CLEAR AIR TURBULENCE STUDIES WITH MICROWAVE RADIOMETERS

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SUMMARY

Two passive microwave radiometers were flown on the Ames CV-990 aircraft during the 1979 Clear Air Turbulence Mission (see reference 1 for a mission description). A 55.3 GHz radiometer was used to measure "altitude temperature profiles", and a 180 GHz radiometer was used for monitoring line-of-sight integrated water vapor content. The measurement of altitude temperature profiles was motivated by the suggestions that: 1) CAT (Clear Air Turbulence) is often found within inversion layers (Haymond, unpublished[1]) and at the tropopause, and 2) CAT severity is related to the static stability (lapse rate) of the layer within which the turbulence is generated (Haymond). The water vapor measurements were motivated by the recent success of Dr. Peter Kuhn (Reference 2) in providing warnings of CAT encounters using an IR sensor that responds to line-of-sight water vapor content. The microwave counterpart has the advantage of not being subject to the confusing influence of cirrus clouds.

INTRODUCTION

It is desirable that a CAT (Clear Air Turbulence) warning system provide the answer to three questions: when, how severe, and how to avoid. The bulk of previous sensor development has been devoted to answering "when", and usually in a qualitative manner (i.e., "soon", or "not soon"). A convincing flight demonstration of severity forecasting and avoidance guidance has not yet been conducted. To the author's knowledge, no CAT sensor is in operational use at the present time.

The intent of the 55.3 GHz sensor evaluation, which will be described briefly here, is to develop a severity forecasting and altitude avoidance capability. The intent of the 180 GHz sensor evaluation is to develop an "improved" (cirrus insensitive) version of the IR CAT warning sensor that is being flight-tested by Dr. Kuhn.

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[1]High Altitude Clear Air Turbulence, 9WS Tech. Rep. #2, 1967, by F. Haymond.

55.3 GHz MEASUREMENTS

The 55.3 GHz radiometer is a modified version of the NIMBUS-6 SCAMS (Scanning Microwave Spectrometer) instrument. Measurements of sky brightness temperature were made at a sequence of elevation angles spaced 4 degrees apart and extending from -16 degrees to +20 degrees. Aircraft-generated parameters were measured every 2 seconds (roll, pitch, pressure altitude, static air temperature, and vertical accelerometer output). The instrument was mounted inside the cabin, with a view through a specially designed microwave-transparent window.

Sky brightness temperatures measured by the 55.3 GHz radiometer are related to the physical temperature of the oxygen molecules along the viewing direction, range-weighted in accordance with an e-folding distance of about 3-kilometers. Elevation angle scanning moves the "applicable altitude" above and below the aircraft altitude in accordance with: h=3km*sin(elevation). As a first approximation, air temperature versus altitude can be estimated from the plot of sky brightness temperature versus elevation angle, with the elevation angle re-scaled to correspond to "applicable altitude". The altitude coverage is typically 1500 m (5000 ft), centered on the aircraft altitude. The altitude resolution is approximately 10% of the altitude coverage (for the instrument described here). This is sufficient for the detection of most inversion layers with thickness exceeding 300 m (1000 ft).

Figure 1 is an example of "altitude temperature profiles" generated from the 55.3 GHz radiometer measurements in the manner described above. The left panel is the most commonly observed profile, exhibiting lapse rates (slopes) of about -7 K/km. Occasionally, the dry adiabatic lapse rate of -9.5 K/km is observed. The right panel was taken while flying within an inversion layer. Note how it is possible to read off the altitudes of the lower and upper boundary of the inversion layer. It is also possible to estimate the lapse rate within the inversion layer. Panels like these are obtained every 17 seconds of flight (3.5 km). It is therefore possible to monitor the various properties of the inversion layer, and to characterize it as unchanging or changeable.

