Status Report on Latest Development in Clear Air Turbulence

M. G. Beard*
Flight Safety Foundation Inc., New York, N. Y.

In 1962 and 1963 there was one jet transport accident and several severe incidents which injured passengers and caused structural damage and/or loss of several thousand feet of altitude because of either convective or clear-air turbulence (CAT). Revised pilot operating instruction for handling turbulence and improved forecasting of CAT has reduced greatly incidents of a drastic nature in 1964 and 1965. The pilot has radar to guide him around storm cores, but he has only the meteorologists' forecasts to tell him where CAT may be encountered. The Air Force, Navy, NASA, FAA, U. S. Weather Bureau, and the airlines are interested in the development of a good CAT detector. In the Fall of 1964, NASA contracted with Flight Safety Foundation to find out and report on all the activities in the United States and the world in the field of CAT forecasting and detection. This is a service to the governmental departments interested in this field and to industry. This paper is a status report about new developments in CAT forecasting; it also is a résumé of the various proposed principles of CAT detection and the detection devices being developed and laboratory and flight tested.

CLEAR air turbulence has been a factor in the operation of airplanes ever since the Wright brothers made the first flight at Kitty Hawk in 1903. CAT bothered the early flyers whose airplanes had marginal control characteristics. It bothered the pilots during World War I. It caused accidents and injuries to the early passenger transports flying at not more than 10,000 ft. The DC-6's and Constellations encountered CAT at 20,000 ft, and there were some violent CAT penetrations with these models just following World War II. Between 1955 and 1960, the Air Force advised the commercial airlines that they could expect CAT between 20,000 and 40,000 ft, based on Air Force experience with the B-47 and other high flying jets. During the years 1960 to 1963, as more jets were introduced into commercial airline service and more military jet bombers were put into service, reports of CAT penetrations of moderate to severe turbulence increased in number; and during 1962 and 1963 there was one jet transport accident, and there were several incidents of a drastic nature on the airlines which injured passengers, caused drastic loss of altitude and/or structural damage. Some of these incidents were caused by weather turbulence in convective areas. In one instance the airplane was on instruments when severe turbulence was encountered. In several of the other incidents the airplanes were in the clear, but in storm areas that are classified as convective turbulence. In this clear air adjacent to storm cells, radar could only help the pilot to the extent that it told him how far from the storm cell he was flying. Radar could give him no indication of CAT ahead on his flight path.

Reports of turbulence throughout the country received by weather stations and traffic control are funneled into the United States Weather Bureau. These reports are published in a coded sheet each month. An analysis of CAT penetrations by turbine-powered aircraft of both military and commercial models for the year 1964 indicates that there were 671 such penetrations of moderate or higher intensity turbulence; 259 or 38.6% of these were by military turbine powered bombers, tankers, and transports; 68 or 10.0% were not identified as to type of airplane; 163 or 24% of these penetrations were reported by the pilots as severe turbulence; and 11 or 1.65% were reported to be extreme turbulence.

Presented as Preprint 65-800 at the AIAA/RAeS/JSASS Aircraft Design and Technology Meeting, Los Angeles, Calif., November 15–18, 1965; submitted December 3, 1965; revision received April 11, 1966.

* Director, Flight Operation Research; now Executive Vice President, Las Americas, Inc., San Antonio, Texas.

It must be remembered that the degree of turbulence reported by the pilots is strictly an individual "seat of the pants" appraisal or judgment by the pilot, which contains all the factors of pilot temperament and nervous condition of the day, weight and size of the airplane, periodic response characteristics of wings and fuselage, speed of the plane, and the wavelength and wave dissipation stage of the turbulence at time of penetration. Recently, Meteorology Research Inc. of Altadena, Calif., has proposed a standard turbulence meter that can be integrated into any air data system having true airspeed sensor. This would be adjusted to compensate for all the airplane characteristics and would indicate a digit on the instrument dial, the digit of which would show the intensity level of the turbulence in the inertial subrange. This is a range of turbulent eddies with dimensions from a few centimeters to several hundred meters. If at some future time it becomes necessary to have more accurate turbulence reports, an instrument of this type would be one possibility.

