

MODIS Reflective Solar Bands On-orbit Calibration and Performance

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Abstract—The design of the MODIS instrument was driven by the scientific community's desire to have near-daily global coverage at moderate resolution (~ 1 km) with a comprehensive spectral coverage from visible to long-wave infrared wavelengths. Since their launches in 1999 and 2002, respectively, the Terra and Aqua MODIS instruments have made continuous global observations and generated numerous data products to help users worldwide with their studies of the Earth's system and its short- and long-term changes. The 20 reflective solar bands (RSB) with wavelengths from 0.41 to 2.2 μm collect data at three nadir spatial resolutions: 250 m, 500 m, and 1 km. The solar diffuser (SD) coupled with the solar diffuser stability monitor (SDSM) provide a reflectance-based calibration on-orbit. In addition, lunar observations and response trends from pseudo-invariant desert sites are used to characterize the response versus scan-angle changes on-orbit. This paper provides a brief overview of MODIS RSB calibration algorithms, as implemented in the latest Level 1B version 6.1, operational activities, on-orbit performance, remaining challenges and potential improvements. Results from the SD and SDSM measurements show a wavelength and mirror side dependent degradation in RSB responses, with the largest degradation at the shortest wavelengths, particularly for Terra MODIS. Aqua MODIS has experienced far less degradation of its optics and on-board calibrators compared to Terra MODIS, resulting in an overall better performance. With the exception of Aqua band 6, there have been no new noisy or inoperable detectors in the RSB of either instrument during post-launch operations. As the instruments age and continue to endure the space environment, the detectors and optical systems degrade. The challenges associated with incorporating these on-orbit changes to ensure a production of high-quality calibrated L1B data products are also discussed in this paper.

Index Terms—Terra, Aqua, MODIS, reflective solar bands, detector, calibration, solar diffuser, solar diffuser stability monitor, moon, uncertainty

I. INTRODUCTION

THE first Moderate-resolution Imaging Spectroradiometer (MODIS), a Proto-Flight Model (PFM), was launched on December 18, 1999 on-board the NASA Earth Observing System (EOS) Terra satellite and the second, Flight Model 1 (FM1), was launched on May 4, 2002 on-board the NASA EOS Aqua satellite. Both are in a Sun-synchronous orbit with Terra at a 10:30 am equatorial crossing time, descending node, and Aqua at a 1:30 pm equatorial crossing time, ascending node. Since launch, both MODIS instruments have been making near-continuous observations and producing numerous scientific and environmental data products to help

understand the Earth's system of atmosphere, land, ocean, and cryosphere [1], [2], [3]. To date, both Terra and Aqua MODIS have successfully operated for more than 18 and 16 years, respectively. Their geo-located and radiometrically calibrated measurements have enabled an unprecedented amount of high quality, long-term data records in support of various studies and applications by the remote sensing science and user community.

The MODIS instrument was developed to extend and enhance key environmental data records derived from heritage Earth-observing sensors with overall improvements in spectral, spatial, and temporal resolutions [2], [3], [4], [5]. MODIS is a cross-track scanning radiometer, which incorporates a two-sided paddle wheel mirror. Its observations are made in 36 spectral bands that include 20 reflective solar bands (RSB) covering the visible (VIS), near-infrared (NIR), and short-wave infrared (SWIR) with wavelengths from 0.41 to 2.2 μm and 16 thermal emissive bands (TEB) covering the mid-wave infrared (MWIR) and long-wave infrared (LWIR) with wavelengths from 3.7 to 14.4 μm . In order to ensure and maintain calibration and data quality over its entire mission, the MODIS instrument was designed with a set of on-board calibrators (OBCs) that include a solar diffuser (SD) and a solar diffuser stability monitor (SDSM), which are used primarily for RSB calibration, and a blackbody (BB) for TEB calibration. In addition, a spectro-radiometric calibration assembly (SRCA) is on-board to track instrument spatial (for both RSB and TEB) and spectral (RSB only) characteristics [6]. Figure 1 is a schematic of the MODIS instrument, showing locations of its OBCs and several key optical components, such as the scan mirror and primary mirror of the sensor telescope. This paper discusses various issues and results from both Terra and Aqua RSB on-orbit calibration and characterization, and their performance, from launch to present. The TEB calibration and performance will be addressed in a separate paper.