INTERPRETATION OF 55.3 GHz MEASUREMENTS

Layers of air that exhibit an adiabatic lapse rate are unable to sustain wind shear. Sub-adiabatic layers (including inversion layers) are able to support wind shear. It is commonly thought that vertical wind shear is the energy source for the turbulent motions associated with CAT. Since large values of wind shear represent a large reservoir of energy for the production of CAT, it is natural to postulate that CAT severity bears a relationship to the magnitude of the wind shear within the layer. Since large values of wind shear can only exist within layers having large, positive lapse rates (i.e., inversion layers), it is natural to suppose that the most severe CAT will be found within inversion layers. Moreover, the greater the lapse rate of the inversion layer, the greater the severity of any ensuing turbulence. These predictions are supported by the measurements of Haymond (Ref. 1), who analyzed 4000 sorties of U2 aircraft, flying above the tropopause. It is important to independently verify these findings, especially for flight below the tropopause. The 55.3 GHz sensor is ideal for such an investigation.

The right panel of Figure 1 is one of a sequence covering a half-hour period. A case study analysis of this data set has been conducted and will be published elsewhere. To summarize, the inversion layer supported a wind shear of 28 knots, averaged 400 m (1300 ft) in thickness, and was generally isothermal when it was 400 m (1300 ft) thick. If it is assumed that the wind profile compressed and expanded as the temperature field defining the inversion layer compressed and expanded, then it is possible to calculate a Richardson number for each hypothetical thickness (Richardson number, Ri, is the ratio of stabilizing forces to overturning forces, or Ri = "potential temperature lapse rate" divided by "wind shear squared"). In this way, it is calculated that when the layer is thinner than about 210 m (700 ft), Ri will be <0.25, which is a theoretical precondition for growth of wind shear driven instabilities. The layer was observed to vary in thickness from a high of 760 m (2500 ft) to a low of 120 m (400 ft) (briefly). When it was at its shallowest, "nibbles" of turbulence were noted. Unfortunately, the aircraft 120 m below the inversion layer when these conditions occurred, and it can only be speculated that the turbulence originated, and was more severe, within the inversion layer.

The observations described in the previous paragraph are significant in several respects. First, the behavior of the inversion layer supports the theoretical portrayal of CAT being formed by the breakdown of Kelvin-Helmholtz waves, which are driven past their stability limit by conditions associated with decreasing Richardson number (to the $<1/4$ region). Second, inversion layers that are very dynamic do not always produce CAT. In other words, CAT sensors that base their "when" warnings on variability of the remotely sensed temperature field must contend with the false alarm problem. Third, if a CAT "when" warning sensor is ever found acceptable for operational use, a radiometer similar to the 55.3 GHz sensor could be deployed for the altitude location of nearby inversion layers, which could then serve for any evasive actions that the pilot deems necessary. It is important to learn how often inversion layers are the source of CAT, or else altitude changes for their avoidance would be fruitless.

During the 1979 CAT Mission there are many instances when CAT was found within inversion layers. On some occasions, during ascents or descents, there is a remarkable association between turbulence intensity and inversion layer location. However, there are many cases where CAT was encountered when the 55.3 GHz sensor did not show the presence of an inversion layer. Many flight hours were spent at low altitudes, near ridge level, searching out topography-generated turbulence. Under these circumstances, inversion layers would not be related to the origin of the turbulence in the same way that can be expected for cruise altitude events. A systematic study of the statistical association of CAT encounters with inversion layer locations will have to be conducted. Although such a study will be performed on the 1979 CAT Mission data in hand, a more definitive analysis should be available in 2 or 3 years, when a highly improved version of the 55.3 GHz radiometer is deployed for a more extensive evaluation on NASA's C-141 aircraft.

