THE 1979 CLEAR AIR TURBULENCE FLIGHT TEST PROGRAM

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SUMMARY

A flight test program for Clear Air Turbulence (CAT) detection and measurement was conducted over the western part of the United States during the winter season of 1979 aboard NASA's Galileo II flying laboratory. A carbon dioxide pulsed Doppler lidar and an infrared radiometer were tested for the remote detection and measurement of CAT. Two microwave radiometers were evaluated for their ability to provide encounter warning and altitude avoidance information. A brief description is given of the program, the four flight experiments, and some examples of the data. This test program was a cooperative effort among several U. S. Government agencies, industries, and educational institutions. The Ames Research Center, Dryden Flight Research Center, Jet Propulsion Laboratory, Marshall Space Flight Center, and the Lewis Research Center of the National Aeronautics and Space Administration cooperated in the experiments in this test program.

INTRODUCTION

NASA has sponsored research and development on the Clear Air Turbulence (CAT) problem for many years. Remote detection and measurement of CAT has been one of the objectives of this research. Remote sensors have two useful features in an experiment such as this: (1) the ability to detect atmospheric features associated with CAT prior to actually entering the turbulent region, and (2) mobility, which allows the experimenter to cover large regions of the troposphere in search of CAT. In situ sensors are also useful since they allow direct measurement of the turbulence by aircraft penetration of the CAT region. In combination, these two types of probes yield more than each considered separately: the in situ sensor data is seen in a larger context, and the remote sensor data is rendered more credible by confirmation where data types overlap. The 1979 CAT Flight Test Program, sponsored by NASA's Aviation Operations Safety Technology Program, made extensive use of both sensor types. Flight evaluations were performed on four advanced technology instruments, each one measuring distinct atmospheric parameters that are related to CAT. It involved a search for CAT using detailed meteorological forecasting methods. The four instruments tested were: (1) a pulsed Doppler lidar measuring the

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velocity spectrum of air volumes, (2) an infrared (IR) radiometer monitoring the variability of line-of-sight water vapor content for the forecasting of CAT encounters, (3) a 180.1 GHz microwave radiometer also sensitive to water vapor content changes, and (4) a 55.3 GHz microwave radiometer that measured "altitude temperature profiles" for relating CAT location to inversion layers and tropopause features.

The flight test program conducted during January through March 1979 provided a common test platform for determining the performance of each CAT instrument system in a variety of turbulent and smooth air conditions, at a wide range of flight levels, and a variety of synoptic atmospheric conditions. This was not a "fly-off" test. Rather, each instrument was evaluated with due consideration given to its state of development. For example, this was an initial "concept demonstration" for the microwave radiometers as they had not been previously tested for the CAT objectives. The flight program provided an opportunity for determining the instrument-peculiar performance features. Each sensor is very briefly described and sample data are given.

TEST DESCRIPTION

The "1979 Clear Air Turbulence Flight Test Program" was conducted aboard NASA 712, a Convair 990 aircraft (ref. 1). The CV-990 was selected because of the space requirements for the lidar, and this led to the availability of space for other CAT sensors. This airborne research laboratory was based at Moffett Field, California, for these tests. It is shown in Figure 1 in its configuration with probes, special windows, and fairings for the CAT test. The infrared radiometer probe was near the front of the aircraft in the window just aft of the main entry door. It contained a small gold-coated mirror for intercepting the IR radiation in the forward direction along the flight path. The Pulsed Doppler Lidar required a special fairing containing a reflecting mirror attached to the lidar telescope which directed the infrared laser radiation outside the aircraft through a germanium window that is transparent to the CO_2 laser radiation. The microwave sensors required that aircraft windows be replaced with a material that was transparent to the sensor's radiation.

No modern laboratory can successfully sustain itself without a computer; neither can the CV-990. The Airborne Digital Data Acquisition System, located in the passenger compartment, which is the experiment area, is used for collection and real-time display of standard cockpit and experiment data. This includes information such as position, altitude, true airspeed, wind velocity, surface temperature, and accelerometer outputs. Such a laboratory requires personnel too. About 25 to 30 people were on each flight with 8 to 10 of them required for operating the flying laboratory and the remainder for operating and monitoring the experiments.

There were three investigators with CAT sensors: (1) P. M. Kuhn, whose work was supported by both NOAA and NASA, developed the infrared radiometer. It has received some testing on other NASA aircraft. (2) B. L. Gary from the

Jet Propulsion Laboratory who investigated the use of microwave radiometry applied to the CAT problem, and (3) the team associated with the pulsed Doppler lidar that was developed by the Raytheon Company for the Marshall Space Flight Center. E. A. Weaver managed this effort and also directed the flight test program.

An essential activity for a CAT flight program is the detailed analyses of synoptic weather data for the forecasting of CAT. L. J. Ehernberger from the Dryden Flight Research Center was the meteorological investigator who oversaw this investigation. The U. S. Navy, U. S. Air Force, National Weather Service, and the National Environmental Satellite Service provided the data and synoptic forecast information on a daily basis which was used for locating the potential areas of CAT. In addition, SRI International, Inc., assisted in the meteorological planning and post-flight analyses. The primary meteorological objectives were to sample CAT associated with: (1) mountain waves, (2) jet streams, (3) cirrus clouds, and (4) other pronounced wind shear zones associated with fronts, troughs, and ridges aloft. Figure 2 lists the investigators and the investigative objectives discussed above.

This test was supported by many groups including nine industrial firms, three educational institutions, and four federal government organizations. These are shown in Figure 3. The four federal government groups included the Department of Defense, Department of Commerce, Department of Transportation, and NASA, which had five centers involved (Marshall Space Flight Center, Dryden Flight Research Center, Ames Research Center, Jet Propulsion Laboratory, and Lewis Research Center). These groups worked together for 24 missions flown between January 12, 1979, and March 28, 1979. An additional six missions were flown where the CAT experiments were operated on a "noninterference basis" with nonCAT-oriented experiments, thus providing additional in-flight experience with the CAT sensors for a total of 140 flight hours.

