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A Thermopile Temperature Sensitivity Calibration Procedure for Eppley Broadband Radiometers

W.L. Smith Jr.
Department of Atmospheric Sciences, Colorado State University
Ft. Collins, CO 80523

Stephen K. Cox
Department of Atmospheric Sciences, Colorado State University
Ft. Collins, CO 80523

Vince Glover
Research Aviation Facility of the Atmospheric Technology Division
National Center for Atmospheric Research, Boulder, CO 80307

ATMOSPHERIC TECHNOLOGY DIVISION

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

TABLE OF CONTENTS

PREFACE

During the Fall of 1986, the National Center for Atmospheric Research Research Aviation Facility Sabreliner and Staff supported the work of Dr. Stephen Cox (Colorado State University) in the Cirrus component of the FIRE (First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment) project. The objective of this Cirrus component was to perform in-depth studies of cirrus clouds over a wide range of space and time scales. In particular the Sabreliner flew above, within, and below the cirrus clouds and measured, among other things, the radiative properties of the clouds and surrounding environment.

The Eppley Laboratories, Inc., visible and infrared radiometers used on the Sabreliner are normally temperature compensated to provide accuracies of $\pm 2\%$ over the temperature range of $-20^{\circ}C$ to $+40^{\circ}C$. However, most of the Sabreliner's irradiance measurements during FIRE were made at temperatures significantly below $-20^{\circ}C$. Consequently, these measurements were subject to temperature errors. The purpose of this Tech Note is to provide temperature correction coefficients for the Sabreliner's visible and infrared irradiance measurements obtained during FIRE and to document the procedures used to derive these coefficients.

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Vince Glover

Vince Glover
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ABSTRACT

Eppley Laboratory, Inc., pyranometers and pyrgeometers have built-in temperature compensation circuitry designed to limit relative errors in the measurement of radiation to $\pm 2\%$ for a temperature range of $-20^{o}C$ to $+40^{o}C$. A procedure developed to verify this specification and to determine the relative sensitivity to temperatures below $-20^{o}C$ is described. Results of this calibration and application to data correction are also presented.

I. INTRODUCTION

Broadband radiometers manufactured by Eppley Laboratories are commonly used to measure irradiance from both ground-based and aircraft platforms. The Eppley precision pyranometer (Model PSP) measures irradiance in the .3-3μm spectral region, while the Eppley pyrgeometer (Model PIR) senses energy in the 4 to 50μm region. The two instruments have the same thermopile construction but different optical filters to achieve the appropriate spectral selection.

The precision pyranometer has been described by Albrecht and Cox (1976) and Robinson (1966). These instruments are typically sent to the manufacturer for calibration relative to a group of reference standards. Calibration of the pyrgeometer is more complex and can be performed following the procedures of Albrecht and Cox (1977). For a description of this instrument, see Albrecht et al. (1974). Several other authors have made contributions in assessing the performance of pyrgeometers. For examples, see Weiss (1981), Bradley and Gibson (1982), and Ryzner and Weber (1982). Foot (1986) points out that the main problem with achieving accurate irradiance measurements from the pyrgeometer is associated with errors caused by temperature gradients within the instrument itself. (Temperature gradient errors are not important to the calibrations described in this Tech Note.)

During the fall of 1986, the ISCCP\FIRE project commenced with the first cirrus Intensive Field Observation (IFO) conducted in central Wisconsin. Due to the nature of this field project, pyranometers and pyrgeometers manufactured by Eppley were flown on NCAR's high-altitude research aircraft, the Sabreliner. Inherent in the construction of these radiometers is temperature compensation circuitry designed to make the instrument sensitivity nominally constant (within $\pm 2\%$) over a temperature range from $-20^{o}C$ to $+40^{o}C$. Because the Sabreliner flew at high altitudes where temperatures were as cold as $-70^{o}C$, it was necessary to determine the relative sensitivity of the radiometers at temperatures below $-20^{o}C$ and apply appropriate corrections to the FIRE radiation data set. A procedure to perform this calibration is outlined below. It is meant to serve as a supplement to the calibration procedures referenced above.

