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APPLICATION OF A SINGLE LASER DOPPLER SYSTEM TO THE MEASUREMENT OF ATMOSPHERIC WINDS

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16. ABSTRACT

The feasibility of employing a single laser Doppler velocimeter (LDV) system to remotely measure one-, two-, and three-dimensional velocity components in atmospheric flow fields is presented.

A focused continuous wave CO_2 laser emitting at the 10.6 μ wavelength is used as the laser source. Scan configurations employed by the LDV system were single-point, two-point, conical, and spiral conical.

Test results including favorable comparisons of velocity components measured by conventional anemometry and the LDV system are presented. The feasibility of using a single-beam LDV employing a conical scan technique for measuring two- and three-dimensional mean winds has been demonstrated. Measurements to 300 m in dense fogs have demonstrated the ability of the LDV system to operate in dense fogs. Conclusions and recommendations for future work are also presented.

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INTRODUCTION

Measurements of atmospheric wind velocity and turbulence with altitude are required in support of the U. S. Army artillery and ballistics operations. Winds have a primary effect on ballistic projectile target accuracy. Current meteorological support consists of instrumented balloon measurements which are made only once in several hours. The accuracy of balloon-type measurements of atmospheric wind velocity is very limited and does not meet the Army's real requirements. At present the rawinsonde data are extrapolated to longer ranges and different terrain conditions. Ideally, what is required is the measurement of the wind velocity along the projectile trajectory. If the wind velocity along the trajectory is known, corrections can be made on the projectile to assure the required accuracy. The laser Doppler systems being developed by the Marshall Space Flight Center (MSFC) offer the potential of providing the atmospheric wind velocity along the projectile trajectory.

The primary objective of the program for the White Sands Missile Range is to determine the feasibility of using a single-beam laser Doppler system for remotely measuring the transverse and radial wind velocity components at ranges of 10 m to 500 m. This program objective complements the planned MSFC laser Doppler program in providing better understanding of the single-beam laser Doppler velocimeter (LDV) system performance and limitations. The results of the program will benefit both the MSFC laser Doppler vortex and clear air turbulence (CAT) programs.

BACKGROUND

The development of laser Doppler systems for the measurement of gas flow velocity and turbulence started in early 1964 at MSFC [1, 2]. These systems utilize the Doppler frequency shift of the laser light when scattered by minute particles suspended in the atmosphere. The velocity is directly determined from the measurement of the difference in frequency between the scattered and reference laser energy and the geometry of the system. That is, the Doppler frequency is directly proportional to the air velocity. The advent of high-power, highly monochromatic lasers has made possible the coherent detection of particle velocities. Marshall Space Flight Center has built and tested a three-dimensional measuring system for wind tunnel applications. This system has proven the capability and accuracy of using laser Doppler systems for the measurement of gas velocity and turbulence [1, 2].

Using the Doppler concept, proven in wind tunnel applications, the feasibility of extending the technique to the measurement of atmospheric wind velocity and turbulence has been demonstrated [3, 4]. Simultaneous single-point wind measurements with laser Doppler systems and cup-type and hot wire anemometers have been performed previously [4]. The laser Doppler measurements utilized the natural particulates that are always present in the atmosphere. The operating wavelength of the atmospheric system is 10.6 μ, in the infrared. Measurements of the atmospheric wind have been performed with the laser Doppler system under extremely low particle concentration conditions at distances greater than 1.6 km (1 mile). Greater distances should be achievable. Measurements have been made in rain, snow, gusty winds, and at wind speeds up to 216 km (135 miles) per hour [5]. After successful atmospheric measurements were accomplished, the laser Doppler technique was applied to particular aeronautical problems. Using the Doppler technique, a clear air turbulence detection system has been developed and flight tested on the NASA Convair 990. Successful velocity measurements were performed at distances up to 8 km (5 miles) in clear air [6]. The focused laser Doppler systems are short-range systems, and the pulsed systems are for long-range applications. The spatial resolution is small for the continuous wave focused system (short range) and long for the pulsed system (long range).

A single-point atmospheric laser Doppler system measuring all three components of the wind velocity has been tested. Comparison tests with a three-dimensional propeller type wind anemometer showed good agreement [4].

The remote sensing capability of laser Doppler systems allows placement of the sensing volume at the location of interest by optical means, which permits rapid scanning over large regions of the atmosphere. The instantaneous nature of the measurement shows potential for a system directed at ballistics applications.

SYSTEM DESCRIPTION

The feasibility study described herein is based upon theoretical and experimental investigations of MSFC's single-beam LDV. A schematic of the single-beam LDV test setup is given in Figure 1. The system centers around a CO_2 continuous wave laser emitting at the $10.6\,\mu$ wavelength (Fig. 2). The laser system is optically focused at a remote location at which a wind velocity measurement is needed. Ever present natural atmospheric aerosols and particulates passing through the laser's focal volume scatter the laser light in all directions. These natural aerosols have been shown to move with the atmospheric motions and, thus, are good tracers from which to infer the true atmospheric flow field [7]. The laser radiation scattered in a direction parallel to the laser beam will be shifted slightly in frequency if the particles have a velocity component parallel to the laser beam. By imposing this scattered radiation with a small amount of the original laser light upon a photodetector, a beat frequency is produced which is known as the Doppler frequency. The relationship which exists between the Doppler frequency and the velocity of the particles (in the direction of the laser beam) is expressed as

$$V = 5.3 \times 10^{-6}\ \Delta f$$

where V is velocity in meters per second and Δf is the difference in frequency of the laser and the frequency of the scattered radiation (scattered laser light from particles in the focal volume of the system).

