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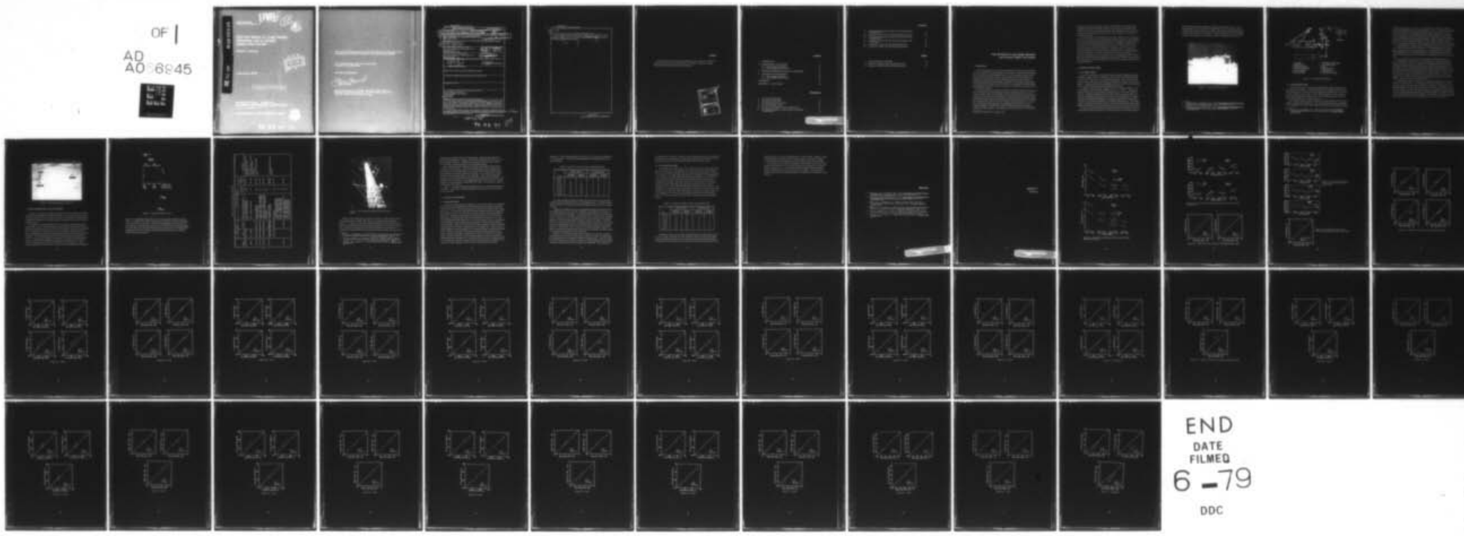

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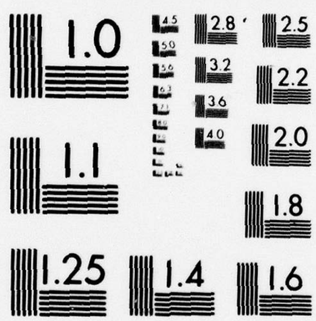

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Field Test Results of a Laser Doppler Velocimeter and an Acoustic Doppler Wind Sounder

FREDERICK J. BROUSAIDES

1 November 1978

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METEOROLOGY DIVISION PROJECT 6670
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

This report has been reviewed by the ESD Information Office (OI) and is releasable to the National Technical Information Service (NTIS).

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FOR THE COMMANDER

John Howard

Chief Scientist

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Acoustic Doppler wind sounder
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A field test program was conducted at Otis AFB, MA to evaluate the potential of two indirect wind sensing techniques as possible support in a warm fog dispersal system. The sensors examined were a Laser Doppler Velocimeter and an Acoustic Doppler Wind Sounder. Data from these devices were correlated with measurements taken by anemometers mounted upon a 61-m meteorological tower.

The average deviation of the Laser Doppler Velocimeter was ± 1.0 m/sec in wind speed and ± 7 deg in azimuth. Five-minute averaging periods were taken

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and four to six altitudes were scanned during each run.

The average deviation of the Acoustic Doppler Wind Sounder for 5-min averages was ±0.9 m/sec in wind speed and ±13 deg in azimuth. In one protracted run using 10-min averages, the deviations were ±0.6 m/sec in wind speed and ±6 deg in azimuth.

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Preface

The author would like to express his appreciation to Mr. Bruce A. Kunkel for constructive review of the manuscript and to Mr. Stuart J. Sheets for his able technical support throughout the field test program.

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1. INTRODUCTION

An increasing number of Air Force requirements exist for the remote sensing of low-level winds where the utilization of direct probes would either be impractical, would perturb the wind field being monitored, or would constitute a safety hazard such as with tower mounted probes. Low-level shear has been identified as constituting a serious hazard to aircraft landings and take-offs, thus critically influencing the operational requirements for Category II and Category III operations. The continuous monitoring of upper level winds is a requirement at the test ranges during prelaunch activities and is also necessary for the effective deployment of Air Force weapons systems.

One of the Air Force Geophysics Laboratory's immediate interests in low-level wind measurement has been in support of a warm fog dispersal system for use at airbases having a high volume of traffic and that are also seriously impacted by fog events. Since the nature of fog development usually precludes its association with high velocity winds, emphasis in this test program was directed toward the examination of winds below about 10 m/sec and whenever possible during fog. Two of the more promising indirect methods of wind profiling include acoustic and laser Doppler techniques. Both methods utilize the Doppler shifting of backscattered energy from moving targets. These targets act as "tracers" and are carried along

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by larger scale wind flow patterns. The acoustic scatterers are turbulent cells varying in velocity and fluctuating in density. Small scale inhomogeneities that contribute to the signal are approximately one-half wavelength (5 cm). In the laser system, radiation is backscattered from dust, fog, salt spray, mist, and other atmospheric aerosols.

Two systems that are representative of the above techniques were selected for performance testing at AFGL's Weather Test Facility at Otis AFB, Massachusetts. The laser system examined was the proprietary Laser Doppler Velocimeter (LDV) owned by the Lockheed Missiles & Space Co., Inc. of Huntsville, Alabama and operated by their personnel during this field program. Data with the LDV were collected during the period of 30 August to 15 September 1977. The Acoustic Doppler Wind Sounder (ADWS) was built for AFGL by the Wave Propagation Laboratory, NOAA, Boulder, Colorado and was operated by in-house personnel. As reference anemometers were located upon a 61-m meteorological tower, data from the systems under test were not required in excess of that altitude except for qualitative examination of the vertical profile or to monitor the strength of signal returns during fog episodes.

2. DESCRIPTION OF THE SYSTEMS

2.1 Laser Doppler Velocimeter

The LDV is contained in a 20-ft Dodge step van which is equipped with power distribution, lights, and air conditioning. Power required for operation is either two 30-A, 110-V circuits or a 6-kVA portable generator. Data was processed in real time with a PDP-11/34 mini-computer and supplied in hardcopy from a teleprinter. For these tests the data processing system was housed in a small portable trailer. Figure 1 shows the two units deployed at Otis AFB.

A diagram of the basic optical system of the LDV is shown in Figure 2. The system utilizes a 20-W CO_2 laser emitting at 10.6 μm. A 12-in., f/2 telescope expands the beam into the atmosphere and optically focuses it into the region of interest. Radiation backscattered from the focal volume is collected by the telescope and subsequently photomixed with a portion of the original beam on a photodetector in a heterodyne configuration. The difference between the transmitted frequency and the returned frequency is the Doppler shift frequency. The detector output is amplified and fed into a spectrum analyzer that extracts the spectral peak. Output from the spectrum analyzer is fed into the PDP-11/34 for data processing.

A set of mirrors mounted upon a turntable is attached to the top of the van. By rotating these mirrors the laser beam can be directed in a circle whose diameter is determined by the range setting and the angle of the elevation mirror. In its present design the LDV can scan up to eight altitudes. The measurement time for a single scan at a given altitude is 5 seconds. The maximum measurement altitude is 640 m and the minimum is 16 meters. Detailed description of the LDV system and theory of operation may be found in a number of reports by the contractor.[1,2]

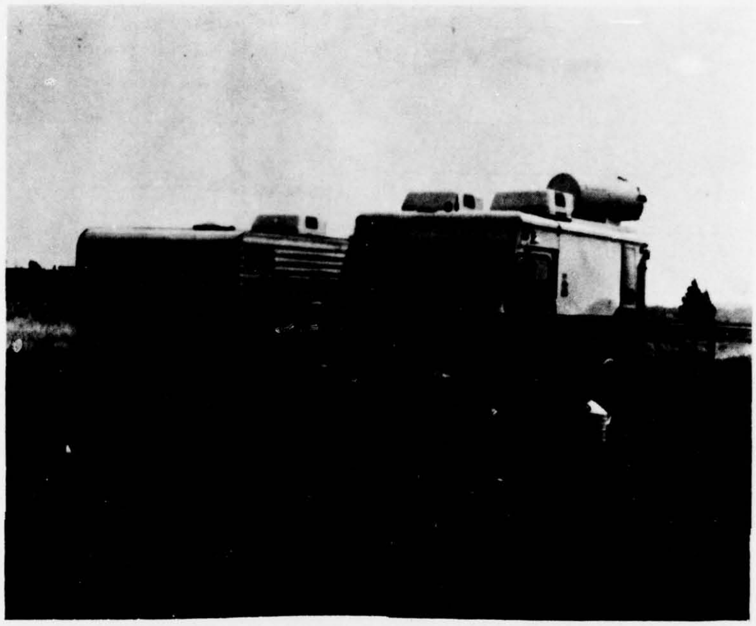

Figure 1. LDV Van and Data Trailer

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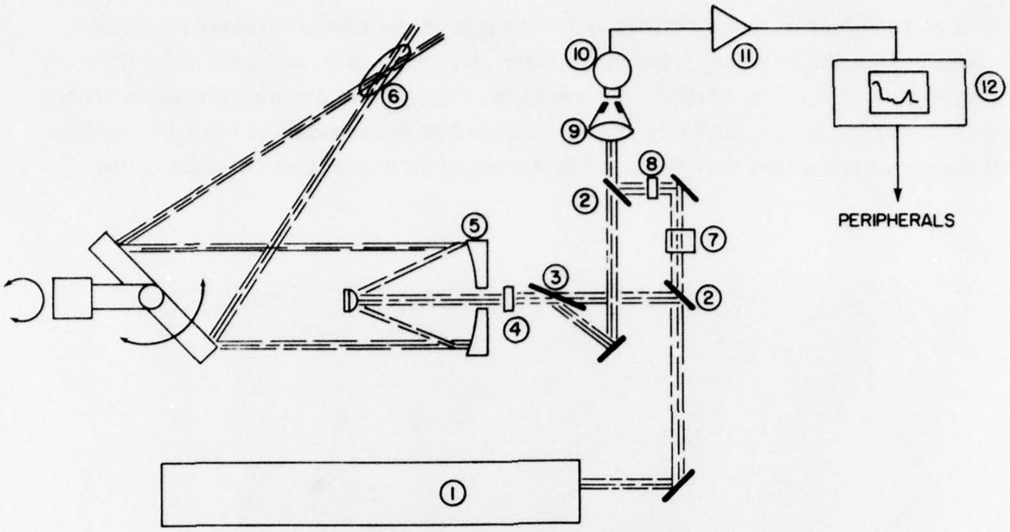
1. Brashears, M. R., and Eberle, W. R. (1977) Verification of Wind Measurement with Mobile Laser Doppler System, Report No. FAA-RD-77-117.
2. Brashears, M. R., and Eberle, W. R. (1977) Verification of Wind Measurement to 450 Meter Altitude with Mobile Laser Doppler System, Report No. FAA-RD-77-181.



1. CO_2 LASER
2. BEAM SPLITTER
3. BREWSTER WINDOW
4. QUARTER WAVE PLATE
5. PRIMARY MIRROR
6. FOCAL VOLUME
7. FREQUENCY TRANSLATOR
8. HALF WAVE PLATE
9. LENS
10. PHOTODETECTOR
11. PREAMPLIFIER
12. SPECTRUM ANALYZER

Figure 2. LDV Optical Configuration

2.2 Acoustic Doppler Wind Sounder

A variety of different commercial and experimental acoustic wind sounding systems have been designed. Most commonly, these are bistatic systems in which the transmitting and receiving antennas are physically separated and are directed toward a common volume in space. These systems contain from one to three bistatic pairs depending upon requirements. For resolution of the full wind-field vector, three bistatic pairs would be required.

The acoustic sounder evaluated in these tests was developed for AFGL for low-altitude, low-wind speed application.[3] The system design is based on an existing NOAA monostatic echo sounder and employs two bistatic pairs orthogonally aligned

3. Kaimal, J.C., and Haugen, D.A. (1977) An acoustic Doppler sounder for measuring wind profiles in the lower boundary layer, J. Appl. Meteorol. 16:1298-1305.

to define the horizontal wind vector. The assumption is made that the average vertical wind component is zero or is insignificant. Since a vertical wind component of sizeable magnitude would degrade the measurement, it is necessary to time average the data over a sufficiently long period to insure that $\overline{V}_z = 0$. The length of the averaging period required over flat terrain, typical of the Otis field site, is a function of altitude and meteorological conditions. Under conditions of thermally stable air 1 to 5 min is generally adequate. In the unstable convective boundary layer, depending upon altitude, a time averaging of 20 min or more may be required.

A major departure in design utilizes a vertically directed receiver rather than the customary vertically directed transmitter. This arrangement is believed to improve the signal-to-noise ratio since this receiver direction normally contains less background noise. One disadvantage of this arrangement is that increased acoustic energy is required of the transmitters to radiate through a wider elevation angle.

The two transmitters which provide the Doppler wind measurement can be varied in frequency by the operator. With this system, optimum performance is obtained at 3000 and 3600 Hz, respectively, providing good sensitivity without infringement upon the monostatic echo sounder which was also incorporated into the system. The echo sounder was not evaluated during this field program. The baseline distance between the transmitter and receiver in these tests was 40 meters. Accurate wind data can be obtained to twice the baseline distance. Above about 60-deg elevation angle the system becomes increasingly sensitive to the vertical Doppler wind component which could thus degrade the measurement of horizontal velocity. The sensor array is shown in Figure 3.

Transmitters are pulsed under software control; the repetition rate and pulse length are variable options. For extraction of Doppler shift frequency, the raw echo is fed back to the input of two tracking wave analyzers. Analog signals of the frequency shift are fed into a Data General Corp. Nova 820 minicomputer for processing. Based upon prior information provided by the operator at the start of the run, the computer determines the correct sampling sequence and calibration factors and sets up the output format for presentation on a teleprinter. The time averaging period can be varied and up to 13 altitudes of wind vectors can be obtained.

