Technical Memorandum ERL WPL-207

CALIBRATION OF INFRARED RADIOMETERS FOR CLOUD-BASE TEMPERATURE REMOTE SENSING: TECHNIQUE AND ERROR ANALYSIS

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ABSTRACT

Absolute radiometric calibration is required for ground-based infrared remote sensing of cloud-base temperature. This requires associating the radiometer's output voltage with blackbody temperatures over the desired measurement range. Insufficient attention to subtle error sources while performing this conceptually simple calibration results in errors many times larger than the 1.0° C uncertainty achievable with a carefully performed calibration. Inadequate blackbody simulation and imprecise voltage measurements contribute most significantly to calibration uncertainty. The purpose of this report is documentation and error analysis of the technique used at the NOAA Wave Propagation Laboratory for calibrating zenith-viewing infrared radiometers. Additional uncertainties that arise in cloud-base temperature measurements for real clouds in the real atmosphere are discussed briefly.

1. INTRODUCTION

Infrared radiometric remote sensing of cloud-base temperature requires accurate radiometer calibration. Insufficient attention to detail during radiometer calibration and operation results in large errors. For example, during a 1990 field experiment, faulty calibration and operation were largely to blame for an 18° C temperature difference between two infrared radiometers viewing the same low, uniform stratus cloud layer.

The infrared radiometers operated routinely by the Wave Propagation Laboratory (WPL) are Barnes PRT-5 systems with custom optical filters (9.95-11.43 μm), and 2° fields of view. This report discusses only calibration and measurement issues relevant to single-channel staring radiometers. Though many aspects of this report are applicable generally, this report does not pursue issues unique to scanning or multichannel radiometer calibration.

The four objectives of this report are addressed sequentially: 1) description of the technique used at WPL for calibrating zenith-viewing infrared radiometers; 2) identification and quantification of errors in this technique; 3) estimation of the uncertainty due to calibration; and 4) discussion of additional uncertainties that arise in measurements of cloud-base temperatures for real clouds in the real atmosphere.

Adequate simulation of a blackbody source and precise measurements are the most critical issues in the WPL calibration technique. Atmospheric measurements involve additional uncertainties such as cloud radiative properties, atmospheric emission, and radiometer-optics contamination. Well-calibrated radiometric cloud-base temperature measurements agree to within 1° C with temperatures measured by radiosondes at cloud heights determined by laser ceilometers (Snider, 1988). Because the uncertainty in verifying the actual cloud-base temperature is usually of comparable magnitude, this calibration technique is sufficiently accurate.

2. INSTRUMENT DESCRIPTION

Figure 1 is a diagram of the optical head of the WPL radiometer[1]. The radiometer's

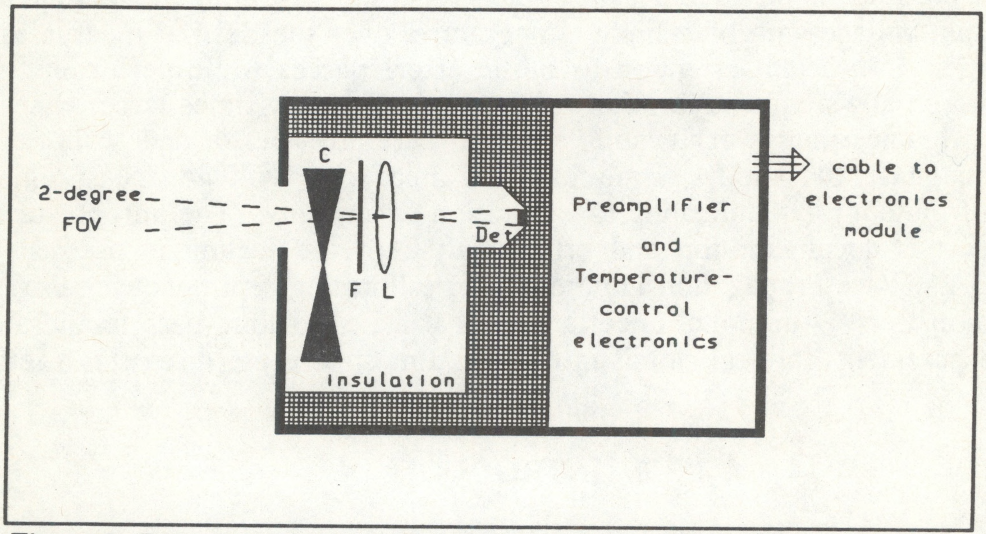

Figure 1. Diagram of the optical head of the single-channel (10.69 μm) infrared radiometers used at WPL.

angular field of view is 2°, the angle formed by rays drawn from the edges of the detector (Det) through the center of the field lens (L). The optical bandwidth is limited by a filter (F) with half-power-transmission wavelengths of 9.948 and 11.428 μm (center wavelength = 10.69 μm). WPL uses these optical filters (from OCLI, Santa Rosa, CA) as replacements for the original Barnes 8-14-μm filters to reduce contamination by atmospheric emission and to equalize the responses due to liquid and ice.