By the Summer of 1963, the airlines began to realize that several new factors had been added to the turbulence problem along with the high-speed, swept-wing jet transport. The increased speed of the jets over the piston transports created turbulence in certain atmospheric structures which would not have bothered the slower airplanes. Power controls in the jets with light control forces gave the pilot the ability to move the controls to feed in higher G's than would be received by the turbulent air. Dutch Roll characteristics of the swept-wing and longitudinal trim capabilities created situations under sudden turbulent air penetrations which never had been experienced in the straight wing piston transports. All of these factors required and received careful analysis. In the Fall of 1963, the airlines conducted intensive training campaigns to educate the pilots in the techniques of handling turbulence encountered by a jet transport. Airline meteorologists refined their methods of forecasting CAT. Flight simulators were used to study pilot reaction to high g's and periodic oscillation. Turbulent air penetration speeds were reviewed in relation to the stall buffet and high-speed buffet limits of the jets, and the recommended turbulent air penetration speeds were raised to give greater margin above the stall. These combined efforts resulted in a decided reduction in the number of drastic turbulent air penetration incidents where passengers were injured, structural damage was experienced, or loss of control and a large loss of altitude resulted. In 1964, there were less of this type of incident than in 1963, and there were very few in 1965.

On December 1, 1964, NASA awarded a contract to the Flight Safety Foundation to assist NASA in keeping abreast of research and development projects directed towards alleviation of problems posed by flight in turbulence. The scope of the contract NSR 33-026-001 is to list and critically evaluate on a continuing basis current projects relating to: 1) forecasting of turbulence; 2) principles of turbulence detection; 3) devices for turbulence detection with particular emphasis on CAT; 4) evaluation of these principles and devices as to suitability for airline use; and 5) listing of incidents involving turbulence, including their effect on airline operation. For the past nine months, visits have been made to organizations working the field of CAT forecasting and detection, and quarterly reports have been made to NASA on the findings of these visits.

Forecasting of Turbulence

Prior to 1964, it was the general practice to forecast CAT areas by using horizontal and vertical wind shear taken from synoptic charts and rawinsonde wind data. This method gave a large block of air several thousand feet in depth, 100 to 200 miles wide, and sometimes 200 to 300 miles long, in which the pilot was advised that he could expect to penetrate turbulence of light to severe intensity. Only about 18 to 20% of the flights passing through these blocks of air would encounter more than light turbulence. This was not very useful in operating an airline, and during 1964, several airline meteorological departments studied the problem with the objective of reducing the block of air in which turbulence is forecasted, so that pilots could expect better reliability in the forecast of moderate to severe turbulence, and so that detours, if made, would be shorter.

Among the airlines that worked on this problem and published improved CAT forecasting methods are: 1) Eastern Air Lines, in their interoffice bulletin 64-18 (December 29, 1964); 2) United Air Lines, meteorological circular 56 (December 21, 1964); 3) Northwest Airlines, in a series of company bulletins on forecasting of CAT (issued during 1964 and 1965); and 4) Delta Airlines, in their in-house bulletin, "Delta Airlines method of analysis and forecasting high level turbulence" (November 18, 1964).

These efforts resulted, generally, in the reduction of the blocks of air in which CAT is forecasted to about one quarter the size of the blocks obtained by the older methods. In these revised systems, light turbulence is not considered important. A large percentage of flights that pass through these smaller forecasted blocks of air now encounter moderate to severe turbulence, and the pilots have great respect for these forecasts. Occasionally, a flight will encounter moderate CAT outside these forecasted blocks, because the art or science of CAT forecasting and the data available do not permit pinpointing all CAT. The 200 miles spacing between rawinsonde stations, and the 12 hr interval between upper air soundings leaves a space and time gap in which sudden local weather changes can occur. Because of analysis and transmission time lag, the forecaster is 4 to 6 hr behind the weather data taken. This makes it difficult to pinpoint accurately turbulent areas the airlines endeavor to avoid. Much of the data are computerized already, and chart drawing is automated; nevertheless, there is need of reducing the time lag between the rawinsonde soundings and CAT forecasting if much better forecasts are made. The U. S. Weather Bureau is studying the problem, but it probably will be a long time before much reduction in time lag occurs. This then puts emphasis on research and development of detection principles and devices as the most logical means of CAT avoidance.

