FLIGHT TESTS OF A CLEAR-AIR TURBULENCE ALERTING SYSTEM

Richard L. Kurkowski
Ames Research Center

Peter M. Kuhn
Raven Systems and Research, Inc.

Lois P. Stearns
NOAA-Environmental Research Laboratories

SUMMARY

Clear-air turbulence (CAT) ahead of an aircraft can be detected in real-time by an infrared (IR) radiometer. The alert time and reliability depend on the band-pass of the IR filter used and on the altitude of the aircraft. Results of flight tests, in a joint NASA/NOAA program, indicate that a band-pass of 20 to 40 µm appears optimal for alerting the aircraft crew to CAT at times before encounter of 2 to 9 min. Alert time increases with altitude, as the atmospheric absorption determining the horizontal weighting is reduced.

INTRODUCTION

Turbulence is the largest single cause of weather-related air carrier accidents in the United States. From 1962 to 1974, turbulence was either a cause of or a contributing factor in 189 of 450 weather-related cases (ref. 1). Of the 189 cases of turbulence, 68 are classified as due to clear-air turbulence (CAT). In one case in April, 1978, 11 persons were injured in a CAT encounter over Orlando, Florida.

CAT, a problem for all aircraft, cannot be seen because it usually has no cloud signature such as that evident in thunderstorm-related turbulence. CAT may develop in a standing wave caused by air moving over mountainous terrain, and is frequently associated with shear-induced Kelvin-Helmholtz (KH) atmospheric waves occurring in a statically stable atmosphere (refs. 2-4). Under certain atmospheric conditions, the character of these waves can become visible (see fig. 1). Arguments suggest that atmospheric regions characterized by internal fronts and a sloping tropopause are favored regions for KH instability and CAT formation.

Although some progress has been made in forecasting CAT, an on-board warning device is needed. Several investigators have proposed and some have flight tested on-board forward-looking CAT sensing infrared (IR) radiometers operating in the CO_2 band of the spectrum (refs. 5-8). However, these devices have been unsatisfactory because of the large number of false alarms. Presumably, this is due to the homogeneous mixture of CO_2 in the atmosphere. Some researchers suggested that CAT might be identified by the water-vapor anomalies. It is well-known that KH waves "roll up" atmospheric layers in which they form and that vertical gradients of water vapor in some regions can be as much as 20 times greater than their initial undisturbed values. A CAT sensing radiometer detecting signals in the water-vapor bands — 6.3 μm and 19.0-37.0 μm — was proposed and preliminary tests of such a radiometer system were conducted on a noninterference basis on the NASA C-141A Kuiper Airborne Observatory (fig. 2) at tropopause levels. A sketch of the aircraft flying in a CAT wave condition is shown in figure 3. Water vapor tends to concentrate in the "breaking waves" and the radiometer detects changes or gradients in water-vapor content as shown by the sample trace. This detection leads the actual encounter as shown by the accelerometer trace.

Results of these initial tests (ref. 9) to detect CAT at an altitude of 13.5 km above sea level indicated that of 51 cases, 80% were CAT alerts followed by CAT encounters, 12% were CAT alerts not followed by CAT encounters, and 8% were CAT encounters not preceded by an IR signal anomaly or CAT alert.

Based on the experience with the device used in the C-141A, a new radiometer was developed (ref. 10) specifically for use in a dedicated joint NASA/NOAA program on CAT detection research using a Learjet aircraft and, subsequently, in the NASA CV-990/CAT experiment program (ref. 11). The overall objectives of the program were to (1) study the most probable mechanisms that allow the passive detection of CAT in the water-vapor IR bands; (2) test all types of jet-level turbulence above and below the tropopause, but generally above the 500-mbar level; and (3) define a simple and reliable IR radiometer system that will alert air crews to CAT encounters 2 to 6 min before the event and one that could be built at a modest cost and that would require little maintenance.

The purpose of this paper is to present the methods and results of the on-board IR CAT detector flight-test program. The various test hardware, aircraft, and aircraft installations are described and the experimental methods are given. This is followed by the results of the flight tests for each of the test-bed aircraft: C-141A, Learjet, and CV-990.

SYMBOLS AND ABBREVIATIONS

A_o	effective detector area, cm^2
B	Planck blackbody radiance, $W/cm^2/sr$
D*	sensor detectivity, cm/Hz/W
Δf	chopping frequency, Hz
G	radiometer gain, dimensionless

g	acceleration of gravity, cm/sec^2
k	radiometer system coefficient, $W/cm^2/sr/V_o$
N	radiance, $W/cm^2/sr$
NEN	noise equivalent radiance, $W/cm^2/sr$
NEP	noise equivalent power, W
N_R	radiometer reference cavity radiance, $W/cm^2/sr$
S	slant path distance, cm
T	temperature, K
U	horizontal velocity, cm/sec
V_E	radiometer offset, V
V_o	radiometer output, V
Z	vertical distance, cm
α	radiometer half-angle aperture, deg
ν	wave number, cm^{-1}
ϕ	filter function, dimensionless
ω	solid angle, sr
Θ	potential temperature, K

DESCRIPTION OF TEST EQUIPMENT

CAT Detector Sensor System

The radiance arriving at the CAT detector comes from two sources: (1) emission from the water vapor in the radiometer field of view; and (2) background emission from clouds, the air-surface interface, or hydrometers. Inhomogeneities in the water vapor crossing the radiometer cone-of-acceptance produce anomalies in the detector response and strong signal gradients which are readily detected as a sharply varying output signal. The radiance observed by the radiometer is represented by

$$N = -\int_{\nu} \int_{S} B(\nu,T)\phi(\nu) \frac{\partial\tau(H_2O)}{\partial s} \, ds \, d\nu + \int_{\nu} B(\nu,T_o)\phi(\nu)\tau_o(H_2O)d\nu \qquad (1)$$

Equation (1) is a representation of the radiative transfer equation. The output voltage of the CAT radiometer may be expressed as

$$V_o = \left(\frac{N - N_R}{k} \mp V_E\right)\left(\frac{1}{G}\right) \tag{2}$$

The design of the radiometer for the Learjet included a double-filter wheel arrangement. The University of Oregon/NOAA-designed filter wheel enabled the experimenters to study the ranging characteristics of several band-passes in the water-vapor spectrum. This modification, employing reststrahlen techniques, permits selection of narrower band-passes within the 20 and 40 μm (500 cm^{-1} to 250 cm^{-1}) spectral band. Such band-passes at, for example, 250 to 325 cm^{-1}, 325 to 400 cm^{-1}, and 400 to 500 cm^{-1}, were examined for CAT alert ranging. The prototype CAT radiometer flown in the Learjet experiments is shown in figure 4.