[1] *The PRT-5 radiometers are now produced by Pyrometer Instrument Co., 234 Industrial Parkway, Northvale, NJ 07647. Similar radiometers are available from Minarad Systems, Inc., 1525 Kings Highway E., Fairfield, CT 06430.*

At the front of the optical head is a temperature-controlled cavity enclosing a bolometer detector, a 10-mm-diameter IrTran-2 (Wolfe and Zissis, 1989) field lens (F/2.8), an optical filter, and a gold-coated chopper (C). When the chopper blocks the radiometer aperture, the detector is illuminated by emission from the radiometer optics. When the chopper is not blocking the radiometer aperture, the detector is illuminated by radiation from the external source and its environment. Thus, the detector responds alternately to emission from the optics and to the combined emission from the optics and the external source. The detector's output is an AC voltage, proportional to the difference in infrared emission from these two sources. Emission from the warm temperature-controlled optics and detector is subtracted from the measurement by the chopper modulation, providing a stable reference that enables absolute calibration.

The AC detector voltage is amplified, bandpass filtered, and synchronously detected. AC amplification is easy to implement and removes DC instability. The bandpass filter, with center frequency of 100 Hz (equal to the chopping frequency) reduces both low-frequency detector noise and high-frequency thermal noise. Synchronous detection produces a DC voltage with magnitude and polarity corresponding to the difference between the external-source and optical-cavity radiances (indicating the difference between the temperatures of the external source and the reference).

3. THE WPL INFRARED RADIOMETER CALIBRATION TECHNIQUE

3.1 Background

Radiometric temperature sensing is based on the theory of blackbody radiation (Spiro and Schlessinger, 1989; Wyatt, 1978). Above absolute zero, any material medium (gas, liquid, solid, or plasma) radiates thermally induced electromagnetic energy. A theoretical blackbody radiates this energy isotropically, with wavelength and temperature dependence according to Planck's law:

$$L_b(\lambda,T) = \frac{2hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda k T_b}\right)-1\right]} , \qquad (1)$$

where $L_b(\lambda,T)$ is blackbody spectral radiance (W m^{-2} sr^{-1} m^{-1}),
h is Planck's constant = 6.6262 x 10^{-34} (J s^{-1}),
c is the velocity of light in vacuum = 2.998 x 10^{-8} (m s^{-1}),
λ is the electromagnetic radiation wavelength (m),
k is Boltzmann's constant = 1.3806 x 10^{-23} (J K^{-1}),
and T_b is the ideal-blackbody temperature (K).

In Equation (1), the spectral radiance is the power radiated per unit area, solid angle, and wavelength. Radiance is a convenient quantity because multiplying it by a sensor's aperture area, solid-angle field of view, and spectral bandwidth gives the received power.

A blackbody absorbs all incident radiation and, to maintain thermal equilibrium, reradiates it. Thus, a blackbody is both a perfect emitter and a perfect absorber of electromagnetic radiation.

Because a theoretical blackbody is not realized perfectly by real media, Equation (1) must be modified to include the emissivity, $\epsilon(\lambda,T)$. The emissivity of a medium is the ratio of its actual radiance, $L(\lambda,T)$, to the radiance of an ideal blackbody ($0 \le \epsilon \le 1$):

$$\epsilon(\lambda,T) = \frac{L(\lambda,T)}{L_b(\lambda,T)} . \tag{2}$$

Accordingly, the radiance of an object with emissivity $\epsilon(\lambda,T)$, at a temperature T and wavelength λ, is

$$L(\lambda,T) = \epsilon(\lambda,T) \frac{2hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]} . \tag{3}$$

An object with emissivity less than unity is called a greybody. A greybody absorbs a fraction, $\epsilon(\lambda,T)$, of all incident radiation, and reflects the balance with reflectivity, $\rho(\lambda,T)$:

$$\rho(\lambda,T) = 1-\epsilon(\lambda,T) . \tag{4}$$

If radiance and emissivity are known at a wavelength λ, the only variable in Equation (3) is temperature, T. Thus, if emissivity is known or estimated, an object's temperature can be determined from a measurement of its thermal radiance. This is the fundamental concept of radiometric temperature sensing.

3.2 Conceptual Description

Radiometric temperature sensing requires association of the radiometer output with a source temperature. This association is possible explicitly through Equation (3) if the radiometer is calibrated in absolute power or radiance units (Wyatt, 1978). In such a technique, the transmittance of the optics between the source and the detector, the spectral responsivity of the detector, and the spectral distribution of all interfering sources (including emission of the optics and the detector, background radiance, etc.) must be considered carefully. Additionally, the spatial uniformity of the detector responsivity, and sometimes the polarization distribution of the source radiation, must be considered.

The technique used at WPL avoids some of these difficulties by associating the radiometer output voltage directly with a known source temperature, with no explicit connection to Equation (3). Voltages recorded with the radiometer pointed at a blackbody-simulator source for a range of known temperatures are used to derive a best-fit calibration equation that expresses target temperature as a function of radiometer output voltage. In this way, the system can be calibrated without exact knowledge of optical transmissivity and detector responsivity (if target temperature, not radiance, is the desired quantity).

A limitation of this method is it assumes that both the calibration source and the remote target radiate identically. Accurate radiometric calibration requires the source to exhibit highly uniform emissivity and to radiate uniformly throughout the radiometer field of view. These are both fundamental characteristics of a blackbody, but are often not realized from low-emissivity targets. Also, low-emissivity targets radiate low power, making the radiometric measurement difficult to perform and uncertain to interpret. Therefore, low-emissivity measurements are usually avoided, and great effort is expended to achieve the highest, most uniform emissivity possible for all calibration targets.

3.3 Detailed Description

Though conceptually simple, recording radiometer voltages as a function of blackbody temperature involves details that must be considered carefully. This section presents a step-by-step description of the technique used at WPL, with important details noted.

