Performance and Long-Term Stability of the Prelaunch Radiometric Calibration Facility for the Clouds and the Earth’s Radiant Energy System Instruments

James K. McCarthy, Herb Bitting, Thomas A. Evert, Mark E. Frink, Theodore R. Hedman, Paul Sakaguchi, and Mark Folkman, Member, IEEE

Abstract—The Radiometric Calibration Facility (RCF) at Northrop Grumman Aerospace Systems was used between 1995 and 2008 to establish the prelaunch calibration of the first six Clouds and the Earth’s Radiant Energy System (CERES) instruments, with the seventh CERES instrument scheduled to be tested in the RCF in 2012. This paper reviews the performance of the RCF radiometric standards, which are the narrow-field blackbody (NFBB) and the short-wave reference source, as well as the RCF transfer active-cavity radiometer, in the context of the CERES prelaunch calibration process. A detailed investigation of the long-term stability of these standards over the 1999–2008 time span of CERES FM5 testing is reported, showing that the RCF calibrations in the long and short waves have remained stable relative to the NFBB absolute reference at levels of 0.06% and 0.5%, respectively, over the eight-year span.

Index Terms—Calibration, global warming, radiometry, radiometers, remote sensing, test facilities.

I. INTRODUCTION

The Clouds and the Earth’s Radiant Energy System (CERES) instruments [1] are high-precision high-accuracy radiometers that provide fundamental measurements of top-of-atmosphere (TOA) radiance, enabling the determination of the Earth’s radiation energy budget [2]. The seven CERES instruments designed, built, and tested by Northrop Grumman Aerospace Systems (NGAS; formerly TRW Space & Electronics) under contract to NASA’s Langley Research Center for the Tropical Rainfall Measurement Mission (TRMM), the Earth Observing System (EOS), the National Polar-orbiting Operational Environmental Satellite System Preparatory Project (NPP), and the Joint Polar Satellite System (JPSS) are listed in Table I.

The CERES instrument design [1] consists of three coaligned telescope assemblies on a two-axis rotating gimbals, with each telescope assembly (comprised of a baffle tube, a spectral filter (N.B., there is no filter in the TC), Cassegrain reflecting telescope optics, and a bolometer detector) measuring TOA radiance in a separate spectral region: a short wave (SW; 0.3–5 μm), a long-wave window (WN; 8–12 μm), and a total channel (TC; 0.3–100 μm). For FM6 currently being built for JPSS-1, the WN channel will be replaced by a broader long-wave (LW) channel that covers 5 to ≥ 50 μm, similar with that used on the Earth Radiation Budget Experiment [3], to both directly observe the broadband-emitted thermal radiance and to facilitate more direct interchannel comparisons.

CERES instruments each contain an on-board internal calibration module (ICM) that consists of concentric-grooved blackbody sources for the LW/WN and TC, and an evacuated tungsten lamp illumination system for the SW channel. The ICM includes a photodiode monitor to trend any drift in the lamp. In addition, on-board mirror attenuator mosaic targets [4] for the SW and TC, which are illuminated by direct sunlight through a solar port, enable monitoring postlaunch sensor gain drift in the solar-reflective spectral region independently of the ICM lamp.

Prior to delivery, each CERES instrument is tested in the Radiometric Calibration Facility (RCF) at NGAS, where the sensor response and ICM radiances are calibrated traceable to the International Temperature Scale of 1990 (ITS-90). The arrangement of calibrators and test targets within the RCF vacuum chamber, as configured for CERES, is shown in Fig. 1. The central carousel can be rotated to permit either the cryogenic transfer active-cavity radiometer (TACR) or the CERES instrument-under-test to view each source in an identical manner; moreover, the fore-optics on the TACR have a similar optical design to a CERES telescope, with identical field-of-view (FOV), aperture, and internal stray-light baffling.

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The authors are with the Northrop Grumman Aerospace Systems, Redondo Beach, CA 90278 USA (e-mail: mark.folkman@ngc.com).

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SW targets on the other end. View the thermal IR targets at one end of the RCF chamber (left) as well as the TACR and CERES instrument-under-test rotates, allowing each radiometer to transfer the absolute calibration over to the RCF short wave reference source (SWRS), against which the CERES TC and CERES WN and TC response, which in turn transfer the absolute ITS-90 calibration to the CERES ICM blackbodies. Separately, TACR measurements of the NFBB are used to transfer the absolute calibration over to the RCF short wave reference source (SWRS), against which the CERES TC and SW channels (and, subsequently, the CERES ICM lamp) are calibrated at 13 wavelengths ranging from 0.42 to 1.96 μm.

In Section II of this paper, we review the absolute radiance knowledge uncertainty of the CERES NFBB source and its performance during CERES ground testing. In Section III, we then examine TACR measurements of the NFBB over the course of the CERES program to date, in order to assess the long-term stability in the radiometric accuracy of both the NFBB and the TACR. Then in Section IV, we consider the TACR calibration transfer to the SWRS over the same time period, and make a similar assessment of the long-term stability in radiometric accuracy. As indicated in Table I, the CERES FM5 instrument has been calibrated in the RCF multiple times (the first in 1999 as spare for the EOS program and the last in 2008 prior to delivery to NPP), offering an independent measure of the radiometric accuracy stability of CERES calibration using the RCF over a span of nine years.

II. NFBB

A. NFBB Design Overview

The NFBB absolute radiance source is the primary standard for the RCF and for the CERES instruments. It consists of thick copper plates arranged to form a right triangle, with the hypotenuse viewed through an opening in the short leg of the triangle. The interior surfaces are coated with 5 mils (0.13 mm) of Chemglaze Z302, which is a high gloss (specular) black paint [9]. The hypotenuse and the long leg meet to form a narrow wedge at an angle of 27°-28°, which was chosen so that direct rays into the sensor FOV, when traced backwards into the cavity, undergo more than seven surface reflections inside the NFBB before possibly escaping the cavity. Hence, the NFBB delivers extremely high emissivity by design; in practice, the NFBB emissivity is limited not by the per-surface emissivity or the number of internal reflections but instead by backscatter from the first surface viewed. Based on measurements at 633 nm of the bidirectional reflectance distribution function (BRDF) of specular black-painted witness samples (where the BRDF was scaled to infrared wavelengths using a model including the effects of surface roughness and particulate contamination) and a conservative view factor analysis of the NFBB, the actual emissivity (as limited by scatter) is computed to be > 0.99994 over the useful spectral range from 3 to 100 μm.