The radiometer has a noise equivalent radiance of 5×10^{-7} $W/cm^2/sr$ employing a blackened chopper blade as a reference and sync generator derived from a noise equivalent power of 0.12×10^{-9} W. Noise equivalent radiance (NEN) and noise equivalent power (NEP) are defined as follows:

$$NEN = \frac{NEP}{A_o \omega \phi} \tag{3}$$

where

$$NEP = \frac{1}{D^*} \sqrt{A_o \Delta f} \quad , \qquad \omega = (0.01245\ \alpha)^2 \tag{4}$$

The detector and blade were not temperature-controlled and "floated" at inside nose cone temperature. This posed no problems in flight to altitudes of 13 km (43,000 ft).

Learjet

Dedicated flight tests were conducted in 1978 using a NASA Learjet model 23 (see fig. 5). The CAT sensor was mounted in the aircraft nose beneath a special shroud (fig. 6). The radiometer was directed upward at a fixed elevation angle of from 7.5° to 15.0°. The experiment instrumentation in the Learjet cabin included a Litton model 51 inertial navigation system (INS), a computer, a data acquisition system, a vertical axis accelerometer, and a side-looking infrared true-air-temperature radiometer.

The on-board data acquisition system for the Learjet was built around the D.E.C. (Digital Equipment Corporation) LSI-II. This is a 16-bit microcomputer with 32 K words of memory. Additional memory was available on a triple floppy disk used for system, program, and data storage. The principal input-output device was a T.I. 745 terminal. A digital magnetic tape recorder was also included in the system. A basic software package was written in Fortran IV to sample the internal clock and eight channels of analog data. The accelerometer data were sampled several hundred times each second; at the end of these 1-sec intervals, maximum peak-to-peak deviations were calculated and recorded on disk or tape (or both) together with the CAT radiometer output voltage, altitude, pitch, roll, and time. The time, accelerometer peak-to-peak deviations, and radiometer output data were printed each 10 sec on the 745 terminal. The system of software included CAT forecast algorithms for real-time use of data flights as well as INS position and wind data. Several CAT forecast algorithms were programmed and examined for on-board CAT alert. These included: (1) a second-difference alert algorithm, (2) an arc-length alert algorithm, and (3) a standard-deviation alert algorithm.

Convair 990 and C-141A

Additional data were taken in the first quarter of 1979 on the Convair 990 Galileo II (fig. 7) during the NASA clear air turbulence missions (ref. 11). Concurrently with those missions and subsequent to them, data were also obtained during routine C-141A Kuiper Airborne Observatory missions.

The infrared radiometer sensor system flown on the CV-990 and on the C-141A had the characteristics shown in table 1. As stated previously, the operating spectral range is in the water-vapor band, that is, 20 to 40 μm. It is a passive device similar to forward-looking infrared (FLIR) sensors.

The location of the IR radiometer CAT detector sensor on-board the CV-990 is shown in figure 8. Figure 9 shows a close-up of the probe tube enclosing a gold-plated right-angle mirror, as mounted in the left-forward passenger window for the experiment. The elevation angle of the radiometer was kept constant at 10°. A similar installation was mounted in the sidewall of the C-141A above the main landing gear. Figure 10 shows the sensor device and chopper system, which are mounted inside the aircraft. The sensor device is about 15 cm in diameter and 18 cm in length. A diagram of the system is shown in figure 11. The radiometer sensor signals that pass through the optics section are fed to the radiometer amplifier. The signals 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.

All CV-990 accelerometer data were recorded at 50 Hz, and radiometer sampling data were recorded at 10 Hz. The C-141A data were logged at varying frequencies.

EXPERIMENTAL METHOD

CAT Alert

A CAT alert may be defined as a warning that CAT is ahead of the aircraft along its projected flight path. False alarms from the IR detector system may be caused by several factors. They may occur because of aircraft motion within the turbulence, by the aircraft being in a roll or turn, and by cirrus clouds or contrails. They may also be caused by electromagnetic interference (EMI) disturbing the radiometer signal and, finally, by a water-vapor disturbance that is not associated with turbulence. False alarms caused by the aircraft in turbulence, in a turn, or EMI were eliminated from the statistical analyses since these could be suppressed in a system for commercial aircraft.

Turbulence Encounter

An encounter is a function of the acceleration imposed on the aircraft by CAT and the time separation between CAT areas. Factors such as the size and speed of the aircraft change the way the aircraft reacts to turbulence. The accelerometer mounting location also affects the recorded peak-to-peak values of the turbulence. Turbulence is measured in g's (gravity values over the normal 1 g). The accelerometer numerical value was derived by taking the maximum g value of each of the 50 tape samples less the minimum value during each second. The net difference was called the "peak-to-peak" accelerometer value. For example, the accelerometer on the C-141A was mounted on the floor of the jet a little to starboard of center. Normal vibration of the aircraft does not exceed 0.02 g's. Originally, an arbitrary 0.1 g was used to define turbulence, but in checking alarms for a possible cause, it was discovered that many alerts were forecasting 0.07, 0.08, and 0.09 g's of CAT with the same vigor as a 0.2 g encounter. It was therefore decided that 0.05 g's would be defined as an encounter on the C-141A aircraft. Since encounters on this aircraft were fairly isolated, only encounters that were separated by 3 or more minutes were considered. (For a commercial version of this instrument, the experimenters believe 30 to 40 sec should be used as the minimum time interval between encounter alerts.)

The accelerometer was mounted on the floor of the Learjet near the center of gravity. The Learjet flies at greater speeds and is a lighter wing-loading aircraft than the C-141A. Consequently, it may react more strongly to a CAT encounter. The value of 0.15 g was assigned as the magnitude of an encounter for this aircraft. Various time interval criteria between CAT encounters were used.

The CV-990 accelerometer was mounted on the floor of the aircraft near the center of gravity. The value of 0.10 g peak-to-peak was assigned as the magnitude for an encounter for the CV-990. A minimum of 30 sec was used to separate encounters or false alarms, if they occurred.

