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INFRARED BACKGROUND MEASUREMENTS

D.G. Murcray
F.H. Murcray
F.J. Murcray
W.J. Williams

Department of Physics
University of Denver
Denver, Colorado 80208

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The objective of this program was to measure the background radiance of the earth and its limb in the infrared from high altitude. Two types of measurements were to be made: high resolution spectral measurements using an interferometer system and moderate resolution measurements, particularly in the 4.3 μm and 15 μm region, using filter radiometers. The high resolution data were to be obtained by means of a liquid-nitrogen

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20. ABSTRACT

cooled (total containment) interferometer system which was to be government-furnished equipment. This instrument was not delivered during the program; hence, no data were obtained. Two filter radiometers were flown on the Stratcom VIII B payload: one with a filter centered at 2362 cm^{-1} and the other at 682.3 cm^{-1}. Data obtained with the 682.3 cm^{-1} unit are presented and compared with the radiant temperatures determined from the rawinsonde runs.

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INTRODUCTION

The infrared background presented by the earth and its atmosphere to a high altitude infrared sensor depends on many factors. A number of these are associated with the viewing geometry and, in particular, whether the field of view includes the solid earth or only the atmosphere above the limb. The background also depends strongly on the wavelength region of interest. It is possible, in theory, to predict this background radiation, at least at altitudes below 60 km where local thermodynamic equilibrium (LTE) applies. In order to make such a prediction it is necessary to know the distribution with altitude of the molecular species present in the earth's atmosphere which have absorption features in the wavelength region of interest. In addition, it is necessary to be able to accurately predict the spectral absorption characteristics of the various species, given the information concerning their altitude distribution. In general this background is dominated by the emission due to the more common gases (CO_2, H_2O, O_3, CH_4, N_2O). In some spectral regions at the higher altitudes and, particularly, over narrow wavelength regions (high resolution) this is no longer the case, and dominant emission may be due to one of the minor constituents (e.g., HNO_3, $CFCl_3$ or $CFCl_2$ in the 10μ to 12μ region). Thus, a complete characterization of this background radiation requires knowledge of the distribution of a number of minor constituents known to be present in the earth's upper atmosphere. It can also depend on the distribution of several molecular species predicted to be present in the upper atmosphere which have not, as yet, been measured (e.g., HO_2NO_2, N_2O_5, $ClONO_2$, etc.). In view of this limited knowledge regarding minor species and the difficulty of predicting emission features of a number of more common species (CH_4, O_3, etc.) over the long paths encountered in viewing the atmosphere close to the limb, it is evident that estimates of the performance of infrared sensors against this background will have to be based on measurements. In fact, such measurements can be used to obtain data on the distribution of many of these constituents.

While the background radiation may be the limiting factor in the performance of various proposed infrared sensors (in many spectral regions) at the higher altitudes, the atmospheric emission is very weak, and very sensitive instruments are required to measure the radiation under the resolution required for this study. In order to achieve this sensitivity the instrument used to make the measurement must be cooled to reduce background noise and to increase its sensitivity, and it should have a large throughput. In order to meet these objectives the Air Force Geophysics Laboratories has had a liquid nitrogen-cooled interferometer system constructed which is capable of a resolution of 0.1 cm^{-1}. One task in this program was to incorporate this system into a suitable balloon-borne payload and to use the system to obtain data on the spectral distribution of the atmospheric background radiation near the limb from altitudes up to 30 km.

In some spectral regions, particularly those associated with CO_2, the emission is greater and sensitivity is not a problem. These emissions are used to determine atmospheric temperature from satellites. Recent comparisions of temperatures inferred from such satellite data with those obtained by standard rawinsonde indicate significant discrepancies between the two profiles. The cause of these discrepancies is being investigated as a second part of this program. Small sensitive radiometers capable of passing fairly narrow spectral intervals have been flown piggyback on a balloon flight performed on another program, and the radiances observed are being compared with those calculated using appropriate computer programs. The work accomplished on these two programs is discussed below.

INSTRUMENTATION

Cold Interferometer System

As mentioned in the Introduction, the cold interferometer for use in this study was to be furnished to the University of Denver by the Air Force Geophysics Laboratory. The system consists of a cat's eye interferometer capable of 0.1 cm^{-1} resolution, and is designed to operate inside a dewar at liquid nitrogen temperatures. The system design configuration supplied to us indicated the gondola preparation for proper operation as a balloon payload was a crucial part of the program. The project consisted of preparing the system environment for operation as a balloon payload by first configuring the gondola to protect the instrument during the balloon flight, and providing a means of integrating the total system into a single unit. The second task was to provide a means of cooling the window on the dewar to temperatures close to $77^{o}K$ in order to reduce the background noise and to increase the sensitivity of the unit. The third task consisted of assuring that packaging the instrument electronics insured that the unit operated properly in the altitude range from the ground through 40 km under either day or night-time conditions.

The importance of the gondola in a balloon experiment cannot be overemphasized. A significant number of expensive payloads have been badly damaged, or in some cases destroyed, by poor gondola design. In addition to protecting the instruments upon return to the ground by parachute after the flight, the gondola also helps reduce the various forces which the equipment is subject to during the launch operation, and ensures a proper environment for the operation of the instrument package. The gondola for this program was constructed of brazed conduit and configured to keep the center of gravity low. The floor of the gondola was reinforced with aluminum I-beams. The rectangular design used makes mounting the various components into the gondola much easier and helps keep the unit upright on impact. This type of construction has been used successfully on a number of past programs. The gondola is suspended from the corners by aircraft cables, and a spreader rectangle keeps the cables from rubbing instrumentation extending above the gondola, while allowing the cables to be short. Crushable paper honeycomb is used as a crash pad to reduce the accelerations on the instruments during impact after the flight.

The antifrost system used for cooling the infrared window on the interferometer dewar also incorporates features which have been used on other balloon-borne systems requiring a cold window. The system consists of a liquid nitrogen dewar which supplies liquid nitrogen to a ring attached with good thermal contact to a window mount. Boil-off dry nitrogen gas is brought from the top of the dewar and introduced into an antifrost baffle system which is mounted around the lens. The flow of the dry nitrogen gas within the baffle keeps frost from forming on the lens. One of the major problems with such a system is maintaining the vacuum seal at the cold window. A number of techniques have been developed for accomplishing this, depending on the window material and size. This problem has been alleviated in recent years with the development of appropriate low-temperature epoxies.

