.

Figures 2 and 3 show plots of wind direction and speed comparing the Climatronics at the 60-m level of tower A with the Propvane. Agreement is excellent in wind direction and speed with slopes of approximately one and correlations, R , greater than 0.99.

2.4 Data Collection System

The primary data collection system at the WTF is a microprocessor-based system. It consists of a microprocessor remote-data-unit (RDU) located at each tower site. The RDU sequentially samples the wind sets every second (every 12 sec for temperature), processes the data into 1-min averages, and transmits digitally the data, upon command of a supervisory microprocessor, for storage on magnetic tape. A backup data acquisition system is also employed that continuously records, on magnetic tape, raw wind sensor voltages at the rate of ten interrogations per minute (temperature at the rate of 5).

3. SLANT WIND SHEAR (SWS) DATA BASE

From the data gathered at the WTF, one long-term period of wind observations was used for this initial test of a slant wind shear offset tower system.

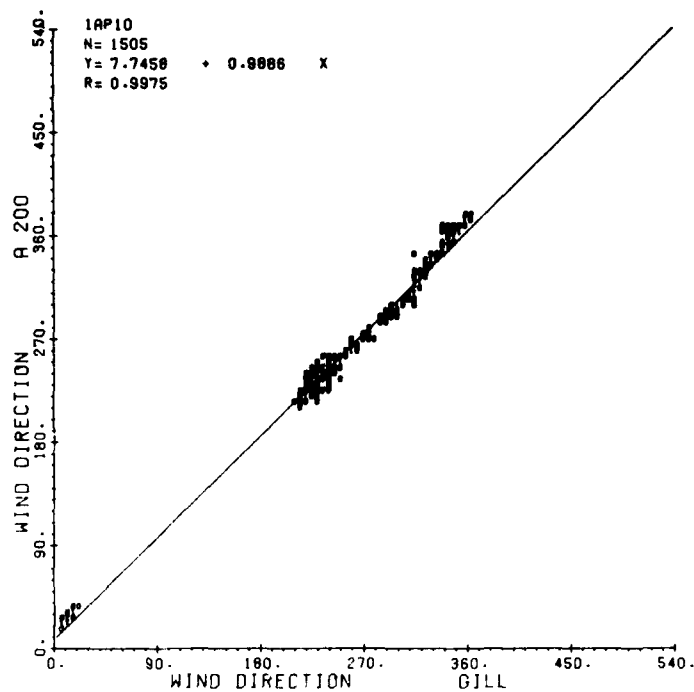


Figure 2. Comparison Between Wind Directions (1-min Averages) Measured by the Climatronics (A200) and R. M. Young (Gill) Sensors Located at the 60-m Level of Tower A

3.1 28 March to 4 May 1981

During this 38-day period in the spring of 1981, major weather events in the form of nine cold-frontal passages occurred. The period could be broadly divided into two regimes as a function of gusty surface winds. During the first period, 181 hr of gusty wind were reported by the FAA observers at Otis AFB. During the second period, only 46 hr of gusty wind were reported. During the first period, six cold-frontal passages occurred, while only three occurred during the latter. Overall, in terms of observable weather, 18 days of no weather were recorded, 12 days with rain and fog, six days with fog only and two days with reported occasional light rain. Only one thunderstorm was reported during the period, however, the data-recording system failed during this period so no thunderstorm downdrafts are included.

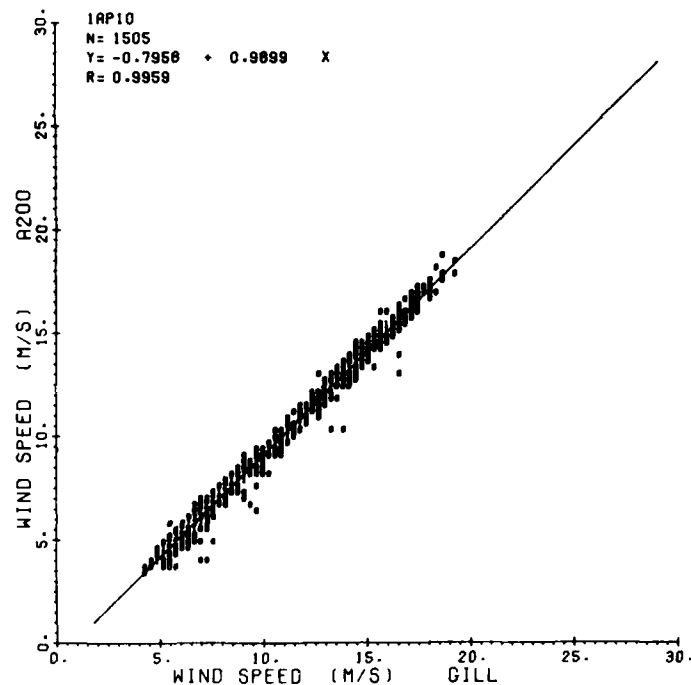


Figure 3. Comparisons Between Wind Speeds (1-min averages) Measured by the Climatronics (A200) and R. M. Young (Gill) Sensors Located at the 60-m Level of Tower A

3.2 Data Editing

One-minute averages of winds from all the sensors were scanned to eliminate obvious instrument malfunctions. Four of the Climatronics instruments were subject to a variety of data drop-outs, the 60-m and 3-m sensor at tower A, the 30-m sensor at tower P and the 30-m sensor at tower Q. This will be reflected in the number of data-pairs in later sections of this paper. A decision was also made at that time to substitute the R. M. Young Propvane data for the 60-m Climatronics data in tower A.

3.3 Wind Set Calibration

The wind sensors were carefully bench-tested before installation. Calibration of the wind speed was accomplished by driving the speed shaft at known rpm and adjusting the signal level to give the proper reading for that speed. Calibration of the wind direction sensor was accomplished by bench-testing the vane through the 0 to 340° range and comparing with voltage output at key directions.