The geographical region where the weather was monitored and studied in detail for mission planning is shown in Figure 4. The search for CAT covered an area bounded on the south by Yuma, Arizona, and El Paso, Texas; Denver, Colorado, on the east; and on the north by Great Falls, Montana, and Portland, Oregon. Flights eventually covered all of this region except for the state of Wyoming.

METEOROLOGICAL SUPPORT

Clear air turbulence is known to be generated by a wide variety of synoptic weather patterns and with diverse combinations of wind shear and static stability. Its natural occurrence can vary from elusive to unexpectedly prolific. As a consequence, it was decided to include meteorological support to: (1) help plan the program sampling objectives in terms of atmospheric structures, (2) improve the selection of flight days and routes, (3) increase continuity between flight experience and post-flight analyses, and (4) evaluate the turbulence encounters with respect to the present CAT forecasting state-of-the-art (ref. 2).

In order to accomplish the test objectives for the instruments carried onboard the CV-990, it was recognized that a number of different atmospheric conditions and turbulence situations would need to be sampled. A comprehensive list of wind shear conditions, temperature gradient profile characteristics, and synoptic patterns significant to the occurrence of CAT or to the direct physical evaluation of each instrument was prepared. This provided the forecaster with a checklist for reviewing the weather conditions each day and identifying the atmospheric regions or locations where the most significant phenomena could be sampled. Program preparation also included technical discussions between the project team and CAT experts from San Jose State University, SRI International, Inc., and the U. S. Air Force Global Weather Center. These discussions were helpful to forecasting CAT regions and to selecting the airplane sampling tracks through these regions.

The project meteorologist began the daily activity by reviewing the standard synoptic and prognostic charts and discussing any specific points of question with the duty forecaster. Selected areas of interest were then examined more closely using rawinsonde data hardcopy and pilot report bulletins available via a COMEDS (Continental U. S. Meteorological Distribution System) terminal. Upper air charts were then plotted and analyzed at selected levels and the rawinsonde data were screened for significant wind shear and temperature gradient structure. Both visual and infrared imagery were also obtained from the laserfax terminal. With these combined resources, potential sampling regions were examined in detail and the project team then selected the mission objectives and flight routing for the day.

Flight results reflected the value of utilizing all available planning tools including the detailed screening of rawinsonde wind shear and temperature gradient profiles. Of sixteen flights routed specifically to sample turbulence, eight encountered significant meteorological variations and amounts of turbulence. On the remaining eight flights, the turbulence encountered was lighter or was due to meteorological conditions which repeated similar patterns sampled on previous missions. The variety of phenomena causing the turbulence encounters included low altitude thermal instability, mechanical ridge line turbulence, mountain wave activity, vertical wind shear (at low, middle, and high altitudes), fronts aloft, and strong thermal advection into a low pressure trough. Jet stream turbulence was encountered over the Pacific Ocean west of the Baja California coast as well as over the continental U. S. In addition, the experiments obtained samples in various ambient scattering conditions associated with marine aerosols, dust, haze, and jet stream cirrus. Only one phenomenon of the initial primary objectives was not sampled - strong localized mountain wave CAT in conjunction with the jet stream at the tropopause. This resulted from an abnormally low frequency of mountain wave conditions during the test period and from emphasis on phenomena at lower altitudes.

The meteorological conditions experienced during the missions confirmed the validity of some of the classical synoptic patterns and criteria for CAT, for example, its association with positive vorticity advection. In addition, the real-time onboard wind and temperature data proved valuable to establish the airplane location relative to wind shear zones and temperature gradients charted in the preflight analyses and to select subsequent tracks and altitudes in the sampling area. Also, the unique combination of experimental instruments demonstrated the added information which may be obtained by use of similar sensors in future flight programs. For example, additional atmospheric structure information can be inferred when data are simultaneously available from radiometers having different wavelengths, lines of sight, and fields of view. Further, the combination of a vertical temperature structure radiometer and a lidar system which could potentially define the vertical wind shear would greatly advance our knowledge of gravity wave activity and CAT by defining local Richardson number and its dynamic variations. Other applications, if such instruments were developed for operational use, could include flight level selection to obtain wind and temperature conditions for optimum performance.

A wide variety of atmospheric conditions were sampled during this CAT flight test program to evaluate the feasibility of the lidar, infrared radiometer, and microwave systems for observing conditions related to CAT. These conditions were acquired by the use of detailed analysis of wind shear and temperature gradients and by the exercise of attentive mission route management as well as with the assistance of the standard meteorological forecast products and pilot reports.

INFRARED RADIOMETER

The infrared radiometer (IR) sensor system has now been tested on 3 NASA aircraft including this CV-990 test (refs. 2, 3). It has an operating spectral range in the water vapor band of 20 to 40 micrometers (ref. 4). It is a passive device similar to Forward Looking Infrared (FLIR) devices, and detects variability of water vapor content integrated along the viewing direction, which is inclined about 11° above the horizon. This variability has been found to be associated with Kelvin-Helmholtz wave action in the atmosphere, which, in the breaking stage, results in shearing and tumbling of air parcels and associated turbulence. However, it is possible to detect developing wave action and the resulting water vapor variability prior to encountering the turbulence. In contrast for nonCAT conditions in clear air, the water vapor content ahead of the aircraft is relatively constant.

The location of the IR radiometer CAT detector onboard the CV-990 is shown in Figure 1. Figure 5 shows a close-up of the 2.5-cm probe tube enclosing a gold, right angle mirror mounted in the left forward passenger window for the experiment. Figure 6 shows the sensor device, the chopper, and the signal processor which were mounted inside the aircraft. The dimensions of the sensor device are approximately 15 cm in diameter and 18 cm in length. The signal processor's size is approximately 10 cm by 15 cm by 8 cm. These three components weigh approximately 5 kg. The specifications for the IR radiometer that was flown on the CV-990 are given in Table 1. The size and weight of the IR radiometer hardware are indicative of the simplicity of its basic operation.

