Correction of drifts in the measurements of the Clouds and the Earth's Radiant Energy System scanning thermistor bolometer instruments on the Terra and Aqua satellites

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ABSTRACT

The Clouds and the Earth's Radiant Energy System (CERES) is an investigation into the role of clouds and radiation in the Earth's climate system. Four CERES scanning thermistor bolometer instruments are currently in orbit. Flight model 1 (FM1) and 2 (FM2) are aboard the Earth Observing System (EOS) Terra satellite and FM3 and FM4 are aboard the EOS Aqua satellite. Terra was launched in December 1999 and Aqua in May 2002. Both satellites are in high inclination near-polar, sun synchronous orbits. Terra crosses the equator at 10:30 am local time in the descending portion of the orbit. Aqua ascends across the equator at 1:30 pm local time. Each CERES instrument on Terra and Aqua measures in three broadband radiometric regions: the shortwave (0.3 – 5.0 μm), total (0.3 – >100 μm), and window (8 – 12 μm). Several vicarious analyses have been developed to aid in monitoring the health and stability of the instruments' radiometric measurements. One analysis is a three-channel inter-comparison of the radiometric channel measurements for each instrument. This procedure can derive an estimate of the shortwave portion of the total channel radiance measurement. A second analysis compares temporally synchronized nadir measurements for each sensor of two instruments on the same platform. The three-channel inter-comparison along with the direct comparison and onboard internal calibrations have been used to identify and correct drifting in the measurements of the CERES instruments. Although these drifts and the correction of the measurements have been previously documented, this paper is a continuation of the efforts to quantify and correct drifting in the measurements using ground-processing software. Previous papers only reported drift correction to the CERES instruments on the Terra platform. In addition to the Terra instruments, this paper documents drift correction to the CERES instruments on the Aqua platform.

Key Words: CERES, Terra, Aqua, shortwave radiance, bolometer stability, nadir footprints

1. INTRODUCTION

The long-term goal of the CERES project is to obtain an understanding of the role of clouds in the radiation budget of planet Earth.[1] Currently five CERES instruments are on three satellite platforms in Earth orbit. The CERES Proto Flight Model (PFM) instrument is aboard the Tropical Rainfall Measuring Mission (TRMM) satellite launched in November 1997.[2] Two CERES instruments, Flight Model 1 (FM1) and 2 (FM2) are aboard the EOS Terra satellite launched in December 1999. And Flight Model 3 (FM3) and 4 (FM4) are on the EOS Aqua satellite launched in May 2002. A voltage regulator failed on PFM after the instrument provided eight months of radiance measurements and PFM is no longer operational. Analyses discussed here are restricted to the radiance measurements by the CERES instruments on the Terra and Aqua satellites. The Terra and Aqua satellites are in high inclination near-polar, sun synchronous orbits. Terra crosses the equator at 10:30 am local time in the descending portion of the orbit. Aqua ascends across the equator at 1:30 pm local time.

Each CERES scanning thermistor bolometer instrument measures in three broadband radiometric regions: the shortwave (0.3 – 5.0 μm), total (0.3 – >100 μm), and window (8 – 12 μm). Each sensor measures filtered radiance. Filtered radiance is the radiance absorbed by the sensor and has not been adjusted for optical effects of the sensor assembly.[2] The filtered radiance is converted to unfiltered radiance with ground software using the spectral response function associated with each sensor.[3] The spectral response function is dependent on the spectral reflectance, spectral absorptance, and

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spectral transmission of the optical surface on each sensor. The unfiltered radiance is the radiance incident to the instrument aperture. Once in flight, the sensors' calibration is monitored regularly using known sources. A tungsten lamp is used as a constant source for the shortwave sensor and blackbodies are used as constant sources for the window and total detectors.[2] In addition to the on-orbit calibrations on the instruments, algorithms using ground software have been developed which can indicate stability of instrument measurements. Use of these algorithms has shown that there has been a drift in the ground-calibrated characteristics of the sensors. Further, this drift is occurring in the shortwave region of the measurements. Two analyses have been implemented that identified this drift, a three-channel inter-comparison of the three radiometric channels per each instrument and a direct comparison of temporally synchronized nadir measurements between each sensor of the two instruments on the same platform.

The three-channel inter-comparison has shown that either the shortwave sensor or the shortwave portion of the total channel sensor has drifted from its ground-calibrated characteristics for both instruments on the Terra satellite. The direct comparison shows that the two shortwave sensors compare between FM1 and FM2 from the beginning of the mission until March 2002 when some slight drifting begins. Further, in-flight calibrations indicate that the shortwave sensors for these instruments are not significantly drifting. These analyses along with ground and on-orbit calibrations were used to isolate the drift as occurring in the shortwave region. Similar analyses applied to the CERES instruments on Aqua indicate a drift in the shortwave sensor measurements of both instruments. This paper will outline the analyses, present further investigation into the shortwave drift, and demonstrate methods for correction using ground software.

2. ANALYSES

2.1 Three-Channel Inter-comparison Using Deep Convective Clouds

The three-channel inter-comparison is done on the measured radiance of nadir views of Deep Convective Clouds (DCC) for the three sensors on each instrument. A theoretical basis for the three-channel inter-comparison, can be found in Priestley, et al.[2] DCC are identified using the window sensor radiance equivalent to brightness temperatures less than 215 Kelvin. Multiple nadir footprints occurring in succession meeting the "cold" (215 K) brightness temperature criteria are grouped as a DCC. At least two footprints are required for DCC. Radiances, fluxes, and geolocation of the footprints comprising a DCC are averaged over all the footprints yielding one radiance, flux, and geolocation per DCC. Further, sampling is restricted to between 35 degrees north and south latitude and less than 60 degrees solar zenith with respect to the footprint. The standard deviation of the window radiance was calculated for each group of footprints comprising a DCC. Most standard deviations were less than 10 percent of the window radiance average. Some standard deviations reached on the order of 25 percent of the window radiance average. However, no DCC points were discarded due to large standard deviations of the window radiance.

Using nighttime averaged radiances of each DCC, a correlation between the nighttime window filtered radiance and nighttime longwave unfiltered radiance is derived. This relationship is nearly linear for these "cold" footprints. Figure 1 illustrates the linear relationship between the nighttime filtered window radiance and the nighttime unfiltered longwave radiance for March 2000 measured by the FM1 instrument. The regression coefficient for a linear relationship is 0.957 and the variance is 0.216 $(\text{watt/m}^2/\text{sr})^2$ which are typical values for all months processed.

