LASER DOPPLER TECHNOLOGY APPLIED TO

ATMOSPHERIC ENVIRONMENTAL OPERATING PROBLEMS

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SUMMARY

Laser Doppler technology is being developed and applied to aviation safety problems in the atmospheric environment. The feasibility ' this technique was established when CO_2 laser Doppler ground wind data were very favorably compared with data from standard anemometers. As re: . of these measurements, two breadboard systems have been deve'oped fo taking research data; a continuous wave velocimeter and a ι ied l ιι system. The scanning continuous wave laser Doppler ·   . er was developed for detecting, tracking and measuring ω .. ιΐι wake vortices. It was successfully tested at an airport where . iocated vortices to an accuracy of 3 meters at a range of 150 meters. ιiie airborne pulsed laser Doppler system was developed to detect and measure Clear Air Tι.bulence (CAT). This system was tested aboard an aircraft, but jet stream CAT was not encountered. However, low altitude turbulence in cumulus clouds near a mountaiι range was detected by the system and encountered by the aircraft at the predicted time. The hardware is being modified to extend the performance and range. The application of these systems, data highlights and test results are presented in this paper.

INTRODUCTION

NASA is sponsoring research and development of Carbon Dioxide (CO_2) Laser Doppler System Technology and its application to aircraft operating problems that are caused by adverse natural and induced atmospheric environments. The breadboard sensors developed under this technology use basically the same principle as conventional Doppler radar. In the laser Doppler system case, coherent laser radiation is Doppler shifted in frequency when it is scattered by the natural aerosols of the atmosphere that are in motion at the velocities of the wind or turbulence. The frequency of the scattered radiation is compared to the frequency of the laser beam by photomixing. The resultant difference frequency is directly proportional to the line-of-sight velocity of the aerosols when the transmitting and receiving optics are aligned on the same axis. This principle is illustrated in figure 1.

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The application of the technology to measure atmospheric winds was started at MSFC about ten years ago by Mr. Milton Huffaker, now of the Wave Propagation Laboratory, National Oceanic and Atmospheric Administration. The feasibility of the atmospheric measuring concept was demonstrated by using a CO_2 laser system to measure ground winds. The data from these measurements compared very favorably with simultaneous cup anemometer, wind-vane sensor, and hot wire anemometer data. These measurements have been discussed in several publications.

The first laser Doppler systems application to aircraft operating prob-lems was the detection and measuring of clear air turbulence. A breadboard airborne system was developed and tested in 1972 and 1973 aboard the Convair 990 aircraft based at the Ames Research Center. During these tests the concept of an airborne laser Doppler system to detect turbulence was successfully demonstrated. Although high altitude jet stream CAT was not found, turbulence in cumulus clouds was detected and encountered by the air-craft as predicted by the laser Doppler system.

In 1969 wake vortices from a DC-3 aircraft were successfully detected by a CO_2 laser Doppler system in a cooperative effort .ith the Langley Research Center. The data from these feasibility tests were reported in the 1971 NASA Aircraft Safety and Operating Problems Conference. Design studies and research activities for the development of an improved breadboard system were initiated after the concept feasibility tests.

In 1973, the Federal Aviation Administration requested the NASA's Marshall Space Flight Center to develop a breadboard scanning continuous wave laser system for detecting, tracking and measuring aircraft wake vortices in the landing corridor of an airport. This system was developed and successfully tested in 1974 and 1975 at the John F. Kennedy International Airport (JFK). The tests provided vortex data and tracks on over 1600 aircraft landings. These two breadboard systems will be discussed in more detail.

There is always a concern for personnel safety when laser systems are used. These systems are designed to meet conservative safety requirements. In addition, ordinary glass and plastics will reflect the CO_2 laser radiation and therefore, will prevent eye damage.

SCANNING LASER DOPPLER VELOCIMETER FOR VORTEX MEASURING

The Scanning Laser Doppler Velocimeter (SLDV) System shown in figure 2 is capable of detecting, tracking, and measuring the velocity patterns of air-craft wing tip vortices as well as general atmospheric turbulence. The SLDV is a continuous wave, focused, coaxial optical system which operates with a CO_2 laser emitting infrared radiation at a wavelength of 10.6 micrometers. This system is installed in an equipment van and consists of a 20 watt very stable CO_2 laser, a modified Mach-Zehnder interferometer, a Bragg cell frequency translator, an F/2 cassegrainian telescope with a 30.5 cm (12 in.) aperture, an infrared detector, a versatile range and angle scanner, a signal

processor, a data algorithm processor, various displays and recording electronics. The system is designed to have a range coverage of 61 to 610 m (200 to 2000 ft.) and an elevation coverage of 3° to 60°. The maximum range and angle scan rates are 7 Hz and 1 Hz, respectively. The system detects Doppler velocities and discriminates those up to 61 m/s (200 ft/s) in increments of 0.55 m/s (1.8 ft/s) and provides a line-of-sight velocity spectrum for the range resolution volume in space associated with the point where the system is focused. The velocity spectrum is processed along with scanner data to provide specific information on velocity magnitude, signal position in space and signal intensity as a function of time.

