# NASA TECHNICAL MEMORANDUM

NASA TM X-64981

(NASA-TM-X-64981) DEVELOPMENT OF A LASER DOPPLER SYSTEM FOR THE DETECTION AND MONITORING OF ATMOSPHERIC DISTURBANCES (NASA) 27 p HC $4.00 CSCL 20E
N76-16419
Unclas
G3/36 13598

## DEVELOPMENT OF A LASER DOPPLER SYSTEM FOR THE DETECTION AND MONITORING OF ATMOSPHERIC DISTURBANCES

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Electronics and Control Laboratory

November 28, 1975



NASA

*George C. Marshall Space Flight Center*
*Marshall Space Flight Center, Alabama*

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
NASA TM X-64981

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Development of a Laser Doppler System for the Detection and Monitoring of Atmospheric Disturbances

5. REPORT DATE
November 28, 1975

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Harold B. Jeffreys and James W. Bilbro

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
National Aeronautics and Space Administration
Washington, D.C. 20540

13. TYPE OF REPORT & PERIOD COVERED
Technical Memorandum

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
Prepared by Electronics and Control Laboratory, Science and Engineering

16. ABSTRACT
The Marshall Space Flight Center has developed a Scanning Laser Doppler Velocimeter System (SLDVS) capable of detecting and monitoring atmospheric disturbances. This system has been used successfully to detect and track wake vortices of landing aircraft and to obtain vertical wind profiles in the atmosphere.

The SLDVS, which is installed in a mobile van, is a focused, continuous wave, $CO_2$ system that determines the line-of-sight velocities of particles in the focal volume by measuring the Doppler shift created by these particles. At present the SLDVS is designed to have a range coverage of approximately 606 m (2000 ft) with a vertical angle coverage of approximately 60°. It is also designed to detect Doppler velocities of up to 61 m/s (200 ft/s) with a velocity resolution of approximately 0.6 m/s (1.8 ft/s). A complete velocity spectrum is provided by the SLDVS at each point in space at which it is focused. This information is further processed to provide specific velocity information in regions of interest.

This report is concerned with the overall operation and performance of the system as well as the description of the individual components that include the following: laser, interferometer, optical translator, transmit/receive optics, detector, scan controller, spectrum analyzer, integrator, velocity processor, data processor, displays, and recording electronics. In addition to the description and operation, the report includes the data handling capabilities of the system. It describes the data processing algorithms and discusses the various types of information that can be retrieved from the data. Examples of some of the data that have been collected are presented.

17. KEY WORDS

18. DISTRIBUTION STATEMENT
Unclassified — Unlimited

| 19. SECURITY CLASSIF. (of this report) | 20. SECURITY CLASSIF. (of this page) | 21. NO. OF PAGES | 22. PRICE |
|---|---|---|---|
| Unclassified | Unclassified | 25 | NTIS |

## ACKNOWLEDGMENTS

The authors are greatly indebted to R. M. Huffaker, E. A. Weaver, R. W. George, G. D. Craig, P. J. Marrero, and C. L. Wyman of the Marshall Space Flight Center Electronics and Control Laboratory for their valuable contributions to the design, development and checkout testing of the Scanning Laser Doppler System.

We also wish to thank the contract personnel of the Raytheon Company, Lockheed Missiles and Space Company, M&S Computing, and Physical Dynamics, Inc. for their valuable contribution in the areas of design, fabrication, and operational testing.

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# DEVELOPMENT OF A LASER DOPPLER SYSTEM FOR THE DETECTION AND MONITORING OF ATMOSPHERIC DISTURBANCES

## I. INTRODUCTION

The Marshall Space Flight Center (MSFC) has developed a Scanning Laser Doppler Velocimeter System (SLDVS) capable of detecting and monitoring the velocity structure of atmospheric disturbances. This system (Fig. 1) has been used successfully to detect, monitor, and measure the velocity structure of aircraft wake vortices and to provide tracks of the vortex movement. It has also been used to obtain vertical wind profiles in a single plane in the atmosphere.

The SLDVS is a continuous-wave, focused, coaxial, 30.5 cm (12 in.) F2 cassegrainian optics system which operates with a $CO_2$ laser transmitter emitting radiation at 10.6 $\mu$m. This system is installed in a mobile van and consists of a very stable single-frequency $CO_2$ laser, a modified Mach-Zehnder interferometer, a Bragg cell frequency translator, transmit and receive optics, an infrared detector, a versatile range and angle scanner, a surface acoustic wave frequency analyzer, a signal discriminator, a data algorithm processor, displays, recording electronics, and hard copy units. The system is designed to have a range coverage from 61 m to 606 m (200 to 2000 ft) and an elevation coverage from 3° to 60°. The maximum range and angle scan rates are 7 Hz and 1 Hz, respectively. The system detects Doppler velocities up to 61 m/s (approximately 200 ft/s) in increments of 0.6 m/s (approximately 1.8 ft/s) and provides a line-of-sight velocity spectrum for the range resolution volume in space associated with the point at which the system is focused. This velocity spectrum is then processed to provide specific velocity/target information as a function of position in space and time.

Aircraft wake vortex and vertical wind profile measurements were performed with two SLDV systems installed at John F. Kennedy International Airport in New York. These measurements were performed in cooperation with the Federal Aviation Agency, the Transportation System Center, and the National Aviation Facilities Experiment Center.

## II. SYSTEM OPERATIONAL DESCRIPTION

The SLDVS operational description can best be communicated by tracing the coherent output radiation from the $CO_2$ laser transmitter through the optics, to the atmosphere, and back to the data algorithm processor and its displays. As shown in Figure 2, the horizontally polarized, collimated 6 mm beam exits from the $CO_2$ laser and impinges on the first beamsplitter which is oriented at 45° to the beam path. Approximately 10 percent of this beam is passed through the beamsplitter to be used as a local oscillator signal. This portion then passes through either a Bragg cell frequency translator or a series of attenuators. In the translated mode, the Bragg cell shifts the frequency by 24 MHz to create an offset zero frequency for which positive and negative Doppler shifts can be observed. In the nontranslated mode, the beam attenuators reduce the local oscillator power to a level for satisfactory operation of the detector. In this mode, positive and negative Doppler shifts and the direction of the velocity cannot be determined. The local oscillator beam is then reflected 90° by a mirror placed at 45° to the beam path. The beam then passes through a half-wave plate, changing the beam polarization from horizontal to vertical, and a recombining beamsplitter where it is mixed with the return signal onto the detector. The main portion of the exit beam from the laser is reflected 90° by the first beamsplitter and passes through a brewster window that is aligned such that it transmits horizontally polarized light and reflects vertically polarized light. The exit beam is then reflected 90° and passes through a quarter-wave plate that changes the polarization of the beam to right-hand circular. The direction of polarization is reversed at the transmit telescope's secondary mirror and again at the primary mirror, such that the radiation impinging on the scanning flat mirror is again right-hand circularly polarized. Upon reflection from the primary, the beam expands to approximately 25.4 cm (10 in.) in diameter, strikes the scanning mirror at 45°, and focuses at positions in space by movement of the secondary mirror and the scanning flat. The right-hand circularly polarized radiation is reflected by atmospheric aerosols in the focal volume of the system as left-hand circular and at the same time shifts the frequency of the beam by an amount proportional to the velocity of the aerosols along the line of sight (Fig. 3). This return signal travels back along the same path as the exit beam until it reaches the quarter-wave plate where, because the direction of polarization has been reversed by the atmospheric backscatter, it is converted to vertical polarization upon passing through. This vertically polarized return signal is then reflected by the brewster window to the recombining beamsplitter where it is mixed with the local oscillator beam. The mixing of these two beams creates an interference pattern that is imaged by the focusing lens on the face of the detector. This pattern varies with time according to the difference frequency of the two beams. The detector converts the radiation energy to electrical energy, and the result is an electrical beat signal that is proportional to the Doppler shift created by the motion of the atmospheric aerosols. This signal is then amplified by the receiver network to the level required for operation of the signal processor. Upon entering the signal processor, the Doppler signal is mixed with a chirp pulse and fed to a surface acoustic wave delay line. The serial output of the delay line is a continuous, analog spectrum analysis of the Doppler signal where the frequency is proportional to time. The signal is then sent to a sample-and-hold unit, the output of which provides a series of discrete spectrum samples (104 samples in the maximum case). Each sample is representative of a particular Doppler frequency interval approximately 100 kHz (approximately 1.8 ft/s) wide. Each sample is then A/D converted and incoherently integrated by summation averaging. At the end of a selected integration time (0.5 ms to 64 ms), a complete Doppler velocity distribution is provided for the aerosols contained in the coherent focal volume of the beam for that time and position in space. The coherent focal volume or range resolving capability of the focused coaxial optical heterodyne systems is expressed in terms of that range element in space that contributes a specified portion of the total backscattered signal at various ranges. The signal-to-noise ratio of coaxial focused systems that heterodyne the scattered return from the atmospheric aerosols is given by