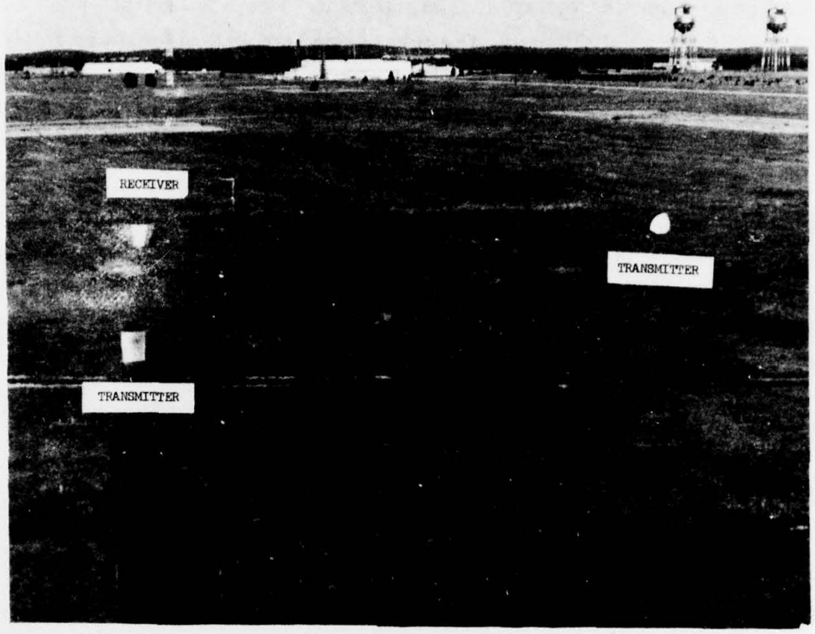


Figure 3. The ADWS Deployed at Otis AFB

3. TOWER INSTRUMENTATION AND DATA ACQUISITION

Figure 4 is a diagram of a section of the Otis Weather Test Facility and details those structures pertinent to this field test program. The primary reference tower is the 61-m east tower; the LDV system, and data van are shown in close proximity. To minimize reflections, the acoustic sounder was deployed at least 99 m from any building or tower.

The reference wind instruments were R. M. Young Co. anemometers (Model 27103) using 19-cm, two-axis Gill propellers (Model 21282) that were located on the south face of the tower at the 16, 30, 47, and 61 m levels. The axis of one anemometer arm pointed toward 26 deg true north. For purposes of these tests and for ease in aligning other sensors, this orientation was taken to be the true north-south direction. All wind directions given in this report are relative to this assumed reference axis. This also applies to the range of observed wind directions given in Table 1. In addition to the propeller anemometers, Climatronics Corp. cup and vane instruments (Model Mark I) were also located at the same levels. These sensors projected from the west face of the tower and were extended out on 8-ft booms.

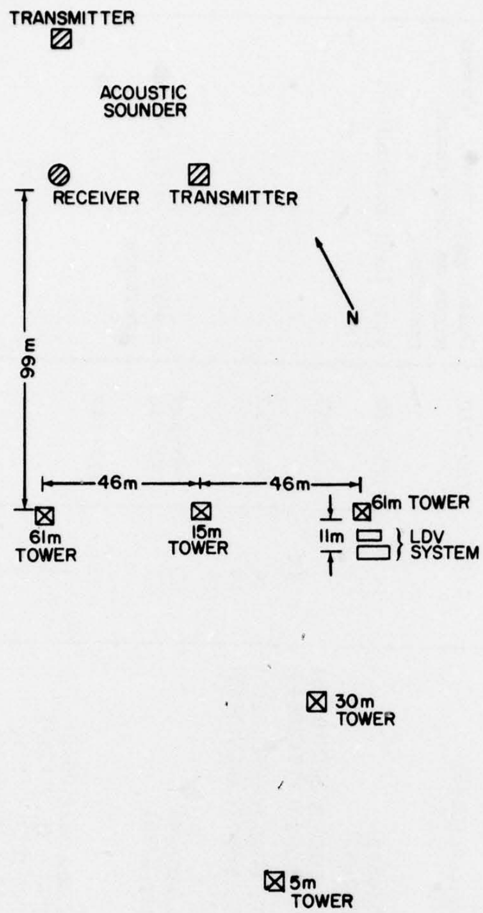


Figure 4. Otis AFB Field Site Layout

Figure 5 is a photograph taken from the tower base showing relative sensor positions. A consistent bias of about 10 deg in wind direction was observed between the two types of tower anemometers. The R. M. Young sensors were used as the primary reference wind sets since both the LDV and the ADWS were specifically aligned with them rather than with the Climatronics Corp. anemometers. An azimuth bias between the two types of reference anemometers would not, however, affect the calculation of total wind speed.

Table 1. Field Test Summary, Otis AFB

Date	Time (local)		Surface Observations			Comments
	LDV	ADWS	Weather and Sky(local time)	Visibility mi	Wind Direction, deg	
8/30/77	0231-0735		Fog, 100 ft OBSCD(0245)	1/2	204-233	Data logger down. Tower winds on strip chart recorder.
			Fog, 100 ft OBSCD(0645)	3/4		
9/2/77	07[illegible]-0813		Fog, ceiling zero(0745)	1/8	199-220	Data logger down. Tower winds on strip chart recorder.
9/10/77	0240-0715	0315-0645	6000 ft BKN(0345)	14	075-120	Very light intermittent rain.
			3000 ft BKN(0645)	14		
9/11/77	0235-0630	0300-0625	1200 ft SCT, 6000 ft BKN(0245)	8	270-282	
			6000 ft BKN, 8000 ft OVC(0645)	8		
9/12/77	0235-0645	0315-0650	3000 ft SCT, 6000 ft OVC(0245)	14	289-332	
			3000 ft SCT, 6000 ft BKN(0445)	14		
			Clear(0645)	14		
9/15/77	0145-0610	0320-0510	Fog and haze(0145)	3	295-350	
	1405-1555	1250-1550	Fog and haze(0345)	1	343-018	ADWS collecting 10-min averages
	1635-1815	1925-2200	Haze(0355)	1/2	017-147	
			Ground fog and haze(0645)	1		
			Haze, 20,000 ft BKN(1245)	4		
			Haze, 15,000 ft OVC(1645)	4		
			Haze, 15,000 ft BKN(1845)	4		
			Haze, 15,000 ft SCT(2200)	4		
11/6/77		2135-0600	Light fog, 100 ft OBSCD(2145)	1/2	354-043	
			Fog, 100 ft OBSCD(2345)	1		
			Fog, 100 ft OBSCD(0145)	1/2		
			Fog, 200 ft OBSCD(0345)			
			Fog, 400 ft OBSCD(0545)	7		

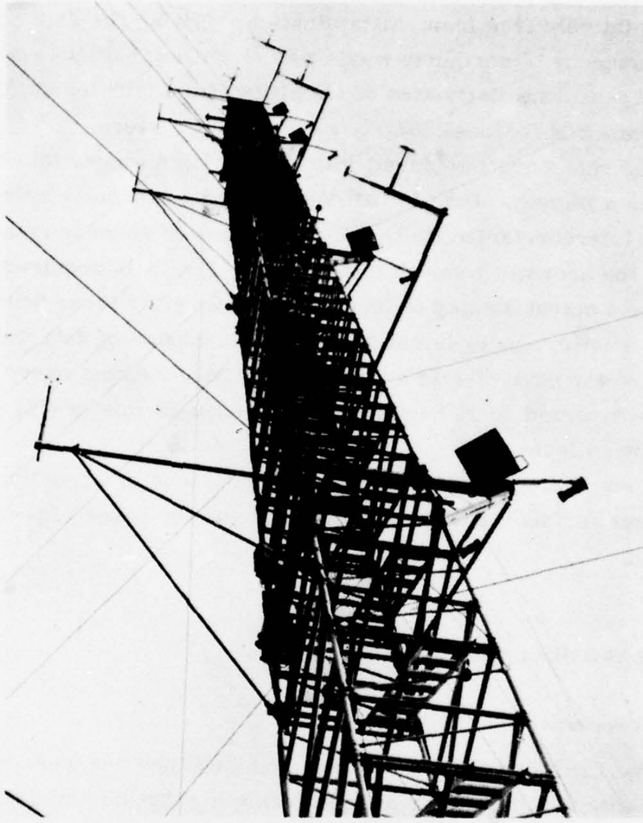


Figure 5. Otis AFB Meteorological Tower and Sensor Array

With the in situ measurement of winds from towers or other fixed structures, care has to be taken to insure that data are not contaminated by shadowing effects.[4,5,6] The type of structure, sensor deployment, wind direction and wind speed are contributing factors to the possible degradation of measurement accuracy. R.M. Young wind measurements from 70 deg through 250 deg in azimuth and Climatronics measurements from 160 deg through 340 deg should, because of their

4. Moses, H., and Daubek, H.G. (1961) Errors in wind measurements associated with tower-mounted anemometers, Bull Amer Meteorol Soc. **42**:190-194.

5. Gill, G.C., Olsson, L.E., Sela, J., and Suda, M. (1967) Accuracy of wind measurements on towers or stacks, Bull. Am. Meteorol. Soc. **48**:665-674.

6. Cermak, J.E., and Horn, J.D. (1968) Tower shadow effects, J. Geophys. Res. **73**:1869-1876.

orientation, be relatively free from contamination. During the data collection period, a high frequency of northerly winds was observed that will reduce the overall correlation of sensors. Estimates of visibility at the four levels of interest were available from EG& G Model 207 Forward Scatter Meters.

Tower instruments were interfaced with a Doric data logger (Model 240) and sampled ten times a minute. Data for all sensors were normally averaged over a 5-min period for intercomparison with LDV and acoustic sounder measurements. For operation of the acoustic sounder in real time, 1 min is required for internal data processing and output display to the teleprinter. After these housekeeping operations, the acoustic sounder is ready for another period of data acquisition. For comparison with tower data, 4-min averages were taken during every 5-min period, except for one 3-hr period on 15 September 1977 when 10-min averages of acoustic sounder data were collected.

Table 1 is a summary of the tests during which laser or acoustic measurements were taken. Local surface weather observations and the range of wind directions are also provided.

4. TEST RESULTS AND DISCUSSION

4.1 Laser Doppler Velocimeter

Testing of the LDV system was delayed for more than one week by the contractor due to problems with both hardware and programming that obviated the acquisition of data in real time. On-line processing of LDV data was not available until 10 September 1977. The first two data collection periods reported, namely 30 August 1977 and 2 September 1977, were recorded on magnetic tape and later processed by the contractor. Subsequent comparison of LDV and tower data for these runs yielded a discrepancy in wind speed which has been attributed by the contractor to an incorrectly positioned elevation angle mirror. This would result in an error proportional to the magnitude of the wind speed but would not have an effect upon the measurement of azimuth. Figures A1 and A2 are time series comparisons of laser and tower wind speed and wind direction measurements for 30 August 1977. Figure A3 shows scatter diagrams of the wind speed data. It may be noted that the agreement between the two sensors is relatively good for azimuth while an offset is present in wind speed. A similar discrepancy is apparent in the data for 2 September 1977 that is shown in Figures A4 and A5. As the elevation angle mirror was not checked and repositioned until 5 September 1977, wind speed data for these two collection periods are unreliable and were not averaged into the overall field program statistics. For other runs, scatter diagrams of LDV and tower measurements are shown in

Figure A6. The average deviation for all runs is ± 1.0 m/sec in wind speed and ±7 deg in azimuth. A summary of the data analysis for individual LDV runs is given in Table 2.

Table 2. Summary of LDV and Tower Wind Measurements

Run	Speed, m/sec		Direction, deg	
	Average Difference	Standard Deviation	Average Difference	Standard Deviation
8/30/77	--	--	3	3
9/2/77	--	--	7	2
9/10/77	0.9	0.7	10	5
9/11/77	0.4	0.3	8	6
9/12/77	1.4	0.4	4	2
9/15/77	0.7	0.6	5	4
9/15/77	1.5	0.6	12	8
9/15/77	1.2	0.3	5	4

LVD signal strength during fog episodes was strong and more than adequate to penetrate beyond the height of the 61-m meteorological tower. The upper altitude range of operation in deep fogs has not been established due to a lack of corroborative data.

Though not a limitation for use in a fog dispersal system, the present conical scan sampling rate of 5 sec could be a limitation for applications which require a more rapid instrument response. For this field program four to six altitude levels were scanned for 5-min averages, thus providing 10 to 15 data points per averaging period. Increasing the time averaging period or monitoring fewer levels would be expected to reduce the experimental scatter and improve correlation. Shadowing of the tower anemometers during a considerable portion of these tests must certainly affect to an unpredictable extent their correlation with both the laser and acoustic sounders. This problem could, of course, be virtually eliminated in future such tests by instrumenting opposite faces of the tower and using data from those sensors more favorably presented to the prevailing winds.

Though it is not expected to pose a serious problem, for LDV use at airfield environments where aircraft intrusion into the range of the sensor is a possibility, scrutiny should be given to aspects of possible eye safety hazard. Since the source is a 20-W CO_2 laser this will not be a concern to closed cockpit-type aircraft where IR radiation would be blocked out by windows and windshields. This might not be the situation for a helicopter. However, for this to present a problem, an individual would have to be within the laser's focal volume (which varies as the square of the range) the position of which is highly transient in the conical scan mode.

4.2 Acoustic Doppler Wind Sounder

The first test run of the acoustic wind sounder for which intercomparison tower data are available was on 10 September 1977. Figure A7 shows scatter diagrams for all runs of acoustic wind speed vs tower anemometer measurements. The runs of 15 September 1977 (1250-1500 EDT) and 6 and 7 November 1977 (2135-0600 EST) were evaluated using the Climatronics Wind Set measurements. Due to the prevailing northerly winds during these runs, the position of these sensors were somewhat more favorable than those of the R. M. Young wind sets. All acoustic sounder runs were taken using 5-min averaging periods except for the run of 15 September 1977 (1250-1550 EDT) that was averaged over 10-min intervals. The deviation of all runs using 5-min averages was ± 0.9 m/sec in wind speed and ± 13 deg in azimuth. With one run omitted, the deviation in azimuth is ± 9 deg. For the run of 15 September 1977, when 10-min averages were used, the deviation in speed was ± 0.6 m/sec and ± 6 deg in azimuth. Data for individual runs are provided in Table 3.

