Validation of CERES instruments aboard the Terra and Aqua satellites

Z.Peter Szewczyk* G.Louis Smith† Kory J.Priestley‡

Abstract

A comparison of unfiltered radiances measured by CERES instruments (FM1 and FM4) operating on two different platforms, Terra and Aqua satellites, is presented. Data for the comparison were collected at orbital crossings in July and August 2002. Using a special scanning mode, viewing geometries of the instruments were matched to provide a large data set for comparing all three channels. In addition, the data collected over Greenland were used for a more stringent test of the consistency of the shortwave radiances. Statistics include different scene types and α tests on compiled averages.

Keywords: CERES validation, unfiltered radiances, Terra-Aqua orbital crossings

1 Introduction

The NASA Earth Observing System (EOS) primary goal is long-term climate observations. There have been two decades of continuous monitoring of the Earth's energy budget to detect climate changes and anomalies. Several different instruments and platforms have been involved in this mission over the years. A great effort has always been put into ensuring that there are time overlaps between these intruments so that the validation can be performed for the consistency and continuity of observations.

Since 1998, Clouds and Earth's Radiant Energy System (CERES) instruments have played an important role in the EOS mission with the launch of the proto flight model (PFM) on board the TRMM (Tropical Rainfall Measuring Mission) satellite. Two CERES instruments, flight model 1 and 2 (FM1 and FM2), have been operating on board the Terra satellite since the beginning of 2000. In May of 2002, two additional CERES instruments (FM3 and FM4) have been put in service on board the Aqua satellite. Validation of the shortwave radiances from the CERES instruments aboard the TRMM and Terra spacecrafts was reported by Szewczyk [1]. Measurements were compared when the satellite ground tracks crossed within 15 minutes, and the instruments viewing angles (azimuth and zenith) were matched within a prescribed tolerance. Once the matched data were extracted, a statistical analysis was performed on both data distributions. It was assumed that the distributions were statistically independent, and to reduce spatial noise, averaging was performed on a 1-deg grid. The general approach followed the work of Haefflin [2].

In order to validate CERES instruments on the Terra and Aqua satellites, a new scanning experiment was quickly designed and implemented just after one month into the service of the Aqua instruments. The validation data acquisition was done in July and August of 2002 when the sun illumination of the northern hemispere was still better than average. During that time, two CERES instruments, FM1 and FM4, were scanning in the same plane in the vicinity of nodes of their sun-synchronous orbits. The scanning experiment could only last 90 seconds for the daytime and 90 seconds for the nighttime data acquisition. Despite the fact it covered only about 3% of all data collected per orbit, it was designed to allow rigorous validation of measurements. The major objective of this work is to establish the relation between radiances measured by the FM1 and FM4 instruments. This paper describes a method for the validation data acqusition and results of comparing radiances.

*Science Applications International Corporation; *e-mail:* z.p.szewczyk@larc.nasa.gov; tel.(757) 825-7023; 1 Enterprise Pkwy, Hampton, VA 23666

†National Institute of Aerospace, Hampton, VA 23681

‡NASA Langley Research Center, Hampton, VA 23681

Table 1: A CERES data record showing sample numbers

space 1	earth	space 2	space 3	earth	space 4
1:50	51:280	281:330	331:380	381:610	611:660

2 Unfiltered radiance validation

The following sections describe CERES radiometric data, the validation data acquisition process, a brief description of the statistics applied to the data, and the results of the radiance comparison.

2.1 CERES radiometric data and modes of operation

A CERES instrument is a scanning thermistor bolometer designed to measure reflected solar radiation and outgoing longwave radiation from the Earth for radiation budget studies[3]. The scanner has three channels: total (0.3 -100 μm), shortwave (0.3 - 5 μm), and a longwave window (8 - 12 μm) which measure different parts of the spectrum. A full sweep across the Earth lasts 6.6 sec, and with a sampling rate of 100 sec^{-1}, it produces 660 samples. A full sweep consists of five parts: (i) a space look on an anti-sun side of a globe, (ii) a scan across the Earth, (iii) a space and internal validation look on the sunny side, (iv) a scan across the Earth again, and (v) a space look again. Since both the Terra and Aqua satellites are in a near circular orbit 705km above the Earth surface, each sample corresponds to a footprint size of 16km by 32km at the nadir. Each data record reflects that sweeping motion, and the maximum of a viewing zenith angle (VZA) is 65° at which a scanner reaches an Earth limb. The Table 1 provides the details of sample positions for the FMx.

