Improvements of On-orbit Characterization of Terra MODIS Short-wave Infrared Spectral Bands Out-of-Band Responses

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Abstract. The short-wave infrared (SWIR) bands (5-7, 26) of Terra MODIS, which are co-located with the mid-wave infrared (MWIR) bands (20-25) on the short and mid-wave infrared (SMIR) Focal Plane Assembly (FPA), have a known issue related to 5.3 µm out-of-band (OOB) thermal leak and electronic crosstalk that was identified prelaunch. As a result, a crosstalk correction algorithm was designed and implemented in the MODIS Level 1B (L1B) calibration. Shortly after the Terra launch, extensive efforts were undertaken to help characterize and mitigate the impact due to the OOB response and crosstalk on the SWIR on-orbit calibration and, consequently, the associated L1B data products. In addition, special night time day mode (NTDM) operations have been regularly scheduled to derive the crosstalk correction coefficients. Since MODIS does not have a spectral band centered at 5.3 µm, its band 28 (7.325 µm) was chosen as the surrogate sending band to simulate the OOB radiances at 5.3 µm. This was largely based on the measurements from the MODIS Airborne Simulator (MAS) spectrometer field campaigns in the early months after the Terra launch. In the case of Aqua MODIS, the magnitude of the SWIR crosstalk was much smaller and band 25 (4.52 µm) was found to be more effective as the sending band for the crosstalk correction. In recent years, the Terra MODIS photovoltaic (PV) long-wave infrared (LWIR) bands (27-30) electronic crosstalk has increased considerably, especially after the spacecraft safe-mode event occurred in February 2016. This accentuated degradation in the PV LWIR performance has also impacted the performance of the SWIR crosstalk correction and thus its calibration and data quality. In this paper, we examine the use of band 25 as the sending band for the Terra MODIS SWIR crosstalk correction and compare its performance with that based on band 28 as the sending band. Results indicate an improvement of on-orbit gain stability for the SWIR calibration and reduced detector to detector and sub-frame to sub-frame striping in the calibrated L1B imagery, especially during the period when the PV LWIR electronic crosstalk has become more severe. This approach has been implemented in the forward production of Terra MODIS Collection 6 and Collection 6.1, starting from July 2019, and is planned to be used for the future reprocessing of MODIS L1B and to help improve the mission-long reflectance calibration and trending stability of the SWIR bands.

Keywords: MODIS, Terra, Aqua, MODIS, SWIR, calibration, out-of-band response, crosstalk correction

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1 Introduction

The MODIS instruments onboard the Terra and Aqua spacecraft have been collectively operating for nearly 40 years, providing frequent global measurements of the Earth's system and producing a broad range of data products that have greatly benefitted the remote sensing community and users worldwide.[1-3] MODIS observations are made in 36 spectral bands. The reflective portion of the spectrum is measured via 20 reflective solar bands (RSB), covering wavelengths from 0.4 to 2.2 µm. The remaining 16 bands, with wavelengths ranging from 3.75 to 14.4 µm, are the thermal emissive bands (TEB).[4] The four short-wave infrared (SWIR) bands (5-7 and 26) covering wavelengths from 1.1 to 2.2 μm are the focus of this paper. These bands are used in deriving a number of atmospheric products that include aerosol optical thickness, atmospheric total column water vapor, cloud fraction and cloud optical depth.[5] Both Terra and Aqua MODIS instruments underwent comprehensive prelaunch characterization performed by the instrument vendor, Raytheon Santa Barbara Remote Sensing. During this process, a large out-of-band (OOB) thermal leak (or response) was found in the Terra SWIR bands. Illustrated in Figure 1 are the in-band (IB) and out-of-band (OOB) combined relative spectral responses (RSR) for Terra MODIS bands 5 and 6, showing the OOB responses (or thermal leaks) were largely peaked at 5.3 μm. Although extensive efforts were made to mitigate the impact prior to the instrument launch, noticeable effects remained and were observed in the on-board calibrator (OBC) measurements and the Earth-view imagery. Similar but much smaller effects were also seen in the Aqua MODIS SWIR bands. Because of this, a correction algorithm was developed and applied to both Terra and Aqua MODIS Level 1B (L1B) calibration.[6-8]

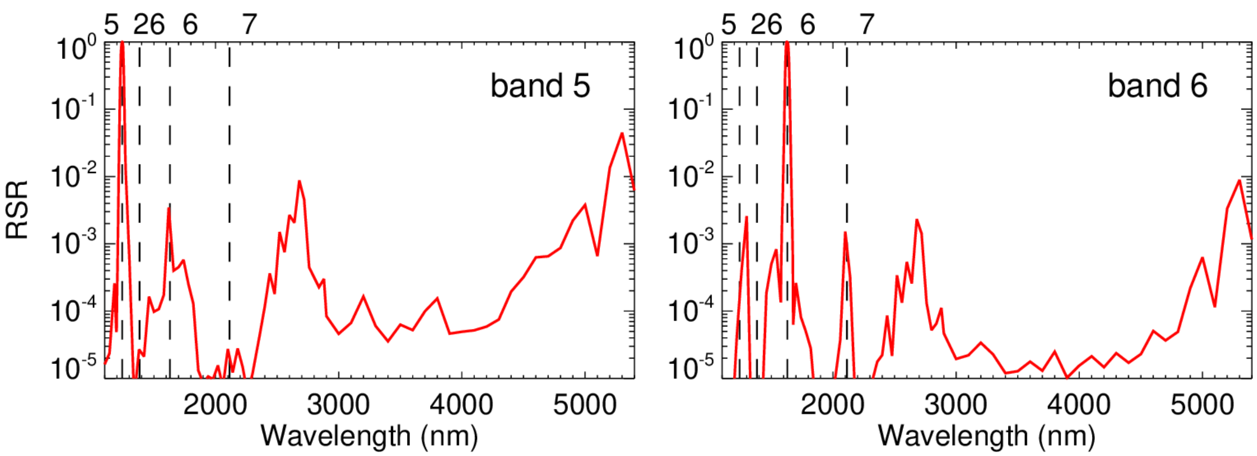


Fig. 1 Relative spectral responses of Terra MODIS bands 5 and 6.

As illustrated in Figure 2, the SWIR bands (5-7, 26) and mid-wave infrared (MWIR) bands (20-25) are located on the same short- and mid-wave infrared (SMIR) focal plane assembly (FPA).

The SWIR OOB responses, mostly peaked at 5.3 µm, are also coupled with more complicated electronic crosstalk from the bands on the same FPA. In an attempt to isolate and characterize the contribution of the OOB thermal leak and the electronic crosstalk from MWIR to the SWIR band signals, special night time day mode (NTDM) operations, which allow the instrument to collect the Earth scene RSB data during spacecraft night time, have been regularly scheduled throughout the missions. Since there are no reflected solar signals during spacecraft nighttime, the responses of SWIR bands are assumed to be caused entirely by the combination of OOB thermal leak (or optical crosstalk) and electronic crosstalk from MWIR bands.

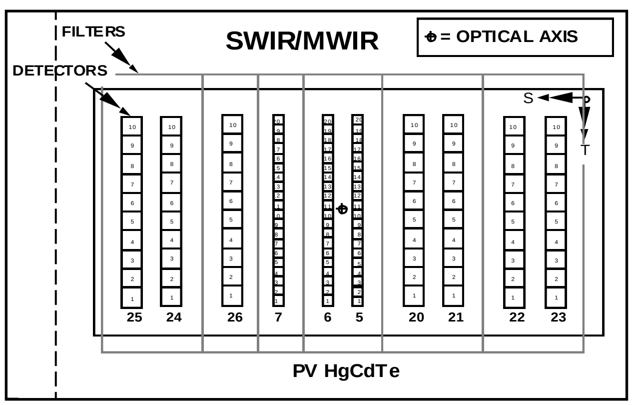


Fig. 2 MODIS short-wave/mid-wave infrared focal plane assembly.