To obtain two- or three-dimensional mean wind information from a single-beam LDV system, two scan configurations were

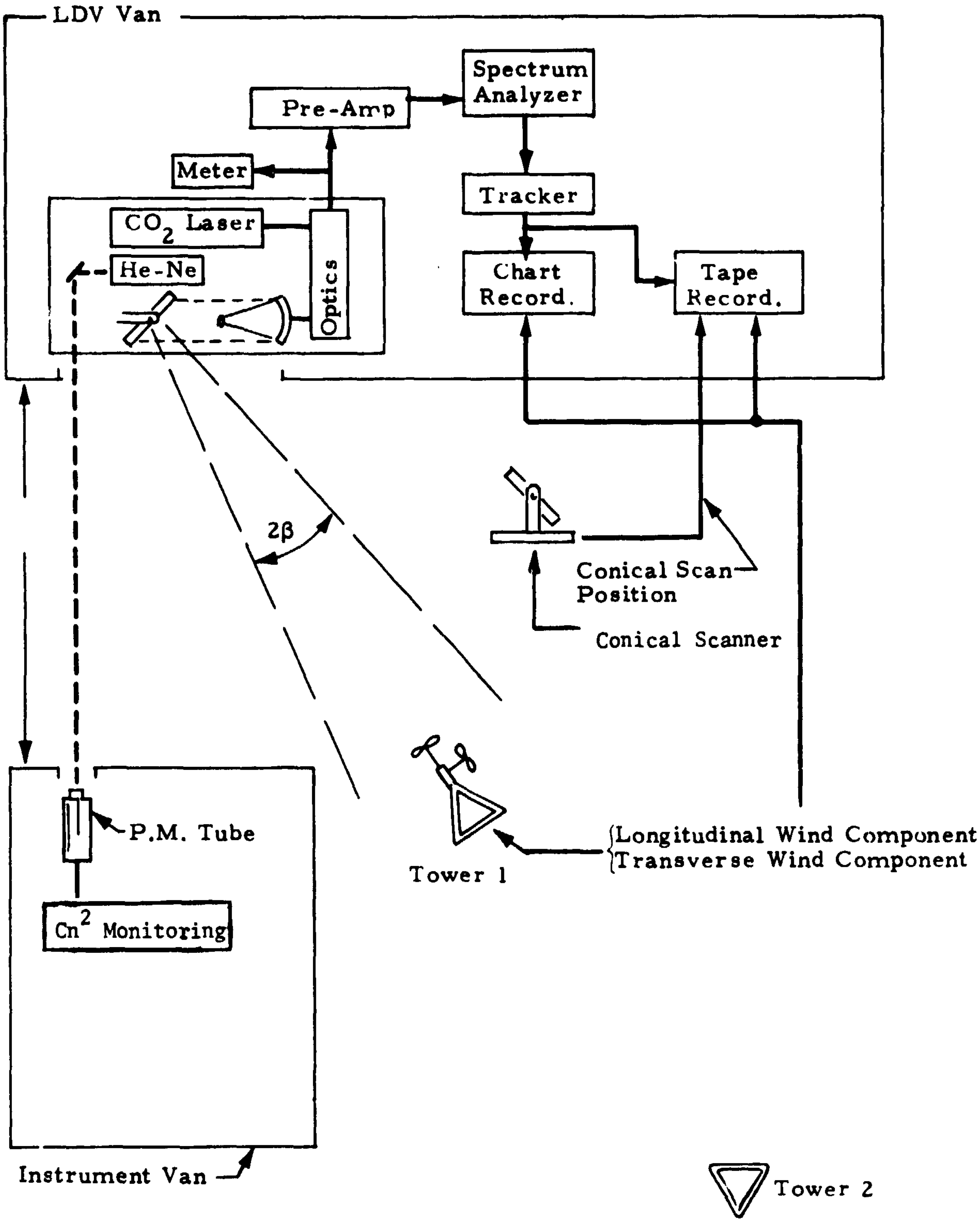

Figure 1. Test setup.