Signals from the atmosphere are received and only the 20 to 40 micrometer signals are fed to the radiometer amplifier. After the signals are amplified they are analyzed in the signal processor which contains the algorithms related to output signal anomaly and CAT threshold alerting. The experimenter had the option of varying the signal processing, including variable threshold levels, during the flight. When the signal activity threshold is exceeded, an alert is displayed on the experimenter's console.

A diagram of the IR radiometer system "scores" from the 1979 CAT Flight Test Program is shown in Figure 7. Ninety-four CAT alerts were given by the system and eighty separate segments of turbulence encounters were documented. Of these, only 4% of the encounters were not preceded by an alert. Out of ninety-four alerts, 18% were "false," i.e., not followed by a turbulence encounter. Other results from the experiment are as follows:

a. The device was found to give satisfactory alerts at all flight levels above 4.4 km altitude (14,500 ft).

b. Turbulence was detected up to sixty km ahead of the aircraft encounter of CAT. (This range can be varied by changing optical filters.)

c. The envelope of maximum alert time varied from one minute at 4.4 km (14,500 ft) to four minutes at 11.3 km (37,000 ft) altitude.

d. The system performs efficiently with less than 8% false alarms in clear air, i.e., when cloud effects are removed from the data. It should be noted however that the sensor was not tested specifically in cloudy conditions and that the total field of view for this IR sensor can pick up false alarms from near nonturbulent clouds such as flights in clear air just above the cloud tops. Additional testing is required to understand the effects of the near cloud conditions on the IR radiometer.

NASA has flown this CAT sensor on other aircraft during the last several years (ref. 3). Analyzing the data from all these tests, CAT alerts from two to nine minutes ahead of an encounter have been recorded at least 80% of the time at altitudes of 5.8 to 12.5 km. Considering these encouraging results, there will be further testing of the IR radiometer on NASA aircraft. The infrared radiometer is already installed on the Kuiper Airborne Observatory (C-141), and there are plans to install it on the CV-990 for use by the flight crews.

TWO MICROWAVE RADIOMETERS

This was the initial "concept feasibility" test for two microwave radiometers developed at the Jet Propulsion Laboratory for other purposes. They were made available for installation on the CV-990 aircraft, but time did not permit their configurations to be optimized for the CAT objectives so they essentially operated as originally developed. A "water vapor radiometer" was operated at a frequency of 180.1 GHz while a "temperature structure radiometer" was operated at a frequency of 55.3 GHz. A brief description of the two radiometers is given below (ref. 5).

The 180.1 GHz "water vapor radiometer" (Figure 8) is shown as it was mounted on the starboard side of the aircraft. The purpose of this was to forecast the occurrence of CAT by monitoring variations of the line-of-sight integrated water vapor content in a manner that is equivalent to that used by the IR radiometer system developed by Dr. Peter Kuhn. This radiometer has the potential advantage of not being influenced by cirrus clouds passing through the line-of-sight (and, hence it should provide fewer "false alarms" than the IR counterpart). Although the expected insensitivity to the confusing influence of cirrus clouds was demonstrated, the 180.1 GHz microwave radiometer failed to provide warnings of CAT encounters. Presumably, this can be explained by the 180.1 GHz radiometer's several fold inferiority in sensitivity to changes in water vapor when compared to the counterpart IR sensor, although a less than optimum viewing geometry (side looking) was employed by the microwave radiometer. The 180.1 GHz radiometer evaluation was done with existing hardware at very low cost and no attempt was made to optimize its configuration for CAT objectives (i.e., employing narrow beam, directing the beam to a forward azimuth, recording the data at greater than 1 Hz rate). Dramatic improvements in 180.1 GHz radiometer technology are being made, and eventually it will be possible to conduct a more meaningful evaluation of this technology for a CAT detection system.

The 55.3 GHz "temperature structure radiometer" was mounted on the port side of the aircraft looking through a high-density polyethylene window as shown in Figure 9. The purpose of the 55.3 GHz temperature structure radiometer (TSR) was to study the altitude association between CAT and unusual structures of the altitude temperature profile. The TSR measured the natural occurring thermal emission of oxygen molecules at a selection of elevation angles above and below the horizon. The raw data, consisting of sky brightness temperature versus elevation angle, was converted in real-time by a desktop calculator to something approximately equivalent to air temperature versus altitude. Altitude Temperature Profiles (ATP) were obtained every seventeen seconds. The ATP plots were subjected to a search for two types of features: (1) a sharp inflection marking the tropopause, and (2) inversion layers defined as a layer within which air temperature increases with altitude (instead of decreasing at the typical rate of -7°K/km). CAT has often been found at the tropopause and within inversion layers. The intended use of this ATP information on commercial air carriers would be to provide altitude guidance away from those altitudes that have the greatest capability for generating CAT (the inversion layers and the tropopause). Another possible use for the ATP is to combine information of the inversion layer's thickness and lapse rate in a way that may forecast, in some statistically acceptable way, the maximum level of turbulence that can be expected from the inversion layers.