Following the development of the SLDV system, aircraft wake vortices and wind profile measurements were performed with two units installed at the JFK Airport. These measurements were performed in cooperation with the Department of Transportation's Federal Aviation Administration (FAA), Transportation Systems Center (TSC) and the National Aviation Facilities Experiment Center (NAFEC).

The test site at JFK Airport was located near the middle marker on Runway 31R which is about 765 m (2500 ft.) from the end of the runway. The site was instrumented with wind anemometers, pressure sensors, acoustic radars, as well as the laser Doppler system which served as the standard for the tests. Two SLDV units were located about 121 m (400 ft.) on either side of the runway centerline as shown in figure 3. This arrangement permitted these two independent sensors to scan a common area perpendicular to the aircraft landing corridor. The area of primary coverage by the laser systems for the vortex problem was 61 m (200 ft.) on either side of the runway centerline and 65 m (215 ft.) altitude.

To cover this primary area, the range position for the focus of the radiation was continuously cycled between a 61 m (200 ft.) and 305 m (1000 ft.) as the angular position for the focus was cycled between 3° and 33°. These two simultaneous movements of the radiation focus in this area perpendicular to the aircraft approach lane mapped out a finger like pattern in elevation for each scan frame. To provide adequate data density in the scanned area, a 7 Hz range scan rate and a 0.2 Hz elevation rate were used. These rates also gave a new frame of data across the vortices every 2.5 seconds. This continuous coverage of the scanned area provided the data for vortex time histories that will be discussed later.

The Doppler shifted radiation from the scanned areas was collected and mixed with the laser beam on an infrared detector where the radiation energy was converted to electrical energy. This electrical signal was then sent to the signal processor where the velocity data were sorted into .55 m/s (1.8 ft/s) increments. This data contained information on the ground wind speeds and the vortex velocities which were generally higher than the wind data. A velocity threshold was set above the peak wind speed so that only the vortex velocities were sent to the data algorithm processor along with

associated signal intensities and the position data obtained from the scanner. These data were then screened using the vortex location algorithm to assure that sufficient data existed to locate a vortex center. Further screening of the data assured that unusable data such as noise spikes were not used. Then, to locate the first vortex, the data were processed using a centroiding technique based on the maximum signal intensity of the usable data from a single frame of the scanned area. After finding the first vortex, the data used in determining its location were eliminated and the real time algorithm proceeded to look for a second vortex. After the second vortex was located, or if a second data area could not be defined, the chosen vortex centroids were displayed in real time and the location information was stored on a disk for later transfer to magnetic tape for use in vortex behavior studies.

Typical vortex tracks are shown in figure 4. The time based plots show altitude and lateral location of the port (0) and sta board (*) vortex centroids with time. When only one vortex was found a single position (S) was denoted for that scan frame. The position of the SLDV's at the test site is shown on the right hand plots of time versus range. The top curves are from SLDV 1 (van 1) and the bottom ones from SLDV 2 (van 2). A Boeing 707 aircraft, experiencing about a 0.9 m/s (3 miles/hr.) head wind, generated the vortex tracks. Most aircraft came over this point of the test site between 35 m (115 ft.) and 55 m (180 ft.) altitude. This one was just above 37 m (120 ft.) as indicated in the plots on the left of altitude versus time. There is general agreement between the data from SLDV 1 and SLDV 2. The better agreement in the data usually occurs at distances less than 152 m (500 ft.) from the SLDV location. The tabular data used in generating these plots is printed simultaneously. Processing of the data in a post processing mode allows all of the real time displays to be regenerated plus plots of peak velocity and peak intensity shown in both altitude and range.

The unthresholded data were also recorded and are being used to determine SLDV system performance and for study of the velocity flow fields. So far, the analysis shows that the vortex locations are within a 3 m (10 ft.) tolerance at 150 m (492 ft.) range and that the SLDV performed according to the theoretical design, thereby fully meeting the sensor development objectives.