Since MODIS does not have a spectral band centered at 5.3 µm, measurements from the MODIS Airborne Simulator (MAS) spectrometer field campaigns in the early months after the Terra launch were used to help identify band 28 (7.325 µm) as the best surrogate to simulate the radiances at 5.3 µm and thus provide a reference for the OOB contribution to the SWIR band radiances. The electronic crosstalk phenomenon involves multiple bands inducing crosstalk signals into the SWIR bands during the on-board analog signal readout. Analysis of lunar images could provide a partial characterization of this crosstalk, but implementation of a precise correction algorithm is complicated.[9] As the OOB and electronic crosstalk effects are difficult to separate, the band 28 signals are used as a reference to simulate the approximate impact of both effects. In the case of Aqua MODIS with smaller OOB and crosstalk effects, band 25 (4.52 μm) was found to be more effective based on the Earth view observations as the sending band for its SWIR OOB/crosstalk correction.[8] Correction coefficients that combine the impact of the OOB leak and electronic crosstalk effects are derived from the NTDM calibrations using a simple linear algorithm to fit the receiving detector responses (bands 5-7, 26) as a function of the reference or sending detector responses (band 28 for Terra and band 25 for Aqua) over the observed earth scene radiances. Throughout this paper, the language of crosstalk (e.g. crosstalk correction coefficients, sending band, and receiving band) is used with the understanding that both OOB leak and electronic crosstalk impacts are addressed together.

As the mission continues, some detectors' responses of the Terra photovoltaic (PV) long-wave infrared (LWIR) bands, including band 28, have been severely contaminated by the on-orbit changes of the electronic crosstalk characteristics of the LWIR FPA characteristics.[10,11] The impact of electronic crosstalk was significantly increased after the instrument reset caused by a spacecraft safe hold event in February 2016. As an effort to restore the PV LWIR detector responses, a lunar-based correction algorithm was formulated to mitigate the impact due to increased electronic crosstalk in the PV LWIR bands and implemented in the Terra MODIS Collection 6.1 (C6.1) L1B.[11] Meanwhile, on-orbit changes in Terra MODIS band 28 crosstalk characteristics, varying from detector to detector, have also imposed additional impact on the efficacy of the SWIR crosstalk correction, which uses the uncorrected band 28 responses as the sending signals. Even with the restored band 28 detector responses, noticeable residual effects, especially after the

February 2016 safe mode event, still exist in the SWIR crosstalk corrected signals of both solar diffuser and Earth view (EV) observations.

In this paper, we propose the use of band 25 as the crosstalk correction sending band for the Terra MODIS SWIR bands and evaluate its performance by comparing with that based on the use of band 28 as the sending band. To certain extent, the proposed change is made based on the fact that the band 25 on-orbit performance has been very stable for Terra MODIS and that its use as the sending band for Aqua SWIR crosstalk correction has been demonstrated to be very effective. This paper extends our previous studies with new updates and enhancements.[12] Results from this study show significant improvements of on-orbit gain stability for the SWIR bands and reduced detector to detector and sub-frame to sub-frame striping in the calibrated L1B imagery, especially after the PV LWIR electronic crosstalk became more severe. Starting from July 2019, the proposed approach has been implemented in the forward production of Terra MODIS Collection 6 and Collection 6.1. To help improve the mission-long reflectance calibration and trending stability of the SWIR bands, this approach will be used in the next reprocessing of all Terra MODIS L1B data products. In Section 2 of this paper, a brief review of the MODIS RSB baseline calibration algorithm is provided with more details focused on the SWIR crosstalk correction algorithm, its initial implementation strategy, and the newly proposed changes. On-orbit performance assessments and results of SWIR crosstalk correction are presented in Section 3. Section 4 discusses other issues related to the change of the crosstalk sending band from band 28 to band 25, as well as the L1B implementation strategy. Finally, a short summary is given in Section 5.

2 On-orbit Calibration Algorithms

2.1 RSB Calibration Algorithm

The MODIS RSB calibration is reflectance-based using its on-board solar diffuser (SD). The SD bi-directional reflectance factor (BRF) was characterized pre-launch by the instrument vendor with traceability tied to the National Institute of Standards and Technology (NIST) standard reference. On-orbit changes of the SD BRF are tracked on a regular basis by a solar diffuser stability monitor (SDSM). The design requirement for MODIS RSB calibration is 2% in reflectance at the specified typical scene radiance of each spectral band and for observations made at scan angles within ±45° relative to instrument nadir. For measurements made at other radiance levels between 0.3 times typical radiance and 0.9 times maximum radiance, an additional 1% uncertainty is added to the requirement specified at typical scene radiance levels.[12]

The calibration is performed for each spectral band, detector, sub-frame, and mirror side. MODIS bands 1-2 are the 250 m resolution bands with each having 40 detectors and bands 3-7 are the 500 m resolution bands with each having 20 detectors. Other MODIS spectral bands make observations at 1 km resolution (nadir) and each has 10 detectors. For each data sample of the 1 km resolution band (detector), there are 16 data samples from the 250 m resolution bands 1-2, which corresponds to measurements by 4 detectors (track direction) and 4 sub-frames (scan direction). Similarly, each data sample of the 1 km resolution band (detector) corresponds to 4 data samples (2 detectors and 2 sub-frames) of the 500 m resolution bands 3-7.

For the RSB, the reflectance calibration coefficient, m_1, is determined from the SD measurement using

$$\boldsymbol{m_1} = \frac{\rho_{SD} \cdot \Delta_{SD} \cdot \boldsymbol{cos(\theta_{SD})}}{\boldsymbol{dn^*_{SD}} \cdot \boldsymbol{d^2_{ES(SD)}}} \cdot \boldsymbol{\Gamma_{SDS}} \tag{1}$$

where ρ_{SD} is SD BRF from pre-launch measurements, Δ_{SD} is SD on-orbit degradation derived from the SDSM, θ_{SD} is the solar zenith angle of the SD view, $\boldsymbol{dn^*_{SD}}$ is the detector response to the SD with corrections applied for the instrument background, temperature, and angle of incidence (AOI), $d_{ES(SD)}$ is the Earth-sun distance in AU at the time of the SD calibration, and Γ_{SDS} is the SD attenuation screen transmission function. For calibration without the SD screen, $\Gamma_{SDS} = 1$. The L1B EV reflectance factor, $\boldsymbol{\rho_{EV}} \cdot \boldsymbol{cos(\theta_{EV})}$, is computed using

$$\rho_{EV} \cdot \boldsymbol{cos}(\theta_{EV}) = \boldsymbol{m_1} \cdot dn^*_{EV} \cdot d^2_{ES(EV)} \tag{2}$$

where $\boldsymbol{dn^*_{EV}}$ is the detector EV response with the same corrections applied as are applied to the SD response and $d_{ES(EV)}$ is the Earth-sun distance in AU at the time of the EV measurement. Details of the MODIS RSB on-orbit calibration algorithm can be found in a number of references.[14-16]

MODIS also performs regular lunar observations through its space view port. Similar equations with corrections for the geometric factors, such as lunar phase and libration angles, sun-moon distance, and moon-sensor distance, can be used to compute and monitor the detector gains. MODIS lunar calibration is referenced to the ROLO model.[17,18] The SD and lunar gains, coupled with detectors' response trends over select pseudo invariant calibration sites (PICS), are used to generate RSB calibration coefficients, including view angle dependent corrections, that are updated via time-dependent Look-up-tables (LUT).[16,19]