The theoretical basis for associating CAT generation with inversion layers is presented in reference 6. It also presents TSR data supporting the hypothesized association of CAT with inversion layers. In Figure 10, a representative set of the data is presented. These are plots of air temperature versus altitude. The altitude coverage is from about one kilometer above flight level to one kilometer below flight level. The temperature values are differences from the static air temperature (SATM). The upper left panel is typical of the most often encountered ATP with the observed air temperature "0" decreasing uniformly from about 0.6 km below the aircraft level to 0.9 km above it. The outside air temperature is 225.4°K. The sloping pattern of colons is where the "0s" would be found for flight within a "dry adiabatic" atmosphere. It is nearly impossible to abruptly generate strong turbulence in the "dry adiabatic" condition. For flight within an isothermal atmosphere the "Os" would overlay the vertical pattern of dots. The panel on the upper right shows a shallow inversion layer above the aircraft altitude. The lower left panel corresponds to flight within an inversion layer. It is the same inversion layer as shown in the upper right panel, but it is taken 15 minutes later. The base and top altitudes for this inversion layer are -0.1 km and ±0.25 km (-300 ft to ±800 ft). The lapse rate within the inversion layer is approximately +4°K/km. The lower right panel corresponds to flight at the tropopause. These are the first "altitude temperature profile" plots that have ever been produced using an airborne remote sensor to the authors' knowledge. The question of whether ATP generation can be done by an airborne sensor has been answered. The next question, more directly related to CAT, is whether ATP information can be useful in avoiding CAT. If CAT is really found more within inversion layers and near the tropopause, then altitude temperature profile information of the type illustrated in these panels could be useful in selecting "smooth" flight levels.

An improved TSR sensor is under construction and intended for installation on the NASA C-141 aircraft, the Kuiper Airborne Observatory. This sensor should provide a five-fold improvement in sensitivity for the measurement of air temperature. A potential several hundred hours of flight evaluation will be available during the next few years. Meaningful statistical analyses on the usefulness of a TSR type sensor for the forecasting of CAT severity and altitude avoidance should then be possible.

PULSED DOPPLER LIDAR

The pulsed Doppler lidar that was tested in this program underwent initial feasibility flight tests in 1972 and 1973. After extensive ground-based testing and modification, ground-based measurements were made of low altitude wind shears after which the lidar was reconfigured to the aircraft mode for the 1979 test (ref. 7). This is the only airborne pulsed Doppler lidar in existence. The lidar is shown in Figure 11 mounted aboard the aircraft about mid-cabin at the emergency door. The transmitter, shown in this figure, includes the master oscillator, the local oscillator, the laser amplifier, the modulator, the optical interferometer, and the telescope. Not shown, but essential to the lidar, are signal processing elements which include a minicomputer used for recording the signal and providing real-time analyses and the display of essential performance information. The range capability of the pulsed Doppler lidar is determined by the lidar's output power and the features of the atmosphere. The signal processing system has a maximum capability of 30 km in range. A signal from 20 km ahead of the aircraft is the most distant signal ever received for this lidar. The per pulse energy level is about 12 to 15 millijoules. Typical ranges are from 3 to 15 km. The atmospheric factors that have the greatest effect on the signal received are: (1) the size and number of aerosols, which provide the backscattered signal, (2) the water vapor, and (3) CO_2 content which contributes significantly to the atmospheric absorption of the CO_2 laser radiation at 10.6 micrometers.

The aerosol tracers essential for received signals were at such a low density that often signals were only received from special conditions such as a dust, cumulus, or cirrus cloud. An example of mountain wave CAT, also illustrating low aerosol density limitation, is given in Figure 12, which shows a cumulus cloud that seeds the atmosphere for the lidar. This is a cloud that cannot be seen on the aircraft's weather radar. Plotted on the geographic coordinates as a heavy black line on the left side of the figure is the flight track made on March 2, 1979, starting at 21:45 Z hours. The aircraft was at flight level 060 (1829 m (6000 ft) MSL.) on the lee side of the Techapi Mountains southeast of White Oak near Edwards Air Force Base, California. Above the flight track are plotted lines indicating the magnitude of the peak-to-peak vertical acceleration from each 5 second time period as recorded near the center of gravity of the aircraft. Using the scale shown above the plot, the length of these lines shows that the aircraft is in turbulence much of this run and especially before the cloud encounter. The lidar obtained data from the cumulus cloud and just after the cloud which is shown as the shaded area along and near the end of the flight track. This cloud is also shown in the photograph at the right. The lidar data is given below the flight track in the shaded area of the plot, representing the cloud location, and for a point just outside the cloud. It "saw" through the cloud to the west data point. The line length is the measured spectral width. This is directly proportional to the gust velocity and has been defined as the predicted gust velocity of the CAT. (There would be almost no spectral width if there were no turbulence.) The lidar data were first recorded about 60 seconds ahead of the turbulence encounter, and shown here is a predicted gust velocity of nearly 10 m/s in two locations. This is indicative of turbulence at the upper end of the moderate turbulence spectrum which is about 10.5 m/s. The scalar value for the measured spectral width is given above the plotted data. There is excellent correlation between the lidar data and the accelerometer data which shows about 0.4 g vertical acceleration in the cloud. The data comparison outside the cloud shows only about a 50% level of predicted CAT versus the actual. The only explanation, so far, for this is again the lack of aerosols outside the cloud. With the lidar's special displays a turbulence patch can be nearly tracked to the point of the aircraft encounter with it. Since the aircraft is already encountering moderate turbulence a precise encounter onset for the lidar measured turbulence cannot be defined in this data set. The picture on the right of this chart is a view of the atmosphere along the flight path ahead of the aircraft. For each CAT case there are pictures taken at the rate of one frame per second to identify these conditions for each set of data. This particular photograph was taken at 21:46:17 Z hours with the aircraft heading at 248.8^{o} and the cloud encountered is the one in the upper part of it. Similar CAT detection sequences were experienced in cirrus clouds, haze, and in other mountain waves.

The aerosol density was low throughout the entire flight test period of 11 weeks. There were aerosol measuring experiments aboard this aircraft during these flights and some of these data are of poor quality; however, the number of large aerosols, those above one micrometer diameter, appeared to be much lower than expected. For the winter of 1979, it appears that the aerosol concentration may have been at least two orders of magnitude lower than the nominal values (ref. 8) used in the pulsed Doppler lidar design. Before definite conclusions and recommendations can be given about the potential capability of the pulsed

Doppler lidar, a better understanding of the variability of the atmospheric aerosol size distribution and density as it relates to CO_2 laser radiation is required. Only when this information is known can realistic projections be made about the future applications of this technology including a prototype system design specification. A small program called the Beta Experiment will attempt to address this problem starting in 1981. Meanwhile, the pulsed Doppler lidar is being modified to measure the wind velocity in the nonprecipitous regions of thunderstorms. This work is part of the NASA's Severe Storms and Local Weather Research and Technology Program. These initial tests are currently planned for the summer of 1981 and should add to the knowledge of the technology and enable better projections to be made concerning its future use. At this time, there are no plans to further test the lidar for detecting and measuring high altitude CAT.