Over 1600 flights on Runway 31R at JFK airport were monitored during the tests yielding vortex information on 13 different types of aircraft. The majority of the data is from B-707's, B-727's, B-747's and DC-8's. Peak vortex velocities of 30.5 m/s (100 ft./s) were measured and the vortices were tracked to a range of 457 m (1500 ft.). The data on vortex tracks were furnished to the Transportation Systems Center shortly after it was collected for analysis of vortex behavior and other studies which were part of the FAA's wake vortex program. Along with the MSFC, the Lockheed Missiles and Space Company, M&S Computing Company and the Raytheon Company participated in the SLDV development program.

When vortex data were not being collected, the data algorithm processor could be configured to give wind profiles in near real time. In this mode, data from the two independent units were processed for time correlation of the scans from the two systems and then spatially correlated to meet certain spatial requirements. These data were then used to determine the vertical and horizontal velocity components associated with a given altitude. A near real time plot of the resulting average horizontal and vertical wind components in the common scan area of the plane between the two sensors is shown in figure 5. Plotted here are the horizontal (X) and vertical (Y) velocity components as a function of altitude using data collected on April 1, 1975. The time correlation for these plots is 1.25 s., with a spatial correlation of 2 m (7 ft.) and the altitude increments are 6 m (20 ft.). From the recorded unthresholded data, similar wind information is available for each of the vortex time histories. This data may be of interest to those studying vortex behavior in ground effect.

A detailed description of the SLDV development is contained in references 1, 2 and 3.

THE CAT SYSTEM

Studies for the design and development of a breadboard pulsed CO_2 laser Doppler system began in 1968. The objective of this effort, illustrated in figure 6, was to determine experimentally whether a pulsed laser Doppler system aboard an aircraft could detect and measure CAT at a reasonable distance ahead of the aircraft, to make it a suitable principle for an onboard aircraft warning system. This is further discussed in references 4 and 5. Toward this goal a breadboard system was built, given an initial checkout, and then flight tested in 1972 and 1973. Following a detailed system and component evaluation, the hardware is being modified to improve the hardware performance, to increase the range and to provide a ground wind measuring capability. Extensive ground based tests are planned. These will be followed in 1978 by a flight evaluation test for CAT.

The CAT system consists of a very stable CO_2 laser, a modulator or pulse gate, a power amplifier, a modified Mach-Zehnder interferometer, an F/3 newtonian telescope, an infrared detector, a filter bank type signal processor, appropriate displays and recording electronics.

The transmitter part of the CAT system uses a master oscillator power amplifier configuration, similar to conventional pulse Doppler radar, to achieve high power output along with the good frequency stability needed for Doppler detection. The output of a frequency stable CO_2 laser is directed to the modulator where it is pulse modulated to drive the power amplifier. The output of the power amplifier goes to a telescope and is then transmitted forward of the aircraft through a Germanium window mounted in a special fairing pod on the side of the aircraft which serves as the view port for the instrument.

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A small portion of the transmitted energy is backscattered by aerosols to the telescope where it is then directed to the infrared detector which is also receiving a small part of the outgoing laser beam. These two beams combine to yield a signal that contains the Doppler frequencies of the aerosols with respect to the aircraft speed. This signal is processed and analyzed by a filter bank to get the velocity and turbulence information of interest.

The primary characteristics of the tested system were a wavelength of 10.6 μm, a pulse length of 1 to 10 s, a pulse rate of 110 to 200 pulses per second, a peak power of 2.2 to 3.0 kW with an average power of 1.5 to 2.5 watts, a telescope diameter of 30.5 cm (12 inches), a signal integration of 50 pulses and a turbulence resolution minimum of 0.6 m/sec (2 ft/s).

The laser and optics equipment, as installed on the aircraft, is shown in figure 7. The signal processing equipment is shown in figure 8. Two similar racks of equipment contain power supplies, timing controls, displays and recorders. The development of this equipment is discussed in reference 6. The Galileo, a Convair 990 aircraft based at Ames Research Center was the flight test aircraft for the CAT system and is shown in figure 9. A special 46 cm (18 inch) diameter fairing shown over the wing was built to house a special window for the CO_2 radiation and a forward reflecting mirror that directed the laser radiation forward along the flight path. A close view of the fairing is shown in figure 10. The reflecting surface inside the fairing is a Germanium window that is transparent to the 10.6 m radiation.

The pulsed laser Doppler equipment shown above was tested aboard the aircraft in August and September 1972 and again in January 1973. Atmospheric Turbulence Targets were located including desert thermal turbulence and mountain wave turbulence, two types of CAT. These CAT encounters came after calibration and performance data were collected.