$$S/N = \frac{\eta \, P_T \, \beta(\pi) \; \pi R^2}{2 \, B \, h \, \nu} \int_{L_1}^{L_2} \frac{dL}{L^2 \left[ 1 + \left( \frac{\pi R^2}{\lambda L} \right)^2 \left( 1 - \frac{L}{f} \right)^2 \right]} ,$$

where

$\eta$ = detector quantum efficiency

$P_T$ = transmitter power

$\beta(\pi)$ = backscatter coefficient

R = radius of the transmitting optics

B = system bandwidth

L = particle range

h = Planck's constant

$\nu$ = frequency of transmitted radiation

$\lambda$ = wavelength of transmitted radiation

f = transmitter/receiver focal length, equivalent to range.

Integration from $L_1$ to $L_2$ yields

$$S/N = \frac{\eta\, P_T\, \beta(\pi)\, \lambda}{2\, B\, h\, \nu} \left\{ \tan^{-1}\left[\frac{\lambda L_2}{\pi R^2} - \frac{\pi R^2}{\lambda f}\left(1 - \frac{L_2}{f}\right)\right] - \tan^{-1}\left[\frac{\lambda L_1}{\pi R^2} - \frac{\pi R^2}{\lambda f}\left(1 - \frac{L_1}{f}\right)\right]\right\} .$$

The resolution of the system can be defined by calculating the length of the range element that produces one-half the coherent backscattered signal received from the entire range $L_1 = 0$ to $L_2 = \infty$. Figure 4 gives the one-half power range resolution for a 30.48 cm (12 in.) $CO_2$ laser optical heterodyne system as a function of range. This volume is defined as the volume from which one-half of the coherent backscattered signal is derived.

This information, along with the position coordinates, is then recorded on high speed, pulsed-code-modulated (PCM) analog tape at a maximum data rate of approximately 2 megabits. The signal next goes through a velocity and signal amplitude discrimination process in which different velocities and amplitudes of the signal may be eliminated, leaving only a selected portion of the spectrum (Fig. 5). This information is further examined by the signal processor and the following information is extracted: Vmax, the velocity with the highest signal strength; Vpk, the highest velocity with signal above the amplitude threshold; Ipk, the magnitude of the highest signal amplitude (digital number between 1 and 256); and N, the total number of velocity cells with signal amplitude above amplitude threshold. This information is sent to the data algorithm processor along with position and time information where it is recorded on tape and/or stored in computer memory for processing on a scan-frame by scan-frame basis in real time. The results of the data algorithm processor are then displayed and automatically hardcopied.

# III. VORTEX DATA COLLECTION

For the John F. Kennedy International Airport aircraft wake vortex test program, two SLDVS units were located near the middle marker of runway 31 right, approximately 121 m (400 ft) on either side of the centerline. This configuration permitted the two independent sensor units to scan a common area perpendicular to the aircraft landing corridor (Fig. 6). This area of prime interest for vortex detection and monitoring is indicated in the figure to be 61 m (200 ft) either side of the runway centerline and 91 m (300 ft) in altitude.

In vortex detection, the velocity threshold is set approximately three velocity cells, 1.8 m/s (6 ft/s), above the peak wind velocity in the scan plane and the amplitude threshold is set approximately 6 dB below the system wind signal amplitude. This allows only those data points that have high S/N and high velocities, i.e., those that are associated with the vortices, to be sent to the data algorithm processor.

The real time vortex location algorithm processes the raw data to locate the vortex centers. The data are screened to ascertain that a sufficient number of data points exist to define a vortex center and that the maximum peak velocity meets an established minimum. If these criteria are not met, a vortex center cannot be defined. When these criteria are satisfied, a correlation region is defined that contains all data points within a given radius of the point possessing the maximum peak velocity. This region is verified as containing a vortex center if B percent of the points possess velocities that are at least A percent of the maximum peak velocity where A and B are specified by the operator. If this requirement is not met, the point having the maximum peak velocity (Vpk) is rejected as a noise spike, and the entire process is repeated until either a noise spike limit is exceeded or a valid region is found. When a valid region is found, the vortex center is computed by the algorithm in Figure 7. This figure also shows the correlation circle drawn about the data point with the maximum peak velocity. Once a vortex center is located, the points that were used to determine its location are eliminated, and an attempt is made to locate a second vortex by repeating the process. After a second vortex center is located, or it has been established that one cannot be defined, the chosen output data are displayed and recorded.

The time-based plots (Fig. 8) display the altitude and horizontal location of the port (*) and starboard (°) vortex centroids as a function of time. When only one vortex centroid is found in the scan plane, an (S) is used to denote its position.

The x-y plots (Fig. 9) display the vortex centroids in the vertical scan plane with scan frame 1 data represented by an A, frame 2 data by B, etc., for 26 frames, at which point the cycle is repeated. The typical time between scan frames for the John F. Kennedy International Airport operation was 2.5 s.

The tabular data outputs (Fig. 10) give the frame number, the number of data points contained in that frame, the number of points contained in the correlation region for each vortex, the number of noise spikes found while determining each vortex center, the minimum and maximum elevation angles at which data points were found, the maximum peak velocities in each correlation region, the time at which the vortex centers were detected, and the location of the vortex centers.

Scatter plots (Fig. 11) display the raw data points in the post-processing mode, showing their location in the vertical scan plane and their velocities within 3 m/s (10 ft/s). The vortex centroids are also displayed. The characters 0 through 9 correspond to 3 m/s (10 ft/s) velocity increments which start at 6 m/s (20 ft/s) for 0 and go to 36 m/s (120 ft/s) for 9. The ten highest velocity data points have the actual velocities printed at the bottom of the display in feet per second. Those ten velocities are plotted as characters A through J.

## IV. WIND PROFILE DATA COLLECTION

For vertical wind profile measurements, the SLDVS was employed in the same configuration as in the vortex measurements. Data acquisition was accomplished using the same basic operating parameters. The amplitude and velocity thresholds of the signal processor were set to ensure atmospheric wind detection and to eliminate signal noise, and the signal integration time was increased (from 2 ms to 8 ms) to reduce the total number of data points in the scan frame. The data from the two independent units were then processed to ensure time correlation between scan frames and data points. After a time correlation was obtained, the data were examined to find the data points from each sensor that could be closely correlated spatially. These points, along with their velocity information, were stored and compared to an input spatial correlation requirement. The spatial correlation parameter requires that data points from the two systems must be located spatially at a distance less than the spatial correlation requirement before they can be used to calculate the vertical and horizontal velocity components. The pairs of data points that met the requirement were analyzed to provide the vertical and horizontal velocity components associated with their common position in the system's scan plane. Figure 12 shows the average horizontal and vertical wind velocity in the common scan area of the plane between the two sensors as a function of altitude. Time correlation, spatial correlation, and altitude increments for the calculations in this figure were 1.25 s, 2 m (7 ft), and 6 m (20 ft), respectively.