The final problem, that of making sure the instrument electronics operate in the balloon environment, again involved a careful analysis of the various units based on previous balloon experience. The results of these analyses were generally routine (i.e., provide a proper temperature environment, potting various high voltage leads to avoid arc-over at the high altitudes, etc.).

Cold Radiometers

The radiometer units are designed for liquid-helium-cooled detectors operating at low background levels; therefore, the internal optics (lens and filters) are heat-sinked to the liquid-helium reservoir. The helium chamber and helium-cooled elements are surrounded with a liquid-nitrogen-cooled shield (except for the entrance aperture). The vacuum seal of the entrance aperture is by a zinc selenide window which is cooled to LN_2 temperatures. Gaseous nitrogen from the LN_2 boil-off is vented just outside the window and flows through the baffle system to provide cooling of the baffle and antifrost for the window. The units are operated DC, i.e. without chopping the incoming beam, since the radiance contributed by elements internal to the window should be negligible in comparison to the lowest signal levels ($\simeq 10^{-10}$ w cm^{-2} sr^{-1} μm^{-1}) expected in any of the applications intended for these units. The window has a low (~0.01) emissivity and is maintained at $< 80^{\circ}K$, so that for most measurements its contribution to the radiance can be neglected.

An internal radiation source, loosely temperature-coupled to the LN_2 shield so that its temperature (which is monitored) is 90° to $95^{\circ}K$, is periodically moved to cover the field of view. For this particular experiment this "flag" served as a nearly zero-level reference, since its blackbody radiance at 15μm for $95^{\circ}K$ ($\sim 1.3 \times 10^{-6}$ w cm^{-2} sr^{-1} μm^{-1}) amounts to about 1% of the blackbody radiance for the minimum atmospheric temperature. The "flag" serves as an in-flight calibration for other experiments where the expected signals are below the micro-watt level.

A system for the calibration of the instruments was prepared utilizing a source constructed to mount on the inner baffle assembly. The source provides a partial seal to the baffle assembly so that an over-pressure of the boil-off LN_2 is maintained, thereby preventing frost on both the blackbody surfaces and instrument window. The blackbody itself consists of a 15° cone machined into a 1-1/2" copper rod. The inner surface is oxidixed to provide a surface of high emissivity. The temperature is monitored at a point 1/16" directly behind the apex of the cone with a Lakeshore Cyrogenics DT500-A diode. The cone is surrounded by a LN_2 reservoir which is insulated with styrofoam. In the calibration procedure the reservoir is filled with nitrogen, and then output vs temperature readings are taken as the copper slowly warms after the LN_2 has evaporated. Both the radiometers were calibrated against this source. Several calibration runs were made, both in the laboratory and at HAFB just prior to the flight. These calibrations are discussed further under Error Analysis.

FLIGHT RESULTS

The cold interferometer system was not received by the University of Denver in time to be used on any balloon flights. Two filter radiometers were flown as part of the Stratcom VIII-B payload. The filters used in these radiometers were chosen to measure the atmospheric emission in the 4.3μm and 15μm CO_2 bands. One radiometer was equipped with a filter centered at 2362 cm^{-1} with a 16 cm^{-1} bandwidth. The other radiometer used a 3.5 cm^{-1} filter centered at 682.3 cm^{-1}. Launch of the instrumentation was at 1257 MST on September 28, 1977 from Holloman AFB, New Mexico, and the unit reached float altitude by 1600 MST. Unfortunately the payload was destroyed in a free-fall because of a parachute malfunction. Primary data recording was to have been by means of an on-board digital magnetic tape recording system. This was backed up by a PCM telemetry system. Since the payload was destroyed, data reduction had to be accomplished using the telemetered data. The 15μm unit functioned well throughout the flight. The 4.3 μm unit apparently malfunctioned shortly after launch. Data from the 15μm unit was recorded from about the 400 mb level through float altitude. The high gain data did not come on scale until the 300 mb pressure level was reached. Samples of the low gain data are available from the telemetry data; however, since primary emphasis of the flight was on the higher altitude, data reduction of the low gain data has been postponed.

DATA REDUCTION

The telemetry data was transmitted in 10-bit PCM format. The data channels were decoded and converted to analog outputs and fed to chart records for real-time viewing. It was necessary, however, to computer-process a tape recording of the original PCM in order to maintain the original 10-bit accuracy of the telemetry. Once this was done, radiance values were generated by converting the 10-bit words to the equivalent voltages and then multiplying the voltages by a factor derived from averaging the slope $\frac{dN}{dV}$ of the four calibration plots.

AUXILIARY DATA

Experience has shown that temperatures measured by rawinsondes attached to payloads of large polyethylene balloons are usually in error, with the errors amounting to several degrees. Presumably this error is caused because the lower ascent rates and large envelopes of these balloons do not provide proper convective flow.

The Atmospheric Sciences Lab at White Sands Missile Range has developed a technique for measuring local atmospheric temperatures from large balloon payloads that overcomes most of the problems encountered with the conventional rawinsonde in this application. This type of apparatus was flown as part of the payload for this flight. However, the data output from this ASL sensor was not entirely compatible with the PCM telemetry, so a considerable amount of effort was required to reconstruct the instrument output from the

PCM data. In addition, the ASL sensors depend on rotation of the gondola to provide a correction for solar input. Since the gondola during this flight was azimuth-stabilized, the usefulness of the ASL data is not clear at this time.

Rawinsonde temperatures for comparison with radiance data were, therefore, obtained from standard rawinsonde ascents made in conjunction with the flight. In addition, rawinsonde runs from several sites surrounding the Holloman area have been collected. The major advantage of an on-board rawinsonde would have been a more exact altitude registration for comparison of the profiles. Since this was not available, the radiance values were plotted as a function of pressure as measured by on-board pressure transducers and are shown in Figures 1 and 2. Blackbody radiance values for measured rawinsonde temperatures were plotted on the same scale as a function of pressure. These curves are shown in Figures 3 and 4, which represent the radiance inferred from a rawinsonde released at 0400 MST from Holloman AFB. Similarly, Figures 5 and 6 show rawinsonde data from HAFB at 1300 MST and 2100 MST from White Sands Missile Range at 1250 MST. Figures 7 and 8 present the 1750 MST significant level rawinsonde data from several sites in the southwest.

