The Ophir Air Temperature Radiometer

Stuart Beaton
NCAR TECHNICAL NOTES

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Preface

An air temperature radiometer manufactured by the Ophir Corporation is available as user-requested instrumentation on the NCAR C-130 aircraft to supplement the standard immersion temperature sensors. It determines atmospheric temperature by measuring the infrared emission of carbon dioxide at 4.3 μm. The characteristic advantages and limitations of the radiometer should be understood when one is using the data it generates. The remote sensing nature of the radiometer makes it relatively immune to the effects of dynamic heating and wetting. On the other hand, it reports the air temperature averaged over tens to hundreds of meters and is sensitive to its pointing angle. The averaging distance increases with increasing altitude and decreases as the atmospheric carbon dioxide mixing ratio increases. In clouds the averaging range is much shorter, on the order of tens of meters. The radiometer has a precision of 0.2 °C when compared to the standard Rosemount sensor for temperatures above –30 °C. It is recommended that the Ophir radiometer primarily be used in level wing flight to measure temperature in clouds when the Rosemount thermometer may be suffering from the effects of wetting.

I would like to thank Mike Spowart and Allen Schanot (NCAR/RAF) and Martin O’Brien (Ophir Corporation) for detailing the history of the radiometer prior to my arrival at the RAF and for helping me to understand how the radiometer is calibrated and the data ultimately used, and to Dave Rogers for reviewing the manuscript.

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1 Introduction

The Ophir air temperature radiometer is currently deployed on the NCAR C-130Q Hercules aircraft. This instrument measures air temperature by remotely sensing the atmospheric radiance in the 4.25 \mu m (2350 cm\(^{-1}\)) carbon dioxide vibrational-rotational absorption band. This technique has some unique properties:

- Fast response is theoretically possible, as there is no mechanical or thermal inertia. However, the signal to noise ratio and distance averaging effects limit the current implementation to 1 Hz.
- The sensor works well in both clear air and clouds.
- Because it integrates the air temperature over a relatively large distance, the thin layer of dynamically heated air next to the aircraft does not cause a discernable error. Thus, the measurement is insensitive to aircraft velocity and no velocity-dependent recovery factors or equations are needed to correct the reported temperature.
- For the same reason the reported temperature will vary with the radiometers vertical pointing angle except in cases where the local atmosphere lacks a vertical temperature gradient.
- The measurements should be correct as the aircraft moves into and out of clouds. They will not be affected by wetting and evaporation as are measurements using resistance elements.

1.1 Aircraft Immersion Air Temperature Sensors

The deceleration of air around an immersion thermometer heats the air so that the temperature transducer, typically a platinum resistance thermometer, reads a temperature above the static air temperature. The air is not decelerated fully to the stagnation point in order to maintain some flow across the sensor and a reasonable response speed, so that the actual temperature, or “recovery temperature” \( T_R \) of the sensor is given by

\[
T_R = T_A + \alpha \frac{V^2}{2C_p}
\]

where \( T_A \) equals the true air temperature, \( V \) is the airspeed, \( C_p \) is the specific heat at constant pressure of the air, and \( \alpha \) is the “recovery factor”, typically near one, for the complete sensor which accounts for the air not being fully brought to zero velocity.

Equation (1) may not remain valid if the sensor is wet by cloud droplets, as generally happens in warm clouds. When saturated cloudy air is heated by deceleration, it will become sub-saturated and can evaporate water off of a wet sensor, thereby cooling it. The sensor will then assume a temperature below \( T_R \) that maintains a balance between evaporative cooling and conduction from the air. In this case, the air temperature calculated from Eq. (1) will be in error. The error increases with wetting of the transducer, airspeed, air temperature, and recovery factor.

Lenschow & Pennel (1974) derived equations which give a temperature independent of the liquid water content. However, they will be inaccurate if the wire is only partially wet.
or there is insufficient liquid water to maintain the assumed evaporation rate. A radiometric temperature measurement has the potential to sidestep these wetting issues and report accurate temperatures in clouds regardless of the liquid water content.

2 Air Temperature Radiometry

2.1 Background

The Ophir air temperature radiometer determines the temperature in a volume of air extending away from the aircraft by measuring its infrared radiance. In a spectral region where the atmosphere is absorptive, in this case the 4.25 μm (2350 cm\(^{-1}\)) absorption band of CO\(_2\) (the only non-negligible atmospheric constituent absorbing in this spectral region), over a sufficiently long optical path the atmosphere is effectively opaque. The thermal emission of the atmosphere is then given by the Planck radiation formula for the spectral radiant exitance (or areance) \(M_{BB}\) of a perfect (unity emissivity) blackbody

\[
M_{BB}(\lambda, T) = \frac{2\pi h c^2}{\lambda^5 \left( e^{hc/\lambda kT} - 1 \right)} \text{W m}^{-2} \text{m}^{-1}, \tag{2}
\]

where \(h\) is Planck’s constant, \(c\) is the speed of light, \(k\) is Boltzmann’s constant, \(T\) is the temperature, and \(\lambda\) is the wavelength. Alternatively, the spectral radiance \(L_{BB}\) is given by

\[
L_{BB}(\lambda, T) = \frac{M_{BB}(\lambda, T)}{\pi} \text{W m}^{-2} \text{m}^{-1} \text{sr}^{-1}. \tag{3}
\]