Absolute temperature knowledge of the emitting surfaces in the NFBB is derived from eight platinum resistance thermometers (PRTs) mounted on the two long copper plates. The absolute calibration of each PRT is ITS-90 traceable with residual errors of ±23-mK RMS (1-sigma). The preliminary design of the NFBB was modeled using the Sinda thermal analysis code, which guided thermal design decisions regarding heater and PRT locations, as well as the design of the temperature-controlled thermal enclosure that surrounds the NFBB cavity. This enclosure is thermally isolated from the NFBB cavity and gold plated in order to thermally shield the blackbody cavity from its surroundings. For the adopted final design, Sinda analysis showed that, upon reaching thermal equilibrium with constant power supplied by the heaters, the worst case temperature nonuniformity across the reflecting surfaces of the NFBB wedge plates was ±7 mK.

The NFBB entrance aperture is defined by a separately temperature-controlled cold plate mask, located just outside the front of the NFBB thermal enclosure. The aperture size (3.8 cm × 4.7 cm) overfills the CERES telescope entrance pupil and FOV. The operating temperature range of the NFBB is from 200 to 320 K; for CERES calibration, a fixed set of 12 NFBB cavity temperatures spanning 205 to 312 K is routinely used, with the cold plate mask held at 190 K.

B. NFBB Absolute Radiometric Accuracy

The CERES program requirement for radiometric accuracy in the thermal infrared (5-100 μm) is 0.5%, of which 0.15% has been allocated to absolute radiance knowledge uncertainty of the NFBB used for prelaunch calibration. The radiometric error tree for this primary standard in the RCF, where the errors are expressed in terms of %-radiance at a temperature of 273 K, is detailed in Fig. 2. By far, the dominant source of actual radiometric error associated with viewing the NFBB is temperature knowledge uncertainty. This error term is mostly due to the following: errors in the supplied PRT calibration curves (±23 mK as cited above); possible bias errors in the PRT resistance measurements; PRT hysteresis and potential lack of repeatability; and the existence of a small but systematic temperature difference ΔT between the temperature of the PRTs mounted to the NFBB copper plates and the skin temperature of the emitting surfaces.
The resistances of seven of the eight PRTs are measured by a multiplexed precision multimeter, using a four-wire approach with current reversal to eliminate inductance and capacitance effects. The amount of current used is kept small (≤ 1 mA), and current is applied only for the short duration of the measurement (less than 1/60 s) so that any PRT self-heating effects should be negligible. The multiplexed inputs to the multimeter also include a precision resistor as a fixed reference that is measured prior to each set of PRT resistances. Application of these techniques is necessary to reduce the potential for bias errors in NFBB temperature measurement to a level comparable to that of the PRT calibration uncertainty. The \( \Delta T \) between the PRTs (mounted in good thermal contact with the high-thermal-conductivity NFBB copper plates) and the emitting specular-black-painted surfaces of the cavity has been investigated analytically, under the worst-case assumption that the back sides of the cavity copper plates (where the PRTs are mounted) are at \( T = 320 \) K and the solid angle of the NFBB entrance aperture is filled by a 77-K surface. This analysis showed that the temperature gradient through the thickness of the copper plates was indeed extremely small (≤ 1 mK), but a worst-case \( \Delta T \) of 24 mK can occur through the paint layer.

To summarize, the absolute radiometric accuracy of the NFBB absolute blackbody as designed, built, and used in the RCF has been shown to surpass the accuracy required for this calibration source by the CERES program.

C. Long-Term Stability of NFBB Radiometric Accuracy

From the foregoing discussion, two main concerns emerge with respect to the long-term stability of the NFBB absolute radiometric accuracy: 1) the possibility of a change over time in the resistance-versus-temperature calibration of the PRTs, and 2) the possibility of a change over time in the NFBB cavity emissivity. The narrow-wedge-angle \( \geq 7 \)-bounce trap design of the NFBB makes its emissivity immune, from a practical standpoint, to small changes in the per-surface absorbance (or reflectance). However, because scatter from the first surface view limits the total emissivity in practice, care is taken to preserve the low BRDF of the viewed surfaces in the NFBB. The NFBB is mounted to the RCF with the viewed wedge surfaces vertical with respect to gravity, thus minimizing the accumulation of particulate contamination on the viewed surfaces. Furthermore, both the blackbody wedge and its surrounding thermal enclosure are sealed cavities, except for the front entrance aperture, which is likewise in a vertical plane relative to gravity. The RCF chamber doors are kept closed when the facility is not in use. Lastly, in this application and others [10]–[14], the urethane-based Z302 specular black paint has proven to be very stable, durable, and robust against deterioration. For these reasons, the high NFBB cavity emissivity is considered extremely stable over time.

To address concern (1) about the long-term stability of PRT resistance-versus-temperature calibration, two approaches for placing upper bounds on any potential PRT calibration drift are possible using available test data: monitoring the set of PRTs in the NFBB for uniformity in the reported temperatures at thermal equilibrium and trending the gain of the cryogenic TACR, as calibrated using NFBB radiance as a function of source temperature. The first approach would reveal individual PRT(s) reporting anomalous temperatures but not any long-term calibration drift that might be common to all PRTs in the NFBB. Conversely, the second approach (to be discussed in Section III) is highly sensitive to any calibration drift common to the majority of PRTs. A third approach, namely removal of the PRTs from the NFBB for ITS-90 traceable recalibration, is also possible but would be undertaken only in the event that one of the two noninvasive approaches were to suggest that recalibration of the PRTs might be warranted.