Figure 2 illustrates the equipment for this technique. This figure represents the blackbody-simulator source by a conical cavity; this is a common, though not necessary, geometry. The radiometer head points into the source, whose temperature is measured by a calibrated thermocouple. Measuring the radiometer output voltage for multiple source

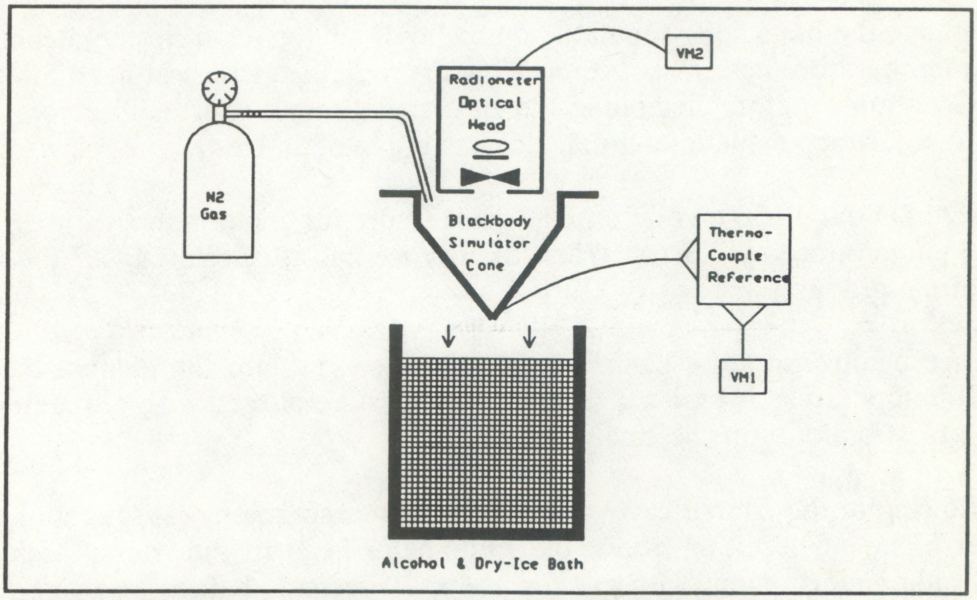

Figure 2. Equipment used in calibration of infrared radiometers.

temperatures over the desired calibration range produces data to which a calibration curve of voltage vs. source temperature may be fit.

Step 1. Set up the equipment as indicated in Figure 2. Because the thermocouple voltage magnitudes are on the order of tenths of millivolts expressed to microvolt precision, the thermocouple voltmeter (VM1) must have microvolt resolution and the highest accuracy possible. The radiometer output, however, is on the order of tenths of volts, so millivolt resolution is sufficient for VM2. Be sure all electrical connections are clean to reduce noise. Fill a thermally insulated container with alcohol, and have crushed dry ice ready for cooling the alcohol.

Step 2. Turn the power on for the radiometer, the voltmeters, and the thermocouple reference-junction box. Let all the equipment warm up and stabilize for at least 20 minutes, preferably for 1 hour. Insufficient warm-up time can result in large errors.

Step 3. Stir the alcohol bath to avoid thermal gradients. Place the source in the alcohol bath and wait for it to achieve thermal equilibrium (a good practice is to wait until the thermistor and radiometer voltages fluctuate less than 1% of their magnitude per second). The alcohol should be deep enough that as much of the source is immersed as possible without alcohol spilling into the cavity. If only part of the source is immersed, thermal gradients will exist across the blackbody cavity. These gradients produce errors that suggest source emissivities greater than unity or temperatures much different from the correct value.

Step 4. Place the radiometer optical head onto the blackbody-simulator source with the detector aimed at the center of the cavity. Record the thermocouple and radiometer voltages. Recording several measurements a few seconds apart improves the statistical quality of the final calibration curve.

Step 5. Remove the blackbody-simulator source and radiometer from the alcohol bath. If the alcohol temperature is less than zero, allow the radiometer optical head to warm up to about 10° C or more before beginning the next measurement to avoid errors caused by variations in the chopper-blade and detector-cavity temperature.

Step 6. Pour in about 40-50 ml of crushed dry ice (more for colder temperatures) to reduce the alcohol temperature by 3-5° C. When the dry ice has all sublimed, stir the alcohol to remove thermal gradients.

Step 7. Once again insert the blackbody-simulator source into the alcohol bath. If the alcohol-bath temperature is below 0° C, the cavity must be purged with nitrogen gas or dry air to avoid frost buildup on the cavity walls.

Note: gas flowing in the source cavity during a cold measurement causes rapid cooling of the chopper blade. Therefore, attach the radiometer head to the source and purge the source-and-radiometer system with gas for about 30 seconds before inserting it into the alcohol. Then, turn the gas off, insert the source into the alcohol, and wait for its temperature to stabilize (≈20-40 seconds) before recording several sets of voltages in the next 1-2 minutes. If the radiometer head seals the aperture of the blackbody-simulator cavity fairly well, frost should not begin to appear on the cavity wall for more than 3 minutes after the gas is shut off.

Step 8. Repeat steps 5-7 until the desired temperature range has been covered, or until the alcohol will get no colder (≈-70° C). The 10.69-μm equivalent blackbody temperatures of cirrus clouds and the clear sky are in the -80 to -100° C range. Because this is colder than can be achieved with alcohol and dry ice, a colder source (e.g., liquid nitrogen) is required for accurate calibration of radiometry for a clear atmosphere or cirrus clouds.