DATA ANALYSIS

In comparing the radiance values at a given pressure one must keep in mind the sensitivity of the 15μm radiance to temperature in the range represented by these plots. At 240°K a temperature

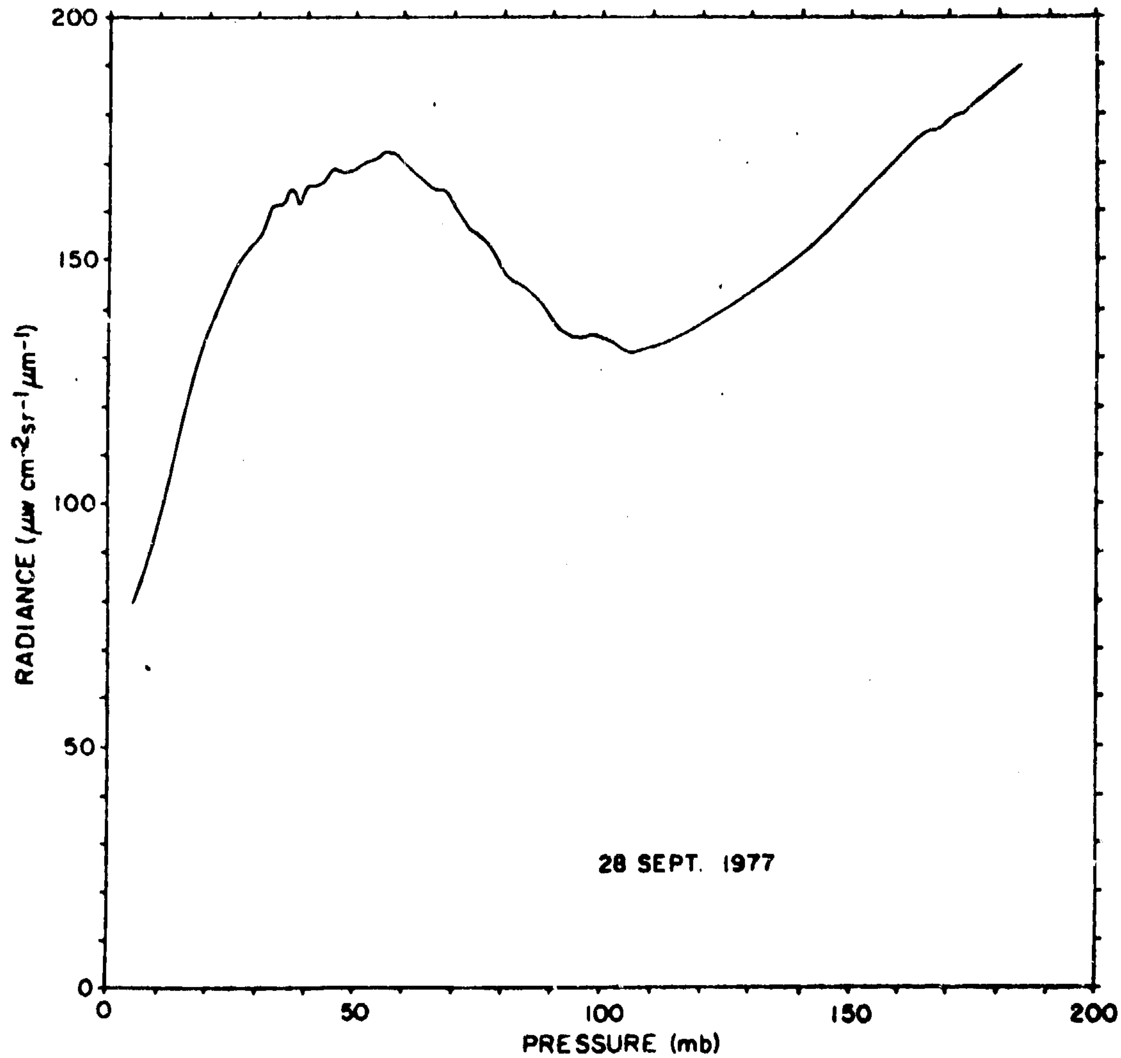

Figure 1. Radiance vs pressure as measured by on-board pressure transducers during the 28 September 1977 flight from Holloman AFB, New Mexico.