Uniformity among the cavity temperatures measured by the PRTs internal to the NFBB is regularly monitored during testing (both CERES calibration testing and RCF validation testing performed to validate the facility’s fitness-for-use prior to CERES calibration). At every NFBB temperature setting, the maximum minus minimum PRT temperature difference \( (T_{\text{max}} - T_{\text{min}})/2 \) is confirmed to be < 50 mK at an NFBB temperature of 205 K, < 60 mK at 295 K, and < 70 mK at 318 K. These criteria correspond to percent errors in TC radiance of \( \leq 0.098\% \), \( \leq 0.081\% \), and \( \leq 0.088\% \), respectively, but in the context of Fig. 2, note that NFBB radiance is derived using the average temperature of seven PRTs. Note furthermore that these criteria only set upper bounds on any long-term drift in the ITS-90 calibration of individual PRTs; resistance measurement errors and differences in the \( ab\ initio \) PRT to PRT calibration residuals account for most of the \( (T_{\text{max}} - T_{\text{min}})/2 \) observed, plus whatever low-level temperature nonuniformity existed within the NFBB at the time of the measurements. The fact that, over a 14-year period, there has been no significant increase in the \( (T_{\text{max}} - T_{\text{min}})/2 \) metric leads to the conclusion...
that the ITS-90 calibrations of individual PRTs have remained in-family over this period to < 50 mK, or well below 0.1% in NFBB radiance. It is also worth noting that the PRTs are supplied in special stress-relieved holders (with factory calibration before and after installation into the holders), and these holders are not subject to any mounting stresses as installed in the NFBB, a fact that also contributes to their high stability over time.

III. TACR Measurements of the NFBB

A. TACR Design Overview

The TACR consists of a liquid-helium-cooled conical-shaped cavity radiometer that operates at a temperature near 4 K. The cone angle of the specular-black-painted copper cavity produces at least four surface reflections for incoming light, absorbing > 0.999 of the incident radiant energy with a spectral response that is extremely flat over the 0.3–100 μm wavelength range. Similar to an ACR instrument operated at the National Institute of Standards and Technology (NIST) [15], it uses electrical power substitution to achieve very accurate (0.05%) measurements of absolute radiant power.

The noise equivalent power of the active cavity is < 2 nW, and it has a dynamic range extending up to 100 μW. The high sensitivity results from operation at cryogenic temperatures, where the heat capacity of the copper active cavity is three orders of magnitude less than at room temperature, whereas the thermal conductivity is greater by an order of magnitude [16].

As used in the TACR, the cryogenic active cavity is coupled to a CERES-like telescope that is also cryogenically cooled. The TACR therefore senses radiance; measurement of absolute radiance using the TACR would require accurate knowledge of the product of telescope optical throughput, aperture area, and FOV solid angle. Knowledge of these parameters enables the TACR, when viewing the NFBB, to provide a consistency check on the NFBB absolute radiance but is not sufficient to independently calibrate the NFBB to the level of absolute accuracy demanded by the CERES program. Instead, the TACR radiance responsivity is calibrated by viewing the NFBB, which fills the TACR telescope aperture and FOV.

The TACR is then used to view the SWRS in the RCF through a series of narrow-band spectral filters. Combining the TACR radiance measurements with knowledge of the relative spectral response of the TACR telescope, it becomes possible to use the TACR to transfer the absolute radiance calibration from the NFBB absolute blackbody over to the SWRS [6].

B. TACR Measurements of NFBB

As a first step in the TACR-based transfer of the absolute calibration from the NFBB to the SWRS, the TACR is aligned to view the NFBB aperture, and measurements of TACR response are made over a range of NFBB cavity temperatures. Typically, a set of six NFBB cavity temperature set points are employed, ranging from 205 to 318 K, with the NFBB cold mask held constant at 190 K. Next, TACR measurements are made with the NFBB cavity held at 205 K, while the temperature of the NFBB cold mask is stepped through a series of seven elevated temperatures ranging from 170 to 350 K. The latter data set is used to determine the amount of out-of-field energy received by the TACR from the cold mask as a function of mask temperature [17]. This enables a correction to be applied for the integrated out-of-field contribution (see Table II, note A) from the 190-K cold mask in the first data set, where the NFBB cavity temperature was varied, and then a linear fit is made to the TACR detected power (in watts) as a function of the in-field radiance from the NFBB cavity (watts per meter^2-sr). The slope of the linear fit is the TACR in-field responsivity. Given the low noise and extremely linear response of the active cavity detector, the fit residuals are quite small (less than 0.1% RMS, 1-sigma).

As shown in Fig. 3, the TACR in-field responsivity, as calibrated against the NFBB, has remained extremely stable over the time period of 1995–2008, with no evidence for any significant trend with time, either upward or downward. Not only do these data indicate extremely consistent TACR responsivity over time but they also provide the additional evidence sought in Section II-C above; namely, the data in Fig. 3 demonstrate that the absolute NFBB radiance derived using the average cavity temperature from the seven ITS-90 calibrated PRTs in the NFBB have not drifted significantly over time. There is no known mechanism that would cause a hypothetical drift in PRT temperatures in the NFBB to be compensated so precisely by an equal-and-opposite hypothetical drift in TACR responsivity. Hence, the data in Fig. 3 are confirmation that the PRT temperature accuracy and the absolute radiometric accuracy of the NFBB cavity have remained stable over the 13-year period from 1995 to 2008 to within our ability to measure (i.e., to within 0.06%, 1-sigma).