Careful alignment procedures were followed to orient the wind sets properly on the towers. A consistency check was made by calculating hourly mean averages on a number of days during daylight hours and for periods with stronger winds and vertical mixing. The mean directions were then checked and adjusted to insure proper consistency of wind direction among the several measurements.

3.4 Wind Averaging Periods

In selecting the frequency and duration of averaging periods for this study, the choice had to be balanced between the amount of data collected and the stability of the average on the one hand, and the necessity to account for aviation-hazardous events on the other. The final choice of 1-min averages was based primarily on the latter of these choices with the realization that this period is most nearly equal to the time interval for an aircraft to descend from the 60-m level to the touchdown point.

3.5 Comparisons of Wind Speed and Direction

Following the post calibration of the wind measurements and the edit of the data base, averages were computed for each sensor for 1, 2, 3, 4, 5, and 10 min. Comparisons of wind direction and speed were then made between sensors at the same height on each tower to determine the effectiveness of the calibration and editing and the matching of the sensors.

Table 1 shows the correlations of instrument pairs for each averaging period. The 1-min wind speed correlations range from 0.86 at the low levels (3-m speeds at towers Q and A) to 0.92 for the high-level winds. The correlation of 0.90 for 30-m speeds at Q and P (separated by about 1000 m) is quite high. As the averaging time increased, the correlations improved. Slopes of the lines of best fit for 1-min averages ranged from 0.89 (between 50-ft winds at Q and P) to 0.97 (between 30-m winds at Q and A). For the 2-min average, these slopes increased to 0.92 to 1.0.

The correlations for wind directions (bottom half of Table 1) are all 0.98 or 0.99 from 1 to 10 min.

Table 2 shows the range of rms error for wind speed and direction. Values range from about 1.2 m sec^{-1} for 1-min average to 0.6 to 0.9 m sec^{-1} for the 10-min average. The wind direction values (bottom half of Table 2) range from 15 to 19 degrees for 1-min averages to 9 to 15 degrees for 10-min averages.

Table 1. Values of Correlation Coefficient for Comparisons (1- to 10-min Averages) Between Instrument Pairs. Part a is wind speed comparison and part b is wind direction comparison

a. Wind Speed Comparison							
Technique	Averages (min)						
	1	2	3	4	5	10	
P30 A30	0.92	0.95	0.96	0.96	0.97	0.98	
Q30 A30	0.92	0.95	0.96	0.96	0.97	0.98	
P15 A15	0.92	0.94	0.96	0.96	0.97	0.98	
Q15 A15	0.92	0.94	0.95	0.96	0.96	0.98	
Q3 A3	0.86	0.89	0.91	0.92	0.92	0.93	
X3 A3	0.89	0.92	0.94	0.94	0.95	0.96	
Q30 P30	0.90	0.93	0.94	0.95	0.96	0.97	
Q15 P15	0.90	0.93	0.94	0.94	0.95	0.96	

b. Wind Direction Comparison							
Technique	Averages (min)						
	1	2	3	4	5	10	
P30 A30	0.99	0.99	→	•	•	•	
Q30 A30	0.99	0.99	→	•	•	•	
P15 A15	0.99	0.99	→	•	•	•	
Q15 A15	0.99	0.99	→	•	•	•	
Q3 A3	0.99	0.99	→	•	•	•	
X3 A3	0.98	0.99	→	•	•	•	
Q30 P30	0.98	0.98	→	•	•	•	
Q15 P15	0.99	0.99	→	•	•	•	

Table 2. Values of Root-Mean-Square Error for Comparisons Between Instrument Pairs. Part a is wind speed (1- to 10-min averages) and part b is wind direction comparisons

a. Wind Speed Comparisons ($m\ sec^{-1}$)							
Technique		Averages (min)					
		1	2	3	4	5	10
P30	A30	1.18	0.96	0.85	0.78	0.73	0.60
Q30	A30	1.27	1.06	0.95	0.88	0.83	0.72
P15	A15	1.20	0.99	0.87	0.80	0.75	0.63
Q15	A15	1.10	0.91	0.81	0.74	0.70	0.58
Q3	A3	1.26	1.14	1.07	1.03	1.00	0.92
X3	A3	1.14	1.01	0.94	0.90	0.87	0.79
Q30	P30	1.30	1.10	1.00	0.94	0.89	0.78
Q15	P15	1.18	1.01	0.92	0.86	0.81	0.70

b. Wind Direction Comparison ($^{\circ}$)							
Technique		Averages (min)					
		1	2	3	4	5	10
P30	A30	14	13	12	12	11	11
Q30	A30	15	12	11	11	10	9
P15	A15	16	14	13	13	12	11
Q15	A15	15	13	12	12	11	9
Q3	A3	15	13	12	11	11	9
X3	A3	19	17	17	16	16	15
Q30	P30	19	17	17	16	16	15
Q15	P15	16	15	14	14	13	12

4. SLANT WIND SHEAR (SWS) STATISTICS

The 1-min averages of wind were used to compile 1-min SWS vectors between the 60-m level of the A tower and the 3-m level of site X. It was of great interest to obtain the frequencies of occurrence of SWS and especially the SWS frequency with respect to surface wind speed, time of day, vertical temperature difference, SWS direction difference, and finally, as a function of averaging intervals.

As a means of relating the SWS measurements to some qualitative scale of intensity, a summary of criteria given by Badner¹¹ for severity of wind shear was followed. The vertical increment of height will be used to preserve the dimensions of a shear and, because it is more easily related to the other measures of wind shear of significance, to aviation. Four categories of intensity were selected as follows:

Light SWS	0.0 to 3.9 m sec ⁻¹ /60 m	(0.0 to 7.9 knots/200 ft)
Moderate SWS	4.0 to 7.9 m sec ⁻¹ /60 m	(8.0 to 15.9 knots/200 ft)
Strong SWS	8.0 to 11.9 m sec ⁻¹ /60 m	(16.0 to 22.9 knots/200 ft)
Severe SWS	≥12 m sec ⁻¹ /60 m	(>23.0 knots/200 ft)

A study of wind shear characterization by Greene et al,¹² chose a value of wind shear of 8.4 m sec⁻¹/100 m to be significant to aircraft operations. This would correspond to a value of 5.0 m sec⁻¹/60 m in Table 2, which lies at the lower end of the moderate category.