The above description is intended to be a user's guide for the infrared radiometer calibration technique used at WPL. The sources, implications, and solutions of errors are described more completely in the following sections.

4. CALIBRATION ERRORS

Though conceptually simple, the calibration technique described in section 3.3 includes potential errors that must be considered carefully for accurate calibration. The most significant of these errors arise from improper simulation of a blackbody source and imprecise measurement of temperatures and voltages.

4.1 Blackbody-Simulator Temperature Uniformity

One of the most important characteristics of a blackbody simulator is temperature uniformity. In WPL's cloud radiometer calibration technique, the calibration temperature is progressively decreased below ambient. Therefore, maintaining temperature uniformity in the blackbody-simulator cavity becomes increasingly difficult.

If different areas of a blackbody simulator are at different temperatures, then its total emission is described by Equation (3) with some average source temperature. Thus, a blackbody simulator only partly immersed in cold alcohol will radiate at a temperature somewhere between those of the cold alcohol and the warm air.

Typical wall emissivities of blackbody simulators are between 0.7 and 0.9; however the emissivity of a black cavity is higher because of multiple reflections within the cavity (Bartell and Wolfe, 1976). Therefore, a small fraction of the radiation from a warm cavity area will be reflected from the cold area (the intended source) into the radiometer field of view. The result is an effective radiating temperature greater than the physical temperature of the immersed portion of the cavity. An incorrect interpretation of this phenomenon could be that the cavity emissivity is greater than unity. Bartell discusses this disturbing idea and shows that uniform temperature is critical for blackbody simulation (Bartell, 1984).

The blackbody simulators used in past years at WPL are conical copper cavities painted black with *3M Chem-Glaze* paint (Wolfe and Zissis, 1989). These cavities are not ideally designed for temperature uniformity because the copper walls usually extend beyond the alcohol-air interface. At the cold end of the calibration, a temperature gradient as large as 90-100° C exists between the alcohol and the air above it. The adverse effect of this can be made negligible if the alcohol depth is maintained to nearly the top of the cavity so that at least 90% of the cavity is immersed.

4.2 Blackbody-Simulator Emissivity

A blackbody simulator requires uniform emissivity nearly equal to unity. If the emissivity varies along the surface of a blackbody simulator, the simulator radiates with some average temperature produced by the temperature and emissivity distribution.

If the emissivity is uniform, but less than unity, several problems occur. First, the simulator will appear to have a lower temperature than it actually has. Second, even if the low emissivity is known and accounted for, the nonzero reflectivity causes radiation from the surroundings (including the radiometer) to be reflected into the radiometer field of view. This is especially troublesome if the unwanted radiation is from a source much warmer than the blackbody simulator, as often is the case in our cloud radiometer calibration technique.

To estimate the magnitude of this error, let the detected radiance be equal to the sum of two components: 1) the radiance emitted by the blackbody simulator, $eL_{bb}(\lambda,T_{bb})$, with L_{bb} equal to the blackbody radiance given by Equation (1); and 2) the radiance emitted by the radiometer and its surroundings, $(1 - e)L_0(\lambda,T_0)$, which is reflected from the cavity to the detector. Thus, the radiance detected by a radiometer with temperature T_0, looking into a blackbody-simulator cavity with emissivity e and temperature T_{bb}, is

$$L_d(\lambda,T_{bb}) = e\,L_{bb}(\lambda,T_{bb}) + (1-e)\,L_0(\lambda,T_0)\,. \tag{5}$$

A typical situation consists of a radiometer at T_0= 291 K (20° C), a cavity with e = 0.963 and T_{bb} = 263 K (-10° C), and center wavelength λ = 10.69 μm. For these parameters, Equation (1) produces L_{bb} = 517.1 μW cm^{-2} sr^{-1} μm^{-1} and L_0 = 848.5 μW cm^{-2} sr^{-1} μm^{-1}. Then, from Equation (5), L_d = 529.4 μW cm^{-2} sr^{-1} μm^{-1}. Using L_d to solve Equation (1) for the equivalent blackbody temperature, T_{eq}, results in T_{eq} = 264.5 K. Thus, the radiometer detects a signal equivalent to blackbody radiation at 264.5 K, whereas the calibration source is actually at 263.3 K. In this case, a 1.2-K error results from reflected ambient radiation.

The result of the above error is to cause the radiometric measurements to be too cold. With no correction for low cavity emissivity, the radiometer output voltage in the above case would be associated with a calibration-source temperature of 263.3 K. However, the calibration source actually radiates with an effective temperature of 264.5 K. Thus, a radiometric measurement of a cloud at 264.5 K will indicate 263.3 K (1.2 K too cold).

To estimate the actual cavity emissivity of our blackbody simulators, we used Figure 6 of Bedford and Ma (1974). This figure is a series of curves showing integrated cavity emissivity as a function of dimensions for conical cavities. For our cones, which have a 42° interior angle, Bedford and Ma (1974) suggest an integrated cavity emissivity of about 0.963. Incorporating this estimate into well-calibrated cloud temperature measurements brings them within about 0.5° C of the "actual" value for uniform, optically thick clouds. Most important, the deviation becomes randomly distributed, with radiometer measurements falling both above and below the estimated actual values. Without this correction, the radiometer temperatures are always colder than the actual temperatures, implying a systematic error.

