A New Pyrgeometer

J. S. Foot

Meteorological Research Flight, Royal Aircraft Establishment, Farnborough, Hants, United Kingdom

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ABSTRACT

Pyrgeometer measurements of the broadband infrared irradiance have hitherto been limited in accuracy because temperature gradients within the instrument produce spurious signals. A new pyrgeometer that has been demonstrated to possess greatly reduced sensitivity to temperature gradients is described. The instrument uses a thermopile evaporated onto a planar substrate with the hot and cold junctions having different adsorption properties. Both laboratory and aircraft flight tests are reported; comparison between the new instrument and an Eppley pyrgeometer is made. Features of the spectral selectivity of the instrument are also presented.

1. Introduction

Eppley Laboratory manufactures a pyrgeometer that is now widely used to measure irradiance in the 4–50 μm spectral region. The instrument uses the same thermopile construction as their precision spectral pyranometer but isolates the longwave radiation by a single dome of either KR55 or silicon, both used with an interference filter to provide shortwave blocking below 4 μm. A thermistor is used to measure the cold junction (or sink) temperature of the thermopile.

Much work has been carried out to assess the performance of these instruments, for example, Albrecht and Cox (1977), Weiss (1981), Bradley and Gibson (1982) and Ryznar and Weber (1982). The main problem is associated with errors caused by temperature gradients within the instrument, particularly the differential temperature between the dome and the sink. The problem is particularly pronounced for unventilated instruments in sunlight; Weiss (1981) reports errors in excess of 90 W m⁻² in these conditions. However, even in laboratory calibrations the effects are significant.

The Hercules aircraft of the Meteorological Research Flight (MRF) has had upward and downward facing pyrgeometers of this type installed on it for a number of years. Some of the work using these instruments is reported by Slingo et al. (1982). During these years, attempts to quantify the errors associated with these pyrgeometer measurements have culminated in the production of a new thermopile designed to minimize the errors caused by temperature gradients. This paper describes the new MRF instrument. Comparison of the performance of the MRF and the Eppley pyrgeometers in laboratory and aircraft flight tests is presented. A short section on the spectral characteristics of the instruments is also included and is equally applicable to both instruments. Although the emphasis of this work has been toward aircraft measurements, the conclusions are also valid for ground-based observation where the MRF pyrgeometer offers a greatly reduced sensitivity to internal temperature gradients.

2. Instruments

a. Pyrgeometer principle

A pyrgeometer consists of a thermopile and a dome. Ideally, the dome transmits all longwave radiation without attenuation but reflects all shortwave radiation and there is, therefore, no thermal emission from the dome. In an ideal instrument the voltage, $E$, from the thermopile is linearly related to the net gain of radiant power. The thermopile absorbs and emits as a blackbody at a measured temperature $T$. For this idealized instrument the incoming irradiance, $L$, is given by

$$L = \frac{E}{\eta} + \sigma T^4,$$

where $\eta$ is the sensitivity of the instrument and $\sigma$ the Stefan-Boltzmann constant.

b. The Eppley pyrgeometer and the aircraft installation

For the Eppley instrument, Albrecht et al. (1974) and Albrecht and Cox (1977) derived a relationship of the form:

$$L = \frac{E}{\eta} + \epsilon_0 T_s^4 - k \sigma (T_d^4 - T_s^4).$$

Here $\epsilon_0$ is the emissivity of the thermopile, which they take to be unity; $T_s$ is the temperature measured close to the sink or cold junction of the thermopile; $T_d$ is the temperature of the dome measured at a single point.
on its rim. The voltage \( E \) is the voltage from the thermopile when linked to a temperature compensation circuit supplied by Eppley. The final term in Eq. (2) is a correction term that represents the exchange of radiant energy between the dome and the thermopile, the constant \( k \) depends upon the emissivity and transmissivity of the dome.