4.1 Frequency of Occurrence of Slant Wind Shear (SWS)

Table 3 shows the frequency of occurrence, percentage frequency, and cumulative frequency of the 1-min average SWS for the 57-m layer between the 60-m level of the A-tower and the 3-m level at site X.

The percentage frequencies are similar to those cited by Badner¹¹ for worldwide frequencies of 2-min vector wind shear for a 30-m layer whose base is 10 m above the ground. The low frequency of high shear events illustrates the problem that faces the meteorologist and the air traffic controllers in recognizing and alerting aircraft of significant shear events.

11. Badner, J. (1979) Low-Level Wind Shear: A Critical Review, NOAA Technical Memorandum NWS FCST-23, 57 pp.

12. Greene, G.E., Frank, H.W., Bedard, A.J., Jr., Korell, J.A., Cairns, M.M., and Mandies, P.A. (1977) Wind Shear Characterization, U.S. Dept. of Transportation, FAA Report No. FAA-RD-77-33, 120 pp.

Table 3. Frequencies, Percent Frequencies, and Cumulative Frequencies of Occurrence of Slant Wind Shear (SWS) Speeds. Intensity levels are indicated on the left

A60-X

SWS Speeds (m sec ⁻¹ /60 m)	Frequency	Frequency %	Cum Freq
<4	26775	59.12	100.00
4	9887	21.83	40.88
5	5122	11.31	19.05
6	2178	4.81	7.74
7	856	1.89	2.93
8	319	0.70	1.04
9	111	0.25	0.34
10	31	0.07	0.09
11	6	0.01	0.02
12	2	*	
Total min	45287		

* <0.01 percent

Table 4 was constructed to determine the relationship of SWS to surface wind speeds. The cumulative frequencies clearly show an association between the slant wind shears greater than 7 m sec⁻¹/60 m and surface winds between 8 and 12 m sec⁻¹. Periods of strong SWS simply did not occur during this period with very light surface winds. The frequency distribution of surface wind speeds is shown in the bottom row.

The time distribution of SWS was examined, Table 5, and reveals that for this set of data the cumulative frequencies of SWS greater than 7 m sec⁻¹/60 m were higher during the daylight hours. The number of 1-min observations per hour are shown on the bottom row. The lower frequency of observations during the early morning (1000 to 1300 GMT) coincides with the periods of daily magnetic data-tape changes.

To determine the association of the SWS with the thermal structure of the lower atmosphere during this period, Table 6 was constructed. Differences between the 1-min averages of temperature at the 60-m level of tower A and the surface

Table 4.1. Cumulative Frequency of Occurrence of SWS Speed ($\text{m sec}^{-1}/60 \text{ m}$) With Respect to Surface Wind Speed (m sec^{-1})

A60-X

Surface Wind	0	1	2	3	4	5	6	7	8	9	10	12	14	16	18	20
SWS																
≥ 0	100	100	100	100	100	100	100	100	100	100	100	100	100	*	*	*
≥ 4	23	20	24	21	38	46	47	60	62	69	72	79	66	*	*	*
≥ 5	4	2	5	5	16	18	24	33	39	49	54	61	49			
≥ 6		*	*	1	4	5	9	15	19	30	35	39	26	*		
≥ 7			*	*	1	1	3	5	9	14	17	18	11	*		
≥ 8				*	*	*	1	2	3	5	15	7	*			
≥ 9				*	*	*	*	1	1	1	1	2	*			
≥ 10				*	*	*	*	*	*	*	*	*	*			
≥ 11								*	*	*	*	*	*			
≥ 12								*	*	*	*	*	*			
N	820	1612	8102	5804	6760	7223	5402	3555	2293	1563	1045	949	151	7	1	45287

* : percent or < 10 observations.

SWS Speed ($\text{m sec}^{-1}/60 \text{ m}$)

Table 6. Cumulative Frequency of Occurrence of SWS Speed ($m \text{ sec}^{-1}/60 \text{ m}$) With Respect to Vertical Temperature Difference ($T_{A60} - T_x$) in Degrees C

A60-X

ΔT	< -2.0	-2.0	-1.5	-1.0	-0.5	0.0	1.0	2.0	3.0	4.0	5.0	6.0
SWS												
≥ 0	100	100	100	100	100	100	100	100	100	100	100	
≥ 4	34	33	27	37	50	50	48	70	66	59	21	
≥ 5	18	18	15	20	22	15	10	18	14	15	4	
≥ 6	8	8	7	9	8	3	1	1	*	4		
≥ 7	3	3	3	3	3	*						
≥ 8	1	1	1	1	1	*						
≥ 9		*	*	*	*	*						
≥ 10		*	*	*	*							
≥ 11			*	*	*							
≥ 12												
N	4478	4580	7018	11753	8449	3699	2151	958	518	340	81	44025

< 1 percent

Table 7. Frequencies of Occurrence of SWS Speed ($m\ sec^{-1}/60\ m$) With Respect to Wind Direction Difference
(DD_{A10}-DD_X)

A60-X

SWS	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101-110	$\geq 111^{\circ}$	
4	16841	6314	1894	734	329	167	88	14	17	23	9	59	26096
4	6343	2308	539	199	114	115	46	20	18	21	3	11	9737
5	3446	1270	246	56	20	23	8	6	6				5082
6	1513	531	87	19	2	6	9	1	2				2170
7	595	216	38	5	1								855
8	224	76	17	1		1							319
9	72	27	11			1							111
10	21	6	4										31
11	5		1										6
12		1	1										2
1	28700	10749	2838	1014	466	313	118	41	43	44	12	71	44409

SWS Speed

Table 8. Frequencies of Occurrence of SWS Speeds as a Function of Averaging Time (1 to 10 min)