2.2 Correction for SWIR Bands OOB Responses

For the SWIR bands, a crosstalk correction algorithm is applied to the signals used for SD calibration as well as the EV reflectance retrieval.[8] As mentioned earlier, measurements from the MAS spectrometer were used to help identify the sending band to simulate the SWIR OOB radiances. The MAS spectrometer was initially developed for the NASA's high-altitude ER-2 research aircraft in support of the MODIS algorithm development. It acquires high spatial resolution imagery in the spectral region from 0.55 to 14.3 μm using 50 spectral bands (or channels). The data acquired from MAS was used to validate and refine many of the MODIS algorithms developed to retrieve geophysical properties. Based on the measurements from the MAS spectrometer, a strong linear correlation was observed between the radiance of the MAS band 40 (5.28 μm) and MODIS band 28 (7.32 μm). The correlation exists because the 7.32 μm and the 5.28 μm bands sample the same properties of the atmosphere. The behavior of the radiance of MAS band 40 as a function of other MODIS bands was also examined and found to be less correlated. Based on these findings, MODIS Characterization Support Team (MCST) decided to use band 28 (7.32 μm) as the surrogate/sending band to simulate the SWIR OOB response. This was further corroborated by evaluating the correlation between each SWIR band and other TEB on the SMIR focal plane.[20]

For Aqua MODIS, the effect due to SWIR OOB response and crosstalk is much smaller than for Terra MODIS. In addition to pre-launch characterization, an extensive assessment of Aqua MODIS SWIR OOB response and electronic crosstalk was performed shortly after launch using different scenes under various conditions. The correlation between the SWIR OOB response and each of the MWIR and LWIR bands was carefully evaluated. Unlike Terra MODIS, it was observed that the best surrogate band for Aqua MODIS appeared to be band 25 and hence it was chosen as the sending band for the OOB/crosstalk correction in Aqua MODIS SWIR calibration and EV retrieval.

On a semi-annual basis, the NTDM data is used to derive crosstalk correction coefficients between the sending band (band 28 or 25) and each of the SWIR bands. A simple linear algorithm is used to fit the data between the sending detector dn and the receiving detector dn (bands 5-7, 26) over the observed earth scene radiances. The response from each sending detector (1 km nadir resolution) is correlated with both sub-frames of the two corresponding detectors of the SWIR bands (0.5 km nadir resolution). In the case of band 26, a simple one-to-one detector mapping is used. The sending band approach is an approximation of the electronic crosstalk effect since the actual bands that send crosstalk are varied and depend on the receiving band. The linear slope is referred to as the effective crosstalk correction coefficient and is derived for each band, detector, sub-frame, and mirror side. The linear correction algorithm is implemented in the MODIS L1B products based on the sending band *dn*, $dn_{sending}$, and the crosstalk coefficient, *x_oob_1*, and can be expressed as,

$$dn_{SWIR-corr} = dn_{SWIR} - x\_oob\_1 \cdot dn_{sending} \quad (3)$$

where dn_{SWIR} and $dn_{SWIR\text{-}corr}$ are the SWIR detector response before and after the crosstalk correction, respectively. The same correction is applied to both the SD calibration and the EV reflectance retrieval.

Electronic crosstalk is also a known issue for the Terra MODIS TEB LWIR PV bands 27-30. The electronic crosstalk phenomenon, identified prelaunch, has increased in magnitude over the course of the Terra mission. This has resulted in detector-detector striping as well as the appearance of ghosts in the earth scene images of these bands.[10-11] The signal contamination for some of the LWIR PV detectors became extremely severe right after the Terra spacecraft safe-hold anomaly that occurred on February 18, 2016, and also put the MODIS instrument in safe mode. Because of this, a correction algorithm using correction coefficients derived from lunar observations has been formulated and implemented in the Collection 6.1 L1B. This has led to significant improvement of L1B radiometric quality for the PV LWIR bands. In addition, the response of several detectors has also been restored because of the crosstalk correction.[11]

Initially, Terra MODIS SWIR correction uses the raw dn (signal) of band 28. As the band 28 crosstalk contamination increases, the uncorrected sending band signal manifests in noticeable sudden gain jumps in the SWIR calibration coefficients and therefore a degraded performance of the SWIR bands' calibration as well as their EV imagery. To keep using Terra MODIS band 28 as the sending band, a correction to its signals would need to be applied to the NTDM data before computing the SWIR crosstalk correction coefficients. This correction would also need to be incorporated in the computation of the SD-based gains as well as in the retrieval of EV scene reflectance or radiance. As the instrument ages, the Terra LWIR electronic crosstalk is expected to continue to change, and likely worsen, which will limit the effectiveness of using band 28 as the sending band in the SWIR correction algorithm, even with PV LWIR crosstalk correction applied. This paper evaluates the use of band 25 as the sending band for the Terra MODIS SWIR crosstalk correction and compares its performance with that based on the use of band 28 as the sending band.

3 Results and Discussions

3.1 Crosstalk Correction Coefficients from NTDM Observations

With the exception of more frequent data collects made at the mission beginning, the NTDM operations have been scheduled on a semi-annual basis over the entire Terra MODIS mission. The *x_oob_1* coefficients with band 25 as the sending band are derived from these measurements using the same algorithm used to derive coefficients with band 28 as the sending band. Figure 3 shows an example of the NTDM results from a collect on day 333 of the year 2006, showing the nighttime responses of bands 5-7 (center-detector) as a function of the sending band responses from band 25. In the case of SF 1, the correction coefficients for band 5 and band 7 are positive whereas that for band 6 are seen to be negative. This is a known behavior attributed to the sequence of clocking of the sub-frames of bands 5-7 (SF 1 is clocked first in the case of bands 5 and 7, SF 2 is clocked first for band 6). For SF 2, the correction coefficients for band 5 and band 7 are negative and band 6 has positive correction coefficients. The negative correlation in SF 2 is a strong indicator of electronic crosstalk whereas the other SF are expected to be dominated by the OOB leak effect.

Figure 4 shows the time series of the OOB crosstalk coefficients, x_oob_1 of Terra MODIS bands 5-7, derived from the NTDM data with band 25 as the sending band. Although the coefficients are derived on a band, detector, sub-frame, and mirror side basis, only the results for the center detector (SF 1 in black and SF 2 in blue) are shown. Before January 1, 2004, fluctuations associated with various changes in instrument configuration (electronic side, formatter side) can be seen with varying impacts across all bands and detectors. Because of this, time-dependent crosstalk correction coefficients are derived and used to compute the mission-long detector gains (m_1) for the SWIR bands from the regular SD measurements. As seen in Figure 4, the x_oob_1 values do not exhibit any temporal dependence in the first four years of the mission after which a gradual downward trend is observed. A simple linear fit is used to model the time-dependence of the x_oob_1 coefficients after January 1, 2004, also shown in Figure 4, and the fitted values are used when applying the crosstalk correction to the SD and EV data in this time period. With band 28 as the sending band, the crosstalk correction coefficients have more changes over the entire mission, varying from detector to detector, as a result from on-orbit changes of band 28 detector crosstalk characteristics, which has made Terra MODIS SWIR crosstalk characterization and correction more challenging.