In their earlier work Albrecht et al. (1974) defined \( k \) as equal to the ratio of emissivity of the inside of the dome to the transmissivity through the dome (from outside to inside). In laboratory calibrations Albrecht and Cox (1977) found \( k \) to be about 4, suggesting that the emissivity was four times the transmissivity of the dome. The dome material used in their work was KRS5 and reference to Touloukian and De Witts (1970b) shows that the transmissivity of KRS5 is larger than its emissivity over the wavelength range of the majority of thermal energy. This inconsistency is probably the result of conduction and convection of heat being the dominant mechanisms for heat exchange between the dome and the thermopile rather than the exchange of radiative heat.

The aircraft presently allows for a fit of four instruments, normally a pair of upward- and downward-facing Eppley pyrgeometers (model PIR) and a pair of upward- and downward-facing pyranometers (model PSP) although it is possible to fit other combinations, for example, two upward-facing pyrgeometers. The procedures outlined by Albrecht and Cox (1977) have been closely followed, namely:

1) The sink temperature, \( T_s \), is sensed and recorded separately rather than being used in an internal circuit made to generate a voltage roughly equal to \( \eta \sigma T_s^4 \), which is then added to the thermopile output.

2) The dome temperature, \( T_d \), is sensed and recorded. The sensor is fixed on the forward facing side of the rim of the dome when the pyrgeometer is installed on the aircraft.

3) The temperature compensation for the thermopile supplied by Eppley is still used. This maintains the sensitivity of the thermopile to within 2% from \(-40^\circ\) to \(+20^\circ\)C.

The temperatures, \( T_d \) and \( T_s \), are measured with linearized thermistor elements. Software is used to further linearize the performance, and an absolute accuracy of 0.25°C is achieved with a relative accuracy between \( T_d \) and \( T_s \) of 0.1°C. Head amplifiers are used to reduce noise problems and a zero check from these amplifiers is carried out routinely.

To put the results of later sections into context, it is useful here to describe briefly the thermal exposure of the pyrgeometer. In flight, \( T_d \) and \( T_s \) take up values above the ambient, \( T_a \), because of dynamic heating. We can define a temperature recovery factor \( \lambda \) by

\[
T_d = T_s(1 + 0.2\lambda M^2),
\]

where \( M \) is the Mach number of the aircraft e.g., see Ower and Pankhurst, 1966, and \( \lambda \) is approximately 0.8 for the downward-facing instrument sited at the end of the instrumented nose probe. For the upward-facing instrument \( \lambda \) is more variable (0.7-1.0), possibly because on the top of the wing (where they are sited) the flow changes with the angle of attack of the aircraft. The outcome is that the pyrgeometer temperatures \( T_d \) and \( T_s \) are typically about 5°C-10°C greater than the ambient temperature, \( T_a \), and \( T_s \) is typically about 0.5°C-1.0°C greater than \( T_d \). The dome may be cooler than the sink because it is aerodynamically smoother than the body of the instrument with which the sink junctions are in good thermal contact. However, because of the much lower thermal mass of the dome, it responds to temperature changes much more rapidly than the sink.

Sunlight preferentially heats one side of the dome. For example, on one occasion, at an airspeed of 150 m s\(^{-1}\), \( T_d \) was 0.3°C higher with the sun shining on the dome thermistor than it was when no sun shone upon it as the aircraft traveled in the reciprocal direction. Temperature gradients across the dome therefore exist in sunlight and are likely to exist without sunlight because dynamic heating will be concentrated on the leading side of the dome.

Equation (2) assumes that, within the body of the instrument, there is no temperature gradient which could generate a temperature differential across the thermopile. Tests conducted at MRF have provided some evidence that this is not a valid assumption. One set of tests used Eppley PSP pyranometers, which have the same type of thermopile as the PIR pyrgeometer fitted in similar bodies but have two glass domes. For the tests, metal covers were placed over the domes to prevent sunlight from reaching the thermopiles. A number of these pyranometers were mounted both upward- and downward-facing on the aircraft. The measured zero signal under steady state conditions, varied by the equivalent of an irradiance of a few W m\(^{-2}\) as the airspeed varied between 90 and 150 m s\(^{-1}\). Another set of tests was conducted with an Eppley pyrgeometer on which the silicon dome had been replaced by an internally blackened aluminum dome. In these tests, conducted with the instrument fitted in an upward-facing position, \( T_d \) was measured at the apex of the dome and a good correlation was found between the output voltage \( E \) and \( (T_d^4 - T_s^4) \). There was, however, a residual voltage change that varied systematically with airspeed over the range 90-150 m s\(^{-1}\). The voltage change was equivalent to a change in irradiance of \(-0.07\) W m\(^{-2}\)/m s\(^{-1}\) calculated using the sensitivity appropriate to the instrument fitted with the silicon dome.