The radiance given by Eq. (3) is illustrated in Fig. 1. The top graph shows the transmission of a 10 meter path of atmosphere at the temperature (8.5 °C) and pressure (898 mb) corresponding to an altitude of 1 km in the 1976 U.S. Standard Atmosphere. In the lower graph is shown the spectral radiance in the more conventional units of W/(cm\(^2\) sr cm\(^{-1}\)) from the same air sample along with the spectral radiance for a 8.5 °C (281.7 K) and a –30 °C (243.2 K) blackbody. See Section 2.2 for the description of the atmospheric model. This Figure illustrates what a high-resolution spectrally-scanning radiometer would measure if looking at either the air sample or at a perfectly black object at 8.5 °C and at –30 °C. In the spectral regions where the atmospheric transmission is near zero its emissivity is near unity and hence its radiance is that of the opaque object at the same temperature. The radiance of a totally absorbing object, either solid or gaseous, is a function of only wavelength and the object’s temperature. Where the air is not opaque (its emissivity is less than one) its radiance is less than that of the blackbody and becomes a function of its opacity. The –30 °C blackbody is included to emphasize how quickly the radiance in this spectral region drops as the temperature is cooled from ground-level temperatures.

The Ophir air temperature radiometer not a scanning radiometer, however. It is a filter-based radiometer—it measures the radiance integrated over a spectral band defined by a narrow-band interference filter, in this case with a spectral bandwidth of about 0.05 micrometer approximately centered on the CO\(_2\) absorption band. The single detector alternately views the atmospheric radiance and the radiance from a small blackbody emitter of known temperature. The difference in radiance between this internal reference blackbody and the external air is measured, and since the radiance of the blackbody is known from its temperature and the Planck equation, the radiance \(L_{ext}\) from the external air can
Figure 1: In the upper graph is the spectral transmission of a 10 m path of air at pressure altitude of 898 mb (1 km MSL). In the lower graph is shown the spectral radiance of that same air sample and of two blackbodies, one at the same temperature as the air (281.7 K) and one at 243 K. The air sample graphs were calculated by the LBLRTM code described in Section 2.2. The blackbody curves were calculated using Eq. (3).
be determined. From this, the \textit{brightness temperature} $T_B$, the temperature at which a perfect blackbody would have the same radiant exitance, can be determined by inverting Eq. (3):

$$T_B = \frac{hc}{\lambda k} \left[ \log \left( \frac{2\pi c^2 h}{\lambda^4 L_{ext}} \right) + 1 \right]^{-1}.$$ (4)

In principle, this should be integrated across the wavelength region the radiometer responds to. In practice, the filter bandpass is narrow enough that the calculation can be carried out at just the center wavelength, 4.29 $\mu$m for this radiometer. If the air outside the radiometer window is at a uniform temperature and completely opaque at all wavelengths passed by the filter, then the brightness temperature equals the air temperature. When these conditions are not met, then the brightness temperature is approximately an average of the air temperature over the pathlength and field of view, including the ground or space if the sample volume extends that far.

2.2 Atmospheric Radiance Modeling

We have modeled the atmospheric radiance which the radiometer will observe using the LBLRTM\textsuperscript{1} version 6.12. This line-by-line radiative transfer modeling software is a successor to the Air Force Research Laboratory FASCOD software. It includes both spectral line absorption (with input from the HITRAN database\textsuperscript{2}) and continuum absorption models for atmospheric gases and aerosols. With this model and the measured filter transmission profile, we can predict the response of the radiometer in different atmospheric profiles, with various mixing ratios of carbon dioxide, and different altitudes and viewing angles (corresponding to aircraft roll angle). No attempt has been made to include the effects of the radiometer’s field of view—where there is a constant vertical lapse rate through the sensed region and the radiometer is looking horizontally, the reduced radiance from cooler air in the field of view above the line-of-sight will be approximately equalled by the increased radiance from warmer air below the line-of-sight.

The atmospheric model used for these calculations was the 1976 U.S. Standard Atmosphere. Molecular and Rayleigh continuum models were included but aerosol absorption was not. Since the radiometer is measuring radiance emitted by CO$_2$, the results are highly dependent on the atmospheric CO$_2$ mixing ratio. Therefore, the CO$_2$ mixing ratio was increased to 358 ppm from the value of 330 ppm in the 1976 Standard Atmosphere. The results with different CO$_2$ mixing ratios can be approximated by scaling the range axis in the following results by the CO$_2$ mixing ratio.

2.3 Ophir Optical Filter Profiles

Two different interference filters have been used on this radiometer. Late in 2001 an interference filter was installed which has a spectral bandwidth of about 26.6 cm$^{-1}$ (0.05 micrometers), about half the width of the previous interference filter. Narrowing the spectral bandwidth reduced the length of the air viewed by the radiometer thereby making it less sensitive to aircraft roll-induced errors. A side effect to the narrower filter is a reduction in the signal, slightly degrading the signal to noise ratio.

