

A Comprehensive Radiometric Validation Protocol for the CERES Earth Radiation Budget Climate Record Sensors

K. J. Priestley, B. R. Barkstrom, R. B. Lee, R. N. Green

NASA Langley Research Center
21 Langley Blvd
Hampton, VA 23681, USA

Abstract—The CERES Flight Model 1 and 2 instruments were launched aboard NASA's Earth Observing System (EOS) Terra Spacecraft on December 18, 1999 into a 705 Km sun-synchronous orbit with a 10:30 a.m. equatorial crossing time. These instruments supplement measurements made by the CERES Proto Flight Model (PFM) instrument launched aboard NASA's Tropical Rainfall Measuring Mission (TRMM) spacecraft on November 27, 1997 into a 350 Km, 38-degree mid-inclined orbit. An important aspect of the EOS program is the rapid archival and dissemination of datasets measured by EOS instruments to the scientific community. On September 22, 2000 the CERES Science Team voted to archive the Edition 1 CERES/Terra Level 1b and Level 2 and 3 ERBE-Like data products. These products consist of instantaneous filtered and unfiltered radiances through temporally and spatially averaged TOA fluxes. CERES filtered radiance measurements cover three spectral bands including shortwave (0.3 to 5 μm), total (0.3 to $<100 \mu\text{m}$) and an atmospheric window channel (8 to 12 μm). The current work summarizes both the philosophy and results of validation efforts undertaken to quantify the quality of the Terra data products as well as the level of agreement between the Terra and TRMM datasets.

INTRODUCTION

Each CERES instrument contains three thermistor bolometer sensors that measure the earth-reflected solar radiance in the 0.3 to 5.0- μm spectral region, earth-reflected and earth-emitted radiances in the 0.3 to $>100\text{-}\mu\text{m}$ spectral region, and earth-emitted longwave radiances in the 8 to 12- μm spectral region. Science requirements have established accuracy criteria of better than 1-percent for the earth-reflected solar radiance measurements and better than 0.5-percent for the earth-emitted radiance measurements [1]. The three sensors are coaligned and mounted on a spindle that scans about the elevation axis. This sensor assembly may also be commanded to simultaneously rotate around the orthogonal azimuthal axis. For optimal spatial coverage the instrument operates in the Fixed Azimuth Plane (FAP) mode whereby the azimuth axis drive is disabled and only the elevation axis operates with the scan plane perpendicular to the satellite ground track, optimal angular coverage is obtained in the Rotating Azimuth Plane (RAP) mode whereby both the elevation and azimuthal drives operate simultaneously. CERES/Terra operational planning ensures that one instrument is always in the FAP mode while the other is in

RAP mode such that both spatial and angular coverage may be obtained simultaneously. A complete description of the CERES instruments may be found in [2].

VALIDATION APPROACH

A complete validation of remotely sensed data products consists of many independent studies whose individual focus is on a specific combination of spatial and temporal scale, as well as data product level. The collection these individual studies, which overall cover large variations of spatial and temporal scales as well as data product levels, will provide insight to an instruments on-orbit performance from many different perspectives. Only after these separate viewpoints are collected and compared can a cohesive picture of the overall end-to-end performance of the instrument and data processing systems be clearly established.

The reader should recognize that lower level data products typically yield the strongest instrument validation results with the least amount of data since they have the least amount of manipulation by scientific algorithms. Higher level products typically require larger, or longer, data sets to acquire strong statistical results since they have undergone more extensive algorithm manipulation. If significant algorithm errors are introduced, they would typically add both noise and bias components on the different level data products and a consistent picture would not emerge as one reviews the results of the independent studies. Recognizing this fact, when anomalous characteristics are found throughout studies covering several different levels of data products, it may be assumed that it was introduced by the lowest level of data product investigated, in this case by an incomplete understanding of the instruments performance.