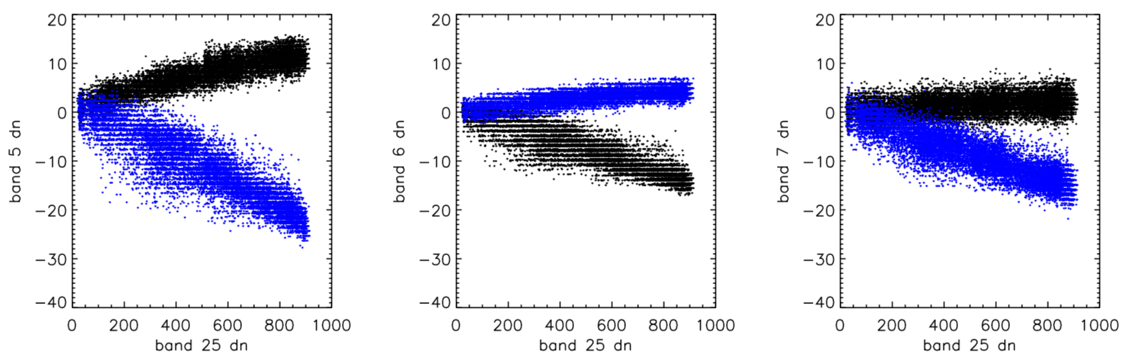


Fig. 3 Examples of Terra MODIS bands 5, 6, and 7 nighttime responses (subframe 1 in black and subframe 2 in blue) versus band 25 responses. Data collected from the NTDM event from day 333 of the year 2006. The responses for the center detector are plotted.

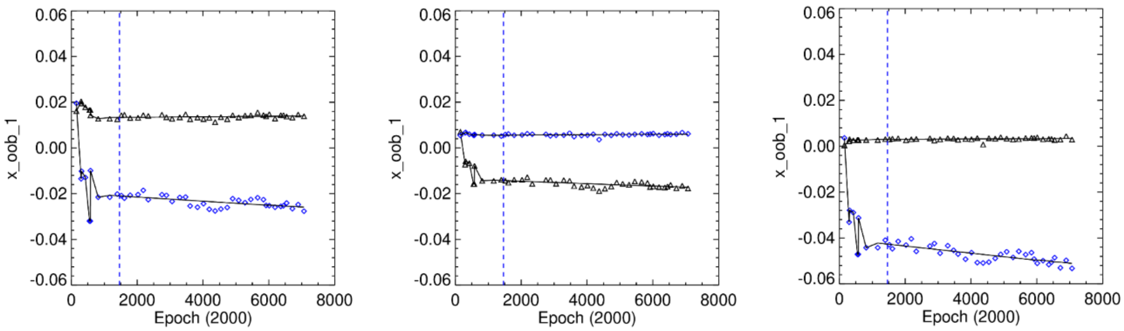
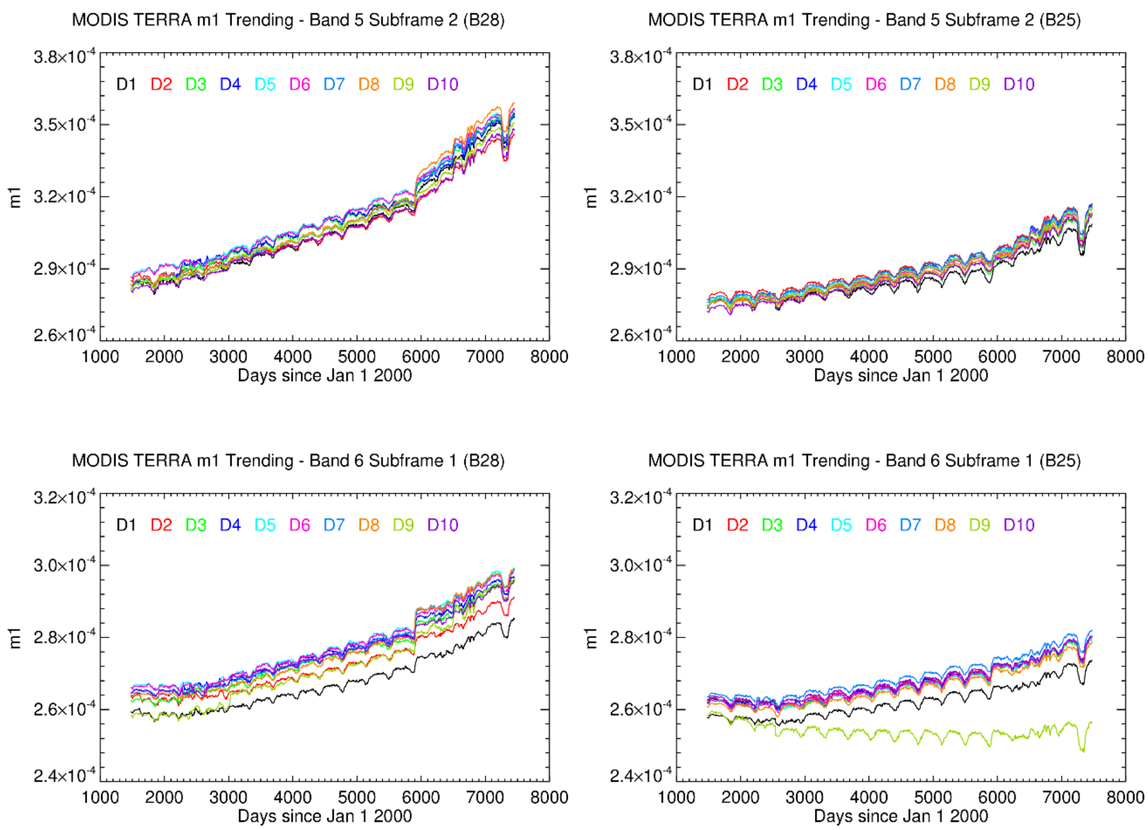


Fig. 4 Crosstalk correction coefficients of Terra MODIS bands 5-7 (center detector) derived from the NTDM events with band 25 as the sending band. Black symbols and blue symbols represent the measured values from each NTDM collect for sub-frame 1 and sub-frame 2 respectively. Lines are fits to the measured data (see text).

3.2 Calibration Coefficients from SD Observations

Using band 25 as the sending band and its corresponding crosstalk correction coefficients, the SD calibration data sets were reprocessed to produce a set of new calibration gains, which are inversely proportional to the calibration coefficients (m_1), for the SWIR bands. Figure 5 shows the mirror side 1 m_1 trending for the Terra MODIS SWIR bands 5-7 (first 10 detectors, sub-frame 1 for band 6, and sub-frame 2 for bands 5 and 7) with their crosstalk corrections applied using sending band 28 (left panel) and sending band 25 (right panel). A clear discontinuity in the m_1 trending is observed for most detectors in the plots in the left panel right after the Terra spacecraft safe mode in February 2016. This is largely caused by the change of band 28 crosstalk behavior. The magnitude of this discontinuity among the SWIR detectors varies from about 0.5% to 3%. In contrast, the plots in the right panel, with band 25 as the sending band, show a much smaller magnitude gain change around the safe mode event. The mirror side 2 m_1 trending has the same behavior as the mirror side 1. It should be pointed out that the magnitude of this discontinuity among the SWIR detectors is somewhat smaller for sub-frame 1 of bands 5 and 7 and sub-frame 2 of band 6. In the early mission of Terra MODIS, several gain adjustments were performed to the SWIR bands in order to minimize the observed crosstalk effects. Furthermore, the SD door experienced an anomaly in July 2nd 2003 (day 1279 from the Figure 5) after which the SD calibrations are performed with the SD screen in a down position. Hence for illustrative purposes, only the data after July 2nd 2003 are shown in Figure 5. Note that detector 9 of band 6 has an out-of-family gain trend in the B25 case, but this detector does not appear significantly out-of-family in the reflectance products, as shown in the next section.