Alert Algorithms

An algorithm is a procedure for solving a mathematical problem that involves a repetition of an operation. Three algorithms were evaluated for processing radiometer voltage to signal a CAT alert. They were arc-length ratio, standard deviation, and a second-difference manipulation. Each algorithm could accept a predetermined number of radiometer voltages and, after computation, compare the results to a threshold value. On the basis of the comparison the computer either signals a CAT alert condition or rejects the results as being below the CAT alert threshold. The threshold itself is the numerical minimum point or boundary at which the effect of subsequent CAT is alerted. This threshold is a value that represents a delicate balance between alerting the observer to as many of the CAT encounters as possible without allowing more false alarms than desired. It had to be experimentally determined for each algorithm in each aircraft.

FLIGHT TEST RESULTS

Learjet Flights

Selection of filters- IR transmission is a strong function of wavelength. The radiometer senses radiant emission in the water-vapor band from varying distances depending on the band-pass of the water-vapor filter. One way of determining the optimum range or "look" distance of the CAT radiometer is to examine a weighting function, which is defined as the derivative of transmittance with respect to the natural logarithm of distance. By selecting the proper filter we can adjust the "range" for the radiometer (which also depends on the altitude). The filters found to give best radiometer performance at 200 mbars (about 12 km (40,000 ft)) were BaF_2 (barium fluoride), SrF_2 (strontium fluoride), and CaF_2 (calcium fluoride). Figure 12 illustrates the calculated weighting function of the three filters used in the Learjet flight experiments. Figure 13 shows the measured band-pass response for the three types of filters. Flight research with this three-filter system began in January, 1978. Because flight data of filter comparisons showed that the SrF_2 filter gave large signal standard deviations and had a longer alert time than the other two filters, it was chosen as the prime filter for further testing.

Encounter data- Approximately 46 hr of flight testing of the CAT detector IR system were completed during the winter 1977-spring 1978 "CAT season." Most of the data flights were conducted in the Denver, Colorado, area, where mountain waves frequently cause clear-air turbulence. Data were acquired at various altitudes from 4.5 to 14 km (15,000 to 45,000 ft).

For these initial Learjet flights, the purpose was to test different filters for optimum reliability and to check on the validity of theoretical time calculations for alerts as they vary with altitude. Turbulence was encountered on about 62 occasions. CAT encounters were defined as aircraft vertical acceleration disturbances of 0.15 g or greater (peak-to-peak). No encounters were considered within turns or during the time when the computer was off. In computing alerts, resetting was necessary when a crystal was changed, when an offset was changed, after an encounter was over, and after a turn was completed. Altitude changes did not affect the alert system except in takeoff and steep descents for landing. A reset was necessary upon reaching initial flight altitude.

The g levels of CAT encountered for 56 cases were as follows: 41 were at 0.15 to 0.29 g; 10 were at 0.30 to 0.48 g; and 5 were at 0.50 g or above.

The alert scores for the flight tests on the Learjet, using the standard deviation algorithm, were as follows:

CAT alert	CAT encounter	Cases	Percent
Ability to predict encounters			
Yes	Yes	60	97
No	Yes	2	3
	Totals	62	100
True/false alarm rate			
Yes	Yes	58	62
Yes	No	36	38
	Totals	94	100

The Learjet radiometer was directly responsible for the large false alarm rate since the electronics displayed a small signal-to-noise ratio. The water-vapor disturbances caused by CAT overrode this effect, thus not changing the true alarm data. However, the abnormally high false alarm rate can be directly traced to the radiometer. Appropriate electronic modifications were made subsequent to these missions.

C-141A Flights

Encounter data- Initial flight experiments onboard the C-141A aircraft made it evident that a broad band-pass (19 to 37 µm) radiometer could predict subsequent turbulence encounters. A report on the initial experiments is contained in reference 9. Figure 14 shows the results obtained in 194 CAT encounters through September, 1977, for flights at an MSL altitude of 13.5 km. The data show that when using an alert algorithm based on standard deviation of the radiometer signals, 80% of the CAT encounters were predicted 6 min beforehand. The false alarm rate was 6% (a false alarm is defined as a predicted encounter that did not occur). The distribution of encounter levels in terms of peak-to-peak g acceleration is shown. The range of acceleration levels for light, moderate, severe, and extreme CAT, used for analysis, is also shown in figure 14. As would be expected, most of the encounters were classified as light or moderate. (The primary mission of the C-141A, i.e., astronomical observations, requires flight in "smooth" air, if possible, and flights are planned accordingly. In addition, most flights are at very high altitudes, well above most weather phenomena.) Results of the early airborne field trials showed that the system does achieve the desired accuracy.

In later flights, additional information was obtained regarding false alarms. In particular, during June and July, 1979, four missions were examined during no-turbulence flight using the arc-length algorithm. (The C-141A in its routine astronomy missions is airborne at a constant altitude for about 6 hr per flight. A small portion of this time is devoted to turning the aircraft so that the astronomer can track his scheduled targets. Much of the flight time, especially in the summer months, is during periods of no turbulence.) Table 2 is a summary of the no-turbulence data that were accrued during the four missions. Only segments of at least 30 min of no turbulence were considered. On June 20, during a 0.5-hr "quiet period," 3 of 5 false alarms can be associated with whispy cirrus; similarly, on July 29 during a 2.5-hr quiet period, there were 11 false alarms that can be associated with cirrus. These clouds were verified by both satellite and water-vapor radiometer readings. Thus, the net clear air flight time is 13.5 hr with 4 false alarms, or about 1 false alarm in 3.4 hr.

Performance of alert algorithms- As stated, three algorithms were studied in the program for use as CAT alerts: running calculations of standard deviations, second-difference, and arc length. Data from the C-141A were used to evaluate these algorithms. Success/false alert statistics for the three algorithms for the 194 cases were as follows:

	Alert		False alert	
	No.	Percent	No.	Percent
Standard deviation	155	80	12	6
Second-difference	134	69	12	6
Arc length	159	82	16	8

The arc length works well but is somewhat sensitive to period chosen (12 sec at 1 data point/sec was selected). The second-difference is very sensitive to the time span chosen. The standard deviation shows good performance and is insensitive to time spans for periods of 12 sec or more. The standard deviation algorithm seems to be the optimum method.

Effect of altitude on alert time- Figure 15 is a graph of the maximum times at which the Learjet and C-141A were alerted before encounters at various altitudes. A curve was plotted through the maximum data down to 5.8 km (19,000 ft). It is not a linear curve since the water-vapor transmission is not linear. The envelope created represents a small number of points and should be considered only representative. It is composed of data points from moist and dry days and thus reflects different atmospheric transmission characteristics. As shown, alert time decreases with decreasing altitude; however, an alert signal is still possible at over 2 min before the encounter at 5.8 km (19,000 ft).