The CAT system data discussion requires a description of the data displays which were regularly photographed during the tests. These pictures are used extensively in the data analysis. One of the displays is a Range Velocity Intensity (RVI) display on which the vertical scale is velocity, range is on the horizontal scale, while intensity shows up as different brightness levels of the data. Figure 11 shows signals received from cirrus clouds at 10 km (33000 ft.) altitude with the aircraft traveling at 890 km/hr (480 knots). The data at the top of the display shows the true air speed of the aircraft out to a range of 20.5 km (11 nautical miles.) A spread or width about this velocity line would indicate turbulence. The brightness at the left of this line shows the high intensity signals received from the clouds at close range. The bottom part of the displays, indicated by the overlapping lines, are the signals from an A scope, which is a signal intensity versus range plot of the unprocessed velocity. In figure 11b, the total range on the A scope is 1/2 the range of the RVI display, so the signals of interest in the top half of the screen, identifying the cirrus clouds are at a range twice the indicated range on the RVI display.

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The data in figure 12 shows three well separated clouds traveling at different speeds ahead of the aircraft. The data spot on the left of the top display shows the true air speed of the aircraft. Turbulence is indicated in both figure 12a and b. The width of the spectral returns on the lower screen indicates extreme turbulence, which is defined as gust velocities above 15 m/s (50 ft/s). A turbulence velocity of 19 m/s (63 ft/s) is shown. Figure 13 is a set of data confirming the encounter by the aircraft of turbulence detected by the CAT system shortly after the time of the data in figure 12. The top plot, 13a, is a display of the turbulence signal intensity versus velocity at a Greenwich mean time of 23:53:10. For a selected range, this display shows the velocity distribution from the filter bank. The peak of the curve is at the flight velocity and when turbulence is detected the peak signal flattens and there is an increase in the width of the velocity. In this display, the measured or selected range in signal time i.e., the round trip time to the turbulence at the speed of light, is 27 μs. This corresponds to a distance of 4 km (2.2 nautical miles). With the aircraft traveling at a speed of 665 km/hr (359 knots) the estimated time to the patch of turbulence is 22 seconds. The aircraft center of gravity accelerometer data was recorded and the signal for this aircraft encounter with the turbulence is shown in figure 13b which is a plot of G load versus time. The top curve is the vertical acceleration trace and the bottom one is a horizontal acceleration trace. The accelerometer data trace starts when the turbulence ahead of the aircraft appears on the intensity velocity display. Between 20 and 30 seconds, there are major changes in the acceleration curves especially the top trace. At 22 seconds, the identified time, the accelerometer already shows a change in G load, the change having started at about 18 seconds. The maximum acceleration is over 0.5 G and occurs at 24 seconds after the turbulence was identified. This set of data indicates that it is possible to identify turbulence ahead of the aircraft with the pulsed laser Doppler system, the CAT system, before it is encountered by the aircraft.

A dust storm in the Kingman, Arizona area was found during the flight on September 6, 1972. The aircraft did not fly into the storm because of the potential damage to the aircraft and the onboard instrumentation and experiments, but the aircraft was flown near it. Strong signal returns were collected by the CAT system and are shown in figure 14. The top set of data shows the increased signal intensity and the spread that is caused by the turbulence and the increased backscattered signal resulting from the dust. As the aircraft started away from the storm the CAT system detected a wind shear as shown on the RVI display. The difference in horizontal velocity measured over 3.0 km (1.6 nautical miles) range was about 50 km/hr (27 knots). The aircraft flew through this shear and its instrumentation recorded a 40 km/hr (22 knots) shear as it passed through the region where the laser system identified the shear.

The flight test results can be summarized as follows:

1. There were no CAT system operating problems resulting from the airborne environment.

2. Nonjet stream turbulence was identified and then encountered near a dust storm and on the east side of the Sierra Mountains in many cumulus clouds. Clear air mountain wave and desert thermal turbulence were identified and en-countered.

3. Wind shear was detected, measured, and encountered near a dust storm.

4. Clear air signals, where there was no turbulence, were measured at ranges of 5 to 9 km (3 to 5 nautical miles) and up to altitudes of 6.7 km (22,000 ft.).

5. Cirrus clouds were identified at altitudes between 7.6 to 11.5 km (25,000 to 38,000 ft.).

6. Three well separated cumulus clouds were detected simultaneously ahead of the aircraft.

The pulsed CO_2 laser Doppler system discussed above has demonstrated some of the capabilities essential to meet the stated objective for this develop-ment; to determine experimentally whether a pulsed laser Doppler system aboard an aircraft can detect and measure CAT sufficiently ahead of the aircraft to make it a suitable principle for an onboard instrument. MSFC supported by the Raytheon Company has been working to find the answer to this objective. The CAT system is now undergoing modifications to improve the performance of the hardware which should result in a transmitted signal that has greater coherence and increased signal strength. These improvements will result in increased detection range to as much as 18.5 km (10 nautical miles). The equipment is also being modified to enable measurement winds from the ground. With these improvements it appears that the stated objective requirements will be met during a future flight test.