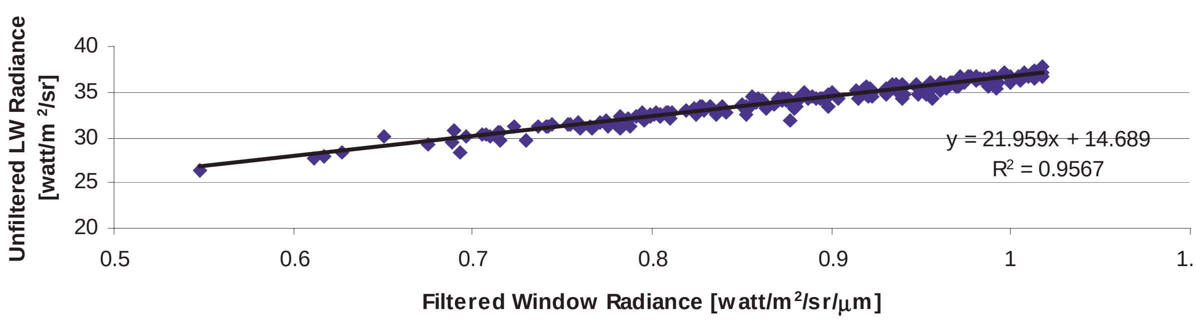

Figure 1: Correlation between filtered window and unfiltered longwave radiance for nighttime DCC in March 2000 detected by FM1.

The resulting regression coefficients are used to generate a derived daytime unfiltered longwave radiance using the window channel. The difference between the measured and derived daytime unfiltered longwave radiance is linearly correlated to the filtered shortwave measurement with a forced zero intercept. A trend plot of the slope of the correlation between the filtered shortwave and the delta longwave over the life of the Terra and Aqua missions is shown in figure 2.

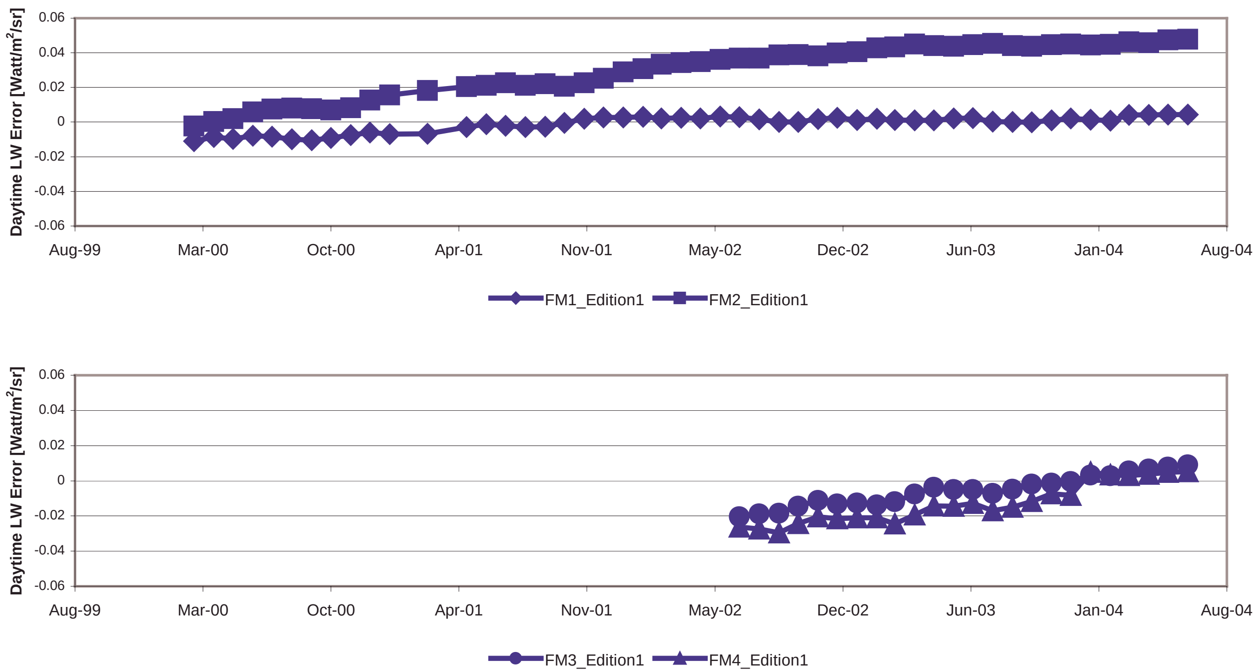

Figure 2: Trending of the ratio of the delta longwave to the measured shortwave channel using the three-channel inter-comparison for BDS and ES-8 Edition 1 data products.

The daytime correlations are quite noisy with the variance often greater than 50 percent of the delta longwave and low correlation coefficients. However, the shortwave and delta longwave should not correlate especially since delta longwave should tend to zero. This still serves as a good trending analysis since nonzero results may indicate a problem. Nighttime correlations are stable in time between filtered window radiance and unfiltered longwave radiance over mission life for both platforms.[4, 5]

2.2 Direct Comparison

The CERES instruments scan from the limb of the Earth on one side of the instrument to the Earth's limb on the opposite side of the instrument and return. One scan takes 6.6 seconds. Each instrument has two nadir footprints, zero viewing zenith angle with respect to the footprint, per scan. The direct comparison analysis pairs the two nadir views of each instrument that are within 1.65 seconds of each other, one quarter of the scan period. These coincident nadir measurements of the two instruments are differenced (FM2 - FM1) for Terra, and (FM4-FM3) for Aqua, and averaged per month based on scene type. Scene types and cloudiness must match between both instruments to be included in the average for a particular scene type. An all-sky condition is also averaged where no restriction on scene type or cloudiness is enforced.

2.2.1 Direct Comparison – Terra, Edition 1 Data Products

The trending of the daytime longwave flux differences between the CERES instruments on Terra using Edition 1 data (ES-8) is shown in figure 3 for various scene types. The trending of the nighttime longwave flux direct comparison is shown in figure 4 and daytime shortwave flux trending is plotted in figure 5.

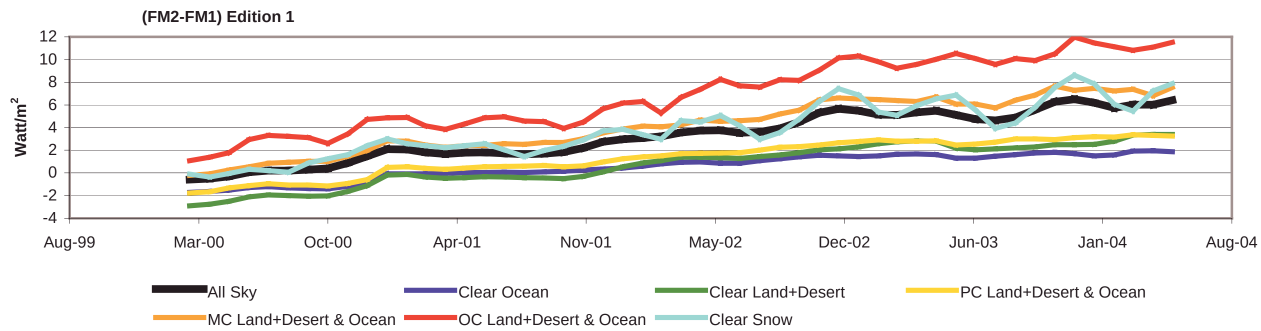

Figure 3: (FM2-FM1), Edition 1 data, difference for daytime longwave flux over mission life for all sky conditions and various cloud and surface types [PC – Partly Cloudy, MC - Mostly Cloudy, OC - Overcast].