C. TACR Out-of-Field Stray Light Correction

The TACR measurements of the NFBB cavity held at 205 K, as the cold mask temperature is varied, permit calculating the integrated out-of-field contribution to the TACR responsivity. This experimental determination is performed independently each time the TACR in-field responsivity is calibrated against the NFBB cavity (see Table II); by analyzing the data to
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### TABLE II
**INTEGRATED OUT-OF-FIELD**a WHILE VIEWING NFBB CAVITY

<table>
<thead>
<tr>
<th>CERES</th>
<th>Test Date</th>
<th>TACR (%)</th>
<th>CERES TC (%)</th>
<th>CERES WN (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM1</td>
<td>Oct. 1996</td>
<td>1.36</td>
<td>0.84</td>
<td>1.14</td>
</tr>
<tr>
<td>FM2</td>
<td>Feb. 1997</td>
<td>1.36</td>
<td>0.80</td>
<td>0.90</td>
</tr>
<tr>
<td>FM3</td>
<td>Apr. 1998</td>
<td>1.38</td>
<td>0.95</td>
<td>0.87</td>
</tr>
<tr>
<td>FM4</td>
<td>Jan. 1999</td>
<td>1.38</td>
<td>0.93</td>
<td>0.95</td>
</tr>
<tr>
<td>FM5</td>
<td>Feb. 2000</td>
<td>1.51</td>
<td>0.90</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Oct. 2006</td>
<td>1.58b</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Oct. 2008</td>
<td>1.26</td>
<td>0.96</td>
<td>0.90</td>
</tr>
<tr>
<td>Mean</td>
<td>1.38</td>
<td>0.93c</td>
<td>0.91c</td>
<td></td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>0.08</td>
<td>0.03c</td>
<td>0.01c</td>
<td></td>
</tr>
</tbody>
</table>

aIntegrated out-of-field is calculated for NFBB mask temperature equal to NFBB cavity temperature; during calibration, NFBB mask is held at 190K so the error term appearing in Fig. 2 is (0.080%)(190K/273K)^2 = 0.019%, since this precision error dominates the total uncertainty in the stray correction.

bThe TACR was slightly misaligned on NFBB cavity; see text and Fig. 3.

cMean and std. deviation for CERES TC and WN based on FM5 only.

assess the experimental uncertainty, the mean value is 1.38% with a standard deviation of ±0.08%. As noted in Fig. 3, the TACR alignment to the NFBB source during the October 2006 calibration was suboptimal; not only did this result in an artificially low TACR responsivity value (see Fig. 3), it also caused an artificial excess in the out-of-field response. These data exhibit no significant systematic trend with time, leading to the conclusion that, over the 12 years from 1996 to 2008, the mirror coatings of the TACR fore-optics have suffered no degradation sufficient to cause a measurable increase in the scattering of out-of-field energy into the TACR detector FOV.

### D. CERES FM5 NFBB Calibration: 2008 Versus 1999

As listed in Table I, the CERES FM5 sensor has been tested in the RCF on more than one occasion. Hence, as a final check on the long-term stability of the NFBB’s absolute accuracy, the results of repeated calibrations of the same CERES FM5 sensor using the NFBB source can be compared. However, the tests performed in 2000 and 2006 were only intended to be interim calibration checks on CERES FM5 and, as such, were not preceded by any sensor functional testing under thermal vacuum environmental conditions. As is well known to those who work closely with CERES calibration data, the bolometers require at least 4 or 5 days in vacuum for their response to stabilize to within 0.2% of their final values and longer (one to two weeks) for the response to stabilize below measurable levels [18]. Therefore, one must assign less weight to the interim CERES FM5 calibration checks in 2000 and 2006 since the detectors were not maintained under vacuum long enough to reach stability.

Conversely, the CERES FM5 calibrations in 1999 and 2008 were conducted following functional testing under thermal vacuum environmental conditions; thus, the vacuum soak times were sufficiently long—more than 12 days, in fact—to ensure the sensor responsivities had fully stabilized. A summary of all FM5 prelaunch gain calibration results performed in the RCF using the NFBB source is provided in Table III.

### IV. TACR CROSS-CALIBRATION TRANSFER TO THE SWRS

#### A. Calibration Transfer Method and Uncertainties

The SWRS in the RCF is a secondary standard used to calibrate the CERES SW and TC in the 0.3–5 μm spectral region [5]. The SWRS radiance is produced by a 250-W quartz tungsten halogen lamp that is located outside the test chamber together with collimating optics, a photofeedback system, and a set of 13 narrow-band spectral filters. The collimated stability-controlled spectrally filtered beam passes through a fused silica window into the RCF chamber, where relay optics focus the beam through the small input port of an 11-cm-diameter Polytetrafluoroethylene (PTFE) integrating sphere. Additional relay optics in proximity to the exit port of the sphere serve to fill uniformly the entrance aperture and field of the sensor under test, that being either the TACR or a CERES telescope depending upon the RCF carousel rotation (see the right side in Fig. 1). Rough coalignment of the TACR and the CERES instrument to the SWRS is established prior to sealing and pumping the chamber for CERES thermal vacuum testing and calibration; the critical alignment of each radiometer to the SWRS is then performed during cryovacuum testing, with RCF carousel rotation and vertical position, TACR stage rotation (or equivalently CERES sensor scan rotation), and SWRS collimator mirror elevation-scan capabilities providing the necessary degrees of freedom.

### TABLE III
**CERES FM5 NFBB CALIBRATIONS OF TC AND WN CHANNEL GAINS**

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Date</th>
<th>TC Gain (counts per W/m²sr)</th>
<th>WN Gain (counts per W/m²sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>Mar. 1999</td>
<td>8.9352 (reference)</td>
<td>10.6538 (reference)</td>
</tr>
<tr>
<td>Plateau</td>
<td>Feb. 2000</td>
<td>8.8666 (Δ: -0.54%)</td>
<td>10.5910 (Δ: -0.59%)</td>
</tr>
<tr>
<td>Oct. 2006</td>
<td></td>
<td>8.9352 (Δ: -0.00%)</td>
<td>10.6472 (Δ: -0.06%)</td>
</tr>
<tr>
<td>Cold</td>
<td>Mar. 1999</td>
<td>8.9088 (reference)</td>
<td>10.6430 (reference)</td>
</tr>
<tr>
<td>Plateau</td>
<td>Feb. 2000</td>
<td>8.8685 (Δ: -0.45%)</td>
<td>10.5813 (Δ: -0.50%)</td>
</tr>
<tr>
<td>Oct. 2008</td>
<td></td>
<td>8.9314 (Δ: +0.25%)</td>
<td>10.6744 (Δ: +0.38%)</td>
</tr>
</tbody>
</table>

| FM5 not held in vacuum long enough for its response to fully stabilize; therefore the most reliable comparison is between Mar. 1999 and Oct. 2008.