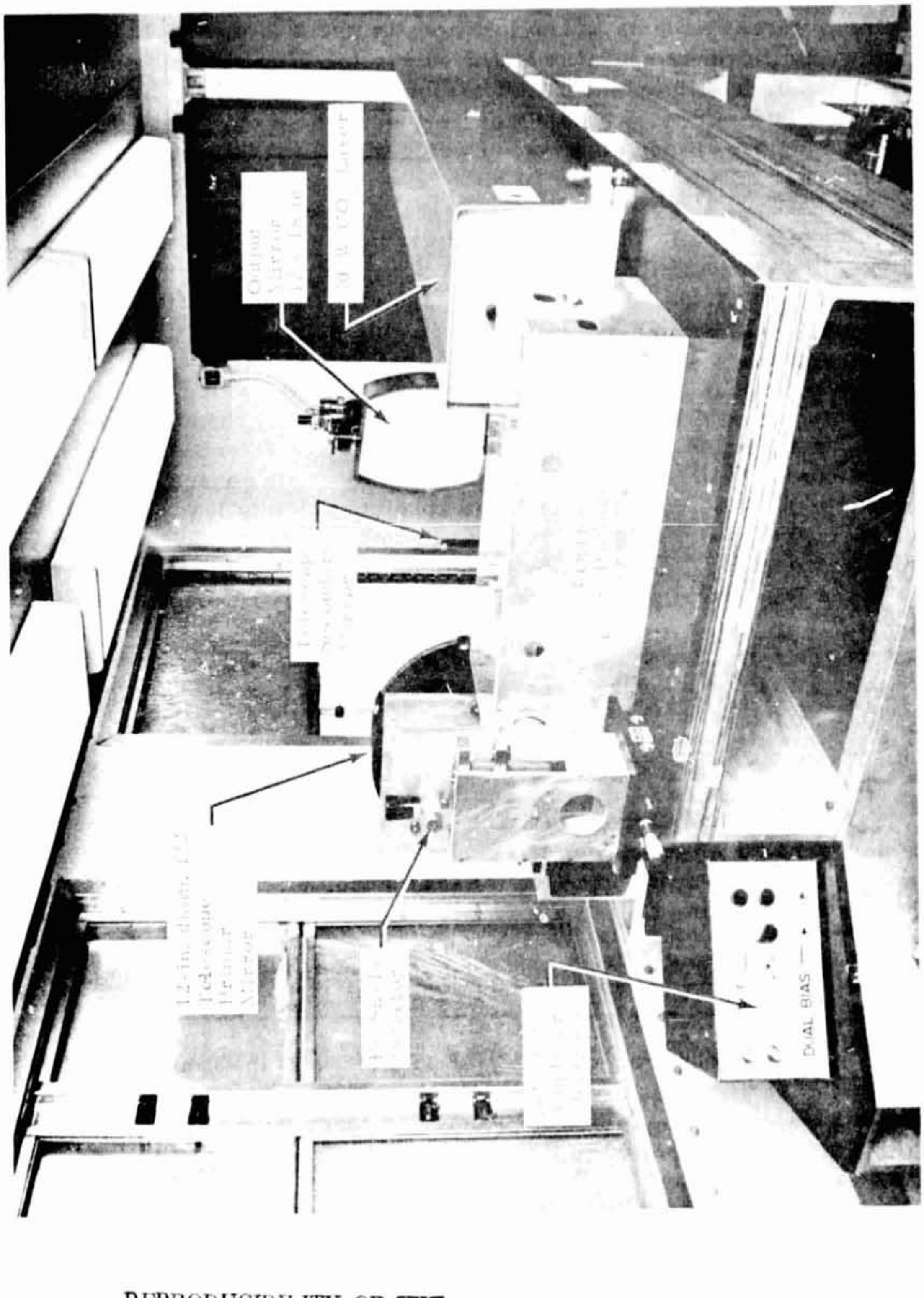

Figure 2. LDV hardware.

tested: (1) a two-point scan configuration and (2) a conical scan configuration. For the two-point scan the LDV system makes velocity measurements at two locations in space from which, by sum and difference operations, the extraction of two-dimensional mean winds is attempted. The two-point scan will not be discussed in detail in this report because of its questionable capability for measuring two-dimensional mean winds with a LDV system (see Section 4.2 of Reference 7.

The conical scan consists of focusing the LDV system at a given elevation and then sweeping the focal volume such that it subscribes a circle in a horizontal plane at a fixed elevation (Fig. 3). The output of the LDV system which is employing the conical scan is also shown in Figure 3. It is seen that the velocity sensed by such a system is a pure harmonic with a DC offset which is a measure of the vertical velocity. However, if only the absolute velocity is sensed, a rectification of all negative velocities occurs. It is noted that the LDV system used for this study senses only absolute velocity. Sensing only the absolute velocity leads to an ambiguity of π in the determination of wind direction. The ambiguity may be resolved, however, by employing a frequency translator with the LDV system. Frequency translators for the single-beam CO_2 LDV systems are presently being developed by MSFC. Figure 4 shows the field test site used for the single-beam LDV system tests. Figure 5 is a close-up photograph of the conical scan hardware.

ACCOMPLISHMENTS

The purpose of this section is to examine the accomplishments which were advanced during the study of the single-beam CO_2 LDV atmospheric interrogation system. The accomplishments of this study are as follows:

1. Proved the feasibility of performing three-dimensional mean wind measurements with a single-beam LDV system.

It has been shown theoretically (Fig. 3) that three-dimensional mean winds may be extracted from the output of a single-beam LDV which is employing a conically scanning focal volume. More detail is presented in Reference 7. It is noted that the present