A synopsis of the key MODIS RSB design specifications is provided in Table I. The 20 spectral bands are listed by wavelength and grouped according to spatial resolution, together with their primary applications. The land and cloud application bands (1 and 2) each have 40 detectors and collect data at a spatial resolution (nadir) of 250 m. The land and cloud properties bands (3-7) each have 20 detectors with a 500 m resolution. The ocean color bands (8-16), atmosphere properties bands (17-19), and cloud detection band (26) each

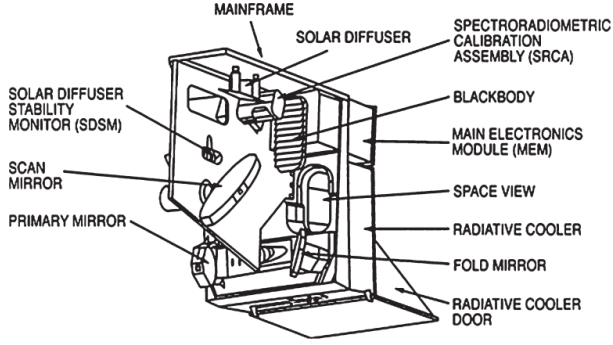


Fig. 1. MODIS scan cavity with on-board calibrators

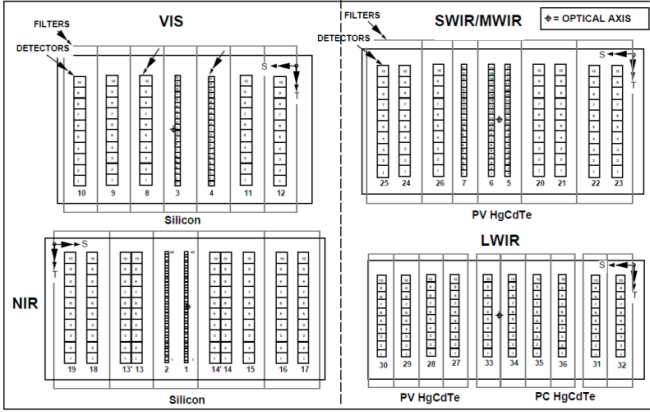


Fig. 2. Layout of the four MODIS focal plane assemblies, showing the location of all bands and detectors, and the overlaid spectral filters. All VIS and NIR bands use Silicon detectors. The SWIR, MWIR, and LWIR bands use either photovoltaic (PV) or photoconductive (PC) HgCdTe detectors.

have 10 detectors and a 1 km resolution. Bands 13 and 14 produce data with both high and low gains using a pair of detector arrays and time-delay integration. The high gain outputs, designated bands 13hi and 14hi, are designed for detection of chlorophyll fluorescence. Figure 2 illustrates the physical layout of the MODIS focal plane assemblies (FPA), showing the location of all spectral bands and detectors. MODIS RSB have a total of 330 individual detectors.

The MODIS primary Level 1B (L1B) data product for the RSB is the top-of-atmosphere (TOA) reflectance factor for the Earth-view (EV) scene, $\rho_{EV} \cos(\theta_{EV})$. The definition of the reflectance factor in terms of the instrument response is given in Section III. The L1B also contains scaling factors to convert the reflectance factor to radiance, $L = \rho_{EV} \cos(\theta_{EV}) E_{sun} / \pi d_{ES}^2$, where d_{ES} is the Earth-Sun distance and E_{sun} is the solar spectral irradiance integrated over the relative spectral response of each MODIS band. The solar irradiance spectrum used for MODIS calibration is a combination of several models to cover different spectral ranges. The typical scene radiances (L_{typ}) of the RSB and their specified signal-to-noise ratios (SNR) at L_{typ} are included in Table I.

The specified uncertainty requirements for MODIS RSB are 2% in reflectance and 5% in radiance at typical radiance levels and for observations within a scan angle range of $\pm$

TABLE I
MODIS RSB SPECIFICATIONS. CW: CENTER WAVELENGTH IN μm . IFOV: INSTANTANEOUS FIELD OF VIEW IN km . L_{typ} : SPECIFIED TYPICAL RADIANCE IN $W m^{-2} \mu m^{-1} sr^{-1}$. SNR: SIGNAL-TO-NOISE RATIO.

