3.0 CERES Scanning Thermistor Bolometer Radiometer

3.1 Instrument

Each CERES instrument package consists of a scanning thermistor bolometer sensor assembly, elevation axis drive system, azimuth axis drive system, and associated electronics, as shown in Figure 3.1. The CERES instruments are being designed, manufactured, and tested by TRW's Space and Electronics Group, Spacecraft and Technology Division, Redondo Beach, CA. Each instrument package contains three radiometric channels. The first is a narrowband shortwave channel that measures the Earth-reflected solar radiance in the 0.3-to-5.0 μm spectral region. The second is an unfiltered total broadband channel that measures both Earth-reflected and Earth-emitted radiances in the 0.3-to->100 μm spectral region. The third is a narrowband channel that measures Earth-emitted longwave radiances in the 8-to-12 μm spectral region. The three sensors are coaligned and mounted on a spindle that scans about the elevation axis. The sensors are designed to have instantaneous fields-of-view which overlap by at least 98 percent. The sensor assembly, which scans about the elevation axis, may also be commanded to simultaneously rotate around the azimuth axis at rates of between four and six degrees per second. Each instrument package has a mass of less than 45 kg and consumes less than 47 W of power during nominal flight operations.

Earth radiation budget measurements will be collected with the sensor assembly scanning in either a normal or short elevation scan profile, as shown in Figure 3.2. All scan cycles are 6.6 s in duration, with the sensor output sampled every 10 ms. One 6.6-s normal scan cycle consists of a scan from space beyond the Earth limb (11 deg) across the Earth to space on the opposite side (169 deg), then a quick scan to a brief pause at the internal calibration sources (194 deg), then back to space (169 deg), and a scan back across the Earth at 63.5 deg/s to space on the opposite side (11 deg). In the short scan mode, the scan begins with a space look (11 deg), followed by a scan across the Earth at 63.5 deg/s. However, in this latter mode the instrument reverses direction at an elevation angle of 145 deg and performs a rapid retrace at a rate of 254 deg/s before reaching the opposite Earth limb in order to avoid viewing the sun directly. These angles are shown in Figure 3.3, which depicts a cross-sectional view of the CERES instrument sliced perpendicular to the elevation plane. Internal calibration sequences will be performed every 14 days on-orbit. During the normal elevation scan cycle, the internal calibration sources will be viewed but they will not be activated.

The cross-track mode, in which the azimuth position is fixed and the sensors scan about the elevation axis in a plane perpendicular to the orbital direction, is the most important operational science measurement configuration. Measurements taken in this mode will be the primary data used by the CERES science team for performing Earth radiation budget studies.

The biaxial scan mode is an operational mode in which the azimuth axis is rotated at a constant rate of 6 deg/s in one direction for 30 s and then rotated in the opposite direction at 6 deg/s for 30 s while the sensor assembly continues to rotate in either the normal or short scan elevation profile. During the biaxial scanning mode, the sensors will measure radiances from the same geographical scenes with varying incident solar radiation and observing geometry. These measurements will be used to compute angular distribution models for converting the unfiltered sensor radiances into fluxes at the top of the atmosphere. The short elevation scan is used to prevent the sensors from viewing the sun and will be used primarily during the biaxial scan mode.

Figure 3.4 displays the sampling patterns on the Earth's surface for (a) the normal cross-track mode, and (b) the biaxial scan mode.

3.2 Radiometric Channels

Each radiometric channel consists of a forward baffle, Cassegrain optics, and a thermistor bolometer detector module assembly comprised of active and reference disks, as shown in Figure 3.5. The sensor has an overall length of 9.2 cm. The f/1.8 Cassegrain module has an 18-mm diameter spherical silvered primary mirror and an 8-mm diameter spherical silvered secondary mirror. In the shortwave and in the window sensor units, filters are located in two places: before the secondary mirror "spider" (the name applied to the three-legged structure that supports the secondary mirror) and in front of the active bolometer detector. The 8-to 12-µm window filter system consists of a 1-mm thick zinc sulfide and a 0.5-mm thick cadmium telluride filter element. Each filter in the shortwave sensor is a 1-mm thick fused, waterless quartz element. The as-measured normalized end-to-end spectral response for each of the three channels on the PFM instrument is shown in Figure 3.6. By end-to-end it is meant that all components in the optical path are accounted for, including mirrors, filters and blackening on the active detector.