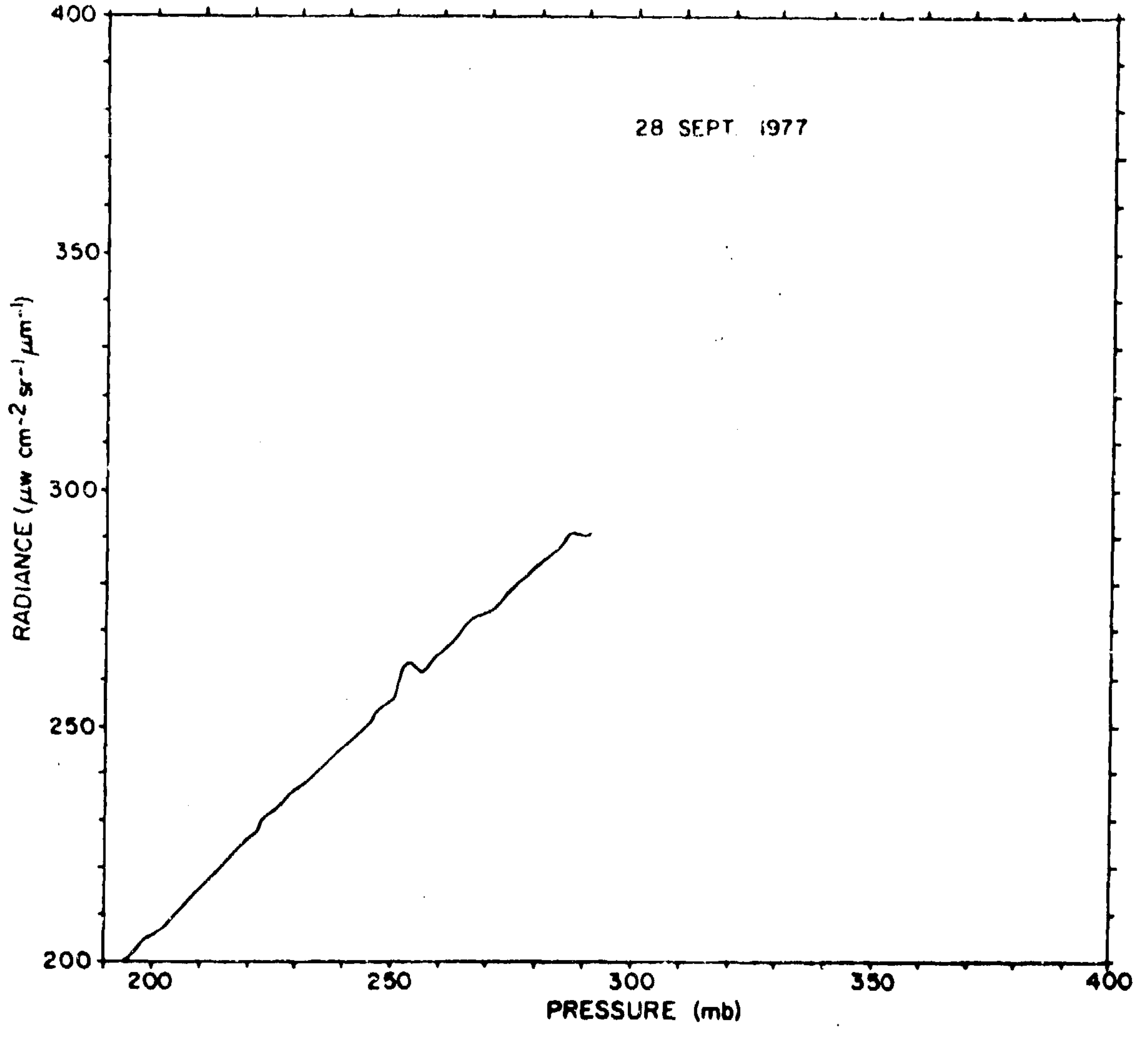

Figure 2. Radiance vs pressure as measured by on-board pressure transducers during the 28 September 1977 flight from Holloman AFB, New Mexico.

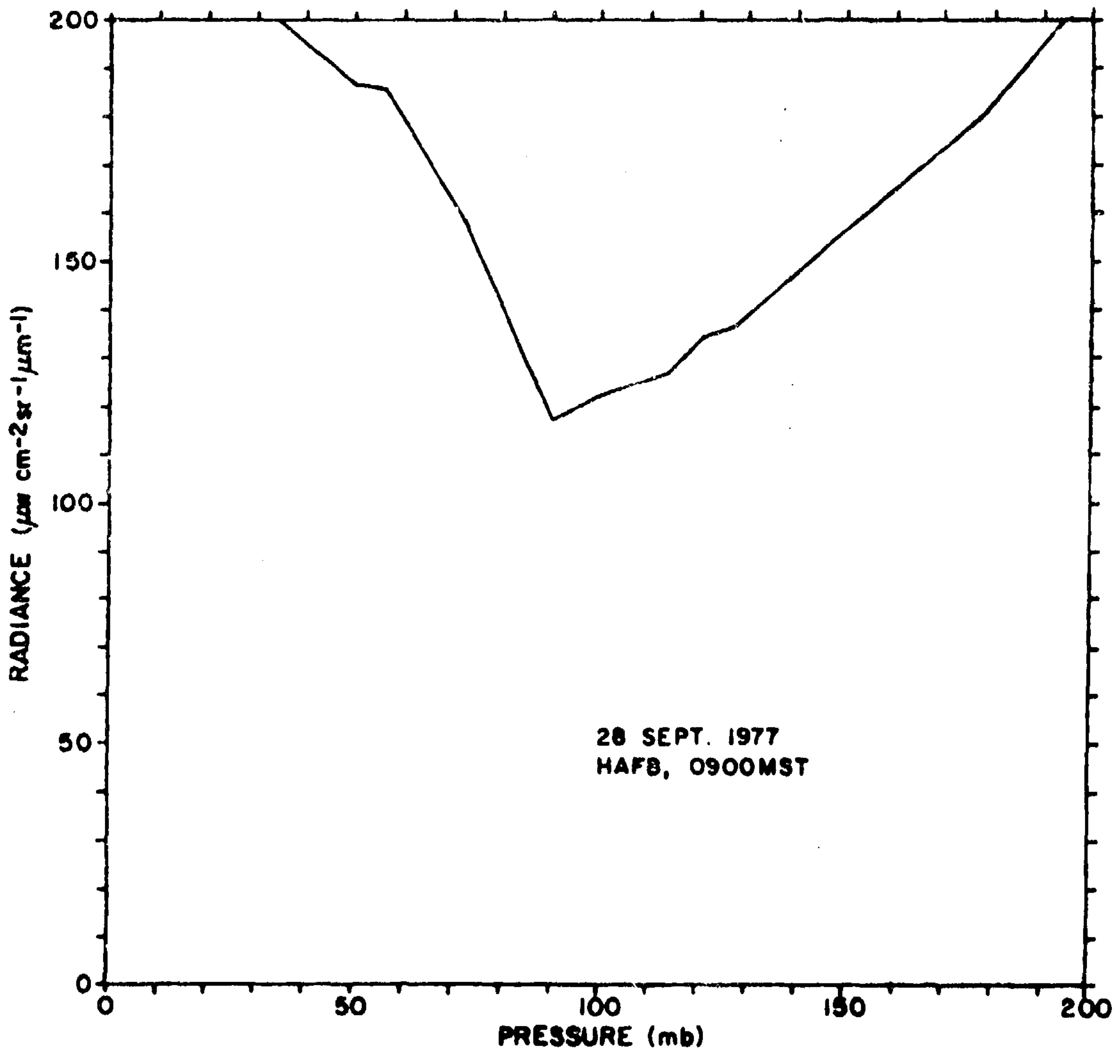

Figure 3. Blackbody radiance values for temperatures measured by HAFB rawinsonde vs pressure obtained by on-board pressure transducers.