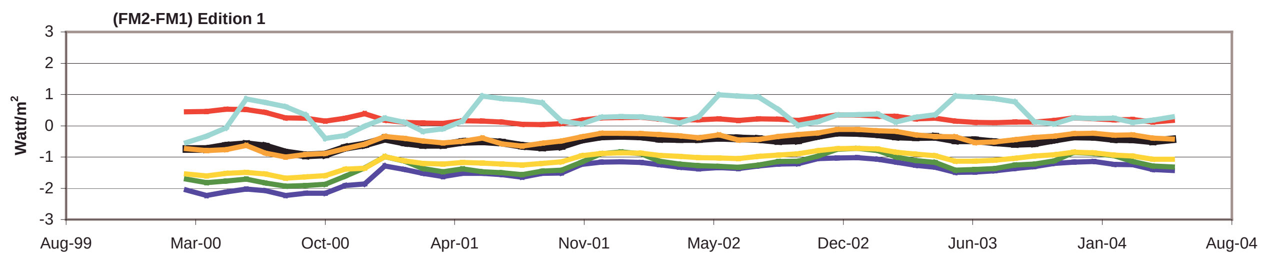

Figure 4: (FM2-FM1), Edition 1 data, difference for nighttime longwave flux over mission life for all sky conditions and various cloud and surface types defined in legend of Figure 3.

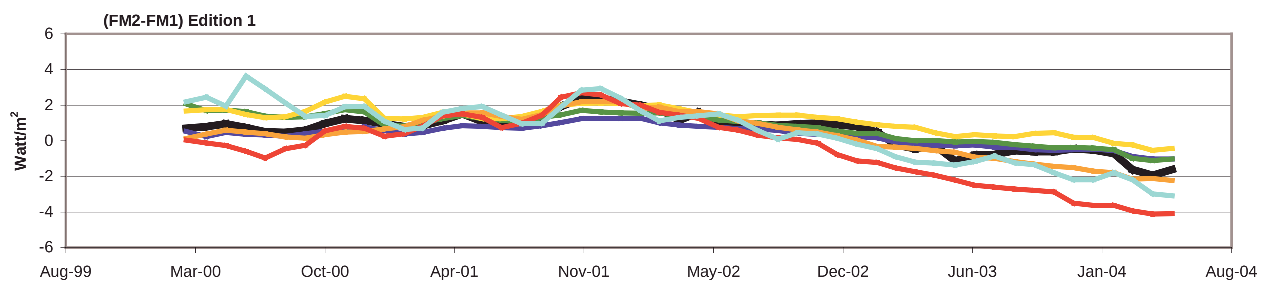

Figure 5: (FM2-FM1), Edition 1 data, difference for daytime shortwave flux over mission life for all sky conditions and various cloud and surface types defined in legend of Figure 3.

A horizontal trend line indicates the sensors of the two instruments are stable with respect to each other. However, the two sensors could be drifting at the same rate and the direct comparison would not indicate a drift since equal trending between the two sensors subtract out. Comparisons between these trending plots indicate that the drift is in the shortwave region of the measurements. The nighttime longwave flux does not indicate any significant change between the two instruments over mission life. However, the daytime longwave flux shows a continuous drift in average values between the two instruments over time. This is more pronounced in the bright scene averages where the difference between the two instruments is greater in magnitude. The daytime shortwave fluxes show almost no drift in average value between the two instruments from March 2000 to March 2002. After March 2002, the difference begins to trend slightly downward. This indicates that either the FM2 shortwave sensor is less responsive, or the FM1 shortwave sensor is more responsive, or a combination of both is occurring over this time period.

2.2.2 Direct Comparison – Aqua, Edition 1 Data Products

The analogous comparisons of the shortwave and longwave fluxes were made for the CERES instruments on Aqua. The daytime and nighttime longwave fluxes and the shortwave flux direct comparisons are shown in figures 6 – 8. Each of these comparisons indicates that the FM3 and FM4 instruments are not drifting significantly in time relative to each other. There is slight upward drift in the daytime shortwave difference.

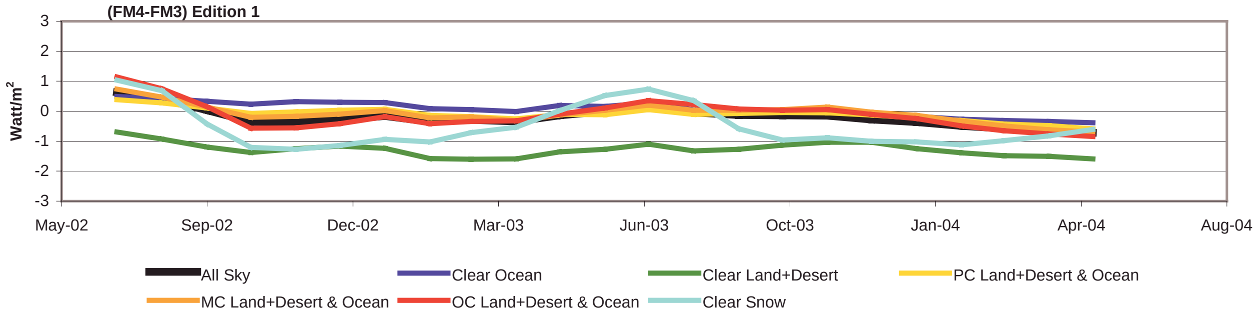

Figure 6: (FM4-FM3), Edition 1 data, difference for daytime longwave flux over mission life for all sky conditions and various cloud and surface types [PC – Partly Cloudy, MC - Mostly Cloudy, OC - Overcast].