Before radiances from target scenes are sensed by the active detector, they are collected by the optical system and projected upon a 0.75-by-1.50-mm truncated diamond precision aperture, illustrated in Figure 3.7. The aperture of the field stop restricts the sensor field-of-view to 1.3-by-2.6-deg, the small angular dimension being in the elevation scan direction. At nadir, the 1.3 by 2.6 deg field-of-view corresponds to a geographical footprint of approximately 10 and 20 km squares for the projected TRMM and EOS spacecraft orbital altitudes of 350 and 705 km, respectively.

The detector module assembly contains both active and reference thermistor bolometer detectors which are 1.50-by-3.0-mm and approximately 40-µm thick mounted on aluminum disks, as seen in Figure 3.8. The active and compensating detectors have time constants of less than 9 and 12 ms, respectively. The PFM shortwave, total, and window active detector time constants were measured to be 8.7, 7.9, and 8.2 ms, respectively. Using a 0.514-µm Argon laser whose power output was known, the TRMM shortwave and total channel responses were measured to be 65.4 and 62.9 VW^{-1} arriving at the active detector. Using a CO_2 laser at 10.6 μm, the TRMM total and 8-to-12-μm window channels had measured responses of 61.5 and 52.1 VW^{-1}, respectively.

In the detector module assembly, the active and the reference detectors are mounted on separate aluminum heatsink disks of 30.76-mm diameter and 3.86-mm thick. The disks are in thermal contact with each other via a 100-μm thick sputtered indium interface and maintained at a constant temperature of 38°C using actively controlled 2.3-W electrical heaters wrapped around the base of the optics housing. The idea is to maintain the detector module assembly at a temperature greater than its structural surroundings such that energy deposited on the detectors will diffuse away from the module into the instrument structure. This methodology simplifies active thermal control since it necessitates the constant addition of thermal energy. The active and reference detectors are covered with absorptive black paint layers of Aeroglaze Z-306 doped with 10 percent carbon black approximately 11 μm thick. The absorptance of the paint layer is greater than 85 percent out to 100 μm [51].

The black paint layer on the active detector absorbs the target scene energy and converts it into sensible heat that causes a measurable change in temperature and thus in the electrical resistance in the thermistor layer of the active detector. Each thermistor is a sintered semiconductor material with a high negative coefficient of electrical resistance. The electrical resistance R can be represented as a function of the local temperature T by [37]

$$R = R_o \exp\left[B\left(\frac{1}{T} - \frac{1}{T_o} \right) \right] \quad , \tag{3.1}$$

where R_o is the electrical resistance in ohms (Ω) at the reference temperature T_o (K), and B is the temperature coefficient of resistance equal to 3400 K. The sintered semiconductor material is a mixture of manganese, nickel, and cobalt oxides having a resistivity of approximately 250 Ω-cm at 298 K. The active bolometer responds to both incoming target radiances and heat conducted to the disk assemblies. The reference detector resistance changes are used to compensate for variations in the channel structure thermal environment. The active and reference detectors are in adjacent arms of a Wheatstone bridge, as seen in Figure 3.9. Thus, the bridge output signal is determined by the scene-dependent energy that is absorbed and sensed by the active detector. The bridge signal is passed through a low-noise pre-amplifier low-pass filter before entering a four-pole Bessel filter, as seen in Figures 3.9 and 3.10 and discussed in Section 3.3.

3.3 Signal Conditioning Electronics

3.3.1 Pre-amplifier

For nominal Earth scenes, the signal leaving the bridge is on the order of tens of millivolts. In order to amplify this signal, a low-noise pre-amplifier is used in conjunction with a low-pass filter, as seen in Figure 3.9. The values for the electrical components are given in Table 3. The low-pass filter has a corner frequency of 320 Hz and the entire pre-amplifier circuit has an electronic gain of approximately 1750 for the PFM total channel. Each of the three radiometric channels has a different electronic gain corresponding to the amount of energy available in their respective passbands.

