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VERIFICATION OF WIND MEASUREMENT TO 450-METER ALTITUDE WITH MOBILE LASER DOPPLER SYSTEM

M.R. Brashears
W.R. Eberle

LOCKHEED MISSILES & SPACE COMPANY. INC.
HUNTSVILLE RESEARCH AND ENGINEERING CENTER
4800 Bradford Drive
Huntsville AL 35807

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16. Abstract

The Lockheed mobile atmospheric unit is a laser Doppler velocimeter system designed for the remote sensing of winds. The capability of the laser Doppler velocimeter accurately to measure winds to 150-meter altitude has been previously demonstrated. To assess the capability of the laser Doppler velocimeter to measure winds at higher altitudes, the system was tested adjacent to the 481-meter instrumented WKY-TV television transmission tower at the National Severe Storms Laboratory test site near Norman, Oklahoma. Comparisons between the laser-measured winds and the anemometer-measured winds are presented. The sources of discrepancies between laser-measured wind and anemometer-measured wind are discussed.

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PREFACE

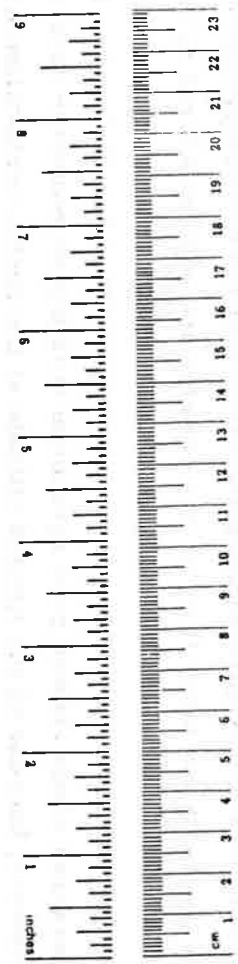
Laser Doppler velocimetry has been under development for approximately ten years. Initially, laser Doppler velocimetry was developed as a research tool. On 25 June 1975, Eastern Airline Flight 66 crashed while making an approach to John F. Kennedy International Airport in New York. The cause of the crash has been attributed to wind shear, and a significant program in wind shear detection resulted. The laser Doppler velocimeter is a candidate for the remote measurement of atmospheric wind and, thus, the detection of wind shear. In order to assess the ability of the laser Doppler velocimeter to measure winds remotely, a test for the comparison of wind measured by the laser Doppler velocimeter and wind measured by tower-mounted anemometers was conducted at the National Oceanic and Atmospheric Administration's Table Mountain test site near Boulder, Colorado. The laser-measured winds showed good agreement with the anemometer-measured winds. However, because of the limited altitude of the tower, verification was limited to altitudes less than 150 meters. In order to validate the laser Doppler velocimeter at altitudes above 150 meters, a test similar to the Table Mountain test was conducted near the 481-meter instrumented WKY-TV television transmission tower at the National Severe Storms Laboratory test site near Norman, Oklahoma. This report describes the results of that test.

The assistance of R. Craig Goff of the National Severe Storms Laboratory in the performance of the tests is gratefully acknowledged.

METRIC CONVERSION FACTORS

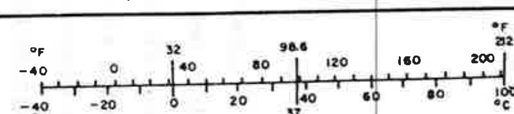
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

1.1 BACKGROUND

Significant effort is currently being devoted to the development of instrumentation to remotely sense atmospheric flow phenomena. Some of the avenues being pursued are active and passive acoustic sensors, optical sensors, and radio methods. A useful survey of such methods is presented in Ref. 1. Two advantages of remote sensors are that flow conditions can be ascertained in regions of space where it would not be convenient to locate instrumentation hardware, and no interference with the flow at the point of interest is introduced by their use. The laser Doppler velocimeter (LDV) is a particularly attractive device for remote sensing of atmospheric phenomena. In the LDV system, the laser radiation backscattered by moving particulates in the atmosphere is used to determine the velocity of the flow. Since it is possible to direct the laser focal volume at a selected sequence of points in space, data from a scanning LDV system can be used to determine the velocity field rapidly and over a range of altitudes. A CO_2 laser Doppler velocimeter system has the following advantages over other remote sensing techniques: (1) the sensing volume can be varied with ease as only optic pointing and focusing operations are involved; (2) the ambient aerosol provides a sufficient scattering target; and (3) the sensing mechanism is non-mechanical, which results in the potential for a high frequency turbulence sensor.

The feasibility of using an LDV system for the remote sensing of low altitude winds and for the detection and tracking of aircraft wake vortices has been demonstrated (Refs. 2, 3, and 4). However, the development of an effective LDV system for monitoring wind, wind shear, and wake vortices required a further refinement and application of the technology.

Previous field testing of the LDV system was accomplished at the John F. Kennedy International Airport (JFK) and at the Wave Propagation Laboratory of the National Oceanic and Atmospheric Administration near Boulder, Colorado (Refs. 5 and 6). Because of the demonstrated capability to measure winds at these test sites, it was deemed appropriate to assess the ability of the laser Doppler velocimeter to measure winds at higher altitudes.

1.2 PROGRAM OBJECTIVES

The primary objective of the tests at the National Severe Storms Laboratory was to verify the ability of the laser Doppler velocimeter to remotely measure winds at altitudes up to 450 m. Additionally, it was desired to measure wind phenomena in thunderstorms which were expected to pass over the test area during the test period. The second objective was only partially accomplished as only one thunderstorm passed near the test area. Its intensity was not sufficient to assess the measurement of wind phenomena in severe storms. However, data were obtained in rain, and the results are presented herein.

1.3 REPORT FORMAT

A brief description of the mobile laser Doppler system is presented in the following sections. A more complete description is presented in Ref. 5. A description of the LDV contained in the Lockheed Mobile Atmospheric Unit (MAU) is presented in Section 2 followed by a description of the computer software algorithms in Section 3. The field tests at the National Severe Storms Laboratory site are described in Section 4, along with analysis of the LDV data and comparisons with the meteorological tower data. Section 5 presents the conclusions and recommendations.

2. LASER DOPPLER SYSTEM DEVELOPMENT

2.1 SYSTEM DESCRIPTION

An LDV remote wind sensor senses air movement by measurement of the Doppler frequency shift of laser radiation backscattered by the atmospheric aerosol. An instrument must incorporate means to transmit the laser radiation to the region of interest, collect the radiation scattered from the atmospheric aerosol, and to photomix on a photodetector the scattered radiation and a portion of the transmitted beam. The difference between the transmitted frequency and the returned frequency is the Doppler shift frequency. The Doppler frequency shift signal is generated at the photodetector and is directly proportional to the magnitude* of the wind-velocity component in the direction of the line-of-sight of the laser beam. This velocity component is hereafter called the line-of-sight velocity. The magnitude of the Doppler shift, Δf, is given by

$$\Delta f = \frac{2}{\lambda} |\overline{V}| \cos\theta,$$

where

$\overline{V}$ = the velocity vector in the region being sensed,

θ = the angle subtended by the velocity vector and the optic system line-of-sight, and

λ = the laser radiation wavelength (10.6 microns for CO_2 laser).

A Doppler shift of 188 kHz results per m/sec of line-of-sight velocity component. Measurement of the Doppler shift frequency, Δf, yields directly the line-of-sight velocity component, $|\overline{V}| \cos\theta$. Some typical advantages of the laser Doppler method are: (1) the Doppler shift is a direct absolute measure of the line-of-sight velocity (for example, a hot wire yields wind speed via a cooling effect on the wire); (2) the ease with which the sensing volume can be varied (only optics pointing and focusing operations being involved); (3) the ambient

*Techniques for resolving the sign of the line-of-sight velocity component are available. They are not discussed here because they were not available for the subject test.

aerosol provides sufficient scattering, thus enabling operation in "clear air" conditions; and (4) the ambient aerosol tracer has a small inertia and responds quickly to variations in airspeed and, thus, can be a good turbulence indicator.

A useful instrument must also incorporate means for scanning the focal volume through a selected sequence of points in space and to effect the required signal processing, on-line readout, and permanent recording requirements. The hardware implementation of the mobile laser Doppler unit used during this investigation is discussed in the following subsections. The overall configuration is summarized in Fig. 2-1.

2.1.1 Basic Laser Doppler Velocimeter Optical System

The optical system is of monostatic design and utilizes a continuous-wave laser. The arrangement depends on focusing the transmitter telescope at the location of interest for its spatial resolution property. Details of the optical arrangement are shown in Fig. 2-2.

A horizontally polarized, 20-watt, continuous-wave CO_2 laser beam (10.6-micron wavelength) emerges from the laser (1) and is deflected 90 degrees by a mirror (2) and by a 90% reflecting beamsplitter (3). The approximately 6-mm diameter beam then passes through a Brewster window (4) and a CdS quarter waveplate (5) which converts the beam to circular polarization. The beam impinges on the secondary mirror (6) and is expanded and reflected into the primary mirror (30-cm diameter) (7) and then focused out into the atmosphere. A small portion of the original laser beam is transmitted through the beamsplitter (3) and is used as a local oscillator after being rotated to vertical polarization by a half waveplate (9). Energy scattered by aerosols at the focal volume (13) is collected by the primary mirror (7), collimated by the secondary (6), and passed through the quarter waveplate (5). A wire stop (16) eliminates most of the secondary mirror reflection of the outgoing beam. The quarter waveplate changes the polarization of the aerosol backscattered radiation from circular to vertical linear polarization. The vertically

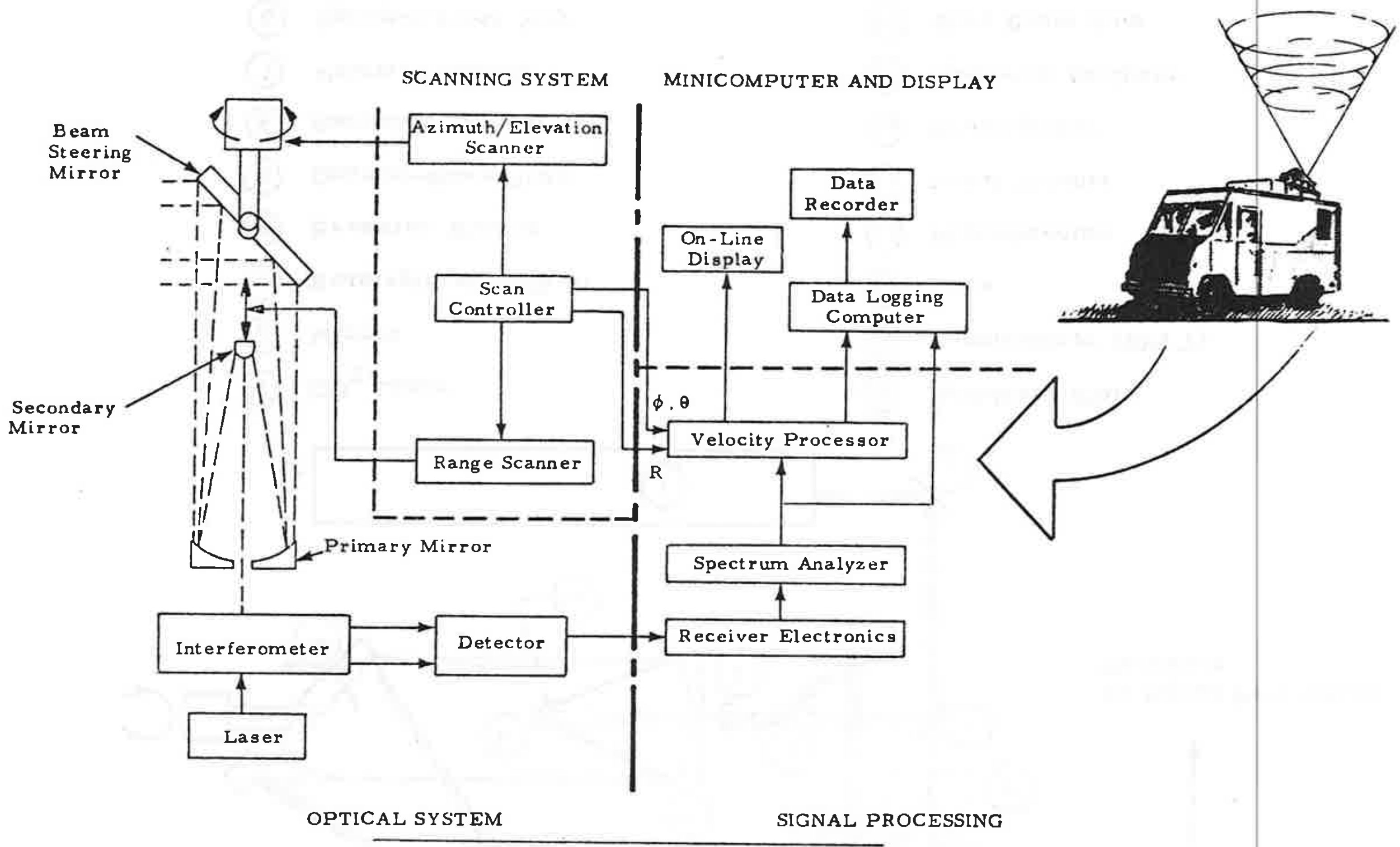
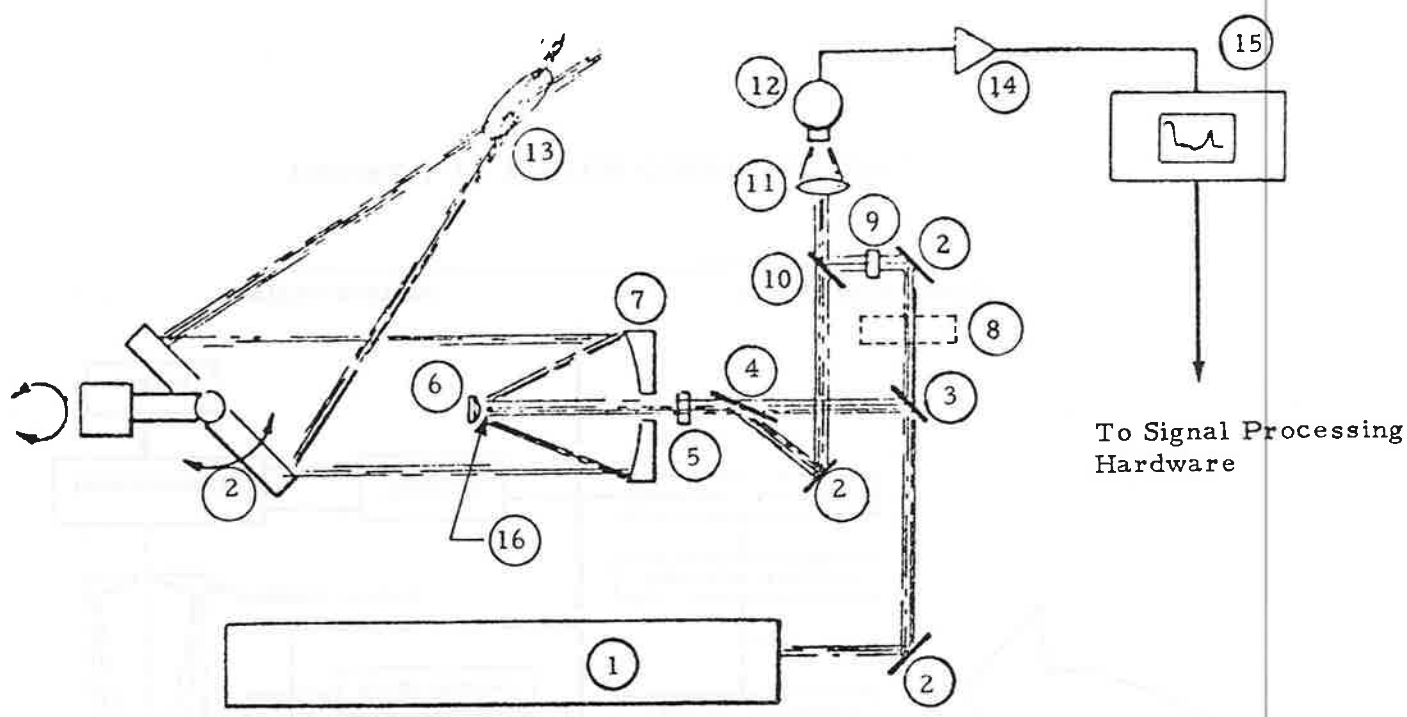


FIGURE 2-1. SYSTEM CONFIGURATION.



1 CO_2 Laser
2 Mirror
3 Beamsplitter (90% R)
4 Brewster Window
5 Quarter-Wave Plate
6 Secondary Mirror
7 Primary Mirror
8 Optional Beam Stop
9 Half-Wave Plate
10 Beamsplitter (90% T)
11 Lens
12 Photodetector
13 Focal Volume
14 Preamplifier
15 Spectrum Analyzer
16 Wire Beam Stop

FIGURE 2-2. TYPICAL OPTICAL COMPONENT CONFIGURATION OF LOCKHEED LASER DOPPLER VELOCIMETER.

polarized beam is approximately 78% reflected off the Brewster window (4) and directed through the beamsplitter (10) where it is combined with the local oscillator radiation. After passing through the collecting lens (11), the two beams are photomixed on the detector (12) in a heterodyne configuration. The electrical output of the detector (12) is amplified (14) with a 5-MHz bandwidth, 20-dB gain low-noise-type preamplifier and fed into a spectrum analyzer (15).

An alternative operating configuration consisted of utilizing the portion of the outgoing beam backscattered into the interferometer by the secondary mirror (6) as the local oscillator beam. This mode of operation is less susceptible to optical misalignment difficulties and was the technique used during this investigation. When incorporated, the optical leg (3)(2)(9) was deactivated by the beam stop (8) and the wire stop (16) was removed.

2.1.2 Optical Scanning System

In order to provide the flexibility to operate in various modes for which the system was designed, a scanning arrangement as shown in Fig.2-3 is used. Modes of operation include vortex tracking (not required for the measurements described in this document) and Velocity Azimuth Display (VAD) for the measurement of atmospheric wind. The mirror assembly, AB, can be rotated about the vertical axis for the scanning in azimuth necessary for the VAD (also called the conical-scan mode of operation). Mirror A is adjusted to control the elevation angle of the beam, thus controlling the cone angle of the conical scan. The scanning hardware as deployed on the mobile van is shown in Fig.2-4.

Range scanning of the system's focal volume is accomplished by varying the distance between the telescope secondary mirror, E, and the primary mirror, D. This is effected by varying the position of the mirror, E, in a controlled manner by an electric-motor/optical-encoder combination.

The operator inputs for the scanning system are made through a control panel incorporating thumbswitch controls and light-emitting-diode

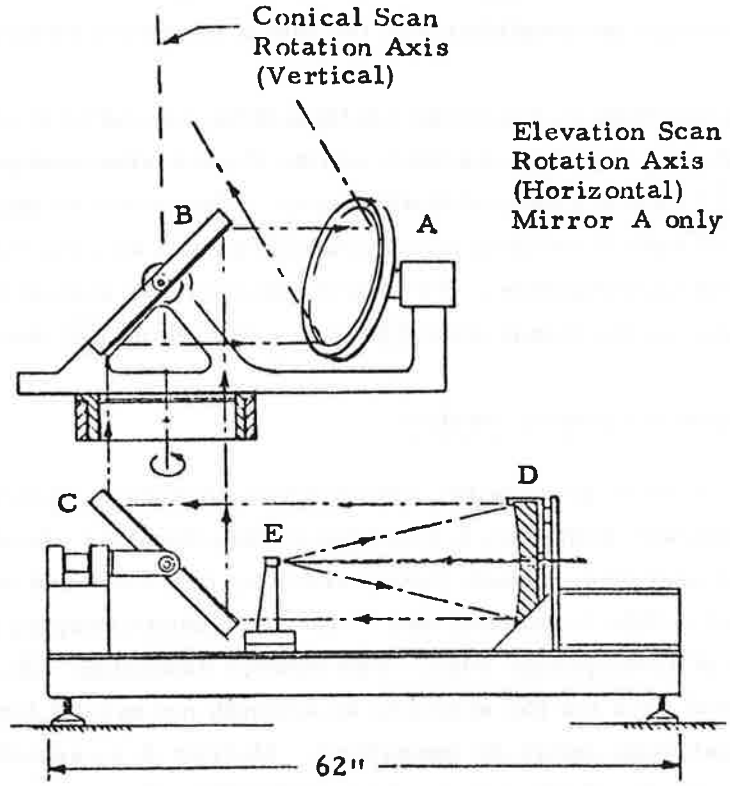


FIGURE 2-3. SCHEMATIC OF SCAN EQUIPMENT ON LASER DOPPLER VELOCIMETER.

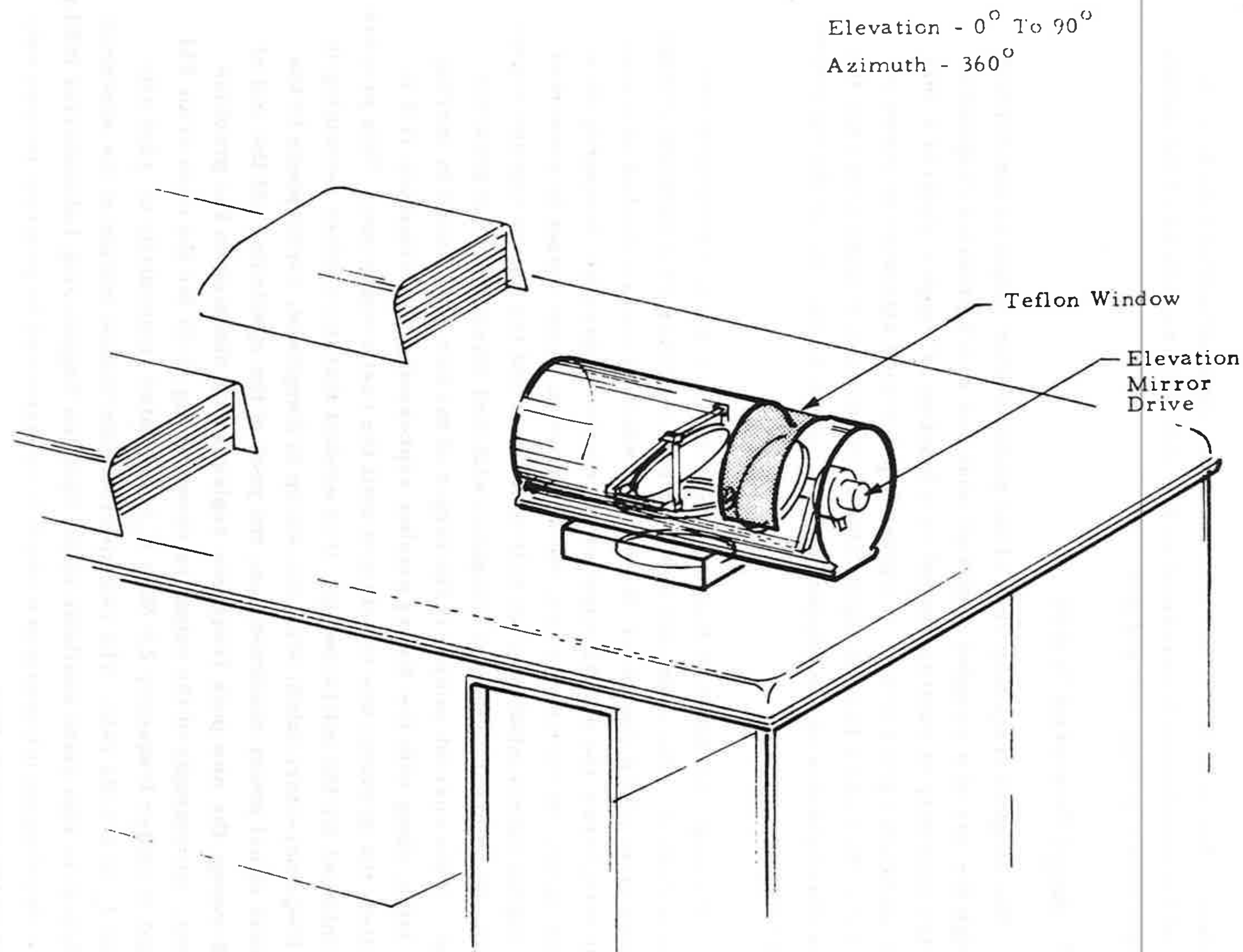


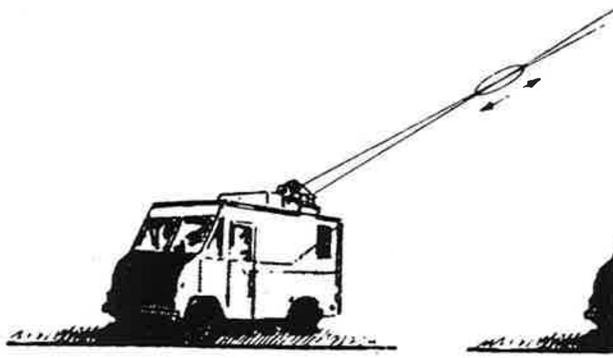
FIGURE 2-4. MULTIMODE SCANNER.

monitors. The system's scan capabilities are summarized in Fig. 2-5. A view of the mobile unit is presented in Fig. 2-6. Interior views of the mobile unit are shown in Figs. 2-7 and 2-8.

2.1.3 Signal Processing System

The Doppler frequency shift of the photodetector output is determined through the use of a sampled spectrum analyzer which provides frequency spectra (intensity of returned signal as a function of Doppler shift) at a rate of 70 signatures per second. A typical Doppler wind signature is shown in Fig. 2-9. To yield a line-of-sight velocity estimate, a voltage which has the same time behavior as the Doppler shift, f_d, given by the peak of the spectrum is generated.

The implementation of this technique is, in essence, a recursive comparison method. The spectrum analyzer scan is driven by a sawtooth voltage derived from a D/A converter, the input to which is counterclocked at a constant rate, hence the digital output of the counter represents frequency on a linear scale. At each new count, the spectrum analyzer output is converted to a digital representation by an A/D converter, and the binary number representing the current sample is compared with that obtained on the previous count. If the current sample is the larger of the two, it is saved by storing in a latch, along with the binary number representing its frequency; if it is smaller, the previous one is retained until the next comparison. This process is continued for the entire sweep. It is evident that the number remaining in the frequency-store latch, when the sweep is completed, corresponds to the highest signal power observed; i.e., the peak of the spectrum. At the end of each sweep, the new peak frequency replaces that obtained on the previous sweep. An example of the output is shown in Fig. 2-10 for the case of an FM signal of center frequency 2.0 MHz (f_o) modulated sinusoidally to $\pm$200 kHz about f_o at a 5-Hz rate. The raw spectral information (output of the spectrum analyzer) is also made available to the Systems Engineering Laboratories (SEL) 810A data-logging minicomputer which is programmed to generate its own estimate of the spectral peak.



RANGE SCAN

Limits		Rates
Upper	Lower	
100 to 999 m	16 to 989 m	0.1 to 6.9 Hz
One-meter increment		0.1-Hz increm.

Also can be stepped between 8 pre-selectable ranges.

ELEVATION SCAN

Limits		Rates
Upper	Lower	
10 to 90°	0 to 90°	0.1 to 0.5 Hz
1-deg. increment		0-1 Hz increm.

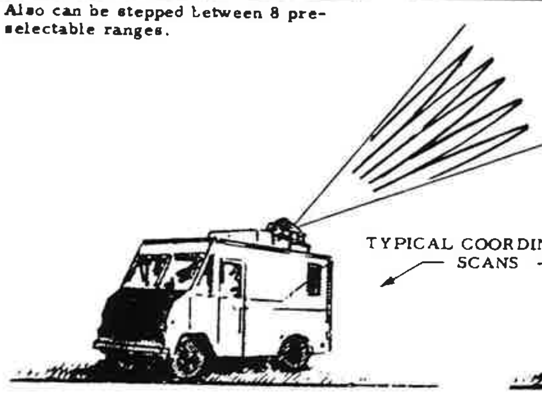
AZIMUTH SCAN

Currently 360° open loop operation
Can be modified for closed loop pointing and scanning

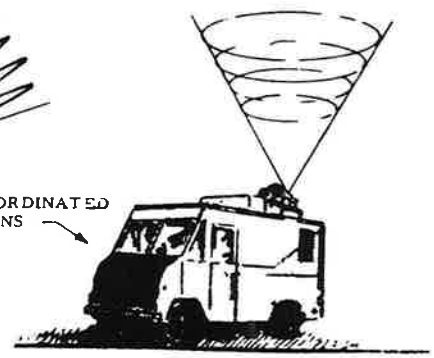
Note:

- Maximum Sampling Rate: 70 Hz

TYPICAL COORDINATED SCANS



Range - Elevation
(for vortex tracks, plume tracks, etc.)



Range - Azimuth
(for wind measurement)

FIGURE 2-5. SCAN CAPABILITIES OF LASER DOPPLER VELOCIMETER.

FIGURE 2-6. LOCKHEED-HUNTSVILLE MOBILE ATMOSPHERIC UNIT.

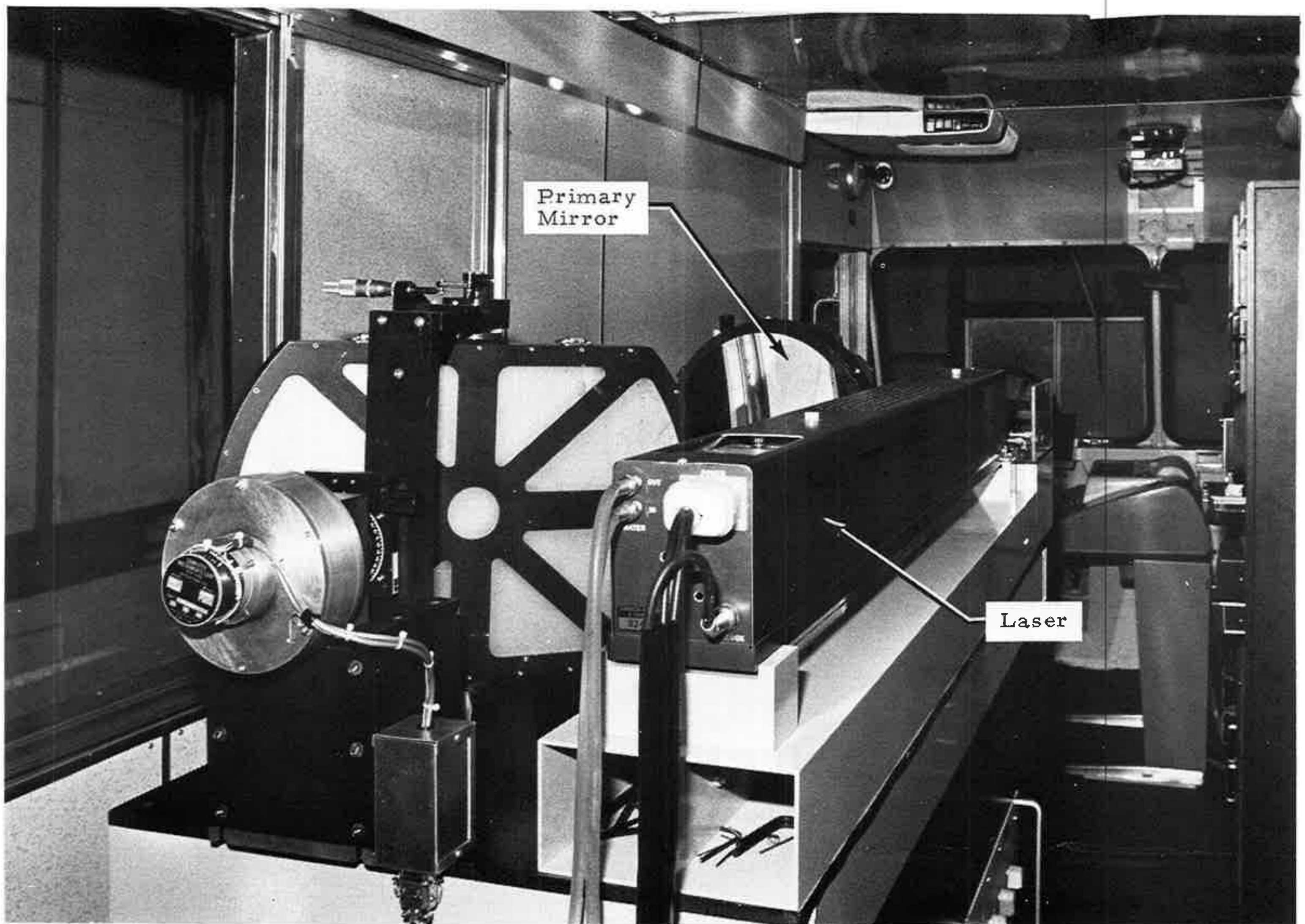


FIGURE 2-7. INTERIOR VIEW OF MOBILE ATMOSPHERIC UNIT LOOKING FORWARD.

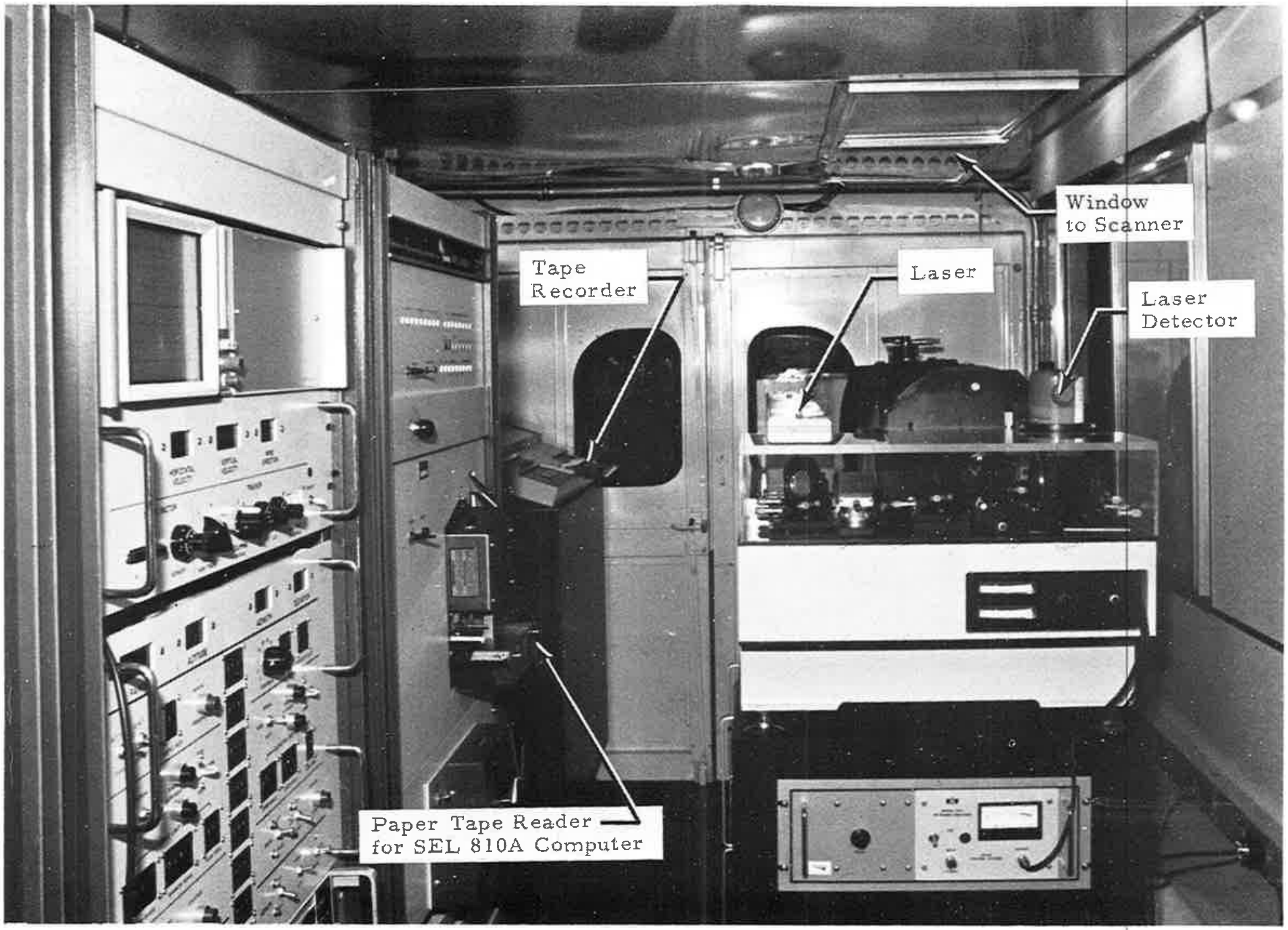


FIGURE 2-8. INTERIOR VIEW OF MOBILE ATMOSPHERIC UNIT.

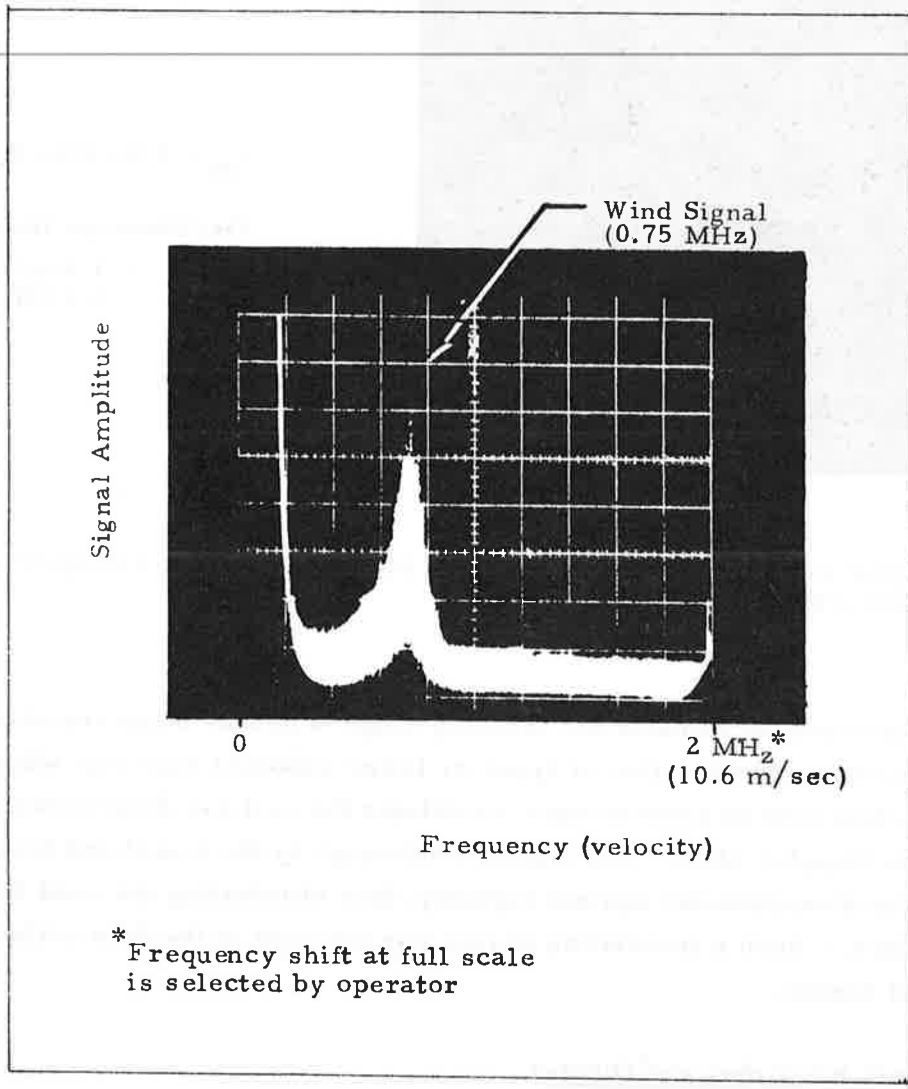
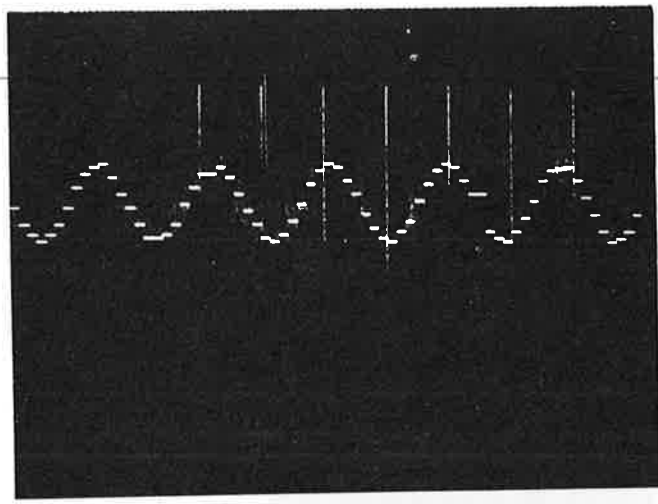


FIGURE 2-9. TYPICAL LASER DOPPLER VELOCIMETER WIND SIGNATURE AS DISPLAYED BY SPECTRUM ANALYZER.



f_m = 5 Hz Sine Wave

Oscilloscope Data

Horiz. = .1 sec/div
Vert. = 1 V/div

FIGURE 2-10. OUTPUT OF SIGNAL PROCESSOR FOR FREQUENCY-MODULATED INPUT.

A provision is included for tracking single-sideband suppressed-carrier signals, with an identification of upper or lower sideband such that when used in conjunction with an acousto-optic modulator the unit can discriminate the sign of the Doppler shift. The signal feedthrough at the translated frequency can also be discriminated against digitally, thus eliminating the need for a "notch filter." Such a translating device was not used in the data collection described herein.

2.1.4 Data Recording and Display

The primary data-gathering function is performed by the SEL 810A general-purpose minicomputer. Data acquired by the Mobile Atmospheric Unit are formatted by the computer software and stored on magnetic tape for subsequent off-line processing. The SEL 7-track tape control and magnetic tape units allow digital recording of data at 800 bpi at 45 ips. The data logged by the computer includes:

All scan volume location parameters
"Mode of operation" identifier
The instantaneous line-of-sight velocity information
The Doppler spectrum peak strength
Full spectrum intensity and frequency information
A data-quality identifier.

Properties of the Doppler spectrum; namely, the amplitude and frequency corresponding to the spectral peak, are obtained as a result of on-line computer processing except for the frequency, which is also obtained by the spectral peak locator (velocity processor) discussed previously. The latter allows some flexibility for on-line operator displays (see below). The velocity processor estimate of the instantaneous line-of-sight velocity, updated at a 70-Hz rate, is available in analog format which can be recorded directly on a stripchart recorder, an option which is extremely useful during the VAD mode of operation for monitoring the characteristic profile.

A view of the computer and associated LDV electronics is shown in Fig.2-11.

2.2 WINDS ALOFT SENSING

Using the basic system outlined previously it is possible, by scanning operations, to determine the three-component wind field at any altitude between 16 and 865 meters. The scanning method employed is commonly referred to as the Velocity Azimuth Display (VAD) technique and was first used by Lhermitte and Atlas in conjunction with a microwave radar (Ref. 7).

The telescope is focused at the altitude of interest, the beam being directed at a zenith angle, α. The beam is then scanned in azimuth, thus tracing out a circle at the selected altitude (Fig.2-12).

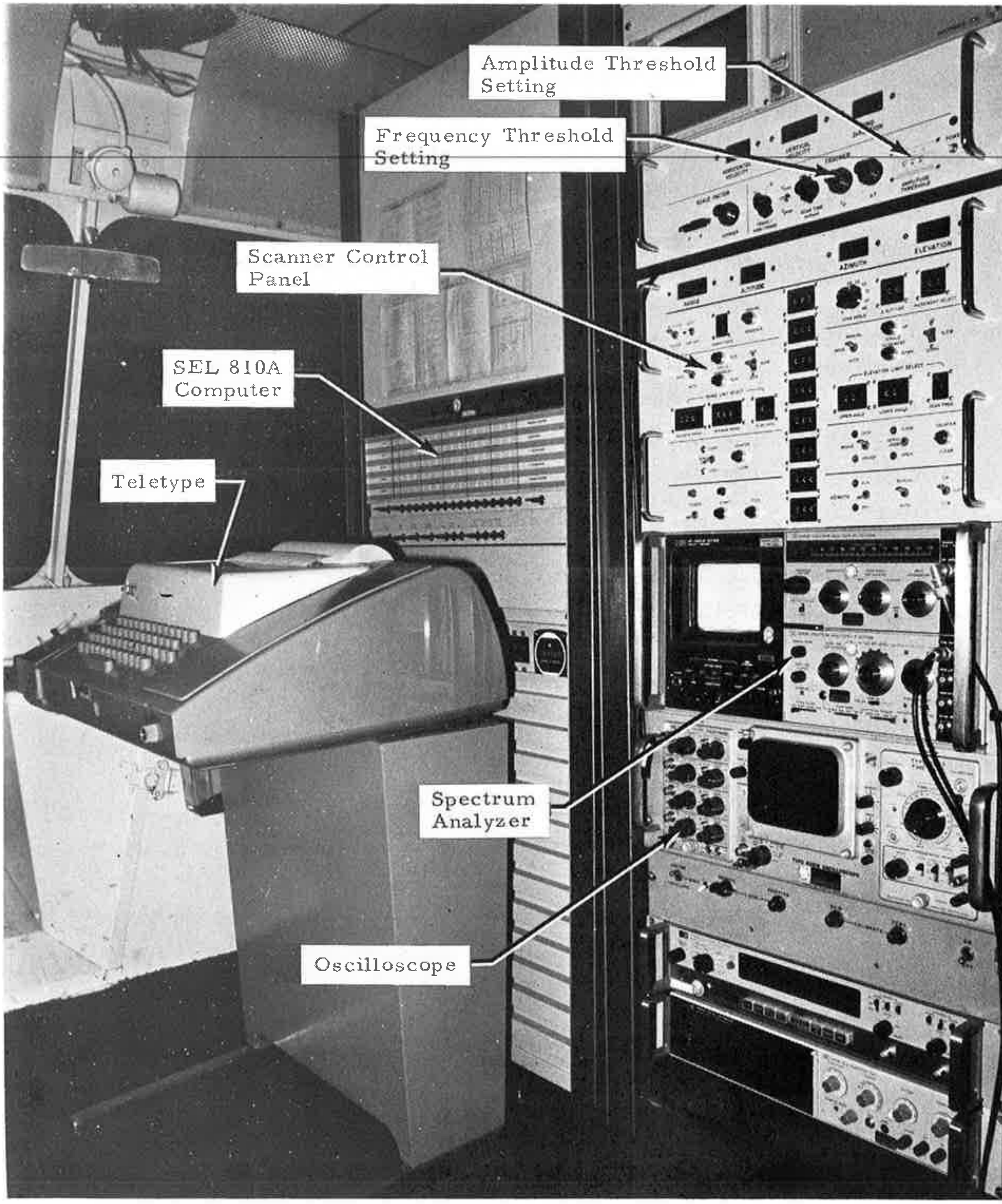
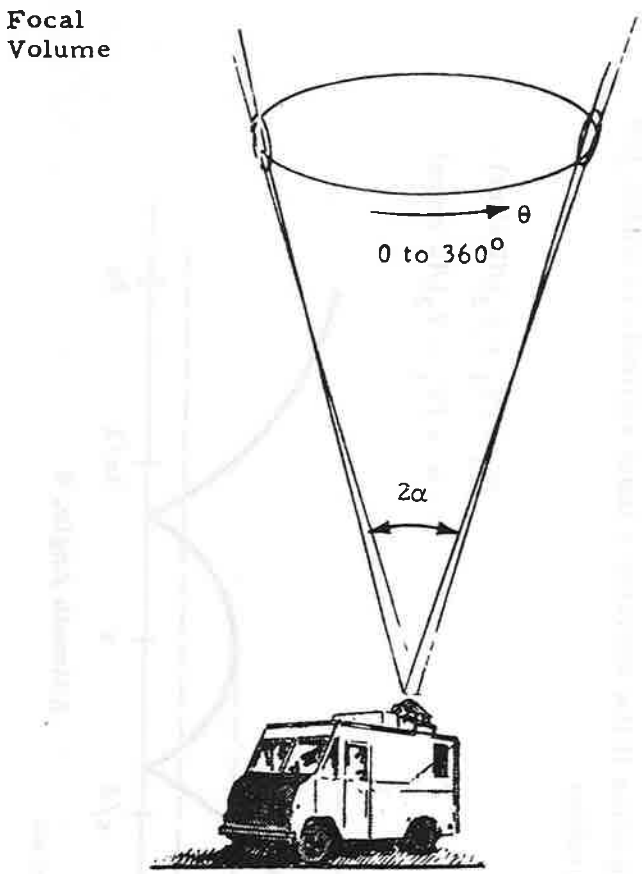
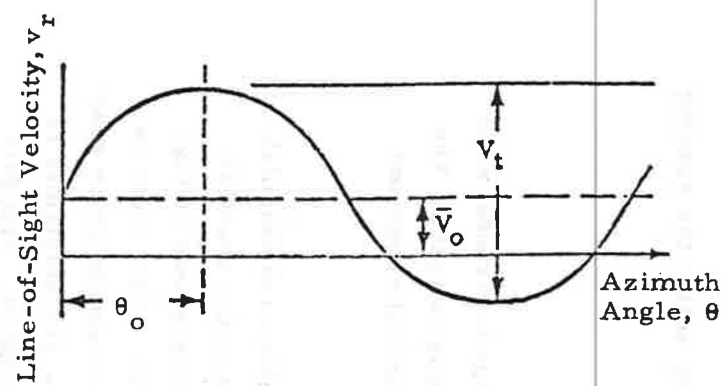


FIGURE 2-11. COMPUTER MAINFRAME TELETYPE AND LASER DOPPLER VELOCIMETER ELECTRONICS.





Calculation of Wind Parameters

w = vertical wind component

= $\overline{V}_o / \cos\alpha$

v_h = horizontal wind component

= $V_t / (2 \sin\alpha)$

θ_o = direction of horizontal wind component

FIGURE 2-12. PRINCIPLE OF VELOCITY AZIMUTH DISPLAY OPERATION.

The instantaneous line-of-sight component of velocity within the sensing volume as measured by the LDV, v_r, is given by

$$v_r = v_h \sin\alpha \cos(\theta - \theta_o) + w \cos\alpha ,$$

v_h and θ_o, respectively, being the speed and direction of the horizontal wind component, and w the vertical component at the height being sampled. The azimuthal dependence of v_r is sufficient to yield the horizontal speed and direction and the vertical component of velocity.

In the present mode of operation, the system is unable to distinguish between positive and negative values of v_r. Therefore, it is the absolute value of v_r ($|v_r|$) that is sensed. This results in a signal as shown in Fig. 2-13 instead of the sinusoidal signal as shown in Fig. 2-12. Thus, there is an ambiguity of 180 deg in the wind direction since it is uncertain which peak in Fig. 2-13 represents looking into the wind. In practice, the ambiguity is removed by the operator recording approximate wind direction. The data processing technique can then calculate exact wind direction. This resolves all wind direction ambiguities if the operator's input estimate is within ± 89 deg of the true wind direction.

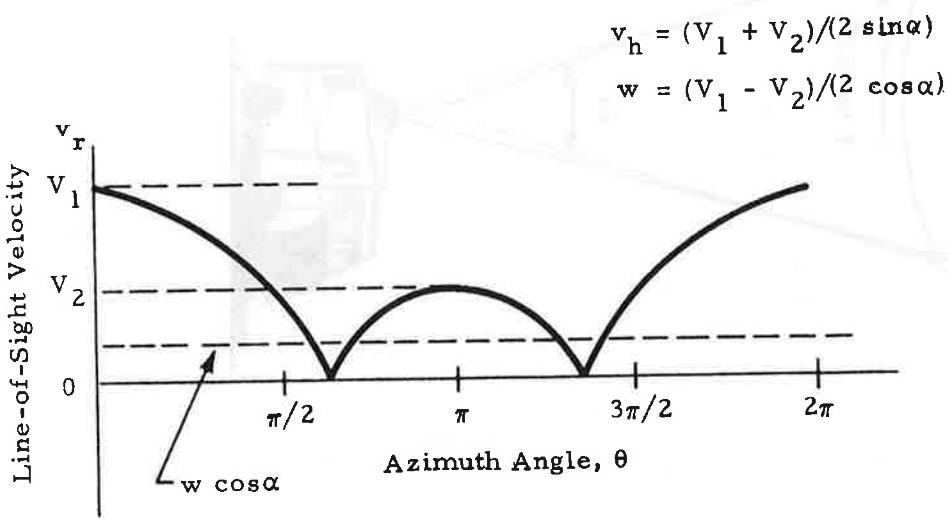


FIGURE 2-13. AZIMUTH ANGLE DEPENDENCE OF MEASURED VELOCITY COMPONENT

While operating in the VAD mode the system is capable of measuring winds at n (n = 1 through 8) altitudes (that can be dialed in by using thumbswitches) in sequence over a total time period of 5np seconds where

5 sec = time for conical sweep at one altitude for this test,

n = number of altitudes to be interrogated, and

p = number of VAD scans at each altitude (can be chosen to be 1 through 7).

During this investigation, all data were taken in the single altitude mode (i.e., n = 1, p = 1), although data were measured at several different altitudes for the various recorded runs of the test.

3. COMPUTER SOFTWARE SYSTEM DEVELOPMENT

Acquisition and processing of the LDV signature are accomplished by means of a compact data-handling system developed specifically for the Lockheed-Huntsville MAU. The general elements of the MAU data acquisiton-and-processing system are shown in Fig. 3-1. The digitized LDV intensity versus frequency signal along with its coordinates in space is fed into the SEL 810 minicomputer. Preprocessing of the LDV signal is carried out on the minicomputer utilizing on-line computer programs written in SEL machine language. Information from the SEL 810 is stored on magnetic tape and is used as an input to the off-line processing algorithms. Off-line processing of the LDV signal is carried out on a Univac 1108 computer with programs written in FORTRAN language and using card inputs with information from the data logs to supplement the data. The final output consists of printouts and plots. A description of the data logger program and the VAD program and the operational characteristics of these programs is given in the following sections.

3.1 DESCRIPTION OF LASER DOPPLER VELOCIMETER SOFTWARE SYSTEM

Data acquisition in the MAU is carried out by the SEL Data Logger program. The Data Logger program preprocesses and records the LDV signal. A flowchart of the Data Logger program is given in Fig. 3-2. A sweeping spectrum analyzer is used to detect the Doppler shift frequency. A diagram of the output of the spectrum analyzer is shown in Fig. 3-3. For each sweep of 10-, 20-, or 50-millisecond duration, the Data Logger saves the maximum amplitude LDV signal, I_{ms}, and its corresponding frequency, V_{ms}, which are above both the amplitude and frequency thresholds. The definition of I_{ms} and V_{ms} and the shape of the characteristic LDV spectrum are shown in Fig. 3-3. The velocity at maximum signal intensity is V_{ms} and is taken

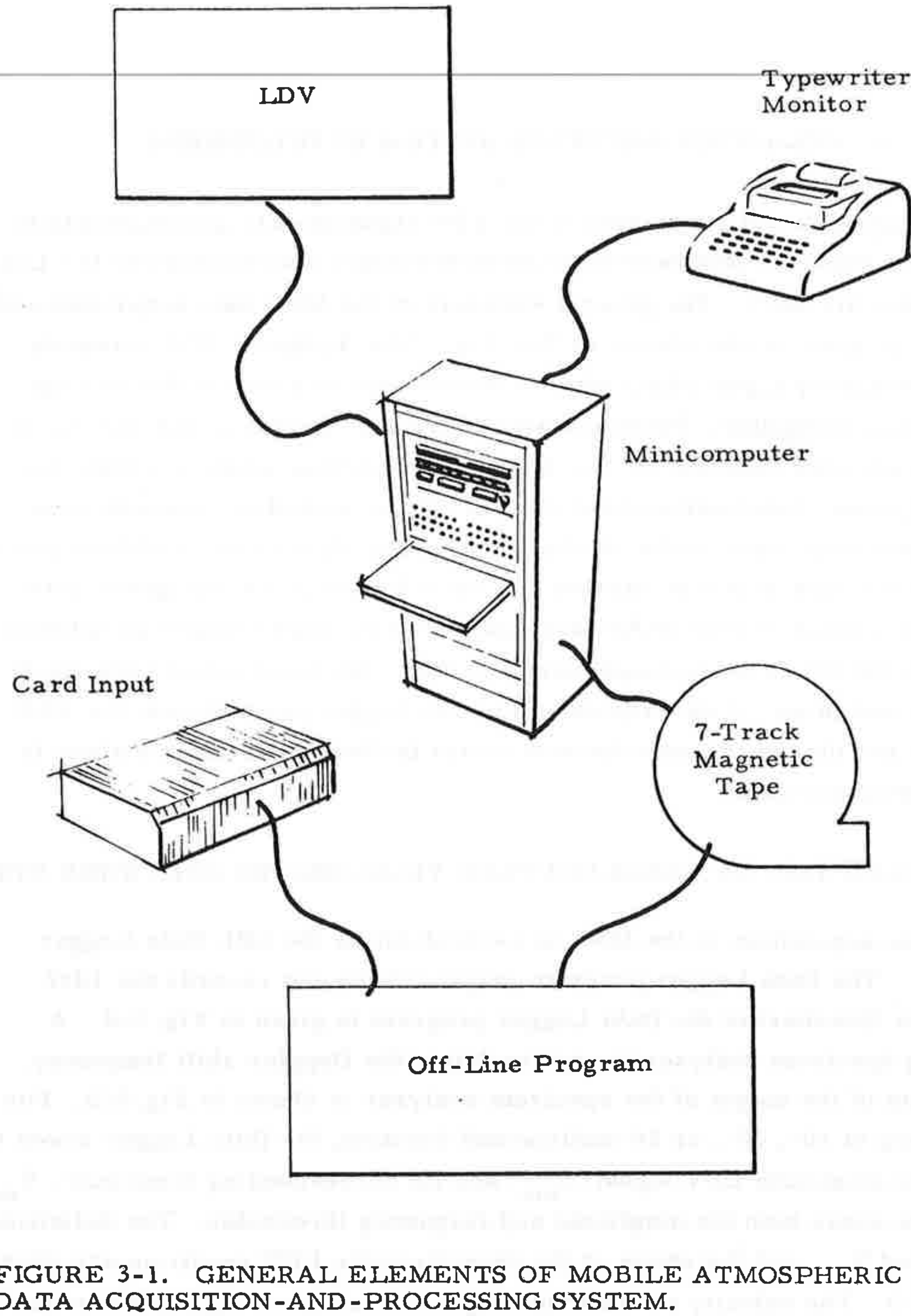


FIGURE 3-1. GENERAL ELEMENTS OF MOBILE ATMOSPHERIC UNIT DATA ACQUISITION-AND-PROCESSING SYSTEM.

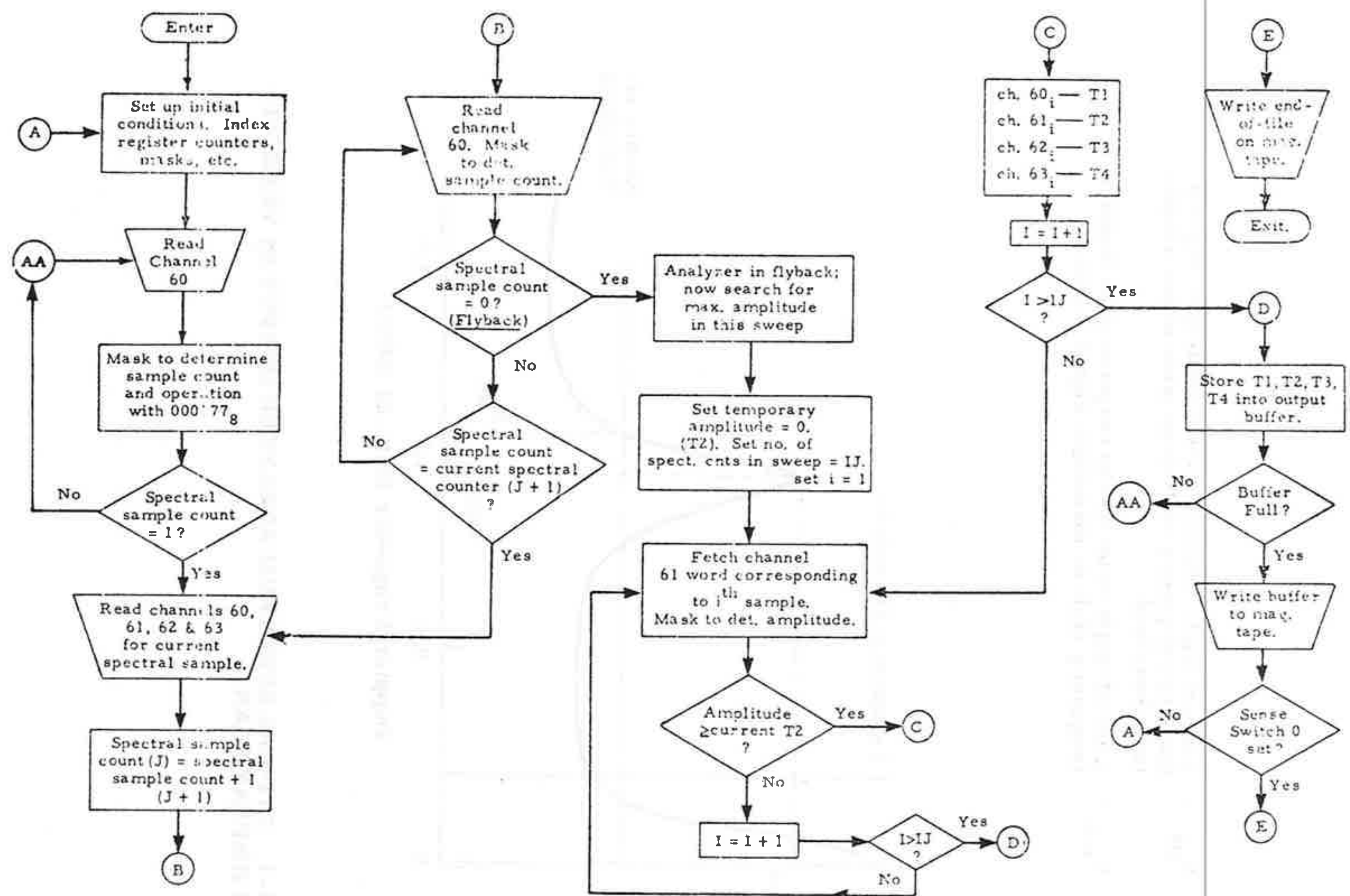


FIGURE 3-2. DATA LOGGER MACRO FLOWCHART.

V_{pk} = Line-of-sight velocity corresponding to highest Doppler frequency shift detectable above amplitude threshold

V_{ms} = Line-of-sight velocity corresponding to Doppler frequency shift at maximum signal intensity

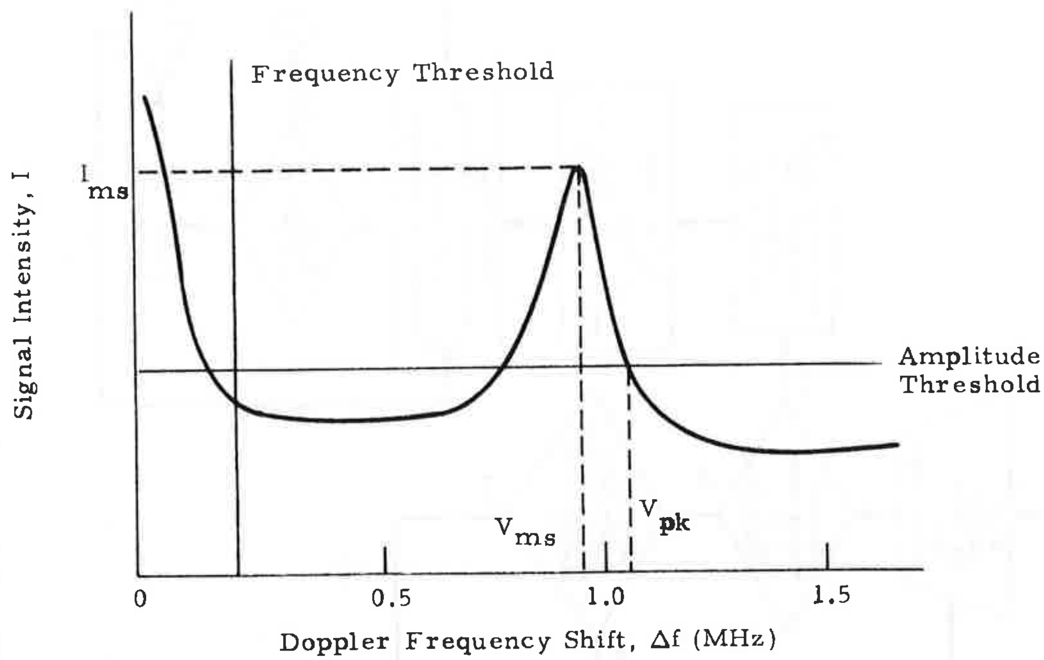


FIGURE 3-3. TYPICAL SPECTRUM ANALYZER OUTPUT IN VELOCITY AZIMUTH DISPLAY SCAN.

to be the characteristic line-of-sight velocity associated with the flow phenomenon. This choice is made because the maximum signal intensity is obtained from the center of the focal volume.

The output from the Data Logger program consists of V_{ms} as a function of time and space. From the output of the Data Logger, the wind field can be reconstructed using off-line processing routines.

Final processing of the LDV measurements is carried out by the VAD program. A macro flowchart of the VAD program is shown in Fig. 3-4. In this off-line program the array of V_{ms} values which is a function of time and space is processed to yield the three-dimensional wind field in the VAD mode. The program is formulated to calculate winds for both the translated and non-translated LDV signal. A translated signal is provided when the LDV system includes a frequency translator which distinguishes between positive and negative values of line-of-sight velocity. A non-translated signal provides only the absolute value of line-of-sight velocity as shown in Fig. 2-13. However, during the course of this research effort, all of the data acquisition-and-processing were done in the non-translate mode.

Three techniques have been implemented to compute the three-dimensional wind components: (1) a peak algorithm where the magnitude and location of the peak signal in the sinusoidal LDV VAD signature are used to compute the velocity components; (2) a spectral processing for the winds using the derectified signal; and (3) a sine curve fit. The final output is a printout (and selected plots) of the wind velocity components as a function of altitude and time. Wind velocity components are given for both rectilinear orthogonal components and cylindrical components.

3.2 OPERATION OF LASER DOPPLER VELOCIMETER SOFTWARE SYSTEM

Operation of the Lockheed-Huntsville MAU involves initialization of the SEL Data Logger program and the recording of the LDV signatures. After

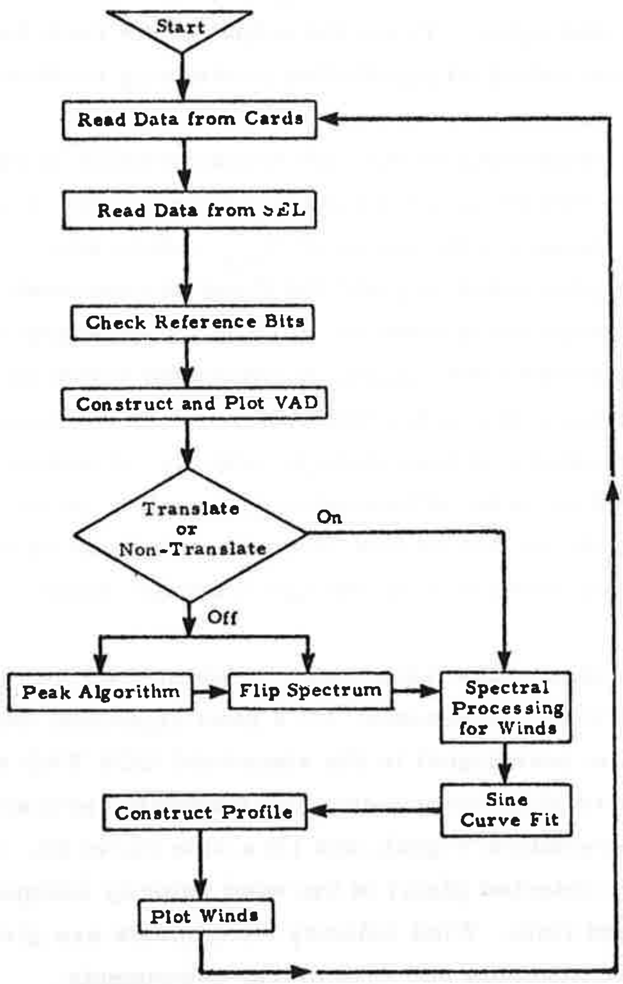


FIGURE 3-4. MACRO FLOWCHART OF OFF-LINE VELOCITY AZIMUTH DISPLAY PROGRAM.

the measurements have been recorded at the proper threshold settings, the VAD program is used to process the data into VAD plots. It is useful to examine the data-processing operations involved in determining the three-dimensional wind velocity field from the LDV measurements in terms of on-line preprocessing and off-line processing.

3.2.1 On-Line Data Processing

The conical scan VAD measurements are preprocessed on the SEL computer and recorded on magnetic tape. The output from the SEL computer consists of the basic V_{ms} signal as well as additional test parameters which are listed in Table 3-1. It is useful to consider the type of data recorded by the SEL during normal operations in the VAD mode.

A dump of a sample output tape from the Data Logger operating in the VAD mode is shown in Fig. 3-5, each row of data corresponding to information recorded for each spectrum-analyzer sweep. The information, packed into four computer words on tape, is separated into 13 columns in the printout with interpretation of the various columns being as follows:

Column	Interpretation
1 (PEAK/MAX)	An indication as to whether the peak Doppler frequency (f_{pk} corresponding to V_{pk} in Fig. 3-4) or maximum signal Doppler frequency (f_{ms} corresponding to V_{ms} in Fig. 3-4) is used. Indication is 0 if maximum signal frequency is used and is 1 if peak velocity signal is used.
2 ($\theta = 0$)	A conical-scan azimuth reference which is nonzero when the reference switch is activated.
3 (NOR/VAD)	An indication as to whether the system is operating in the normal (vortex track) (1) or VAD (0) mode.
4 (SWEEP SPEED)	Sweep speed of the spectrum analyzer trace in msec/cm
5 (DIG TRCK)	The computer-calculated estimate of f_{pk} (percent of full scale).
6 (DATA ACCEPT)	An indication that there is (1) or is not (0) an output above the frequency and amplitude thresholds during a sweep.

TABLE 3-1

INPUT FROM SYSTEMS ENGINEERING LABORATORIES COMPUTER

Each VAD run is in a separate file. The following data are recorded for each spectrum analyzer sweep.

1. Spectral Sample Count Across Spectrum Analyzer Sweep, Corresponding to V_{max}
2. Amplitude at Above Point
3. Data Acceptable Flag
4. Flag for Spectrum Analyzer Sweep Speed
5. Flag for Translator
6. Flag for Positive or Negative Frequency (used only when translator is used)
7. Flag for V_{pk} or V_{ms}
8. Flag for Conical Scan or Normal Scan

For Conical Scan

9. Height above Van
10. Flag for Azimuth Switch
11. Cone Angle

WORD NO. 1					WORD NO. 2				WORD NO. 3		WORD NO. 4	
PEAK/MAX	0=0	NER/VAD	SWEEP SPEED	DIG TRCK	DATA ACCEPT	+/-	TRANS/NRN	SPECTRUM INTNSITY	NER RNIN	ALT (M)	TRNC TRCK	CONE ANGLE
1	C	C	1C	38	1	1	C	232	1	323	37	3C
1	C	C	1C	38	1	1	C	208	1	323	36	3C
1	C	C	1C	39	1	1	C	16C	1	323	37	3C
1	C	C	1C	39	1	1	C	254	1	323	36	3C
1	C	C	1C	36	1	1	C	192	1	323	38	3C
1	C	C	1C	38	1	1	C	190	1	323	35	3C
1	C	C	1C	38	1	1	C	144	1	323	36	3C
1	C	C	1C	40	1	1	C	190	1	323	36	3C
1	C	C	1C	41	1	1	C	142	1	323	38	3C
1	C	C	1C	40	1	1	C	144	1	323	4C	3C
1	C	C	1C	42	1	1	C	144	1	323	39	3C
1	C	C	1C	2	1	1	C	1023	1	323	41	3C
1	C	C	1C	40	1	1	C	190	1	323	127	3C
1	C	C	1C	39	1	1	C	140	1	323	38	3C
1	C	C	1C	41	1	1	C	14C	1	323	38	3C
1	C	C	1C	41	1	1	C	200	1	323	4C	3C
1	C	C	1C	39	1	1	C	28C	1	323	4C	3C
1	C	C	1C	40	1	1	C	254	1	323	37	3C
1	C	C	1C	42	1	1	C	238	1	323	38	3C
1	C	C	1C	41	1	1	C	126	1	323	41	3C
1	C	C	1C	39	1	1	C	222	1	323	37	3C
1	C	C	1C	39	1	1	C	150	1	323	38	3C
1	C	C	1C	40	1	1	C	254	1	323	38	3C
1	C	C	1C	41	1	1	C	192	1	323	38	3C
1	C	C	1C	39	1	1	C	208	1	323	39	3C
1	C	C	1C	40	1	1	C	190	1	323	37	3C
1	C	C	1C	41	1	1	C	256	1	323	39	3C
1	C	C	1C	38	1	1	C	160	1	323	0	3C
1	C	C	1C	42	1	1	C	128	1	323	37	3C
1	C	C	1C	38	1	1	C	178	1	323	41	3C
1	C	C	1C	41	1	1	C	162	1	323	36	3C
1	C	C	1C	39	1	1	C	144	1	323	39	3C
1	C	C	1C	41	1	1	C	126	1	323	35	3C
1	C	C	1C	41	1	1	C	144	1	323	40	3C
1	C	C	1C	41	1	1	C	256	1	323	4C	3C
1	C	C	1C	42	1	1	C	126	1	323	127	3C
1	C	C	1C	42	1	1	C	182	1	323	4C	3C
1	C	C	1C	38	1	1	C	176	1	323	40	3C
1	C	C	1C	43	1	1	C	200	1	323	37	3C
1	C	C	1C	40	1	1	C	146	1	323	42	3C
1	C	C	1C	37	1	1	C	128	1	323	39	3C
1	C	C	1C	43	1	1	C	128	1	323	36	3C
1	C	C	1C	35	1	1	C	160	1	323	39	3C
1	C	C	1C	41	1	1	C	128	1	323	33	3C
1	C	C	1C	41	1	1	C	126	1	323	127	3C
1	C	C	1C	37	1	1	C	128	1	323	40	3C
1	C	C	1C	39	1	1	C	150	1	323	34	3C
1	C	C	1C	40	1	1	C	126	1	323	38	3C
1	C	C	1C	38	1	1	C	126	1	323	36	3C
1	C	C	1C	35	1	1	C	128	1	323	36	3C

FIGURE 3-5. DUMP OF SAMPLE OUTPUT TAPE FROM DATA LOGGER (With System Operating in Velocity Azimuth Display Mode).

Column	Interpretation
7 (+/-)	An indication as to the sense of the Doppler shift: 1 = moving toward MAU, 0 = moving away from MAU.
8 (TRANS/NON-TRANS)	An indication as to whether or not a frequency translator was incorporated. During this investigation, it was not incorporated. 1 = Yes, 0 = No.
9 (SPECTRUM INTENSITY)	Peak amplitude of the Doppler spectrum in region above a frequency threshold (arbitrary units ranging from 0 to 1024).
10 (NBR ROTN)	Number of successive VAD scans for a particular altitude.
11 (ALT (M))	Altitude of VAD for particular sweep in meters.
12 (LTRNC TRCK)	On-line frequency-tracker estimate of f_{pk} (should be approximately equal to column 5).
13 (CONE ANGLE)	Half-angle of VAD cone in degrees.

3.2.2 Off-Line Data Processing

Three algorithms for calculating the mean wind speed and direction from the VAD signature have been developed. For each of these algorithms, mean wind speed and direction are calculated for each 5-second VAD sweep. Standard deviations of wind speed and direction can be calculated from multiple VAD sweeps. The data output of the LDV system operating in the VAD mode are line-of-sight velocities measured at a selected number (usually 350 in the current Lockheed system) of distinct points around the VAD cone. Recall that the line-of-sight velocity signature is theoretically sinusoidal in the VAD mode (cf., Fig. 2-12).

For all the processing algorithms, preprocessing of the data occurs; the preprocessing includes:

a. Save line-of-sight velocities for one rotation of scanner.

b. If two or more rotations occur at the same altitude, average with previous rotation(s).

c. Assign azimuth angle to each point (assuming constant rotation rate).

d. Edit data to eliminate spurious points. Eliminated points are declared unacceptable.

e. Plot line-of-sight velocity versus azimuth angle.

The edit criterion for the elimination of spurious points is that the i^{th} point is eliminated if

$$|v_{r,i} - v_{r,i+1}| > .2\, v_{r,i+1},$$

and

$$|v_{r,i} - v_{r,i-1}| > .2\, v_{r,i-1}.$$

A sample plot of unedited line-of-sight velocity versus azimuth angle is shown in Fig. 3-6. Unacceptable data points are shown as zero velocity.

3.2.2.1 Peak Algorithm

For the calculation of wind velocity by the peak algorithm, the procedure is:

a. Filter data with an n-point moving average.

b. Identify the two peak velocity points, V_{p1} and V_{p2}, that occur at a minimum of 90 degrees apart.

c. Compute the magnitude of the horizontal component of the wind

$$V_h = \frac{V_{p1} + V_{p2}}{2 \sin\alpha}.$$

d. Compute horizontal wind angle with help of estimated wind direction.

e. Compute the vertical component of the wind

$$w_v = \frac{V_{p1} - V_{p2}}{2 \cos\alpha}.$$

f. Derectify VAD signal if no translator is present and plot derectified signal. The signal is derectified, so that the positive peak of the derectified signature is the peak which is closer to the estimated wind direction recorded by the operator at the time the data are measured.

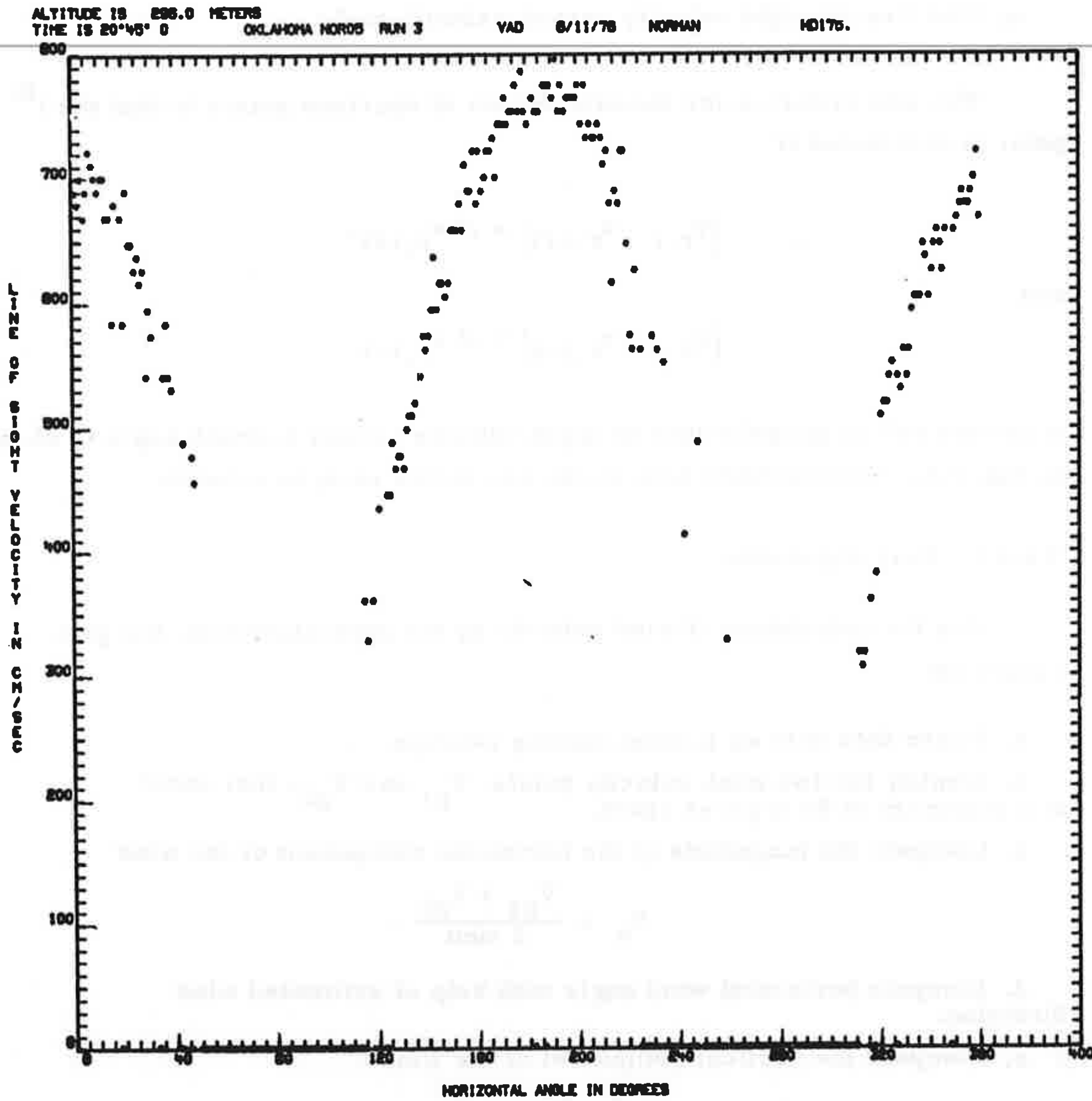


FIGURE 3-6. SAMPLE OUTPUT PLOT FROM VELOCITY AZIMUTH DISPLAY PROGRAM (Unedited).

The purpose of the filter is the elimination of nonuniformities in the data. This is especially important for the peak algorithm. The individual data points are filtered with an n-point moving average filter (n is usually 21). Thus, each line-of-sight point is filtered by

$$\overline{V}_{r,i} = \left[V_{r,i-\frac{n-1}{2}} + \ldots + V_{r,i-1} + V_{r,i} + V_{r,i+1} + \ldots + V_{r,i+\frac{n-1}{2}} \right] / n,$$

where $\overline{V}_{r,i}$ is the filtered value of the line-of-sight velocity to be used in further calculations. A plot of the filtered line-of-sight velocities for a 21-point filter is shown in Fig. 3-7. Additional samples of the LDV signature (including raw data, filtered data, and derectified data) are presented in Appendix A.

When the LDV data are measured, an approximation of the wind angle is recorded. The calculated wind angle is the azimuth angle of the peak which is closer to the estimated wind angle. For small values of vertical velocity the wind angle plus 90 deg is the angle at which the line-of-sight velocity is theoretically zero. This angle is used for the derectification of the line-of-sight signal. A plot of the derectified (edited, but unfiltered) line-of-sight velocity is presented in Fig. 3-8.

3.2.2.2 Fourier Coefficient Algorithm

The Fourier coefficient algorithm (or spectral algorithm) computes the fundamental harmonic of the line-of-sight velocity. The Fourier series for a generalized periodic function is

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos nx + b_n \sin nx),$$

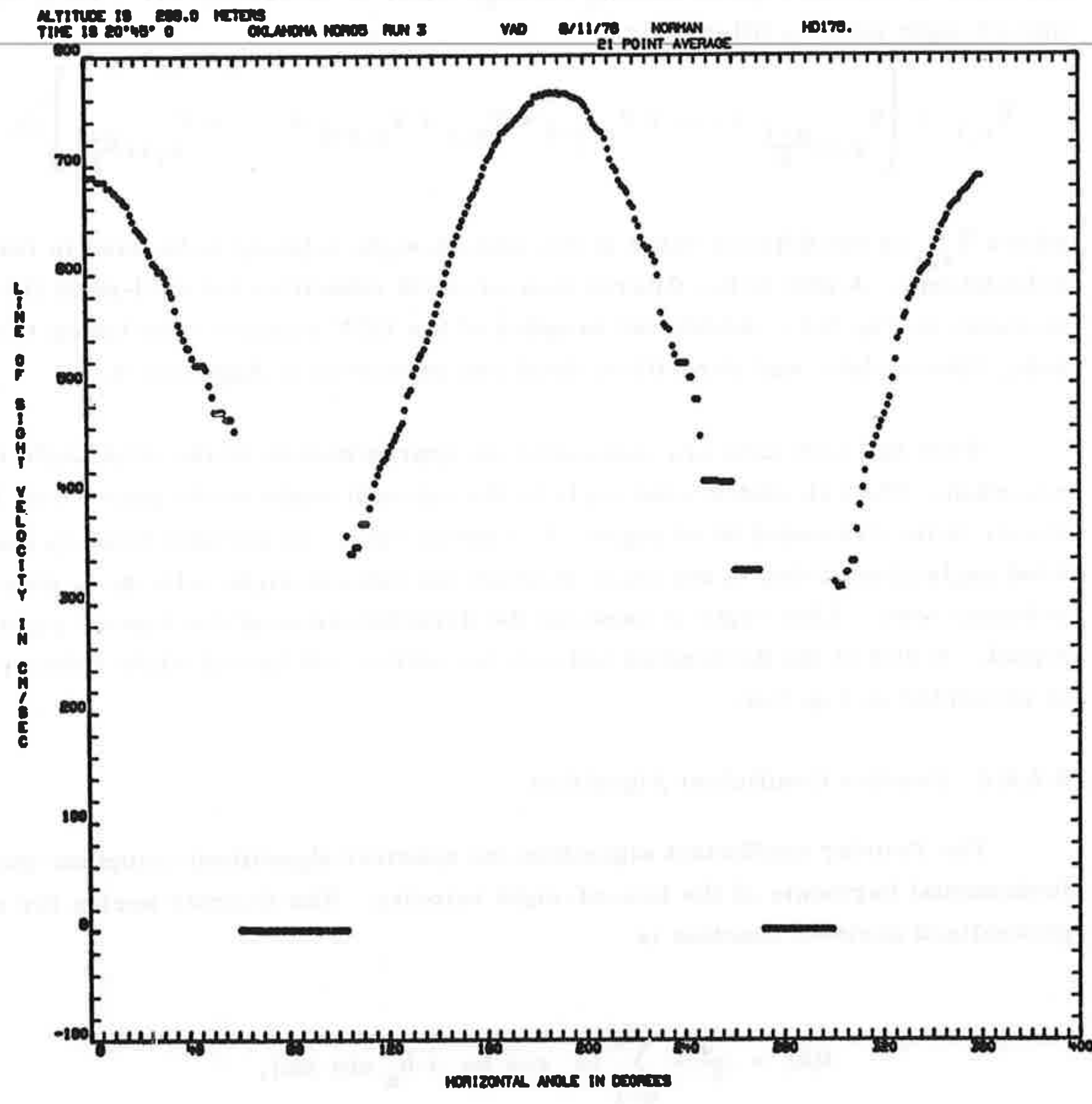


FIGURE 3-7. FILTERED LINE-OF-SIGHT VELOCITY FOR VELOCITY AZIMUTH DISPLAY MODE.

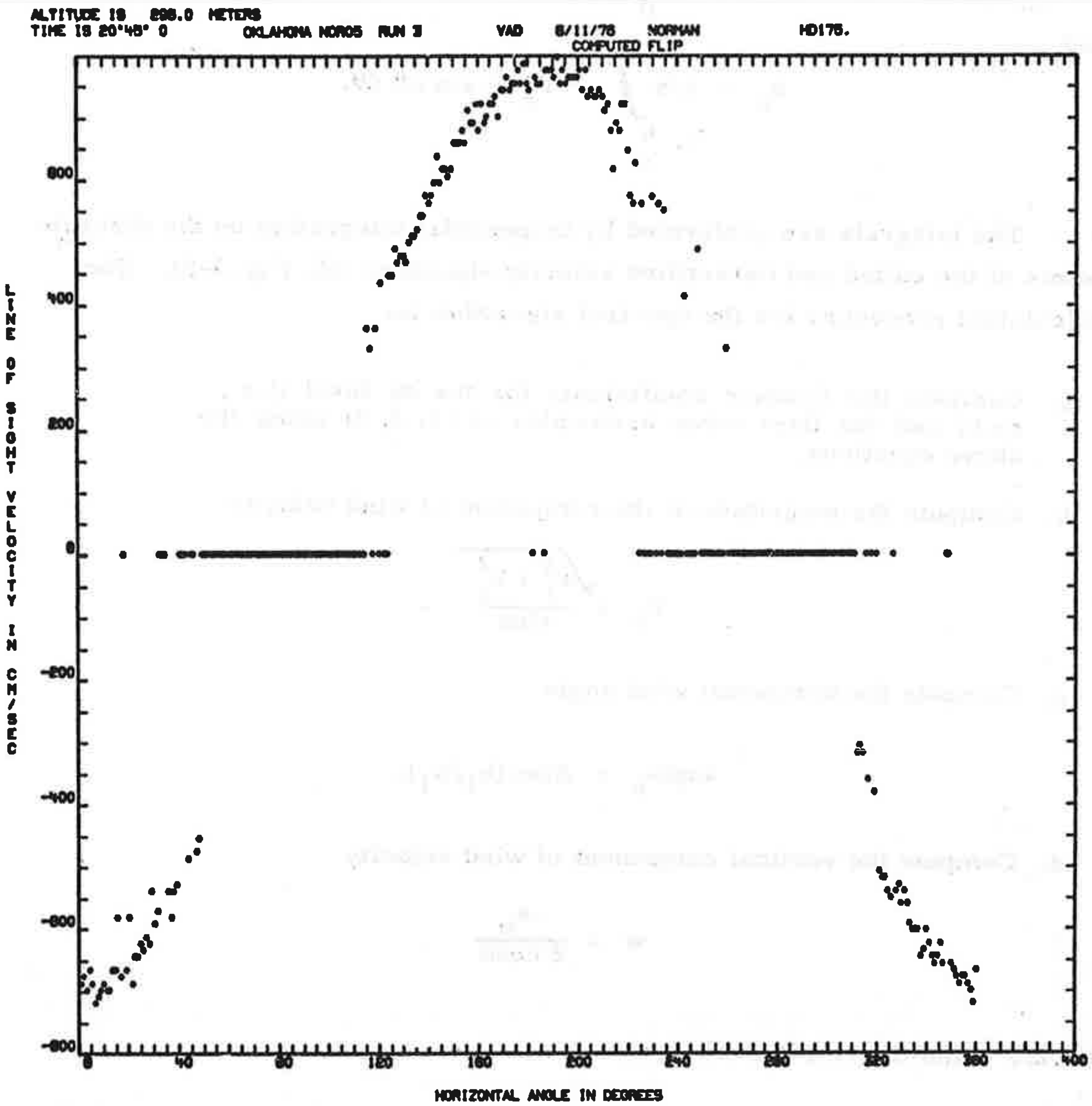


FIGURE 3-8. DERECTIFIED LINE-OF-SIGHT VELOCITY FOR VELOCITY AZIMUTH DISPLAY MODE (Edited, but Unfiltered).

where

$$a_n = 1/\pi \int_0^{2\pi} V_r(\theta) \cos n\theta \, d\theta,$$

and

$$b_n = 1/\pi \int_0^{2\pi} V_r(\theta) \sin n\theta \, d\theta.$$

The integrals are performed by trapezoidal integration on the discrete points of the edited and derectified velocity signature (cf. Fig. 3-8). The calculation procedure for the spectral algorithm is:

a. Compute the Fourier coefficients for the dc level (i.e., $n = 0$) and the first three harmonics ($n = 1, 2, 3$) using the above equations.

b. Compute the magnitude of the component of wind velocity

$$V_h = \frac{\sqrt{a_1^2 + b_1^2}}{\sin\alpha} .$$

c. Compute the horizontal wind angle

$$\text{angle}_h = \text{Atan}\,(b_1/a_1).$$

d. Compute the vertical component of wind velocity

$$w = \frac{-a_o}{2\cos\alpha} .$$

3.2.2.3 Sine-Curve-Fit Technique

The line-of-sight velocity signature is sinusoidal for a uniform wind. Therefore, the best sinusoidal wave which fits the data in a least-squares sense is determined by finding the values of the coefficients A, B, and C which minimize (summing over all acceptable data points)

$$\sum_i (V_i - C - A\cos\theta_i - B\sin\theta_i)^2,$$

where V_i is the line-of-sight velocity (derectified) at point i, and θ_i is the azimuth at point i. A, B, and C are obtained from

$$\left[\sum_i \cos^2\theta_i\right]A + \left[\sum_i \cos\theta_i \sin\theta_i\right]B + \left[\sum_i \cos\theta_i\right]C = \sum V_i \cos\theta_i,$$

$$\left[\sum_i \cos\theta_i \sin\theta_i\right]A + \left[\sum_i \sin^2\theta_i\right]B + \left[\sum_i \sin\theta_i\right]C = \sum V_i \sin\theta_i,$$

$$\left[\sum_i \cos\theta_i\right]A + \left[\sum_i \sin\theta_i\right]B + nC = \sum_i V_i.$$

The steps for calculating the wind using the least-squares algorithm are:

a. Find the least-squares curve fit for a sine wave to minimize

$$\sum_i (V_i - C - A\cos\theta_i - B\sin\theta_i)^2,$$

where

V_i is line-of-sight velocity at point i,
θ_i is azimuth at point i, and
C, A, and B are coefficients to be calculated.

b. Compute the magnitude of the horizontal component of velocity:

$$V_h = \frac{\sqrt{A^2 + B^2}}{\sin\alpha}$$

c. Compute the horizontal angle:

$$\text{Angle}_h = \text{Atan}(B/A).$$

d. Compute the vertical component of wind velocity:

$$w_v = \frac{-C}{\cos \alpha} .$$

4. DATA COLLECTION AT NATIONAL SEVERE STORMS LABORATORY TEST SITE

4.1 TEST DESCRIPTION

During June 1976, the mobile laser Doppler velocimeter was deployed adjacent to the WKY-TV tower north of Oklahoma City. The meteorological instruments on the 481-m tower are operated by the National Severe Storms Laboratory (NSSL) of the National Oceanic and Atmospheric Administration. The tower was instrumented with propeller anemometers at the surface and at altitudes of 25, 45, 89, 177, 266, and 444 m.

A diagram of the test site is shown in Fig. 4-1, and a table of test runs is shown in Table 4-1. Meteorological data from the tower were recorded at 2-sec intervals. Table 4-2 summarize the data recorded. The data recorded at 2-sec intervals were averaged over appropriate time intervals for comparison with LDV-measured wind.

By standard meteorological convention, the wind direction is the direction from which the wind comes. Therefore, when wind is given in speed-direction coordinates, the direction is the direction from which the wind comes, measured from true north. The coordinates chosen for the test are shown in Fig. 4-1. For wind expressed in rectangular coordinates the positive u component represents wind coming from the positive x direction (i.e., from north to south). Similarly, a positive v component represents wind coming from the positive y component (i.e., from west to east). For example, a wind coming from 045 deg has a positive u component and a negative v component. The vertical component, w, is positive for upward air motion.

4.2 TEST OBJECTIVES AND OPERATING PROCEDURE

The primary objective of the test was the verification of the capability of the laser Doppler velocimeter to perform accurate wind measurements to

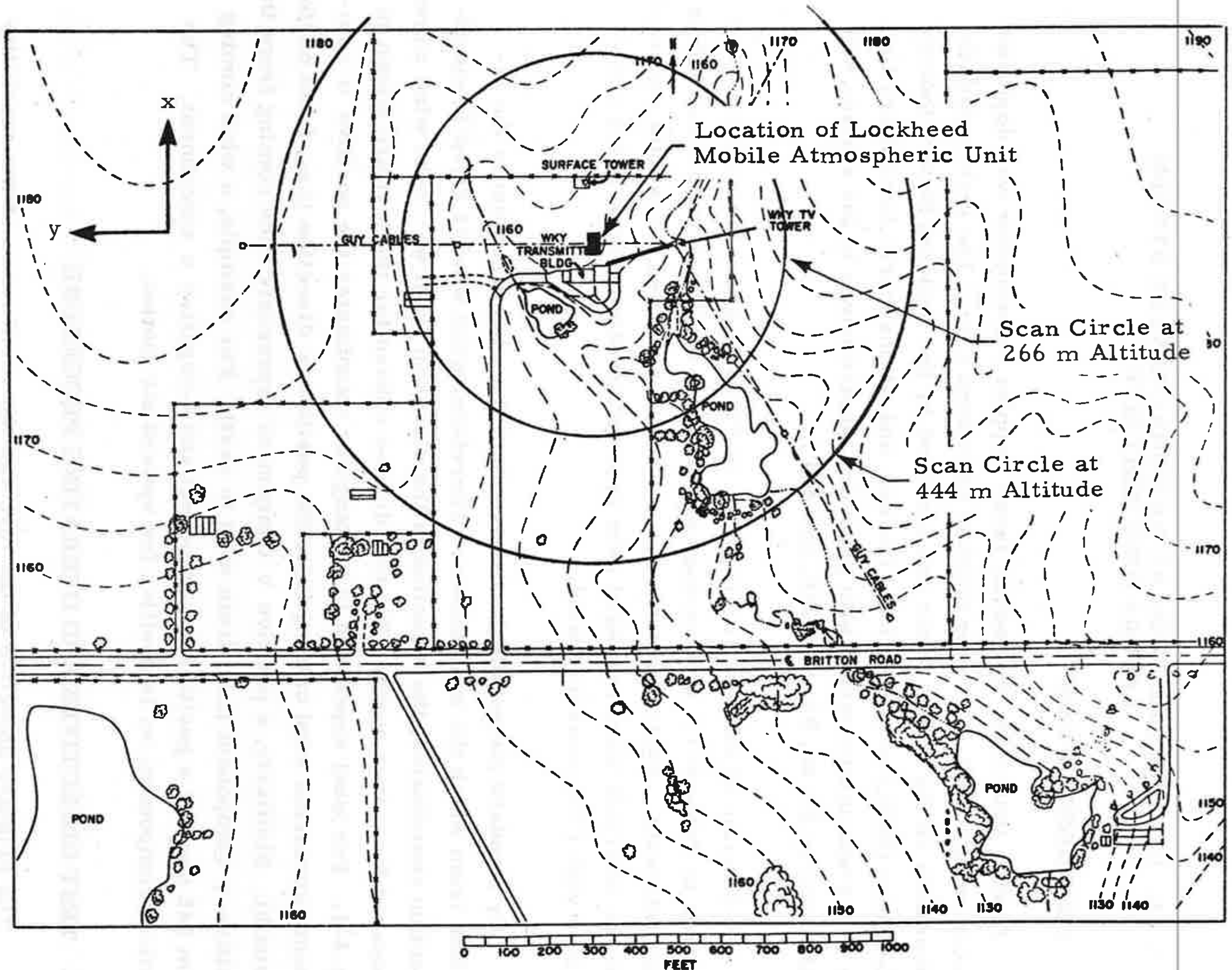


FIGURE. 4-1. DIAGRAM OF THE NATIONAL SEVERE STORMS LABORATORY TEST SITE (Ref. 8).

TABLE 4-1. SUMMARY OF LASER DOPPLER VELOCIMETER WIND MEASUREMENTS AT NATIONAL SEVERE STORMS LABORATORY TEST FACILITY.

Date	Run No.	Altitude AGL	Start Time (CST)	Stop Time (CST)	Comments
6/7/76	100	266	16:22	17:01	
6/8/76	100	444	09:25	09:54	
	201	444	09:52	10:01	
	302	266	11:22		
	303	177	12:54		
	304	45	14:37	16:21	
6/9/76	100	45	11:14	12:10	
	201	45	12:27	12:45	
	302	177	12:58	13:37	
6/10/76	100	444	22:22	24:27	Printed Time Wrong 2 Altitudes
	201	266	24:27	02:27	
	302	177	02:30	03:32	Lost (Bad Tape)
	403	45	03:38	04:37	Lost (Bad Tape)
6/11/76	100	45	17:55	19:00	
	201	177	19:05	20:31	
	302	266	20:40	22:41	
	403	444	22:47	00:25	
	504	444	00:31	01:17	Printed Time Wrong 2 Altitudes
6/13/76	100	444	17:53	18:49	
	201	444	18:55	18:59	
6/14/76	100	45	11:15	12:33	
	201	177	12:37	14:04	
	302	266	14:17	15:14	
6/14/76	100	444	21:45	22:57	Lost (Bad Tape)
	201	444	23:10	23:23	Lost (Bad Tape)
6/15/76	100	45	01:06	01:55	
6/17/76	100	45	09:35	11:06	
	201	177	11:19	12:50	
	302	266	13:03	14:34	
	403	444	14:47	15:26	
	101	444	19:26	22:41	Wind Shifts at 21:42 and 22:15
	202	444	22:44	23:07	
	303	444	23:09	23:15	
	404	444	23:18	23:36	
6/21/76	101	444	08:39	09:44	
	202	444	09:46	10:32	
	303	266	10:36	12:07	
	404	177	12:16	13:38	
	505	45	14:43	16:14	
6/23/76	101	444	21:13	21:53	Full Spectrum Data
	202	444	21:53	22:06	Rain Began
	303	444	22:38	22:45	
	404	266	22:46	23:41	
	505	45	00:14	00:53	Rain Stopped

TABLE 4-2. METEOROLOGICAL DATA RECORDED FROM WKY-TV TOWER

Parameter	Unit	Altitude (m)
Wind Speed*	m/sec	Surface, 26, 45, 89, 177, 266, 444
Wind Direction*	deg	Surface, 26, 45, 89, 177, 266, 444
Temperature	deg C	Surface, 26, 45, 89, 177, 266, 444
Wet Bulb Temperature	deg C	Surface
Relative Humidity	percent	89, 266, 444
Vertical Velocity Component**	m/sec	26, 45, 89, 177, 266, 444
Pressure	millibar	Surface, 444

*Wind speed and direction were measured by Bendix Model 120 aerovanes.

**Vertical component of velocity was measured by R.M. Young Model 1200 propeller anemometers.

an altitude of 444 m. As shown in Table 4-1, measurements were made at 45, 177, 266, and 444 m. For all runs, measurements were made at one altitude at a time, although the altitude was occasionally changed during a run. Therefore, all averaged data are based on 12 scans per minute. A secondary objective was the measurement of wind phenomena in thunderstorms and a demonstration of the ability of the LDV to measure wind in rain. A small quantity of data was obtained in rain.

4.3 ANALYSIS OF WIND MEASUREMENTS

4.3.1 Effect of Measurement Altitude

Appendix A shows several typical VAD signatures similar to those shown in Figs. 3-6, 3-7, and 3-8. Figures 4-2 and 4-3 show signatures (unedited and unfiltered) for altitudes of 45 and 444 m. Intuitively, it might be expected that the data from 444 m would exhibit more scatter than the data measured at 45 m. It is noted that the focal volume (i.e., the volume of space from which measurements are taken) includes altitudes of 45 m ±0.8 m for the 45-m data, and includes altitudes of 444 m ±82 m for the 444-m data. However, the signatures show that the sinusoidal curve for the high altitude is very well defined, and no ambiguity about the data occurs. It is noted that wind variation with altitude is much less significant at the higher altitude (i.e., out of the earth's boundary layer) and this may account for the well-defined curve of Fig. 4-3.

4.3.2 Presentation of Measurements Made

The winds measured by the LDV are tabulated for typical runs in Appendix B. A sample of the output is shown in Table 4-3.

The date is the test site date on which the run was initiated. All times are Central Standard Time. The height is the indicated altitude (m) on the laser focusing system. Before each test run, the laser ranging system is calibrated to assure that the actual altitude of the data is the desired altitude. The following interpretations are placed on the columns in Table 4-2.