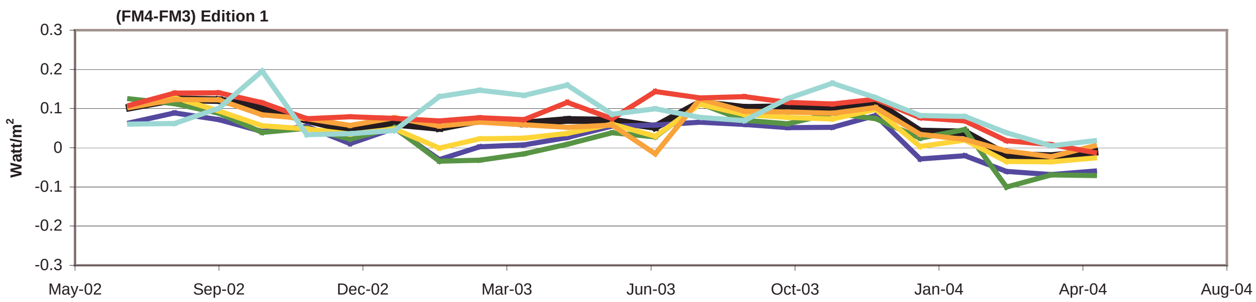

Figure 7: (FM4-FM3), Edition 1 data, difference for nighttime longwave flux over mission life for all sky conditions and various cloud and surface types defined in legend of Figure 6.

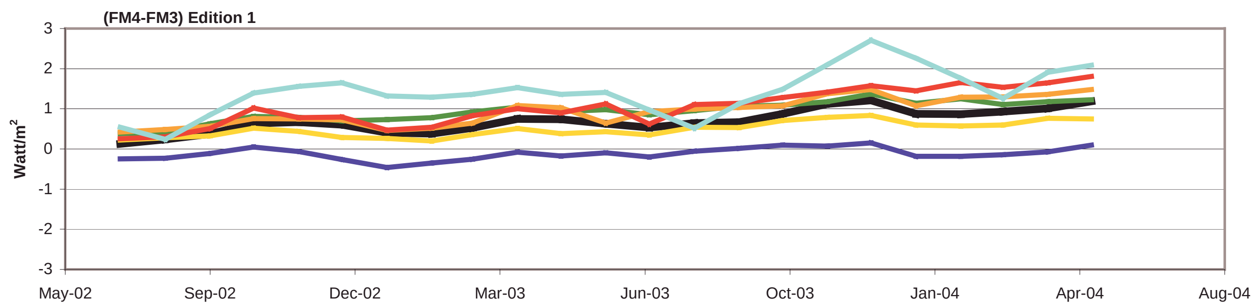

Figure 8: (FM4-FM3), Edition 1 data, difference for daytime shortwave flux over mission life for all sky conditions and various cloud and surface types in legend of Figure 6.

2.3 On-Board Calibrations

Gain coefficients are used to convert CERES measurements from electronic count values to radiance units. These coefficients are determined during ground calibrations of the instruments.[6] Once in flight, on-board calibrations are performed weekly to reassess the gain.

2.3.1 On-Board Calibrations - Terra

Figure 9 shows the history of the percent deviation from the ground derived gain coefficients determined from on-orbit calibrations for the three sensors on both instruments. Over mission life, the gains of the total channel sensors for both CERES instruments have increased while the window and shortwave sensor gains have remained somewhat constant although the window sensors have a lower signal to noise ratio.

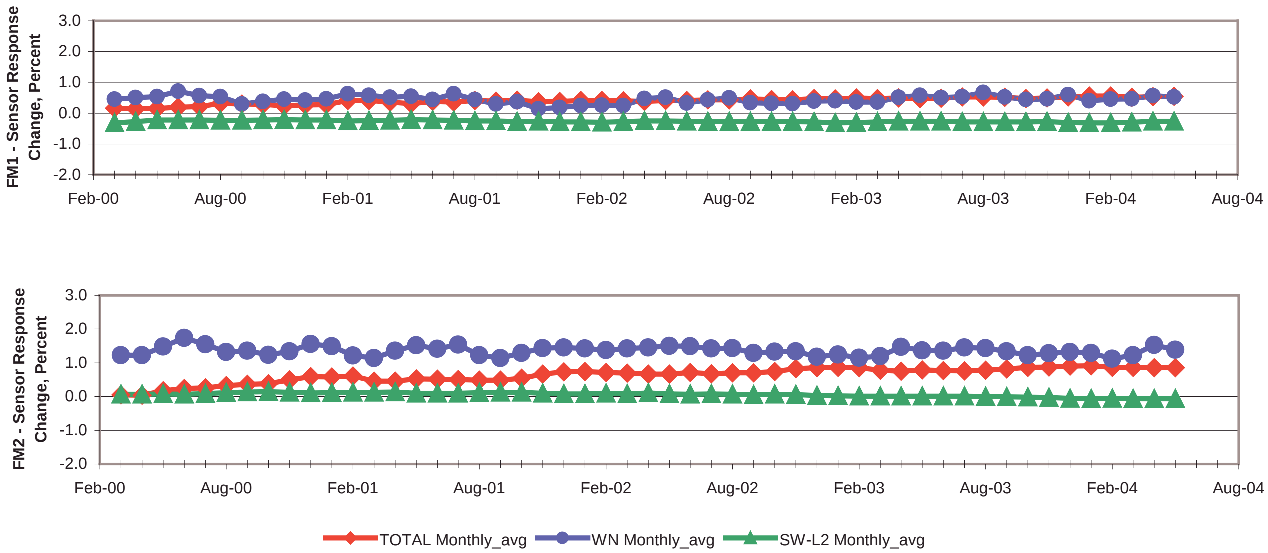

Figure 9: Monthly averaged percent deviation from ground derived gains during on-orbit calibrations for all three sensors of both Terra CERES instruments.

2.3.2 On-Board Calibrations - Aqua

The analogous calibrations for the CERES instruments on Aqua are shown in figure 10. The in-flight calibrations indicate slight drifting in the shortwave sensors of both instruments on the Aqua platform.

