ASSESSMENT OF THE MODIS SCAN MIRROR ON-ORBIT RESPONSE CHANGES

Kevin Twedt,[1] Amit Angal,[1] Tiejun Chang,[1] Xiaoxiong Xiong[2]

[1]Science Systems and Applications Inc., 10210 Greenbelt Rd, Lanham, MD 20706
[2]Sciences and Exploration Directorate, NASA Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

The MODIS instrument on NASA's Terra and Aqua spacecrafts is a multispectral radiometer with a whiskbroom scanning design, using a two-sided scan mirror as the primary Earth-facing optical element. Accurate characterization of the on-orbit changes of both sides of the scan mirror is crucial to the calibration of the Level 1B data products. This paper reviews the performance of the Terra and Aqua MODIS scan mirrors over the missions for both the reflective solar and thermal emissive bands, including degradation in gain and response versus scan angle, and differences between the two mirror sides. Particular attention is given to a recent electronic reset event experienced by Terra MODIS in 2022 that led to changes in the zero-signal bias and gain characterization between the two mirror sides. Calibration algorithm changes were made to mitigate the impact of this event, leading to reduced mirror side striping in the Earth scene imagery.

Index Terms— MODIS, Terra, Aqua, calibration

1. INTRODUCTION

The two MODIS instruments have been providing the Earth science remote sensing community with continuous near-daily Earth imagery for more than two decades. MODIS is a multispectral scanning radiometer that records imagery in 36 spectral channels spanning the visible through thermal infrared: 20 reflective solar bands (RSB) spanning wavelengths from 0.41 μm to 2.2 μm and 16 thermal emissive bands (TEB) spanning wavelengths from 3.7 μm to 14.4 μm [1-2]. MODIS has a whiskbroom scanning design that collects images in successive swaths using a two-sided scan mirror. Radiometric calibration for all bands must be made for each side of the scan mirror separately to ensure that the Earth scene imagery, radiance, reflectance, and brightness temperature products are accurate and free of any artifacts, such as image striping, arising from differences between the two sides of the scan mirror.

In this paper, we review the performance of both sides of the MODIS scan mirror and the impact of mirror side (MS) differences on the calibration algorithms used in NASA's Level 1B (L1B) data products. Differences in on-orbit degradation between the two mirror sides lead to differences in the on-orbit gain and response versus scan angle function (RVS) that impact the calibration. This degradation is tracked and corrected on-orbit using various calibration sources: an on-board solar diffuser (SD) for the RSB, and on-board blackbody (BB) for the TEB, regular observations of the Moon, and pseudo-invariant Earth targets such as Saharan desert sites and deep convective clouds (DCC). Though the reflectivity of the scan mirror has decreased by about a factor of two on-orbit at the shortest wavelengths for both Terra and Aqua MODIS, careful calibration of these changes allows us to keep the mirror side differences in the RSB reflectance and radiance to within a fraction of a percent in most cases.

Additionally, differences in the on-board electronic processing of the signals from the two mirror sides can impact how the calibration needs to be applied. This is most evident in the performance around times of electronic reset events, most of which occurred in the first few years of the missions but have also occurred recently for both Aqua (2018) and Terra (2022). These electronic reset events can cause a reversal of the electronic background signal bias between the readouts of the two mirror sides, termed mirror side correlated noise (MSCN) [3]. In general, the impact is small and only manifests at low signal levels, both in the calibration views and for low radiance Earth scenes. We discuss recent changes made to the calibration of Terra MODIS following a command processor (CP) reset in March 2022. For the RSB, an adjustment is made to the SD calibration to reduce the Earth scene striping for a few select bands. For the TEB, an adjustment is made to the zero-signal offset term in the quadratic calibration equation. A similar mitigation strategy was previously demonstrated to work for Aqua MODIS TEB following a formatter reset in January 2018 [4]. Following these calibration updates, the impact of the 2022 CP reset event on mirror side striping in the L1B products is minimized, as demonstrated by reflectance and brightness temperature trends from typical scenes.

2. SCAN MIRROR REFLECTANCE CHANGES

The scan mirror is the first and primary element in the MODIS optical path shared by all bands. It is exposed directly to the Earth-scattered solar radiation which has led to degradation of its reflectivity over the Terra and Aqua missions, particularly in the visible (VIS) wavelength range. The reflectivity of both sides of the scan mirror was characterized in pre-launch testing, and both sides of the scan mirror have experienced on-orbit degradation that varies with wavelength and with the angle of incidence (AOI) of light off the scan mirror. While there is no way to conclusively determine the absolute change in reflectivity of the scan mirror on orbit, separated from the rest of the optical system, we can partially assess its performance by looking at the overall system gain and how it varies with mirror side and with AOI.