The fields of meteorology and radiophysics deal with the same environment, namely, the atmosphere. There has been, in the past, a great lack of communication between scientists of these two disciplines. Recently, an international colloquium was held in Moscow during the month of June 1965, between eminent meteorologists and radiophysicists to discuss the fine-scale structure of the atmosphere. Dr. E. R. Reiter, Professor of Department of Atmospheric Science, Colorado State University and Dr. H. Panofsky of Pennsylvania State University attended this conference for the United States. This conference has accomplished much in clearing up some of the controversies concerning the origin and structure of CAT and has outlined the areas where flight research is required to fill in the unknown. As Dr. Reiter succinctly expresses, "Although much has been unraveled of the 'Mystery of CAT' there are still more questions than answers. It seems that each 'Because' breathes at least one other 'Why'."

The results of this colloquium are summed up in Dr. Reiter's conclusions:

> In summarizing the results of the conference as evident from reports and discussions, and placing the author's biassing emphasis on clear-air turbulence (which would certainly not be shared by radio-physicists who attended the conference) one may state the following:
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> 1) The search for the physical nature of CAT may be considered as close to its conclusion. Opinions expressed earlier (Reiter, 1960), that CAT in a stable environment is caused by gravity waves, have finally been substantiated by observational evidence. These gravity waves seem to be breaking up into isotropic turbulence. Within this range of isotropy lies CAT experienced by standard jet aircraft of present design.
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> 2) Supersonic transport aircraft may experience difficulties especially in the velocity region of Mach 1 and slightly beyond, because the high levels of turbulent energy experienced presently as CAT extend with "$-\frac{5}{3}$" slope of the spectrum curve to longer waves which may be felt as CAT by supersonic airplanes.
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> 3) Mathematical treatment of interaction of waves with turbulence, especially under conditions of vertical wind shear, still awaits formulation.
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> 4) CAT spectra, although quite dependable over a large wavelength range, are still sparse. Especially spectra of severe CAT measured with improved instrumentation are still lacking. Detailed meteorological "background" information on vertical shears and thermal stratification are still needed. Data on small-scale temperature fluctuations in CAT regions would be invaluable.
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> 5) Detailed exploration of atmospheric structure and spectrum characteristics in the proximity, but outside of CAT regions would be extremely helpful in studying the processes that lead to the formation of waves and their breakdown into turbulence.
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> 6) Design and testing of airborne equipment for the remote detection of CAT should make use of the recent findings on CAT structure outlined above. Cooperation between radio-physicists and meteorologists should prove highly fruitful in this field. Detailed atmospheric structure can, without doubt, be detected by remote sensors. With the establishment of specifications for turbulence energy levels at various wave numbers characteristic of CAT, given from the power spectra measured by Shur (1962), Vinnichenko et al. (1965) and Reiter and Burns (1965), the electronic engineers should find a wide-open field of activity.

This is an excellent statement concerning the additional flight testing necessary to obtain the basic data required for the design of good CAT detectors. Government funding of projects to instrument and equip adequately enough research airplanes to implement well-planned research projects in this field would give the radio-physicists and instrument designers the basic facts for the design of CAT detectors. Most of the design criteria and premises are taken now from theory. This is one of the reasons why CAT detectors are being designed, based on almost the entire electromagnetic spectrum.

Incidents

During the years 1962 and 1963, one jet transport was lost, and several jet transports were upset or badly shaken by both convective and clear-air turbulence. In several of these incidents, several thousand feet of altitude were lost before control of the aircraft was regained. In most of these incidents passengers received minor to severe injuries. In one of these incidents, an engine was lost, and in one incident