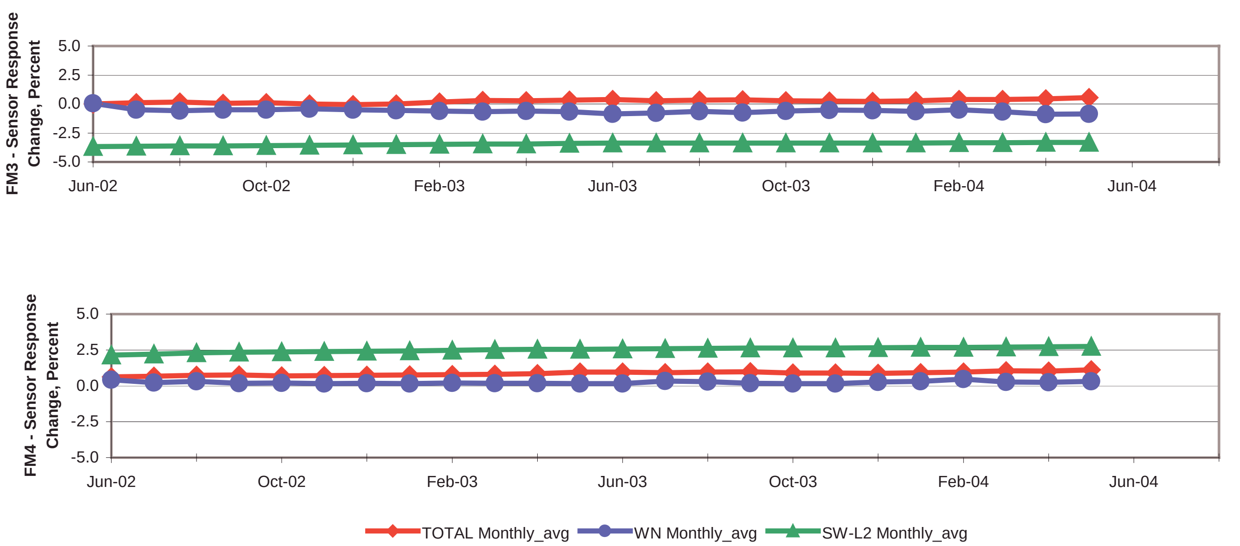

Figure 10: Monthly average of percent deviation from ground derived gains during on-orbit calibrations for all three sensors of both Aqua instruments.

3. DISCUSSION

3.1 Terra

The three-channel inter-comparison indicates that the ratio of the shortwave portion of the total channel sensor to the shortwave channel sensor is increasing with time (figure 2). This drift is more pronounced in the FM2 instrument and initiates at the beginning of the mission. The drift in the FM1 instrument is less and appears to initiate after March 2001.

The direct comparison shows that the average difference of coincident daytime longwave nadir measurements between the two instruments is increasing in time, figure 3. Trending plots do not show a drift in nighttime longwave measurements, figure 4. The window channel sensor is stable in time during both daytime and nighttime. Internal calibrations do not show drift in shortwave channels. Thus, the shortwave portion of the total channel sensor may be too responsive causing the total channel to read high and this mis-reading is increasing with mission time. The daytime unfiltered longwave radiance and flux are derived in part by subtracting the shortwave sensor value from the total sensor value. If the total channel errs falsely high, the resulting longwave value will be falsely high for daytime when shortwave values are nonzero. When shortwave is zero during nighttime, the drift is not detected by these analyses.

Mean longwave radiances over the tropical ocean remain very stable over time with a mean variation of about 0.7 percent over a 5-year period. This has been shown by measurements taken by the Earth Radiation Budget Satellite (ERBS) instrument.[7] Thomas[8] applied this technique to the CERES instruments on Terra and found that the daytime minus nighttime differences between monthly averaged longwave unfiltered radiances has increased about 0.25 percent from March 2000 to December 2003 for the FM1 instrument. The drift in the FM2 instrument was about 1 percent. This is consistent with the findings here and indicates drifting of CERES instruments' measurements is occurring in the shortwave region of the total channels. Also, it is consistent that FM2 has a larger drift.

3.2 Aqua

The three-channel inter-comparison, figure 2, indicates a drift in either the shortwave channel or the shortwave portion of the total channel. The direct comparisons do not indicate significant drifting. The in-flight internal calibrations indicate small drifting in the total and shortwave sensors of both instruments, figure 10.

4. DRIFT CORRECTION

4.1 Correcting drift using ground software

The drifting of the sensors' measurements on the CERES instruments has been corrected using ground software. Reducing the gain in the total channel sensor with time will reduce and thus, correct the total channel sensor measurements. A numerical scheme was devised to reprocess raw CERES data from beginning of the mission with gain coefficients linearly adjusted with time over mission life. In addition, the spectral response functions were also incorporated into the scheme to spectrally filter the shortwave portion of the total channel sensor. In this study, the shortwave portion of the total sensor is defined for radiance of wavelengths $\leq 3\ \mu m$. The longwave portion of the total sensor is defined for radiance with wavelengths $> 3\ \mu m$. As with the gain coefficient adjustment, the spectral response function was made to linearly vary with time over mission life.

4.1.1 Drift Correction – Terra, Edition 2 Data Products

FM1, FM2 level-0 data were reprocessed starting with March 2000 to December 2003 with linearly varying gains and spectral response functions. Although the software was written to apply time-varying gain and spectral response functions to all three sensors, only the total channel for both instruments was applied time-varying gain coefficients, figure 11. Initial radiometric gain values for March 2000 were adjusted for ground-to-flight shifts detected by the internal calibrations. Time-varying spectral response functions were applied to the shortwave portion of the total sensor of the FM1 instrument after February 2001. The FM2 instrument has had time varying spectral correction to the shortwave portion of the total channel sensor since the beginning of the mission, figure 12. Spectral response corrections have been applied to the shortwave sensor of FM2 since the beginning of 2003.

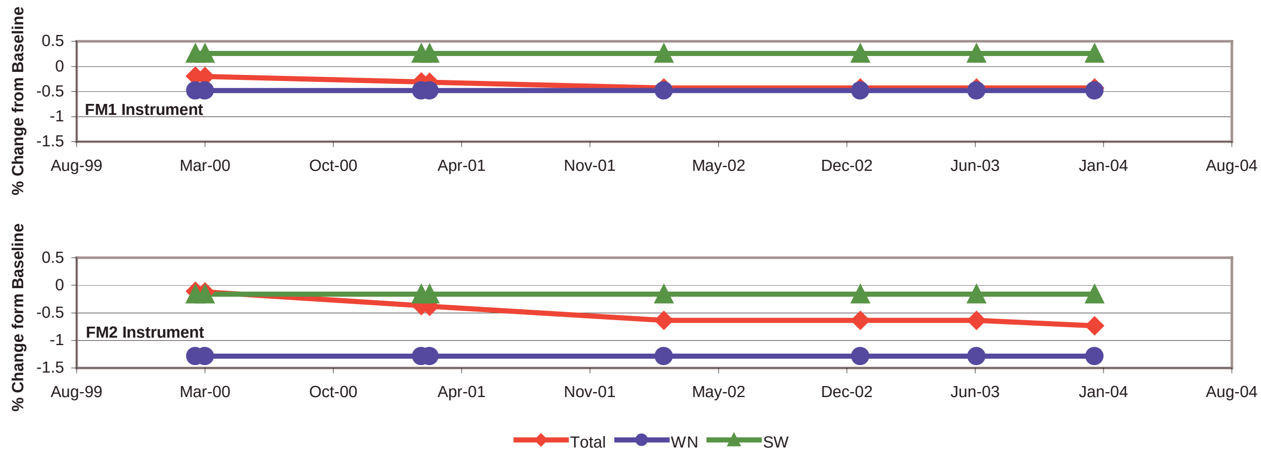

Figure 11: Percent deviation from on-ground derived gains for all three sensors of both CERES instruments on Terra.