A60-X

	SWS Speed (m sec ⁻¹ /60 m)	1 min avg	2 min avg	3 min avg	4 min avg	5 min avg	10 min ave
Light	0-0.9	1236	1457	1585	1560	1540	1469
	1-1.9	5164	5047	5017	5030	5016	4843
	2-2.9	8625	8352	8274	8273	8188	8151
	3-3.9	11293	11065	11274	11342	11500	11807
Moderate	4-4.9	9683	9586	9924	10172	10226	10412
	5-5.9	5116	4606	4328	4142	4071	3740
	6-6.9	2172	1580	1386	1279	1234	1033
	7-7.9	865	840	405	328	251	139
Strong	8-8.9	311	130	78	49	47	10
	9-9.9	112	31	16	3	1	
	10-10.9	31	4	1			
	11-11.9	6	1				
Severe	12-12.9	2					
Total		44616	42399	42288	42178	42074	41604

site at X were used for stability determination. It is clear from an examination of the frequency of observation of temperature differences, that the majority of observations ranged from isothermal to lapse conditions. The highest frequency of observations occurred between -0.5°C and -1.5°C . It is also clear that the majority of significant SWS for this case occurred during unstable temperature conditions.

It was also of interest to determine the distribution of SWS speed events with respect to wind direction differences. Therefore, a frequency table, Table 7, was constructed that relates SWS speeds to the difference in wind directions between the A60 tower level and the surface site, X. The row sums show the SWS speed frequency, while the column sums show the frequency of occurrence of wind direction differences in $\pm 10^{\circ}$ increments. For this data base the majority of significant SWS events occurred with direction differences of forty degrees or less. Finally, the frequency of SWS speeds as a function of averaging interval was calculated, Table 8. Periods ranged from 1- to 10-min. The primary result was the gradual elimination of the severe and strong SWS events between the 1- and 10-min averaging periods implying that most of the severe and strong SWS events in this study were of short duration.

5. SPECIFICATION OF SLANT WIND SHEAR (SWS)

For the purpose of this study, the SWS representation of the true wind shear along the simulated runway was calculated as the shear between the 1-min average vector winds measured at the 60-m level of tower A and the 3-m location at site X, (see Figure 1).

$$\Delta V_{\text{TRUE}} = V_{A_{60}} - V_x$$

Our primary objective then was to determine how well ΔV_{TRUE} was specified at a given time by various combinations of wind shear measurements calculated between tower A and the two offset towers at P and Q and the surface site X. The following shears were calculated:

Test 1 Between 30- and 15-m winds measured at tower A and surface winds measured at site X,

$$\Delta V_1 = K_1 V_{A_{30}} - V_x$$

$$\Delta V_2 = K_2 V_{A_{15}} - V_x$$

Test 2 Between 30-m winds measured at offset towers, P and Q, and surface winds measured at site X,

$$\Delta W_3 = K_1 W_{P30} - W_x$$

$$\Delta W_4 = K_1 W_{Q30} - W_x .$$

Test 3 Between 15-m winds measured at offset towers, P and Q, and surface winds measured at site X,

$$\Delta W_5 = K_2 W_{P15} - W_x$$

$$\Delta W_6 = K_2 W_{Q15} - W_x .$$

Test 4 Between surface instruments at towers A and Q and at Site X. Represents capability of current surface networks measurements,

$$\Delta W_7 = W_{A3} - W_x \text{ (~300-m surface separation)}$$

$$\Delta W_8 = W_{Q3} - W_x \text{ (~550-m surface separation) .}$$

The extrapolation coefficients K_1 and K_2 were obtained using a smaller sample of data that included high and low wind speeds. Ratios were formed from winds averaged over 1 hr for the 60-, 30-, and 15-m winds. Figure 4 shows a plot of the hourly ratios for U_{A60}/U_{A15} for all wind speeds. A diurnal variation is quite apparent as is the scatter represented by the length of a unit standard deviation. Figures 5 and 6 represent the data stratified by winds equal to or less than 4 m sec^{-1} at the 15-m level and those greater than 4 m sec^{-1} . Two sets of hourly constants, K_2 , were derived from these graphs as a function of wind speed. Two sets of hourly constants, K_1 , were also obtained in a similar manner for the 30-m wind speeds except the dividing wind speed selected was 5 m sec^{-1} . Thus, the appropriate constants to extend the 1-min average 15-m or 30-m wind speed to 60 m were functions of time and wind speed.

6. EVALUATION OF SWS SPECIFICATION TESTS

Specification of SWS by the four tests (eight separate data-pairs) were verified separately using each data-pair as a zero-lag predictor. Correlations and rms errors were obtained and 2 x 2 contingency tables were constructed for two thresholds of SWS severity. The first, $4 \text{ m sec}^{-1}/60 \text{ m}$, follows the criteria stated in Section 4 and separates the shears in two categories, light and the combined cases

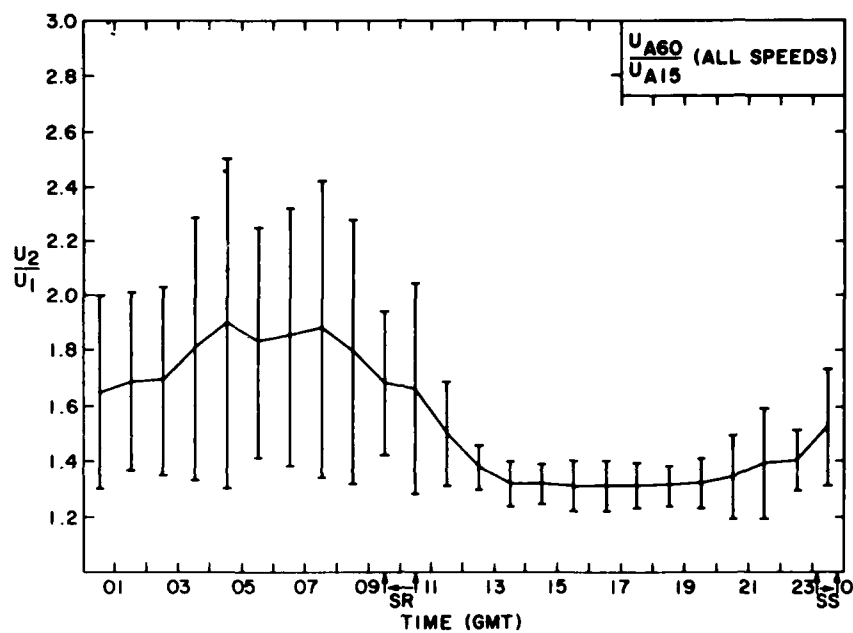


Figure 4. Ratio of 1-hr Averages of Wind Speed Measurement at the 60- and 15-m Level of Tower A as a Function of Time of Day. Vertical bars indicate 1 standard deviation