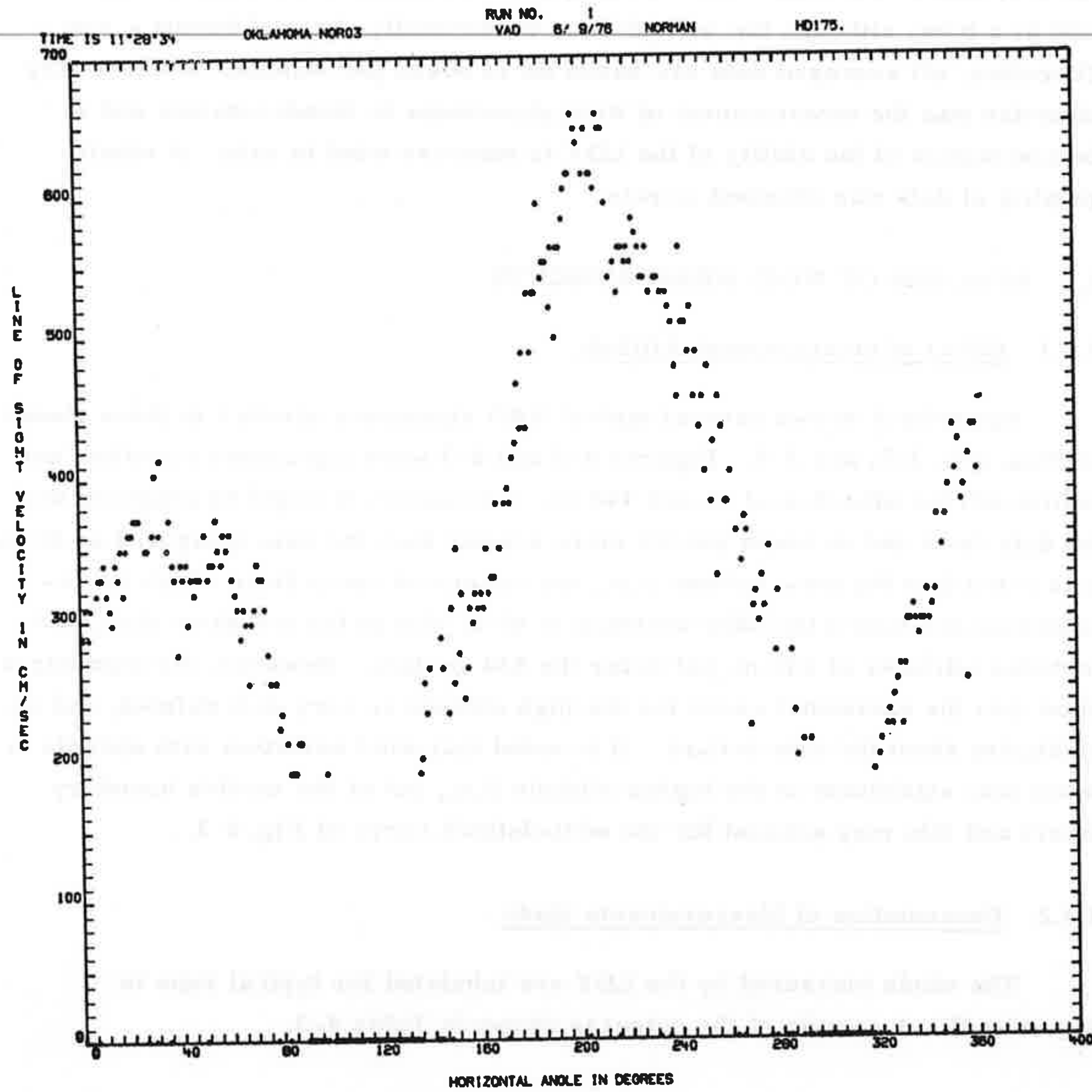


FIGURE 4-2. LINE-OF-SIGHT VELOCITY SIGNATURE AT 45-M ALTITUDE

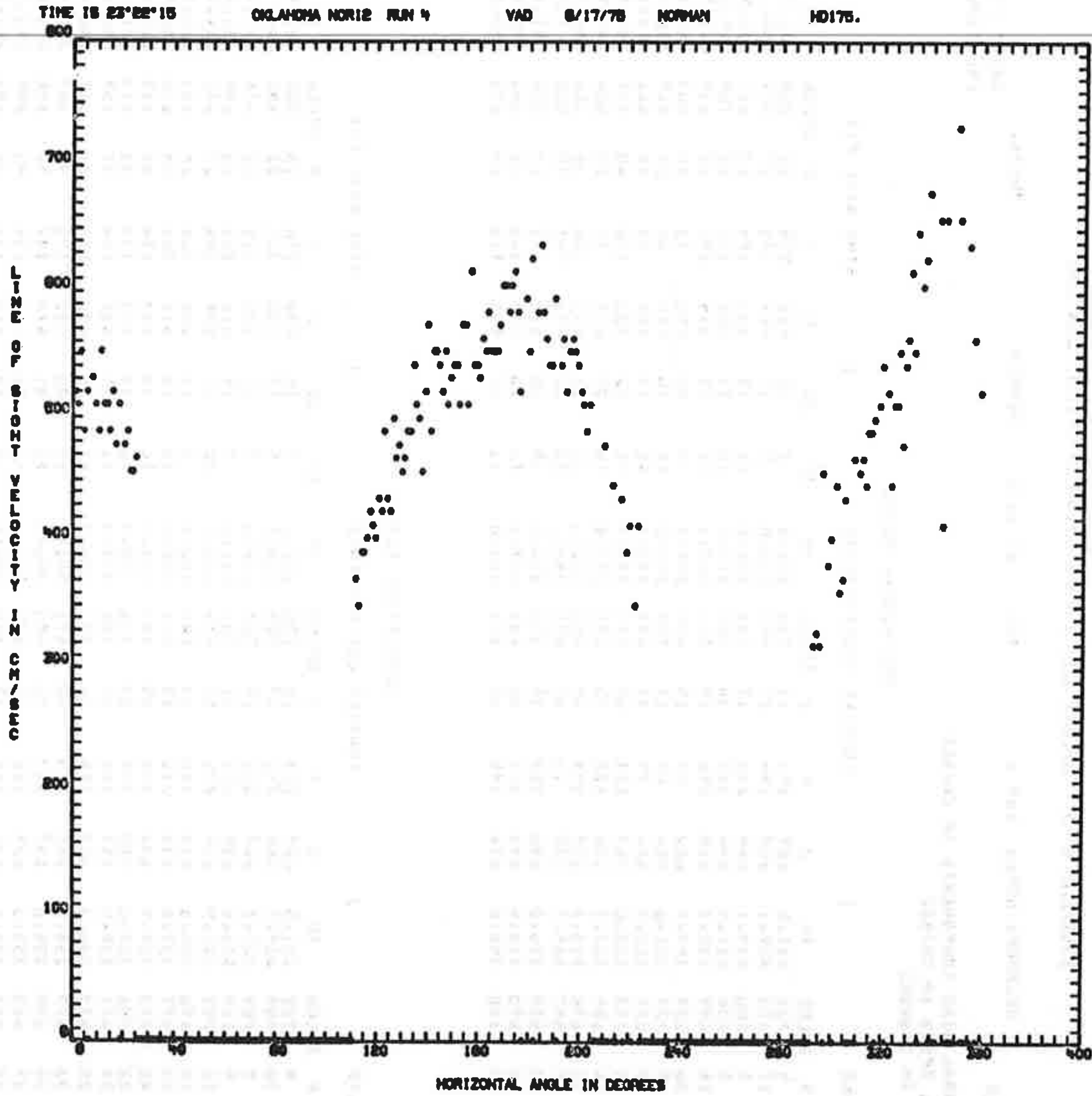


FIGURE 4-3. LINE-OF-SIGHT VELOCITY SIGNATURE AT 444-M ALTITUDE.

TABLE 4-3. SAMPLE TABULATED WIND DATA.

OKLAHOMA NOR62 RUN 3 VAD 6/ 8/76 NORMAN HD175.

HEIGHT = 175. METERS

START TIME 13:15: 0
END TIME 13:30: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE-MINUTE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	644	290	4	722	331.5	659	293	12	730	331.6	7	15	648	270	15	708	332.9	66
2	572	174	17	693	338.1	652	186	27	687	340.0	8	19	621	172	29	651	340.3	64
3	645	136	7	700	344.1	658	210	17	702	337.8	11	18	634	188	19	667	338.9	73
4	577	346	9	738	321.4	546	387	30	708	317.4	12	21	559	371	28	708	319.5	78
5	569	244	16	649	332.9	560	290	28	651	328.1	11	21	534	281	29	619	327.9	68
6	615	114	30	629	344.9	623	56	25	638	349.7	8	20	593	73	25	603	347.9	57
7	729	55	18	739	351.0	756	68	17	759	350.3	12	15	727	38	26	729	352.4	47
8	664	-3	53	667	355.9	686	79	46	699	348.7	10	19	658	28	55	661	353.1	40
9	679	276	42	768	332.0	759	118	58	776	346.1	16	20	703	130	60	717	344.9	63
10	568	237	66	659	333.7	676	128	73	696	344.8	15	24	618	71	83	626	348.9	65
11	452	397	45	646	313.7	599	249	64	658	332.3	13	26	641	168	35	666	340.9	83
12	450	178	89	547	334.9	575	16	83	595	354.1	22	22	541	-57	80	555	1.5	57
13	354	251	63	528	320.2	540	109	75	578	343.4	18	30	531	42	67	536	351.0	54
14	364	363	52	590	310.5	596	157	52	627	341.2	10	20	547	102	58	563	345.5	62
15	627	93	73	660	346.5	676	148	62	697	343.0	10	17	663	118	64	678	345.2	58

CUMULATIVE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	644	290	4	722	331.5	659	293	12	730	331.6	7	15	648	270	15	708	332.9	66
2	609	234	10	708	334.7	656	242	19	709	335.6	8	17	635	223	22	681	336.4	65
3	621	202	9	706	337.7	657	232	18	707	336.3	9	17	635	212	21	676	337.2	67
4	610	240	9	714	333.5	628	272	21	707	331.4	9	18	615	253	23	684	332.6	70
5	602	240	11	701	333.4	615	275	23	696	330.8	10	19	599	258	24	672	331.7	70
6	604	220	14	690	335.3	616	240	23	687	333.8	9	19	598	228	24	661	334.3	68
7	621	197	14	697	337.5	635	216	22	697	336.1	10	18	616	202	24	670	336.8	65
8	627	171	20	693	339.9	642	198	25	697	337.8	10	18	622	179	28	669	339.0	61
9	633	182	22	701	339.0	655	189	29	706	338.7	10	19	631	174	32	674	339.6	62
10	628	187	26	697	338.5	657	183	33	705	339.3	11	19	629	164	37	669	340.5	62
11	613	206	28	692	336.3	652	189	36	701	338.7	11	20	630	164	37	669	340.6	64
12	598	204	33	679	336.2	645	174	40	691	340.0	12	20	622	145	40	659	342.4	63
13	580	207	36	668	335.0	637	169	43	683	340.3	12	21	616	137	42	650	343.0	63
14	565	218	37	663	333.3	634	168	43	679	340.3	12	21	611	134	43	644	343.2	62
15	569	210	39	662	334.1	637	167	45	680	340.5	12	20	614	133	45	646	343.3	62

TABLE 4-3 (Concluded)

HEIGHT = 175. METERS　　OKLAHOMA NORG2　RUN 3　　VAD　6/ 8/76　NORMAN　　HD175.

START TIME 13:15: 0
END TIME 13:30: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE-MINUTE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	82	156	25	75	12.7	83	113	25	82	8.9	82	96	25	82	7.6
2	171	329	22	59	31.9	44	117	15	51	9.7	30	102	18	38	8.8
3	72	240	36	56	20.4	62	123	20	47	10.7	58	85	15	51	7.8
4	292	171	20	121	29.7	236	104	28	92	21.8	226	116	23	93	21.5
5	92	194	37	72	17.9	103	152	15	73	15.3	83	139	19	64	13.7
6	54	70	21	51	6.6	64	129	20	52	12.3	73	76	16	63	8.1
7	57	108	29	57	8.3	36	30	26	35	2.3	46	21	21	45	1.8
8	41	58	16	41	5.0	58	102	17	38	9.5	39	48	19	40	4.2
9	184	182	41	95	18.8	93	98	41	78	8.4	87	49	29	85	4.3
10	65	167	20	22	16.6	36	106	30	27	9.1	22	72	20	20	6.7
11	173	178	23	33	22.3	98	90	28	65	10.4	83	72	38	83	6.5
12	83	256	17	39	29.1	56	157	31	39	16.2	60	116	30	64	11.7
13	195	251	28	49	36.7	86	165	25	37	18.8	78	65	30	80	6.6
14	233	199	16	50	31.0	40	118	19	42	11.1	55	94	20	62	9.3
15	97	173	27	48	17.6	48	80	10	37	7.3	43	79	19	29	7.3

CUMULATIVE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	82	156	25	75	12.7	83	113	25	82	8.9	82	96	25	82	7.6
2	134	256	24	68	23.7	66	125	22	71	10.0	63	109	23	70	8.9
3	118	252	28	64	22.8	64	123	21	63	10.1	60	102	20	64	8.5
4	177	240	26	82	25.5	138	136	23	71	16.2	128	126	21	73	15.1
5	164	231	28	84	24.1	134	138	22	74	16.0	124	128	21	75	14.9
6	152	218	28	84	22.6	125	159	21	74	16.9	117	139	20	78	15.2
7	149	213	28	82	21.8	126	159	22	74	16.7	118	145	20	77	15.4
8	140	211	30	78	21.4	121	159	23	70	16.5	112	148	22	74	15.5
9	145	210	32	83	21.2	123	155	27	75	16.0	112	142	25	76	14.8
10	141	206	34	80	20.8	118	152	30	72	15.5	107	140	29	74	14.4
11	152	212	33	79	22.0	117	149	31	72	15.2	105	135	30	74	13.9
12	154	215	36	86	22.6	115	157	34	76	15.9	105	147	32	80	14.9
13	170	218	37	93	24.1	116	158	35	79	16.1	105	145	32	86	14.6
14	182	219	36	93	25.4	113	155	34	79	15.8	104	142	32	88	14.3
15	179	219	36	90	25.1	110	151	33	77	15.4	102	139	32	85	14.0

4.3.2.1 One-Minute Means

One-minute means were calculated for each minute of the 15-minute time period. The minutes of the time period are tabulated in the first column. Each of the numbers in this group is an average of the 12 VAD scans that occur at the given altitude during 1 min.

4.3.2.1.1 Peaks

The 1-min mean u, v, and w components of wind as calculated by the peak algorithm are tabulated. The w component is the vertical component and is positive vertically upward. Speeds are given in centimeters per second and angles are given in degrees.

The data calculated from the basic VAD data are horizontal wind speed, wind direction, and vertical component of wind velocity. The u and v components are calculated from horizontal wind speed and direction. The speed is the 1-min average of the horizontal component of velocity, and "TH" is θ_0, the direction of the horizontal component of wind. The u and v averages are calculated by averaging the u and v values of the individual VAD scans rather than from averaged values of u and v. Thus, if S is wind speed,

$$u_i = -S_i \sin\theta_{0,i} ,$$

and

$$v_i = -S_i \cos\theta_{0,i} ,$$

where the i subscript refers to the individual VAD scans. The averages for n scans in the 1-min average are (for data discussed herein, n = 12)

$$\overline{S} = \sum S_i/n , \qquad (i=1, \ldots, n)$$

$$\overline{\theta}_0 = \sum \theta_{0,i}/n ,$$

$$\overline{u} = \sum u_i/n ,$$

and

$$\overline{v} = \sum v_i/n .$$

It is noted in general that

$$\overline{u} \neq -\overline{S} \sin\overline{\theta}_0 ,$$

$$\overline{v} \neq -\overline{S} \cos\overline{\theta}_0 ,$$

and

$$\overline{S} \neq \sqrt{\overline{u}^2 + \overline{v}^2} .$$

The averaging characteristic represented by the above equations also results from resolving cup and vane anemometer data into components and averaging or when comparing averaged data from cup and vane anemometers with averaged data from propeller anemometers. The characteristic is particularly pronounced in light and variable wind conditions.

4.3.2.1.2 Fourier Coefficients

Results are shown for wind calculations performed using the spectral algorithm. The symbols have the same meaning as for the peak algorithm. The "2D" is the magnitude of the second harmonic and is the average of $\sqrt{a_2^2 + b_2^2}$ where a_2 is the second Fourier cosine coefficient and b_2 is the second Fourier sine coefficient. Similarly, "3D" is the average of $\sqrt{a_3^2 + b_3^2}$. The magnitude of these numbers is an indication of turbulence with the frequency of the turbulence increasing with the number of the harmonic.

4.3.2.1.3 Sine Fit

Results are shown for the least-squares sine fit algorithm with similar meanings of the symbols as for the other two algorithms. The "SP" is the standard deviation of the actual line-of-sight velocity points referenced to the best sine fit. As such, it is an indication of atmospheric turbulence.

4.3.2.2 Cumulative Means

The cumulative means are averages of individual VAD scans taken over the time period indicated. For example, the 3-min cumulative mean is the average of the VAD scans taken over the first 3 min of the 15-min time period. They are not averages of the 1-min means. The two averaging methods would be identical if the number of VAD scans in each 1-min average were always identical. The 15-min cumulative means are the averages over the 15-min averaging period.

4.3.2.3 1-Min Standard Deviations

This section lists the standard deviation of each of the variables for each 1-min time period. Each standard deviation is the standard deviation of the six VAD scans in the 1-min period.

4.3.2.4 Cumulative Standard Deviations

The cumulative standard deviations are analogous to the cumulative means. They are the standard deviations of the individual VAD scans taken over the time period indicated. In general, the cumulative averages of the standard deviations are not averages of the 1-min means because of the mathematical definition of standard deviation.

4.3.3 Averaging Time Selection

In the tabulated data, the 15-min averaging periods were chosen to start on the quarter hours. However, if the start and stop time of an individual run were such that more 15-min averages could be extracted from the available data by starting the averaging periods at times other than the quarter hour, the starting time which yielded the most 15-min averages was used. Data runs lasting less than 15 min were not processed.

4.4 DATA ANALYSIS

4.4.1 Comparison of Results for Various Algorithms

From the tabulated data, it is noted that the spectral algorithm gives a value of wind speed which is higher than that for the other two algorithms. In previous studies (e.g., Ref. 6), the spectral algorithm gave a lower value of wind speed. For the previous studies, the Fourier coefficients were calculated by summation around the VAD scan with an application of an analytically-derived correction factor to compensate for the absence of data points which lie below the velocity threshold. In general, the wind speeds obtained by this method were lower than the wind speeds measured by the other two algorithms as well as those measured by the tower.

In order to correct this condition, the method of calculating the Fourier coefficients was changed to trapezoidal integration of the edited, derectified signal. This technique obviates the need for a correction factor because it effectively places a straight line across the gap in the derectified signature caused by the velocity threshold (cf., Fig. 3-8). However, the technique causes the wind speed to be biased high. The cause of the bias is yet to be identified.

A comparison between laser-measured winds and tower-measured winds is shown for the three algorithms in Figs. 4-4, 4-5, and 4-6. The peak algorithm exhibits a slightly high bias, the spectral algorithm exhibits a significantly high bias, and the least-squares sine algorithm exhibits little systematic bias. It is noted that two significant wind shifts occurred during the run, and a wide range of wind speeds is shown. The comparison presented in Ref. 6 showed that the sine algorithm appears to be the most reliable data processing algorithm. This conclusion is confirmed by Figs. 4-4, 4-5, and 4-6. The conclusion of a high bias for the modified Fourier algorithm (i.e., trapezoidal integration) is based on comparison with the sine algorithm, which had previously been validated in Ref. 6, as well as comparison with anemometer-measured data. Since the sine algorithm appears to be the most reliable data processing algorithm, further comparison with the meteorological tower is presented for the sine algorithm only.

4.4.2 Effect of Averaging Period on Wind Results

The convergence of the wind data with increasing averaging times is shown in Figs. 4-6 through 4-9. Similar data for selected runs for 1-, 3-, 6-, 9-, 12-, and 15-min averages are shown in Appendix C. Wind direction data are also presented. The scatter for wind direction is significantly less than that for

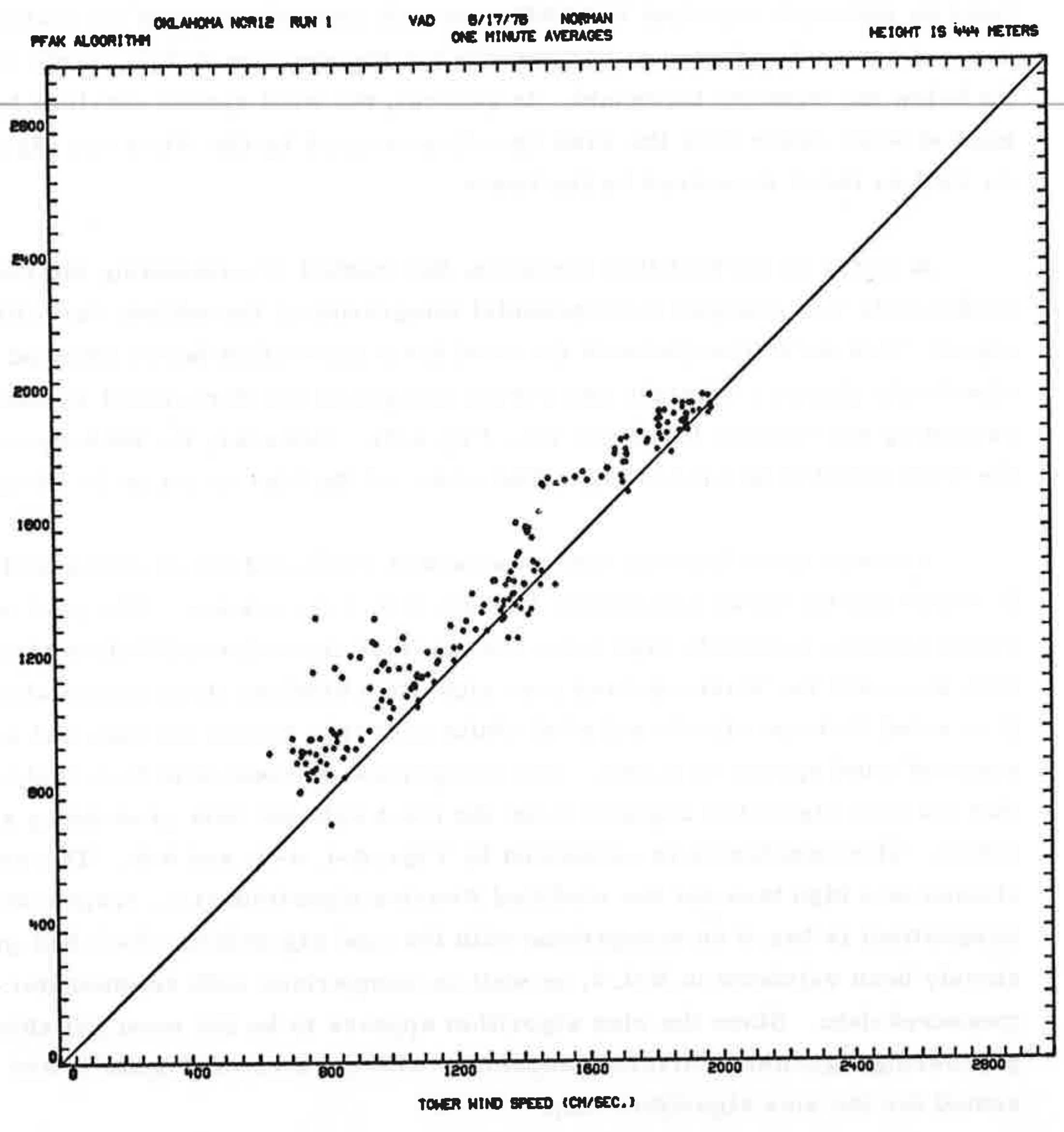


FIGURE 4-4. 1-MIN AVERAGES OF WIND SPEED USING PEAK ALGORITHM.

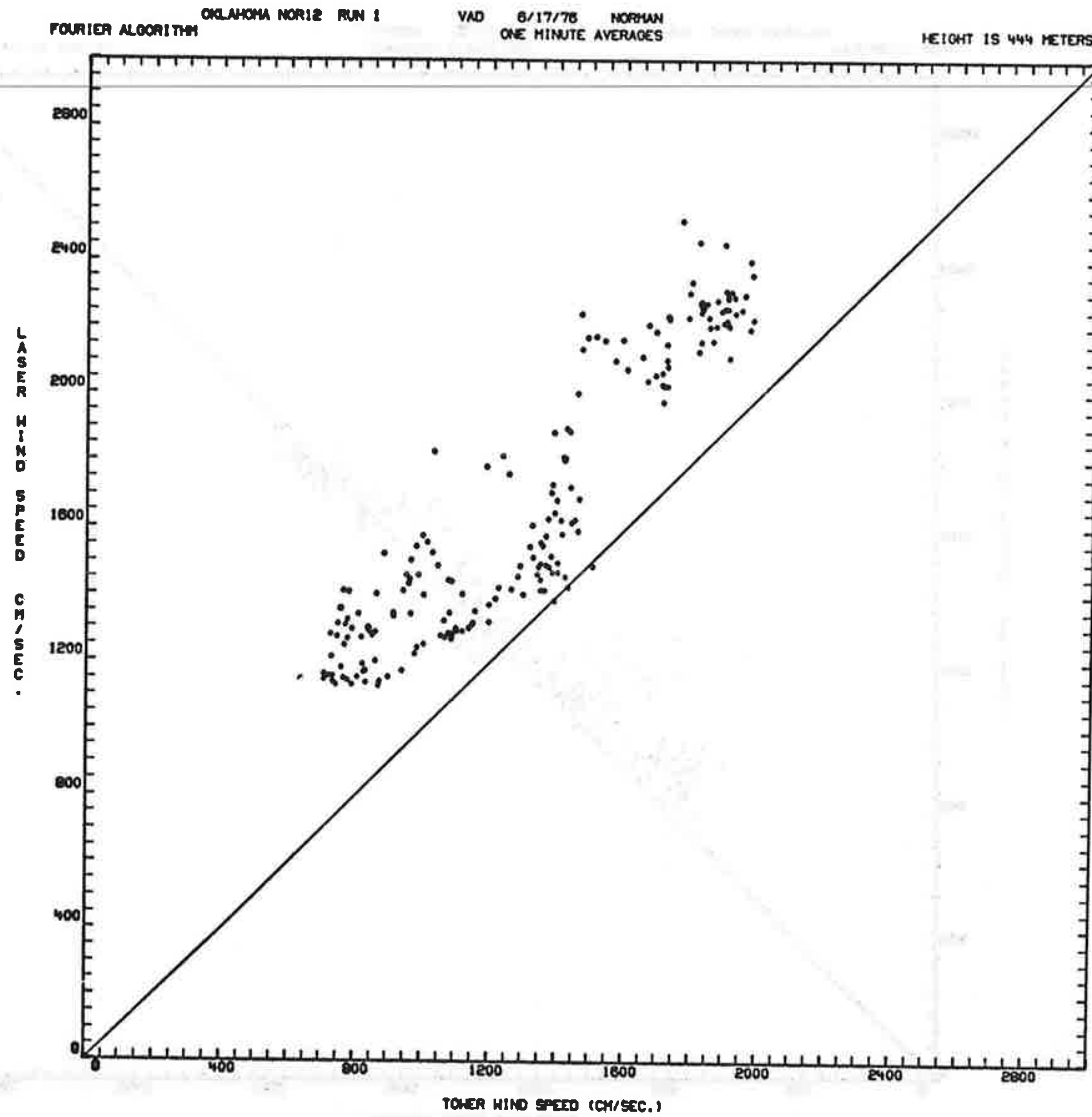


FIGURE 4-5. 1-MIN AVERAGES OF WIND SPEED USING SPECTRAL ALGORITHM.

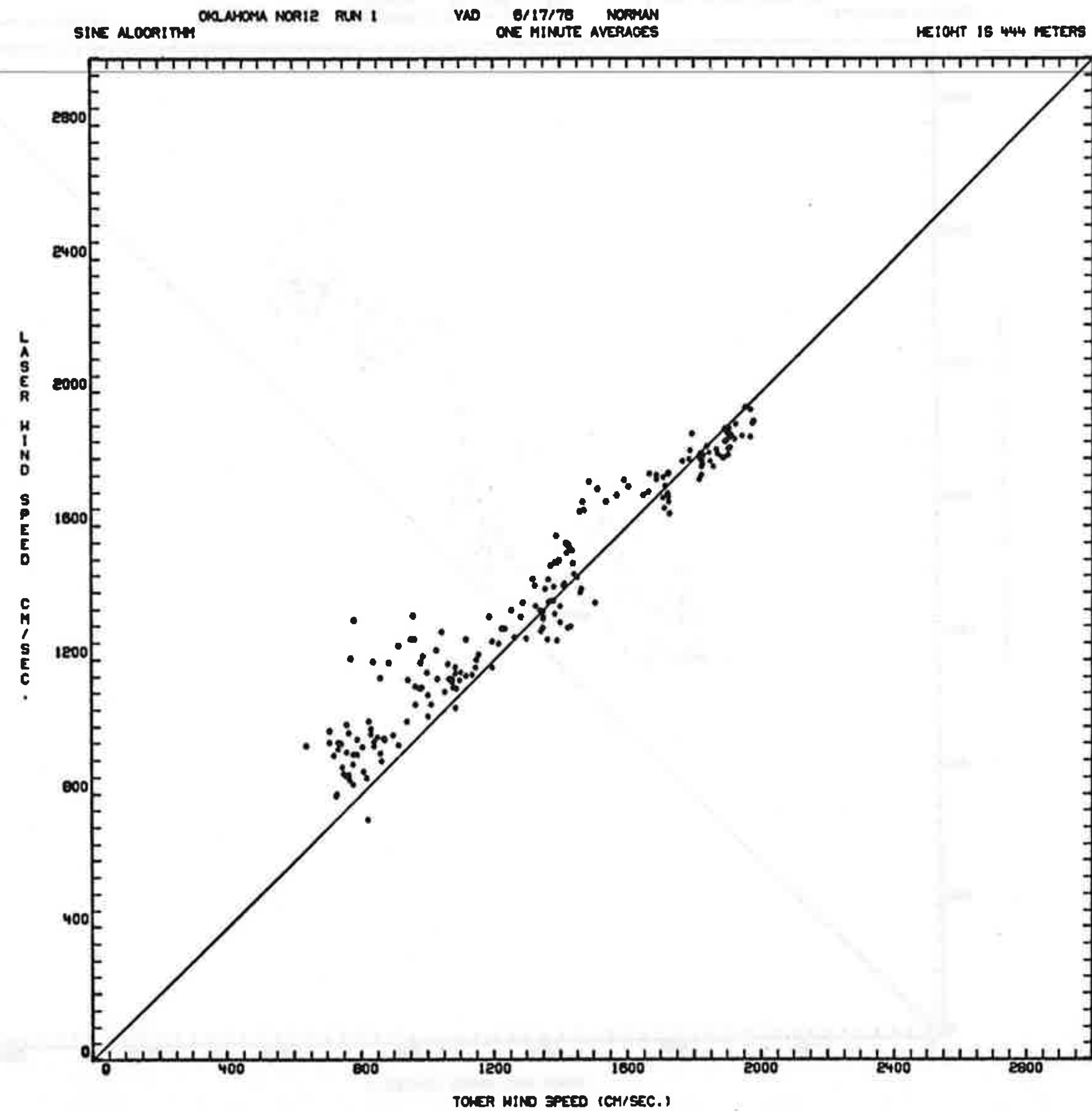


FIGURE 4-6. 1-MIN AVERAGES OF WIND SPEED USING SINE ALGORITHM.

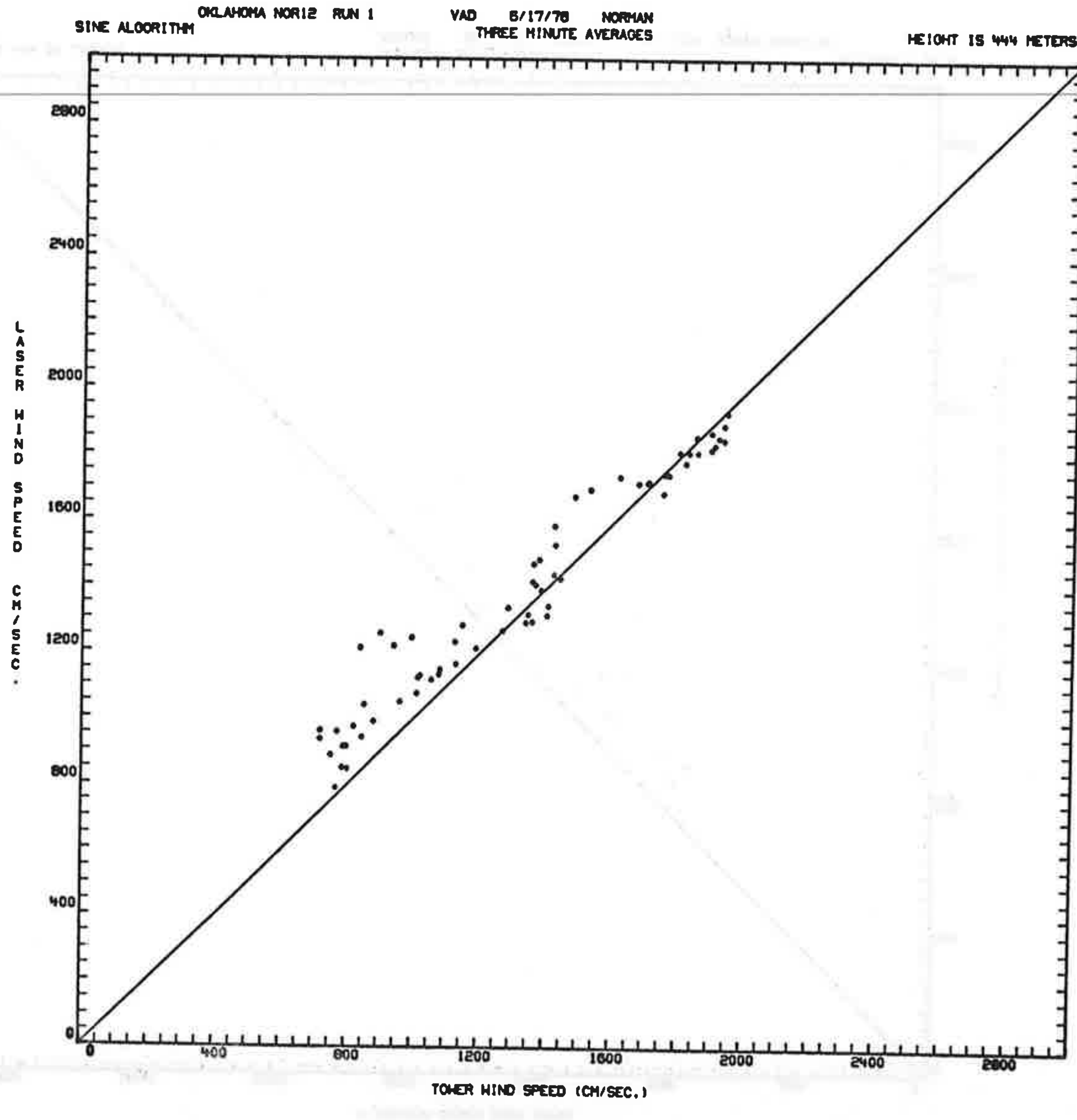


FIGURE 4-7. 3-MIN AVERAGES OF WIND SPEED USING SINE ALGORITHM.

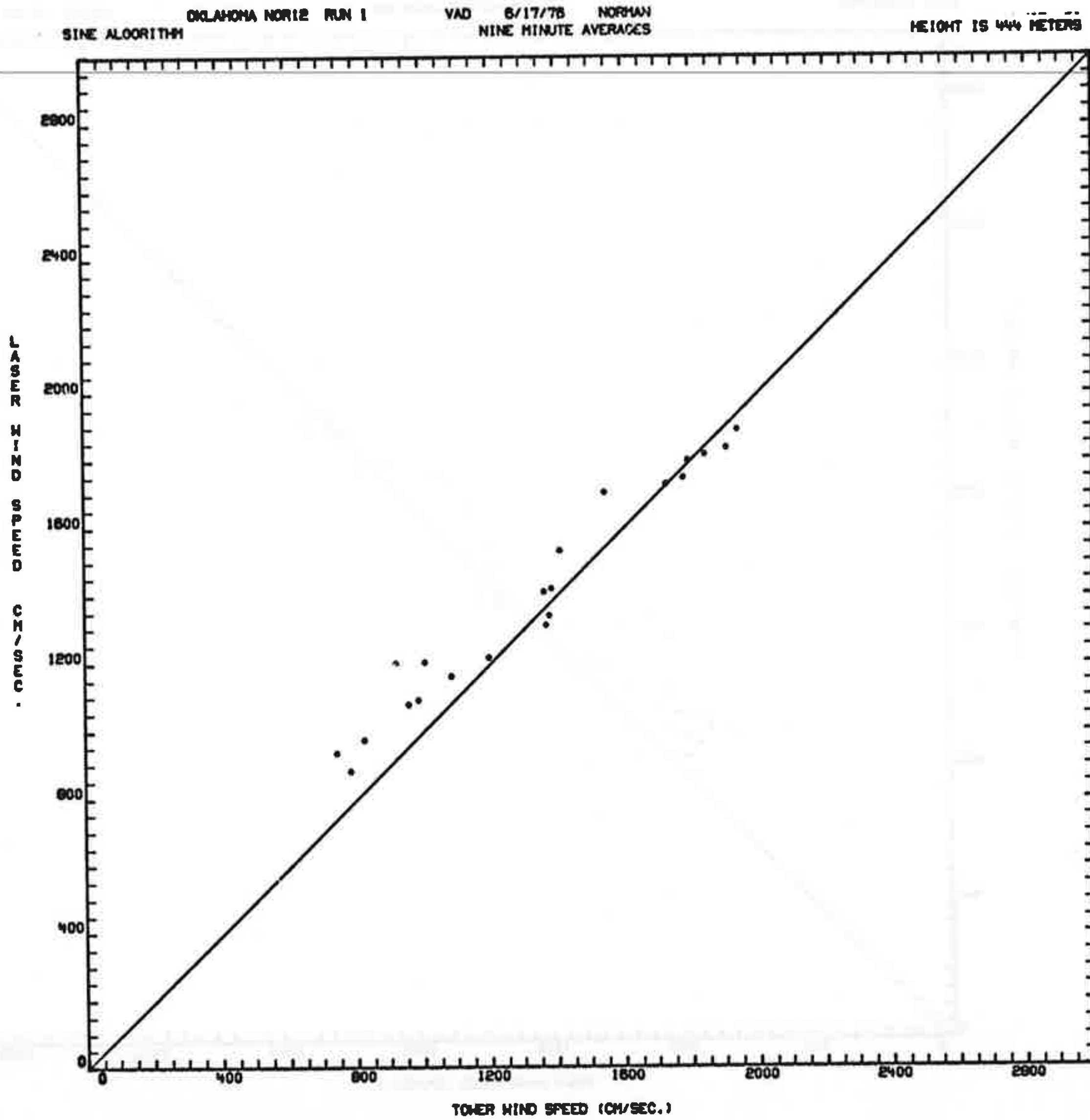


FIGURE 4-8. 9-MIN AVERAGES OF WIND SPEED USING SINE ALGORITHM.

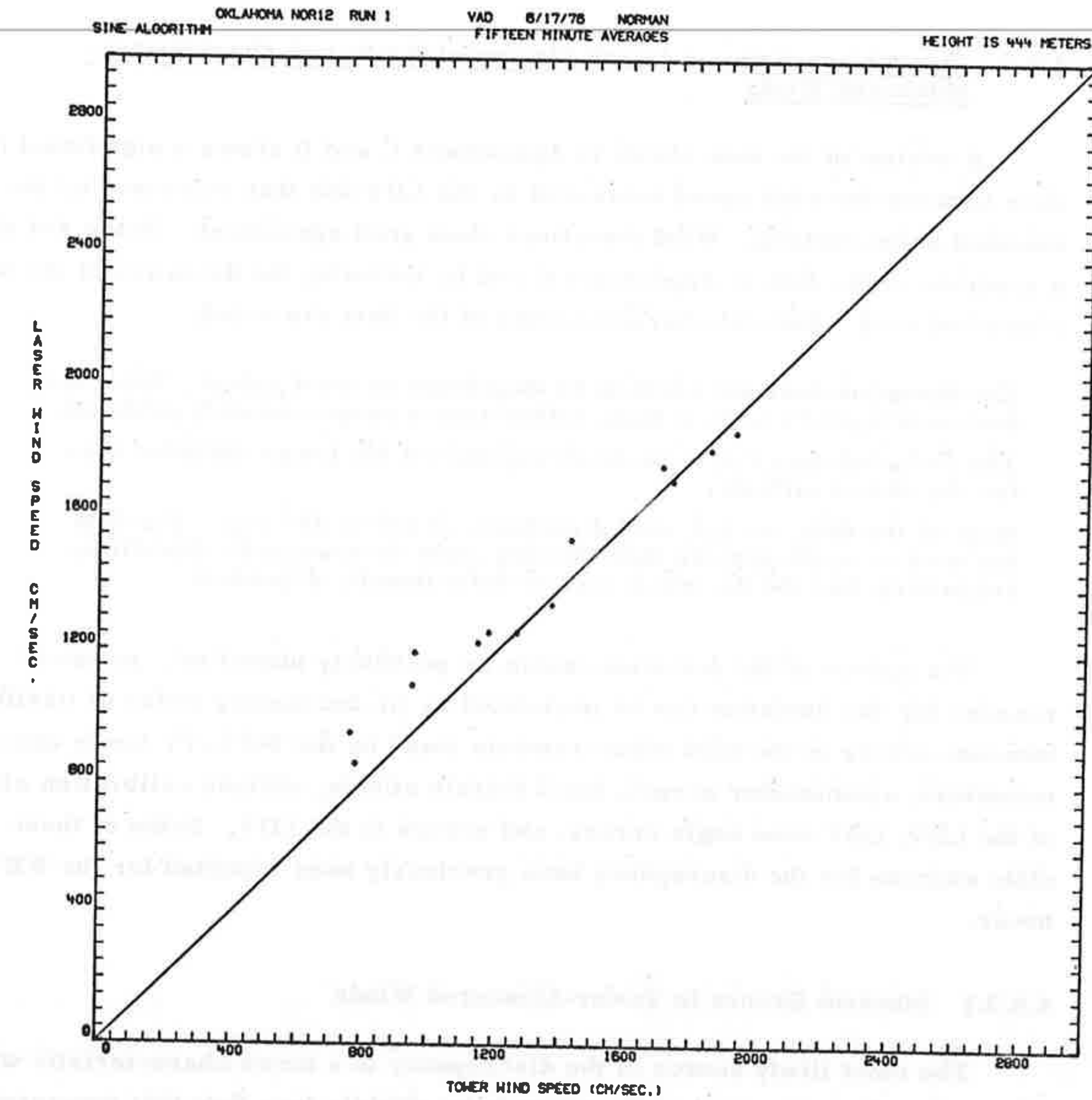


FIGURE 4-9. 15-MIN AVERAGES OF WIND SPEED USING SINE ALGORITHM.

wind speed. Appendix D shows 3-min and 15-min average comparisons for runs not presented in Appendix C.

4.4.3 Comparison Between Laser-Measured Winds and Anemometer-Measured Winds

A review of the data shown in Appendixes C and D shows a significant difference between the wind speed measured by the LDV and that measured by the tower-mounted anemometers. Wind directions show good agreement. Table 4-4 shows a synopsis of the data in Appendixes C and D, including the deviation of the laser-measured wind. Several characteristics of the data are noted:

- The deviation does not seem to be dependent on wind speed. Thus, the deviation appears to be a bias, rather than a proportionality problem.
- The deviation appears to be more significant for lower altitudes than for the 444-m altitude.
- Most of the data are for wind directions of 150 to 200 deg. The data for wind azimuth greater than 200 deg show no systematic deviation, suggesting that the deviation may be directionally dependent.

The source of the deviation cannot be positively identified. However, reasons for the deviation can be postulated as (in decreasing order of likelihood): inherent errors in the wind measurements made by the WKY-TV tower anemometers, anemometer errors, local terrain effects, altitude calibration errors of the LDV, LDV cone angle errors, and errors in the LDV. Some of these possible sources for the discrepancy have previously been reported for the WKY-TV tower.

4.4.3.1 Inherent Errors in Tower-Measured Winds

The most likely source of the discrepancy is a tower characteristic which causes the wind measured at the tower to be slightly less than that measured in the vicinity of the tower. It is noted that previous tests of the LDV at other locations have failed to indicate any systematic discrepancy between laser-measured winds and the anemometer-measured winds, whereas a discrepancy between anemometer-measured winds and winds measured by different techniques has previously been reported for the WKY-TV tower.

TABLE 4-4. DEVIATION BETWEEN LASER-MEASURED WIND SPEED AND ANEMOMETER-MEASURED WIND SPEED.

Run No.	Altitude (m)	Anemometer Wind Speed (m/sec)	Wind Direction (deg)	Wind Speed Deviation (m/sec)
3-1	45	6-9	170-200	1
3-2	45	5-9	160-180	1
5-1	45	5-10	160	2
8-1	45	7-14	160-180	1.5
10-1	45	3-5	170	1.5
11-1	45	7-10	160-180	1
13-5	45	4-9	130-180	2
3-3	177	5-8	170-200	2
5-2	177	11-16	160	0
8-2	177	11-16	165	1.5
11-2	177	6-11	170-180	1.5
13-4	177	5-9	150-170	2
2-3	266	2-6	130-170	2.5
4-2	266	14-17	160	3
5-3	266	16-19	160	-2
8-3	266	9-15	170	1.5
13-3	266	3-9	150-180	2
2-1	444	5-6	160	1
4-1	444	15-16	170	2
5-4	444	18-21	160	0
6-1	444	19-20	170	1
6-2	444	19-20	170	-2
7-1	444	8-15	160-180	0 to -2
11-4	444	9-13	160	0.5
12-1	444	6-20	180-280	0
12-2	444	5-8	220	0
13-1	444	6-9	180	2
13-2	444	6-8	170-180	2
14-1	444	19-21	180	0

A comparison between laser-measured wind speed and anemometer-measured wind speed as measured at Table Mountain, Colorado, is shown in Fig. 4-10 (from Ref. 6). From these data, it is seen that agreement is usually within ±30 cm/sec and is always within 1.5 m/sec. The altitudes roughly correspond with the lower two altitudes of the WKY-TV tower. The validity of the LDV and the least-squares sine fit algorithm has been established from the Table Mountain test.

Reference 9 reports a test in which the winds measured by anemometers on the WKY-TV tower were compared with observations from double-theodolite pilot ballons and tetroons. The results from Ref. 9 are shown in Fig. 4-11. Several observations about the data are significant:

The wind direction is approximately equal to that during the LDV tests.

The discrepancy between the anemometer-measured wind speed and balloon-observed wind speed ranges from approximate agreement to the anemometers underestimating wind by approximately 2.5 m/sec. The same discrepancy range was observed with the LDV.

These results suggest that the discrepancy between laser-measured winds and anemometer-measured winds is due to the underestimating of winds in the vicinity of the tower by the tower-mounted anemometers.

4.4.3.2 Anemometer Errors

Table 4-3 shows that the greatest deviation between the laser-measured wind and the anemometer-measured wind occurs at an altitude of 266 m. The anemometer data also show an anomaly at 266 m. Table 4-5 shows the 1-min mean wind speeds as measured by the anemometers during the early part of run 13-3. At 10:40, the measured wind at 266 m is significantly less than that at 177 m or 444 m. Although this condition does not occur universally, it occurs for a significant number of 1-min averages throughout the run. The magnitude of the deviation and its frequency of occurrence suggests that at least one anomaly exists in the anemometer data. The sign of the anomaly at 166 m in Table 4-5 supports the fact that the greatest deviation between laser-measured wind and anemometer-measured wind occurs at that altitude.

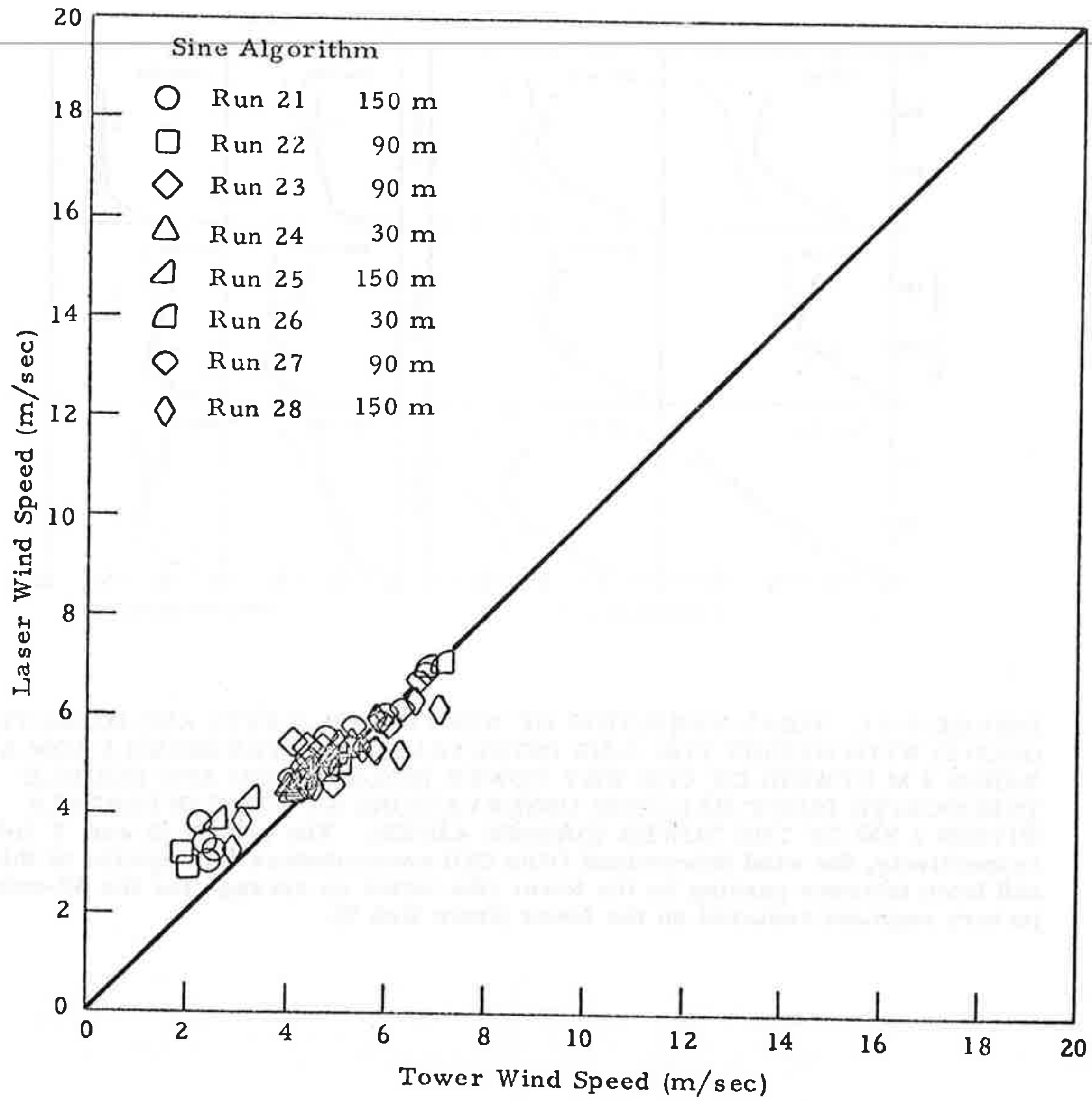


FIGURE 4-10. COMPARISON OF LASER AND TOWER 15-MIN MEAN WIND SPEED USING LEAST-SQUARES SINE ALGORITHM.

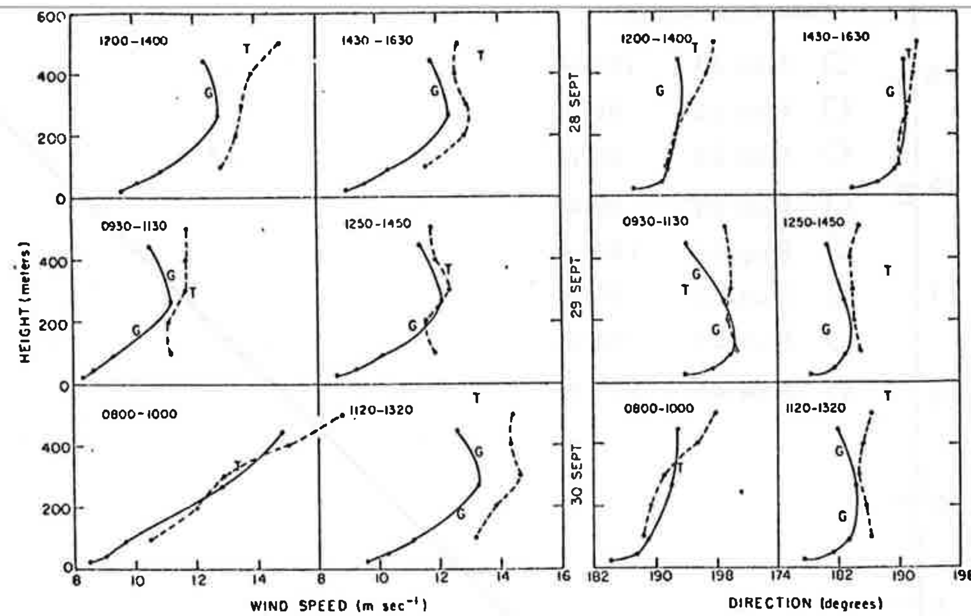


FIGURE 4-11. MEAN VARIATION OF WIND SPEED (LEFT) AND DIRECTION (RIGHT) WITH HEIGHT FOR 2-HR INTERVALS, AS DETERMINED FROM AEROVANES 3 M UPWIND OF THE WKY TOWER (SOLID LINES) AND DOUBLE-THEODOLITE PILOT-BALLOON OBSERVATIONS AT 6-MIN INTERVALS WITHIN 2 KM OF THE TOWER (DASHED LINES). The letters G and T indicate, respectively, the wind determined from Gill anemometers 3 m upwind of the tower and from tetroons passing by the tower (the latter an average for the 40-min trajectory segment centered on the tower (from Ref. 9).

TABLE 4-5. 1-MIN WIND AVERAGES FROM ANEMOMETERS RUN 13-3

Altitude (m)	Wind Speed at Indicated Time (m/sec)						
	10:40	10:50	11:00	11:10	11:20	11:30	11:40
2	3.34	3.74	3.09	4.54	5.31	4.46	4.49
26	4.73	6.18	5.56	6.12	6.38	4.03	7.25
45	5.74	6.90	5.32	6.87	7.20	4.60	8.22
89	7.34	7.18	5.95	7.49	7.97	5.65	8.88
177	7.71	6.66	7.14	7.08	7.99	6.59	8.09
266	5.82	4.08	6.79	7.04	7.74	7.96	6.92
444	7.25	5.58	7.12	7.35	8.36	9.18	6.32

4.4.3.3 Local Terrain Effects

Figure 4-1 shows the end of a gully at a bearing of approximately 160 deg from the tower. Reference 8 shows that the gully extends for 2.6 km south-southeast of the tower and has an elevation of approximately 30 m below that of the tower at a distance of 1.6 km south-southeast of the tower. For most of the test, the wind was blowing up the gully. The terrain effects of the gully could cause the wind measured at a point (i.e., the tower) to be different from that measured over an area (i.e., the LDV). This possibility is supported by the fact that no systematic deviation exists when the wind azimuth is greater than 200 deg. However, the data for wind azimuth other than 150 to 200 deg are too sparse to draw meaningful conclusions.

The possibility of local terrain effects is further supported by the vertical component of wind as measured by the tower-mounted anemometers. Typical magnitudes of the vertical component of wind at the 26-m altitude are .7 to .8 m/sec, and they are both positive and negative. Vertical wind components above 1 m/sec are not uncommon, particularly at the higher altitudes. The magnitude of the vertical velocity component often approximates 10% of the horizontal wind speed. Table B-1 shows magnitudes of the vertical velocity component which are significantly greater than those measured in other tests. It is noted that when the wind shifted to 205 deg (page B-10), the vertical component became insignificant. This suggests a local terrain effect.

4.4.3.4 Laser Doppler Velocimeter Altitude Calibration Errors

Before every run, the LDV ranging system was calibrated to assure that the actual altitude was the desired altitude of measurement. From the data shown in Table 4-5, if anomalous points are removed, the variation in wind speed with change of altitude is not sufficient to cause deviations as large as shown in Table 4-4, even if altitude calibration was wrong. Therefore, LDV altitude calibration errors cannot be the source of the deviations shown in Table 4-4.

4.4.3.5 Laser Doppler Velocimeter Cone Angle Errors

As discussed in Section 3.2.2.3, the equation for the magnitude of the horizontal component of wind is

$$V_h = \frac{\sqrt{A^2 + B^2}}{\sin\alpha},$$

where α is the cone angle and A and B are defined in Section 3.2.2.3. Obviously, an error in α will cause an error in the calculated value of wind speed with the error being proportional to the wind speed. Since the cone angle is constant from day to day (the elevation mirror is held firm by a brake), this error would not show variations from day to day. However, Table 4-4 shows that day-to-day variations in the wind-speed deviation occur. Therefore, it is concluded that cone angle error is not the source of the deviation between laser-measured wind speed and anemometer-measured wind speed.

4.4.3.6 Laser Doppler Velocimeter Errors

It is possible that LDV system errors and/or errors in the VAD concept as implemented in the Lockheed LDV are the source of the discrepancies between laser-measured winds and anemometer-measured winds. However, in three other laser-anemometer wind comparisons, the agreement has been very good. Reference 6 reports a comparison conducted at the Table Mountain test site of the National Oceanic and Atmospheric Administration near Boulder, Colorado. Figure 4-10 shows a sample comparison between the laser-measured wind speed and the anemometer-measured wind speed. The discrepancy is much less than that shown in Table 4-4 for the WKY-TV comparisons. Reference 10 describes a test conducted at Otis AFB, Massachusetts, in September 1976. A comparison between laser-measured wind speed and anemometer-measured wind speed (Ref. 11) showed excellent agreement. A similar test in 1977 showed excellent agreement with laser-measured winds calculated in real time (Ref. 11).

4.4.3 Turbulence

Figure 4-12 shows the VAD signature (21-point moving average) for conditions which were extremely turbulent. Other signatures taken for this run

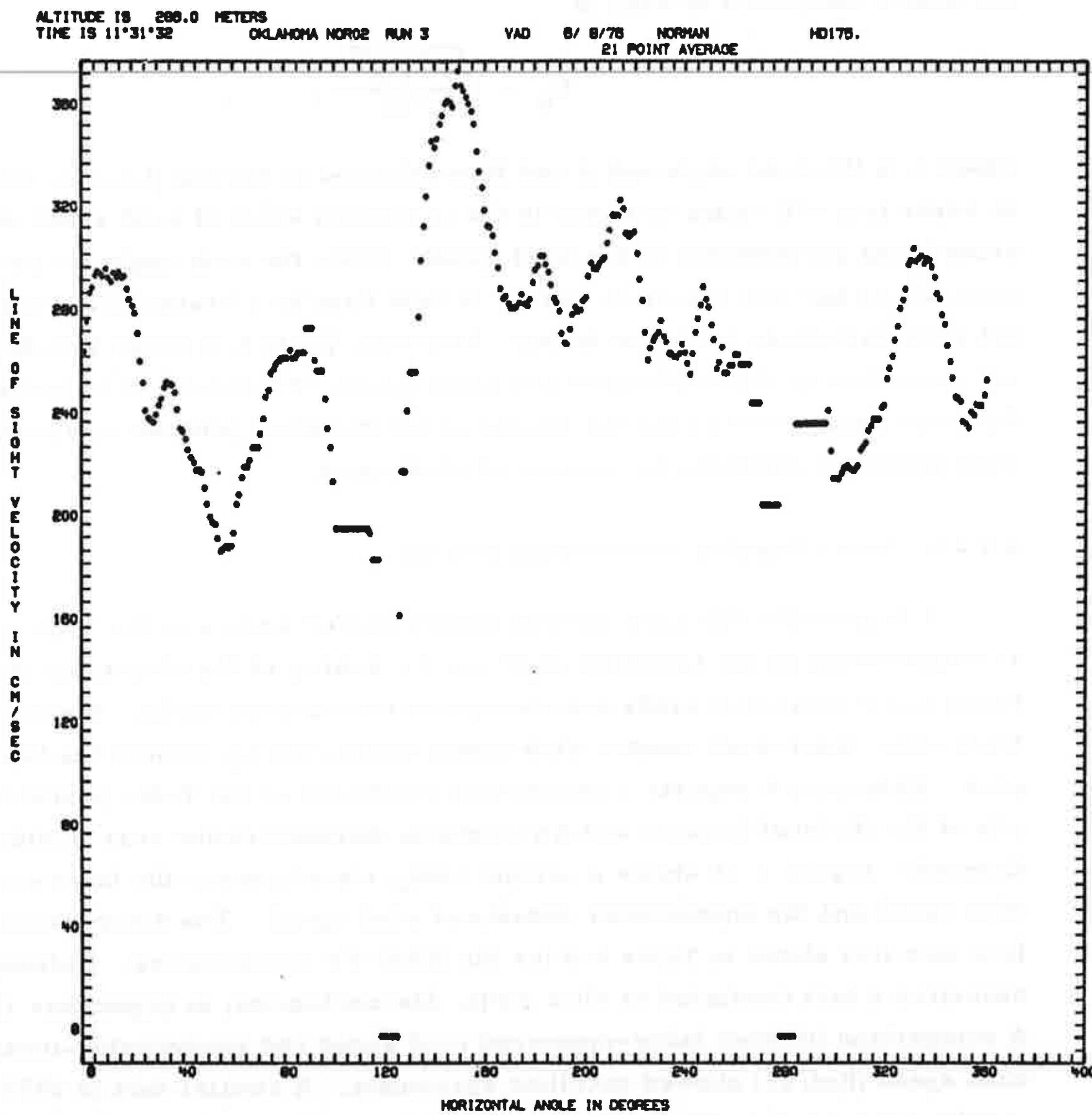


FIGURE 4-12. LINE-OF-SIGHT VELOCITY SIGNATURE IN HEAVY TURBULENCE.

show the same characteristic. The fluctuations may be identified as turbulence because they are not averaged out by a 21-point moving average (as random system noise would be), the other VAD signatures measured near the same time exhibit similar characteristics, and the signature characteristics do not occur as significantly for other runs.

The column labeled "SP" on the tabulated wind data (Table 4-3 and Appendix B) is the standard deviation of the difference between the actual line-of-sight velocity and the sine wave calculated by the least-squares curve fit. As such, it is a measure of atmospheric turbulence. For example, for the 1-min average from which Fig. 4-12 was taken, SP has a value of 73 cm/sec. For less turbulent data, SP has a value between 20 and 50 cm/sec. Therefore, the value of SP is an indication of the atmospheric turbulence.

The capability of the LDV to measure turbulence should be studied in more depth and further exploited. It is noted that the LDV can measure turbulence at higher frequencies than can be accomplished by anemometers. Also, the LDV can measure velocity fluctuations over space, whereas an anemometer can only measure velocity fluctuations over time at a fixed location.

4.4.4 Double VAD Signature

Figure 4-13 shows a distinct double VAD signature. Two distinct signatures are discernable, and it appears that two winds are being measured. The characteristic is not anomalous because it appears on many of the signatures measured at approximately the same time.

A double VAD signature has appeared previously in snow (Ref. 6), and can be plausibly explained in snow. For the present condition, a plausible explanation is not clearly evident. The phenomenon could be wind shear. The focal volume covers an altitude of 278 m $\pm$25 m. Wind shear may easily be sufficiently large to cause a difference in wind speed as shown in Fig. 4-13, especially with the small quantity of turbulence indicated by the well-defined sine curves in Fig. 4-13. The wind shear could result from stratification of a very stable atmosphere, which often occurs at night. Table 4-1 indicates that this run was taken shortly after midnight.

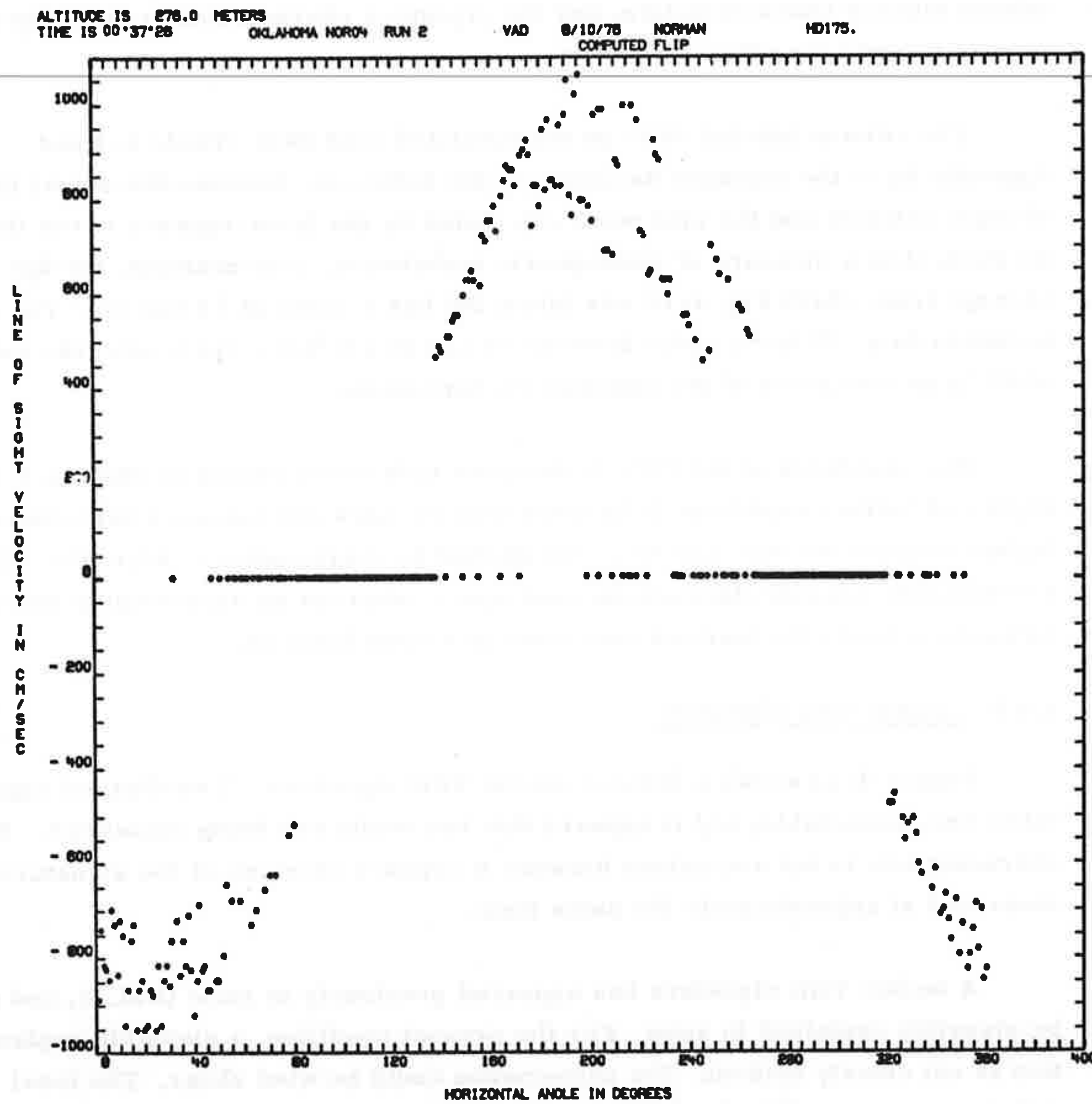


FIGURE 4-13. VELOCITY AZIMUTH DISPLAY LINE-OF-SIGHT VELOCITY SIGNATURE SHOWING A DOUBLE SIGNATURE.

4.4.5 Data Recorded in Rain

On 23 June 1976, data were recorded in rain. In the analysis of data in rain, it is helpful to examine the characteristics of data recorded in rain. Figure 4-14 shows the geometry of the measurement when a significant vertical component is imposed on the airborne particulates (such as raindrops). The vertical component is shown upward to coincide with previously accepted notation for the development of the equations. In rain, the vertical component, w, is negative. For laser reflection from raindrops, the magnitude of the line-of-sight velocity component is

$$v_r = \sqrt{v^2 + w^2} \cos(\pi/2 + \tan^{-1} w/v - \alpha) ,$$

where $\sqrt{v^2 + w^2}$ is the speed of the raindrops (assuming that the horizontal component of drop velocity equals the horizontal wind component), and

$$\pi/2 + \tan^{-1} w/v - \alpha$$

is the angle between the velocity vector of the raindrops and the line-of-sight direction of the LDV. For small, negative values of w, the effect of the vertical component is to increase the line-of-sight velocity on the upwind side of the LDV and to decrease the line-of-sight velocity on the downwind side of the LDV. On the downwind side, the velocity component of the raindrops may become almost perpendicular to the line-of-sight, and the line-of-sight velocity component vanishes on the downwind side.

The beginning of the rain is shown sequentially in Figs. 4-15, 4-16, and 4-17. Figure 4-15 presents data acquired before the rain began and shows a normal VAD signature. Figure 4-16 shows both reflections from natural aerosol and from raindrops. The sign convention of the derectified line-of-sight velocity signature is that the positive portion of the signature is on the upwind side of the VAD scan. Therefore, according to the previous paragraph, the highest signature is the signature from rain. Figure 4-17 shows data in rain. Only one negative velocity point occurs. Some of the plots have no negative velocity points. This could easily result from the trajectory of the raindrops being

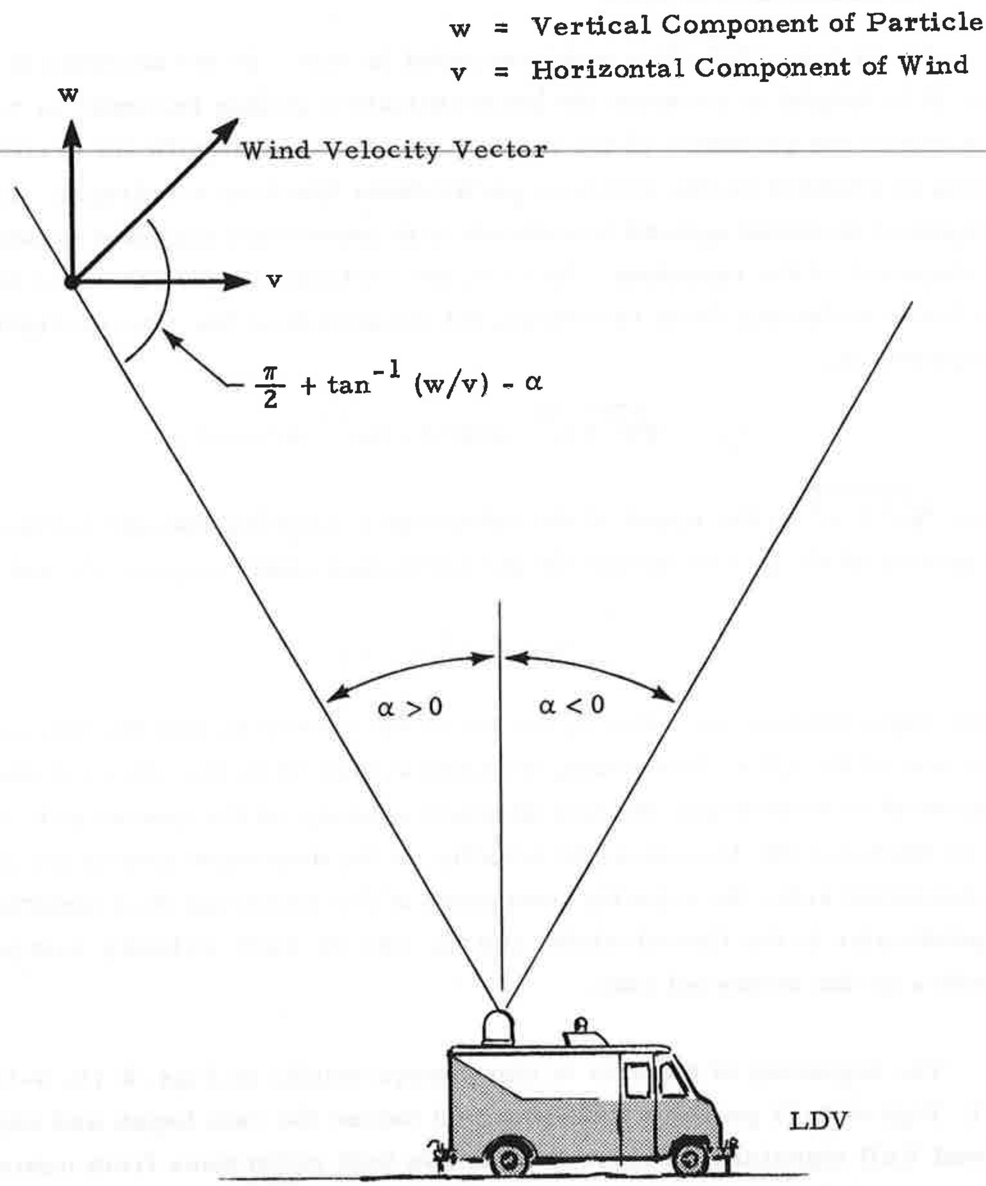


FIGURE 4-14. GEOMETRY OF LINE-OF-SIGHT VELOCITY COMPONENT WITH A VERTICAL COMPONENT ON PARTICLE.

approximately perpendicular to the line-of-sight direction of the LDV on the downwind side.

It is postulated that the cause of the missing data was that the frequency threshold setting was set too high. The log sheet shows the setting as 500 kHz (~2.7 m/sec); however, only two points below 4 m/sec appear in Figs. 4-15, 4-16, and 4-17. In future measurements in rain, it will be necessary for the operators to be aware that rain causes a decrease in the line-of-sight velocity on the downwind side of the scan, and threshold settings must be made accordingly.

Three additional comments are relevant to wind measurement in rain. First, the SEL-810 data logging program used for the rain data was different from that used in the rest of the test. After the test described herein, it was determined that the data logging program occasionally skips data (about one-half second skipped for every third scan). The problem has been corrected, but it may account for some of the lack of data for negative line-of-sight velocities. Second, all rain data were recorded at the 444-m altitude. It is expected that the signal strength from raindrops may be stronger at a lower altitude. The focal volume of the LDV is proportional to R^4 (R is range). The laser intensity at the detector is proportional to R^{-4}. If the number density of particles (number of particles per unit volume of atmosphere) is large, the number of particles from which a scattered signal is received is proportional to the focal volume, the R^4 term cancels the R^{-4} term, and the returned laser intensity is constant with changing range. This is the condition for natural atmospheric aerosol. For a low number density of particles (as for rain), the number of particles in the focal volume at a given instant in time is small. Increasing the focal volume size does not mean that the number of particles in the focal volume will increase. Therefore, the returned laser intensity may decrease with increases in range for a small number of particles. The effect of range on returned laser intensity in rain is a subject for further investigation.

Third, it is known that rain removes aerosol from the air. This causes no problem if there are raindrops from which the laser beam can be reflected.

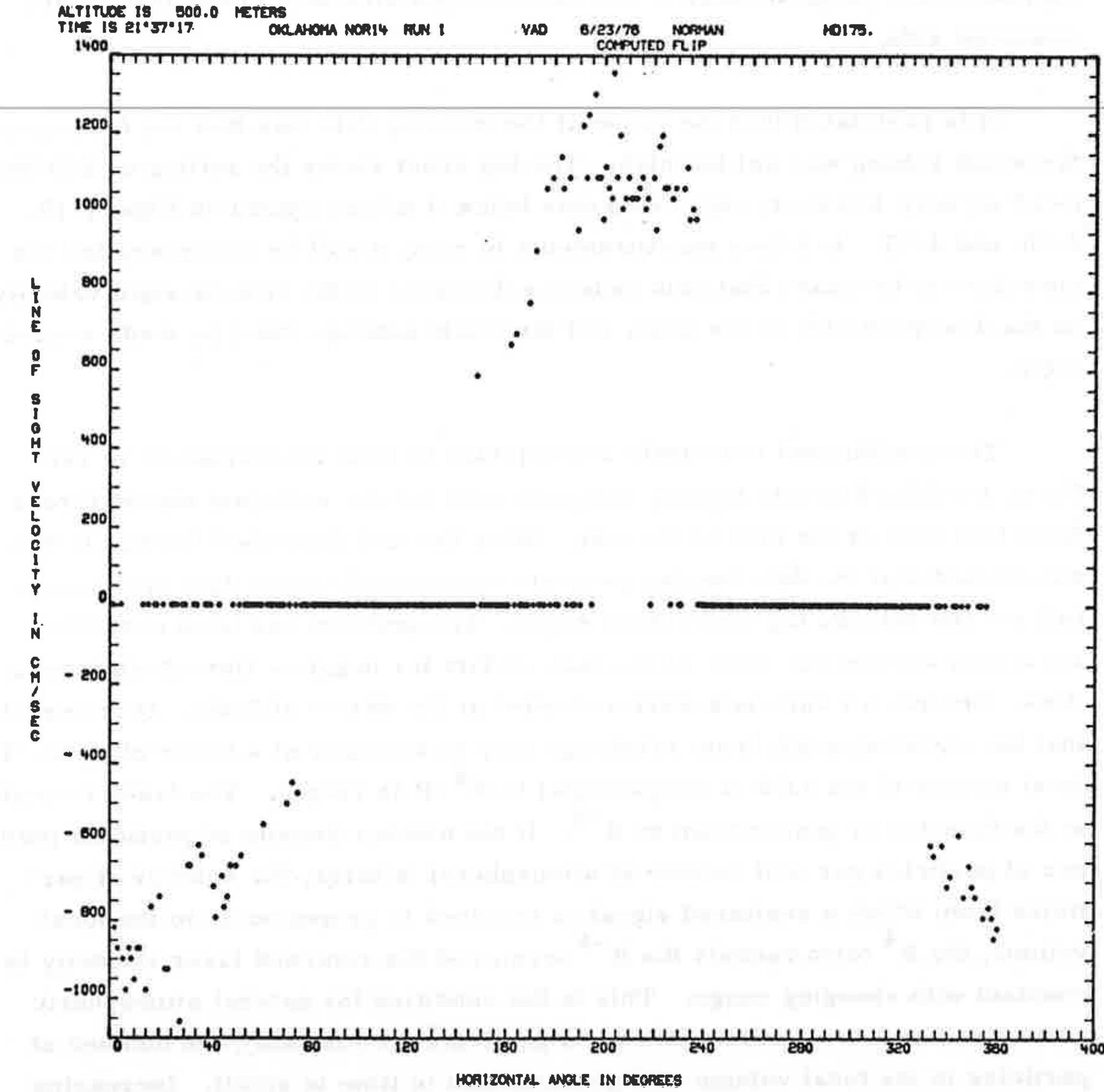


FIGURE 4-15. VELOCITY AZIMUTH DISPLAY SIGNATURE BEFORE BEGINNING OF RAIN.

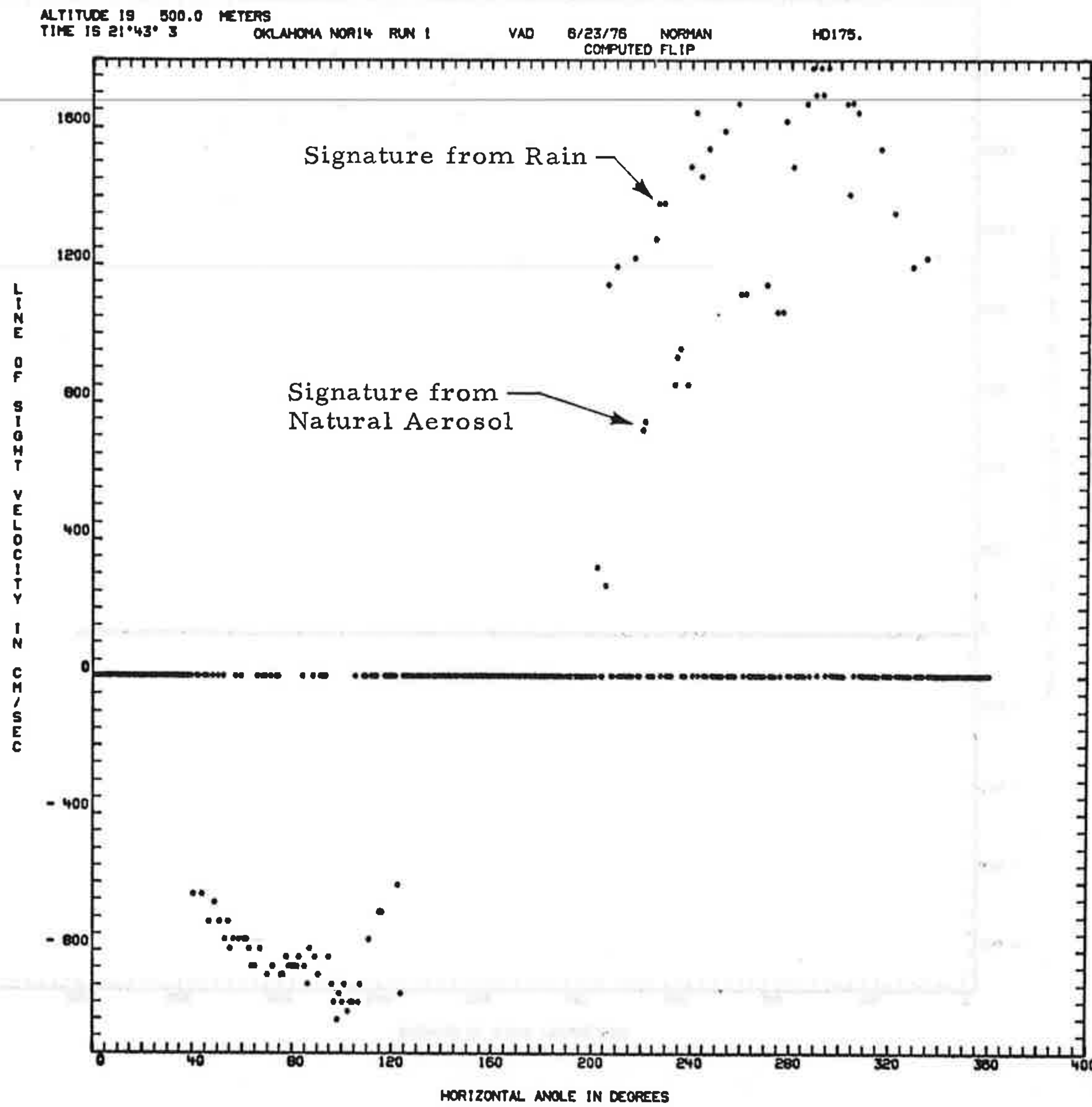


FIGURE 4-16. VELOCITY AZIMUTH DISPLAY SIGNATURE AT THE BEGINNING OF RAIN.

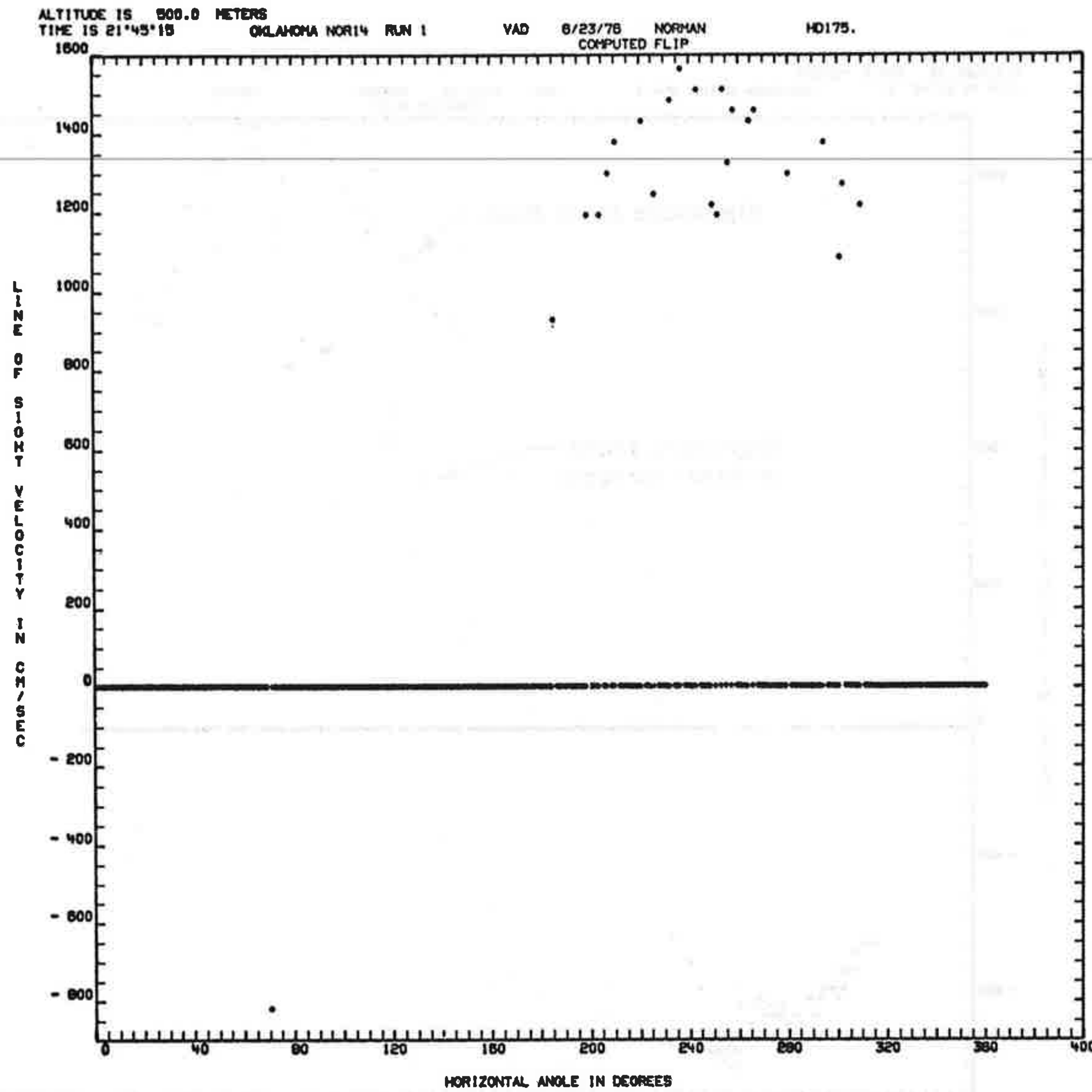


FIGURE 4-17. VELOCITY AZIMUTH DISPLAY SIGNATURE DURING RAIN.

However, the adequacy of the natural aerosol after the rain stops has not been evaluated. From the Table Mountain tests (Ref. 6) the aerosol remaining in the air after a snow was barely adequate. At lower altitudes the quantity of natural aerosol is much greater than at Table Mountain. Therefore, the lack of natural aerosol after a rain is not expected to be a problem, but verification is necessary.

5. CONCLUSIONS AND RECOMMENDATIONS

The Lockheed laser Doppler velocimeter appears to be able to measure wind accurately to an altitude of 450 m. A discrepancy of 0 to 3 m/sec was observed between the laser-measured wind speed and the anemometer-measured wind speed. The discrepancy occurred at all altitudes. The discrepancy does not indicate a deficiency in the LDV because the discrepancy occurred at altitudes at which the accuracy of the LDV had previously been verified, and a discrepancy between anemometer-measured winds and winds indicated by double theodolite balloons has previously been reported at the WKY-TV tower. The wind speed discrepancy may be directionally dependent. A conclusion could not be reached because almost all data were from the same direction. Directional agreement between laser-measured winds and anemometer-measured winds was good with almost all data in agreement within ±10 deg for 3-min averages and within ±5 deg for 15-min averages. Occasionally, differences of ±20 deg were observed.

The measurement of wind in rain was inconclusive. Deficiencies in the data were noted, but very simple remedies exist. It is expected that a better signal would be obtained at a lower altitude. For wind shear measurement for aircraft approaches, the altitudes of interest are less than 444 m. The glideslope altitude is approximately 444 m at the outer marker, and it is usually the region inbound from the outer marker which is of most concern for wind shear related to aircraft approaches. A more complete measurement and analysis program for wind measurement in rain is appropriate.

6. REFERENCES

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10. Brashears, M.R. and W.R. Eberle, "Remote Wind Measurement in Fog Using Laser Doppler Velocimetry," Air Force Geophysics Laboratory Technical Report AFGL-TR-76-0313, Lockheed Missiles & Space Company, Huntsville, AL, December 1976.

11. Brousaides, F.J., Personal communication.

Appendix A

TYPICAL VELOCITY AZIMUTH DISPLAY SIGNATURES

Typical VAD signatures are presented in sets of three. The sets may be identified by the run number and time given in the legend. The first figure of each set is the raw data. The second figure shows data which have been edited and filtered, and the third figure of each set shows the derectified signature (edited, but unfiltered).

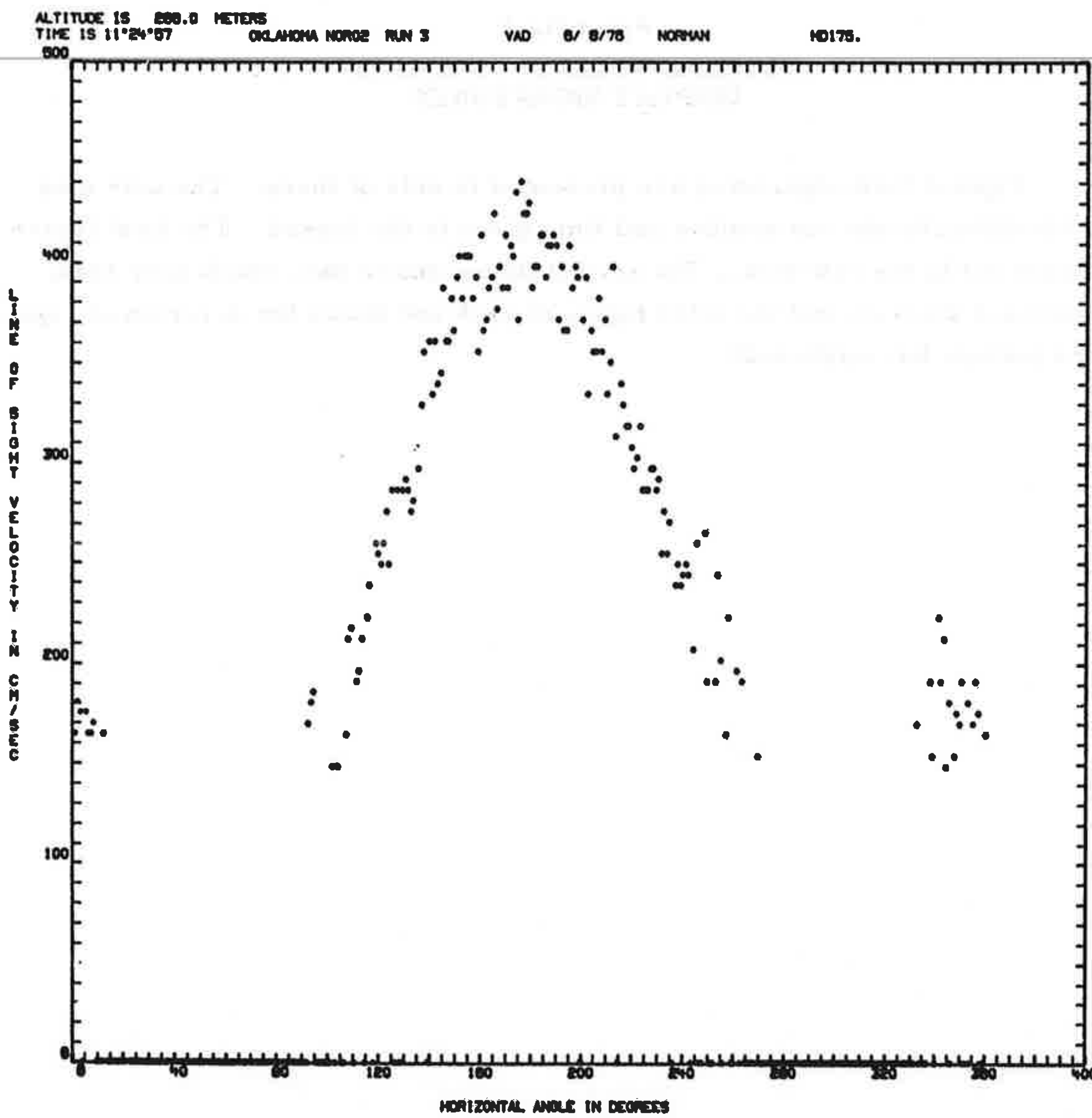


FIGURE A-1. TYPICAL LASER DOPPLER VELOCIMETER SIGNATURES.