A CERES instrument can operate in several different scanning modes. However, science data measurements are done mostly in a crosstrack (XT) mode or a rotating azimuth plane scan (RAPS) mode. In the former, the scanning plane is perpendicular to the velocity vector; in the latter, the scanning plane rotates at a constant rate between 90° and 180° with the azimuth relative to the spacecraft of 90° coinciding with the velocity vector. The programmable azimuth plane scan (PAPS) is a variant of the RAPS mode. In this mode, the head orientation follows a prescribed schedule, so that a target is in the scanning plane. Azimuth adjustments can be made every scan, 6.6sec, or any multiple of that. In the current application, one azimuth adjustment of FM1 and FM4 is made and kept constant for about 90sec or 14 scans.

2.2 Collecting validation data

Validation of the radiances from the CERES scanning radiometers aboard the Terra and Aqua spacecrafts can be performed by radiometric comparison between measurements. This can be accomplished by having an instrument on each spacecraft scan the same scenes from the same direction within a short time interval.

2.2.1 Time constraints

The Terra and Aqua satellites are in 81.8° and 98.2° sun-synchronous orbits, respectively flying in opposite directions. Their equatorial crossing times are 10:30AM and 1:30PM, and therefore they arrive at nodes (approximately 70°N and 70°S latitudes) of their intersecting orbits about 15 minutes apart. It is therefore clear that the vicinity of the nodes presents an opportunity for the comparison providing viewing geometries of each instrument match. The northern crossing is around noon over the Arctic, and the southern crossing is around midnight over the Antarctic. To compare the shortwave channels, it is best to use the maximum insolation, corresponding to the northern summer solstice, i.e. June 20, or as soon thereafter as possible.

2.2.2 Geometry constraints

The scanning plane orientation with respect to the Sun of an instrument depends on the scanning head orientation with respect to the orbital plane and the satellite heading. In the vicinity of a node the separation between scanning planes is about 46° when both instruments are in a normal, crosstrack scanning mode. By rotating the head of each instrument, the scanning planes can coincide and produce measurements suitable for the comparison. A CERES instrument scans across the Earth, and an elevation angle of the scanner determines the viewing zenith angle of each footprint. The viewing zenith angle must be within 10° of each other to produce a valid footprint (viewed from the same direction) for comparing all three channels. Reflective light of each footpprint changes with its orientation to the principal (Solar) plane; therefore, the relative azimuth (RAZ) angle difference needs to be less than 20° to compare shortwave measurements. By lining up scanners, the RAZ condition is satisfied for almost all observations. And finally, since the solar zenith angle is the same for each instrument, shortwave measurements do not need to be normalized with respect to each other.

2.2.3 Sites constraints

The best comparison scene location is Greenland, since its interior is covered by an ice sheet 2 miles thick. The picture of Greenland as a plane parallel sheet of ice may not be too realistic, because there may be features such as moguls, crevasses, etc. In this case, there are shadows on the side and extra insolation on the sunlit side, creating a more complex scene. However, the Greenland site still appears to be the most homogenous one this part of northern hemisphere can offer. Therefore, it is used to verify the measurement consistency in the most ideal conditions. The remainder of the terrain at 70°N is the Arctic Ocean, which has much melt water over the ice with much more complex reflective properties. There is also a strip of nothern Syberia and Canada with bare land and some vegetation exposed at this time of the year. Therefore, radiance measurements for various scenes are also collected to be able to compare spectral responses of both instruments.

2.2.4 Viewing direction constraints

The best comparison viewing direction is in the plane normal to the principal plane, which is designated as the minor plane. There are far fewer features in this plane for the plane parallel radiative transfer, as forward or backward scatter occur in the principal plane. Effects of shadows can be reduced by scanning in the minor plane. Scanning in any other plane views the sunlit side features and also the shadows more than scanning in the minor plane. For this reason, the scanners on Terra and on Aqua are rotated to have the scan axis in the principal plane, i.e. due South as the spacecrafts cross the orbital plane intersection at noon. The principal plane rotates only slightly as the spacecrafts move about nodes of their orbits, so the instrument head is kept at the same relative azimuth during the comparison data collection period of about 90 seconds. Although the dynamic range of the nighttime data is minimal, the same procedure is followed for the Antarctic intersection to facilitate data processing.

2.2.5 Spatial noise constraints

Daytime scenes are very dynamic in their nature, affected by a cloud cover, terrain, the direction and the time of observations. Measurements of even seemingly homogeneous scenes have wide range, but in general the scene type is fairly constant within a 20-minute time span. Since Terra crosses a node only 15 minutes before Aqua does, the time differential is of lesser importance. However, the spatial variations are much more pronounced; therefore, averaging over gridded data is used to reduce the dependence of radiance measurements on the spatial noise. The size of a $1^\circ \times 1^\circ$ gridbox changes with the geolocation, but in the vicinity of orbital nodes remains almost constant at 120km by 40km. For a gridpoint to be valid, it is required that at least 20 footprints lie in it or that at least 75% of its area is covered. If the condition is satisified, then an average is computed as a measurement to be compared.