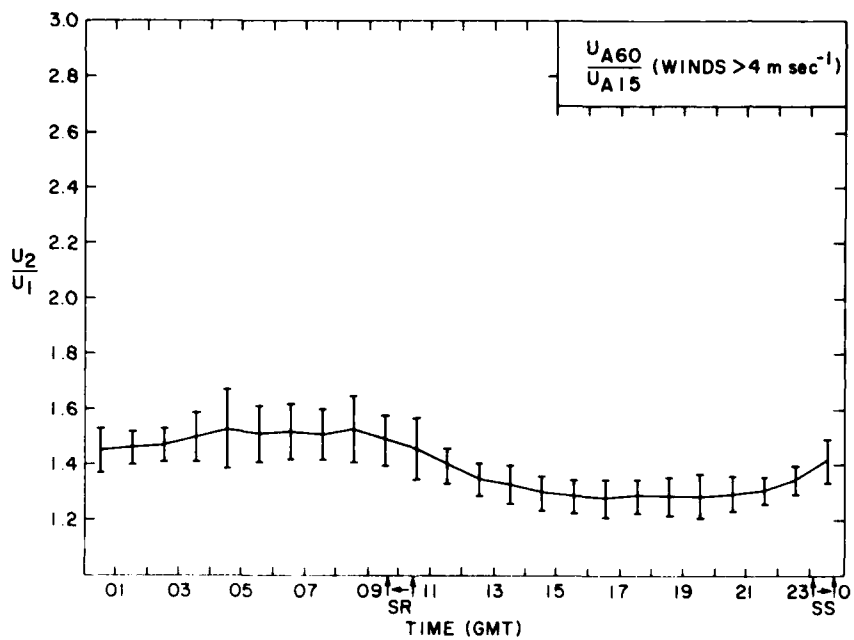


Figure 5. Ratio of 1-hr Averages of Wind Speed (greater than 4 m sec⁻¹) Measurement at the 60- and 15-m Level of Tower A as a Function of Time of Day. Vertical bars indicate 1 standard deviation

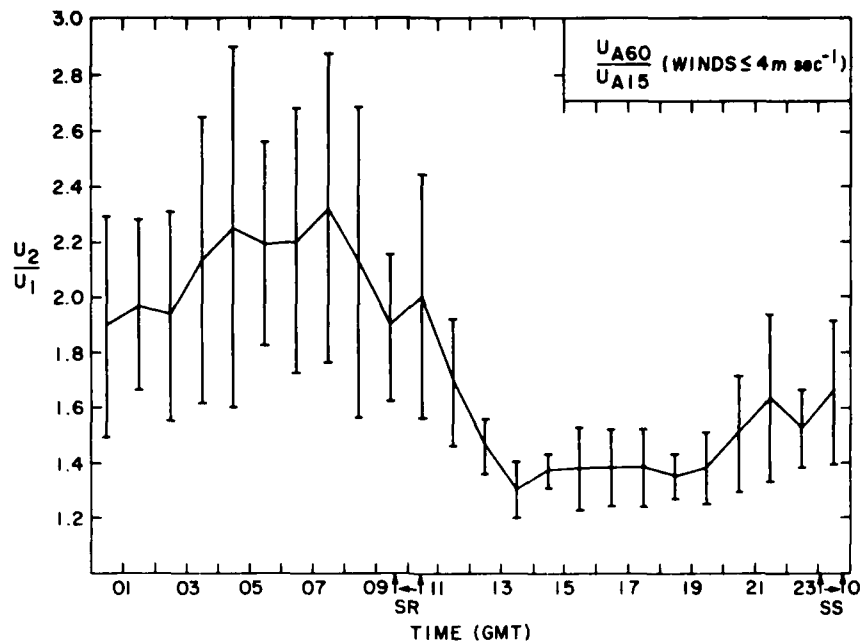


Figure 6. Ratio of 1-hr Averages of Wind Speed (less than or equal to 4 m sec^{-1}) Measurement at the 60- and 15-m Level of Tower A as a Function of Time of Day. Vertical bars indicate 1 standard deviation

of moderate, strong, and severe. The second threshold, $8 \text{ m sec}^{-1}/60 \text{ m}$, divides the wind shear cases between light and moderate on the one hand and strong and severe on the other.

6.1 Correlations

Table 9(a) shows the correlations of SWS speed for the four tests. As expected, correlation is highest (0.84) for the closest sensor, the 30-m level of tower A. The 15-m level of tower A was second with a correlation of 0.73. The 30-m sensors on the offset towers P and Q ranked third and fourth, while the P and Q 15-m sensors tied for fifth at 0.57. The surface sensors had the lowest correlation. Time averaging the data through 10 min gave corresponding improvements in the correlations except for the surface pair A3-N, which decreased with longer averaging periods.