Band	CW	IFOV	L_{typ}	SNR	Primary Use
1	0.645	0.25	21.8	128	Land/Cloud/Aerosols Boundaries
2	0.858	0.25	24.7	201	
3	0.469	0.5	35.3	243	Land/Cloud/Aerosols Properties
4	0.555	0.5	29.0	228	
5	1.240	0.5	5.4	74	
6	1.640	0.5	7.3	275	
7	2.130	0.5	1.0	110	
8	0.412	1.0	44.9	880	Ocean Color/ Phytoplankton/ Biogeochemistry
9	0.443	1.0	41.9	838	
10	0.488	1.0	32.1	802	
11	0.531	1.0	27.9	754	
12	0.551	1.0	21.0	750	
13	0.667	1.0	9.5	910	
14	0.678	1.0	8.7	1087	
15	0.748	1.0	10.2	586	
16	0.869	1.0	6.2	516	Atmospheric Water Vapor
17	0.905	1.0	10.0	167	
18	0.936	1.0	31.6	57	
19	0.940	1.0	15.0	250	
26	1.375	1.0	6.0	150	Cirrus Clouds Water Vapor

45°. This is achieved by referencing on-orbit calibration to the pre-launch measurements of the bidirectional reflectance factor (BRF) of the on-board SD. In addition to the SD BRF, MODIS RSB pre-launch calibration and characterization included measurements of many key parameters that are critical for instrument calibration, such as sensor response versus scan-angle (RVS), relative spectral response (RSR), SNR, and polarization sensitivity [7]. On orbit changes (degradation) in the SD BRF are tracked using the on-board SDSM. As both missions continue, various methods have also been developed to track changes in the RVS and other important calibration parameters.

Section II of this paper briefly describes key events of instrument operations and RSB related calibration activities for both Terra and Aqua MODIS. This is followed by an overview in Section III of RSB on-orbit calibration algorithms that include the use of SD calibrations, lunar calibrations, on-orbit RVS characterization, and SWIR crosstalk correction. Details of RSB on-orbit performance are presented in Section IV. An update of MODIS RSB L1B calibration uncertainty is provided in Section V. Discussed in Section VI are various challenging issues and potential improvements for RSB on-orbit calibration. Finally, a short summary is given in Section VII.

Although both the Terra and Aqua missions have far exceeded their specified design life of 6 years, the MODIS instruments continue to operate normally and their OBCs remain capable of performing various on-orbit calibration functions. On-orbit degradation of the SD BRF continues to be monitored by the SDSM, together with other alternative approaches. The changes in RSB responses are generally consistent for both Terra and Aqua MODIS, with shorter wavelength bands showing larger changes, especially for the early years of each mission. As expected, MODIS on-orbit operation and calibration approaches and many of the lessons learned have been applied to other Earth-observing sensors,

such as the VIIRS on S-NPP and JPSS-1, OLI on Landsat 8, and ABI on GOES-16 and -17.

II. INSTRUMENT ON-ORBIT OPERATIONS AND RSB CALIBRATION ACTIVITIES

The OBCs are used routinely to derive and track the instrument calibration parameters. The OBC operational activities are executed using built-in commands that are uploaded as needed by the MODIS Instrument Operations Team (IOT). Key activities include regular SD/SDSM operation, SRCA operations in three different modes (radiometric, spatial, and spectral), electronic calibrations (ECAL), and quarterly BB warm-up cool-down (WUCD) operations. Each MODIS instrument also views the Moon on a near-monthly basis via carefully planned spacecraft maneuvers to ensure observations in a constrained phase angle range. The nadir door on Terra MODIS was first opened on February 24, 2000. The instrument operated initially using the primary (A-side) electronics and formatter; however due to increased noise associated with the formatter, it was switched to the redundant (B-side) electronics starting on October 30, 2000. The B-side power supply failed on July 2, 2001 and as a result the operations were switched back to the primary electronics. After continued issues with the A-side formatter, the instrument was switched to a cross-strapped configuration (A-side electronics cross-strapped with B-side formatter) starting on September 17, 2002. Over the mission lifetime, the instrument has experienced a few safe mode transitions due to instrument or spacecraft anomalies, with the latest such event occurring in February, 2016. An outgas operation of the instrument was performed as a part of the standard recovery procedure before resuming science operations starting February, 24, 2016. The major impact of the safe mode event was to the Terra PV LWIR bands, which had a significant change to their electronic crosstalk behavior, which also has some impact to the MODIS SWIR bands, as to be discussed in Section VI.