# V. CONCLUSION

The Marshall Space Flight Center has developed a Scanning Laser Doppler Velocimeter System capable of detecting and monitoring atmospheric disturbances. It has been used successfully to detect, monitor, and measure aircraft wake vortices of landing aircraft in an airport environment and to measure atmospheric winds. The data obtained, which include more than 1700 aircraft landing operations, have been more than sufficient to permit calculations of vortex transport, vortex velocity profiles, vortex circulation strengths and vertical atmospheric winds profiles for the scan plane perpendicular to the aircraft landing corridor.

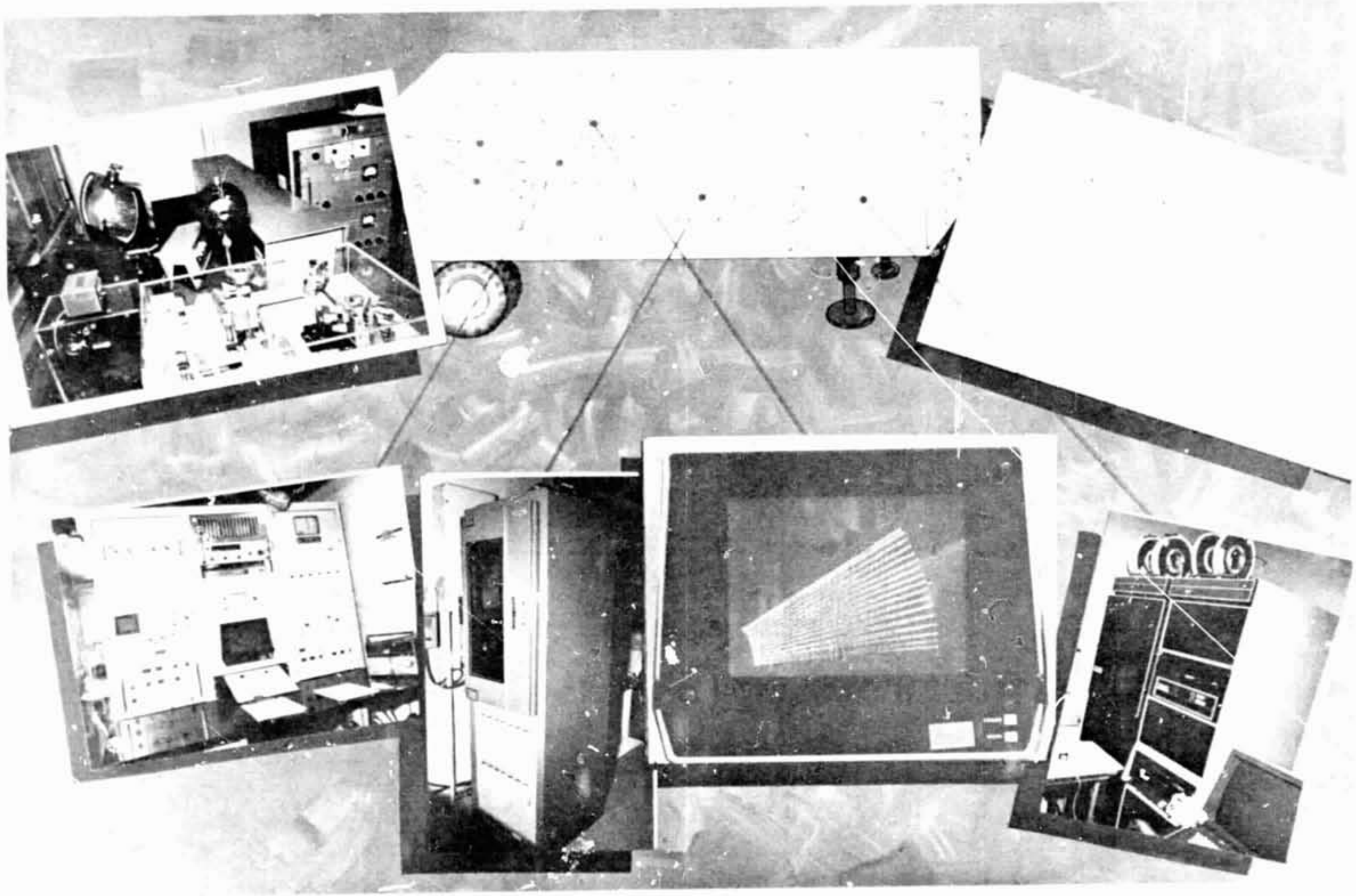
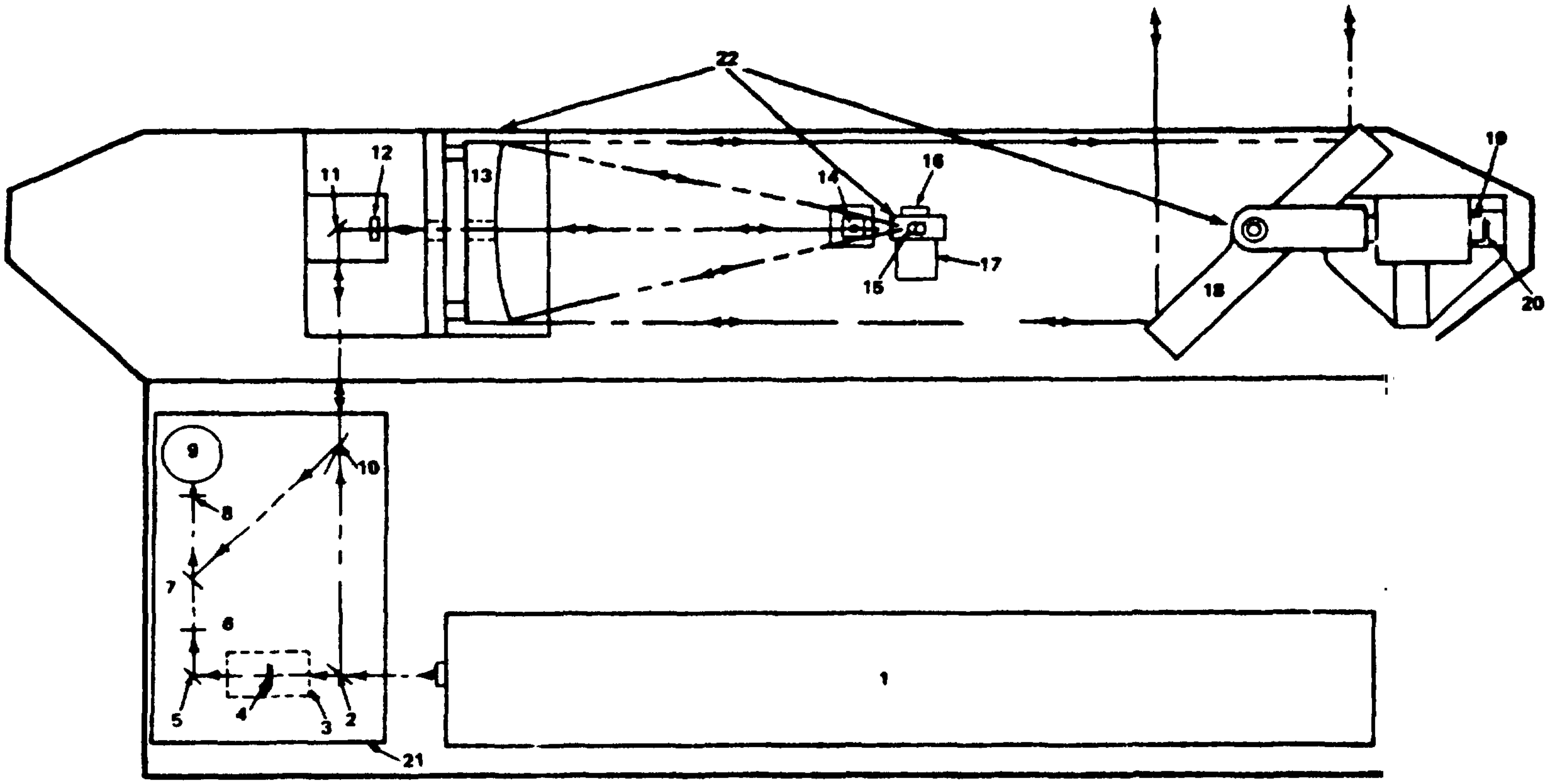


Figure 1. Scanning Laser Doppler Velocimeter System.