Comparing the 2008 results to those from 1999, the TC gain remained stable to one quarter of 1% over the nine-year period, whereas the WN channel gain remained stable to just to four tenths of 1%. Some of this variation is undoubtedly the result of statistical errors in the calibrations themselves (e.g., 0.1% RMS residuals are typical in linear fits to the CERES response as a function of NFBB radiance), such that the 2008–1999 differences in FM5 calibrations reported in Table III cannot be attributed entirely to long-term drift in the NFBB source radiance. For reference, the program-level CERES on-orbit radiometric performance requirements for the measurement of terrestrial infrared radiation are accuracy of ≤ 0.5% and stability of ≤ 0.1% per year. The CERES FM5 infrared ground calibration results listed in Table III, for a nine-year time span, demonstrate performance that clearly supports achieving those mission requirements.
As described in Sections II-B and II-C, the absolute radiance of the NFBB as a function of cavity temperature is used to calibrate the effective throughput (i.e., the spectrally weighted area \( \times \) solid angle product) of the TACR in the thermal infrared, both for in-field and out-of-field incident radiance (the latter by varying the temperature of the NFBB cold mask with the cavity held at cold temperature). The RCF carousel is then rotated to enable the TACR to measure the radiant power received by the active cavity from the SWRS using each of its 13 spectral bandpass filters. The calibration transfer of the absolute NFBB radiance scale to the secondary standard SWRS radiance via the TACR is accomplished by applying the known TACR in-field responsivity in the infrared (IR) (to convert radiant power at the active cavity to input radiance) along with two correction terms: the first being the relative spectral response of the TACR in the SWRS filter bandpass normalized to that in the thermal infrared (spectrally weighted by the Planck function of the NFBB), and the second being a correction for the SWRS radiance received by the TACR outside the in-field region, as defined by the NFBB cold mask.

The spectral response of the TACR is the product of the spectral absorptance of the active cavity receiver and the spectral reflectance of the TACR telescope fore-optics. Owing to the trap design of the active cavity receiver and its high-absorptance coating, its spectral response is very high (> 0.999) and, hence, very flat over a broad spectral range from the visible to the far infrared. The TACR telescope mirrors are made of polished nickel onto which a high-efficiency protected silver coating is vacuum deposited. Accurate knowledge of the relative spectral reflectance characteristics of these mirrors has long been recognized [5], [6] as a crucial requirement in order for the TACR to be used as intended (namely, to transfer the long-wave NFBB absolute calibration over to the SWRS secondary standard throughout the solar-reflective region) with the high accuracy needed for the CERES mission. Consequently, extreme care was taken to thoroughly characterize these mirrors prior to installation of the fore-optics onto the active cavity radiometer. Absolute reflectance measurements were made over the spectral range of 0.35–5 \( \mu \text{m} \) at TRW’s Absolute Reflectance Measurement Station (Redondo Beach, CA), as well as at the U.S. Navy’s research facility at China Lake, CA. In addition, both a grating spectrometer and the CERES Fourier Transform Spectrometer Facility [19] were also used to obtain spectrally continuous relative spectral reflectance measurements for use interpolating between the absolute reflectance measurements made at discrete wavelengths. Merging these four reflectance measurement data sets (two absolute and two relative) and cross-checking each one individually against the merged product showed agreement to within \( \pm 0.2\% \) [6]. Lastly, because the TACR is operated at cryogenic temperatures (with the temperature of the telescope mirrors near 20 K), measurements were also made at China Lake to characterize the relative reflectance shift from room temperature down to 20 K.

By design, the SWRS floods the entrance aperture of the sensor under test over a FOV that is approximately 3.2° by 7°, whereas the NFBB cold mask aperture purposely confines flood illumination of the sensor by the NFBB cavity to an FOV measuring 2.6° by 4.5°. While both sources overfill the field stop of the TACR fore-optics (matched to that of the CERES telescopes) including allowances for optical blur and scan motion, the SWRS delivers radiance to the TACR fore-optics (as well as to the CERES telescopes) from field angles that are considered out-of-field in the context of the NFBB-based absolute calibration of the TACR. Hence, a correction is required for the somewhat greater out-of-field response stimulated by the SWRS compared with the NFBB, as part of the calibration transfer from the NFBB to the SWRS. The magnitude of this correction is based on mapping the TACR out-of-field response function by scanning across a point source [6].

In actual practice, at each wavelength used during SWRS calibration, 180-degree rotations of the RCF carousel are employed to obtain TACR measurements of the SWRS output radiance both before and after the CERES sensors view the SWRS. By comparing the before and after measurements of the SWRS made using the TACR, the short-term stability and repeatability of the SWRS as a secondary standard can be characterized. As expected, the short-term stability is poorest in the blue, where SWRS lamp drift errors of \( \leq 0.2\% \) RMS are typical (see Fig. 4) but drift errors as large as 0.4% are observed in some cases [20]. Note, however, that in Fig. 4, the largest outliers belong to the February 2000 calibration. In addition to lamp stability, other factors that may contribute to a lack of repeatability of SWRS measurements are temperature-induced drifts of the SWRS filter bandpass and nonuniformity in the radiance from the SWRS integrating sphere coupled with small alignment differences from run to run. Analyses show these other factors are small compared with instability in the lamp output.

A summary of the absolute radiometric uncertainty tree for the SWRS narrow-band radiance obtained via calibration transfer from the NFBB using the TACR is shown in Table IV.

### B. CERES FM5 SWRS Calibration: 2008 Versus 2000

Similar to the check of the long-term stability of the NFBB using calibrations of the TC and WN channels of CERES FM5 performed years apart (see Section III-D), this section investigates the long-term stability of the CERES FM5 TC and SW calibrations using the SWRS performed years apart.

Unfortunately, a mechanical malfunction of the RCF carousel that swings the TACR and the CERES instrument-under-test...
between the long-wave and short-wave ends of the chamber (see Fig. 1) required that the March 1999 calibration testing of FM5 be terminated before the short-wave calibration of CERES could be completed. Consequently, the February 2000 short-wave calibration of CERES FM5 must be used here as the baseline reference, in the absence of a 1999 short-wave calibration.