\textsuperscript{1}LBLRTM is available from Atmospheric & Environmental Research Inc., Lexington, MA. \url{http://rtweb.aer.com}

\textsuperscript{2}Available from the Atomic and Molecular Physics Division, Harvard-Smithsonian Center for Astrophysics, \url{http://www.hitran.com}
The normalized filter transmission profiles for both the previously-installed and the currently-installed filters are shown in the top graph of Fig. 2, along with the LBLRTM-calculated atmospheric transmission of 10 m and 100 m horizontal paths at a pressure of 540 mb (5000 m MSL) in the lower graph. The filter profiles are based on fitting the filter manufacturers spectral scan to a mathematical curve consisting of a Gaussian curve for the filter center and a Lorentzian curve to fit each wing of the profile. As shown, the previous filter was very well centered on the CO$_2$ absorption band, but the relatively large width (49.3 cm$^{-1}$ full width at half-maximum) resulted in significant transmission beyond the high-frequency edge of the CO$_2$ band. For example, at 2400 cm$^{-1}$ where the filter transmission is still nearly 10%, even a path of air 10 km long is far from opaque, with a transmission of 53%. Since the altitude for this calculation is only 5 km, it was quite possible for the radiometer to actually see to the ground when the right wing is lowered during right hand turns and measure a combined air-ground brightness temperature. During left turns the brightness temperature is too low because the radiometer is measuring cooler air
at higher altitudes.

While the currently-installed filter has a bandwidth of 26.6 cm$^{-1}$, nearly one-half that of the previous filter, it sits about 10 cm$^{-1}$ below the band center so that there is still considerable atmospheric transmission even at long range as will be shown in the next section. Improving on this filter would be difficult. It cannot be made much narrower, as its 1% bandwidth is nearly the state-of-the-art, and a narrower filter would further reduce the signal to noise ratio. Likewise, it would be difficult to get a manufacturer to commit to making a filter with a center wavelength tolerance significantly tighter than the error present in this filter.

The filter models were calculated to best fit the transmission curve supplied by the filter manufacturer. However, it is difficult to accurately read small values of transmission from a 0–100% graph. The uncertainty in the model is high in the wings, which is important in terms of calculating the filter viewing distance. Although the Lorentzian curve fits well down to the few-percent transmission level, further out from the center wavelength this model may slightly overestimate or underestimate the filter transmission. While this results in an under- or over-estimate of the actual averaging path, the error is unlikely to exceed 10%.

### 2.4 Atmospheric Transmission Modeling

Using LBLRTM with the standard atmosphere described above, the spectral transmission of the atmosphere $\tau_A(\lambda)$ was calculated for horizontal pathlengths from 1 m to 10 km in a 1, 2, 5 sequence at pressures of 898, 540, and 265 mb (altitudes of 1, 5, and 10 km MSL). The normalized band-integrated effective atmospheric transmission $\tau_{eff}$ for the previous and current filters was then calculated from

$$
\tau_{eff} = \frac{\int \tau_A(\lambda) \tau_F(\lambda) d\lambda}{\int \tau_F(\lambda) d\lambda}
$$

(5)

where $\tau_F$ is the filter spectral transmission curve shown in Fig. 2. The integral was over the range from 2100 to 2500 cm$^{-1}$ to completely include the filter bandpass. The result is shown in Fig. 3. At 898 mb, even over a path as short as 1 m the center of the CO$_2$ band is opaque enough that the effective transmission is only 62%. Pure Beer’s-law absorption, which gives a straight line on this semi-log scale, is seen at short distance and low altitude where the transmission is dominated by the center of the absorption band. As the center becomes opaque beyond about 10 m, the transmission is dominated by the filter wings which extend past the edges of the CO$_2$ band center. These effective transmission curves can be viewed in two manners: as the range weighting function for the radiometer filters, or as the emissivity $\epsilon = 1 - \tau_{eff}$ of the air as a function of range using a given filter. Compared with the previous filter, beyond a few meters the current filter more heavily weights the near air than the distant air, effectively giving it a shorter viewing distance. With the previous filter, over 10% of the signal could come from air (or ground and sky) from beyond 100 m even at a low altitude of 898 mb (1 km). With the current filter it is less than 5%.

The spectral radiance of the atmosphere $L_A(\lambda)$ was also calculated using LBLRTM for each of these pathlengths and altitudes. The integrated radiance of the atmosphere $L_{ext}$ was then calculated from

$$
L_{ext} = L_{BB}(\lambda_0, T_A) \frac{\int L_A(\lambda) \tau_F(\lambda) d\lambda}{\int L_{BB}(\lambda) \tau_F(\lambda) d\lambda}
$$

(6)
Figure 3: Atmospheric transmission integrated over the filter bandpass at pressure altitudes of 898, 540, and 265 mb (1, 5, and 10 km) for the previous filter and the currently installed filter.
where $L_{BB}$ is the exitance for a perfect blackbody given by the Planck radiation formula, Eq. (3), $\lambda_0$ is the center wavelength (4.29 $\mu$m), and $T_A$ is the air temperature. The brightness temperature was then calculated from Eq. (4). This brightness temperature is the temperature the radiometer would report if viewing a sample of air of the given pathlength and state parameters with empty space beyond that length. The results are shown in Fig. 4. The model atmospheric temperature for each of the three altitudes is also shown for comparison.

These plots illustrate how the air nearer to the radiometer is weighted more heavily in the average brightness temperature than the more distant air. For example, at an altitude of 1 km MSL (898 mb and temperature of 281.7 K) and a horizontal viewing angle (constant temperature and pressure), with the current filter the atmosphere within 1 m of the radiometer is responsible for the first 261 K of the reported air temperature (21 K below actual). The next 9 m contributes 17 K to bring the brightness temperature to 4 K of the true temperature. It requires another 90 m to bring the brightness temperature to within 1 K of the true temperature. After a path of 5000 m, the brightness temperature levels off about 0.4 K below the true temperature, probably due to accumulated errors in the models. The previous filter actually is better at very short ranges at higher altitudes since it is better centered on the CO$_2$ band. However, it ultimately has a longer effective viewing path because of its higher transmission outside of the CO$_2$ band.