1. LASER
2. BEAM SPLITTER
3. BRAGG CELL
4. ATTENUATOR
5. 45° MIRROR
6. HALF WAVE PLATE
7. BEAM SPLITTER
8. FOCUSSING LENS
9. DETECTOR
10. BREWSTER WINDOW
11. 45° MIRROR
12. QUARTER WAVE PLATE
13. PRIMARY MIRROR
14. SECONDARY BACKSCATTER ATTENUATOR
15. SECONDARY MIRROR
16. SERVO MOTOR
17. SHAFT ENCODER
18. SCANNING MIRROR
19. SERVO MOTOR
20. SINE COSINE POT
21. INTERFEROMETER
22. TELESCOPE

Figure 2. Optics subsystem.

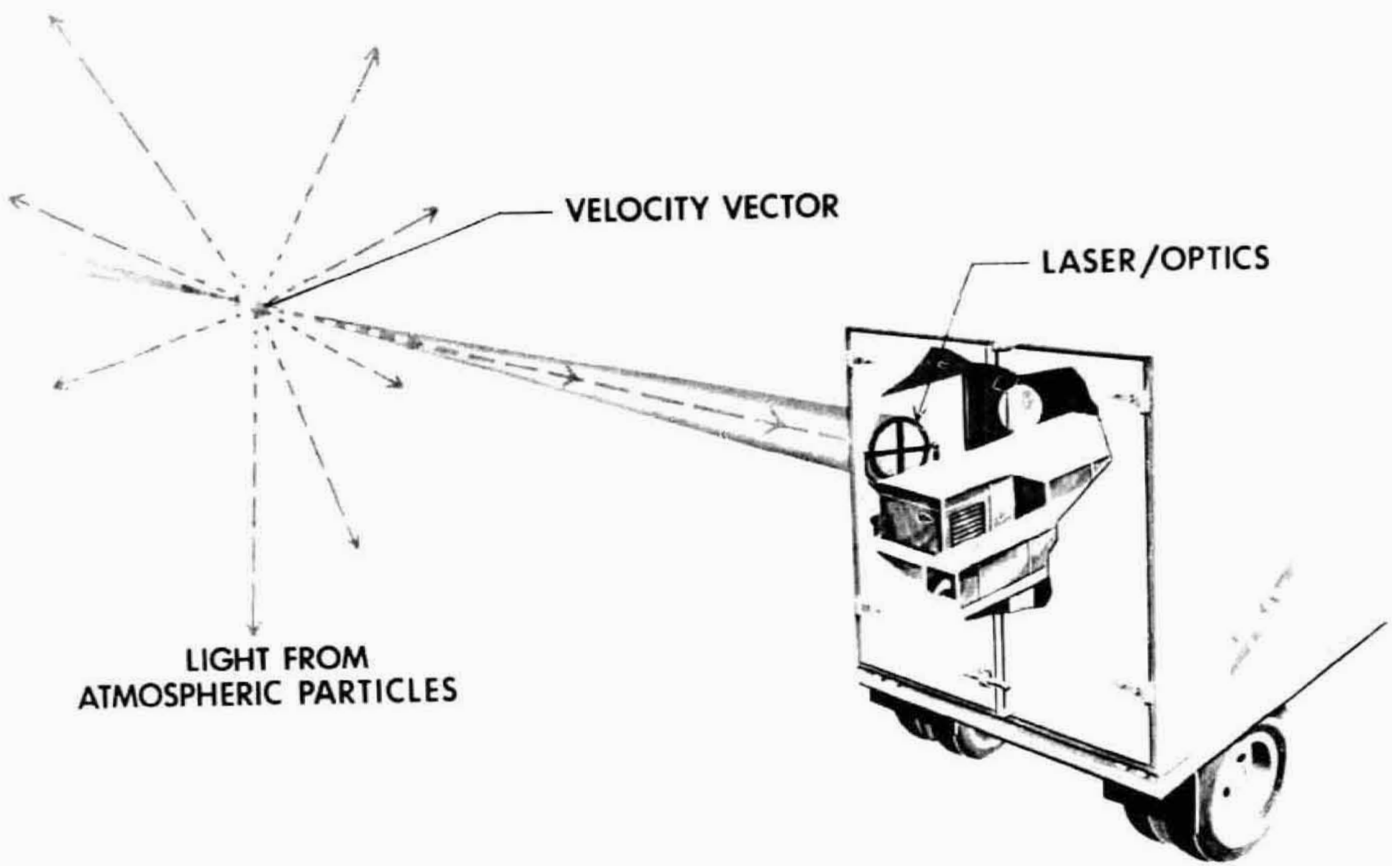



Figure 3. Laser Doppler line-of-sight velocity detection.