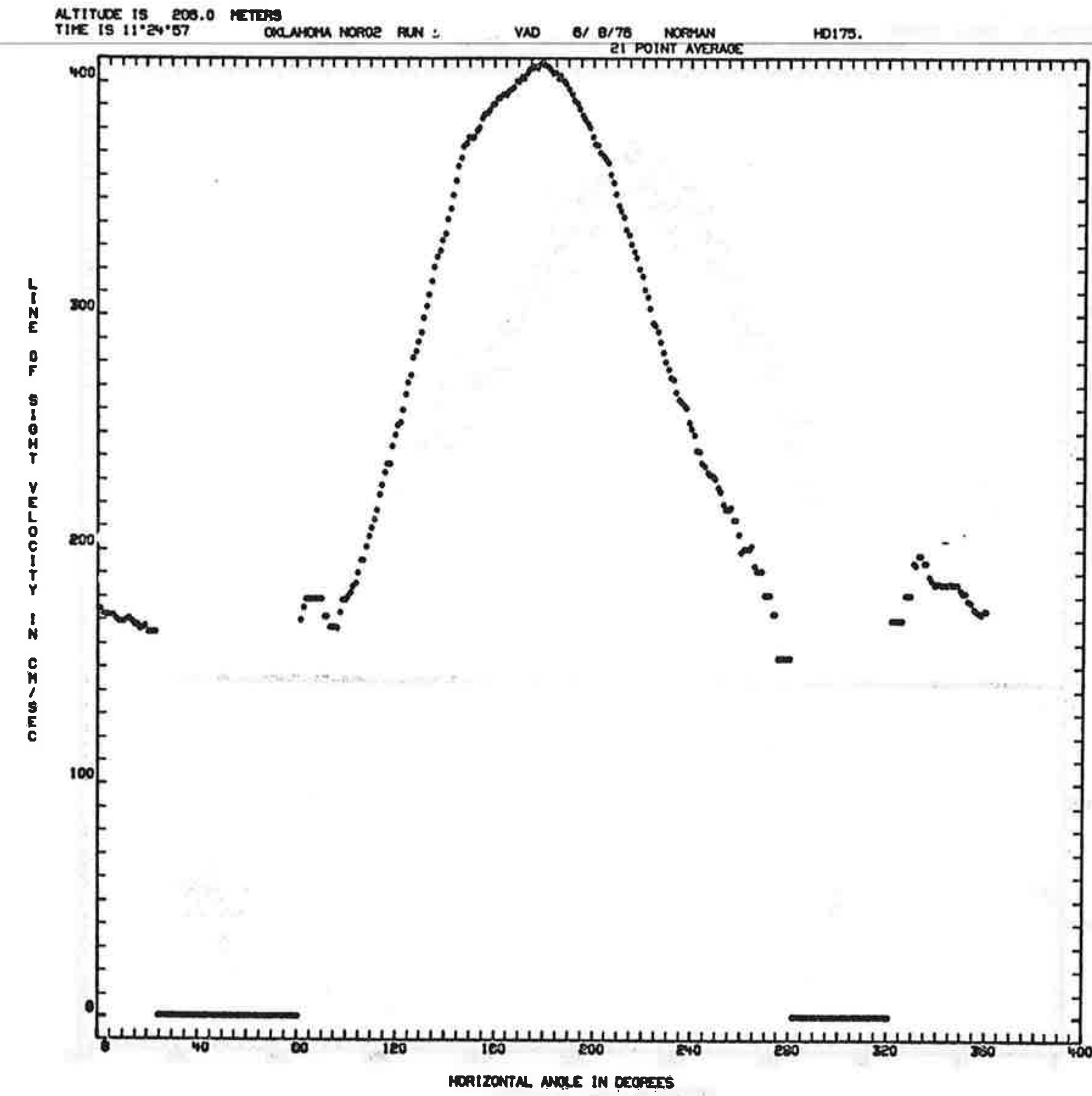


FIGURE A-1 (Continued)

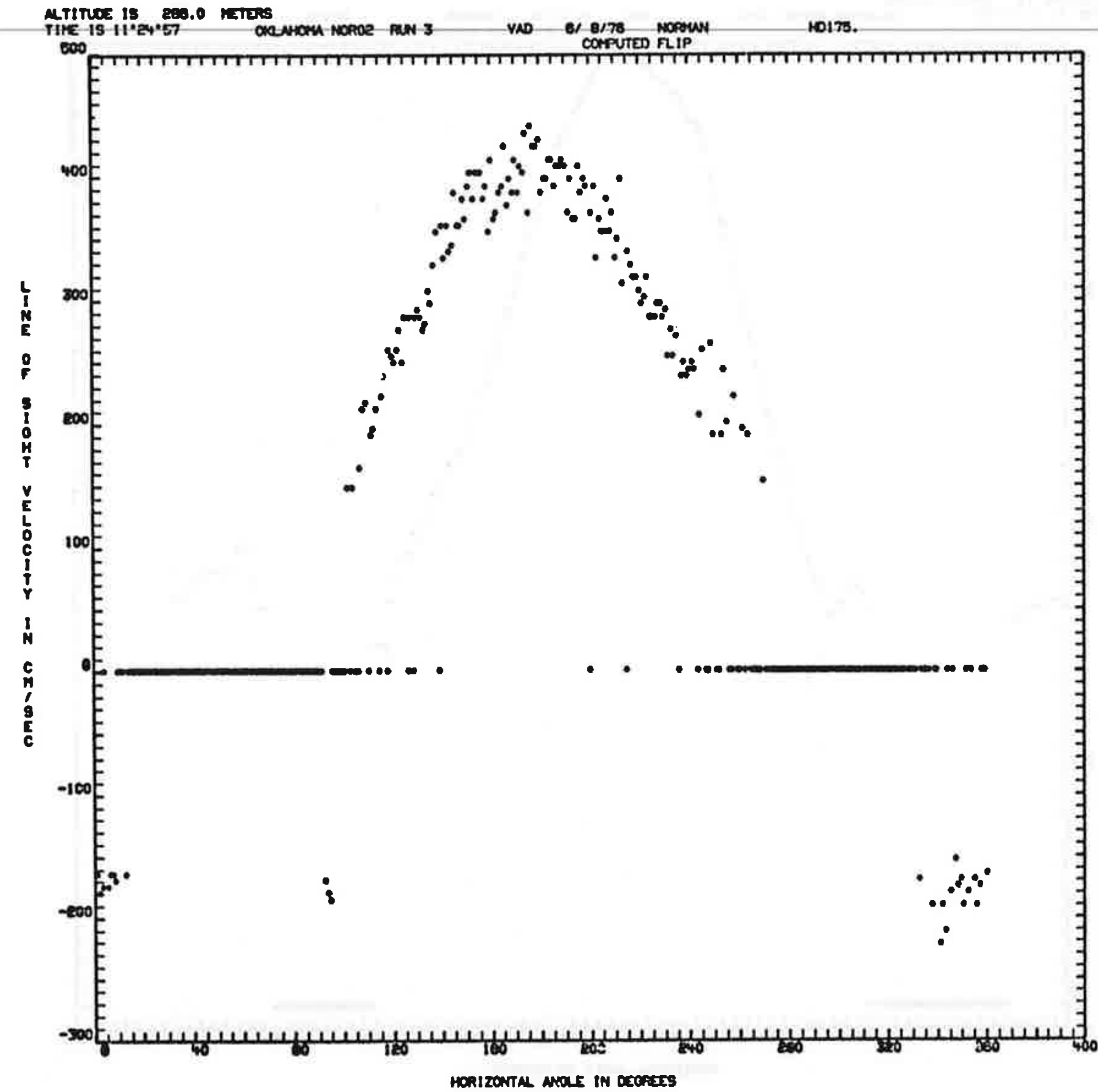


FIGURE A-1 (Continued)

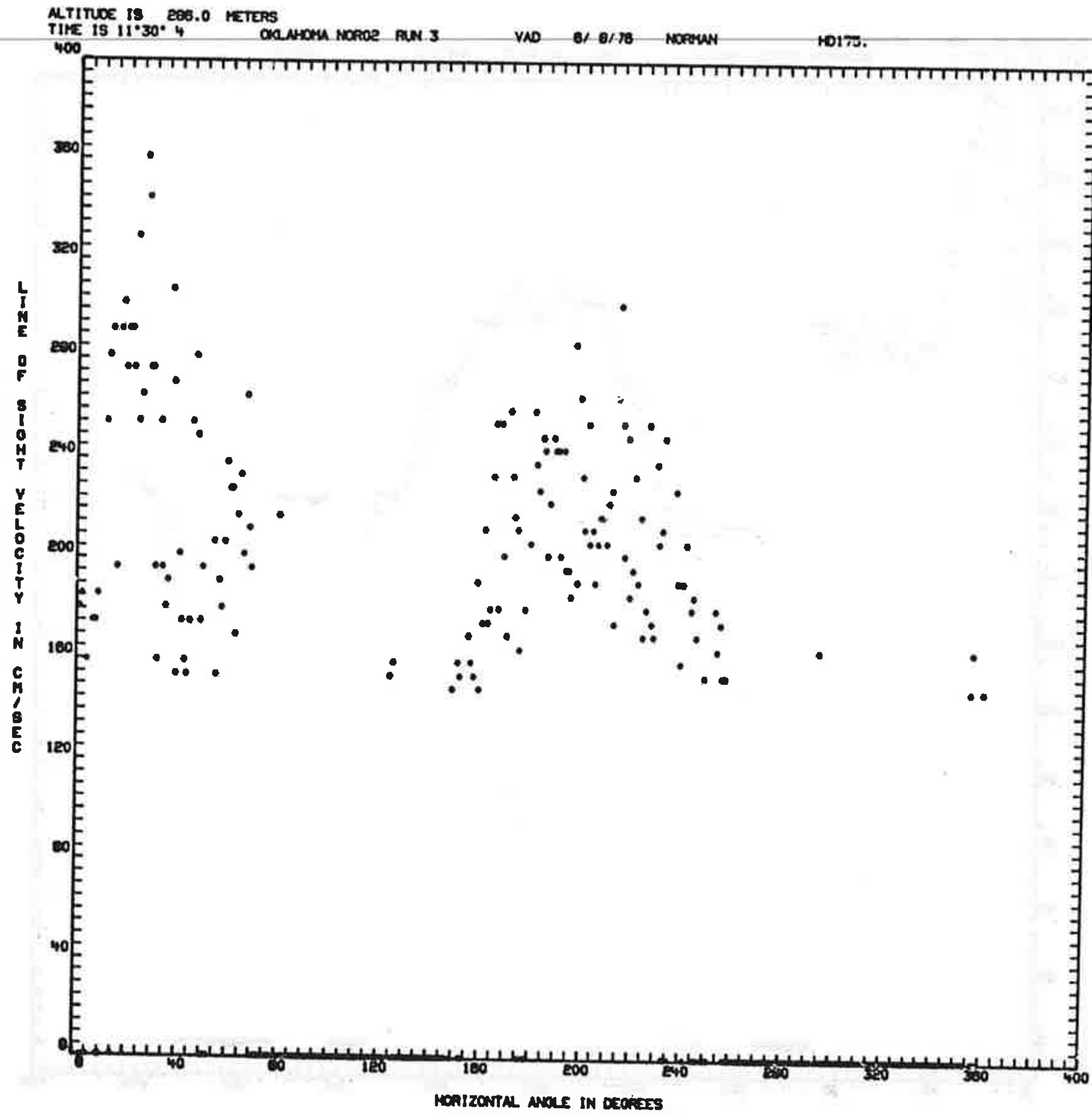


FIGURE A-1 (Continued)

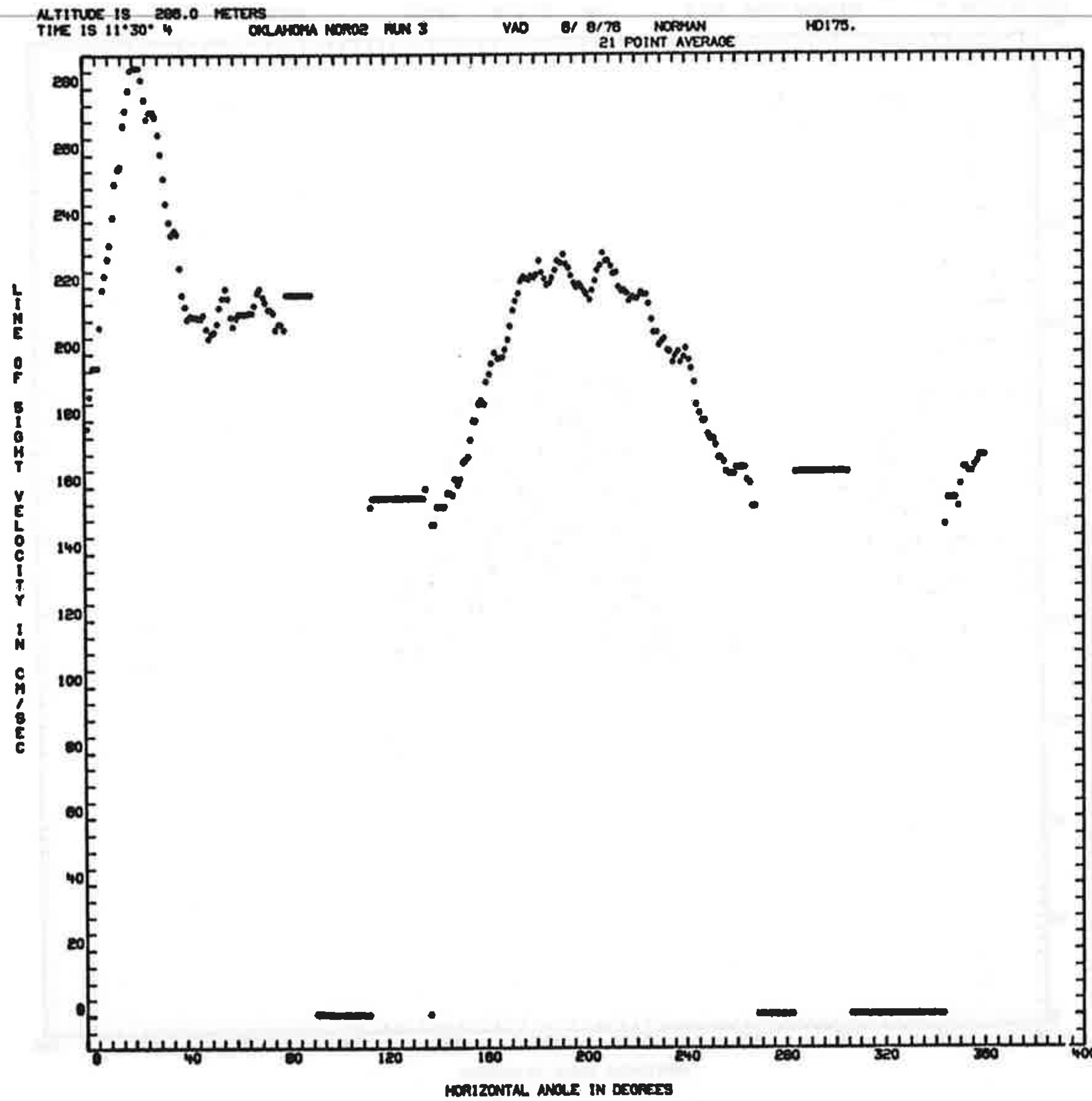


FIGURE A-1 (Continued)

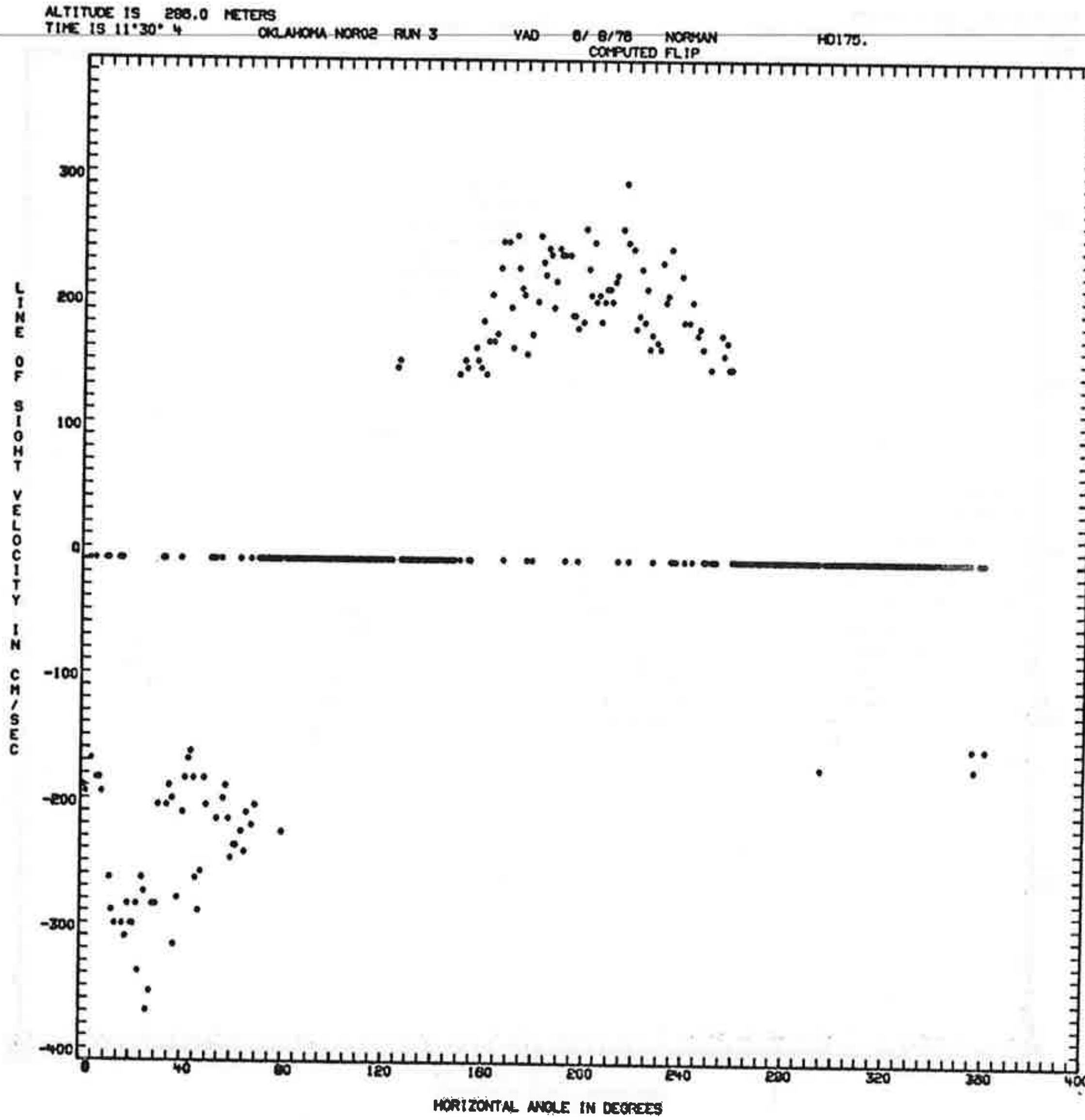


FIGURE A-1 (Continued)

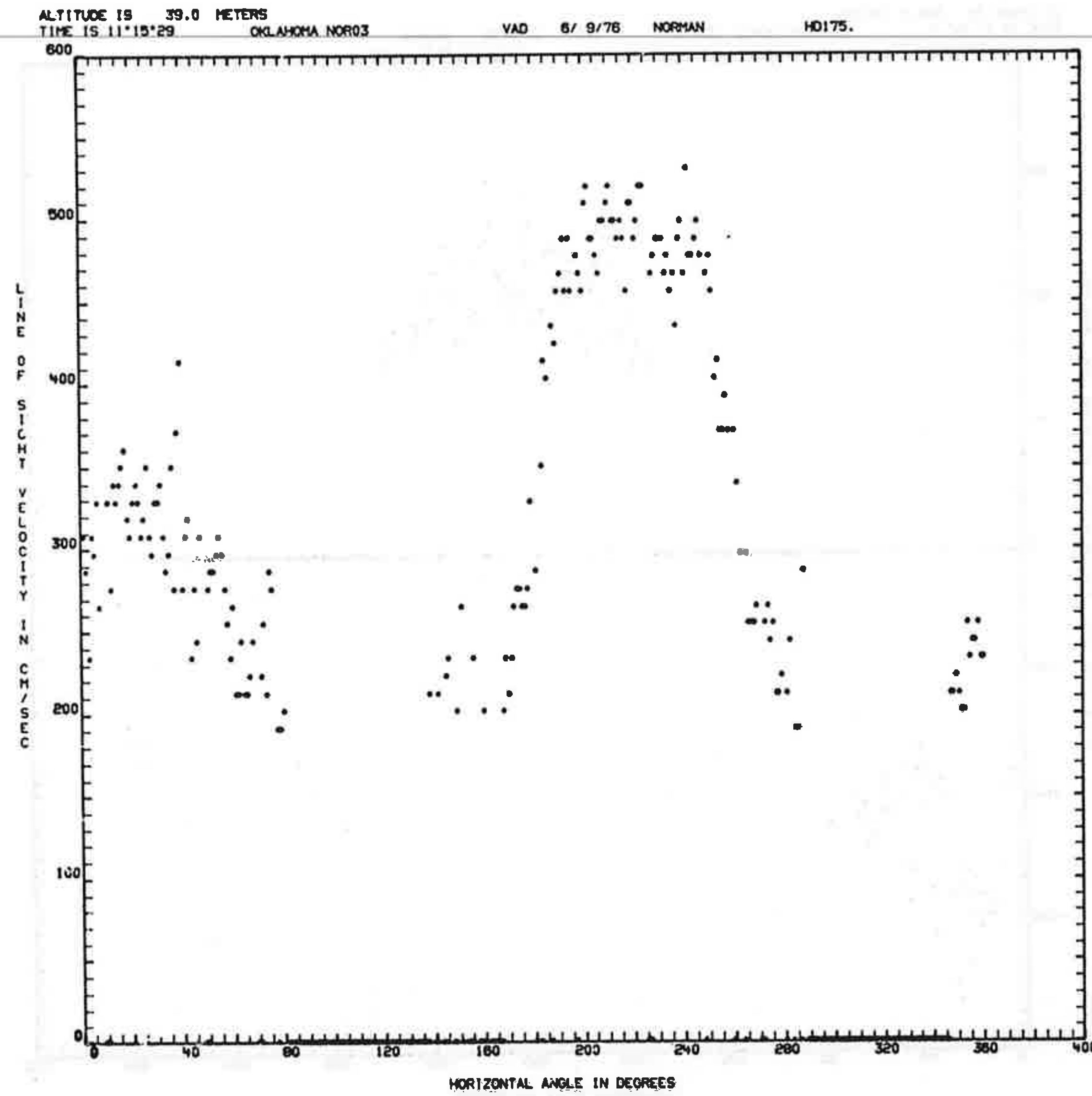


FIGURE A-1 (Continued)

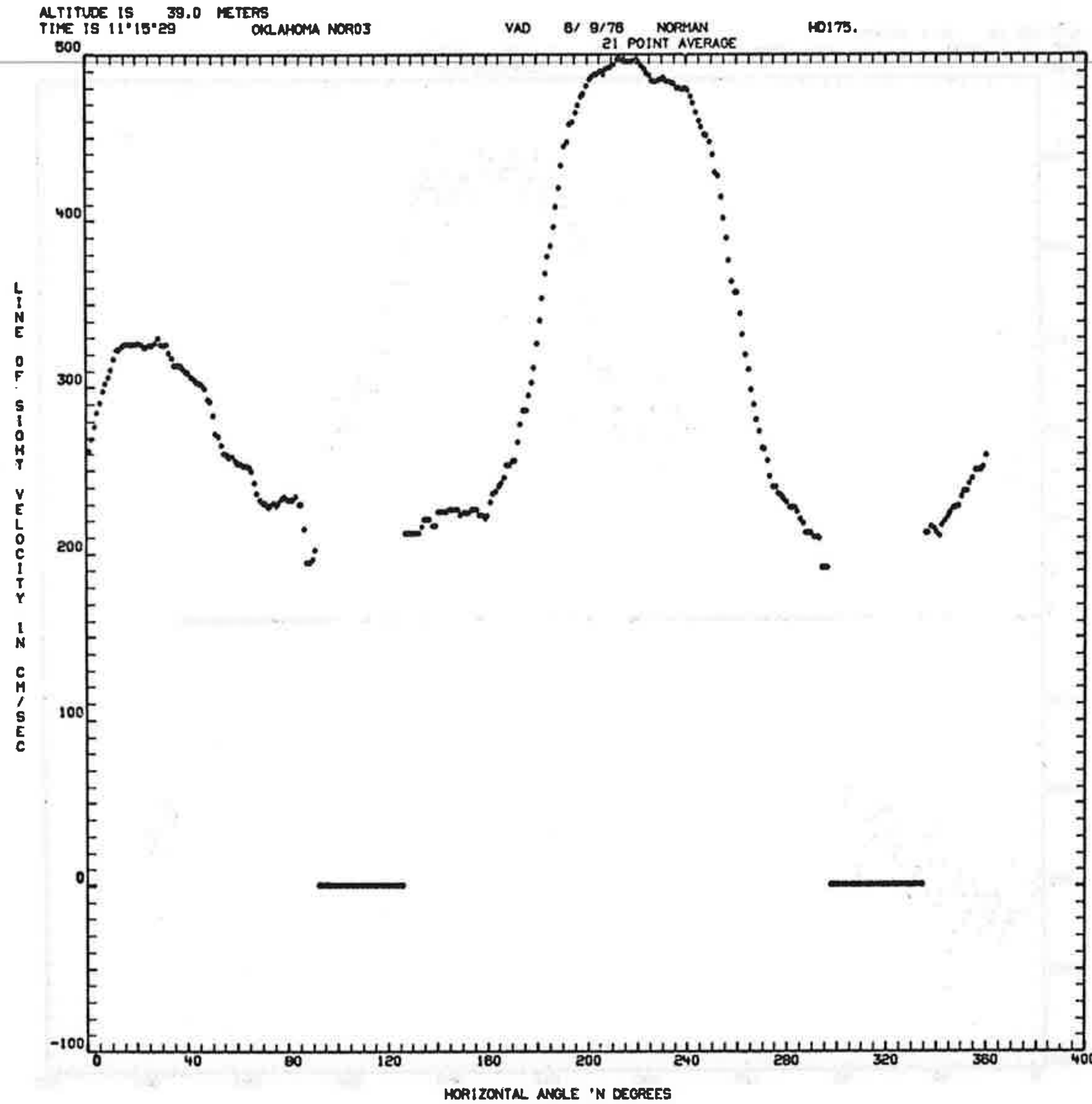


FIGURE A-1 (Continued)

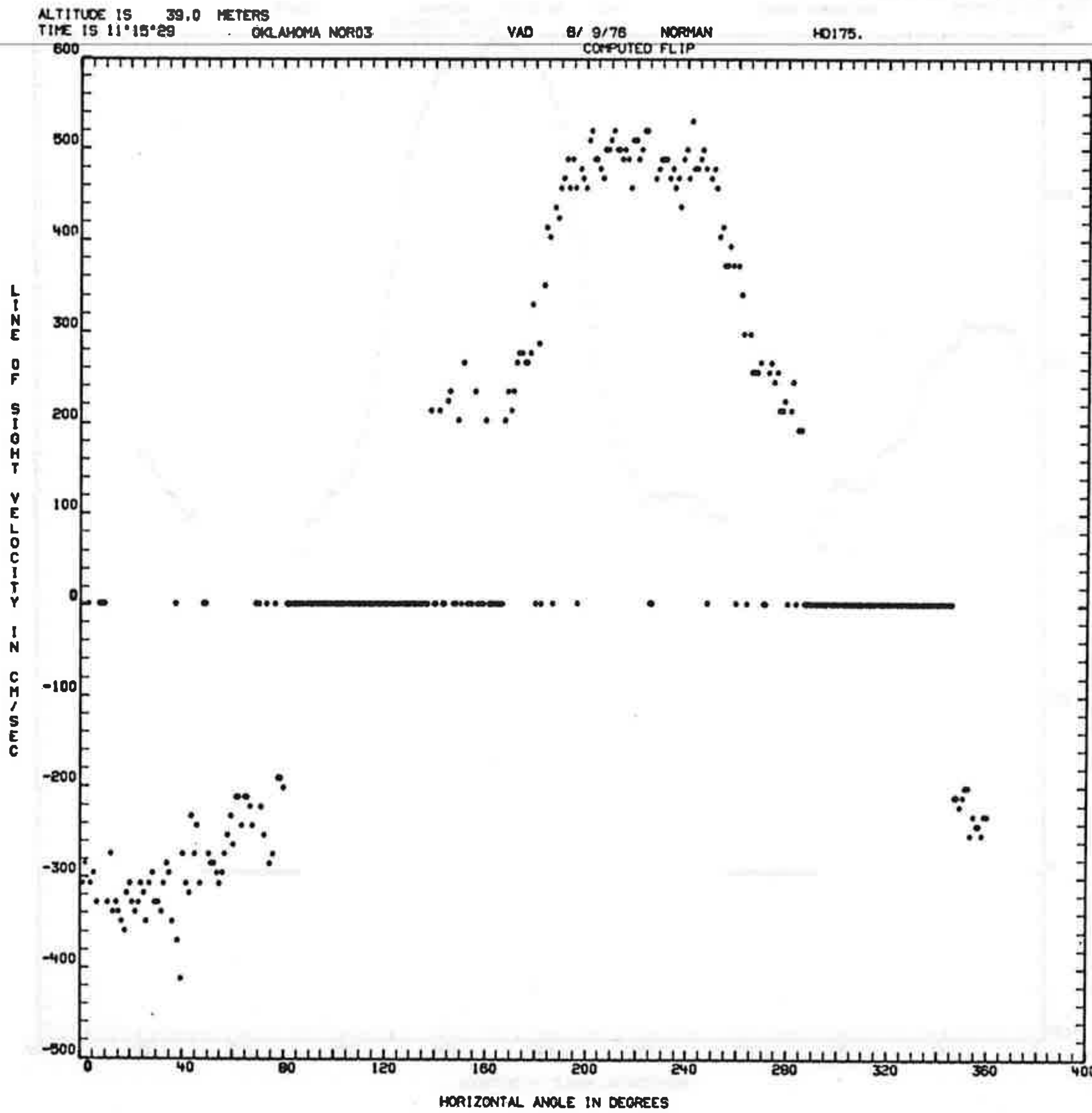


FIGURE A-1 (Continued)

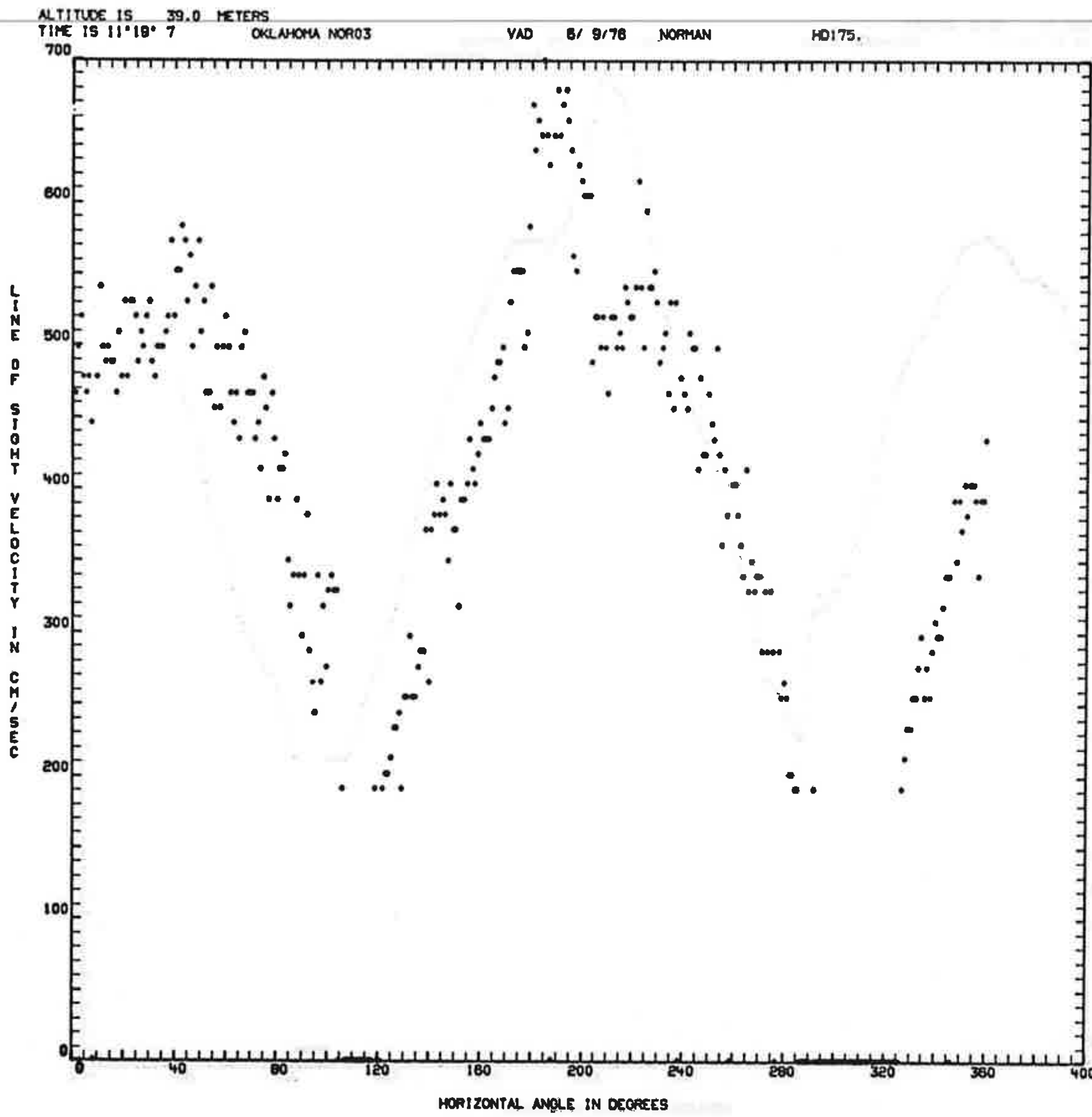


FIGURE A-1 (Continued)

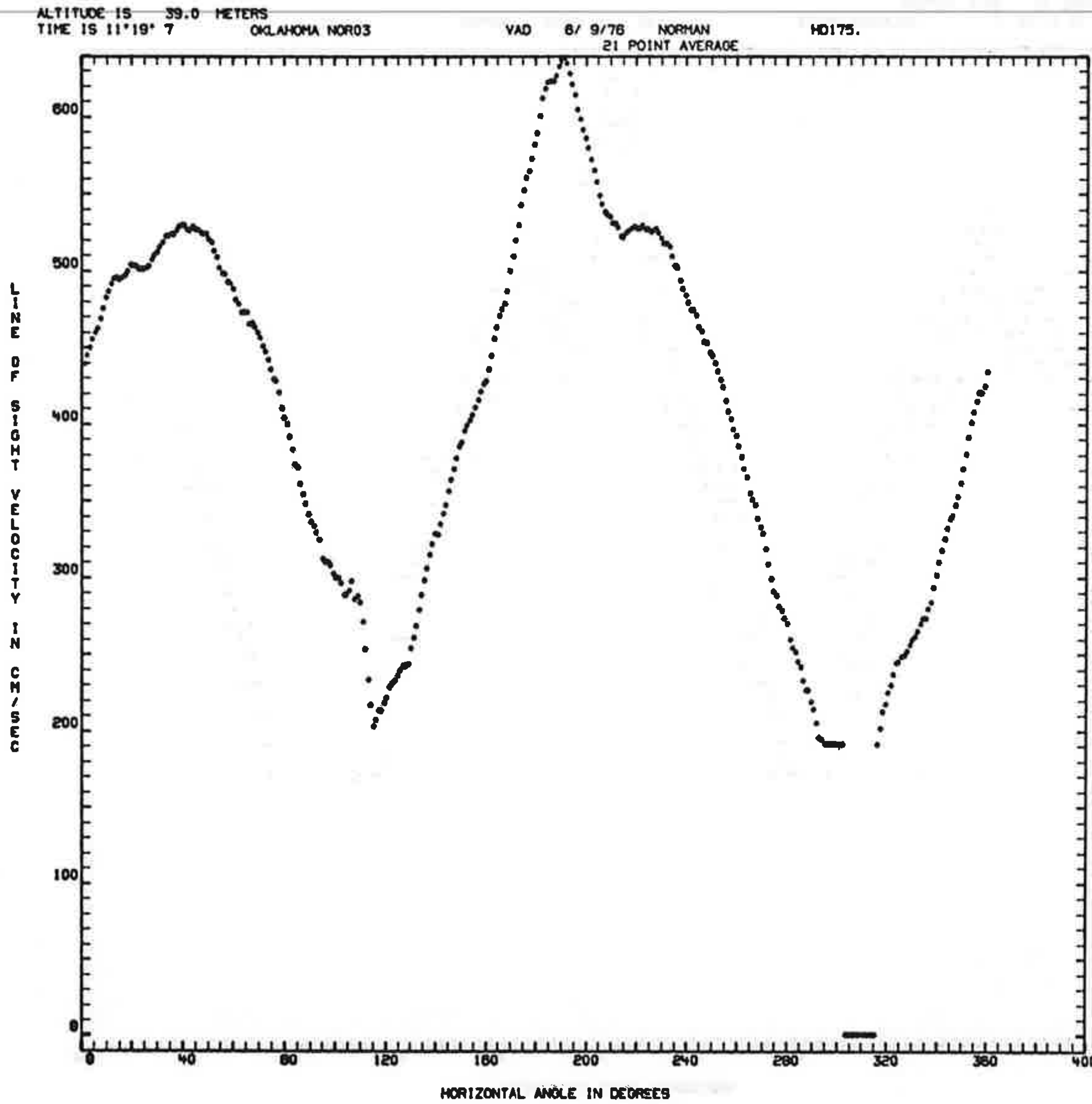


FIGURE A-1 (Continued)

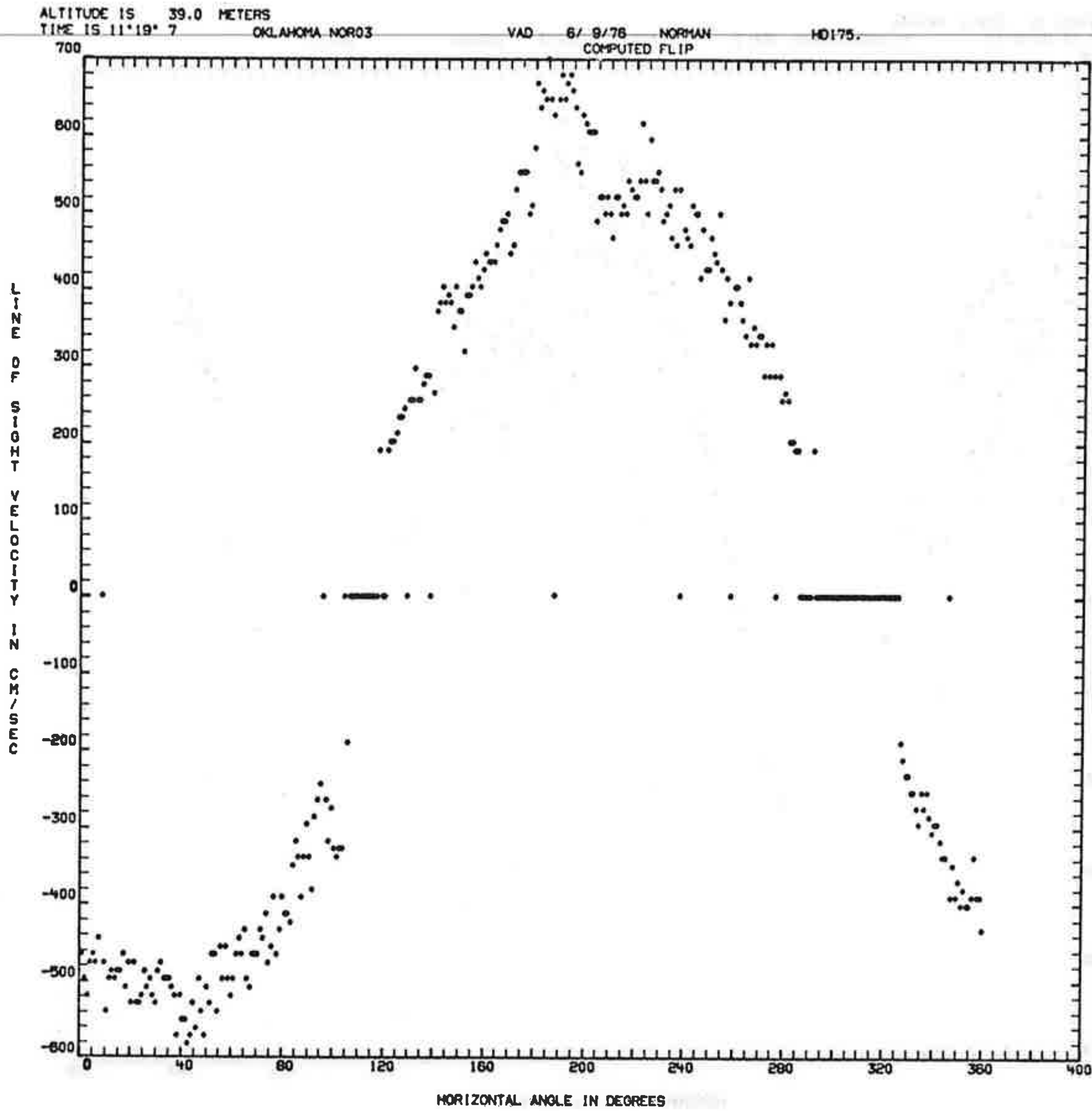


FIGURE A-1 (Continued)

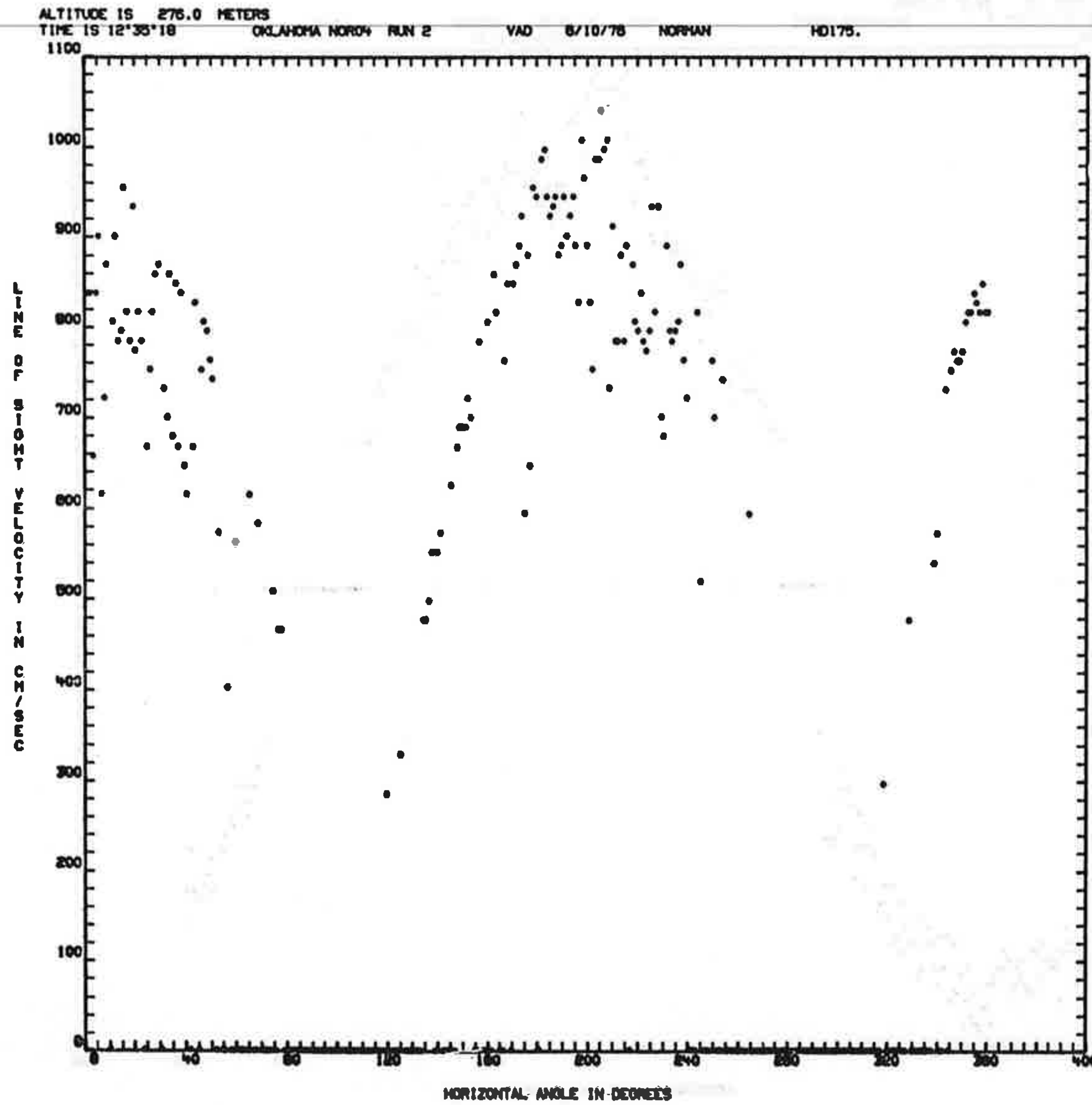


FIGURE A-1 (Continued)

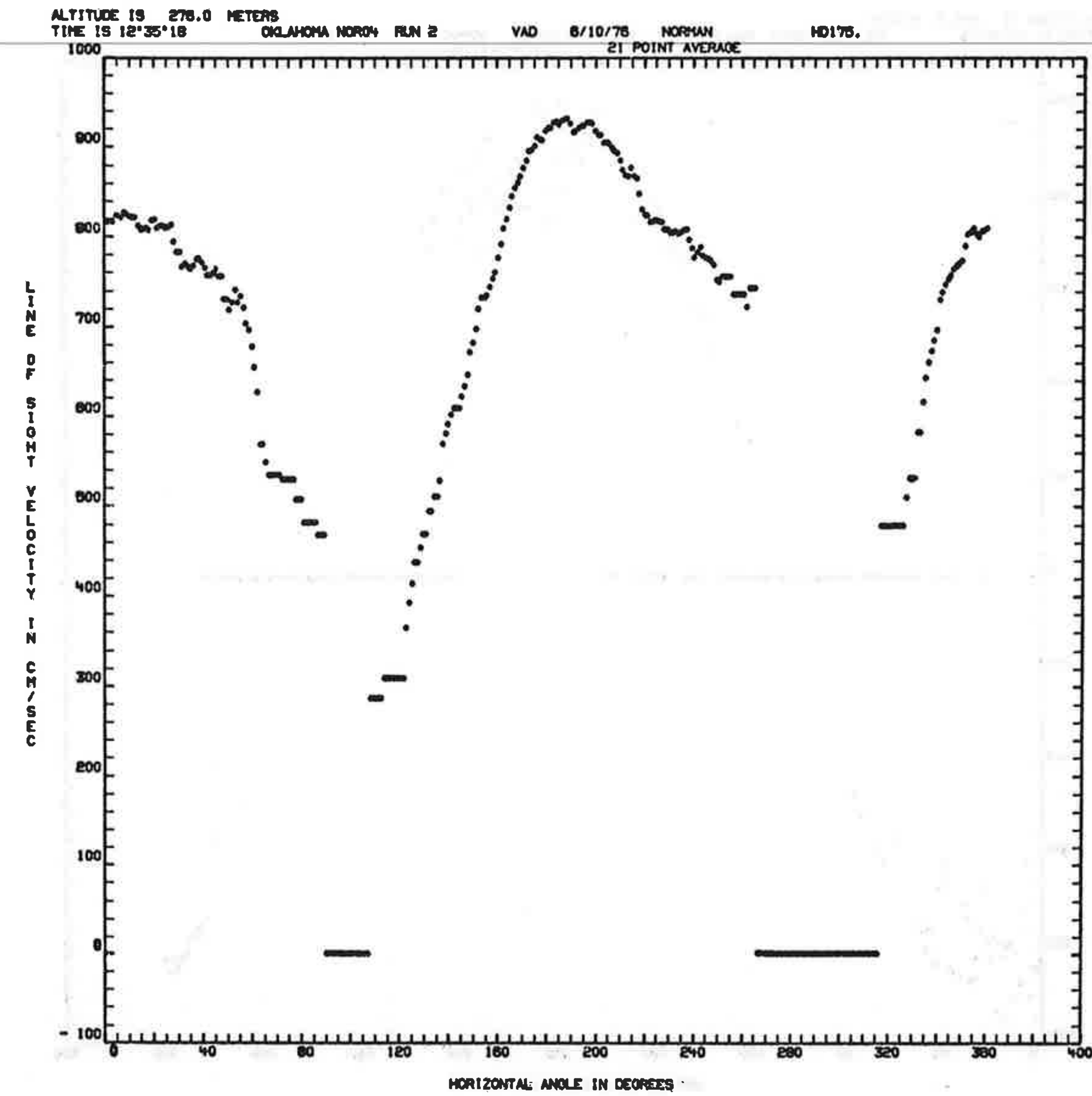


FIGURE A-1 (Continued)

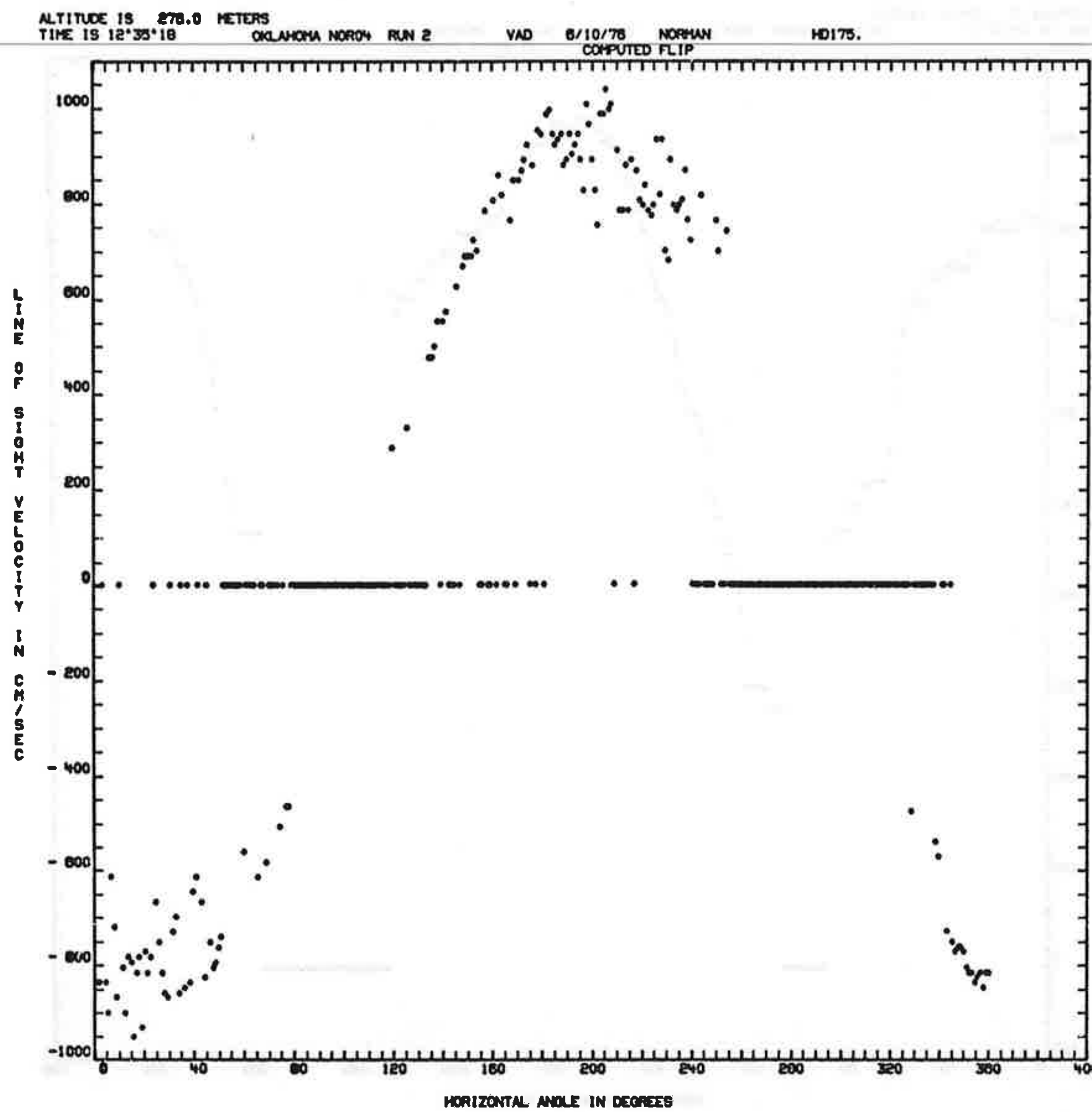


FIGURE A-1 (Continued)

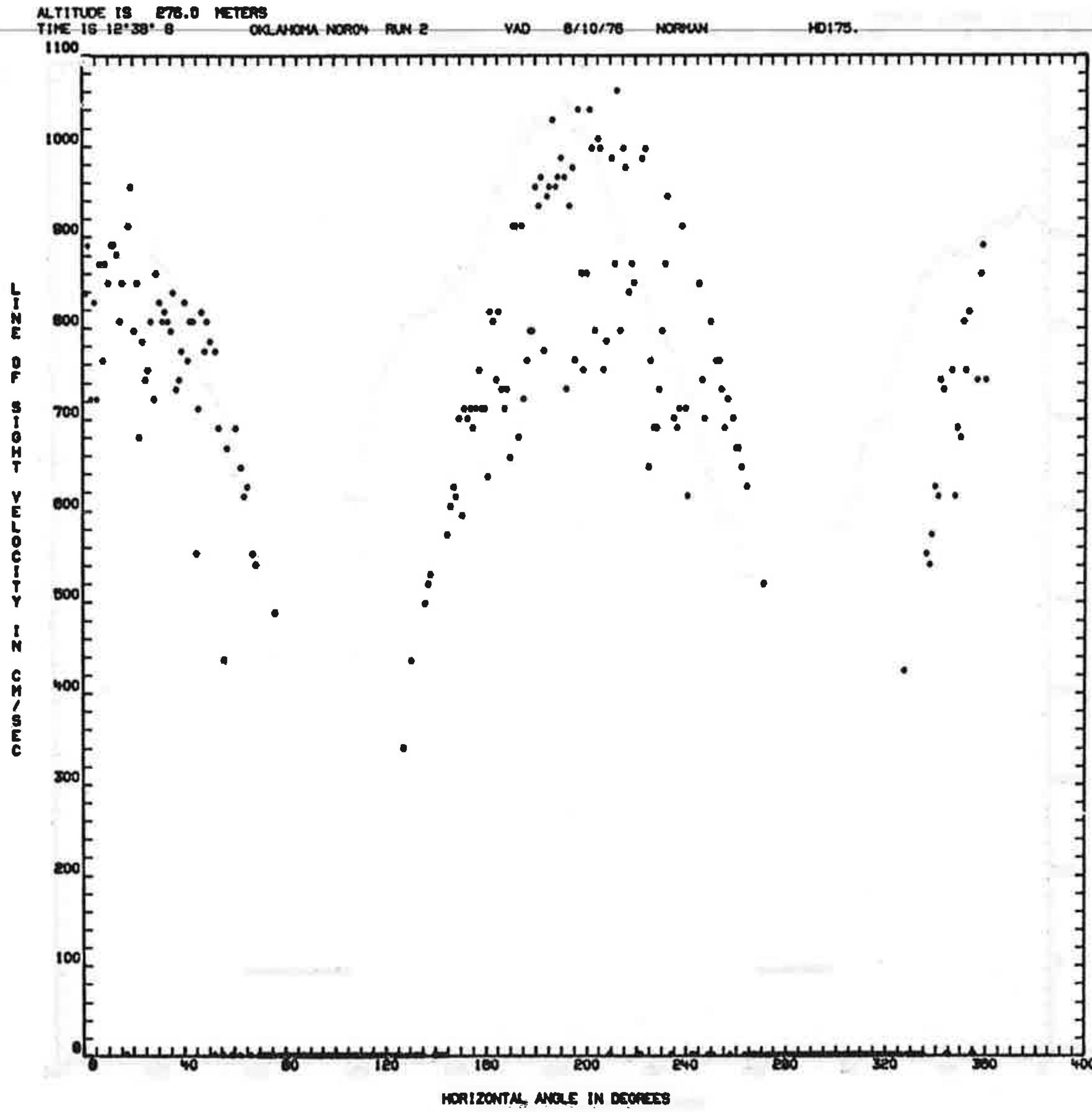


FIGURE A-1 (Continued)

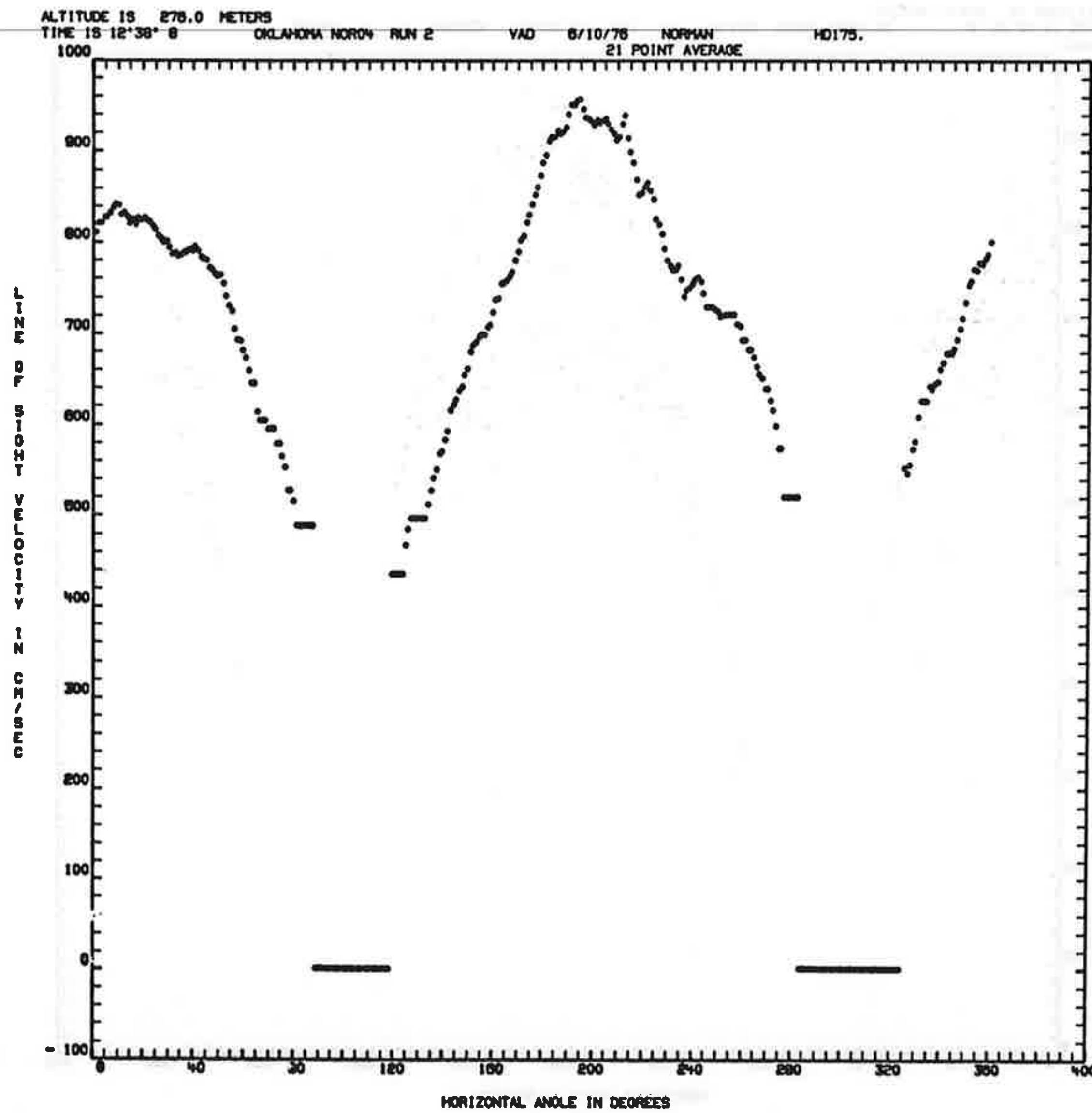


FIGURE A-1 (Continued)

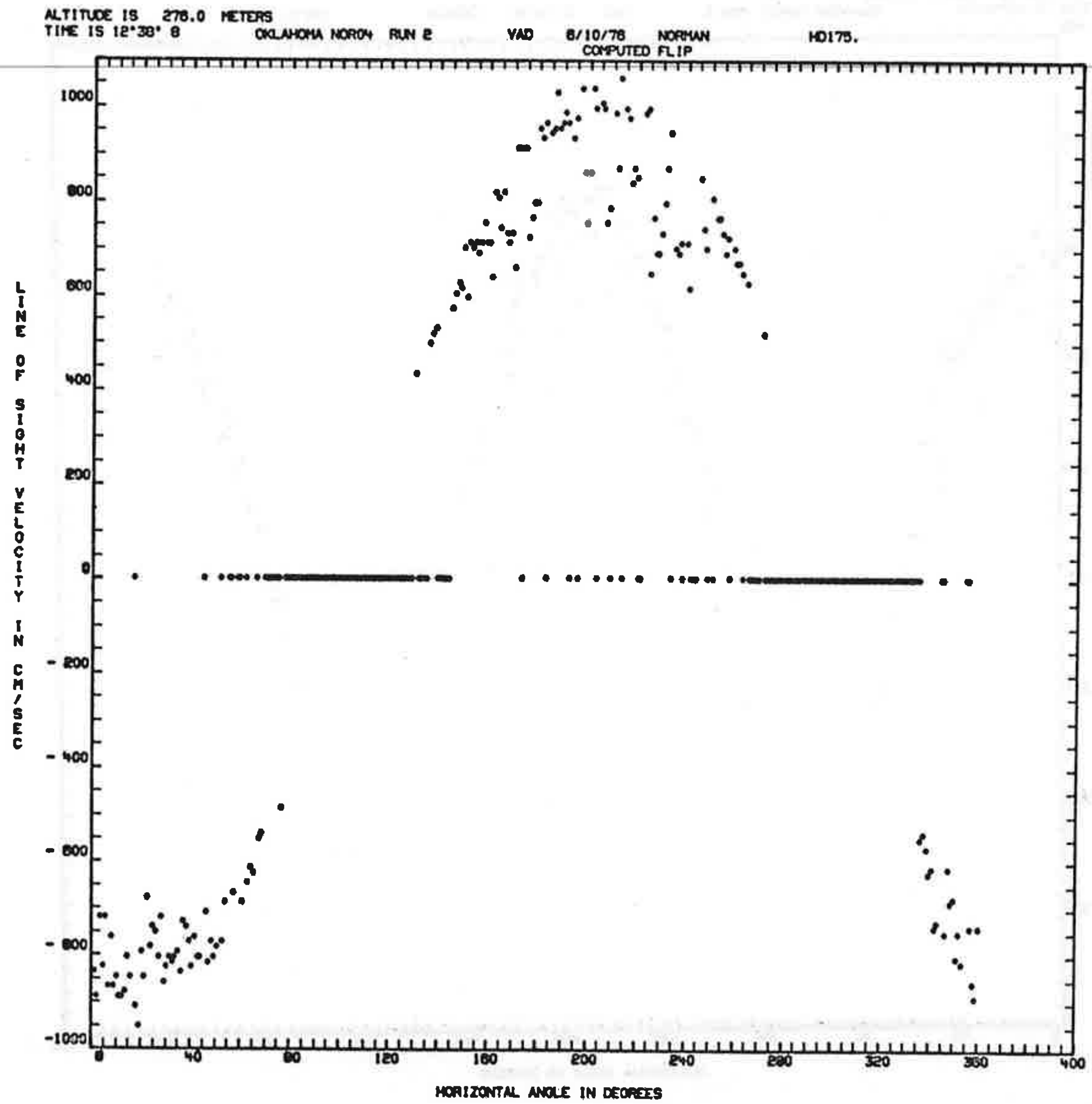


FIGURE A-1 (Continued)

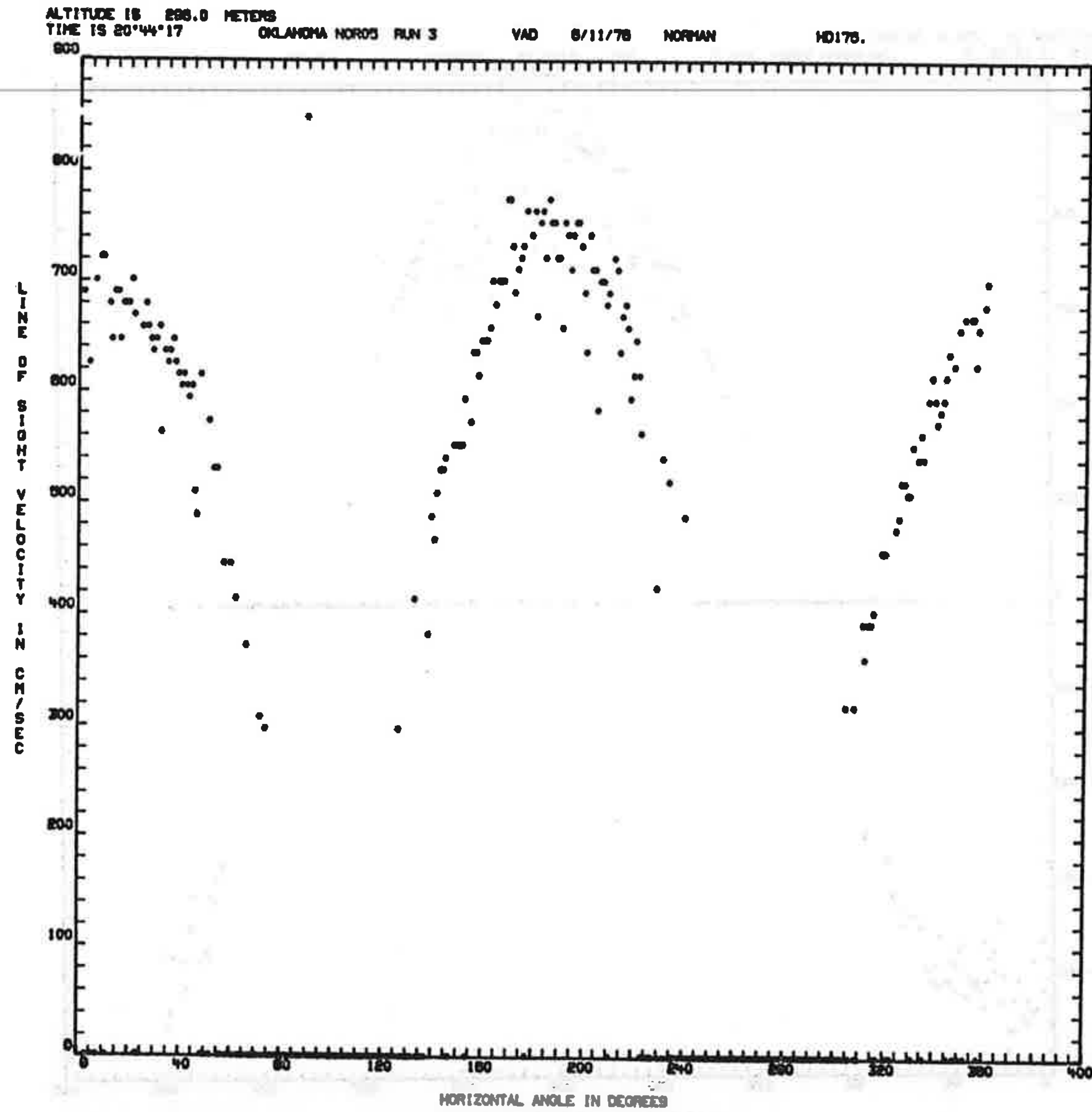


FIGURE A-1 (Continued)

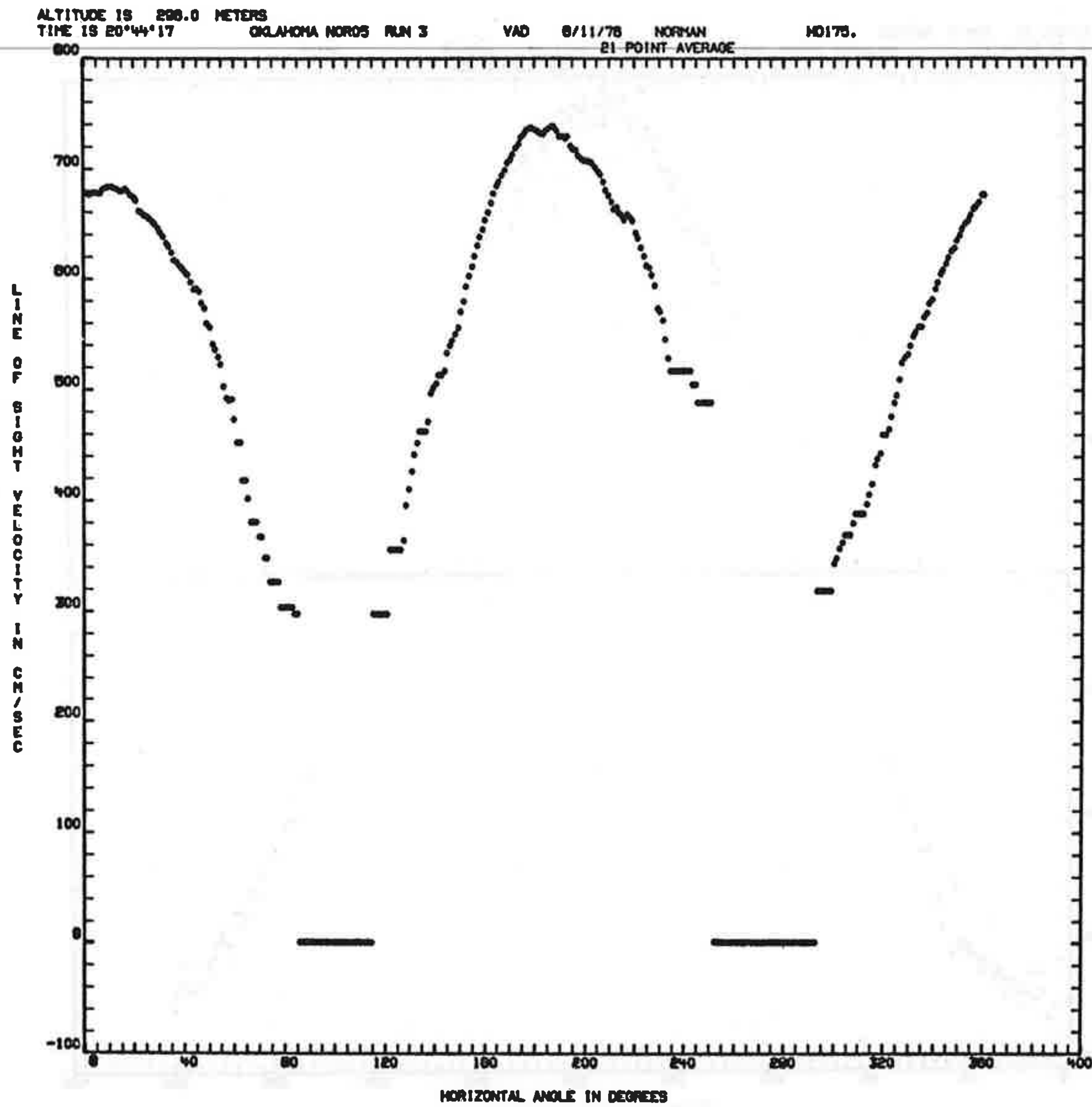


FIGURE A-1 (Continued)

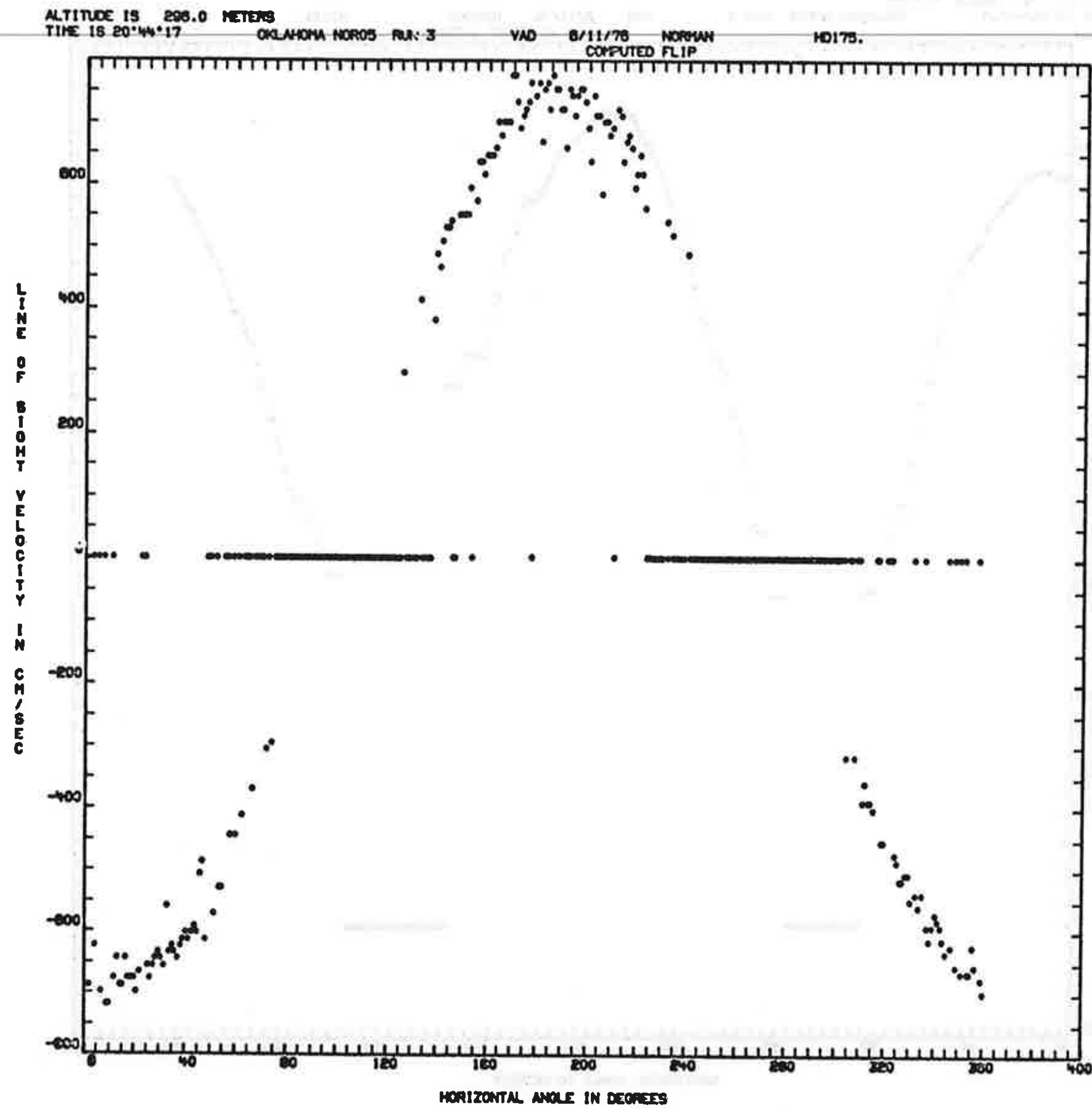


FIGURE A-1 (Continued)

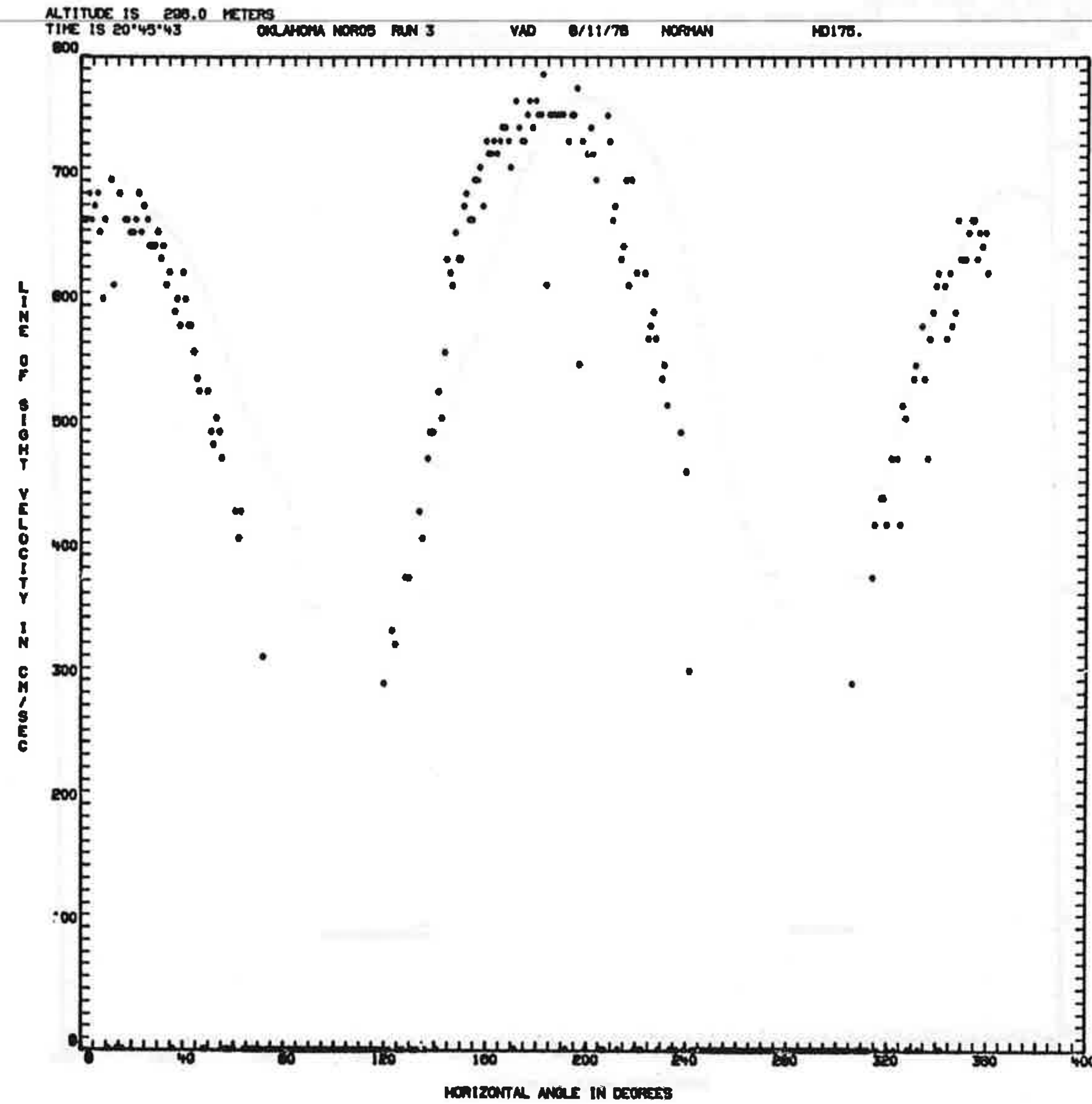


FIGURE A-1 (Continued)

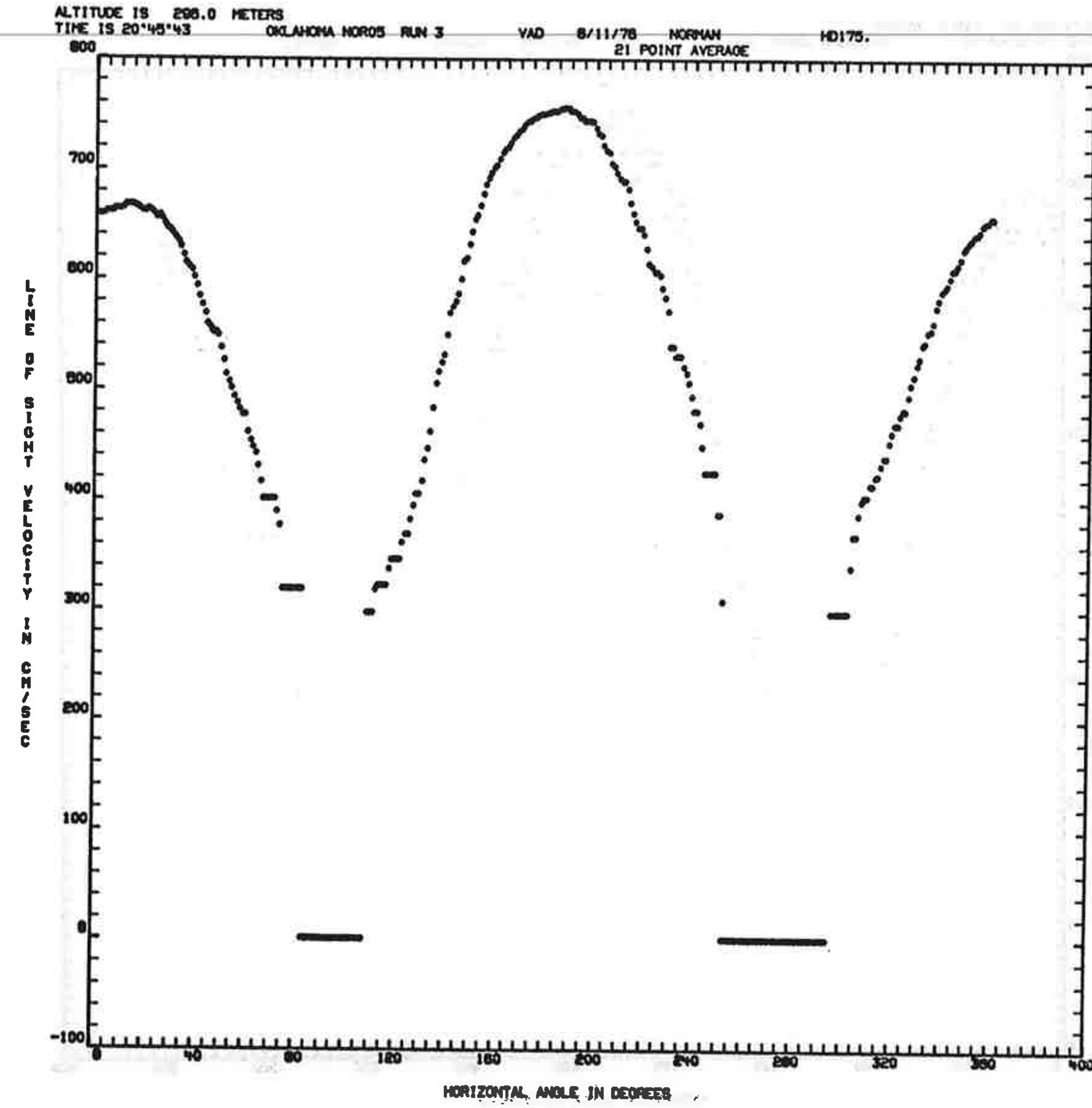


FIGURE A-1 (Continued)

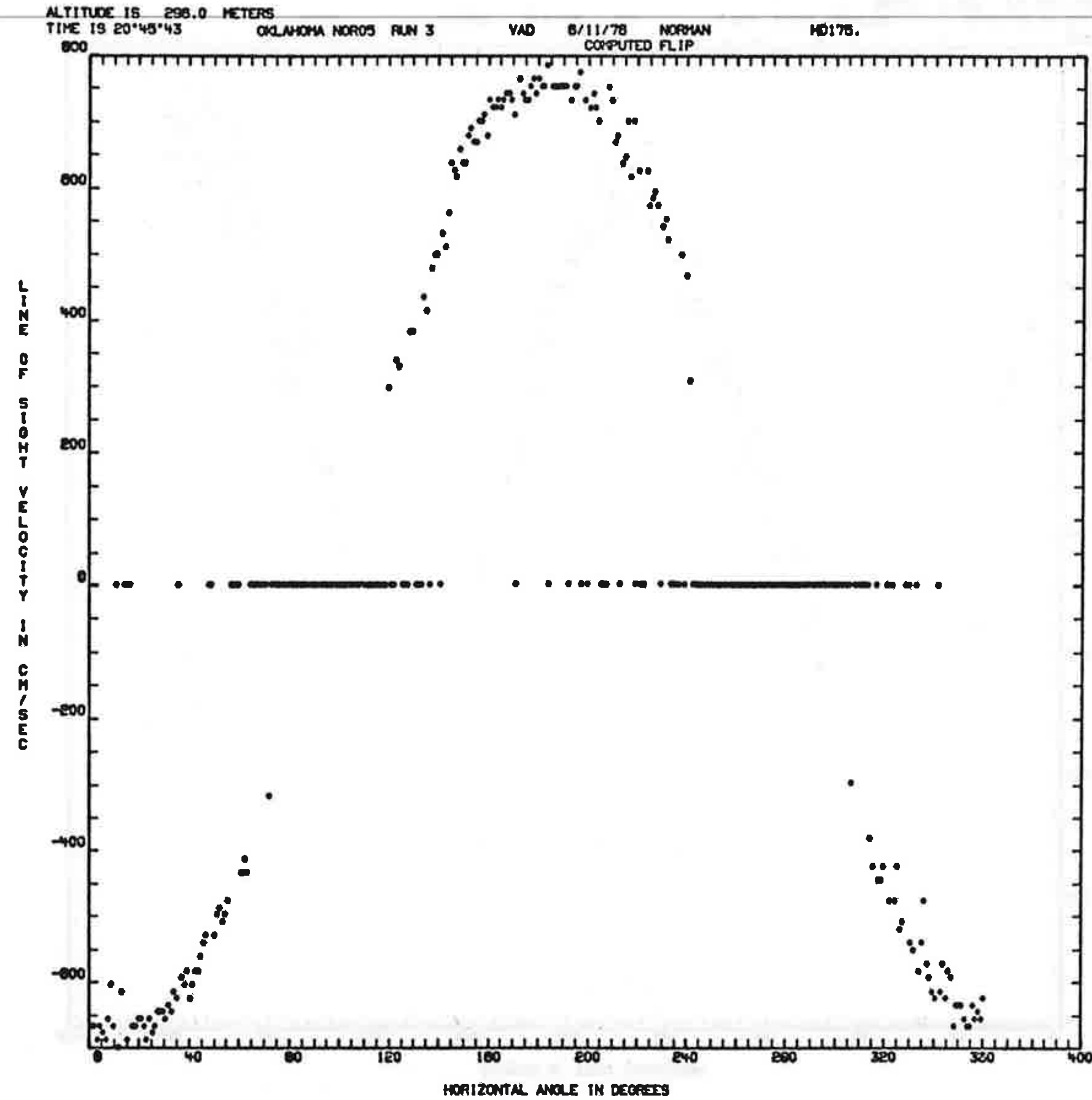


FIGURE A-1 (Continued)

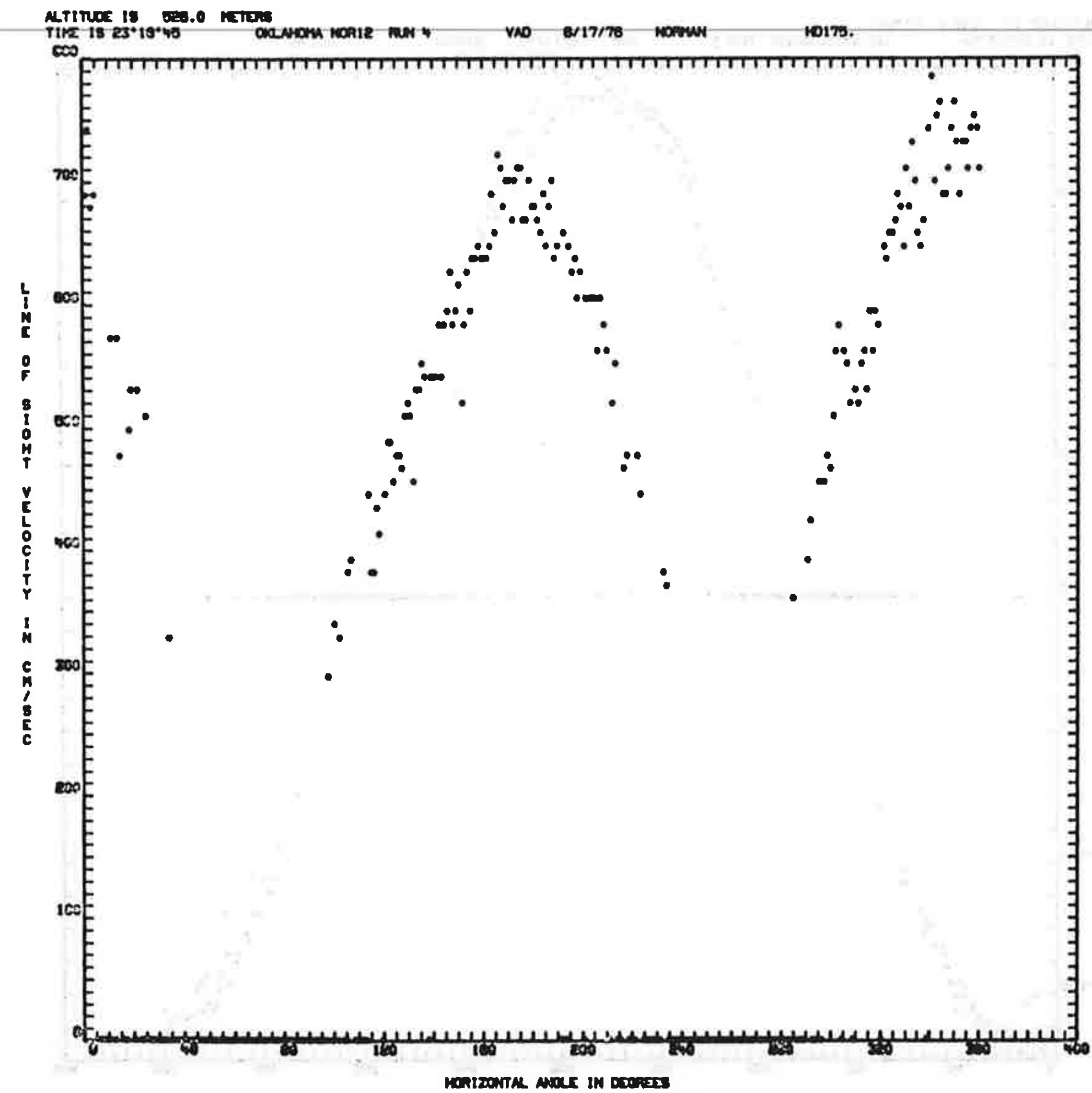


FIGURE A-1 (Continued)

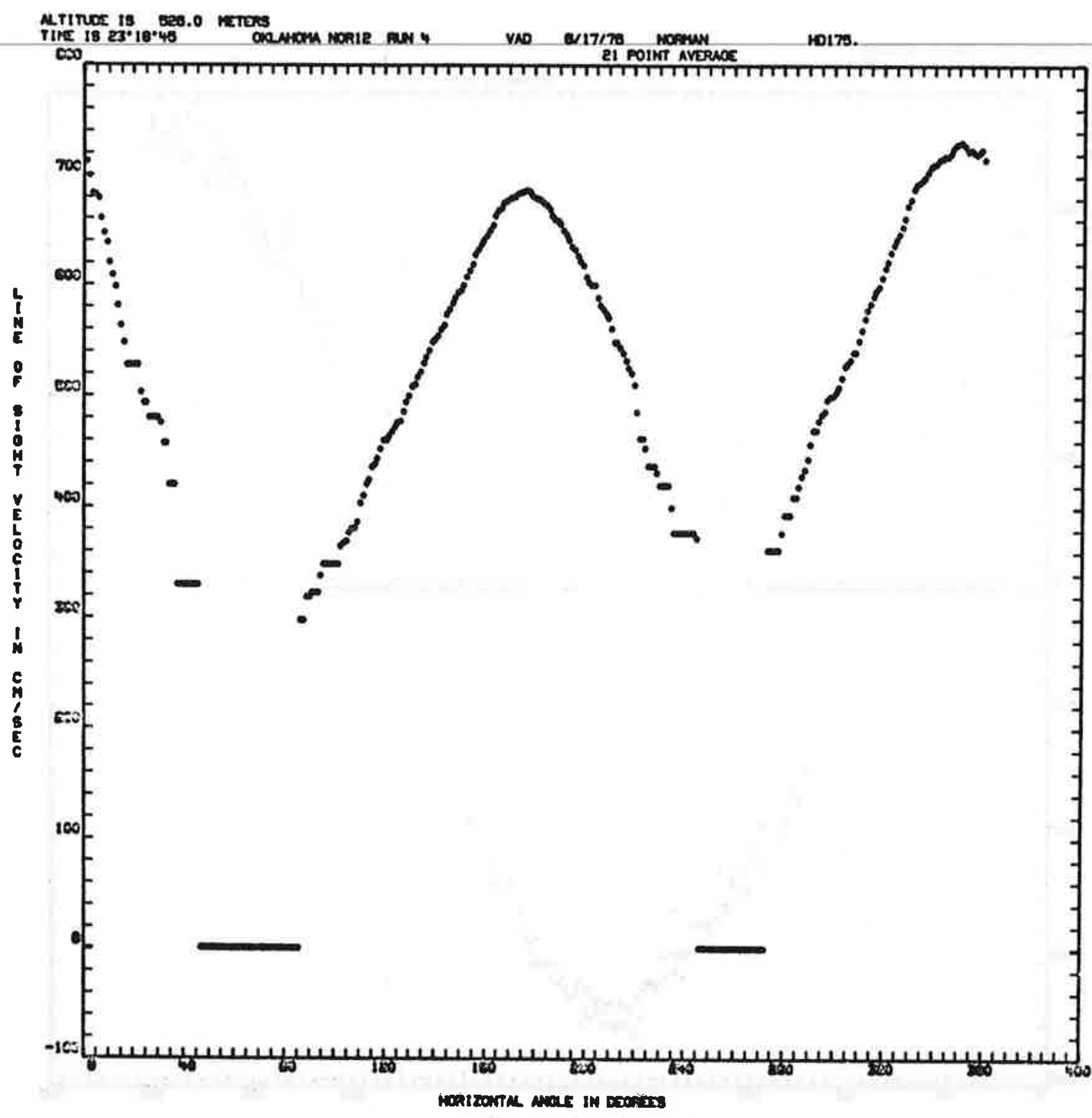


FIGURE A-1 (Continued)

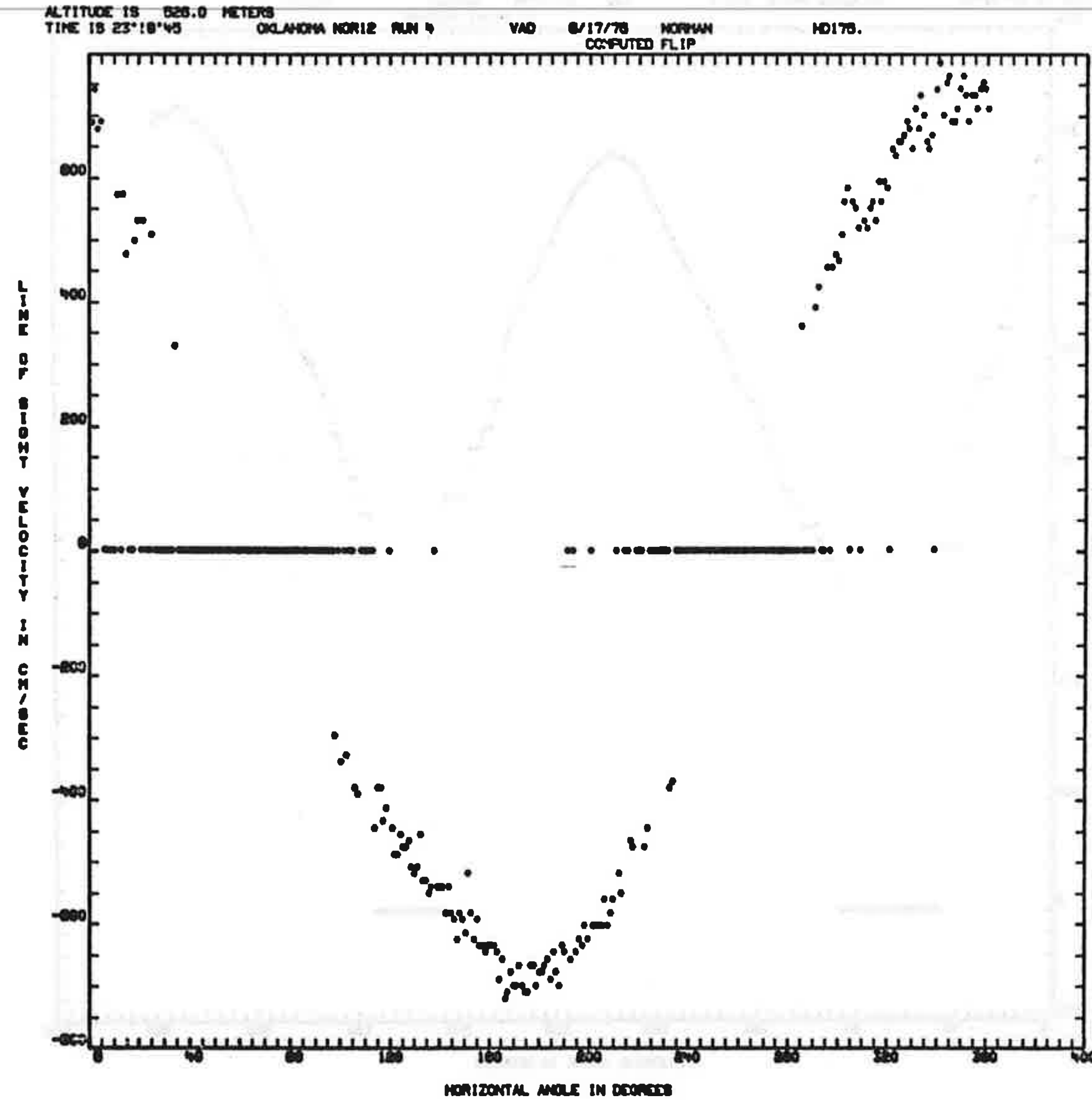


FIGURE A-1 (Continued)

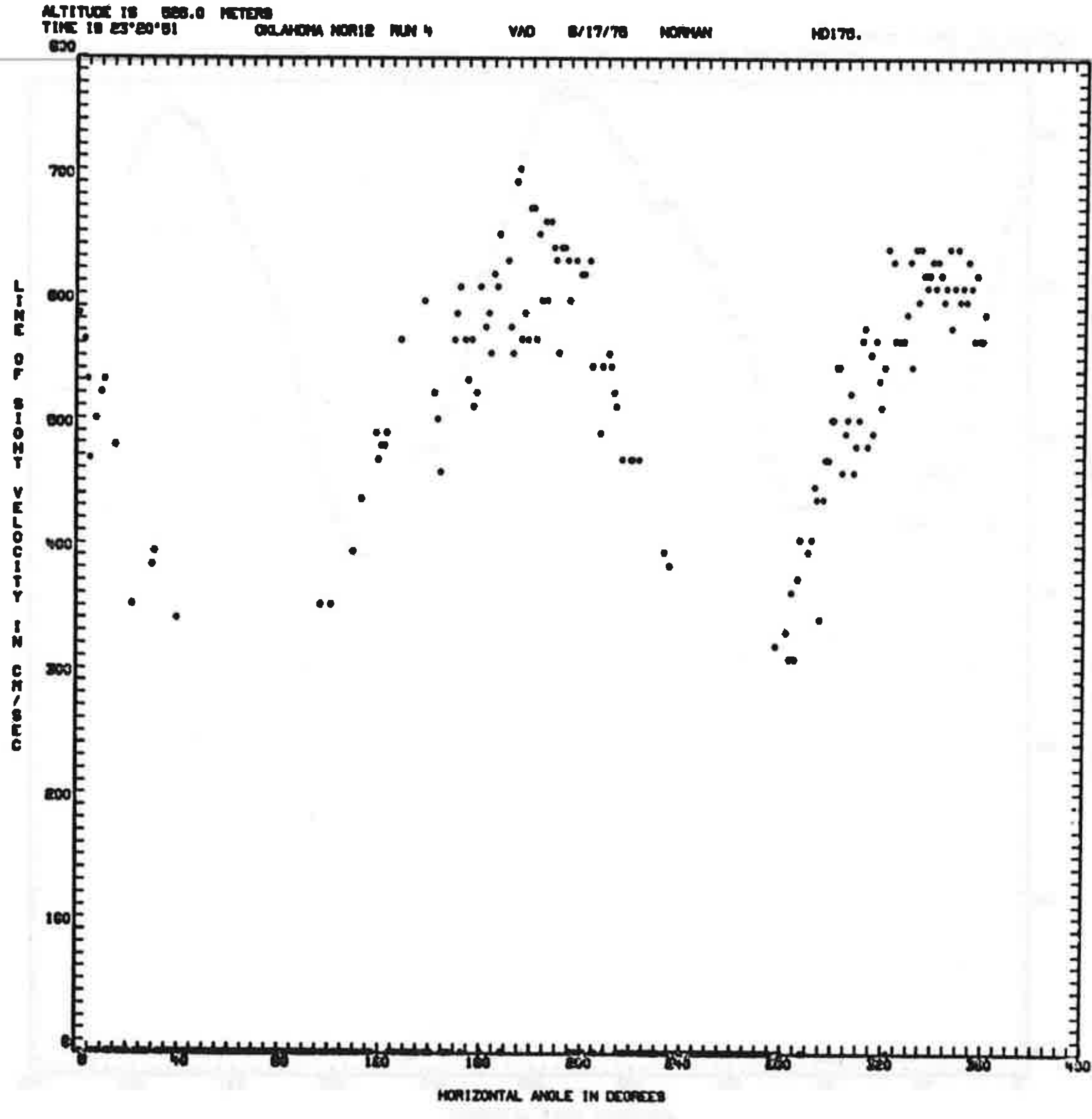


FIGURE A-1 (Continued)

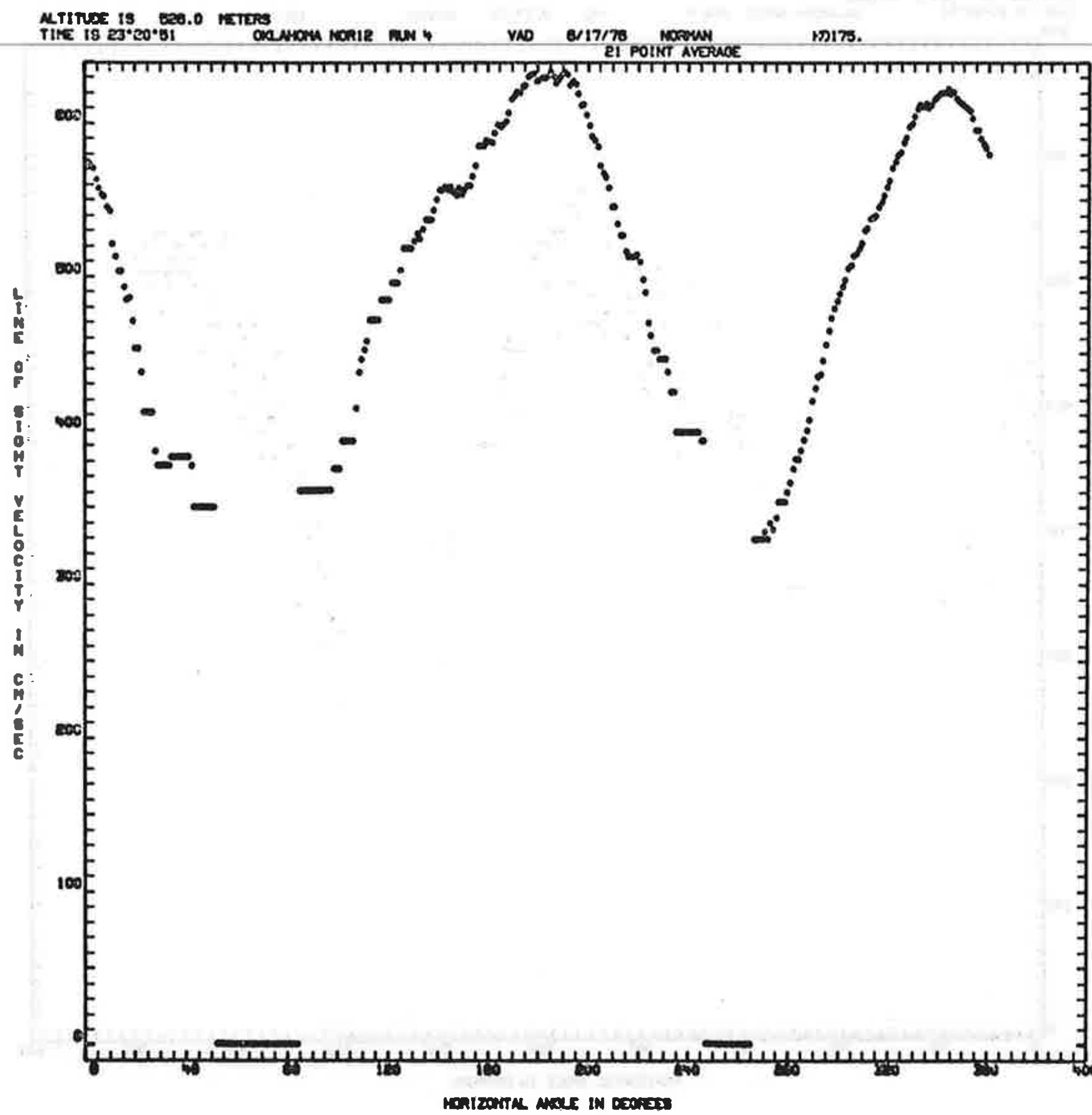


FIGURE A-1 (Continued)

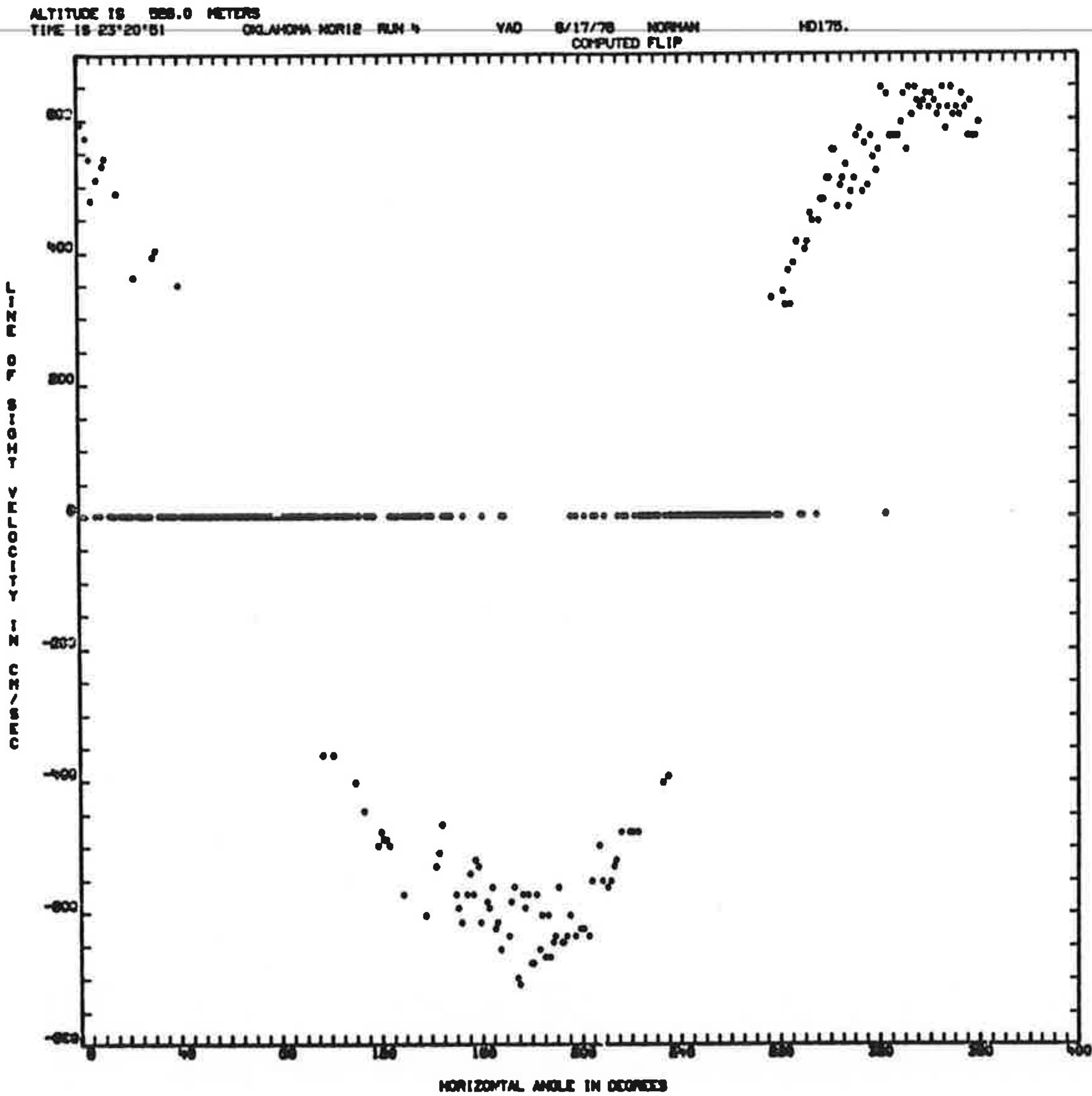


FIGURE A-1 (Concluded)

Appendix B

TYPICAL TABULATED DATA

Typical tabulated data sheets are presented. The tabulated data show typical comparisons of the results of the various algorithms, typical values of vertical component of wind, typical values of the second and third harmonics for the Fourier (spectral) algorithm, and typical values of the standard deviations of the various parameters. A complete set of tabulated data exists at the Department of Transportation, Transportation Systems Center, Cambridge, Massachusetts.

TABLE B-1

TYPICAL TABULATED WIND DATA FROM LASER DOPPLER VELOCIMETER

OKLAHOMA NOROS RUN 1 VAD 6/11/76 NORMAN HD175.

HEIGHT = 38. METERS

START TIME 18: 0: 0
END TIME 18:15: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE MEANS

	PEAKS				I	FOURIER COEFFICIENTS						I	SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-1127	-80	-68	1145	171.4	-1263	-68	-64	1272	172.3	7	20	-1132	-51	-66	1139	172.8	49
2	-1177	-195	-48	1211	166.0	-1312	-191	-54	1337	167.4	8	19	-1192	-165	-52	1214	167.7	45
3	-1100	-248	-44	1138	162.8	-1273	-274	-41	1308	163.1	8	23	-1115	-223	-48	1140	164.1	44
4	-1010	-153	-29	1033	166.7	-1182	-208	-37	1210	165.3	10	19	-999	-154	-30	1019	166.4	52
5	-1091	-238	24	1173	163.1	-1165	-409	15	1275	156.1	15	20	-1078	-313	6	1148	159.1	74
6	-1080	-152	-48	1106	167.5	-1255	-156	-42	1274	168.3	7	21	-1096	-108	-50	1109	170.0	47
7	-897	17	-8	948	176.2	-1126	30	-4	1146	177.1	8	24	-935	49	-8	950	178.7	44
8	-1004	-109	-32	1035	168.4	-1168	-64	-18	1176	172.5	9	26	-1013	-17	-24	1018	174.6	60
9	-1099	-56	-83	1109	172.6	-1250	-12	-82	1256	174.9	12	18	-1101	-14	-79	1107	174.6	49
10	-1029	-38	-46	1039	173.3	-1194	-83	-46	1202	171.4	8	21	-1007	-59	-44	1013	172.0	44
11	-970	-165	-36	1004	165.8	-1165	-135	-40	1182	169.0	6	21	-982	-98	-38	996	170.0	48
12	-892	-95	-15	931	169.0	-1102	-92	-2	1126	170.6	11	25	-917	-44	-10	929	172.6	50
13	-900	23	-3	912	176.8	-1123	-21	-19	1132	174.3	9	20	-909	31	-8	915	177.3	44
14	-978	-143	-33	1001	167.4	-1131	-141	-23	1155	168.3	9	20	-974	-99	-21	993	169.9	57
15	-991	28	-29	1009	176.6	-1150	-63	-32	1158	172.3	11	22	-999	-16	-28	1005	174.2	55

CUMULATIVE MEANS

	PEAKS				I	FOURIER COEFFICIENTS						I	SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-1127	-80	-68	1145	171.4	-1263	-68	-64	1272	172.3	7	20	-1132	-51	-66	1139	172.8	49
2	-1152	-137	-58	1178	168.7	-1288	-129	-59	1304	169.8	7	20	-1162	-108	-59	1177	170.3	47
3	-1136	-172	-54	1165	166.9	-1283	-175	-53	1305	167.7	8	21	-1147	-144	-56	1165	168.3	46
4	-1104	-167	-47	1131	166.8	-1257	-184	-49	1281	167.1	8	20	-1110	-147	-49	1128	167.8	47
5	-1101	-182	-33	1140	166.1	-1238	-229	-36	1280	164.9	10	20	-1103	-181	-38	1132	166.1	53
6	-1098	-177	-35	1134	166.3	-1241	-218	-37	1279	165.4	9	20	-1102	-169	-40	1128	166.7	52
7	-1069	-148	-31	1107	167.7	-1224	-182	-32	1259	167.1	9	21	-1077	-137	-35	1102	168.4	51
8	-1061	-144	-31	1099	167.8	-1218	-168	-31	1250	167.7	9	21	-1070	-123	-34	1092	169.2	52
9	-1065	-134	-37	1100	168.4	-1221	-150	-36	1250	168.6	9	21	-1073	-110	-39	1094	169.8	52
10	-1061	-124	-38	1094	168.9	-1218	-143	-37	1245	168.8	9	21	-1067	-105	-39	1086	170.0	51
11	-1054	-128	-38	1086	168.6	-1214	-142	-38	1240	168.9	9	21	-1059	-105	-39	1078	170.0	51
12	-1040	-125	-36	1073	168.6	-1204	-138	-35	1230	169.0	9	21	-1047	-99	-37	1065	170.2	51
13	-1030	-114	-34	1061	169.2	-1198	-129	-33	1223	169.4	9	21	-1037	-90	-35	1054	170.7	50
14	-1026	-116	-33	1056	169.1	-1193	-130	-33	1218	169.3	9	21	-1032	-91	-34	1050	170.7	51
15	-1023	-107	-33	1053	169.6	-1150	-126	-33	1214	169.5	9	21	-1030	-85	-33	1047	170.9	51

TABLE B-1 (Continued)

HEIGHT = 38. METERS   OKLAHOMA NORDS RUN I   VAD 6/11/76   NORMAN   HD175.   START TIME 18: 0: 0 END TIME 18:15: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	77	181	52	78	9.0	89	121	45	86	5.6	110	109	40	107	5.7
2	83	201	24	69	9.9	53	171	43	62	7.3	59	160	33	61	7.6
3	118	152	37	122	7.4	99	96	37	82	4.8	104	65	23	102	3.4
4	99	147	54	91	8.5	85	143	41	70	7.1	97	116	39	88	6.9
5	117	365	64	108	18.0	162	298	63	96	14.8	127	232	50	92	12.4
6	85	181	42	77	9.8	82	142	32	72	6.7	61	129	28	64	6.6
7	137	294	31	75	20.6	63	214	35	61	10.8	74	160	29	69	9.9
8	178	215	44	157	13.1	104	122	26	106	5.8	149	98	33	148	5.8
9	90	135	45	88	7.1	78	111	53	75	5.3	92	97	42	88	5.4
10	63	139	38	65	7.6	46	101	45	40	5.0	58	77	40	55	4.6
11	88	199	29	77	11.7	45	142	24	52	6.8	60	133	20	68	7.4
12	134	240	43	106	16.5	84	211	36	65	11.3	107	134	33	101	8.9
13	74	142	36	76	8.9	50	142	48	47	7.3	70	103	38	72	6.3
14	99	163	42	111	8.7	79	183	47	67	9.4	96	173	33	106	9.5
15	112	187	41	109	11.0	70	123	49	71	6.0	113	101	38	112	5.9

CUMULATIVE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	77	181	52	78	9.0	89	121	45	86	5.6	110	109	40	107	5.7
2	82	196	41	80	9.7	76	158	43	80	6.9	92	146	37	93	7.1
3	97	189	40	95	9.4	83	156	42	80	7.0	97	137	33	96	6.8
4	111	178	45	110	9.1	94	152	42	87	7.0	116	131	36	114	6.8
5	112	227	57	110	11.4	116	209	53	89	10.0	118	168	45	109	8.8
6	108	219	55	106	11.1	111	201	50	86	9.6	111	164	43	103	8.6
7	132	248	53	121	13.2	113	220	50	95	10.6	121	180	42	117	9.7
8	139	236	52	127	13.2	113	214	48	99	10.3	126	177	41	124	9.5
9	135	228	53	123	12.7	109	210	51	97	10.1	122	173	44	120	9.3
10	129	223	52	120	12.3	105	203	50	94	9.7	119	166	43	117	9.0
11	129	220	50	119	12.3	102	198	48	92	9.5	117	163	42	117	8.8
12	137	221	50	125	12.6	105	199	48	96	9.6	123	161	42	122	8.8
13	138	220	50	129	12.5	104	197	48	96	9.5	125	161	42	126	8.8
14	136	216	49	129	12.3	104	196	48	96	9.5	124	162	42	125	8.9
15	134	216	48	128	12.3	103	192	48	96	9.3	123	159	41	124	8.7

TABLE B-1 (Continued)

HEIGHT = 38. METERS   OKLAHOMA NORDS RUN 1   VAD   6/11/76   NORMAN   HD175.   START TIME 18:15: 0
END TIME 18:30: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE MEANS

	PEAKS				I	FOURIER COEFFICIENTS						I	SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-968	-217	-36	1003	162.6	-1146	-155	-28	1166	167.7	10	25	-983	-143	-35	1002	167.0	52
2	-905	-1	-41	928	175.4	-1110	-67	-37	1121	172.1	10	21	-911	-36	-39	920	173.4	43
3	-1054	-97	-66	1066	170.0	-1210	-185	-54	1229	166.6	8	18	-1048	-127	-55	1060	168.4	46
4	-1013	23	-17	1032	177.0	-1160	-74	-4	1169	171.9	9	22	-1006	-39	-8	1012	173.4	52
5	-1008	-102	-53	1026	170.0	-1163	-151	-38	1183	168.1	8	22	-1002	-116	-43	1016	169.1	48
6	-879	-190	-2	914	163.5	-1081	-187	-10	1100	165.7	8	22	-888	-158	-5	905	165.4	48
7	-890	-39	0	916	173.1	-1104	-69	-10	1112	171.9	9	24	-902	-34	-6	907	173.4	46
8	-970	-111	-47	986	169.1	-1100	-117	-34	1121	169.6	15	18	-951	-119	-45	965	168.6	66
9	-1061	-97	-55	1078	170.1	-1200	-21	-41	1213	174.7	11	21	-1050	-13	-43	1057	175.0	64
10	-1155	-62	-48	1173	172.5	-1272	-73	-50	1283	172.2	7	21	-1142	-57	-46	1155	172.6	50
11	-1209	20	-92	1231	176.1	-1316	-2	-74	1326	175.2	7	20	-1196	13	-79	1207	175.9	60
12	-1155	22	-54	1178	176.7	-1273	-29	-55	1281	174.3	9	19	-1142	3	-46	1152	175.9	57
13	-1039	20	-32	1062	176.5	-1208	-35	-23	1216	173.9	13	23	-1043	2	-24	1051	175.8	63
14	-1026	-10	-11	1047	174.5	-1203	-14	-3	1210	174.7	8	21	-1029	13	-5	1036	176.1	53
15	-1066	73	-26	1096	179.0	-1209	124	-24	1226	181.2	6	23	-1073	125	-31	1092	181.9	54

CUMULATIVE MEANS

	PEAKS				I	FOURIER COEFFICIENTS						I	SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-968	-217	-36	1003	162.6	-1146	-155	-28	1166	167.7	10	25	-983	-143	-35	1002	167.0	52
2	-935	-104	-39	964	169.3	-1127	-109	-33	1142	170.0	10	23	-946	-87	-37	960	170.4	47
3	-974	-102	-47	997	169.5	-1154	-134	-39	1171	168.9	9	21	-979	-100	-43	992	169.7	47
4	-984	-69	-39	1006	171.5	-1156	-118	-30	1170	169.7	9	22	-986	-84	-34	997	170.7	48
5	-989	-76	-42	1010	171.2	-1157	-125	-32	1173	169.3	9	22	-989	-91	-36	1001	170.3	48
6	-971	-94	-36	995	169.9	-1145	-135	-28	1161	168.8	9	22	-973	-102	-31	986	169.6	48
7	-959	-86	-31	983	170.4	-1139	-125	-26	1154	169.2	9	22	-963	-92	-27	974	170.1	48
8	-961	-89	-33	984	170.2	-1134	-124	-27	1150	169.3	10	22	-961	-95	-29	973	169.9	50
9	-972	-90	-35	994	170.2	-1142	-112	-28	1157	169.9	10	22	-971	-86	-31	983	170.5	52
10	-991	-87	-36	1013	170.5	-1155	-108	-31	1170	170.1	9	22	-989	-83	-32	1000	170.7	52
11	-1010	-78	-41	1032	170.9	-1169	-99	-34	1184	170.6	9	21	-1007	-74	-36	1018	171.2	52
12	-1023	-69	-42	1044	171.4	-1178	-93	-36	1192	170.9	9	21	-1019	-67	-37	1030	171.6	53
13	-1024	-62	-42	1046	171.8	-1180	-89	-35	1194	171.1	10	21	-1020	-62	-36	1031	171.9	54
14	-1024	-58	-39	1046	172.0	-1182	-83	-33	1195	171.4	9	21	-1021	-57	-34	1032	172.2	53
15	-1027	-50	-39	1049	172.5	-1184	-70	-32	1197	172.0	9	21	-1024	-45	-34	1036	172.8	53

TABLE B-1 (Continued)

HEIGHT = 38. METERS OKLAHOMA NUROS RUN 1 VAD 6/11/76 NORMAN HD175. START TIME 18:15: 0 END TIME 18:30: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE STANDARD DEVIATIONS

	PEAKS				I.	FOURIER COEFFICIENTS				I	SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	111	136	35	96	8.5	95	145	30	88	7.4	102	124	24	95	7.5
2	78	206	27	77	12.8	42	135	38	46	6.9	76	122	30	80	7.4
3	142	118	60	136	7.0	99	91	47	88	5.0	152	73	47	148	4.8
4	65	197	34	61	11.1	43	117	37	45	5.7	60	96	25	60	5.5
5	92	163	19	97	9.0	54	149	27	53	7.3	70	114	17	71	6.6
6	42	165	41	53	10.1	35	77	32	39	3.9	46	61	28	49	3.8
7	67	211	38	43	13.9	36	103	26	36	5.3	41	85	22	45	5.2
8	118	134	50	120	7.7	87	177	32	86	9.3	86	113	32	94	6.3
9	109	161	51	105	8.8	75	174	41	71	8.5	112	122	31	111	6.7
10	90	195	47	86	9.7	54	151	39	55	6.7	66	159	38	64	8.0
11	99	233	34	90	11.3	68	160	42	68	6.9	85	160	33	85	7.7
12	122	232	38	121	11.4	96	139	46	96	6.3	113	146	39	111	7.4
13	114	223	63	113	12.2	75	131	37	78	6.0	87	126	35	91	6.6
14	78	214	49	79	11.7	50	119	31	48	5.7	84	108	33	82	6.2
15	97	247	36	85	13.6	75	166	29	72	8.0	82	154	23	80	8.4

CUMULATIVE STANDARD DEVIATIONS

	PEAKS				I.	FOURIER COEFFICIENTS				I	SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	111	136	35	96	8.5	95	145	30	88	7.4	102	124	24	95	7.5
2	98	204	31	93	12.6	73	144	34	72	7.3	95	132	27	95	8.0
3	125	179	44	117	11.0	90	133	39	87	6.8	124	117	35	122	7.1
4	113	190	43	106	11.4	80	131	41	78	6.6	111	114	36	109	6.9
5	109	184	40	104	10.9	75	134	39	73	6.7	104	114	33	102	6.8
6	109	185	42	104	11.1	76	128	38	74	6.5	104	110	34	102	6.6
7	108	189	43	101	11.5	72	127	37	71	6.4	100	109	34	100	6.6
8	108	183	44	103	11.1	75	132	37	74	6.7	98	109	34	98	6.5
9	112	180	45	107	10.8	78	141	37	76	7.1	103	113	34	103	6.7
10	123	181	46	118	10.7	85	142	38	83	7.1	113	118	34	113	6.8
11	136	187	47	131	10.8	95	146	40	93	7.2	125	125	36	125	7.0
12	140	193	47	136	10.9	99	146	41	97	7.2	129	128	37	129	7.2
13	138	196	48	134	11.1	98	146	41	95	7.1	127	129	37	126	7.2
14	135	197	48	131	11.1	95	145	41	93	7.1	124	129	37	123	7.2
15	133	202	48	129	11.4	94	155	40	92	7.5	122	137	36	122	7.6

TABLE B-1 (Continued)

OKLAHOMA NOR06 RUN 2 VAD 6/12/76 NORMAN HD175.

