PULSED DOPPLER LIDAR FOR THE DETECTION OF TURBULENCE IN CLEAR AIR

E. A. Weaver, J. W. Bilbro, J. A. Dunkin, S. C. Johnson, W. D. Jones
National Aeronautics and Space Administration

C. E. Harris, C. A. DiMarzio
Raytheon Company

SUMMARY

The Carbon Dioxide Pulsed Doppler Lidar System developed by the Marshall Space Flight Center was tested in 1978 and 1979 to measure turbulence in clear air. In a 1978 ground test, this remote detection system was used to measure wind shear in the gust fronts of thunderstorms at the Kennedy Space Center. The flight test of the lidar system in the winter of 1979 was for airborne measurements of clear air turbulence over the western part of the United States. A brief description of the Doppler lidar is presented in this overview along with representative data from the two tests.

INTRODUCTION

NASA, as part of the Aviation Safety Technology Program and for more than a decade, has been sponsoring research and development of carbon dioxide (CO_2) laser Doppler system technology for its application to aircraft operating problems - specifically, those problems resulting from both naturally and artificially induced adverse atmospheric environments. A pulsed Doppler lidar system was developed from this technology by the Raytheon Company for the Marshall Space Flight Center in 1979 to 1972 (ref. 1,2). Following its development, it was evaluated in an engineering checkout test to determine if it could operate in the aircraft environment and be used for the advanced detection and measurement of clear air turbulence (CAT) (ref. 3). This earlier system test was described in a paper presented at the 1976 Aircraft Safety and Operating Problems Conference (ref. 4). After the initial test, the lidar, while retaining its airborne capability, was modified for operation as a ground-based instrument system.

In 1976, the Department of Transportation asked NASA to evaluate the use of CO_2 Doppler lidars in the measurement of wind shear in the airport terminal area as part of the ongoing laser Doppler technology program. In support of this evaluation, tests of the pulsed Doppler lidar were conducted in 1978 at two locations: Oklahoma City, Oklahoma, and Kennedy Space Center (KSC), Florida. Wind velocity changes in the gust fronts of thunderstorms were measured at the normal glide slope elevation (3°). These wind shears were clearly visible in both the real-time and post processed data displays. One data set from this test program is discussed in this paper.

After these tests the lidar was placed in its airborne configuration for a CAT flight test program. This test was conducted from January through March 1979. The objective of the test was to evaluate the lidar's performance from the airborne platform and establish its ability to provide data on the advanced detection of turbulence. Mountain wave CAT, CAT in cirrus clouds, and CAT in haze/dust were detected and measured by the lidar in advance of their encounter by the aircraft. Selected data from this flight test program are presented.

SYSTEM DESCRIPTION

The pulsed Doppler lidar was developed to measure atmospheric wind velocities and turbulence that could be hazardous to aircraft operations. Its operation is similar to that of a microwave Doppler radar. For a pulsed Doppler lidar, coherent infrared laser radiation is transmitted from the system and shifted in frequency when it is scattered by the naturally entrained aerosols in the atmosphere. The frequency of the backscattered radiation received by the system from the aerosol reflection is compared to the frequency of the outgoing laser beam by photomixing. The resulting difference frequency is the Doppler shift which is directly proportional to the line-of-sight velocity of the aerosol motion.

The lidar's transmitter, shown in Figure 1 as it was mounted on the CV-990 aircraft, is the central element of the system having a master oscillator power amplifier (MOPA) configuration. The system's simplified block diagram, shown in Figure 2, illustrates this configuration. The primary components are two lasers, the modulator, the power amplifier, an interferometer, a telescope, a detector, the signal processors, and several displays. To provide a better understanding of the system, each element in the block diagram is briefly described (ref. 5).

The master oscillator is a very stable, continuous wave CO_2 laser that provides about eight watts of linearly polarized radiation at a wavelength of 10.6 micrometers. A small portion of this radiation is used to stabilize the frequency of the master oscillator and to maintain the frequency offset of the second laser which serves as a local oscillator (LO) for the system. In the laser optical path the cadmium telluride electro-optic modulator is used to chop the radiation into a pulse train that is variable in repetition rate and in width. The pulse width can be varied between two and eight microseconds equivalent to pulse lengths of 600 to 2400 meters, while the pulse repetition rate may be varied from one pulse to two hundred pulses per second. The resultant pulse train passes through an indium-antimonide optical isolator which prevents reflections from entering the master oscillator and causes its frequency to change. The pulse train next passes through the power amplifier that has six discharge tubes cascaded to provide a gain of approximately 36 dB. Upon exiting the power amplifier the pulse train passes through a Brewster window, then through a quarter-wave plate which converts the radiation from linear to circular polarization. The pulse train finally passes into a 30 cm diameter telescope where it is expanded to approximately 24 cm, collimated, and transmitted into the atmosphere. The energy is then directed to a specific location in the atmosphere by a scanner mirror system that provides nearly hemispherical coverage for the ground-based opeartion. In the flight configuration, the energy is directed by a fixed flat from the telescope forward along the flight path of the aircraft through a 35.5 cm diameter, 1.9 cm thick germanium window that serves as an aircraft pressure bulkhead to the atmosphere.

The directed laser energy is scattered by aerosols naturally entrained in the atmospheric wind. Some of the scattered light is reflected back along the same optical path that the transmitted beam traveled. As mentioned previously, it has been Doppler shifted in frequency by an amount proportional to the radial (line-of-sight) velocity component of the aerosols. It is the measurement of this Doppler shift that allows the wind velocity component to be determined. The backscattered part of the laser radiation collected by the telescope is transmitted back through the quarter-wave plate. Because the polarization of the reflected radiation is rotated 180° from the transmitted laser light it is reflected by the Brewster window to the detector through a combining beam splitter. Also coming to the detector through the combining beam splitter is the laser beam from the very stable LO laser. The LO is tuned to a frequency that is offset by 10 MHz from the master oscillator frequency. This allows not only the magnitude of the radial velocity to be measured, but also its direction as well.