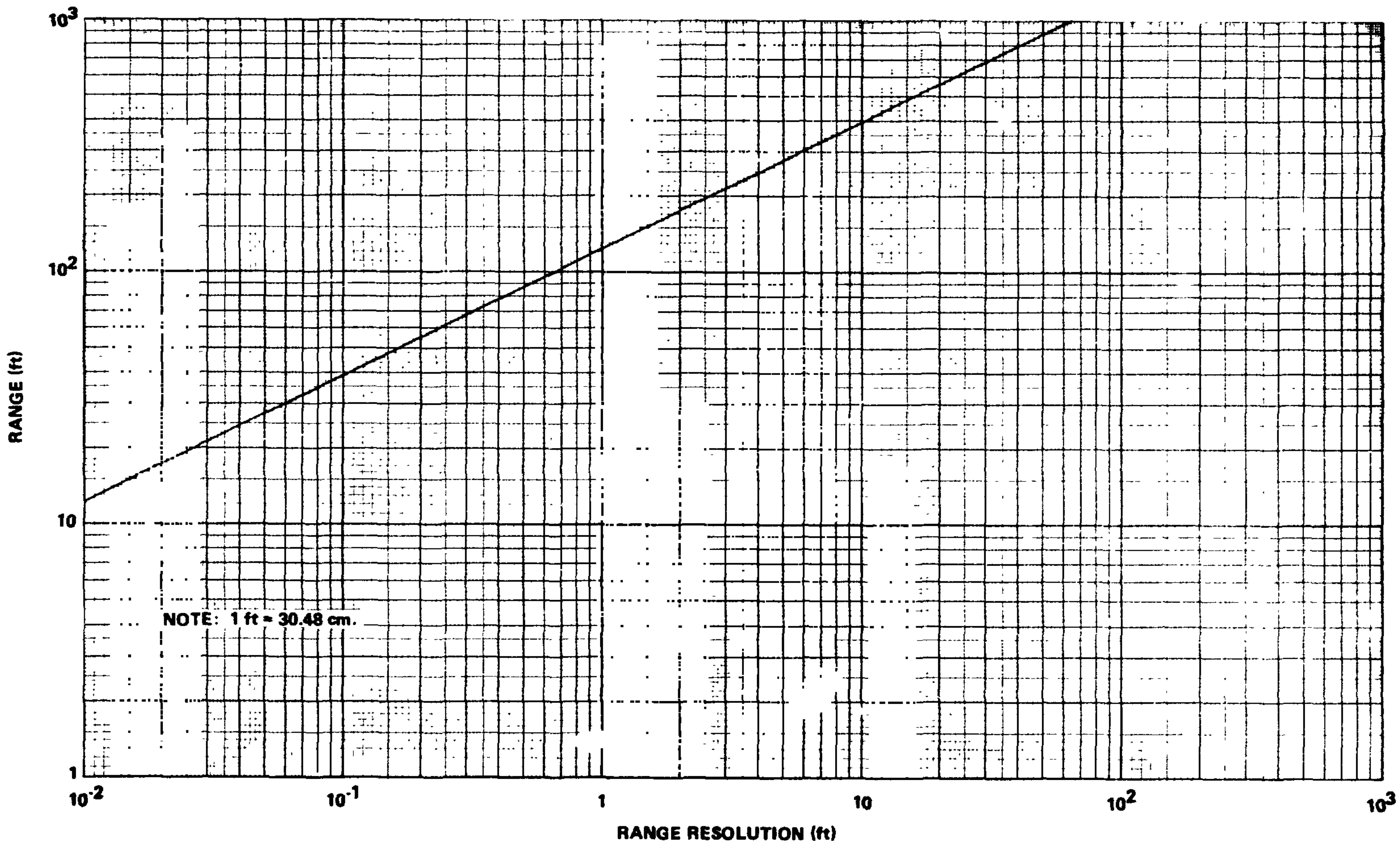



Figure 4. One-half power range resolution versus range for 30.48 cm (12 in.) $CO_2$ optical heterodyne system.

$V_{pk}$ = VELOCITY OF HIGHEST CHANNEL ABOVE AMPLITUDE THRESHOLD

$V_{max}$ = VELOCITY OF THE CHANNEL HAVING THE PEAK SIGNAL

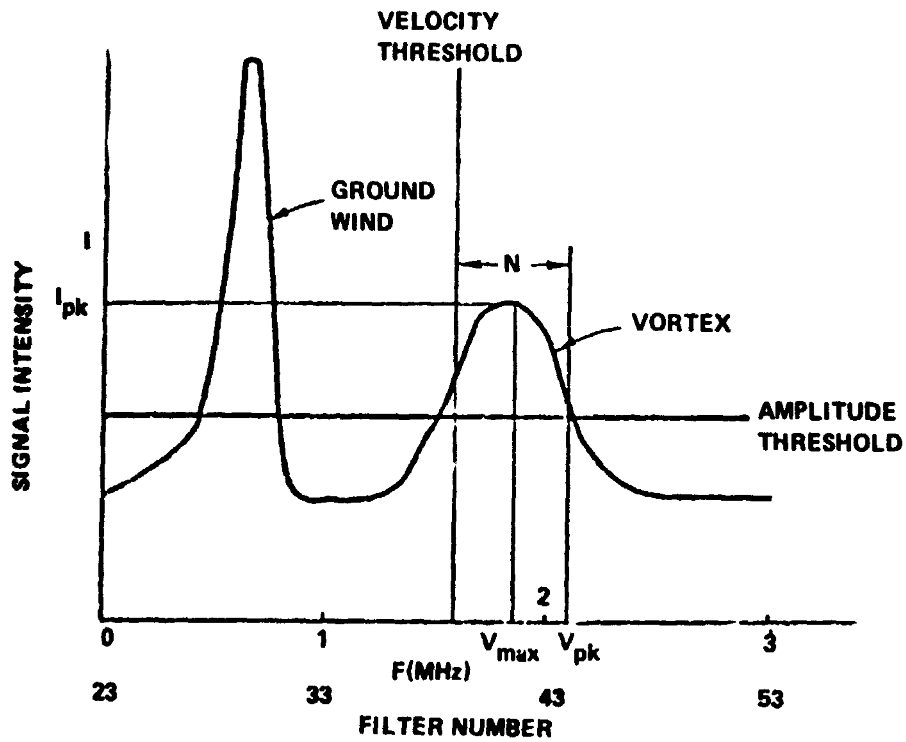



Figure 5. Typical vortex spectrum.

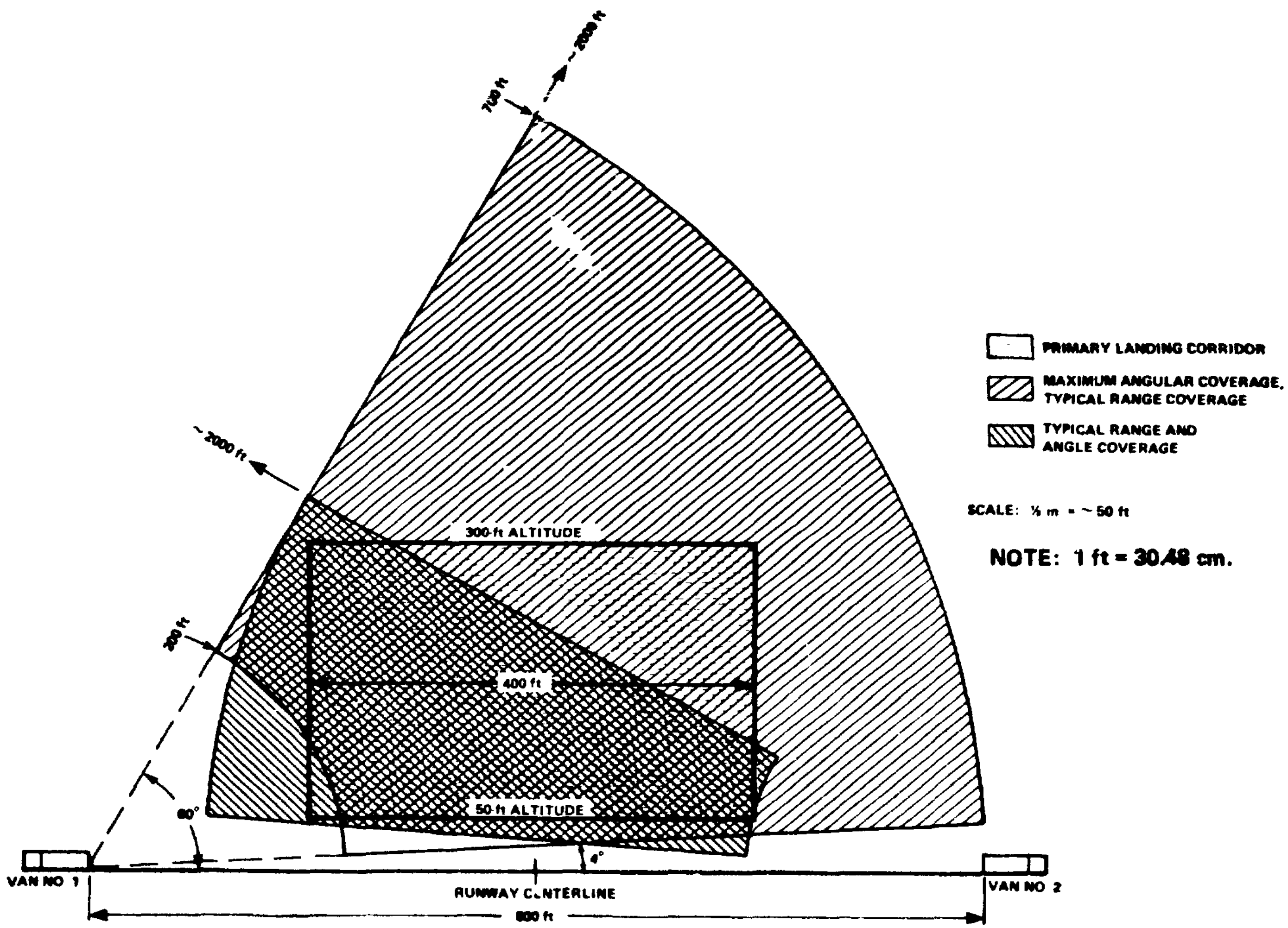



Figure 6. Typical scan coverage requirements with resulting system scan requirements.