Figure 1 shows the gain changes measured by the solar diffuser and the gain MS ratio, both normalized to mission start, for a few RSB of Terra MODIS. Figure 2 shows the same for Aqua MODIS. For both instruments, the shortest wavelength VIS bands have the largest changes in gain over the mission and have the largest differences in gain between the two mirror sides. It is expected that the large majority of this gain change is due to a decrease in the reflectivity of the scan mirror. For both instruments, the MS gain differences become very small for wavelengths above 0.6 µm.

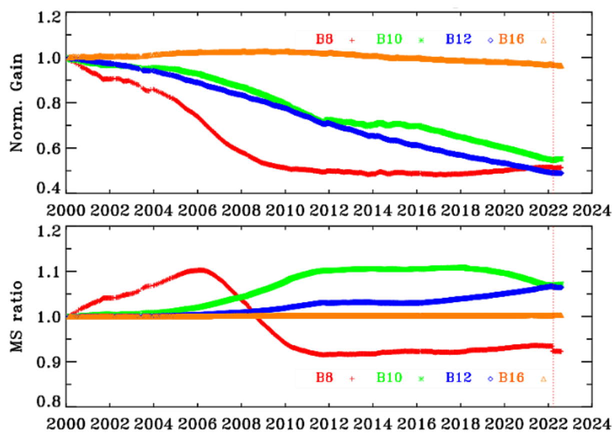

Figure 1. (top) Terra MODIS gain changes over the mission measured by the solar diffuser for MS 1 bands 8 (0.412 µm), 10 (0.488 µm), 12 (0.551 µm), and 16 (0.869 µm). (bottom) Ratio of gain change for MS 1 over MS 2. The vertical dotted line is at the time of the March 2022 CP reset.

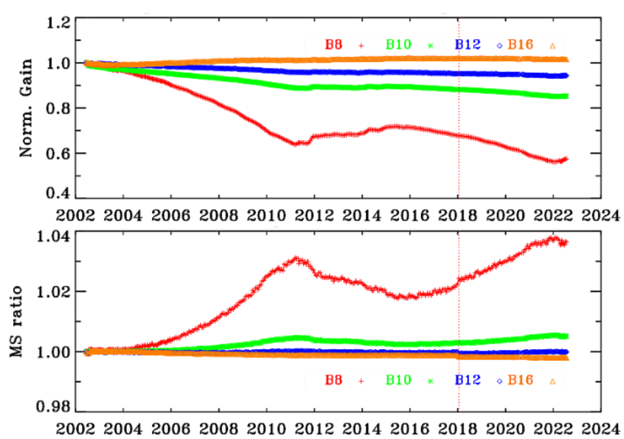

Figure 2. Same as Fig. 1, but for Aqua MODIS. The vertical dotted line is at the time of the January 2018 formatter reset.

For the thermal bands, the changes in gain over the mission and the differences in gain between the two mirror sides are comparatively small and more stable throughout the mission. The reason for the degradation in the reflectivity of the scan mirror is not known but is likely due to exposure of the mirror's surface to Earth-scattered solar radiation. The difference in degradation seen between the two mirror sides for the VIS bands may be due to slight differences in the level of surface contaminants on the mirror surface which were inadvertently introduced either during pre-launch testing, the launch process, or outgas operations performed after launch or after instrument anomalies. For both the RSB and TEB, differences in the performance between the two mirror sides do not pose any inherent problem. The differences are characterized well by the on-board calibrators and the calibration is updated regularly, so the L1B imagery is free of any major mirror side striping artifacts.