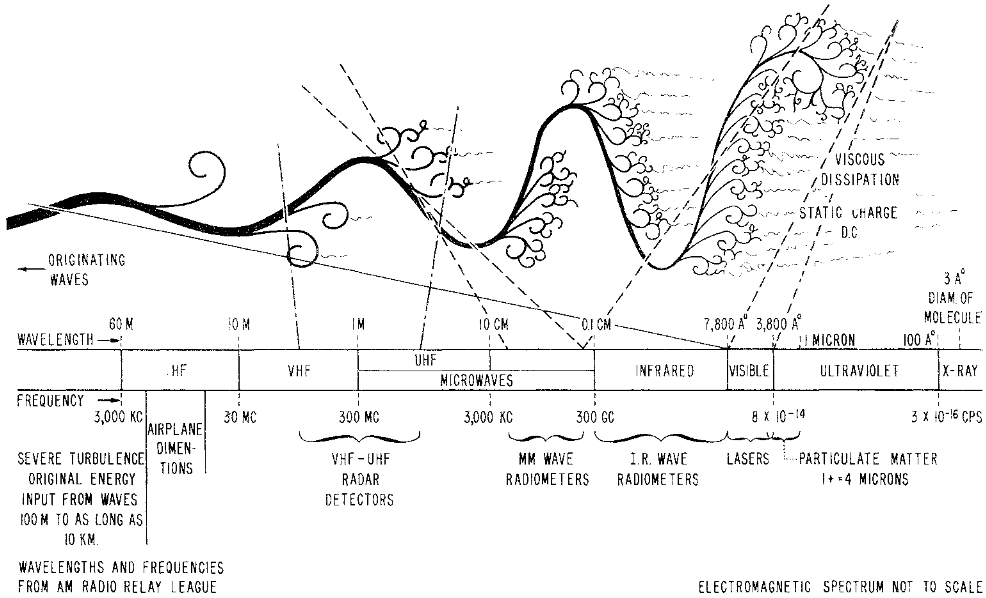

Fig. 1 Gravity wave dissipation program indexed with electromagnetic spectrum.

an engine was nearly lost. One factor that assisted greatly in the analysis of what took place during the incident was the record from the crash recorder, carried by all jet transports. Although the number of channels on the existing crash recorders are not sufficient to make a thorough analysis, there is sufficient data on the time, altitude, airspeed, g, and heading traces to derive a large amount of information that gives good clues as to the meteorological aspects of the incident, and frequently, the pilot inputs, which in most cases added considerably to the g forces, can be derived from the recorder readout.

CAT usually is considered distinctly and separately from convective turbulence. Detailed analysis on all turbulent incidents of a drastic nature reveals the fact that many of the incidents that are classified as convective turbulence (as has been noted previously) occurred when the airplane was flying in clear air in a convective area where radar was of no assistance to the pilot, other than keeping him at a supposedly safe distance from the turbulent core of the storm. In such instances, a CAT detector would have been of just as much value to the pilot in showing him turbulent areas ahead of his flight path as the radar was in keeping him away from the core of a storm he was skirting. For this reason, in this study we are considering air free of clouds or precipitation in a convective area in the same category with respect to CAT detection, as clear air outside of convective areas. In fact, a study of the severe and drastic incidents indicates that a CAT detection device will be more valuable to the pilot in avoiding the severe and extreme turbulence in the vicinity of storm areas than in avoiding moderate to severe CAT outside convective areas which are subject to fairly good forecasting.

CAT Detection Principles and Devices

There is more interest in the instrument and electronics field and among research organizations for the development of CAT detection than was evident on the surface when the project first started. We have interviewed companies that are working on principles of CAT detection, based on the entire electromagnetic spectrum from microwaves at the one end and, literally, to d.c. at the other end (static charges being considered d.c.). More specifically, devices are being experimented with in the vhf and uhf radar band, the microwave bands, the infrared bands, the laser, ruby and ultraviolet bands and d.c., or static electricity. CAT detectors also are being considered based on ozone detection, pressure pulse sensing, and refractrometers.

As it frequently occurs, when a new problem arises, people who have devices and are looking for problems to which the device may be applied, immediately endeavor to adapt the device to the new problem. If the device fits the problem, a solution sometimes is obtained quickly without going through the tedious process of research, design, and development. This might prove to be the case in CAT detection, as there are sensors and instruments available to be adapted to all of the previously mentioned detection principles.