In the February 2000 calibration campaign, the long-wave calibration recheck using the NFBB was done first; note here again that four to five days minimum are required in vacuum for the CERES sensor responsivity to stabilize [18] to within 0.2%, and this is known to have affected the long-wave calibrations made in 2000 (see Section III-D and Table III). However, the short-wave calibrations were performed after the long-wave calibrations, during days 4 and 5 under vacuum, with the CERES sensor response on the cusp of stability. Absent a short-wave calibration from 1999, the February 2000 short-wave CERES calibration (but not the 2000 CERES long-wave calibration) is regarded as the next-most-reliable data set for comparison to the 2008 CERES short-wave calibration data.

A consistency check on relative spectral responses of the CERES TC and SW channels, relative to the RSR of the TACR, comes from comparing the CERES counts and TACR signals (in nanowatts) detected from the SWRS as a function of wavelength, setting aside for this exercise the TACR radiance calibration using the NFBB and the TACR RSR. This consistency check, as performed on the CERES FM5 data from both 2000 and 2008, is presented in Fig. 7. As both the TACR active cavity and the CERES bolometers have very flat spectral responses and similar fore-optics (except for the spectral filter in the CERES SW channel), similar relative spectral response characteristics (e.g., agreement to within ±2% among measurements at any single wavelength) are expected and observed.

### C. TACR Spectral Characteristics and Stability Over Time

With reference again to the 2008 versus 2000 calibrations of CERES FM5 described in the previous section, the same TACR fore-optics and associated relative spectral response contributed to both the CERES TC and CERES SW channel calibrations separated by eight years. Had the TACR spectral response characteristics changed significantly between 2000 and 2008, this change in TACR spectral response would appear as a unidirectional change in both Fig. 5 for TC and Fig. 6 for SW. However, the CERES FM5 test data plotted in Figs. 5 and 6 do not provide any evidence for a unidirectional change in spectral response common to both CERES channels, such as could be attributed to a change in the TACR spectral response characteristics.

To further explore the possibility of a trend over time common to both the SWRS calibrations of CERES TC and SW channels between 2000 and 2008, the differences (as a percentage of the mean end-to-end responsivity) between
Fig. 8. CERES FM5 end-to-end responsivity percent differences from the mean responsivity for that CERES channel at that wavelength, as calibrated in 2000 and 2008 using the SWRS and calibration transfer via the TACR.

Each responsivity measurement and the mean of all the FM5 measurements of that CERES channel at that wavelength are plotted in Fig. 8. Noteworthy perhaps is that the 2000 FM5 responsivity values (filled and open square symbols) are, on average, 0.5% lower than the 2008 FM5 responsivity values plotted in Fig. 8. However, note that the offsets between the 2000 and 2008 FM5 end-to-end responsivities exhibit little to no significant wavelength dependence. Therefore, rather than this being evidence for a change in the TACR spectral response characteristics (which if present and due to degradation of the protected silver coatings on the TACR mirrors would definitely be expected to exhibit a much more pronounced change at the blue end of the spectral range in Fig. 8), we interpret the small differences present between the 2000 and 2008 FM5 responsivity residuals in Fig. 8 as nothing more than an artifact of the CERES instrument’s relatively short duration under vacuum prior to the SWRS calibrations in 2000, compared with the >12 days in 2008. The low response of CERES FM5 during the SWRS calibration of TC and SW in 2000 (due to the short duration under vacuum) is also evident in Table III, where the NFBB calibrations of the TC gave a low response compared with both the 1999 and 2008 calibrations where the sensor had much longer durations in vacuum prior to calibration.

V. DISCUSSION

The preceding sections presented the CERES calibration process using the RCF together with many of the checks performed to track the long-term stability of the CERES calibrations as performed in the RCF. The summary flowchart in Fig. 9 illustrates just how interconnected is this network of calibration tests, the checks on long-term stability of the sources, and internal self-consistency of the calibrations. Confidence in the results of CERES prelaunch calibrations using the RCF rests not only on the absolute radiometric accuracy error budgets for the individual sources or on the stability over time of an individual calibration; that confidence stems also from this interconnected network of consistency checks taken as a whole.

The cryogenic TACR is integral to many of these checks (those illustrated using dashed lines in Fig. 9), given its very broadband yet flat spectral response, high sensitivity, high dynamic range, and CERES-like fore-optics and FOV. While the TACR is not used as an absolute radiometer to calibrate the NFBB radiance, the optical transmission in the infrared $\tau_{IR}$, aperture area $A$, and FOV solid angle $\Omega_{FOV}$ of the TACR are sufficiently well known that TACR measurements of absolute power on the detector (in watts, tied to the NIST electrical scale) can be converted into radiance and used as a check on the NFBB absolute radiance (based on the NFBB’s intrinsically high emissivity, by design, and the ITS-90 absolute calibration of the NFBB PRTs). Any discrepancies larger than $\pm 0.4\%$ absolute, or larger than $\pm 0.1\%$ relative to past measurements (see again Fig. 3) are outside the expected bounds and therefore are investigated to understand the cause.

Similarly, as discussed in Section IV-A, during the process of calibrating CERES using the SWRS, measurements of the SWRS using the TACR are obtained before and after the CERES measurements of the SWRS. The TACR data not only transfer the NFBB absolute radiance calibration over the SWRS but also provide checks on the short-term stability of the SWRS. Furthermore, the relative spectral response shapes of the CERES and TACR are intercompared (see Fig. 7) for consistency within the expected bounds of approximately $\pm 0.6\%$ (see Table IV).