### 2.5 Slant Path

Since the radiometer viewing angle is fixed relative to the aircraft, approximately parallel to the right wing, we have calculated the spectral radiance for slant paths through the atmosphere looking $\pm 25$ degrees from horizontal. These are typical roll angles for the C-130 during turns. These calculations were done to determine how sensitive the reported temperature is to the aircraft roll angle. Unlike the pathlength calculation in the previous section, these calculations were carried all the way to space or to the ground. The aircraft altitude for the calculation was 540 mb (5 km MSL). This atmospheric model was the same 1976 Standard Atmosphere with a 6.5 K/km lapse rate and a CO$_2$ mixing ratio set to 358 ppm. The spectral radiance is shown in Fig. 5. Between 2300 and 2375 cm$^{-1}$ both calculations show the same radiance since here, at the center of the CO$_2$ band, the atmosphere is so opaque that the radiance is that from only a few meters away. Outside of the CO$_2$ bandcenter the radiance increases with downward-looking paths because we are seeing the lower, warmer atmosphere and even the warm ground. Conversely, the radiance decreases when looking up because one is looking to colder air and eventually to empty space.

With the current filter, looking $25^\circ$ upward from horizontal decreases the brightness temperature by 0.2 °C. A downward $25^\circ$ look angle to an altitude of zero, but not including the ground radiance, increases the brightness temperature by 0.5 °C. Thus there is a 0.7 °C change in brightness temperature as the aircraft rolls $\pm 25^\circ$. This temperature change corresponds to an altitude change of 108 m in the model atmosphere. From simple geometry we can define an effective radius from the aircraft $R_{eff}$ such that a $\pm 25^\circ$ roll will cause an altitude change of 108 m and a corresponding temperature change of 0.7 °C. For the current filter $R_{eff} = (108/2)/\sin(25) = 128$ meters. Note that the radiometer is not actually measuring the air temperature just at a point 128 m away. This effective range is only used

---

2Note that this difference is only present in the modeling. It will not exist in the reported measurements.
Calculated Brightness Temperatures

Figure 4: The calculated brightness temperature for the previous and current filters at altitudes of 898, 540, and 265 mb (1,5, and 10 km MSL) as a function of the horizontal pathlength through the atmosphere.
Figure 5: The calculated spectral radiance for slant paths to space and to the ground starting from a pressure altitude of 540 mb (5 km). The viewing angle is ±25° from horizontal, and the ground temperature is set to 293 K and unity emissivity, using the 1976 Standard Atmosphere with 358 ppm CO$_2$. Also shown is the transmission profile of the currently installed interference filter.
to estimate the error induced by aircraft roll at this altitude. For the previous filter this calculation yields \( R_{\text{eff}} = 180 \text{ m} \), with correspondingly larger roll-induced changes. These predicted roll-induced temperature changes are in line with what has been seen in flight tests as will be shown in Section 4, which increases our confidence in the mathematical model of the filter.

Because the radiometer is collecting radiation from a infinitely long path, albeit with decreasing response to more distant air, the brightness temperature will always change as the radiometers viewing angle looks up or down. The magnitude of the change will depend on the roll angle, the vertical temperature gradient, the aircraft altitude, cloud density, and the atmospheric \( \text{CO}_2 \) density. This effect could be eliminated only by mounting the radiometer on a stabilized gimbal so that it looks horizontally even as the aircraft rolls. The radiometer cannot be placed in a forward-facing position, which would largely avoid the look angle problem, because of water collecting on a forward-facing window (see Section 2.7) whereas in an aft-facing position it would measure the engine exhaust.

### 2.6 Cloud Transmission

Because water and ice are highly absorbing throughout much of the infrared spectral region, their absorption can fill in the wings of the filter bandpass where \( \text{CO}_2 \) is not absorbing. As a result, the viewing distance of the radiometer will be greatly shortened when the aircraft is in cloud. The LBLRTM program uses a minimal version of LOWTRAN 7 to supply the attenuation due to aerosols, clouds, fogs, and rain. Further details can be found in the LOWTRAN7 Users Guide (Kneizys et al. 1988). The radiance calculated for a 10 m path at a pressure of 898 mb in strato-cumulus cloud (base at 0.66 km, top at 2 km) is shown in Fig. 6 along with the same path in clear air as was shown in Fig. 1. Outside of the \( \text{CO}_2 \) band the clear air radiance goes to zero since the air is completely transparent (emissivity equals zero). In the case of the in-cloud path there is a strong underlying radiance throughout the entire spectral region due to the continuum emission from liquid water. This 10 m path in cloud has a maximum transmission of 63\%, and hence an emissivity of 37\%, at all wavelengths in this spectral region. Therefore the radiance continuum follows the shape of a blackbody curve but reduced to 37\% of a perfect blackbody. This can be seen by comparing it to the center of the \( \text{CO}_2 \) absorption band which is opaque (unity emissivity) over this pathlength.