CV-990 Flights

Encounter data- The data flights of the CV-990 were dedicated to the study of clear air turbulence. The aircraft crew and scientists looked for and found turbulence. The flight altitudes ranged from 4.4 to 11.3 km (14,500 to 37,000 ft). During the 30 missions and 140 hr of flight, 94 CAT alerts were given by the system and 80 separate segments of turbulence encounters were documented. Only 4% of the encounters were not preceded by an alert. Of the 94 alerts, 18% were false, that is, they were not followed by a turbulence encounter.

A diagram of the "scores" from the CV-990/CAT experiment with regard to the IR radiometer system is shown in figure 16. Other results from the experiment were as follows:

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

2. Turbulence was detected at distances up to 60 km (37 miles) ahead of the aircraft. (This range can be varied by changing optical filters.)

3. The envelope of maximum alert time varied from 1 min at an altitude of 4.4 km (14,500 ft) to 4 min at 11.3 km (37,000 ft).

Analysis- The emphasis in the CV-990 data analysis was on answering the following questions:

1. Which sample rate (frequency) of the radiometer is optimum?

2. Which algorithm yields best results?

3. What time period (or number of points) yields the optimum algorithm score?

4. Are the new electronics adequate to significantly decrease the false alarm rate?

Analysis of the data led to the following answers:

1. The radiometer voltage sample rates that yield acceptable results are one and two samples per second. More frequent sampling with the use of either the standard-deviation or arc-length algorithm gives poor results.

2. Either standard deviation or arc length yield excellent forecasts and minimal false alarms. However, standard deviation seems to cause an alert to be given to some of the more severe events that the arc-length algorithm overlooks; consequently, it is recommended. A combination of the two does not improve the forecast score, however, since most of the turbulence encounters are predicted and a very small increase in the prediction is offset by a larger increase of false alarms. Therefore, either algorithm is recommended, but with the standard-deviation algorithm somewhat preferred.

3. At a sample rate of 1 sample per 2 sec, a sample-size choice of either 6 or 30 points yields the best forecast before an alarm. This may be less desirable than the 12 sec of $N = 6$. If one sample per second is used, $N = 5$ yields excellent results.

4. The improved electronics had a significant effect on the reduced false-alarm rate compared to the Learjet data.

ONGOING AND SUGGESTED FURTHER STUDY

Further study is under way wherein NASA pilots will evaluate the system during the 1980-81 CAT season (roughly November through March) during regular operations of the C-141A and CV-990 NASA flying laboratories. In addition, United Airlines and the Colorado Air Guard are considering independent evaluations of this type of CAT alert system.

Four alternatives seem worthy of further investigation to improve the detector system. They are:

1. Use a narrower field of view in the radiometer.

2. Scan in a forward mode.

3. Obtain a mosaic of the water vapor ahead of the aircraft by changing the type of detector (still within the same band-pass).

4. Use a discriminating detector.

The first of these alternatives is the least expensive. It may not improve the system; nevertheless, it should be investigated. The second alternative would add to the cost of the radiometer on a commercial level, but probably would be more effective. The third would be the most desirable, but would cost a great deal to research; however, the ultimate cost to the consumer would be almost the same as the second alternative. The microprocessing equipment may be more complex due to the pattern-identification capabilities. The fourth alternative would again require a special detector capable of looking at two forward points. This would achieve a scan-like discrimination on a small scale and would be more economical than a scanning radiometer.

SUMMARY AND CONCLUSIONS

Clear-air turbulence was detected and the air crew alerted at least 80% of the time that CAT was encountered during the studies; moreover, the alert may be signaled as many as 2 to 9 min before encounter, depending on aircraft flight level. At this time, no correlation was found between the intensity of alarm and the intensity of encounter. Also, no correlation was found between the frequency of alarm and intensity of encounter. Radiometer voltages recorded at the rate of one per second showed a slightly better alert rate than those recorded at the rate of two per second. Thresholds for alerts depend on the gain of the radiometer. They also vary slightly with the amount of moisture present. Clouds have a strong effect on the false-alarm rate of the CAT detector system. If nonturbulent (dissipating, lenticularis, or whispy cirrus) clouds are present, one may expect about one false alarm per hour. If the atmosphere is cloudless, the expectation of false alarms should not exceed a maximum of one every 3 or 4 hr. It may be concluded that the radiometer has been shown to be an effective clear-air-turbulence detecting device when cloud effects are eliminated.

REFERENCES

1. Airline Pilot (Technical Talk), vol. 46, no. 4, April 1977, p. 38.
2. Patnaik, P. C.; Sherman, F. S.; and Corcos, G. M.: A Numerical Simulation of Kelvin-Helmholtz Waves of Finite Amplitude. J. Fluid Mech., vol. 73, 1976, p. 215.
3. Reiter, E. R.: Stratospheric-Tropospheric Exchange Processes. Rev. Geophys. Space Phys., vol. 13, 1975, pp. 459-474.
4. Possiel, N.; and Scoggins, J. R.: Curvature of the Wind Profile in the Troposphere Versus Regions of CAT and non-CAT in the Stratosphere. Mon. Weather Rev., vol. 104, 1976, pp. 57-62.
5. Collis, R. H.: Method and System for Detecting Clear Air Turbulence. U.S. Patent 3,696,670, 1972.
6. Smith, S. D.; and Houghton, J. T.: Radiometer Apparatus. U.S. Patent 3,498,132, 1970.
7. Anderson, H. C.: A Measuring System. U.S. Patent 3,056,958, 1962.
8. Astheimer, R. W.: The Remote Detection of Clear Air Turbulence by Infrared Radiation. Applied Optics, vol. 9, Aug. 1970, pp. 1789-1797.
9. Kuhn, P.; Caracena, F.; and Gillespie, C. M., Jr.: Clear Air Turbulence: Detection by Infrared Observations of Water Vapor. Science, vol. 196, 1977, pp. 1099-1100.
10. Kuhn, P. M.: Improved Method and Apparatus for Detecting Clear Air Turbulence. U.S. Patent Application 950,943, Oct. 1978.
11. Weaver, Edwin A. et al.: The 1979 Clear Air Turbulence Flight Test. 1980 Aircraft Safety and Operating Problems, NASA CP-2170, 1981. (Paper 16 of this compilation.)