2.3 A Terra-Aqua validation campaign

A Terra-Aqua campaign of the validation data acquisition was started on July 4 and was run until August 22, 2002. Each day could produce validation data from up to 30 orbital crossings, and during the campaign the data from about one thousand orbital crossings were collected. Roughly half of all the data were collected for the nighttime longwave and window radiances in the southern hemisphere. Greenland-only data were defined by the longitude 30°W - 48°W and latitude 70 ± 2°N resulting in 130 passes of both satellites over Greenland. Having collected such a large amount of data enabled the data processing with greatly reduced spatial noise and improved statistical significance of differences. Meaningful statistics were computed even when all measurements were divided up into subsets based on ERBE-like scene identification.

There are several plots shown in the paper that illustrate the data acquisition process and scanning patterns. Figure 1 shows shortwave radiances measured by FM1 for all orbital crossings on 07/10. Figure 2 shows shortwave radiances measured by FM4 for all orbital crossings on the same day. Figure 3 shows a single pass over Greenland of FM1 that clearly shows the scanning plane orientation orthogonal to the solar plane. Figure 4 shows the same for FM4. Figures 3 and 4 show simply a subset of data collected on 07/10/2002.

2.4 Statistics

Radiance measurements of CERES instruments collected over a given period of time form two sets of values which can be analyzed for their statistical equivalence. A sample in each set is an average value of a "real" radiance measured by each instrument for a given gridpoint. Since each gridpoint has two averages associated with it, an analysis of their difference provides information about the discrepency between the measurements. Ideally, one would argue that if that difference is zero over the entire set of paired gridpoint averages, both instruments measurements are consistent. In practice, a set of differences is likely to follow a normal distribution with the mean and variance. In such a case, a standard statistical measure of consistency is the α-confidence test based on the Student's t distribution. The test gives an interval for the mean which is likely to contain any new average computed when more data have become available. This likelihood, α, is typically set to 95%.

One can argue that in order to ensure statistical independence of measurements, data collected during each orbital crossing should be lumped together. A statistically independent sample would then be an average computed for all the data collected in close proximity of time and space. This approach would produce one average for each orbital crossing per instrument, and a set of such differences between the two instruments' averages could be analyzed as in the other approach. Both approaches are being used in this work and are reported in the next section.

2.5 Results

The Terra-Aqua (FM1-FM4) validation campaign was run for almost two months. This presented an opportunity to investigate the consistency of measurements with time. Therefore, it was decided to analyze the collected data in four time periods: 7/04-10, 7/11-21, 7/22-29, and 8/08-22. The data gap between 07/30 and 08/07 was caused by either of the instruments being off-line. Tables 2, 3, 4, and 5 show the comparison of radiances of all three wavelengths for daytime and nighttime. Measurements for longwave and shortwave radiances are in $[Wm^{-2}sr^{-1}]$ and for the window channel are in $[Wm^{-2}sr^{-1}\mu m^{-1}]$; and the differences are reported as FM4$-$FM1. The 95% confidence interval for averages, α-test, is computed by assuming that the average radiance for each orbital crossing is one statistically independent sample. The tables also contain the spread of the differences and the number of orbital crossings for each period.

The tables show very consistent measurements between instruments. The shortwave radiances are slightly $(-0.4 \pm 0.1\%)$ underestimated by the FM4 for all the data, but the difference does not change with time. It is clear that the α-test would have produced an even tighter interval than 0.1 had all four time periods been combined into one. The FM4 slightly overestimates $(0.7 \pm 0.0\%)$ the daytime longwave radiances, but the difference remains constant, and its 95% confidence value is zero. Only the nighttime window channel

Table 2: Statistical analysis of unfiltered radiances for July 4-10, 2002

radiance	μ_{FM4}	μ_{diff}	μ_{diff}[%]	σ_{diff}	N_{orbX}	α-test
SW	96.7	-0.38	**-0.4**	0.93	79	0.2
LWday	77.1	0.53	**0.7**	0.20	79	0.1
LWnite	55.6	0.05	**0.1**	0.10	82	0.0
WNday	5.5	0.05	**0.9**	0.03	79	0.1
WNnite	3.1	0.03	**1.0**	0.01	82	0.1

Table 3: Statistical analysis of unfiltered radiances for July 11-21, 2002

radiance	μ_{FM4}	μ_{diff}	μ_{diff}[%]	σ_{diff}	N_{orbX}	α-test
SW	93.0	-0.41	**-0.4**	0.67	124	0.1
LWday	77.5	0.54	**0.7**	0.17	124	0.0
LWnite	55.0	0.05	**0.1**	0.1	129	0.0
WNday	5.6	0.05	**0.9**	0.02	124	0.1
WNnite	3.0	0.03	**1.0**	0.01	129	0.1

shows a relative difference of 1%, but its absolute value is an order of magnitude smaller than those of the other channels.