An important part of MODIS calibration is having good characterization of the RVS, which comes from the variation in the reflectivity of the scan mirror as a function of AOI. For the RSB, MODIS is capable of tracking changes in the RVS using its on-board calibrators in a limited way, by looking at differences in the gain changes measured from different sources. The SD and the Moon take observations at different AOI, 50.2° and 11.2° respectively. The difference between the two trends is used to derive a linear change in RVS over the missions. For some RSB, this level of characterization is sufficient. However, for some of the VIS bands on both Terra and Aqua, data from pseudo-invariant calibration sites on the Earth are used to track the on-orbit changes in response at multiple angles and better characterize the AOI and time-dependence of the RVS changes [1]. Figure 3 shows the RVS for MS 1 of both Terra and Aqua MODIS at beginning of scan (BOS; AOI of 10.5°) and end of scan (EOS; AOI of 65.5°) at three different times in the mission as a function of band center wavelength. Note the RVS is normalized to one at the SD AOI of 50.2°. Like the results in Fig. 1 and Fig. 2, the RVS change is largest for the shortest wavelength VIS bands and has a clear wavelength dependence. Overall, Terra has larger RVS changes than Aqua. The RVS at TEB wavelengths has been kept constant and not been updated since early mission for Terra and since pre-launch for Aqua. The TEB RVS performance has been assessed on-orbit using data from spacecraft pitch maneuvers and from select Earth scenes, such as open ocean scenes and the Dome Concordia (Dome-C) site in Antarctica, and found to be very stable over time for both MODIS instruments [2].

The scan mirror also has some sensitivity to linear polarization that was measured during pre-launch testing for both MODIS instruments. For Terra MODIS, this polarization sensitivity has changed on-orbit by different amounts for the two mirror sides, which impacts the gain and RVS calibration in the visible wavelength range, as well as the retrieval of Earth scene radiances in a scene-dependent way. For Aqua MODIS, there are no indications of any significant changes in polarization sensitivity over time.

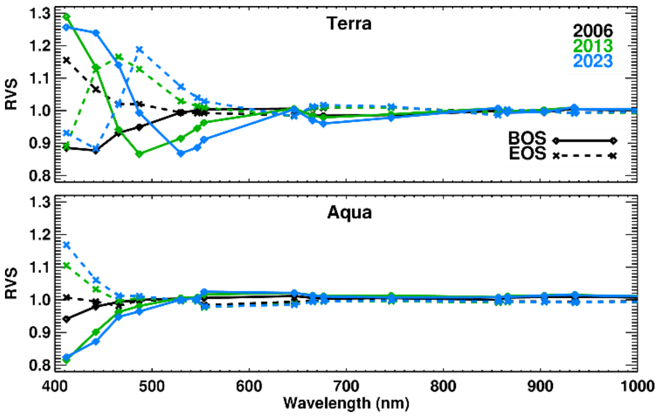

Figure 3. RVS as a function of wavelength at different times in the mission at beginning of scan (BOS) and end of scan (EOS) for (top) Terra MODIS and (bottom) Aqua MODIS.

3. MIRROR SIDE CORRELATED NOISE

A few times during the Terra and Aqua missions, MODIS has experienced a reset of the command processor or formatter electronics that led to changes in the behavior of the on-board electronic readout for one mirror side relative to the other. There were several of these events during the first few years of the Terra mission, and one more recent CP reset event which happened on March 15, 2022. For Aqua MODIS, the most recent such event was a formatter reset on January 4, 2018.

Figure 4 shows examples of the changes in behavior that can happen around these electronic reset events. The baseline digital number (DN) recorded between the two mirror sides is displayed for different calibration data sectors: the SD, the BB, and the deep Space View (SV) port. In principle, the two mirror sides should see the same average signal as each other when viewing any of these three data sectors, but in all cases there is a fraction of a DN difference between the two mirror sides. A similar difference, of varying magnitude, exists for most bands. Around the time of reset events, the DN bias between the two mirror sides reverses direction, as can be seen here for both the January 2018 Aqua reset and the March 2022 Terra reset. The reason for the baseline offset between the two mirror sides and the reversal of this offset around reset events is not precisely known but is believed to be electronic in origin. Since these unexpected biases in the signal levels are less than 1 DN in magnitude, they are negligible for most scenes, which have signal levels of hundreds to a few thousand DN (maximum 12-bit signal of 4096). But the biases can have notable impacts for low radiance scenes that have signal levels of less than 100 DN.

For the TEB, calibration is primarily done using an on-board BB, however, the BB is limited in its ability to assess performance at very low radiance (cold) scenes. Analysis of data from quasi-DCC (qDCC) and Dome-C, both reliably stable and low brightness temperature scenes, show that these electronic reset events have a clear impact on the mirror side performance for several TEB. Since the TEB use a quadratic calibration algorithm, adjustments to the offset term (a_0) can effectively remove the impact.