Photomixing of the LO and the received beams occurs at the detector which is a mercury-cadmium-telluride photodiode. The signal from the detector is amplified and then passed through a filter bank to obtain the signal frequency spectra. The frequency resolution can be set for 125 kHz, 250 kHz, and 500 kHz matching pulse widths of 8, 4, and 2 microseconds. The corresponding velocity resolution is 0.6 m/s, 1.2 m/s, and 2.4 m/s. Typically, the transmitter operated at 140 pulses per second with an integration of 50 pulses. This provided 3 data sets per second with a data set consisting of the spectral distribution averaged over 50 pulses in a single range cell.

The signal from the signal processor is displayed in real time in two forms as shown in Figure 3. In this first display, which is the range velocity indicator (RVI), the wind velocity is shown as a function of range. It has a maximum range of 30 km corresponding to 200 microseconds elapsed time. The brightness of the signal is an indication of its intensity. In the second display, which is the intensity velocity indicator (IVI), the signal intensity for each velocity at a selected range is shown. The width of the spectrum at the e^{-2} point (near the spectrum base) is a measure of the turbulence or gust velocity in the selected measurement volume.

The frequency/velocity information is further processed by an online minicomputer for displays in real time and is recorded for post test analyses. Data processing after the test can be performed using both the online minicomputer and the MSFC 1108 central site computer. The parameters of the plots can vary according to the requirements of the specific investigation. This plotting capability was first used with the lidar in the wind shear test program.

WIND SHEAR FEASIBILITY TESTS

Abrupt wind speed changes over very short flight path distances can cause sudden variation in the airflow over the wing when these wind shears are encountered by aircraft. This causes the aircraft to deviate from the planned course. At times, particularly during takeoff or landing, a wind shear encounter has resulted in serious and fatal accidents. One source of hazardous wind shear is a thunderstorm with its associated gust fronts, down drafts, and turbulence. NASA is studying these and other meteorological conditions that cause the invisible wind gradients. The agency has also sponsored sensor development to remotely detect them and provide advanced warning to the pilots about these conditions before their aircraft enter the critical opeational zones of the airport.

A study of the NASA pulsed Doppler lidar applied to glide slope wind shear detection showed these measurements to be feasible (ref. 6), so the lidar was deployed to the Kennedy Space Center during the 1978 summer thunderstorm period as part of the NASA-DOT Wind Shear Test Program. The lidar was positioned 0.6 km NE of the Vertical Assembly Building and 5.5 km from the Florida Coast Line (Figure 4). It was essential that the data be collected as it would be at an airport so the lidar scanned a 320^{o} azimuth sector at an elevation of 3^{o} and at a 2 ^{o}/s scan rate. During the one month test period, three storms were monitored that showed the existence of well defined gust fronts with associated wind shear. The July 29, 1978, case was selected for discussion in this paper (ref. 7).

The selected data consist of wind flow-field plots obtained from an anemometer network at KSC and the pulsed Doppler lidar velocity plots (ref. 8). The lidar plots show mean radial wind velocity as a function of scan position and range with the lidar located at the center of the plot and surrounded by circular range increments of 2 km. The areas coded 1 through 9 indicate increasing velocities toward the center of the plot and the A through I codes indicate increasing velocities away from it. Each number or letter represents a velocity bin of 2.5 m/s. Groups of 3 velocity bins are indicated by the different designs on the plots. Adjacent velocity groups are separated by solid lines.

The first wind flow-filed plot in Figure 5 indicates the penetration of the lidar scan plane by a sea breeze front at approximately 1500 EDT. This resulted in a predominant wind direction from the southeast behind the front but from the southwest preceding the front. By 1530 EDT a second sea breeze front, with wind from the northeast, has pushed into the scan plane resulting in convergence at the site - winds approaching from virtually all directions. By approximately 1600 EDT (third plot), a col had formed slightly to the west of the lidar site. At this point the wind was approaching from the west and east, but was receding to the north and south. Simultaneously, a storm was forming over the Indian River to the west and within a half hour had passed over the site and out to sea as indicated in the final plot of Figure 5.

The laser Doppler velocity data corresponding to these events are shown in Figure 6. The first of the plots, generated at 1532 EDT, indicates approaching velocities from all but a small area to the north of the site. At 1542 EDT the wind was flowing toward the north and by 1552 EDT had evolved so that the wind was flowing almost uniformly toward the northwest. Five minutes later, a high velocity approaching wind was observed to the west, while just south of it was a high velocity receding wind for a total wind speed change of approximately 25 m/s. By the next scan, a highly turbulent region was encountered with both approaching and receding velocities in excess of 16 m/s. At 1611 EDT the flow had become much more uniform with relatively high winds toward the southeast.

The wind velocity variations associated with thunderstorm gust fronts were measured on three occasions during the KSC test with the lidar. It is capable of measurements to a range of 6 km. The wind shears along a single lidar line-of-sight can be measured, but it appears that by scanning in azimuth the presence of fronts and the direction of shears are more readily identified.

LIDAR FLIGHT TEST FOR CLEAR AIR TURBULENCE

Clear air turbulence cannot be visually located because it has no feature to identify it in the atmosphere. In that sense it also resembles wind shear. CAT is considered a problem for all aircraft so areas of potential CAT are identifid on the synoptic weather charts, but avoidance of all these regions cost both time and energy while passenger injury and/or aircraft damage may result from CAT encounters. These costs have resulted in a requirement for more accurate location of CAT and providing advance warning of it. Therefore, part of NASA's CAT research effort is the development of sensors to detect and measure the severity of CAT ahead of aircraft with sufficient warning for possible evasive maneuvers by the pilot.