The preceding sections have also investigated the agreement between the 2008 CERES FM5 calibrations and those that were performed in 1999 and 2000. For the long-wave (WN and TC), the consistency in the CERES FM5 responsivity calibrations from 1999 and 2008 (see Table III), showing less than a 0.4% change over nine years, supports the TACR-based conclusion on the long-term stability of the NFBB absolute radiance (see Fig. 3). For the short-wave (SW and TC), the consistency over wavelength in the CERES FM5 responsivity...
calibrations from 2000 and 2008 (see Fig. 8), showing an offset of the 2000 responsivities of no more than than 0.5% in mean value (when both the SW and TC data are combined) relative to the 2008 FM5 responsivities and no pronounced departure from the mean offset at the shortest wavelengths, offer no evidence to suggest a significant degradation in the spectral response of the TACR fore-optics in the short-wave. This refutes the assertion in [21] that degradation of the TACR fore-optics short-wave spectral response could change the CERES short-wave prelaunch responsivity calibrations by 1% between each of the TRMM, EOS Terra, and EOS Aqua missions. However, as summarized in Table 1, the CERES prelaunch calibrations for those three missions were performed within a relatively brief (3.25-year) span, over which time Matthews [21] postulated an overall change of 2% in the CERES short-wave prelaunch calibration. For this to be true, the short-wave throughput of the TACR fore-optics would have to be degrading relative to the long-wave throughput at a rate of 0.6% per year. However, in fact, comparing the CERES FM5 prelaunch calibrations across a much longer (8.5-year) time span, the short-wave responsivity data in Fig. 8 demonstrate stability of the short-wave calibration to within 0.5% in the mean of SW and TC. Taken at face value, this constrains any degradation in the TACR fore-optics to less than 0.06% per year, which is an order of magnitude less than the implausible degradation in TACR relative spectral response asserted in [21].

While highly suggestive that the relative spectral response of the TACR fore-optics is indeed very stable, the 2008 versus 2000 comparison of CERES FM5 SW and TC responsivity calibrations in the short-wave region, presented in Fig. 8, cannot by itself not rule out the possibility (which we regard as slim, given the interwoven network of cross-checks in Fig. 9) that the TACR fore-optics and CERES FM5 telescope optics could be degrading in nearly exactly the same manner, at nearly exactly the same rate (hence, consistent with Fig. 8 but not implying stable relative spectral response for the TACR fore-optics by themselves). Note that the TACR fore-optics and CERES instruments are not stored together nor have they experienced similar intervals and durations of usage outside of storage: When not in use, the TACR and its fore-optics are bagged for protection, and under GN2 purge inside the RCF chamber, the doors of which are kept closed. Meanwhile, over the period 1999–2008, the optics within the EOS flight spare CERES FM5 sensor’s rotating telescopes were kept covered inside the fully bagged FM5 instrument under dry Nitrogen purge, and the entire FM5 instrument was stored on a granite bench inside a class-100 cleanroom. In summary, the simplest and most plausible explanation that can be drawn from Fig. 8 is that the TACR fore-optics’ relative spectral response has remained stable to within ±0.25% over the eight-year period from 2000 to 2008 and, furthermore, that the CERES FM5 short-wave responsivity of TC and SW have remained stable as well.

Characterization testing to recheck the TACR fore-optics’ relative spectral response against the original TRW and China Lake spectral response data sets is expected to be performed at the conclusion of the calibration of CERES FM6 in the RCF that occurred in Spring 2012.

VI. Conclusion

Recent investigations to assess the performance and long-term stability of the principal CERES calibrators NFBB and TACR in the Northrop Grumman RCF have demonstrated that the radiometric accuracy of the absolute blackbody standard has remained stable to better than ±0.06% over the 14-year period from 1995 to 2009. Furthermore, the transfer of this calibration to the SWRS secondary standard via the TACR has yielded calibrations of the CERES FM5 sensor in the short wave region that are self-consistent to within 0.5% or better for measurements separated by a span of eight years (2000–2008). These long-term stability and self-consistency checks are part of an interconnected network of cross-checks used to assess and track the radiometric performance of the RCF calibrators NFBB, TACR, and SWRS in the manner that they are employed in the prelaunch calibration of the CERES instruments.

Based on these results, we are confident that the recent and future prelaunch calibrations of the CERES FM5 and FM6 instruments will enable them to extend the EOS CERES legacy of high-accuracy Earth radiation budget observations.

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References


Herb Bitting received the B.S. degree in chemistry from the University of Notre Dame, Notre Dame, IN, where he published a paper describing the photophysics of an electron-transfer reaction in a constrained solid-state medium, and the Ph.D. degree in physical chemistry from the University of California, Los Angeles, having utilized time-resolved (on timescales from femtoseconds to microseconds) pump-probe laser spectroscopy to describe the proton-pump mechanism of a photosynthetic bacterium and picosecond-resolved fluorescence anisotropy decay to elucidate the functional mechanism of a local anesthetic.

He has 21 years of professional experience in the fields of sensor calibration, precision radiometry, electrooptical testing, infrared materials, and contamination physics. He led the design, construction, and utilization of several cryovacuum test stations at Raytheon Space and Airborne Systems, El Segundo, CA. These radiometric calibration facilities contained point, extended, and flood sources for measuring an instrument’s absolute responsivities, nonuniformity corrections (flat-fielding), and for generating bad detector maps. He also designed and wrote the specification for a spectral response test set that was used to assess a flight system’s performance against spectral requirements, such as relative spectral accuracy, center wavelength, bandwidth, and integrated out-of-band response. He is currently a Senior Scientist with Northrop Grumman Aerospace Systems, Redondo Beach, CA, where he has led the ground calibration and optical alignment efforts for six Clouds and the Earth’s Radiant Energy System (CERES) spaceborne instruments. This entailed instrument-level measurements of radiometric gains, optical alignment of the internal channel to external sources, sensor stability with respect to time and temperature, zero-radiance scan offsets, and sensor point response functions in addition to sensor-level characterizations including signal-to-noise ratio, response time constant, relative radiant spectral response, radiometric responsivity, off-axis response, and coalignment of the fields of view. He is the author of over 20 publications in refereed scientific journals and the holder of two U.S. Patents.

Dr. Bitting was the recipient, along with the entire CERES Team at Northrop Grumman, of NASA Group Achievement awards for his work on the Tropical Rainfall Measurement, Terra, and Aqua missions.