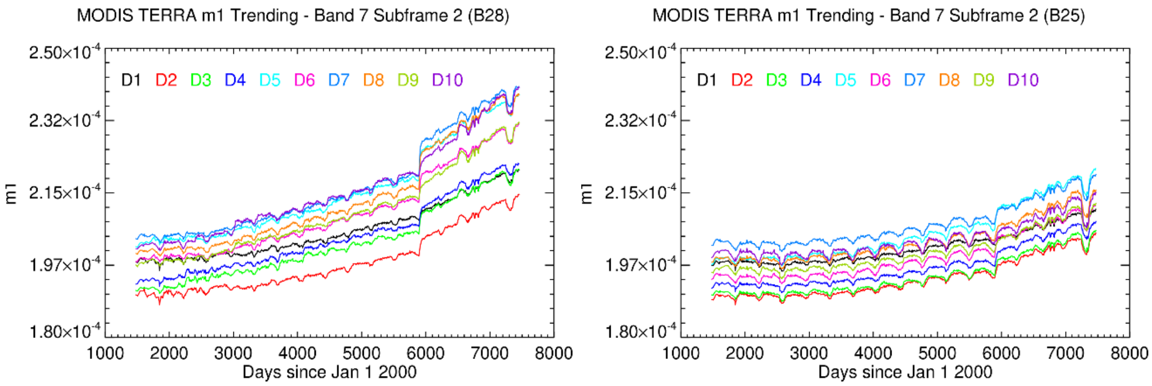


Fig. 5 Calibration coefficients (m_1) of Terra MODIS bands 5-7 (mirror side 1; first 10 detectors; sub-frame 1 for band 6; sub-frame 2 for bands 5 and 7) using band 28 (left) and band 25 (right) as the sending band.

3.3 L1B Impact Assessments

The band 25-based NTDM coefficients and SD calibration gains are used to evaluate the impacts on the L1B products. Several different granules covering Terra's operational timeline were processed and used to evaluate the performance. The results from two specific granules are shown here as examples. Two North African desert granules, one before (2010121.0640) and one after (2019131.0910) the 2016 safe mode are chosen, and per-detector histograms, binned by radiance, for each of these scenes are plotted. The left panels of Figures 6 and 7 show the results from C6.1 using band 28-based SWIR correction and right panels shows the results using the new band 25-based approach. The detectors are denoted by different colors and no separation for mirror sides or sub-frames is shown here. In the case of the 2010 granule (Figure 6), the difference between the left panel and right panel histograms, in terms of separation between detectors, is very small. A marginal improvement is seen in band 6, where detector 1 (in black), which is seen out of trend with other detectors with band 28 as the sending band, comes in-family with band 25 used as the sending band. As band 26 is a cirrus detection band, the histogram is clustered at a low radiance value that can be attributed to lack of cirrus features in the chosen scene. Overall, this is an expected behavior as the PV LWIR crosstalk impacts on the sending band 28 are known to be less before the February 2016 safe mode event.

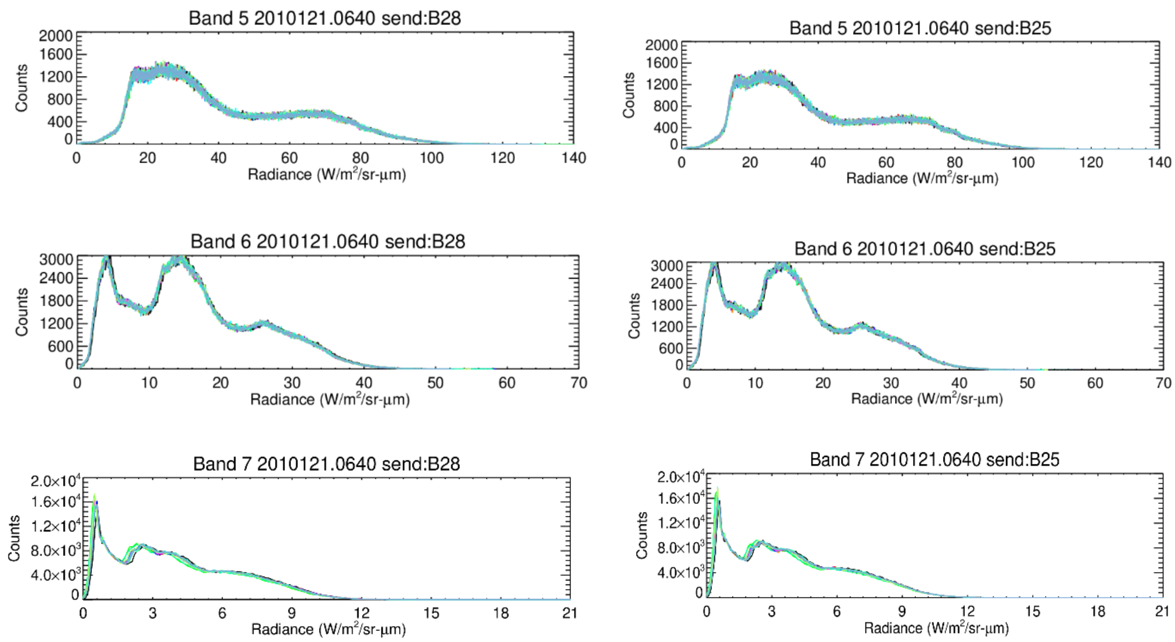


Fig. 6 EV radiance histograms using band 28-based (left panel) and band 25-based (right panel) approach for 2010121.0640 granule.

In the case of the 2019 granule (Figure 7), a clear separation between the per-detector histograms is observed in the left-panel plots. In contrast, the right panel plots show improvement in terms of the divergence of the per-detector histograms. Several post-safe mode granules were examined to confirm a similar improvement. The improvement in the per-detector histograms translates into a reduced detector-detector striping in the calibrated L1B products. Two detectors in band 5 (light blue and light green colors) continue to be out of trend in both cases and correspond to the two detectors 3 and 5 that have shown out-of-family behavior recently and have been flagged accordingly in the L1B quality assurance (QA) LUT.

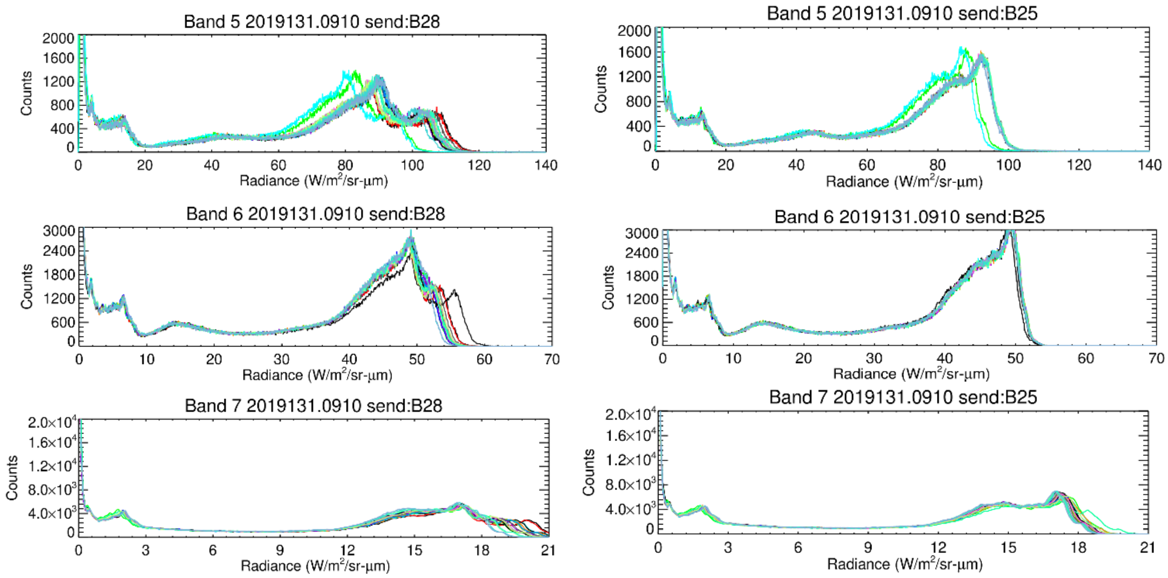


Fig. 7 EV radiance histograms using band 28-based (left panel) and band 25-based (right panel) approach for 2019131.0910 granule.