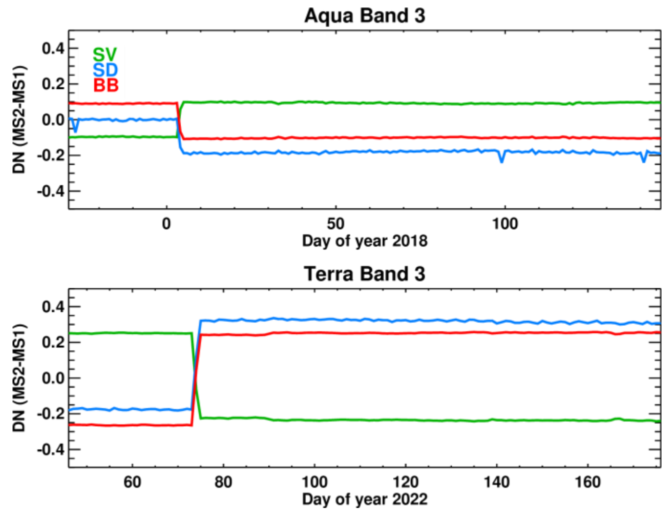

Figure 4. Trends of the MS difference (MS 2 – MS 1) in DN as a function of time for different calibrator sectors of Terra band 3 around (top) Aqua 2018 formatter reset event and (bottom) Terra 2022 CP reset event. Values are averaged over all detectors and many granules per day.

For the several electronic reset events that happened for both Terra and Aqua MODIS early in the mission, the impact of these MS bias flips was primarily seen in the photoconductive TEB detectors in bands 31-36. A recent re-evaluation of the calibration during this period was made in preparation for the Collection 7 (C7) L1B reprocess, and some changes were made to the offset term to reduce the MSCN impact [3]. In contrast, for the January 2018 Aqua event, the impact was mostly on the photovoltaic (PV) TEB detectors. Again, a change to the offset term was made to derive an effective correction for the MS ratio change [4].

For the March 2022 Terra event, both the RSB and PV TEB (bands 20-25 and 27-30) saw some significant impacts. Following the reset, discontinuities in the C6.1 performance were observed in both qDCC trends and in intercomparison of Terra TEB with the Infrared Atmospheric Sounding Interferometer (IASI). Once again, adjustments to the offset coefficients proved effective. For most of the Terra mission, the a_0 values in the look-up tables (LUT) have been set to zero for MS 1 and the a_0 values for MS 2 are defined to be the difference between the a_0 values from the quadratic fit of BB cool-down measurements. After the CP reset, the definitions were reversed: a_0 for MS 2 is now defined to be zero and a_0 for MS 1 is the difference of the measured values for the two mirror sides. A LUT update was made to the Collection 6.1 (C6.1) forward L1B in mid-May 2022. Figure 5 shows the performance of Terra band 20 qDCC brightness temperature trend over the mission. In the plot, there is one point for every calendar month of the mission. Following the March 15, 2022 event, there are three points (March partial month, April full month, and May partial month) which are clearly outside the trend, showing the degraded performance of the calibration prior to the LUT update in May. Since the LUT update, the performance has been restored to the previous trend. Several other TEB were also affected, by varying amounts, but all TEB have had stable performance since the LUT update. In C7, the a_0 update is applied at the time of the anomaly, so the trends will be smooth with no outliers.

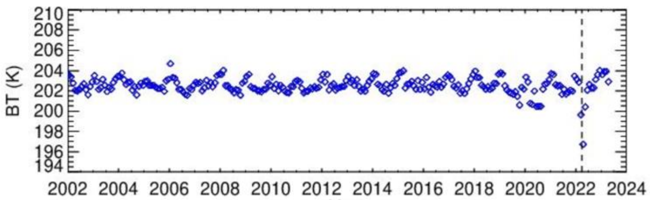

Figure 5. Brightness temperature trend of Terra C6.1 band 20 over quasi-DCC. The vertical dashed line indicates the time of the March 2022 event.

For the RSB, the SD-derived gains show a change in the MS ratio at the time of the CP reset. The bands that show the largest MS ratio jump are the ones with the lowest signal when viewing the SD, where the MS offset switch has the largest impact, for example bands 3 and 4. Unlike the TEB, the RSB calibration uses a simple linear algorithm with no offset term, so the observed SD gain changes are applied equally to all scenes. Without any correction of the SD gain, jumps in the MS reflectance ratio for standard reference desert sites and DCC were observed after the reset, both in C6.1 L1B trends and in reflectance trends using the C7 algorithm. Since the desert and DCC data have relatively high signals, the MS offset switch has negligible direct impact to those scenes, but the shift in the SD-derived gain gets carried through to a shift in the reflectance.