3.3.2 Bessel filter

As mentioned in Chapter 2, ringing and overshoot should be avoided when the conditioning electronics filter the signal. This means that the input and output of the filter must be a linear function of frequency. The net effect of this linear relationship is that all frequency components of a signal transmitted through it are delayed by the same amount of time.

The Bessel filter provides the best approximation to the ideal of “perfect flatness” of group delay in the passband because it has a linear relationship between frequency and phase shift. The Bessel filter pays for this desired characteristic by being less than optimal in the flatness of the passband, and in the steepness of attenuation. By this, it is meant that the shape of the attenuation near the corner frequency is not as sharp as that produced by other types of filter networks.

Because of these characteristics, a four-pole Bessel filter was deemed the best choice for use in the CERES instruments; its schematic may be seen in Figure 3.10 with component values listed in

Table 4. Based upon the expected frequency spectra from the source signal, it was decided to choose component values for the filter such that a corner frequency of 22 Hz was obtained. The transfer function for the as-built Bessel filter is

$$F(s) = \frac{2009e^{6}}{s^{4} + 661.31s^{3} + 0.2e^{6}s^{2} + 30.37e^{6}s + 2009e^{6}}, \tag{3.2}$$

and has poles located at

$$s_{1,2} = -191.559 \pm 57.34i$$

$$s_{3,4} = -139.096 \pm 175.792i$$

Figures 3.11 and 3.12 display the Bode diagram and phase angle diagram of the as-built four-pole Bessel filter, while Figure 3.13 displays the filtering function for a step input of unity magnitude. Note that Figure 3.13 verifies that overshoot or ringing in the filtered signal is minimal.

3.4 Ground Calibration

The following overviews borrow generously from Lee [18,60] and Jarecke [54].

Ground calibrations are intended to define the sensor gain and offset terms that are presented in Eq. 3.3. Gain terms for each CERES flight sensor are determined in the TRW Radiometric Calibration Facility (RCF) illustrated in Figure 3.14. The RCF is 2.44 m in diameter and 3.66 m in length. This facility was used in the early 1980’s to calibrate the Earth Radiation Budget Experiment (ERBE) flight scanning thermistor bolometer radiometers. The RCF has since been updated to include an accurate narrow field-of-view blackbody (NFBB) with an out-of-field-of-view mask, a shortwave reference source (SWRS) with minimum longwave variations and better spectral characterizations; a point response function source (PRFS), a constant radiance reference (CRR) that is an offset-variation measuring instrument, an improved solar simulator, and a cryogenically cooled transfer active-cavity radiometer (TACR). The TACR is an electrical substitution radiometer. Detailed descriptions of the calibration facility and its calibration sources are presented by Folkman [61], Jarecke [54], and Lee [18].

3.4.1 Longwave sources

The gains and offsets of the CERES total and longwave window channel sensors are determined using longwave radiances. The shortwave sensors are also exposed to longwave radiances in order to determine the impact of longwave leaks and the longwave heating of the shortwave filter system upon the sensors' output signals. As noted in Figure 3.6, the shortwave sensors have longwave radiance leaks in the 60-to-200-μm spectral region.

The narrow-field-of-view blackbody is the reference source for all of the CERES longwave and shortwave calibrations. The NFBB aperture opening is 3.8 by 4.7 cm. It has copper walls that are coated with a Chemglaze Z-302 specular black paint. As illustrated in Figure 3.15, it is 21.5 cm deep and has a calculated emittance greater than 0.999952 [56] in the direction of the instrument being calibrated. It has eight platinum resistance thermometers (PRTs), seven of which are used for temperature knowledge with the eighth used for temperature control. Using PRTs, the NFBB radiances are calculated using a temperature-based model tied to the ITS-90. The NFBB aperture opening is surrounded by a thermally controlled, diffuse black mask that covers the sensor out-of-field-of-view not covered by the NFBB. During the sensor gain determination processes, the temperature of the NFBB can be controlled at different levels between 200 and 320 K, while the mask temperature is typically maintained at 170 K. The out-of-field response is determined from measurements of the NFBB mask radiances when its temperature is varied between 170 and 380 K and of the in-field NFBB with its temperature held constant near 200 K.