CONCLUDING REMARKS

The results from the test of the IR radiometer are very encouraging. It gave CAT alerts at all flight levels although it appears to give better warning information at altitudes above 4 km. Because of its small size and weight, it is the sensor that shows strong potential for operational development and possible application to the commercial aircraft fleet. Further study is underway wherein NASA pilots will evaluate the system during the 1980-81 "CAT Season" in regular flight operations of the C-141 and CV-990 flying laboratories based at the NASA's Ames Research Center. In addition, United Airlines and the Colorado Air National Guard are considering independent evaluations of this type of CAT sensor.

The microwave temperature structure radiometer (55.3 GHz) was successful in historically providing the first "altitude temperature profiles" using an airborne sensor. The altitude temperature profile data now in hand show that on some occasions CAT is strikingly well-correlated with inversion layer altitudes whereas on other occasions CAT is encountered in the absence of near inversion layers. More flight hours of data are needed to provide estimates of the fraction of the time useful avoidance guidance can be generated from altitude temperature profile information. It is planned to further test this radiometer in a "CAT" configuration aboard NASA's C-141 aircraft.

The 180.1 GHz water vapor radiometer is apparently not sensitive enough to measure the small variations of water vapor content from which the IR CAT detector generates its warnings. Much better 180.1 GHz radiometers tailored to the CAT observing requirements could be built with present microwave technology, and would merit consideration for development in the near future.

The pulsed Doppler lidar appears to be a useful sensor for meteorological research in its present configuration which is based on 1970 technology. However, as an operational CAT sensor it is large and complex. The primary question concerns the aerosol density in the atmosphere and the backscatter coefficient or signal return from the aerosols at the CO_2 laser frequencies. In its role as a research tool, it is planned to collect velocity data on the winds in the nonprecipitous regions of thunderstorms in the summer of 1981.

The success in finding CAT during this 1979 season when the conditions for it were somewhat unfavorable is a credit to the detailed meteorological analyses and forecasting efforts used for this test, and to the routing flexibility exercised by the CV-990 flight crew. In the viewpoint of the authors, the most significant accomplishment has been to indicate the advantages of synergistic combinations of onboard remote sensors for observing the local dynamic atmospheric structure associated with gravity waves and CAT.

ACKNOWLEDGEMENTS

The authors wish to thank the more than 150 people who had a part in this test program. Especially noted are the efforts of the Raytheon Company and M&S Computing Company whose untiring efforts made the testing of the lidar a reality. The meteorological team consisting of NASA, Navy, Air Force, and NOAA personnel enabled early and exacting mission planning so essential for a successful rate of encountering CAT. The CV-990 aircraft personnel and specifically George Alger, the Mission Manager, and those associated with preparing and operating each flight, provided outstanding support to the program. The teamwork necessary for a test program of this size was outstanding and a credit to all who supported the mission. Finally, special appreciation is hereby expressed for the many years of financial and personal support provided by NASA/OAST's Aviation Safety Technology Branch.

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TABLE 1 - INFRARED RADIOMETER PERFORMANCE AND OPTICAL DATA

PERFORMANCE DATA

OPERATING SPECTRAL RANGE	20 μ m TO 40 μ m
CAVITY REFERENCE TEMPERATURE	– 20 C
OUTPUT VOLTAGE	+ 10 VDC TO – 10 VDC
A TO D CONVERSION	12 BIT (5mv/bit)
NOISE EQUIVALENT POWER	2.5 X 10^{-8} watts
RESPONSE TIME (TIME CONSTANT)	50 Hz

OPTICAL DATA

DETECTOR TYPE	1 mm X 1 mm LITHIUM TANTALATE CHIP
OPTICAL FILTER	INTERFERENCE BAND PASS (20 TO 40 μ m)

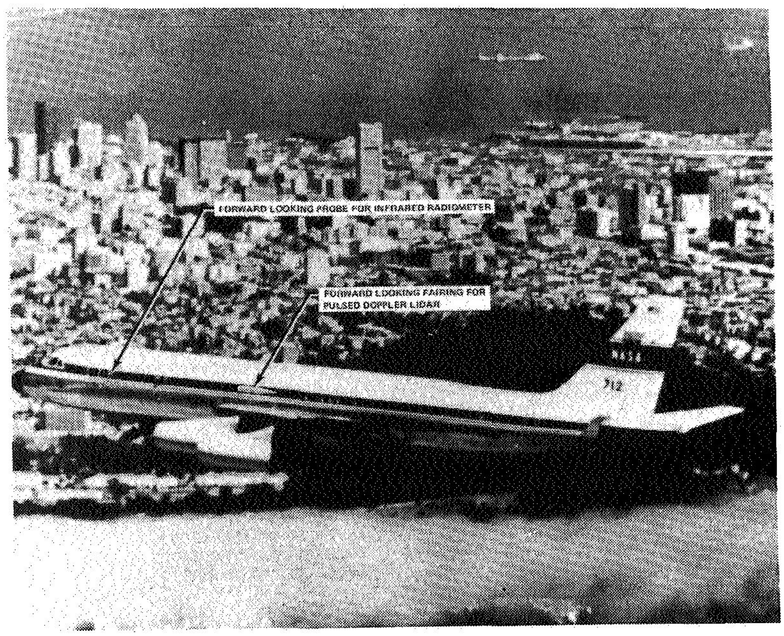

Figure 1.- Convair 990 aircraft.