II. LABORATORY SETUP

Six Eppley radiometers were flown on the Sabreliner during the FIRE first cirrus IFO. Of these six, two pyranometers and one pyrgeometer were available for this particular calibration at RAF. Because this calibration is concerned with radiometer thermopile characteristics only, the calibration procedure can be simplified by converting all instruments to visible radiometers.

This conversion requires only that the domes be visibly clear. The three radiometers were mounted inside an environmental chamber at RAF so that they faced a plate glass window in the door. A light source was mounted outside of the chamber and was shown through the window to illuminate the radiometers. In addition, an extra pyranometer was mounted on the outside of the chamber to monitor any changes in the light source output. Signals from the radiometers were passed through a datalogger to a computer where thermopile output, chamber temperature, room temperature, and the sink temperature of the pyrgeometer were recorded and monitored in real time. For a visual depiction of the laboratory setup, see Fig. 1.

III. CALIBRATION PROCEDURE

The temperature of the insulated environmental chamber was controlled so that data could be sampled every $5^{o}C$ from $+26^{o}C$ to $-63^{o}C$. Again, because we were concerned with thermopile characteristics only, the calibration procedure was simplified by ensuring that the radiometers were in thermal equilibrium when data were recorded. The sink temperature of the pyrgeometer was the best indication of the temperature of the thermal mass of the radiometer. So, at each calibration point (i.e., each $5^{o}C$ chamber temperature increment), the sink temperature of the pyrgeometer was monitored with respect to the chamber temperature to determine when the pyrgeometer was in thermal equilibrium. While the temperature of the chamber's environment could be changed rather rapidly, it was found to take nearly an hour for the thermal mass of the pyrgeometer to achieve thermal stability. Since the pyranometers and pyrgeometer are nearly identical in construction and thermal mass, it was assumed that all radiometers in the environmental chamber reached thermal equilibrium at the same time.

The instrument output was sampled at 1 Hz and recorded in 10-s averages. The source was blocked at each calibration point by covering the plate glass window, thus shielding the radiometers from all shortwave radiation, to measure the dark current of the instruments. (Because of losses through the window of the environmental chamber the dark current for the reference radiometer represented a smaller percentage of the irradiance than did the dark current for those radiometers inside the environmental chamber. Consequently, the reference radiometer dark current was not recorded or used for data correction.) Because of the long time required to reach thermal equilibrium at each calibration point, it took several days to cover the entire temperature range from +26°C to -63°C using 5-degree intervals. At the beginning of each day, a normalizing factor was determined for each radiometer to account for changes in geometry, window losses, line voltage and other effects. These data relate the output voltage of each radiometer being calibrated to the output voltage of the pyranometer monitoring the source while all radiometers are at the same room temperature. The normalizing constant,

$$p = [\, V_c(Tr) - V_d(Tr)\,]/V_m(Tr)$$

where Tr = room temperature

V_m = voltage output of source monitor

V_c = voltage output of radiometer being calibrated

V_d = dark voltage of radiometer and

p = function relating V_c to V_m at Tr,

allows determination of a relative sensititivty for each radiometer referenced to the room temperature response. The temperature-dependent output is then

$$q(T) = [V_c(T) - V_d(T)]/V'_m(Tr)$$

where T = temperature of chamber and consequently of the thermal mass of the radiometers being calibrated and

q = function relating V_c at T to V_m at Tr

V'_m= voltage output of source monitor at the time of the measurement at temperature T.

If the source is constant, $V'_m(T) = V_m(Tr)$ and $q(Tr) = p$; otherwise $V'_m(Tr)$ corrects for changes in source intensity. The relative sensitivity is

$$K_{26}(T) = q(T)/p,$$

where the sensitivity is normalized to 1 at $Tr = 26°C$.

Thus, the relative sensitivity $K_{26}(T)$ is normalized to express the temperature dependence of each radiometer's thermopile given a constant source of energy and with respect to some reference temperature, taken here to be the room temperature (Tr) of 26°C.