TABLE 1.- CV-990 AND C-141A AIRCRAFT RADIOMETER SPECIFICATIONS

Performance data	
Operating spectral range	20 to 40 μm
Cavity reference temperature	-20° C
Output voltage	+10 Vdc to -10 Vdc
A to D conversion	12 bit (5 mv/bit)
Noise equivalent power	2.5×10^{-8} W
Response time (time constant)	50 Hz
Optical data	
Detector type	1- by 1-mm lithium tantalate chip
Optical filter	band-pass, 20-40 μm

TABLE 2.- C-141A: NO-TURBULENCE AREAS DATA

Date, 1979	Cirrus included		Cirrus excluded	
	Duration, hr	No. false alarms	Duration, hr	No. false alarms
June 20	3.5	5	3.0	2
July 11	2.5	5	2.5	0
July 13	6.5	0	6.5	0
July 29	4.0	13	1.5	2
	16.5	18	13.5	4

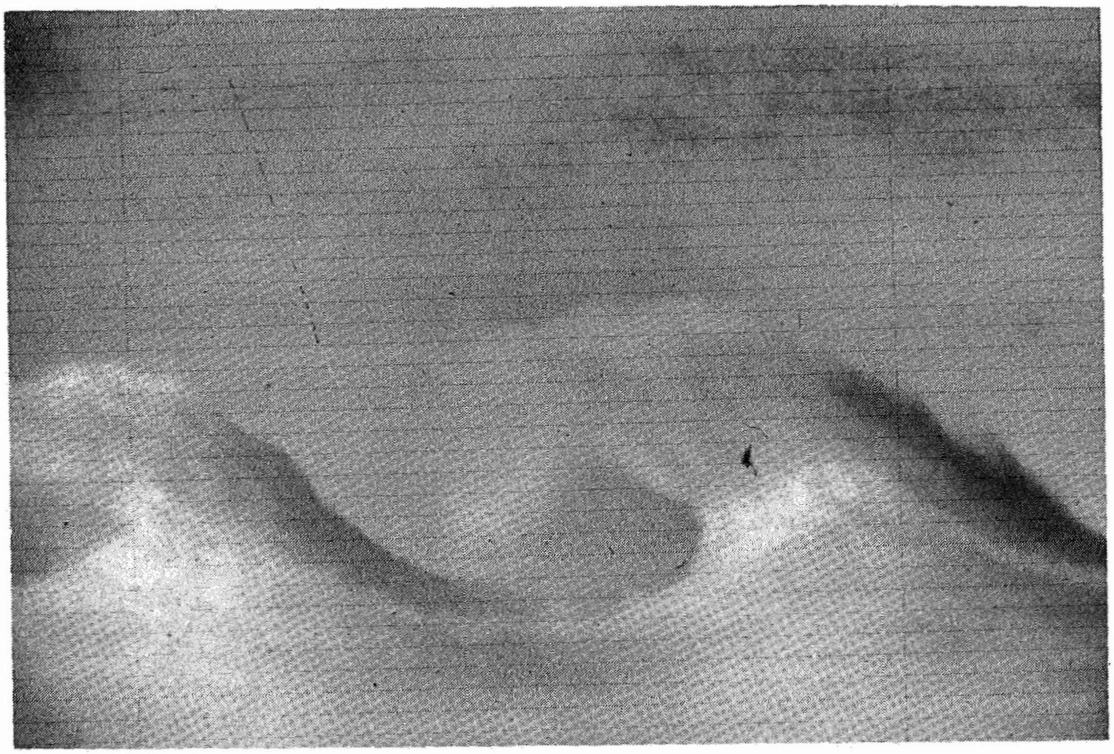

Figure 1.- Kelvin-Helmholtz atmospheric wave.

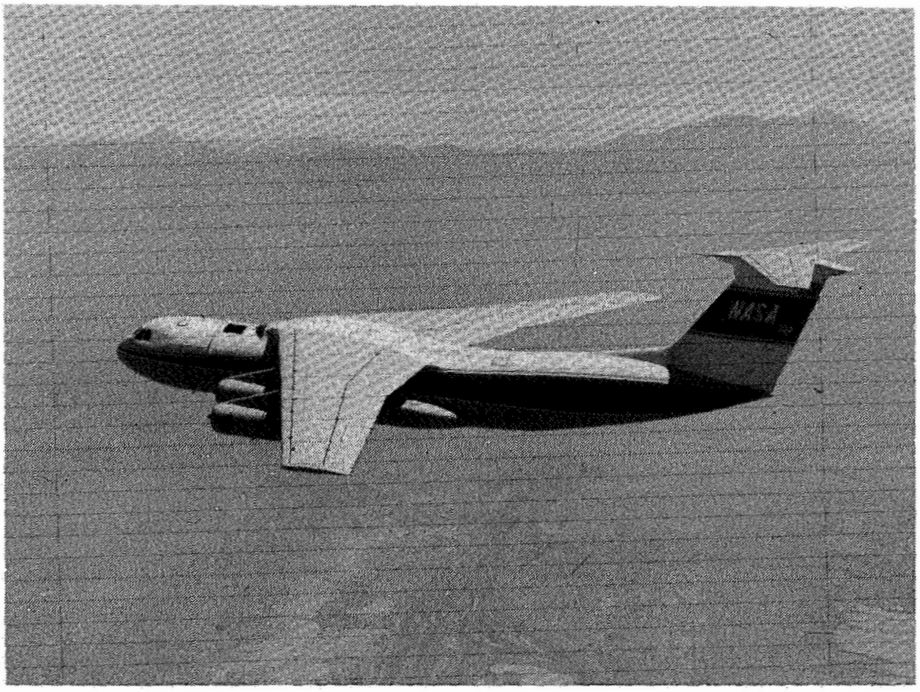

Figure 2.- NASA C-141A Kuiper Airborne Observatory.