The requirement for a CAT sensor was the basis for a study applying CO_2 laser Doppler technology that required using recognized models for the atmosphere's optical properties (ref. 9). The study results showed that an advanced technology CO_2 pulsed laser Doppler system could meet the CAT sensor requirements so a flightworthy breadboard CO_2 pulsed Doppler lidar was developed to test the feasibility of detecting CAT. (These test results are summarized in reference 4.) Further laboratory tests were followed by modifications and ground-based tests. Then in December 1978 the lidar was installed aboard the NASA Convair 990 aircraft for CAT detection and calibration flight testing. The lidar's transmitter (Figure 1) was placed so that the telescope's forward reflecting mirror was inside the special fairing at the emergency door on the port side of the aircraft (Figure 7). Because the lidar occupied about half of the onboard floor space, three other sensors in various stages of development for application to the CAT problem were also tested. The other CAT sensors and the flight test program are further described in reference 10; however, selected information from the reference is presented as background for the lidar data cases and the test results.

When flight testing CAT detection sensors the overriding requirement is to find clear air turbulence. Once it is located the goal is to remotely detect and measure it with sensors. To locate CAT during the test program, the meteorological conditions were closely monitored daily as each flight was based on a detailed meteorological forecast covering the western part of the United States (Figure 8). For each day CAT was the first mission priority and on a CAT flight day the mission centered around the most probable CAT area. Where there was not a reasonable probability for CAT the next mission priority was CAT sensor calibration. If neither of the CAT missions could be met the nonCAT experiment objectives were followed. Based on the above mission priority, thirty flights were made between January 12 and March 28, 1979. Sixteen flights were for CAT, another eight were primarily for lidar performance and calibration in conditions other than CAT, although some CAT data were often collected, and finally, six flights were for other experiment objectives. From these flights, three data cases were selected that illustrate the lidar's capability and are representative of all the lidar CAT flight test data, and they are presented in this paper.

One of the lidar performance flight tests was to determine how the lidar signal return (measuring true airspeed) varied with altitude, especially in a relatively small geographical location, both over land and just off the coast. The meteorological conditions required for the test are a clear day with wind speeds relatively low at all flight levels from the surface to 12 km. In 1973, during a similar test along the coast, the mixing of salt particles into the upper altitudes, often in layers, was observed. These observations were made just after many frontal systems entered California from over the Pacific Ocean. In this flight test a similar frontal history occurred prior to Flight A-12 on February 12, 1979, which was a test to make an altitude profile of the lidar signal return. The test was conducted just off the California Coast near Monterey Bay. The aircraft was flown in a race track like pattern with one side about 60 km long and about 5 km between the north and south tracks. The first data were collected at an altitude of 75 m with the aircraft climbing at the end of each track. The final altitude was 10.7 km.

The results of this test are summarized in Figure 10. The CAT lidar detected air signals from 3 km ahead of the aircraft to an altitude of 2.5 km. Between 2.5 and 8.5 km there was one altitude, 4.9 km, where low level signals were collected. Signals were again detected from 8.5 to 10.7 km. These high altitude signals came from very thin cirrus cloud particles. From the data it was concluded that the many frontal systems prior to the flight did not transport many sea salt particles to altitudes above 2.5 km. Only one possible layer was found at 4.9 km. The data collected on this flight were typical of the entire 30 flights with aerosol concentrations significantly lower than the predictions based on commonly used atmospheric models (ref. 9).

One type of CAT planned for observation during this test was the Sierra mountain wave. For this, at least 20 m/s wind speeds from a direction perpendicular to the ridge line of the mountains are minimum conditions for large CAT areas that disturb the atmosphere sufficiently to propogate the CAT to the tropopause. During the 1979 test these conditions did not occur so this type of CAT could not be observed. Mountain wave CAT, having about a one km altitude thickness, could occasionally be found near the mountain ridge line. The next two lidar data cases are both mountain wave CAT conditions observed during less than minimum wind conditions required for the Sierra wave.

On March 28, 1979, Flight A-30, mountain wave turbulence was found near Vermejo Park, NM (near the New Mexico - Colorado border). The aircraft was at flight level 152 (4600 m) and on a heading of 132° with the wind at 10 m/s from 270°. The plot in Figure 10 shows the lidar spectrum from 3 km ahead of the aircraft. There are two peaks in this spectrum at 170 m/s and 178 m/s. The narrow peak at 178 m/s is associated with the cloud shown in the photograph on the right side of Figure 10. The broad peak, centered about the true airspeed, 170 m/s, is about 8 m/s wide. (This width is often represented by a scalar value.) The broadness of this return is indicative of turbulence within the lidar beam and was one of the strongest CAT conditions detected by the lidar during the 1979 test. Only the edge of this turbulence was encountered by the aircraft because the aircraft was turned to avoid undesirable terrain features. This CAT spectrum is classified as moderate turbulence. Further evidence that CAT should exist in the area was a 12 m/s wind speed decrease within a distance of 25 km which is a wind shear conducive for moderate-to-severe turbulence. The spectral width (in this case 8 m/s) can be represented as a scalar value so that the variation of the turbulence along the flight path can be evaluated. This type of data presentation is used in the next data case.

The data shown in Figure 11 from March 2, 1979, Flight A-18, not only show the turbulence variation along the flight path but also illustrate the lack of lidar signals caused by a low atmospheric aerosol density. Shown in the photograph in Figure 11 is a cumulus cloud, not visible on the aircraft's weather radar, that provided the aerosols essential for lidar measurements. Plotted on the geographical coordinates is the flight track made on Run 7 starting at 2145Z when the aircraft was on a 248.8° heading at flight level 060 (1.8 km MSL) on the lee side of the Tehachapi Mountains. This track is southeast of White Oak, a private landing field, near Edwards Air Force Base, California. The shaded area near the west end of the flight track represents the cumulus cloud. Above the flight track are plotted lines representing the magnitude of the peak-to-peak vertical accelerations from each 5 second time period of flight as recorded by the accelerometers located near the center of gravity of the aircraft. The acceleration plots show that the aircraft was in turbulence for most of Run 7, and especially before the cloud encounter. The lidar data shown as lines below the flight track represent the measured spectral width which is directly proportional to the wind gust velocity. There are no lidar data east of the cloud because the aerosol density is too low. In the clouds however are plotted several spectral width lines, some nearly 10 m/s, indicating moderate-to-severe turbulence. The change in the lidar's gust velocities appears to follow the corresponding change in the peak-to-peak accelerations. In this data set the lidar "saw" through the cloud to a west data position and tracked this cell to the lidar's minimum range of 3 km. In comparing the data west of the cloud, the lidar predicted CAT at about half of the intensity encountered by the aircraft. So far this case is explained by the lack of sufficient aerosols needed to provide the broad spectrum that would compare more favorably with the encountered vertical acceleration. Since the aircraft is encountering moderate turbulence prior to the location of the lidar data, a precise encounter for the lidar measured turbulence cannot be shown. Similar CAT detection sequences were found in cirrus clouds and in other mountain waves where either clouds or dust provided the aerosols.