Table 3. Summary of ADWS and Tower Wind Measurements

	Speed, m/sec		Direction, deg	
Run	Average Difference	Standard Deviation	Average Difference	Standard Deviation
9/10/77	1.4	0.7	4	3
9/11/77	1.2	0.7	5	4
9/12/77	0.7	0.5	12	7
9/15/77	0.9	0.8	7	6
9/15/77	0.6	0.5	6	4
9/15/77	0.7	0.6	34	27
10/6/77	0.6	0.4	17	5

The utility of the acoustic sounder during fog dispersal operations that involve the use of large combustors for heat production has not yet been determined Noise generated by light rain was not found to adversely affect sounder operation. Even intense jet aircraft noise in the vicinity of the receiver beam width, if of short duration relative to the time-averaging period, can be tolerated. However, intense and sustained high-level noise, such as that generated by combustor operation, might be expected to unacceptably degrade the acoustic measurements of winds.

Though the acoustic sounder was deployed in these tests to optimize the acquisition of wind data to 80 m for use in fog dispersal, this should not be construed as being its upper limit. It is expected that by extending the baseline distance between transmitter and receiver the range can be doubled. Wind sounding to greater altitudes should be possible through the incorporation of additional acoustic drivers.

References

1. Brashears, M. R., and Eberle, W. R. (1977) Verification of Wind Measurement with Mobile Laser Doppler System, Report No. FAA-RD-77-117

2. Brashears, M. R., and Eberle, W. R. (1977) Verification of Wind Measurement to 450 Meter Altitude with Mobile Laser Doppler System, Report No. FAA-RD-77-181.

3. Kaimal, J. C., and Haugen, D. A. (1970) An acoustic Doppler sounder for measuring wind profiles in the lower boundary layer, J. Appl. Meteorol. **16**:1289-1305.

4. Moses, H., and Daubek, H. G. (1961) Errors in wind measurements associated with tower-mounted anemometers, Bull Amer Meteorol Soc. **42**:190-194.

5. Gill, G. C., Olsson, L. E., Sela, J., and Suda, M. (1967) Accuracy of wind measurements on towers or stacks, Bull. Am. Meteorol. Soc. **48**:665-674.

6. Cermak, J. E., and Horn, J. D. (1968) Tower shadow effects, J. Geophys. Res. **73**:1869-1876.

Appendix A

Field Test Data

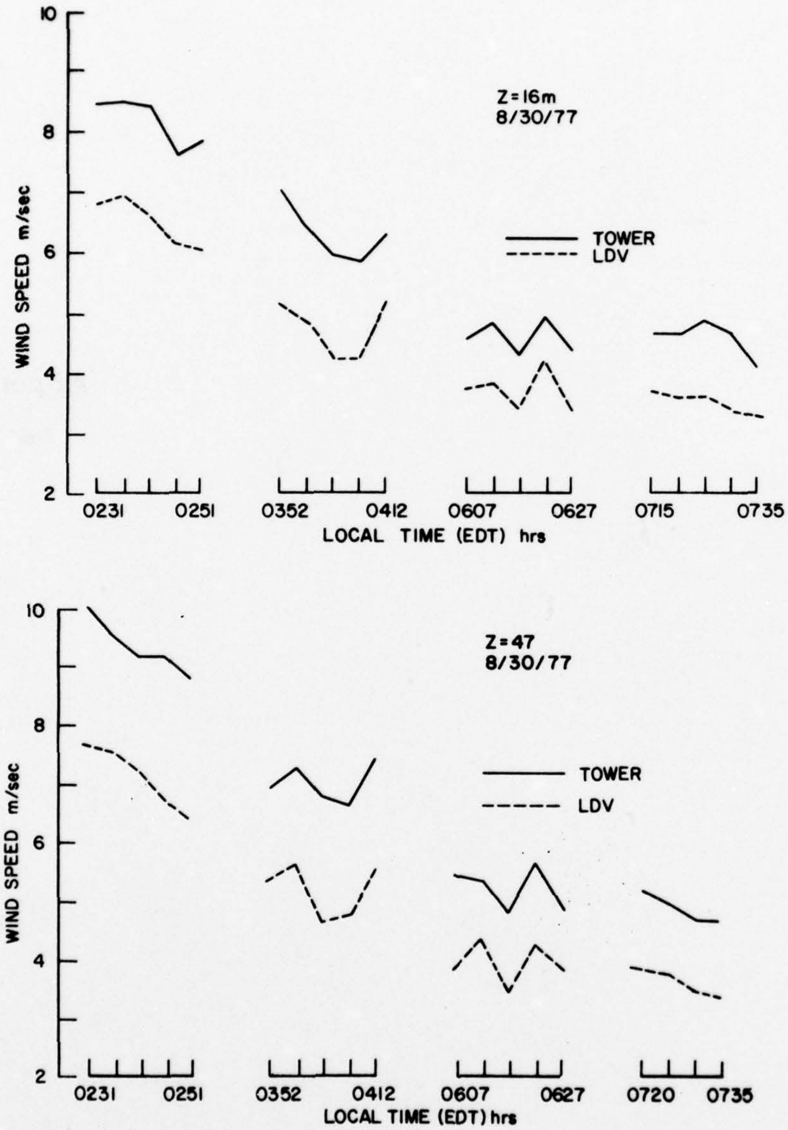


Figure A1. Time Series Comparison of Tower and LDV Wind Speed Measurements

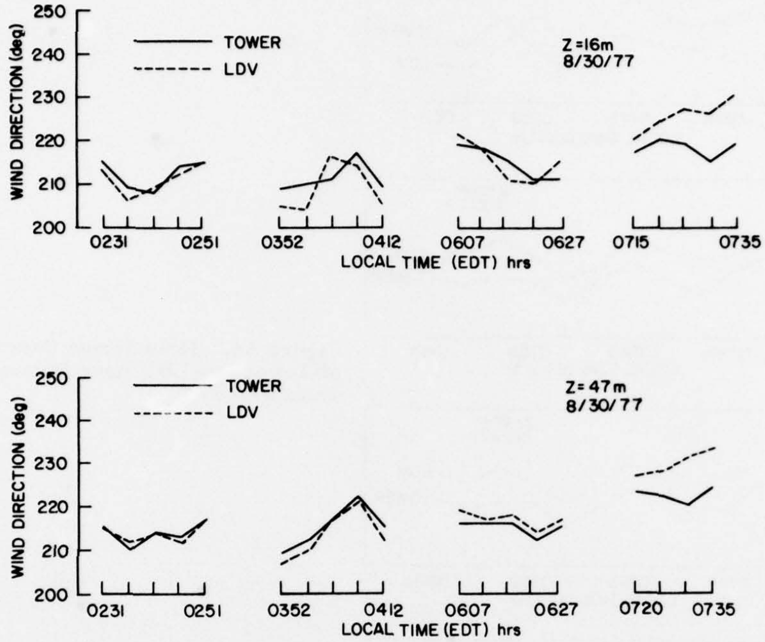


Figure A2. Time Series Comparison of Tower and LDV Wind Direction Measurements

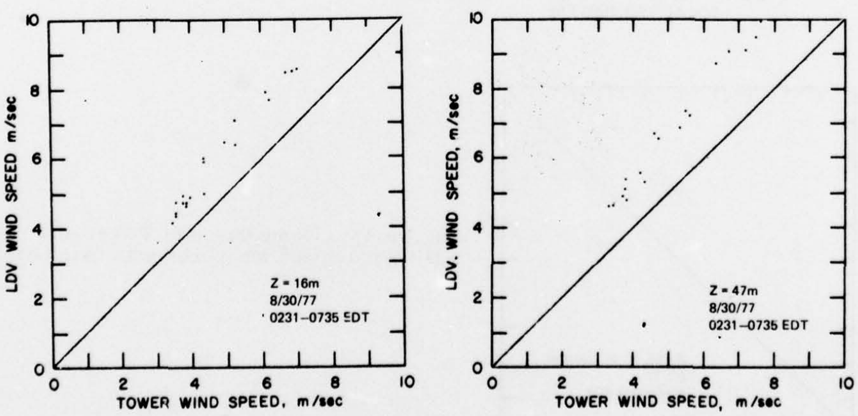


Figure A3. Comparison of Tower and LDV Wind Speed Measurements

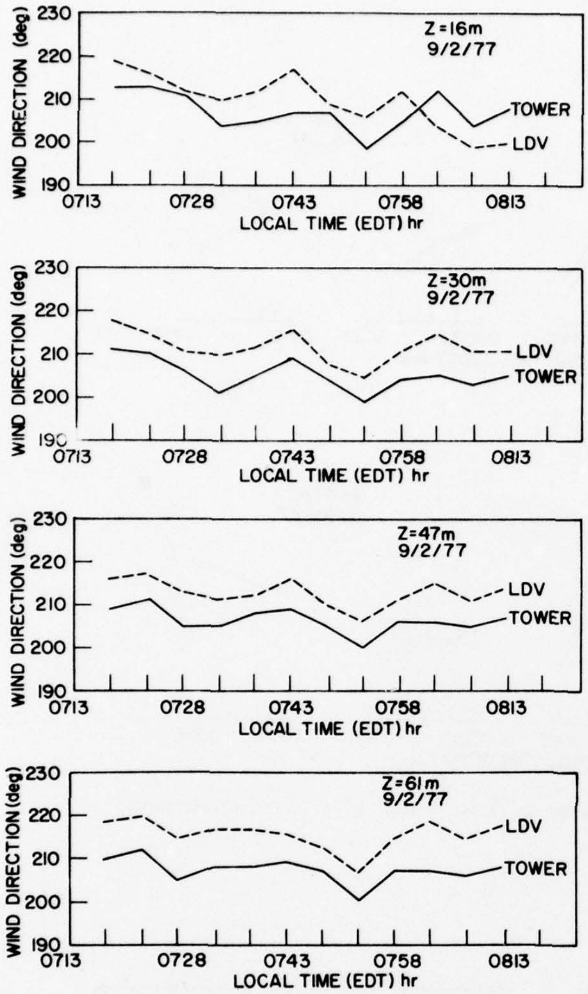


Figure A4. Time Series Comparison of Tower and LDV Wind Direction Measurements

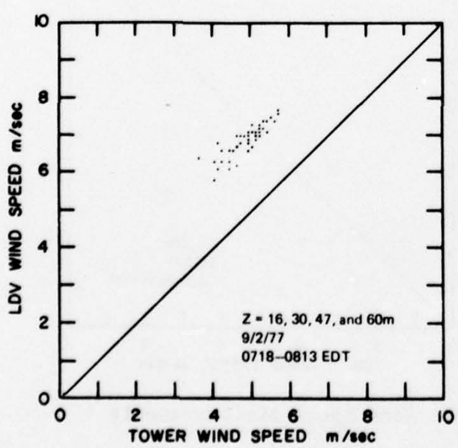


Figure A5. Comparison of Tower and LDV Wind Speed Measurements (All Levels)

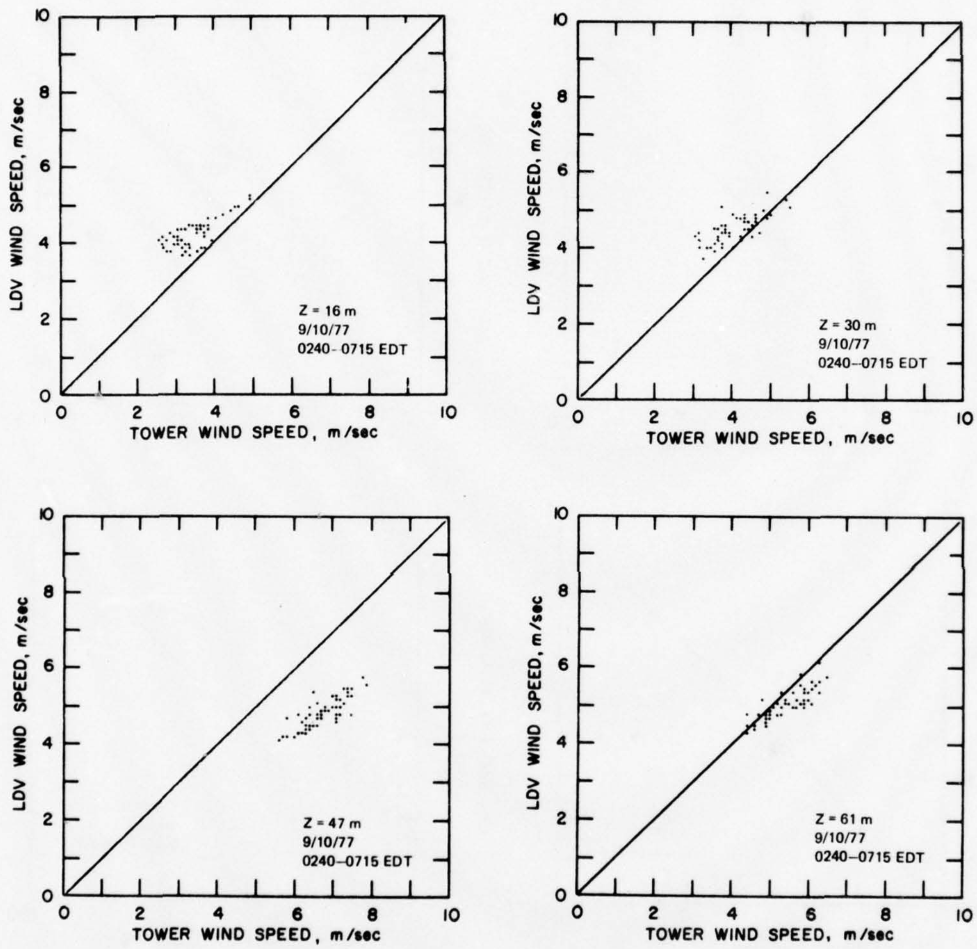


Figure A6. Comparison of Tower and LDV Wind Measurements

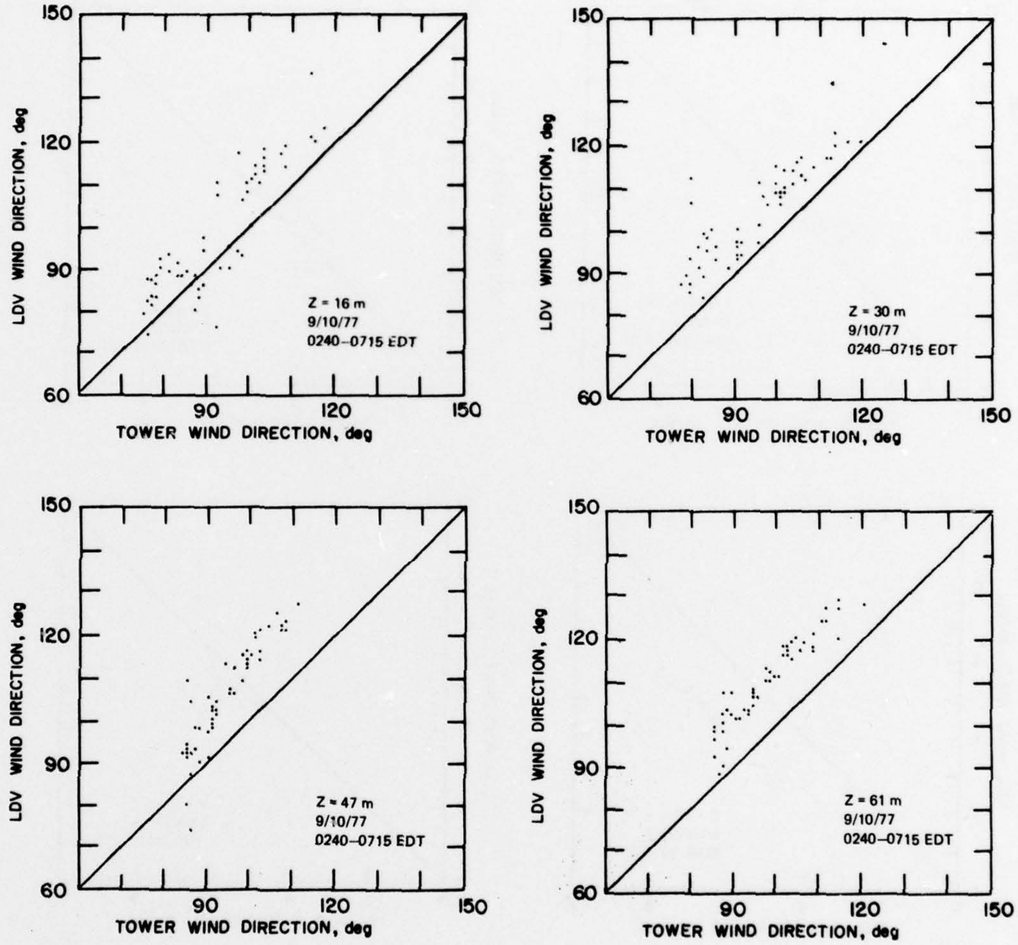


Figure A6. (Cont)