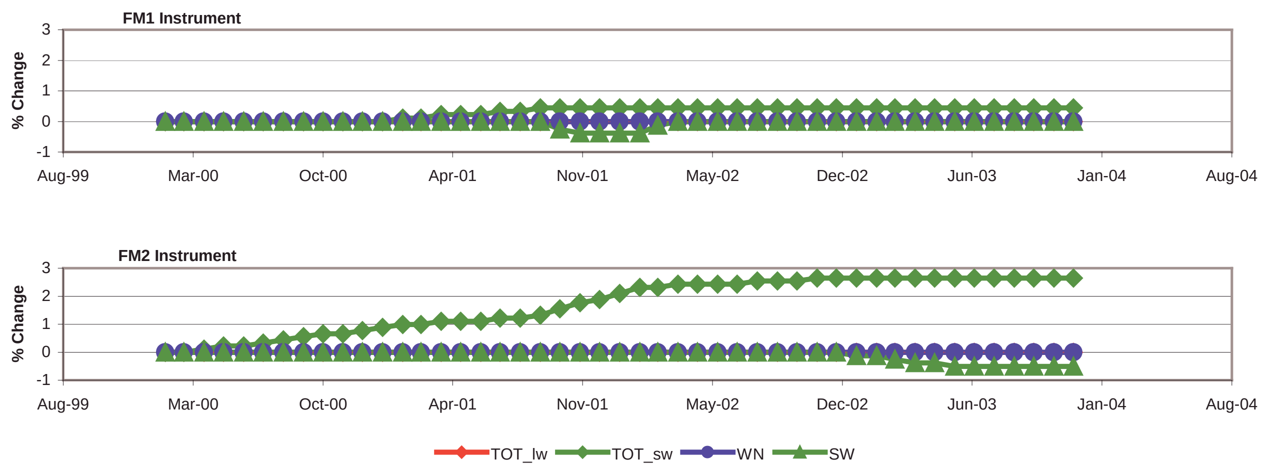

Figure 12: Percent deviation from initial spectral response functions for all three sensors of both CERES instruments on Terra.

4.1.2 Drift Correction – Aqua, Edition 2 Data Products

FM3, FM4 level-0 data were reprocessed starting with July 2002 to February 2004 with linearly varying gains and spectral response functions. The shortwave and total sensors for both instruments have time-varying gain coefficients, figure 13. The shortwave sensor was adjusted since the beginning of the mission, and the total sensor adjustment began at the beginning of 2003. Initial radiometric gain values for July 2002 were adjusted for ground-to-flight shifts detected by the internal calibrations. Time-varying spectral response functions were applied the shortwave portion of the total sensor of both instruments since the beginning of the mission, figure 14.

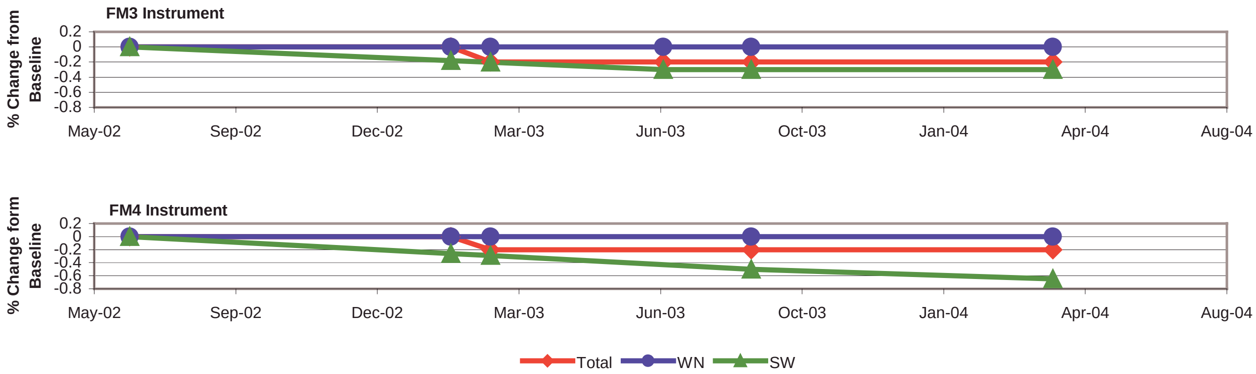

Figure 13: Percent deviation from initial on-orbit derived gains for all three sensors of both CERES instruments on Aqua.

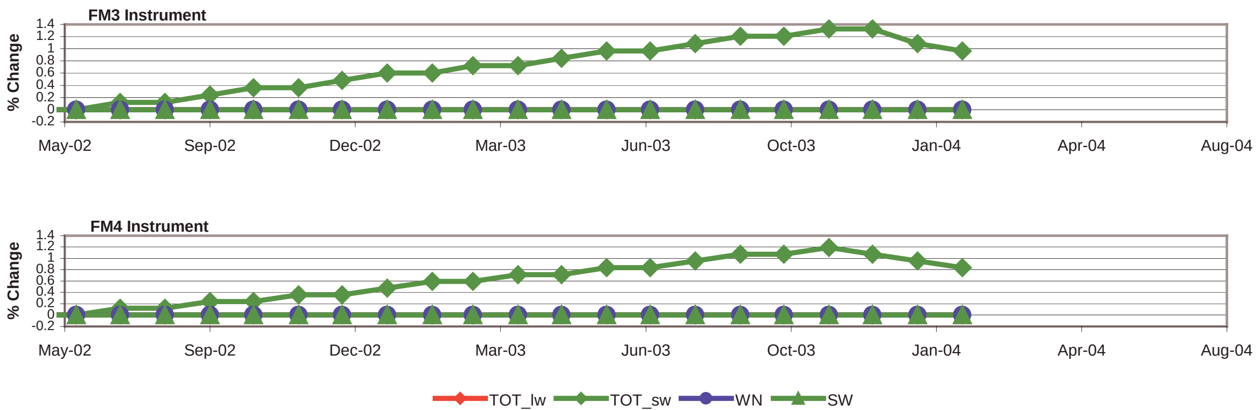

Figure 14: Percent deviation from initial spectral response functions for all three sensors of both CERES instruments on Terra.

4.2 Three-Channel Inter-comparison Using Deep Convective Clouds, Edition 2 Data Products

The three-channel inter-comparison analysis was recomputed for the Edition 2 data products that contain the time-varying gains and spectral response functions discussed in the previous section.

4.2.1 Three-Channel Inter-comparison Results for CERES Instruments on Terra

The improvement of the three-channel inter-comparison using unfiltered radiances (figure 15) is pronounced. The drift in ratio of delta longwave to shortwave in FM2 is removed. No change in spectral response functions was applied to the FM1 instrument for the year 2000, so the improvement here is due solely to time-varying gain coefficients in the total channel sensor.