180 GHz MEASUREMENTS

The 180 GHz radiometer was borrowed from a different project, and has been described in Reference 3. The wide bandwidth channel was used during the 1979 CAT Mission. The radiometer was mounted inside the cabin, with a view through a microwave transparent window (high-density polyethelene, with 1/4 wave grooves). The viewing direction was 12 degrees elevation and 50 degrees right of forward. The antenna beamwidth was 5 degrees. The radiometer output was gated every 2 seconds, and the sensitivity was typically less than 1 K. At the frequency of 180 GHz, the atmosphere is approximately 50% transparent at an altitude of 6 km (20 000 ft) (for the viewing direction used). At 180 GHz, the principal source of opacity (and, hence, emission) is molecular water vapor. Roll compensation was not applied, which greatly complicated the task of extracting atmospheric related variations. Small frequency drifts occurred at random times, creating gain drifts, which occasionally complicated isolation of atmospheric effects. It should be noted that radiometers for operation at frequencies as high as 180 GHz are difficult to build, and their state of the art is improving rapidly.

The basis for Dr. Peter Kuhn's CAT warning capability is that shear-driven Kelvin-Helmholtz waves disturb the flatness of an interface separating overlying air masses that are characterized by different absolute humidities (Ref. 2). The variations in line-of-sight water vapor which are measured by an IR sensor in an aircraft that is underflying the interface region are revealing a process that is intimately related to the generation of CAT. I have suggested (Ref. 4), using simple geometrical arguments, that if warning times of several minutes can be generated from viewing directions that are inclined upward by 7 degrees and greater, there must be an annulus of disturbed air, surrounding the CAT region, that is recognized by the IR CAT sensor. The IR CAT sensor, in other words, issues its warning before its viewing cone intercepts that part of the air containing the CAT.

The reasoning described in the previous paragraph convinced us that, in spite of the off-forward viewing direction (that an inside-the-cabin installation would require), a fair evaluation might still be possible of the merits of a 180 GHz sensor as a forecaster of CAT encounters if it were included in the 1979 CAT Mission. As stated in the introduction, the motivation for installing and operating the 180 GHz radiometer is that it would not be subject to the confusing influence of cirrus clouds, which leads to false alarms for the IR CAT sensor. The scattering and absorbing cross section of ice crystals is orders of magnitude smaller at 180 GHz than at 30 microns, where the IR CAT sensor operates.

RESULTS OF 180 GHz MEASUREMENTS

As expected, cirrus clouds had no noticeable effect on the 180 GHz radiometer output. This much had been demonstrated on previous flights by Waters (private communication, 1977).

A few of the 100 total hours of 180 GHz data have been cleansed of roll-related fluctuations. Plots of RMS variation were constructed, and correlations with light and moderate CAT encounters were sought. No correlations were found! Dr. Peter Kuhn, whose IR CAT sensor was installed on the same aircraft, reports successful warnings throughout the 1979 CAT Mission.

There are 6 differences between the 180 GHz radiometer and the IR CAT sensor that can be considered as potential explanations for the difference in their performance:

1. Sensitivity, 10 versus 5 microns of precipitable water vapor (estimated)
2. Beamwidth, 5 degrees versus 2 degrees
3. Off-forward viewing direction, 50 degrees versus 0 degrees
4. Elevation, 12 degrees versus 7 degrees
5. Sampling rate, 2 seconds versus 0.1 second
6. Sensitivity to roll variations

Item 4 is probably not important. Item 1 is perhaps more important than it appears. The 180 GHz radiometer output was definitely "radiometer noise" limited, and not "sky noise" limited, whereas the IR CAT radiometer appears to have been "sky noise" limited! Although the sampling rates appear to be significantly different, the IR CAT sensor is reported to produce warnings when the raw data stream is converted to a sequence of 1-second averages. Indeed, the earlier data from this sensor (Ref. 2) shows variability on time-scales far longer than 2 seconds, during times that are associated with flight through turbulence. At this time, there is no unique explanation for the difference in performance between the two sensors.

A greatly improved 180 GHz radiometer could be built with present technology. It is possible that all the shortcomings in performance relative to the IR CAT sensor, that are listed above, could be overcome. (It should not be forgotten, however, that any microwave counterpart to an IR sensor can be expected to cost more to produce.) The principal result of the 180 GHz flight experience is that any microwave counterpart to the IR CAT sensor will have to be significantly better than the 180 GHz radiometer described above.