HEIGHT = 550. METERS

START TIME 1:30: 0
END TIME 1:45: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-1857	846	-43	2096	199.9	-2551	888	-60	2707	194.7	8	22	-1944	700	-37	2073	195.3	103
2	-1909	888	-47	2142	200.5	-2508	888	-51	2666	195.0	8	23	-1939	784	-41	2098	197.4	109
3	-1866	840	-43	2118	199.7	-2470	679	-39	2569	190.7	8	21	-1978	610	-39	2077	192.6	97
4	-1895	928	-27	2175	201.7	-2660	1002	-53	2855	196.2	13	19	-1928	812	-27	2101	198.4	118
5	-1880	885	-8	2139	201.1	-2602	822	-30	2735	193.0	12	20	-1975	632	-12	2080	193.2	114
6	-1809	785	-32	2031	199.1	-2487	707	-58	2593	191.3	13	21	-1912	582	-43	2004	192.4	98
7	-1805	1065	-34	2118	205.8	-2686	859	-27	2825	193.2	6	15	-1910	746	-34	2056	196.7	100
8	-1956	894	-39	2177	200.0	-2563	706	-45	2664	190.8	10	20	-2019	674	-40	2132	193.9	95
9	-1721	1118	-30	2097	208.5	-2443	608	-38	2530	189.4	12	24	-1934	575	-36	2026	192.0	123
10	-1763	1010	-38	2089	205.5	-2468	667	-50	2562	190.6	9	25	-1934	645	-43	2044	194.0	113
11	-1860	878	-39	2112	200.7	-2402	608	-42	2482	189.7	8	24	-1951	564	-42	2035	191.6	107
12	-1845	629	0	2077	191.5	-2494	690	-45	2595	191.0	10	25	-1951	642	-39	2058	193.6	114
13	-1683	1148	-48	2099	209.7	-2512	703	-59	2612	191.1	10	25	-1976	605	-53	2072	192.5	105
14	-1713	989	-43	2021	205.3	-2357	599	-50	2443	189.7	12	22	-1871	548	-41	1957	191.7	112
15	-1806	973	-52	2117	203.8	-2521	643	-62	2609	189.8	9	22	-1908	609	-57	2008	193.2	114

CUMULATIVE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-1857	846	-43	2096	199.9	-2551	888	-60	2707	194.7	8	22	-1944	700	-37	2073	195.3	103
2	-1883	867	-45	2119	200.2	-2529	888	-55	2687	194.8	8	22	-1942	742	-39	2086	196.3	106
3	-1877	858	-45	2119	200.0	-2510	818	-50	2647	193.5	8	22	-1954	698	-39	2083	195.1	103
4	-1881	874	-40	2132	200.4	-2545	862	-51	2696	194.1	9	21	-1948	725	-36	2087	195.9	107
5	-1881	877	-34	2133	200.5	-2557	854	-46	2704	193.9	10	21	-1953	706	-31	2086	195.3	108
6	-1869	861	-33	2116	200.3	-2545	829	-48	2685	193.4	11	21	-1946	685	-33	2072	194.8	107
7	-1860	891	-34	2116	201.1	-2565	833	-45	2705	193.4	10	20	-1941	694	-33	2070	195.1	106
8	-1871	891	-34	2124	201.0	-2565	818	-45	2701	193.1	10	20	-1950	692	-34	2077	195.0	104
9	-1854	917	-34	2120	201.8	-2551	794	-44	2681	192.7	10	21	-1948	678	-34	2071	194.6	106
10	-1845	926	-34	2117	202.2	-2543	781	-45	2669	192.5	10	21	-1947	675	-35	2069	194.6	107
11	-1846	922	-35	2117	202.0	-2530	765	-45	2652	192.2	10	21	-1947	665	-36	2065	194.3	107
12	-1846	899	-32	2114	201.2	-2527	760	-45	2647	192.1	10	22	-1948	663	-36	2065	194.2	108
13	-1833	918	-33	2113	201.9	-2526	755	-46	2645	192.1	10	22	-1950	658	-37	2065	194.1	107
14	-1825	923	-34	2106	202.1	-2514	744	-46	2630	191.9	10	22	-1944	650	-38	2058	193.9	108
15	-1823	927	-35	2107	202.2	-2514	737	-47	2629	191.7	10	22	-1942	648	-39	2054	193.9	108

TABLE B-1 (Continued)

OKLAHOMA NORM6 RUN 2 VAD 6/12/76 NORMAN HD175.

HEIGHT = 550. METERS

START TIME 1:30: 0
END TIME 1:45: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE STANDARD DEVIATIONS

	PEAKS					I. FOURIER COEFFICIENTS					I SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	194	459	43	48	13.7	175	191	58	187	3.8	73	164	34	65	4.6
2	190	362	40	66	10.9	148	144	45	133	3.4	60	162	34	80	4.2
3	284	497	44	86	15.6	130	207	71	162	4.1	61	171	31	74	4.6
4	310	457	45	62	14.7	306	248	70	288	5.5	121	169	47	55	5.5
5	300	432	40	71	14.3	146	183	54	166	3.4	79	156	51	69	4.4
6	241	446	39	64	14.5	91	202	66	105	4.4	68	126	40	61	3.7
7	129	300	51	101	8.6	223	150	54	229	2.9	72	161	42	85	4.3
8	141	324	45	61	9.3	133	164	39	147	3.3	60	125	23	70	3.2
9	272	357	41	74	12.1	165	257	70	172	5.8	52	182	36	53	5.1
10	277	425	39	69	13.9	134	165	48	129	3.8	85	116	27	64	3.6
11	218	449	37	67	13.5	119	124	43	110	3.1	66	127	30	61	3.7
12	310	691	107	134	24.3	133	183	71	116	4.2	50	135	33	73	3.4
13	288	438	35	70	14.3	145	125	44	150	2.6	53	149	26	44	4.2
14	205	394	75	103	12.5	95	231	59	94	5.5	84	164	34	90	4.8
15	279	469	47	74	14.9	174	187	60	170	4.3	87	126	43	78	3.8

CUMULATIVE STANDARD DEVIATIONS

	PEAKS					I. FOURIER COEFFICIENTS					I SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	194	459	43	48	13.7	175	171	58	187	3.8	73	164	34	65	4.6
2	190	406	41	61	12.1	160	166	51	160	3.5	66	165	33	72	4.5
3	222	432	41	69	13.2	152	204	58	168	4.2	66	176	32	72	4.8
4	242	434	42	71	13.4	206	227	60	219	4.6	81	180	36	68	5.1
5	252	430	44	70	13.5	195	218	59	208	4.4	81	178	40	68	5.1
6	250	431	43	79	13.6	183	221	60	199	4.5	80	176	40	73	5.0
7	237	420	44	82	13.1	195	212	60	208	4.3	80	174	40	75	4.9
8	230	408	44	82	12.6	188	210	57	202	4.2	81	169	39	77	4.7
9	238	408	43	81	12.8	189	225	59	205	4.6	79	174	38	76	4.9
10	243	409	43	80	12.9	186	222	58	201	4.5	79	169	37	75	4.7
11	240	411	42	79	12.9	185	221	56	202	4.5	78	168	37	74	4.7
12	245	443	50	85	14.3	181	218	57	197	4.4	76	165	36	74	4.6
13	251	447	49	84	14.4	178	213	56	194	4.3	74	164	36	72	4.6
14	250	442	51	88	14.3	179	217	56	195	4.5	78	166	36	78	4.6
15	251	443	51	87	14.3	178	216	57	193	4.5	79	164	36	79	4.6

TABLE B-1 (Continued)

HEIGHT = 550. METERS OKLAHOMA NOR96 RUN .AD 6/12/76 NORMAN HD175.

START TIME 1:45: 0
END TIME 2: 0: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-1888	911	-48	2129	201.3	-2487	736	-55	2600	192.0	13	21	-1912	690	-35	2038	195.3	112
2	-1710	1079	-27	2083	207.7	-2439	697	-63	2547	191.4	15	21	-1877	654	-50	1994	194.7	110
3	-1788	963	-53	2067	203.7	-2381	600	-49	2465	189.5	12	24	-1921	545	-52	2001	191.3	105
4	-1715	859	-47	1973	202.2	-2290	575	-55	2368	189.5	10	23	-1838	461	-53	1900	189.5	105
5	-1807	677	-44	1960	196.1	-2315	478	-59	2371	187.1	13	20	-1870	408	-58	1920	187.8	104
6	-1751	855	-51	2035	201.5	-2297	661	-50	2399	191.5	8	26	-1873	595	-48	1972	193.1	113
7	-1750	862	-12	2023	201.4	-2320	594	-35	2400	189.8	12	22	-1884	497	-32	1952	190.2	110
8	-1551	1000	-13	1958	208.3	-2286	637	-3	2376	191.1	11	25	-1754	530	-19	1836	192.3	109
9	-1664	997	-41	2026	205.9	-2381	785	-20	2525	193.4	14	16	-1808	660	-40	1944	195.3	107
10	-1862	848	-17	2089	199.9	-2424	667	-48	2521	190.8	11	20	-1914	602	-31	2009	192.9	103
11	-1571	1155	-12	2027	211.6	-2334	651	-39	2435	190.9	10	24	-1834	575	-19	1931	192.8	117
12	-1677	992	5	1991	206.0	-2327	660	-34	2426	191.3	11	23	-1838	542	-35	1923	191.9	101
13	-1564	1176	-30	2061	211.9	-2351	753	-69	2478	193.2	12	26	-1882	614	-46	1985	193.5	118
14	-1732	993	-21	2054	205.3	-2374	676	-52	2485	191.4	10	25	-1904	619	-42	2010	193.5	113
15	-1605	1130	-27	2010	210.5	-2360	654	-53	2454	190.9	10	26	-1852	546	-50	1935	191.9	109

CUMULATIVE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-1888	911	-48	2129	201.3	-2487	736	-55	2600	192.0	13	21	-1912	690	-35	2038	195.3	112
2	-1795	998	-37	2105	204.6	-2462	715	-59	2572	191.7	14	21	-1894	671	-43	2015	195.0	111
3	-1793	986	-43	2092	204.3	-2434	676	-56	2536	190.9	13	22	-1903	628	-46	2010	193.7	109
4	-1773	954	-44	2062	203.8	-2397	650	-55	2493	190.6	13	23	-1887	586	-48	1982	192.7	108
5	-1779	901	-44	2042	202.3	-2382	617	-56	2470	189.9	13	22	-1883	552	-50	1970	191.7	107
6	-1775	893	-45	2041	202.2	-2367	625	-55	2457	190.2	12	23	-1882	559	-49	1971	192.0	108
7	-1771	889	-40	2038	202.1	-2360	620	-52	2449	190.1	12	23	-1882	550	-47	1968	191.7	108
8	-1743	903	-37	2028	202.9	-2351	623	-46	2440	190.2	12	23	-1866	547	-43	1951	191.8	109
9	-1735	913	-37	2028	203.2	-2354	640	-43	2449	190.6	12	22	-1860	559	-43	1950	192.1	108
10	-1748	906	-35	2034	202.8	-2361	642	-44	2456	190.6	12	22	-1865	564	-42	1956	192.2	108
11	-1731	929	-33	2033	203.6	-2359	643	-43	2454	190.6	12	22	-1862	565	-40	1959	192.3	109
12	-1727	934	-30	2030	203.9	-2356	645	-42	2452	190.7	12	22	-1860	563	-39	1951	192.3	108
13	-1715	952	-30	2032	204.4	-2356	652	-44	2454	190.9	12	22	-1862	566	-40	1954	192.3	109
14	-1716	955	-29	2034	204.5	-2357	654	-45	2456	190.9	12	23	-1865	570	-40	1958	192.4	109
15	-1709	967	-29	2032	204.9	-2357	654	-45	2456	190.9	11	23	-1864	569	-41	1956	192.4	109

TABLE B-1 (Continued)

OKLAHOMA NOR06 RUN 2 VAD 6/12/76 NORMAN HD175.

HEIGHT = 550. METERS

START TIME 1:45: 0
END TIME 2: 0: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	225	323	32	86	10.5	115	184	52	111	4.1	99	136	25	95	3.9
2	288	437	36	80	14.3	195	219	64	192	5.0	85	149	38	83	4.3
3	186	357	37	80	11.0	120	224	81	144	4.9	52	128	30	70	3.4
4	268	406	51	99	14.2	120	187	80	134	4.3	37	127	44	42	3.8
5	170	324	48	96	10.4	126	178	56	137	4.1	85	139	22	79	4.2
6	233	570	42	103	17.3	151	208	51	160	4.8	67	164	29	53	4.9
7	233	514	50	110	16.0	167	154	65	175	3.5	73	111	33	80	3.1
8	389	564	36	86	20.5	149	108	48	155	2.4	54	91	35	45	3.0
9	302	540	59	118	17.4	120	335	84	192	6.7	83	286	25	106	8.1
10	202	389	47	64	12.1	99	190	73	108	4.2	41	95	30	40	2.7
11	300	494	63	71	16.6	104	264	41	141	5.8	76	183	34	81	5.4
12	209	372	30	43	12.4	102	183	58	108	4.2	32	149	20	26	4.5
13	391	564	91	128	18.9	108	209	66	91	5.0	81	135	32	79	3.9
14	268	424	41	54	14.0	154	287	65	140	6.8	59	168	39	50	4.9
15	285	360	52	103	13.2	106	160	49	130	3.3	57	124	28	76	3.4

CUMULATIVE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	225	323	32	86	10.5	115	184	52	111	4.1	99	136	25	95	3.9
2	270	388	35	84	12.8	160	200	58	158	4.5	92	141	32	90	4.0
3	242	373	36	84	12.0	151	213	66	160	4.7	81	148	31	83	4.2
4	248	382	40	101	12.5	156	210	69	169	4.6	77	160	35	89	4.5
5	235	385	41	108	12.4	153	214	66	170	4.7	79	170	33	90	4.8
6	233	418	41	106	13.3	155	212	63	169	4.7	76	169	32	84	4.8
7	232	430	44	106	13.6	157	204	64	170	4.5	76	163	32	84	4.6
8	265	448	44	107	14.7	157	194	64	169	4.3	85	155	34	91	4.4
9	269	456	45	108	14.9	154	217	66	173	4.7	86	175	33	92	5.0
10	265	449	46	106	14.7	150	214	67	169	4.6	84	169	33	90	4.8
11	272	457	48	103	15.0	146	218	65	166	4.7	84	170	33	89	4.9
12	267	450	48	100	14.8	143	215	64	162	4.7	81	168	32	86	4.8
13	280	461	52	102	15.2	141	215	64	158	4.7	81	166	32	86	4.8
14	278	458	51	99	15.1	141	221	64	156	4.9	80	166	33	85	4.8
15	279	453	51	99	15.0	139	217	63	154	4.8	79	163	33	84	4.7

TABLE B-1 (Continued)

OKLAHOMA NORO3 RUN 3 VAD 6/ 9/76 NORMAN HD175.

HEIGHT = 175. METERS

START TIME 13: 0: 0
END TIME 13:15: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE MEANS

	PEAKS					I FOURIER COEFFICIENTS							I SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-976	394	-66	1088	196.9	-1049	286	-61	1098	190.7	6	14	-985	320	-63	1049	193.4	65
2	-803	480	8	951	206.6	-908	433	15	1010	200.9	7	17	-836	426	42	940	202.4	53
3	-801	552	43	983	210.3	-885	503	50	1022	205.0	8	15	-813	497	52	955	207.0	71
4	-813	303	-11	913	195.8	-982	247	26	1018	189.6	15	19	-847	215	7	877	189.7	67
5	-942	240	36	995	189.5	-947	297	1	1003	192.7	14	18	-873	298	13	929	194.0	82
6	-779	484	57	935	207.5	-862	474	24	986	204.4	7	18	-786	463	35	914	206.1	58
7	-815	562	18	997	210.1	-857	561	12	1031	208.9	9	16	-784	529	9	950	209.5	58
8	-786	655	-10	1029	215.2	-839	596	10	1043	210.6	9	16	-738	613	43	965	214.9	65
9	-734	759	94	1061	221.3	-766	650	-1	1008	215.8	15	9	-917	646	24	967	217.6	77
10	-596	601	56	865	220.7	-691	657	30	957	219.1	8	18	-628	590	33	863	218.6	49
11	-529	633	-23	836	225.5	-657	695	-12	966	221.9	8	19	-551	592	-23	813	222.5	44
12	-605	625	5	895	221.6	-704	624	0	955	216.9	8	17	-608	568	0	845	218.4	54
13	-865	225	10	911	189.7	-959	202	25	983	187.3	12	20	-868	215	13	898	189.4	57
14	-730	299	6	804	197.7	-836	302	-1	897	195.1	13	21	-740	295	4	804	197.2	57
15	-781	493	23	938	207.9	-880	449	37	995	202.6	9	20	-811	448	29	932	204.5	73

CUMULATIVE MEANS

	PEAKS					I FOURIER COEFFICIENTS							I SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-976	394	-66	1088	196.9	-1049	286	-61	1098	190.7	6	14	-985	320	-63	1049	193.4	65
2	-886	439	-27	1017	202.0	-976	362	-21	1052	196.0	7	15	-908	375	-23	993	198.1	58
3	-859	476	-4	1006	204.7	-946	408	1	1042	198.9	7	15	-877	415	0	980	201.0	63
4	-847	431	-6	982	202.4	-956	366	8	1036	196.5	9	16	-869	363	2	953	198.0	64
5	-865	394	2	984	199.9	-954	353	6	1030	195.8	10	17	-870	350	4	949	197.3	67
6	-851	409	11	976	201.1	-939	372	9	1023	197.2	10	17	-856	369	9	943	198.7	66
7	-846	432	12	979	202.4	-927	401	10	1024	198.9	9	17	-845	393	9	944	200.3	65
8	-839	459	9	985	204.0	-916	424	10	1026	200.3	9	17	-832	419	8	947	202.1	65
9	-827	493	19	994	206.0	-899	450	8	1024	202.1	10	16	-819	446	10	949	203.9	66
10	-804	504	23	982	207.4	-879	470	10	1018	203.8	10	16	-800	460	12	941	205.3	64
11	-780	515	18	969	209.0	-859	490	8	1013	205.4	10	16	-779	471	9	929	206.8	62
12	-765	525	17	962	210.1	-846	502	7	1008	206.4	9	16	-764	480	8	922	207.8	62
13	-772	503	17	959	208.6	-854	480	9	1006	204.9	10	17	-771	460	8	920	206.5	61
14	-769	488	16	948	207.8	-853	467	8	999	204.3	10	17	-769	449	8	912	205.8	61
15	-770	489	16	947	207.8	-855	466	10	998	204.1	10	17	-772	449	9	913	205.7	62

TABLE B-1 (Continued)

OKLAHOMA NORO3 RUN 3 VAD 6/ 9/76 NORMAN HD175.

HEIGHT = 175. METERS

START TIME 13: 0: 0
END TIME 13:15: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE STANDARD DEVIATIONS

	PEAKS					I, FOURIER COEFFICIENTS					I SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	102	279	51	87	14.8	45	151	18	35	8.1	54	160	17	38	9.1
2	120	125	54	42	10.5	41	74	42	41	4.2	38	50	46	36	2.8
3	109	103	18	47	8.3	45	79	26	36	4.7	41	43	21	33	3.0
4	115	273	61	48	18.5	106	101	43	106	5.7	53	63	43	54	4.1
5	106	211	47	93	12.9	81	140	33	74	8.4	72	112	27	79	6.8
6	110	149	20	40	11.1	58	48	21	45	3.5	43	30	15	28	2.8
7	78	98	41	38	6.9	104	79	23	67	6.2	64	68	26	36	5.2
8	71	100	39	57	6.0	95	160	16	69	9.7	33	109	19	56	5.9
9	71	93	32	49	5.8	73	56	36	47	4.5	64	34	34	56	2.7
10	126	130	28	21	12.0	74	70	28	61	5.0	25	37	20	21	2.7
11	100	94	16	28	9.3	83	114	20	59	7.5	58	49	12	29	4.9
12	165	146	29	48	14.1	107	141	15	65	9.9	92	119	18	26	10.1
13	66	178	20	66	11.4	65	73	18	70	3.9	43	62	16	38	4.2
14	76	142	19	46	11.1	48	132	21	66	7.7	58	93	18	45	7.1
15	102	136	38	40	10.1	83	99	28	38	7.2	71	68	26	34	5.7

CUMULATIVE STANDARD DEVIATIONS

	PEAKS					I, FOURIER COEFFICIENTS					I SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	102	279	51	87	14.8	45	151	18	35	8.1	54	160	17	38	9.1
2	140	213	64	96	13.4	83	137	51	59	8.1	87	126	52	66	7.9
3	136	191	63	84	12.5	84	137	56	54	8.3	87	121	57	60	7.9
4	131	225	62	87	14.7	91	146	53	71	8.7	80	140	53	74	8.6
5	131	234	61	87	15.1	88	147	50	72	8.7	78	136	49	75	8.4
6	131	224	60	83	14.8	91	143	47	70	8.7	80	132	47	70	8.4
7	125	217	58	78	14.2	96	151	44	69	9.3	82	137	44	66	8.9
8	121	218	56	78	14.1	100	164	42	69	10.1	85	152	42	65	9.8
9	121	229	60	79	14.5	108	171	41	67	10.8	90	161	41	64	10.5
10	139	223	59	84	14.9	122	175	40	69	11.5	103	159	40	67	10.9
11	157	218	58	91	15.3	135	182	40	70	12.3	123	157	40	74	11.6
12	164	214	56	90	15.6	139	182	38	71	12.5	129	156	39	75	11.9
13	161	226	54	90	16.2	138	193	37	71	13.1	128	166	37	73	12.5
14	157	227	53	96	16.1	134	195	36	76	13.0	124	167	36	77	12.4
15	154	221	52	93	15.8	131	190	37	74	12.7	122	162	36	75	12.1

TABLE B-1 (Continued)

OKLAHOMA NORO3 RUN 3 VAD 6/ 9/76 NORMAN HD175.

HEIGHT = 175. METERS

START TIME 13:15: 0
END TIME 13:30: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-867	389	-21	957	199.7	-914	346	-20	981	196.2	8	16	-854	352	-33	926	197.9	59
2	-878	123	-47	926	182.6	-904	216	-66	933	189.0	8	19	-840	248	-77	879	191.9	63
3	-872	70	-82	945	178.1	-972	243	-66	1006	189.6	8	16	-912	229	-73	945	189.6	59
4	-885	259	-81	930	192.0	-954	305	-70	1005	193.2	8	16	-881	299	-78	933	194.2	49
5	-838	197	-67	878	188.9	-910	181	-69	930	186.8	5	16	-847	200	-75	873	188.8	41
6	-830	133	-73	846	184.7	-885	152	-77	900	185.3	7	13	-830	174	-79	850	187.3	33
7	-796	148	-73	824	186.2	-886	120	-70	898	183.2	8	16	-825	140	-74	840	185.2	43
8	-795	89	-55	807	182.1	-880	68	-45	885	179.9	6	18	-804	95	-51	812	182.3	36
9	-752	249	-31	808	193.8	-840	209	-43	872	189.6	9	19	-770	206	-42	800	190.6	52
10	-750	498	-28	910	208.9	-865	342	-5	944	197.6	11	21	-793	349	-6	875	199.4	67
11	-736	344	-13	864	200.7	-817	340	-24	894	198.3	17	22	-742	322	-9	819	199.4	65
12	-799	88	60	970	184.2	-899	218	45	937	189.0	16	23	-807	244	59	853	192.2	82
13	-789	503	57	955	207.9	-825	573	39	1007	210.1	10	18	-761	526	55	928	210.1	60
14	-915	76	19	984	180.6	-994	193	59	1032	187.1	14	16	-899	229	47	949	191.1	63
15	-942	-146	-23	991	167.0	-1005	34	-36	1021	176.8	12	19	-937	45	-25	947	177.8	62

CUMULATIVE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-867	389	-21	957	199.7	-914	346	-20	981	196.2	8	16	-854	352	-33	926	197.9	59
2	-873	251	-35	941	190.8	-909	278	-44	956	192.5	8	18	-847	298	-56	901	194.8	61
3	-873	192	-50	942	186.7	-929	267	-51	972	191.5	8	17	-868	275	-62	915	193.1	60
4	-876	209	-58	939	188.0	-935	276	-56	980	191.9	8	17	-871	281	-66	920	193.3	58
5	-868	206	-59	926	188.2	-930	256	-59	970	190.8	7	17	-866	264	-68	910	192.4	54
6	-862	194	-62	913	187.6	-922	239	-62	958	189.9	7	16	-860	249	-70	900	191.6	51
7	-852	187	-63	900	187.4	-917	221	-63	949	188.9	7	16	-855	233	-70	891	190.6	49
8	-845	175	-62	889	186.8	-913	203	-61	942	187.8	7	16	-849	216	-68	882	189.6	48
9	-835	183	-59	880	187.5	-905	204	-59	934	188.0	7	17	-840	215	-65	873	189.7	48
10	-826	216	-56	883	189.8	-901	218	-53	935	189.0	8	17	-835	229	-59	873	190.7	50
11	-818	228	-52	881	190.7	-893	229	-50	931	189.9	9	18	-827	237	-54	868	191.5	52
12	-816	216	-43	889	190.2	-894	228	-43	932	189.8	9	18	-825	238	-45	867	191.6	54
13	-814	239	-35	894	191.6	-888	256	-36	938	191.4	9	18	-820	261	-37	872	193.1	54
14	-821	228	-31	900	190.9	-895	251	-29	945	191.1	10	18	-826	259	-31	877	192.9	55
15	-829	204	-30	906	189.3	-903	237	-30	949	190.2	10	18	-833	245	-31	882	191.9	56

TABLE B-1 (Continued)

OKLAHOMA NORD3 RUN 3 VAD 6/ 9/76 NORMAN HD175.

HEIGHT = 175. METERS

START TIME 13:15: 0
END TIME 13:30: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	72	90	19	47	6.4	50	70	26	40	4.5	44	56	24	41	3.6
2	76	278	35	91	17.3	51	70	21	49	4.4	57	68	19	61	4.2
3	220	312	30	92	25.3	61	80	21	59	4.6	66	82	18	66	4.9
4	117	105	34	104	7.7	64	70	31	60	4.2	77	52	27	81	2.8
5	69	165	17	35	11.5	36	54	16	30	3.6	37	53	12	29	3.8
6	38	92	17	32	6.3	26	55	19	24	3.5	27	43	9	26	2.9
7	57	145	22	36	10.7	44	77	20	45	4.9	55	56	10	49	4.2
8	55	98	19	47	7.3	46	51	24	45	3.9	54	43	17	53	3.2
9	83	153	27	63	11.5	72	89	29	63	6.2	73	43	31	68	3.5
10	79	122	18	46	8.7	125	127	20	72	10.3	84	103	17	47	8.4
11	135	277	46	53	20.8	77	104	41	38	8.0	99	99	30	57	9.0
12	148	571	149	167	33.8	81	149	37	79	9.3	63	126	27	59	8.6
13	117	173	24	72	11.9	42	76	20	59	3.7	58	54	22	55	3.6
14	206	326	51	125	23.4	120	190	46	87	11.6	164	163	45	114	12.5
15	88	291	53	117	15.6	79	179	27	78	10.3	59	130	15	63	7.9

CUMULATIVE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	72	90	19	47	6.4	50	70	26	40	4.5	44	56	24	41	3.6
2	73	246	31	73	15.6	50	95	33	50	5.7	51	81	31	57	4.9
3	135	279	38	78	19.8	61	91	31	58	5.5	63	87	28	62	5.4
4	130	248	39	84	17.7	62	87	32	59	5.2	66	80	28	67	4.9
5	120	232	35	80	16.5	58	90	29	58	5.3	62	82	26	64	5.0
6	112	217	33	80	15.4	57	93	29	60	5.5	59	83	24	63	5.1
7	108	208	32	82	14.7	56	100	28	61	5.9	60	89	23	65	5.4
8	104	200	31	84	14.1	56	108	28	63	6.4	61	96	23	68	5.9
9	106	196	32	85	14.0	62	106	28	66	6.3	67	92	25	73	5.7
10	106	212	32	83	15.0	72	116	32	67	7.4	70	101	30	70	6.7
11	112	221	36	80	15.8	76	120	34	66	7.9	77	104	33	71	7.3
12	115	266	62	93	17.8	76	122	43	67	8.0	76	105	46	70	7.4
13	115	271	65	93	18.1	76	151	47	69	9.5	77	129	52	71	8.8
14	125	277	66	98	18.6	84	154	53	74	9.7	87	131	56	76	9.0
15	126	292	65	101	19.3	88	165	52	77	10.3	90	141	54	77	9.7

TABLE B-1 (Continued)

HEIGHT = 285. METERS   OKLAHOMA NORD2 RUN 3   VAD 6/ 8/76   NORMAN   HD175.   START TIME 11:30: 0   END TIME 11:45: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE MEANS

	PEAKS					I	FOURIER COEFFICIENTS							I	SINE WAVE FIT					
MIN	U	V	W	SPEED	TH		U	V	W	SPEED	TH	2D	3D		U	V	W	SPEED	TH	SP
1	-540	120	4	560	188.9		-591	62	10	600	181.9	10	21		-536	96	11	547	186.1	50
2	-670	-18	26	703	173.7		-700	62	4	713	180.7	8	19		-682	65	0	693	181.0	73
3	-692	-108	6	707	166.9		-688	-41	-4	701	172.3	13	20		-655	-39	-5	666	172.3	69
4	-583	-70	-17	596	168.0		-607	81	-5	616	183.2	10	21		-558	55	-11	564	181.1	53
5	-542	-107	-30	615	165.9		-618	-141	-17	637	162.5	13	21		-560	-126	-28	575	162.7	47
6	-705	-72	-62	711	169.5		-748	-32	-37	751	172.9	11	18		-673	-17	-49	677	173.8	47
7	-491	-361	-103	671	137.8		-693	-209	-102	732	158.3	14	18		-659	-170	-112	683	161.1	49
8	-452	-355	-77	663	136.3		-618	-227	-87	665	155.2	19	30		-611	-132	-89	630	163.4	63
9	-522	-178	-77	587	156.8		-639	-112	-63	659	165.4	16	23		-559	-77	-73	568	167.5	36
10	-674	-52	0	711	170.4		-754	-83	-23	765	169.2	16	24		-685	-12	-17	690	174.7	51
11	-526	-244	-83	649	148.2		-685	-122	-82	705	164.9	12	18		-622	-75	-89	630	168.4	42
12	-618	-103	-56	649	166.3		-695	-48	-64	700	171.3	11	21		-634	-30	-61	637	172.8	41
13	-671	-251	-67	728	155.0		-721	0	-77	730	176.0	7	19		-688	-14	-74	694	174.7	51
14	-640	59	-72	669	179.7		-684	47	-75	691	179.5	10	24		-680	69	-63	687	181.4	53
15	-402	-307	-106	542	138.6		-610	-27	-90	621	172.8	14	21		-592	-59	-84	598	169.7	45

CUMULATIVE MEANS

	PEAKS					I	FOURIER COEFFICIENTS							I	SINE WAVE FIT					
MIN	U	V	W	SPEED	TH		U	V	W	SPEED	TH	2D	3D		U	V	W	SPEED	TH	SP
1	-540	120	4	560	188.9		-591	62	10	600	181.9	10	21		-536	96	11	547	186.1	50
2	-605	50	15	632	181.3		-646	62	7	657	181.3	9	20		-609	80	5	620	183.6	62
3	-636	-5	11	658	176.2		-661	26	3	672	178.1	11	20		-625	38	1	636	179.6	64
4	-623	-21	4	643	174.2		-647	39	1	659	179.4	10	20		-609	42	-1	619	180.0	61
5	-607	-38	-2	637	172.6		-642	3	-2	654	176.0	11	20		-599	9	-6	610	176.6	59
6	-623	-43	-12	649	172.1		-659	-1	-8	670	175.5	11	20		-611	5	-13	621	176.1	57
7	-603	-91	-26	653	166.9		-664	-33	-22	680	172.9	11	20		-619	-21	-28	630	173.9	56
8	-584	-124	-32	654	163.1		-659	-57	-30	678	170.8	12	21		-618	-35	-36	630	172.6	56
9	-578	-130	-37	647	162.5		-656	-63	-34	676	170.2	13	21		-611	-39	-40	624	172.0	54
10	-587	-122	-33	653	163.2		-666	-65	-33	685	170.1	13	21		-618	-36	-38	630	172.3	54
11	-581	-134	-38	653	161.8		-668	-70	-37	687	169.6	13	21		-619	-40	-42	630	171.9	53
12	-584	-131	-40	652	162.2		-670	-68	-39	688	169.7	13	21		-620	-39	-44	631	172.0	52
13	-591	-140	-42	658	161.6		-674	-63	-42	691	170.2	12	21		-625	-37	-46	635	172.2	52
14	-594	-126	-44	659	162.9		-675	-55	-45	691	170.8	12	21		-629	-30	-47	639	172.8	52
15	-582	-138	-48	651	161.3		-670	-53	-48	686	171.0	12	21		-627	-32	-50	636	172.6	51

TABLE B-1 (Continued)

OKLAHOMA NORGZ RUN 3 VAD 6/ 8/76 NORMAN HU175.

HEIGHT = 285. METERS

START TIME 11:30: 0
END TIME 11:45: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	117	68	18	105	9.4	87	72	12	81	7.6	98	32	10	94	4.7
2	56	212	30	17	18.3	25	118	16	18	9.7	33	103	14	27	8.7
3	40	93	28	48	7.3	37	128	21	38	10.5	26	111	20	31	9.4
4	78	95	13	70	9.9	41	59	17	37	5.7	45	47	9	45	4.8
5	137	247	28	49	29.0	49	49	21	45	4.6	38	30	16	38	3.0
6	36	45	19	35	3.7	40	45	21	37	3.7	44	61	19	42	5.3
7	215	200	25	54	25.7	88	85	25	65	8.3	66	53	18	72	3.8
8	189	303	68	97	29.3	51	85	19	37	7.9	61	74	19	63	6.8
9	87	191	38	30	20.5	38	112	27	30	10.0	28	49	32	26	4.9
10	108	211	33	78	19.1	91	100	26	91	7.6	43	80	20	44	6.6
11	218	215	29	63	28.2	70	104	26	57	9.2	59	53	20	56	5.1
12	91	165	38	82	15.5	60	58	22	57	5.0	70	44	24	71	3.8
13	51	124	21	39	10.1	59	107	20	57	8.6	54	87	21	55	7.2
14	48	194	33	52	16.9	27	81	20	23	6.8	46	52	16	43	4.6
15	114	169	8	34	21.9	35	113	17	30	10.7	29	58	14	28	5.6

CUMULATIVE STANDARD DEVIATIONS

	PEAKS					FOURIER COEFFICIENTS					SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	117	68	18	105	9.4	87	72	12	81	7.6	98	32	10	94	4.7
2	112	170	27	104	16.2	83	96	14	81	8.5	103	76	13	101	7.3
3	101	165	27	95	15.3	73	118	18	72	10.1	87	106	16	85	9.7
4	98	153	28	93	14.5	70	109	18	69	9.4	83	94	16	83	8.7
5	110	176	31	86	18.3	67	123	20	65	11.0	79	109	19	78	10.5
6	108	162	37	84	16.8	75	114	24	71	10.2	79	103	25	77	9.8
7	137	203	48	81	22.0	77	133	41	74	11.7	79	116	43	79	10.6
8	151	232	53	82	25.0	76	143	45	70	12.7	77	117	45	77	10.8
9	147	228	54	81	24.5	73	140	44	67	12.5	75	112	45	76	10.4
10	146	227	53	83	24.1	80	137	43	74	12.1	76	109	44	76	10.1
11	154	228	53	81	24.8	79	135	44	73	11.9	74	106	45	74	9.8
12	150	223	52	81	24.2	78	130	43	72	11.5	74	102	44	74	9.5
13	147	219	51	81	23.5	78	130	43	71	11.4	74	101	43	74	9.3
14	143	223	51	79	23.5	75	130	43	69	11.4	74	102	42	73	9.4
15	149	224	51	82	24.1	75	129	43	69	11.3	72	100	42	72	9.2

TABLE B-1 (Continued)

HEIGHT = 285. METERS OKLAHOMA NOR02 RUN 3 VAD 6/ 8/76 NORMAN HD175. START TIME 11:45: 0 END TIME 12: 0: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-521	-45	-83	575	169.2	-576	-121	-38	601	163.1	20	22	-519	-56	-41	531	169.4	59
2	-660	-147	-68	694	162.5	-711	-192	-49	742	160.0	14	20	-651	-122	-62	664	164.7	45
3	-514	-277	-88	594	147.2	-567	-312	-73	652	146.5	17	24	-595	-178	-61	626	158.7	45
4	-452	-211	-101	541	150.3	-592	-116	-85	612	164.2	16	15	-526	-90	-87	536	165.7	34
5	-574	-161	-81	630	158.5	-609	-240	-68	659	153.7	9	16	-582	-158	-69	606	160.0	39
6	-638	-144	-86	663	162.9	-649	-174	-44	676	160.5	11	15	-609	-153	-66	631	161.4	47
7	-532	-361	-56	768	139.6	-665	-383	-39	790	145.3	9	16	-646	-340	-58	749	147.6	69
8	-667	-139	-18	695	164.2	-686	-222	-17	725	157.5	8	15	-665	-164	-21	688	161.6	52
9	-781	-118	-4	797	166.8	-799	-166	-2	822	163.6	13	17	-753	-137	-11	770	165.0	51
10	-743	-213	-79	787	159.9	-787	-134	-67	811	166.5	13	17	-740	-91	-80	754	168.9	51
11	-636	-77	-92	689	166.2	-697	-61	-99	714	170.1	11	16	-648	-37	-103	660	171.6	39
12	-346	-315	-32	612	131.0	-589	-207	-54	632	155.6	15	21	-540	-162	-54	571	158.3	56
13	-648	-196	10	688	158.6	-727	-189	-3	755	161.0	10	19	-634	-172	-5	660	160.5	46
14	-647	-118	-12	673	164.4	-663	-179	-44	699	160.7	20	16	-606	-146	-44	628	162.2	51
15	-579	-63	-84	599	168.6	-660	-142	-78	681	163.1	13	13	-579	-55	-80	585	169.9	37

CUMULATIVE MEANS

	PEAKS					FOURIER COEFFICIENTS							SINE WAVE FIT					
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	2D	3D	U	V	W	SPEED	TH	SP
1	-521	-45	-83	575	169.2	-576	-121	-38	601	163.1	20	22	-519	-56	-41	531	169.4	59
2	-587	-94	-76	632	166.0	-641	-155	-43	669	161.6	17	21	-582	-87	-51	595	167.1	52
3	-564	-153	-80	620	159.9	-617	-206	-53	663	156.7	17	22	-586	-117	-54	605	164.4	50
4	-536	-167	-85	600	157.6	-611	-184	-61	651	158.5	17	20	-571	-110	-62	588	164.7	46
5	-544	-166	-84	607	157.8	-611	-196	-62	652	157.5	15	20	-574	-120	-64	592	163.7	44
6	-559	-162	-84	616	158.6	-617	-192	-59	656	158.0	14	19	-579	-126	-64	598	163.4	45
7	-555	-190	-80	637	156.0	-623	-219	-56	675	156.2	14	18	-589	-155	-63	619	161.2	48
8	-569	-184	-73	644	157.0	-631	-219	-52	681	156.4	13	18	-598	-156	-58	628	161.2	49
9	-594	-176	-65	662	158.1	-651	-213	-46	698	157.2	13	18	-616	-154	-52	644	161.7	49
10	-608	-180	-66	674	158.3	-664	-205	-48	709	158.1	13	18	-628	-148	-55	655	162.4	49
11	-611	-171	-68	675	159.0	-667	-192	-52	709	159.2	13	18	-630	-138	-59	656	163.2	48
12	-589	-182	-65	670	156.7	-661	-194	-53	703	158.9	13	18	-623	-140	-59	649	162.8	49
13	-594	-183	-60	672	156.9	-666	-193	-49	707	159.1	13	18	-624	-143	-55	649	162.6	49
14	-598	-178	-56	672	157.4	-666	-192	-48	706	159.2	13	18	-622	-143	-54	648	162.6	49
15	-596	-171	-58	667	158.2	-665	-189	-50	705	159.4	13	17	-619	-137	-56	644	163.1	48

TABLE B-1 (Concluded)

OKLAHOMA NORG2 RUN 3 VAD 6/ 8/76 NORMAN HD175.

HEIGHT = 285. METERS

START TIME 11:45: 0
END TIME 12: 0: 0

U, V, W ARE ORTHOGONAL WIND COMPONENTS IN CM/SEC
SPEED IS HORIZONTAL SPEED IN CM/SEC
TH IS WIND AZIMUTH IN DEGREES

ONE MINUTE STANDARD DEVIATIONS

	PEAKS				I,	FOURIER COEFFICIENTS				I	SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	121	228	38	75	26.1	96	115	27	85	12.1	44	99	24	43	10.8
2	77	146	29	44	13.4	73	65	33	54	6.4	56	37	27	52	3.6
3	70	94	27	47	10.5	70	49	24	60	5.5	68	62	24	64	6.0
4	124	180	14	28	23.2	36	96	14	26	9.3	21	42	9	24	4.3
5	125	175	27	58	19.5	67	49	18	51	5.7	56	37	17	45	4.9
6	28	108	26	38	9.0	26	73	14	32	5.9	19	60	13	27	5.0
7	344	276	41	50	35.1	111	157	28	32	13.9	93	144	29	37	13.0
8	47	144	28	57	11.8	73	61	15	66	5.6	68	42	12	68	3.6
9	82	98	17	80	7.2	96	78	20	92	5.9	73	67	13	68	5.5
10	54	149	30	68	10.4	94	141	18	97	10.3	52	113	22	59	8.6
11	190	188	25	47	24.9	70	136	22	55	11.8	59	108	21	33	10.9
12	308	275	29	41	41.8	75	78	23	52	8.6	68	73	33	51	9.7
13	65	120	27	58	10.4	50	71	34	57	4.9	50	56	21	56	4.9
14	126	128	47	109	13.0	102	126	24	97	11.2	88	71	23	90	6.7
15	62	130	23	32	14.0	53	73	21	45	6.6	31	57	12	25	5.9

CUMULATIVE STANDARD DEVIATIONS

	PEAKS				I,	FOURIER COEFFICIENTS				I	SINE WAVE FIT				
MIN	U	V	W	SPEED	TH	U	V	W	SPEED	TH	U	V	W	SPEED	TH
1	121	228	38	75	26.1	96	115	27	85	12.1	44	99	24	43	10.8
2	123	196	34	86	20.9	108	99	30	100	9.7	83	81	27	82	8.3
3	113	189	32	77	20.1	103	113	31	89	11.1	78	86	26	77	8.6
4	124	187	30	76	21.1	91	115	31	81	11.1	73	78	27	74	7.7
5	124	183	29	73	20.6	86	107	29	75	10.4	69	74	25	69	7.4
6	119	173	29	71	19.2	81	102	28	71	9.8	65	72	24	66	7.1
7	166	201	32	87	22.8	86	129	28	81	11.3	73	113	29	81	9.8
8	161	195	38	86	21.9	87	122	30	81	10.7	76	107	27	83	9.2
9	168	187	42	98	21.0	103	119	33	94	10.5	91	103	30	93	8.9
10	166	183	41	102	20.1	110	123	32	99	10.8	95	105	30	96	9.1
11	168	185	41	99	20.6	107	130	35	96	11.4	92	110	33	92	9.6
12	196	197	41	97	24.1	107	127	34	96	11.2	94	107	33	92	9.6
13	190	192	45	94	23.3	105	123	36	94	10.9	91	104	35	90	9.3
14	186	188	47	95	22.8	104	123	35	94	10.9	91	102	34	90	9.1
15	180	187	46	94	22.5	102	121	35	92	10.7	89	102	34	88	9.1

Appendix C

COMPARISON OF LASER-MEASURED WIND AND TOWER-MEASURED WIND FOR 1-, 3-, 6-, 9-, 12- AND 15- MINUTE AVERAGING PERIODS

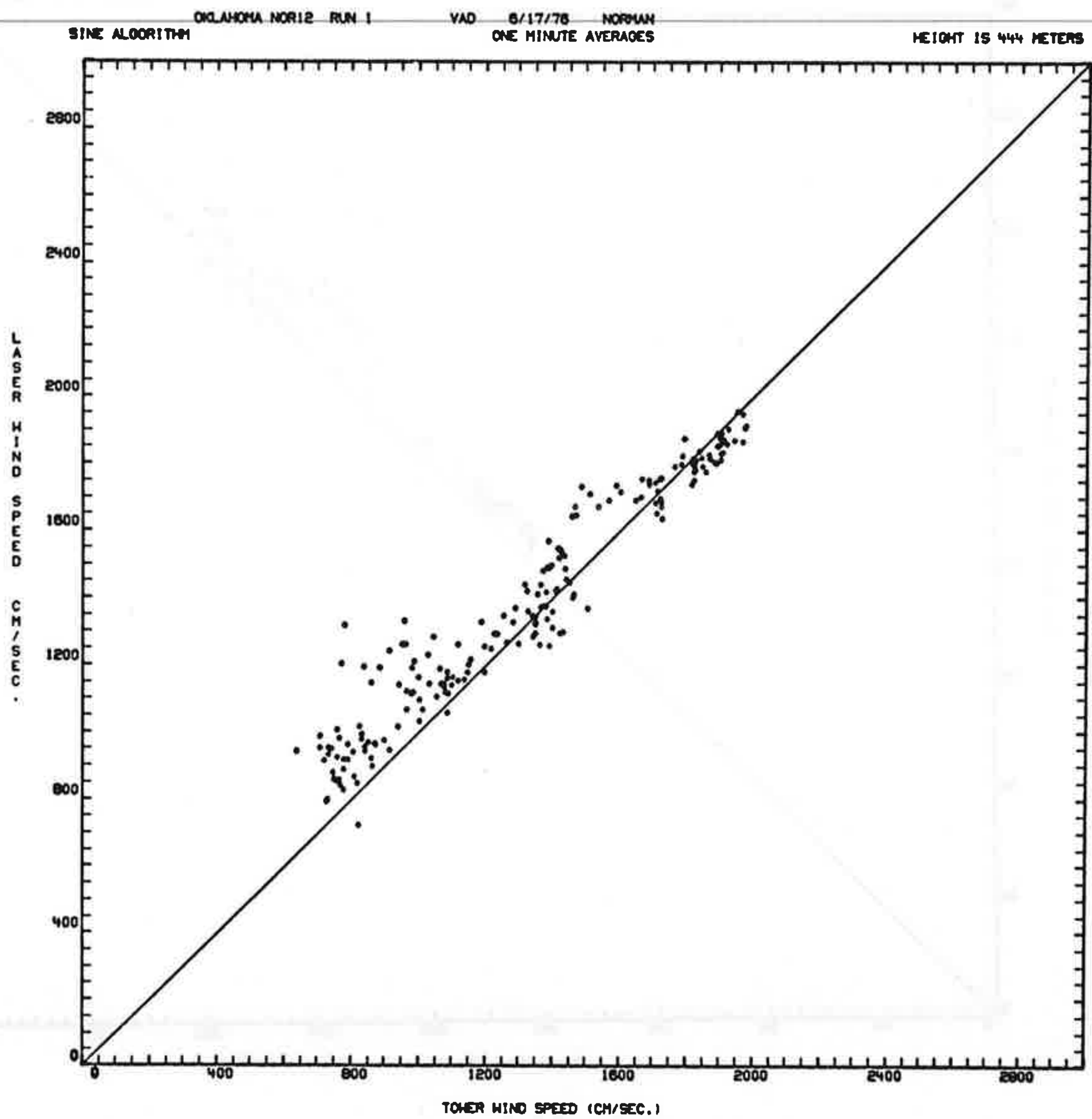


FIGURE C-1. COMPARISON OF LASER-MEASURED WINDS WITH ANEMOMETER-MEASURED WINDS.

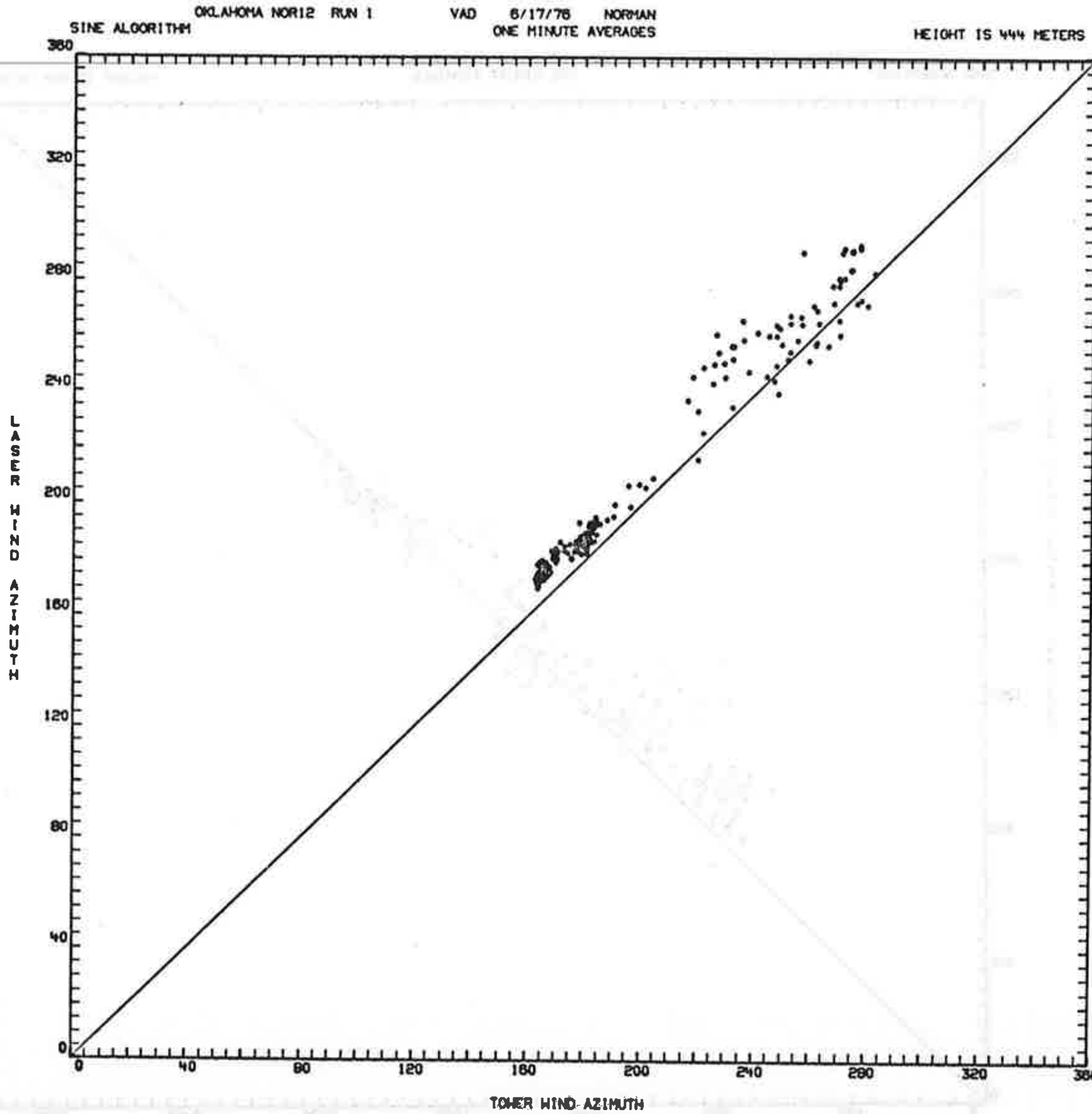


FIGURE C-1 (Continued)

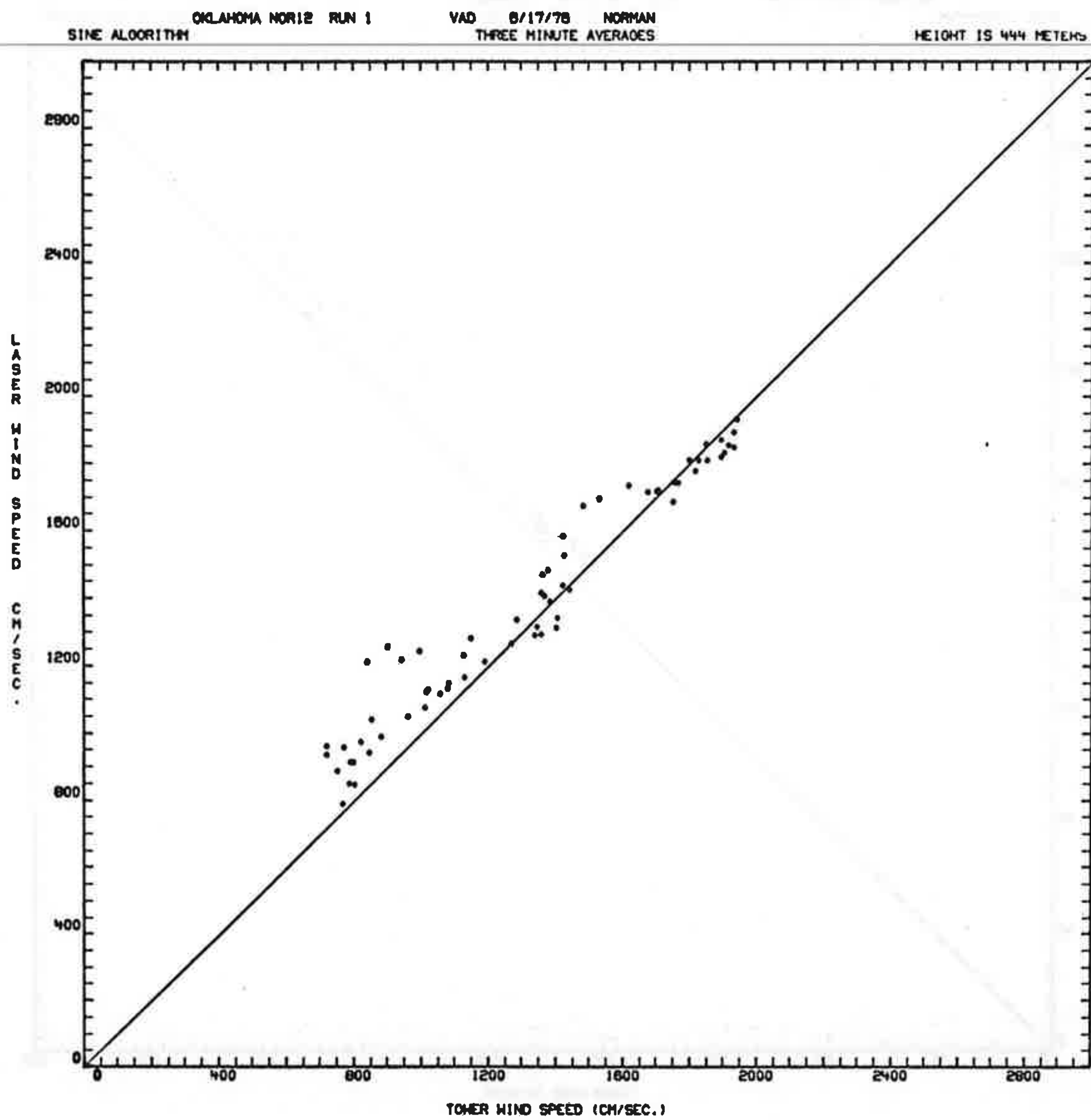


FIGURE C-1 (Continued)

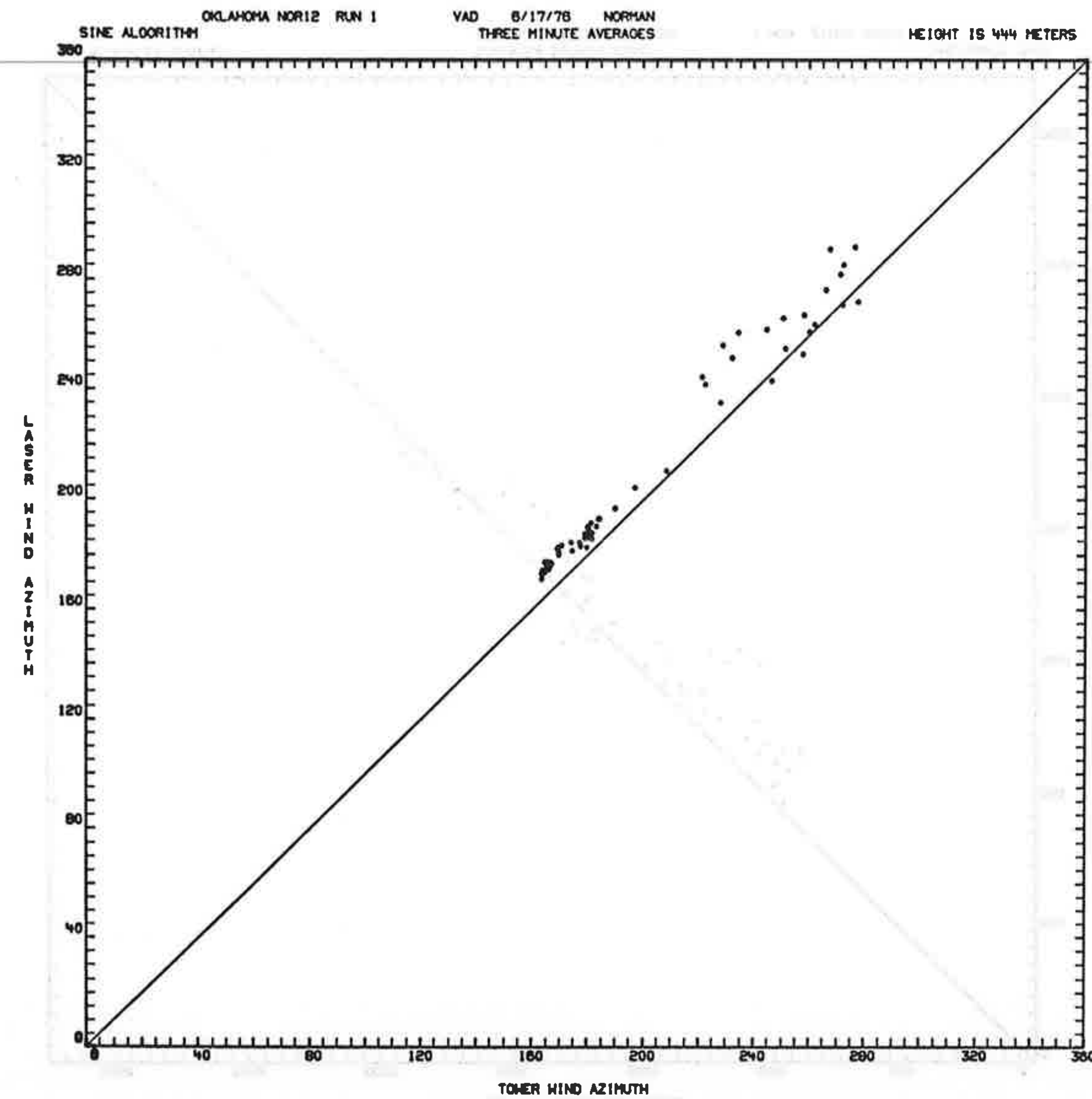


FIGURE C-1 (Continued)

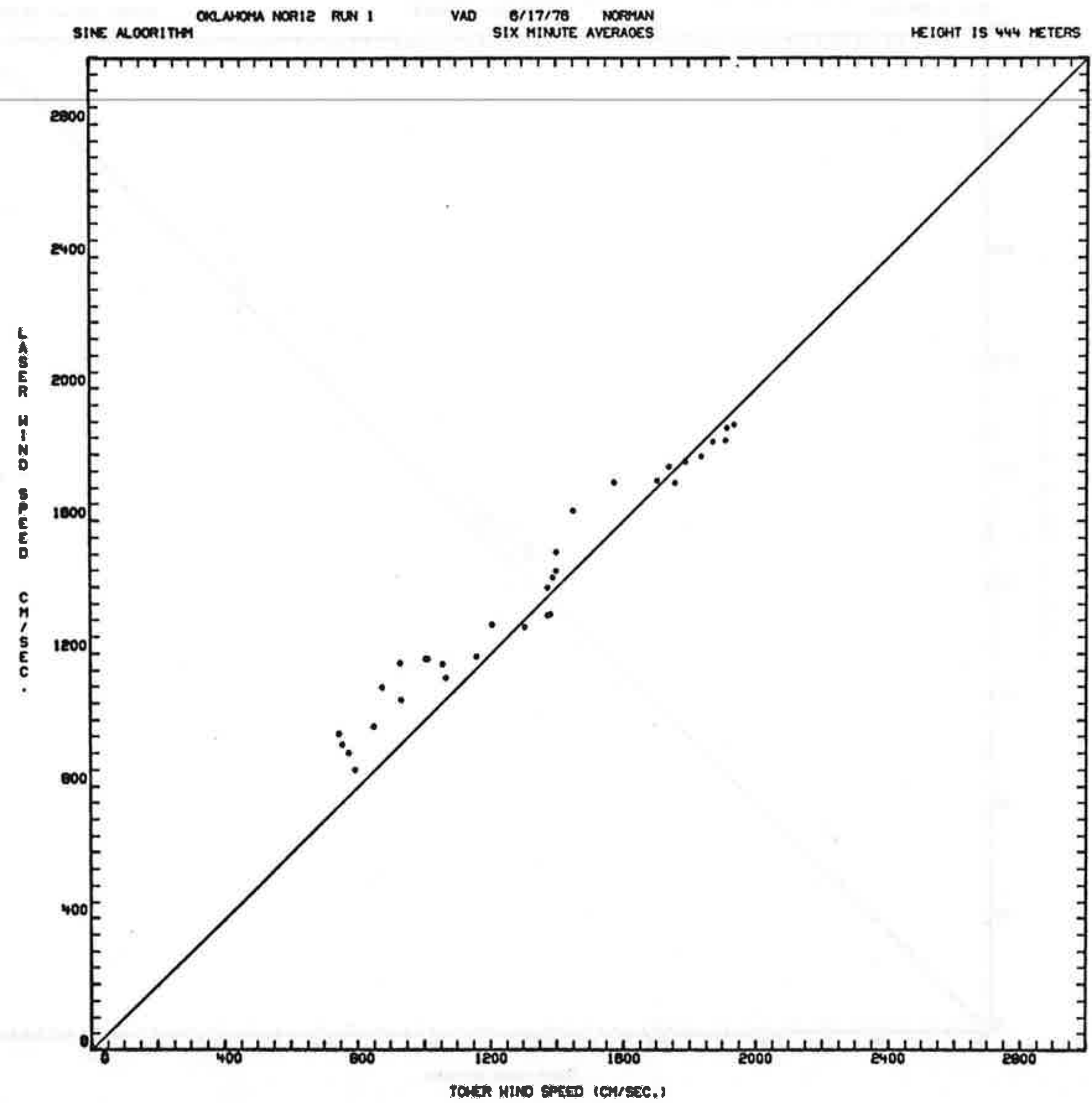


FIGURE C-1 (Continued)

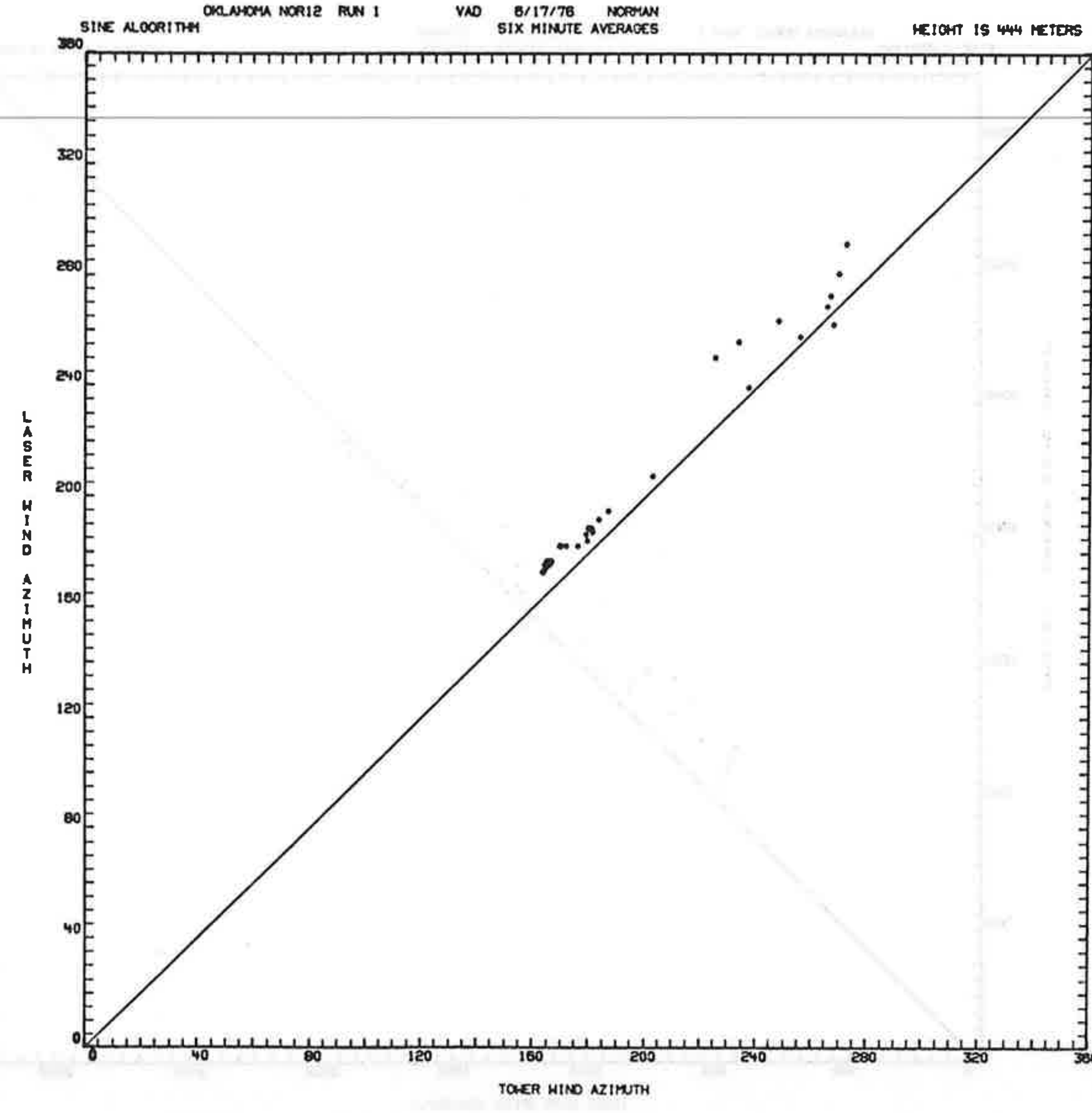


FIGURE C-1 (Continued)

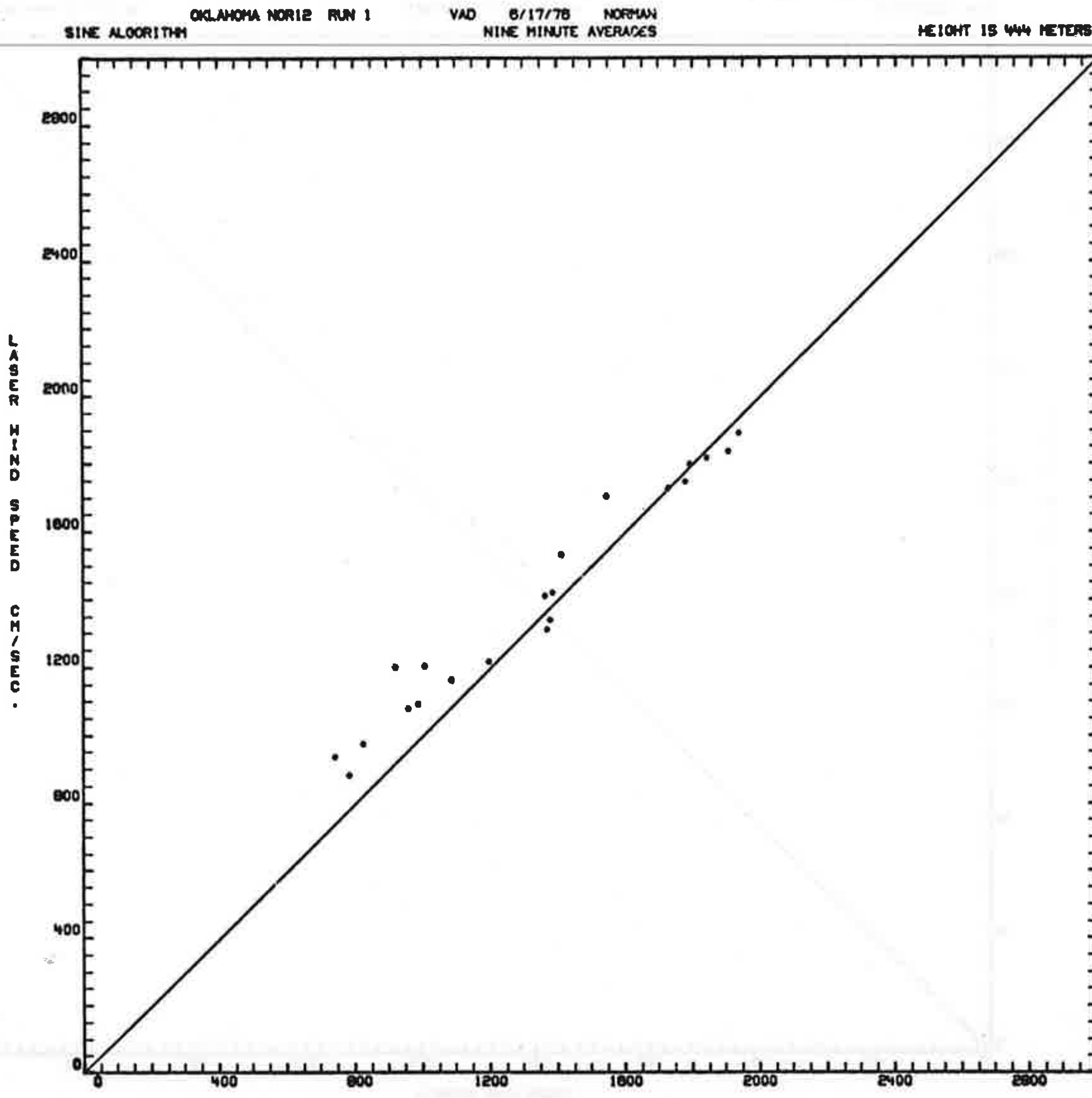


FIGURE C-1 (Continued)

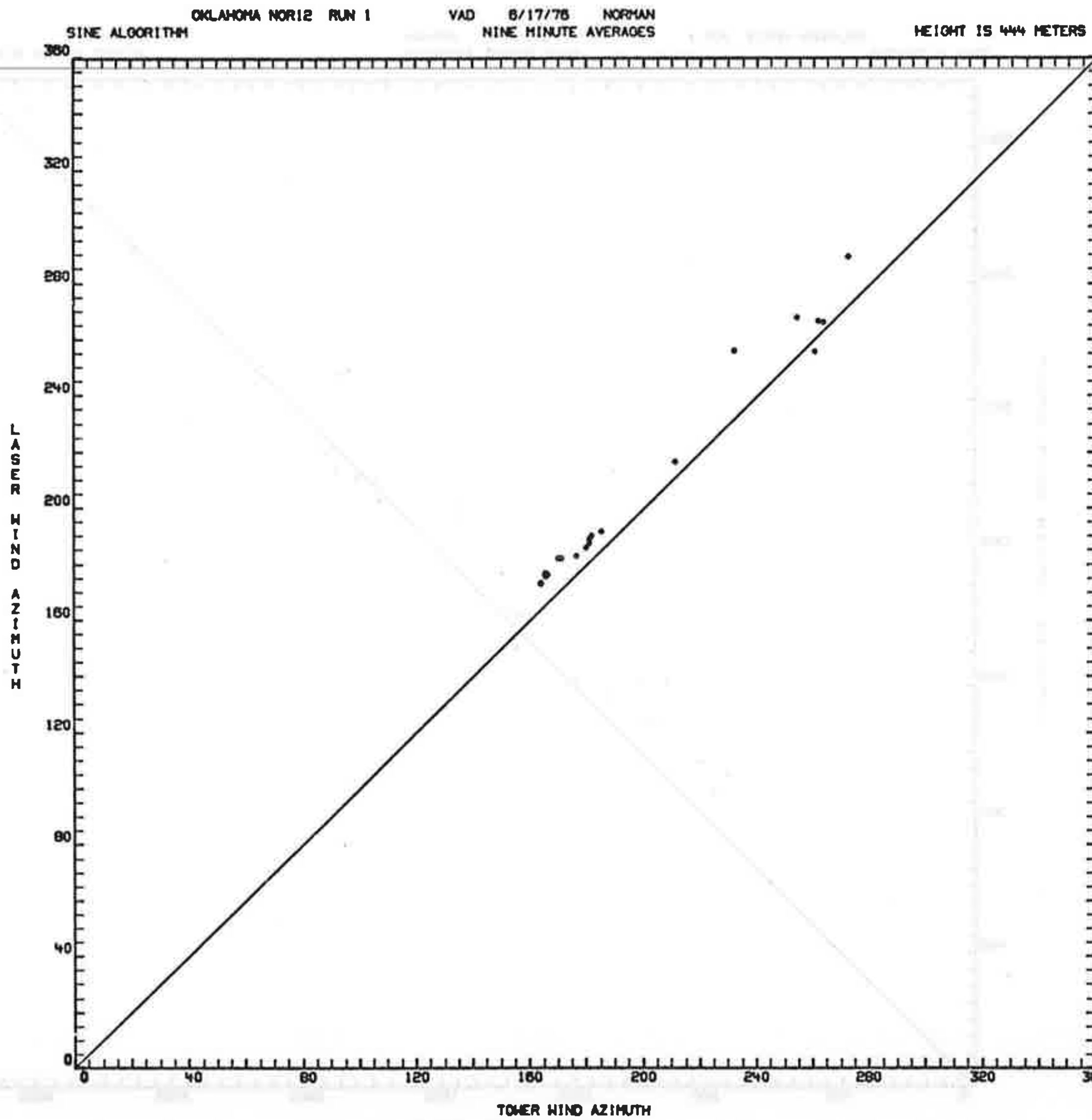


FIGURE C-1 (Continued)

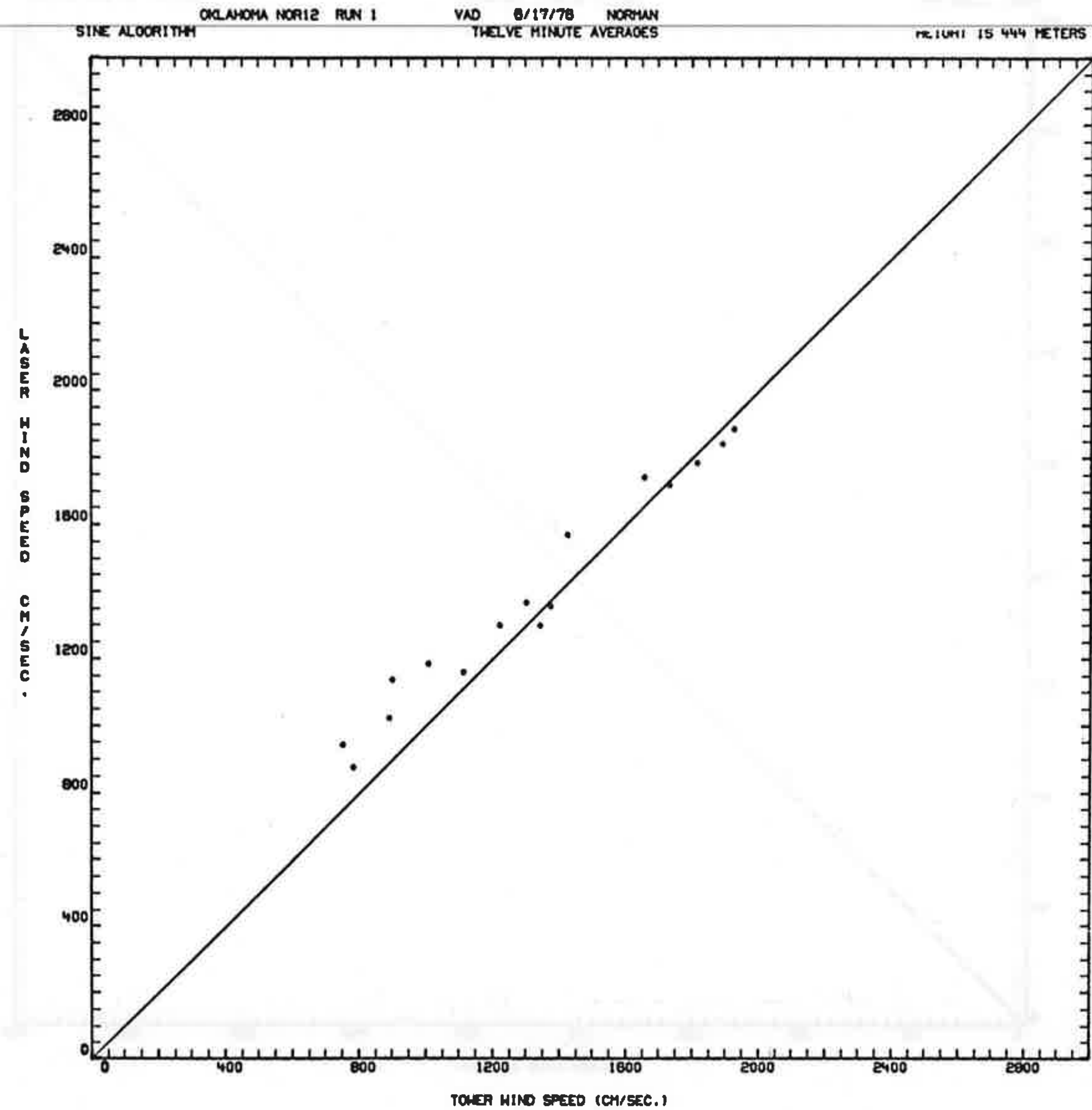


FIGURE C-1 (Continued)

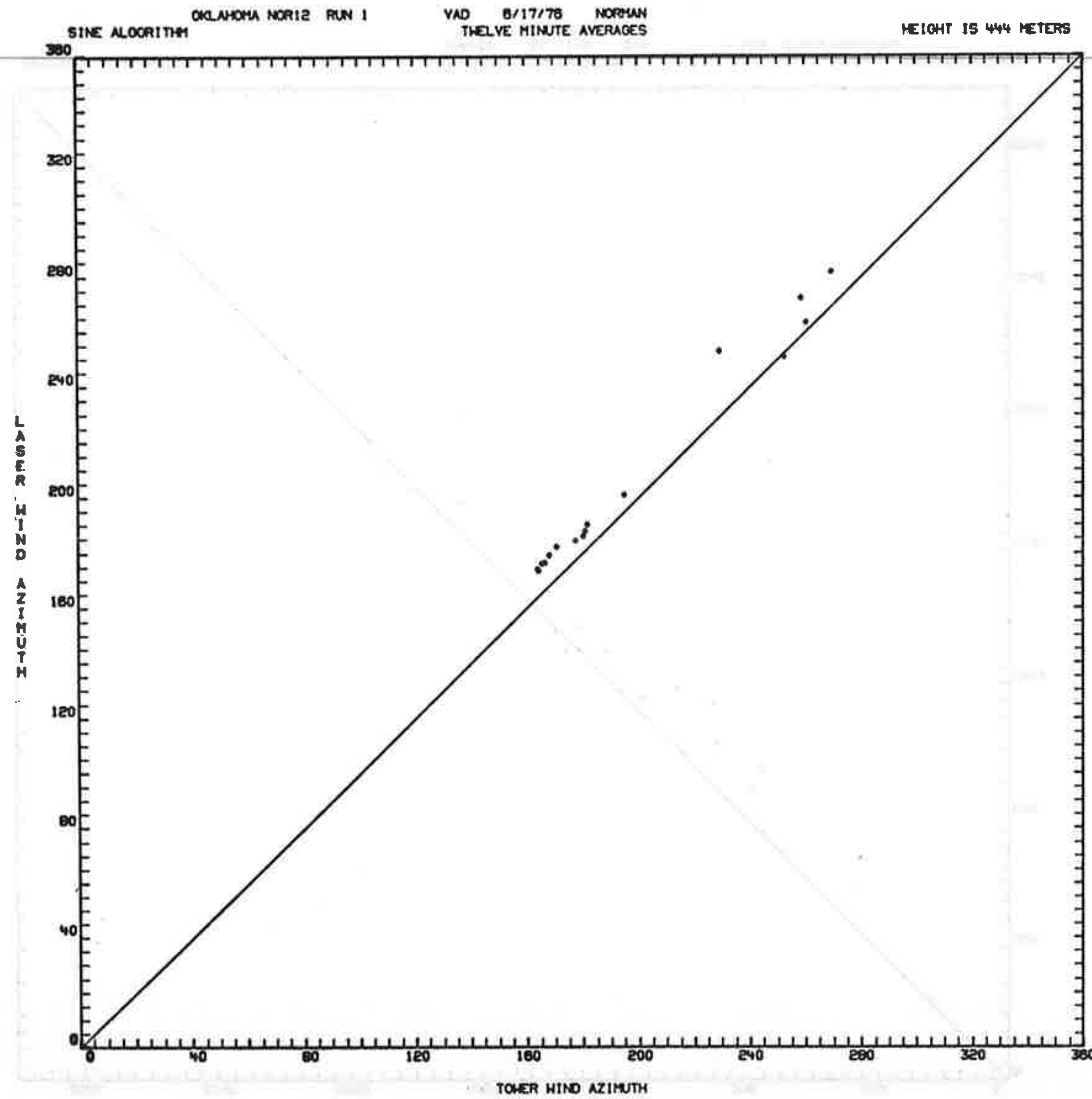


FIGURE C-1 (Continued)

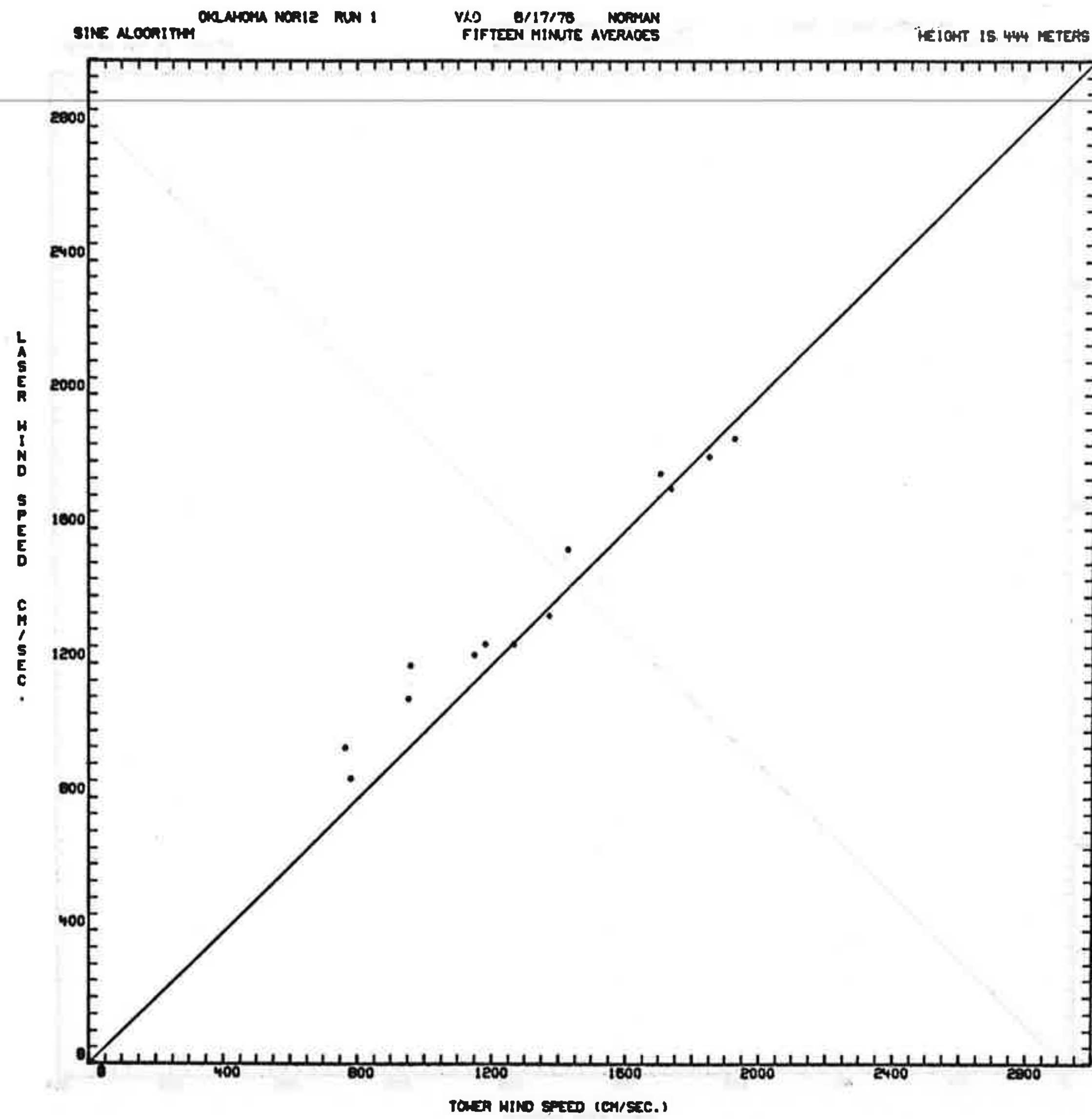


FIGURE C-1 (Continued)

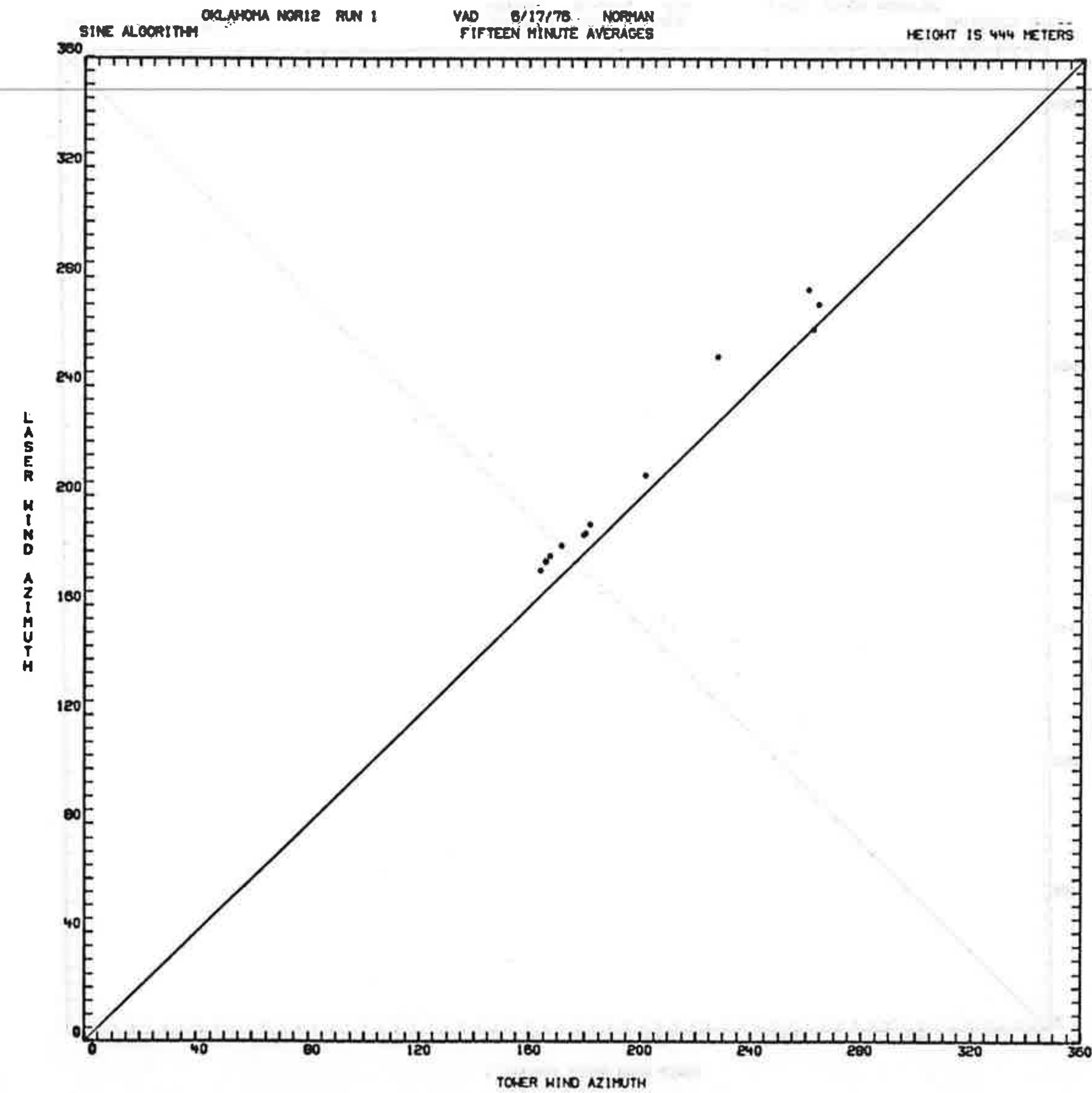


FIGURE C-1 (Continued)

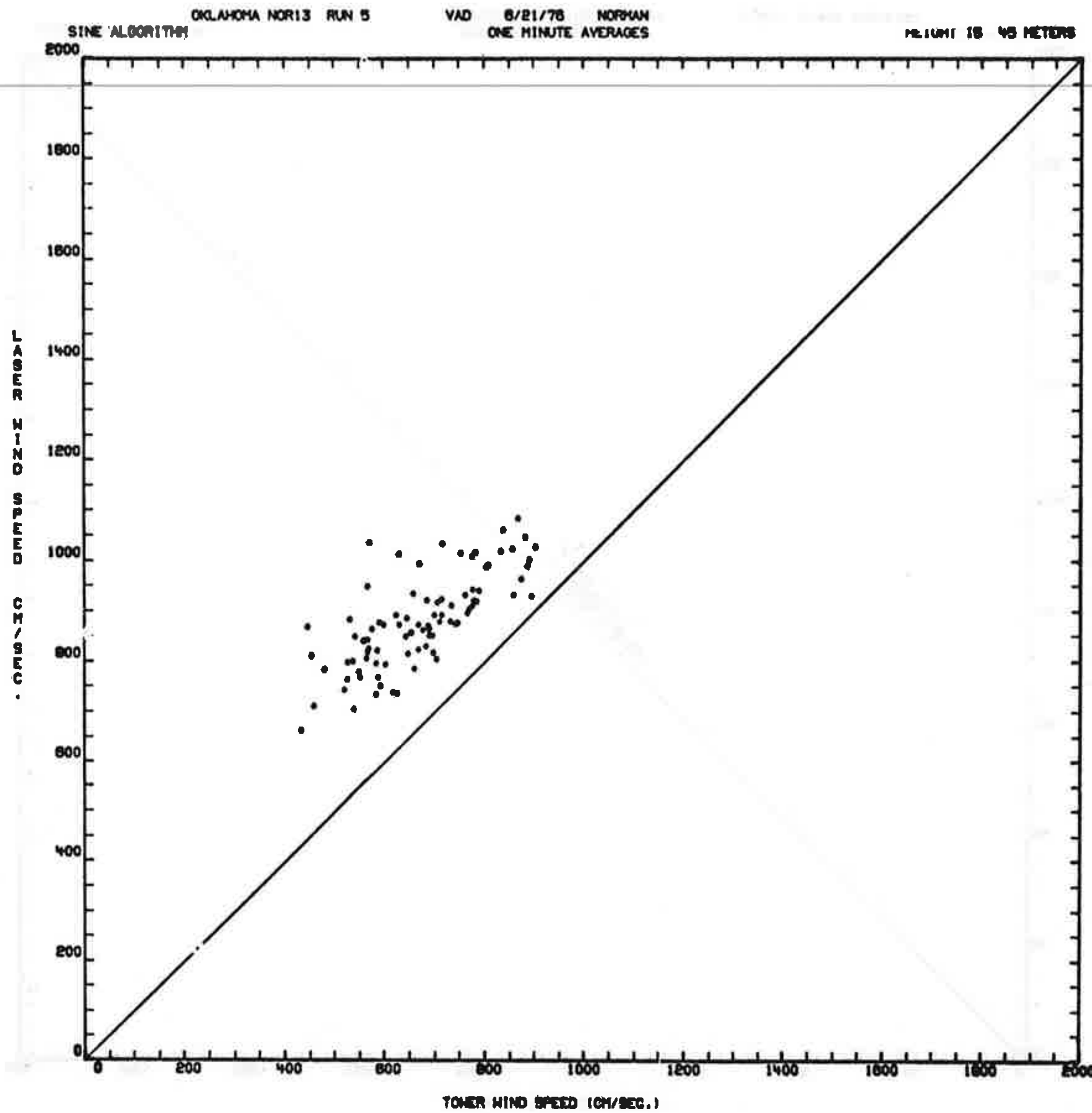


FIGURE C-1 (Continued)

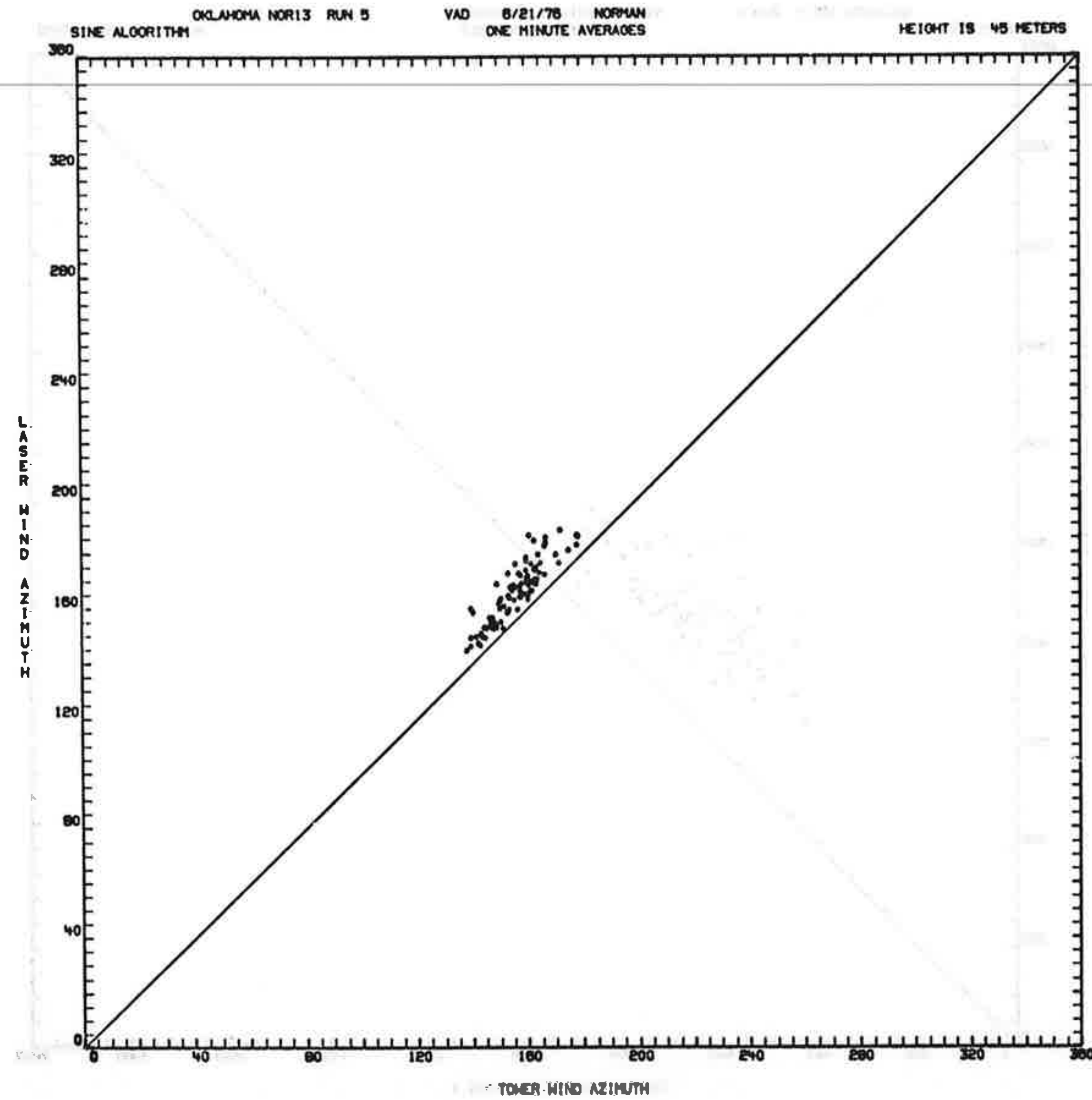


FIGURE C-1 (Continued)