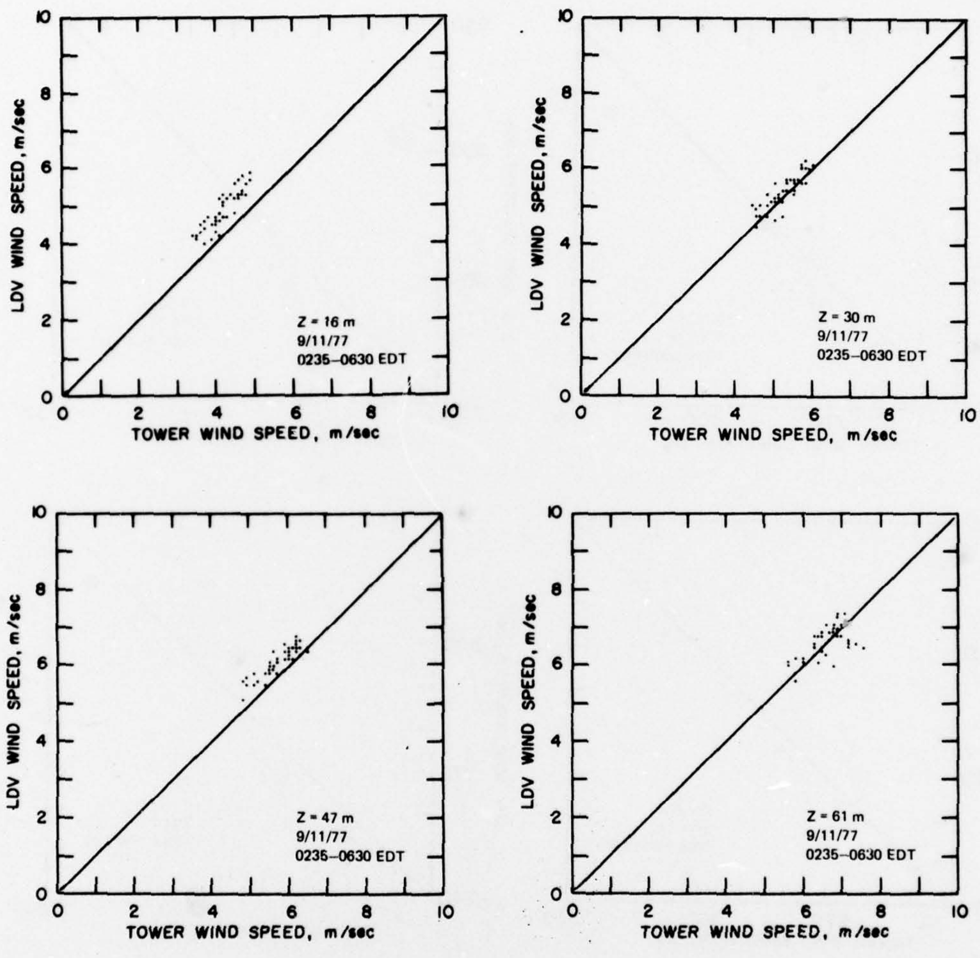
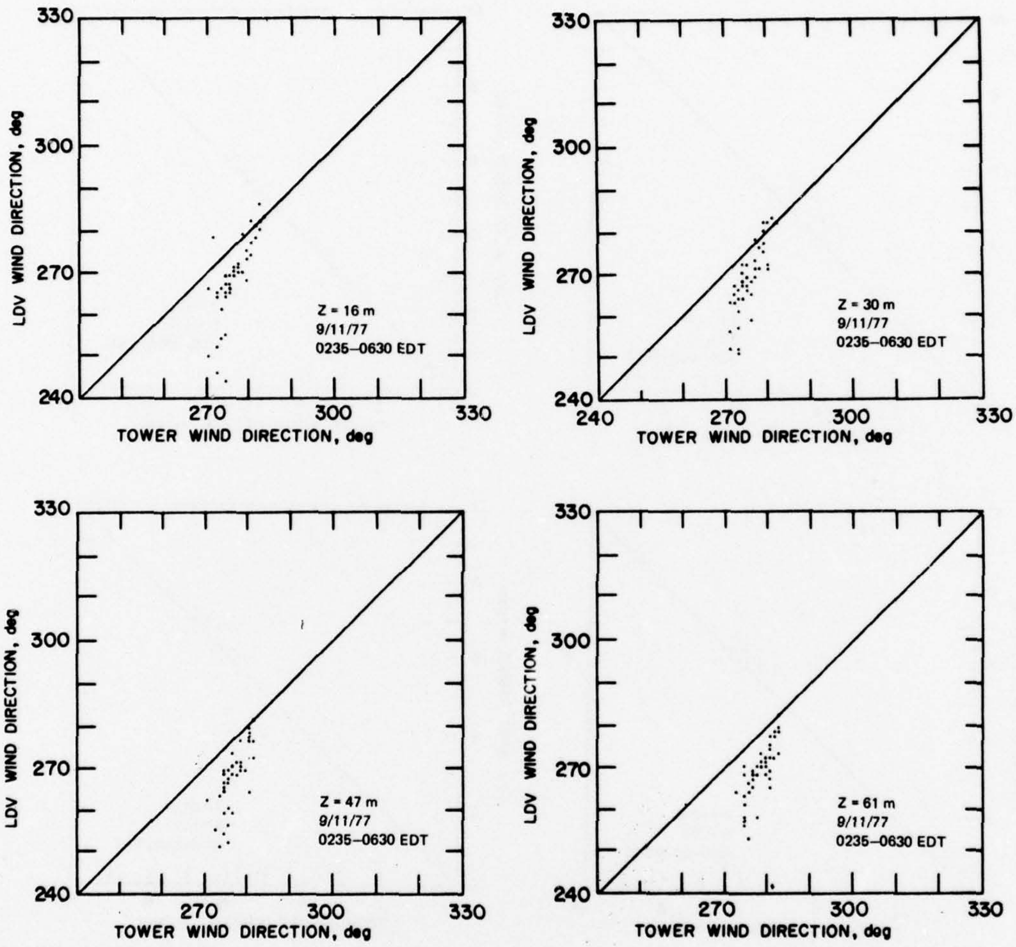


Figure A6. (Cont)



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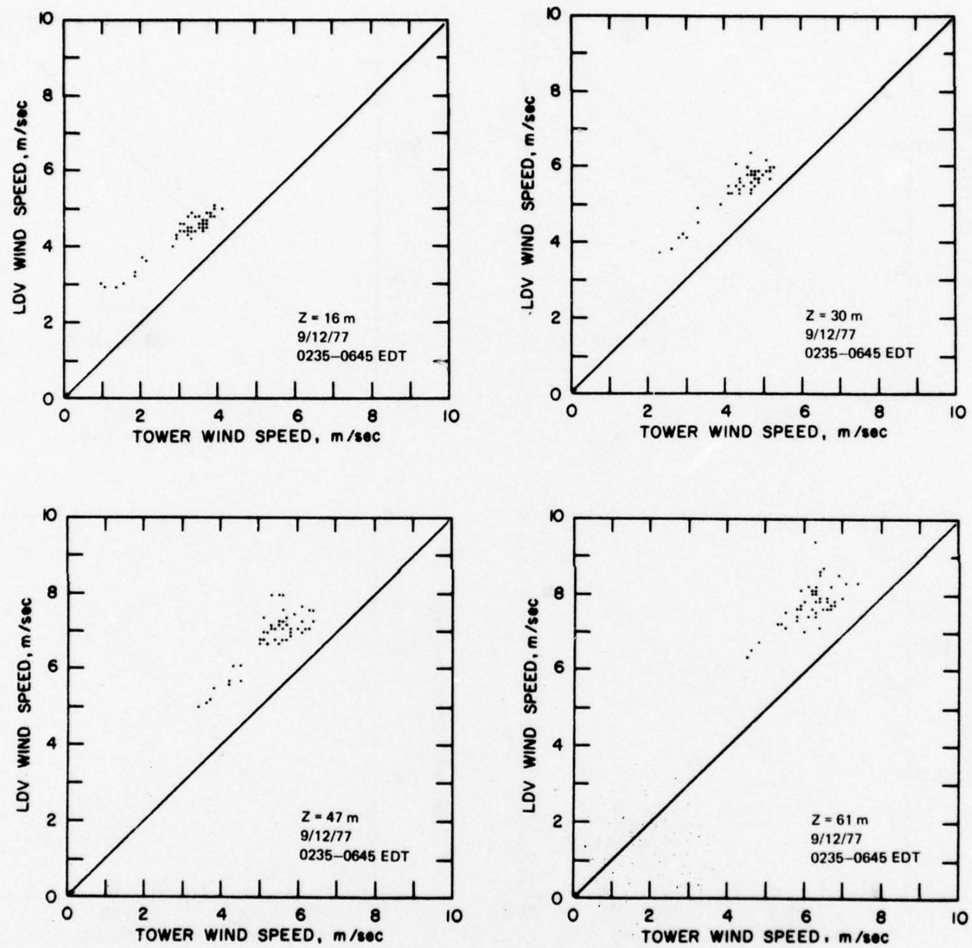

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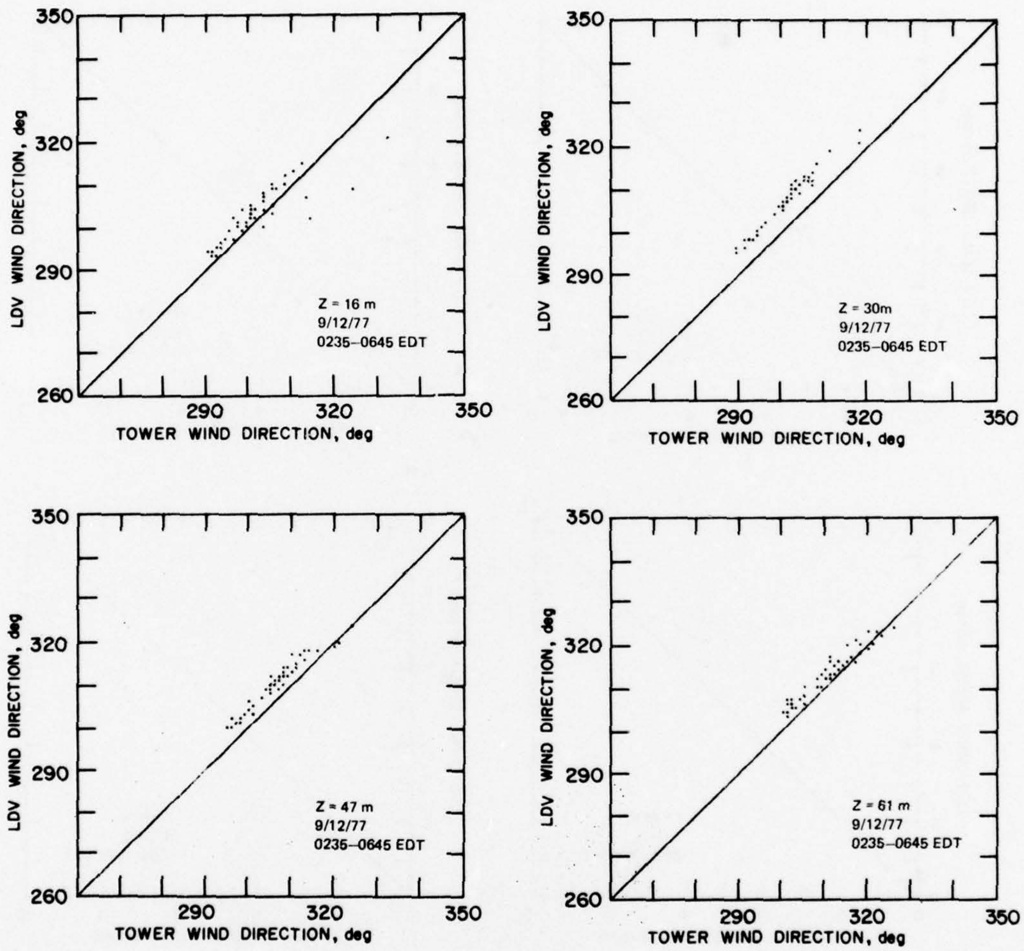