Figure 3 shows temperature errors caused by calibrating with a conical cavity that has 0.963 integrated emissivity. The error at the ambient temperature (+18° C) is zero because

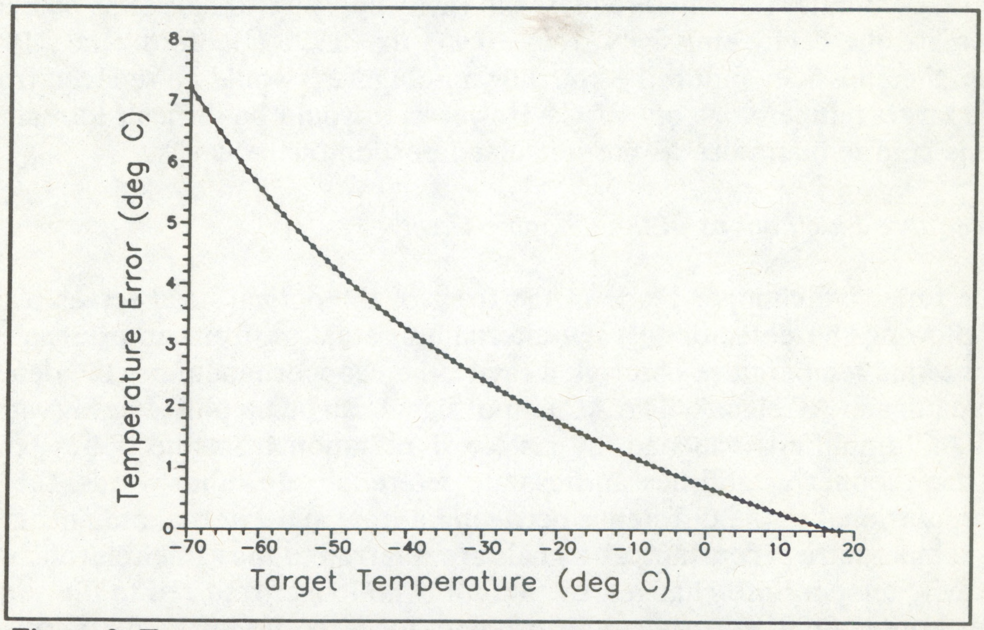

Figure 3. Temperature error caused by radiance from the warm (18-deg. C) surroundings reflected into the detector from a blackbody-simulator having an integrated cavity emissivity of 0.963.

the reflected ambient radiation exactly compensates for the lower cavity emissivity. However, the error grows with decreasing target temperature because the reflected ambient radiation increases the total cavity radiance beyond that of a blackbody at the cold source temperature. In Colorado, optically thick winter-storm clouds have base temperatures in the range of 0° C to -20° C; summer clouds are warmer, in the range of 0° C to +20° C. Optically thin clouds, in either season, appear very cold (-30° C and colder) because the measured temperature results from the combined cloud and clear-sky radiances. The clear-sky equivalent blackbody temperature is about -90° C at 10.69-μm wavelength. Thus, the effect of an emissivity less than unity is particularly important for radiometry of thin clouds or the clear atmosphere.

If the emissivity is known relatively well, this effect can be accounted for, at least approximately. However, an improved blackbody simulator with higher emissivity is a better solution (Bartell, 1981; Bedford et al., 1985). WPL recently constructed new inner-cone cavities (Bedford et al., 1985) for calibrating an infrared spectrometer (Shaw et al., 1991). These cavities have integrated emissivities of approximately 0.996, and could remove much of the calibration uncertainty caused by the low emissivity of the cones currently used for radiometer calibration. However, the large thermal mass of the inner-cone cavities would increase the time required to achieve thermal equilibrium when the source temperature is varied during calibration.

An alternate approach would be to improve the design of the currently used cones. Adding a black annular lid which reduces the cavity aperture to half of its present diameter would increase the cavity emissivity from ~0.963 to ~0.990 (Bedford et al., 1985). If this were done, the emissivity-induced error shown in Figure 3 would be reduced from 1.2° C to 0.3° C at a target temperature of -10° C. However, it would be difficult to maintain the lid at the same cold temperature as the immersed portion of the cavity.

4.3 Temperature Fluctuations in the Chopper Cavity

The reflective chopper blade at the front of the optical head serves two functions. First, by allowing the detector to view alternately radiation from an external source and from the internal temperature-controlled cavity, the chopper modulates the detector output voltage, creating an AC signal. The AC output signal can be amplified easily with feedback-stabilized AC amplifiers. Second, by reflecting radiation from the optics back into the detector, the chopper establishes an absolute reference. In other words, the AC output signal is proportional to the difference between internal and external radiances. As long as the cavity temperature is constant, all signals are referred to the same reference. But, if the chopper-cavity temperature changes, the output is no longer referred to the same absolute reference. Lorenz (1991) discusses this problem for airborne infrared radiometers.

During calibration the radiometer optical head is very near the cold blackbody simulator, and the chopper cavity begins to cool. If the gas that is used to purge water vapor from the blackbody simulator is allowed to flow during calibration, the chopper-cooling problem is aggravated through convection. Figure 4 shows two time series of measured chopper-cavity temperature. Figure 4a shows data taken with gas flowing, and Figure 4b shows data taken without gas flowing. In Figure 4b, the blackbody simulator and radiometer head were placed together, purged with nitrogen gas for 30 seconds, and then placed in the cold alcohol with the gas turned off. From Figure 4, it is clear that convective cooling of the chopper cavity prohibits accurate calibration when the gas is flowing. Instead, the system should be purged before immersion in alcohol (see Step 7, Section 3.3).