CONCLUDING REMARKS

The pulsed CO_2 Doppler lidar has been successfully demonstrated in both the ground-based and airborne flight operations. As a ground-based system, it has detected wind shears in thunderstorm gust fronts to a range of 6 km. It has also demonstrated operation under light rain conditions (5 mm/hr). Typical ranges achieved during operation as a ground-based unit were from 3 to 6 km. Ranges as far as 16 km were achieved on days with low humidity and high aerosol densities. When in the airborne configuration, the lidar detected clear air turbulence in advance of the aircraft encountering CAT. The data provided by the lidar included turbulence location and intensity with intensity being indicated by the measured spectral width which is proportional to the wind gust velocity.

Lack of aerosols inhibited operation of the lidar throughout the flight test program usually restricting measurements to low altitudes and close ranges. The ranges at which CAT was detected were inadequate to provide sufficient warning (30 s minimum, 2 to 4 min preferred). While higher per pulse energies will allow detection at longer ranges, it is uncertain at this time as to how much improvement can be realized or even how much is required to match the extreme aerosol density variation. Based on the data from the flight test, the aerosol density appears to be considerably below that predicted by the models which were used in the lidar system design. A test designed specifically to measure the backscatter profile (a function of the aerosol density, size, and composition) is planned for 1981. This test will help determine the potential for future CO_2 lidar systems.

The lidar, developed for aviation safety research involving atmospheric winds, is a unique and valuable research tool. It can provide meteorologists with heretofore unavailable data concerning the variability of the atmospheric winds. The measurement potential can be greatly increased using 1980 technology; however, extensive applications will depend upon considerable reduction in cost and size and simplification of operation.

REFERENCES

1. Jelalian, A. V., Keene, W. H., Sonnenschein, C. M., "Development of CO_2 Laser Doppler Instrumentation for Detection of Clear Air Turbulence," Raytheon Company Report ER72-4243, NASA Contract NAS8-24742, May 1972.

2. Sonnenschein, C. M., Jelalian, A. V., Keene, W. H., "Development of CO_2 Laser Doppler Instrumentation for Detection of Clear Air Turbulence," Raytheon Company Report ER70-4203, NASA Contract NAS8-24742, June 1970.

3. Harris, C. E., Jelalian, A. V., "Development of CO_2 Laser Doppler Instrumentation for Detection of Clear Air Turbulence," Raytheon Company Final Report ER78-4392-1, NASA Contract NAS8-28424, September 1979.

4. Weaver, E., Bilbro, J., Dunkin, J., Jeffreys, H., "Laser Doppler Technology Applied to Aviation Safety Problems," NASA SP-416, pp. 287-301, October 1976.

5. DiMarzio, C. A.; and Bilbro, J. W.: "An Airborne Doppler Lidar", Heterodyne Systems and Technology - Part II, NASA CP-2138, 1980, pp. 529-540.

6. Kalafus, R. M., "Wind Shear Requirements and Their Application to Laser Systems," FAA-RD-77-123, Final Report to FAA, DOT/TSC, Cambridge, MA, 1978.

7. DiMarzio, C., Harris, C., Foley, D., "Thunderstorm Velocity Measurements Using A Coherent CO_2 Laser Weather Monitoring System," Raytheon Company Report, ER78-4417, NASA Contract NAS8-32555, December 15, 1978.

8. DiMarzio, C., Harris, C., Bilbro, J., Weaver, E., Burnham, D., Hallock, J., Pulsed Laser Doppler Measurements of Wind Shear," AMS Bulletin, Vol. 60, No. 9, September 1979.

9. McClatchey, R., Fenn, R., Selby, J., Volz, F., Garing, J., "Optical Properties of the Atmosphere," AFCRL 72-0497, August 24, 1972.

10. Weaver, E. A., Ehernberger, L. J., Gary, B. L., Kurkowski, R. L., Kuhn, P. M., Stearns, L. P., "The 1979 Clear Air Turbulence Flight Test Program," 1980 Aircraft Safety and Operating Problems, NASA CP-2170, 1981. (Paper 16 of this compilation.)