Table 9(b) gives the correlations of the SWS direction. The closest sensor-pair, A30-N, again had the highest correlation. The remaining offset-tower combination compared similarly with correlations ranging from 0.88 to 0.91. The shear directions measured by the surface sites correlated the poorest. Time averaging produced improved correlations with shear directions as it did with

Table 9. Values of Correlation Coefficient for Comparisons of SWS Speed (1- to 10-min Averages) Measured by Eight Test Systems With the Runway SWS Speed (A60-X)

a. SWS Speed							
Test	Technique	Averages (min)					
		1	2	3	4	5	10
1	K ₁ A30-X	0.84	0.86	0.88	0.88	0.89	0.90
	K ₂ A15-X	0.73	0.76	0.78	0.79	0.80	0.82
2	K ₁ P30-X	0.64	0.70	0.74	0.76	0.78	0.82
	K ₁ Q30-X	0.61	0.66	0.69	0.71	0.72	0.76
3	K ₂ P15-X	0.57	0.62	0.65	0.67	0.68	0.72
	K ₂ Q15-X	0.57	0.60	0.62	0.64	0.65	0.69
4	A3-X	0.21	0.18	0.16	0.14	0.13	0.09
	Q3-X	0.29	0.28	0.28	0.29	0.30	0.34

b. SWS Direction							
Test	Technique	Averages (min)					
		1	2	3	4	5	10
1	K ₁ A30-X	0.94	0.95	0.95	0.96	0.96	0.96
	K ₂ A15-X	0.89	0.90	0.91	0.91	0.92	0.92
2	K ₁ P30-X	0.91	0.92	0.93	0.94	0.94	0.95
	K ₁ Q30-X	0.88	0.90	0.91	0.91	0.92	0.92
3	K ₂ P15-X	0.90	0.92	0.92	0.93	0.93	0.94
	K ₂ Q15-X	0.90	0.92	0.92	0.93	0.93	0.94
4	A3-X	0.71	0.73	0.74	0.75	0.75	0.77
	Q3-X	0.52	0.51	0.50	0.50	0.49	0.48

shear speeds except for the surface site combination Q3-X, which decreased slightly.

6.2 Root-Mean-Square Errors

The rms errors for specifying the SWS speed are shown in Table 10(a). The results are similar to those seen in the correlations. Test 1, consisting of the sensors nearest to the runway, has the lowest rms error. Test 2 results, consisting of the 30-m offset sensors, are second, while the 15-m offset sensors, test 3, and the surface sensors, test 4, rank third and fourth.

Averaging of the SWS speeds produces improvements in the errors in all cases except for test 4, the surface sensors.

Table 10(b) gives the rms errors for specifying the SWS direction. The smallest errors, 34° and 36° , are achieved by the A30-X and P30-X observations. The next group are essentially equal with errors ranging from 43° to 48° for the remaining tower instruments. Errors are largest, 80° and 102° for the ground-based wind systems, A3-X and Q3-X.

Averaging the observations produces an improvement in the errors in all cases except Q3-X where the error remains essentially the same.

6.3 SWS Speed Specification

In 1975, Donaldson et al¹³ introduced the terminology CSI as a means of evaluating the merit of severe weather predictors. The CSI, sometimes referred to as Threat Score (TS) (for example, Hering and Geisler⁷), accounts for two classes of error; false alarms and missed threats. An example of the 2×2 contingency table constructed for each test is shown in Figure 7. The data represent the zero-lag prediction of SWS above or below the speed threshold of $4 \text{ m sec}^{-1}/60 \text{ m}$ by the K₁ A30-X predictor.

The matrix is divided into quadrants labeled x, y, z, and w. The sum of x and y gives the total number of observed SWS speeds whose magnitude is considered moderate or greater. The sum $w + z$ represents the total number of SWS speed observations below the threshold, $4 \text{ m sec}^{-1}/60 \text{ m}$. The quantities x and w represent correct forecasts, y stands for missed threats and, finally, z represents the number of false alarms. Equations and calculations for the probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI or TS) are shown below the figure.

13. Donaldson, R. J., Dyer, R. M., and Kraus, M. J. (1975) An objective evaluator of techniques for predicting severe weather events, Proceedings of Ninth Conference on Severe Local Storms, pp. 321-326.

Table 10. Values of Root-Mean Square Error For Comparisons Measured by Eight Test Systems With Runway SWS (A60-X). Part a is SWS speed (1- to 10-min averages) comparisons and part b is SWS directions ($^{\circ}$) comparisons

a. SWS Speed ($m\ sec^{-1}$)							
Test	Technique	Averages (min)					
		1	2	3	4	5	10
1	K ₁ A30-X	1.04	0.90	0.83	0.79	0.77	0.70
	K ₂ A15-X	1.39	1.22	1.13	1.08	1.05	0.95
2	K ₁ P30-X	1.41	1.18	1.07	1.00	0.94	0.81
	K ₁ Q30-X	1.52	1.31	1.20	1.13	1.08	0.96
3	K ₂ P15-X	1.72	1.51	1.41	1.33	1.28	1.16
	K ₂ Q15-X	1.59	1.41	1.31	1.25	1.20	1.08
4	A3-X	2.53	2.54	2.55	2.57	2.58	2.61
	Q3-X	2.79	2.82	2.85	2.86	2.88	2.92

b. SWS Direction ($^{\circ}$)							
Test	Technique	Average (min)					
		1	2	3	4	5	10
1	K ₁ A30-X	34	33	31	31	30	29
	K ₂ A15-X	46	45	44	43	43	42
2	K ₁ P30-X	36	34	32	31	30	28
	K ₁ Q30-X	46	43	42	40	40	38
3	K ₂ P15-X	43	41	40	39	38	37
	K ₂ Q15-X	48	46	45	44	43	42
4	A3-X	80	78	76	75	74	70
	Q3-X	102	103	104	105	105	106