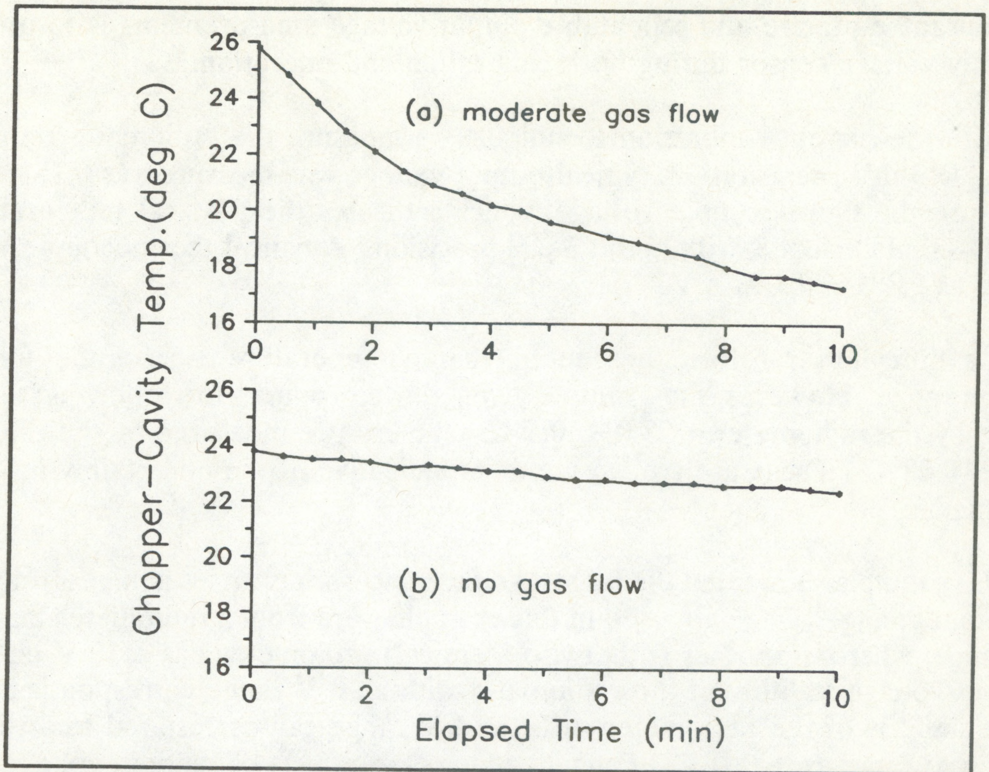

Figure 4. Time series of chopper-cavity temperature while the radiometer head looks into a -40 deg. C cone with and without nitrogen gas flowing.

Calibration measurements must not be taken too soon after placing the blackbody simulator into the alcohol (see Step 3, Section 3.3). It is equally important both to wait long enough to avoid temperature gradients on the blackbody simulator and not to wait so long that the chopper cavity is cooled excessively. A good technique is to wait for about 20-40 seconds before taking data, but to avoid taking data after the blackbody simulator has been in the alcohol for about 2 minutes. Figure 4b indicates that the chopper cavity cools about 0.35° C in 2 minutes. However, with gas flowing, the chopper cavity cools more than 2° C in 2 minutes. Figure 4 shows data taken with an alcohol temperature of about -40° C. The chopper cavity will cool less rapidly at warmer alcohol temperatures, and more rapidly at colder alcohol temperatures.

4.4 Voltage Errors

Given that adequate accuracy is achieved in blackbody simulation, the next significant issue is the precision to which radiometer and thermistor voltages can be measured. This is important during both calibration and operation. Imprecise voltage measurement during calibration increases the calibration uncertainty. Furthermore, even with an accurate calibration, the cloud-temperature uncertainty is increased if the output voltage is measured imprecisely during radiometer operation. Though WPL does not currently do it, the best way to guarantee precise and repeatable output voltage measurements is to use the same high-quality voltage sensor during both calibration and operation.

With the current calibration technique, we measure the radiometer output voltage with roughly 3-mV precision. A typical output voltage was measured as 0.783 ± 0.003 V. We measure the thermocouple voltage, which indicates the physical temperature of the blackbody-simulator cone, with about 3-μV precision. A typical thermocouple voltage was measured as 0.883 ± 0.003 mV.

It is difficult to transform these numbers into temperature uncertainties for the entire calibration range. However, the example given above produces the following: temperature measured by the radiometer ≈ 23.0 ± 0.5° C; temperature measured by the thermocouple ≈ 22.32 ± 0.08° C. These are typical numbers indicative of the uncertainty in the voltage measurements.

This example shows that the largest voltage uncertainty arises in measuring the radiometer output voltage. The data used in this example were from a radiometer that has a 1-V output range, whereas another (otherwise identical) radiometer has a 10-V output range. The output-voltage stability of the radiometer with a 10-V range corresponds to ± 0.1° C, while the stability of the radiometer with the 1-V range can correspond to a temperature fluctuation as large as ± 1.0° C. Thus, to reduce the effects of random voltage variations and voltmeter precision, the radiometers should be operated with a 10-V output range.

4.5 Frost in the Blackbody-Simulator Cavity

At temperatures below 0° C, frost will form on the surface of the blackbody simulator. This will alter the source radiance and destroy the calibration. To avoid frost, it is necessary to purge the cavity of water vapor. At WPL we do this by sealing the blackbody-simulator cavity with the radiometer head, and purging the system with nitrogen gas. As mentioned before, large variations in chopper temperature occur rapidly if the gas is allowed to flow during a cold measurement; therefore, the cavity should be purged before being placed in alcohol. At an alcohol temperature of about -40° C, following a 30-second nitrogen purge, frost did not form on the cavity walls until 7 minutes after the source was placed in alcohol during several frost tests. If the cavity is purged well before being placed in alcohol and data is taken within 2 minutes following, frost should be no problem.