1979 CLEAR AIR TURBULENCE (CAT) FLIGHT TEST
TEST OBJECTIVES

OBJECTIVE:

- EVALUATE 4 SENSORS FOR THE DETECTION AND MEASUREMENT OF CAT AND METEOROLOGICAL TARGETS OF OPPORTUNITY.
    - CAT FORECASTING TECHNIQUES
    - INFRARED RADIOMETER – 20 – 40 MICROMETERS
    - MICROWAVE RADIOMETERS – 180.1 GHZ
    - MICROWAVE RADIOMETERS – 55.3 GHZ
    - DOPPLER LIDAR – 10.6 MICROMETERS

TYPES OF CAT:

- MOUNTAIN WAVE
- JET STREAM
- CAT IN CIRRUS CLOUDS
- CAT IN FRONTAL WIND SHEARS, TROUGHS, RIDGES

Figure 2.- Test objectives.

1979 CAT FLIGHT TEST

NATIONAL AERONAUTICS & SPACE ADMINISTRATION

NASA HEADQUARTERS
AMES RESEARCH CENTER
DRYDEN FLIGHT RESEARCH CENTER
JET PROPULSION LABORATORY
LEWIS RESEARCH CENTER
MARSHALL SPACE FLIGHT CENTER

DEPARTMENT OF TRANSPORTATION

FAA – AIR TRAFFIC & AIRWAY FACILITIES
TRANSPORTATION SYSTEMS CENTER

INDUSTRY

BARNES ENGINEERING COMPANY
COMPUTER SCIENCES CORPORATION
EXOTIC MATERIALS
INFORMATICS PMI
M & S COMPUTING, INC.
NORTHROP SERVICES
RAYTHEON COMPANY
SRI INTERNATIONAL, INC.
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DEPARTMENT OF COMMERCE

NATIONAL OCEANIC & ATMOSPHERIC ADMINISTRATION

ENVIRONMENTAL RESEARCH LABS
NATIONAL WEATHER SERVICE
NATIONAL ENVIRONMENTAL SATELLITE SERVICE

DEPARTMENT OF DEFENSE

U. S. AIR FORCE

AIR WEATHER SERVICE
EDWARDS FLIGHT TEST CENTER
GLOBAL WEATHER CENTER

U. S. NAVY

MONTEREY – FLEET NUMERICAL WEATHER CENTER
MOFFET FIELD – NAVAL WEATHER DETACHMENT

EDUCATION

ALABAMA A&M UNIVERSITY
UNIVERSITY OF COLORADO
UNIVERSITY OF OREGON

Figure 3.- Groups participating in 1979 CAT flight test.

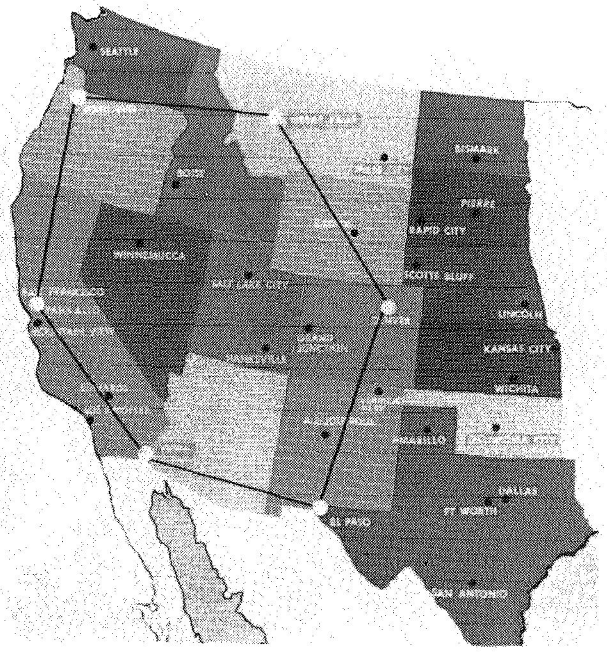

Figure 4.- 1979 flight test region.

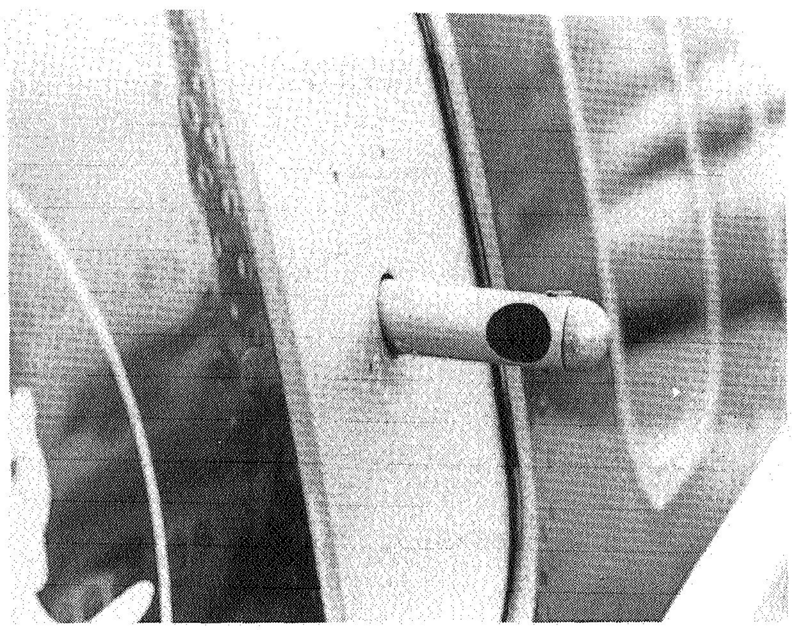

Figure 5.- Infrared radiometer forward looking probe with gold-coated mirror.