IV. RESULTS

Results of this calibration for the available radiometers are shown in Fig. 2. Within the electronically compensated temperature range of +40°C to -20°C, our results depict nominal instrument sensitivity within about 2.5%, close to Eppley's ±2% specification. Outside of this range (i.e., below -20°C), errors could be as large as 7% at -63°C. A third order polynomial proved a good fit to these data. These curves are also shown in Fig. 2. The corresponding coefficients for these curves are listed in Table 1 and have been used to correct the data collected on board the Sabreliner during FIRE. Since two of the pyranometers flown on the Sabreliner were unavailable for this post-mission calibration, an average was taken of the two pyranometer curves that were developed and this average curve was used to correct the data collected by the pyranometers that were unavailable for calibration. Similarly, one pyrgeometer was also unavailable, so the curve developed from the calibrated pyrgeometer was also applied to data collected by the pyrgeometer that was unavailable.

V. APPLICATION TO DATA CORRECTION

The application of this relative calibration to data correction is straight-forward, because the original manufacturer's calibrations were done at room temperatures near the 26^{o}C reference temperature used in this relative calibration. Eppley Laboratories states in their calibration documentation that the adopted calibration temperature for the pyranometer is 25^{o}C. For the pyrgeometers, the calibration procedure following the methods of Albrecht and Cox (1977) dictates that the temperature of the radiometer thermopile be near the temperature of the laboratory. Albrecht et al. (1974) report that the sink temperature is representative of the thermopile sensor temperature because the temperature difference between the hot and cold junctions of the thermopile is, at most, 0.5 K for typical irradiance measurements in the atmosphere. The relative sensitivity (K(T)), determined in section III, can be applied directly to the pyranometer measurements to get the corrected irradiance value. For example,

$$SWCORR = K(Ts) * C * V$$

where V = pyranometer thermopile output voltage

C = calibration constant supplied by Eppley to convert thermopile output voltage to units of irradiance (i.e., W/M**2)

K(Ts) = the relative sensitivity at a temperature Ts which is the sink temperature of an adjacent pyrgeometer

SWCORR = the corrected irradiance.

For the pyrgeometer, an equation derived by Albrecht et al. (1974) and Albrecht and Cox (1977) of the form

$$H = \frac{E}{\eta} + \epsilon\,\sigma T_s^{\ 4} - \beta\,\sigma(T_d^{\ 4} - T_s^{\ 4})$$

where

$\epsilon =$ emissivity of the thermopile (usually taken to be unity)

$\sigma =$ Stefan Boltzmann constant

$T_d, T_s =$ dome temperature and sink temperature, respectively

$\eta,\ \beta =$ calibration constants

E = thermopile voltage

H = incoming irradiance

can be further corrected for temperature sensitivity by applying K(Ts) to the first term such that

$$H\ CORR = \frac{1}{K(T_s)} * \frac{E}{\eta} + \epsilon\,\sigma\,T_s^{\ 4} - \beta\,\sigma(T_d^{\ 4} - T_s^{\ 4})$$

where $H\ CORR$ is H but corrected for temperature sensitivity.

However, because the infrared irradiance (from the pyrgeometer) is the sum of several terms, the effect of the temperature sensitivity correction will be somewhat less for the pyrgeometer data than for the pyranometer data. Several FIRE data sets were analyzed to determine the magnitude of error between corrected and uncorrected pyranometer and pyrgeometer measurements. Irradiance errors for the pyrgeometer were found to be, at most, 2-3 W/m**2, which is within the noise of the instrument. Because the temperature sensitivity corrections apply directly to the pyranometer measurements, errors could be as large as 7% of the uncorrected measurements at -63^{o}C. In addition, errors as large as 10% were found in cloud fractional absorptance (CFA) calculations (See Ackerman and Cox (1981) for description of CFA).

VI. SUMMARY

A calibration procedure to correct Eppley broadband radiometers for thermopile temperature sensitivity has been presented. This calibration should be performed prior to field work where radiometers of this type, particularly the pyranometer, may be exposed to temperatures beyond the range of the internal temperature compensation circuit.