Aqua MODIS has operated in a single configuration, B-side electronics and formatter since launch. Similar to Terra, there were some early mission spacecraft anomalies that led the MODIS instrument to transition to safe mode, but they did not have any impact on the long-term operations of the instrument. The MODIS RSB on-board radiometric calibration system consists of a SD panel with BRF (characterized pre-launch) and a SDSM assembly used to track the on-orbit degradation of the SD. The SD provides a full aperture target for a reflectance-based calibration. The SD panel is made of a space-grade Spectralon and has near-Lambertian reflectance. It's BRF was characterized pre-launch by the sensor vendor (Santa Barbara Remote Sensing) using reference diffuser samples traceable to the reflectance standards of the National Institute of Standards and Technology (NIST). The retractable SD screen (SDS) is a thin, metal plate patterned with hundreds of pinholes and is part of the SD aperture door assembly. The SDS attenuates the solar illumination used to calibrate the high-gain ocean color bands (8-16) which saturate when viewing the SD under direct solar exposure. The SD door (SDD) covers both the SD and SDSM views to the sun and

TABLE II
SDSM DETECTOR SPECIFICATIONS. CW: CENTER WAVELENGTH IN μm .

SDSM detector	CW	MODIS band	CW
1	0.412	8	0.412
2	0.466	3	0.469
3	0.530	11	0.531
4	0.554	4	0.555
5	0.646	1	0.645
6	0.747	15	0.748
7	0.857	2	0.858
8	0.904	17	0.905
9	0.936	18	0.936

normally remains closed when there is no SD/SDSM event to prevent excessive exposure of the SD panel.

The SDSM is a radiometer with a solar integration sphere (SIS) containing nine embedded detectors ranging from 0.41 to 0.94 μm that closely match nine of the MODIS RSB. Table II provides a summary of the SDSM detector wavelengths and the corresponding MODIS VIS/NIR spectral bands. A fixed SDSM screen, separate from the SD screen, is placed in the Sun view path so that the Sun view response and the SD view response of the SDSM detectors have about the same magnitude. Typically, the SDSM is operated during each SD calibration event and provides data that tracks the change of the SD BRF. The optical system within the SDSM assembly provides three sequential measurements of (1) direct sunlight through the SDSM screen, (2) reflected diffuse sunlight from the SD plate, and (3) a dark view for measuring SDSM detector offsets. Since the same optics, detectors, and electronics are used for the Sun view and the SD view, slow changes in SDSM detector response, optical transmission, or electronics stability bear minimal impact on the measured SD degradation. The SD degradation at MODIS RSB wavelengths is calculated via interpolation of the nine SDSM wavelengths and is applied in deriving the RSB calibration coefficients

The SD and SDSM operate together as a system for the calibration of the RSB. A typical RSB calibration consists of two sets of SD observations, implemented in consecutive orbits: one with the SDS in place (SDD open) and another without the SDS. In the case of Terra MODIS, the SD/SDSM was operated on a daily basis for a week post-launch and on a weekly basis thereafter. Starting in Feb 2002, the operational frequency was switched to a bi-weekly basis. In May 2003, the SDD motor showed inconsistent response to repeated movement commands and therefore a decision was made to set the SDD to a permanent open position with the SDS in place. This configuration facilitates an SD calibration every orbit with the tradeoff of frequent solar exposure leading to an increased rate of on-orbit SD degradation. Although the SD calibration measurement is acquired every orbit, the SDSM continues to be operated only at regularly scheduled intervals, currently once every three weeks.

Contrary to Terra MODIS, the SDD for Aqua MODIS has operated normally throughout the 16+ years of the mission and is kept closed except during calibration events. Currently, the SD/SDSM calibration without the SDS is performed once every six weeks and the calibration with the SDS is scheduled once every three weeks. There are a specified number of SDD

step motor movements guaranteed by the manufacturer and the reduction in the frequency of SD/SDSM calibrations since launch conserves the remaining margin.