Chart Fig. 1 is an attempt to index the portion of the electromagnetic spectrum covered by proposed CAT detection devices with a stylized or diagrammatic gravity wave dissipation somewhat in accordance with Dr. Reiter's theory of the breakdown of a gravity wave into isotropic turbulence. The danger in the association made in this diagram is that it may be assumed that the CAT detection devices see only their respective wavelengths in the gravity was dissipation diagram. This is probably the case in one of the principles proposed, but as will be discussed in following paragraphs, it is not right for most of the devices proposed or under development.

According to Dr. Reiter's theory, the high-energy, long-wavelength gravity waves progressively break up into smaller vortices and turbulence until the energy of the powerful waves is dissipated into very small, short wavelength isotropic turbulence and heat, in a manner similar to the ocean waves approaching a beach and breaking down into combers and foam. The portion of the waves which really shakes an airplane is the longer wavelengths, both by their own velocities and motion and by the velocity of the plane passing through them. Shorter wavelengths of a few feet produce "choppy air" effects, and the short wavelengths of inches and millimeters hardly affect the airplane. It has been questioned why scientists are developing and flight testing CAT detectors that are based on wavelengths in the visible spectrum (7800 to 3800 A) and even proposing devices in the ultraviolet range. Since the purpose of this paper is to give a comprehensive report on the state of the development of CAT forecasting and detection, the various principles of detection proposed will be discussed.

Lasers

The laser principle is the newest (it is hardly four years old), yet its potentials in many scientific and industrial fields have created intense development activities throughout the optics and electronics fields. Considerable ground testing of lasers to determine what lasers can see in the atmosphere has been accomplished in California by Stanford Research Institute for Air Force Cambridge Research Laboratories (AFCRL) and in conjunction with Lear Siegler, and by Honeywell at Rawlinsville, Calif. for AFCRL looking at mountain waves, and in the laboratory at Minneapolis to determine, if possible, whether lasers can see molecular motion. The University of the West Indies, in conjunction with AFCRL, has been probing the upper atmosphere with lasers for about two years to determine the concentrations of particulate matter at altitudes above 25,000 ft. Professor Franken of the University of Michigan has been flying a Lear Siegler laser in a small airplane for almost a year with funding from the Navy to determine whether lasers can see backscatter from particulate matter in the atmosphere and to correlate the backscatter returns with CAT. Recently, a Lear Siegler laser has been installed in a T-33 by NASA at Langley Field to correlate, if possible, laser backscatter from particulate matter with CAT.

The hopes of the people working with lasers for CAT detection are based on the theory that in any given volume of quiescent air, particulate matter is uniformly distributed. When turbulence enters this volume of air, the uniform distribution of particulate matter is upset, and the waves, eddies, vortices and swirls of the wave dissipation form concentrations of particulate matter. When a pulse or continuous wave (CW) laser beam impinges upon these concentrations of particulate matter, the intensity of the backscatter can be differentiated from that returned from a uniform distribution. Doppler laser senses relative motion of particulate matter parallel to the motion of the plane. In turbulent air, the omnidirectional motion of the air currents will move a certain portion of the particles parallel to the direction of the plane, the motion of which is sensed by doppler laser.

Referring to the diagram, it is seen that all portions of the gravity wave dissipation will have turbulent motion and from the theory should have concentrations of particulate matter. Therefore, laser detectors of all three types should sense turbulence from a wide wavelength spectrum of the wave dissipation. The small amount of flight testing and ground observations with lasers as has yet not obtained good correlations to prove these theories. Upper air probings from the ground at Jamaica indicate that there are concentrations of particulate matter in the upper atmosphere which do not appear to be associated with turbulence. Whether such concentrations would give false signals on the CAT detector must be determined by actual flight testing. Only pulse ruby lasers have been used in CAT detection experimental work thus far. CW laser power requirements are high, and the equipment would be heavy for airborne use. Doppler laser has only been proposed. The possibility of eye damage to pilots, should a laser beam be projected into a cockpit of an approaching plane, has given caution to flight testing of lasers. The intensity level of laser beams which will produce eye damage is being investigated by several laboratories. Until this intensity is determined, and flight tests are made to determine whether a laser beam of this intensity can project 30 or more miles ahead to detect backscatter from particulate matter and to prove this theory of particulate matter concentration in CAT eddies and to correlate these concentrations with CAT, it will be very difficult to determine how good lasers will be as CAT detectors. It may be possible to treat cockpit windshields to protect pilots eyes from laser beam injury without deterioration of the optical qualities, but little or no work has been done with this at the present time. In summation, lasers as CAT detectors for commercial transports appear to be a long way off.