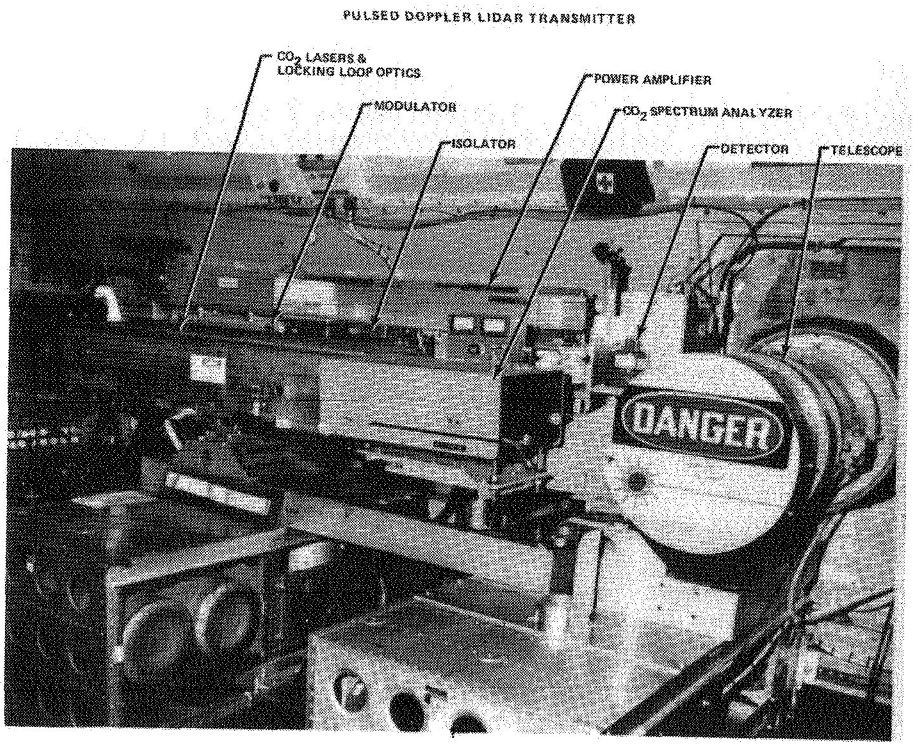


Figure 1.- Pulsed doppler lidar transmiter with some components identified.

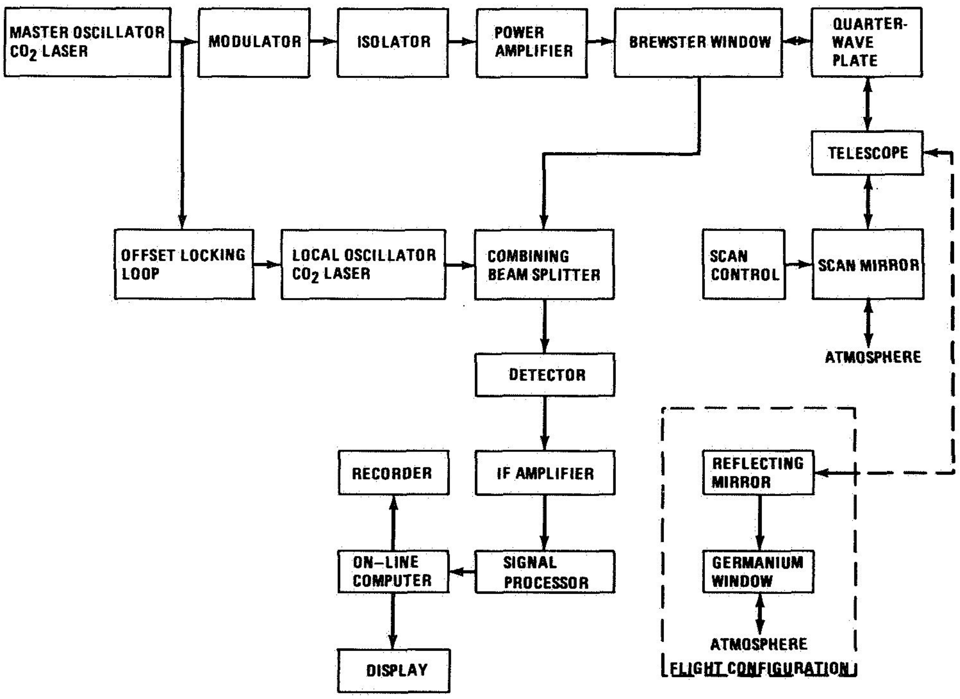


Figure 2.- Pulsed doppler lidar block diagram.

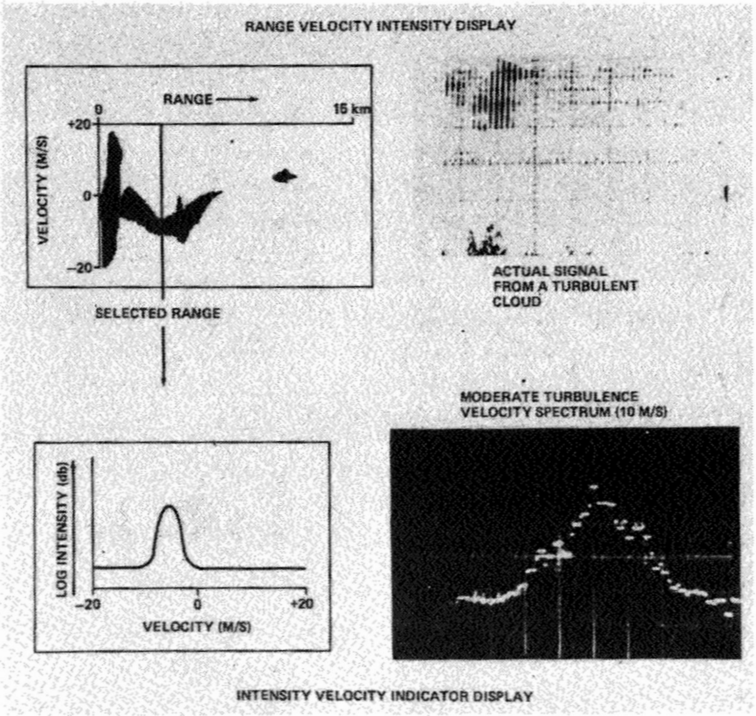


Figure 3.- CAT detection real-time displays.