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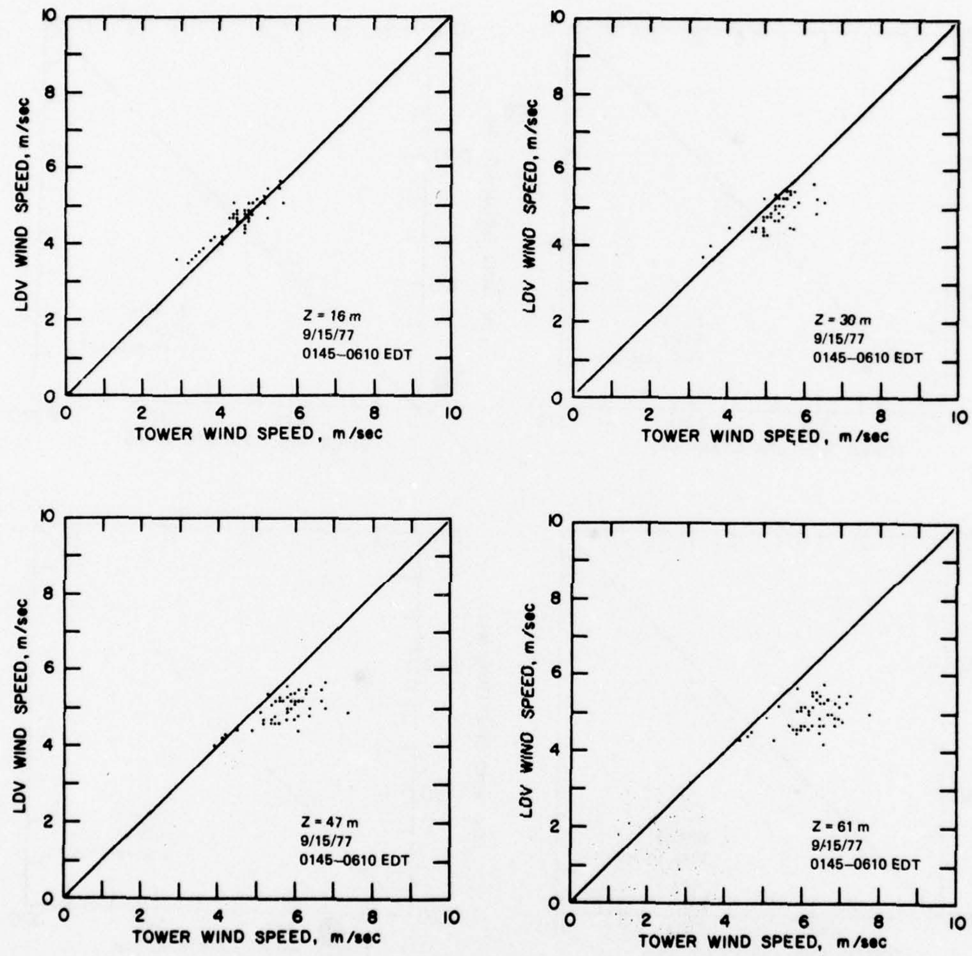

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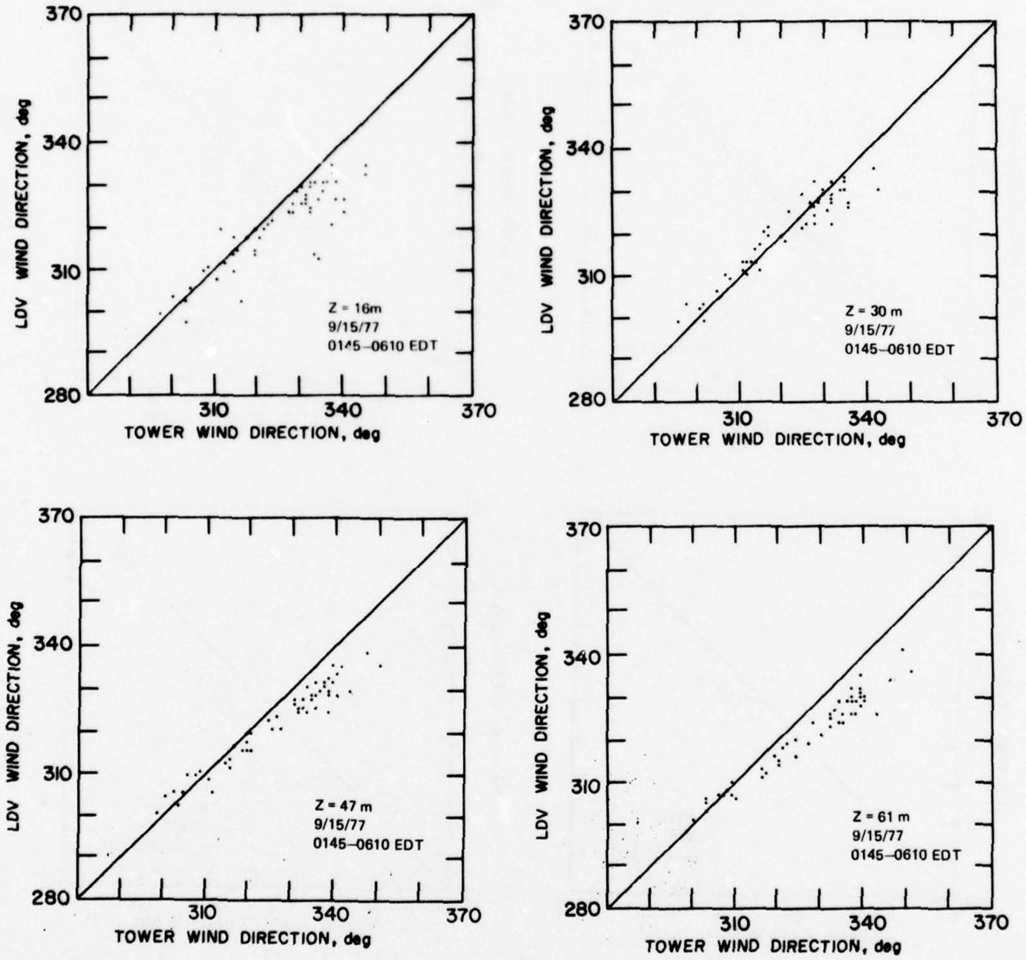

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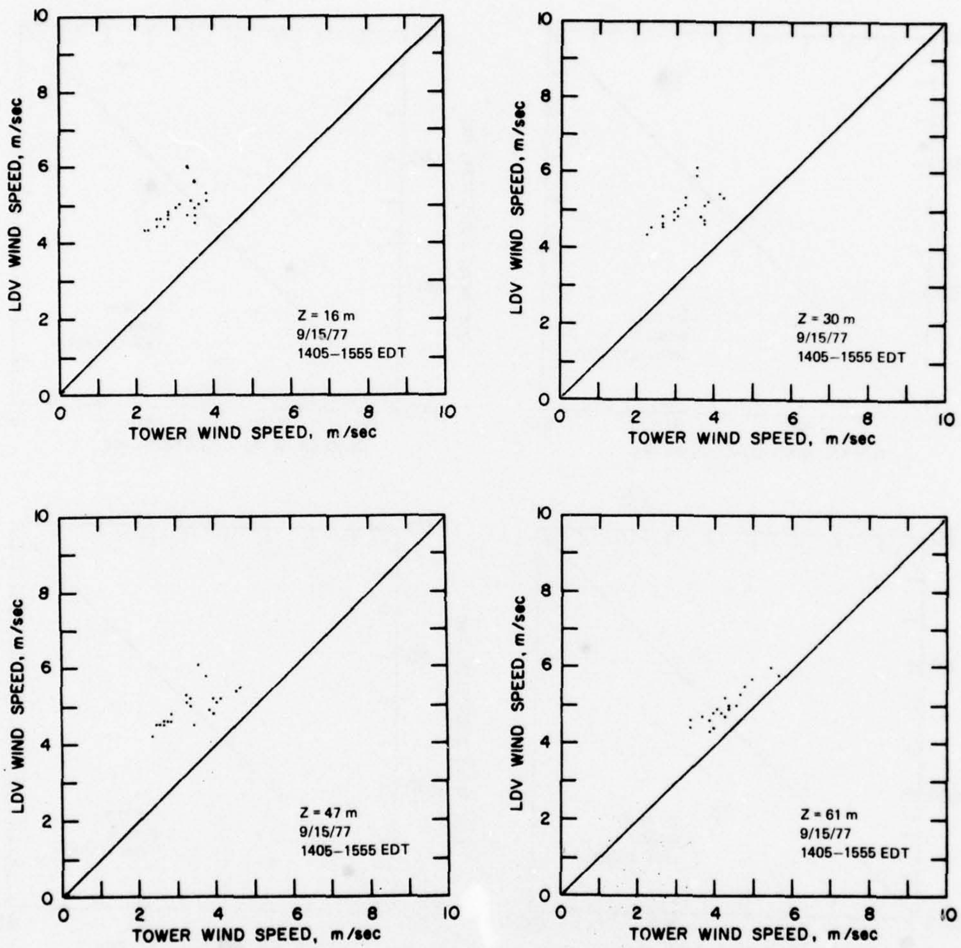

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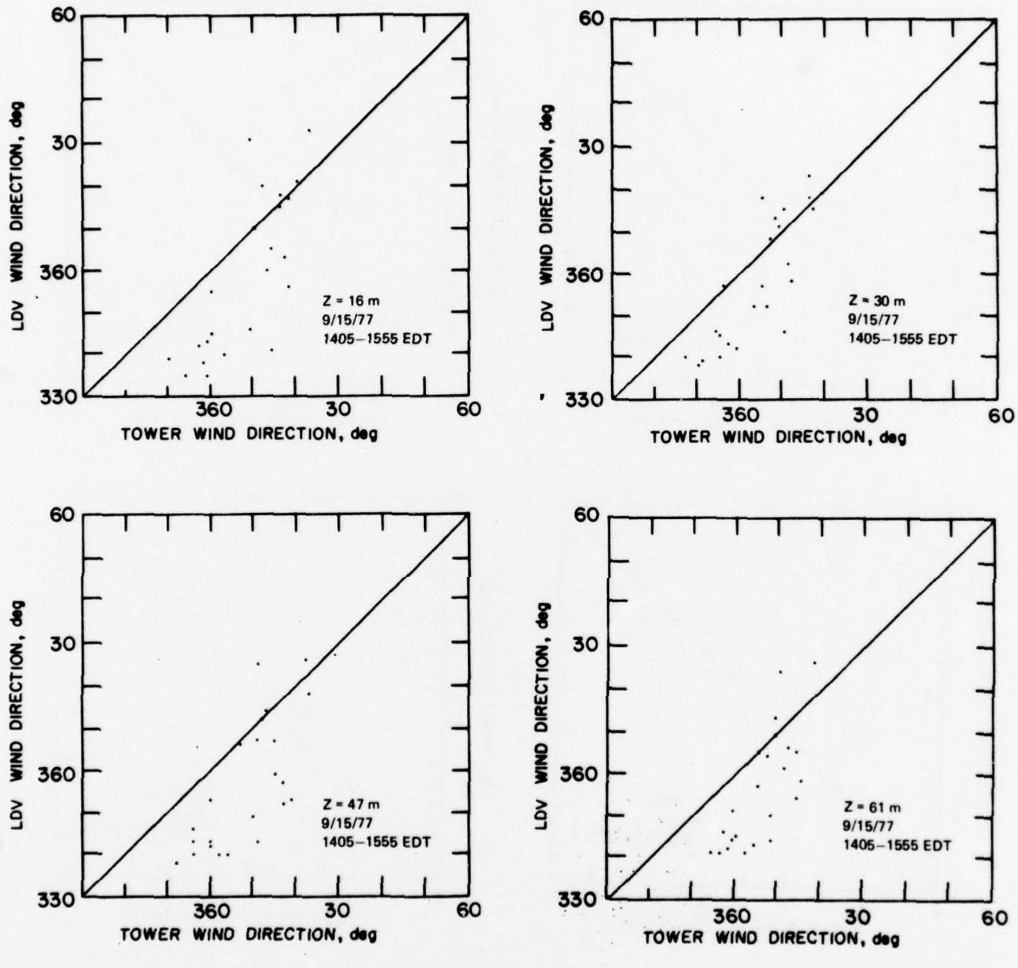

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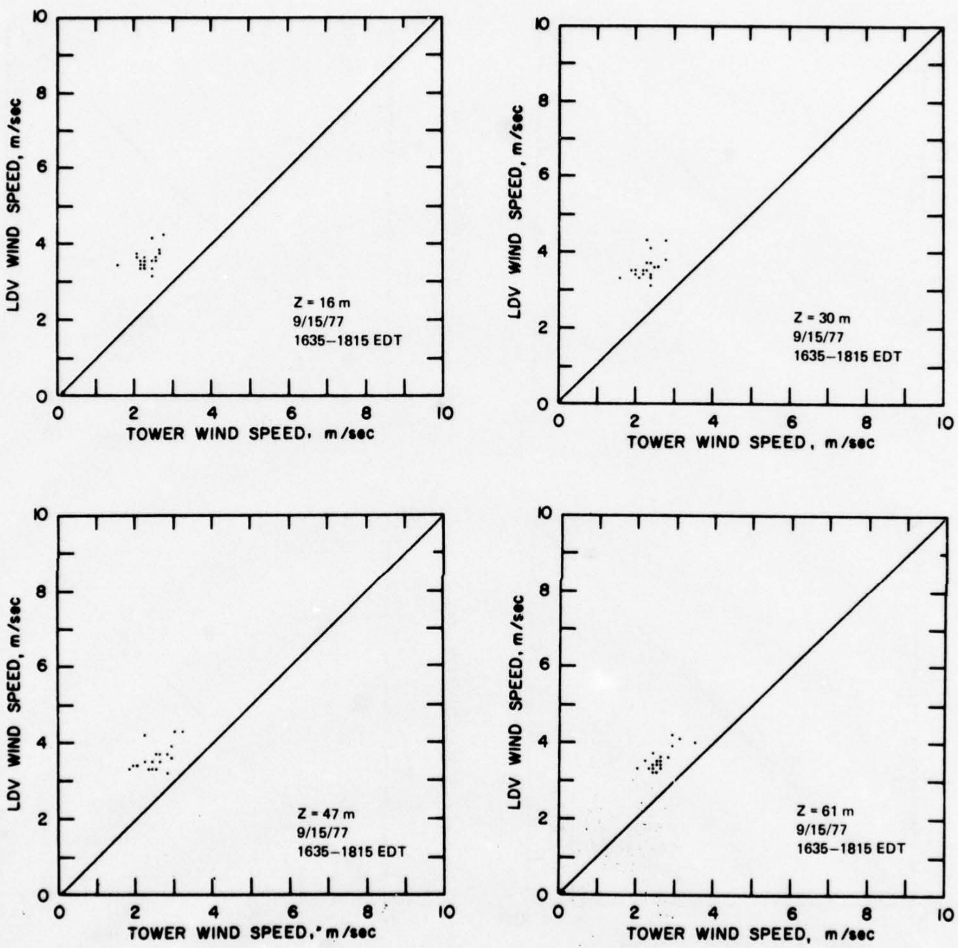