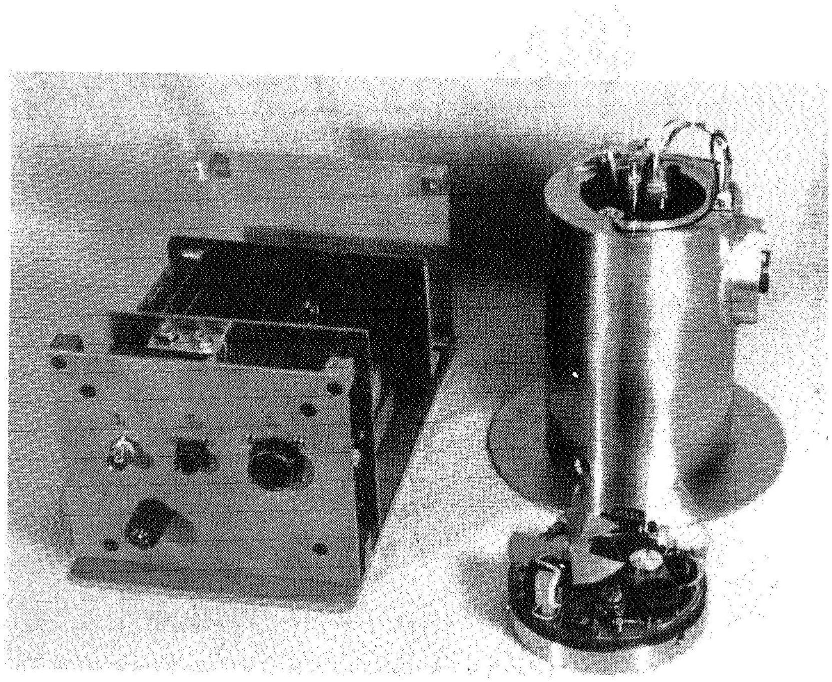

Figure 6.- Infrared radiometer sensor and chopper.

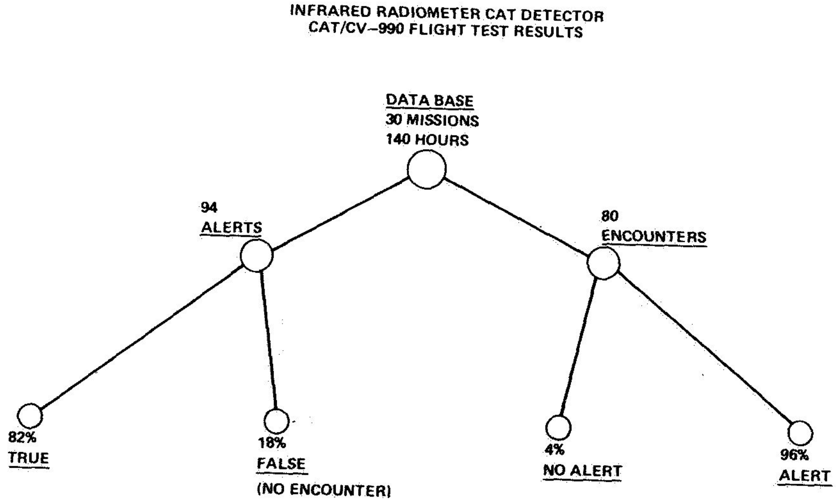

Figure 7.- Infrared radiometer flight test results on CAT data (CV-990).

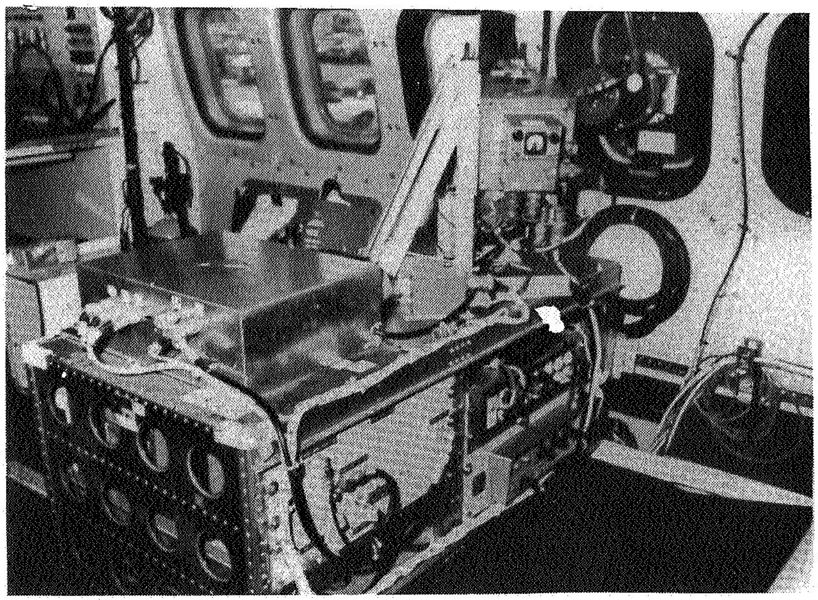

Figure 8.- Microwave radiometer in the water vapor band.

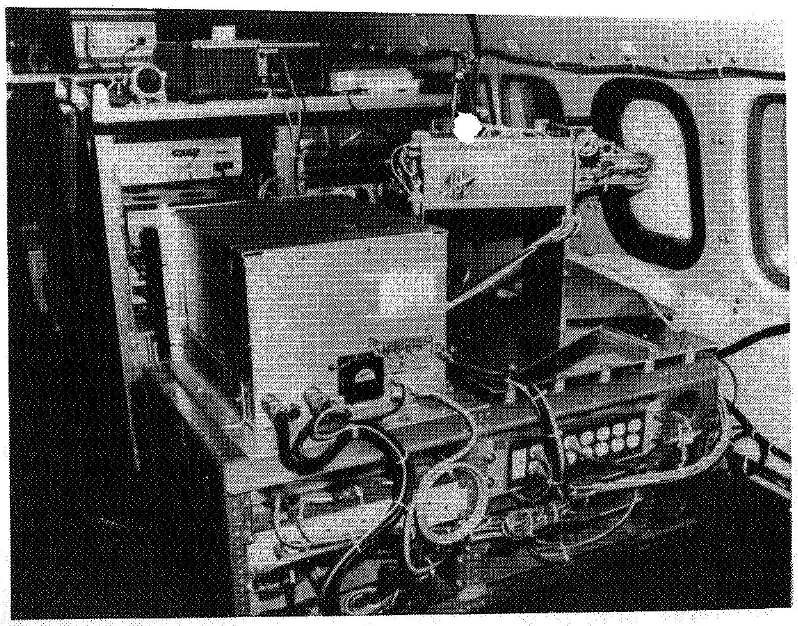

Figure 9.- Microwave radiometer in the oxygen band.