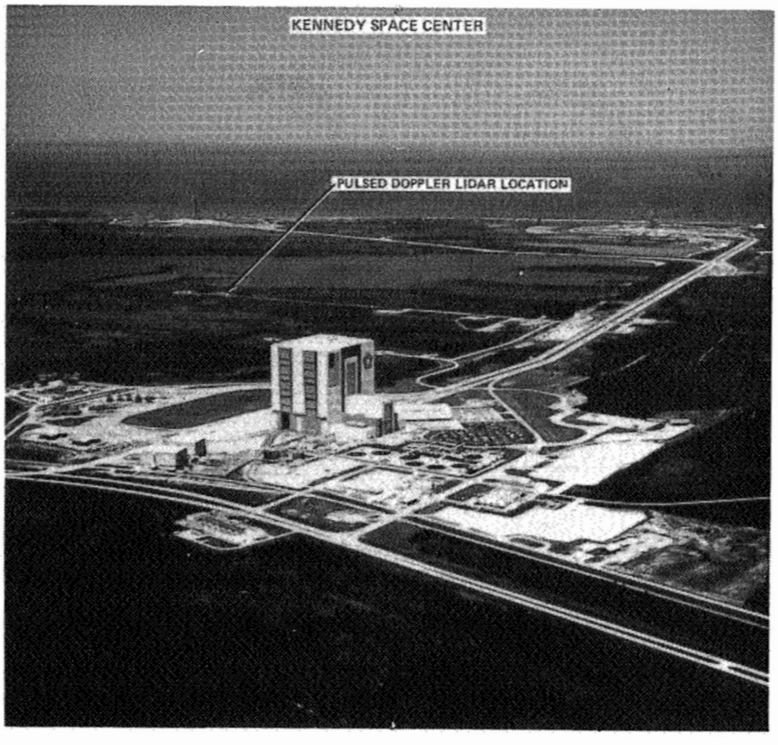


Figure 4.- Kennedy Space Center lidar test site.

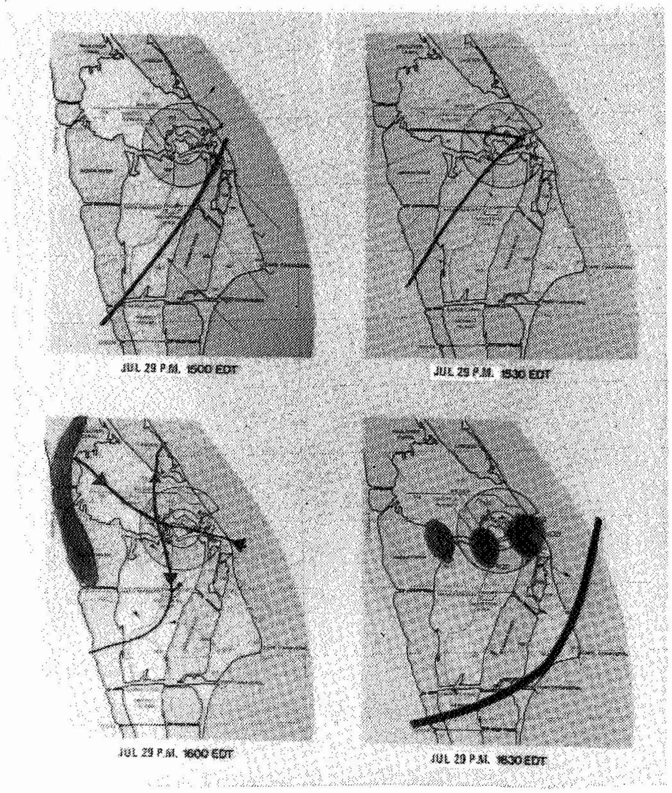


Figure 5.- Wind flow-field plots. Anemometer data, July 29, 1978.

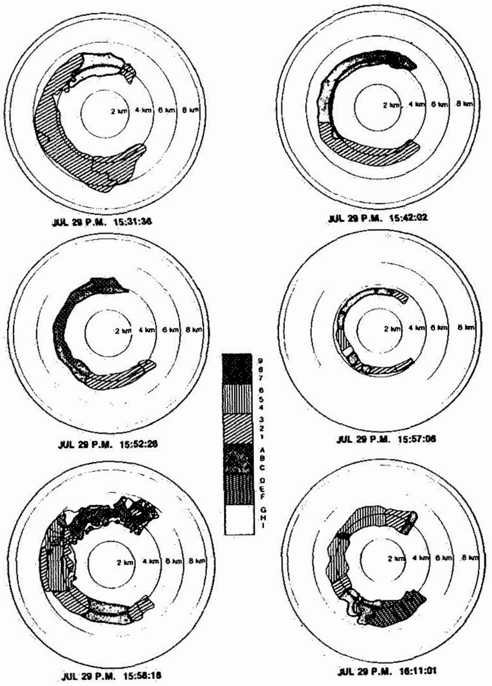


Figure 6.- Wind flow-field plots. Lidar data, July 29, 1978.

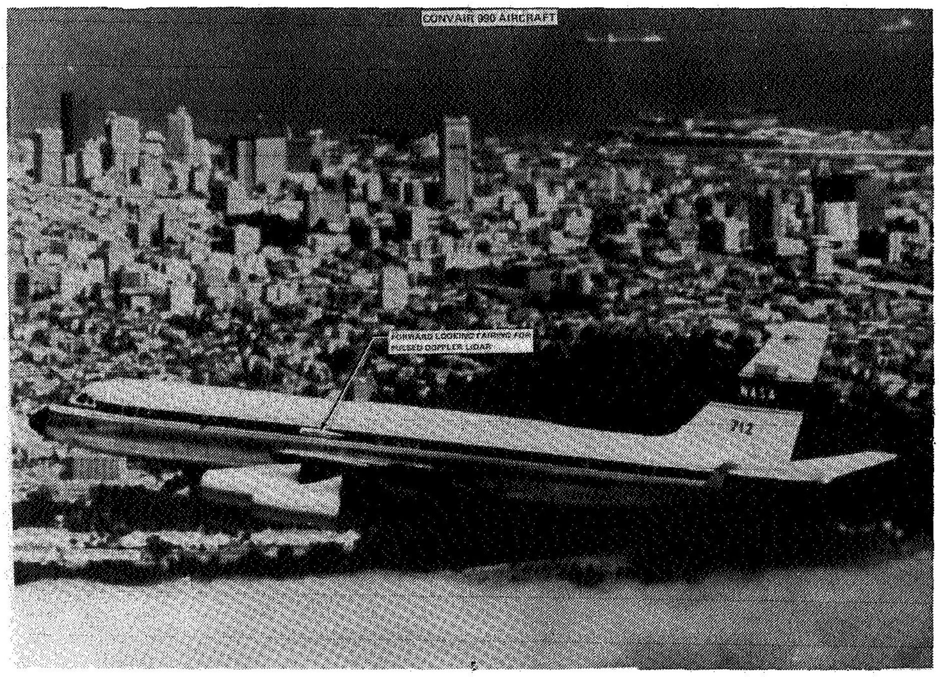


Figure 7.- Convair 990 aircraft used in clear air turbulence flight test.