As discussed in a previous section, measurements of shortwave radiances over Greenland play an important role in verifying the consistency of both instruments. Table 6 shows the comparison of shortwave radiances. For the very bright scene, the relative difference is 0.2% and 0.1% with the tolerance of 0.2% and 0.3% for July and August, respectively. This means that the average radiances for FM1 and FM4 are within 0.3% with the probability of 0.95 for all 52 orbital crossings shown in the table. Based in this result one can simply state that both instruments measure the same radiance if a source is fairly uniform and homogenous.

A series of scatter plots is presented to visualize the differences between each gridpoint for all the validation data. Each plot represents the data collected for different scene types, which follow the ERBE-like classification. In order to show the consistency of the spectral response, clear sky and overcast scenes are plotted. Figure 5 shows scatter plots of daytime longwave, daytime window, and shortwave for clear ocean, clear land, and overcast conditions. These plots contain all the data collected during the validation campaign. Figure 6 shows scatter plots of nighttime data collected over Antartica for overcast conditions. Figure 7 shows a scatter plot of shortwave radiances collected over Greenland. A distinction is made in the plot between data collected in July and August. It is important to note that the results of these comparisons of unfiltered radiances are based on FM1 data taken from an ES8 (ERBE-like) Edition2 data product and FM4 data from an ES8 Edition1 data product.

Table 4: Statistical analysis of unfiltered radiances for July 22-29, 2002

radiance	μ_{FM4}	μ_{diff}	μ_{diff}[%]	σ_{diff}	N_{orbX}	α-test
SW	91.1	-0.36	**-0.4**	0.75	107	0.2
LWday	76.9	0.56	**0.7**	0.18	107	0.0
LWnite	55.0	0.06	**0.1**	0.11	111	0.0
WNday	5.5	0.05	**0.9**	0.03	107	0.1
WNnite	3.0	0.03	**1.0**	0.01	111	0.1

Table 5: Statistical analysis of unfiltered radiances for August 8-22, 2002

radiance	μ_{FM4}	μ_{diff}	$\mu_{diff}[\%]$	σ_{diff}	N_{orbX}	α-test
SW	83.7	-0.35	**-0.4**	0.60	208	0.1
LWday	75.3	0.52	**0.7**	0.17	208	0.0
LWnite	55.5	0.08	**0.1**	0.13	215	0.0
WNday	5.3	0.04	**0.8**	0.02	208	0.1
WNnite	3.0	0.03	**1.1**	0.01	215	0.1

Table 6: Statistical analysis of unfiltered shortwave radiances over Greenland

period	μ_{FM4}	μ_{diff}	$\mu_{diff}[\%]$	σ_{diff}	N_{orbX}	α-test
7/04-29	167.2	0.29	**0.2**	1.05	35	0.2
8/08-22	142.8	0.14	**0.1**	0.88	17	0.3

3 Closing Remarks

It has been shown that the experiment in which CERES scanners, FM1 and FM4, on Terra and Aqua were scanning in the plane perpendicular to the Solar plane provided a set of valuable validation data. By repeating it over an extended period of time, a large amount of validation data were collected. This in turn allowed the computation of significant statistics to support the claim that the radiance measurements have 1% consistency regardless of the scene type. Moreover, Greenland-only data indicate that the 1% consistency is far exceeded when a source of radiation is more uniform and homogenous.

Several standard statistical measures have been computed to compare and validate unfiltered radiances. They indicate that measurements of FM1 and FM4 belong to the same distribution. The $\alpha - test$ shows that there is the 95% likelihood that radiances measured by each instrument are within 1% as was established for various scene types.

It is important to underscore the fact that the validation effort involving CERES instruments constitutes a basis for establishing the consistency in long-term Earth's energy budget measurements.

4 Acknowledgements

This work was supported by the Earth Science Enterprise and the NASA Langley Research Center under contract NAS1-19570 to Science Applications International Corporation (SAIC.)

References

[1] Z. Peter Szewczyk. A recovery and comparison of shortwave radiances measured by CERES instruments operating on TRMM and TERRA satellites. In *Remote Sensing of Clouds and the Atmosphere VII*, volume 4882, pages 488–497, 2002. SPIE paper No.4882-96.

[2] M. Haefflin et al. Inter-calibration of CERES and SCARAB Earth radiation budget datasets using temporally and spatially collocated radiance measurements. *Geophysical Research Letters*, 28(1):167–170, 2001.

[3] B.A. Wielicki et al. Clouds and the Earth's Radiant Energy System (CERES): an Earth observing system experiment. *Bul. Amer. Met. Soc.*, 77:853–868, 1996.