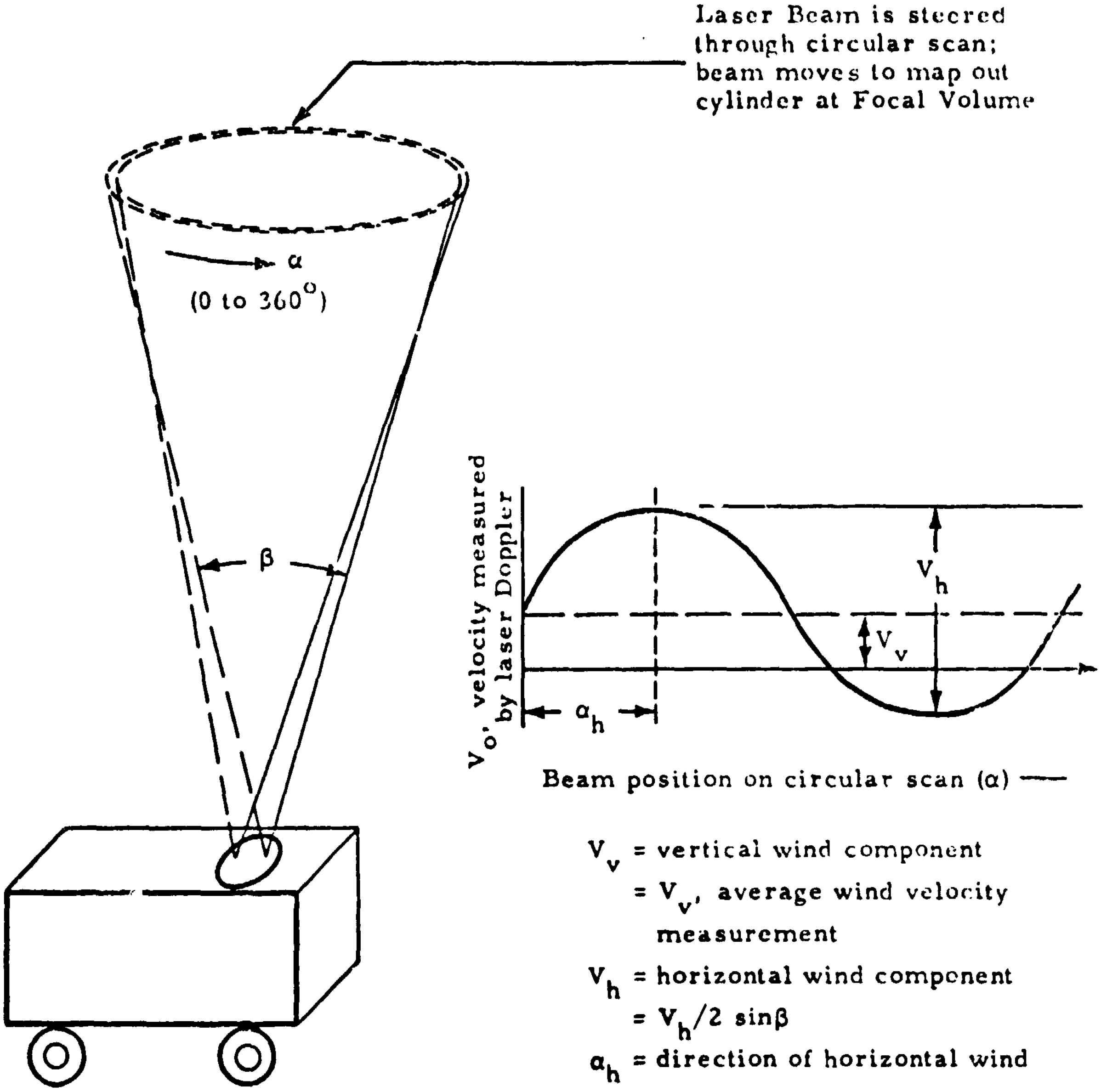

Figure 3. Determination of average wind profile from conical scan with single-component laser Doppler velocimeter.