In summary, we conclude that the dome temperature cannot be measured satisfactorily at a single point and within the body of the instrument there may be other temperature gradients which give significant errors. The
experiences outlined here undermine confidence in using the correction term $k_0(T_d^a - T_s^a)$ in Eq. (2). Moreover, if Eq. (2) is not accurate, any sensitivity determined using it is also suspect. Albrecht and Cox (1977) found in their aircraft tests very variable values of $k$ from 1.0 to 3.7. They associated the variability with the siting of the instruments, ambient temperature or altitude and the angle of attack of the aircraft. These differences may all be related to the problems just discussed.

c. MRF pyrgeometer

Rather than attempting to apply a correction term, a more sound approach is to reduce the correction terms so they become negligible. To reduce the instrument’s dependence on temperature gradients, the hot and cold junctions should be brought closer together and the differential temperature generated must be dependent solely on the radiative balance rather than on the total heat balance.

This approach has been used in some pyranometers where the hot and cold junctions are exposed on the same surface with their radiative characteristics defined by black and white paints (see Robinson, 1966). A similar technique can be used in the infrared where the two junctions now have high and low emissivities. For such an instrument Eq. (2) should hold exactly; the correction term will then only apply to emission from the dome, as conduction and convection of heat will be seen identically by the two types of junction.

To have the hot and cold junction interlaced on a surface will also greatly reduce sensitivity to temperature gradients within the body of the instrument.

Figure 1 shows a sketch of the MRF thermopile and indicates where it is fitted into an Eppley pyrgeometer body. The sensor is evaporated onto a 16 mm-diameter glass microscope slide of thickness 0.15 mm; this is glued into a machined recess in the body of the instrument. The thermopile consists of 12 pairs of antimony and bismuth thermocouples arranged in a circular pattern.

Gold is used to connect between these metals and alternate gold stripes are painted with optical black paint (3Ms Nextel 2010). The differential effect is generated between the different emissivities of the paint ($e > 0.99$) and the gold ($e < 0.01$). Both these values are spectrally very constant from 4 to 100 $\mu$m (e.g., see Smith, 1984; Touloukian and De Witt, 1970a). The construction of evaporated antimony and bismuth thermocouples where the cold junction is in contact with a heat sink has been documented by Asheimer and Weiner (1964). Further details on the construction of the thermopile are given in Foot (1985).

The temperature coefficient of the thermopile’s sensitivity was determined by monitoring the output voltage as the temperature of the instrument was gradually reduced. A constant change in the incoming radiant power was provided by alternatively screening and un-screening a filament lamp. The instrument was made responsive to shortwave radiation by replacing the silicon dome with a glass one. The temperature coefficient obtained was approximately $-0.1\% \, ^\circ\text{C}^{-1}$ as the temperature of the sink varied between $40^\circ$ to $-20^\circ$C. This value has been used to correct all subsequent analyses, the sensitivities quoted here being normalized to $0^\circ$C.

The time constant for the instrument could also be established with a lamp as a source and this was found to be of order 1 second—very similar to the Eppley instrument.