CONCLUDING REMARKS

Presented above are two of the breadboard CO_2 laser Doppler systems that have been developed to help resolve aviation safety problems. Research and development is continuing on both of these breadboard systems to advance the systems technology and to take advantage of the advances in the state-of-the-art. Studies on applying this technology to measure pollution, wind shears, and severe storm winds are part of the overall program. Experience of value to these studies was gained when a ground based CW laser system was used to collect data on dust devil velocities. The advancement of this technology may lead to other applications for measurements of the atmosphere. The interest in these advances is based on the demonstrated results to date which are now summarized.

Laser Doppler technology has been used to successfully measure natural and induced atmospheric turbulence that affect aircraft and airport operations. Two breadboard systems have been developed and tested for making atmospheric velocity measurements.

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1. A ground based continuous wave CO_2 SLDV tracked aircraft wing tip vortices and measured ground winds at an airport providing unique high quality test data on aircraft vortices.

2. A pulsed CO_2 laser Doppler system has measured true air speed, winds aloft, non-rain cloud locations, wind shear and turbulence. These feasibility measurements have lead to special application system studies.

The technology is advancing and will result in significant reductions in hardware size weight and power requirements while increasing range capability and data handling capability and capacity. This may then lead to the commercial use of these developments in solving some aircraft safety operating problems.

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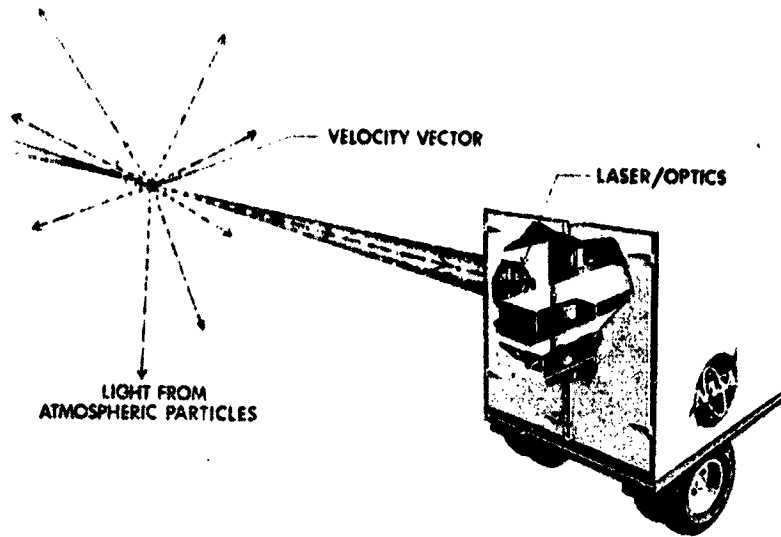
Figure 1.- Laser Doppler principle.
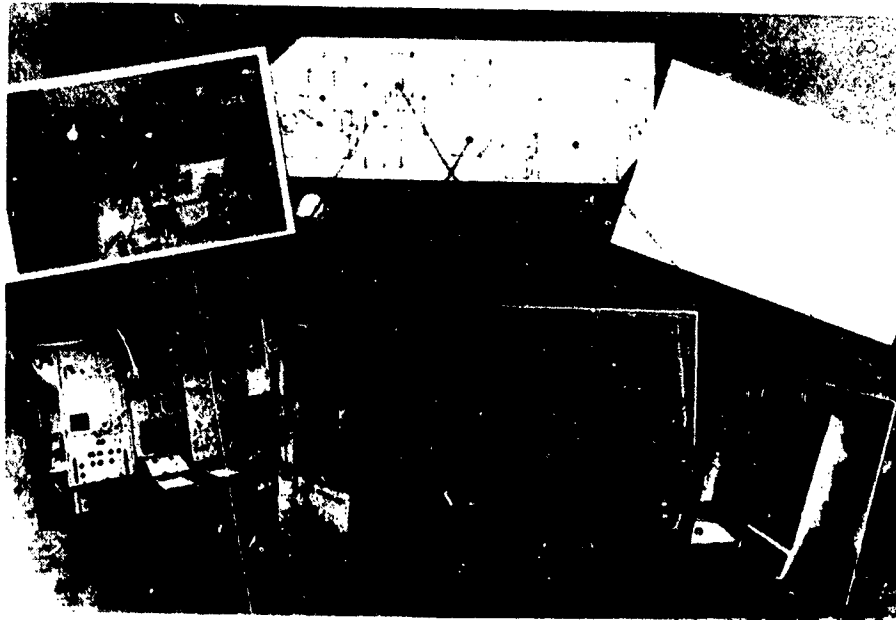
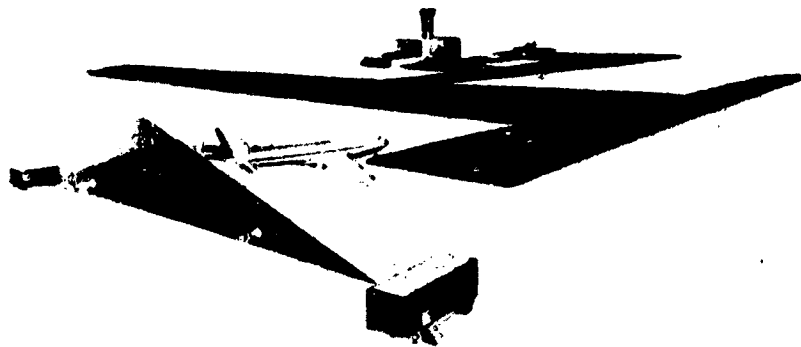Figure 2.- Scanning laser Doppler velocimeter.