As was done for the radiance calculation in Section 2.4, the brightness temperature calculation was carried out for pathlengths starting at 1 m in a 1,2,5 sequence at a pressure of 898 mb. The resulting calculated brightness temperatures as a function of range is shown in Fig. 7 for the currently installed filter. Over a short distance the difference is slight because most of the radiance is from the opaque center of the \( \text{CO}_2 \) band. At the band center for example, one meter of cloud is equal to about 1.1 m of clear air. It is at the longer pathlengths, where the center of the band is opaque and the brightness temperature is determined by transmission in the wings, that the effect of the cloud is most pronounced. For example, 10 m of this strato-cumulus cloud equals 20 m of clear air, and the cloud is completely opaque by the time the pathlength reaches 100 m. Such a cloud 100 m or more in extent along the viewing path appears as a perfect, unity emissivity blackbody over the entire spectral region. In general, a cloud can be considered opaque to broadband thermal radiation once the liquid water path exceeds about 20 g m\(^{-2}\) (Fu, 2003). In this particular spectral region the absorptivity is slightly greater so that with 0.15 g m\(^{-3}\) liquid water content (Pelon et al., 1998) the stratocumulus cloud is opaque in less than 100 m,
Figure 6: The LBLRTM-LOWTRAN 7 calculated radiance for a 10 m path in clear air and in strato-cumulus cloud. The calculation is for a pressure of 898 mb, an altitude of 1 km MSL. Note the emission continuum outside of the CO$_2$ absorption band for the in-cloud path. Also shown is the transmission profile of the currently installed interference filter.
Figure 7: The calculated brightness temperature as a function of viewing pathlength for paths in strato-cumulus cloud and in clear air at a pressure altitude of 898 mb with the currently installed filter. The data for clear air are the same as in the top graph of Fig. 4. The model atmosphere temperature is shown by the line at 281 K.
that is, a liquid water path of 15 g m$^{-2}$. In clear air, on the other hand, it takes at least 5000 m for the weak absorption lines to fill in the edge of the filter bandpass so that the band-integrated transmission approaches zero (the emissivity approaches unity) and the brightness temperature becomes that of the actual air temperature.

If the roll-induced error calculations from Section 2.5 are done for this case, it is found that the roll-induced error in clouds is negligible since the effective viewing path is so short. The effective range $R_{eff}$ for roll-induced error could not be determined from the LBLRTM code—different look angles gave the same result. However, it can be estimated as the range where the in-cloud brightness temperature is the same as the clear air brightness temperature at $R_{eff} = 128$ m. This procedure gives the effective range in cloud to be less than 20 m.

### 2.7 Interferences

Because the radiometer measures the thermal radiance of the atmosphere away from the aircraft, it requires no corrections for aerodynamic heating or evaporative cooling. However, it will respond to any material on the window which is not transparent at 4.25 μm. If the window is contaminated with an IR-absorptive, and hence IR-emissive, substance then heating and cooling of the window will cause measurement errors. In particular, water is strongly absorbing in this region, with an absorption coefficient of 200 cm$^{-1}$ (Downing and Williams, 1975) for liquid water, and about 450 cm$^{-1}$ for ice (Warren, 1984). Therefore a water film only 0.050 mm thick has a transmission of $e^{-1}$ and if this film is on the radiometer window then $(1 - e^{-1})$ or 67% of the measured radiance will come from this water film. Since these particles or film can be affected by dynamic heating and evaporative cooling, care is taken in mounting the radiometer to protect the window from water droplets and particle impaction.

In clouds, the ice particles and water droplets behave as infrared-black particles and the measured radiance will be that from atmospheric carbon dioxide as well as that emitted by water droplets and ice at their respective temperatures. Since the atmospheric carbon dioxide is so opaque at line center the majority of the measured radiance will still indicate the air temperature, while the ice or water, whose temperature is expected to be close to the air temperature, is seen only through the edge of the CO$_2$ band. As a result, the averaging path is significantly shortened while any error in the temperature reading is expected to be less than the measurement precision.

The optical design and optical coatings minimize errors from internal radiance reaching the detector. By monitoring the internal temperatures the radiance which does reach the detector can be accounted for through calibration.

Because of the strong atmospheric absorption and weak Rayleigh scattering in the midwave infrared, neither scattered solar radiation nor backscattered hot exhaust radiance have been found to give rise to errors. However, direct radiation from the sun at the edge of the filter band where it is not absorbed by atmospheric CO$_2$ is seen by the radiometer. This can increase the radiometric temperature by 20 °C or more. However, it is usually seen for only five to ten seconds as the aircraft is turning and is momentarily pointing the radiometer upward such that the sun appears within the radiometers roughly 15 degree field of view. See Section 4.5 for an example.
3 Hardware

There have been a couple of different versions of the Ophir air temperature radiometer installed on NCAR aircraft. Most recently, in order to fix an electronics problem which was seen in 2001 during the EPIC (Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System) program, we replaced some of the printed circuit boards with spare boards from a later version of the radiometer. The symptom was instantaneous jumps of a few tenths of a degree in the reported blackbody and housing temperatures. Since the outside radiance is determined by comparing it to the reference blackbody radiance calculated from its temperature, these apparent jumps in reference temperature generated similar jumps in the reported air temperature. This problem was eventually solved by replacing a number of the printed circuit boards. A slight incompatibility between the new and old printed circuit boards caused the temperature-controllable reference blackbody to be driven as cold as possible at all times with the newer boards. This caused excess heating inside the optical head and the temperatures to be very slow to equilibrate when the air temperature changed. In October 2002, the thermoelectric cooler for this blackbody was disconnected so that the blackbody was allowed to float at the optical head temperature, the same operating mode as was used prior to the circuit board change. By keeping the reference blackbody near to the outside air temperature, the dynamic range required of the detector and signal processing electronics is minimized. This reduces the effect of non-linearities and drift and allows higher gain electronics for improved sensitivity and precision.