NOTE: To convert feet to meters, multiply by 0.3048; to convert meters to feet, multiply by 3.2802.

$$X_{VC} = \frac{\sum V_i I_i X_i}{\sum V_i I_i} \quad \text{POSITION IN RANGE}$$

$$Y_{VC} = \frac{\sum V_i I_i Y_i}{\sum V_i I_i} \quad \text{POSITION IN ALTITUDE}$$

V = VORTEX VELOCITY ($V_{max}$ OR $V_{pk}$)

I = DOPPLER SIGNAL INTENSITY

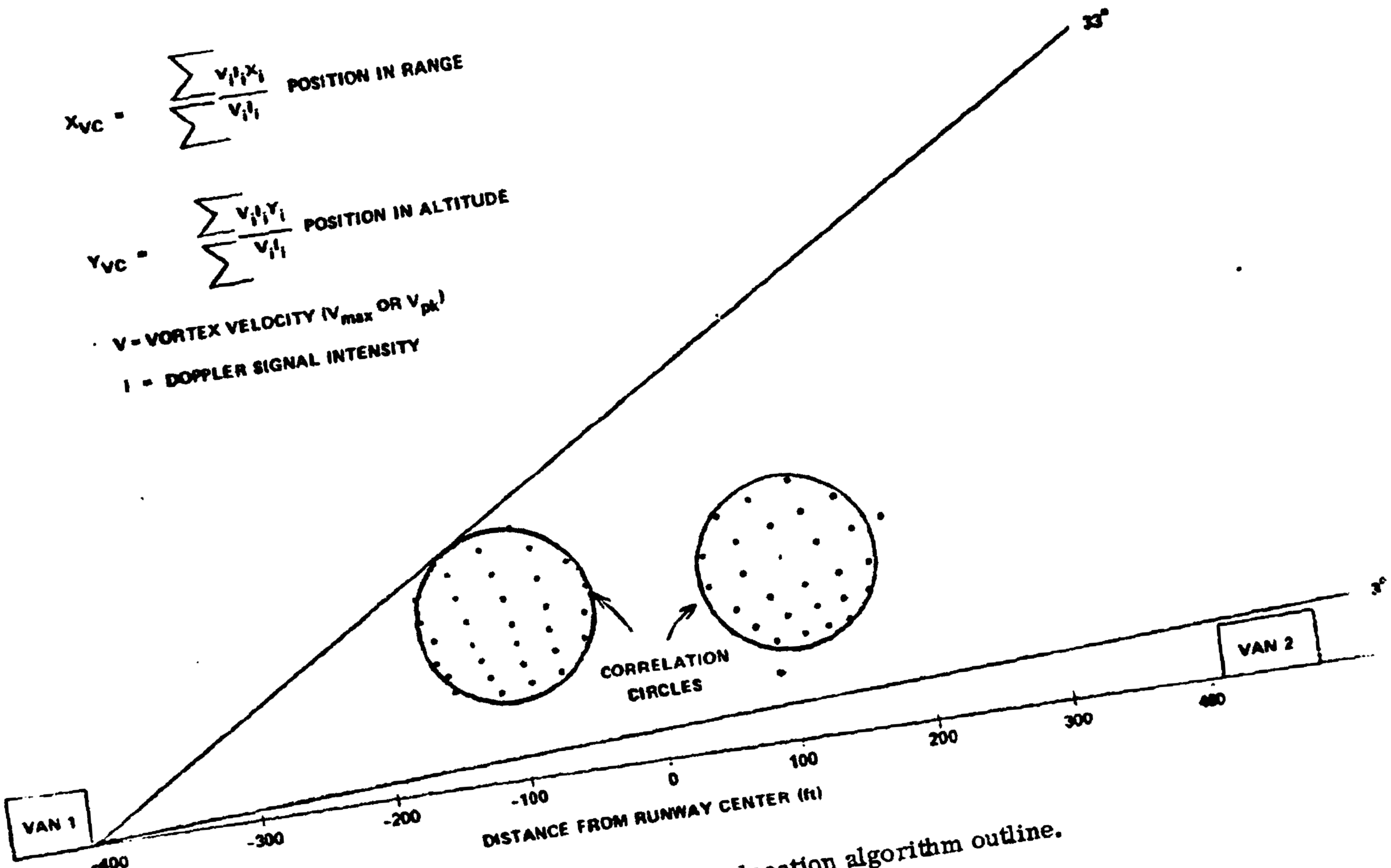
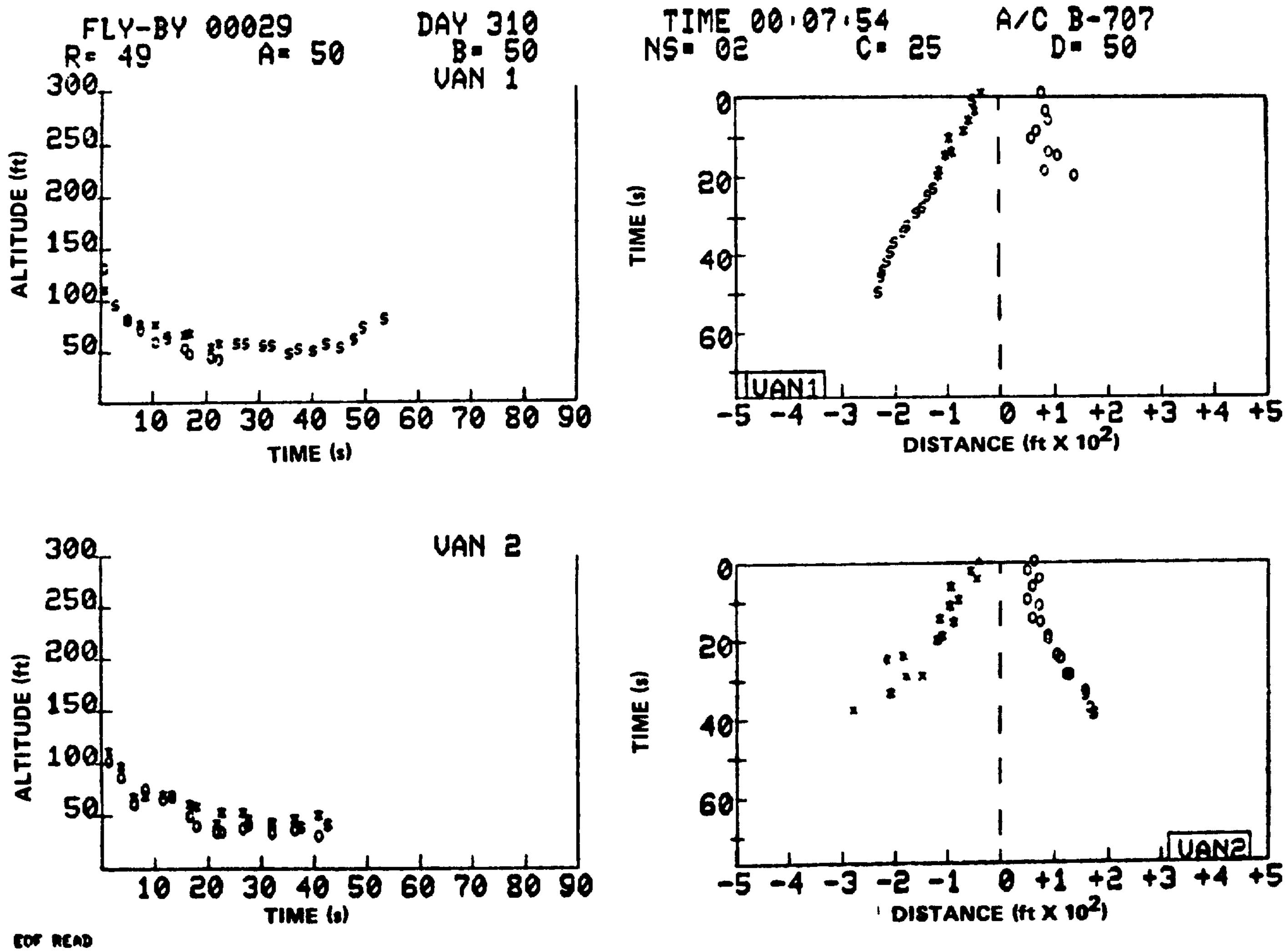
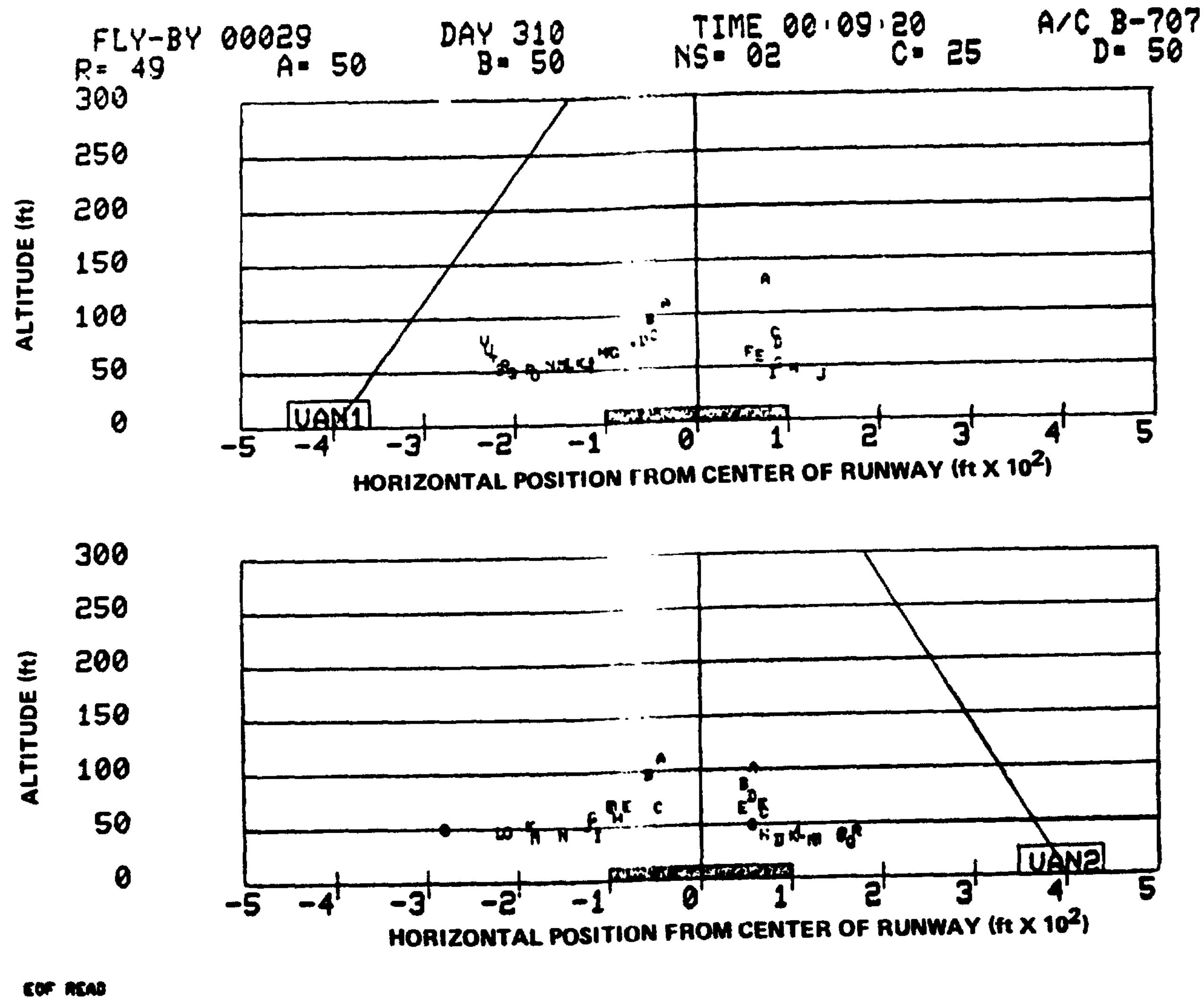