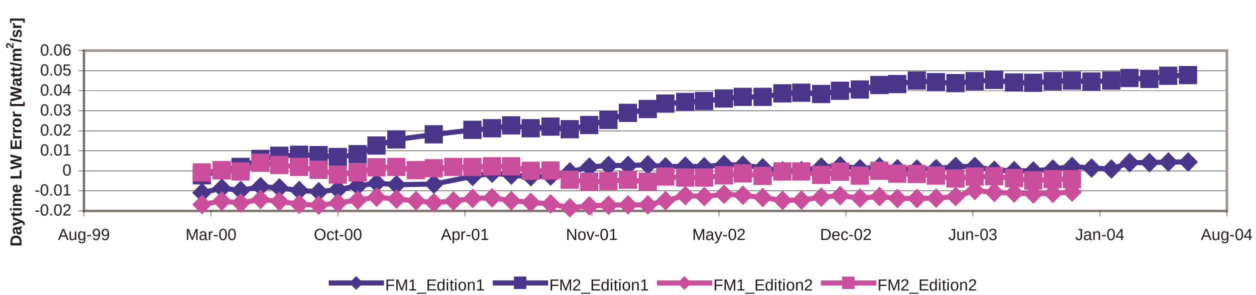

Figure 15: Trending of the ratio of the delta longwave to the measured shortwave channel for the Terra instruments using the three-channel inter-comparison. Edition 2 data products implement corrections to gains and spectral response functions.

4.2.2 Three-Channel Inter-comparison Results for CERES Instruments on Aqua

As with the CERES instruments on Terra, the improvement of the three-channel inter-comparison using unfiltered radiances (figure 16) is pronounced. The drifts in ratio of delta longwave to shortwave in both FM3 and FM4 are nearly totally removed. The drifts were removed primarily by reducing the gains of the shortwave sensor and to a lesser extent, the total sensor, and adjusting the spectral response of the shortwave portion of the total sensor for both instruments.

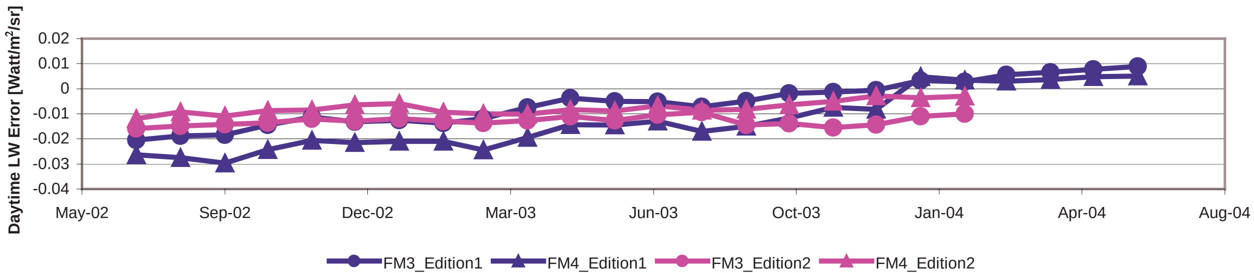

Figure 16: Trending of the ratio of the delta longwave to the measured shortwave channel for the Aqua instruments using the three-channel inter-comparison. Edition 2 data products implement corrections to gains and spectral response functions.

4.3 Direct Comparison, Edition 2 Data Products

The direct comparison analysis was recomputed for the Edition 2 data products that contain the time-varying gains and spectral response functions discussed in the previous section.

4.3.1 Direct Comparison Results for CERES Instruments on Terra

When directly comparing coincident nadir measurements, the daytime longwave differences, figure 17, show the most improvement with implementing the time-varying drifts and spectral corrections. These results can be compared with the Edition 1 data shown in figure 3.

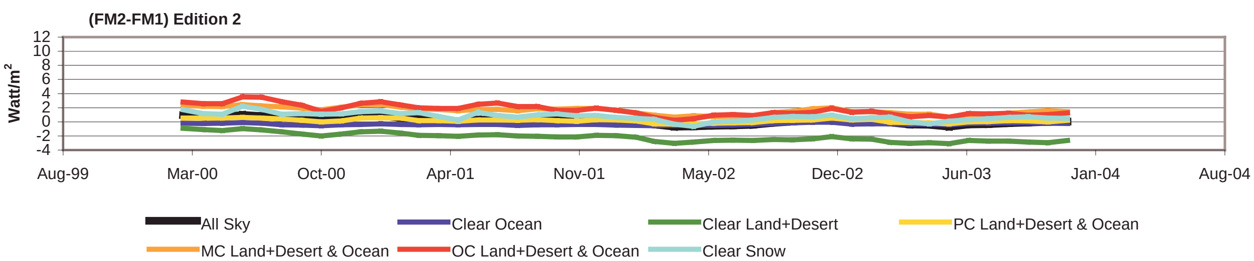

Figure 17: (FM2-FM1), Edition 2 data, difference for daytime longwave flux over mission life for all sky conditions and various cloud and surface types [PC – Partly Cloudy, MC - Mostly Cloudy, OC - Overcast]. Edition 2 data products implement corrections to gains and spectral response functions.

The nighttime longwave differences, figure 18, are about the same as previous, figure 4. The shortwave flux shown in figure 19 shows that the downward trending of the difference after March 2002 (figure 5) has been removed. These results indicate that corrections to the total channel sensor did not have an adverse effect on the values dependent upon the total sensor measurement (longwave is derived by subtracting shortwave from total).

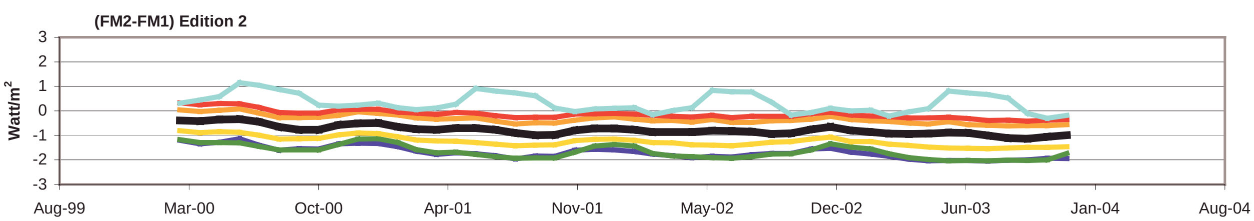

Figure 18: (FM2-FM1), Edition 2 data, difference for nighttime longwave flux over mission life for all sky conditions and various cloud and surface types defined in legend of Figure 17.