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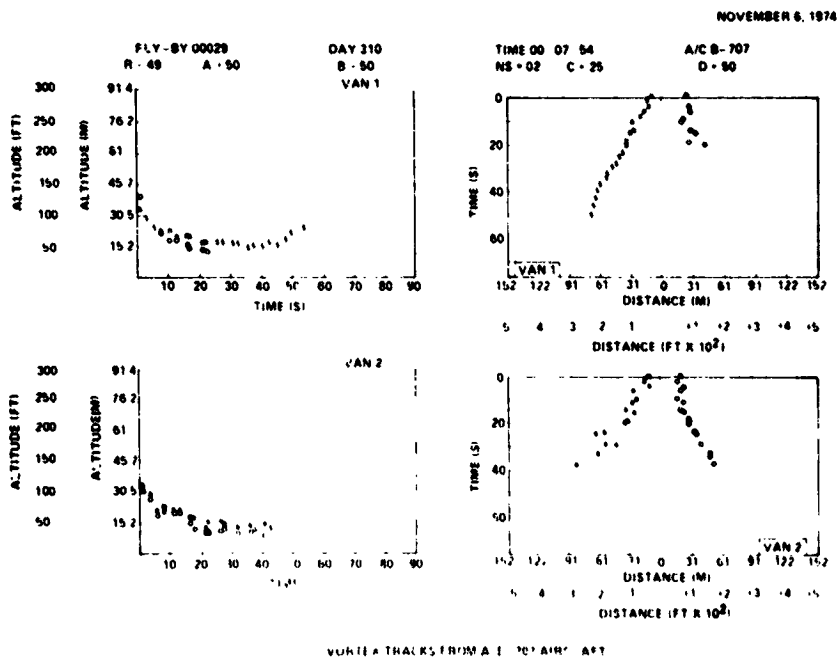Figure 3.- Scanning laser Doppler velocimeter.
JFK Airport operations.
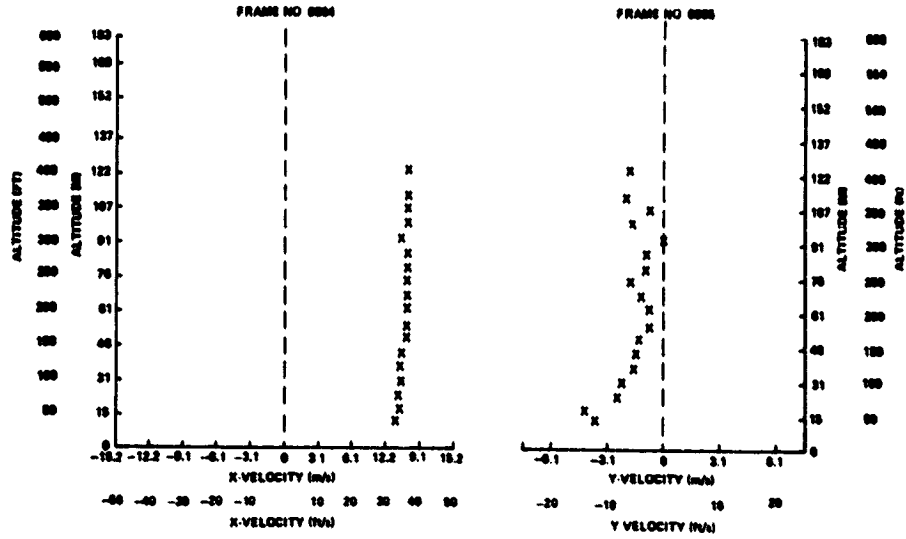

Figure 4 - SLDV data.