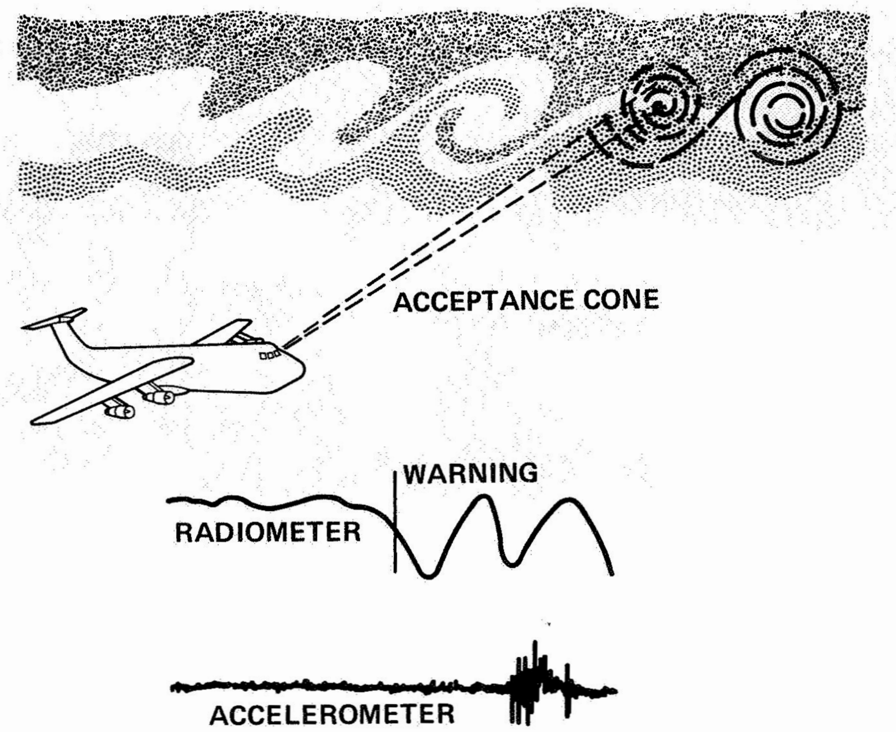

Figure 3.- CAT detection.

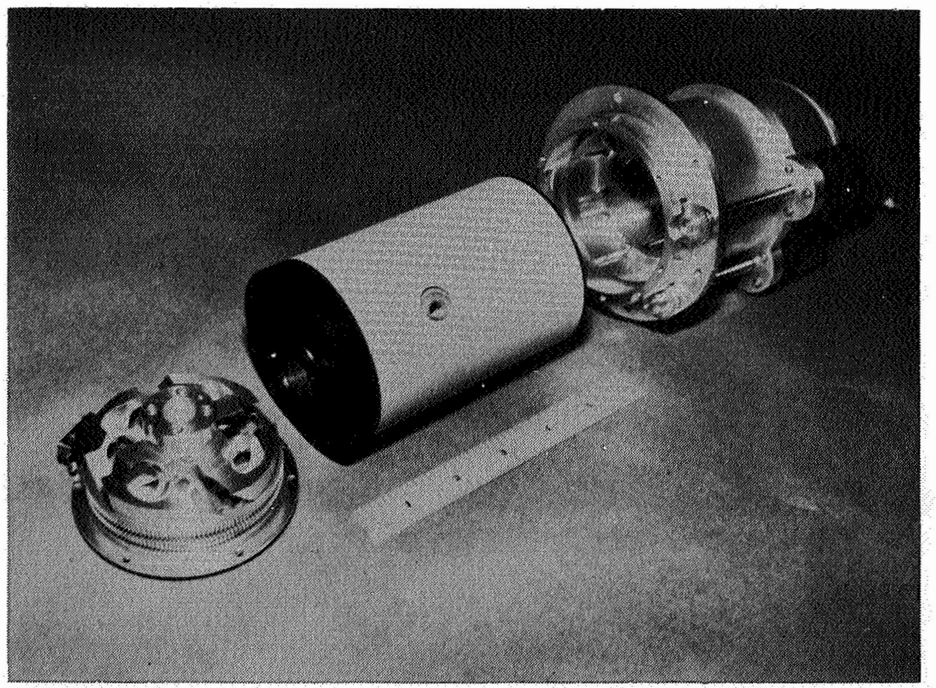

Figure 4.- CAT radiometer used in Learjet tests.

Figure 5.- NASA Learjet model 23.

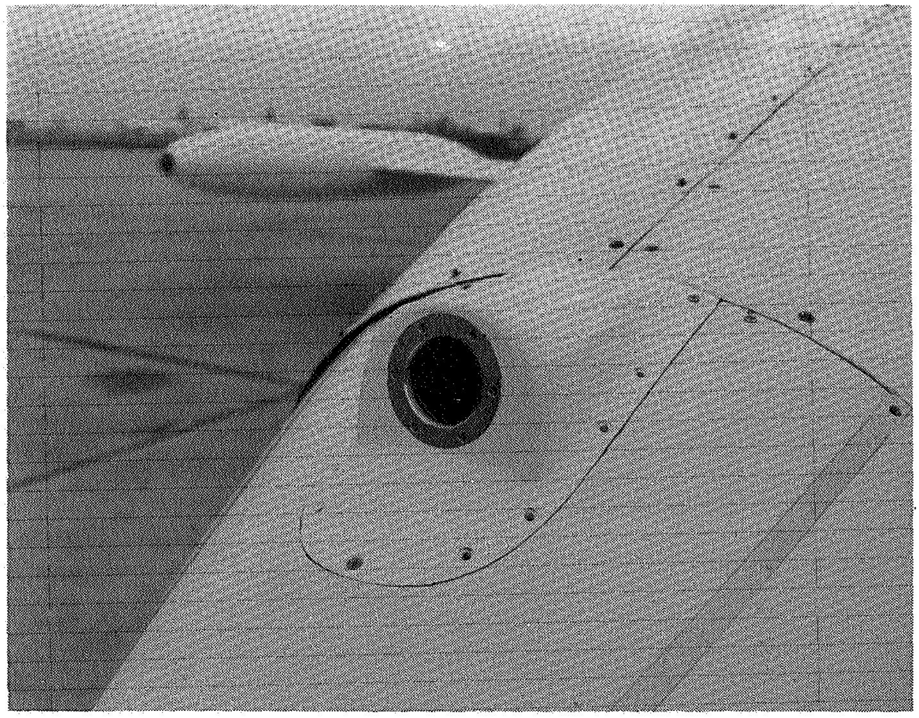

Figure 6.- CAT sensor installation on the Learjet.

Figure 7.- NASA Convair 990, Galileo II.

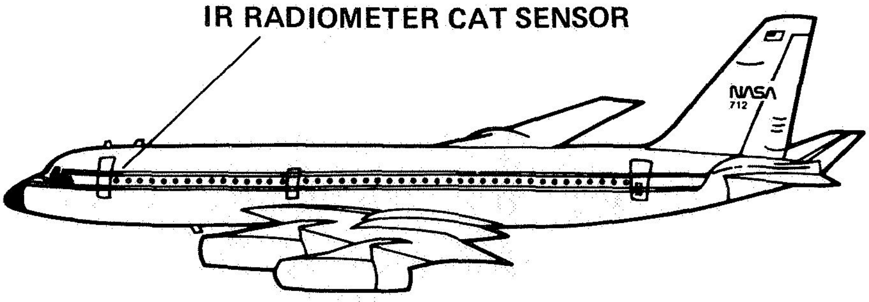

Figure 8.- CAT sensor location on the CV-990 airborne laboratory.