4.6 Total Blackbody-Temperature Measurement Uncertainty

With careful attention to the details noted earlier, infrared radiometric temperature measurements in a controlled environment can be expected to have an uncertainty of about ±1.0° C. Estimates of the uncertainty due to each of the error sources were squared, summed, and the square-root taken, to arrive at this number. This process assumes statistically independent error sources (Bevington, 1969). The numbers used for the uncertainty elements are estimates based on calibration experience and laboratory experiments. All are achievable with proper attention to each item, as described in the previous sections.

Blackbody-simulator temperature uniformity and measurement appear to have an uncertainty of ±0.4° C (σ_{bb} = blackbody standard deviation ≈ 0.8° C). Output-voltage measurements produce less than ±0.5° C temperature uncertainty (σ_v ≈ 1.0 ° C). The output-voltage stability produces a temperature uncertainty of ±0.15° C for the 10-V radiometers (σ_{10V} ≈ 0.30° C), and ±0.75° C for the 1-V radiometers (σ_{1V} ≈ 1.5° C).

If the blackbody simulator is constructed and maintained carefully, the effect of a cavity emissivity less than unity can be accounted for and the systematic error due to this bias removed. Chopper-cavity cooling may result in a bias of up to 0.3° C (σ_c ≈ 0.6° C). Though this bias resembles a systematic error, it is actually random because it results in a variety of radiometer output voltages for a constant source temperature during a 2-minute calibration measurement.

Thus, the standard deviation for a worst-case calibration is

$$\sigma_1 V = \sqrt{\sigma_{bb}^2+\sigma_v^2+\sigma_{1V}^2+\sigma_c^2} \approx \sqrt{(0.8)^2+(1.0)^2+(1.5)^2+(0.3)^2} \approx 2.0°C \tag{6}$$

for the 1-V-range radiometer, and

$$\sigma_{10} V = \sqrt{\sigma_{bb}^2+\sigma_v^2+\sigma_{10V}^2+\sigma_c^2} \approx \sqrt{(0.8)^2+(1.0)^2+(0.3)^2+(0.3)^2} = 1.35°C \tag{7}$$

for the 10-volt-range radiometer. Therefore, the accuracies of the temperature measurements from these two radiometers are

$$T_1 V \approx T_0 \pm 1.0°C \tag{8}$$

and

$$T_{10} V \approx T_0 \pm 0.67°C, \tag{9}$$

where

T_{1V} is the temperature measured by the 1-volt radiometer (° C),
T_{10V} is the temperature measured by the 10-volt radiometer (° C),
and T_0 is the actual cloud-base temperature (° C).

It must be emphasized that these values are for the WPL infrared radiometers, properly calibrated with the technique described in this report, operating in a laboratory.

5. ADDITIONAL UNCERTAINTIES IN THE ATMOSPHERIC MEASUREMENT

Clouds are not ideal blackbodies and the atmosphere is not a controllable laboratory environment. Therefore, the uncertainty in remote measurements of cloud-base temperature exceeds that for a laboratory measurement of a controlled source. Also, verifying the actual cloud-base temperature is difficult.

5.1 Cloud Radiative Properties

Though many clouds are optically thick, they rarely have uniform emissivity or temperature. If the radiometer "sees" partly into the cloud, or sees a broad area of the cloud base, then it integrates radiation from an inhomogeneous source with a distribution of emissivities and temperatures. Also, clouds may be optically thick in one area and optically thin in another. Even worse, the radiometer field of view may be only partly filled by a cloud. In this case, the measured temperature is an average of the cloud and clear-sky temperatures, weighted by the radiometer's beam pattern.

If clouds had flat bottoms with unity emissivity, a radiometer could measure the true cloud-base temperature. But, since cloud bottoms are not usually defined so ideally, the temperature measured by the radiometer (even for an optically thick cloud) is actually better described as an average temperature over some bulk parcel of cloud near the bottom. Hence, the measured temperature may differ from that at the actual cloud base.

These issues are all critical to the interpretation of cloud remote sensing data, but it is not possible to define a single value for their resulting uncertainty. Rather, the user should consider them carefully while operating radiometers or interpreting their data.

5.2 Atmospheric Emission

The atmosphere between the radiometer and the cloud emits infrared radiation. This clear-air radiance increases the measured cloud temperature. Figure 5 shows the clear-air atmospheric transmission from 8 to 14 μm, calculated with the MODTRAN computer code (Berk, et al., 1989). The region from 8 to 14 μm is referred to as the "10-μm window," but it obviously is not a perfectly transparent channel. The optical half-power bandwidth of the WPL radiometers is indicated on Figure 5 from 9.95 to 11.43 μm. This bandwidth contains emission primarily from water vapor, carbon dioxide, and ozone. Also evident from Figure 5 is that the original 8-14-μm radiometer filter would cause even greater errors because of the increased clear-sky emission.

The equivalent blackbody temperature of the clear sky at 10.69 μm is typically between -80 and -100° C. Consequently, the clear atmosphere emits a small signal compared with a stratus cloud at -10° C, but emits a large signal compared with a cirrus cloud at -60° C. Interference of atmospheric emission in cloud-temperature remote sensing is therefore most critical for high, thin clouds, and for lower clouds in humid air.