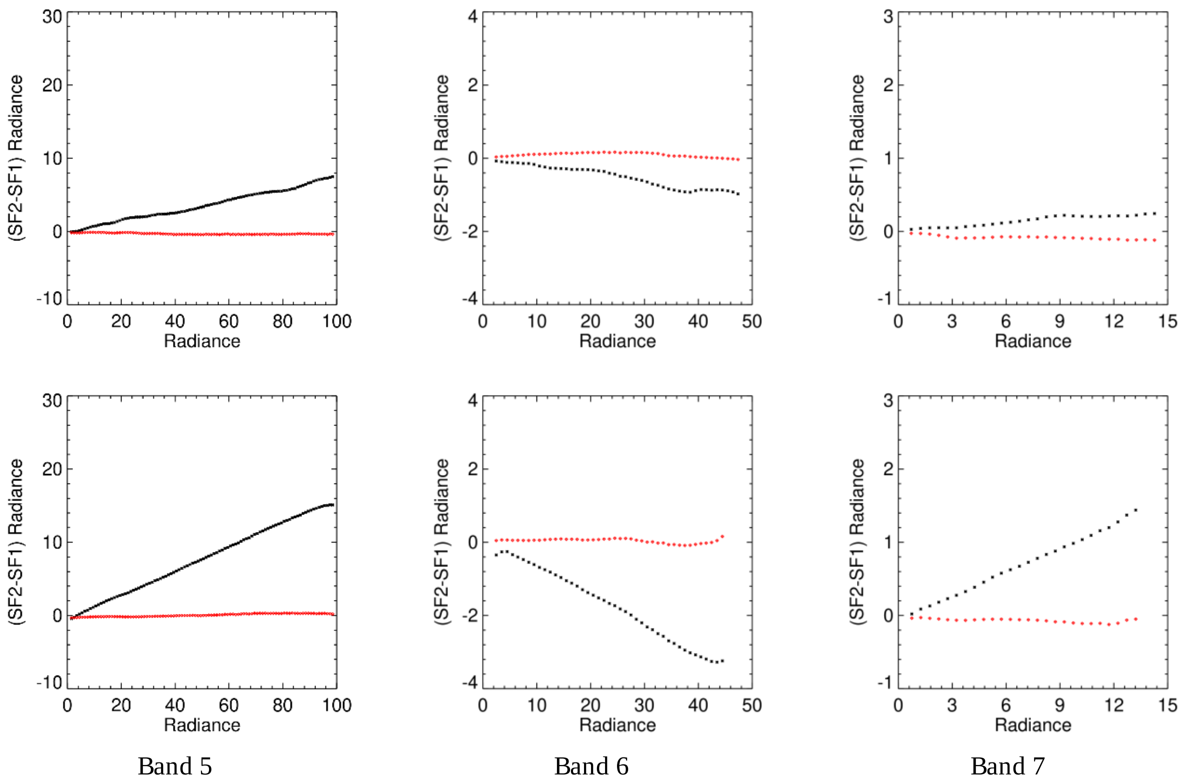
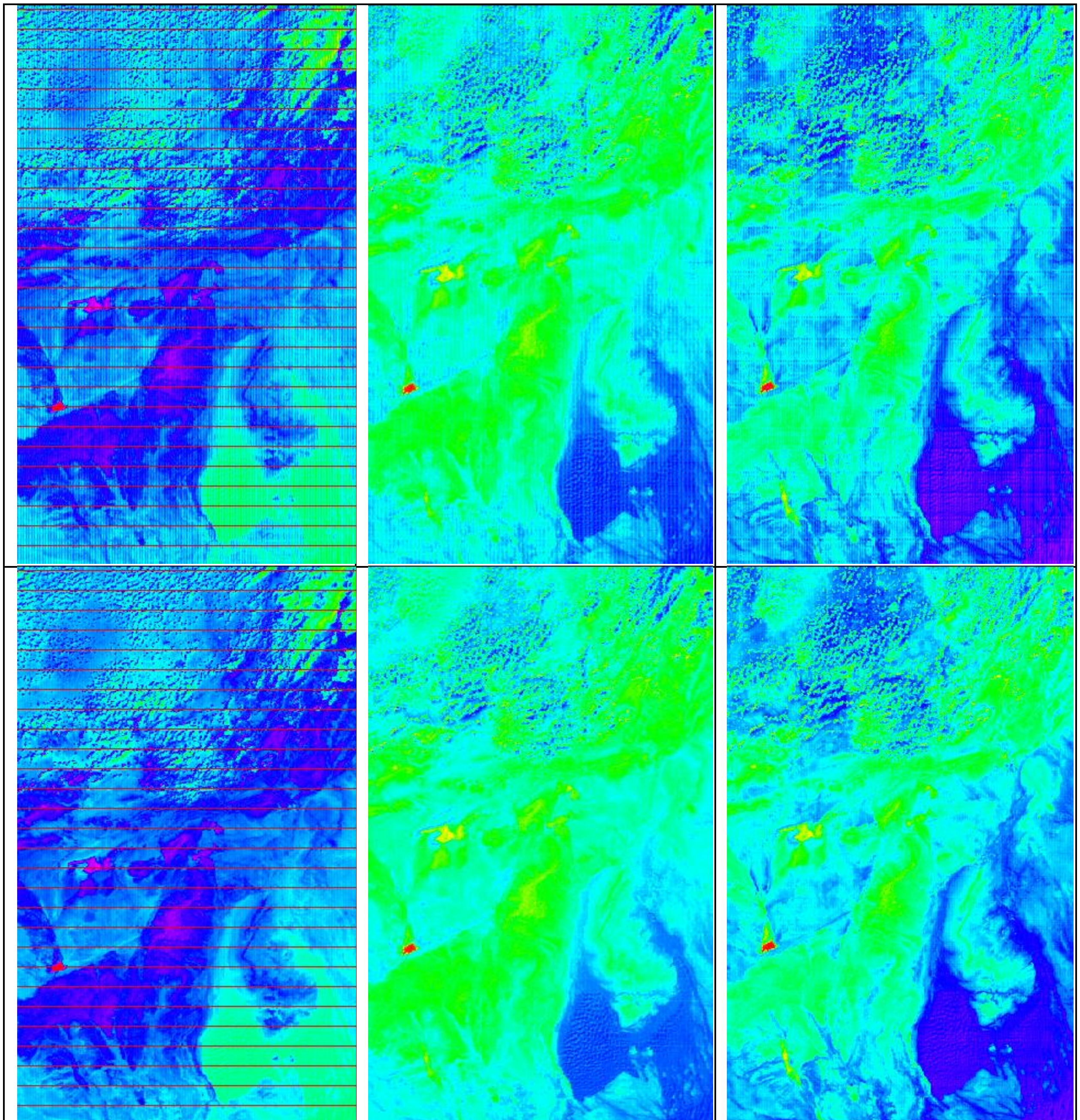


Fig. 8 Radiance difference between the two sub-frames (band-averaged) as a function of radiance for sets of granules over 1-orbit from two different years in the mission: 2010 (top) and 2019 (bottom). The red color is for band-25 based SF difference and black is for band-28 based (C6.1) difference. The differences are binned as a function of radiance. The radiance has units of W/(m^2-Sr-μm).

During the prelaunch characterization using the ground blackbody calibration source (BCS), significant SF differences were observed at temperatures greater than 350 K. SF 1 showed a positive response and SF 2 showed negative responses confirming the presence of an electronic crosstalk in these bands. In addition to band, detector, and mirror side, the SWIR crosstalk coefficients as well as the RSB gain coefficients are SF dependent. Therefore, any inadequacy in the coefficients for an individual SF will result in SF striping in the calibrated radiance products.