Project Trapcat

For several years since the war, Eastern Air Lines' meteorologist Paul Kadlec has been studying the relationship between observed temperature change and CAT. Litton built him a portable instrument that indicated rate of temperature change and total temperature change, which could be plugged quickly into the DC-8 air data system. The Weather Bureau funded a small change in the DC-8 instrumentation to accommodate the portable rate of change indicator. His many observations with this instrument indicated a correlation between an average temperature change of 0.7°C/min for 5 min, and a total temperature change of 3.5°C in 5 min (after the first winter's operation, revised to 1°C to 1.2°C/min for a total of 2.5°C in 2 min), and CAT with a warning of 1 to 3 min when both these quantities had been reached. The FAA funded this project for building ten recording sets of instruments that five airlines were to have flown on their DC-8's and 707's the Winter of 1964–1965. Delays, however, prevented the installations getting into operation until March and April, 1965, on three airlines. The instruments have been modified, and Project TRAPCAT is to get under way again this October.

The rate of temperature change of 0.7°C/min is for the DC-8 cruising speed of $0.83M$, which makes the system unusable in climb and descent. It would be less for slower planes and higher for faster planes. There is some evidence that the temperature change principle works best when approaching jet stream CAT normal to the jet stream, and that there may be little or no temperature change when approaching a CAT area along or parallel to the jet stream. There is no correlation yet for the CAT conditions in mountain wave and other types of gravity waves with respect to temperature gradients surrounding the turbulent areas. Research and development groups working on radiometric sensors in the infrared (IR) band are watching Project TRAPCAT with great interest. If a good correlation is proven, the IR sensors have a good chance of working as the radiated energy and temperature originate at the same source.

Infrared IR

Radiometric sensors in the IR band are well developed for industrial scientific applications, and their abilities and limitations are better known than those of lasers. IR sensors fall in the category of a well-developed device looking for a problem. They work on the principle of sensing heat energy from the dissipation of gravity waves in the atmosphere. A simple IR sensor can detect direction of the heat source, but since this is a passive system, it cannot indicate range except indirectly. By selecting a spectral interval "which provides sufficient radient intensity for detection at 20 miles, but which is sufficiently absorptive to preclude detection at significantly greater ranges" an approximate range is obtained. Assumptions made are that a 2 min warning (approximately 20 miles) will be satisfactory and that a temperature difference of 2°C will exist between the turbulent and nonturbulent air where CAT exists. Because of the interrelationships between transmissivity, absorption, and emissivity, absorption bands of CO_2 and H_2O are used. Airborne IR detectors are proposed using the 6.3-μ water vapor band and the 15-μ CO_2 band.

A CAT detector in the IR band based on the use of spectrometers is proposed, which indicates range. An airborne model is being designed and may be test flown within a few months as an in-house project, as it is not yet funded by a government agency. Adverse considerations for a CAT detector in the IR band are: 1) lack of range information in the simpler designs and coarse range indication in the more sophisticated designs; 2) probably limitations similar to those of the temperature rate of rise and total temperature rise principle; 3) the probability that this principle will be subject to false signals from heat sources on the ground, especially at the lower altitudes; and 4) the IR band is subject to absorption by water vapor, and its range will be limited under these conditions.

Favorable considerations are: 1) most of the components of even the more sophisticated designs have been used in other applications and can be adapted to an airborne unit in relatively short time; 2) the optics and electronics are not complicated, and an airborne test unit could be developed in a relatively short time; 3) there are no factors detrimental to human beings; 4) the quantities and factors to be flight tested and explored to determine the suitability of the IR principle for an airborne CAT detector are better known than for some of the other principles, and the flight test program could be less expensive; 5) maintenance costs should be low, and the devices should be durable and reliable; and 6) most of the designs are light and occupy little space.

