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Clear Air Turbulence: Detection by Infrared Observations of Water Vapor

Abstract. *"Forward-looking" infrared measurements of water vapor from the C-141A Kuiper Airborne Observatory of the National Aeronautics and Space Administration Ames Research Center show large, distinctly identifiable, signal anomalies from 4 to 10 minutes in advance of subsequent encounters with clear air turbulence (CAT). These anomalies are characteristically different from the signals not followed by CAT encounters. Results of airborne field trials in which the infrared radiometer was used indicate that, out of 51 situations, 80 percent were CAT alerts followed by CAT encounters, 12 percent were "false alarms" (CAT alerts not followed by CAT encounters), and 8 percent were CAT encounters not preceded by an infrared signal anomaly or CAT alert.*

The prediction of turbulence at high altitudes (9 to 20 km), especially in clear air, is a problem for both subsonic and supersonic flight. Clear air turbulence (CAT) refers to all forms of turbulence occurring in clear air which do not involve convective forces.

Several investigators have proposed and some have flight-tested infrared (IR) radiometers sensing temperature fluctuations related to CAT in the CO_2 band of the spectrum (*1, 2*). These techniques have not been totally satisfactory because of a rather high failure rate. Some researchers have suggested that it might also be possible to identify CAT on the basis of water vapor anomalies (*1*). To our knowledge, no one has flight-tested a CAT-sensing radiometer detecting signals in the water vapor bands, at 6.3 μm and at 19.0 to 37.0 μm.

Such a radiometer system has been developed and is flying on the National Aeronautics and Space Administration C-141A Kuiper Airborne Observatory (Fig. 1). The goals are (i) to develop a simple water vapor radiometer system of modest cost that can operate unattended and can achieve accuracy in alerting air crews to CAT encounters from 4.0 to 10.0 minutes before the event and (ii) to study the most probable mechanisms which allow the passive detection of CAT in the water vapor IR bands.

The CAT radiometer employs bandpass filters transmitting from 280 to 520 cm^{-1} or from 1540 to 1670 cm^{-1}. The unit, weighing less than 3.2 kg, is installed "looking" forward in the right wheel well of the C-141A heavy jet. The optical system consists of the following components in the order given: a KRS-5 lens, the interference filter, and the detector. A second channel of the same radiometer contains a filter (9.5 to 11.5 μm) to differentiate between clouds ahead and a true water vapor signal anomaly. The radiance arriving at the detector comes from two sources: (i) emission from the water vapor along the column in the field of view of the radiometer and (ii) background emission from clouds or hydrometeors. The radiance (in watts per square centimeter per steradian) may be represented by

$$N = -\int_\nu\int_s B(\nu,T)\,\phi(\nu)\frac{\partial\tau(H_2O)}{\partial s}\,ds\,d\nu + \int_\nu B(\nu,T_0)\,\phi(\nu)\,\tau_0(H_2O)\,d\nu \qquad (1)$$

where B is the Planck function (in watts per square centimeter per steradian per wave number), ν is the wave number (in reciprocal centimeters), T is the temperature (in degrees Kelvin), ϕ is the filter-detector function, τ is the water vapor transmission, s is the slant path distance (in centimeters), T_0 is the source temperature (in degrees Kelvin), and τ_0 is the total water vapor transmission along the slant path to a source from the detector.

The radiometer is directed upward at a fixed elevation angle of from 2.5° to 7.5°. Inhomogeneities in the water vapor emission entering the 2° cone of acceptance of the radiometer produce anomalies in the detector response and strong signal gradients which are readily detected as sharply varying output signals. After subsequent testing we will also operate the radiometer at elevation angles below the horizontal for anomalies beneath flight level.

Generally, there are two conditions under which CAT may develop. The first is a standing wave in the lee of a mountain barrier which occurs when statically stable air is carried over the mountain. The second condition results from waves formed in statically stable layers in the atmosphere that are subjected to sufficiently strong vertical wind gradients (shear). These shear-induced waves are commonly referred to as Kelvin-Helmholtz (KH) waves. A considerable body of experimental evidence suggests that KH instability is an important mechanism for generating CAT (*3*). When KH waves are of sufficient amplitude, they become unstable and develop into three-dimensional turbulence. Dutton and Panofsky (*4*, p. 944) have stated that "at least some of the clear air turbulence results from the hydrodynamic instability of internal fronts in accord with the Kelvin-Helmholtz model."

The onset of KH instability in a statically stable but sheared atmospheric layer is determined by the value of the local Richardson number,

$$Ri = \frac{\dfrac{g}{\theta}\left(\dfrac{\partial\theta}{\partial z}\right)}{\left(\dfrac{\partial U}{\partial z}\right)^2} \qquad (2)$$

Here g is the acceleration of gravity, θ is the potential temperature, z is the height, and U is the horizontal wind velocity. Basically Ri is a measure of the ratio of the potential energy required to overturn a stable layer to the kinetic energy available from the mean shear to accomplish this. A necessary but not sufficient condition for KH instability is expressed by $Ri \leq 0.25$.

Arguments suggest that regions characterized by internal fronts and sloping tropopause are favored areas for KH instability and CAT formations (*5*). These regions, which are statistically linked with the occurrence of CAT, can be identified on the synoptic charts. However, it is virtually impossible to predict in advance when and where individual patches of CAT will occur. Thus, the necessity for an on-board alert system has long been recognized.