To evaluate the sub-frame differences in the calibrated L1B product, an orbit of test data was used to produce a band-25 based L1B to compare it with the current C6.1 L1B. Two orbits, one from mid-mission (2010) and one from late mission (2019), were chosen for this evaluation. The binned sub-frame difference was plotted as a function of C6.1 L1B radiance from both data-sets for bands 5-7 and is shown in Figure 8. In both 2010 and 2019, the band 25 based SF difference is near zero and represents a significant improvement over the C6.1 product. It is also observed that the divergence between the SF differences between the two versions has increased noticeably in 2019 as compared to the 2010 data-set. This is an expected phenomenon as the electronic crosstalk has increased over time.

Figure 9 shows the Earth scene image comparison at 500 m resolution from the HKM MODIS L1B product. The top panel of plots shows the C6.1 (band 28 sending) images from March 2016 for bands 5, 6 and 7. The bottom panel plot shows the generated L1B images with SWIR crosstalk correction using band 25 as a sending band. In the case of band 5, the horizontal fill value corresponds to the inoperable detector 4. The vertical striping observed in the top-panel plots corresponds to the sub-frame striping that is seen to be reduced in the bottom panel (band 25).



Band 5 (top-B28, bottom-B25)	Band 6 (top-B28, bottom-B25)	Band 7 (top-B28, bottom-B25)

Figure 9. Improvement in the sub-frame striping in the HKM product 2016098.1055

The long-term reflectance trending over the PICS from the Saharan desert is monitored on a routine basis to assess the performance of the MODIS RSB on-orbit, particularly at short-wavelengths. The temporal stability of the PICS implies that any deviation in the multi-year reflectance trend is attributed to an inadequate on-orbit calibration. Figure 10 shows the normalized reflectance trends from a Libyan desert PICS at a near-nadir viewing angle for bands 5 and 6. The trends for band 7 are also calculated but not shown in Figure 10, but the trends for band 26 are generally not reliable over desert sites. The C6.1 trends (red symbols) show an upward drift, particularly after the Feb, 2016 safe hold event, when the PV LWIR crosstalk impacts increased. For bands 5, 6, and 7, the band 25-based reflectance (blue symbols) trends lower than the C6.1 reflectance and does not show an upward drift or any change in trend after the safe hold. The band 25-based reflectance is flat over the mission for band 5 and band 7 at nadir, but there may be a slight downward trend for band 6. More investigation of these trends, including any potential variation with viewing angle, is reserved for future studies.

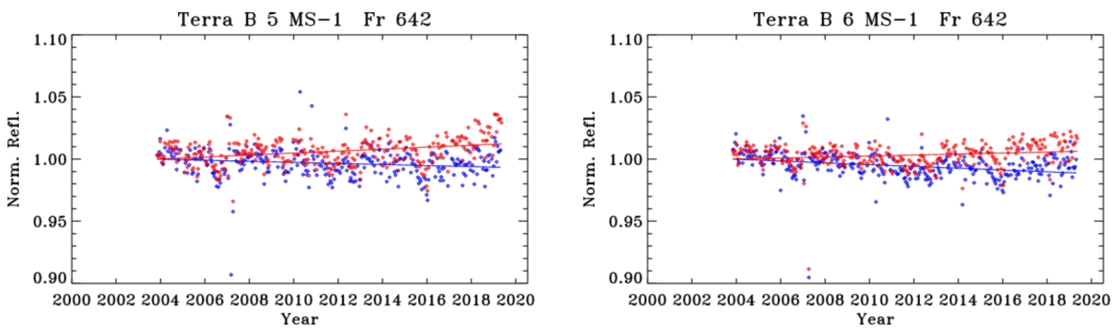


Fig. 10. Normalized reflectance trends for Libya desert site near nadir for mirror side 1 of bands 5 and 6. Red: C6.1 with band 28 as sending band; Blue: band 25 as sending band using new algorithm.

4 Implementation in Forward Production and Future Reprocessing

The results shown in the previous sections suggest that a change in the existing approach is warranted to maintain and improve the quality of the C6.1 L1B. It is demonstrated that with the use of band 25 as a sending band, the short-term and long-term stability of the gain as well as the calibrated products is improved, particularly after the Feb 2016 safe mode event. However, implementing this change in the forward production of current C6/C6.1 needs some additional considerations. Although this approach improves the detector and subframe striping, the band-averaged TOA radiance values generated using band 25 as a sending band differ somewhat from those in the original C6/C6.1 L1B (based on band 28), especially after the Feb 2016 safe mode. Switching the sending band from band 28 to band 25 without any additional correction or scaling would produce a small but noticeable radiance shift in the L1B product at the time of implementation. To avoid a discontinuity in the various science products that use these bands, a scaling factor is derived and applied to the forward m_1 LUTs.

The scaling factors are determined from three sets of L1B comparison tests from dates in 2017, 2018, and 2019, each using a set of granules covering one full orbit. For each 1-orbit set of granules, a radiance ratio is calculated between the C6.1 radiance and that calculated using band 25 as the sending band. The band-averaged radiance ratios at the typical radiance level are calculated for all three dates and the three values are averaged to get scaling factors as shown in Table I.

Table I. Scaling Factors used in C6.1 for MODIS SWIR bands after 2019184.1200

Band	**5**	**6**	**7**	**26**
L_{typ}	5.4	7.3	1.0	6.0
Scaling Factor	1.023	1.022	1.037	0.998

These scaling factors are applied to the delivered m_1 LUTs for the forward production of C6/C6.1 L1B. Only one scaling ratio is applied for each band, the same for all detectors and sub-frames within the band. With these scaling factors applied to the m_1 LUTs, the band average C6/C6.1 L1B radiance at the typical radiance level should trend smoothly at the time of the sending band switch. However, due to the nature of electronic crosstalk, the impact of the sending band switch will be scene dependent, depending on the relative dn levels of band 25, band 28, and the SWIR bands, so some scenes may see a noticeable radiance shift, particularly at low radiance levels.

Overall, the L1B product for the SWIR bands should be more stable with less detector and subframe striping going forward, as was demonstrated in Figs. 6-9. The sending band switch was made to all of the relevant LUTs starting with granule 2019184.1200 in the C6/C6.1 L1B. The scaling factors will continue to be applied to the forward m_1 LUTs for the remainder of C6/C6.1 processing. In addition, the crosstalk coefficient LUT, x_oob_1, will continue to be updated in the forward LUT deliveries to follow the time-dependent trends (Fig. 4). Typically, an x_oob_1 update will be made after each NTDM data collection is performed and the time-fitting of the measured crosstalk coefficient trends is updated. For future Terra MODIS L1B Collections, the OOB/crosstalk correction using band 25 as the sending band and time-dependent crosstalk coefficients is planned to be implemented from mission beginning.

5 Summary

As Terra MODIS continues to operate beyond its design life, the performance of its on-orbit calibration needs to be constantly and carefully monitored. A challenging issue for the SWIR bands since prelaunch characterization has been the presence of electronic crosstalk and an OOB response. Mitigation algorithms using NTDM collects have been implemented since the early days of operation, relying on the signal from band 28 in the LWIR focal plane as a sending band to approximate the combined impact of crosstalk and OOB impacts. Due to on-orbit changes of electronic crosstalk, the LWIR PV bands have experienced a significant degradation in their performance, especially after the February 2016 safe mode event. This has made the original approach of using band 28 as the sending band for SWIR crosstalk correction less effective. An alternative approach is proposed that uses band 25 as the sending band, as band 25 on-orbit performance has been very stable and it has also worked well as the sending band in Aqua MODIS SWIR crosstalk correction. In support of this change, band 25 is used to re-derive the NTDM coefficients along with the SD gains over the Terra mission. The impact of this approach on the L1B product is evaluated using several tests on EV L1B data and comparisons to the existing C6.1 L1B. Both the detector striping and the subframe striping observed in the 500 m EV product are significantly reduced with the use of band 25 as the sending band. More importantly, the per-detector gain measurements from the SD calibration show improved stability, particularly around and after the time of the 2016 safe mode. Though the improved algorithm is applied to all SWIR bands (5, 6, 7, and 26), the results in this paper focus mostly on bands 5, 6, and 7. The impact of crosstalk on band 26 is less than it is for the other SWIR bands and band 26 does not have problems with sub-frame striping since it is a 1 km resolution band. The newly proposed SWIR crosstalk correction with band 25 as the sending band has already been implemented in the forward production of C6/C6.1 L1B since July 2019 and worked very effectively. As expected, this approach will be used over the entire Terra mission in the next version of the L1B.