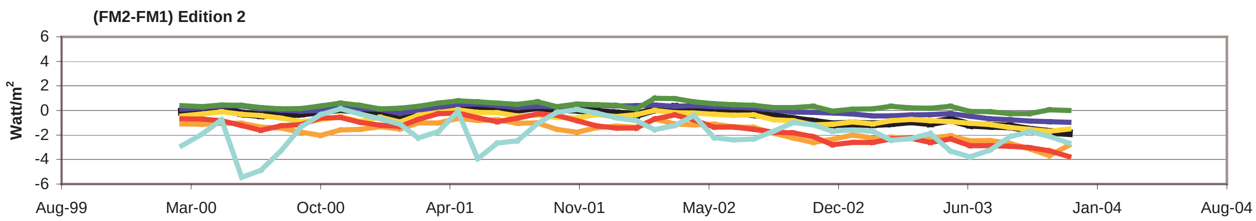

Figure 19: (FM2-FM1), Edition 2 data, difference for daytime shortwave flux over mission life for all sky conditions and various cloud and surface types defined in legend of Figure 17.

4.3.2 Direct Comparison Results for CERES Instruments on Aqua

The direct comparison analysis does not show significant variation between the Aqua CERES instruments with either the Edition 1 or Edition 2 data products. This is a case where both instruments are drifting in their respective measurements at nearly the same rate. The applied time-varying gains and spectral response adjustments were quite similar between the two instruments (figures 13, 14). These corrections removed drifting seen in the three-channel inter-comparison analysis, and not introduce other drifting detected by the direct comparison.

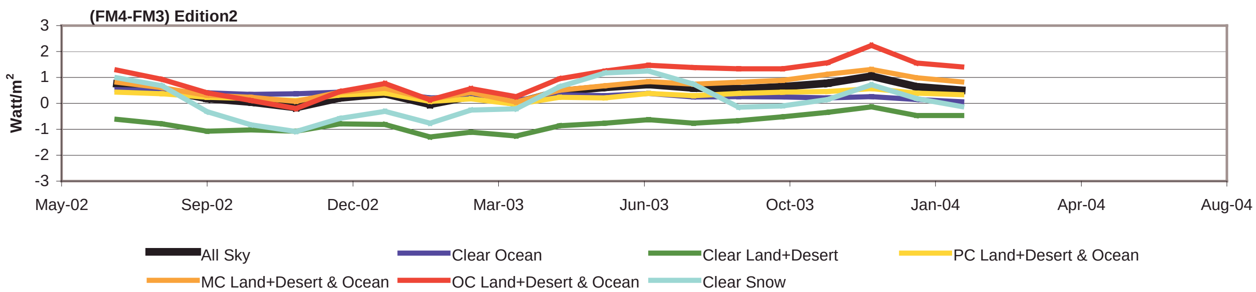

Figure 20: (FM4-FM3), Edition 2 data, difference for daytime longwave flux over mission life for all sky conditions and various cloud and surface types [PC – Partly Cloudy, MC - Mostly Cloudy, OC - Overcast]. Edition 2 data products implement corrections to gains and spectral response functions.

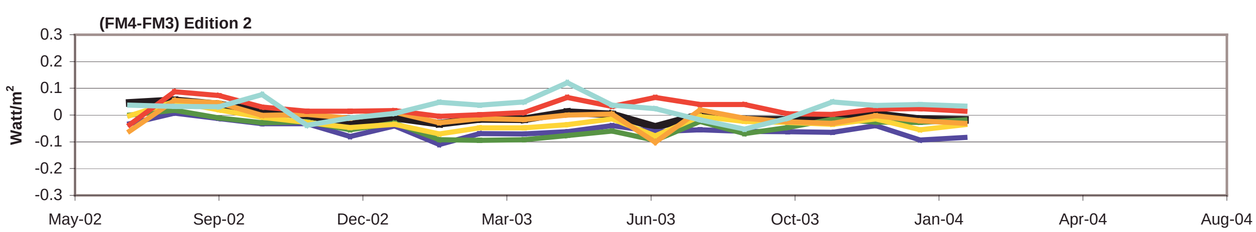

Figure 21: (FM4-FM3), Edition 2 data, difference for nighttime longwave flux over mission life for all sky conditions and various cloud and surface types defined in legend of Figure 20.

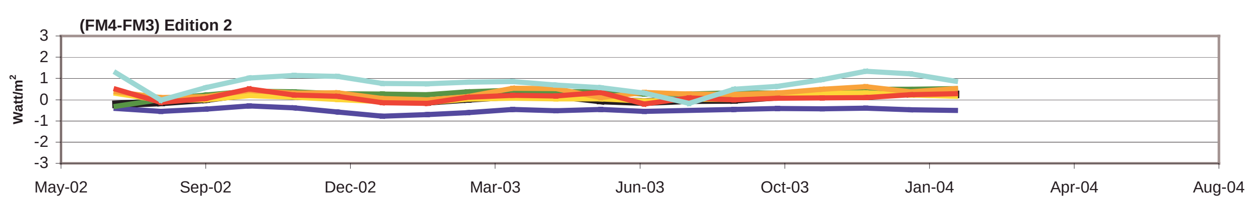

Figure 22: (FM4-FM3), Edition 2 data, difference for daytime shortwave flux over mission life for all sky conditions and various cloud and surface types defined in legend of Figure 20.

5. CONCLUSIONS

Analyses have been developed using ground-based software to aid in monitoring the stability of the CERES instruments' radiance measurements in space. The three-channel inter-comparison is used to detect inconsistencies between the three sensors on one instrument. The direct comparison can detect inconsistencies between coincident measurements between two instruments on the same platform. Implementing these analyses on the CERES instruments on the Terra satellite has shown that the ratio of the shortwave portion of the total channel sensor to the shortwave sensor is increasing with time, especially in the FM2 instrument. The direct comparison shows that the differences between instruments, seen mainly in the daytime longwave values, are increasing with time. The shortwave portion of the total channel sensor is too responsive on the FM2 instrument. Also, the FM1 instrument is under responsive in its shortwave sensor. The analyses applied to the CERES instruments on Aqua indicate that the total and shortwave sensors required a reduction in their gain. In addition, both instruments required spectral response adjustments to the shortwave portion of the total sensor. Both adjustments were nearly equal. Thus, the two instruments were drifting at nearly the same rate and the direct comparison shows similar results both before and after applying time-varying gains and spectral response adjustments. Applying time-varying gains and spectral corrections has removed these drifts from the CERES instruments on both satellite platforms. The drift-corrected CERES Level-1, Edition 2 (BDS, ES-8) data products are available. Additional work needs to be done to isolate the causes of drift in the CERES detectors and more exact methods of removing the drift using ground software.

ACKOWLEDGMENTS

This work was done under NASA contract NAS1-02058. Funding was provided by NASA's Science Mission Directorate.

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