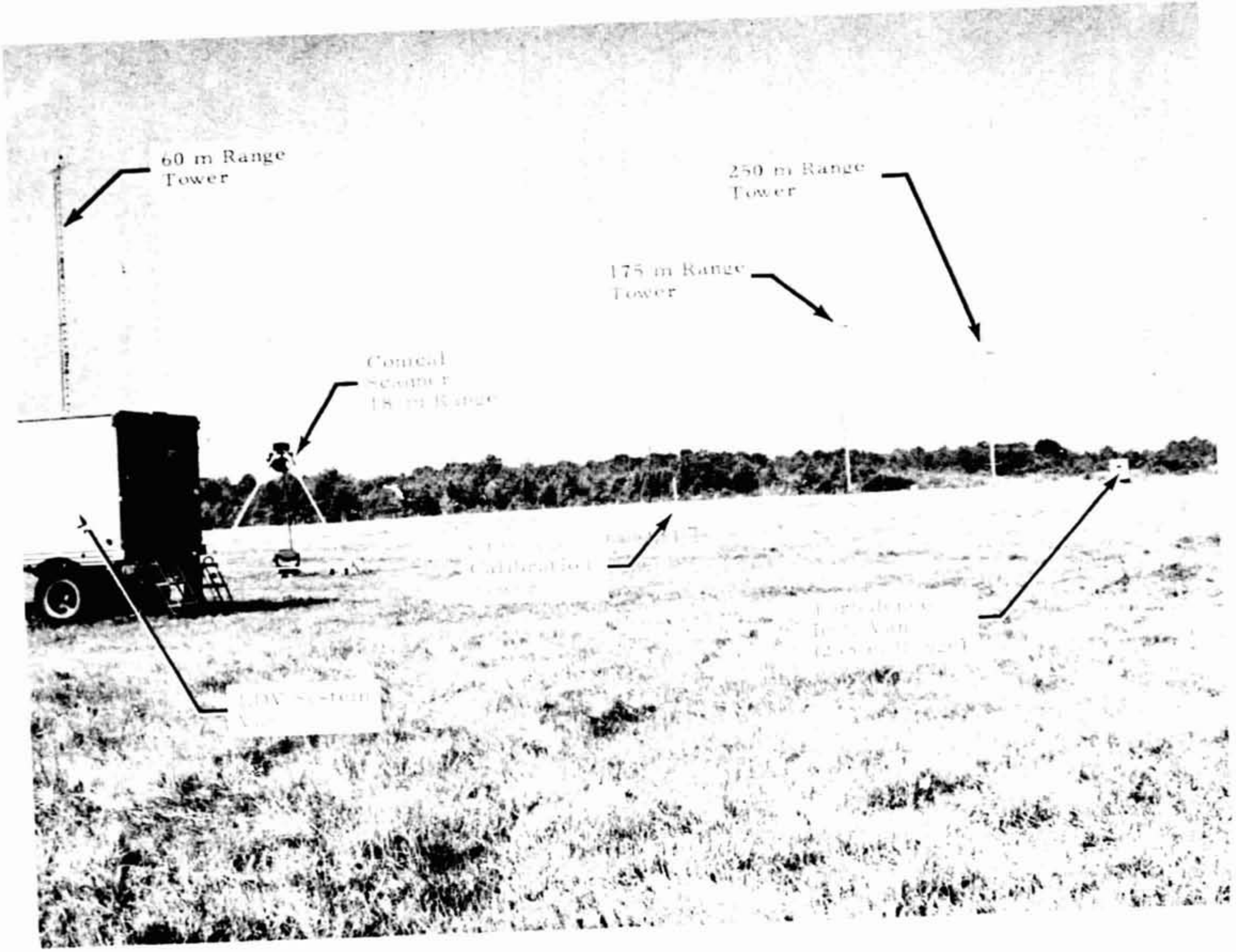

Figure 4. Field test site.

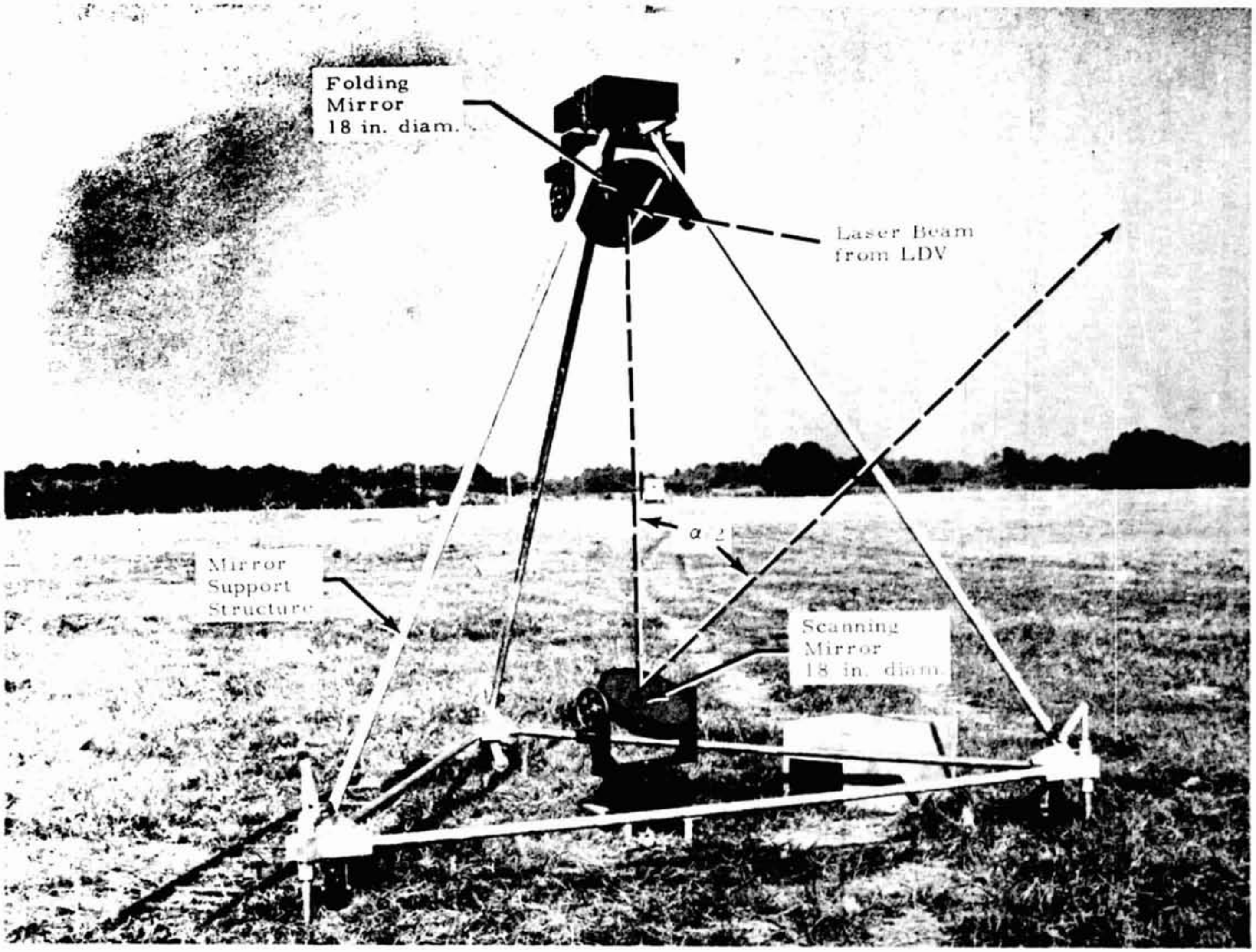

Figure 5. Conical scan hardware.

system measures the absolute wind velocity; however, the true wind velocity could be measured with the present system if a frequency translator, which resolves the directional sense of the wind, is employed. Frequency translators are presently being developed for MSFC's LDV systems and will hopefully be in use by early 1975.

2. Demonstrated the capability of making two-dimensional mean wind measurements with a single-beam LDV system employing a conical scan.