In addition, the new interference filter was installed late in 2001 as described in Section 2.3.

At this time the greatest potential for improvement lies in upgrading the electronics for improved stability in the following three areas: detector temperature control (which directly affects the detector responsivity), amplifier gain, and reference blackbody temperature measurement. The optics and thermoelectric-cooled HgCdTe detector are still appropriate for this application. Lead selenide is an acceptable alternative. Quantum well and quantum dot detectors operating above cryogenic temperatures are not yet ready for routine use but their narrow wavelength responsivity, and electrically tunable in some designs, may make them the detector of choice sometime in the future.

An additional change that might improve the low-temperature performance and stability would be cementing the interference filter directly onto the detector inside the cooled, temperature-stabilized detector can.

3.1 Sensor Mounting

On the C-130 the Ophir radiometer is installed in the right-hand wing pod. In level flight it points horizontally at a right angle to the fuselage. In this location it avoids looking through regions where the pressure is significantly different from the ambient atmosphere and the temperature changes in such regions. Since it is not gimbaled it will point up or down as the aircraft rolls giving rise to errors in the reported temperature as predicted in Section 2.5 and seen experimentally—see Fig. 11 for an example.

3.2 Sensor Design

Figure 8 shows a block diagram of the Ophir radiometer. A gold-coated chopper wheel,
Figure 8: The block diagram of the Ophir air temperature radiometer. Only one of the two blackbodies is shown. The external window is at the right. Behind it is the chopper wheel, the 4.3 μm interference filter, the focusing lens and then the detector can. Inside the detector can is the HgCdTe detector, the thermistor to monitor the detector temperature, and the thermoelectric cooler for the detector. The AD590 are temperature-current transducers. The TEC driver supplies the power to the thermoelectric coolers for the detector and controlled blackbody. The entire optical system is kept near the external air temperature by air circulating between the inner and outer cans of the optical head.
placed just inside the window, alternately passes external radiation or reflects radiation from the internal reference blackbody through the narrow-band interference filter, approximately centered on the CO$_2$ absorption band, and onto a thermoelectrically cooled HgCdTe detector whose temperature is monitored by a thermistor. The AC-coupled detector signal, whose magnitude is proportional to the difference in radiance between the air and the reference blackbody, is amplified and bandpass filtered to match the 2500 Hz chopper frequency. Each half-cycle is integrated by means of a voltage to frequency converter followed by a counter before being passed to the 68HC11 microcontroller. The microcontroller also controls the detector’s temperature and bias current, monitors the temperature of the reference blackbodies and of two locations within the optical head, and records the motor speed. These parameters are placed in the serial data output stream from the radiometer.

### 3.3 Data Output

The measurements necessary to calculate the air temperature are transmitted to the aircraft data system once per second over an RS422 serial interface in the form of A/D converter counts. These counts are then converted to the appropriate temperatures and signal voltages, and the air temperature calculated. The temperature and voltage data stored in the flight data file consists of the detector bias voltage (designated ODETDC), two optical head internal temperatures (OTSNT and OTBNCH), the detector temperature (OTDET), the floating and controlled blackbody temperatures (OTBBF and OTBBC), the motor speed (OSMOTR), and the detector signal (ODSIGC) which is proportional to the difference in radiance between the reference blackbody and the air. The air temperature is calculated with these parameters as inputs to a least-squares fit as described below.

### 3.4 Calibration

Two blackbodies are available for supplying the reference radiance which the detector compares to the air radiance. One blackbody, the controlled blackbody designated OTBBC, could be driven warm or cold by a thermoelectric cooler. The other, OTBBF, was left to equilibrate to the temperature of the optical head which is kept near the outside air temperature by venturi-driven forced ventilation through the air space between the inner and outer cans (Fig. 8). By comparing the temperature of these two blackbodies and the detector signal, an in-flight calibration of detector and electronics could be performed. Combined with lab calibrations using external blackbody sources to account for optics transmission the radiometer should give an absolute air temperature measurement. However, it was found that such calibrations were not sufficiently stable and accurate. Instead, the instrument calibration is based on a linear least-squares fit to match the Rosemount immersion thermometer temperature during flight periods when the Rosemount is considered reliable. The fit is calculated from

\[
M_{\text{air}} - M_{\text{bbc}} = A_1 V_{\text{det}} + A_2 + A_3 M_{\text{snt}}
\]

where $M_{\text{air}}$ is the radiant exitance, Eq. (2), of the air calculated using the Rosemount-reported temperature and at the filter center wavelength, $M_{\text{bbc}}$ and $M_{\text{snt}}$ is the radiant exitance of the reference blackbody and the stray exitance calculated from the blackbody temperature OTBBF and the optical head temperatures OTSNT, respectively, and $V_{\text{det}}$ is the detector signal ODSIGC. The coefficients $A_1$, $A_2$, and $A_3$ are the calculated least-squares fit
coefficients. Ideally, both $A_2$ and $A_3$ would be zero, but these terms account for electronics offsets and stray radiance from inside the optical head. Calibrating the radiometer this way eliminates problems caused by component drift and only precise relative temperature measurements are needed, rather than highly accurate absolute temperatures. The calibration is checked before and after each project and if necessary, a new fit is generated to account for component drift.