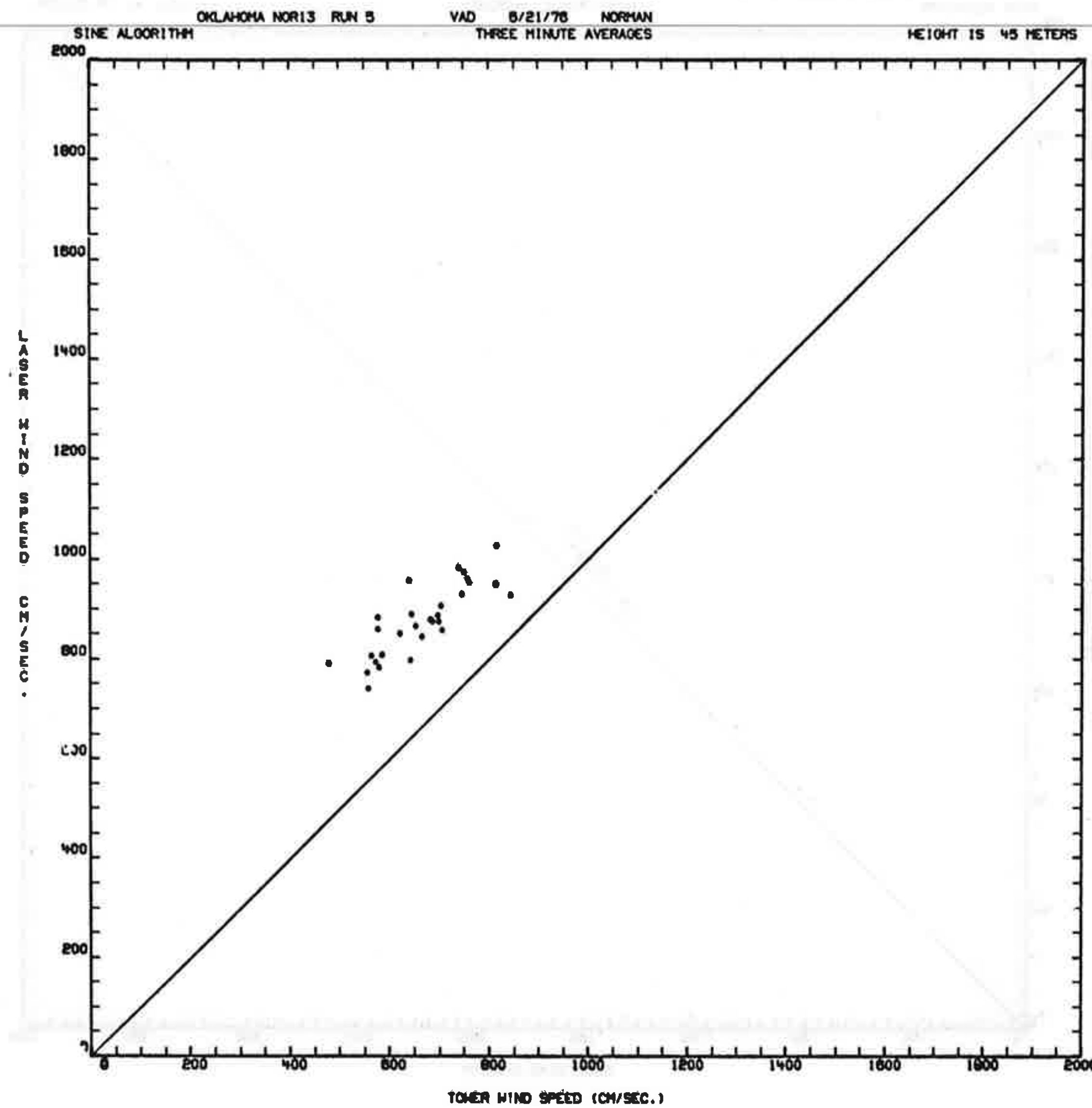


FIGURE C-1 (Continued)

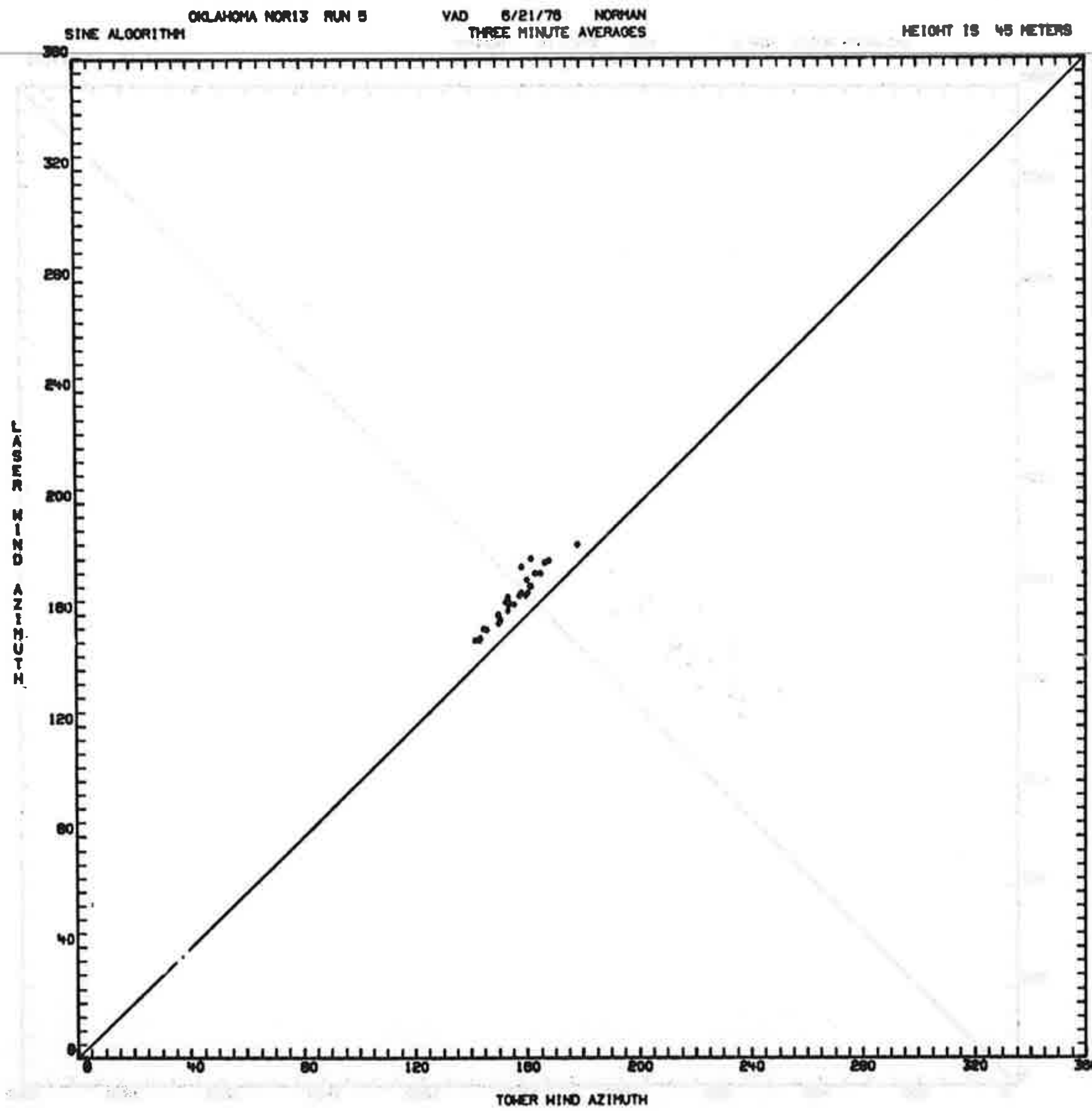


FIGURE C-1 (Continued)

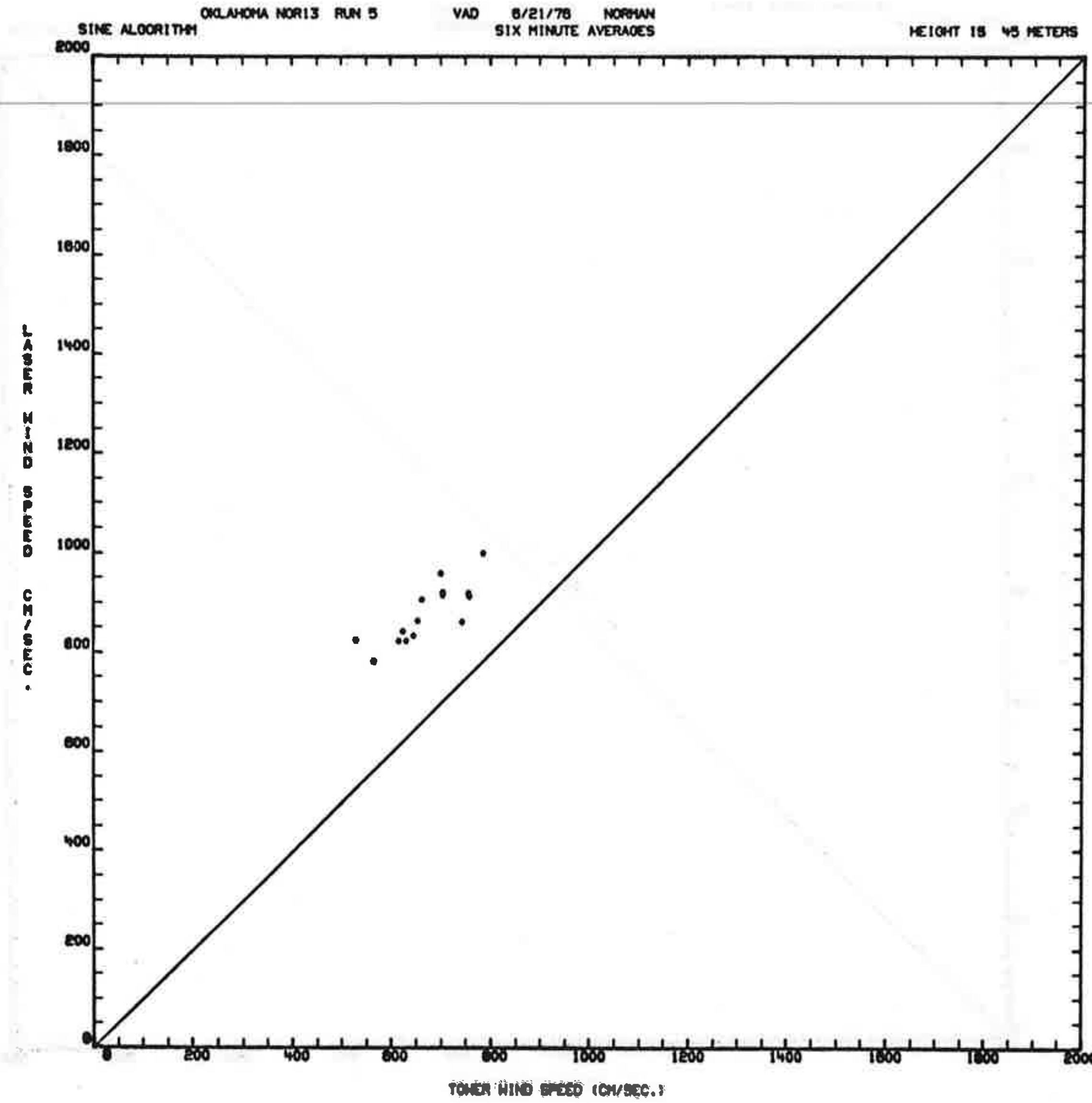


FIGURE C-1 (Continued)

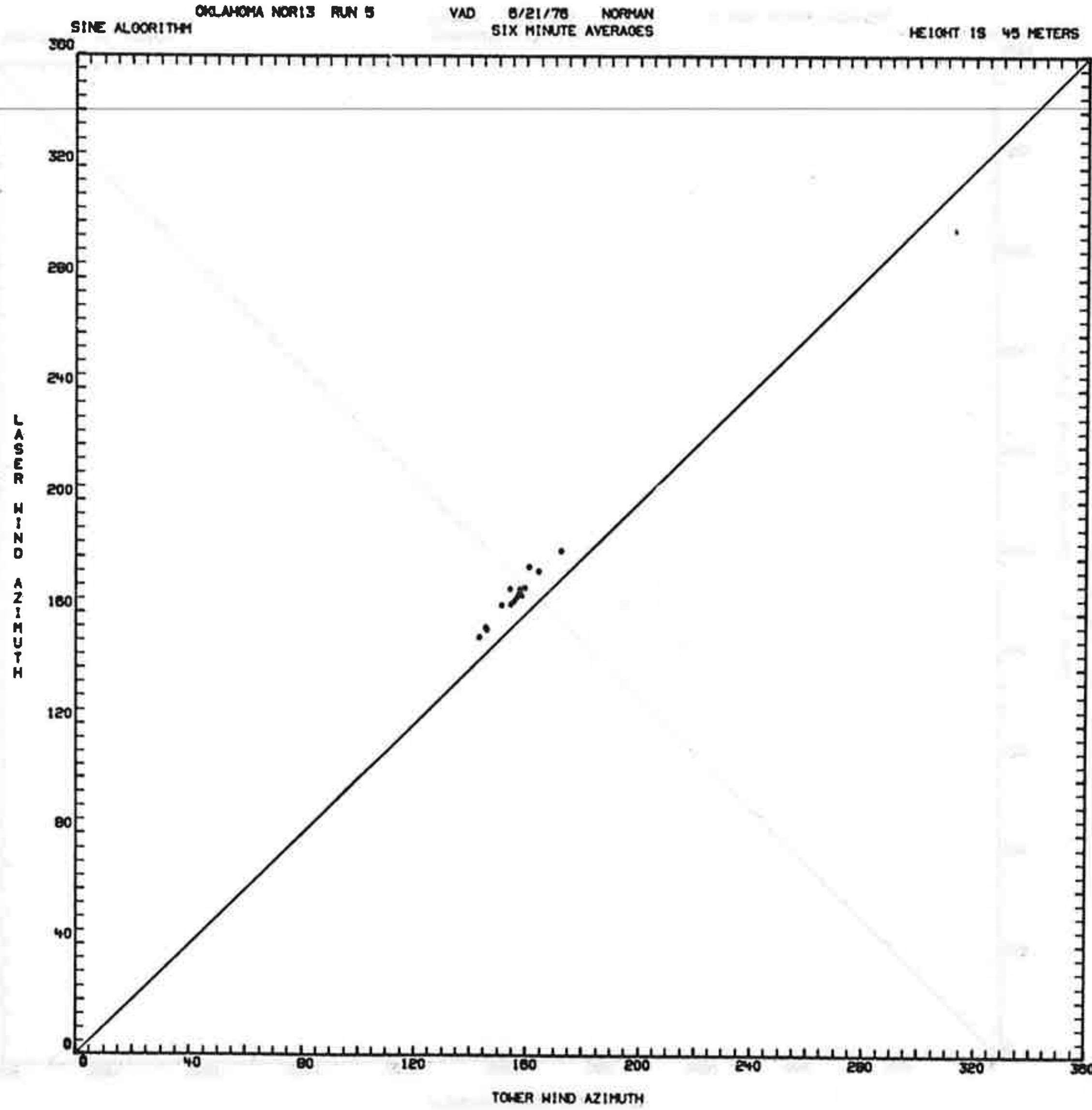


FIGURE C-1 (Continued)

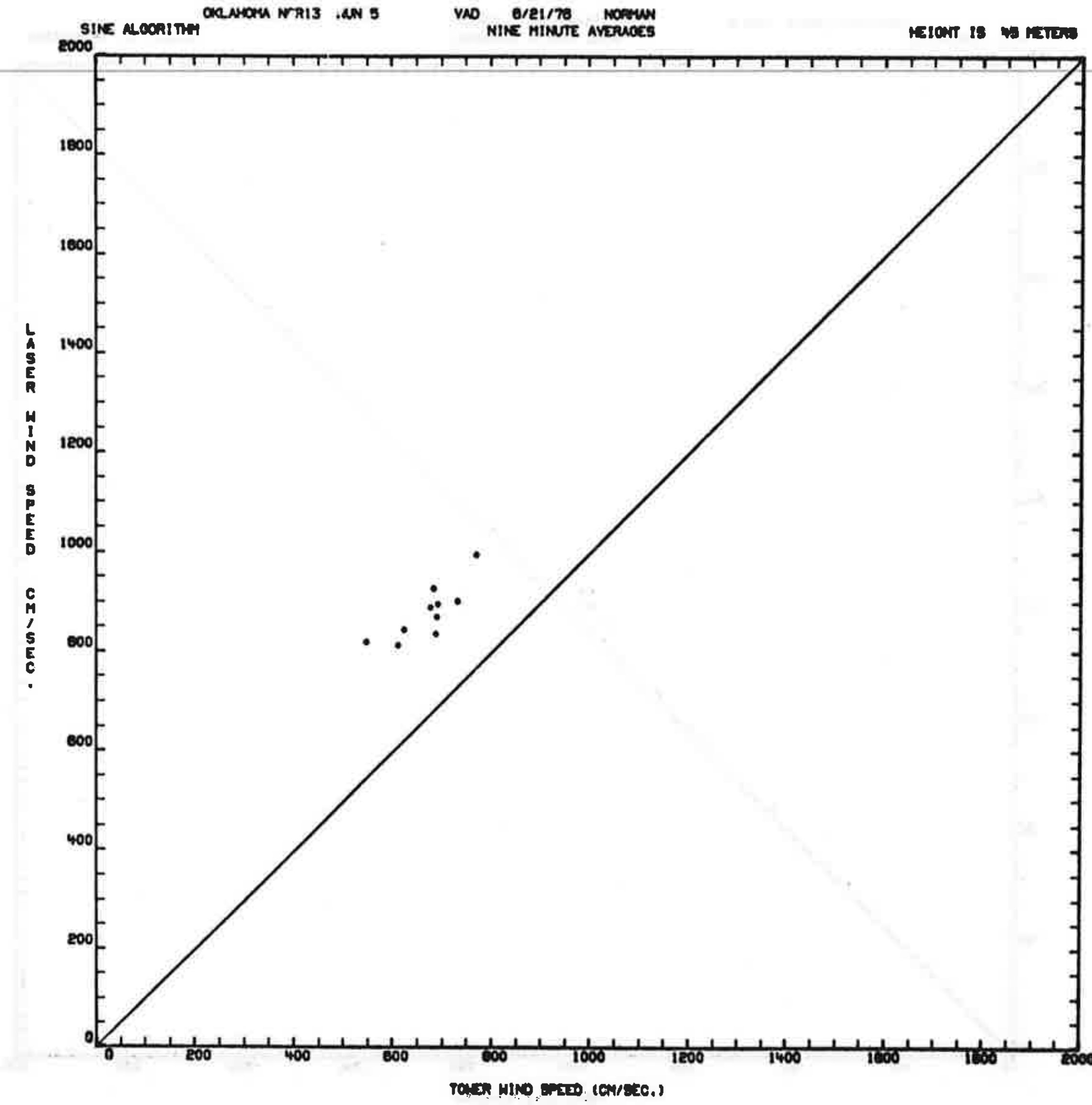


FIGURE C-1 (Continued)

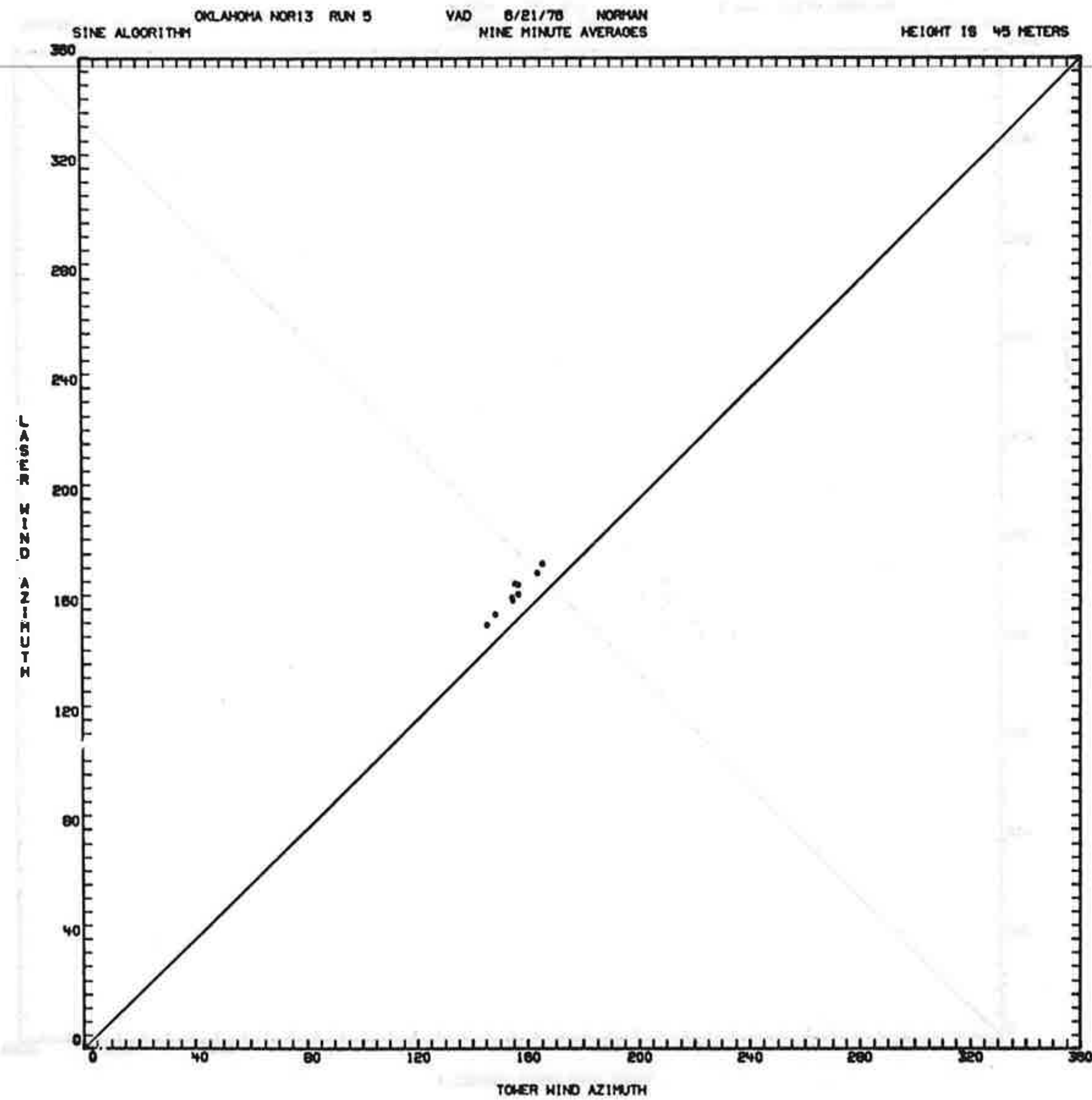


FIGURE C-1 (Continued)

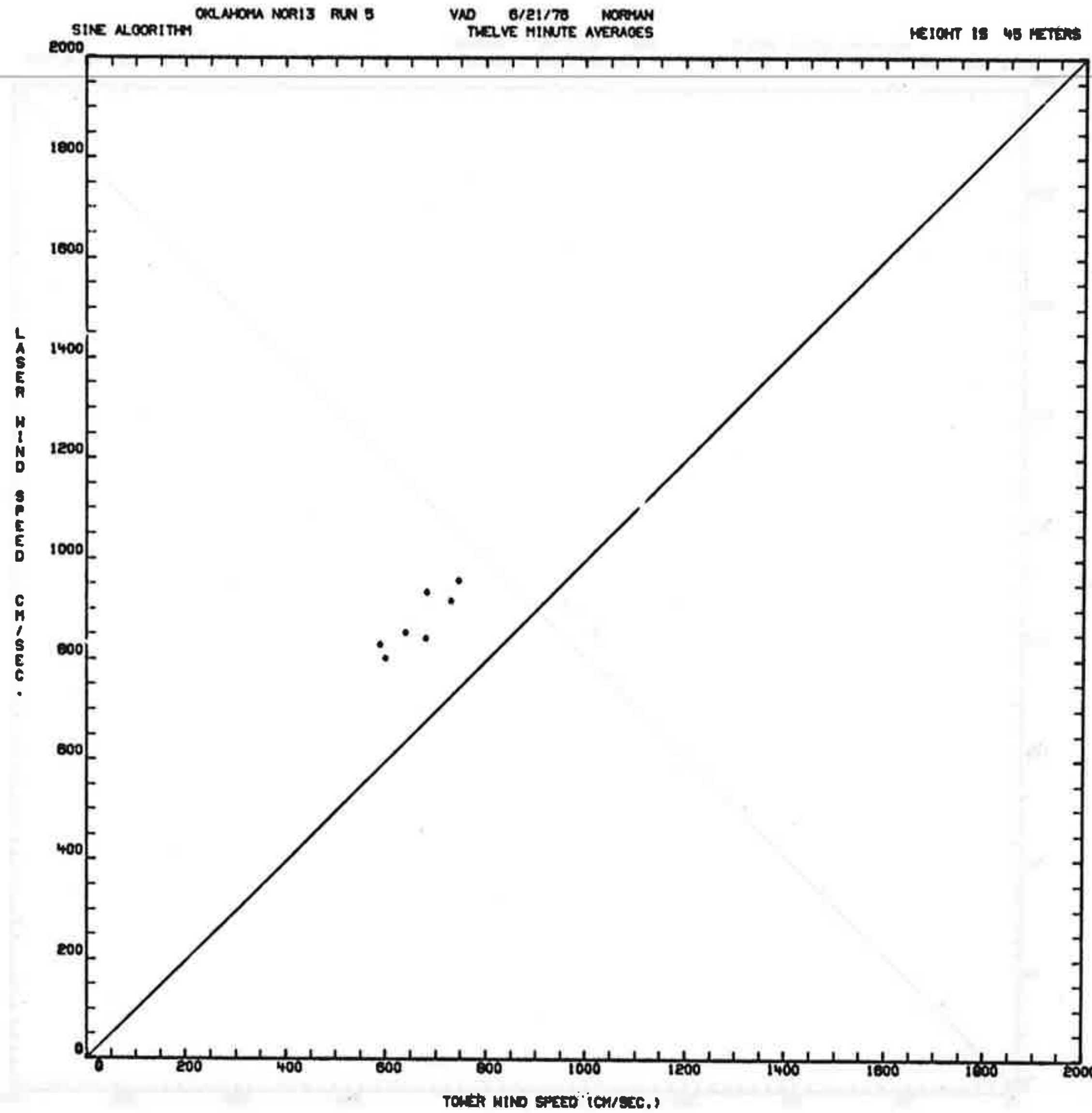


FIGURE C-1 (Continued)

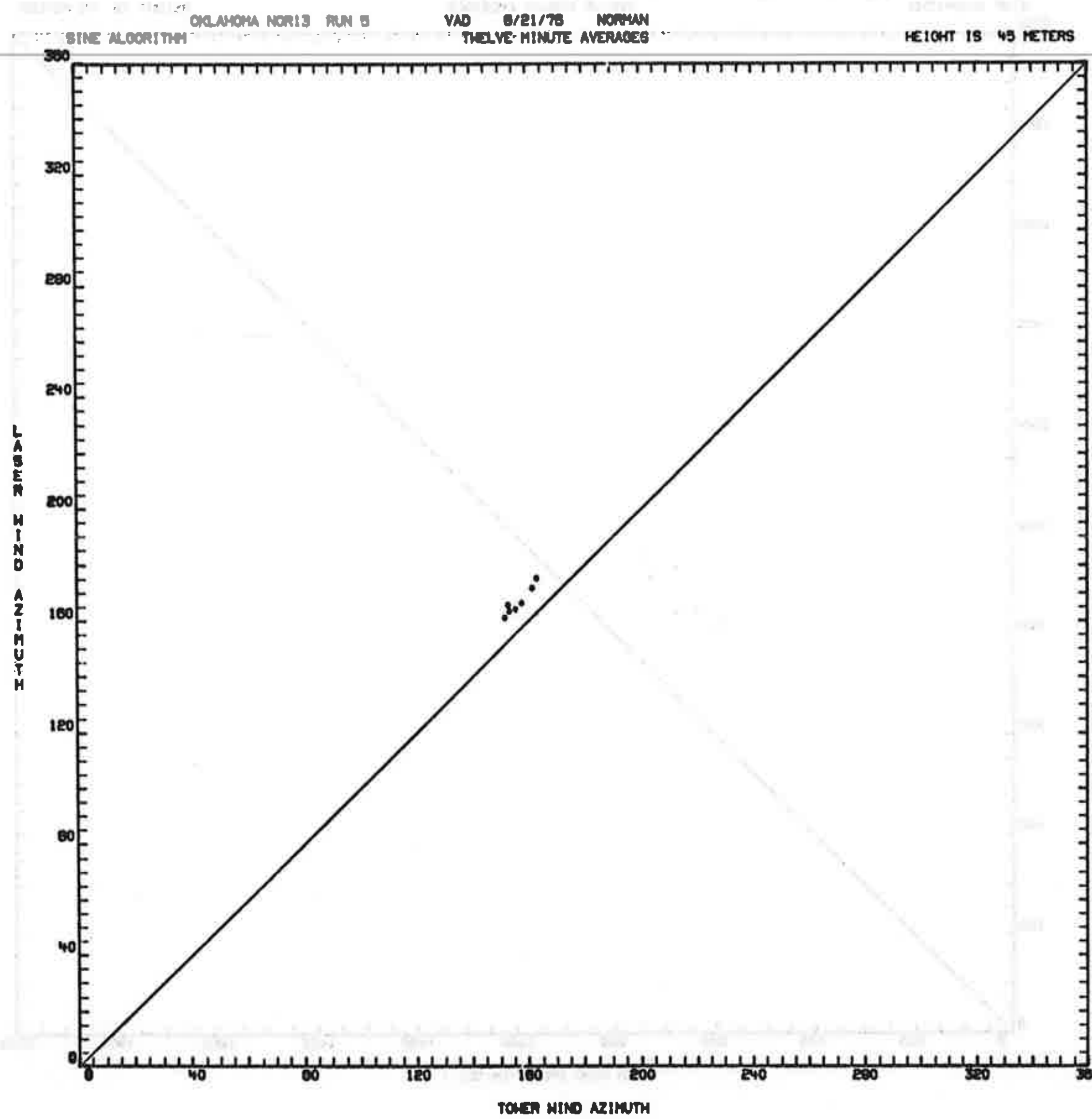


FIGURE C-1 (Continued)

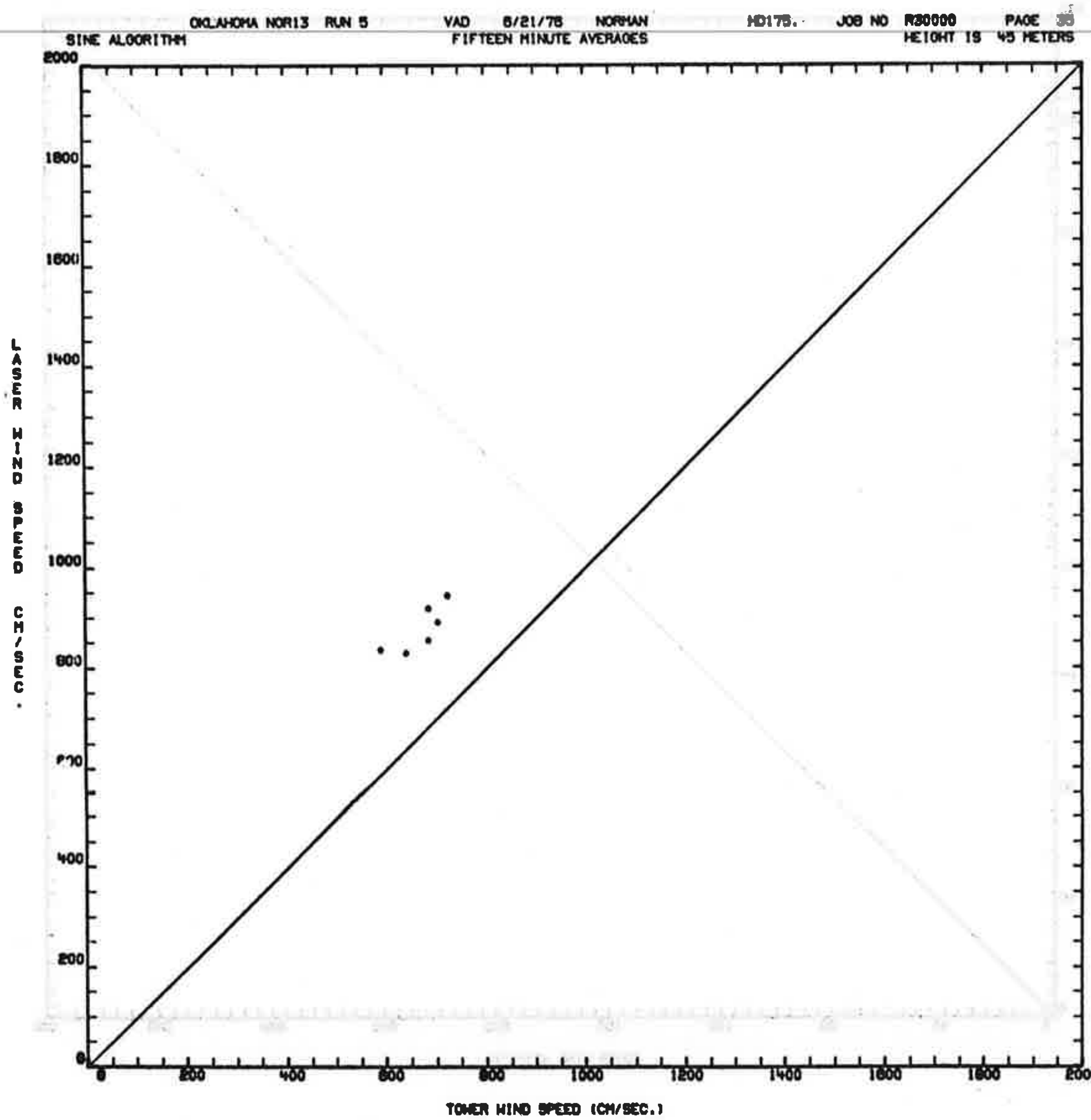


FIGURE C-1 (Continued)

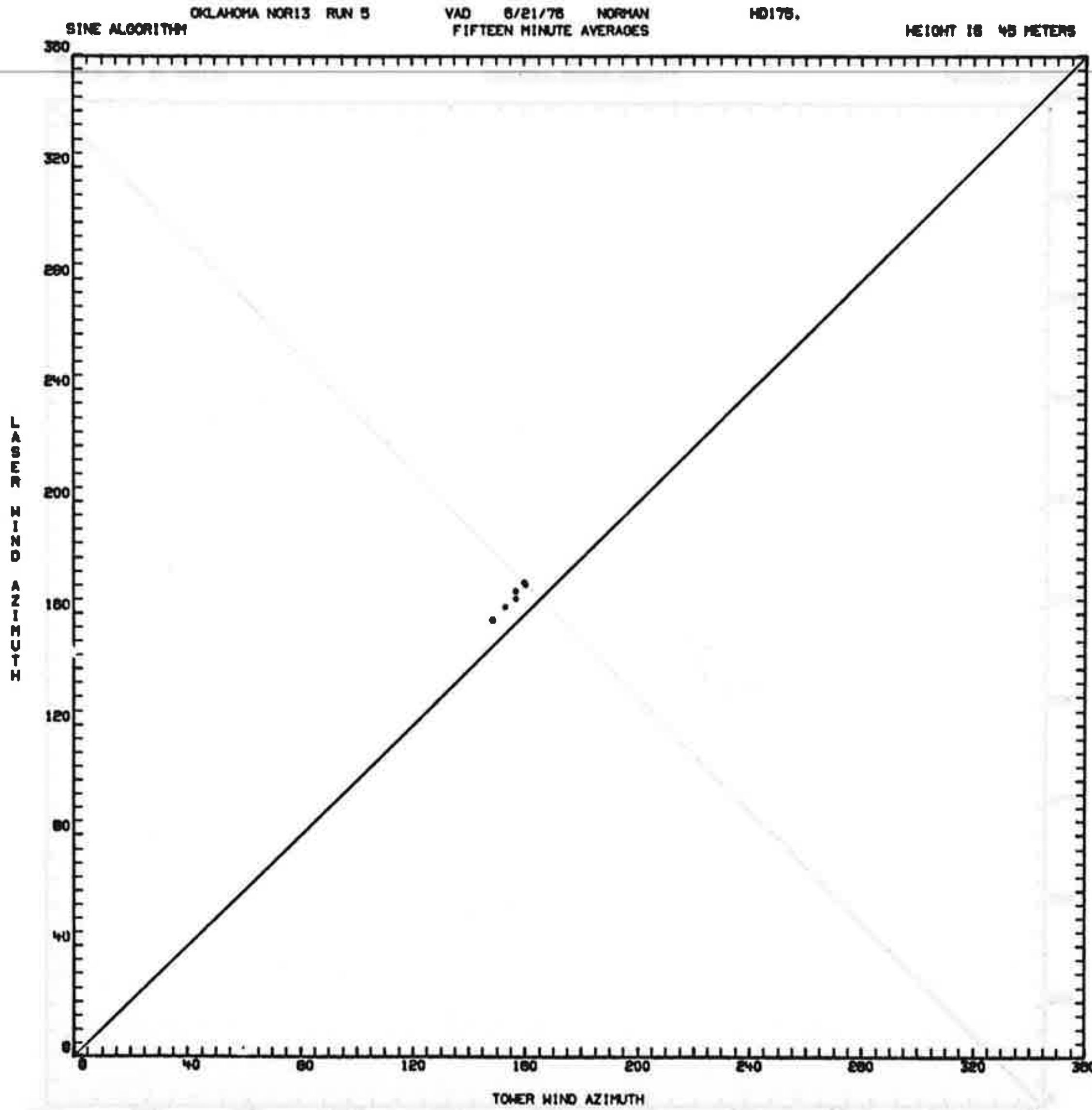


FIGURE C-1 (Continued)

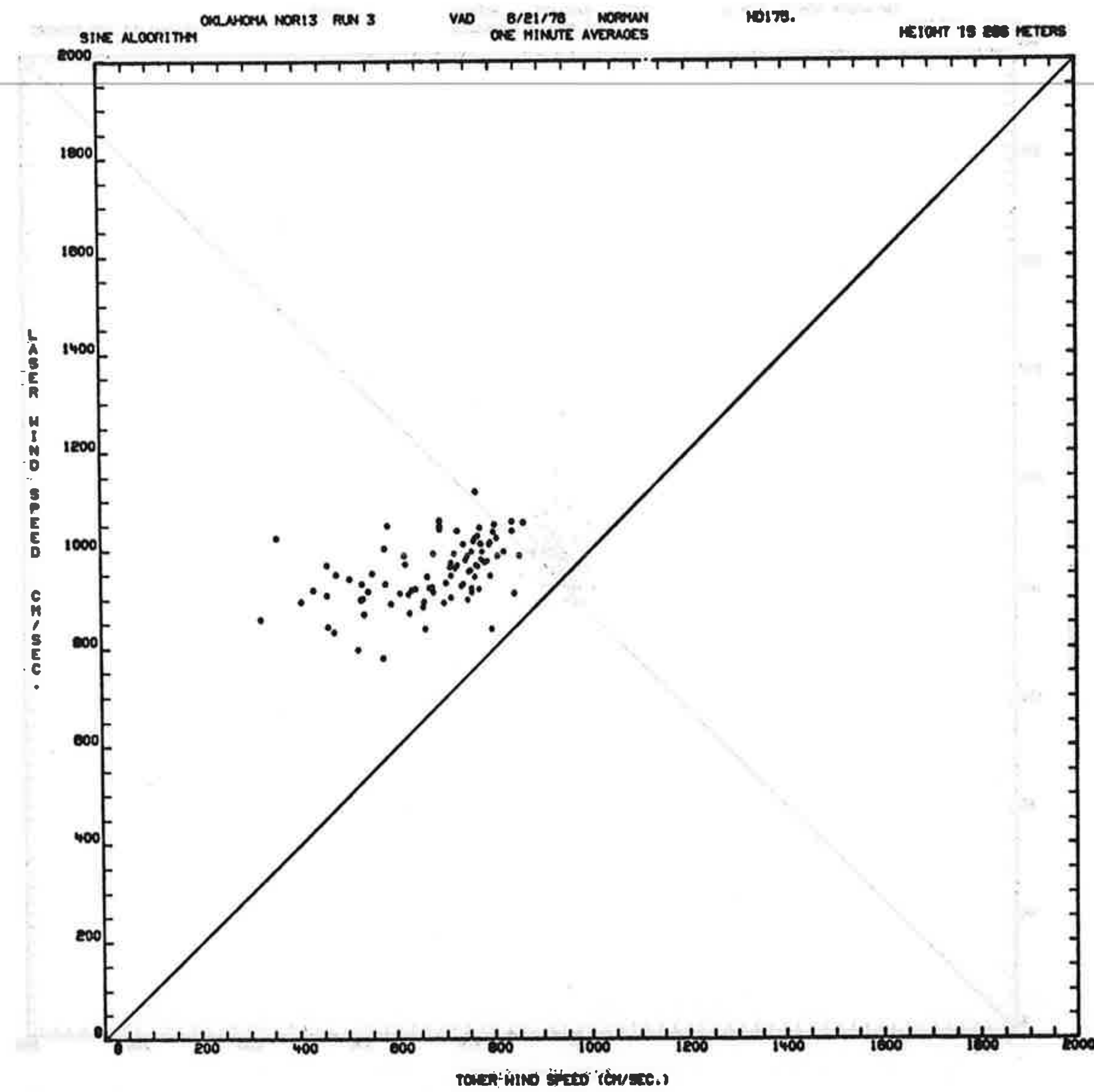


FIGURE C-1 (Continued)

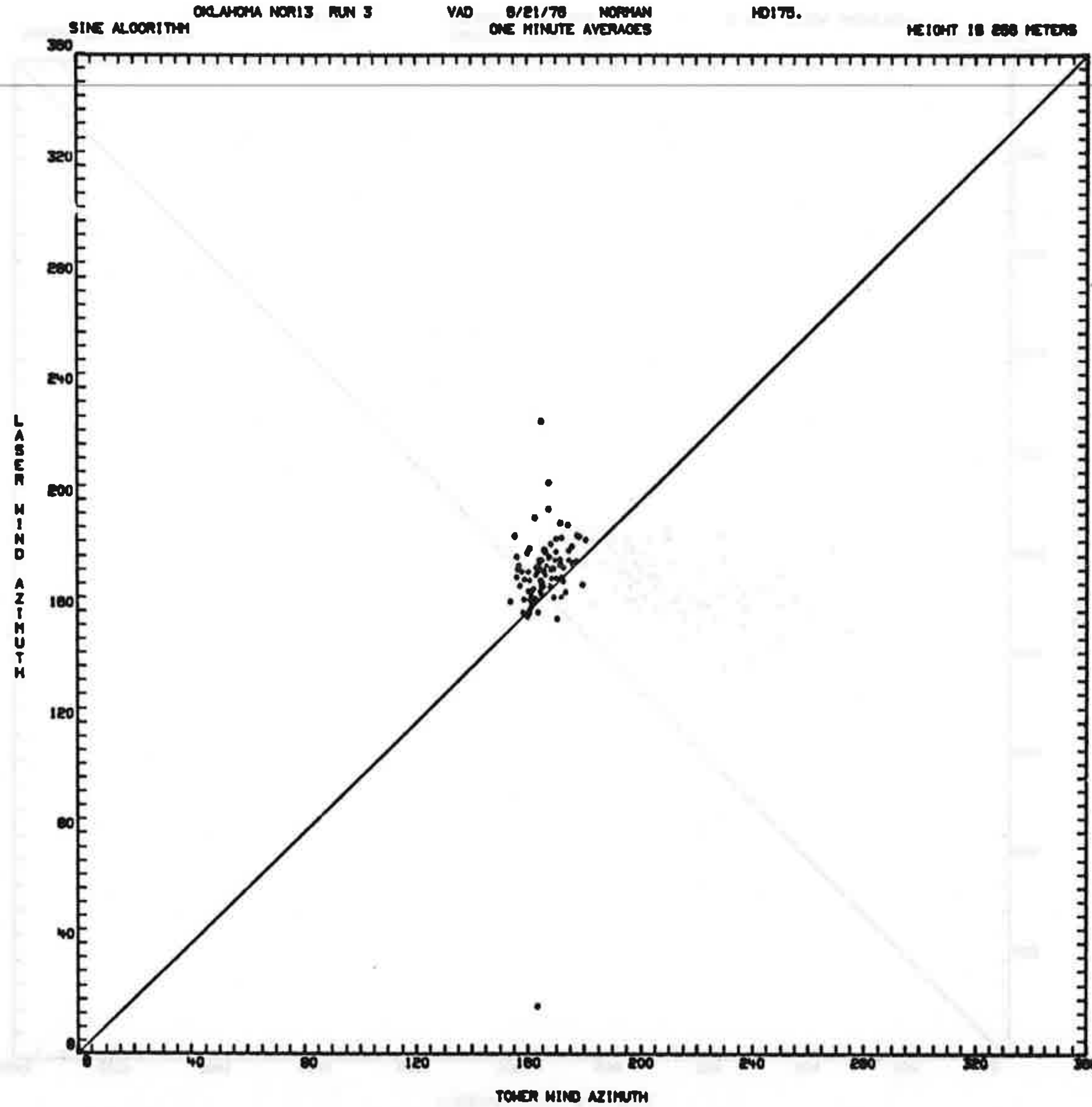


FIGURE C-1 (Continued)

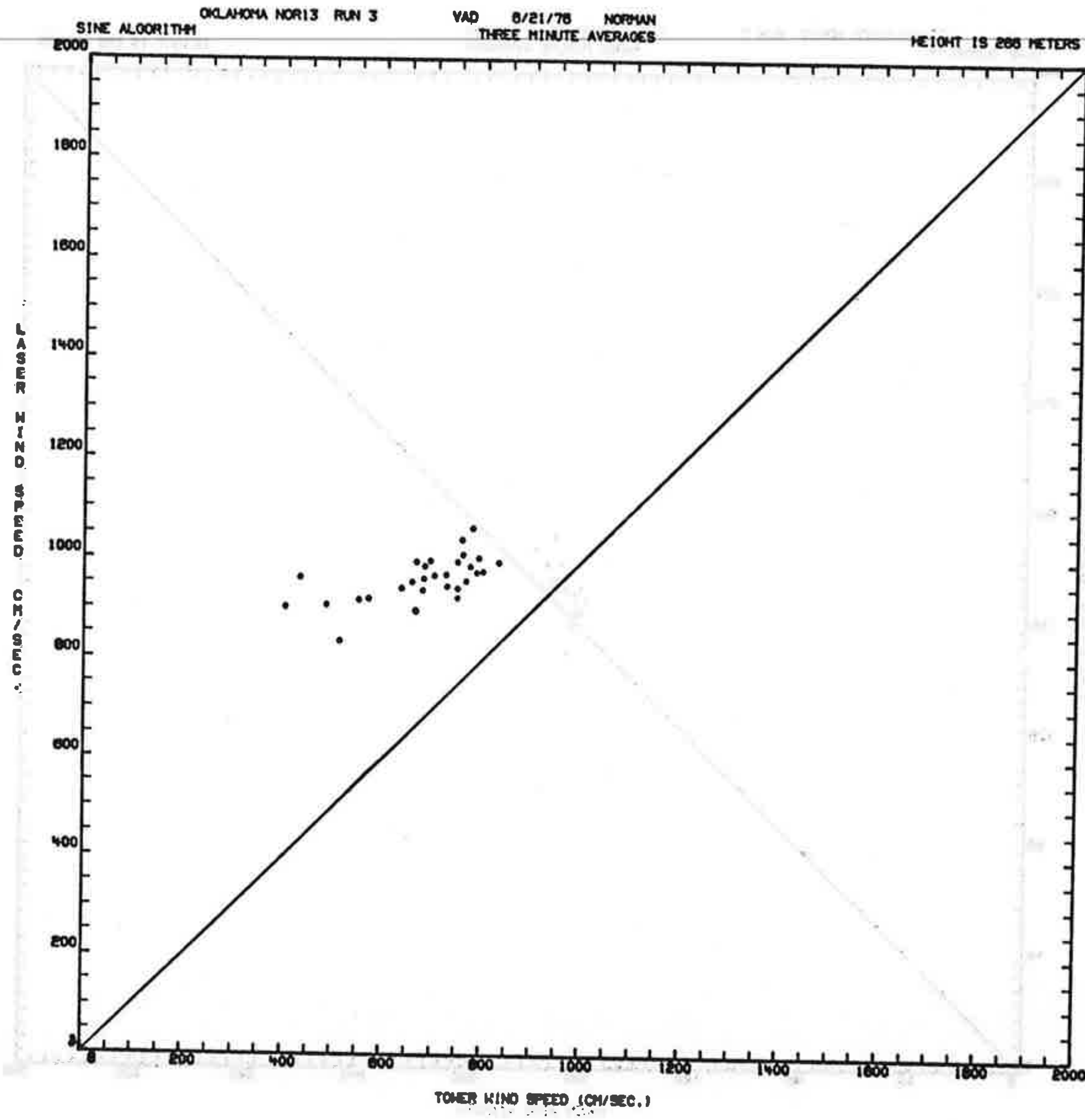


FIGURE C-1 (Continued)

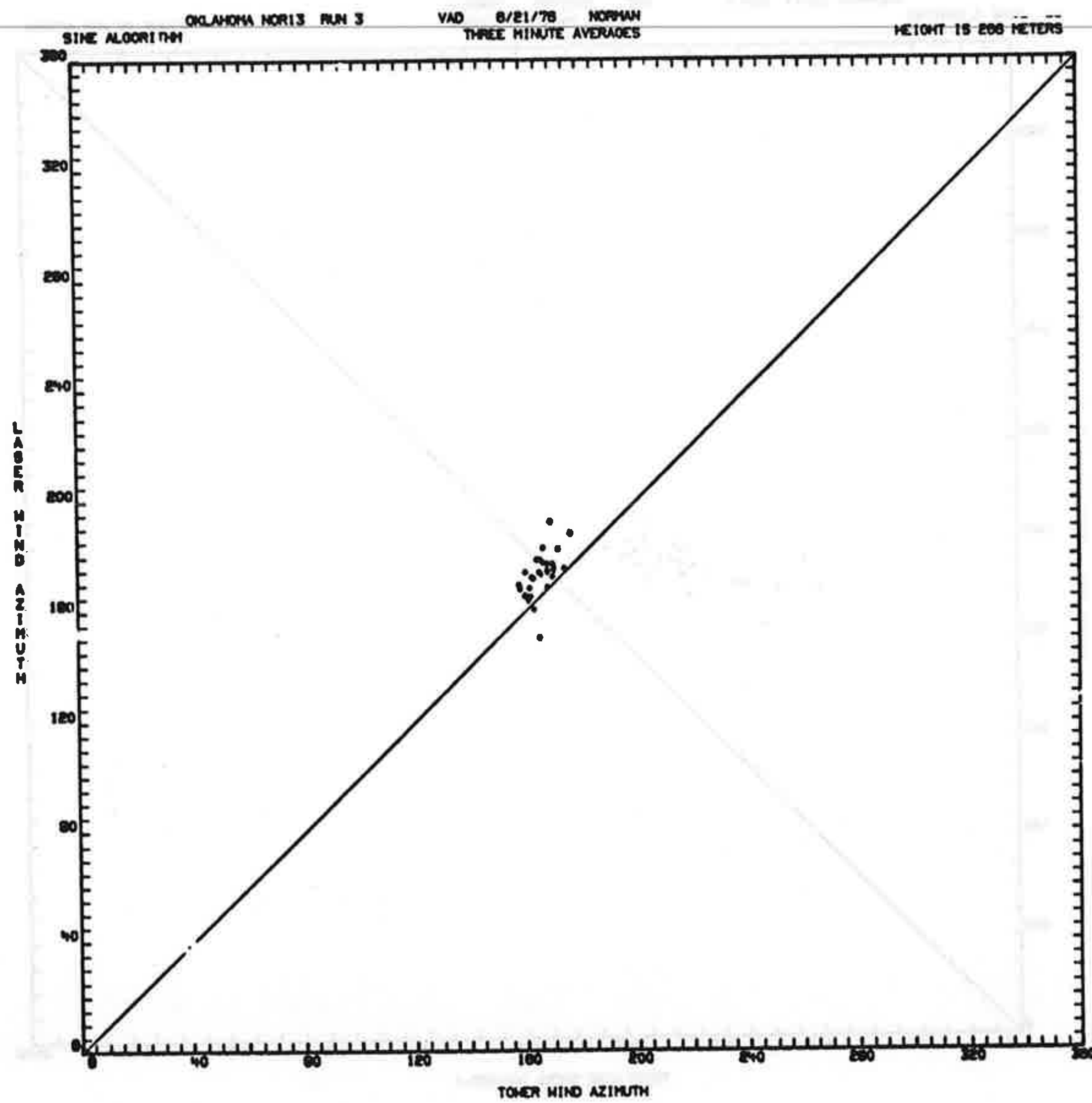


FIGURE C-1 (Continued)

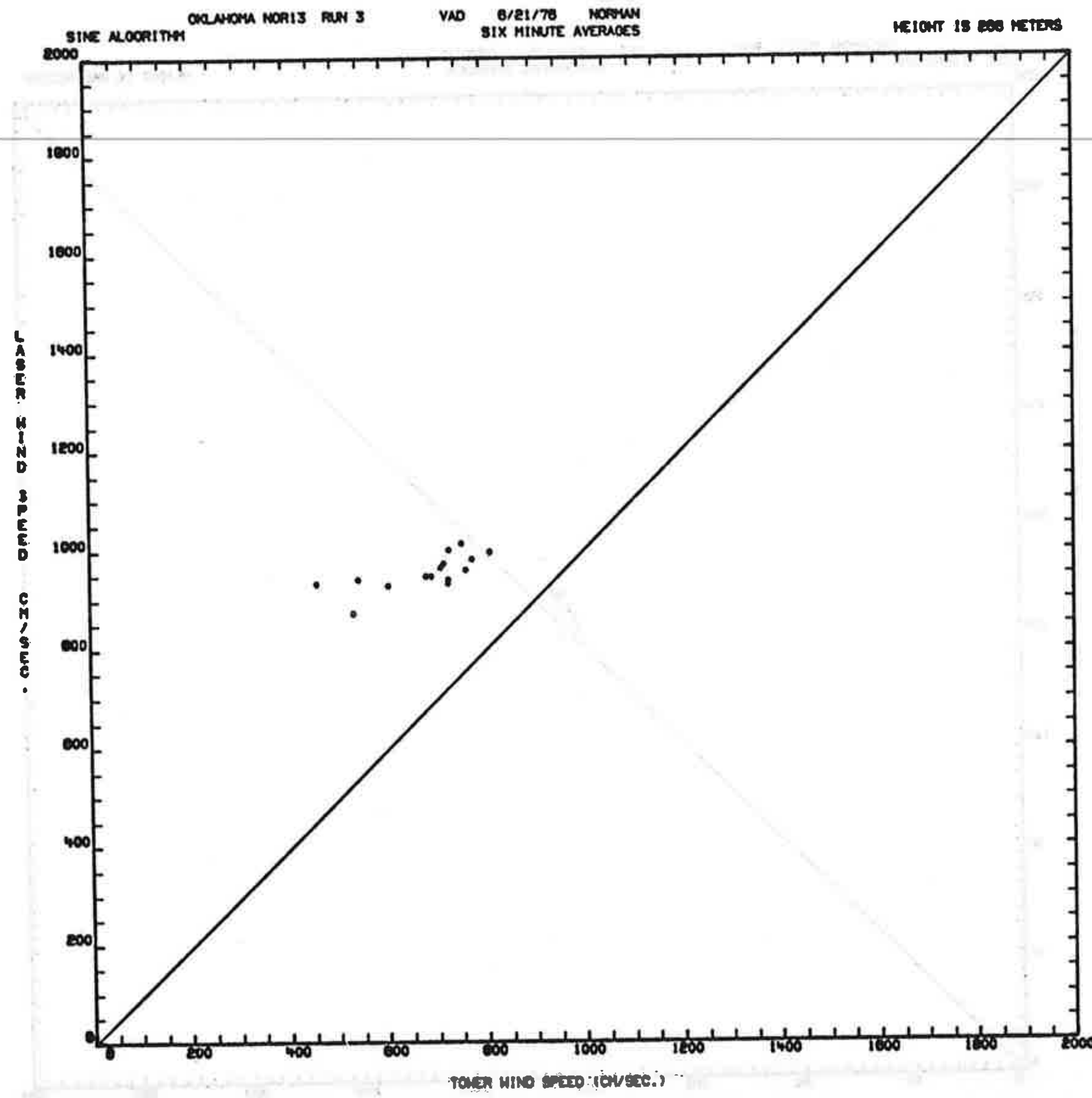


FIGURE C-1 (Continued)

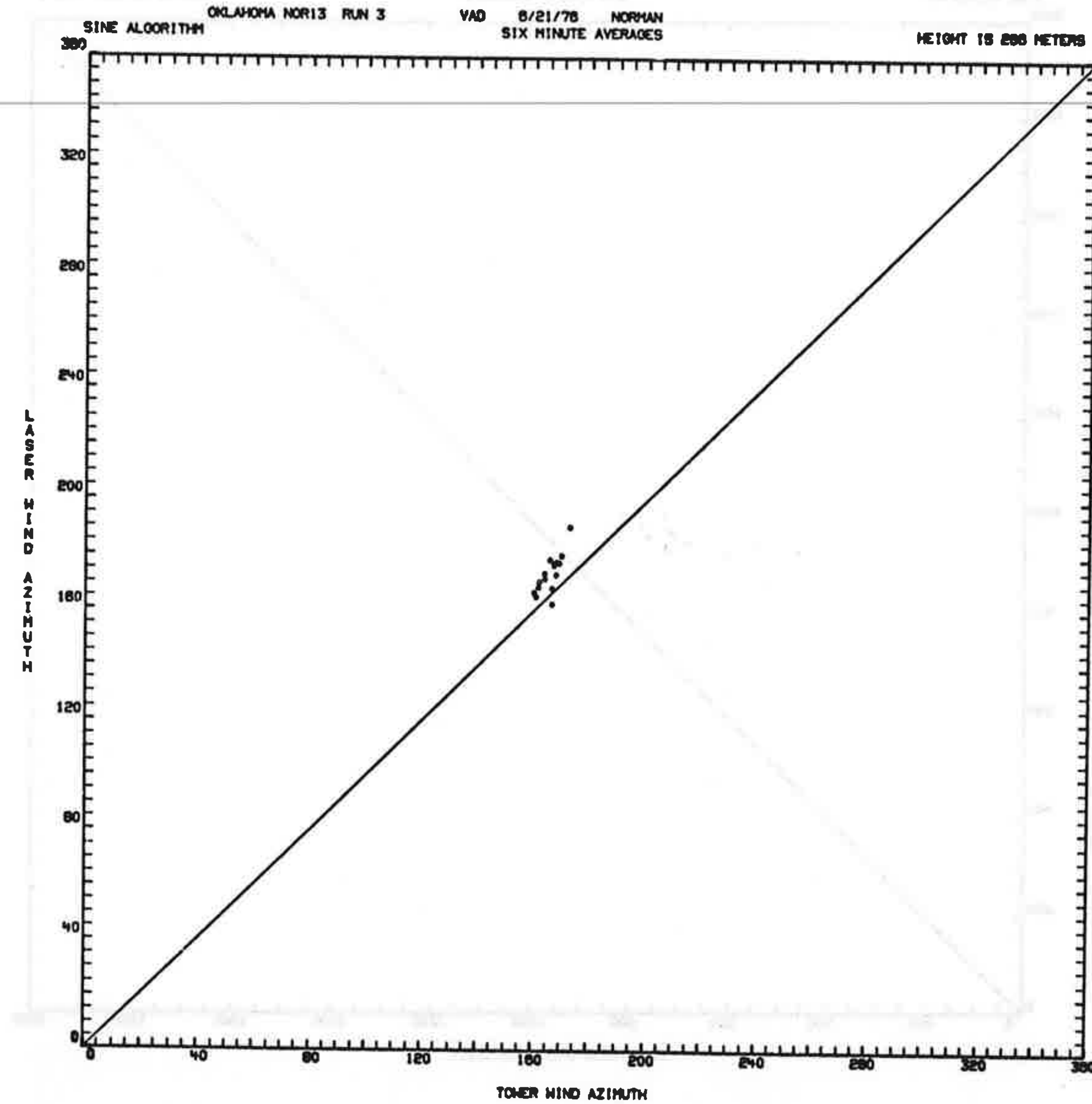


FIGURE C-1 (Continued)

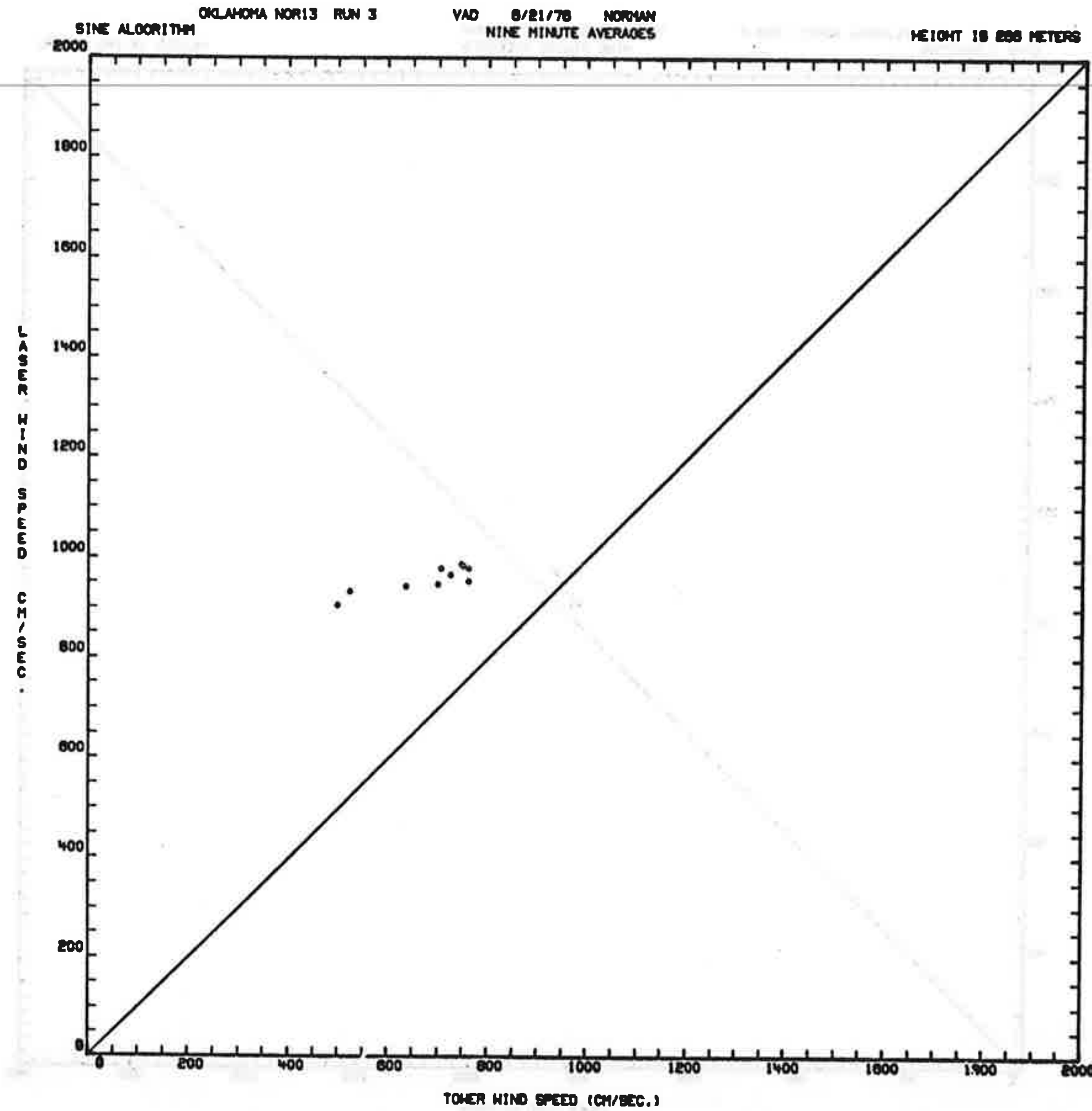


FIGURE C-1 (Continued)

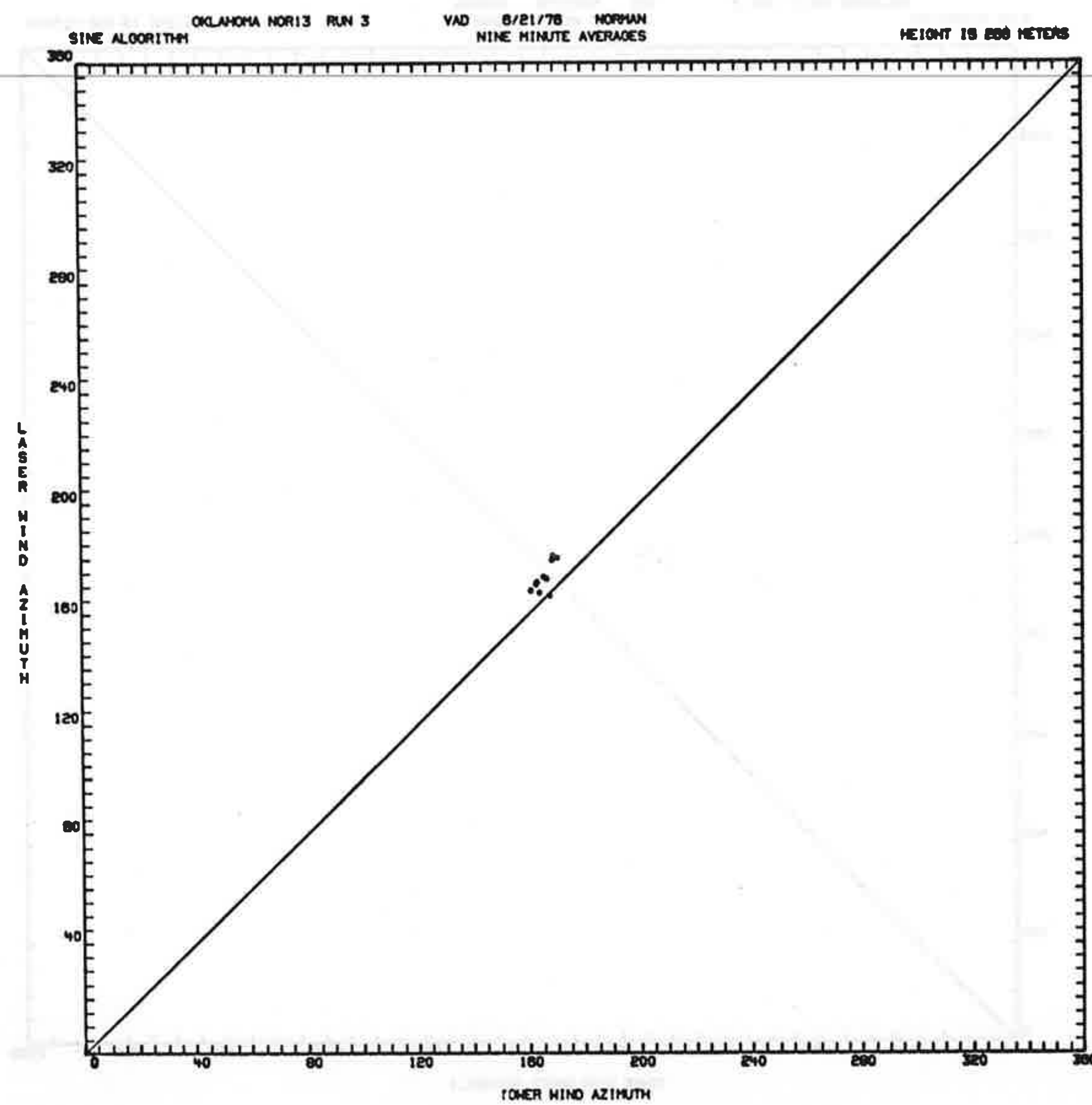


FIGURE C-1 (Continued)

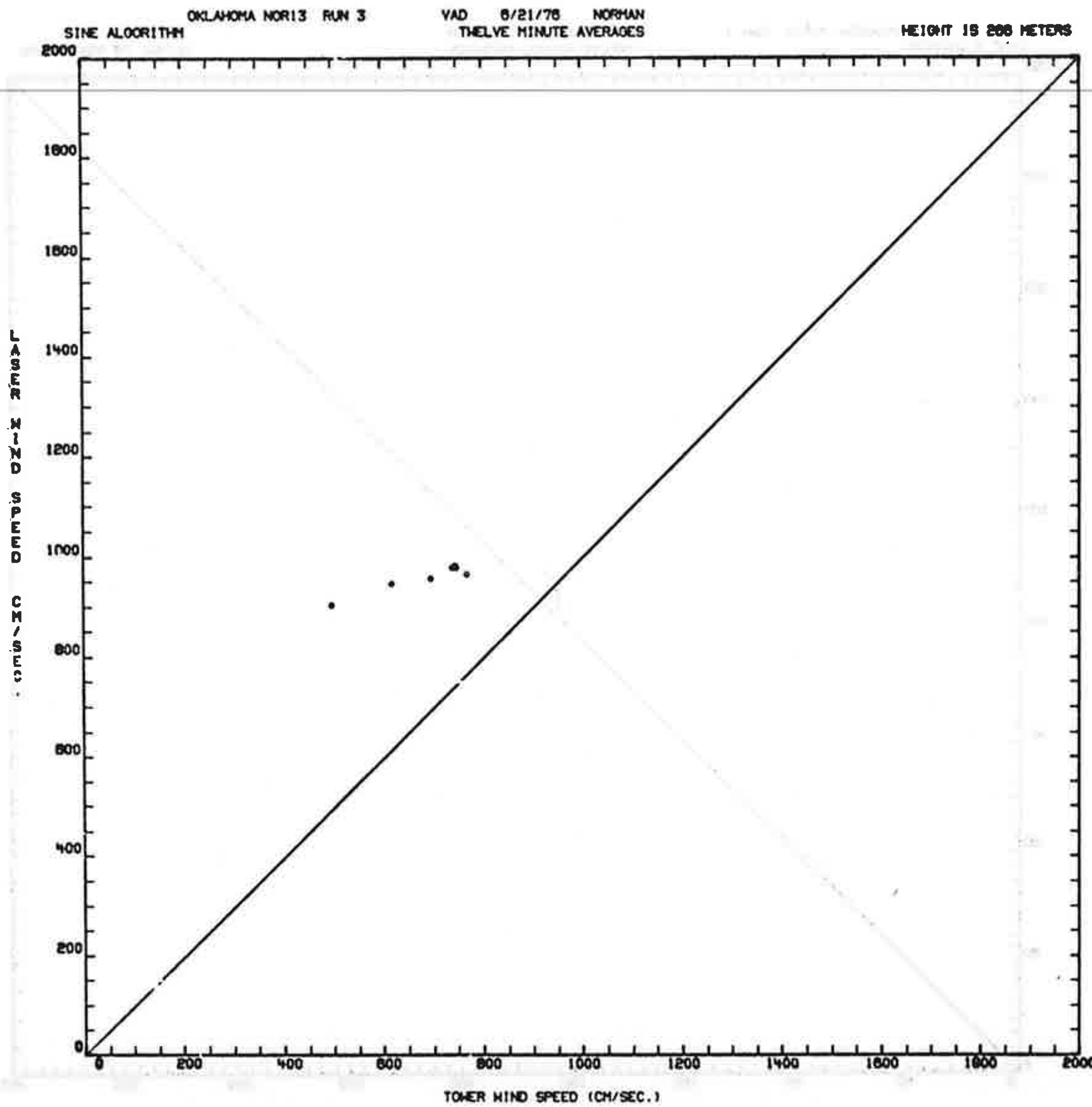


FIGURE C-1 (Continued)

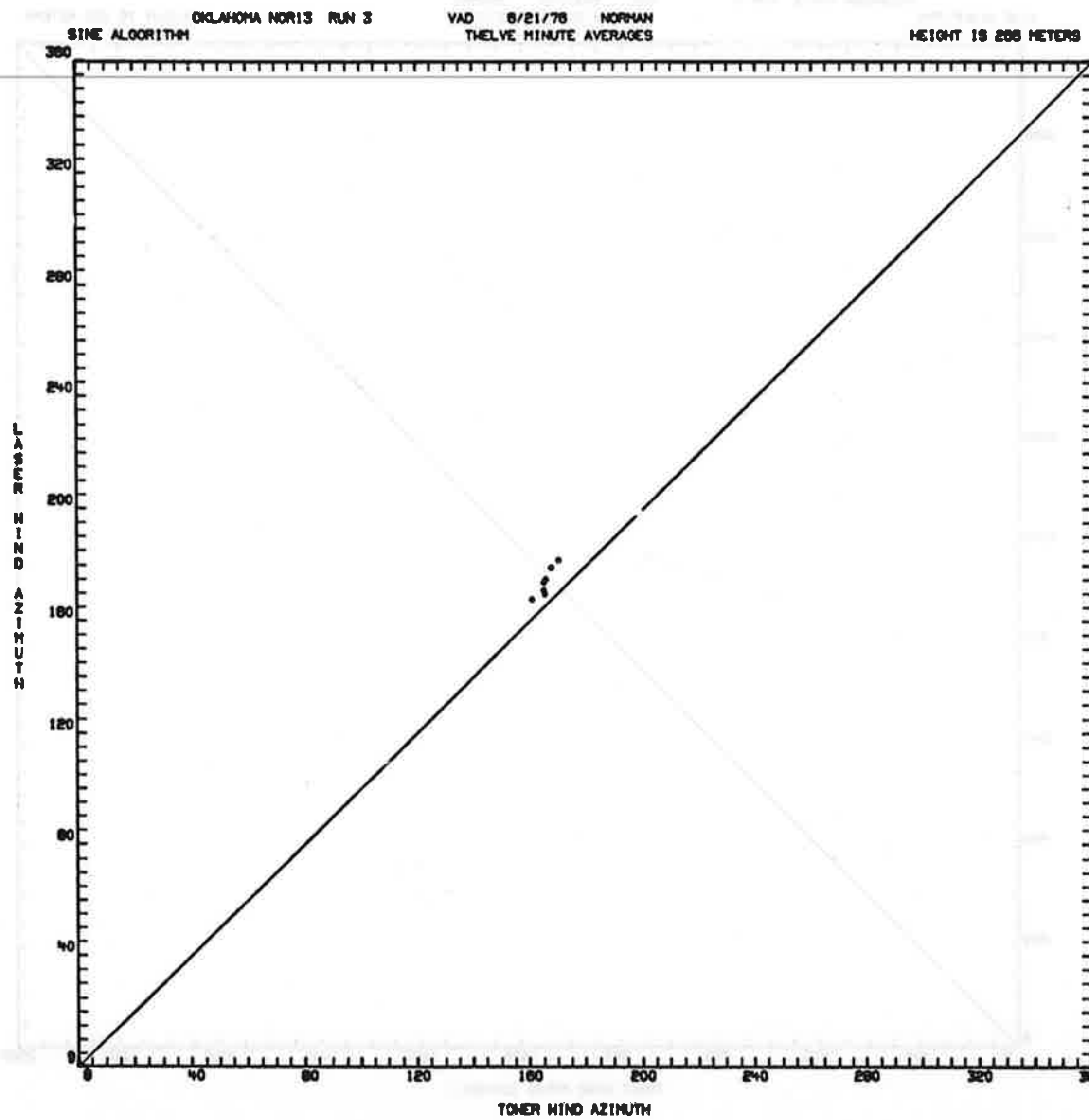


FIGURE C-1 (Continued)

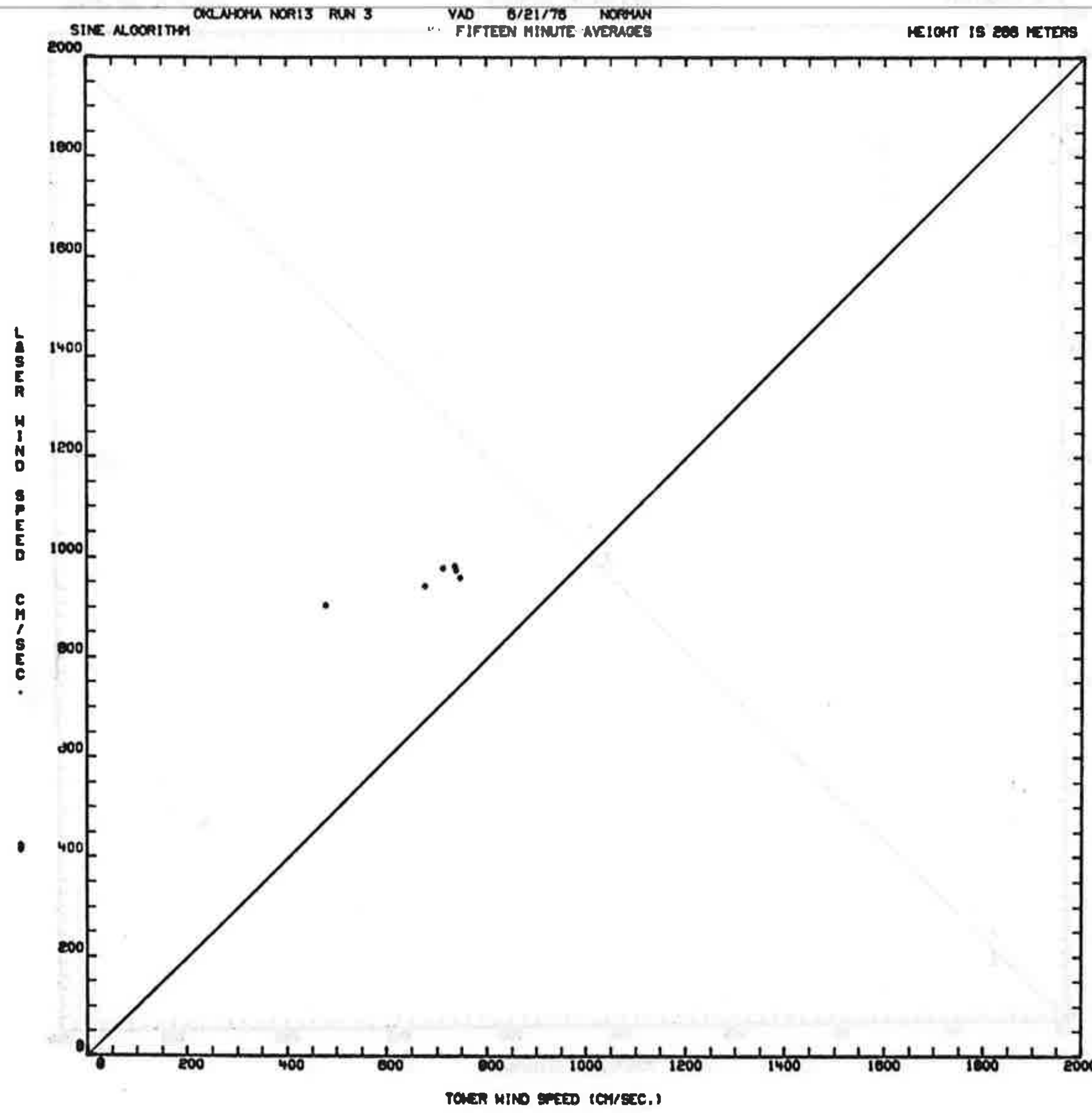


FIGURE C-1 (Continued)

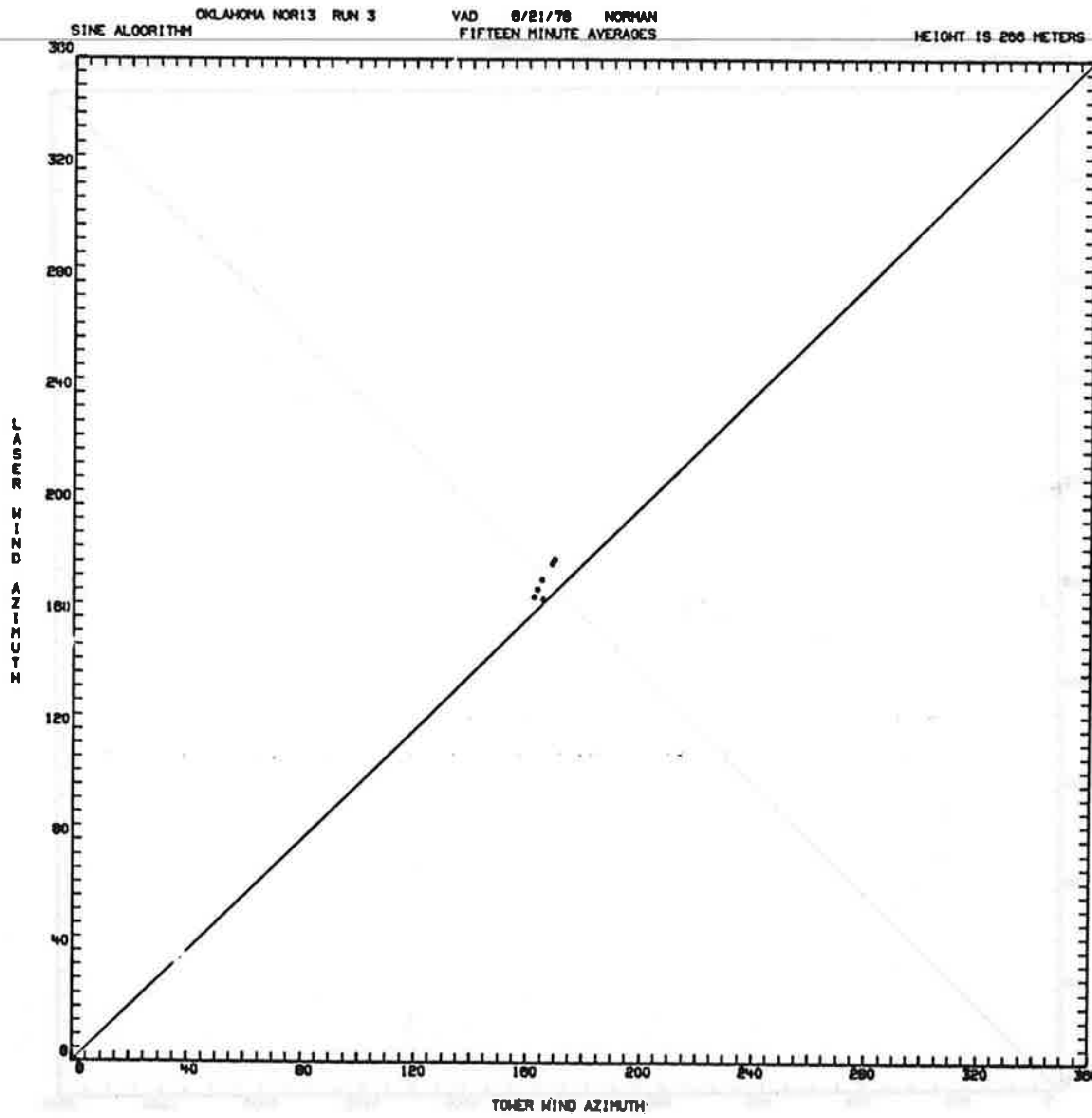


FIGURE C-1 (Concluded)

Appendix D

COMPARISON OF LASER-MEASURED WIND AND ANEMOMETER-MEASURED WIND FOR 3- AND 15-MINUTE AVERAGING PERIODS

Figures for the 15-min averaging period are eliminated whenever the run is sufficiently short that there are less than three 15-min averages.

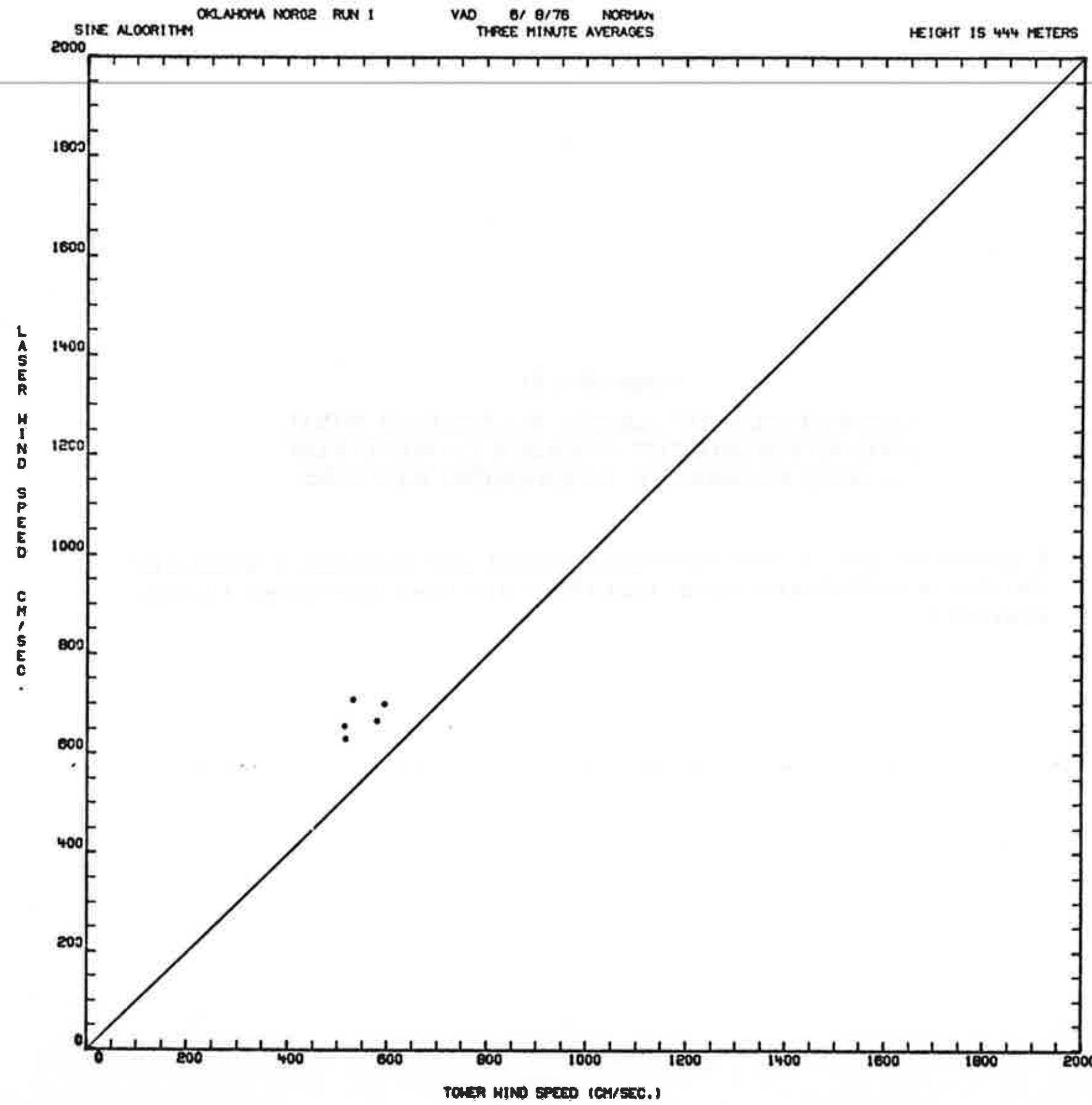


FIGURE D-1. COMPARISON OF LASER-MEASURED WINDS WITH ANEMOMETER-MEASURED WINDS.

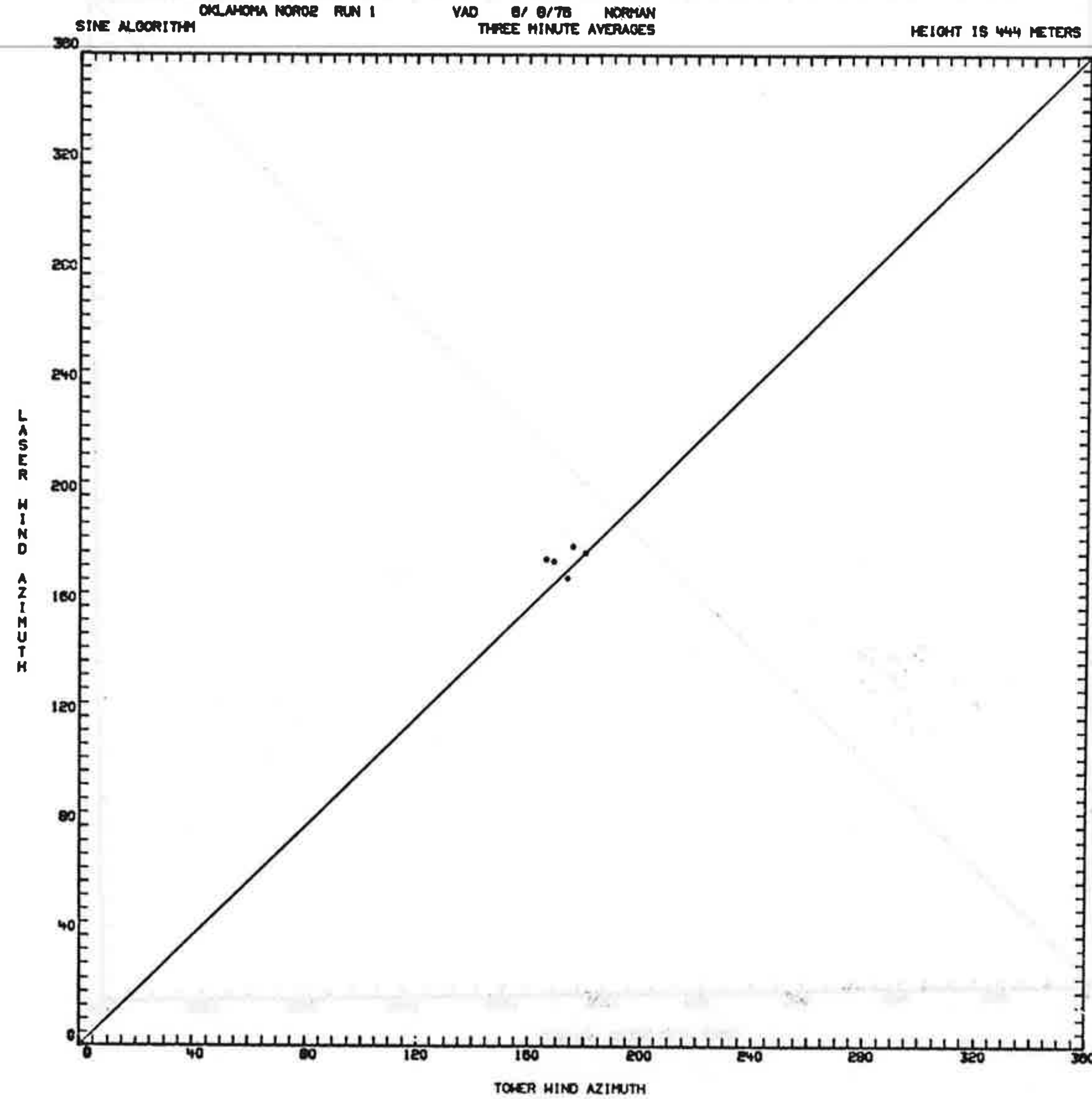


FIGURE D-1 (Continued)

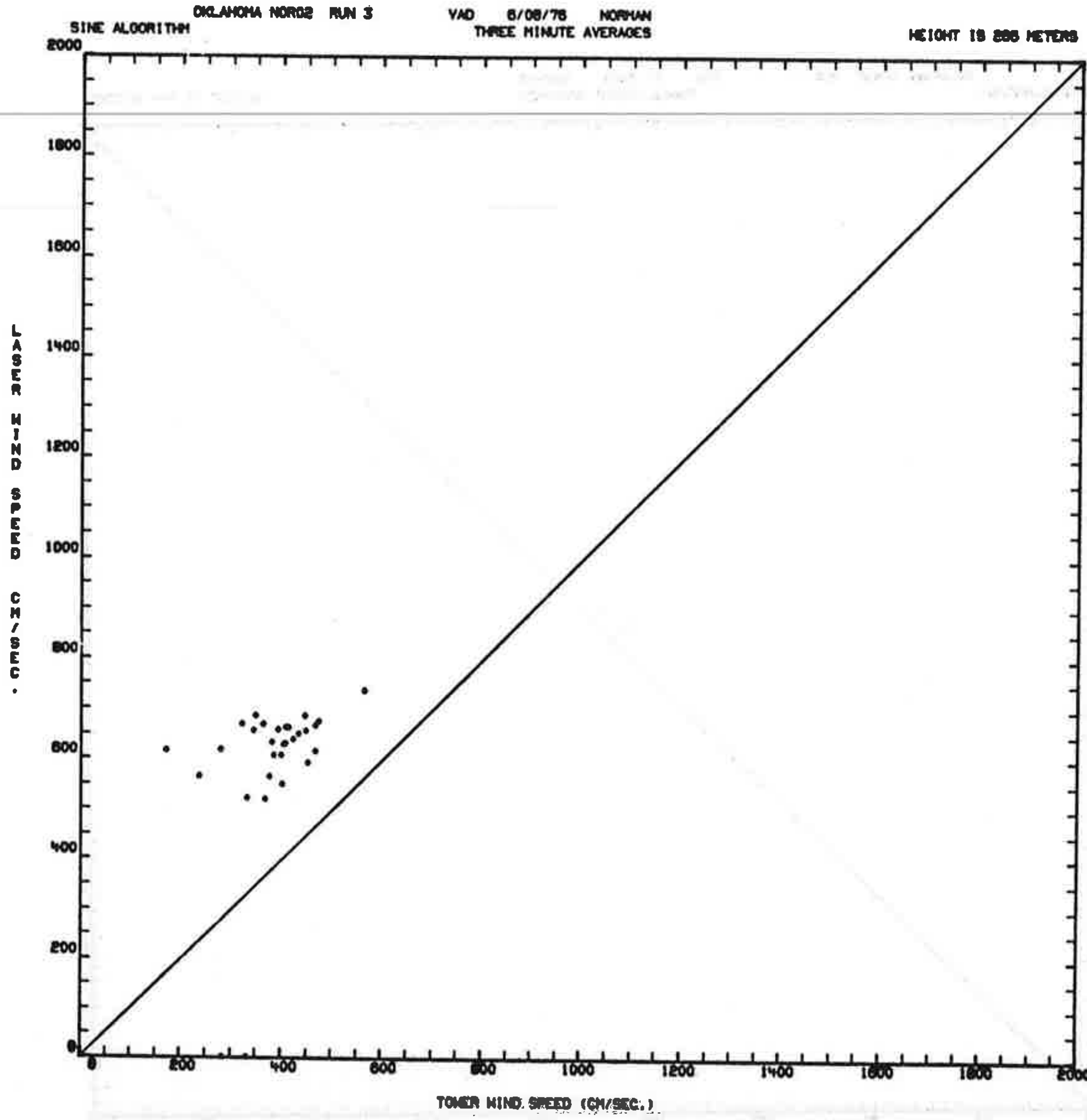


FIGURE D-1 (Continued)

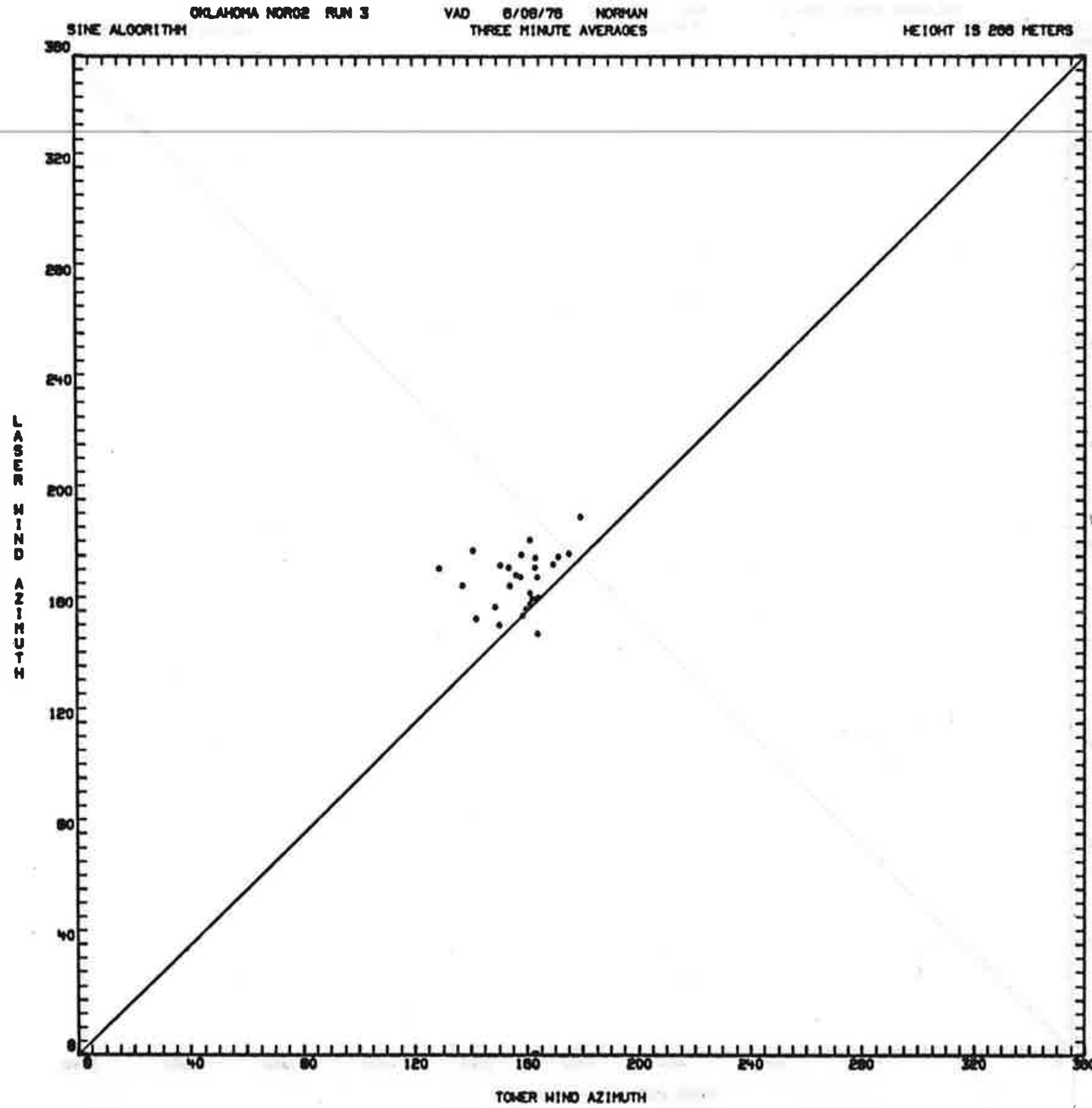


FIGURE D-1 (Continued)

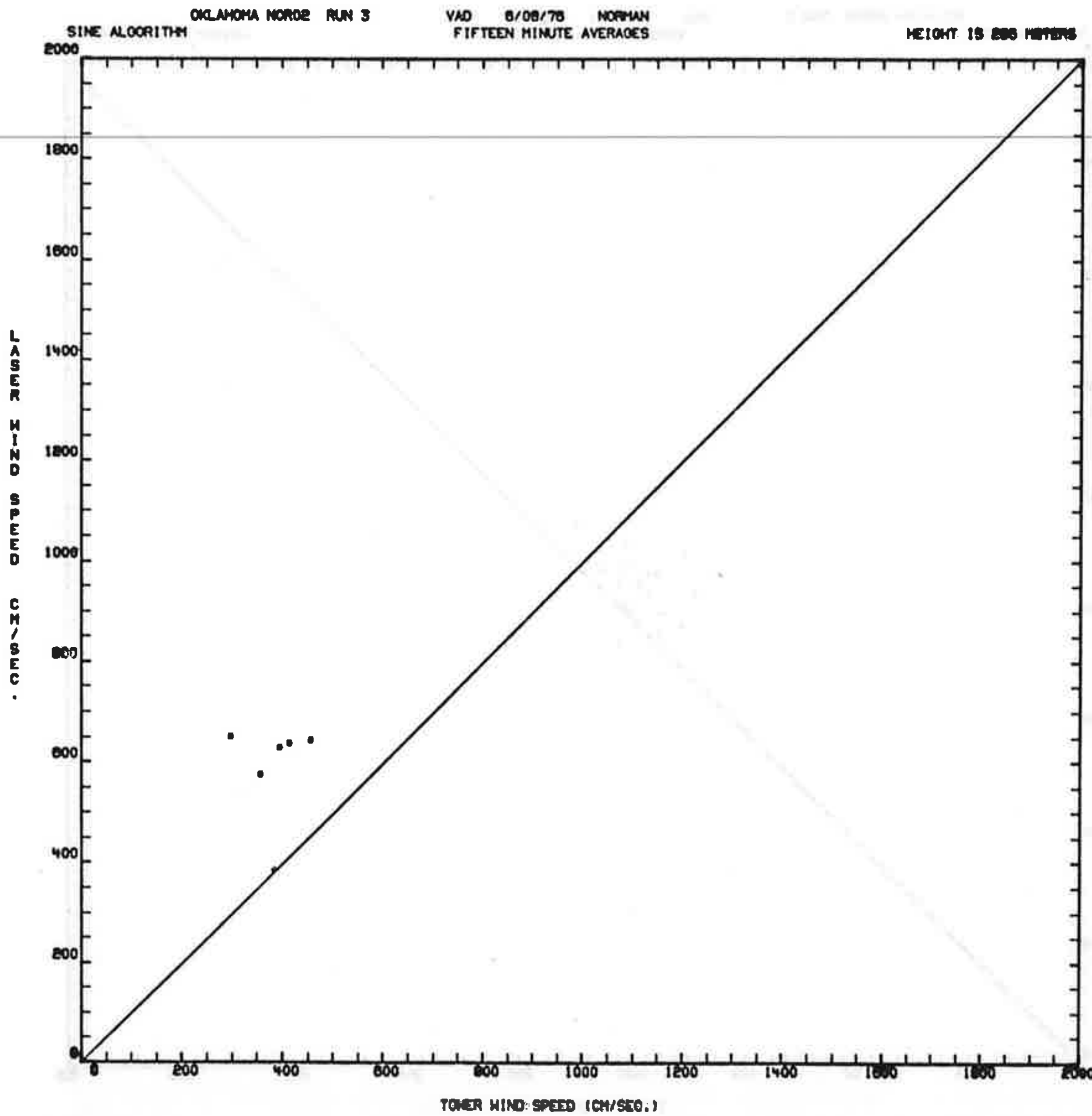


FIGURE D-1 (Continued)

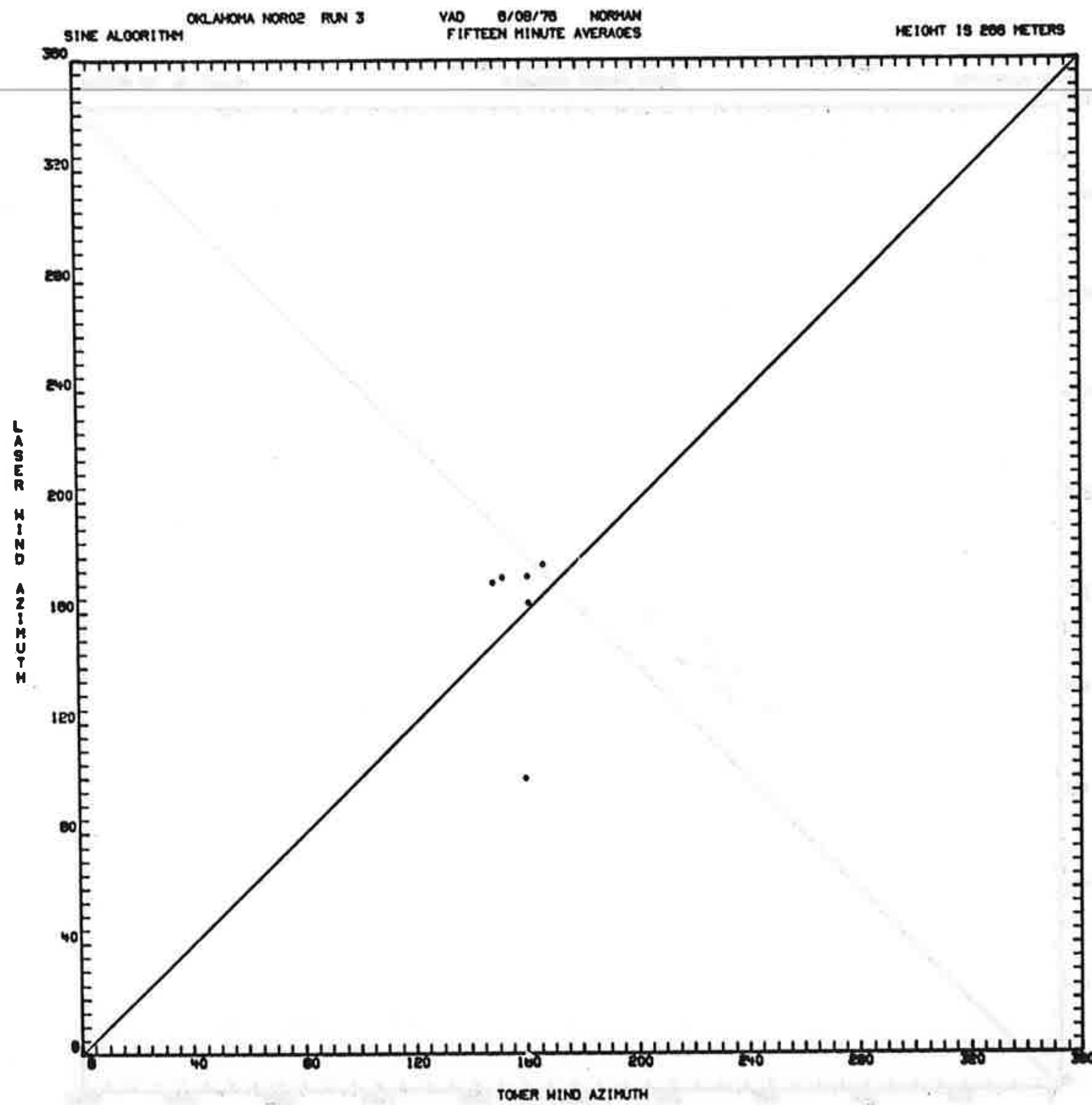


FIGURE D-1 (Continued)