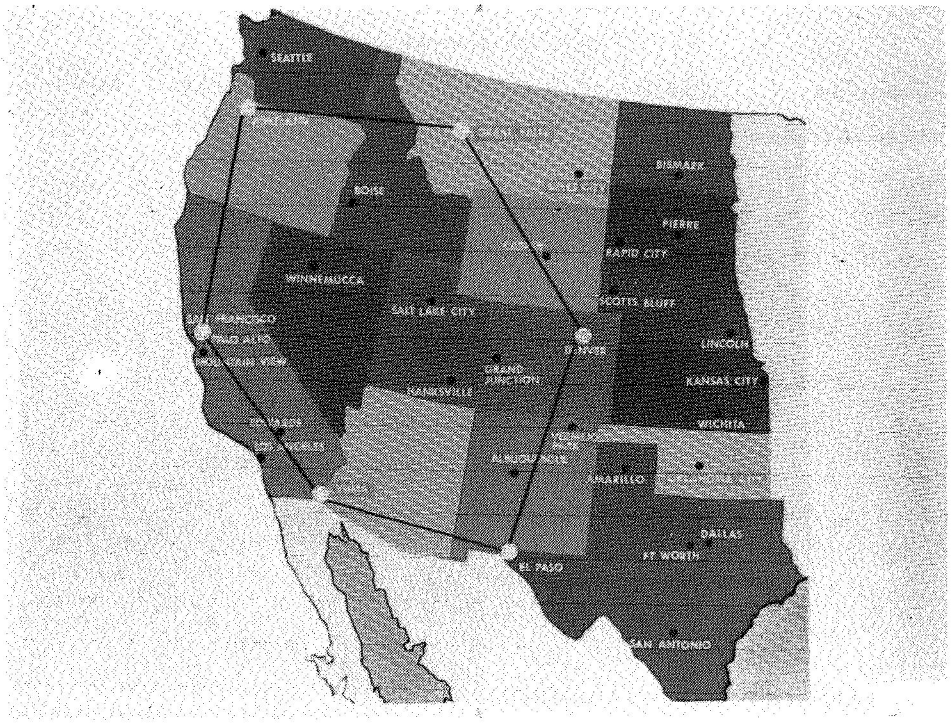


Figure 8.- 1979 CAT flight test region.

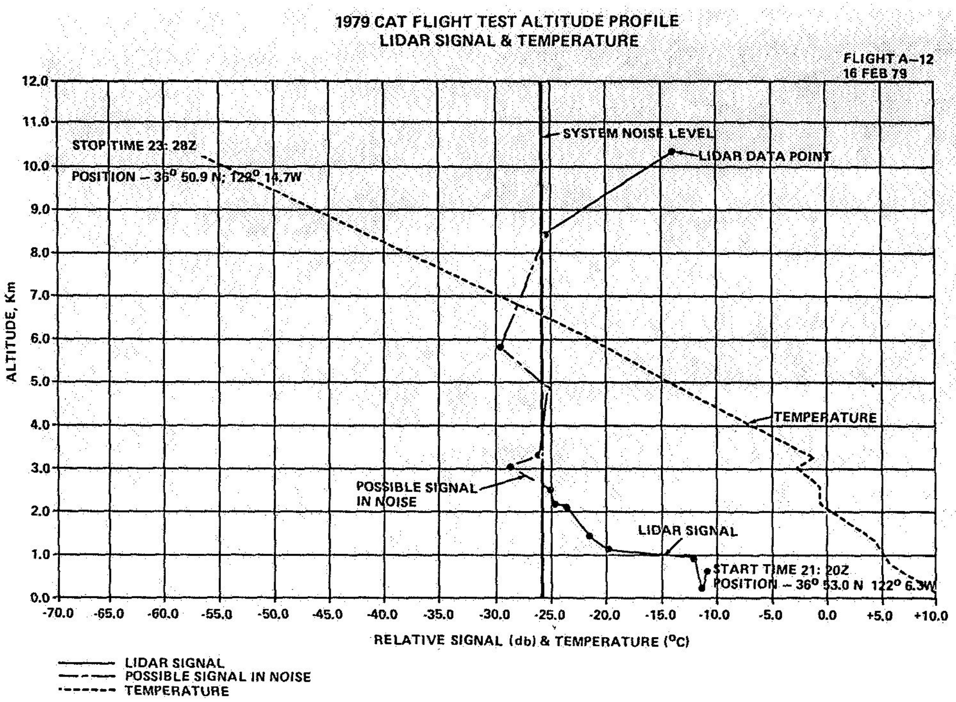


Figure 9.- Lidar signal level variation with altitude.