The instrument space view (SV) port is an opening that provides dark system-level background measurements for each detector. Each scan over the SD and SV calibration sectors collects a 50 sample set for the 1 km resolution bands. The higher resolution bands record samples at a higher rate of 4 subsamples (0.25 km resolution bands) or 2 subsamples (0.5 km bands) for each sample of a 1 km band. The SV port also provides a view of the Moon. Because of its excellent stability in terms of surface reflectance, the Moon provides an additional source to track the long-term relative gain changes of the RSB on orbit. Typically, there are about 9-10 lunar observations, with associated roll maneuvers, scheduled per year. Observation times are chosen so that the relative phase angle is consistent for all observations by each instrument. In addition, the Moon is also observable for several consecutive orbits, about 3 to 4 times in a year, through the SV port without requiring any spacecraft maneuvers. Calibration results from these unscheduled lunar observations are also applicable after accounting for the different relative geometries and varying phase angles. The SD calibration events and the scheduled lunar observations provide the primary on-orbit measurements for calibration of the MODIS RSB.

The MODIS instruments also perform other scheduled calibration activities on a regular basis that are used mostly for instrument performance monitoring. The SRCA performs regular calibrations in radiometric, spatial, and spectral modes. The radiometric calibrations were designed to be an independent way to track on-orbit gain changes, but lamp failures early in the mission and subsequent operational changes made the long-term radiometric trends unreliable, although the data still provides a reliable trend to track the relative differences in response of the two scan mirror sides. The SRCA spatial and spectral calibrations have been used to track the on-orbit stability of the band-to-band registration and relative spectral response of the MODIS RSB [8], [9]. Regular electronic calibrations are also performed to monitor on-orbit changes in the electronic gain of individual detectors [10]. While the SRCA and electronic calibrations continue to provide valuable data on the MODIS RSB performance, the results are not currently used in the reflectance and radiance calibration algorithms.

In addition to data from the regularly scheduled on-orbit calibration activities, the MODIS RSB calibration algorithms also rely on data from regular observations of Earth targets. As the missions continue to operate for more than a decade beyond their designed life, the two primary on-board sources, the SD and the Moon, prove insufficient to perform accurate characterization of the on-orbit RVS. Hence, the EV response trending from pseudo-invariant desert targets are incorporated into the RVS calculation to supplement the on-board measurements from the SD and Moon. Currently in MODIS Collection 6.1, this approach is implemented for bands 1-4, 8, 9 of both instruments and additionally band 10 of Terra MODIS. As both missions continue, it is expected that this approach will be extended to other RSB.

III. ON-ORBIT CALIBRATION ALGORITHMS

As described in Section II, the RSB calibration is based primarily on the results derived from regular SD/SDSM calibration events. Lunar data supplemented by EV data are the main inputs in determining the RVS relative to the detector response at the SD view angle. The current approach has built on the knowledge gained through previous iterations of calibrations and years of on-orbit operations. Additionally, input from the MODIS science team and user community has been incorporated into the current calibration strategy where applicable.

A. Solar Diffuser Calibration

The L1B product for RSB is a TOA reflectance $\rho \cdot \cos \theta_{EV}$, which is defined as

$$\rho_{EV} \cdot \cos \theta_{EV} = m_1 \cdot dn_{EV}^* \cdot (d_{ES_EV})^2, \quad (1)$$

where ρ_{EV} is the EV scene BRDF, θ_{EV} is the corresponding solar zenith angle, m_1 is the calibration coefficient that is inversely proportional to the detector's gain and d_{ES_EV} is the Earth-Sun distance in AU. dn_{EV}^* is the detector's EV response, in units of digital number (counts), adjusted from raw count (DN_{EV}) by

$$dn_{EV}^* = (DN_{EV} - \langle DN_{SV} \rangle) \cdot \frac{(1 + k_{Inst} \cdot (T_{Inst_EV} - T_{Ref}))}{RV_{SEV}}. \quad (2)$$