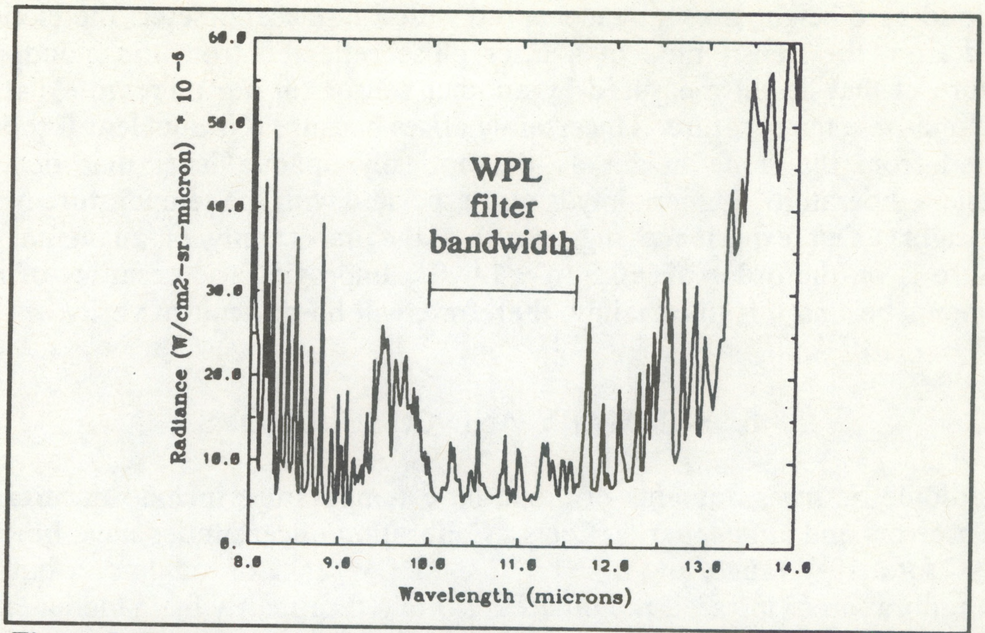

Figure 5. Emission spectrum of a clear atmosphere (1976 U.S. standard atmosphere model). The optical half-power bandwidth of the WPL radiometers is indicated.

WPL's radiometers operate in the semi-arid eastern plains of Colorado with low humidity. We have calculated the atmospheric radiance using radiosonde profiles from this region and have shown that errors due to atmospheric emission in our cloud temperature measurements rarely exceed 0.2° C. In more humid climates, however, the error can be 0.5° C or more. This is especially true if the clouds are higher than 2 km above the ground.

5.3 Contamination of Radiometer Optics

During several field experiments, the optics of our radiometers have collected dust, rain, or other contaminants. The resulting warm film on the optics introduces a bias that increases at colder source temperatures (as the warm-film radiance becomes a larger fraction of the received radiance). To avoid this problem, we house our radiometers in containers that have a vertical viewing port. A fan blows air through the container and out the viewing port to keep rain, dust, and other contaminants from falling on the optics.

5.4 Verification of Actual Cloud-Base Temperature

Another related uncertainty occurs in verification of cloud height. This does not affect the accuracy of the radiometric measurement, but rather reduces the accuracy of the "actual" cloud-base temperature. Therefore, the accuracy to which we can establish an independent verification of our radiometric measurements is reduced.

Cloud-base height is usually measured with a laser ceilometer: the cloud's range is calculated from the transit time of a laser pulse reflected from the cloud. Then, the temperature at that height measured by another sensor (*in situ* or remote) is used as the "actual" cloud-base temperature. Uncertainty arises because it is not clear if the laser beam is reflected from the same height as the optically opaque level that determines the radiometric temperature. Uncertainty is also asociated with the temperature measurement at that height. Our experience suggests that the uncertainty of an actual cloud-base temperature is on the order of ±0.5 to ±1.0° C. Improving the accuracy of radiometric measurements beyond this uncertainty, therefore, will be difficult to verify.

6. SUMMARY AND CONCLUSIONS

Radiometric measurements of cloud-base temperature include uncertainty due to calibration errors and atmospheric effects. Calibration uncertainties have been estimated as ±0.67° C for a 10-V range, and as ±1.0° C for a 1-V range of radiometer output voltage. Absolute calibration of infrared radiometers is limited primarily by inadequate simulation of a blackbody source and by imprecise measurements of voltages and temperatures during calibration and operation. Extreme care must be taken to maintain uniform temperature and emissivity in a blackbody simulator. Large biases can result from reflected radiation when a blackbody simulator with emissivity less than unity is operated at low temperature.

Atmospheric effects add errors, but it is difficult to quantify these effects, since they are situational instead of systematic or random. Some of the more significant atmospheric effects that can affect infrared radiometric measurements have been described briefly.

Because the actual cloud-base temperature can be verified only to within about ±1° C, our present calibration technique is adequate. Further calibration improvements would be difficult to verify. However, two improvements that would reduce the effort involved in calibration and reduce the chance for serious errors are to use a blackbody simulator with higher emissivity and to use the same output-voltage sensor for both calibration and operation.

7. ACKNOWLEDGEMENT

I thank Mark Jacobson of WPL for many useful discussions of infrared radiometer calibration technique and potential errors. He also designed and constructed the weather-proof enclosure mentioned in section 5.3.

I also thank Jack Snider and Judy Schroeder of WPL for their comments which helped make this a better document.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1991 - 573-002/41001