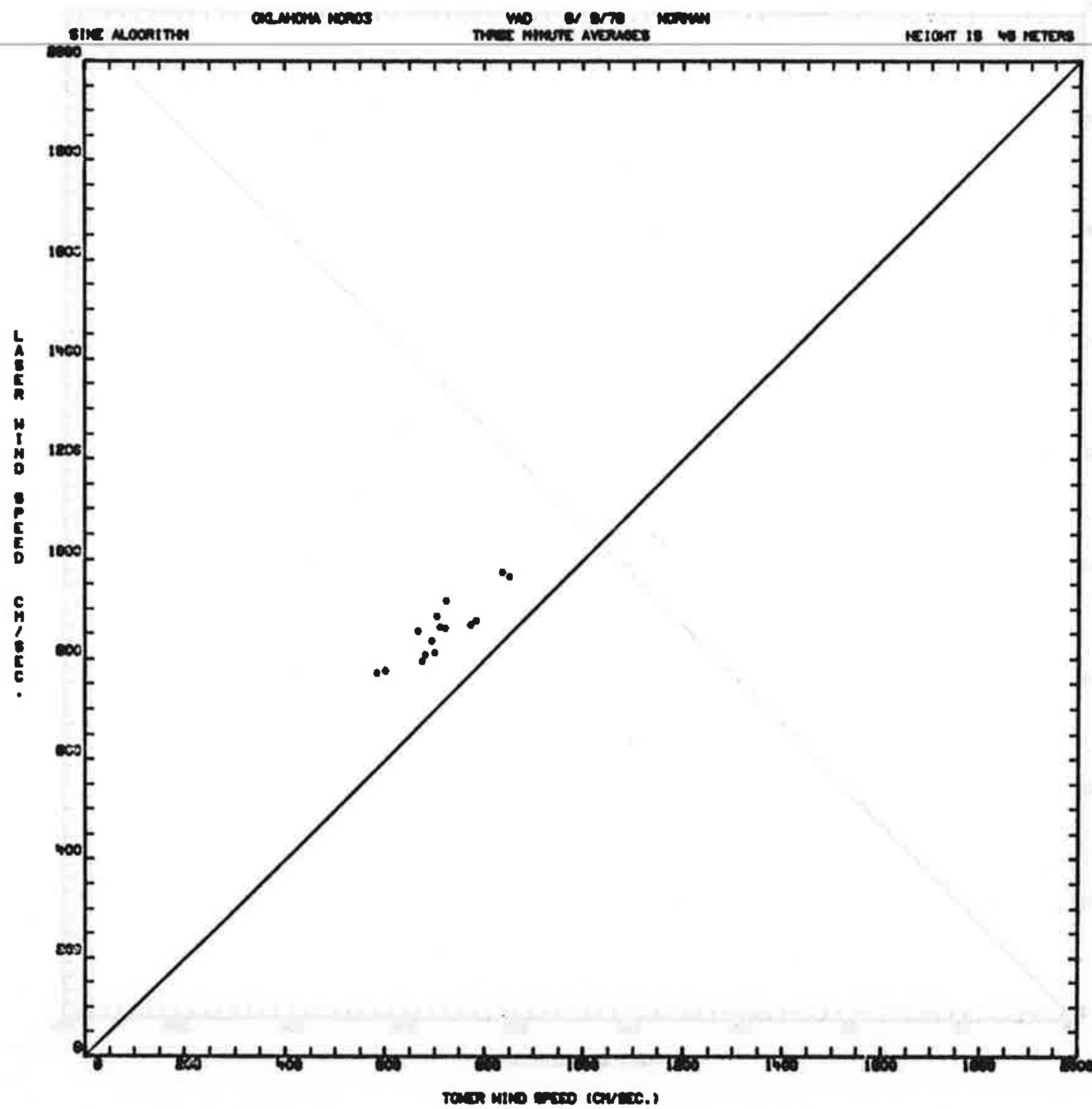


FIGURE D-1 (Continued)

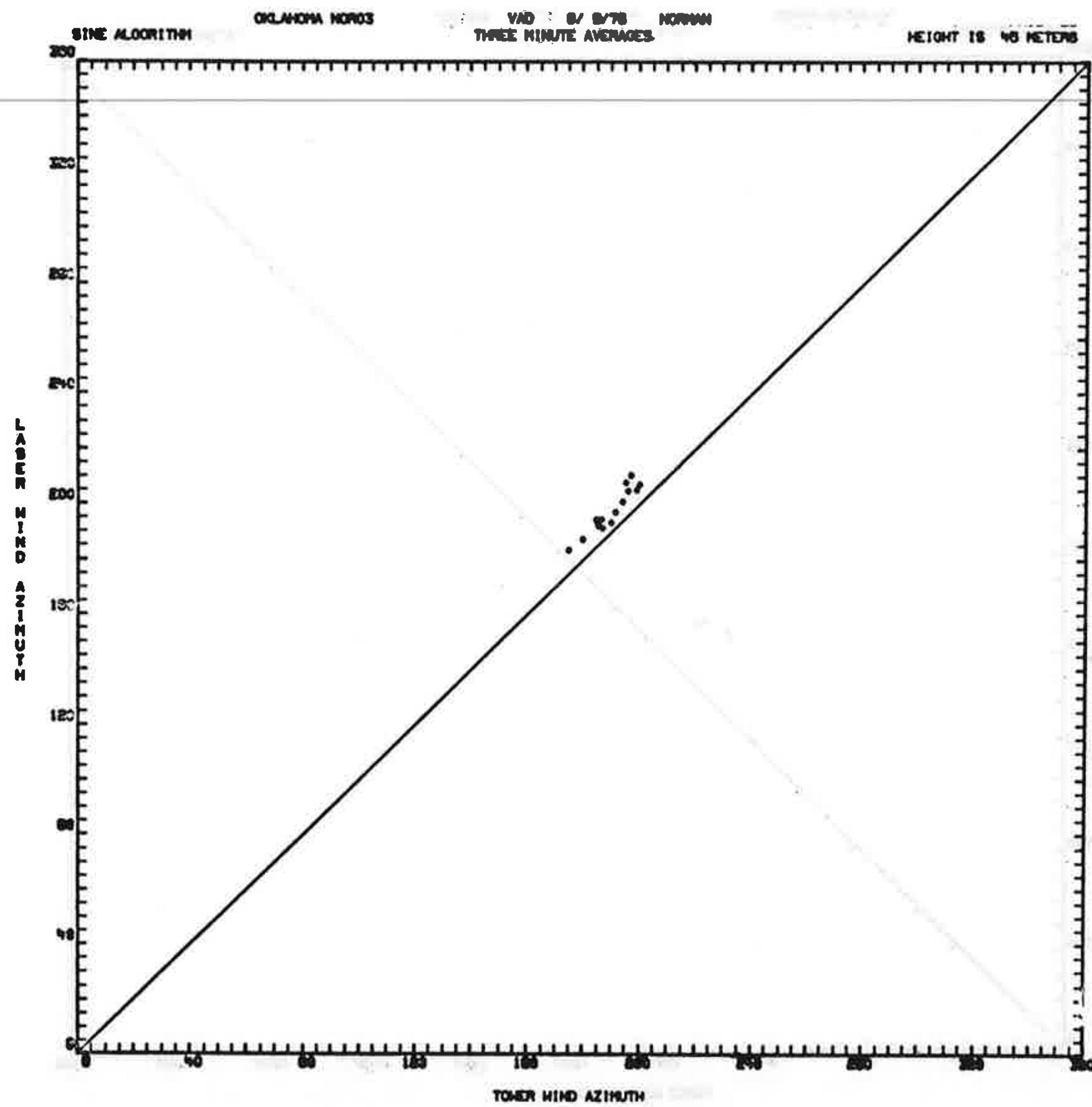


FIGURE D-1 (Continued)

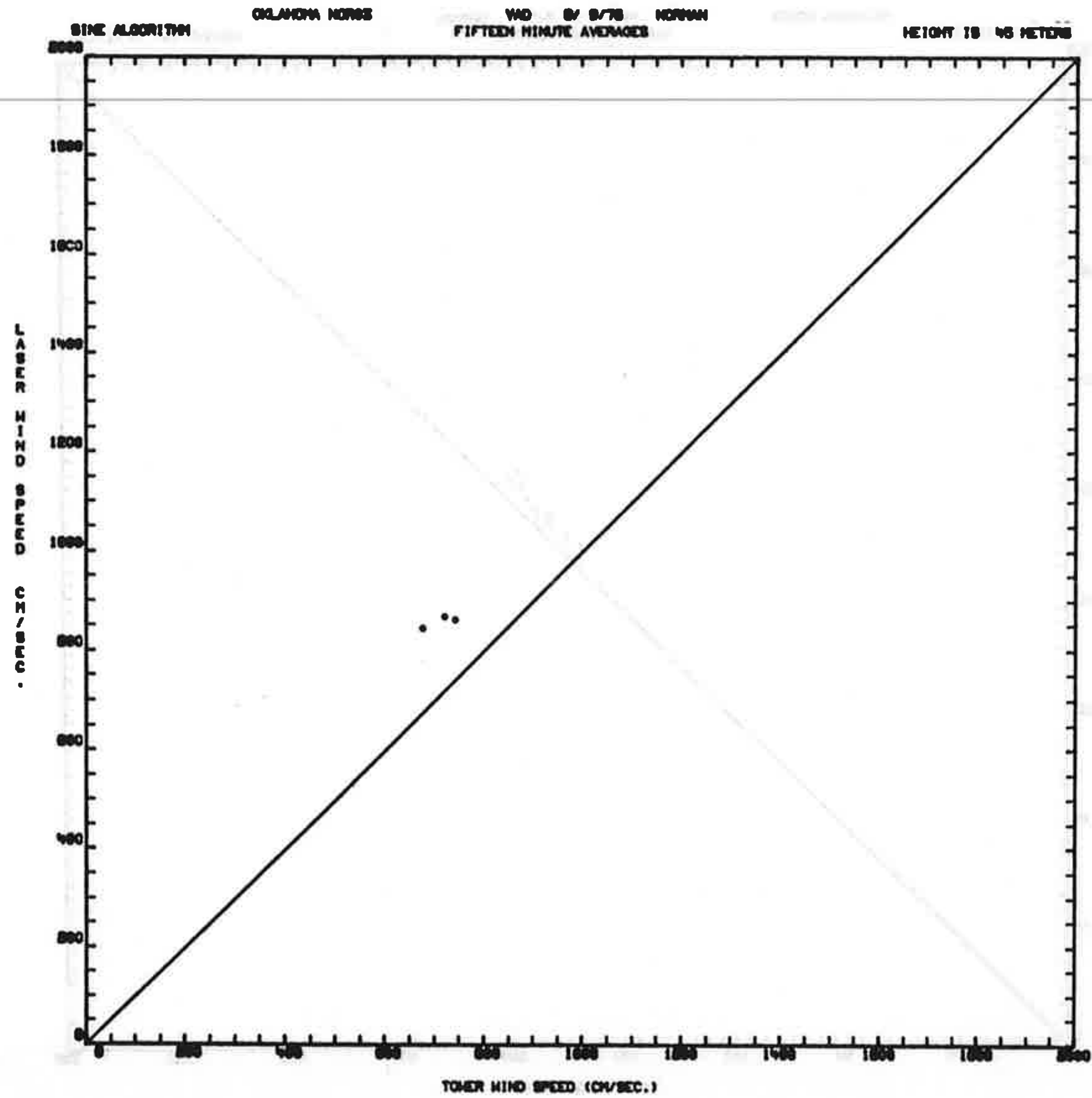


FIGURE D-1 (Continued)

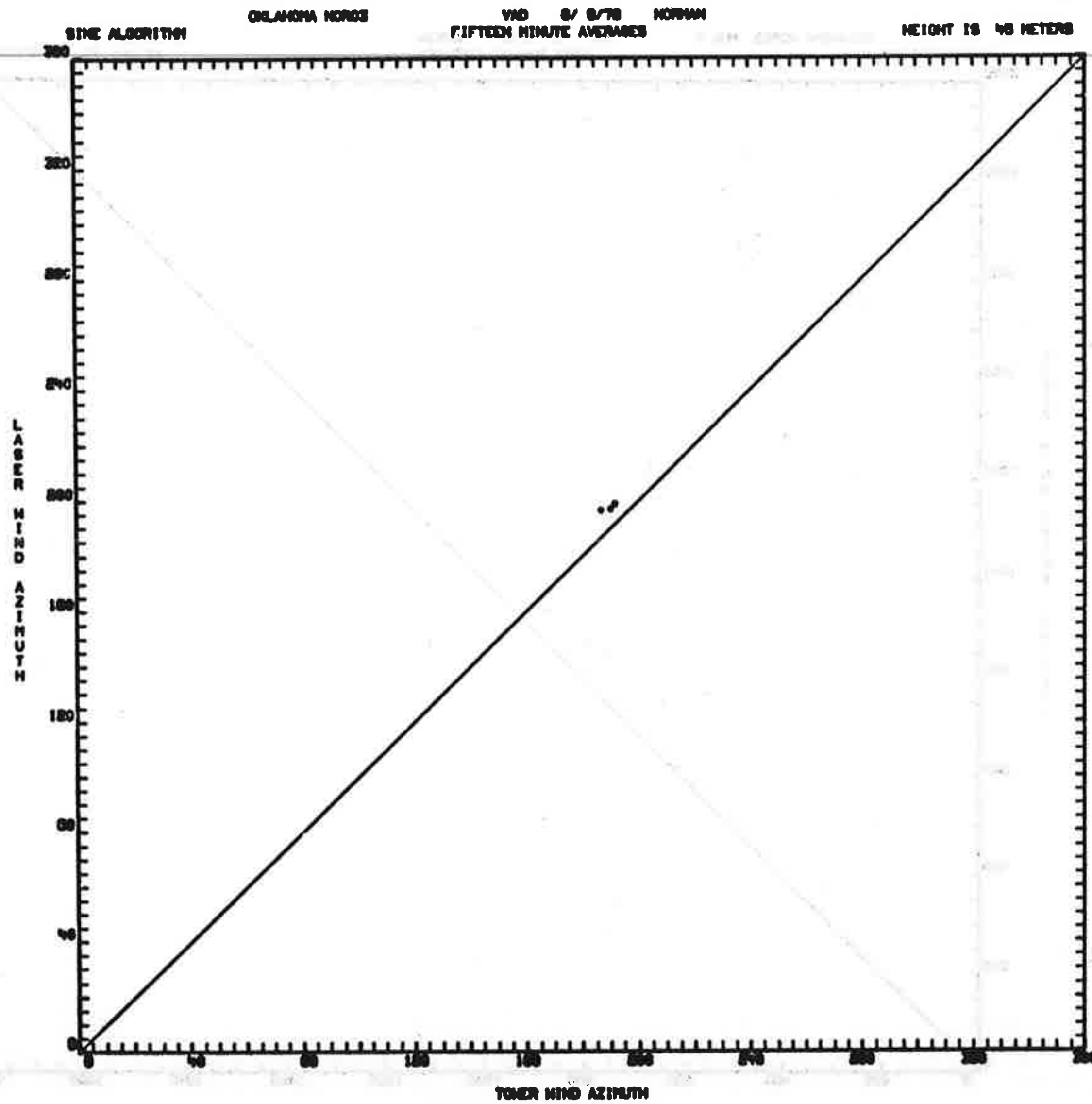
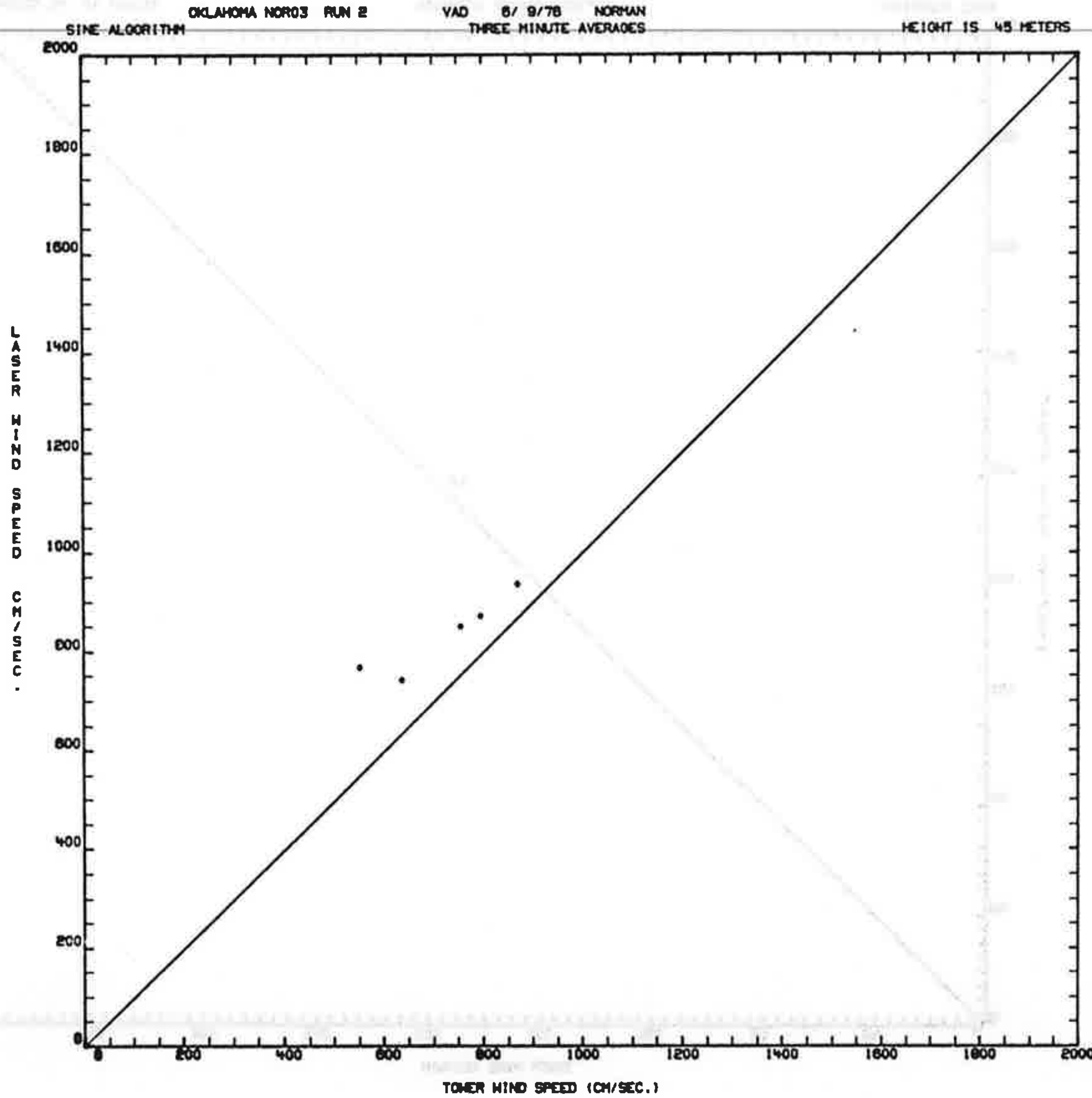


FIGURE D-1 (Continued)



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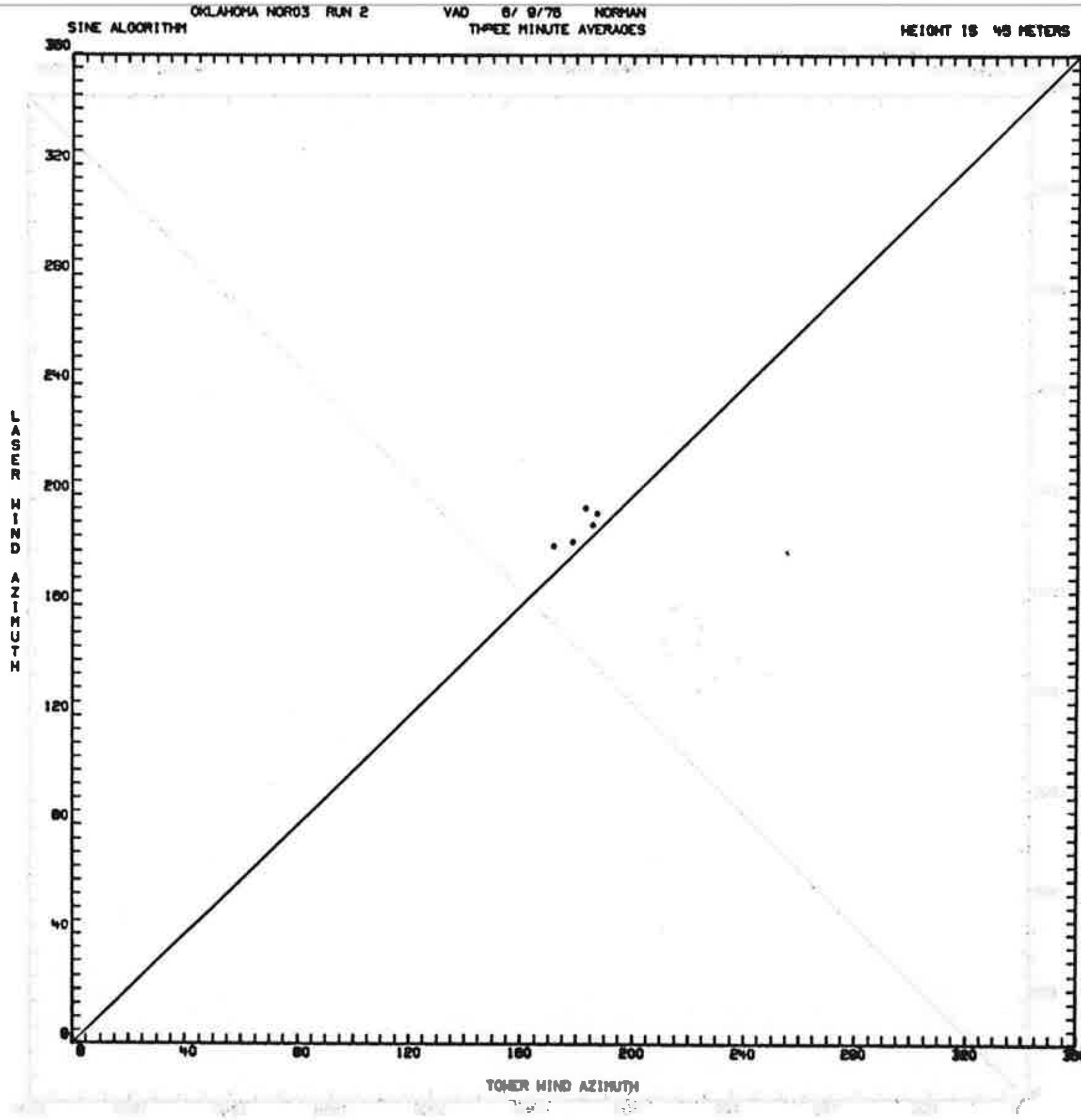

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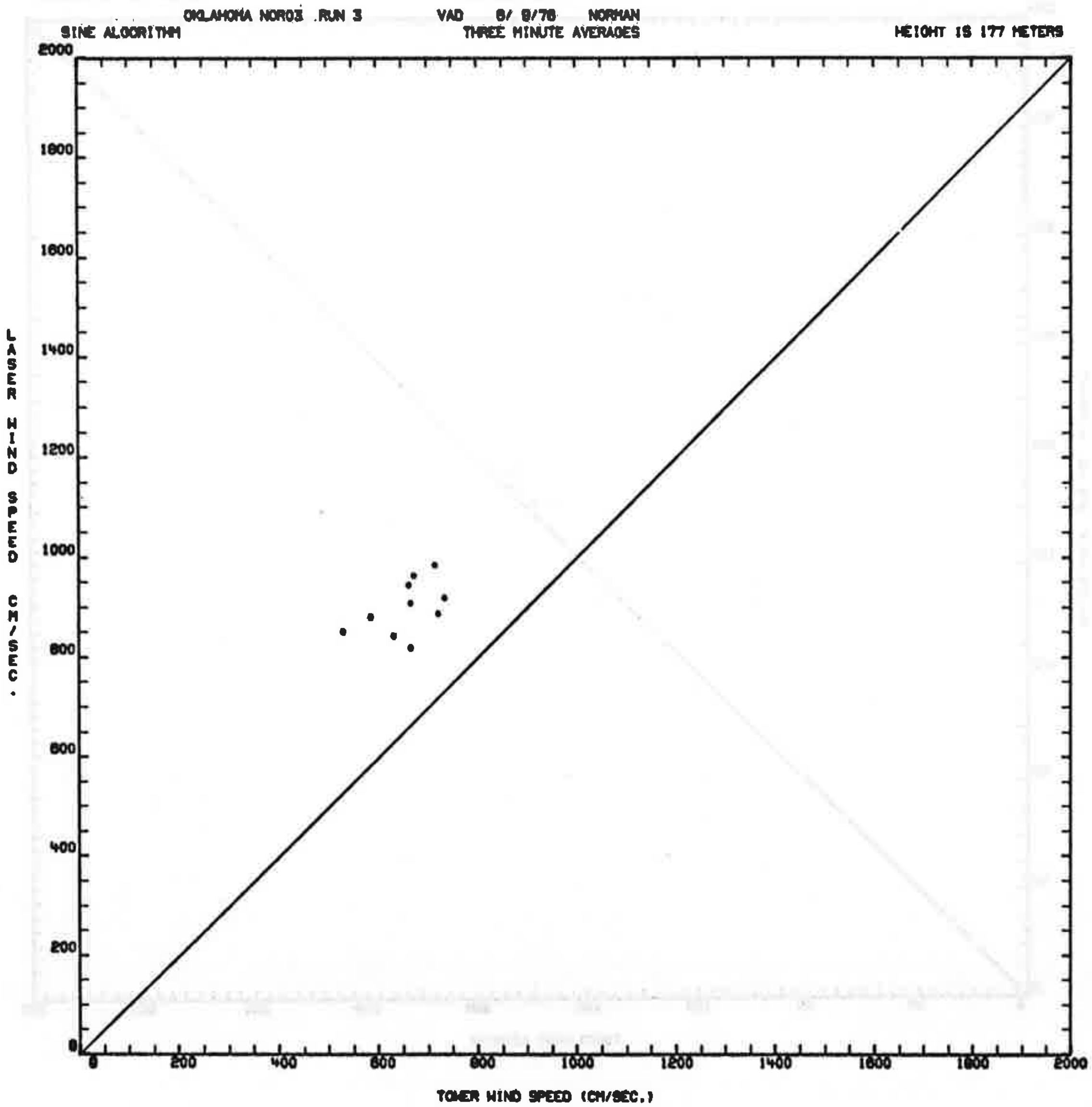

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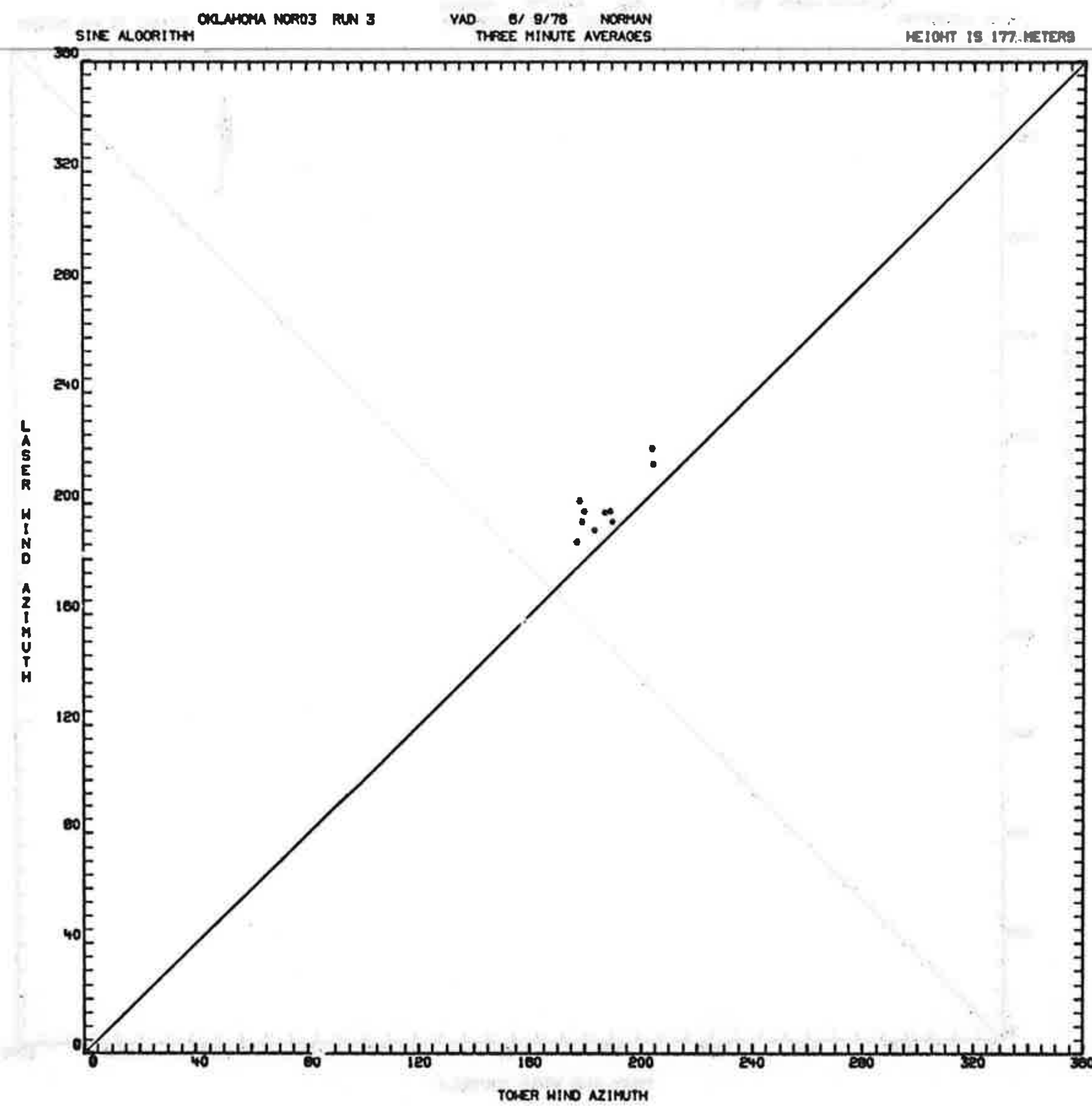

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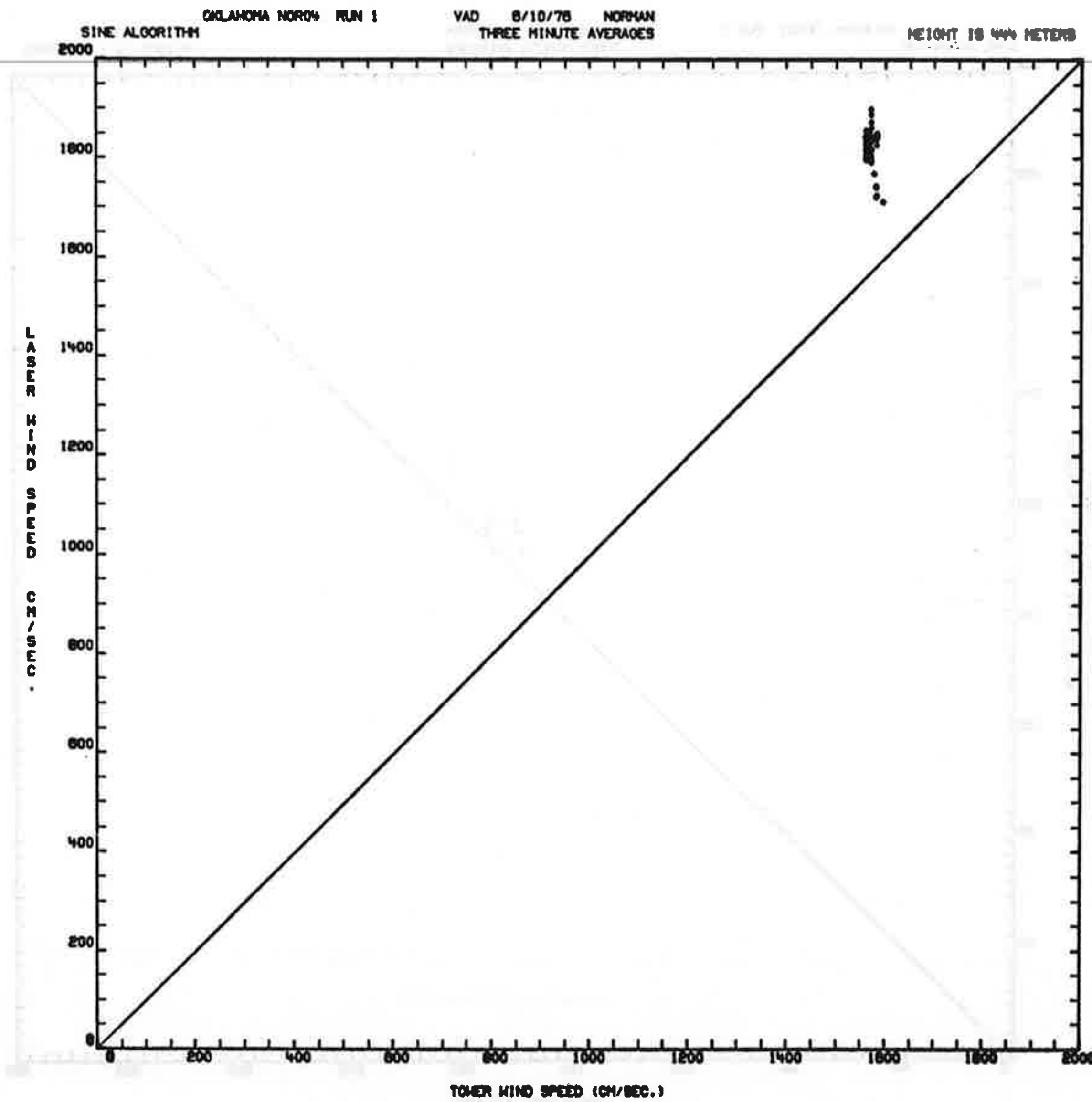

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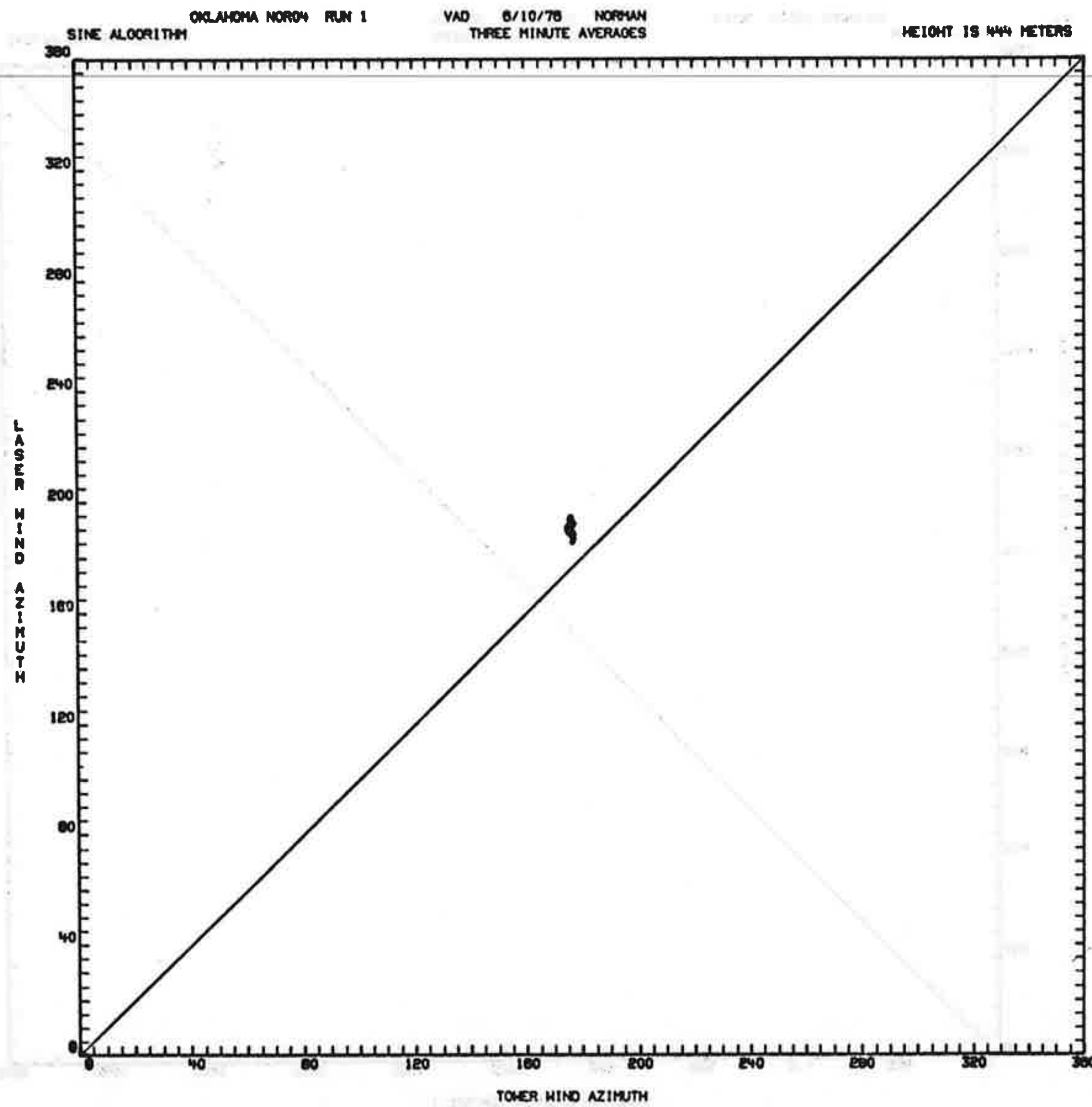

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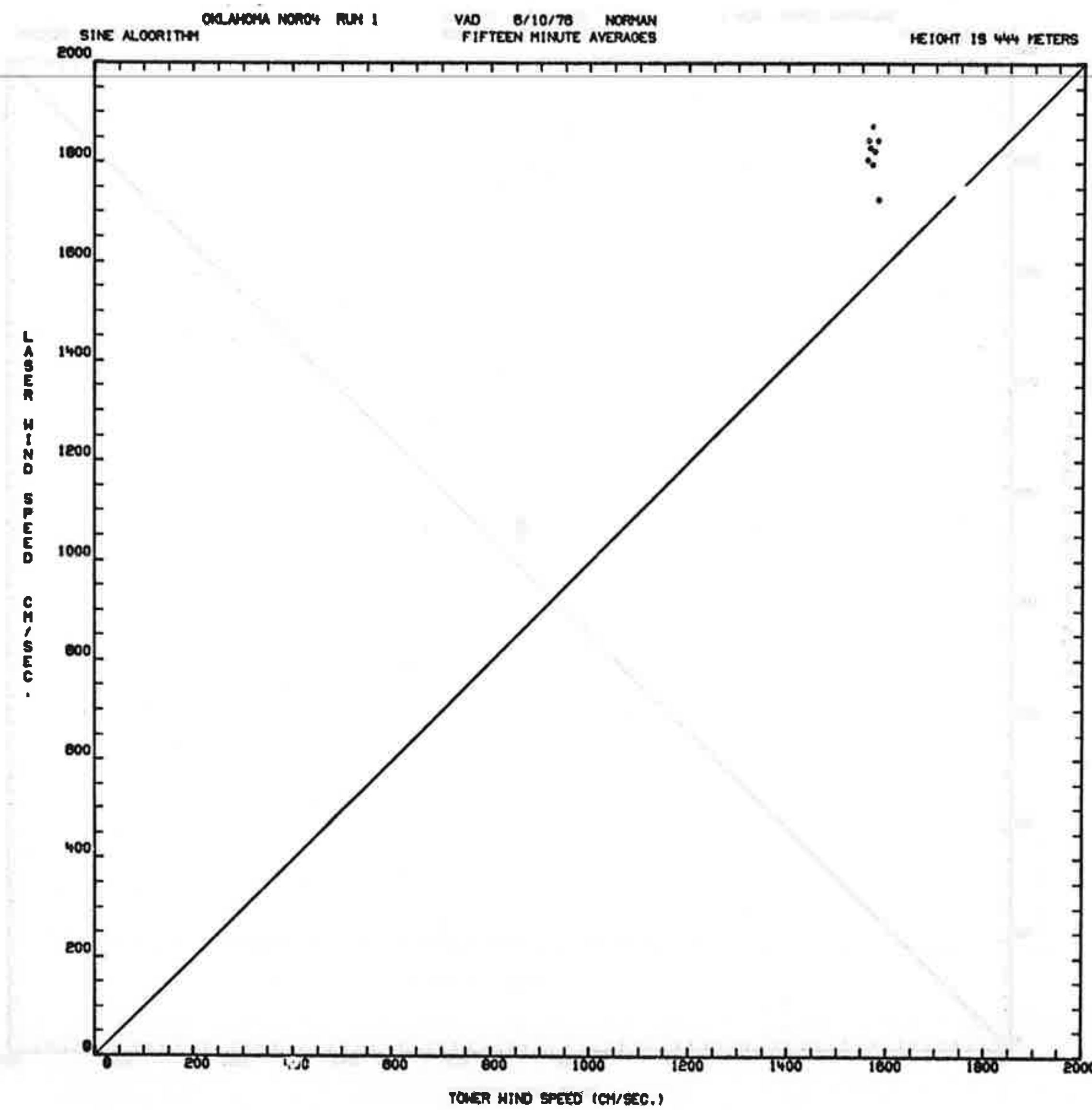

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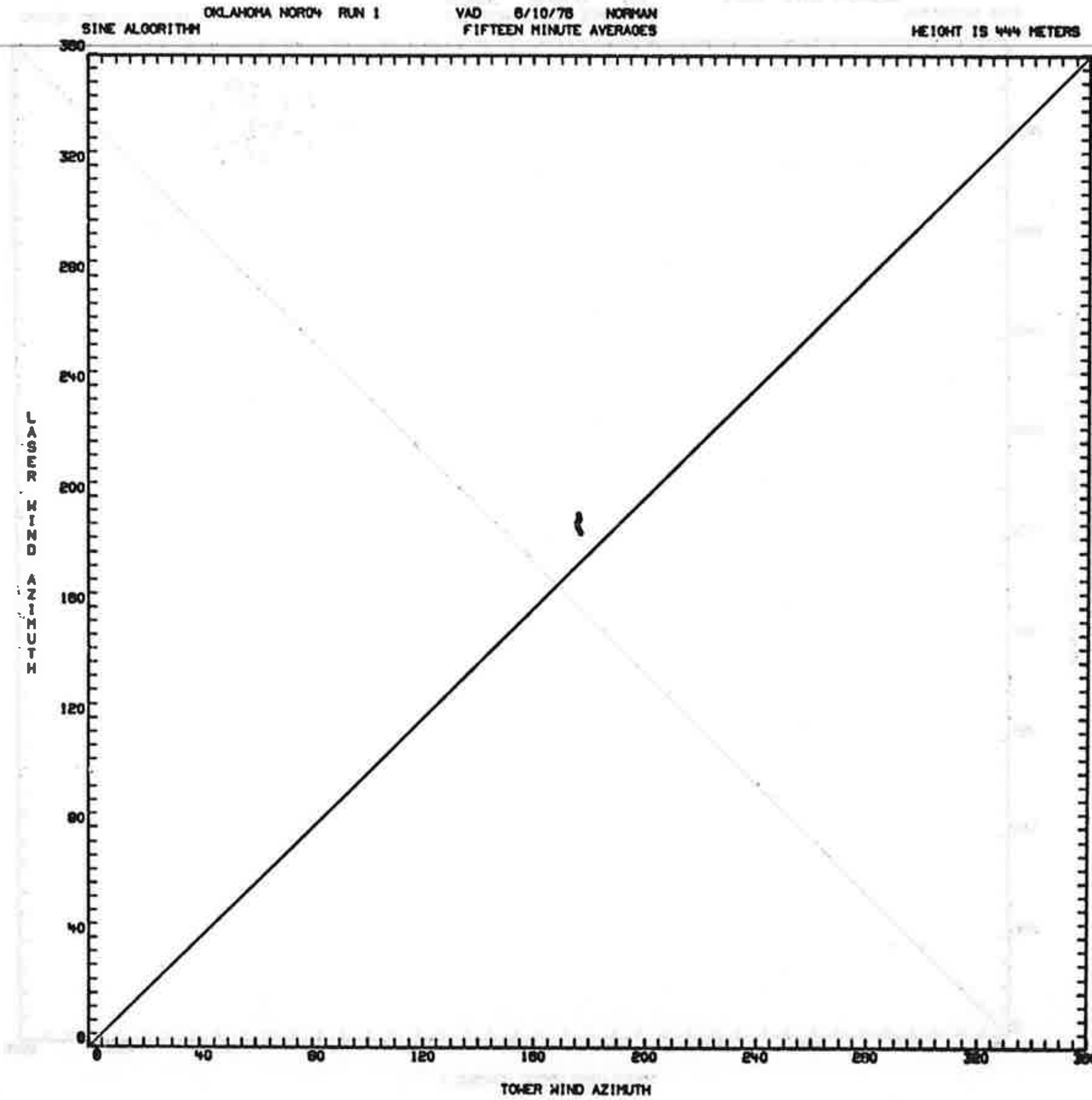

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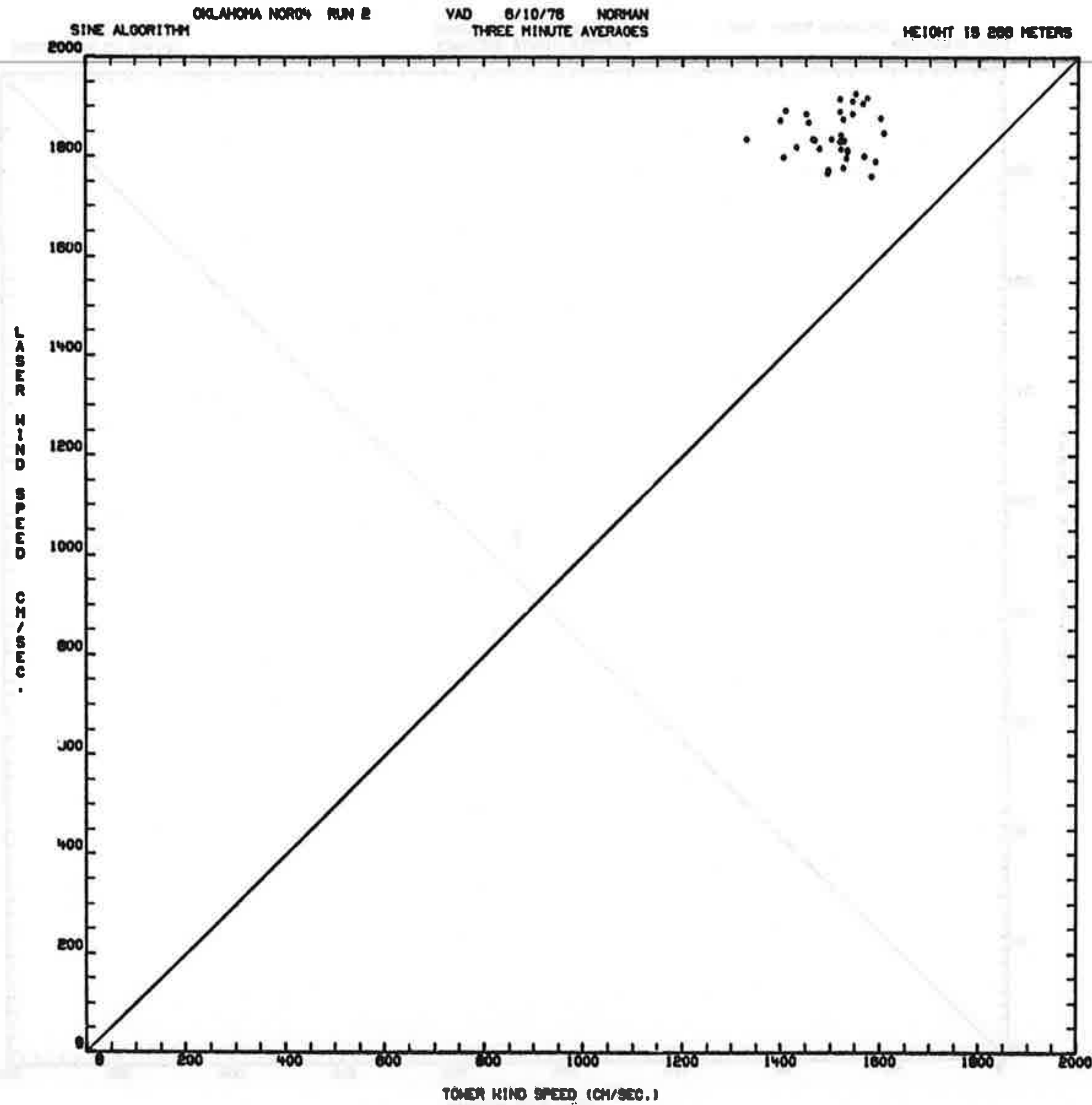

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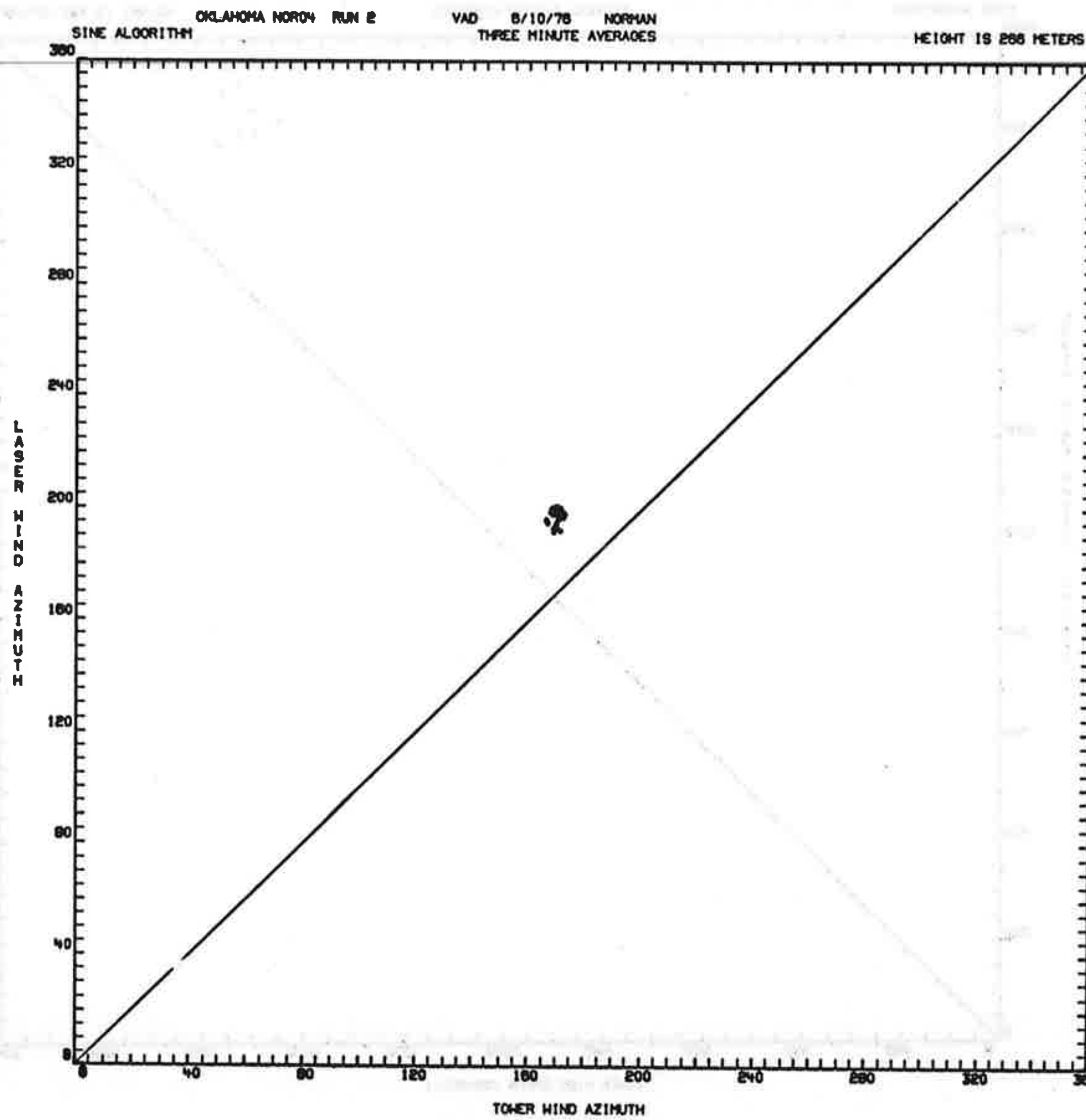

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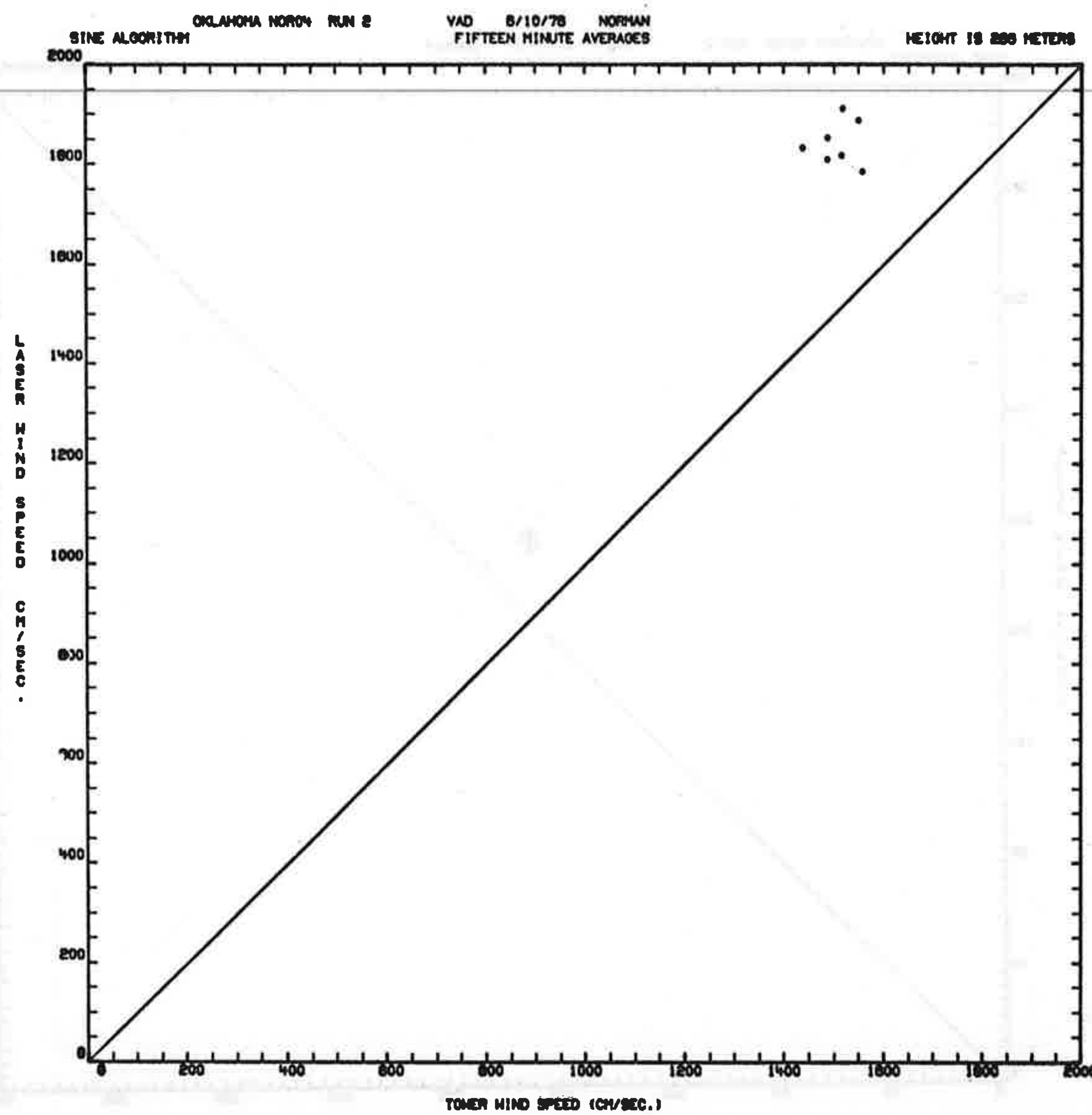

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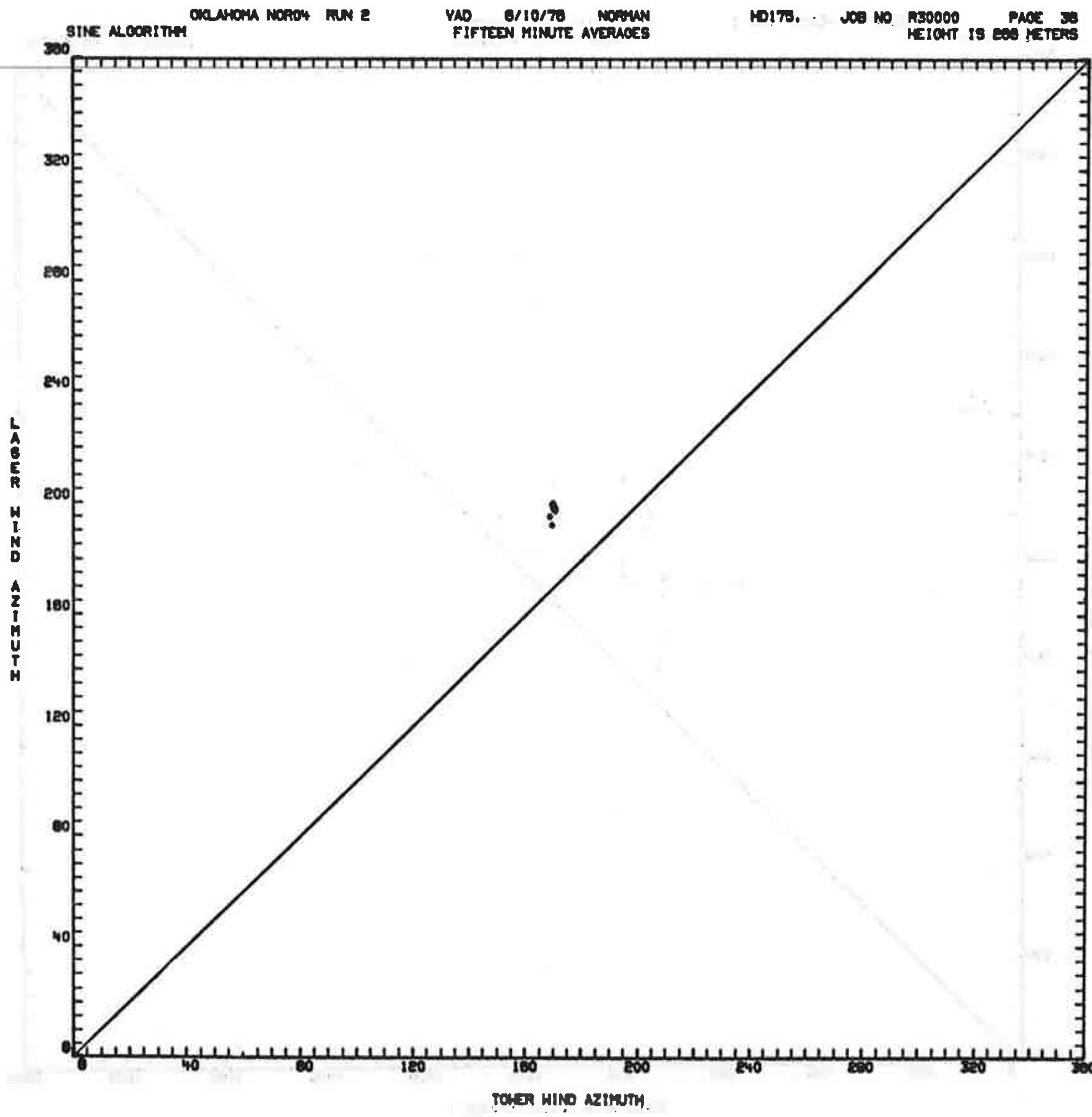

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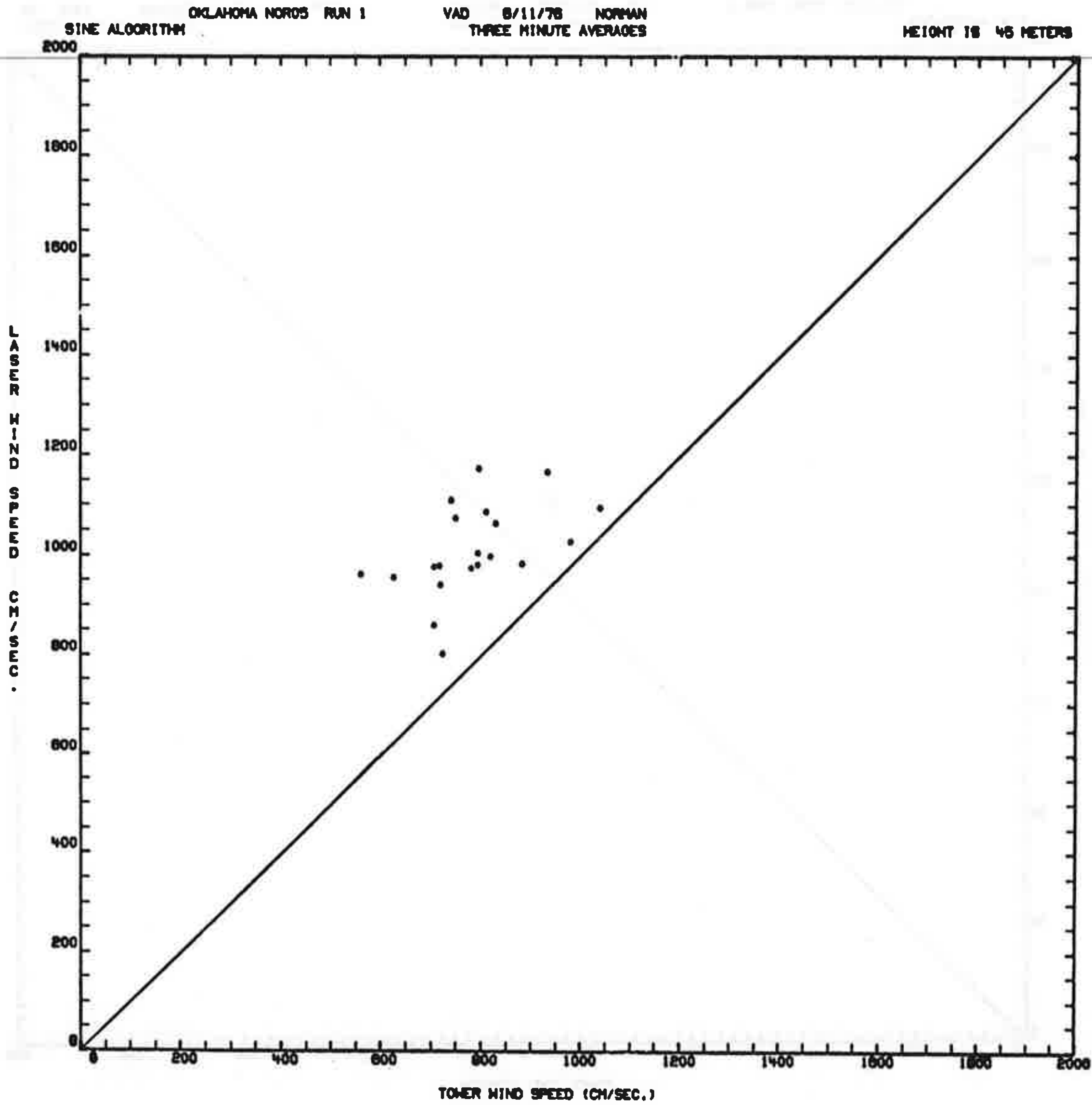

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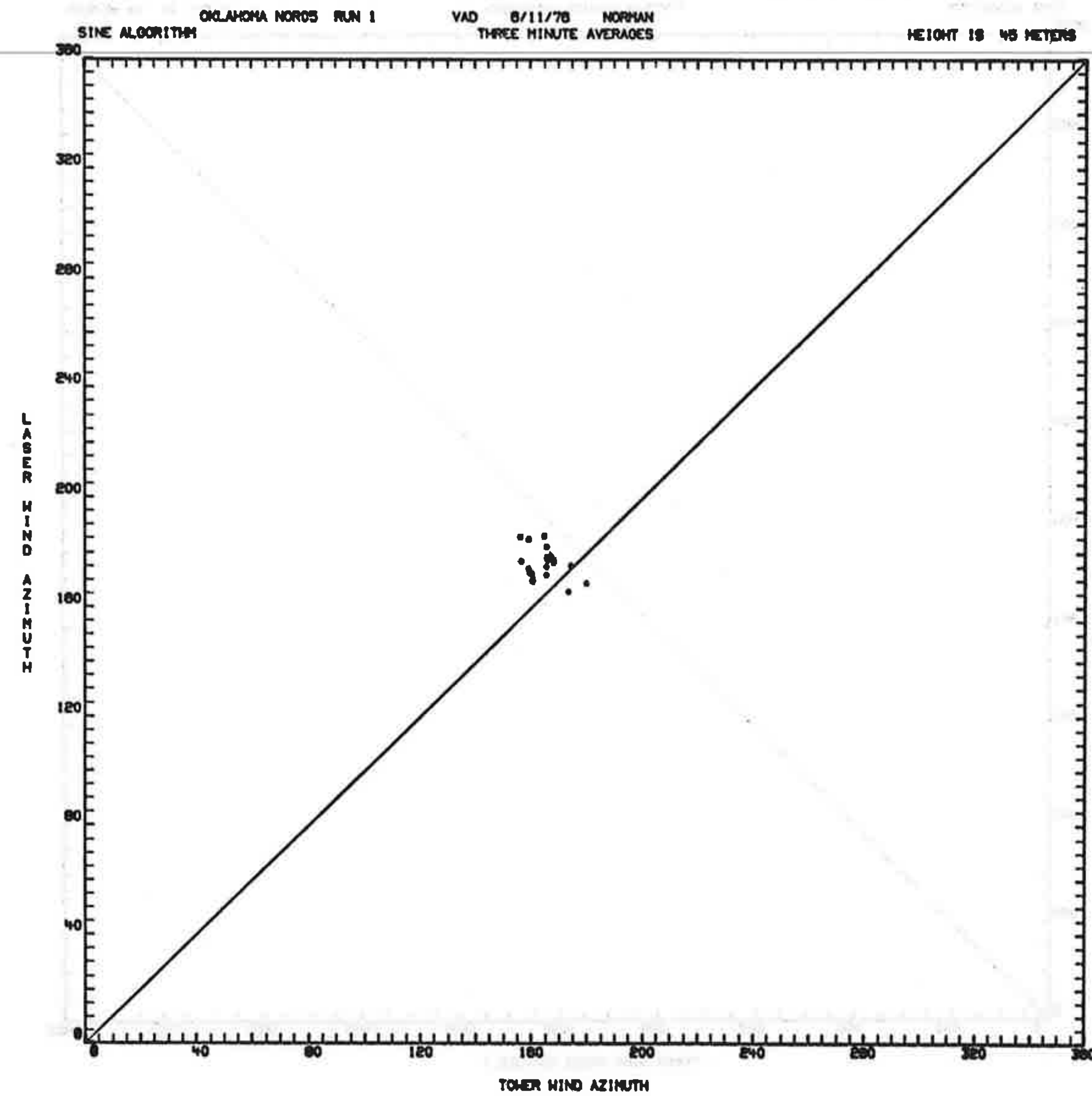

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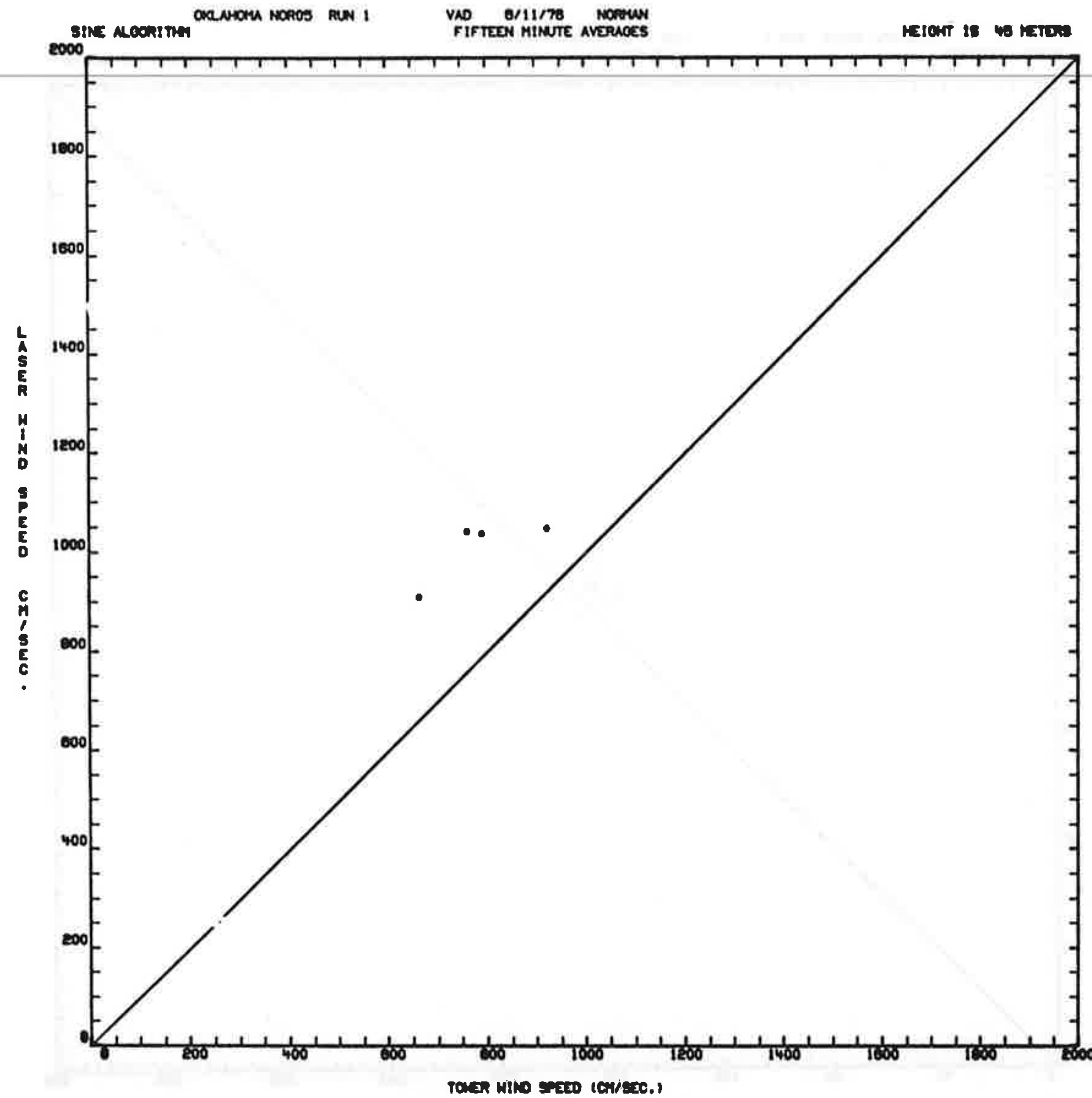

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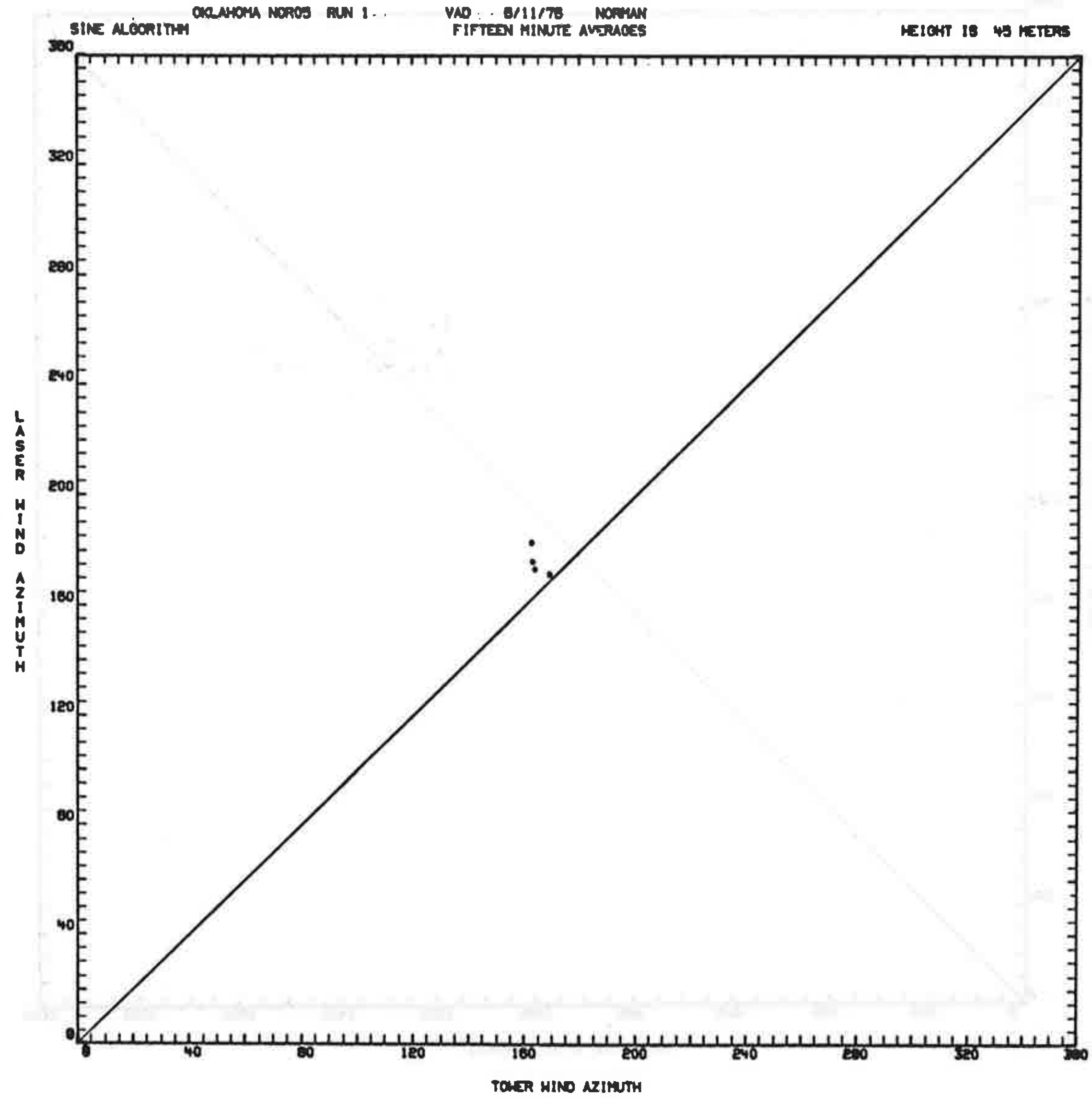

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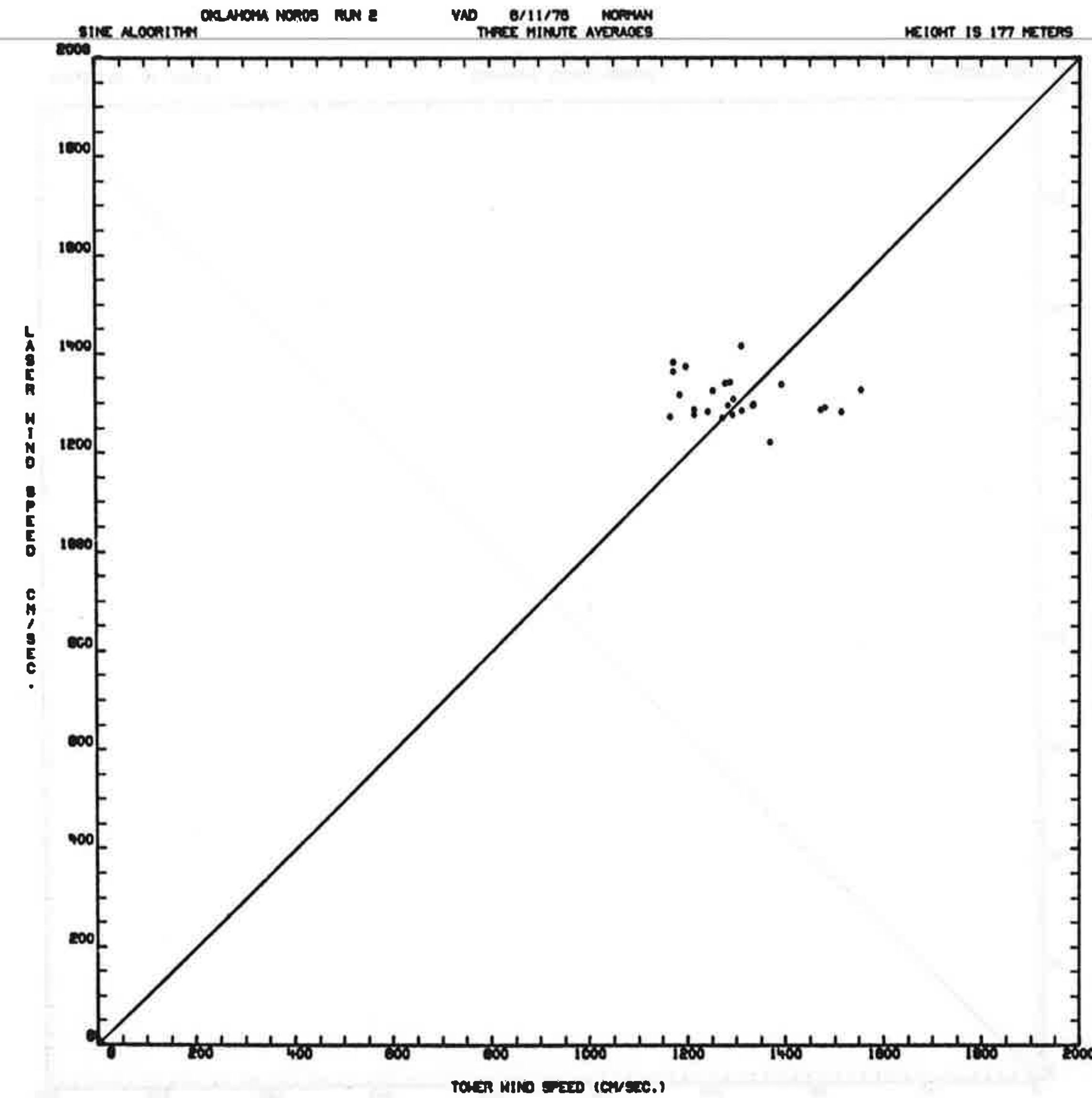

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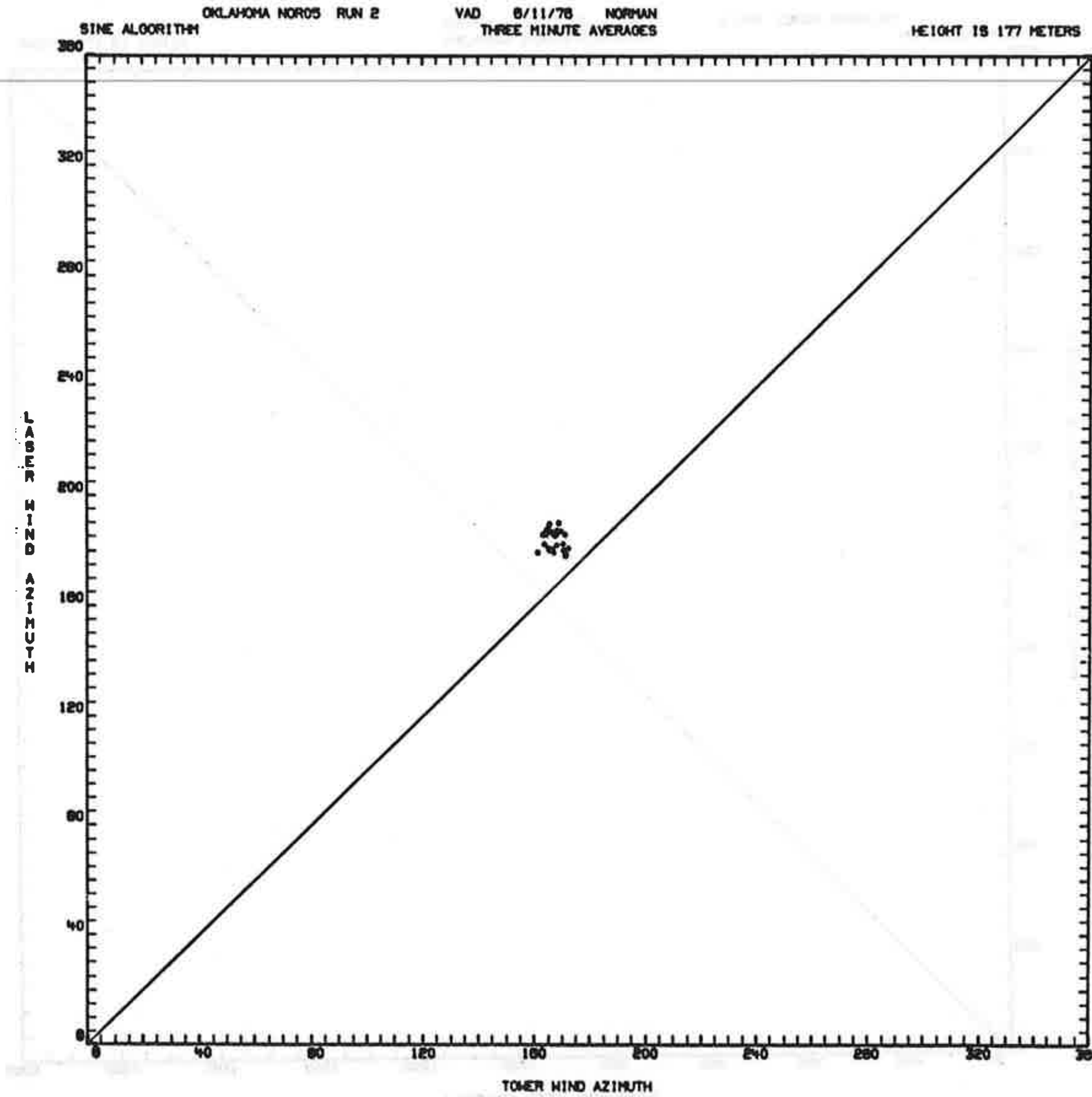

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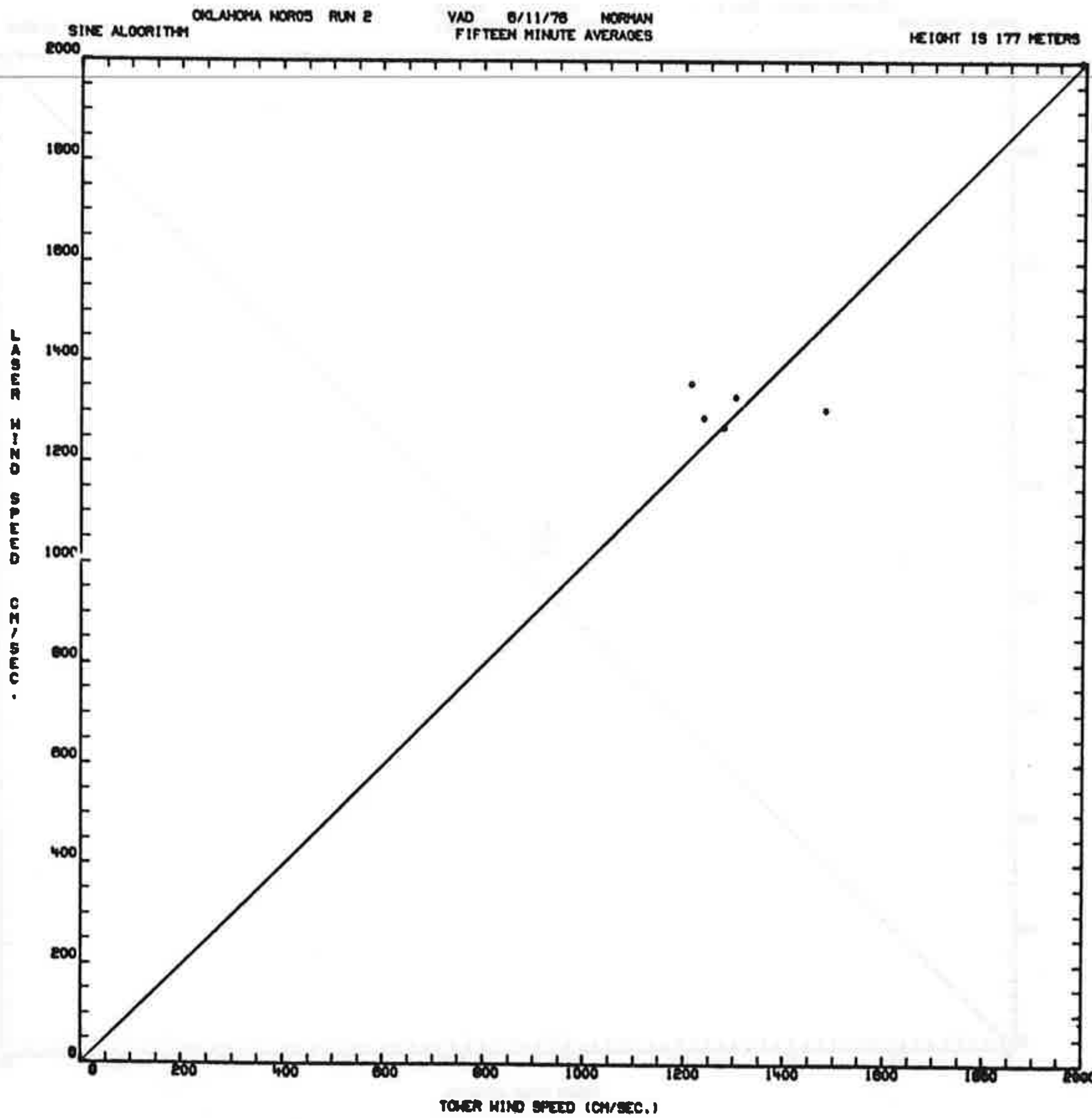

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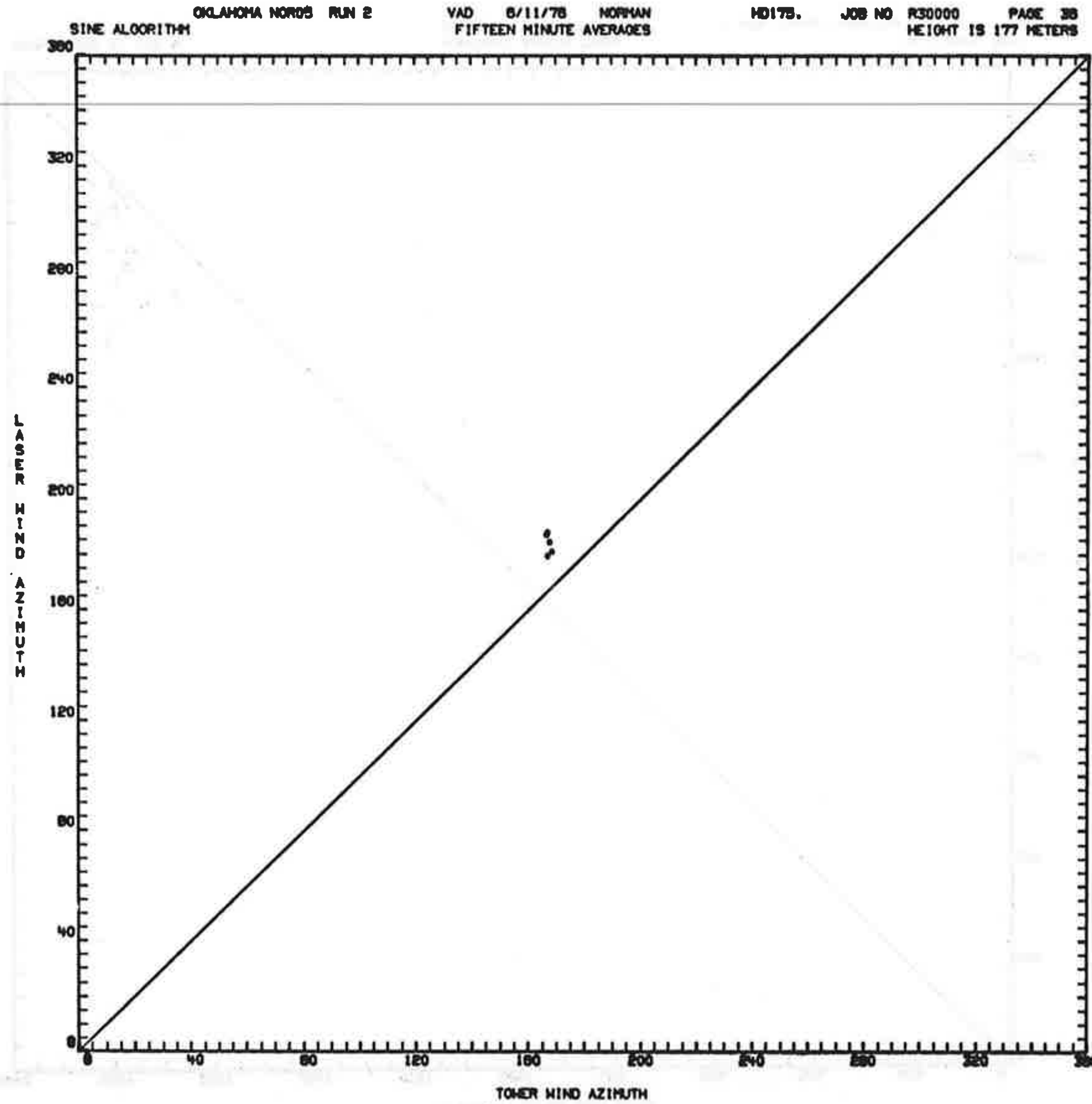

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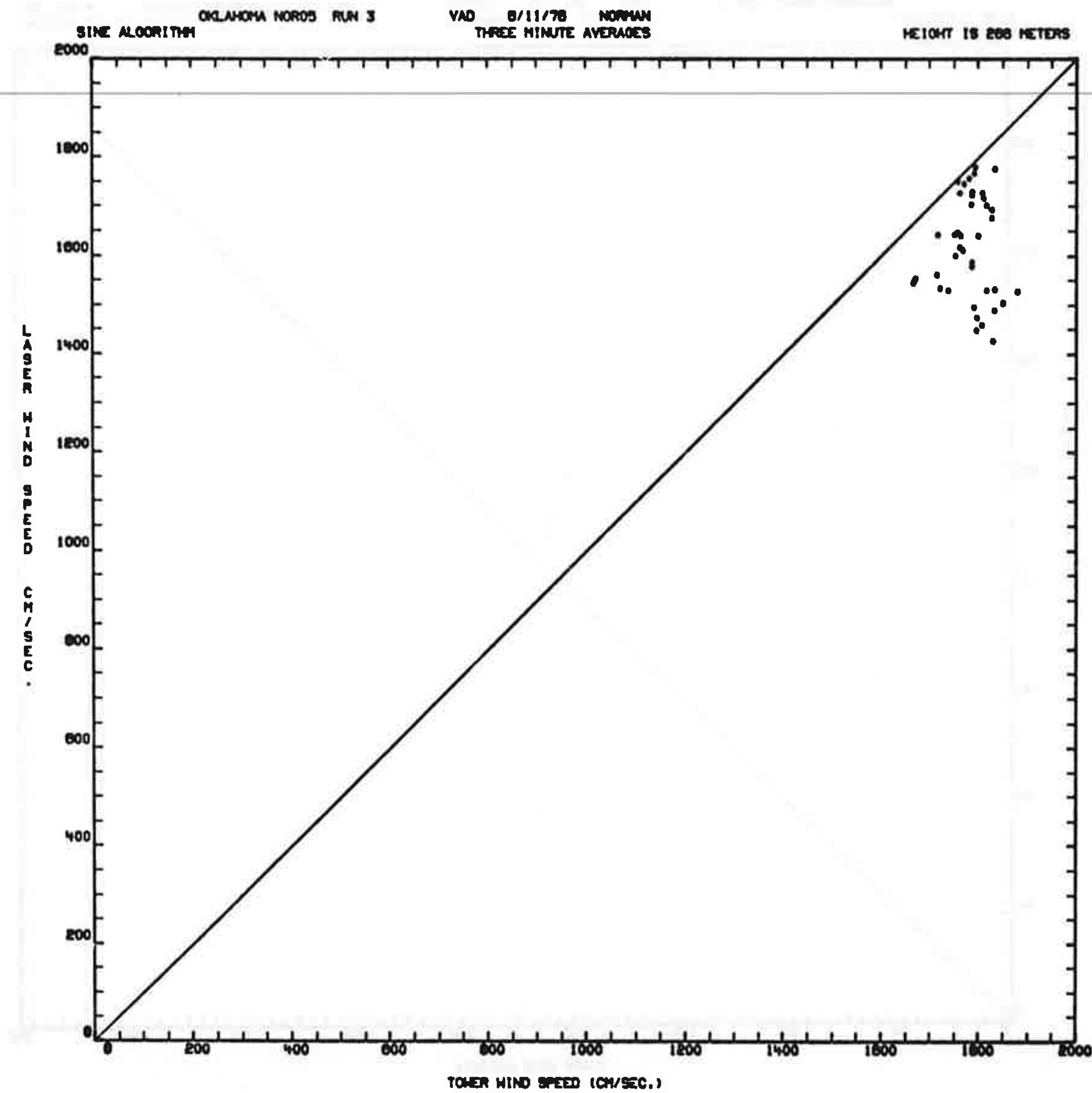

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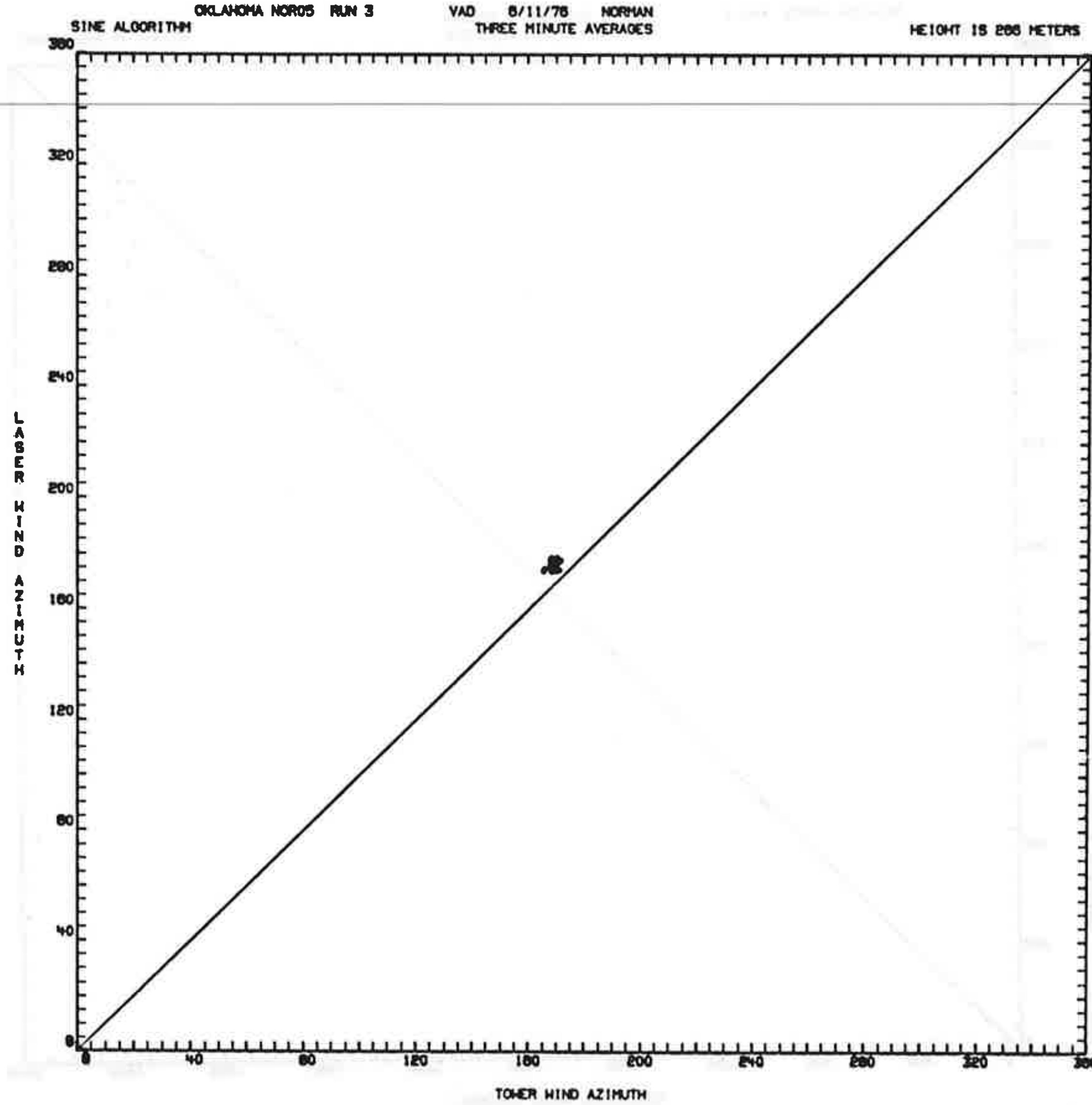

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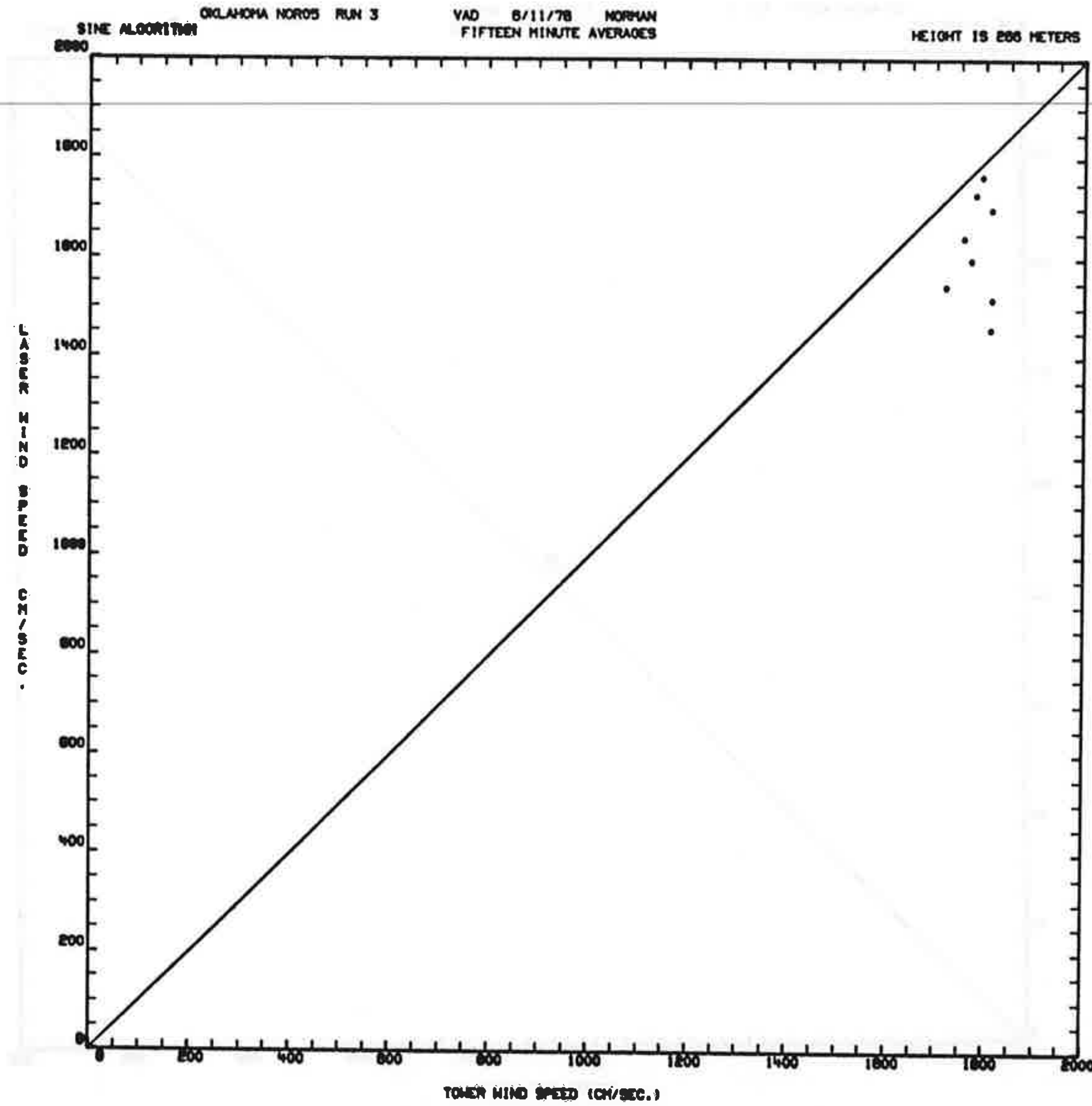

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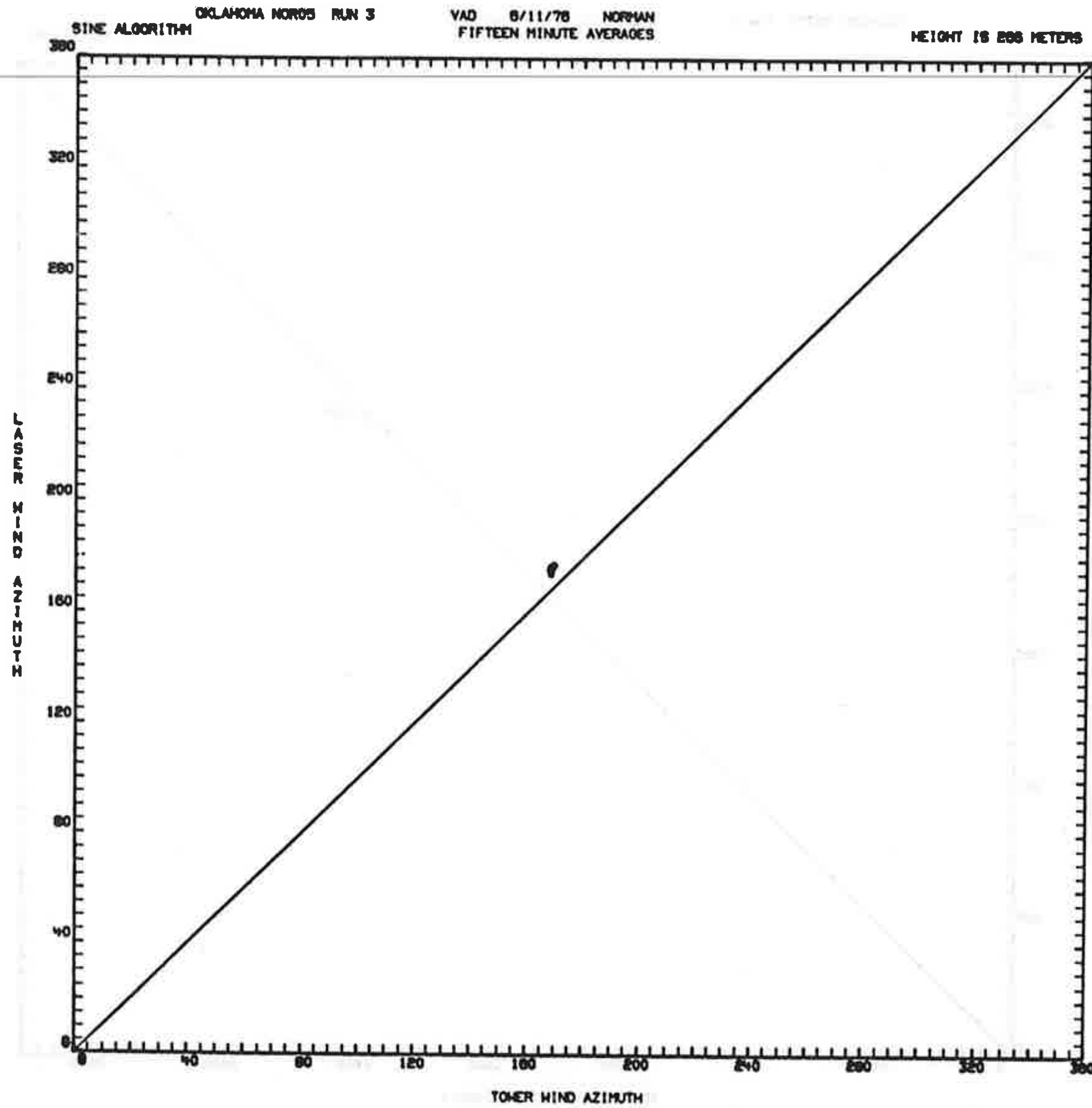