The longwave gain determination for each CERES sensor consists of alternating staring observations at the NFBB and at the cold space reference (CSR) blackbody identified in Figure 3.14. The CSR blackbody is a 12.7 cm diameter, concentrically grooved, anodized black aluminum emitting structure with a stray-light baffle. The structure has two PRTs that can be used for temperature control or knowledge and is maintained at a constant operating temperature near 84 +/-0.1 K, using liquid nitrogen.

3.4.2 Shortwave sources

The shortwave reference source is used to determine the gains of both the shortwave sensor and the shortwave portion of the total channel sensor. For the CERES ground calibrations, a shortwave reference source (SWRS) system was developed which minimizes possible longwave heating effects from using an integrating sphere. The system uses an electrical substitution radiometer to transfer the NFBB temperature-based radiometric scale to the shortwave source. The radiometer is identified as the transfer active-cavity radiometer (TACR) in Figure 3.14. The radiometer, which operates near 4 K, is equipped with the same telescope and field stop aperture design geometries as those for the CERES sensors, in order to duplicate the CERES field-of-view and aperture area. The TACR makes power measurements at an accuracy of +/- 0.05 percent with a noise equivalent power of 2.0 nW and has a 1.0-s time constant. During its calibration, the TACR measures longwave radiances from the NFBB. The resultant TACR signals are regressed against the corresponding NFBB radiances in order to determine the gain and offsets that are required to place the TACR on the NFBB radiometric scale.

The SWRS consists of a 250-W quartz tungsten halogen source lamp, a variable area aperture, 17 narrowband optical filters, a broadband potassium diphosphate (KDP) filter, relay reflective optics, an 11-cm diameter Spectralon integrating sphere, and associated optics. The sphere exit port is 3.6 deg in the scan direction and 7.5 deg in the cross-track direction. The SWRS lamp output can be maintained at the 0.1-percent stability level for as long as 14 hrs. The radiance ($Wm^{-2}sr^{-1}$) leaving the sphere has been mapped at the 0.3-percent uniformity level over the exit port.

During the calibration of each flight sensor set, the SWRS is calibrated using the TACR. The longwave window sensors are calibrated with shortwave radiances to determine the impact of shortwave leaks or shortwave heating of the window filter system upon its output signal.

3.5 Inflight Calibration

Two different in-flight calibration systems are built into the CERES instrument package. They will be used to determine shifts or drifts in the sensor responses. The location of the in-flight calibration systems are shown in Figure 3.3. At the elevation angle of 194 deg, the primary in-flight calibration system is called the internal calibration module (ICM). The ICM and the sensors will carry the ground calibration radiometric scale into orbit. As shown in Figure 3.16, the ICM consists of 2.75-cm diameter, concentric grooved, anodized black aluminum blackbody sources for the total and longwave window channel sensors, and an evacuated tungsten lamp source, known as the shortwave internal calibration source (SWICS), for the shortwave sensor.

At an elevation angle of 236 deg, the second system, a solar diffuser plate, is called the mirror attenuator mosaic (MAM). The shortwave and total channels will be calibrated using solar radiances reflected from the MAMs.

3.5.1 Longwave Sources

The internal blackbodies can be operated at any temperature between ambient and 320 K. Embedded in the blackbodies, platinum resistance thermometers (PRTs) indicate the temperatures of the blackbodies' emitting surfaces. Before being placed in the ICM blackbody structure, the PRTs are calibrated in a temperature-controlled oil bath to verify that the correct coefficients are used in the PRT temperature equation. After the PRTs are placed into the blackbody structure, the blackbodies are immersed in a temperature-controlled oil bath to verify that the PRTs are indicating the same temperature as the controlled bath.