The feasibility of making two-dimensional mean wind measurements was demonstrated for ranges and heights to 500 m. The same system as described in Figure 3 was employed; however, since only absolute magnitude of velocity may presently be measured, only two-dimensional information was recovered from the output. Figure 6 is a direct comparison of the horizontal wind measured by a cup anemometer and the single-beam LDV system employing a conical scan configuration.

3. Demonstrated, using a spiral scan, the ability to measure the vertical profile of the horizontal wind for ranges to 500 m.

A logical extension to making the two-dimensional wind measurement at a single elevation is to continually vary the focal range of the system and thus produce a spiral scan which, in effect, allows the determination of the vertical profile of the horizontal wind. This is perhaps the most desirable scan configuration for measuring mean horizontal winds with a single LDV system. Figure 4-17 of Reference 7 shows a typical output.

4. Based on the experimental and theoretical evidence, it has been concluded that the two-point scan system employing a single LDV unit is not a desirabie approach.

A two-point scan configuration was employed (Figure 4-21, Reference 7) in an attempt to measure radial and transverse wind components, the idea being that knowing the wind vector at two locations would allow one to theoretically calculate the wind components

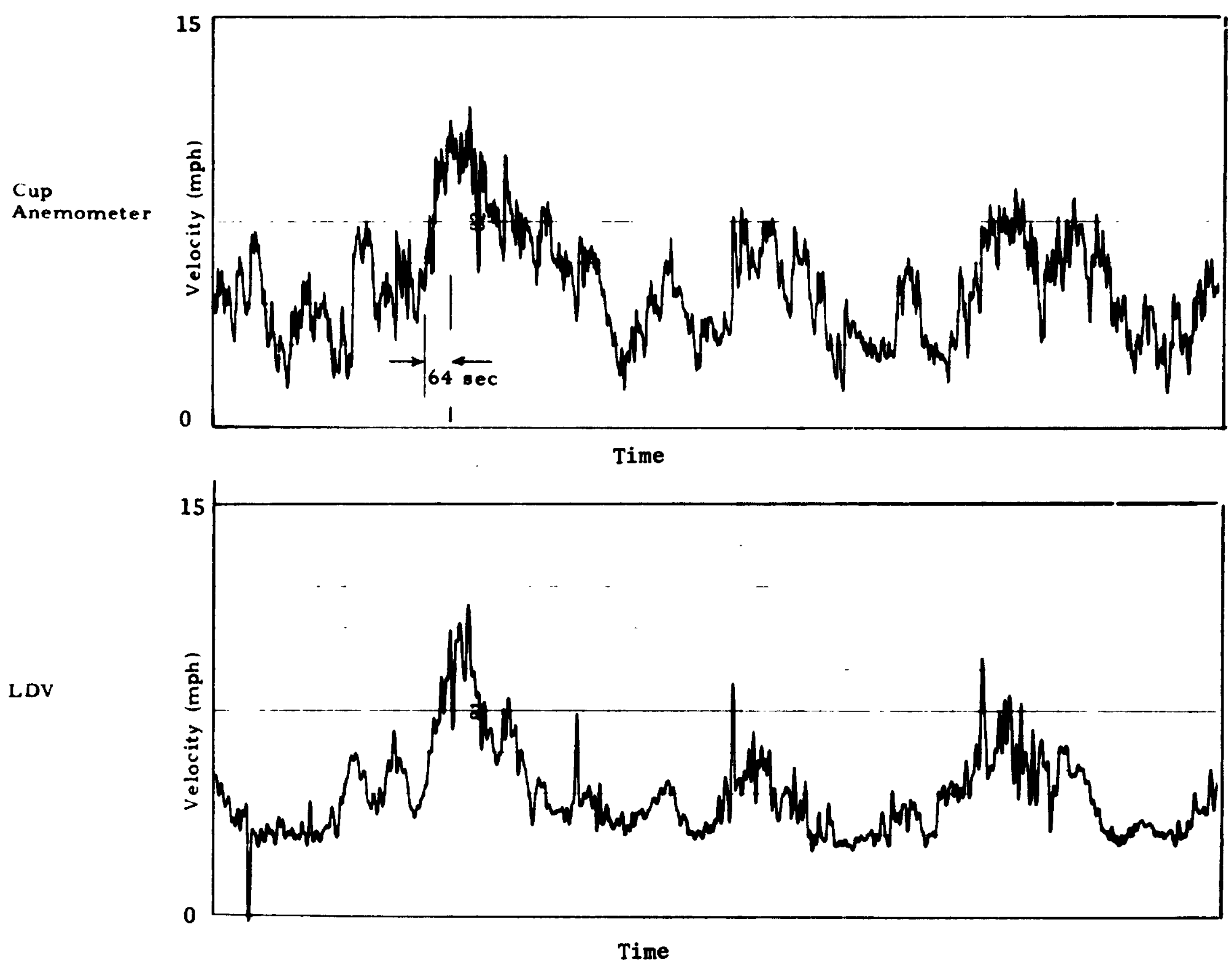

Figure 6. Comparison of horizontal wind measured by a cup anemometer and a single-beam LDV system (both systems sensing at an elevation of 70 feet).

in any direction lying within the plane of the measurements. This scan configuration has been deemed undesirable both from a theoretical and experimental standpoint because theory indicates that the expected error, due to uncertainty in atmospheric flow directions, can be very large. Also, the present system cannot discriminate direction sense, which is necessary to make a true vector addition or subtraction; the atmosphere is generally not constant such that the LDV system consistently senses flow in one direction at both of the sensing locations. Figures 4-22 and 4-23 of Reference 7 show comparisons of axial and transverse winds by LDV and conventional anemometry. The axial winds measured with both systems compare favorably. The comparison of transverse winds measured with both systems is not highly correlated, however. An arc type scan appears to be more favorable where more localized two-dimensional information is needed.