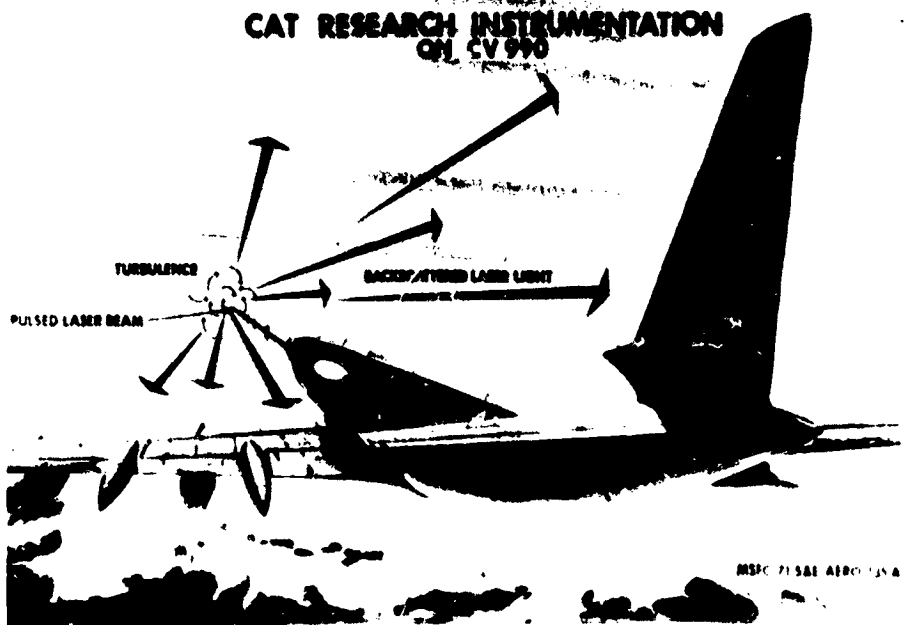Figure 5.- SLDV wind profile at JFK Airport.

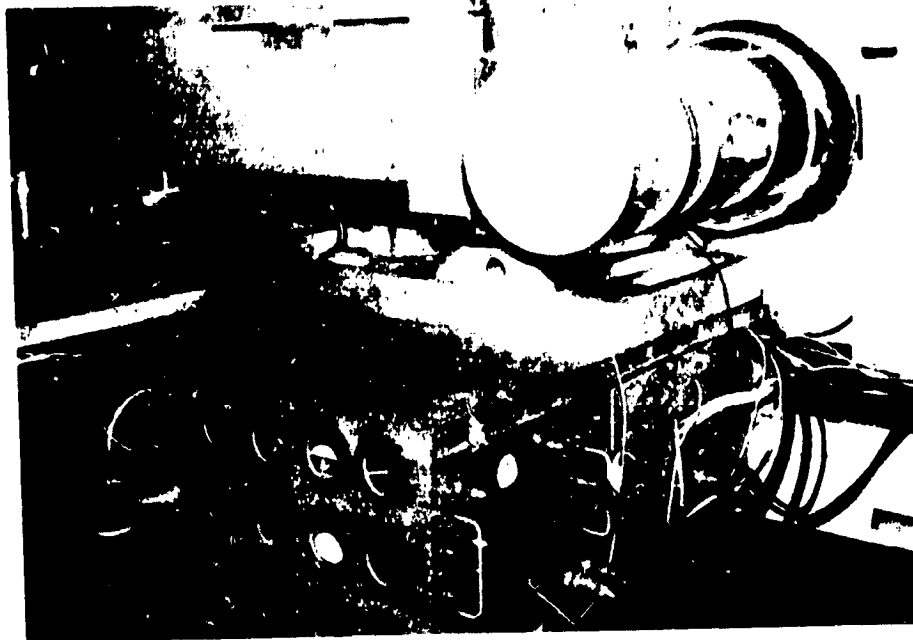Figure 6.- CAT research instrumentation on CV 990.