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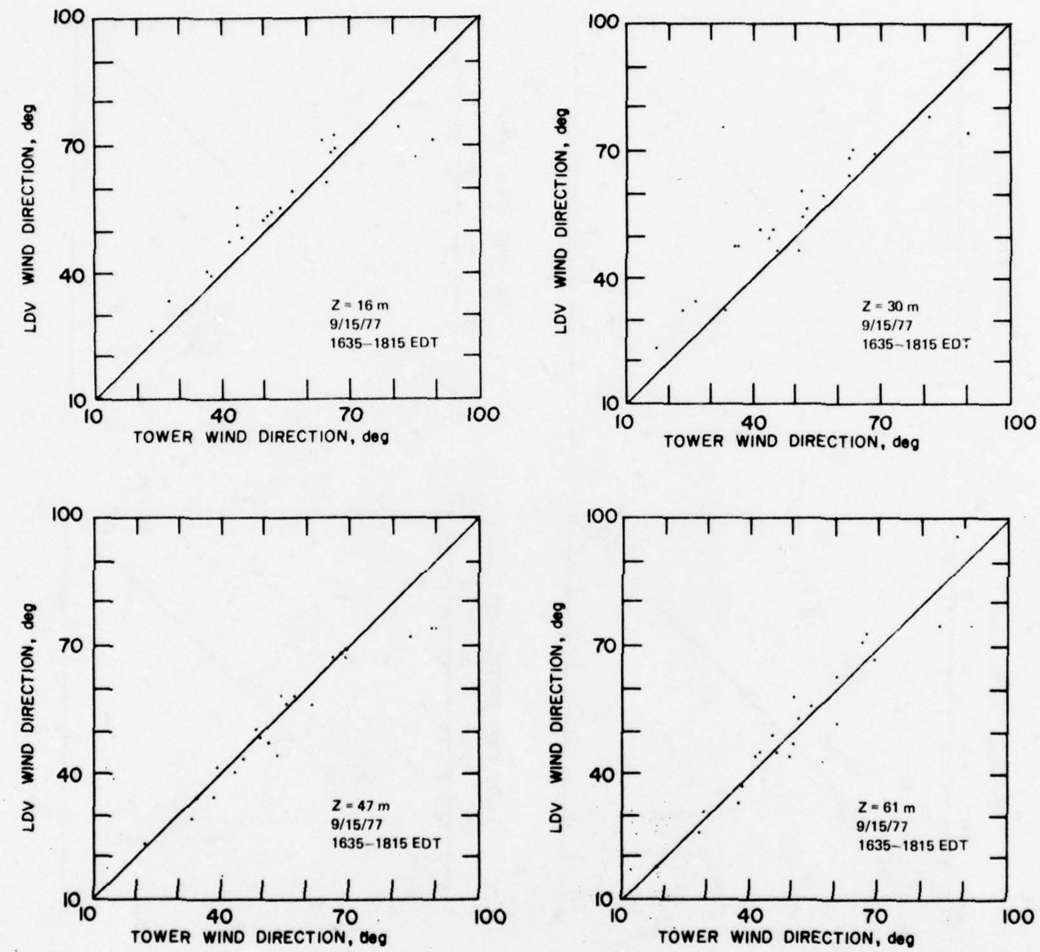

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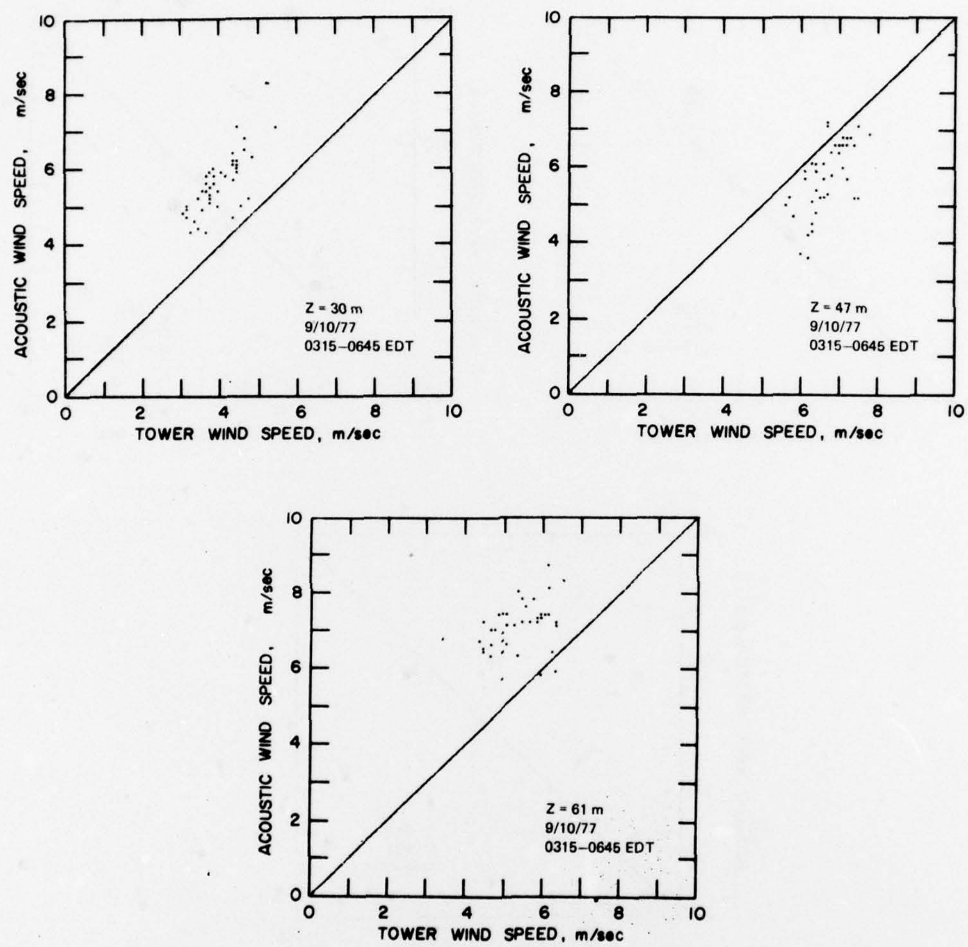
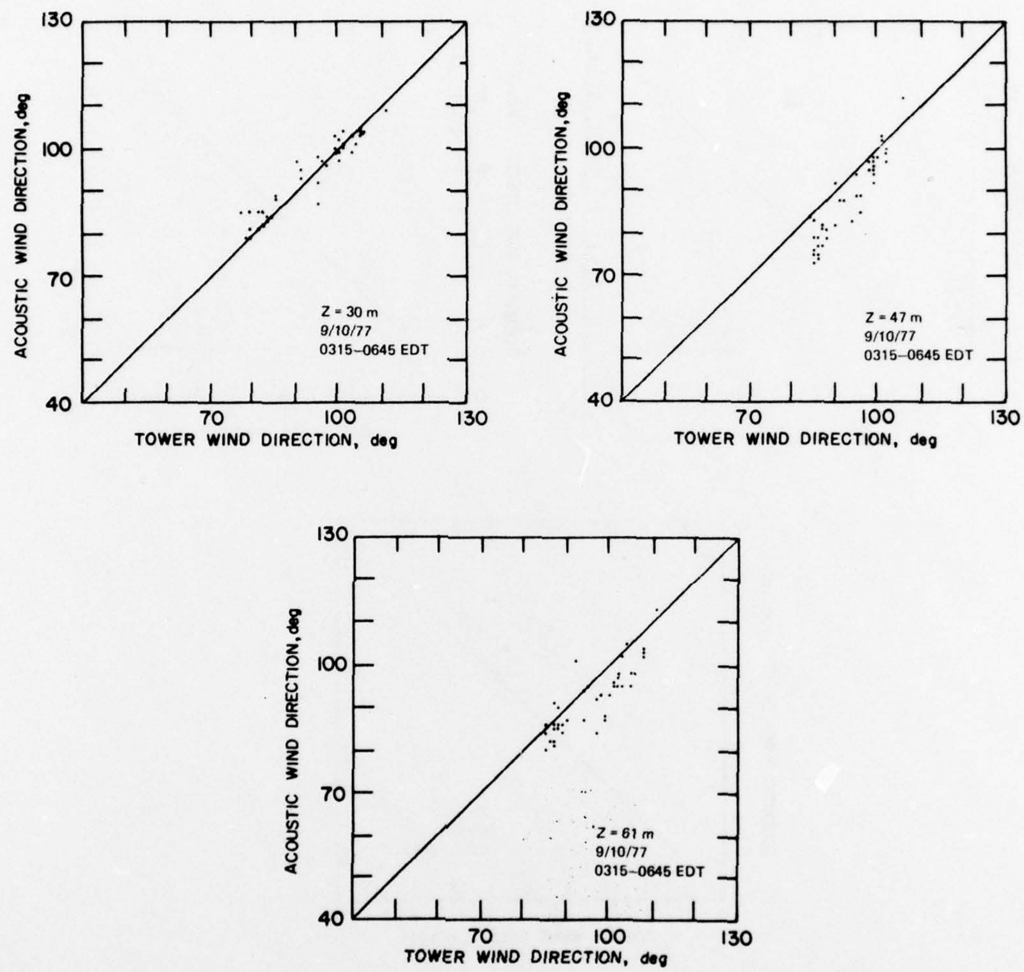


Figure A7. Comparison of Tower and ADWS Wind Measurements



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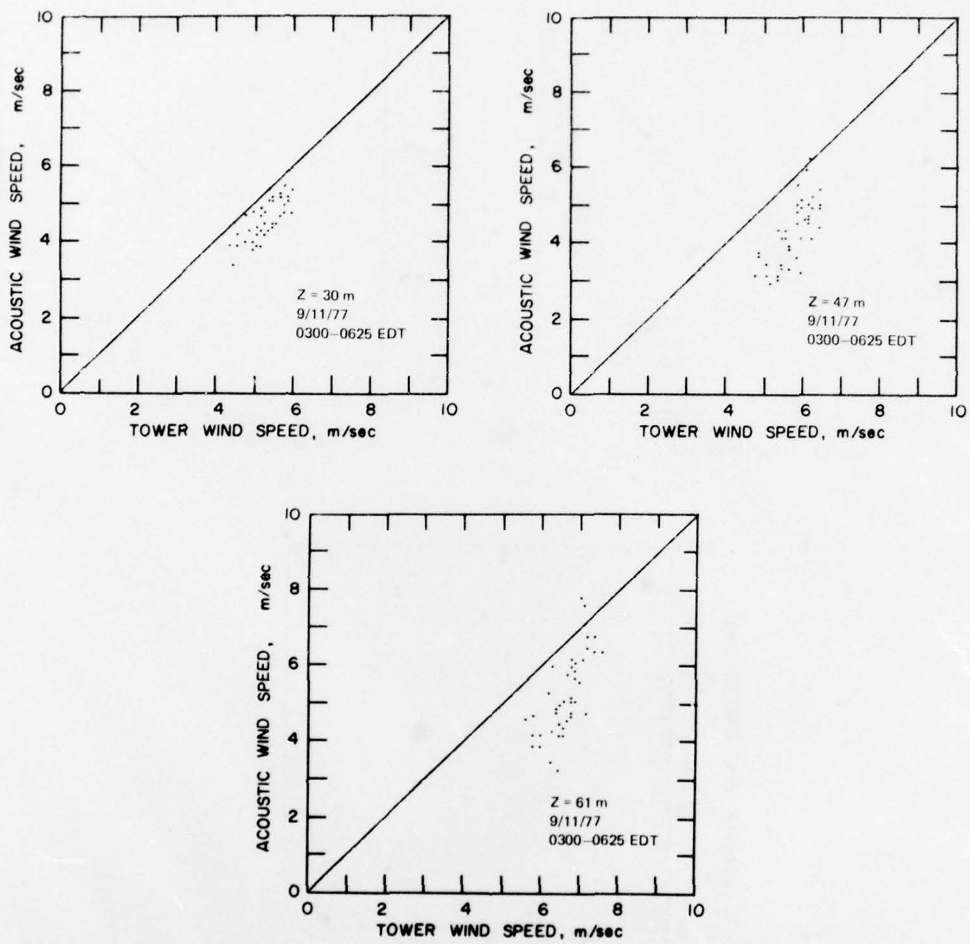

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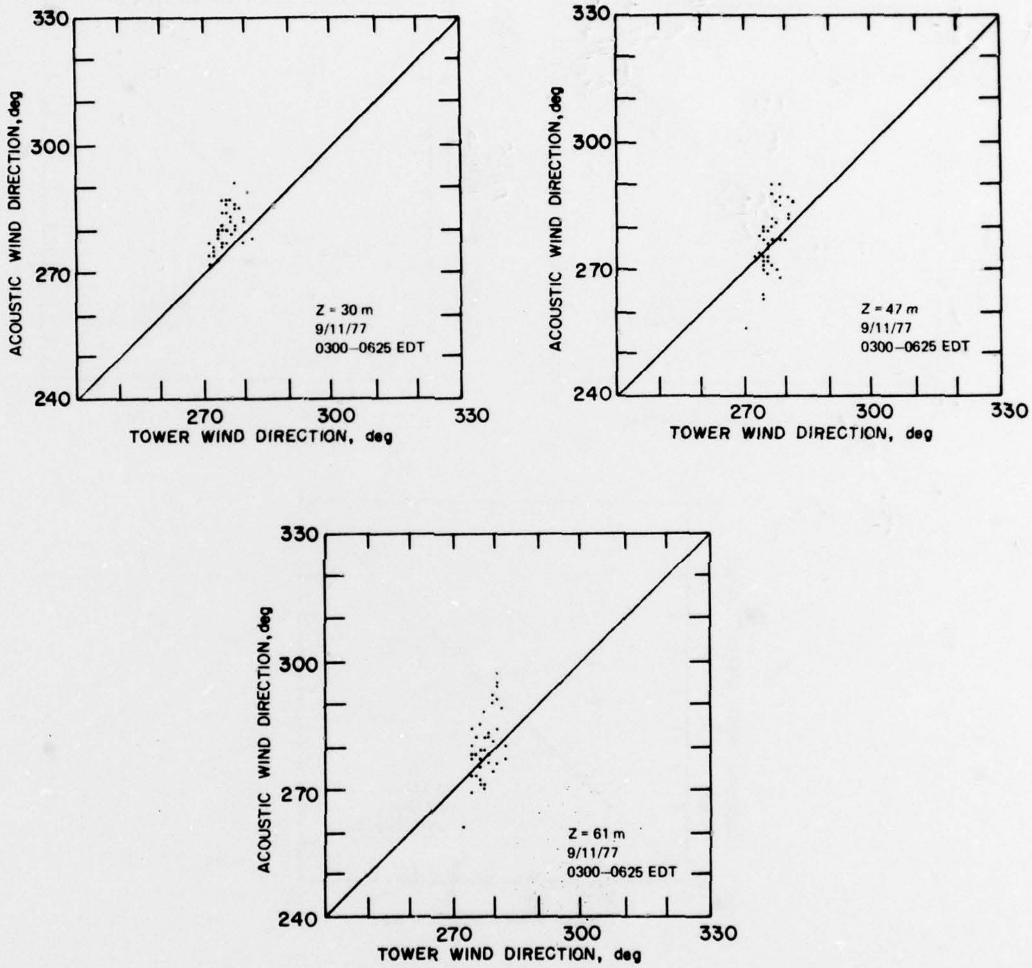