To correct the problem, a constant MS scale factor is applied to the SD calibrated m_1 values after the time of the CP reset to force the MS ratio of the m_1 values to be stable across the reset. The adjusted SD m_1 values are then used in the calibration algorithm to derive the delivered m_1 and RVS LUTs. Figure 6 shows an example trend of the reflectance MS ratio over the Libya 4 site using the C7 algorithm for Terra band 3 at frame 800 of the Earth view data sector. In the top panel, the trend is calculated using the SD-derived m_1 without any MS scaling factor applied and a clear drop of 1% is seen at the time of the CP reset. In the bottom panel, the scaling factor is applied starting at the time of the CP reset and the reflectance MS ratio is restored to a smooth trend.

A MS scaling factor was calculated and applied to bands 3, 4, and 8 in the C6.1 L1B product starting in November 2022. In C7, the scaling factors will be applied to the LUTs from the time of the CP reset. This calibration update should minimize the impact of the CP reset on scenes of typical and high radiance, but changes in MS difference will likely persist for lower radiance scenes. For the SWIR bands, a change in the MS ratio of the crosstalk coefficients is also observed at the time of the CP reset, though it is unclear if this is due to a change in the crosstalk behavior or an artifact of how the MSCN impacts the derivation of crosstalk coefficients. The crosstalk coefficient values have been updated in the LUTs and appear to be performing with the same level of effectiveness as before. The SD m_1 MS scale factor may also need to be extended to the SWIR bands in the future to further improve their performance following this anomaly.

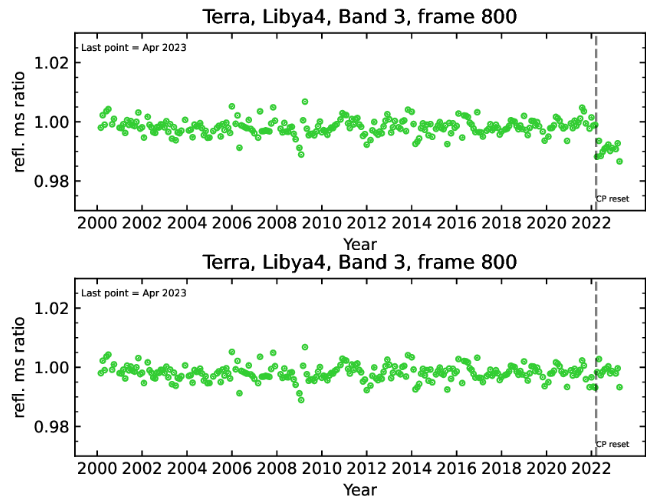

Figure 6. Reflectance MS ratios from the Libya 4 desert for Terra MODIS band 3 frame 800 (top) before and (bottom) after the application of the MS scale factor to the SD data.

Following these TEB and RSB calibration updates, the impact of the 2022 Terra CP reset event on mirror side striping in the L1B products is largely removed. The established framework can also be used for any similar future instrument events.

ACKNOWLEDGEMENTS

We thank other MCST members for their contributions to this work, especially Kevin Vermeesch for his help generating the figures and Brent McBride for a technical review of this text.

REFERENCES

[1] Xiong, X., A. Angal, K. Twedt, H. Chen, D. Link, X. Geng, E. Aldoretta, Q. Mu, "MODIS Reflective Solar Bands On-Orbit Calibration and Performance", IEEE TGRS, vol 57, issue 9, pp 6355-6371, 2019.

[2] Xiong, X., A. Wu, T. Chang, T. Wilson, Y. Li, N. Chen, A. Shrestha, C. Perez Diaz, "On-orbit calibration and performance assessments of Terra and Aqua MODIS thermal emissive bands", J. of Applied Remote Sensing, vol. 15 (1), 2021.

[3] Wu, A., N. Chen, A. Shrestha, and X. Xiong, “Impact of mirror-side correlated noise on radiometric calibration of MODIS thermal emissive bands,” Proc. SPIE 11829, 118291A, 2021.

[4] Chang T., A. Shrestha, C. Perez Diaz, N. Chen, A. Wu, T. Wilson, Y. Li, X. Xiong, "MODIS thermal emissive bands calibration improvements for Collection 7", Proc. SPIE 11858, 118580R, 2021.