3. Laboratory calibration

In the calibrations a black temperature controlled cone was placed over an instrument complete with its silicon dome. The temperature of the cone, $T_c$, was varied slowly so that every reading was taken in a condition close to thermal equilibrium; values of $E$, $T_c$, $T_d$, and $T_s$ were recorded. An estimated value of sensitivity, $\eta'$, ignoring the last term in Eq. (2), can be defined by

$$ L = \frac{E}{\eta'} + \sigma T_s^a, $$

where $L = \sigma T_c^a$. From Eqs. (4) and (2) taking $\epsilon = 1$,

$$ \eta' = \eta(1 + k(T_d^a - T_s^a)/(T_c^a - T_s^a)). $$

FIG. 1. Diagram of the MRF thermopile and the construction of Eppley pyrgeometer body. The thermopile consists of evaporated strips of gold, antimony and bismuth; alternate gold strips lie within three black-painted symmetrical segments.
Figure 2 shows plots of $\eta'$ against $(T_d^4 - T_s^4)/(T_c^4 - T_s^4)$ for the Eppley and MRF pygeometers. The intercept on the $\eta'$ axis is $\eta$ and the slope is $k$. Thus for the Eppley instrument $\eta = 4.2 \, \mu V/W \, m^{-2}$ and $k = 3.5$ and for the MRF instrument $\eta = 0.69 \, \mu V/W \, m^{-2}$ and $k = \pm 0.5$. A later redesigned layout with 36 pairs of junctions has a sensitivity similar to Eppley pygeometers. The value of the ordinate depends upon the thermal coupling between the plate holding the dome and the body. For the Eppley instrument two sets of points are identified. One set has the plate screwed down firmly, and the other has the plate screws slackened, which reduces the thermal contact by lifting the plate about 0.2 mm. The results shown here for the MRF pygeometer were taken with the plate loose so that a greater variation in the ordinate values were obtained.

To determine $k$ more accurately for the MRF instrument, it is necessary to generate a larger difference in the value of $T_d - T_s$. This can be achieved, as in Albrecht and Cox (1977), far from thermal equilibrium with rapidly changing temperatures. For this work the pygeometer was exposed to longwave radiation from a room that remained at a fairly constant temperature. The dome was then momentarily warmed with a hot air blower. Values of $E$, $T_d$ and $T_s$ were recorded for a period of a few minutes as the temperatures reached a new equilibrium. Equation (2) can be solved assuming $L$ (i.e., $T_c$) is constant. This gave $k = 0.32$ with a standard deviation of 0.05. When this technique was repeated for the Eppley instrument, the $k$ obtained was 3.2 with a standard deviation of 0.3, consistent with the value obtained above. This indicates that thermal equilibrium, if not reached, does not introduce large errors.

Five separate calibrations of the new instrument have been performed, some before and some after a two month period when the instrument was fitted to an aircraft and flown 22 times. These calibrations had an rms deviation of 2% of the mean value, and there was no significant change with either time or whether the target was warmer or cooler than the instrument.

4. Aircraft test

For the aircraft tests the Eppley and MRF pygeometers were fitted side by side in the upward-facing position on the aircraft. Flight data were gathered in clear sky conditions in an area over the sea to the southwest of the United Kingdom. Three types of tests are described that demonstrate the reduced sensitivity of the new instrument to temperature gradients. Simultaneously with the measurements of downward irradiance ($L_\downarrow$), air temperature and humidity were measured throughout the experiment and there was no evidence of any change in these variables. It is therefore reasonable to assume that the values of $L_\downarrow$ obtained during the period of the flight should be constant at any particular level; this is a basic assumption applied to the following analysis of the results.

a. Level flight

At a fixed altitude on three separate occasions the aircraft carried out four level runs at two or three different airspeeds. Changes in the pitch attitude of the aircraft were kept to less than $2^\circ$. The resulting small change in the scene viewed has a negligible effect on the measured $L_\downarrow$; for example, rolling the aircraft by $5^\circ$ does not change the measured $L_\downarrow$. After a few minutes to allow the temperatures to stabilize, the mean irradiance was calculated for both instruments on the assumption that $k$ was zero. The standard deviation of these irradiances was typically 1–2 W m$^{-2}$ over a five-minute flight run. Table 1 shows the results at each level in the form of a mean and standard deviation of the four measured quantities at each flight level. The table also shows the linear coefficient describing how $L_\downarrow$ varies with true airspeed, and, independently, the value of $k$ derived to minimize the variation in $L_\downarrow$ using linear regression techniques.