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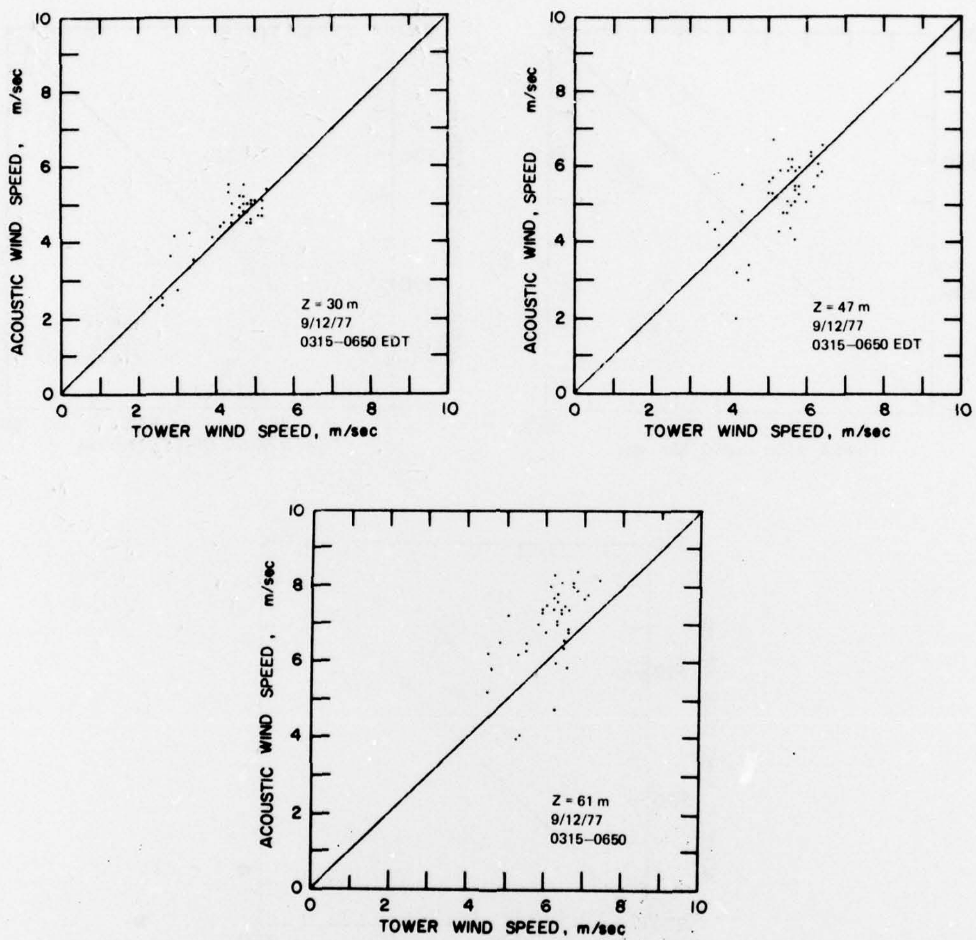

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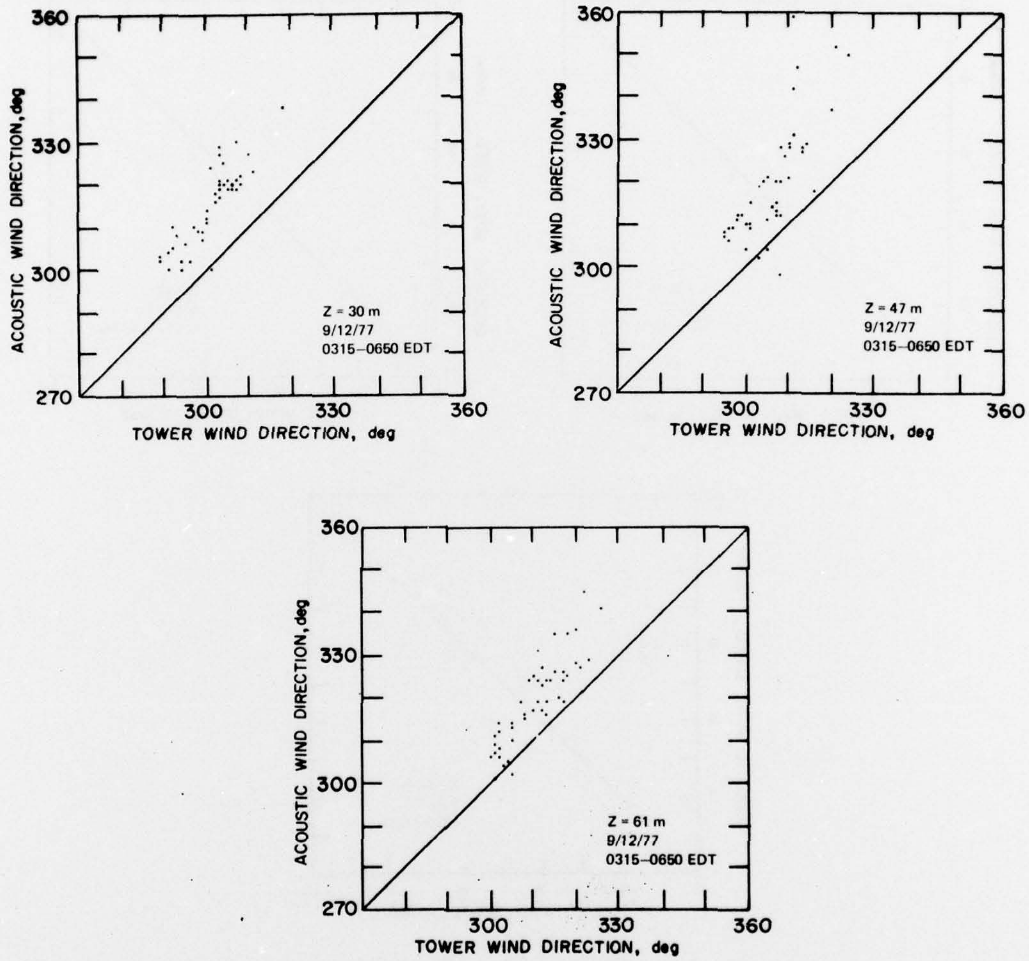

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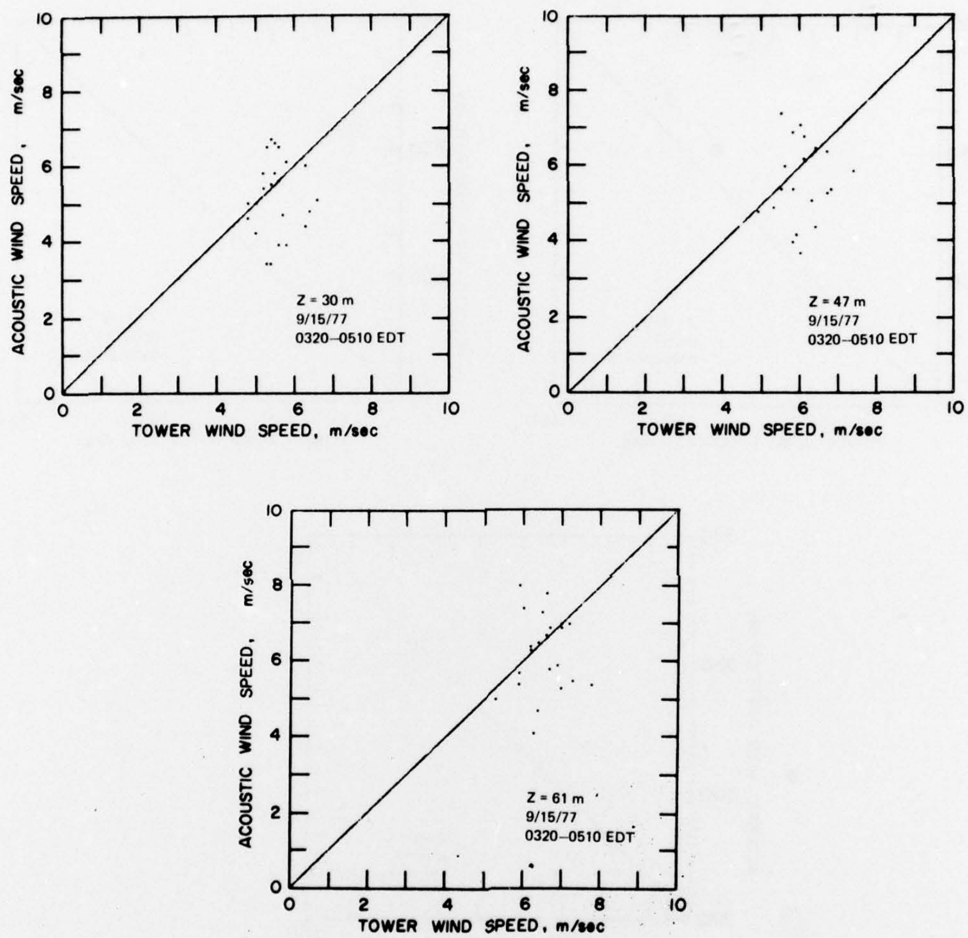

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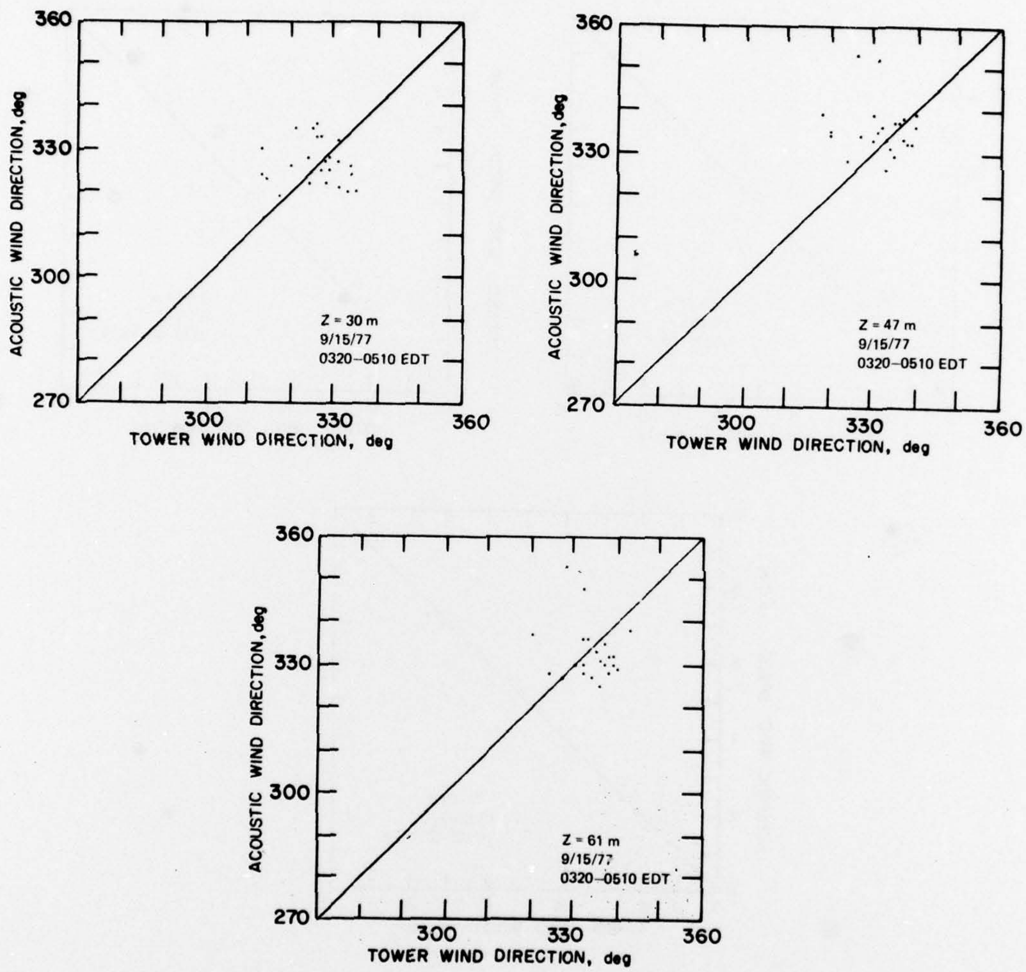

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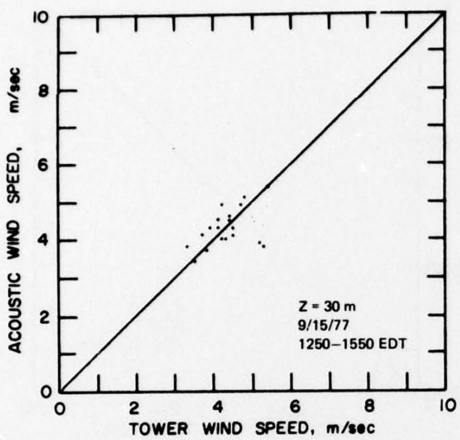