$\langle DN_{SV} \rangle$ is the average detector background response as observed through the SV port. Note that when the moon is visible through the SV port, the average SV response used in Equation 2 is replaced by the detector response to the on-board BB. k_{Inst} is the instrument temperature correction coefficient characterized pre-launch. This temperature correction factor is defined for each instrument, band, detector, and sub-sample. T_{Inst_EV} is the instrument temperature during the observation and T_{Ref} is its reference value determined from pre-launch measurements. RV_{SEV} is the relative system response at the EV pixel scan angle. The RVS at the scan angle of the solar diffuser is defined to be 1 ($RV_{SD} = 1$). The RVS at all other scan angles is band, detector, and mirror side dependent and is explained in detail in Section III-C. The calibration coefficient, m_1 , is derived from the SD calibrations using the following expression:

$$m_1 = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{dn_{SD}^* \cdot (d_{ES_SD})^2} \cdot \Gamma_{SDS} \cdot \Delta_{SD}, \quad (3)$$

where θ_{SD} is the solar zenith angle of the SD view, dn_{SD}^* is the digital number (counts) from the SD, corrected in the same manner as dn_{EV}^* , and d_{ES_SD} is the Earth-Sun distance in AU at the SD observation time. The BRDF of the SD is denoted as ρ_{SD} and was characterized pre-launch. Δ_{SD} is the SD degradation factor as measured by the SDSM. Γ_{SDS} is the vignetting function used for the calibration measurements that incorporate the SD screen. This applies for the ocean color bands (bands 8-16) because they reach saturation levels when the SD screen is in the open position during SD calibrations. The remaining RSB are calibrated with the screen open and

for these bands $\Gamma_{SD} = 1$. Starting from July 2003, Terra MODIS SD door was permanently set to open with its screen in close position. Since then, a non-unity vignetting function has been used for all Terra MODIS RSB. The SDSM is only designed to track the SD's degradation at wavelengths less than $1 \mu\text{m}$ and additional corrections are necessary to account for the degradation at SWIR wavelengths. More details on RSB SD/SDSM calibrations can be found in the following references [6], [11], [12].

The on-orbit SNR characterization of the MODIS reflective bands is performed by tracking the band and detector responses of the sunlight-illuminated SD panel during regularly-scheduled SD calibration events. The SNR is computed at varying signal levels and then scaled to the typical radiance level for each band [13] (see L_{typ} in Table I).

B. Lunar Calibration

With a roll maneuver, both Terra and Aqua MODIS can be scheduled to view the Moon. Both MODIS instruments observe the Moon within a fixed range of phase angles (between 55° and 56° for Terra MODIS and from -56° to -55° for Aqua MODIS). Since launch, there have been 183 and 169 lunar observations for Terra and Aqua MODIS, respectively, as of September 2018.

The lunar surface has a very stable reflectance in the visible and near-infrared spectral regions and the Moon is a well-studied target. Similar to the SD, the Moon can be used as a calibrator to track the on-orbit gain changes of the MODIS optical system. Since the Moon is observed through the SV port, the instrument gains derived from the lunar calibrations are for a different angle of incidence (AOI) on the scan mirror than those from the SD calibrations. Determining calibration coefficients at multiple scan angles allows for the derivation of on-orbit changes to the RVS of the scan mirror, as discussed in Section III-C.

The lunar calibration coefficient is defined and calculated by

$$m_1^{moon} \propto \frac{f_{PA} f_{LA} f_{OS}}{dn_{Moon}^* d_{SM}^2 d_{MM}^2}, \quad (4)$$

where $f_{PA} f_{LA} f_{OS}$ denote the corrections for the phase angle, libration angle and oversampling factor respectively, and the d_{SM} and d_{MM} denote the distances between the Sun and the Moon and MODIS and Moon. The oversampling factor is needed as multiple overlapping lunar scans are used. These correction factors are obtained from the results of the ROLO lunar model developed by Kieffer et.al [14]. The inverse of the lunar calibration coefficient, $1/m_1^{moon}$, normalized to its value at the start of the mission, tracks the on-orbit gain change of the MODIS RSB at the AOI of the SV. In the case of high gain ocean bands (13-16), the detectors experience saturation while viewing the Moon. Hence, a ratio approach using an unsaturated band as a reference is applied to derive the lunar response trending [15]. Note that the lunar observations are not used as an absolute calibration reference, but are only used to track on-orbit changes in the detector gains. The absolute reflectance calibration is still tied to the pre-launch SD characterization. [16].