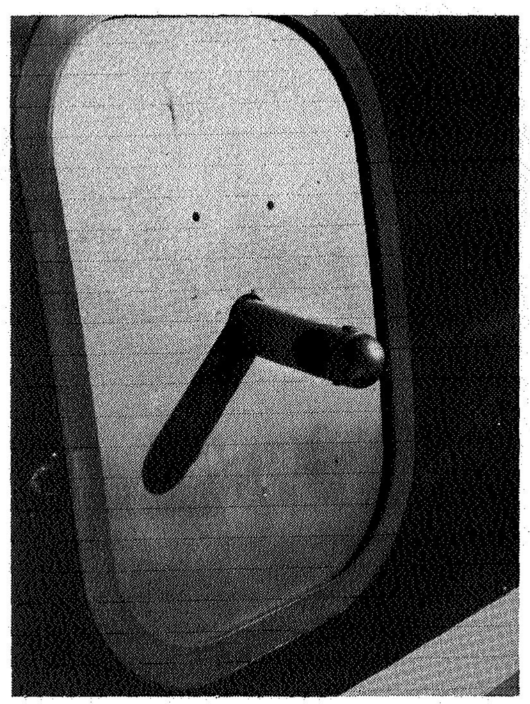

Figure 9.- CAT sensor installation on CV-990.

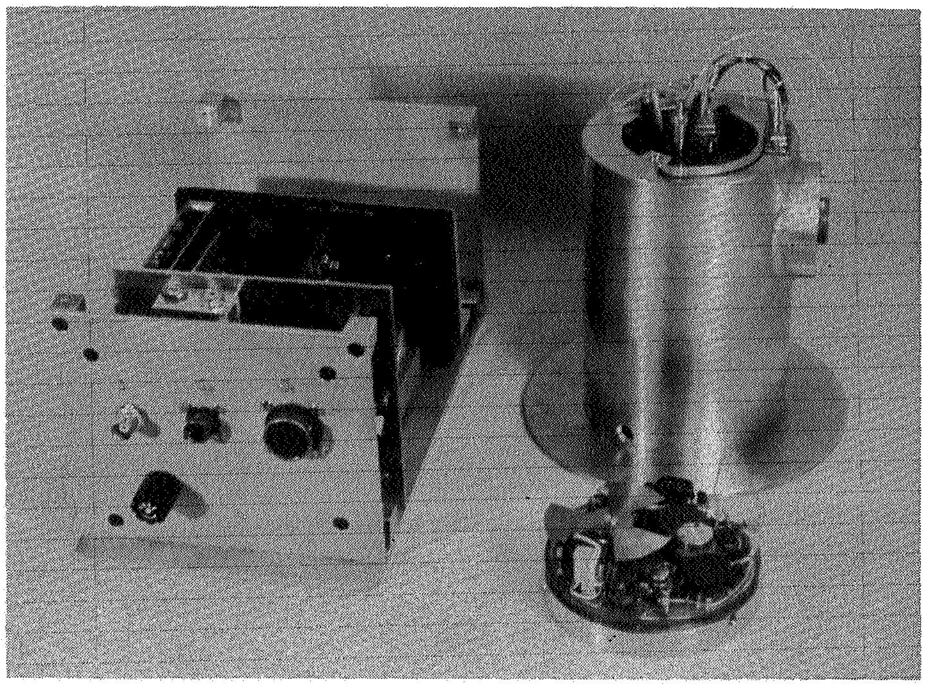

Figure 10.- CAT sensor device and chopper system.

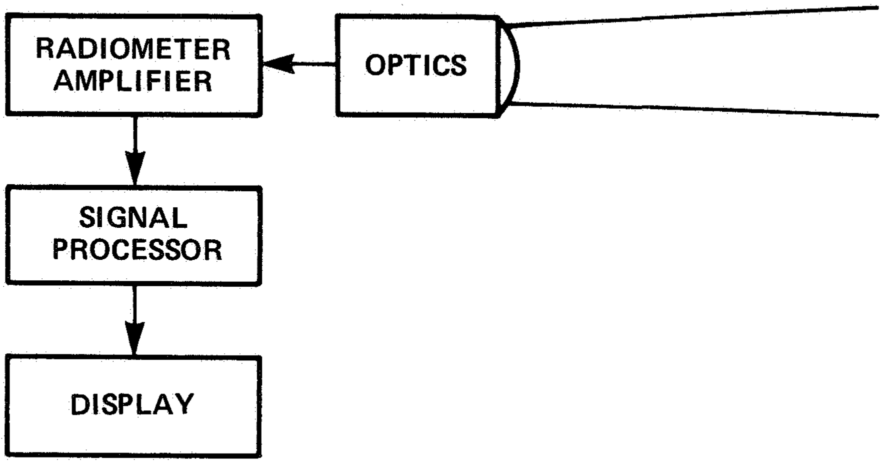

Figure 11.- Infrared radiometer CAT detector system diagram.

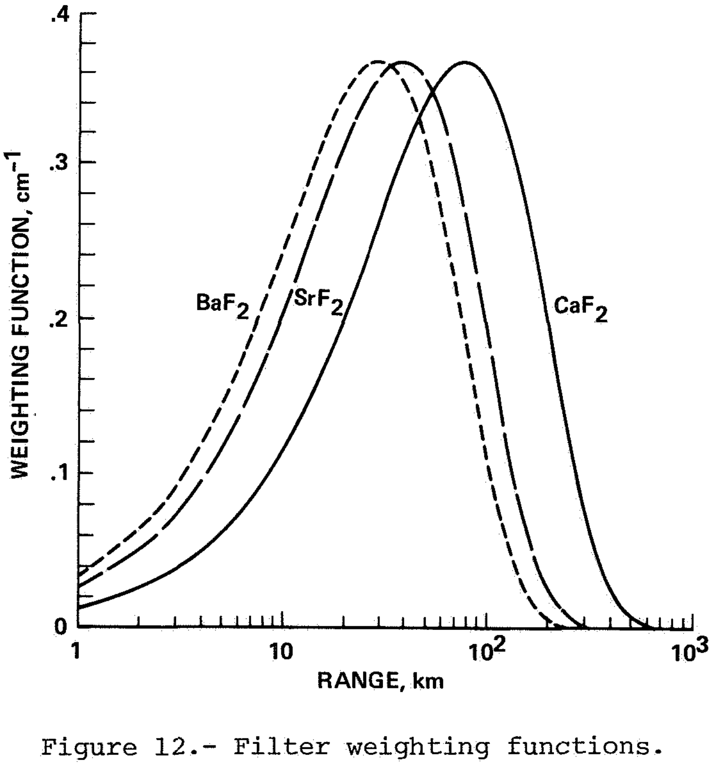

Figure 12.- Filter weighting functions.