5. <u>Direct comparisons with conventional anemometry are shown to be in good agreement for ranges to 300 m.</u>

The direct comparison of LDV and anemometer measurements of one-dimensional wind vectors shows them to be in good agreement. Figure 7 presents an on-line comparison of a single-beam LDV system and a conventional anemometer. Comparison of LDV and anemometer outputs has shown good agreement for ranges from 15 to 300 m.

6. <u>Demonstrated the ability of the CO_2 single-beam system to perform velocity measurements through and in dense fogs.</u>

Section 5 of Reference 7 presents data taken up to 300 m in simulated dense fogs. These data show that the LDV system is operable in dense fogs. The fog penetration ability of the CO_2 laser has been shown to be superior to that of a visible laser (see Figure 5-9 of Reference 7). Figure 8 shows a Doppler return from MSFC's airborne clear air turbulence laser system giving returns through 2.5 miles of cumulus cloud [6]. Again indicating the ability of the CO_2 laser system to perform in fog-like environments, the CO_2 LDV system was found to be capable of measuring velocity over a wide range of fog densities [7].

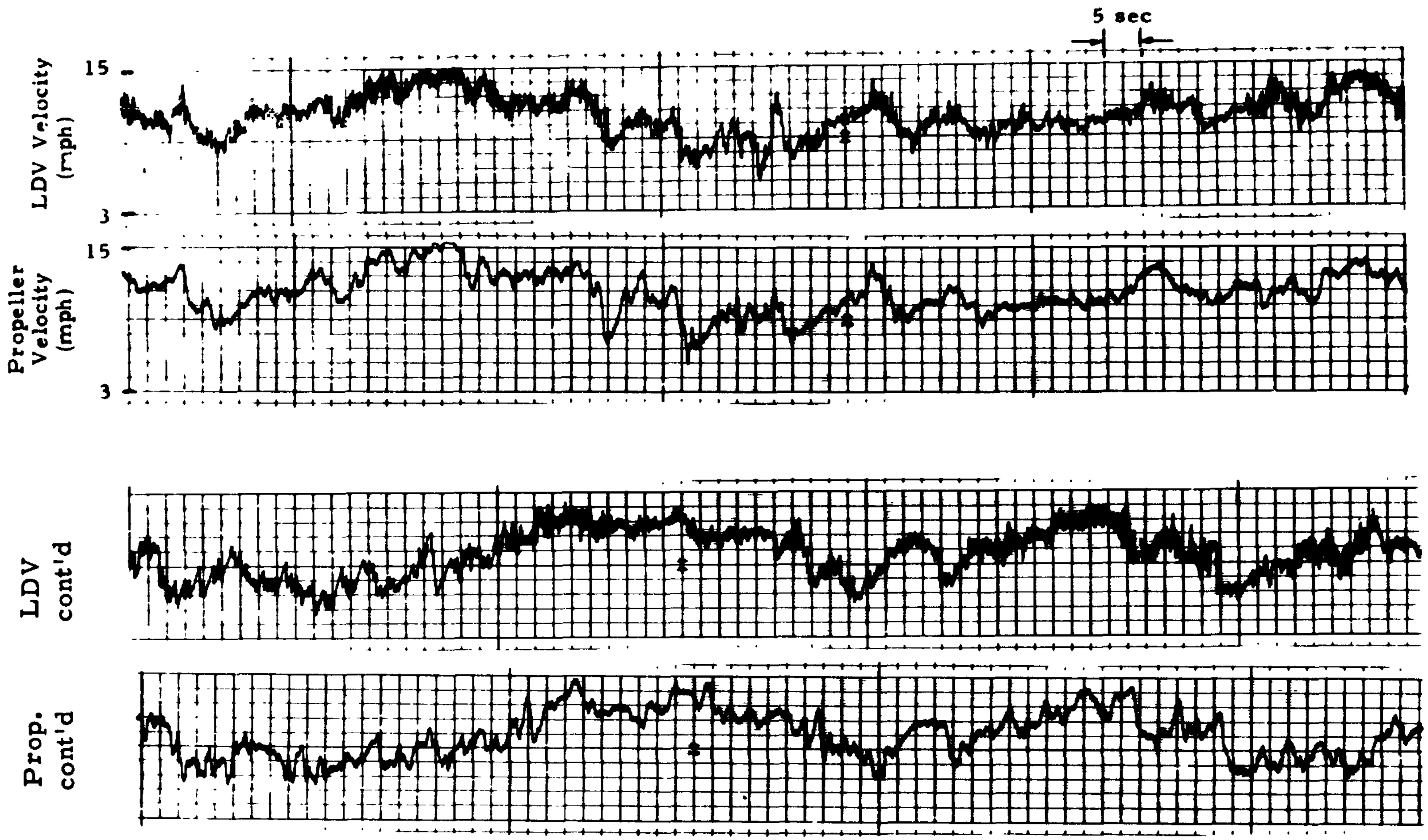

Figure 7. Comparison of LDV radial velocity indication against that of a propeller anemometer at a range of 193 feet.