C. Response Versus Scan Angle

MODIS views the Earth's surface, SV, and the on-board calibrators via a rotating, two-sided scan mirror, seen in Figure 1. Using both sides of the scan mirror, MODIS collects data over five sectors, the SD, BB, SRCA, SV, and EV sequentially with a scan period of 1.477 seconds. The AOI of light on the scan mirror varies from 10.5° to 65.5° during the EV sector. Light from the OBCs is incident on the scan mirror at AOIs of 50.2° for the SD, 26.2° for the BB, 38.2° (equivalent to EV nadir) for the SRCA, and 11.2° for the SV. The gain of the MODIS RSB at the AOI of the SD is captured by the m_1 derived from SD calibrations. A RVS function is used to describe the dependence of the MODIS response at different AOI.

The RVS was measured pre-launch for both Terra and Aqua MODIS RSB. On-orbit measurements have shown that there have been significant changes to the RVS and as expected the changes are wavelength-dependent. Considering the two MODIS instruments were well preserved before launch, the variations of the MODIS RSB RVS from prelaunch to the first on-orbit measurement are assumed to be negligible. Thus the RVS (the RV_{SEV} term in Equation 2) can be expressed as

$$RV_{SBDM} = RV_{BM}^{pl}(\theta) RV_{BDM}^{oo}(\theta, t), \quad (5)$$

where $RV_{BM}^{pl}(\theta)$ and $RV_{BDM}^{oo}(\theta, t)$ denote the pre-launch RVS for band B and mirror side M and the on-orbit RVS change for band B, detector D, and mirror side M from the time t_0 (when nadir door was first opened). Since the RSB RVS is normalized at the AOI of the SD, the on-orbit RVS change can be expressed as

$$RV_{BDM}^{oo} = \frac{g_{BDM}(\theta, t)}{g_{BDM}(\theta_{SD}, t)}, \quad (6)$$

where $g_{BDM}(\theta, t)$ and $g_{BDM}(\theta_{SD}, t)$ are the on-orbit gain change at the corresponding AOI and that of the SD, respectively.

The MODIS RSB on-orbit gain change can be tracked by the SD/SDSM calibration, lunar observations, and response trending over selected pseudo-invariant EV sites. The knowledge of the absolute radiance of the observed objects may not be necessary to track the on-orbit gain change, but their reflectance must exhibit a temporal stability. The response ratios of the two mirror sides at any AOI can also be obtained from selected EV sites. These ratios can be used to calculate mirror side differences of the on-orbit gain over the entire scan angle range and contribute to deriving the on-orbit RVS. As the response trending over the EV sites has an additional uncertainty due to the atmospheric viewing conditions, it exhibits a much noisier behavior as compared to the OBC measurements. For most MODIS RSB, using the SD and lunar measurements and the EV mirror side ratios is sufficient to track the on-orbit RVS change and is the preferred method. But for some RSB, especially the short-wavelength bands, the EV response trending is needed to accurately track the on-orbit RVS change due to either large uncertainty of the SD calibration or the necessity to track the on-orbit gain change at multiple AOI, or both. [17], [18].

MODIS bands 5-7 and 26 are the SWIR bands. No evidence has demonstrated that the RVS for these bands has any noticeable change for either instrument since launch. Thus, pre-launch RVS is applied for these bands in all MODIS L1B versions. For Terra bands 11-19 and Aqua bands 10-19, SD and lunar calibrations sufficiently track the on-orbit gain change at the AOI of the SD and that of the SV. For these bands, the RVS on-orbit changes for mirror side 1 are derived from the SD and lunar calibrations, assuming a linear dependence in the gain as a function of AOI. For mirror side 2, the RVS is derived by combining SD and lunar measurements with EV mirror side ratio data, using the mirror side 1 RVS as a reference. This approach has performed well throughout the mission for these bands.

For Terra MODIS bands 1-4 and 8-10 and Aqua MODIS bands 1-4 and 8-9, the response trending over the pseudo-invariant desert sites reveals that the linearity assumption about the AOI dependence of the RVS on-orbit variation may not be adequate after 6 years on-orbit. Comparison between the desert response trending around the AOI of the SD and the SD response trending also reveals that the SD measurements are inadequate in accurately characterizing the on-orbit gain change for Terra bands 1-4 and 8-9, especially for the past few years. For the above-mentioned bands, the on-orbit RVS change is characterized using lunar and desert response trending. As the instruments continue to age, this approach may be necessary for determining the on-orbit RVS change of other ocean color bands [19].