James K. McCarthy received the B.S. degrees in astronomy and physics from the Pennsylvania State University, State College, and the Ph.D. degree in astronomy from the California Institute of Technology (Caltech), Pasadena, in 1988, having designed and built a charge coupled device (CCD)-based echelle spectrograph for the 2.1-m Struve Telescope at McDonald Observatory, University of Texas at Austin. He worked for three years as an Experimental Physicist with the Advanced Imaging Sensors Division, Pixel Vision, Inc., Huntington Beach, CA, engaged in the design and development of custom CCDs for scientific and medical imaging applications. From 1991 to 1998, he was an Assistant Professor of astronomy at Caltech, where his research efforts were devoted to ground-based optical instrumentation (CCDs, broadband imaging instruments, and grating spectrometers) for the Palomar and Keck Observatories, and to using high-resolution stellar spectroscopy to better understand the late stages of stellar evolution, as well as the chemical evolution of galaxies. Since 2000, he has also been an Adjunct Professor of physics with Loyola Marymount University, Los Angeles, CA, where, annually on a part-time basis, he teaches the advanced undergraduate physics laboratory course. He is currently a Senior Electro-Optical Instrument Scientist with Northrop Grumman Aerospace Systems (formerly TRW Space & Electronics), Redondo Beach, CA, where, for the past ten years, he has been supporting the development of remote sensing payload instruments for the National Polar-orbiting Operational Environmental Satellite System, in particular with the development by the Raytheon Company of the Visible-Infrared Imaging Radiometer Suite. He is the author of over 30 research papers in peer-reviewed scientific journals, and additionally has contributed over 45 papers to scientific and technical conference proceedings. He is a holder of one U.S. patent.

Dr. McCarthy is a member of the American Astronomical Society, the Astronomical Society of the Pacific, and the American Meteorological Society.

Thomas A. Evert received the B.S. degree (magna cum laude) in electrical and electronics engineering from the California State Polytechnic University, Pomona. His 30-year career with Northrop Grumman Aerospace Systems (formerly TRW Space & Electronics), Redondo Beach, CA, has focused on electrooptical systems development and has included significant roles on the Halogen Occultation Experiment and the Earth Radiation Budget Experiment (ERBE; the predecessor to Clouds and the Earth’s Radiant Energy System (CERES)), as well as on the CERES program from its inception. From 1990 to 1994, he led the CERES Systems Engineering team through the instrument development phase and, from 1994 to 1999, assumed the role of Instrument Chief Engineer during the flight instrument production phase. In the latter role, he led the efforts that tailored the baseline instrument design for a variety of host platforms (Terra, Aqua, National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project, and NPOESS), and he was responsible for the analysis and verification of the functional, as well as radiometric, performance of each CERES flight instrument. In 2009, he transferred to Northrop Grumman, but has been contracted to support current CERES Flight Model 6 efforts in the role of a Subject Matter Expert. He is the author of a number of papers associated with the ERBE and CERES projects.

Mr. Evert was the recipient, along with the entire CERES Team at Northrop Grumman, of NASA Group Achievement awards for the Tropical Rainfall Measurement, Terra, and Aqua missions, and the NASA Distinguished Public Service Medal for his work on world-class space-based climate sensors in 2009.
Mr. Hedman received the B.S. degree in physics with an emphasis in modern optics from San Diego State University, San Diego, CA, in 1989 and the A.S. degree in laser and electrooptics technology from Moorpark College, Moorpark, CA, in 1983.

His senior thesis studies involved characterizing diffractive optical elements written onto programmable spatial light modulators and was published in a peer-reviewed scientific journal. Since 1989, he has been with Northrop Grumman Aerospace Systems (formerly TRW Space & Electronics), Redondo Beach, CA, where he is currently a Senior Electrooptical Engineer. He has over 20 years of experience working in the fields of multispectral and hyperspectral sensors, with emphasis in the areas of optical and focal plane alignment, electro-optical sensor characterization, calibration, and test. He has worked on a variety of airborne and space-based imaging and nonimaging technology from Moorpark College, Moorpark, CA, in 1983.

Mr. Hedman is a member of the Society of Photooptical Instrumentation Engineers. He was the recipient, along with the entire CERES Team at Northrop Grumman, of the NASA Group Achievement awards for Tropical Rainfall Measurement Mission, Terra, and Aqua missions.

Mark E. Frink received the B.S. degree in chemistry from the University of California, Riverside, and the Ph.D. degree in chemistry from the University of California, Santa Barbara in 1984, having researched applications of photochemistry and photophysics with inorganic metal complexes.

He did his postdoctoral training with the National Radiation Laboratory, Notre Dame, IN, where he continued his research into photon–matter interactions. He is currently a Senior Electro-Optical Sensor Engineer and the Deputy Project Manager on the Clouds and the Earth’s Radiant Energy System (CERES) Project with Northrop Grumman Aerospace Systems (formerly TRW Space & Electronics), Redondo Beach, CA, where for the past 24 years he has been supporting the development of remote sensing payload instruments for multiple government programs. He worked as the Technical Manager for the acquisition of the Visible–Infrared Imaging Radiometer Suite sensor from the Raytheon Company for the National Polar-orbiting Operational Environmental Satellite System Program, and also previously, he was the Payload Accommodation Engineer responsible for interfacing the Geosynchronous Imaging Fourier Transform Spectrometer sounder from Utah State University’s Space Dynamics Laboratory onto a Northrop Grumman spacecraft. Since 1991, he has been involved with the Radiometric Test Facility and legacy CERES flight instrument testing, having developed the Glowbar Source and the optical chain used to determine the CERES point response function. He performed most of the component-level spectral measurements on the CERES bolometer materials and channel filters from 0.3 to > 100 μm on a Fourier transform spectrometer test station. He was a Test Conductor on most of the CERES instrument-level test crews for thermal vacuum and calibration for final performance measurements. Prior to joining TRW, he worked for two years as a Staff Project Engineer at Hughes Aircraft working on laser damage to optical materials. He is the author of over 20 research papers in scientific journals, and additionally has contributed several papers to scientific and technical conference proceedings.

Dr. Frink was the recipient, along with the entire CERES Team at Northrop Grumman, of NASA Group Achievement awards for Tropical Rainfall Measurement Mission, Terra, and Aqua missions.