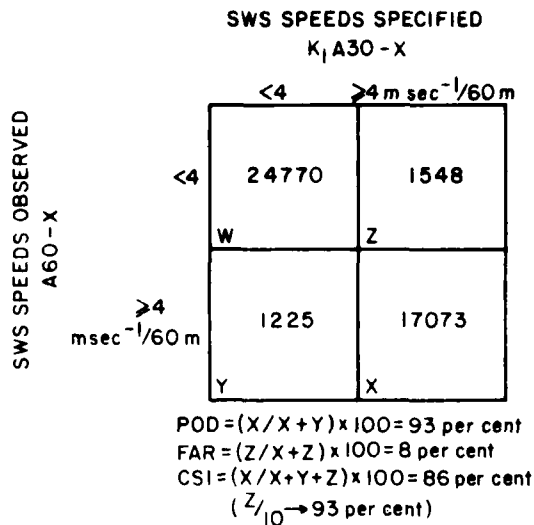


Figure 7. Contingency Table That Illustrates the Method of Computing the SWS Speed Verification Scores: Probability of Detection (POD), False Alarm Ratio (FAR), and Critical Success Index (CSI). This example refers to the SWS speed threshold of $4 \text{ m sec}^{-1}/60 \text{ m}$, which separates light from moderate and greater values of SWS intensity

Donaldson, et al¹³ noted that for catastrophic events, a higher false alarm rate is preferred to a failure of detection. Therefore, a significance factor was added to the CSI determination and given a range of from 1 to 10 depending on the severity of the event. Since an aircraft-threatening wind-shear condition is obviously in the severe category, z was divided by 10 and, in this particular case, shows a corresponding CSI-index increase from 86 to 93 percent.

Summaries of POD, FAR, and CSI (unmodified and modified) for two threshold values of SWS are given in Table 11. Test 1, consisting of the A tower instruments at lower levels (30 and 15 m), produced the best combined scores of POD, FAR, and CSI for both thresholds of SWS. A significant increase in FAR is seen for the higher threshold, Table 11(b). This increase is attributable to the coefficients, K₁ and K₂. In many cases they produced overestimates of the wind shear.

Test 2, the 30-meter towers P and Q located 500 m from the runway, shows a decreased POD, slight increase in FAR, and somewhat lower CSI when compared to test 1, Table 11(a). This decrease in success is attributed to the lateral separation of the observations. Test 2 at the higher threshold, Table 11(b) shows a more dramatic decrease in POD and increase in FAR. The low number of

Table 11. Values of Probability of Detection (POD), False Alarm Ratio (FAR), and Critical Success Indices (CSI) - Modified and Unmodified for Specification (Zero-lag Prediction) of Runway SWS Speeds by Eight Test Systems. Part a threshold equal to $4 \text{ m sec}^{-1}/60 \text{ m}$ and part b threshold equal to $8 \text{ m sec}^{-1}/60 \text{ m}$

a. SWS Speed Threshold ($4 \text{ m sec}^{-1}/60 \text{ m}$)					
Test	Technique	POD %	FAR %	CSI - %	
				Z	Z/10
1	K_1 A30-X	98	8	86	93
	K_2 A15-X	88	18	74	87
2	K_1 P30-X	77	19	65	76
	K_1 Q30-X	75	17	65	74
3	K_2 P15-X	80	25	63	78
	K_2 Q15-X	77	25	61	75
4	A3-X	4	11	4	4
	Q3-X	5	10	5	5

b. SWS Speed Threshold ($8 \text{ m sec}^{-1}/60 \text{ m}$)					
Test	Technique	POD %	FAR %	CSI - %	
				Z	Z/10
1	K_1 A30-X	91	61	38	80
	K_2 A15-X	83	73	26	68
2	K_1 P30-X	54	81	16	66
	K_1 Q30-X	54	85	14	42
3	K_2 P15-X	48	86	12	37
	K_2 Q15-X	56	78	18	33
4	A3-X	0	0	0	0
	Q3-X	0.5	0	0.5	0.5

occurrences of SWS speeds above this threshold when coupled with the estimates of K_1 gave rise to these departures. The high value of the modified CSI, 66 percent, for K_1P30-x compared to the value of 42 percent for K_1Q30-x is due to a smaller data sample for that sensor combination and a consequent lower number of false alarms.

Test 3, the 15-m towers P and Q located 500 m from the runway, shows comparable PODs with test 2 (30-m towers) for both thresholds but a somewhat higher FAR at the lower threshold. Of significant interest however, is the fact that the CSI values of test 3 are equivalent to the values of test 2 at the lower threshold, indicating the 15-m winds are as good as the 30-m winds in specifying SWS over the runway. At the higher threshold, ignoring the higher value of 66 percent due to the small data sample, test 3 values of CSI and modified-CSI are almost equivalent to test 2 values.

Test 4, the surface SWS systems, show an almost total lack of ability to specify SWS speed over the runway at either threshold for this data sample.

6.4 SWS Direction Specification

Evaluation of the SWS direction specification was achieved through 4×4 contingency tables divided into 90 degree categories, Figure 8. Columns show the SWS direction specification for a particular test, in this case K_1A30-X . Rows show the actual SWS direction measured by the A60-X system. The margin totals show the frequency of SWS directions that occurred compared with those specified by the test. Summation of the principal diagonal and division by the total number of observations shows 89 percent correctly specified for this particular test.

The measures POD, FAR, and CSI are only appropriate for the evaluation of threshold (2×2) statistics. Since the SWS direction specification involved 4×4 contingency tables, calculations of post agreement and prefigurance, Panofsky and Brier,¹⁴ were used. Postagreement percentages, placed in the lower right-hand side of each square, show the extent to which the observations confirm the zero-lag predictions. The post agreement percentages are column sums. Prefigurance percentages, shown in the upper left-hand side of each square, are a measure of the extent to which the zero-lag predictions give accurate notice of the event. This measure, applied to the unit squares making up the principal diagonal, is somewhat analogous to the POD. It should be noted that prefigurance percentages are row sums.

14. Panofsky, H. A., and Brier, G. W. (1965) Some Applications of Statistics to Meteorology, The Pennsylvania State University, University Park, Pa.