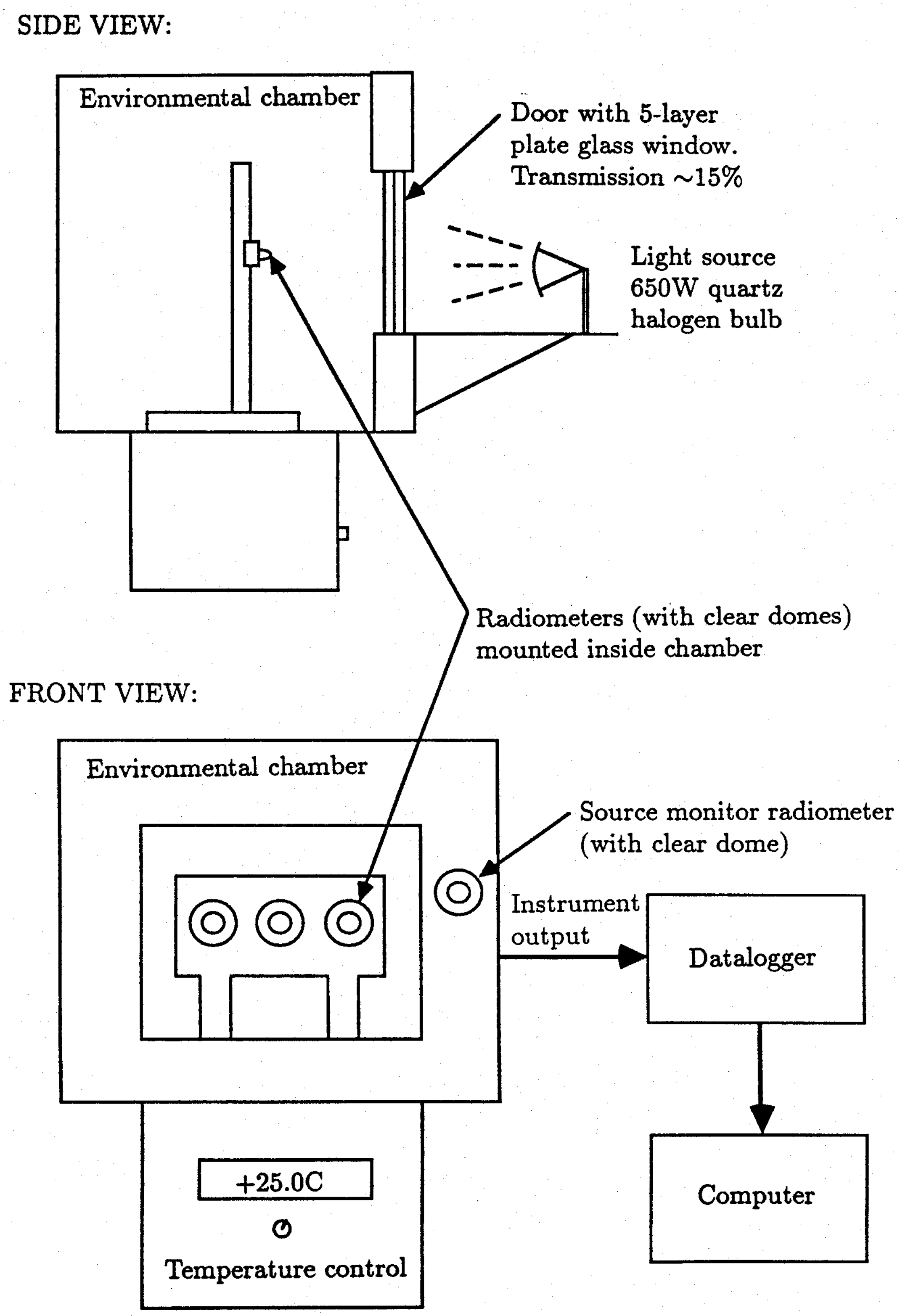

Fig. 1. Schematic arrangement of radiometers and calibration equipment

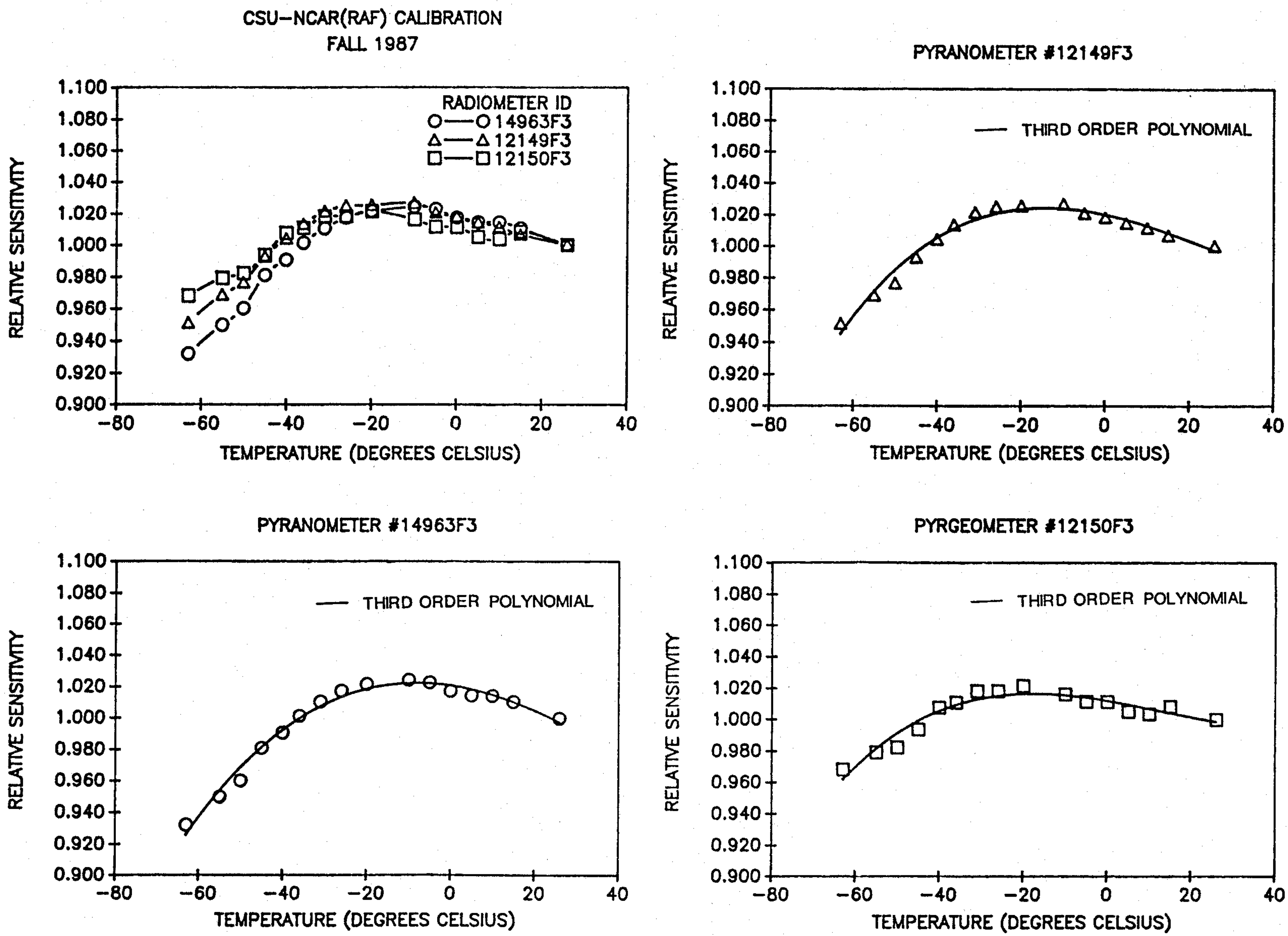

Fig. 2. Results of the temperature sensitivity calibrations for the FIRE project radiometers available for this study

Table 1

Coefficients for the third order polynomial representation of the relative sensitivity (K) for $-63^\circ C \leq Ts \leq +26^\circ C$ where

K(Ts) = a + b*Ts +c*Ts**2 + d*Ts**3

Radiometer Serial No.	a	b	c	d
14963F3	1.0212	-3.8166E-4	-2.2971E-5	1.1316E-7
12149F3	1.0201	-5.8376E-4	-1.6416E-5	1.8673E-7
12148F3*	1.0207	-4.8271E-4	-1.9694E-5	1.4994E-7
14962F3*	1.0207	-4.8271E-4	-1.9694E-5	1.4994E-7
12150F3	1.0123	-4.5256E-4	-7.7408E-6	1.9354E-7
12151F3*	1.0123	-4.5256E-4	-7.7408E-6	1.9354E-7

* Indicates that radiometer was unavailable for this calibration.

Ts is sink temperature of nearest pyrgeometer

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