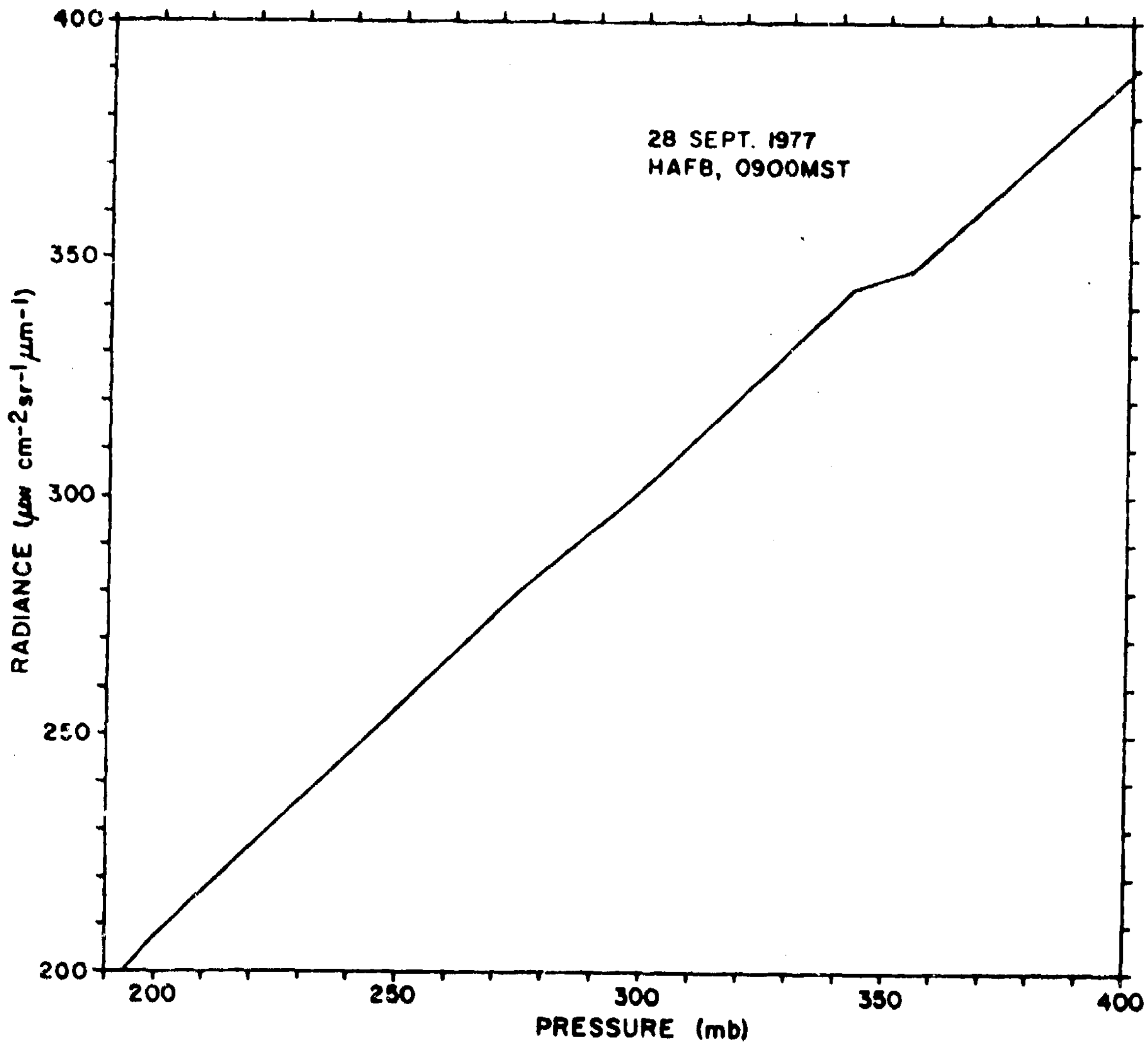

Figure 4. Blackbody radiance values for temperatures measured by HAFB rawinsonde vs pressure obtained by on-board pressure transducers.