Table 1 also shows modeled values of irradiance, $L'_\downarrow$, obtained from the radiation scheme of Roach and Slingo (1979); an example comparison of this scheme with others is given by Slingo and Wilderspin (1985). The temperature and humidity profiles measured by the aircraft sensors between 3 and 9 km, together with similar data from nearby radiosonde ascents, were used as input data for this calculation. The results at the 3.1 and 6.1 km levels are not critically dependent on the radiosonde data. The range of $L'_\downarrow$ values is based on an uncertainty of $\pm 0.5^\circ C$ and $\pm 10\%$ in atmospheric
temperatures and relative humidity used in the model. These limits are consistent with the variability observed between different profiles. A small correction \((L_\text{L} - L_\text{L}')\) to the modeled values has been made to account for the transmission properties of the silicon dome so that modeled and measured values are directly comparable; this is described fully in section 5.

At each of the levels there was a reduction in the calculated irradiance with increasing airspeed for the Eppley instrument. This change, \(-0.07\) to \(-0.10\) W m\(^{-2}\)/m s\(^{-1}\), is similar to that reported in a different test in section 2b. At two of the three levels, the data from the Eppley instrument showed no consistent pattern as a function of \(\sigma(T_d^4 - T_s^4)\) but at one level a good correlation was noted. The value of computed \(k\) which minimized the variation of \(L_\text{L}\) at this level was \(-4.2\) as compared to \(+3.2\) and \(+3.5\) found in the laboratory calibrations. Albrecht and Cox (1977) also found large differences between laboratory and in-flight values of \(k\). Using \(k = 3.4\) for the Eppley in Table 1 substantially increases the standard deviation at each level. This feature of the change of \(L_\text{L}\) always being negatively correlated with airspeed and sometimes correlated (in this case positively) with \(\sigma(T_d^4 - T_s^4)\) has been common to a number of similar tests on different Eppley pyrgeometers, some instruments showing a dependence of airspeed greater than 0.1 W m\(^{-2}\)/m s\(^{-1}\) in magnitude. As suggested in section 2b, one explanation for this result is that there are, within the body of the instrument, temperature gradients that vary with airspeed. These gradients are not necessarily related to the value of \(T_d^4 - T_s^4\). An alternative explanation is that the sensitivity, \(\eta\), used to compute \(L_\text{L}\) is in error. It is possible to optimize \(\eta\) so that there is no significant change in \(L_\text{L}\) with airspeed; for the results given in Table 1 this can be achieved by increasing the sensitivity by 35\%. However, this change increases the measured irradiances by approximately 40–50 W m\(^{-2}\) to values completely out of line with the modeled values shown in Table 1.

In contrast, the MRF pyrgeometer showed less variability at each of the three levels. Only in one case was there a statistically significant (at only 80\% level) trend of \(L_\text{L}\) with airspeed, but this result was influenced by one of the four values which, for instrumental reasons, had a much higher noise level (standard deviation 3 W m\(^{-2}\)) than did the other three and, for this reason, is suspect.

Summarizing Table 1, the irradiance measured with the MRF instrument showed little or no dependence on airspeed compared to those measured by the Eppley, which varied by about 7 W m\(^{-2}\) over the speed range of the aircraft. For the Eppley there was no single value of \(k\) found to reduce this dependence on airspeed. The largest difference in the mean irradiances measured by the two instruments was 7 W m\(^{-2}\) (this would be larger if \(k = 3.4\) for the Eppley). At this level of agreement it would be unwise to make judgements on the basis of the modeled values.