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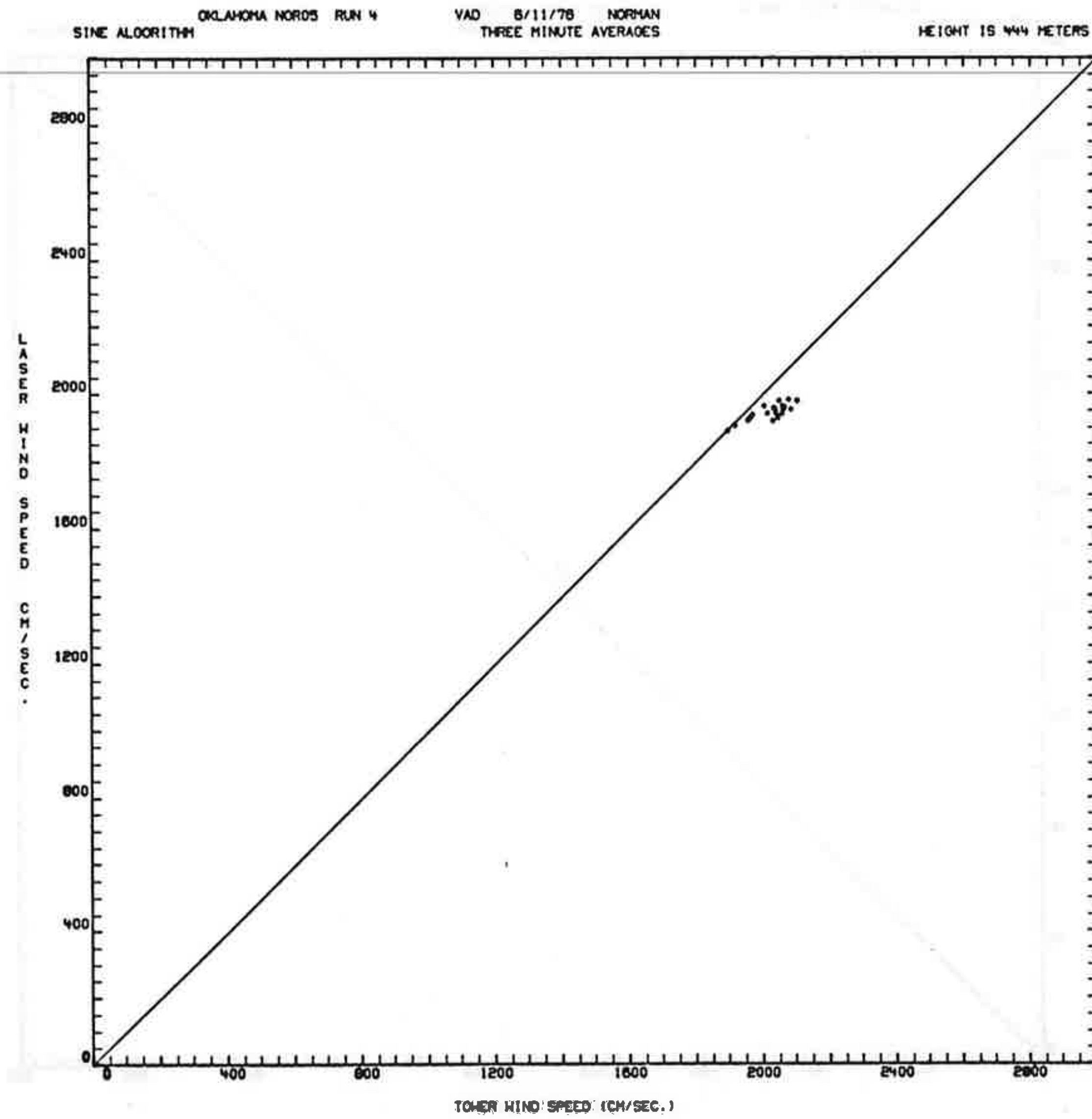

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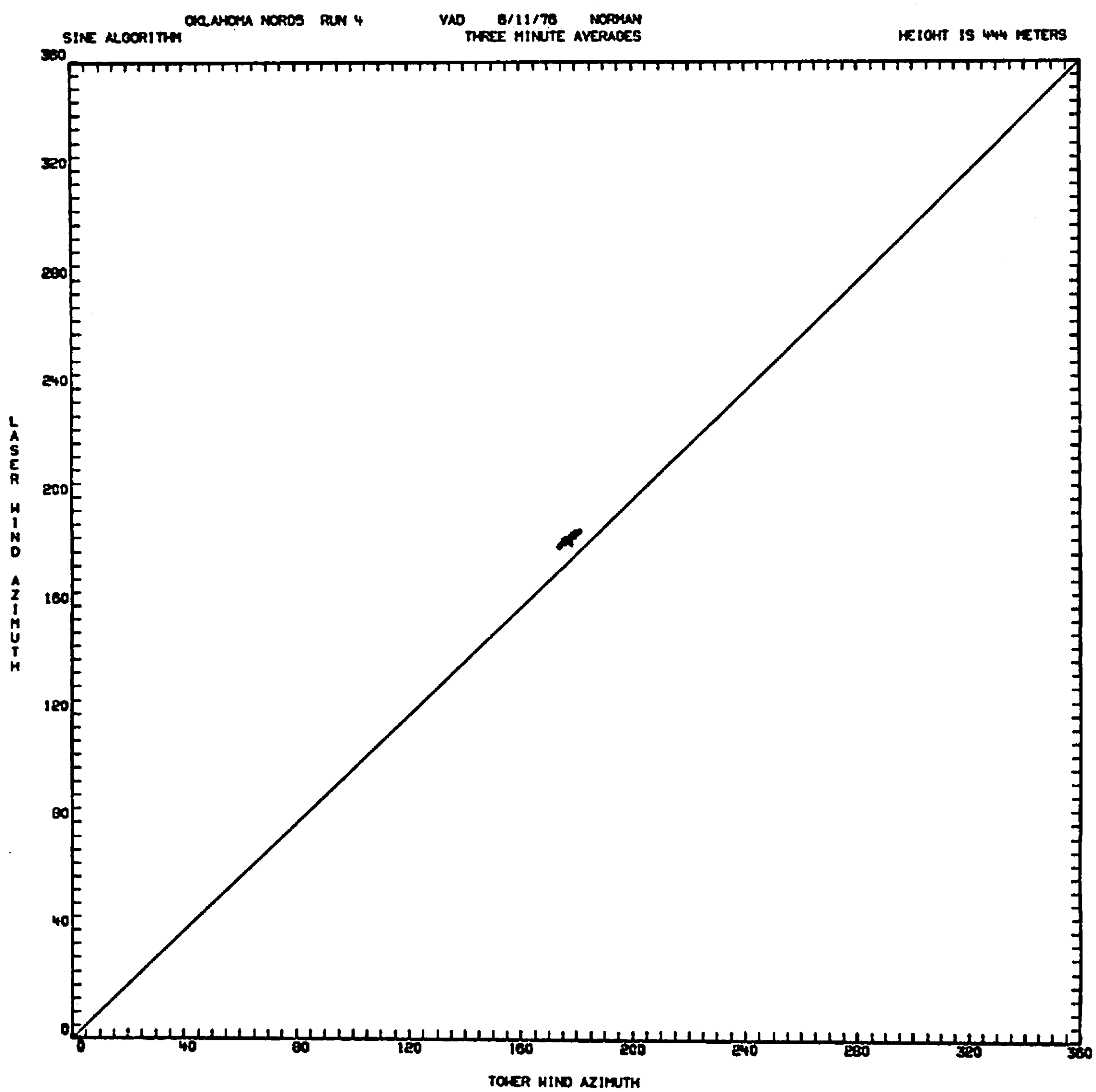

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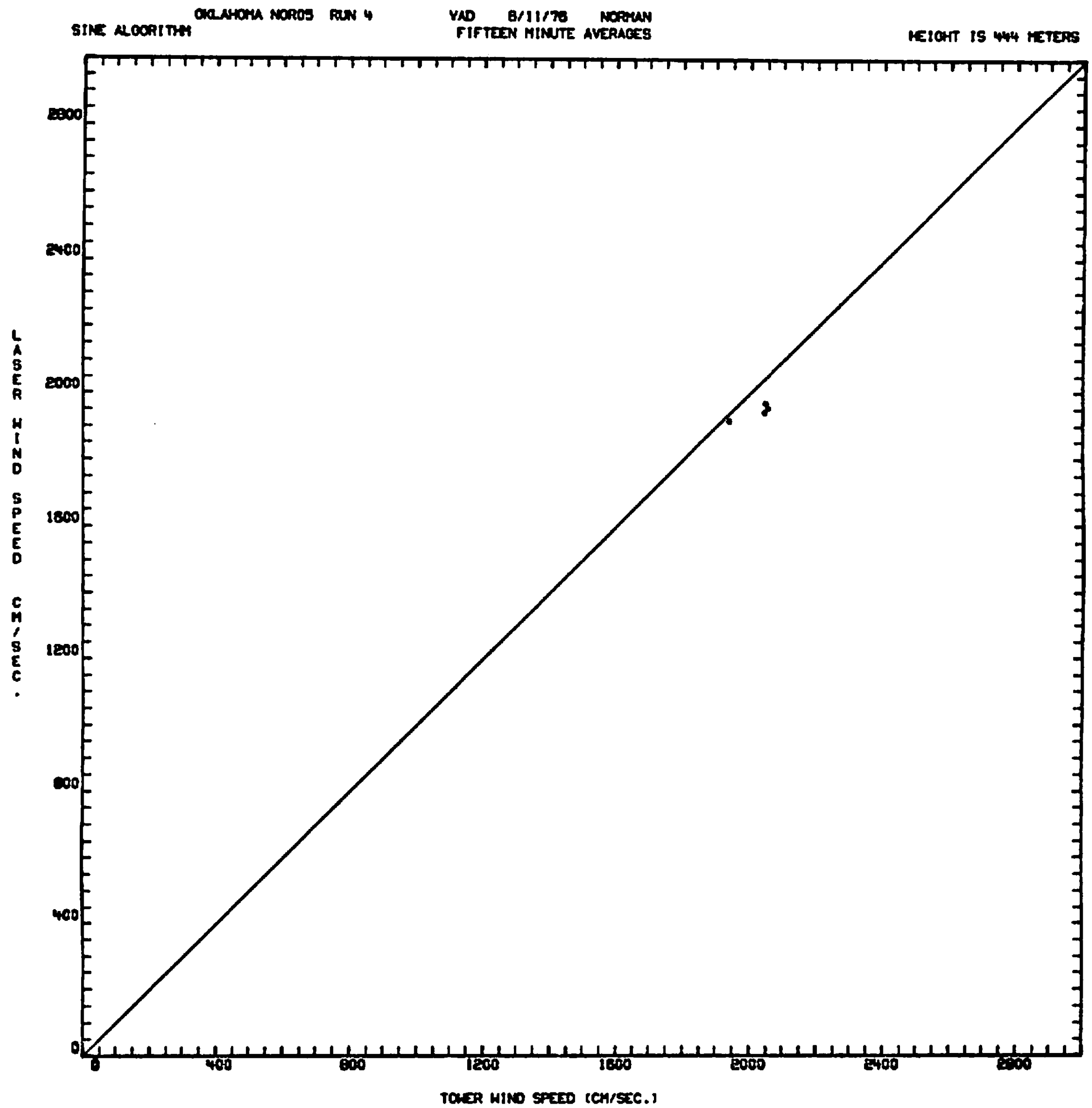

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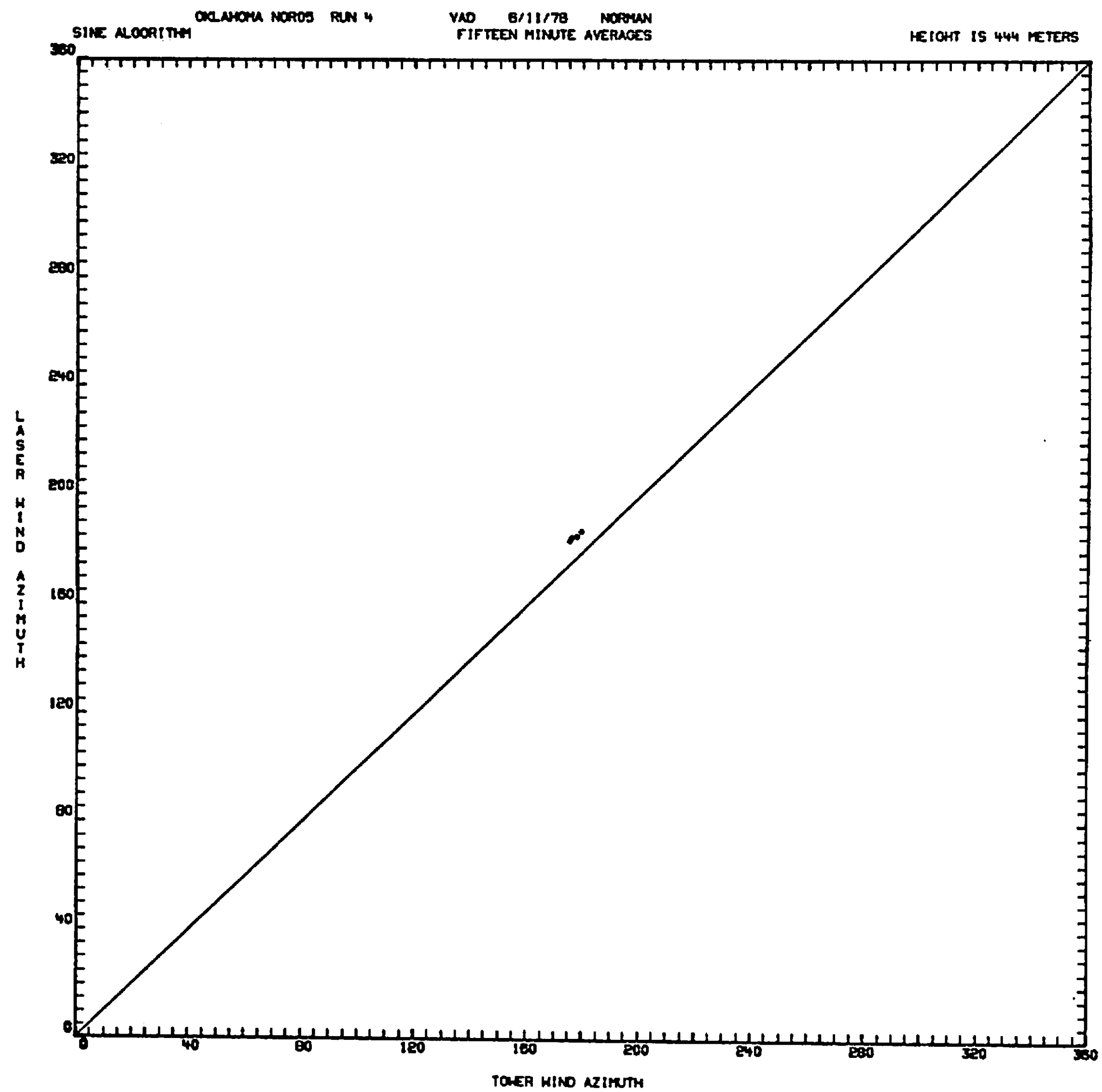

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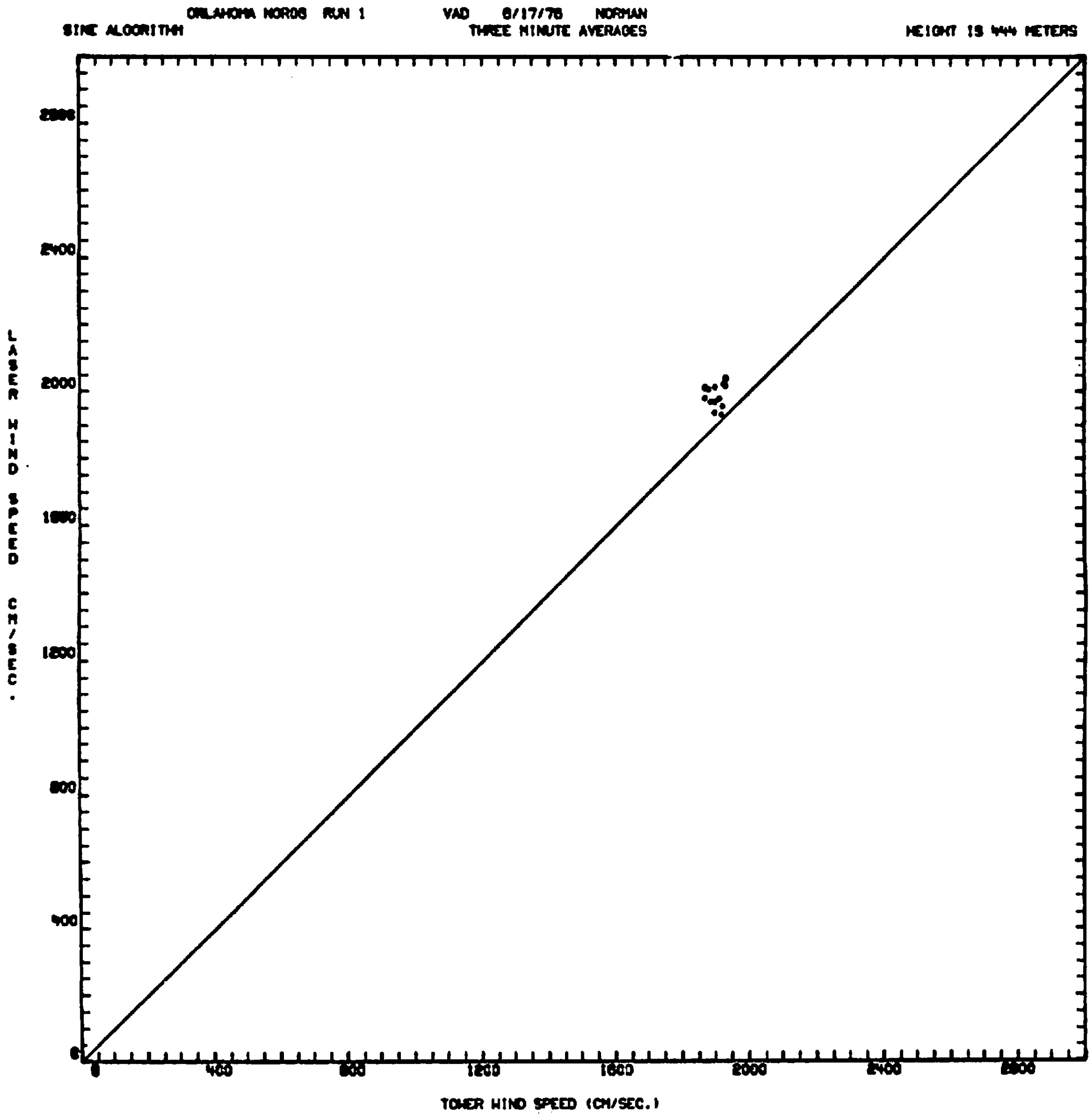

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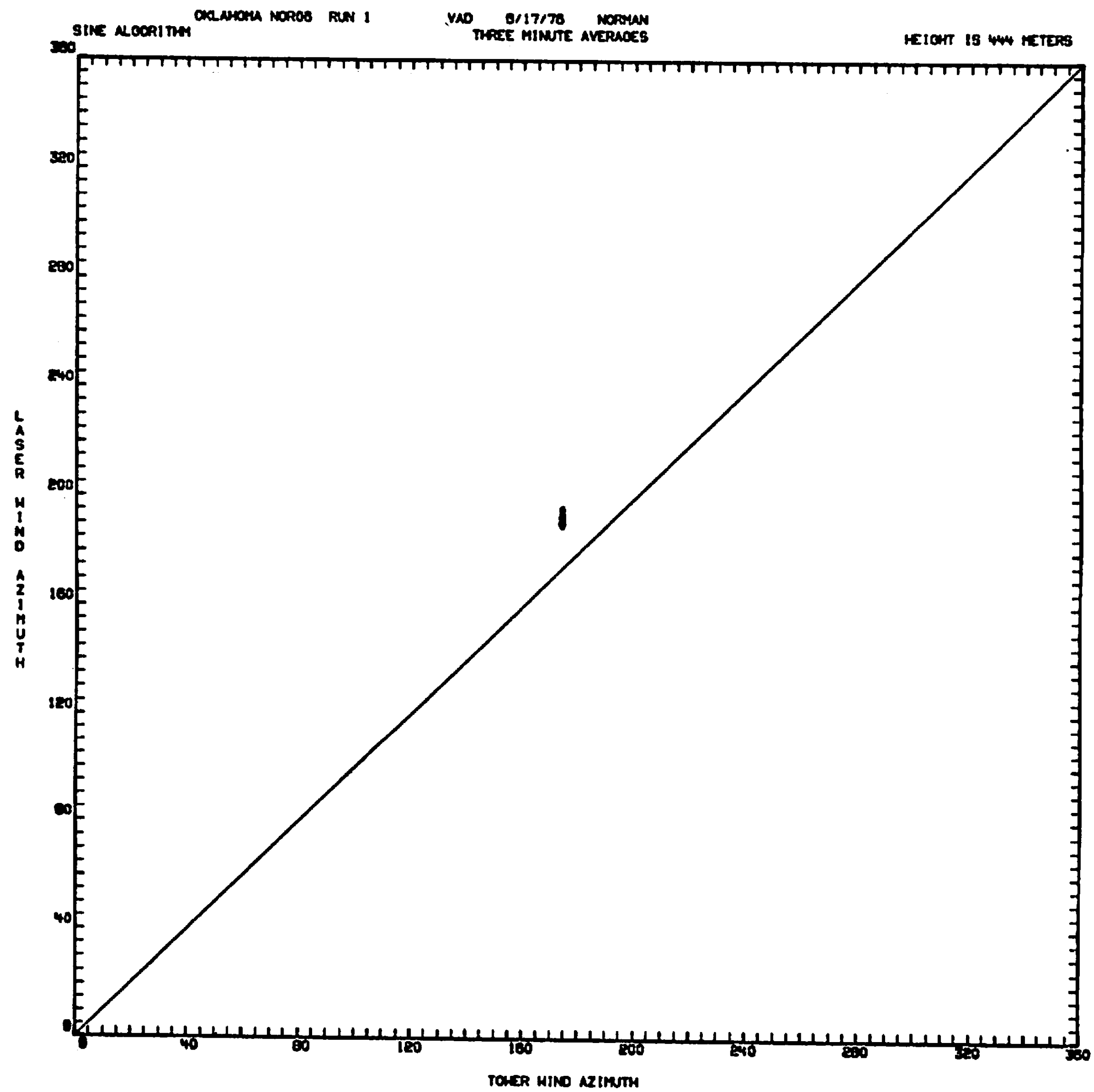

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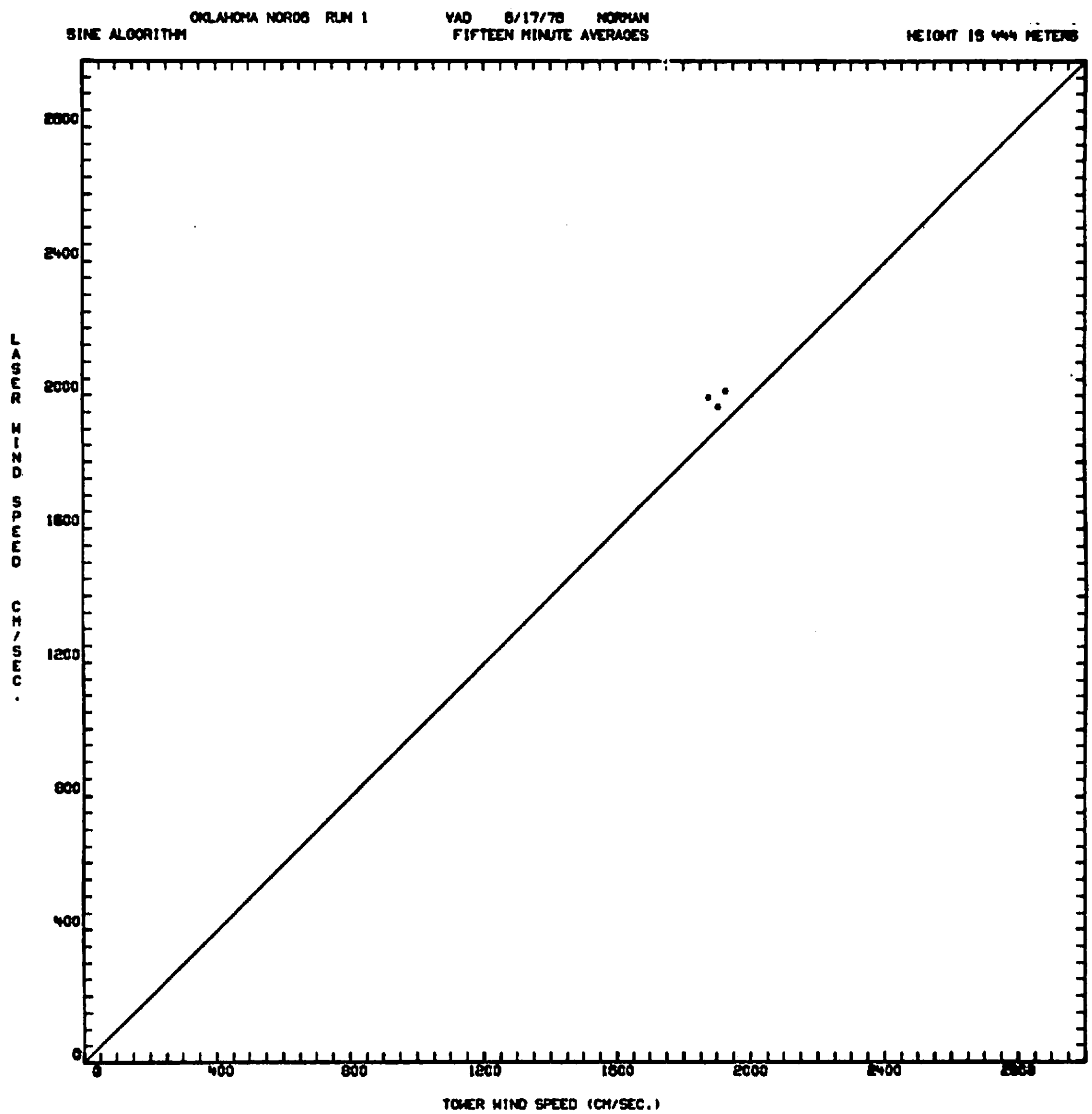

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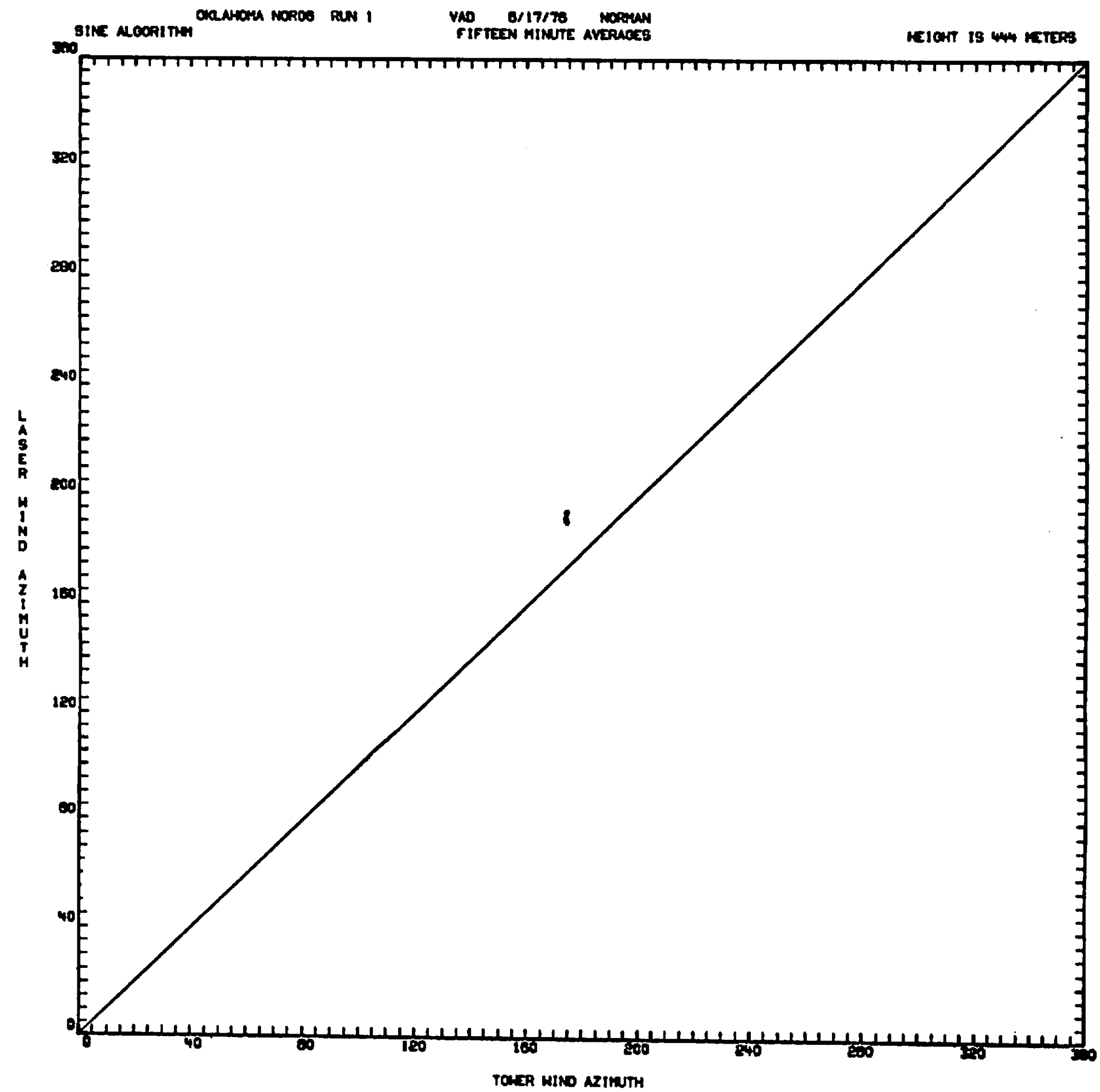

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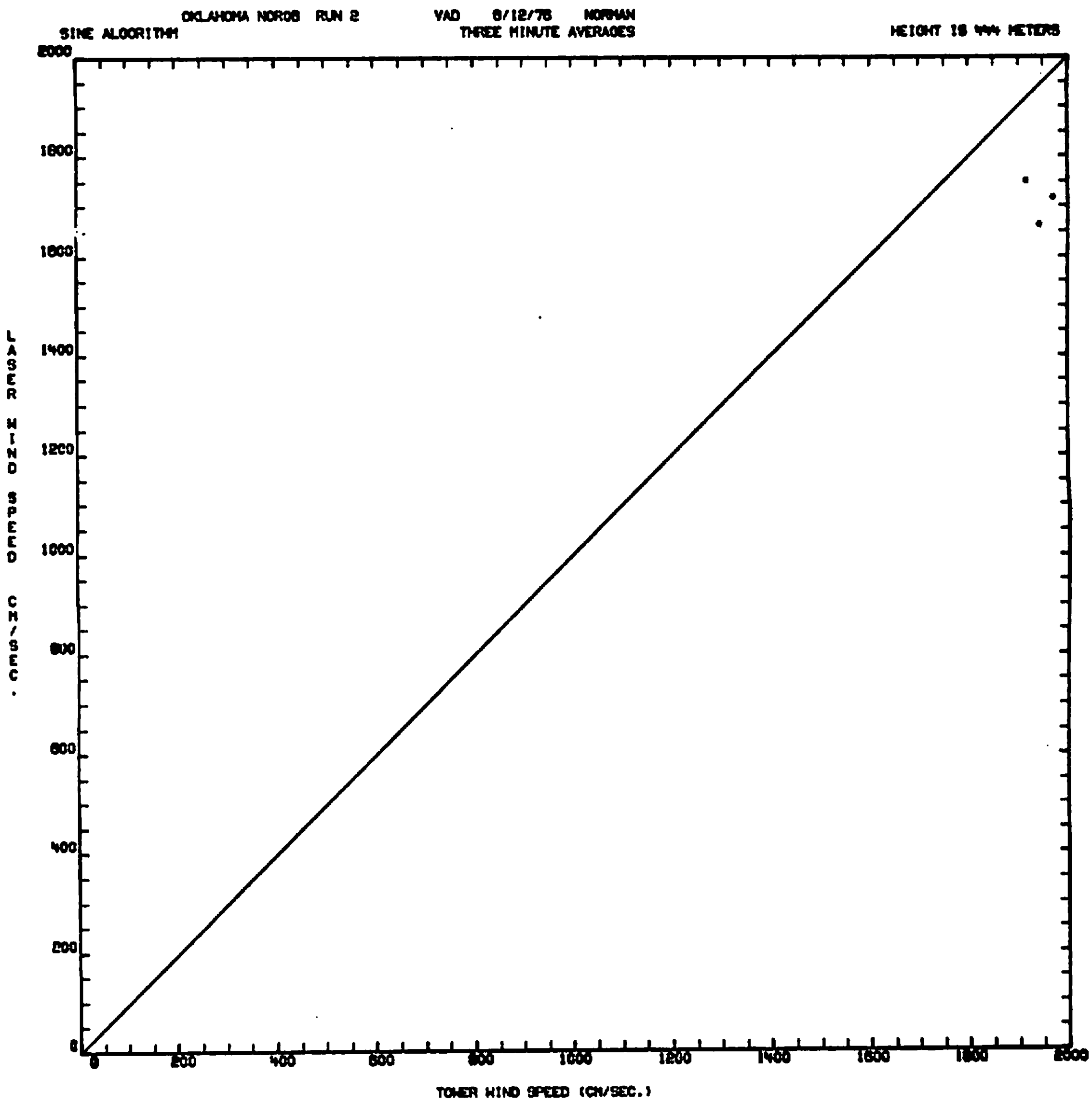

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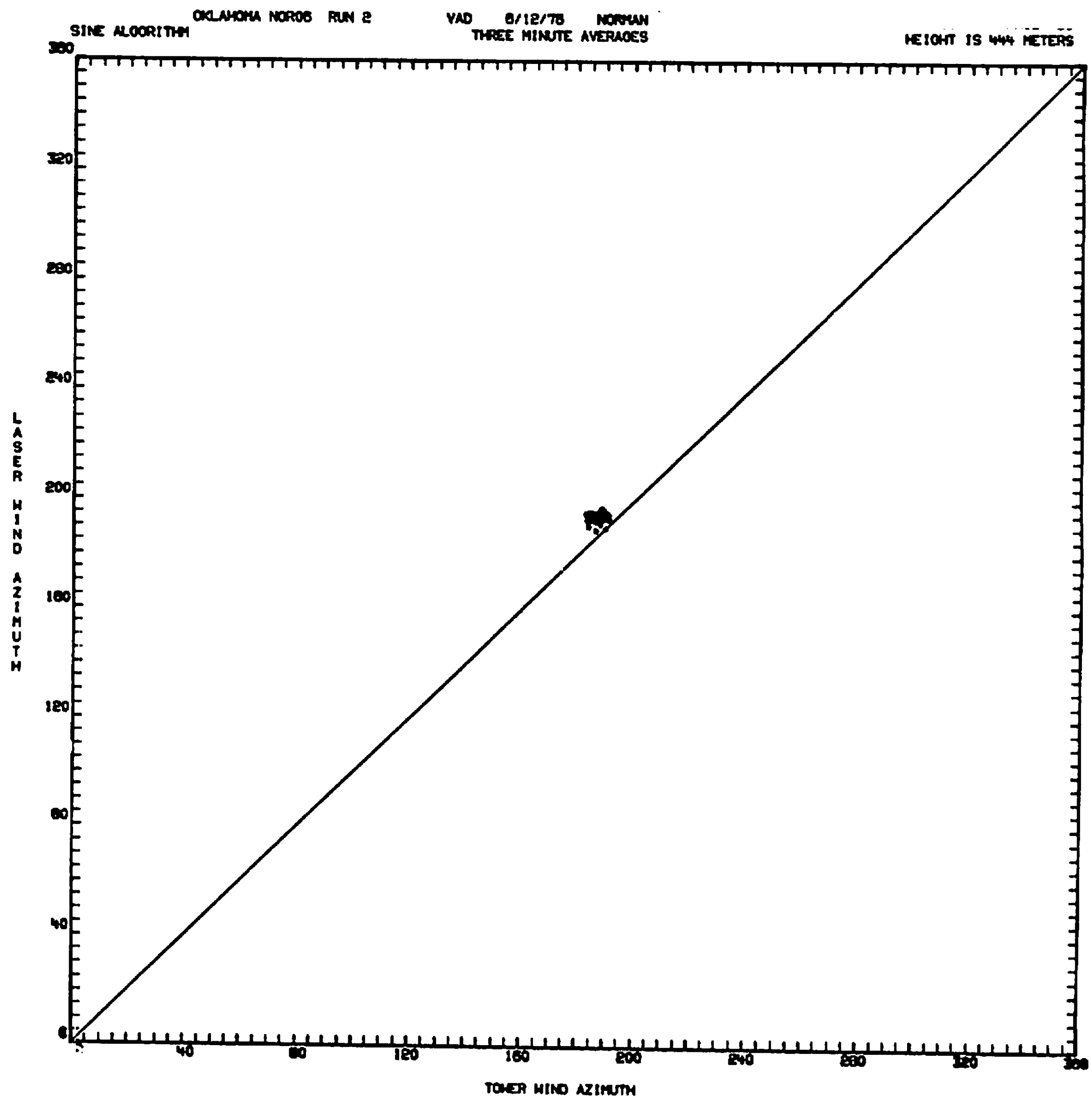

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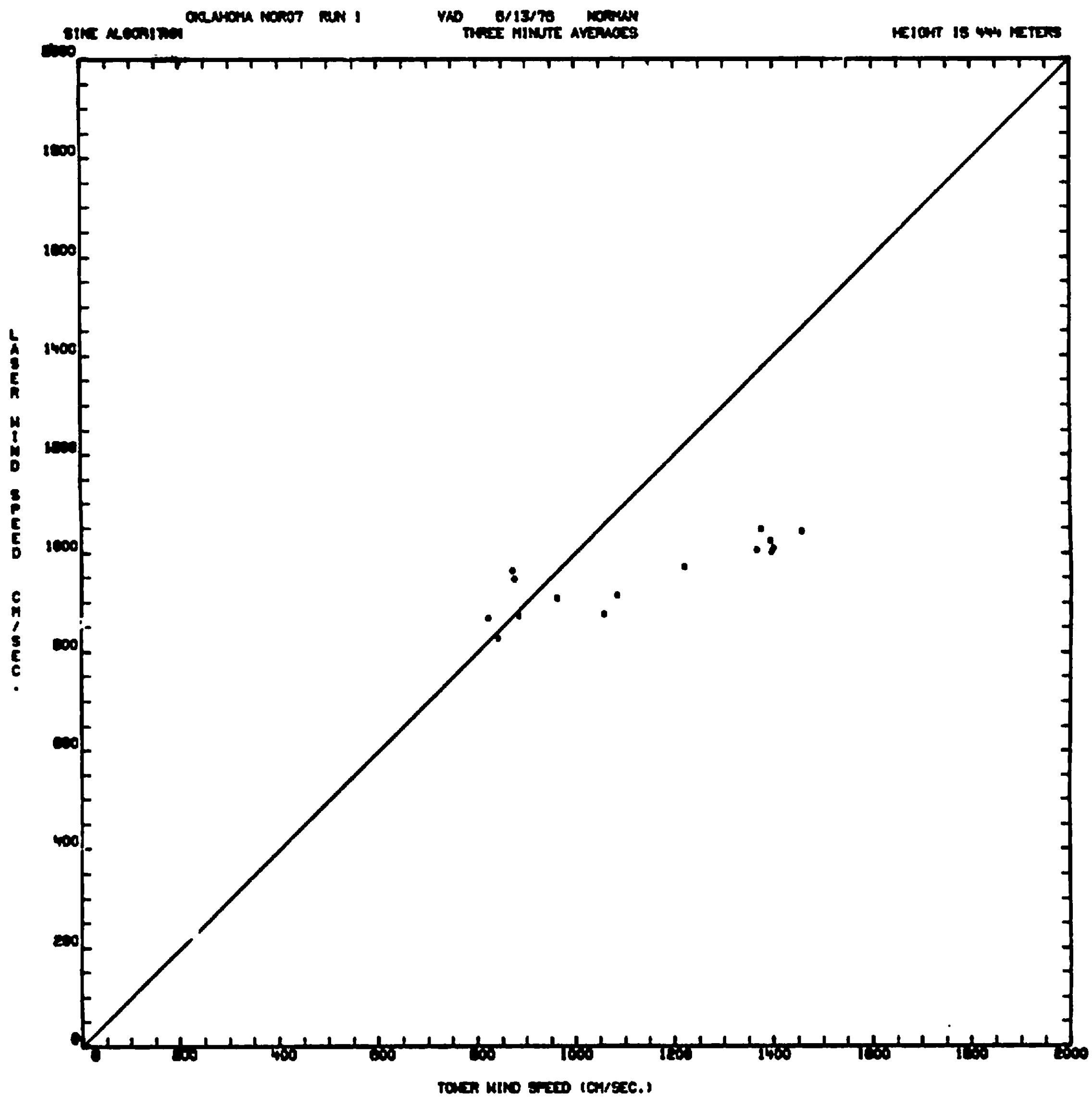

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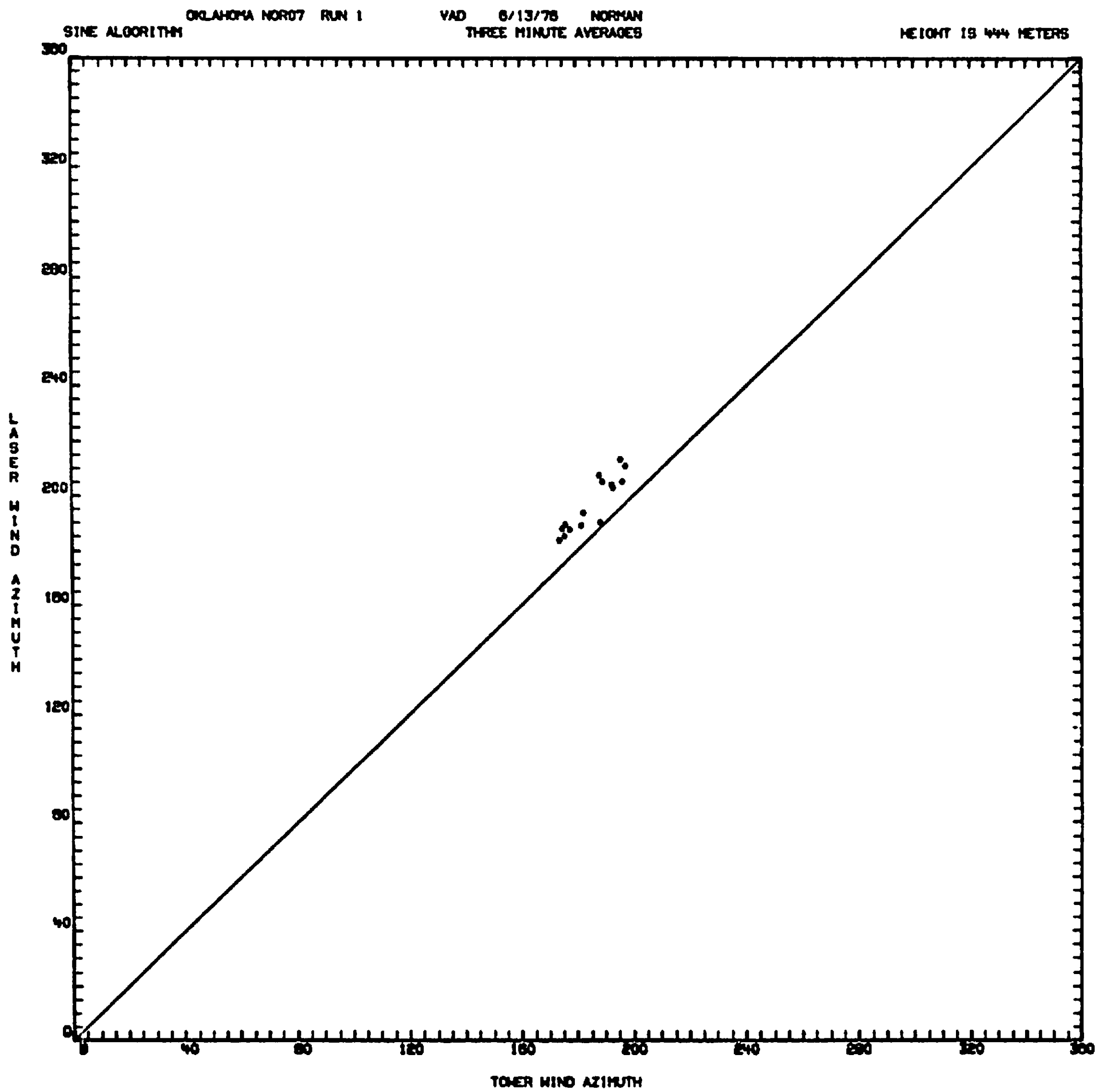

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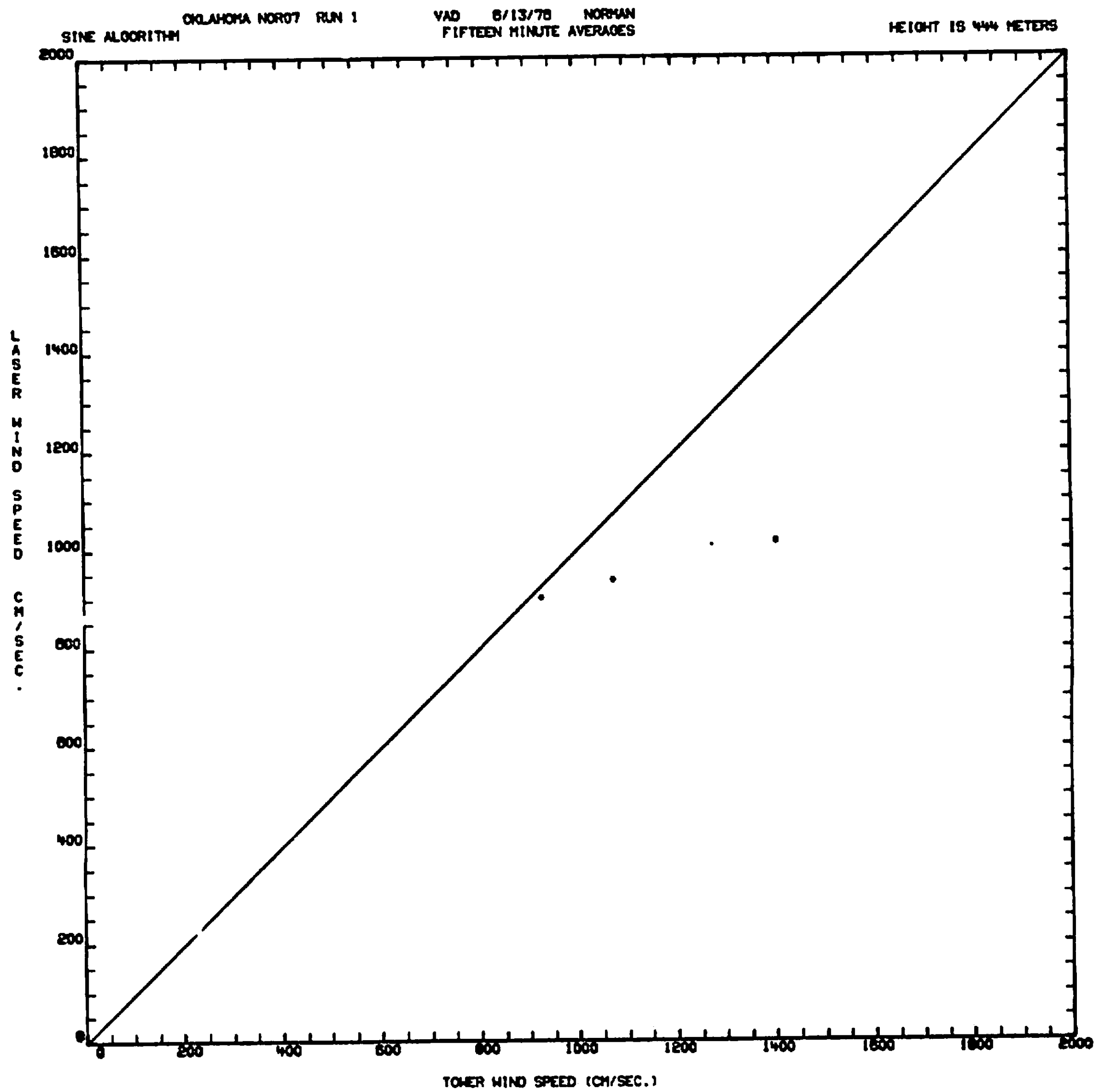

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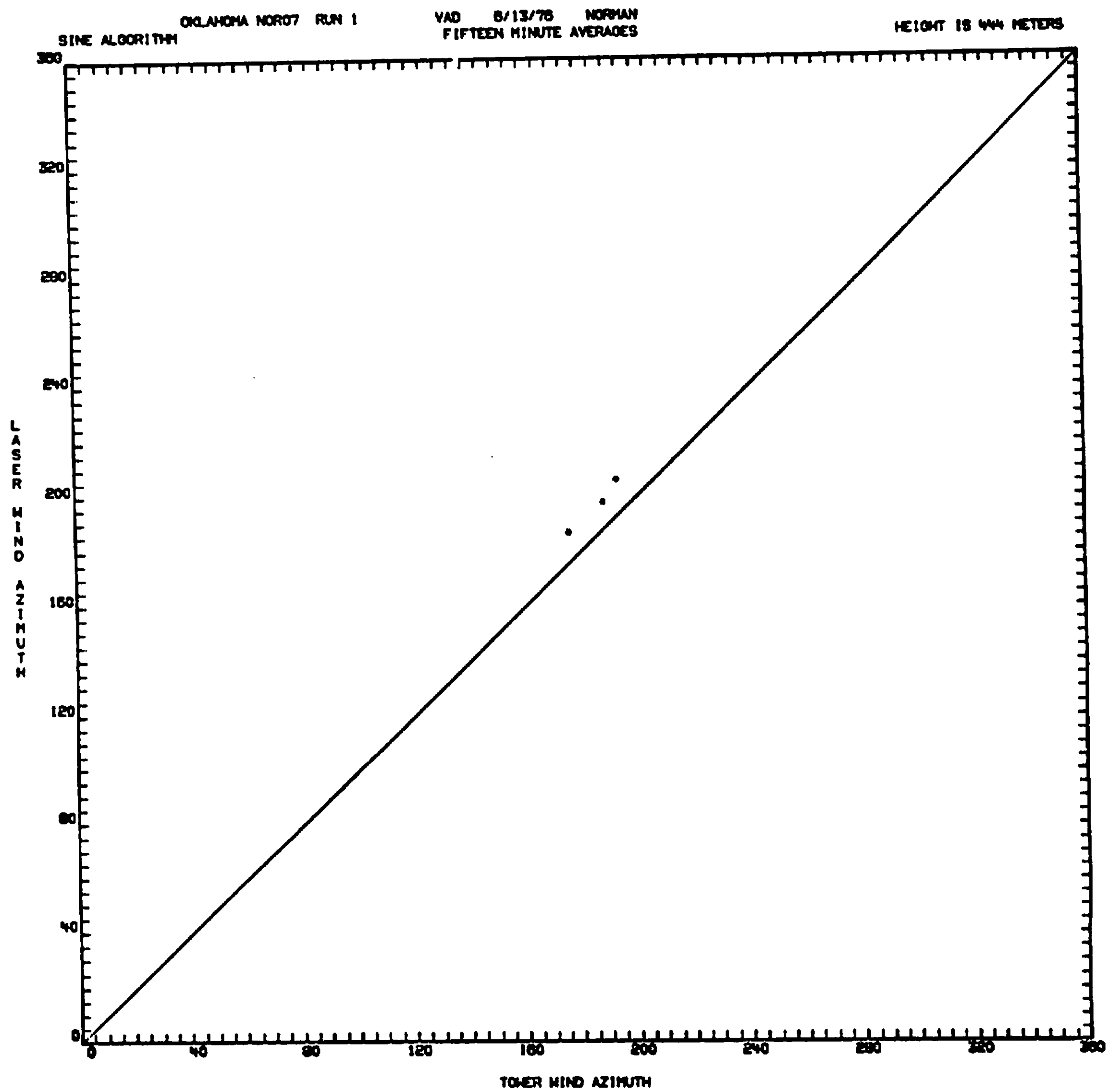

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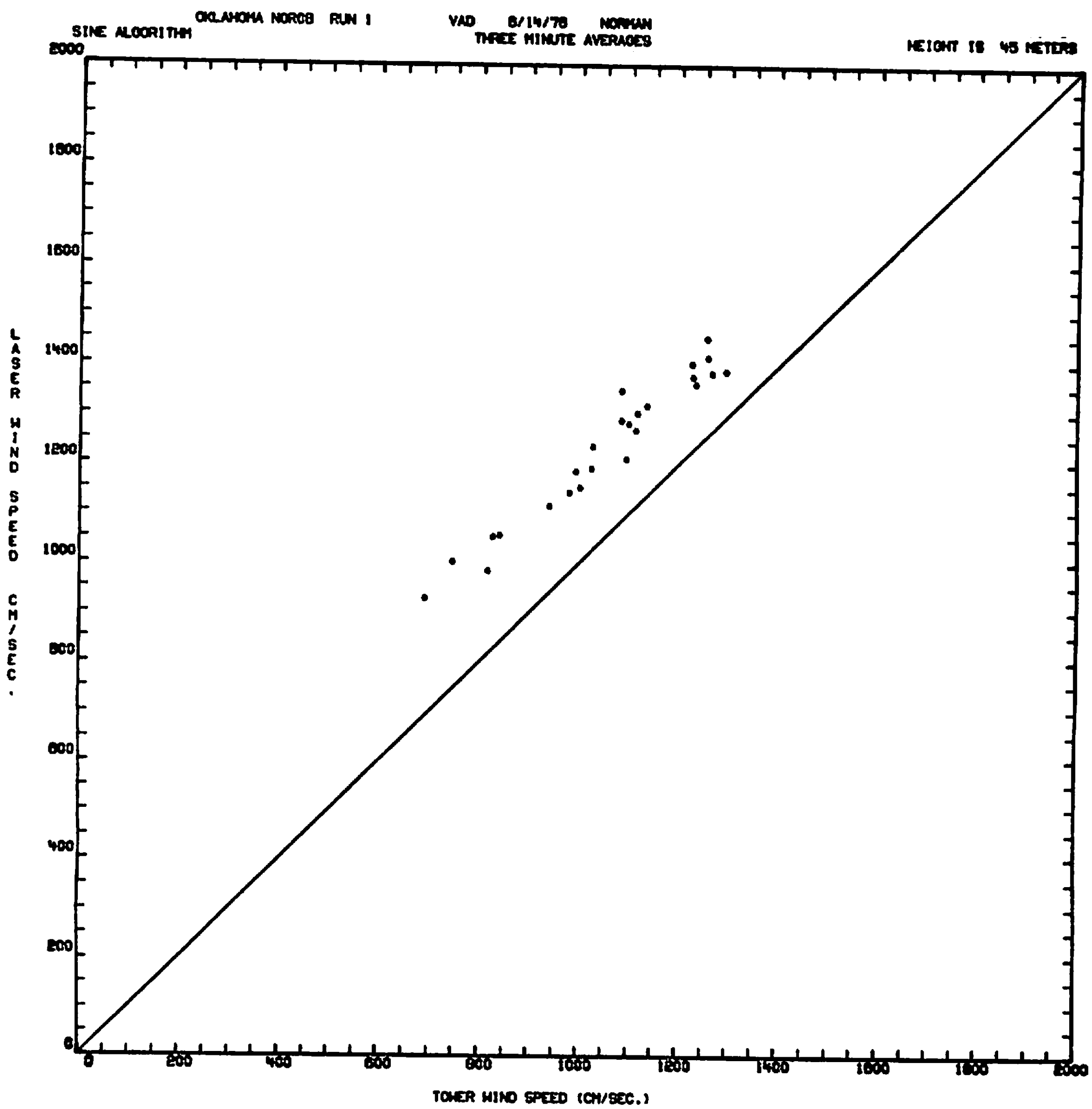

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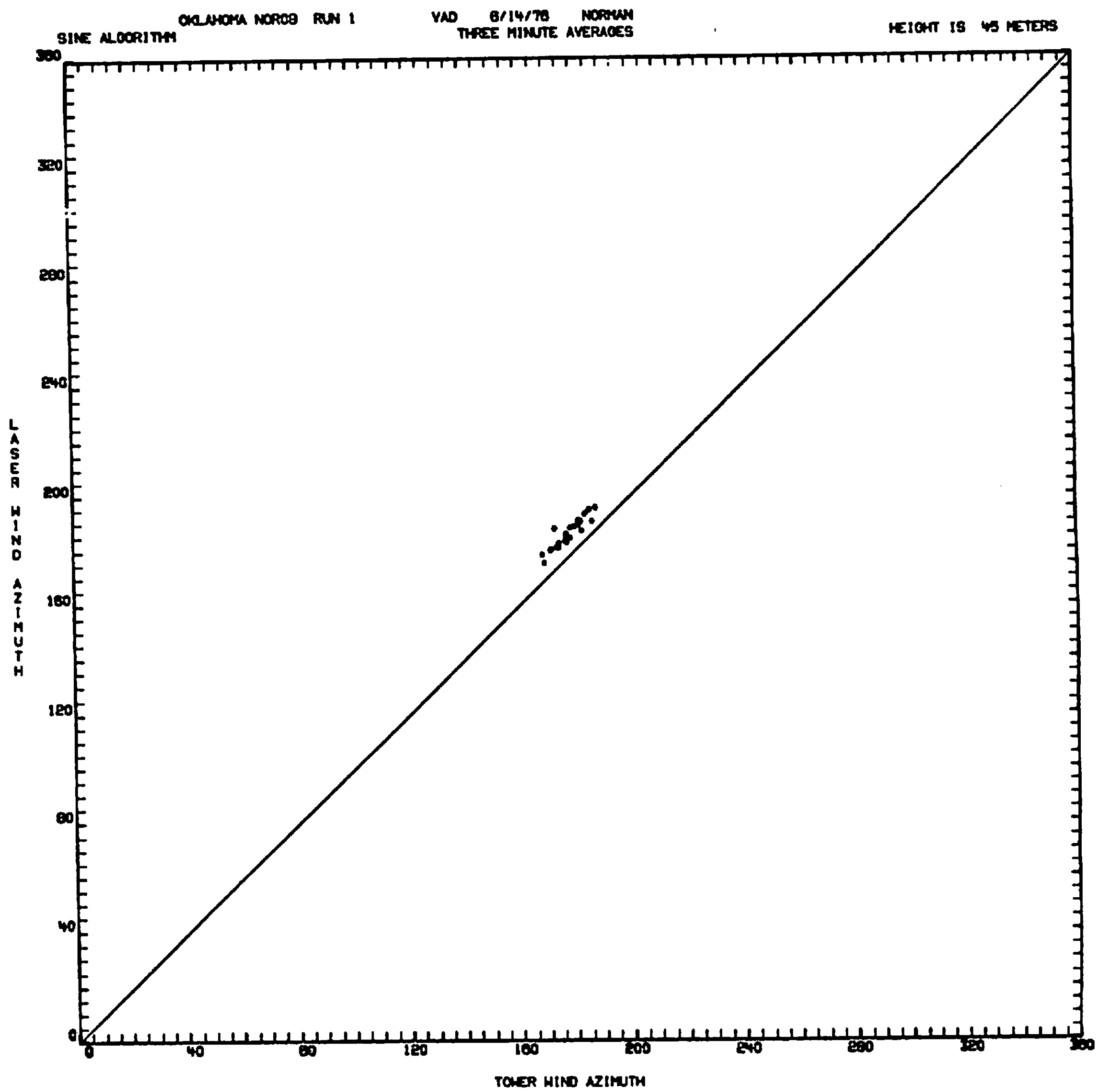

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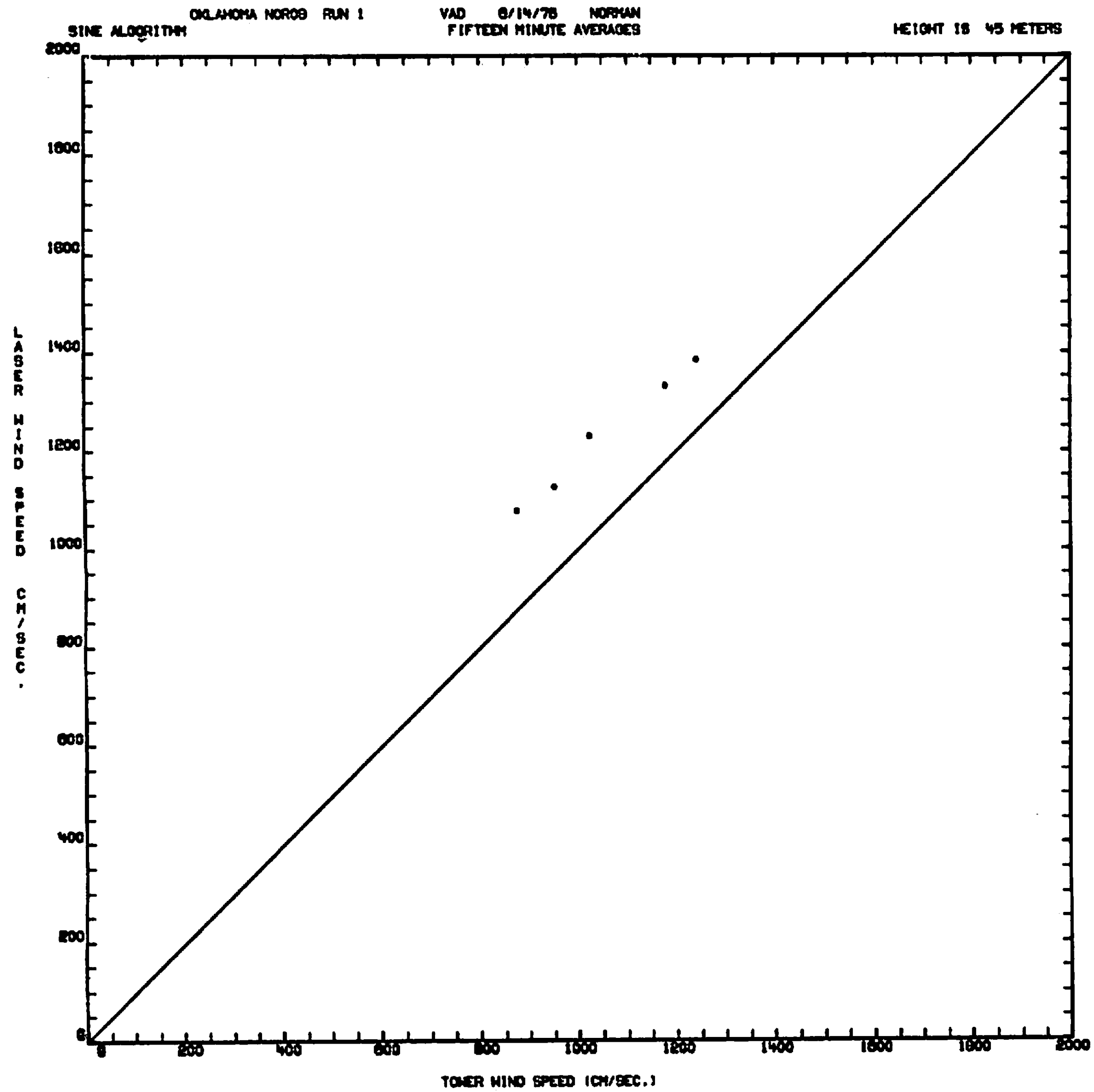

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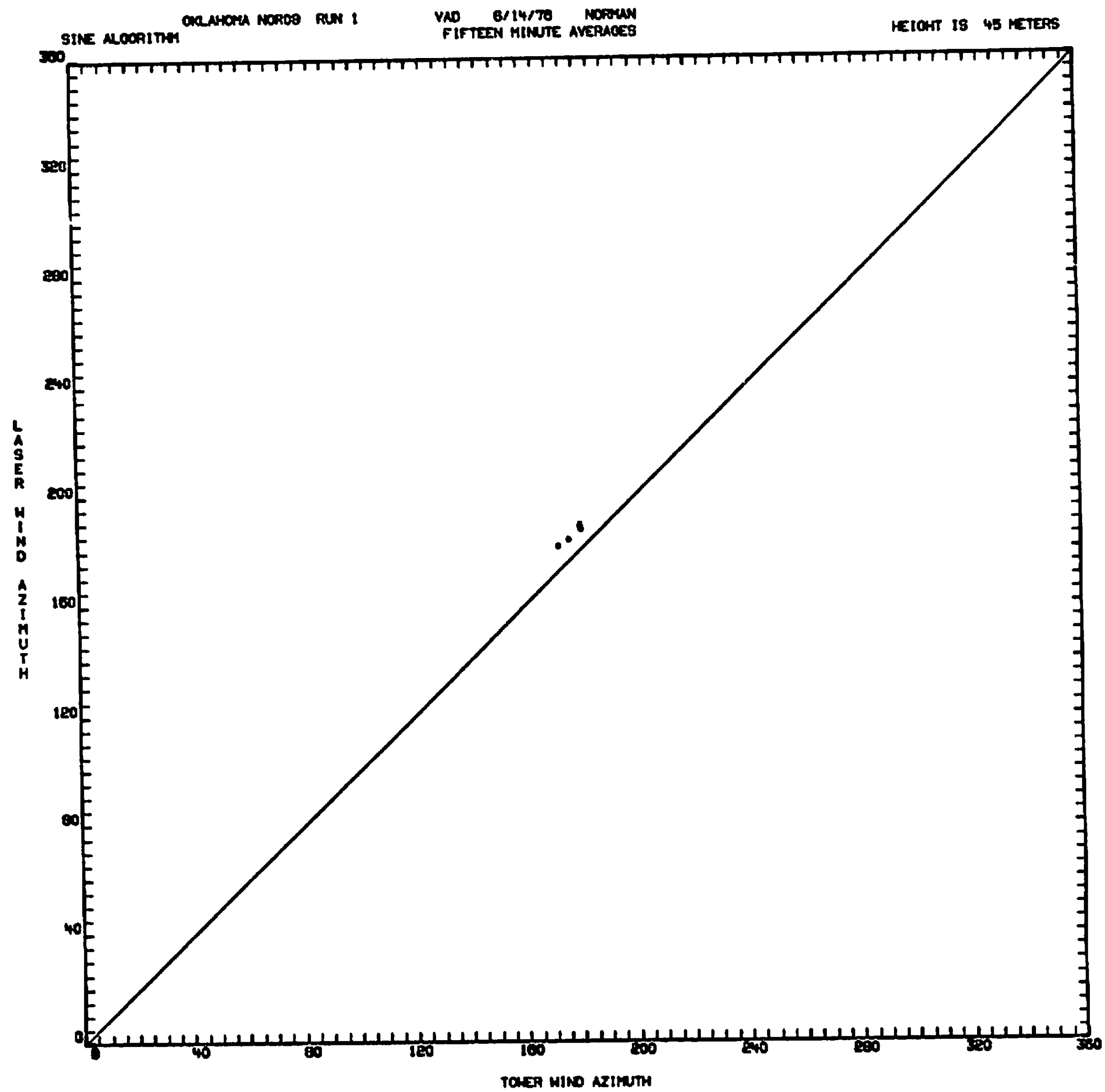

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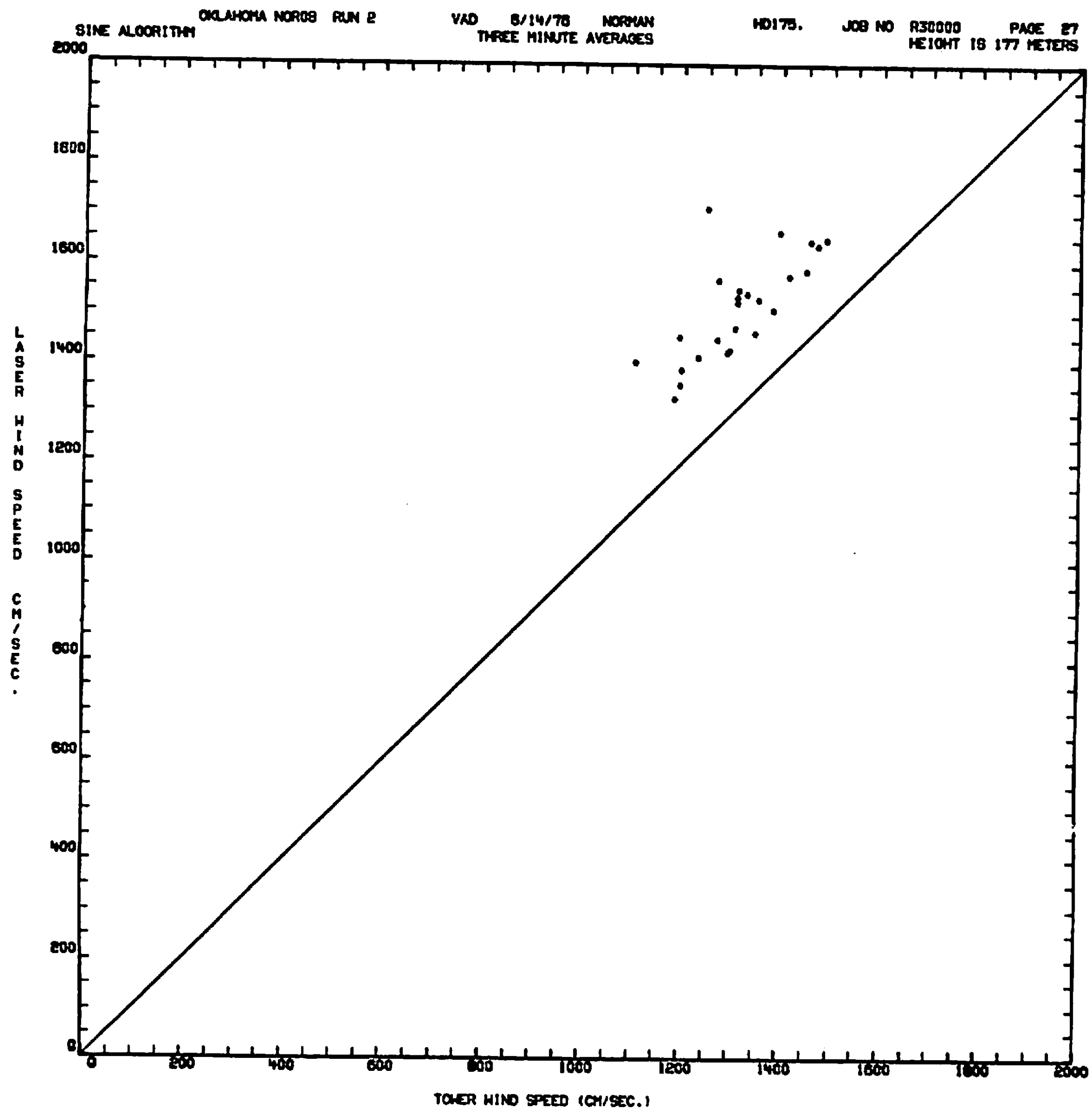

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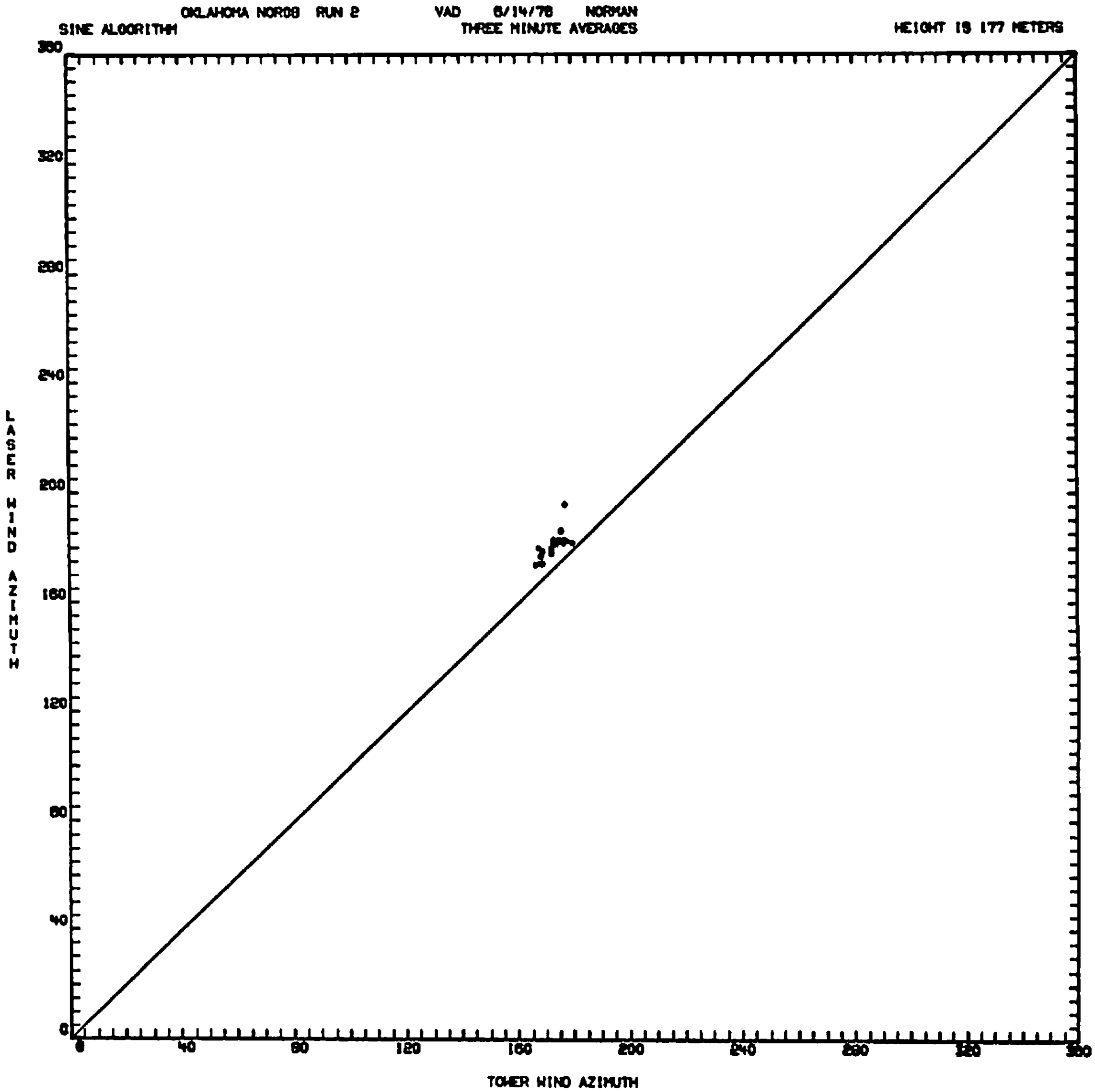

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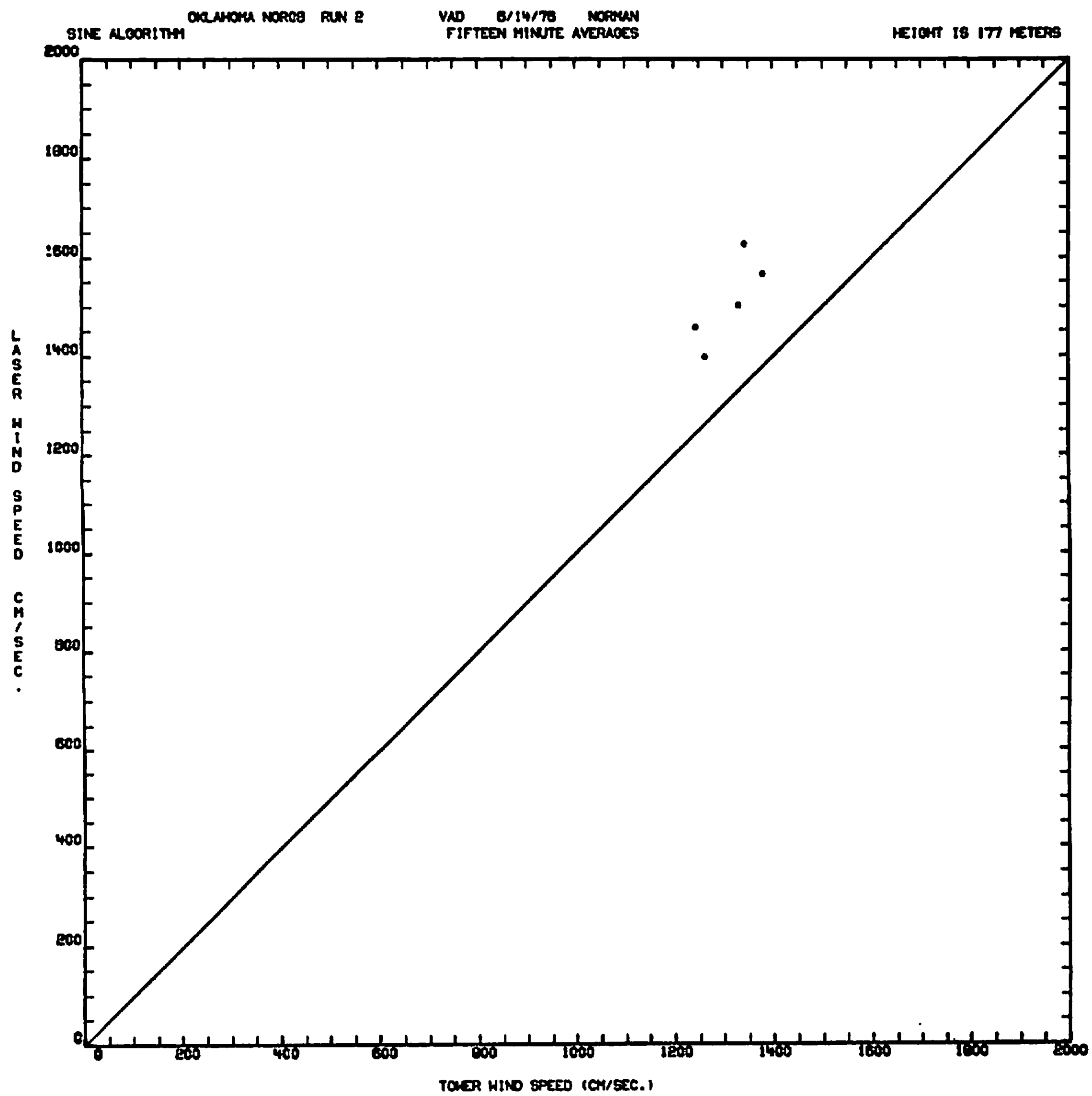

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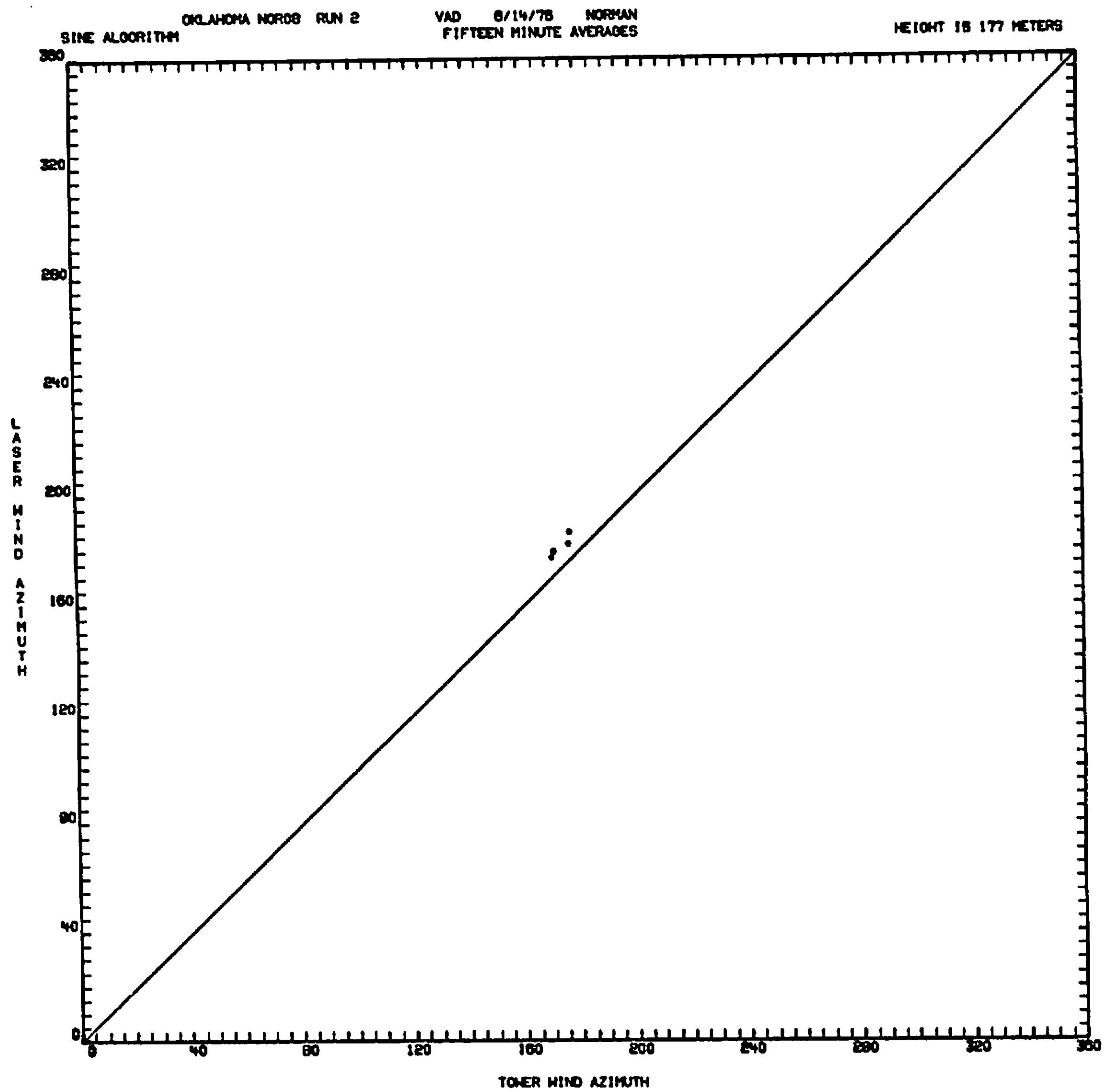

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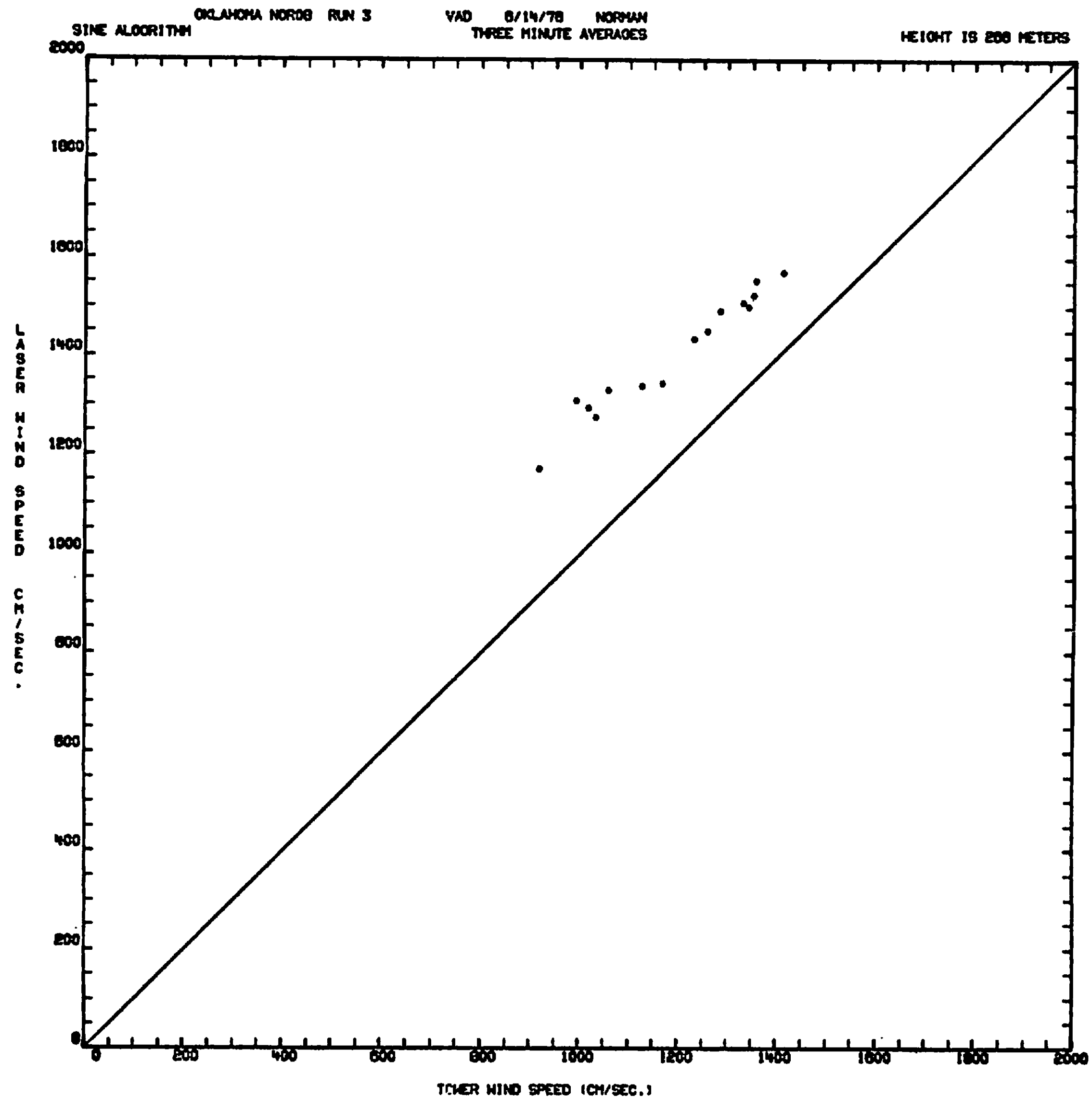

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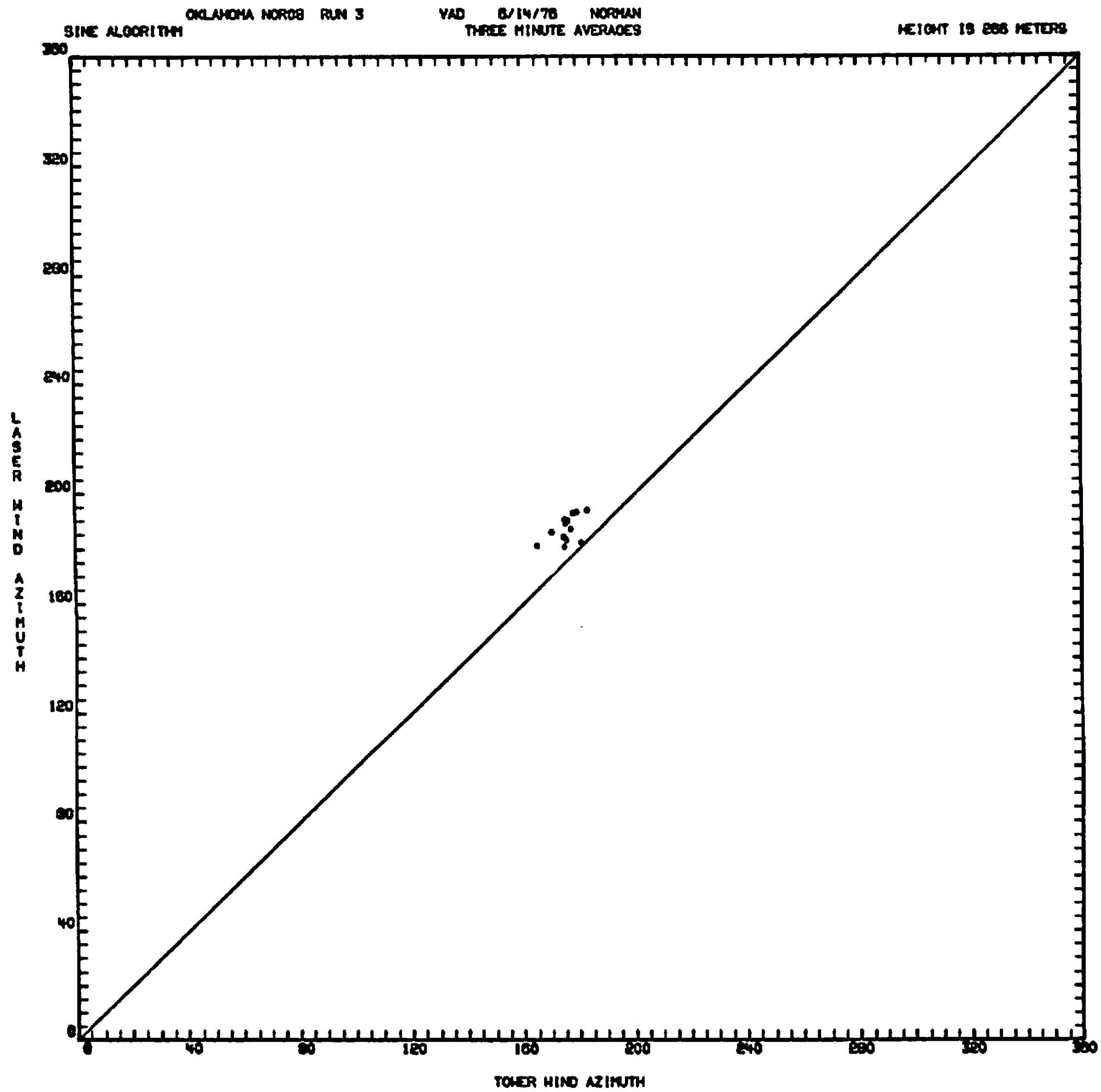

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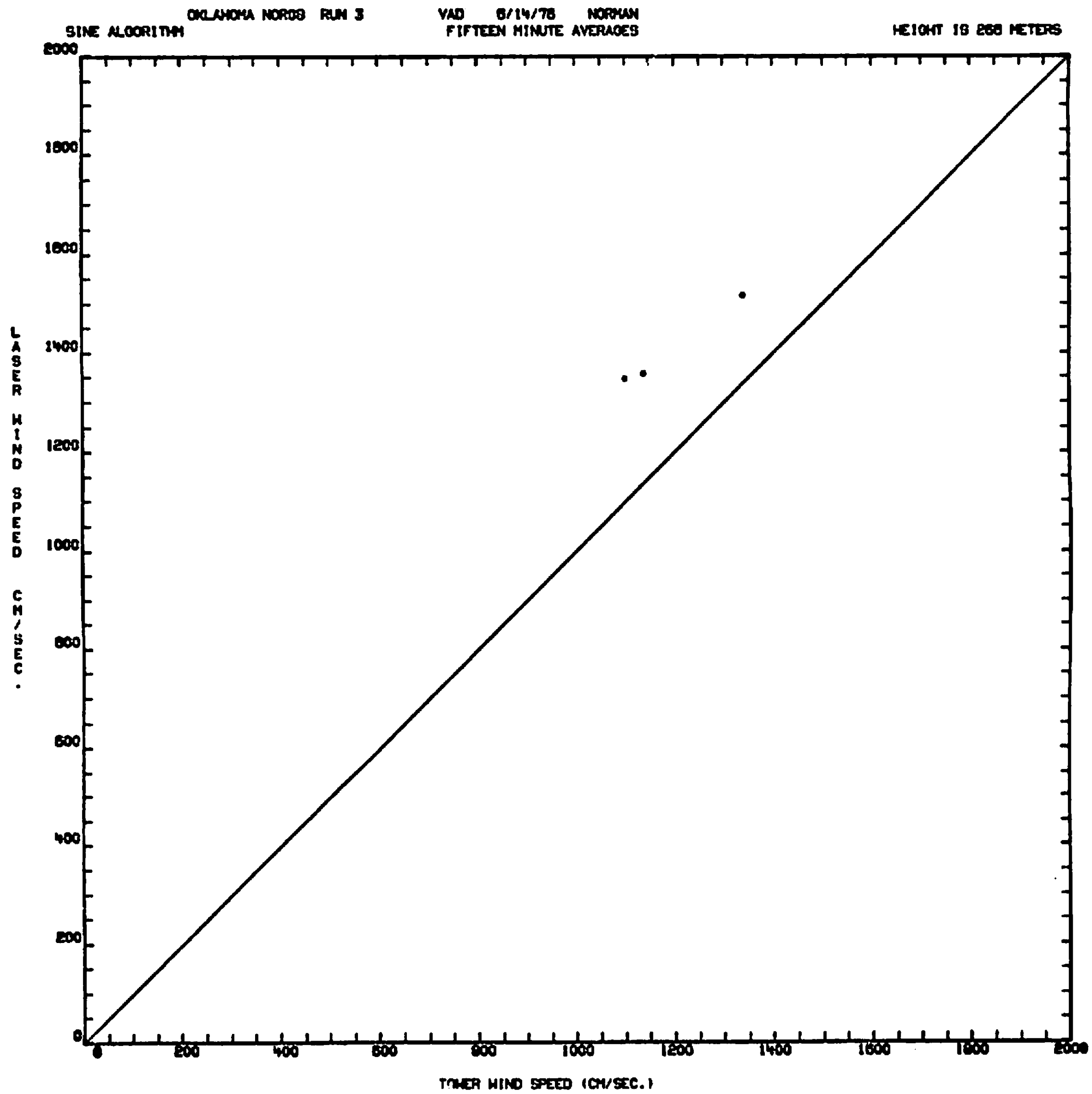

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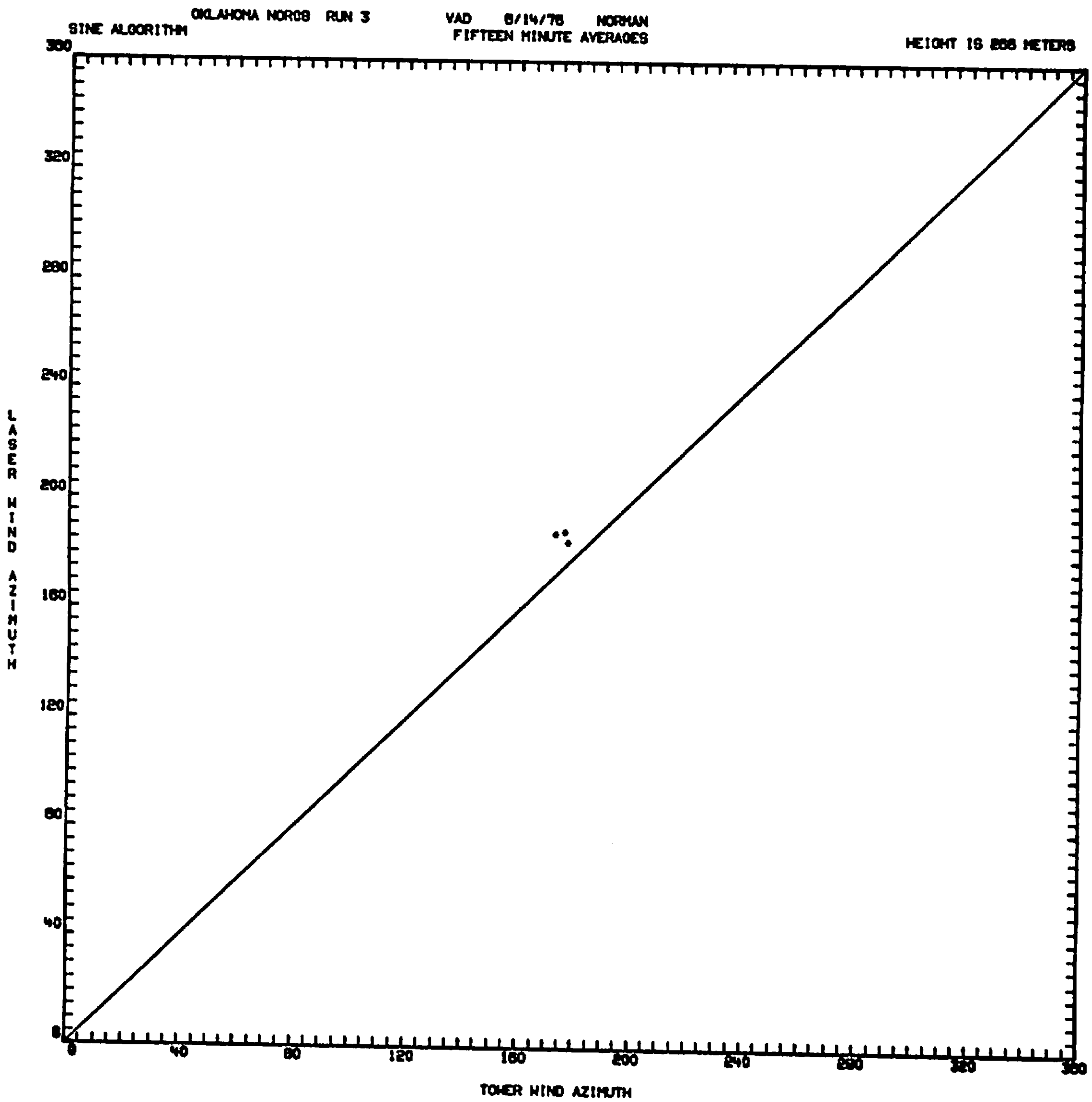

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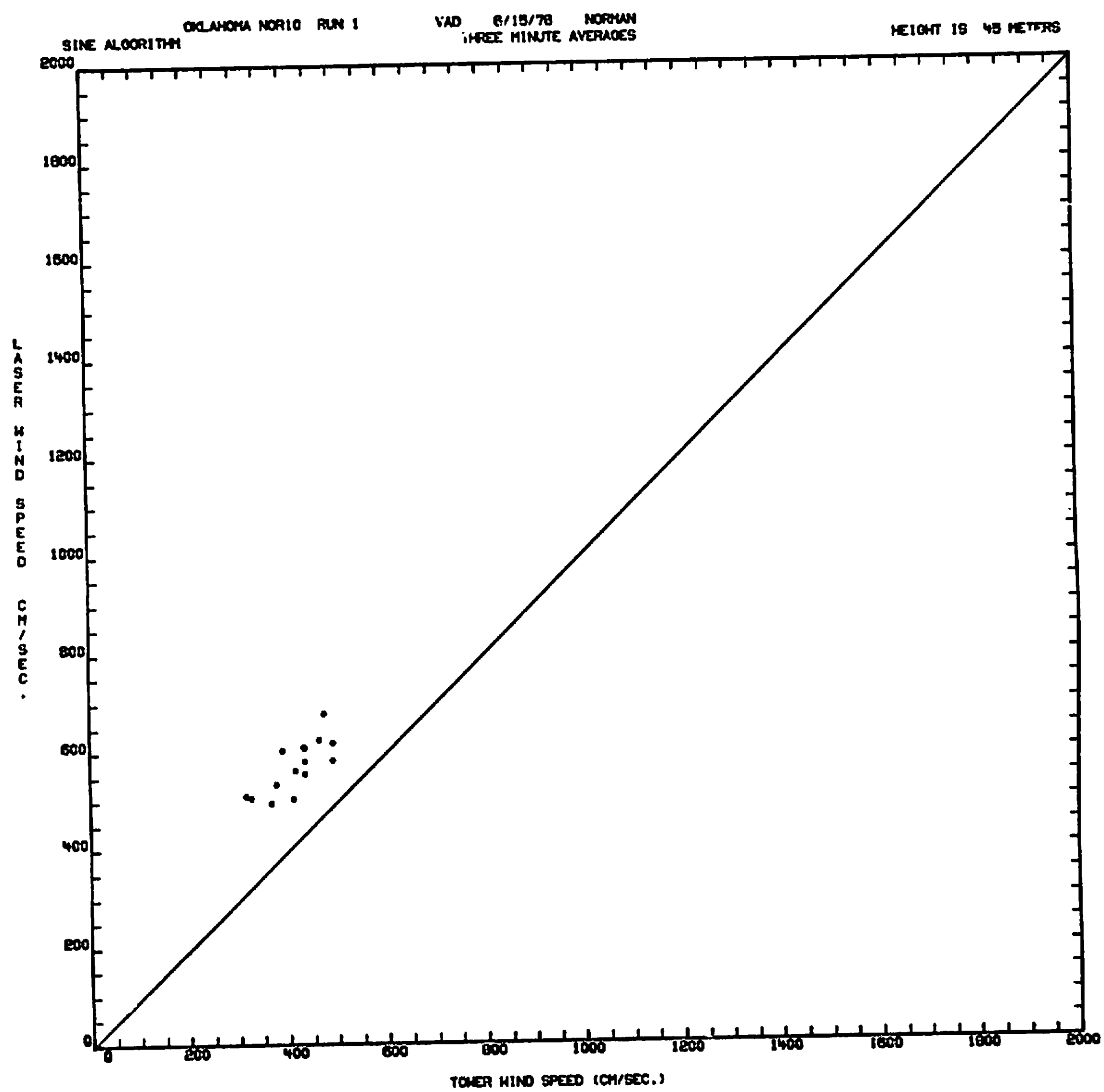

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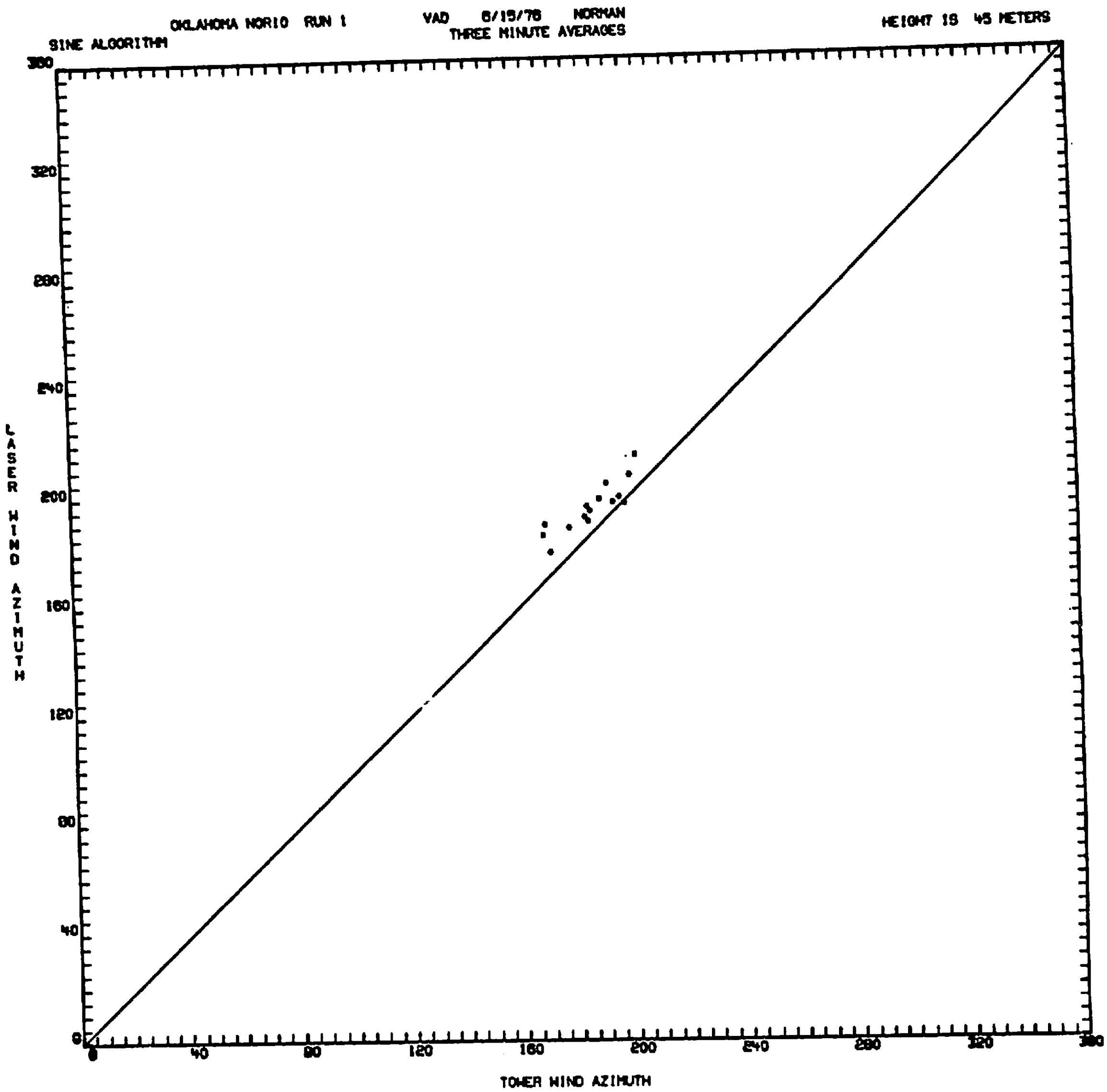