The housing and blackbody temperatures are measured with AD590L temperature-to-current transducers. Since the output of the AD590 is not read directly there is also an empirical linear calibration to convert the A/D counts reported by the microcontroller to temperature. For the most part, errors in this calibration get folded into the coefficients in Eq. (7). The 0.4 °C non-linearity of the AD590L (over the temperature range from –55 to +150 °C) and the 0.1 °C reproducibility limit the lower bound of the temperature uncertainty. When the radiometer is used for in-cloud temperatures during periods the Rosemount thermometer may have been wet, calibrating the radiometer to the Rosemount before or after the wetting may reduce the uncertainty.

3.5 Sample Rate Limitations

This averaging pathlength calculated above shows that there is little to be gained by sampling the data faster than roughly 1 Hz even though the microcontroller can be programmed to do so. At typical C-130 speeds, a 1 Hz sample rate corresponds to a sample every 125 m. In order to measure higher-frequency components, such as small scale turbulence on the 10–15 m size scale, it would be necessary to measure at 10 Hz. However, the radiometer is still going to smooth out the data over its roughly 100 m viewing path.

The other factor arguing against faster sampling is the signal to noise ratio. For short periods of time the noise, as determined by the standard deviation of the difference from the Rosemount probe, is about 0.1 °C. In Gaussian statistics the signal to noise ratio is proportional to the square root of the integration time, so increasing the sample rate to 10 Hz can be expected to increase the noise level to over 0.3 °C. The 1 Hz sample rate is a good compromise between acquiring the most data, and the spatial smoothing and signal to noise ratio.

4 Flight Tests

4.1 Previous Testing

An earlier design of the radiometer was previously tested on the NCAR King Air during a field project over the Gulf of Mexico in 1985 (Cooper, 1987, Lawson and Cooper, 1990). While the temperature range encountered was relatively narrow and warm, from –5 °C to +20 °C, the radiometer was found to work well under most conditions. In particular, the radiometer maintained accurate temperature measurements as the aircraft exited warm clouds whereas the immersion thermometers showed a transient drop in temperature which was ascribed to water evaporating from the wet sensor. Airspeed appeared to noticeably affect the reported radiometric temperature, and rapid air temperature changes introduced transient errors. These problems were possibly due to temperature non-uniformities of the reference blackbody as its average temperature varied (Nelson, 1986). In that version of the radiometer, outside air was directed through the interior
4.2 Current Testing

The radiometer as currently configured was tested on flight 112RF08 on 17 December 2002. This flight included six touch-&-go\textsuperscript{4} maneuvers, seen as temperature spikes between time

\textsuperscript{4}In a touch-and-go, the aircraft comes in for a landing but touches down only briefly before ascending again.
71000 and 76000 in Fig. 9, and a speed run\(^5\) at 5500 m altitude (~3500 m AGL) at -25 °C. Calibration was performed by doing a least-squares fit to the C-130 Rosemount de-iced probe ATWH (also designated the reference temperature ATX for this flight) using all data between takeoff and final touchdown. The radiometer variables used were the detector signal (ODSIGC), controlled blackbody temperature (OTBBBC), and one optical head temperature (OTSNT).

The fit is very good as can be seen in Fig. 9. The root-mean-square difference between the two sensors is 0.20 °C. This includes the times when the aircraft was rolling in turns as well as the times when the aircraft was on the ground during the touch-and-go maneuvers. As expected, the radiometric temperature respectively increased or decreased when the aircraft roll caused the radiometer to look downward to warmer air or upward toward cooler air. Whenever there is weight on the aircraft wheels during the touch-and-go maneuvers the heater for the de-iced Rosemount probe is automatically shut off. Abrupt changes in the ATX temperature reported just as the plane lifted off are most likely artifacts of the heater coming on again. The radiometer and the Rosemount were in good agreement within 30 seconds after takeoff. Excluding the periods when the aircraft had a roll angle of greater than 5° and was within 30 seconds of takeoff reduces the RMS difference to 0.18 °C. Figure 10 shows a histogram of the difference between the Rosemount sensor and the Ophir radiometer during these airborne, near-level flight periods. At least some of the low-end tail is due to differences occurring as the aircraft was still coming out of a roll. Of the nearly 10,000 one-second samples, 95% are within -0.4 °C and +0.3 °C of the Rosemount temperature.

4.3 Speed-induced Error

This 112RF08 flight included the speed run shown in Fig. 11. The 0.5 °C drop in reported temperature at 77,580 UTC occurred when the aircraft rolled 25 degrees into a 180 degree right-hand turn. This pointed the right wing downward so that the radiometer was viewing warmer air below the aircraft, resulting in the difference going negative. The 0.5 °C drop in reported temperature is in agreement with the calculations in Section 2.5.

Plotted in Fig. 12 is the airspeed and temperature difference data for the the speed run from 150 m/s to 130 m/s after the turn. As can be seen, there is essentially no correlation between airspeed and radiometric temperature. Over the 125 to 150 m/s speed range the spread in the data well exceeds the possible speed-induced error, the small value of which may also be due to error in the recovery factor for the Rosemount sensor or the atmosphere not uniform and in steady-state. This is in contrast to what had been found for the original radiometer where Cooper (1987) reported that changing the speed from 90 to 120 m/s caused a change of 0.6 °C in the radiometric temperature. The better performance seen here is probably due to better reference blackbody temperature uniformity discussed in Section 4.1.