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References

[1] W. L. Barnes and V. V. Salomonson, "MODIS: a global image spectroradiometer for the earth observing system," Crit. Rev. Opt. Sci. Technol. 47, 285–307 (1993).

[2] V. V. Salomonson, "An overview of the earth observing system MODIS instrument and associated data systems performance," in IEEE Int. Geoscience and Remote Sensing Symp., Vol. 2, pp. 1174–1176 (2002).

[3] X. Xiong, M. D. King, V. Salomonson, W. Barnes, B. N. Wenny, A. Angal, A. Wu, S. Madhavan, and D. Link, "Moderate Resolution Imaging Spectroradiometer on Terra and Aqua Missions", John Wiley & Sons, Ltd, 9781118945179, 53-89, (2015).

[4] X. Xiong, K. Chiang, J. Esposito, B. Guenther, and W. Barnes, "MODIS on-orbit calibration and characterization," Metrologia 40(1), S89 (2003).

[5] M. D. King, S. Platnick, W. P. Menzel, S. A. Ackerman, and P. A. Hubanks, Spatial and Temporal Distribution of Clouds observed by MODIS onboard the Terra and Aqua satellites," IEEE Transactions on Geoscience and Remote Sensing 51(7), 3826-3852 (2013).

[6] W. L. Barnes, T. S. Pagano, and V. V. Salomonson, "Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1," IEEE Transactions on Geoscience and Remote Sensing 36(4), 1088-1100 (1998).

[7] W. L. Barnes, X. Xiong, X., and V. V. Salomonson, "Status of Terra MODIS and Aqua MODIS," Advances in Space Research 32(11), 2099-2106 (2003).

[8] Xiong, X., Chiang, K.-F., Adimi, F., Li, W., Yatagai, H., and Barnes, W. L., “MODIS correction algorithm for out-of-band response in the short-wave IR bands,” Proc. SPIE 5234, 605-614 (2004).

[9] T. Wilson and X. Xiong "Subsample difference correction for Terra MODIS SWIR bands 5-7 using lunar observations", Proc. SPIE 10785, 107851B (2018)

[10] J. Sun, S. Madhavan, X. Xiong, and M. Wang, "Investigation of the Electronic Crosstalk in Terra MODIS Band 28", IEEE Transactions on Geoscience and Remote Sensing, 53 (10), 5722 - 5733, (2015).

[11] T. Wilson, A. Wu, A. Shrestha, X. Geng, Z. Wang, C. Moeller, R. Frey, and X. Xiong, “Development and implementation of an Electronic Crosstalk Correction for bands 27-30 in Terra MODIS Collection 6,” Remote Sensing 9(6), 569 (2017).

[12] X. Xiong, A. Angal, and Y. Li, "Improvements in the on-orbit calibration of the Terra MODIS short-wave infrared spectral bands", Proc. SPIE - Earth Observing Missions and Sensors: Development, Implementation, and Characterization V, 10781(107811C), (2018).

[13] X. Xiong, A. Angal, W. L. Barnes, H. Chen, V. Chiang, X. Geng, Y. Li, K. Twedt, Z. Wang, T. Wilson, et al., "Updates of Moderate Resolution Imaging Spectroradiometer on-orbit calibration uncertainty assessments", Journal of Applied Remote Sensing, 12(3),034001, (2018).

[14] X. Xiong, J. Sun, W. Barnes, V. Salomonson, J. Esposito, H. Erives, and B. Guenther, “Multiyear on-orbit calibration and performance of Terra MODIS reflective solar bands,” IEEE Transactions on Geoscience and Remote Sensing 45(4), 879-889 (2007).

[15] X. Xiong, J. Sun, X. Xie, W. L. Barnes, and V. V. Salomonson, “On-orbit calibration and performance of Aqua MODIS reflective solar bands,” IEEE Transactions on Geoscience and Remote Sensing 48(1), 535-546 (2010).

[16] X. Xiong, A. Angal, K. A. Twedt, H. Chen, D. Link, X. Geng, E. Aldoretta, and Q. Mu, "MODIS Reflective Solar Bands On-Orbit Calibration and Performance", IEEE Transactions on Geoscience and Remote Sensing, 57 (9), 6355-6371, (2019).

[17] H. H. Kieffer and T. C. Stone, "The spectral irradiance of the Moon," J. Astron.,129, 2887–2901, (2005).

[18] J. Sun, X. Xiong, W. L. Barnes, and B. Guenther, "MODIS Reflective Solar Bands On-Orbit Lunar Calibration," IEEE Transactions on Geoscience and Remote Sensing 45(7), 2383-2393 (2007).

[19] J. Sun, X. Xiong, A. Angal, H. Chen, A. Wu, and X. Geng, Time-dependent Response versus Scan angle for MODIS reflective solar bands," IEEE Transactions on Geoscience and Remote Sensing 52(6), 3159-3174 (2014).

[20] C. Moeller, H. Revercomb, S. Ackerman, P. Menzel, and R. Knuteson, "Evaluation of MODIS thermal IR band L1B radiances during SAFARI 2000," Journal of Geophysical Research: Atmospheres 108(D13) (2003).

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Biographies and photographs for the other authors are not available.

Caption List

Fig. 1 Relative spectral responses of Terra MODIS bands 5 and 6 (IB: red, OOB: black).

Fig. 2 MODIS short-wave/mid-wave infrared focal plane assembly.

Fig. 3 Examples of Terra MODIS bands 5, 6, and 7 nighttime responses (subframe 1 in black and subframe 2 in blue) versus band 25 responses. Data collected from the NTDM event from day 333 of the year 2006. The responses for the center detector are plotted.

Fig. 4 Crosstalk correction coefficients of Terra MODIS bands 5-7 (center detector) derived from the NTDM events with band 25 as the sending band. Black symbols and blue symbols represent the measured values from each NTDM collect for sub-frame 1 and sub-frame 2 respectively. Lines are fits to the measured data (see text).

Fig. 5 Calibration coefficients (m1) of Terra MODIS bands 5-7 (mirror side 1; first 10 detectors; sub-frame 1 for band 6; sub-frame 2 for bands 5 and 7) using band 28 (left) and band 25 (right) as the sending band.

Fig. 6 EV radiance histograms using band 28-based (left panel) and band 25-based (right panel) approach for 2010121.0640 granule.

Fig. 7 EV radiance histograms using band 28-based (left panel) and band 25-based (right panel) approach for 2019131.0910 granule.

Fig. 8 Radiance difference between the two sub-frames (band-averaged) as a function of radiance for sets of granules over 1-orbit from two different years in the mission: 2010 (top) and 2019 (bottom). The red color is for band-25 based SF difference and black is for band-28 based (C6.1) difference. The differences are binned as a function of radiance. The radiance has units of W/(m2-Sr-µm).

Figure 9. Improvement in the sub-frame striping in the HKM product 2016098.1055

Fig. 10. Normalized reflectance trends for Libya desert site near nadir for mirror side 1 of bands 5 and 6. Red: C6.1 with band 28 as sending band; Blue: band 25 as sending band using new algorithm.

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