### b. Profiles

Large temperature gradients within the pyrgeometers can be created when the aircraft is ascending or descending, and vertical profiles of \(L_\text{L}\) can be compared under different conditions. Table 2 provides details of three profiles carried out on 10 December 1984 with no cloud above the aircraft. The measured air temperatures at any level were within 1° of each other between any of the profiles, indicating that the airmass was reasonably uniform. Figure 3a–d shows the measured downward irradiance for the three profiles, (a)

### Table 1. Summary of measurements made on three separate occasions during straight and level flight.

<table>
<thead>
<tr>
<th>Date</th>
<th>Height (km)</th>
<th>Air temp (°C)</th>
<th>Airspeed range (m s(^{-1}))</th>
<th>Modeled (L_\text{L}') (W m(^{-2}))</th>
<th>Instrument</th>
<th>Measured (L_\text{L}), mean and S.D. with (k = 0) (W m(^{-2}))</th>
<th>Airspeed dependent (W m(^{-2})/m s(^{-1}))</th>
<th>(k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Nov</td>
<td>3.1</td>
<td>-10.2 ± 0.4</td>
<td>60–157</td>
<td>No aircraft sounding made</td>
<td>Eppley</td>
<td>152.6 ± 4.5</td>
<td>-0.07</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MRF</td>
<td>150.8 ± 1.0</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>10 Dec</td>
<td>3.1</td>
<td>1.1 ± 0.1</td>
<td>91–156</td>
<td>201.8–208.4</td>
<td>Eppley</td>
<td>217.7 ± 2.8</td>
<td>-0.08</td>
<td>-4.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MRF</td>
<td>210.8 ± 1.7</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>10 Dec</td>
<td>6.1</td>
<td>-20.2 ± 0.2</td>
<td>100–160</td>
<td>112.5–116.5</td>
<td>Eppley</td>
<td>109.4 ± 2.9</td>
<td>-0.10</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MRF</td>
<td>110.8 ± 1.8</td>
<td>-0.05</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### Table 2. Summary of conditions during profiles.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Height range (km)</th>
<th>Ascent rate (m s(^{-1}))</th>
<th>Mean pitch of aircraft</th>
<th>Average rate of change of ambient temperature (°C s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.7 to 3.1</td>
<td>-5</td>
<td>1.3°</td>
<td>+0.035</td>
</tr>
<tr>
<td>2</td>
<td>3.1 to 6.1</td>
<td>+5</td>
<td>5.5°</td>
<td>-0.036</td>
</tr>
<tr>
<td>3</td>
<td>9.1 to 3.1</td>
<td>-10</td>
<td>-7.0°</td>
<td>+0.074</td>
</tr>
</tbody>
</table>
and (b) are for Eppley and (c) and (d) for the MRF pyrgeometers. The two graphs for each instrument are with $k = 0$ and $k$ as determined in the laboratory.

The separation between the values obtained at any level for the Eppley instrument with $k = 0$ is very large, about 40 W m$^{-2}$. If $k$ is given the value of 3.4 then the differences are greatly reduced but are still about 10 W m$^{-2}$; better agreement can be attained by selecting a particular, different value of $k$ for each pair of profiles. In the case of the MRF instrument the agreement between the values is much closer and there is little to choose between $k = 0$ or 0.3.

c. Stabilization after profiling

After the rapid descent, identified as profile number 3 in Table 2, the aircraft stabilized rapidly to a fixed altitude, airspeed and pitch angle for a period of seven minutes. Figure 4 shows the measured downward irradiances for the two instruments as a time series. Without any correction term, the MRF instrument
shows a much more stable output in contrast to the Eppley instrument. Applying the correction using the laboratory values of \( k \) brings the calculated irradiance for the Eppley to a reasonable constant value. For the MRF instrument there is again little merit in choosing \( k = 0.3 \), as \( k = 0 \) gives an equally stable response.

The \( k \) value determined for the Eppley instrument in the laboratory is approximately valid when correcting data that have large temperature gradients generated by rapid environmental changes. Under such circumstances the main temperature gradient is caused by the different thermal time response of the dome and the body of the instrument to the changing environment. There will, however, be significant residual errors caused by nonuniformity of the dome temperature and temperature gradients within the body of the instrument. In steady state conditions these residual errors appear to be the dominant ones and there is no advantage in applying the \( k(T_d - T_s) \) correction term.