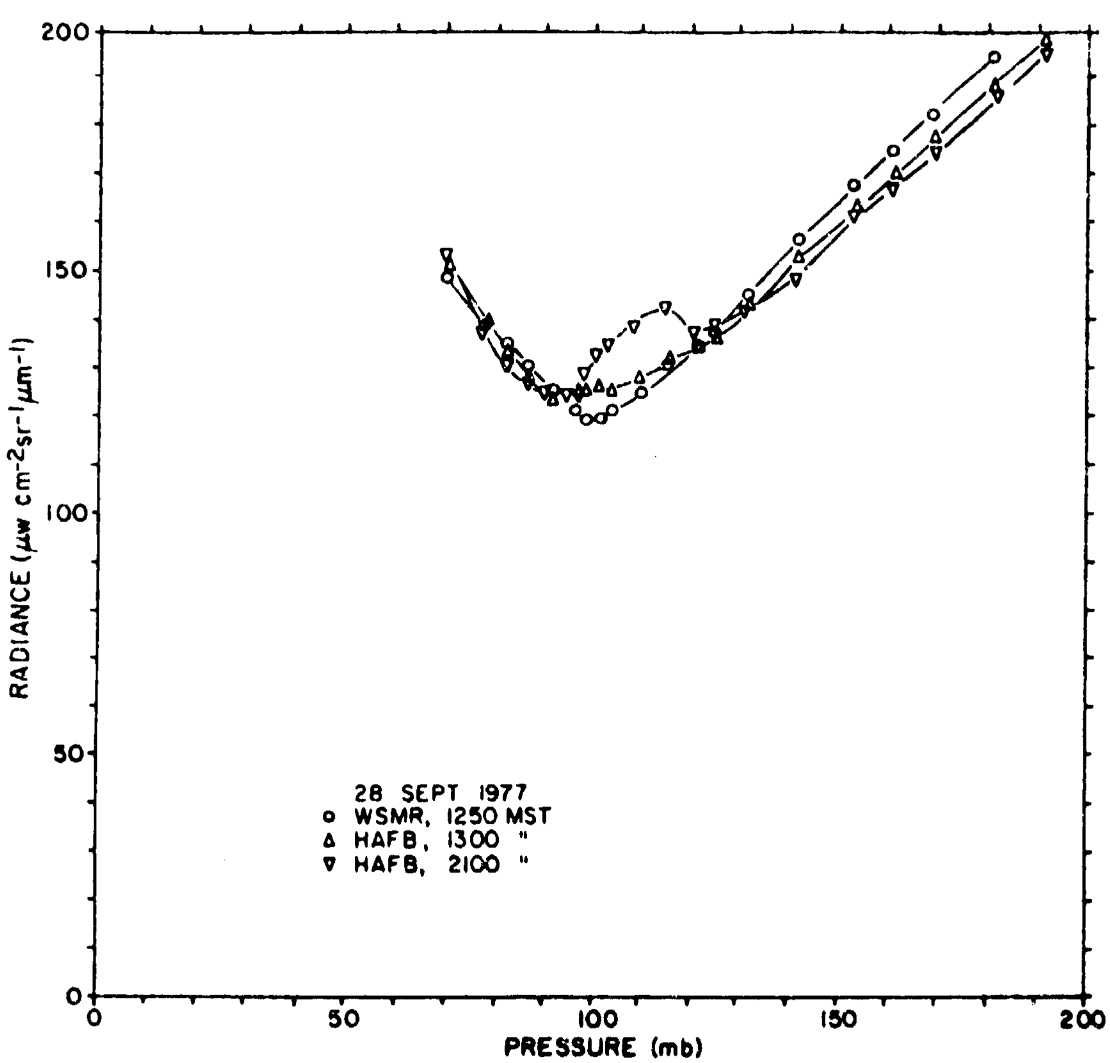

Figure 5. Rawinsonde data for 28 September 1977 from Holloman AFB and White Sands Missile Range.

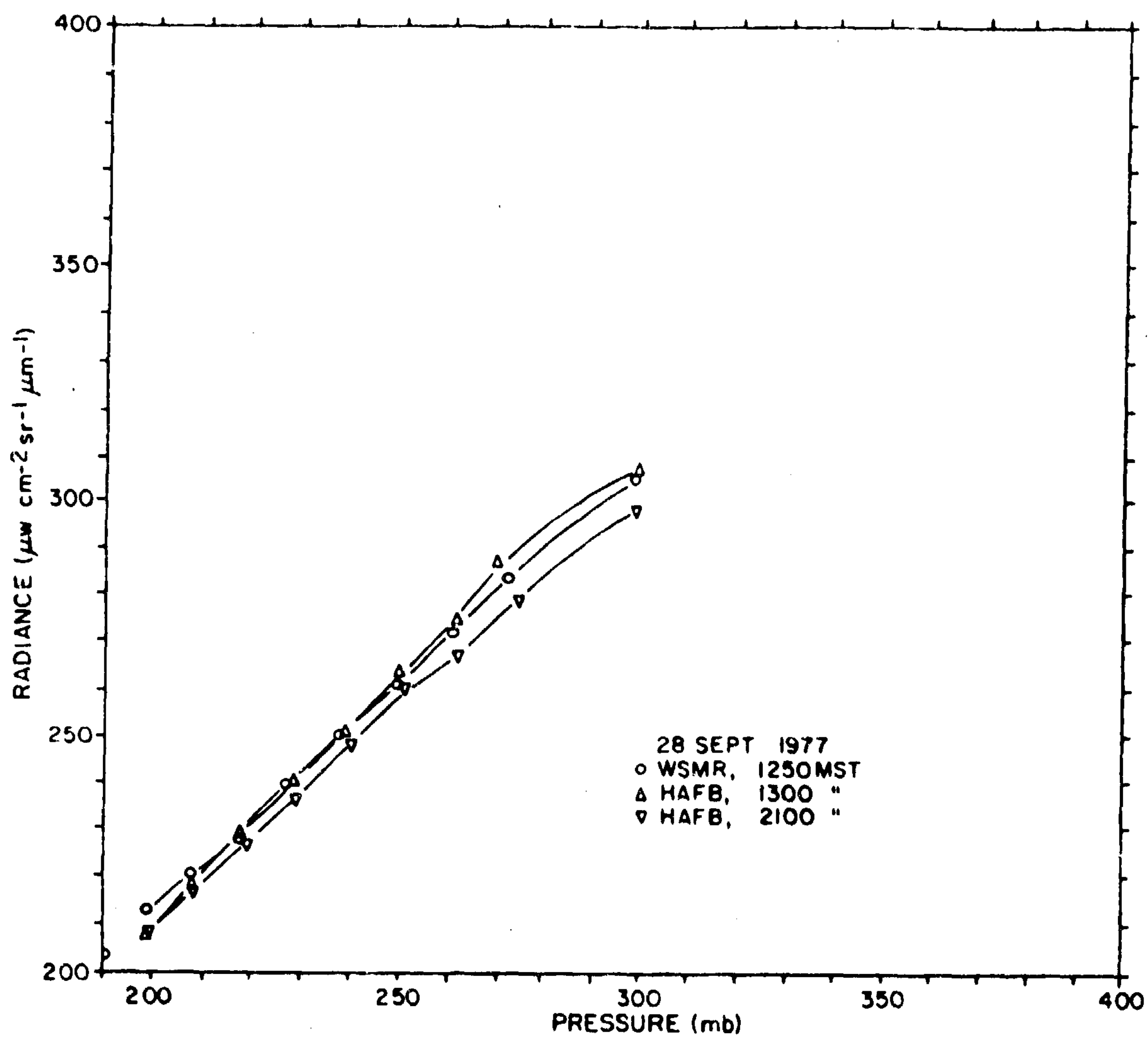

Figure 6. Rawinsonde data for 28 September 1977 from Holloman AFB and White Sands Missile Range.