4.4 Power Spectral Density

For the original radiometer, Cooper (1987) found that the power spectral densities of the radiometric temperature and the immersion thermometer were well matched at low frequency and followed the 5/3 slope expected for inertial subrange turbulence until the

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\(^5\) In a speed run the aircraft altitude is held constant while the airspeed is varied.
Figure 10: Histogram of the difference data (ATX – OAT) for flight 112RF08. Each bin is 0.05 °C wide. Excluded from the histogram are the time periods when the aircraft had a roll angle in excess of ±5° or when on the ground and within 30 seconds of liftoff.
Figure 11: The airspeed and Rosemount - Ophir temperature difference (ATX – OAT) during a speed run. The altitude was 5530 m. The dip in the difference plot at UTC=77580 is due to aircraft roll.
Figure 12: The correlation between the airspeed and temperature difference (ATX–OAT) in the speed run after the turn.
frequency exceeded about 4 Hz. Above this frequency the response of the radiometer rolled off, most likely due to the extended averaging path of the radiometer smoothing out the small scale fluctuations. Figure 13 shows the power spectral density of the current radiometer for a 10 minute period at low altitude (~500 m AGL) between touch-and-go landings. Again, the 5/3 slope line is followed very well until the 1 Hz sampling rate limits the maximum frequency. At one time we attempted acquiring data directly from the pre-amplifier output to get a faster sampling rate, but the data were too noisy to be useful. Because of the extended sampling range discussed previously, we now see that high-frequency sampling would be of little scientific value anyway.

4.5 Sensitivity to Sunlight

As was discussed in Section 2.7, direct solar radiation at the edge CO₂ band can be transmitted through the atmosphere and detected by the radiometer. Figure 14 shows a portion of the IDEAS-2 flight 112RF05 on 24 November 2002 where this occurred. The aircraft was repeatedly flying over the same ground track while descending from 4500 m to 3400 m MSL. As the aircraft executed 180° turns the radiometer was pointed upward at 25° such that the sun came into its field of view. The resulting spikes in reported air temperature are up to 25 °C above the normal temperature and last about 5 seconds as the aircraft turns. At each spike the aircraft heading is about 135 degrees which puts the radiometer, mounted on the right wing pod facing outward, looking southwest at 225 degrees. The spikes are seen only when the aircraft is at negative roll angles which points the radiometer upward. When the radiometer is pointed downward (positive roll angle) and the same heading, at T=2500 for example, the spike is not seen.

4.6 Low Temperature Errors

As was seen in Fig. 1, the radiance in the 4.2 μm spectral region decreases rapidly as the temperature goes below 0 °C. At -30 °C the radiance is 14% of the radiance at +10 °C, and at -45 °C it is only 5.5% of its +10 °C value. This is a result of being on the short-wavelength (high-wavenumber) side of the spectral radiance maximum. This drop in radiance at low temperature may explain significant errors seen in flights early in 2002 when the temperature dropped to as low as -45 °C. This is believed to be due to the lack of signal from the air combined with the effects of stray radiance from inside the optical can. If radiance from the thermolectric coolers or pre-amplifier increases the detector signal during the reference portion of the chopper cycle it would increase the apparent radiance difference between the reference and the air so that the calculated air temperature is lowered. For accurate radiometric measurements at temperatures below -35 °C it is probably necessary to operate in the 15 μm CO₂ band as there is virtually no signal left to measure in the 4.2 μm band.

5 Conclusions

The Ophir air temperature radiometer can accurately measure air temperature away from the aircraft boundary layer. It is especially useful for measuring temperatures in clouds where its averaging range is lessened by emission from the cloud particles, as well as under conditions where the Rosemount probe may be suffering from wetting errors such as when
Figure 13: The power spectral density of a 512 second sample during the October 2002 flight (112RF08) starting at 72,600 UTC. The altitude was 500 m AGL. Included is the 5/3 slope line expected for inertial sub-range turbulence.
Figure 14: A portion of the 112 RF05 flight on 24 November 2002 showing the Ophir temperature (OAT), the aircraft roll angle and true heading. The actual time is from 21:29 to 22:11 UTC, 15:29 to 16:11 local Daylight Savings Time. The sharp spikes in the Ophir-reported air temperature are the result of the sun coming into its field of view as the aircraft turns.
within or immediately upon leaving clouds. The precision is about 0.2 °C when using a regression algorithm relative to the Rosemount immersion thermometer.

In clear air the radiometer measures an average of the air temperature over hundreds of meters, but heavily weighted to the air closest to it. For this reason, as well as signal to noise considerations, the maximum usable sample rate is around 1 Hz. Also, it is subject to errors on the order of 0.5 °C induced by aircraft roll of 25° during turns at typical C-130 flight altitudes. In low altitude turns it is quite possible for the ground temperature to be averaged into the reported radiometric temperature. This problem was more pronounced prior to January 2001 when the new interference filter was installed.

In clouds the averaging path is much shorter because of the continuum absorption and emission of liquid water and ice particles. The effective range for estimating roll-induced errors is on the order of tens of meters. With this short of an averaging distance, in a standard lapse rate atmosphere the roll-induced error will be less than the precision of the measurement.

Because the Ophir radiometer is calibrated to match the Rosemount probe there is little reason to use the radiometric temperature in clear air where the Rosemount is not affected by wetting. Therefore it is recommended that the Ophir radiometric temperature primarily be used in level flight to measure temperature in clouds when the Rosemount thermometer may be suffering from wetting effects.
References