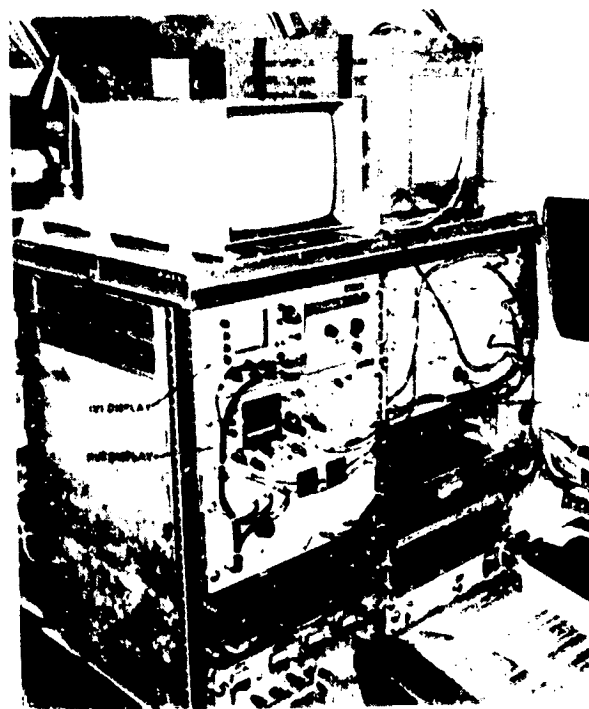Figure 7.- CAT system, laser, optics and telescope assembly
on CV 990 aircraft.

Figure 8.- CAT system signal processor and displays assembly
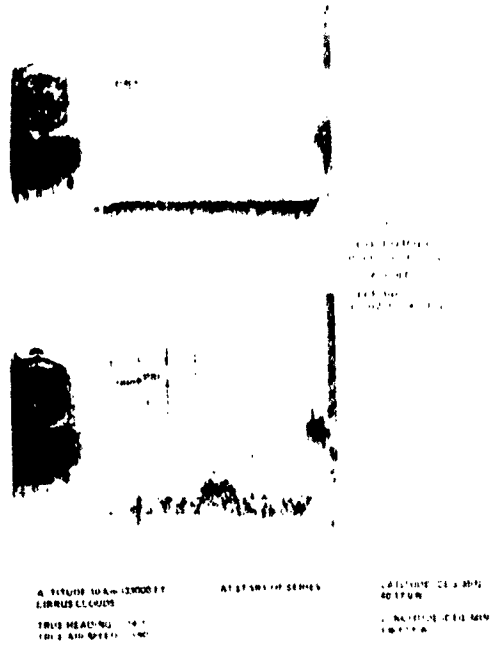on CV 990 aircraft.

Figure 9 - Convair 990 aircraft.

Figure 10. - Aft engine location on CV 990 aircraft.

Figure 11.- CAT system data. Cirrus cloud returns.
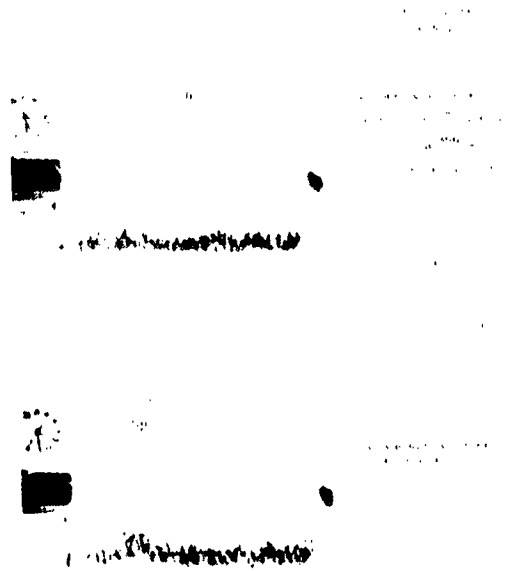
Figure 12.- CAT system data. Cumulus clouds.
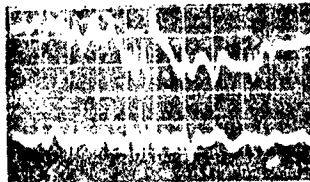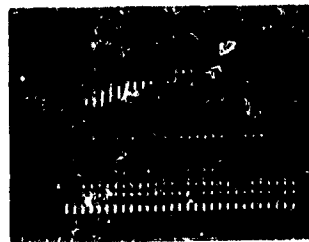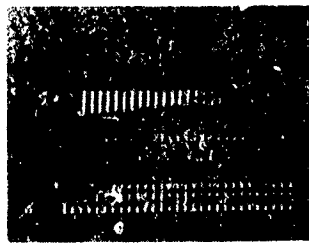
Figure 13.- CAT system data. Cloud
turbulence correlation data.

Figure 14.- CAT system data. Dust storms.