		SWS DIRECTIONS SPECIFIED				TOTAL
		K ₁ A30-X				
		0-90	90-180	180-270	270-360	
SWS DIRECTIONS OBSERVED A60-X	0-90	88 → 5895 89 ↓	3 206 4 ↓	3 182 1 ↓	6 411 4 ↓	(100) 6694
	90-180	6 → 263 4	89 4040 81	5 220 1	* 19 *	(100) 4542
	180-270	* → 51 1	3 632 13	96 19824 88	* 86 1	(100) 20593
	270-360	3 → 443 6	1 89 2	18 2237 10	78 10020 95	(100) 12789
TOTAL		(100) 6652	(100) 4967	(100) 22463	(100) 10536	44618

Figure 8. Contingency Table That Illustrates the Method of Computing the SWS Direction Verification Scores: Postagreement and Prefigurance. Prefigurance values (percent) are located in the upper left-hand corner of each square and are summed along rows. Postagreement values (percent) are located in the lower right-hand corner of each square and are summed along columns. Total percentage correct can be obtained by summing the occurrences in the principal diagonal and dividing by the total number of observations

Summaries of the postagreement and prefigurance percentages for the principal diagonal squares are given in Table 12. In addition, the overall percentage correct specifications are given in Table 12(a).

Examination of Table 12 shows that test 1 (30 m) has the highest overall percentage values of postagreement and prefigurance. One of the outstanding features of both tables is the near equivalence of postagreement and prefigurance values of test 1 (15 m), test 2 (excluding P30 because of smaller data sample size) and test 3. This is reflected also in the columns labeled total percent correct where values range from 76 to 80 percent for these tests. This has great operational potential because it indicates the high percentage of SWS directions, which are likely to be correct or on which reliance can be placed (postagreement), and also the percentage of SWS direction events, which are likely to be correctly specified (prefigurance).

Test 4, the ground-based wind-shear systems, shows much lower values of postagreement and prefigurance than the other three tests. The surface system, however, does a somewhat better job of specifying SWS direction than it does in specifying SWS speed.

Table 12. Values for Principal Diagonal Elements of Specification (Zero-lag Predictions) of Runway SWS Directions by Eight Test Systems. Part a is postagreement values (percent) with the right-hand column containing total percentage of correct forecasts for all directions. Part b is prefigurance (percent), that is, percent time each diagonal element was correctly forecast

(a) Postagreement (percent)						
Test	Technique	0-90	90-180	180-270	270-360	% Correct
1	K ₁ A30-X	89	81	88	95	89
	K ₂ A15-X	81	65	79	85	78
2	K ₁ P30-X	79	72	93	93	90
	K ₁ Q30-X	78	60	83	80	79
3	K ₂ P15-X	84	63	88	79	80
	K ₂ Q15-X	78	60	83	80	76
4	A3-X	50	21	62	60	49
	Q3-X	50	21	62	60	49

(b) Prefigurance (percent)					
Test	Technique	0-90	90-180	180-270	270-360
1	K ₁ A30-X	88	89	90	78
	K ₂ A15-X	76	77	92	57
2	K ₁ P30-X	77	89	94	86
	K ₁ Q30-X	74	76	87	69
3	K ₂ P15-X	91	85	89	79
	K ₂ Q15-X	74	76	87	69
4	A3-X	41	46	51	41
	Q3-X	27	35	33	21

7. SUMMARY AND CONCLUSIONS

The extensive array of windset-instrumented towers operating at the AFGL Otis Weather Test Facility provides the basis for detailed investigation of the variability of the local or mesoscale wind field and the occurrence of significant SWS events. Analysis of data collected during a 38-day period in 1981 demonstrates the existence of strong and severe shear occurrences, their frequency of occurrence and their association with various other parameters, surface wind speed, time of day, vertical temperature difference, and wind shear direction differences. In this particular data set, significant SWS events occurred with strong surface winds, during daytime hours (and the related unstable temperature lapse rates), and with small differences in wind direction between the 60-m level of the tower and the surface.

Tests to see how well SWS values calculated between offset towers and a surface site could specify (zero-lag prediction) the SWS values along a hypothetical runway were carried out. Not surprisingly, correlations of test SWS speeds with true SWS speeds decrease with distance from the runway and with height difference from the 60-m decision height. These correlations improved with an increase in data-averaging time, but this averaging process decreased the number of SWS occurrences of strong and severe SWS, conditions that would be of vital significance to safe aircraft operation. Correlations of the SWS direction vector were quite high compared to the speed correlations and showed only a minor drop with distance and height. Root-mean-square errors in SWS speed and direction showed an increase with distance and with decreasing height.

The surface-based SWS systems (test 4) showed, by far, the lowest correlations between SWS speeds and directions. The rms errors of the surface systems SWS speed and direction were the highest of any test, 2.53 to 2.79 m sec^{-1} for SWS speed and 80° to 102° for SWS direction.

Contingency table comparisons of the various test-configuration specifications revealed that a 15-m tower located 500 m from the center line of a runway has a comparable probability of detection of moderate or greater SWS with a 30-m tower at the same location. The 15-m tower does have a slightly higher false alarm ratio but when the severity of the event is considered, a modified-critical success indicator shows the 15-m tower is equal to the 30-m tower. The ability of the offset tower systems to discriminate between light-moderate and strong-severe SWS was not as great. Here again the 15-m tower was not significantly different from the 30-m tower. The test of the surface SWS systems showed they were essentially incapable of detecting any of the significant SWS events and had CSI values of ranging from 5 to 0. Analysis of the data showed the 30- and 15-m tower system achieved success rates ranging from 76 to 80 percent in specifying SWS

direction vectors in the correct quadrants. The surface SWS system rated much lower, 29 to 49 percent.

Of greatest interest is the finding that a 15-m SWS system is equivalent to a 30-m system at the same offset distance from the runway in specifying SWS. The implication that a 15-m tower system located closer to the runway, still satisfying the conditions of AFR 86-14, might have an even greater probability of detection of significant SWS events presents a prime topic for future work. Further work is indicated on the coefficients used to extrapolate the 15- and 30-m winds to the 60-m level. There is also need for a larger data sample to add to the number of SWS events in the strong and severe range.

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