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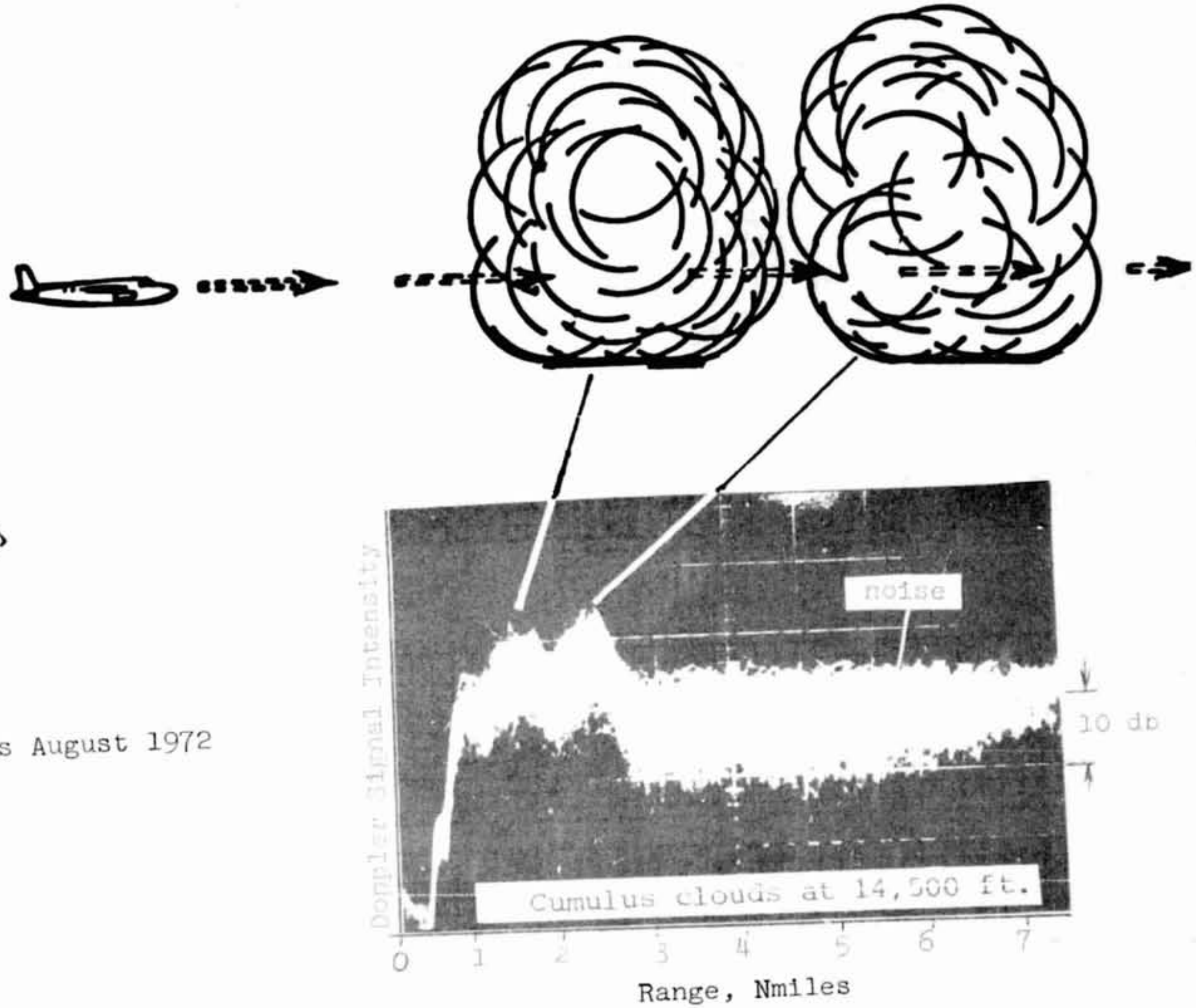

Figure 8. Laser Doppler CAT system. Range-intensity display of cumulus cloud encounter.

7. <u>Field use has shown that the system has not been limited because of high refractive index fluctuations due to turbulence over the range of interest.</u>

Refractive index homogeneities have been shown not to limit MSFC's single-beam LDV system over the ranges of interest in this investigation.

CONCLUSIONS

1. The single-beam LDV system has been shown to be a feasible method for remotely measuring one-, two-, and three-dimensional wind fields.

2. A conical scan is used by the single-beam LDV system when measuring two- and three-dimensional mean winds.

3. The LDV system used for this study measures absolute velocity and, therefore, is presently incapable of sensing true wind direction; i.e., there is an ambiguity of π in the wind direction. That is to say, a north wind would produce the same Doppler shift as that of a south wind of equal strength.

4. The ambiguity of wind direction may be solved with the use of a frequency translator employed properly within the system. Such frequency translators are presently being developed by MSFC.

5. Allowing the focal range to continually increase while using the conical scan configuration with a single-beam LDV system yields a spiral scan from which a vertical profile of the horizontal wind may be obtained.

6. The LDV system has been shown to be operational in simulated heavy fog conditions.

7. One-dimensional wind velocity comparisons measured with conventional anemometry and the LDV system have shown good agreement for ranges to 300 m.

8. The single-beam LDV system has shown good promise of becoming a reliable wind sensor for remotely measuring one-, two-,

and three-dimensional mean winds and one-dimensional turbulence.

9. The CO_2 single-beam LDV system utilizes a CO_2 laser emitting at 10.6 μ, which is in the infrared region of the electromagnetic spectrum. Radiation in this wavelength is difficult to detect.

10. The single-beam LDV system appears applicable for the remote measurement of winds for ballistic applications.

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APPROVAL

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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

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