Whether or not a radiometric device in the IR band will be a satisfactory CAT detector for airline use can only be determined by building a prototype and putting it through the necessary flight tests.

Millimeter Radiometers

The advantage of the (mm) band radiometer for CAT detection is that this band is not sensitive to water vapor in the atmosphere. With ground based units, it has been possible to measure gradients in frontal air masses. By changing frequencies, it is possible to look at both sides of the absorption band and probe at different distances using 65 to 75 Gc at ranges varying from 1 to 50 km. Millimeter frequencies have been used for mapping from airplanes, and icebergs have been detected through a cloud layer from an airplane. Millimeter ground units have detected thermal columns in the atmosphere on clear days before clouds have formed at the condensation level. Information on the value of mm frequencies was published in the minutes of the World Congress of Meteorology, 1964. Development work is being done on an airborne unit, but no proposal for funding by a government agency has been made.

Millimeter would appear to have the advantage over the IR band in being able to see through clouds and therefore should have advantages for use in convective areas where severe CAT may be encountered, and under conditions that radar does not indicate turbulence to the pilot.

Radiometers in both the IR and mm bands probably look at the smaller wave lengths of the gravity wave dissipation spectrum since they both sense heat energy. Therefore, in Fig. 1 they are represented as receiving heat energy from a relatively broad band of the wave dissipation diagram. Millimeter radiometers have been used already as airborne equipment, and an airborne CAT detector could be developed in relatively short time. About the same amount of flight testing would be required as for the IR detectors to determine their suitability for airline use.

Vhf Radar Detector

One of the most interesting developments in CAT detection has been going on at Boeing in Seattle. Since 1963, using a bi-static radar installation, Boeing engineers have monitored the 75-Mc Hobart fan marker. The receiver antenna and fan marker occupy a large common volume at jet stream levels. Meteorites and jet transports passing through this common volume give characteristic returns on the scope. Jet streams show great activity.

Pursuing their experimental work further, Boeing has built a large 40-ft parabolic-dish monostatic antenna in the ground at the Inglewood test site shooting vertically. Whenever CAT is indicated on the bistatic 75-Mc radar, the monostatic radar at Inglewood is fired up. A flight test program is scheduled to verify the scope indications by a pilot's "seat of the pants" observation while flying through the turbulence over the radar antenna, at the altitude indicated. Boeing has further plans to install a Yagi antenna along the back of the −80 prototype and investigate the possibilities of an airborne vhf radar CAT detector.

Since the vhf radar receives backscatter from the refractive index or refractive eddies at the wavelength to which it is tuned, it sees only this wavelength in the wave dissipation process. CAT wavelengths of 1 to 3 m are long enough to have an effect on even a large airplane. They are much closer to the dimensions of an airplane than those of any of the other principles of CAT detection proposed. In this respect, it would be desirable to choose a wavelength as long as feasible, still keeping the antenna within a size tolerable on an airplane.

A vhf radar probably would require more space and be heavier than the other proposed CAT detectors, unless some scheme could be found to share the antenna with the weather radar. Flight observational work on operational uses of airborne radar took about six months, strung out over a total program of about three years from 1945 to 1948, and I would estimate considerable less time for a vhf CAT radar test program if the right time of the year and the right locations were chosen for the tests. At best, it appears that vhf radar is at least two years off, if it should prove effective for CAT detection.

Static Charge Detectors

It has long been known that there is a static charge build-up in the vicinity of some turbulent air areas. Stanford Research Institute, with AFCRL funding, is working on the correlation of static charge build-up with CAT. United Air Lines agreed to install a recording unit on ten of their DC-8's and operate the sets in schedule operation to get as much data as possible about this correlation. The DC-8 is suited admirably for such an installation, as the fin cap is isolated electrically from the rest of the structure, with two 1.5-MΩ resistors in parallel. The current flowing through one of these resistors to the static dissipators on the top of fin and rudder is recorded continuously. The pilot indicates turbulence by pushing an event marker switch. Accelerations encountered in turbulence are recorded on the crash recorder. Phase I of this project is completed, and Stanford Research Institute and United Air Lines are considering Phase II. The results indicate thus far that there is a correlation between CAT and static charge, which usually gives some warning. There have been instances where there was no CAT warning by static charge indications. The spread in warning time varies considerably from seconds to as much as 18 min in one instance. Phase II will have a recorder with channels for time, accelerations, static field meter, current from tail static dissipators, radome charge, and ambient temperature. An attempt will be made to determine whether the charge comes from the turbulence air or is a triboelectric effect produced by particulate matter. With acceleration on the same tape as the static charge recordings, better correlation will be possible.