It is well known that KH waves "roll up" the atmospheric layers in which they form and that the vertical gradients of water vapor in some regions are as much as 20 times greater than their initial undisturbed values. Figure 1 depicts schematically how a transition to KH waves results in the entrainment of water vapor into the breaking waves. As the

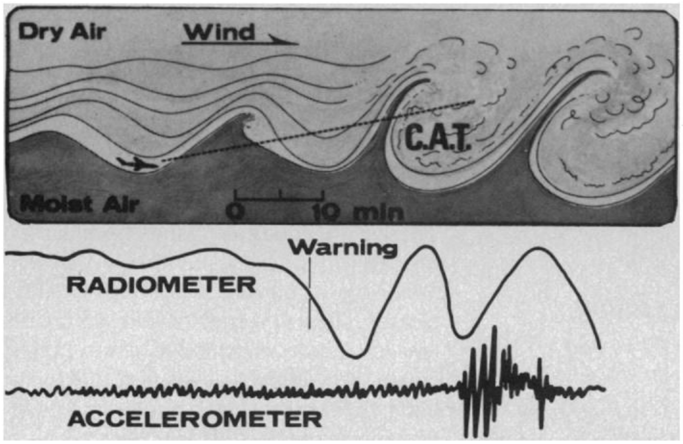

Fig. 1. Schematic showing the C-141A heavy jet in advance of the breaking KH waves. Lines in the lower portion show hypothetical radiometer and accelerometer traces.

water vapor along the slant path changes in response to the KH waves, the radiometer signal fluctuates correspondingly. The output signal is proportional to the optical mass of water vapor along this path, and sharp gradients in its distribution lead to large second derivatives with respect to time in the voltage output signal. In a region undisturbed by CAT, as one would expect, the radiometer signal is relatively stable and is associated with the longer-term synoptic variations of atmospheric water vapor.

Infrared transmission is a strong function of wavelength. The radiometer senses radiant emission in the water vapor band from varying distances depending upon the pass band 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 may be defined as the derivative of transmittance with respect to the natural logarithm of pressure. These functions describe approximately the relative sensitivity of the radiant power observations in the IR bands to water vapor fluctuations at various distances ahead of the aircraft. The "range" for the radiometer can be adjusted by the selection of the proper filter. Our present choice of the filter region is the pass band from 280 to 520 cm^{-1}, which gives a maximum range of 160 km.

The alert condition for the subsequent onset of CAT is communicated through low-cost microprocessing of the radiometer output voltage. A short (60-second), continuously updated, voltage time series is used. The second derivative in the output voltage, $\bar{E}$, is monitored, and is represented by

$$C = \frac{d^2\,\bar{E}}{dt^2} \simeq \frac{\Delta^2\bar{E}}{\Delta t^2} \qquad (3)$$

Here $\bar{E}$ represents the mean voltage output of each succeeding 30-second interval, Δt. Within each time interval there are 15 observations of voltage. We have found the CAT alert criterion for C to be 0.4 volt sec^{-2} for the radiometer used.

Figure 2 illustrates typical analog records of radiometer output (left) and accelerometer output (right). In this example four out of five occurrences of CAT were predicted by the radiometer output signal within 4 to 10 minutes of occurrence. Full scale on the IR radiometer output is 10.0 volts; full scale on the accelerometer output record is 0.5g, peak to peak. Recorders are synchronized in time with each minor division on the vertical scale representing 0.75 minute. The radiometer requires a short time history of output signal (60 seconds) to detect the water vapor gradients ahead of the aircraft that are related to CAT. Preliminary results indicate that the water vapor radiometer will detect CAT encounters with acceptable reliability from 4 to 10 minutes in advance of the encounter. The results also suggest that the radiometer output may indicate the severity of the ensuing encounter and that further experimentation on varying bandwidth, field of view, and elevation angle is warranted.

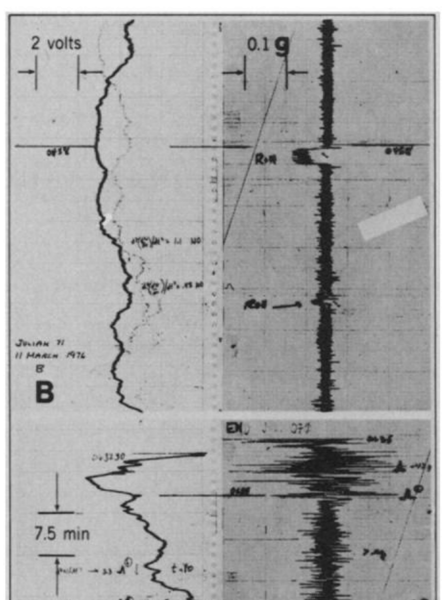

Fig. 2. Dual traces of CAT radiometer output (left) and accelerometer (right). (Top) A situation without CAT with a normal radiometer output ($C < 0.4$ volt sec^{-2}). (Bottom) Situations characterized by CAT encounters with anomalous radiometer outputs ($C > 0.5$ volt sec^{-2} in all cases); alert times range from 4 to 10 minutes. Altitude, 13.5 km; date of measurements, 11 March 1976.

Results of the use of the IR radiometer to detect CAT incidents and alerts at an altitude of 13.5 km above sea level indicate that, out of 51 situations, 80 percent were CAT alerts followed by CAT encounters, 12 percent were CAT alerts not followed by CAT encounters, and 8 percent were CAT encounters not preceded by an IR signal anomaly or CAT alert. These results encompass all CAT incidents, whether predicted or not, having a vertical acceleration of at least 0.2g. The minimum alert time for positive verification is 4.0 minutes, and the maximum alert time is 10 minutes. Our results indicate that a simple radiometer sensitive to radiant emission in the water vapor bands can be used in conjunction with a relatively inexpensive microprocessor (to convert the radiometer signal to a display system) to produce an inexpensive, although reliable method for early CAT warning.

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