Figure 7. Vortex location algorithm outline.




NOTE: 1 ft = 30.48 cm.

Figure 8. Sample time-based plot.




NOTE: 1 ft = 30.48 cm.

Figure 9. Sample x–y plot.

FLY-BY 00029 DAY 310 TIME 00:06:37 A/C B-707
R= 49 A= 50 B= 50 NS= 02 C= 25 D= 50

| FR | DATA PTS | COR PT P | COR PT S | NOISE P | NOISE S | ANGLE MN | ANGLE MX | PK P | VEL S | TIME | | PORT POS X | PORT POS Y | STARB POS X | STARB POS Y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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| 02 | 0010 | 016 | 000 | 00 | 02 | 13 | .5 | 046 | 000 | 002 | 2 | -053 | 031 | | |
| 03 | 0014 | 020 | 000 | 02 | 00 | 38 | 20 | 045 | 026 | 004 | 6 | -050 | 070 | 093 | 076 |
| 04 | 0030 | 019 | 004 | 00 | 00 | 07 | 19 | 041 | 036 | 006 | 9 | -061 | 072 | 067 | 067 |
| 05 | 0037 | 019 | 0.1 | 00 | 00 | 05 | 15 | 039 | 037 | 009 | 5 | -071 | 072 | 066 | 056 |
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| 07 | 0036 | 015 | 019 | 00 | 00 | 04 | 12 | 014 | 041 | 015 | 3 | -054 | 061 | 085 | 248 |
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| 09 | 0048 | 030 | 009 | 00 | 00 | 03 | 11 | 079 | 136 | 022 | 3 | -118 | 041 | 093 | 230 |
| 10 | 0036 | 023 | 025 | 00 | 00 | 03 | 14 | 037 | | 021 | 7 | -161 | 252 | 134 | 036 |
| 11 | 0018 | 017 | 020 | 00 | 00 | 00 | 13 | 039 | 000 | 025 | 1 | -129 | 252 | | |
| 12 | 0026 | 025 | 000 | 00 | 00 | 05 | 15 | 043 | 000 | 026 | 0 | -142 | 252 | | |
| 13 | 0024 | 020 | 000 | 00 | 00 | 05 | 14 | 041 | 000 | 030 | 0 | -151 | 370 | | |
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| 17 | 0036 | 033 | 002 | 00 | 00 | 24 | 19 | 039 | 100 | 039 | 6 | -206 | 045 | | |
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| 22 | 0008 | 008 | 000 | 00 | 00 | 22 | 26 | 037 | 200 | 052 | 0 | -217 | 075 | | |