Currently, the CERES team has developed eleven primary independent studies to a level mature enough to be used for validation at the 1-percent level. Table 1 lists these eleven studies as well as the data product investigated, the corresponding spatial and temporal scales as well as the metric and spectral band which the individual studies cover. The current effort summarizes the results of nine of these efforts (Theoretical Line-by-Line and Time Space Averaging are excluded due to space limitations) and lays out the cohesive story which emerges. Detailed descriptions of the individual studies are outside

Table 1. List of Primary On-Orbit CERES Instrument Validation Studies

		Product	Spatial Scale	Temporal Scale	Metric	Spectral Band
On-Board	Internal BB	Filtered Radiance	N/A	N/A	Absolute Stability	TOT, WN
	Internal Lamp	Filtered Radiance	N/A	N/A	Absolute Stability	SW
	Solar	Filtered Radiance	N/A	N/A	Relative Stability	TOT, SW
Vicarious	Theoretical Line-by-Line	Filtered Radiance	>20 Km	Instantaneous	Inter-Channel Theoretical Agreement	TOT, WN
	Theoretical Unfiltering Algorithm Validation	N/A	N/A	N/A	N/A	N/A
	Inter-Satellite (Direct Comparison)	Unfiltered Radiance	1-deg grid	1 per crossing	Inter-Instrument Agreement, Stability	TOT, SW, WN
	Tropical Matched Pixels (Direct Comparison)	Unfiltered Radiance	Pixel	Daily	Inter-Instrument Agreement	TOT, SW, WN
	Tropical Mean (Geographical Average)	Unfiltered Radiance	20N – 20S	Monthly	Inter-Channel Agreement, Stability	TOT, WN
	DCC Albedo	Unfiltered Radiance	>40 Km	Monthly	Inter-Instrument Agreement, Stability	SW
	DCC 3-Channel	Unfiltered Radiance	>100 Km	Monthly	Inter-Channel Consistency, Stability	TOT, SW
	Time Space Averaging	Fluxes	Global	Monthly	Inter-Instrument Agreement, Stability	LW, SW

the scope of this manuscript; therefore references which do provide such descriptions are supplied as appropriate.

A. On-board Calibration Equipment

Two different calibration systems reside in each CERES flight model. The primary Internal Calibration Module (ICM) provides traceability of the ground calibration radiometric scale into orbit for all three channels and provides broadband stability measurements over the mission lifetime. The ICM consists of 2.75-cm-diameter, concentric grooved, anodized aluminum blackbody sources for the total and window channel sensors, and an evacuated tungsten lamp source, known as the Shortwave Internal Calibration Source (SWICS), for the shortwave sensor. During weekly internal calibration sequences, the blackbodies are maintained at three distinct temperature levels between ambient and 40 K above ambient (~285 – 325 K) and the SWICS lamp is cycled between four discrete radiance levels between 0 and 400 Wm⁻²sr⁻¹.

The second on-board system, the Mirror Attenuator Mosaic (MAM), is designed to monitor long-term on-orbit stability of both the shortwave and shortwave portion of the total channels using solar radiances reflected from the MAM diffuser plates. Solar calibration procedures conducted biweekly include measurements of the diffuser plate before the sun drifts into the field-of-view, when the sun is in the field-of-view, and after the sun has drifted out from the field-of-view. A complete description of both systems may be seen in [2].

B. Unfiltering Method

Since the reflective and transmissive properties of materials used in optical instruments are wavelength

dependent, measurements made by these instruments contain spectrally dependent artifacts which must be removed. For CERES these artifacts are removed using unfiltering algorithms as outlined in [3]. Loeb's algorithms model unfiltered radiances as linear functions of the measured filtered radiances where the regression coefficients are the Spectral Correction Coefficients (SCC). Values for the SCC's are dependent upon the spectral response function, $S_{i\lambda}$, of a given instrument channel, where λ is wavelength and i = SW, TOT, WN for the shortwave, total, and window channels, respectively. The SCC's are determined using a theoretical database of spectral radiances determined from MODTRAN + DISORT radiative transfer calculations at high spectral resolution from typical surfaces, such as ocean, land, desert, snow, and cloud. $S_{i\lambda}$ is measured as part of the instrument calibration and characterization procedures prior to launch.

The Terra Edition 1 unfiltering algorithm uses the CERES spectral response functions derived entirely from ground test data. These functions will be modified in the upcoming Edition 2 Terra ES-8 release to incorporate knowledge gained from the vicarious validation efforts discussed in the current paper. Anticipated changes will affect mainly the total channel spectral response functions of both the FM1 and FM2 instruments.

To estimate possible errors introduced by the unfiltering process, a second independent spectral radiance database was used along with the measured CERES $S_{i\lambda}$ to calculate the theoretical filtered radiances for approximately 10,000 test cases representative of clear and cloudy conditions over ocean, land and snow. The unfiltering algorithm, with coefficients determined by the original spectral radiance database, was then used to unfilter the filtered radiances for the theoretical test cases.