3.5.2 Shortwave sources

The SWICS consists of an evacuated tungsten lamp source, diffusing optics, and a folding relay mirror. The system is designed to operate at four discrete radiance levels, including off, between 0 and 400 $Wm^{-2}sr^{-1}$. Based on the ERBE experience, it is expected that the SWICS will provide stability of greater than 0.3 percent over the life of the mission.

Each MAM consists of baffle-solar diffuser plate systems that guide incoming solar radiances into the instrument fields of view of the shortwave and total channel sensors. The MAM diffuser plate consists of an array of spherical aluminum mirror segments that are separated by a black paint reflecting surface. Thermistors are located in each MAM plate and MAM baffle.

The MAM calibration procedure includes measurements of the MAM before the sun drifts into the MAM baffle field-of-view, of the MAM when the sun is in the field-of-view, and after the sun has drifted out of the view. During the MAM scan cycle of 6.6 s, the sensors make staring radiance measurements of first the MAM, second the ICM, and then cold space. The ICM is not activated during the MAM calibrations.

3.6 Flight Algorithms

In order to preserve continuity with the ERBE long-term data sets, the initial CERES data reduction algorithms will follow the procedures developed for the Earth Radiation Budget Experiment (ERBE). The filtered radiance ($Wm^{-2}sr^{-1}$) measured by each sensor unit can be expressed by

$$\begin{aligned}\tilde{L}(t - t\ ) = A_V[m(t) - \overline{m}(t_k) - o(t)] + \frac{t - t_k}{\Delta t}\{A_S[\overline{m}(t_{k+1}) - m(t_k)] \\ + A_H[T_H(t_{k+1}) - T_H(t_k)] + A_D[V_D(t_{k+1}) - V_D(t_k)] \\ + A_B[V_{bias}(t_{k+1}) - V_{bias}(t_k)]\} \quad ,\end{aligned} \tag{3.3}$$

where

$$t_{k+1} = t_k + \Delta t \quad .$$

Quantities used in Eq. 3.3 are:

$m(t)$ = instrument output signal at time t (counts)

$\overline{m}(t_k)$ = mean instrument output signal when viewing cold space at the beginning of every scan, t_k (counts)

$o(t)$ = sensor zero-radiance offset which varies with elevation angle/geometry (counts)

A_V = gain corresponding to the change in output signal ($Wm^{-2}sr^{-1}ct^{-1}$)

A_S = gain corresponding to a drift in the signal output during two adjacent space looks ($Wm^{-2}sr^{-1}ct^{-1}$)

A_H = gain corresponding to a change in the measured heatsink temperature during two adjacent space looks ($Wm^{-2}sr^{-1}T_H^{-1}$)

A_D = gain corresponding to a change in magnitude of V_D during adjacent space looks ($Wm^{-2}sr^{-1}V_D^{-1}$)

A_B = gain corresponding to a change in magnitude of V_{bias} during adjacent space looks ($Wm^{-2}sr^{-1}V_{bias}^{-1}$)

$T_H(t_k)$ = heat sink temperature measurement at t_k or most recent time (K)

Δt = total scan period of 6.6 s

t = sampling instant (s)

$V_{bias}(t)$ = sensor bridge bias voltage measurement at time t or most recent value (counts)

$V_D(t_k)$ = drift balance digital to analog converter (DAC) voltage at time t or most recent value (counts)

τ = average time lag between the instrument optical field-of-view and point spread function centroid (s)

C = digital to analog conversion factor, 409.5 digital counts/volt

The housekeeping data $T_H(t_k)$ and $V_D(t_k)$ are transmitted to Earth once every scan and thus are not available for every sample during the scan. The gains are determined by regressing sensor counts, heat sink temperature measurements, bias voltage levels and DAC voltage levels against the calculated filtered radiances, respectively. The sensor gain A_V is statistically the most important coefficient since the product of A_V and the sensor counts accounts for more than 90 percent of the total calculated filtered radiance, $\tilde{L}$.