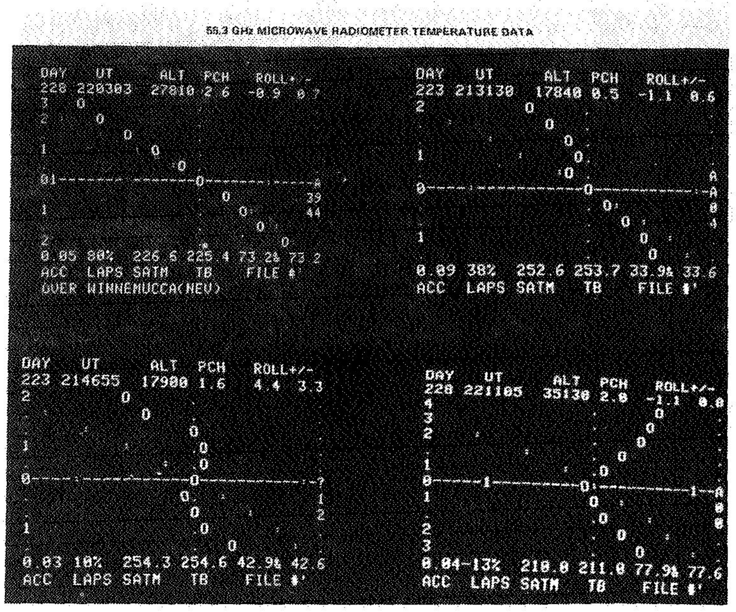

Figure 10.- Altitude temperature profiles generated from 55.3 GHz microwave radiometer data.

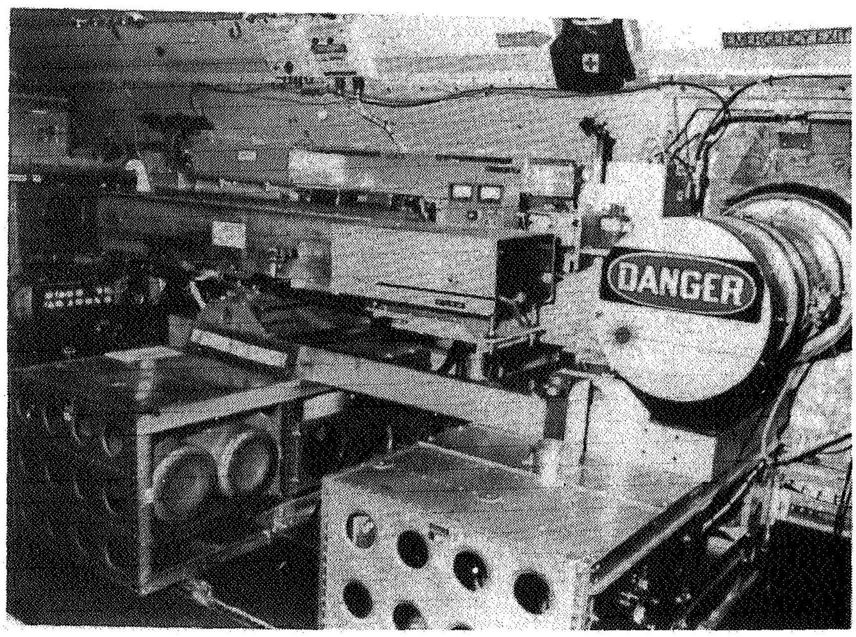

Figure 11.- Pulsed Doppler lidar using a CO_2 laser.

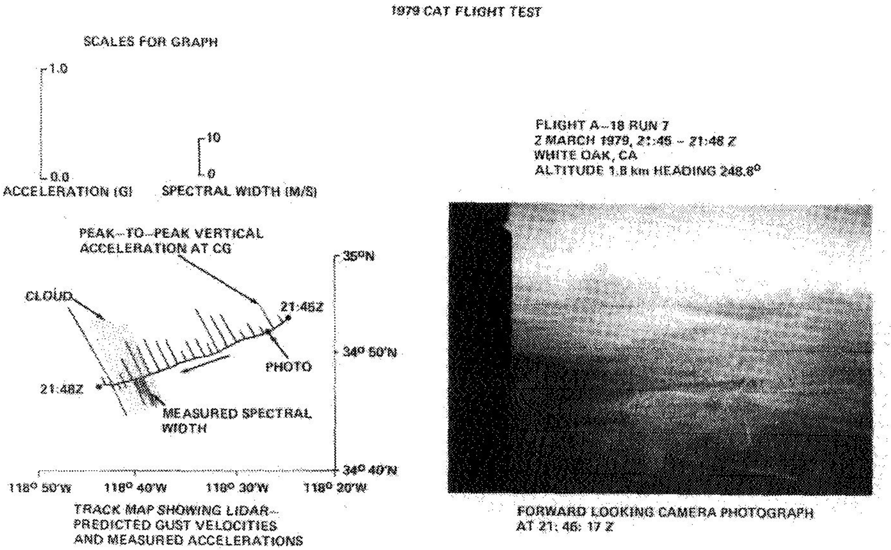

Figure 12.- CAT and cloud turbulence encounter (lidar).