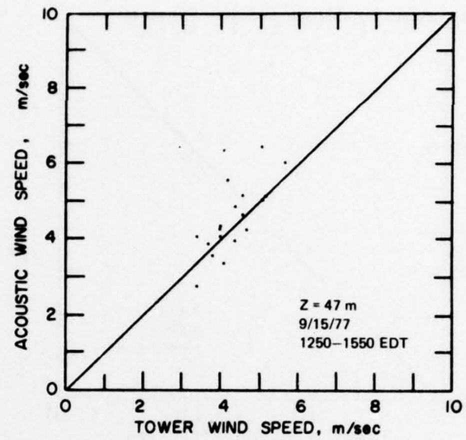

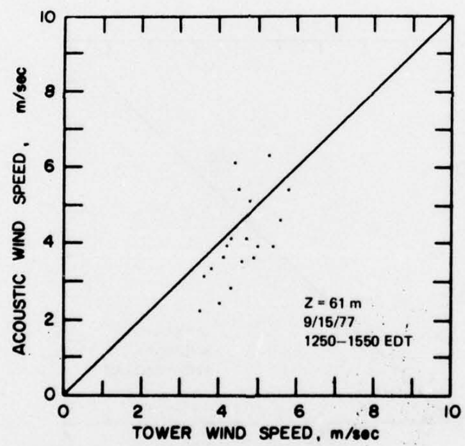

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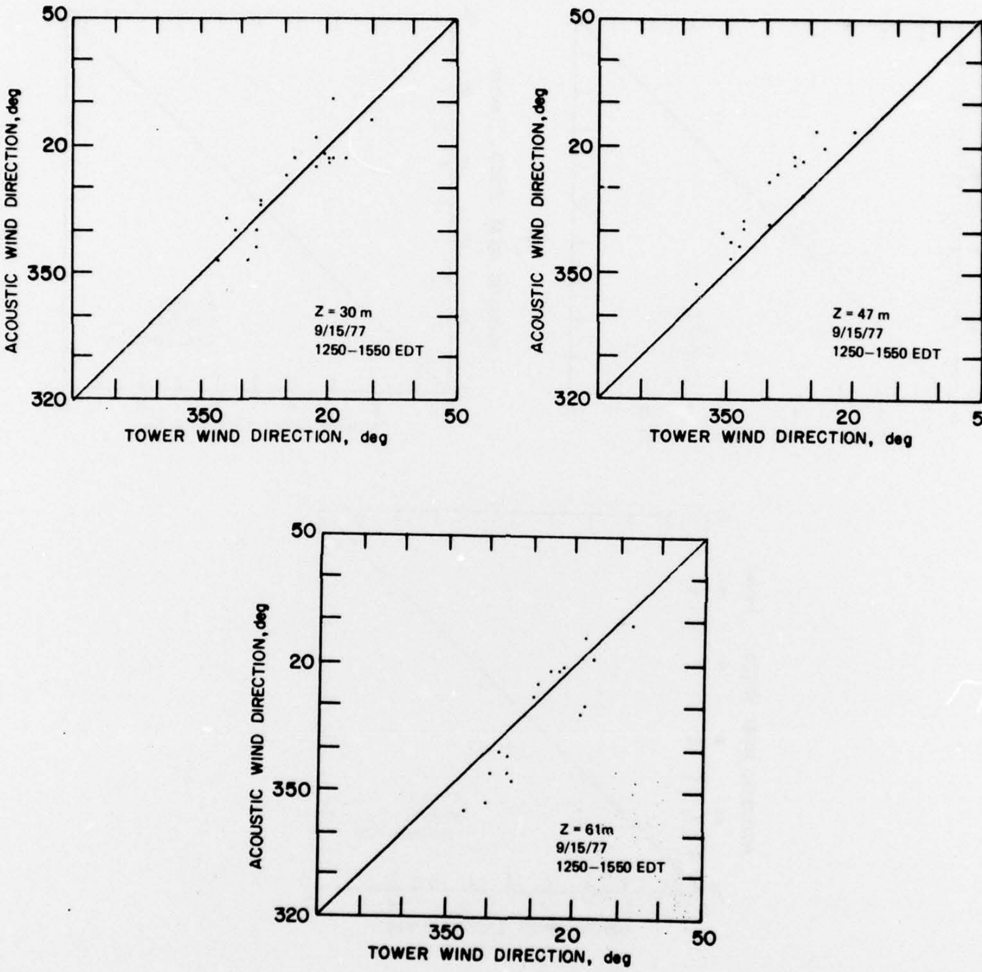

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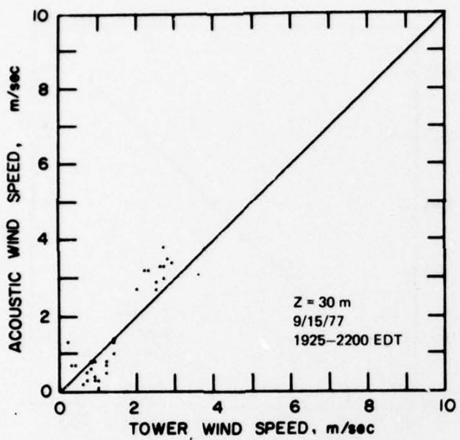

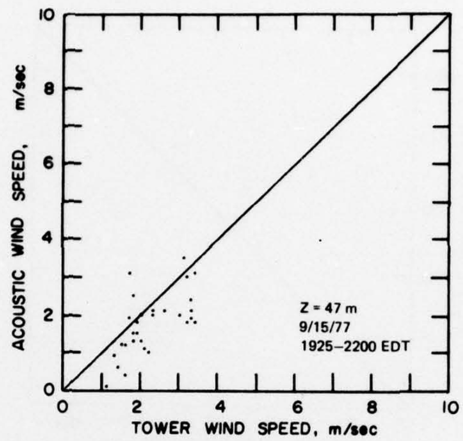

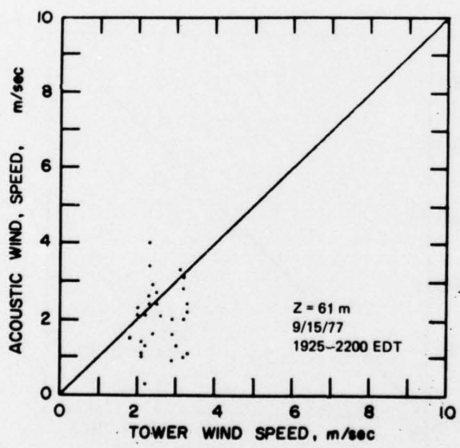

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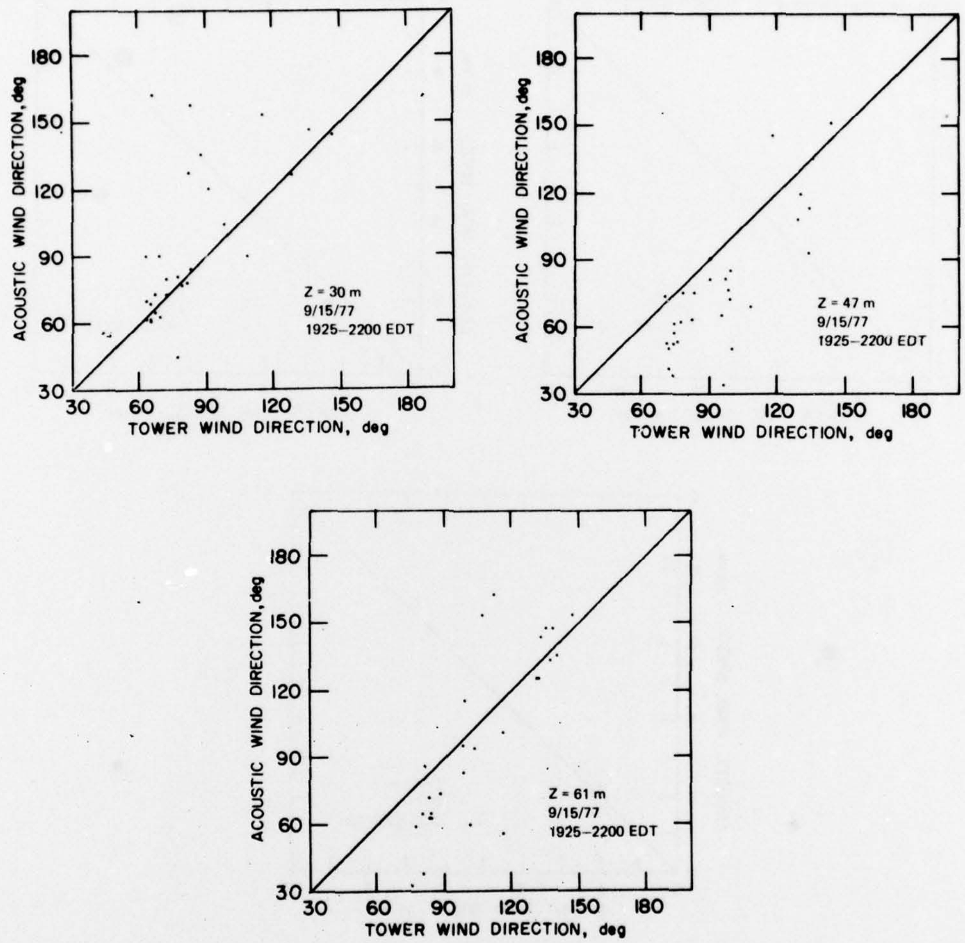

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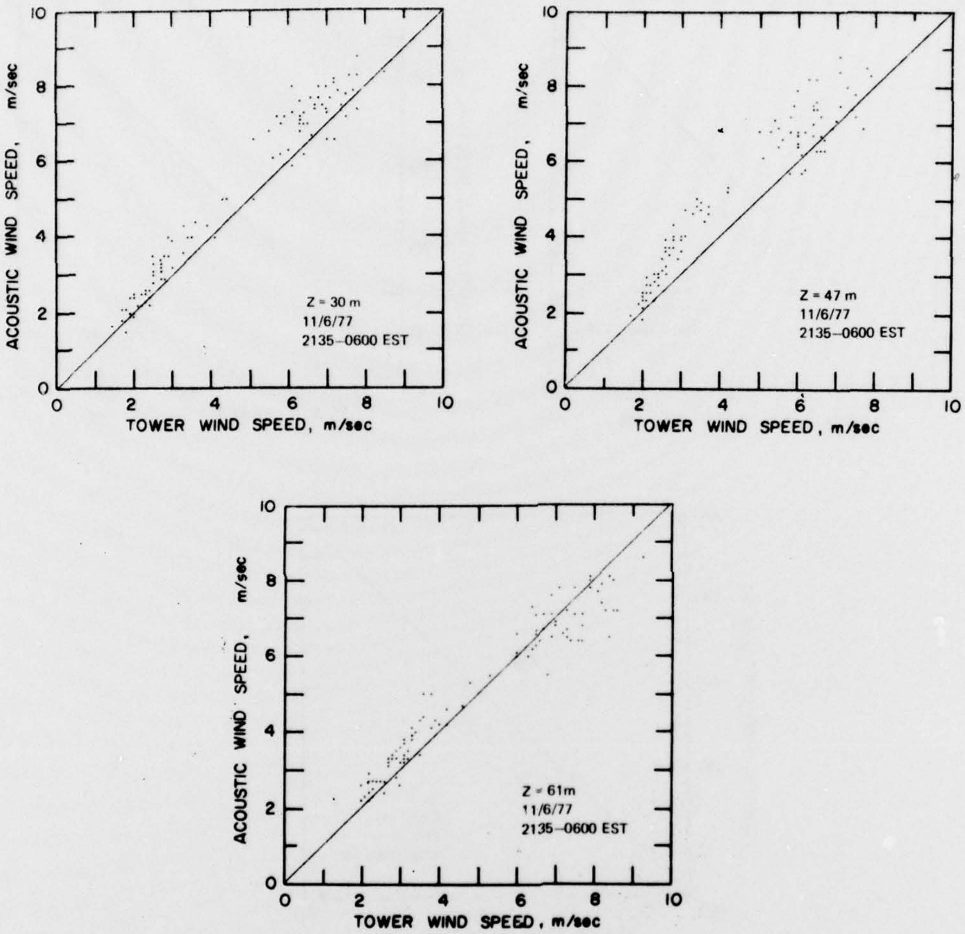

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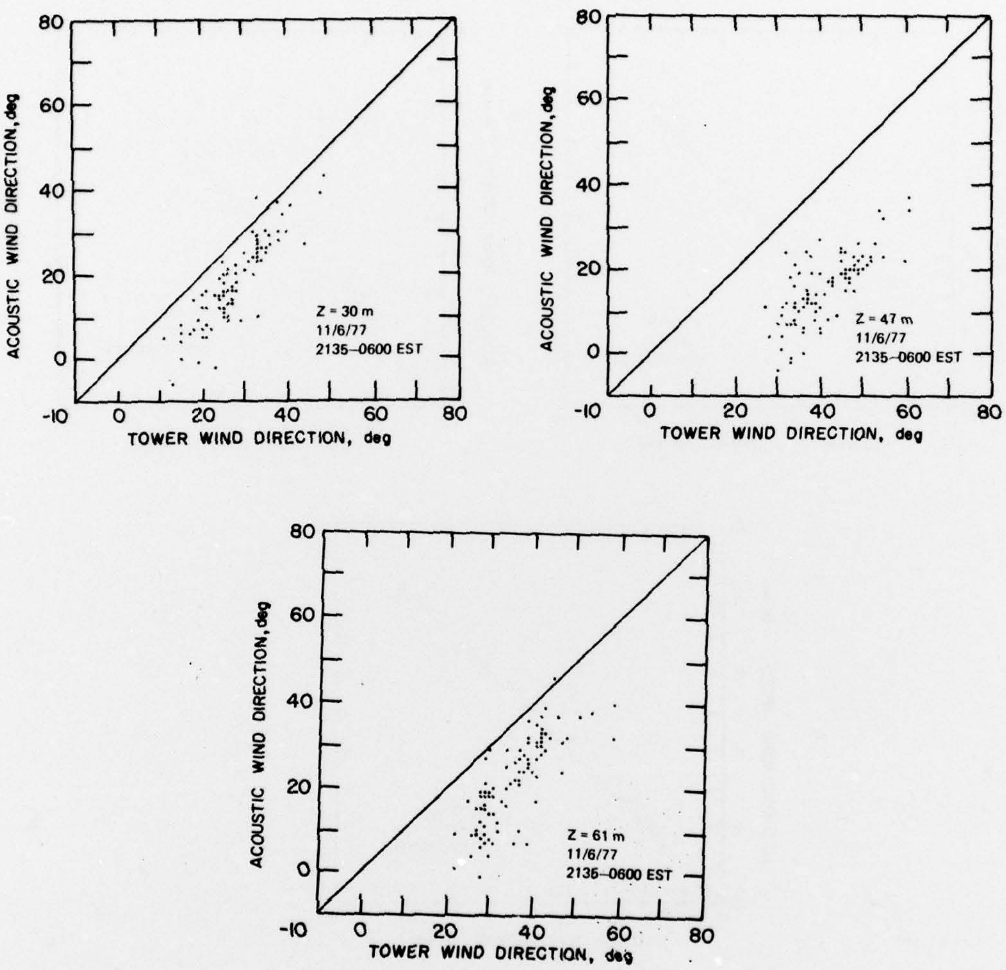

Figure A7. (Concluded)