5. Spectral response of pyrgeometers

In the work described above it is assumed that the instrument has a flat spectral response over the infrared from 4 to 100 \( \mu \)m. Spectral structure can be introduced by the dome or the black paint (and in the case of the MRF instrument the evaporated gold). The emissivity of the paint and the gold vary very little with wavelength from 4 to 100 \( \mu \)m (see Smith, 1984; Touloukian and De Witts, 1970a); the most significant assumption is therefore that the transmission of the dome is constant.

Figure 5 shows the measured transmission curve for the silicon dome fitted to the MRF pyrgeometer. Data presented by Touloukian and De Witts (1970a) indicate that the transmission properties of silicon extend from 50 to 100 \( \mu \)m at much the same value as at 25 \( \mu \)m. This is assumed to be the case here although this assumption does not greatly affect the conclusions.

First, one can determine how the mean transmission of the silicon, weighted by the Planck function for a blackbody source, varies with the temperature of that blackbody. For a change of blackbody temperature from 246 to 300 K the mean transmission increases by a factor of 1.014. Such a small change would not have been detected during calibration given that the repeatability of the sensitivities measured in the laboratory was of the same magnitude. With atmospheric radiation the effect of the variable transmission of the dome may be more significant. Because of the absorption features shown in Fig. 5, calculations should be performed using an atmospheric model with sufficient resolution to resolve these features. As a first approximation the 5-band model of Roach and Slingo (1979) has been used and a mean transmission for the silicon dome for each of the bands calculated, arbitrarily weighting the response within the band to the Planck function for a black body at 246 K. For the particular atmospheric profile measured on 10 December 1984 the results from each band have been adjusted to take account of sensitivity variations and a corrected irradiance \( L' \) obtained; these are the basis of the values given in Table 1. The value of the change of irradiance calculated by this, \( L - L' \), is shown in Table 3 for four altitudes in the troposphere. At ground level the
Table 3. Difference between modeled irradiance, $L_1$, and the irradiance taking into account the silicon dome transmission, $L_1'$, for the atmospheric profile on 10 December 1984.

<table>
<thead>
<tr>
<th>Height (km)</th>
<th>$L_1 - L_1'$ (W m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1</td>
<td>+0.8</td>
</tr>
<tr>
<td>6.1</td>
<td>−0.3</td>
</tr>
<tr>
<td>3.1</td>
<td>−3.9</td>
</tr>
<tr>
<td>0.0</td>
<td>−6.0</td>
</tr>
</tbody>
</table>

difference is significant. This is because a larger proportion of the energy shifts to below 8 μm at low altitudes due to the higher water content and higher temperatures and below 8 μm the transmission of silicon is highest.

The errors that arise from silicon transmission can to some extent be mitigated by the use of KRS5 as the dome material and some Eppley pyrgeometers are equipped this way. The transmission of KRS5 below 50 μm is much more constant than is that of silicon (see Touloukian and De Witts, 1970b) but the material does not transmit above 50 μm. For some applications, particularly for surface stations, KRS5 may be preferable to silicon domes, although KRS5 has the disadvantage of deteriorating over prolonged exposure to the atmosphere (Weiss, 1981). In either case a correction for the effects of dome transmission should be used.

6. Discussion

The laboratory and aircraft tests described in this work substantiate the idea that a thermopile constructed on a planar substrate with differential absorption properties is a substantial improvement compared to a thermopile working with a separate heat sink. During calibrations the effect of temperature gradients can be ignored for the MRF instrument with the planar sensor, whereas it is essential to take account of and assume a form for them in the Eppley device. Used on an aircraft, the MRF instrument was less susceptible to changes of airspeed or air temperature than was the Eppley. Similar improved performance is anticipated for ground station applications when the instrument is unventilated.

In the future it is intended that the new instrument will become standard on the MRF Hercules. From the tests carried out it seems unnecessary to continue to monitor the dome temperature, as in level flight the correction term will not be significant (<1 W m$^{-2}$).

The analysis of the spectral response of both the MRF and the Eppley pyrgeometers indicates that if absolute accuracies approaching 5 W m$^{-2}$ are required, then it is necessary to take account of the spectral characteristics of the dome, particularly at ground level when using silicon domes.

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