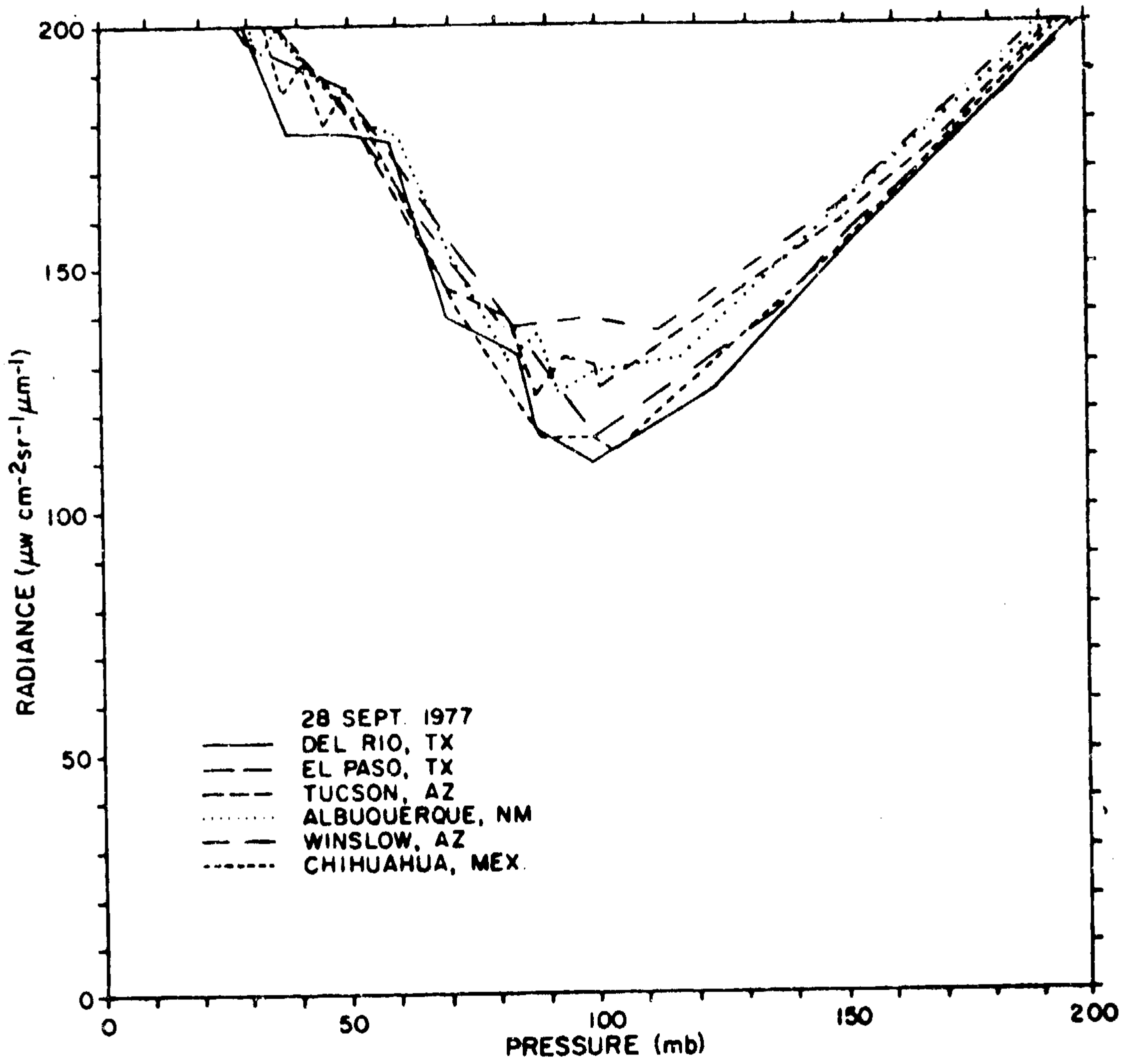

Figure 7. Rawinsonde data for 28 September 1977 at 1750 MST from various sites in the southwest.