The static charge indicator in its present state of development merely indicates proximity of a CAT area. There have been proposals for locating static field meters on wing tips and tail in circuitry which would indicate direction and possibly range of CAT. The Stanford Research Institute-United Air Lines device is the simplest now being considered seriously, and if the device gives reasonable good warning with reliability of moderate to severe turbulence, it would be an inexpensive device for the DC-8 operators until a better CAT warning device is developed.

Other CAT Detection Principles

There are several proposals for CAT detectors which should be mentioned briefly.

Ozone Detector

It is known that whenever the jet stream penetrates the tropopause downward, ozone is swept into the propopshere from the stratosphere. There is always an area of turbulence in the vicinity of this penetration. AFCRL has implemented a U-2 with a standard O_3 detector and accelerometer to explore the correlation of O_3 with CAT. From the limited flying on this project to date, no conclusions have been drawn. It is known that O_3 concentrations exist in several areas where there is no CAT, especially just above a high cloud deck with intense sunlight. Although there will be some correlation between O_3 and CAT, there probably will be many times when there will be no CAT.

Infrasonic Pressure Wave Sensor

Turbulence produces pressure waves that probably travel a considerable distance beyond the turbulent air mass. If these can be sensed, they might be a good CAT indicator. United Air Lines has plans to install sensitive pressure transducers at suitable locations free of airplane induced pressure aberrations and having resonant response rates that would not give false indications from pressure pulses or "noise" produced by the airplane. This will be a difficult thing to do as the pressure pulses at 5 to 10 miles from the turbulent areas must be very feeble, and the airplane induced pulses are strong at 0.7–0.9 M speeds.

With one sensitive pressure transducer on the airplane, proximity to a CAT area might be indicated. With two or more transducers correctly located, direction might be possible. Range information is not possible with this passive system. The great difficulty with this system is to segregate and sense small pressure pulses in the atmosphere surrounding CAT from the strong pressure pulses generated by various parts of the airplane at high speeds and from the engine inlets and tailpipe jet streams.

CAT Detectors for the Supersonic Transport

It is generally agreed that speed is a factor in the reaction of an airplane to atmospheric turbulence. In certain meteorological structures the slow plane undulates easily through, whereas the fast plane gets a good buffeting. Although not many hours have been flown at supersonic speeds, there is evidence that the supersonic transport (SST) will be subject to CAT at its cruising altitudes above 50,000 ft. While interviewing scientists and engineers who are working on CAT detection, we have frequently asked how the particular device will function at supersonic speeds. It has been the hope that whatever device is developed for subsonic jets will be suitable for the SST. No one to date has attempted to determine whether a laser beam scanning ahead will be deflected or bent by the shock wave sufficiently to upset its accuracy. All heat sensing devices must get through the 500° to 600°F at the nose of the instrument to sense a few degrees temperature rise. No one knows whether the triboelectric effect of particulate matter in the stratosphere will overwhelm whatever static fields may exist around CAT at Mach 2 or 3 of the SST to make a CAT detector based on this principle ineffective. If *C*- and *X*-band radar will work at Mach 2 and 3, the vhf radar CAT detector may not have too much difficulty in overcoming the refractive index at the shock wave. It is notable that a CAT detector has been listed as one of the unsolved problems of the SST.

It was stated in the first pages of this article that many areas of basic research must be accomplished before the necessary scientific information about the atmosphere will become available to designers of CAT detectors. A committee is now being formed under the Chief of the U. S. Weather Bureau, to be composed of government representatives from all the agencies having an interest in this subject. One of the main objectives of this committee will be to see that research in the voids of knowledge about turbulence in the atmosphere is accomplished. This is a constructive move and should hasten the development of a good CAT detector.