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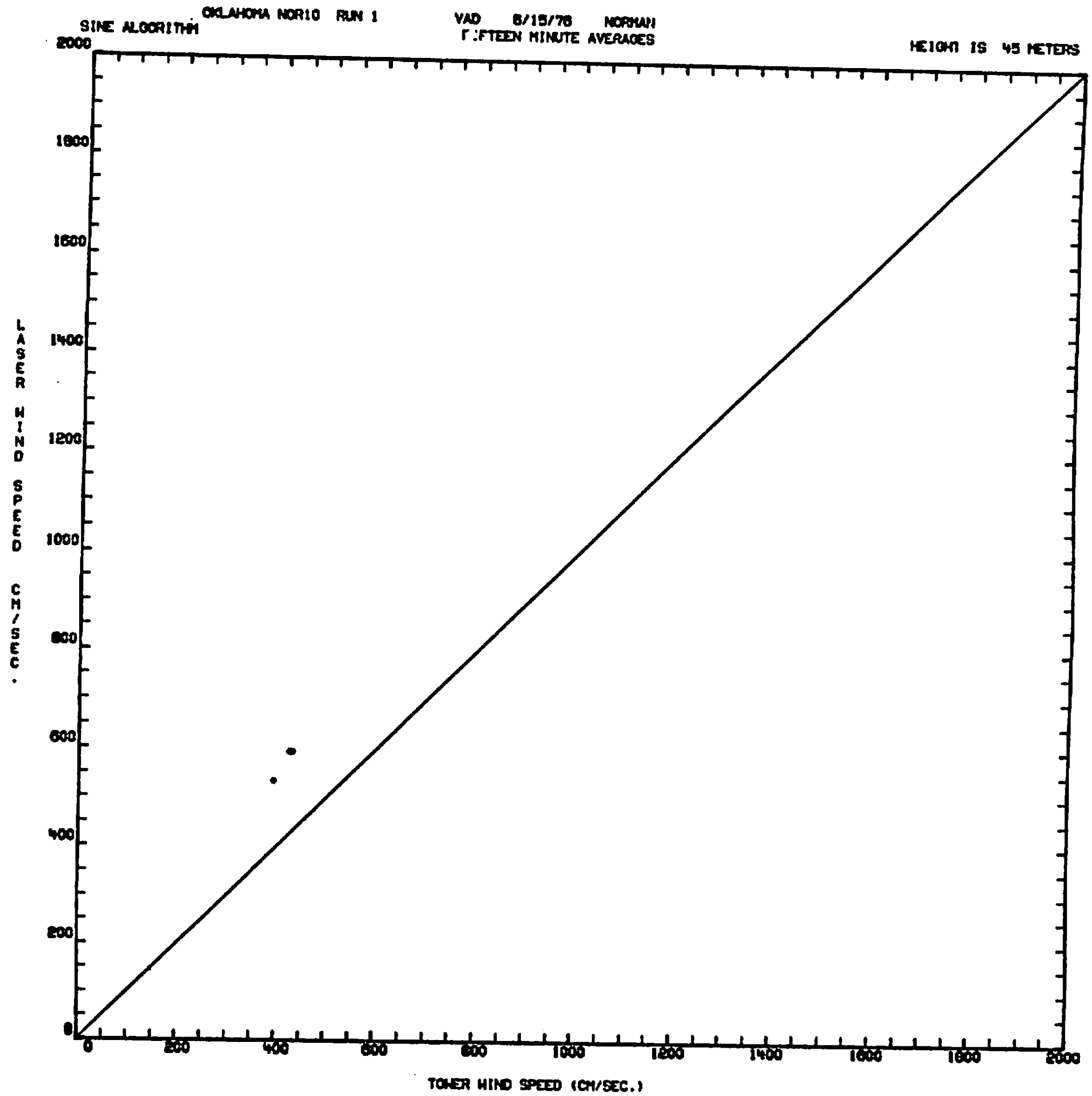

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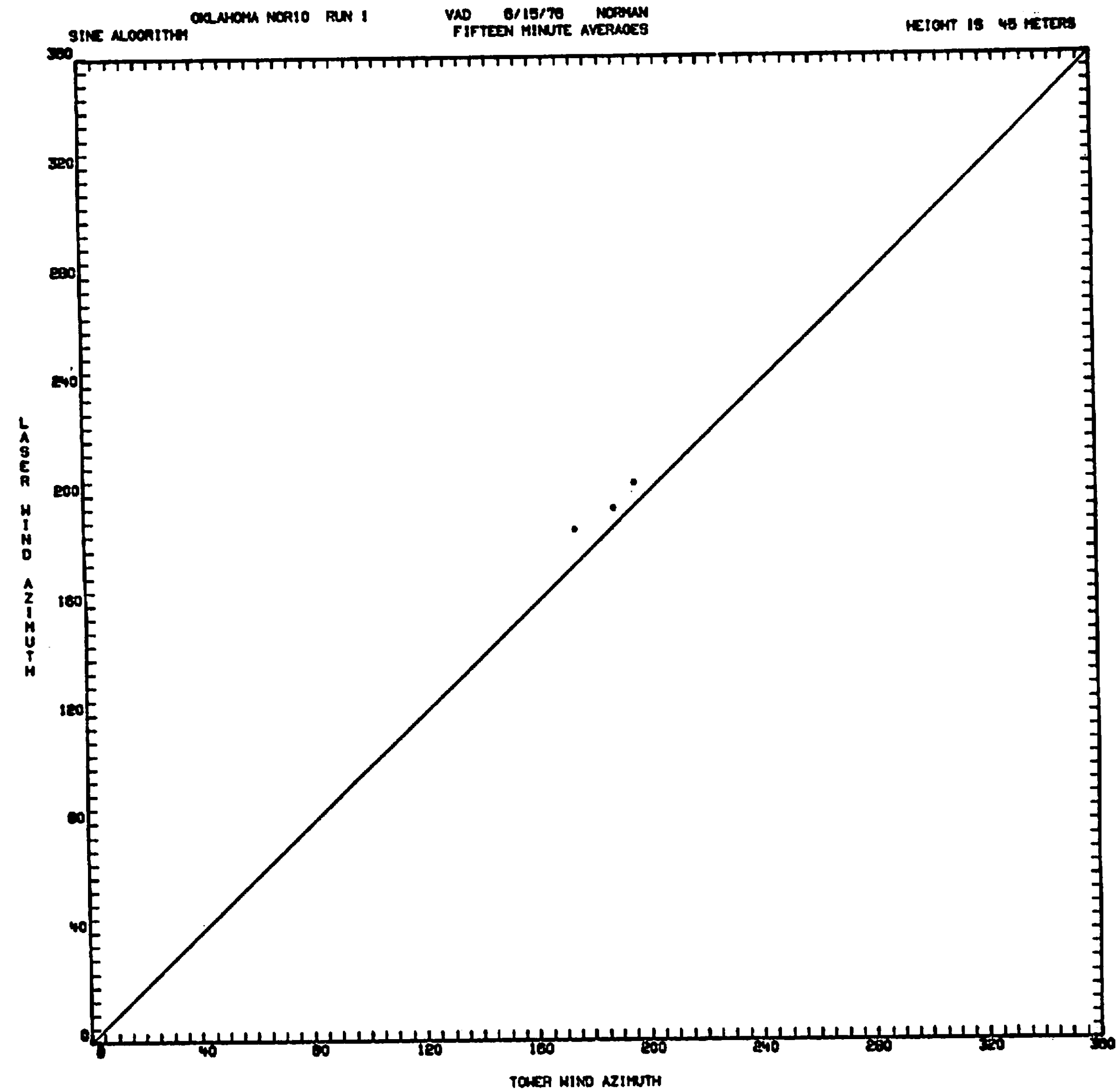

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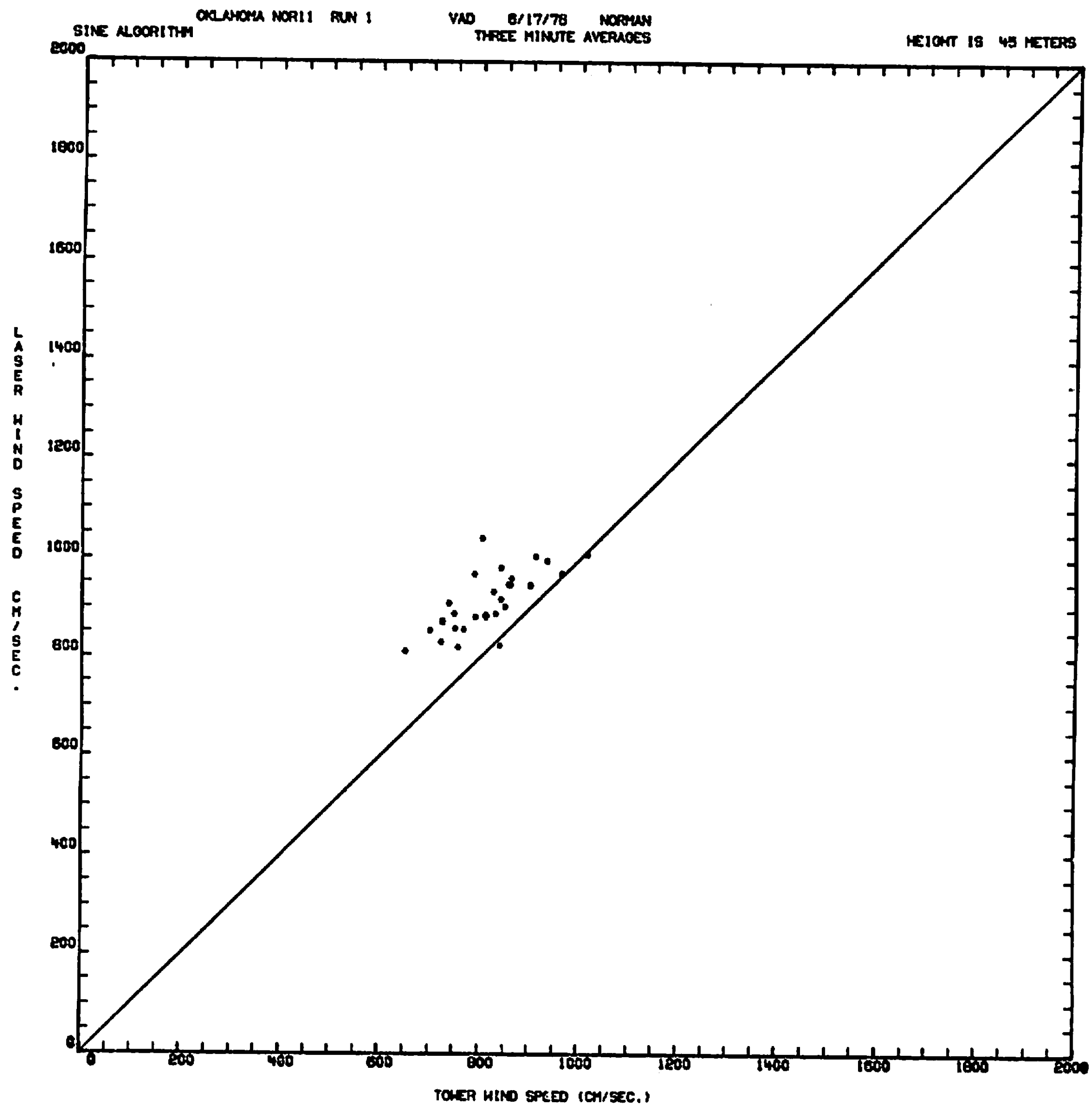

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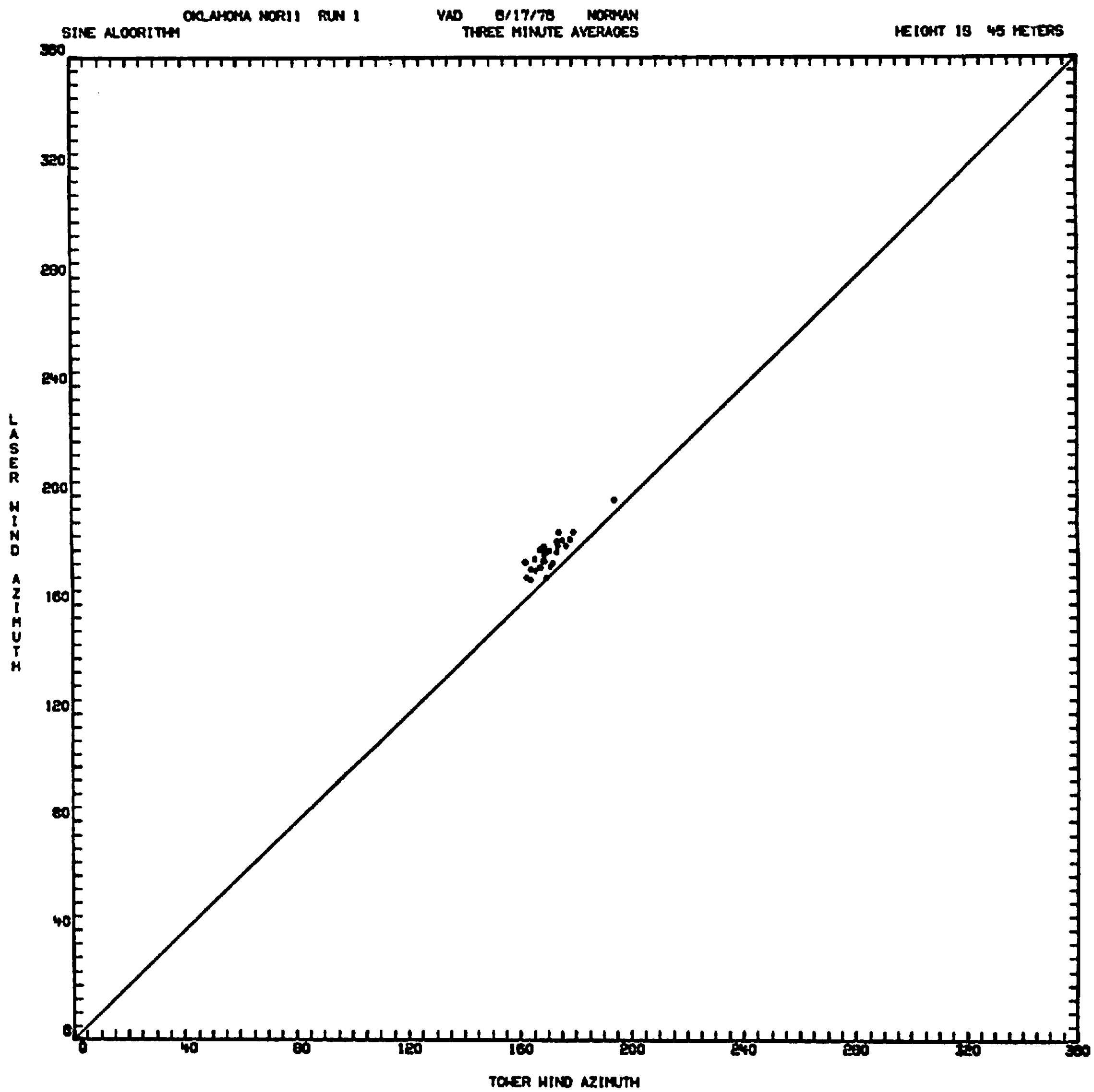

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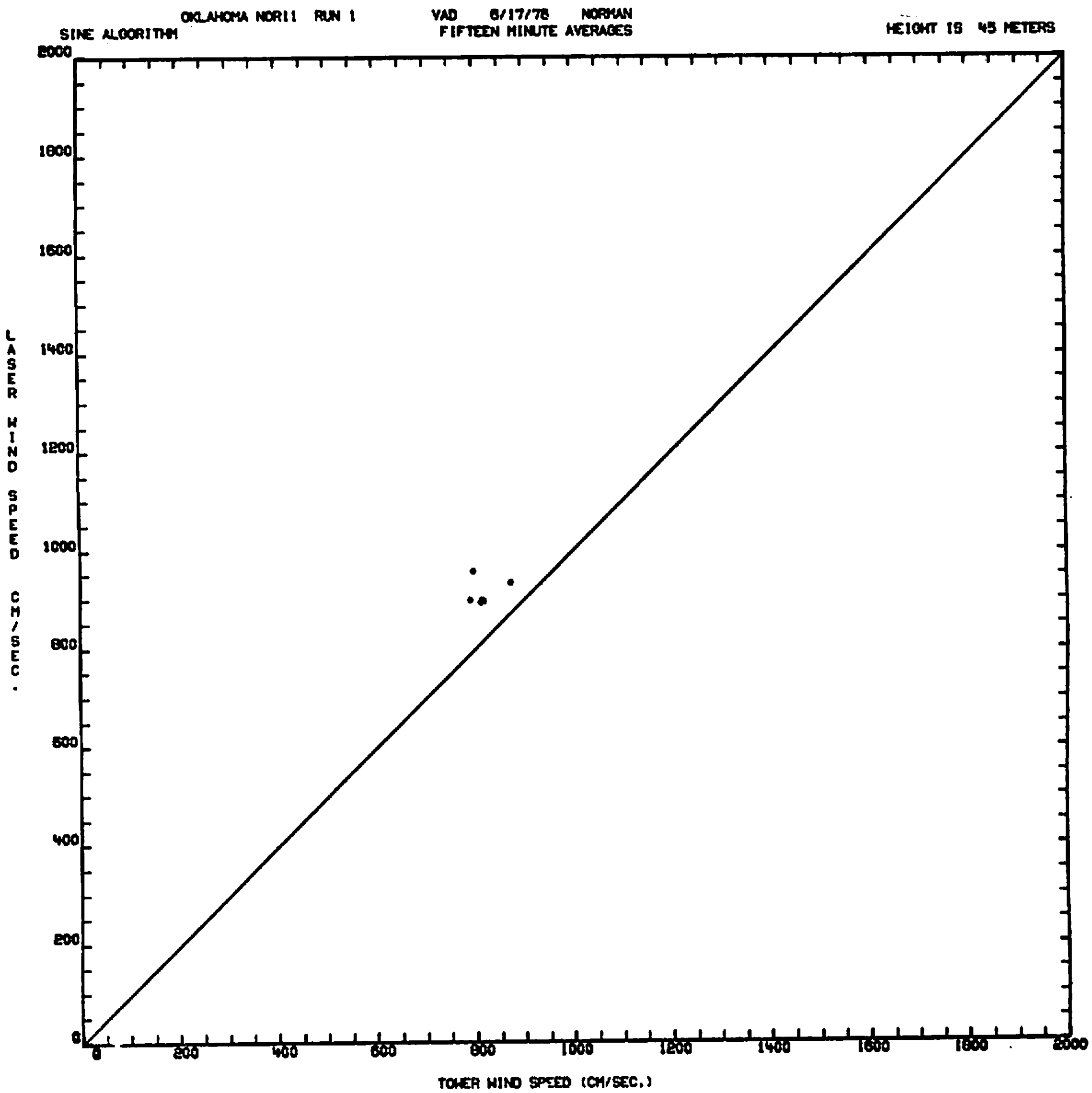

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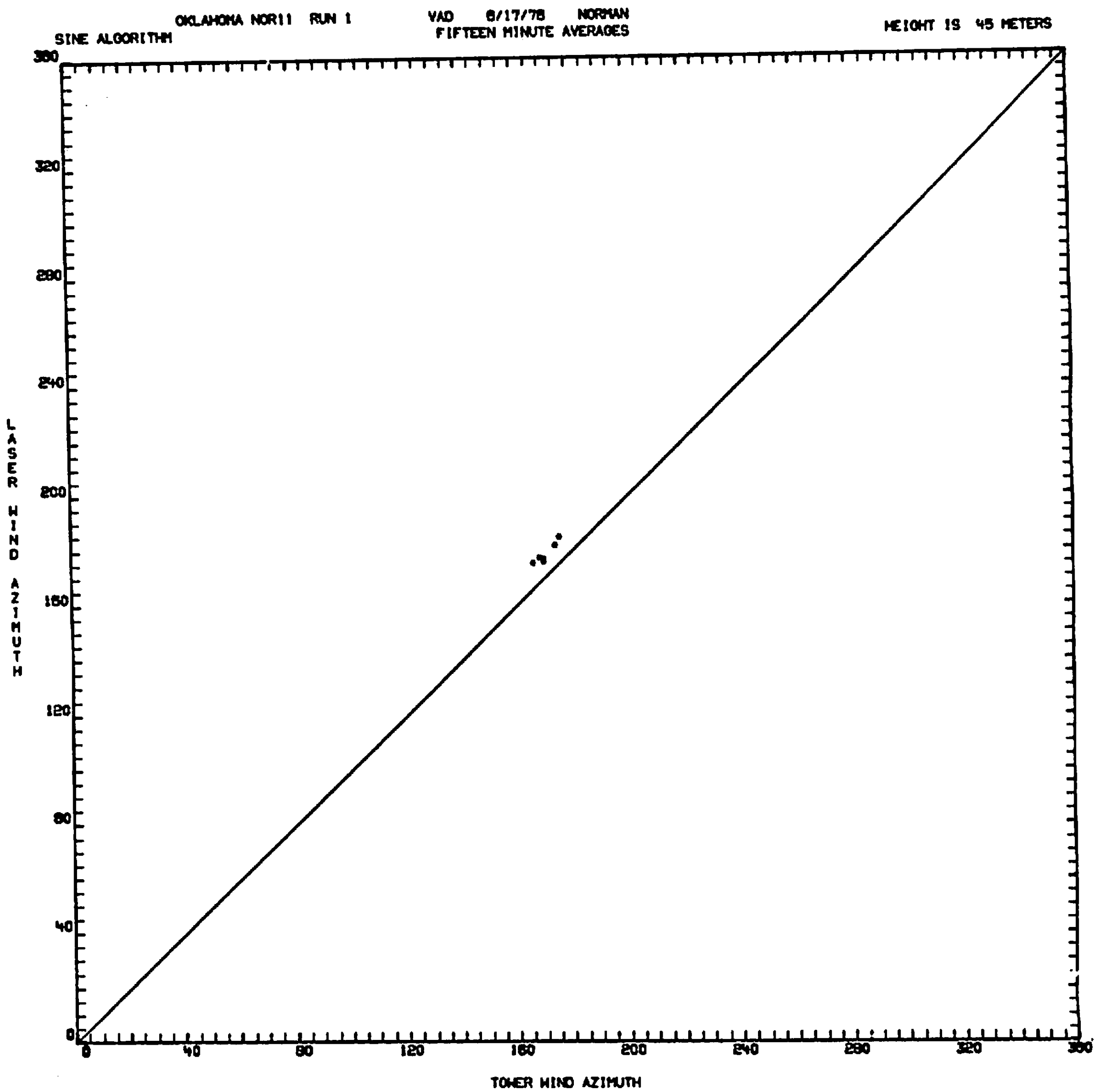

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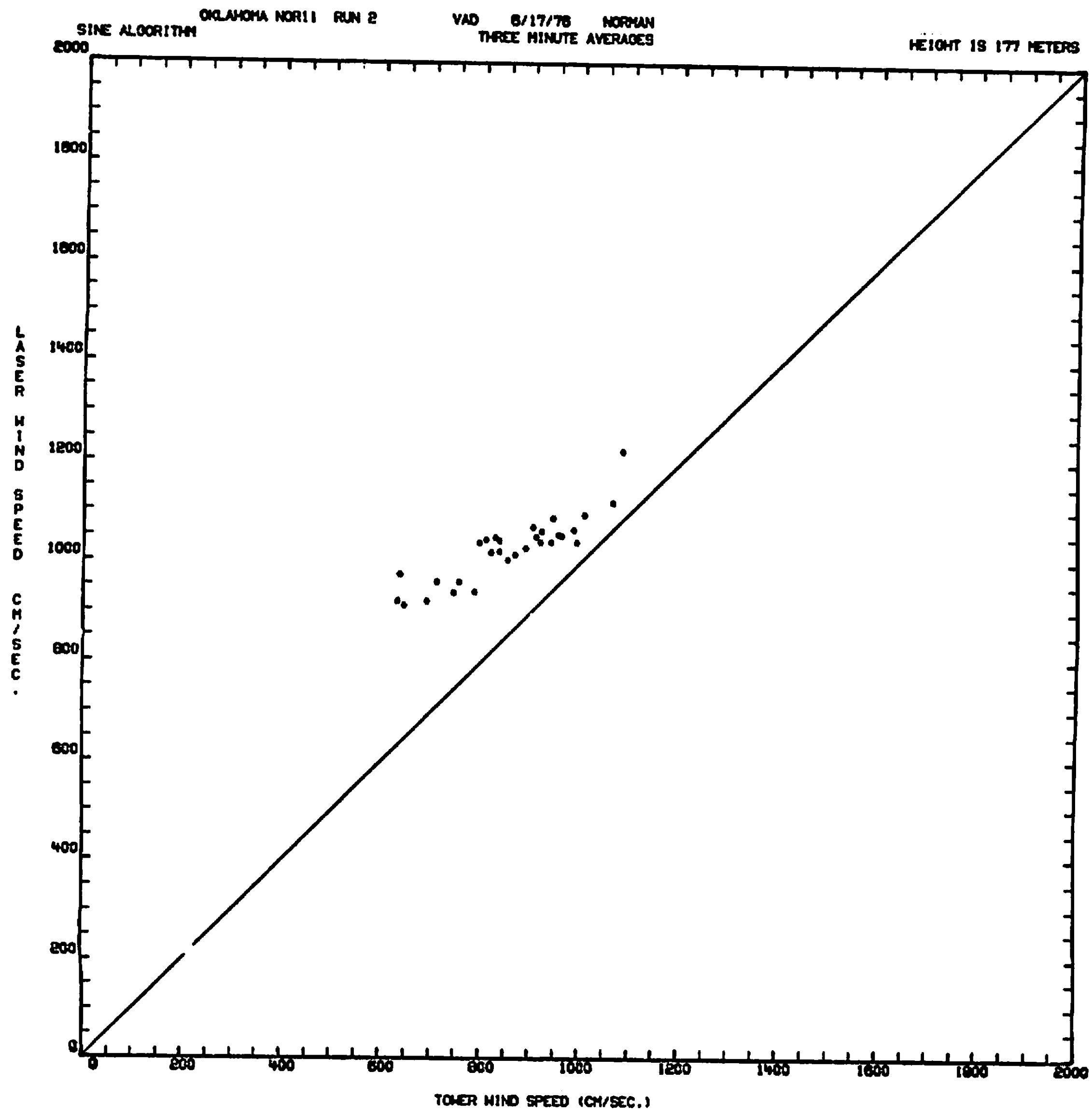

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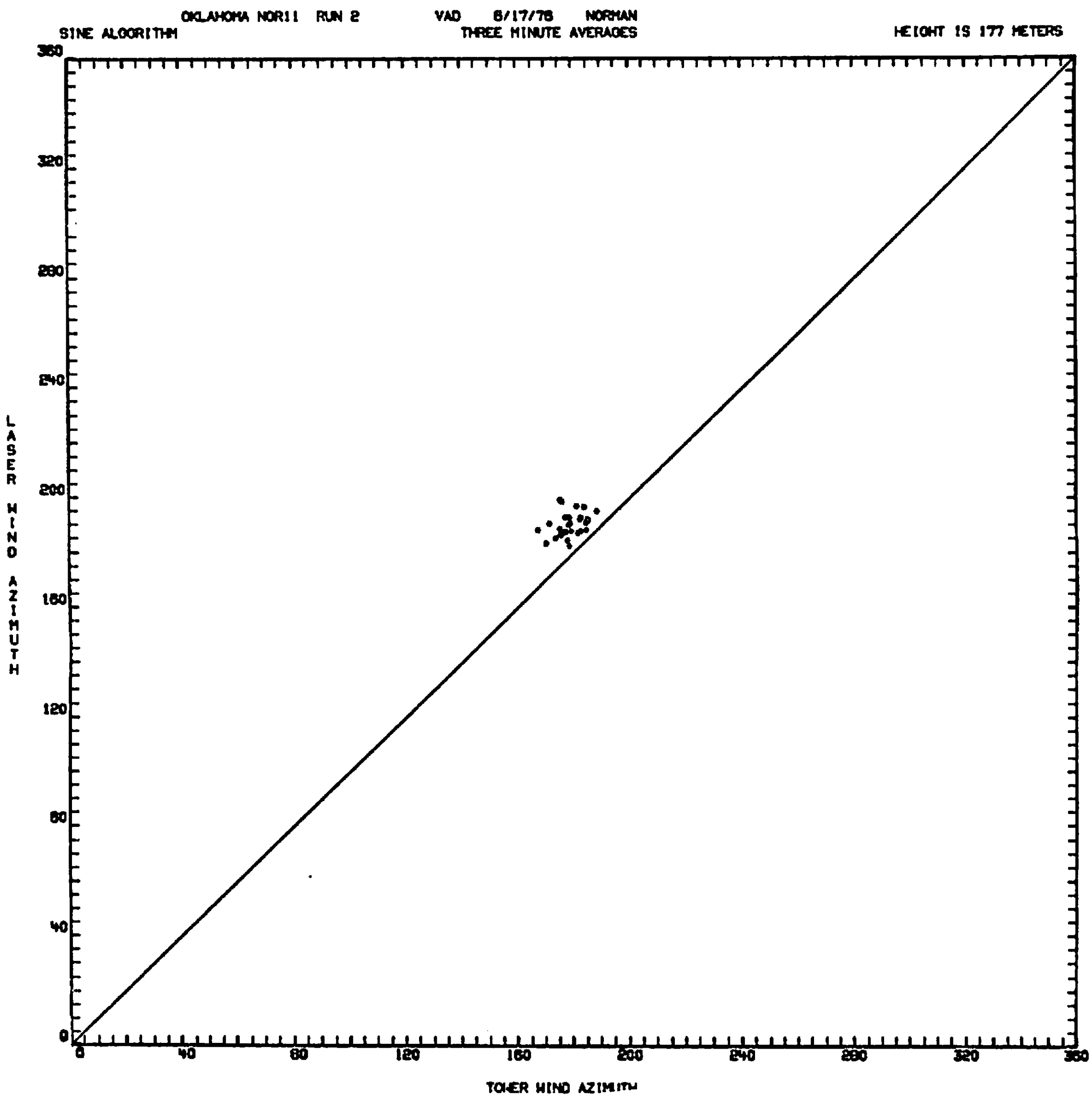

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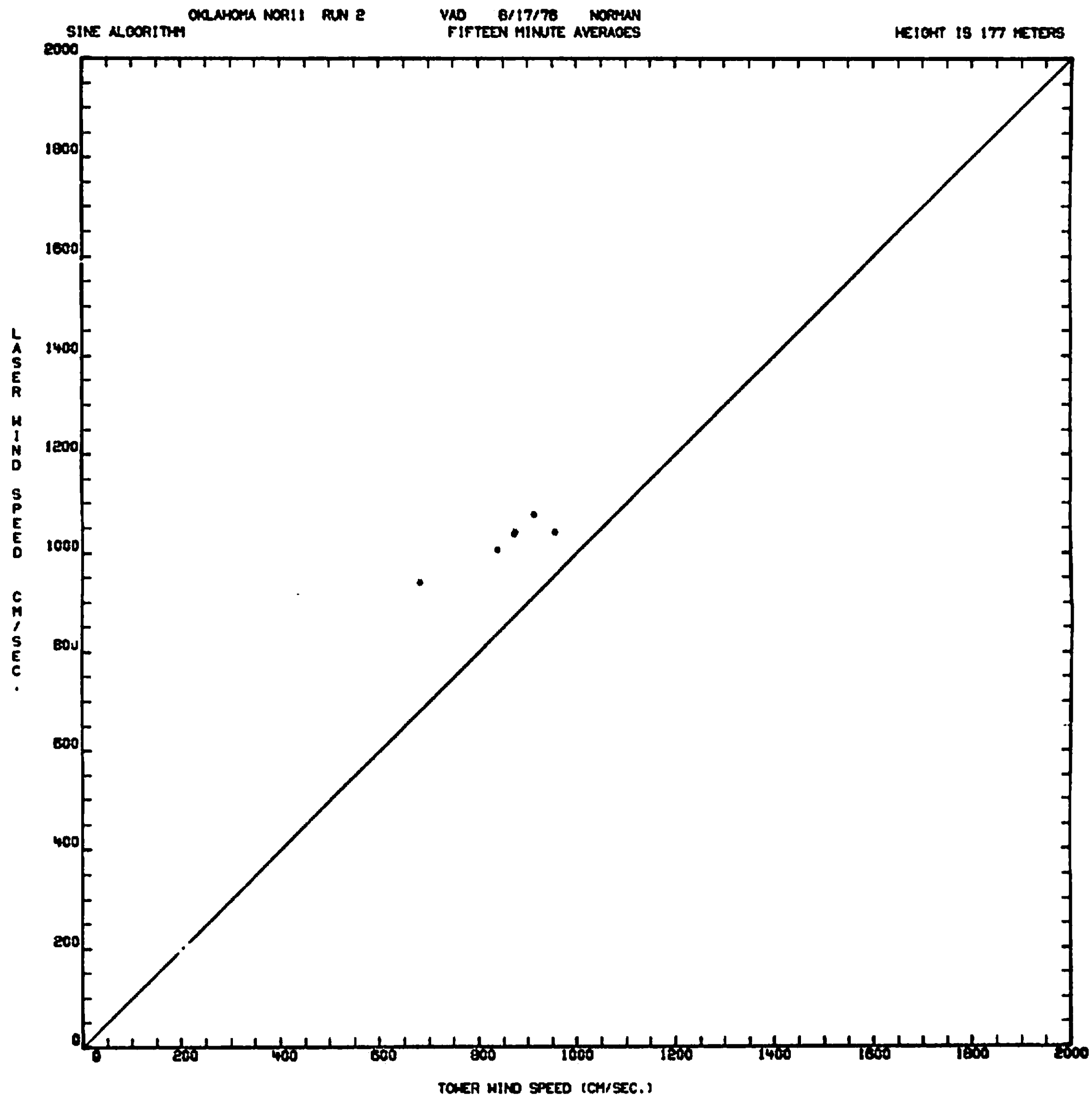

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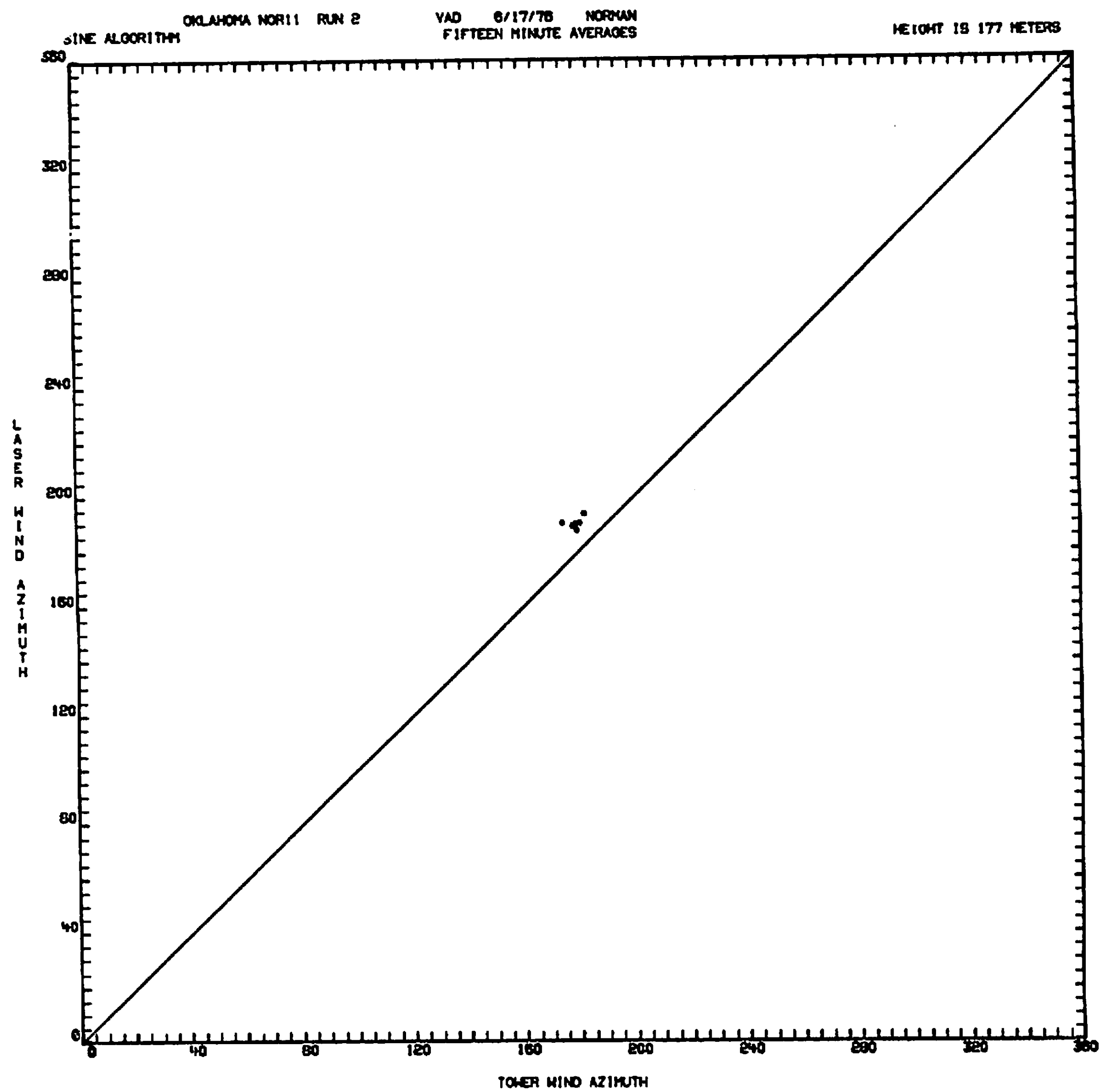

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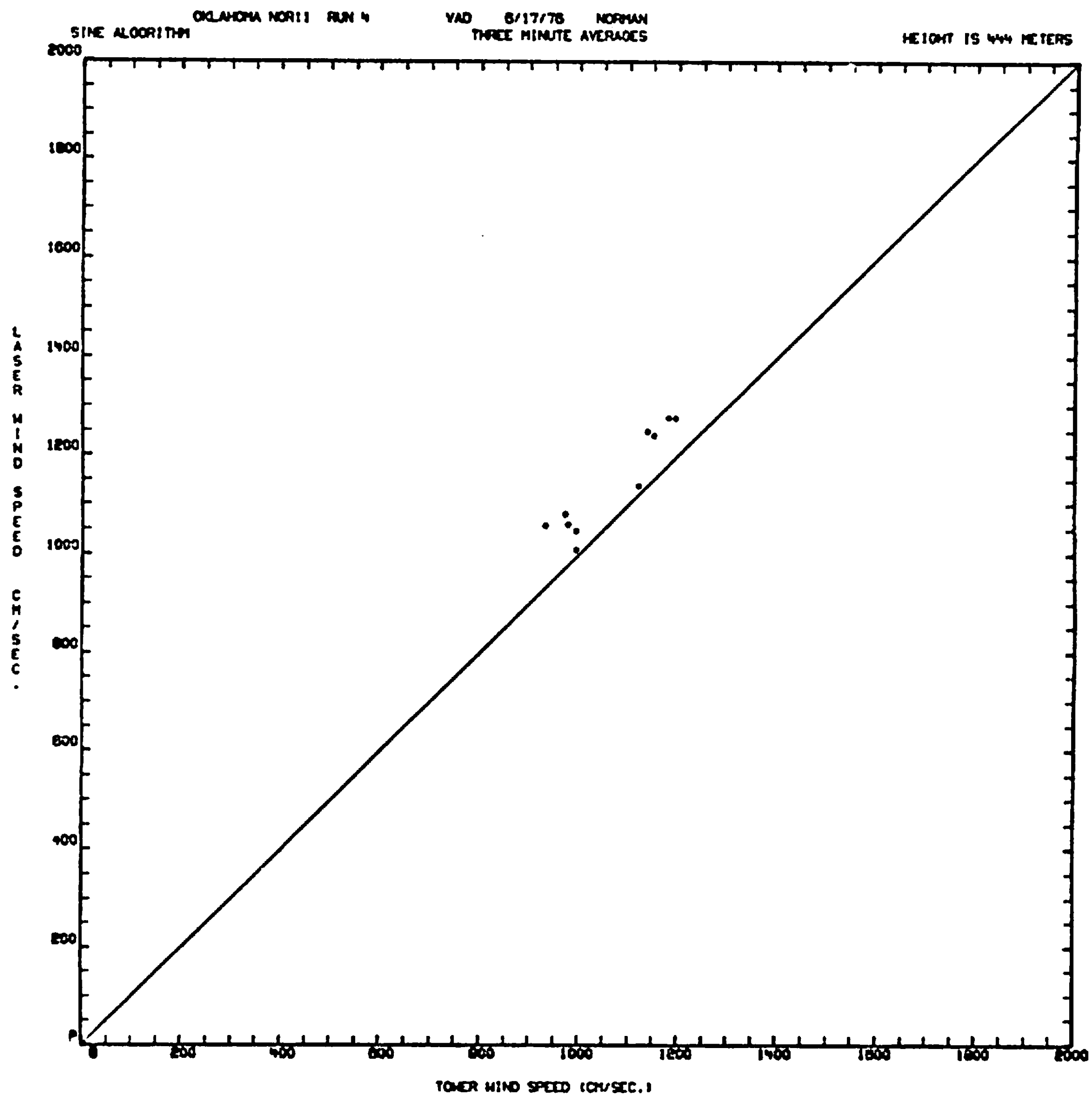

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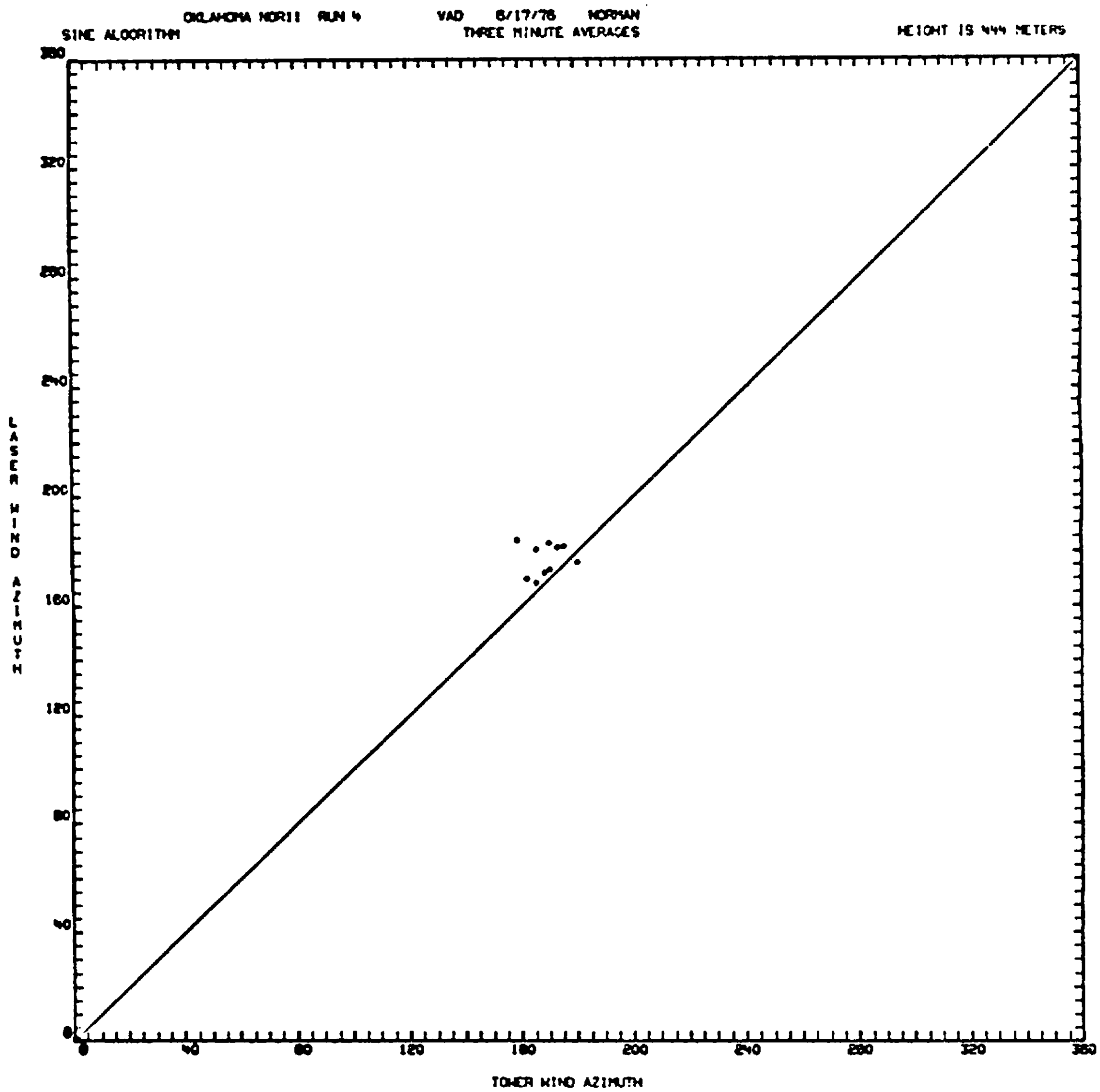

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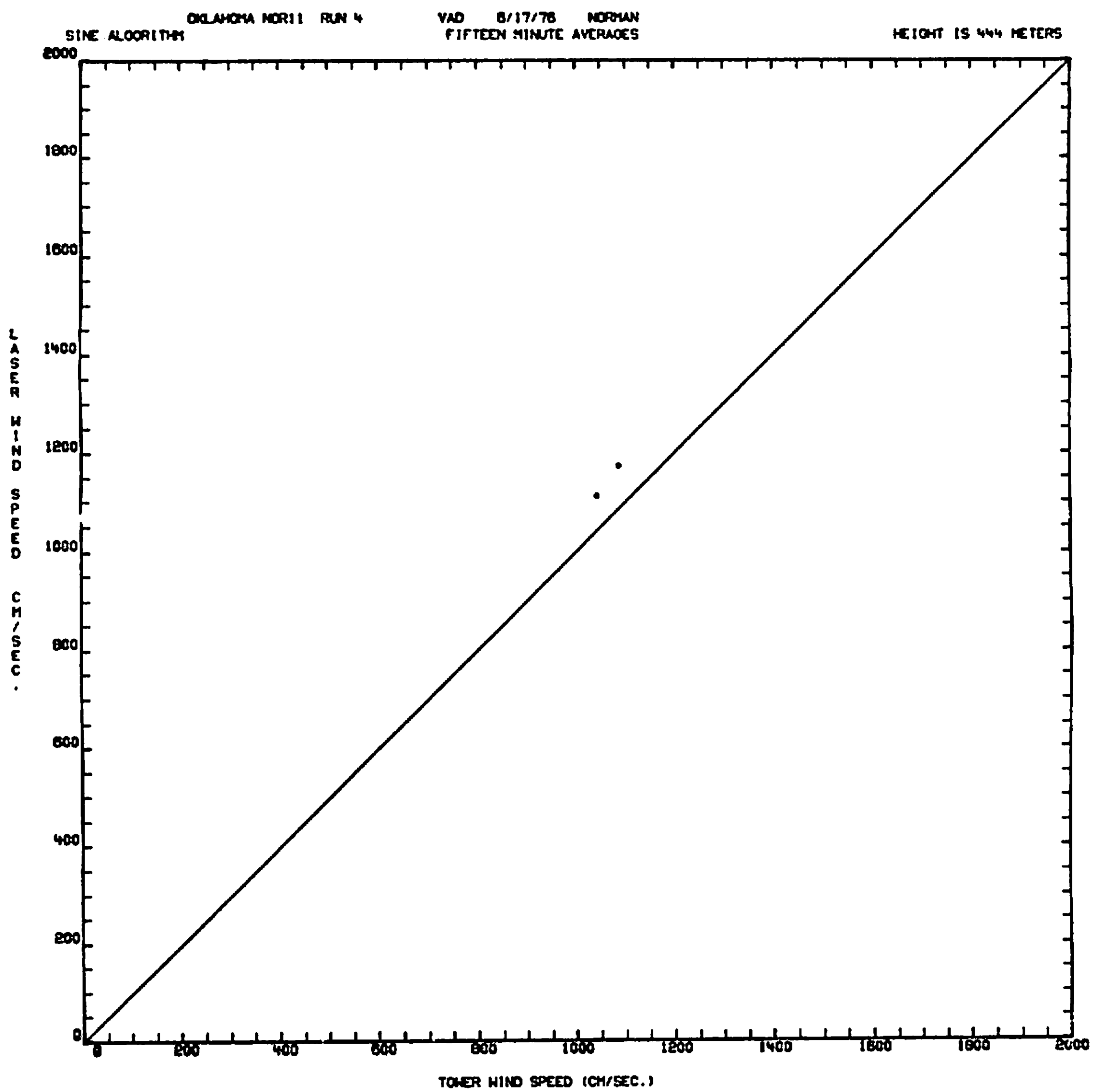

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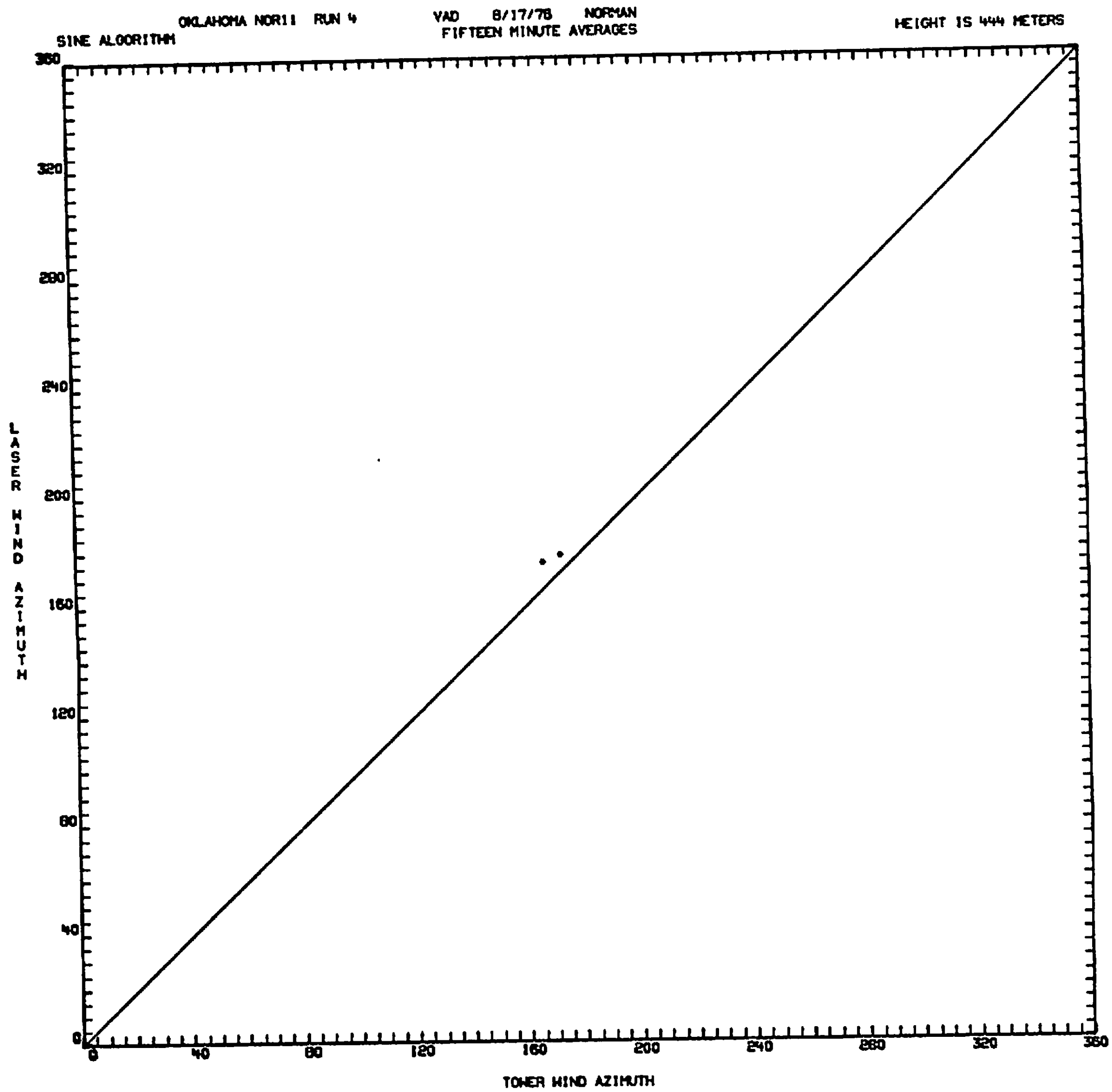

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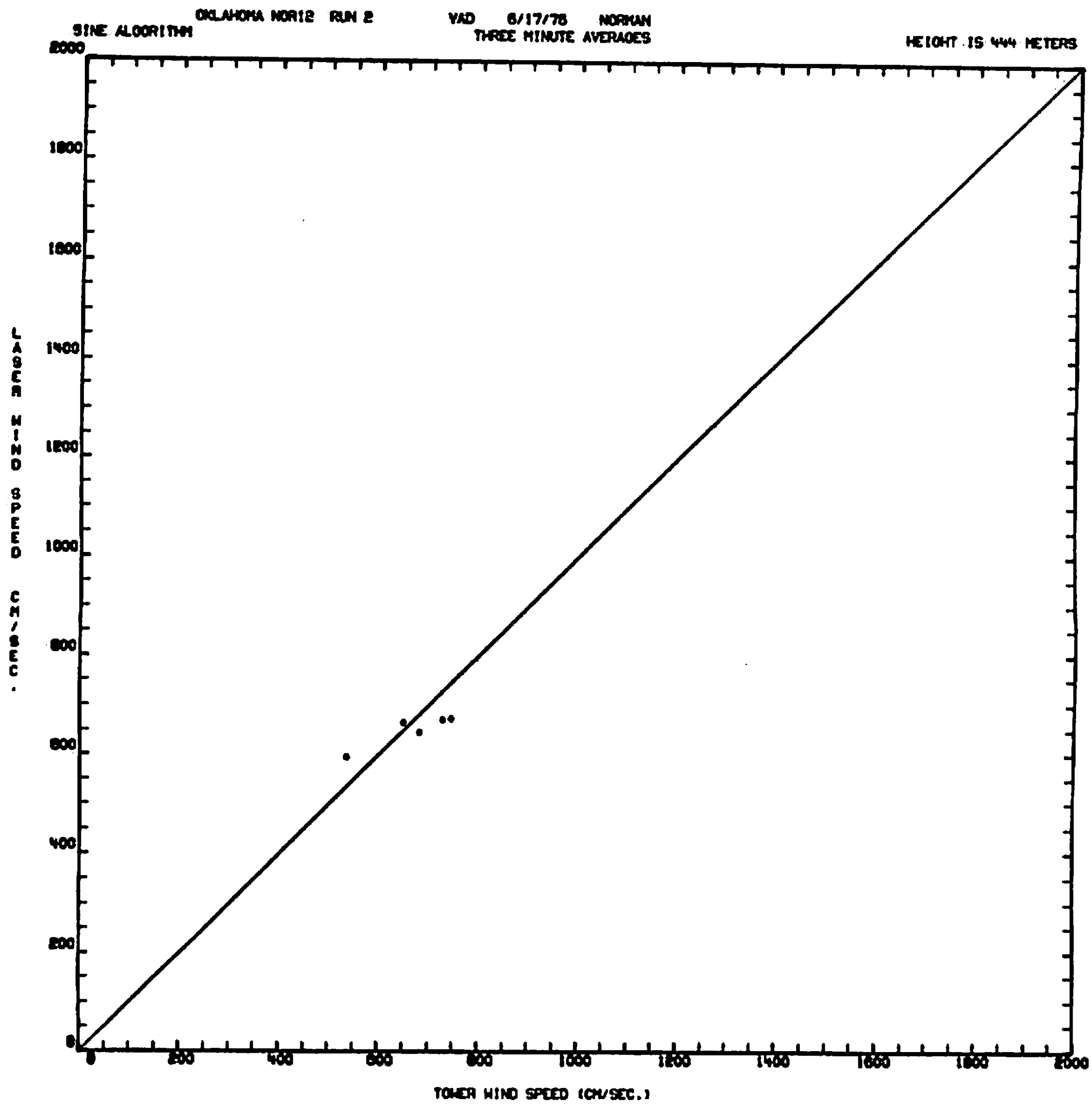

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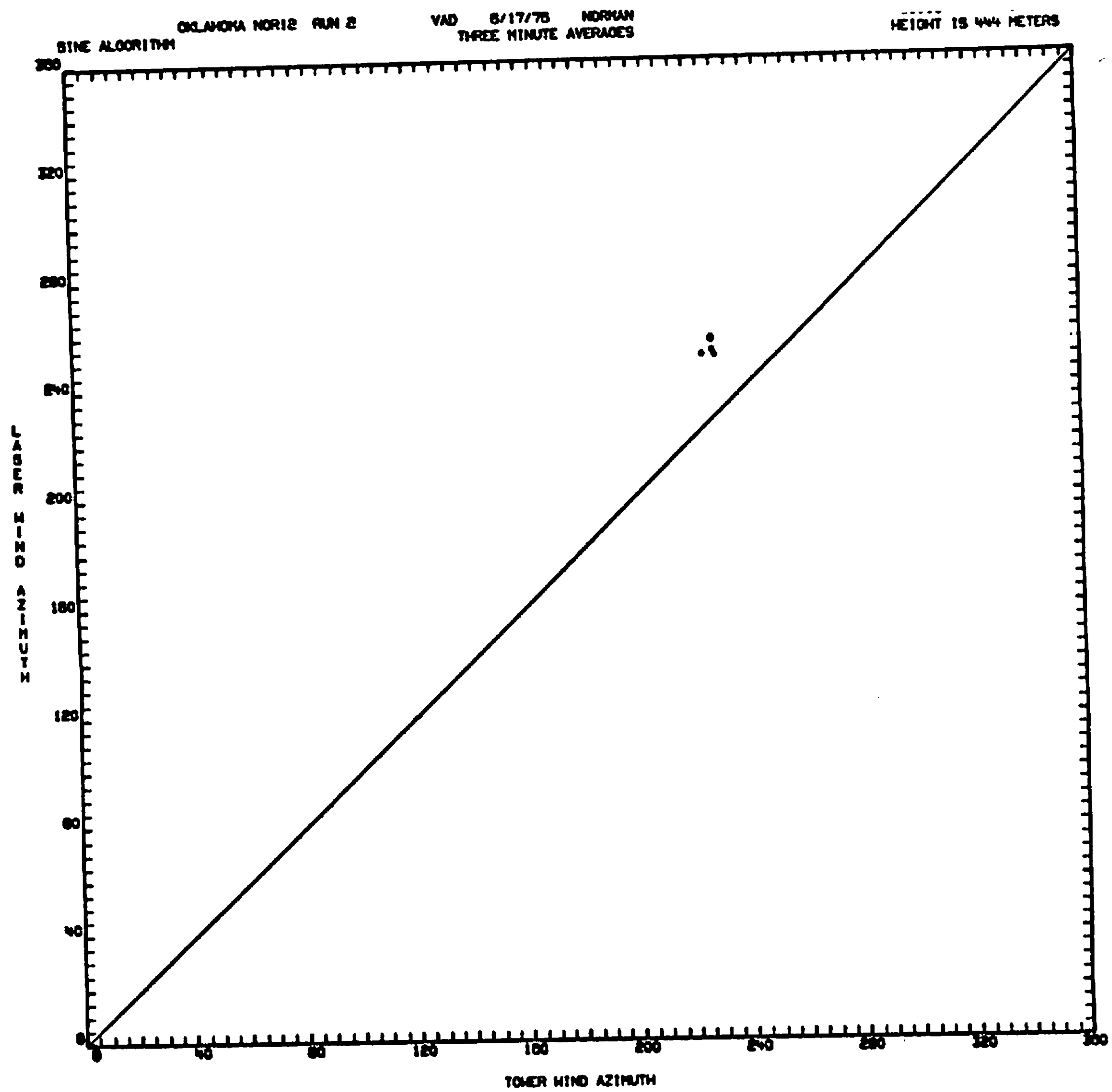

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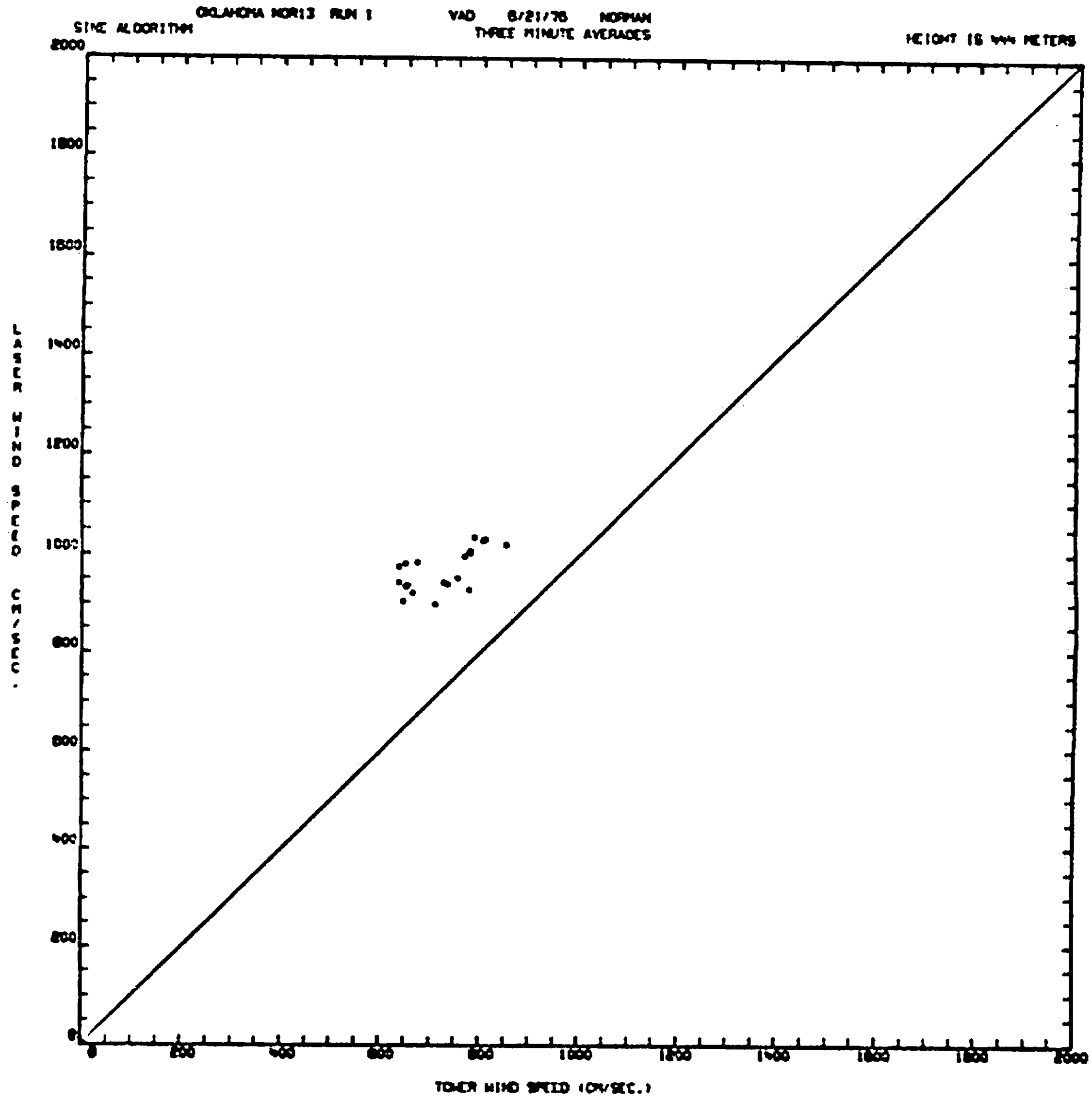

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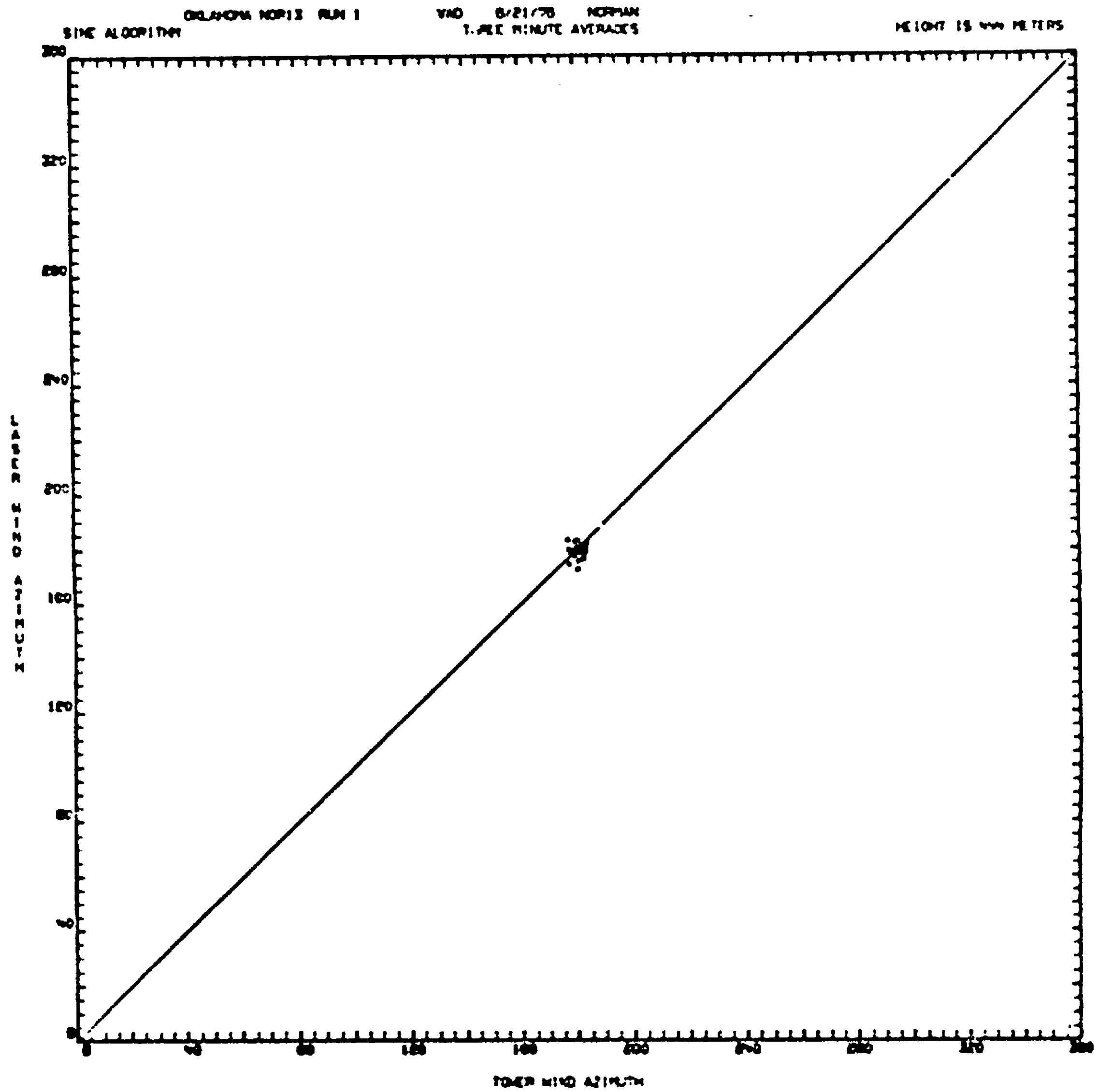

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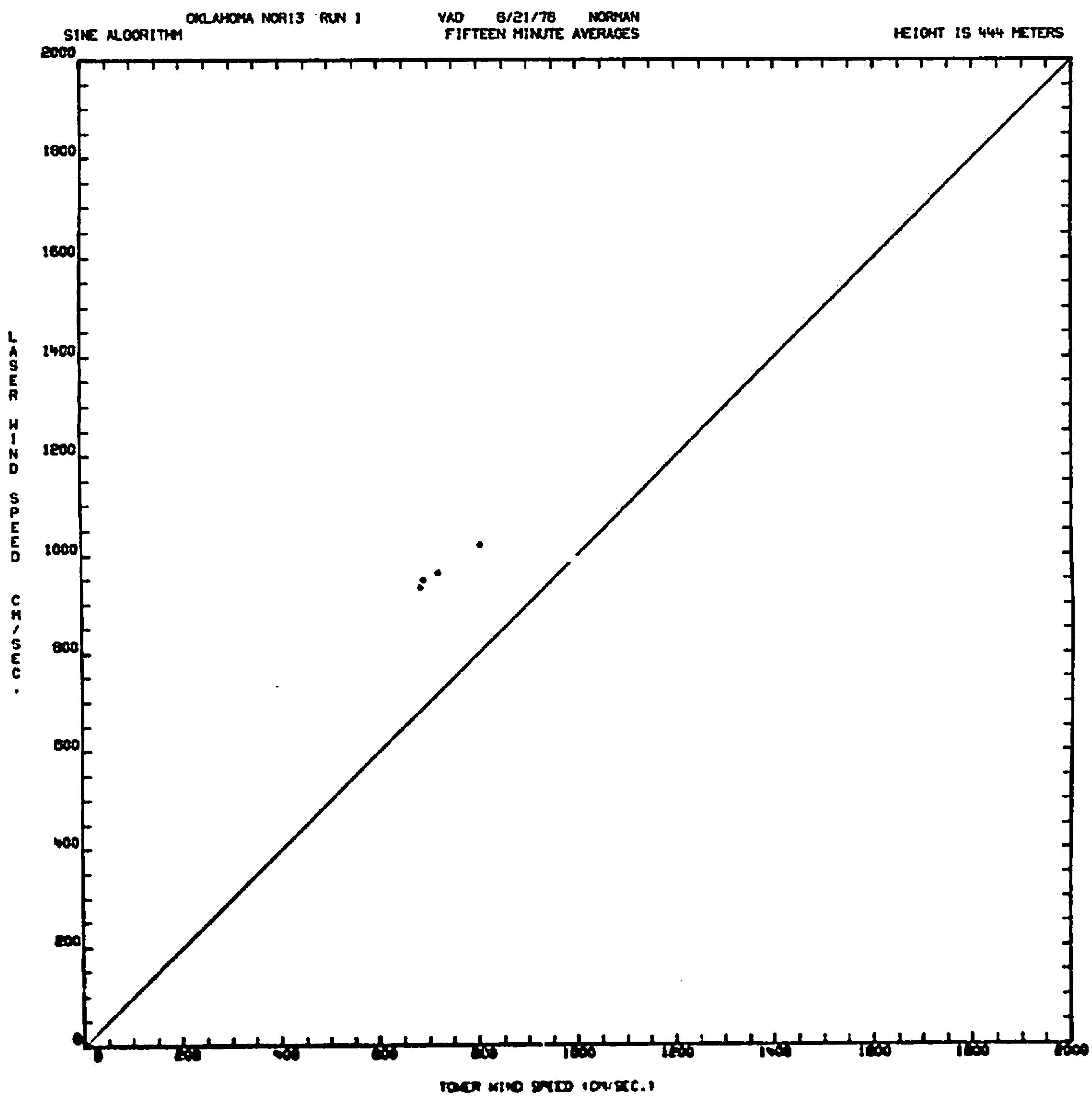

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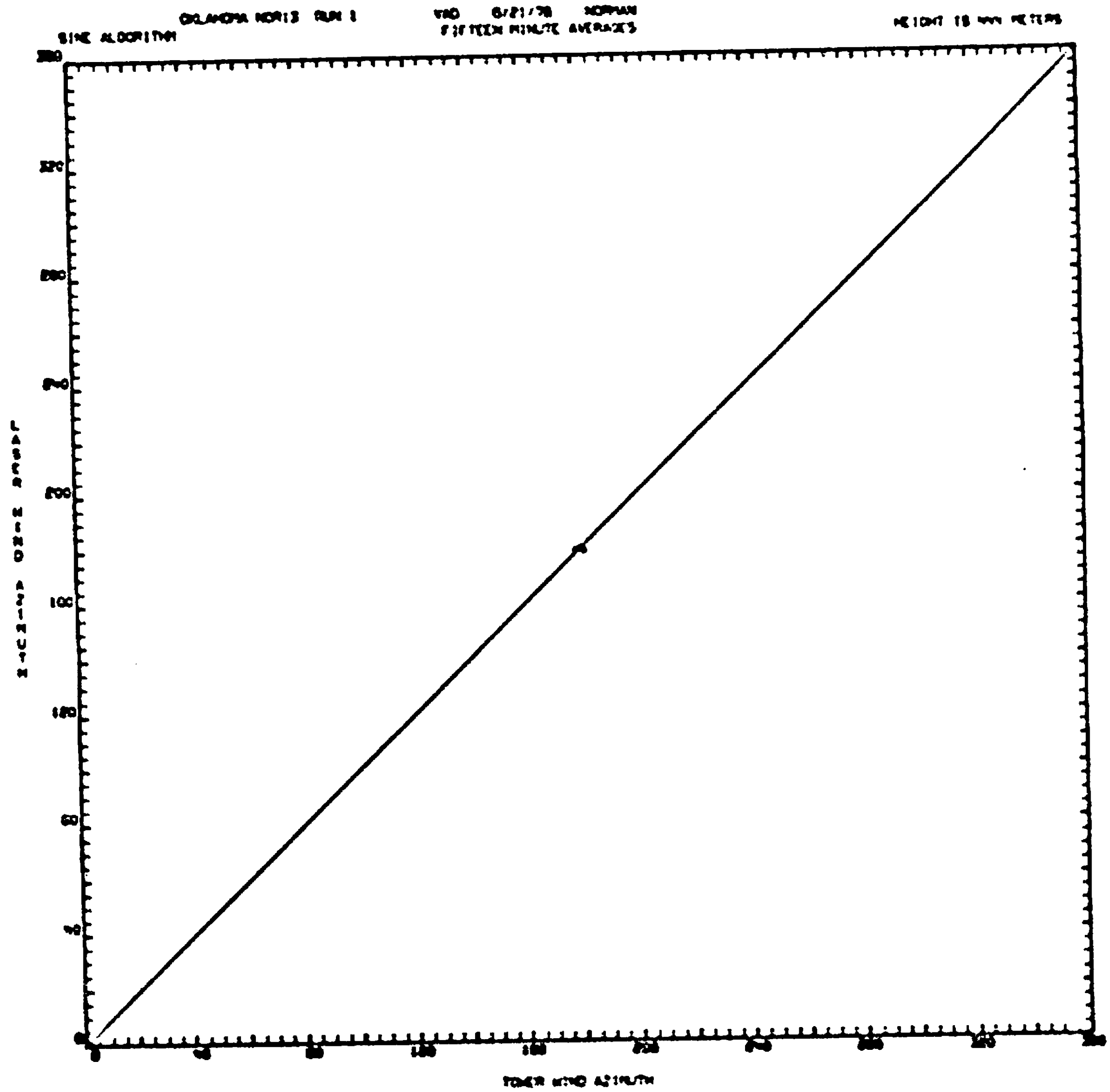

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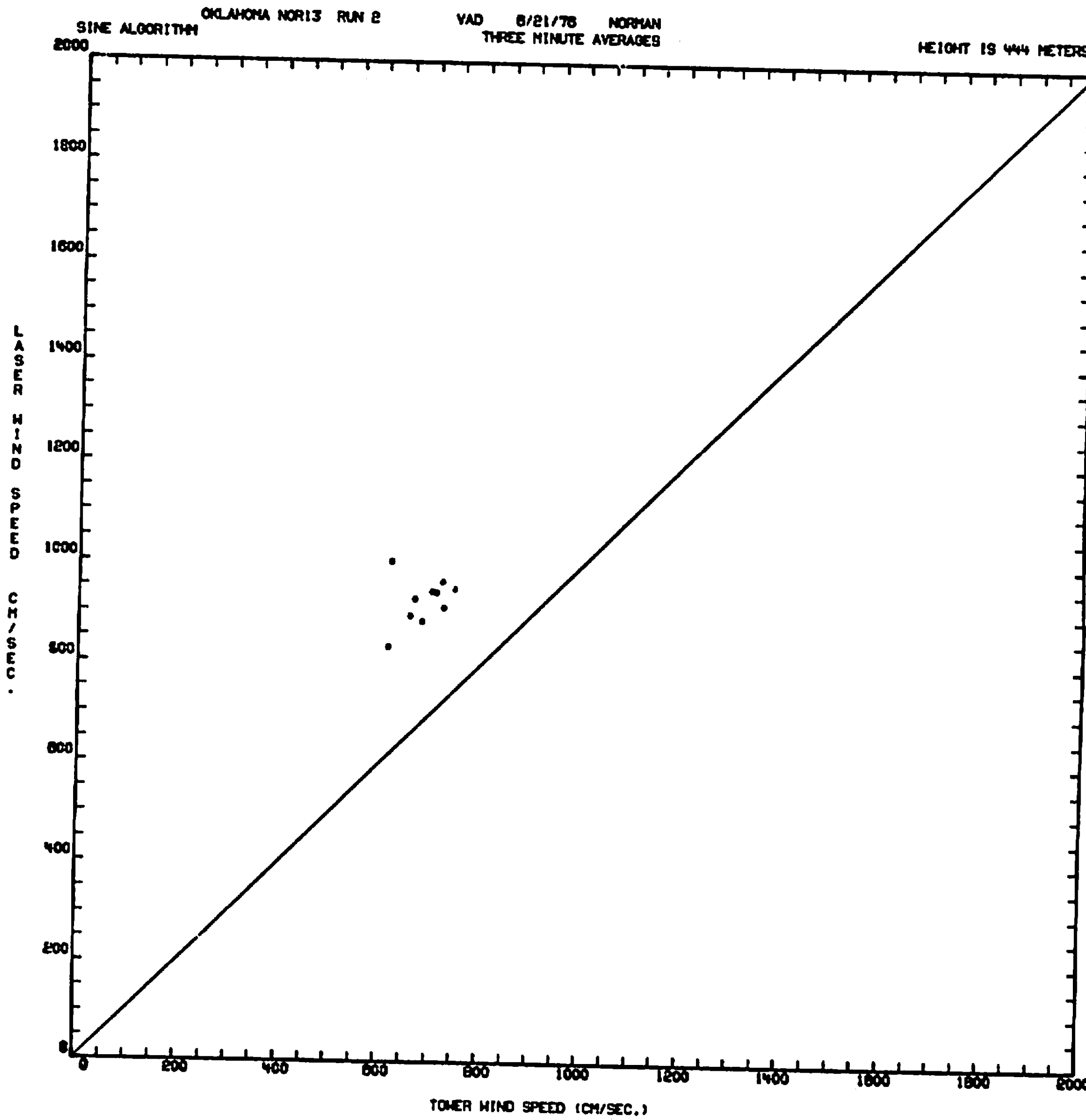

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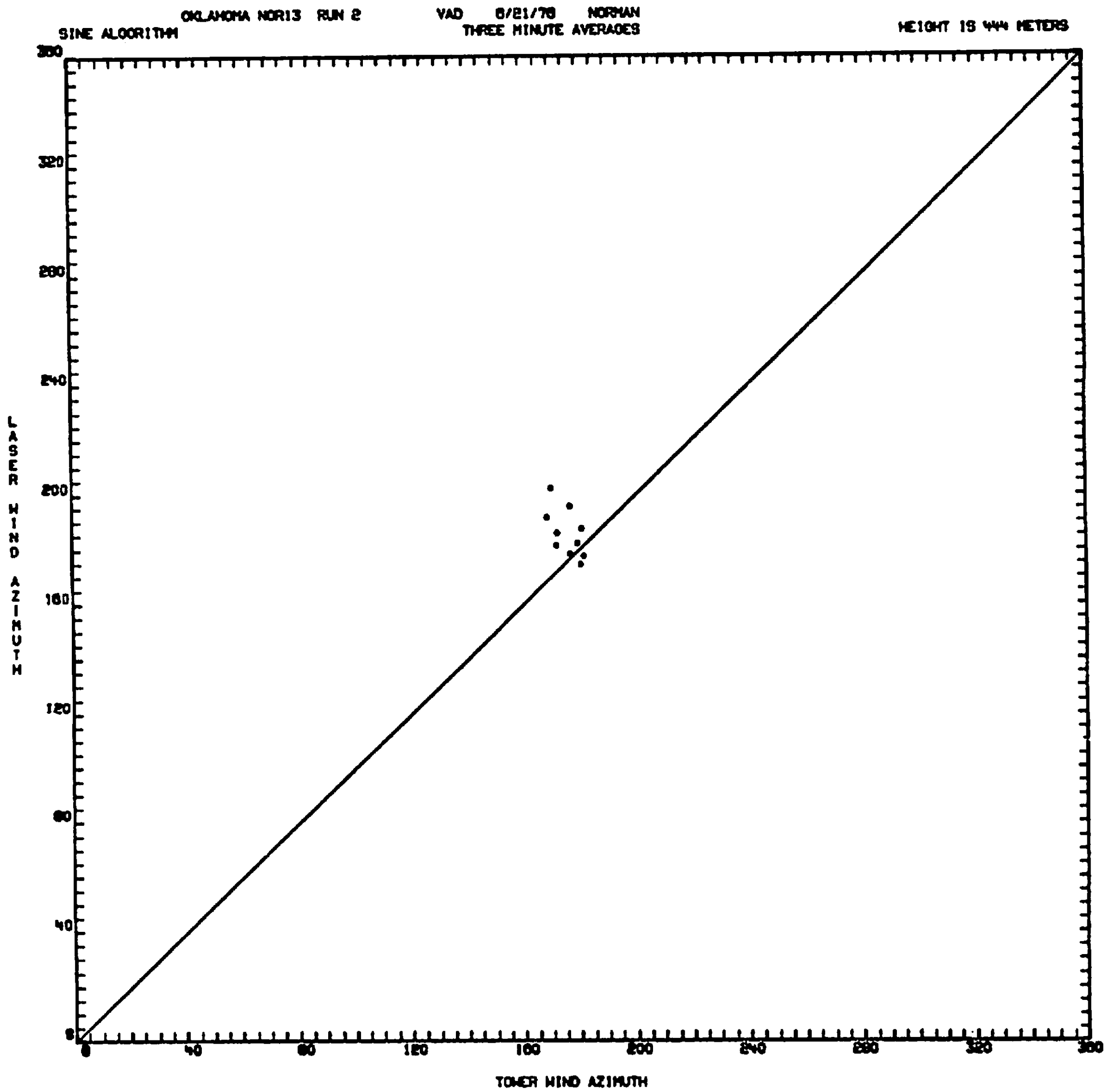

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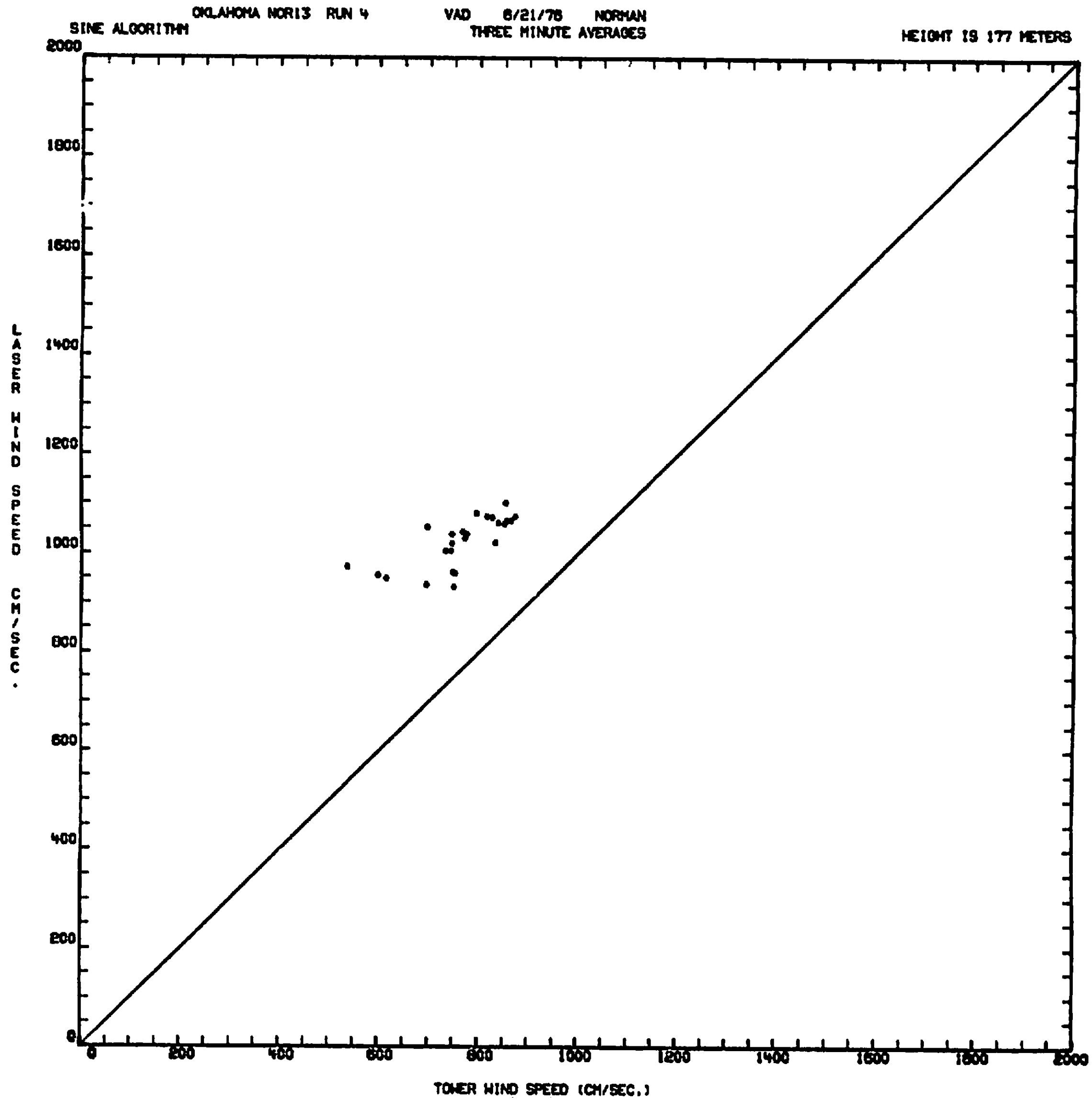

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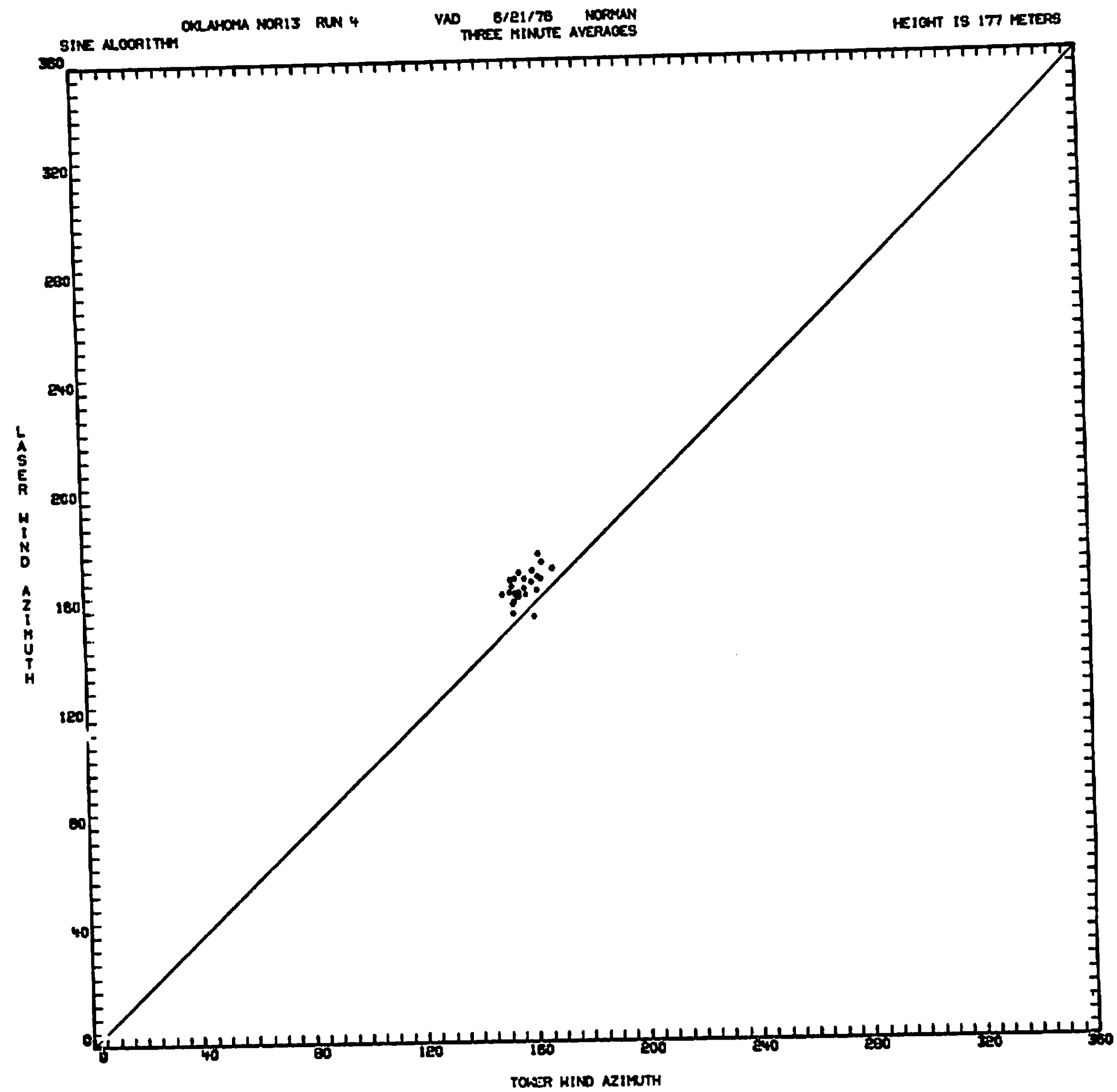

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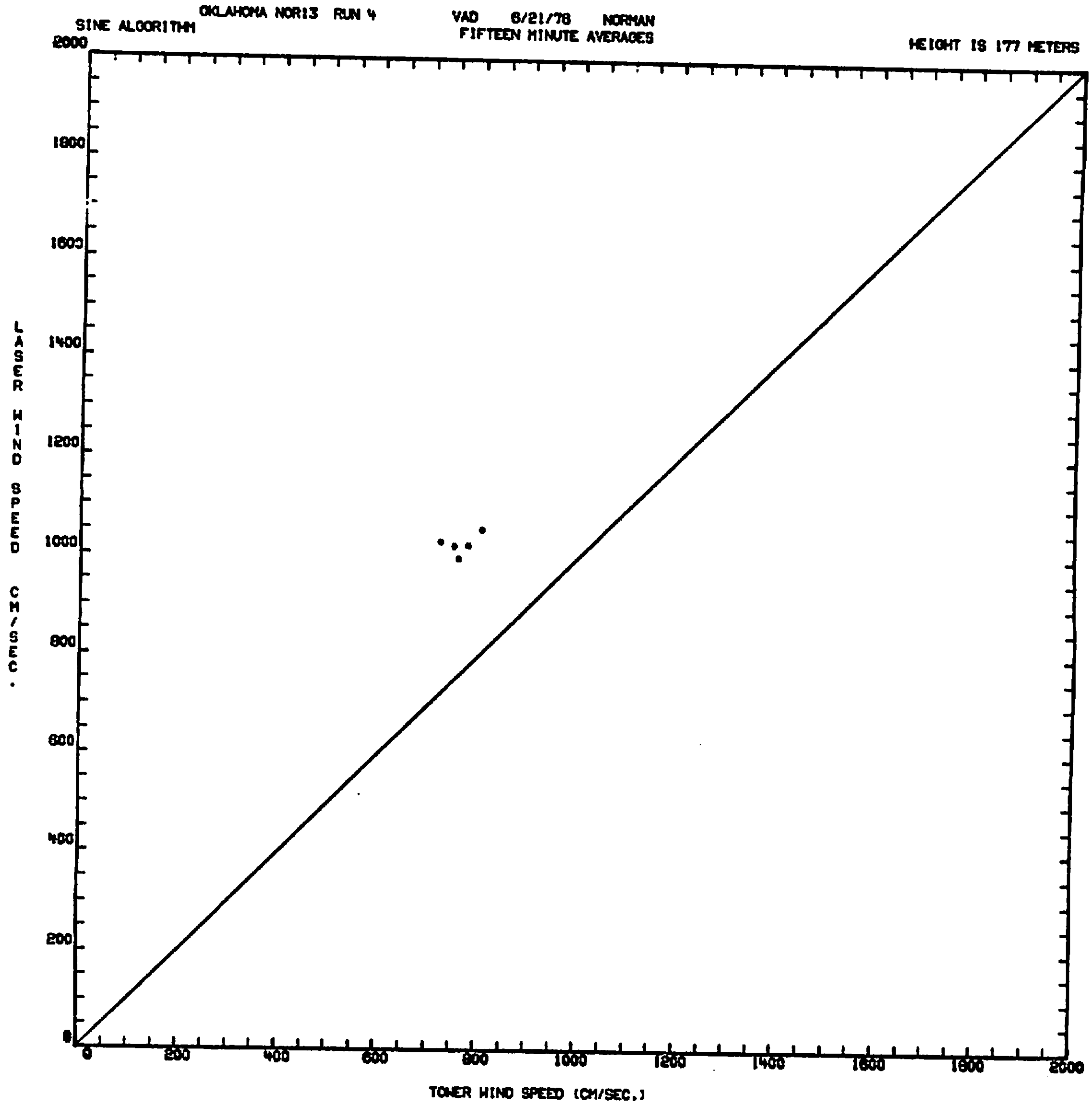

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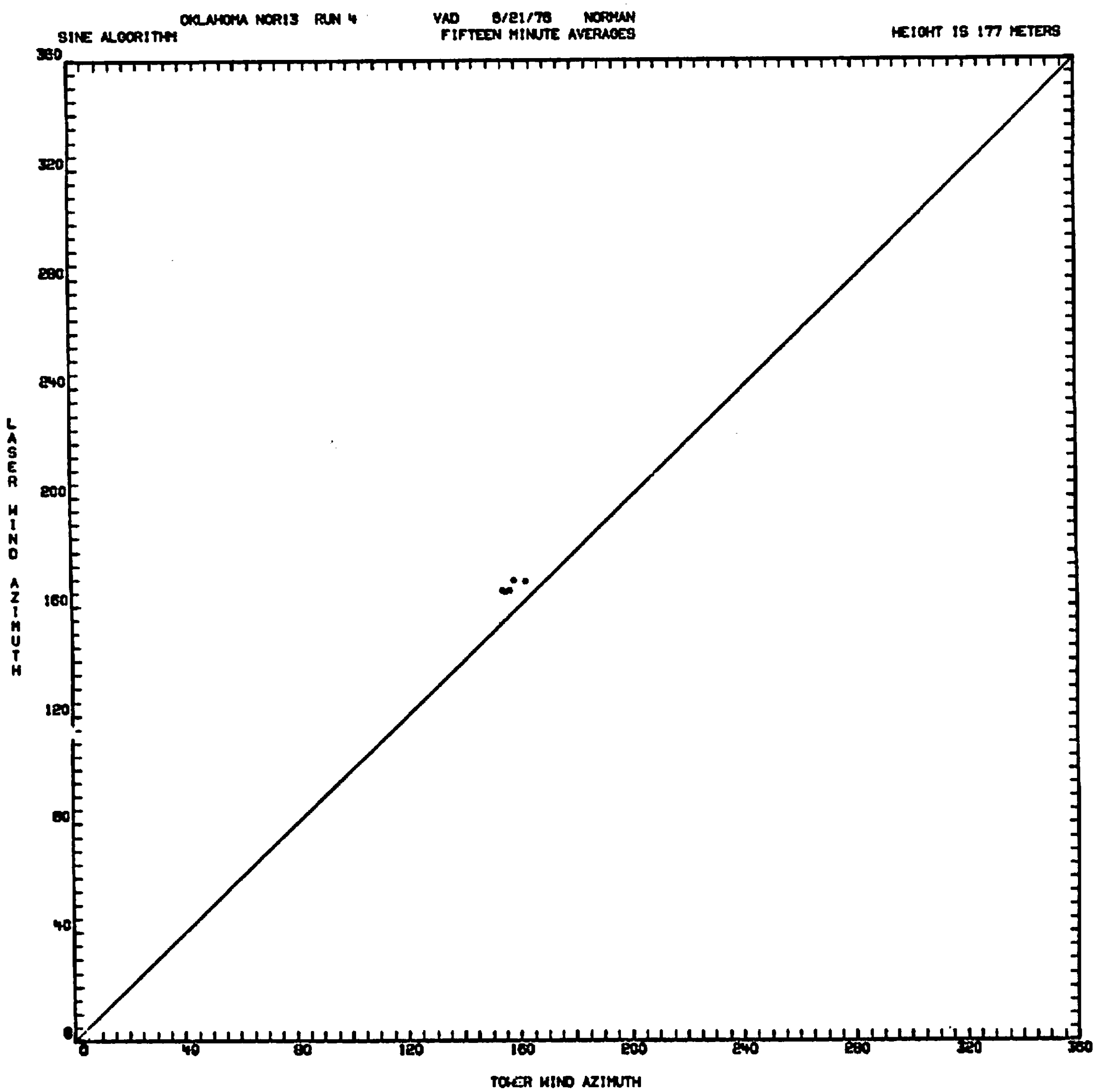

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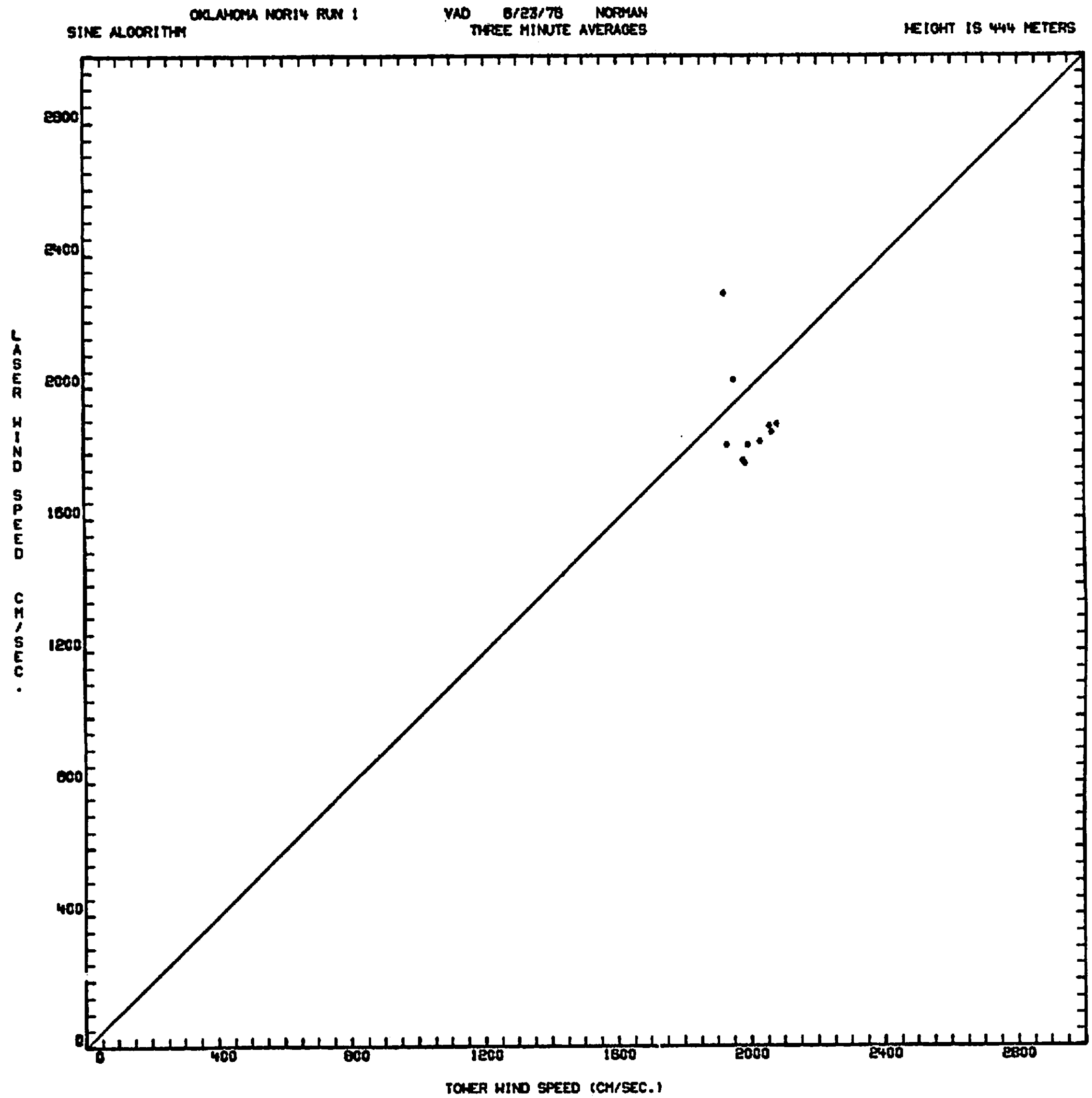

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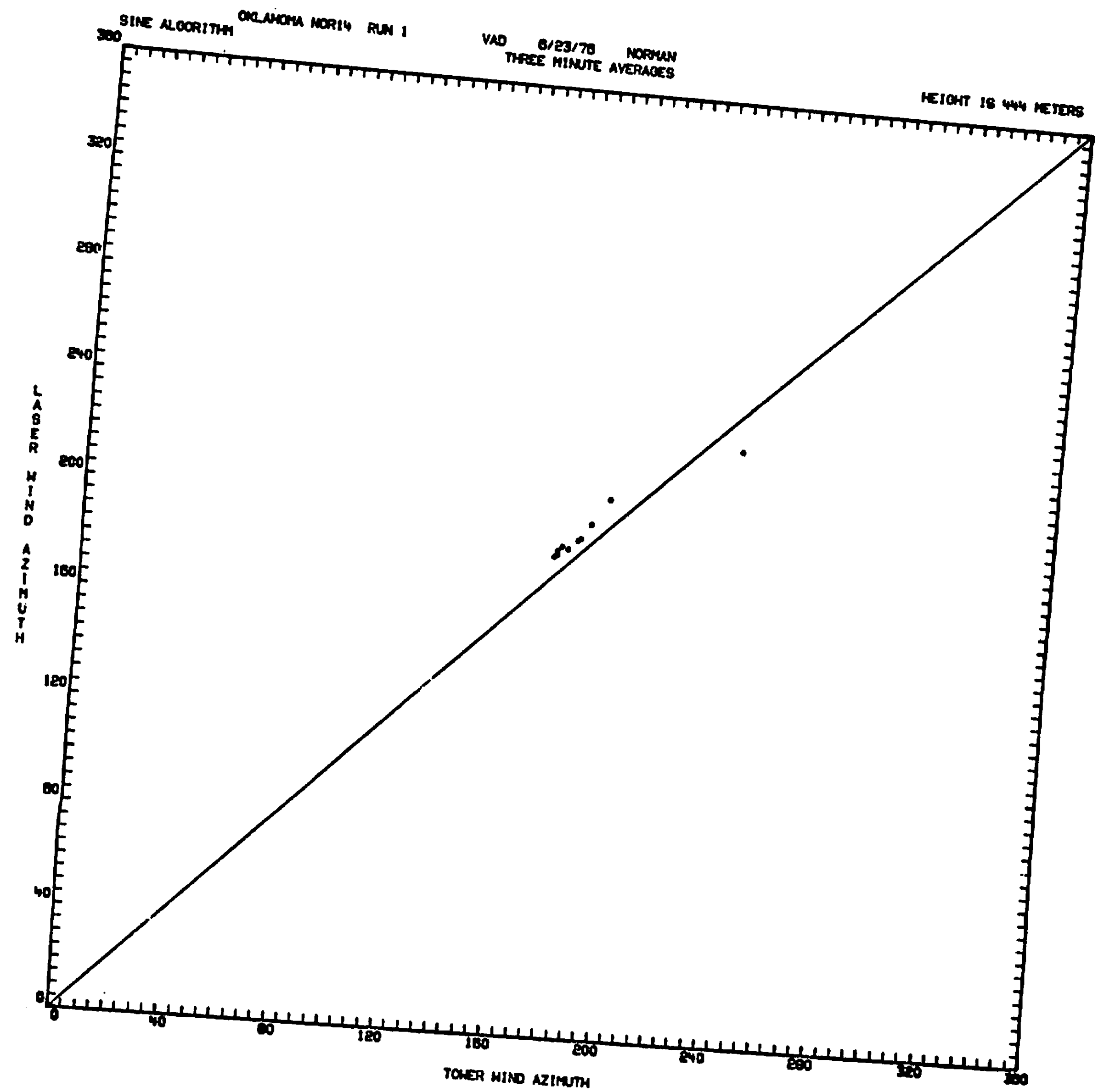

FIGURE D-1 (Concluded)

Appendix E

REPORT OF INVENTIONS

The purpose of the work performed under this contract and reported herein was the further verification of the capability of an existing remote sensing device to measure atmospheric winds accurately. It was desired to provide verification of the accuracy of the laser Doppler velocimeter to higher altitudes than the highest altitude of previous tests.

Because the purpose of the test was the use of established techniques on an existing device, no innovation, discovery, improvement, or invention was made.

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