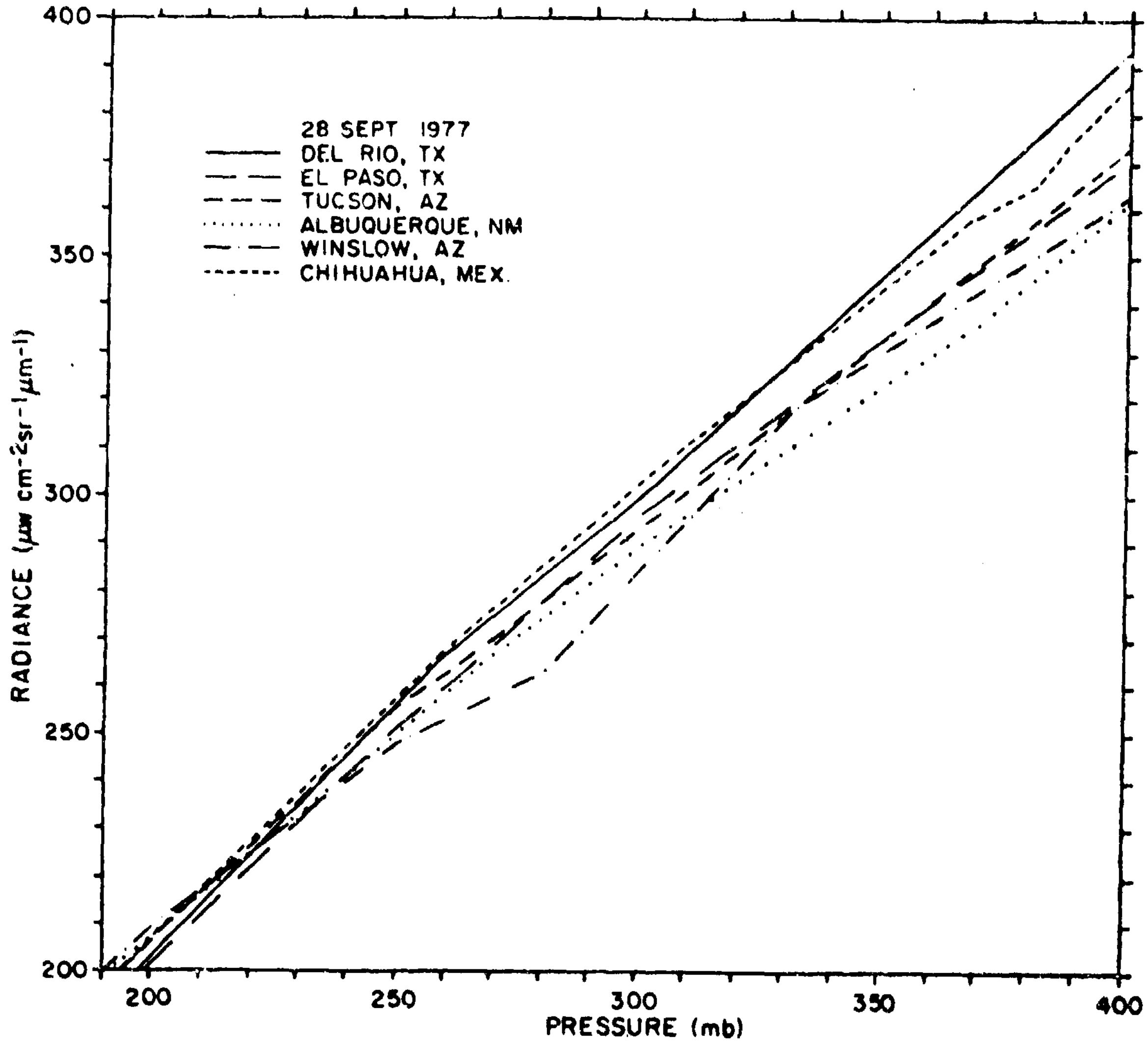

Figure 8. Rawinsonde data for 28 September 1977 at 1750 MST from various sites in the southwest.

change of $1^{o}K$ represents a change of $5.1 \mu w \; cm^{-2} sr^{-1} \mu m^{-1}$ in the $15 \mu m$ radiance of a blackbody.

Comparison of the radiometer data (Figures 1 and 2) with the HAFB rawinsonde released at 0900 MST (Figures 3 and 4) shows excellent agreement in the 300-200 mb range. In fact, on the average, the agreement is within the $0.1^{o}K$ to which the rawinsonde temperatures are given. Although there are fine structure differences of several tenths of a degree, it is tempting to cite the good agreement and consider both sets of data validated. However, through this same altitude region, a WSMR rawinsonde launched at 1250 MST shows considerable (1^{o} to 2^{o}) departure from the 0900 MST HAFB rawinsonde and, to a lesser extent, from the HAFB rawinsonde launched at 1300 MST less than 15 miles away (Figures 5 and 6). On the other hand, a rawinsonde launched at 2100 MST from HAFB shows excellent agreement with both the 0900 MST and the radiometric data.

The data from the three HAFB runs tends to converge in the 200-120 mb region where the temperature spread is considerably less than $1^{o}K$. The radiometer data lies within the spread of these three runs. All the runs show large divergence through the 120-80 mb regions, even discounting the large "lump" in the 2100 MST run. Unfortunately, the radiometer data through this region may show the influence of increased atmospheric transmission within the filter bandpass. Some fraction of the radiation emitted from higher, warmer layers may be reaching the altitude of the balloon payload (the radiometer unit was looking up at a 20^{o} angle). By 60 mb the atmospheric path has obviously become partially transparent, even for the total remaining path, since the radiance level begins to decrease with altitude although the temperature continues to increase.

The temperature structure above the 100 mb region is still calculable, but the calculation becomes less precise and changes from a simple operation with a hand calculator to a complex problem requiring large computer capacity. These computations are to be performed, but are not completed at this time.

The altitude for which the simple Planck function calculation would be sufficient could be extended by working in a wavelength region where the CO_2 absorbs more strongly, or by using a more nearly horizontal field-of-view for the instrument. The first of these was intended with the 4.3μm radiometer, but was negated by the instrument failure. The second was not practical for this flight because the upward look-angle is necessary for the prevention of window frost at the lower altitudes. Future flights will include a mechanism for rotating the look-angle towards the horizon at the high altitudes.

SUMMARY AND CONCLUSIONS

The radiometer data agree (to better than 0.5°K) over fairly extensive altitude ranges with each of three rawinsondes launched from Holloman Air Force Base at 0900, 1300 and 2100 MST. However, the agreement with each one does not hold throughout the 300-120 mb range.

The major possible source of error in the radiometric data is in the calibration constant (see Error Analysis), which would result in consistent differences with the rawinsonde runs. The agreement with portions of the various rawinsondes, particularly where two or more agree strongly, suggests that the radiometric data is valid throughout the 300-120 mb, but that an individual rawinsonde sounding may be in error by as much as $2^{o}K$ or more for portions or all of the ascent.

ERROR ANALYSIS

The random noise level of the radiometer signal was below the least count of the PCM A to D converter, and therefore, the quantization noise of the PCM encoder ($\pm$ 1/1023) dominates the random component of the error in the radiometer signal. The pressures for the radiometric data were taken from three on-board pressure transducers covering the range from 1000-0 mb. A partial check on the validity of the indicated pressures was made by comparing the outputs in the short ranges where the transducer useful ranges overlap. Agreement within $\pm$ 1 mb was found. Since the authors are not familiar with the accuracy of the standard rawinsonde pressure readings, they have been used exactly as reported.

The accuracy of the radiometric data is primarily a question of the accuracy of the calibration. Errors in the calibration procedure can be produced by blackbody emissivity too far from unity, errors in the measurement of blackbody temperature, and temperature gradients within the blackbody. The calibration procedure used was designed to minimize these effects or, at least, to reveal their presence at a significant level. For each calibration run, the blackbody was cooled until the copper rod from which it was machined was immersed in LN_2 and the temperature sensor checked against the boiling point of LN_2 for the ambient pressure. For the CO_2 experiment the radiance level at this temperature was too low to produce a measurable output. With the blackbody emission at this low level an appreciable deviation of the source from unit emissivity would be revealed by a residual signal, due to reflectance of radiation from the comparatively warm baffles. A reflectivity of 0.003 or less would show up under these conditions.

After the LN_2 evaporates and the cavity begins to warm, voltages are obtained at ~5°K intervals over the temperature range, resulting in approximately 40 output voltage vs. radiance points per run. Plots of these points exhibit excellent linearity. Typically, the maximum departures of individual points from the best straight line do not exceed 2% of the reading. The slope of the best straight line is computed and used as the calibration coefficient for reduction of the data. The calibration coefficient utilized for reduction of the flight data was actually the average of the slopes of four runs, none of which deviated from the mean by more than ± 0.5%.

The linearity of the output with radiance over a signal range approaching three orders of magnitude provides good evidence as to the lack of gradient effects on temperature measurement errors, since neither of these is likely to remain constant over the side temperature range of the calibration. In short, the systematic error in the radiance measurements should not be as large as 1%.