Errors in the method were determined by comparing these estimated unfiltered radiances with the true radiance from the test cases.

C. TRMM/Terra Direct comparisons

Unfiltered radiances measured by FM1 and FM2 on Terra were also compared to radiances measured by the TRMM/PFM instrument for March of 2000. These measurements are matched in time, space and viewing geometry to provide comparisons independent of angular and diurnal models. Comparisons of SW radiances require both the solar zenith and the relative azimuth angles to be matched. This is obtained by rotating the azimuth gimbal of one instrument such that scan planes of both instruments are parallel. For LW and nighttime WN comparisons only the zenith angles are matched. Daytime WN radiances also require measurements that are matched in both solar zenith and relative azimuth since heating of land surfaces can vary with azimuth.

Observations from separate spacecraft are considered coincident if the orbital crossings occur within ± 15 minutes of each other. Spatial resolution discrepancies between the two Terra and TRMM instruments, caused by the different orbital altitudes, are reduced by averaging radiances on a 1-deg grid. Zenith angles are matched to within ± 5 deg and relative azimuth angles are required to be within ± 10 deg. Differences found between Terra and TRMM may be attributed to uncertainties in either radiometric calibration or the spectral unfiltering process described above. A more detailed description of this comparison method can be found in [4].

D. Tropical Ocean All-Sky Measurements

The concept of spatially and temporally averaged Tropical Ocean All-Sky measurements, or Tropical Mean's (TM), were also used to validate Terra unfiltered radiances. The TM is the average of all nadir radiance measurements for ocean all-sky between ± 20 degrees latitude. It is typically calculated on either a daily, monthly, or yearly time frame. Approximately 2000 measurements meet the criteria for any given day. Reference [5] presents the original work completed in tropical ocean all-sky measurements as a validation criteria.

Direct comparisons are obtained by differencing the nearly simultaneously measured nadir pixels of the FM1 and FM2 instruments over the Tropical oceans on a sample by sample basis. Days with the same number of nadir radiance measurements for both the Terra FM1 and FM2 instruments in March, April, and May 2000 were chosen for analysis. Nighttime LW radiances are determined by the total channel and thus represent the performance of the LW portion of the total channel, LW/TOT. It is assumed for this study that the LW/TOT channel performs no

different during the day than it does at night. Daytime LW measurements are determined by subtracting the SW channel measurements from the TOT channel measurements, thus any inconsistencies in the calibration of the SW and SW portion of the TOT channel, SW/TOT, result in daytime LW errors.

A monthly averaged nighttime TM has been determined for several instruments, using the 5 year (1985-1990) data set from the Earth Radiation Budget Experiment scanner instrument on the ERBS spacecraft as our reference.

E. Tropical Deep Convective Cloud Studies

A 3-channel intercomparison of Tropical Deep Convective Clouds (DCC) was used in conjunction with direct measurements of Tropical DCC SW Albedo to assess both the consistency of the SW channel and SW portion of the total channel on a single instrument and to determine the consistency of the two SW channels. Being able to compare the two SW channels directly allows the determination of which channel is responsible for any apparent inconsistencies (i.e. SW or SW/TOT) in the 3-channel intercomparison. Since tropical DCC's occur in only about 1% of the nadir measurements, results are determined on a monthly basis in order to ensure a statistically adequate sample size. Detailed descriptions of the algorithms used for these two studies may be found in [2,6,7].

The Tropical DCC systems are found for each instrument by using their respective window channels. Since we limit the study to nadir views it is expected that each instrument should find the same DCC systems. Additionally since the diurnal variation for DCC clouds is small one should find on average roughly the same number of systems both day and night. The FM-1 window channel consistently finds fewer systems during the day than at night, suggesting a larger than expected ($\sim 0.2\%$) day versus night bias on this channel.

OBSERVATIONS

Results from the internal calibration measurements demonstrate that the Terra FM1/FM2 instruments have carried the ground based radiometric scale into orbit with shifts of less than 0.33% for all but the two window channel sensors. These two sensors demonstrate shifts from ground to flight at the 0.5% level which are traceable to insufficient settling time allowed under vacuum during the original ground radiometric calibrations. Errors introduced by the spectral unfiltering algorithms used in the inversion process are generally less than 0.5% for SW, 0.4% for LW and 0.2% for WN radiances. For the most extreme cases of high cold deep convective clouds errors introduced in LW unfiltered radiances may approach the 1% level.