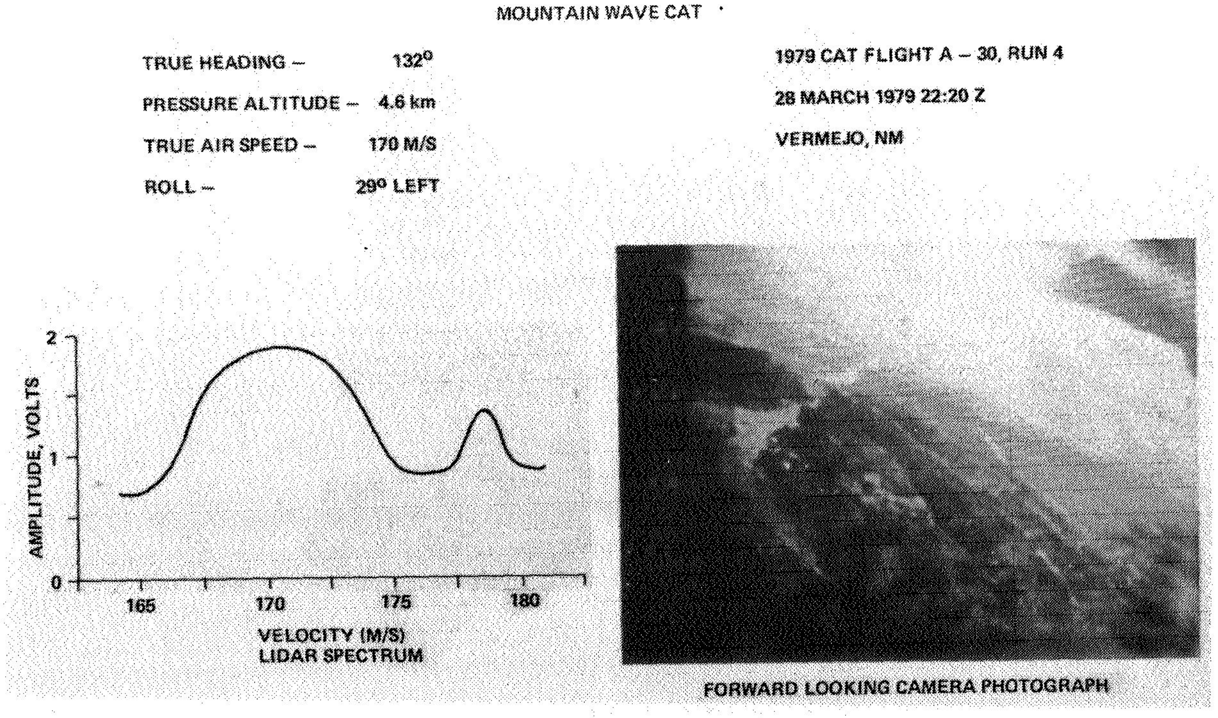
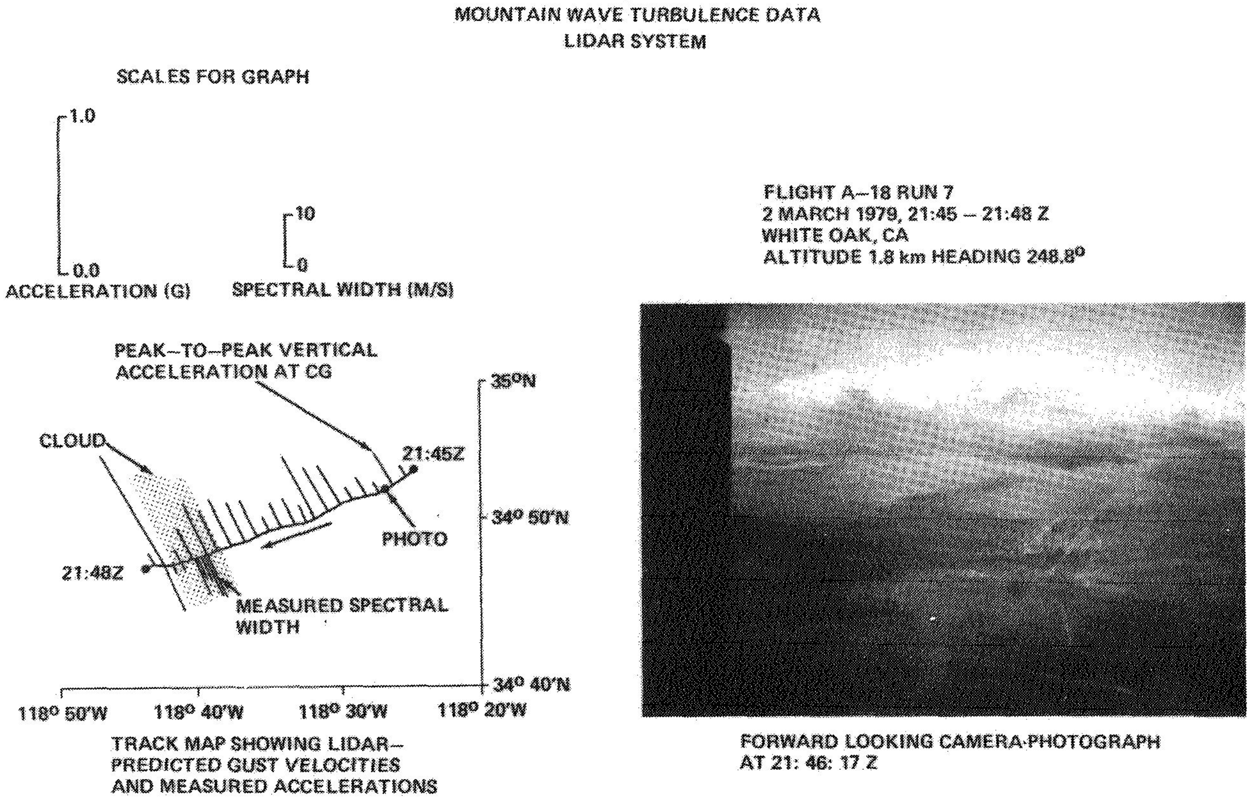


Figure 10.- Pulsed doppler lidar clear air turbulence measurement.



MOUNTAIN WAVE TURBULENCE DATA
LIDAR SYSTEM

FLIGHT A–18 RUN 7
2 MARCH 1979, 21:45 – 21:48 Z
WHITE OAK, CA
ALTITUDE 1.8 km HEADING 248.8°

TRACK MAP SHOWING LIDAR–PREDICTED GUST VELOCITIES AND MEASURED ACCELERATIONS

FORWARD LOOKING CAMERA-PHOTOGRAPH AT 21: 46: 17 Z

Figure 11.- CAT and cloud turbulence encounter (lidar).