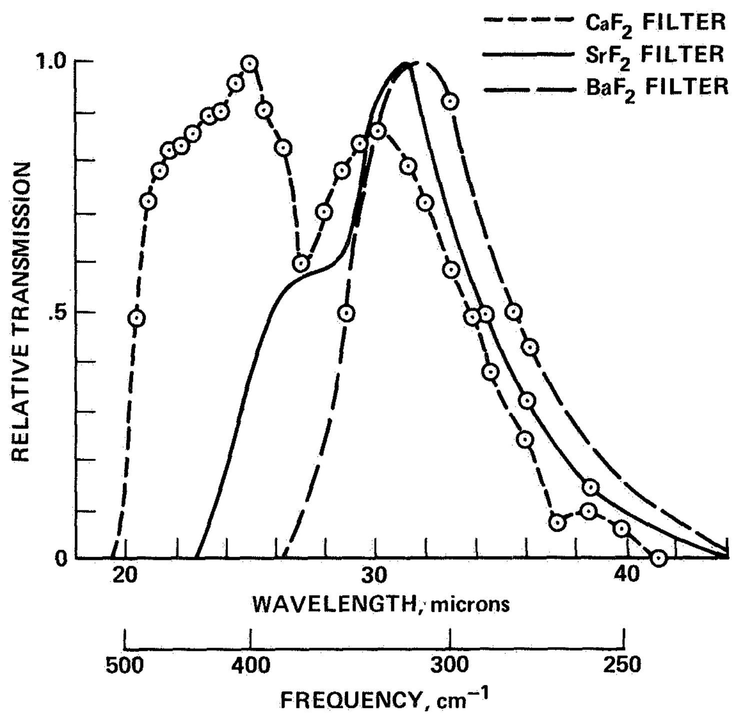

Figure 13.- Measured filter response.

• ABILITY TO PREDICT ENCOUNTER			
CAT ALERT	CAT ENCOUNTER	CASES	%
YES	YES	155	80
NO	YES	39	20
		194	100
• TRUE/FALSE ALARM RATE			
CAT ALERT	CAT ENCOUNTER	CASES	%
YES	YES	155	94
YES	NO	10	6
		165	100
• ENCOUNTER LEVELS			
G LEVEL		CASES	%
LIGHT (0.15 < 0.30)		155	80
MODERATE (0.30 < 0.50)		36	19
SEVERE (0.50 < 1.0)		3	1
EXTREME (> 1.0)		0	0
		194	100

Figure 14.- Encounter prediction statistics: C-141A data; MSL altitude 13.5 km (44,290 ft).

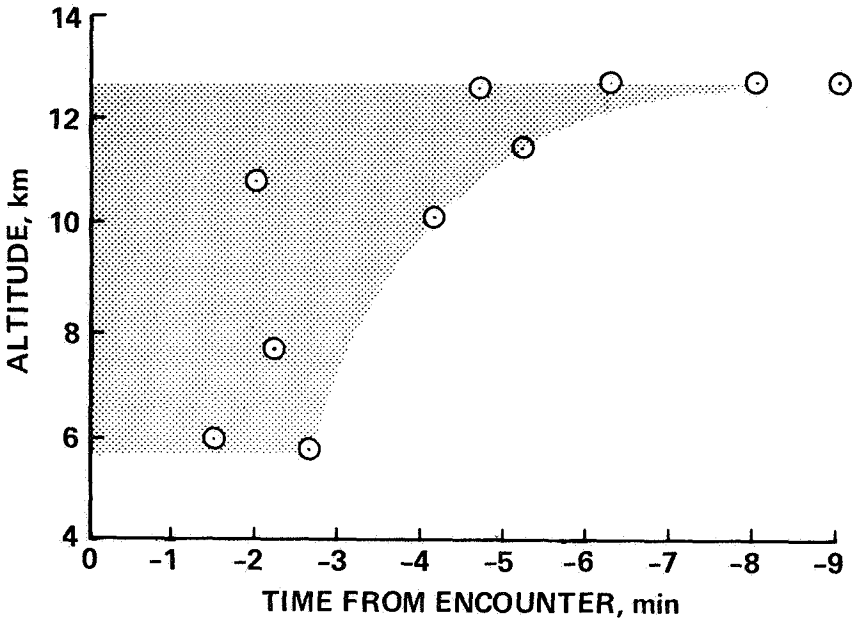

Figure 15.- Onset of alert before an encounter envelope.

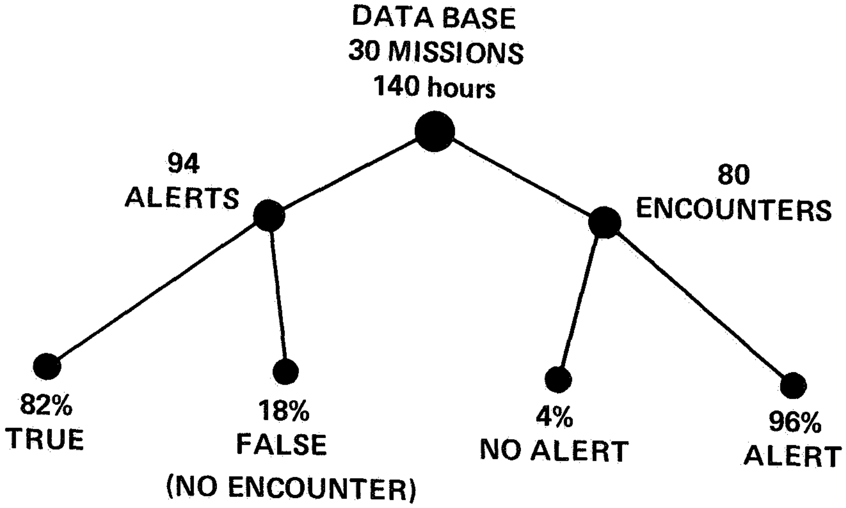

Figure 16.- Infrared radiometer CAT detector: CAT/CV-990 flight-test results.