Vicarious validation studies which include Terra/TRMM direct comparisons, Tropical Ocean All Sky measurements and Tropical Deep Convective Cloud 3-Channel and Albedo comparisons demonstrate a consistent story over several different temporal and spatial scales. Both the Terra/TRMM direct comparisons (Instantaneous, 1-deg grid) and Tropical Mean measurements (Monthly, Zonal average) suggest the FM1 WN channel measurements are lower than the FM2 WN measurements at the 0.9% level and that the longwave portion of the FM1 total channel is higher than FM2 by 0.6%. The WN channel results also agree with the ground to flight traceability shifts measured by analyzing the internal calibration results. For SW radiances, both the Tropical Mean direct comparison measurements (Daily, co-located pixels) and Tropical Deep Convective Albedo (Monthly, >40Km average) studies demonstrate the two Terra SW channels are on the same radiometric scale to better than 0.3%. The Tropical Deep Convective Cloud 3-channel intercomparison (Monthly, >100 Km) and Tropical Mean direct comparison LW measurements (Instantaneous, co-located pixels) suggest an inconsistency between the FM1 SW channel and SW portion of the TOT channel at the 1% level. Since both the Tropical Mean direct comparison SW measurements and Tropical Deep Convective Cloud Albedo measurements demonstrate the FM1/FM2 SW measurements are on the same radiometric scale to better than 0.3% the inconsistency must reside in the SW portion of the FM-1 total channel.

The TRMM/Terra direct comparisons demonstrate that both the TRMM and Terra instruments are on the same radiometric scale to within 0.5% for five of the six channels. The FM2 WN channel measurements display a discrepancy at the 1% level due to the aforementioned WN channel calibration error. Further, the Tropical Mean monthly measurements demonstrate that the Terra/FM2 LW and SW radiances agree with both ERBS and TRMM to about 0.2%. They also show that the FM1 radiances have both a LW and SW problem, with the SW problem in the shortwave portion of the total channel, but still agree with ERBS and TRMM to about 1.0%.

This collection of validation activities has rigorously demonstrated that pre-launch calibration goals of 1-percent for earth reflected solar and 0.5-percent for earth emitted

radiance measurements have been satisfied in the Terra Edition 1 instrument and ERBE-Like data products. Knowledge gained during these studies will be applied to refine the algorithms and coefficients utilized in the release of the Terra Edition 2 instrument and ERBE-Like data products. It is anticipated that the Edition 2 products will be released approximately three months subsequent to the Terra spacecraft performing a Deep Space Calibration maneuver tentatively scheduled for late 2001.

REFERENCES

- [1] Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System Experiment, *Bull. Amer. Meteor. Soc.*, **77**, 853-868.
- [2] Priestley, K. J., B. R. Barkstrom, R. B. Lee, R. N. Green, S. Thomas, et al., 2000: Postlaunch radiometric validation of the Clouds and the Earth's Radiant Energy System (CERES) Proto-Flight Model on the Tropical Rainfall Measuring Mission (TRMM) spacecraft through 1999, *J. of Appl. Meteor.*, In Press.
- [3] Loeb, N. G., K. J. Priestley, D. P. Kratz, E. B. Geier, R. N. Green, et al., 2000: Determination of unfiltered radiances from the Clouds and the Earth's Radiant Energy System (CERES) Instrument, *J. of Appl. Meteor.*, In Press.
- [4] Haeffelin, M., B. Wielicki, J. P. Duvel, K. Priestley, M. Viollier, 2000: Inter-calibration of CERES and ScaRaB Earth radiation budget datasets using temporally and spatially collocated radiance measurements, *Geophysical Research Letters*, In Press.
- [5] Green, R. N., and L. M. Avis, 1996: Validation of ERBS scanner radiances, *J. Atmos. Oceanic Technol.*, **13**, 4, 851-862.
- [6] Currey, C., G. L. Smith, and B. Neely, 1998: Evaluation of the Clouds and the Earth's Radiant Energy System (CERES) scanner pointing accuracy using a coastline detections system, *Proc. of SPIE*, **3439**, 367-376.
- [7] Currey, C. and Green, R., 1999: Validation of the CERES shortwave measurements over desert and cloud scenes, *Am. Meteor. Soc.*, 10th conference on atmospheric radiation, 567-570.