| FR | DATA PTS | COR PT P | COR PT S | NOISE P | NOISE S | ANGLE MN | ANGLE MX | PK P | VEL S | TIME | | PORT POS X | PORT POS Y | STARB POS X | STARB POS Y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 01 | 0010 | 024 | 025 | 00 | 00 | 11 | 18 | 028 | 025 | 000 | 0 | -047 | 106 | 055 | 097 |
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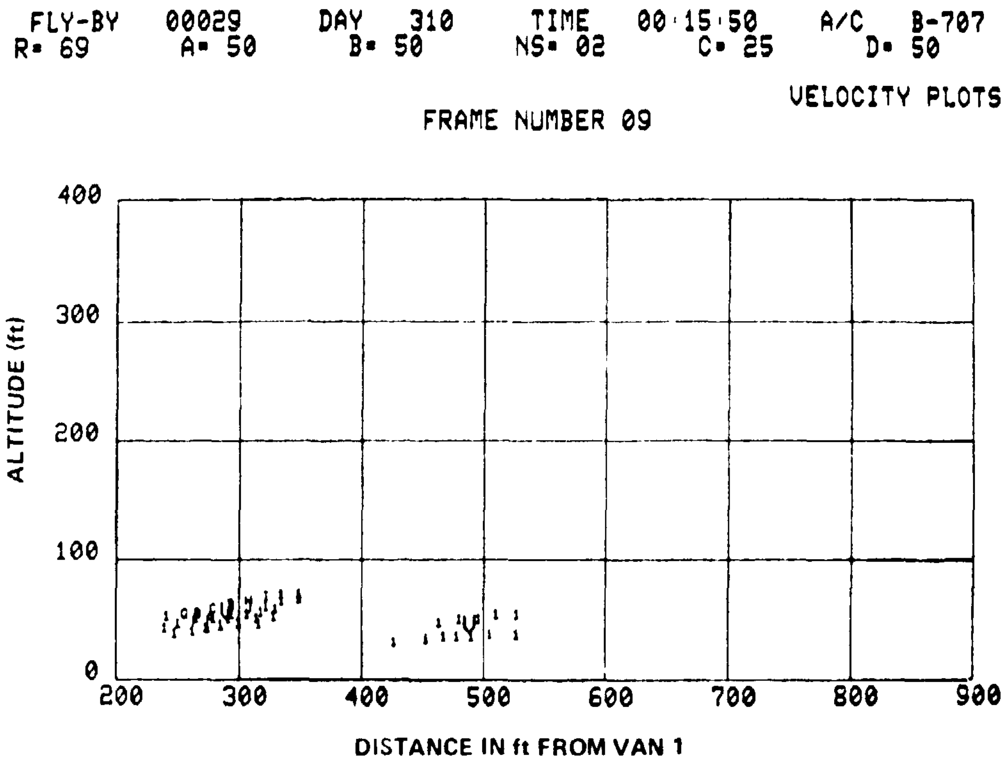
| 25 | 0035 | 000 | | 00 | | 03 | 06 | 014 | | | | | | | |

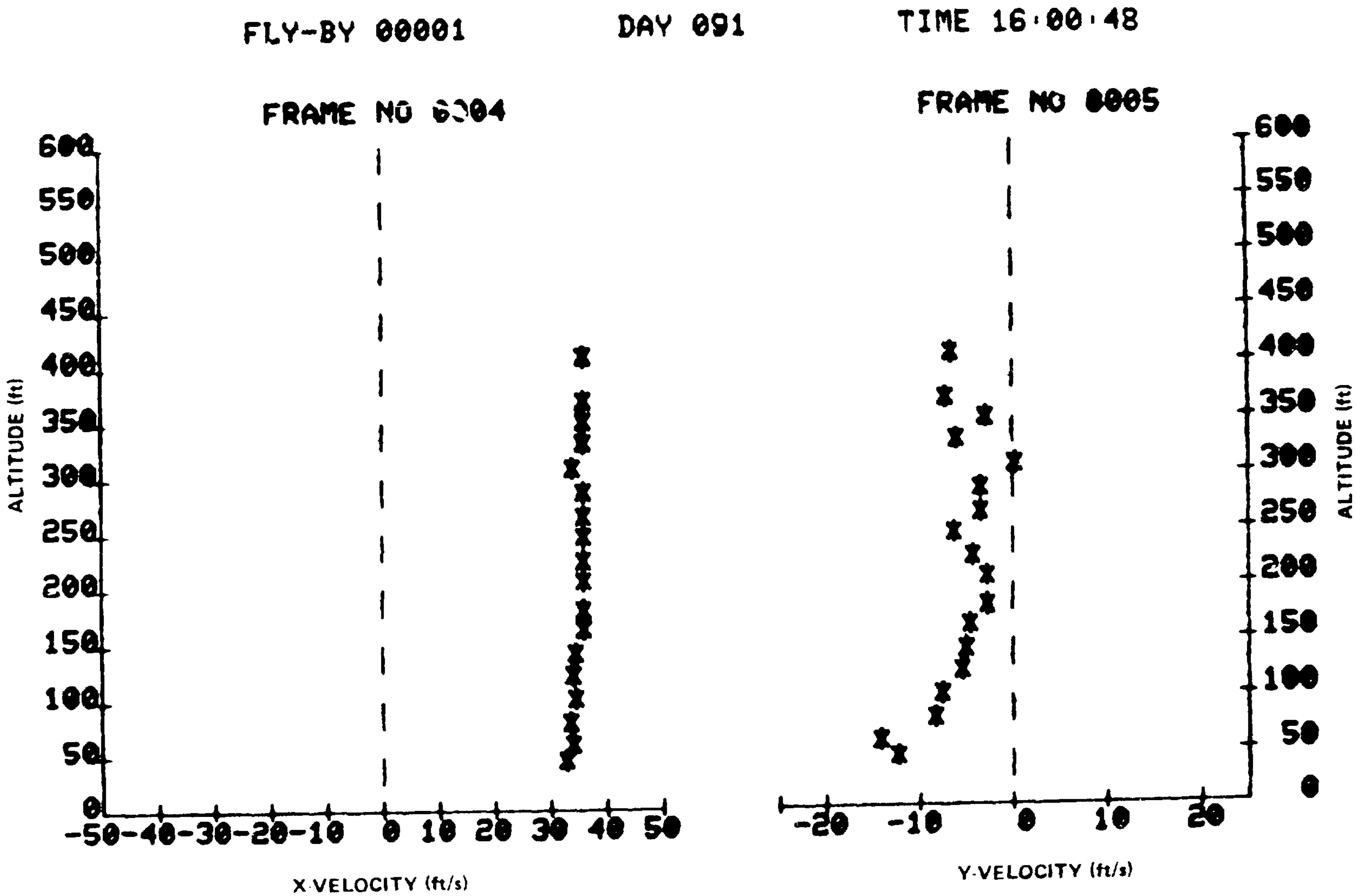
Figure 10. Sample tabular data output.




A=039 B=037 C=037 D=037 E=037 F=037 G=036 H=036 I=036 J=036

NOTE: 1 ft = 30.48 cm.

Figure 11. Sample scatter plot.




NOTE. 1 ft = 30.48 cm.

Figure 12. Wind profile.

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# APPROVAL

## DEVELOPMENT OF A LASER DOPPLER SYSTEM FOR THE DETECTION AND MONITORING OF ATMOSPHERIC DISTURBANCES

By Harold B. Jeffreys and James W. Bilbro

The information in this report has been reviewed for security classification. The report, in its entirely, has been determined to be unclassified and contains no information concerning Department of Defense or Atomic Energy Commission programs.

This document has also been reviewed and approved for technical accuracy.

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