CONCLUDING REMARKS

The 55.3 GHz airborne radiometer is the first of its type. It was used to measure, for the first time, "altitude temperature profiles". The sequence of profiles, spaced 17 seconds apart (3.5 km), enable inversion layer and tropopause properties to be studied. On some occasions, the altitude distribution of CAT severity correlated remarkably well with inversion layer location. On other occasions, turbulence was not located within 55.3 GHz measured inversion layers. These may be cases of topography-generated CAT, where inversion layers would not necessarily be expected. Evidence has been obtained supporting the hypothesis that CAT is generated within layers containing levels of wind shear that cannot be supported by the layer's lapse rate; i.e., that Kelvin-Helmholtz wave breakdown can generate CAT.

The 180 GHz radiometer failed to warn of CAT events. It is suggested that the radiometer's sensitivity (1 K) was inadequate for detecting the small variations in line-of-sight water vapor content, which are reportedly responsible for the success of Dr. Peter Kuhn's IR CAT warning sensor. The 180 GHz radiometer was not affected by cirrus clouds, which should justify its continued consideration for future sensor development.

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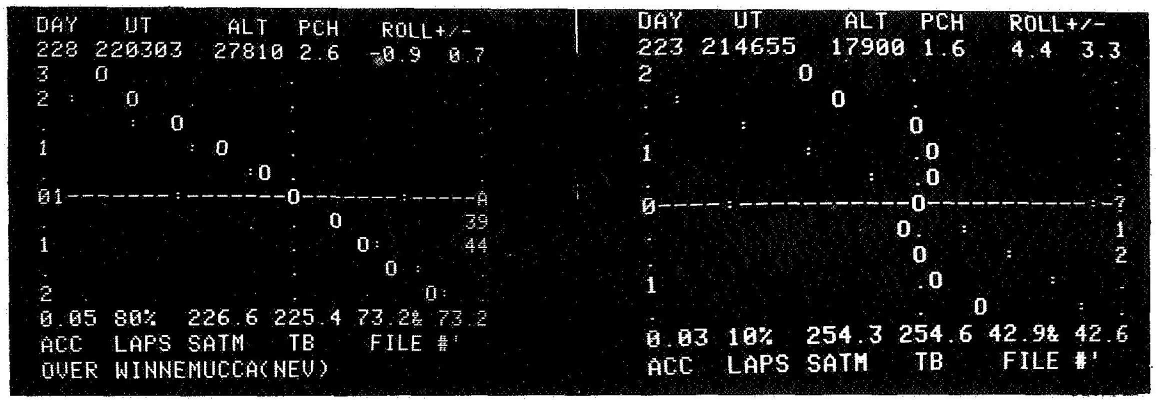

The JPL airborne passive microwave sensor that was test-flown in a NASA research aircraft demonstrated that "altitude temperature profiles" can be measured remotely, and in real time. The panel on the left shows that from 610 m (2000 ft) below aircraft to 910 m (3000 ft) above, observed air temperature "0" decreased uniformly with altitude. The dashed horizontal line, corresponding to aircraft altitude (8476 m (27 810 ft) for this panel), has the temperature scale coded with semicolons 10 K apart. Temperature at aircraft altitude is 225.4 K. The sloping pattern of semicolons correspond to an "adiabatic" atmosphere, in which it is nearly impossible to generate turbulence. The panel on the right illustrates an inversion layer at aircraft altitude (5456 m (17 900 ft)). The boundaries of the layer are at 90 m (300 ft) below and 400 m (1300 ft) above. If a "yes/no" type of turbulence detector shows that CAT is imminent, the pilot could use the information contained in this panel to request an assignment to a lower altitude, and thereby underfly the region of greatest turbulence.

Figure 1.- Clear air turbulence studies with microwave radiometers.