D. Special considerations: SWIR crosstalk

The out-of-band (OOB) response identified in the SWIR bands of Terra MODIS during prelaunch characterization has significant impact on the radiometric accuracy, if uncorrected. An optical leak to the SWIR bands, from the MWIR range, centered at $5.3 \mu\text{m}$, was identified during the spectral characterization prior to launch. Additionally, the electronic crosstalk from other SWIR and MWIR bands adds further complexity to the calibration mechanism for these bands. In comparison with Terra MODIS, the impacts of OOB response are smaller in Aqua MODIS. Consequently, an algorithm to mitigate the impacts of the OOB response has been implemented in the L1B for both MODIS instruments. Special instrument operations, termed Nighttime Day Mode (NTDM) collects and operated bi-annually, collect RSB Earth scenes during the orbit night-time. Any signals observed in the SWIR bands during NTDM operations can be treated as a combination of optical leak and electronic crosstalk. Using a linear mapping algorithm between the representative sending band (band 28 for Terra and band 25 for Aqua) and recorded signal, correction coefficients are derived for each detector of the SWIR bands. With the exception of the early mission electronic configuration changes for Terra MODIS, these correction coefficients have remained fairly stable until recent years [11], [20]. More discussion related to this is included in Section VI.

IV. ON-ORBIT PERFORMANCE

A. SD degradation

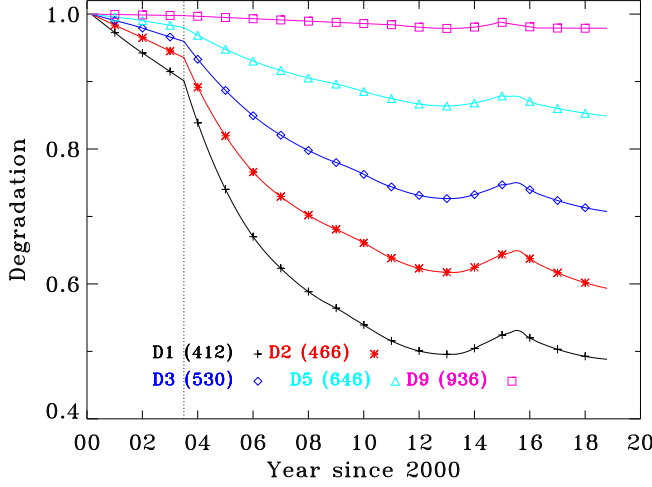
The BRf of the MODIS SD was characterized prelaunch by the instrument vendor. On-orbit, its change is monitored by the SDSM at nine wavelengths between $0.412 \mu\text{m}$ to $0.936 \mu\text{m}$. It is vital to account for the SD's BRf changes on-orbit in an accurate manner. The various details of the methodology applied to track the SD on-orbit degradation along with more recent improvements have been documented earlier [21] [22], [23], [24]. The fitted SD degradation at select wavelengths as derived from the SDSM and normalized to mission start is shown in Figures 3 and 4. Each curve is the result of a piecewise fitting to the data from individual SDSM calibrations. A common pattern of a higher rate of degradation at short wavelengths is observed in both instruments.

Shortly after launch, significant ripples were observed in the Sun-view response of each SDSM detector on Terra MODIS. It was confirmed to be due to the misalignment of the key elements associated with the SDSM attenuation screen. A similar effect was also observed in Aqua MODIS. Work was undertaken to model the SDSM screen and results from this study confirmed and quantified the misalignment and its impact on the Sun-view response. To mitigate these impacts, a normalization approach, where each SDSM detector's response was normalized to the response of detector 9 ($0.936 \mu\text{m}$), was adopted. The success of this approach is based on the underlying assumption that the degradation at $0.936 \mu\text{m}$ is minimal. This normalization approach worked reasonably well through the design life (6 years) of the two instruments; however, measurable degradation at the $0.936 \mu\text{m}$ wavelength was observed thereafter. An empirical approach using a look-up-table constructed from SDSM data was adopted starting with Collection 6 to account for the degradation at the detector 9 wavelength. The results shown in Figures 3 and 4 include this correction at the detector 9 wavelength.

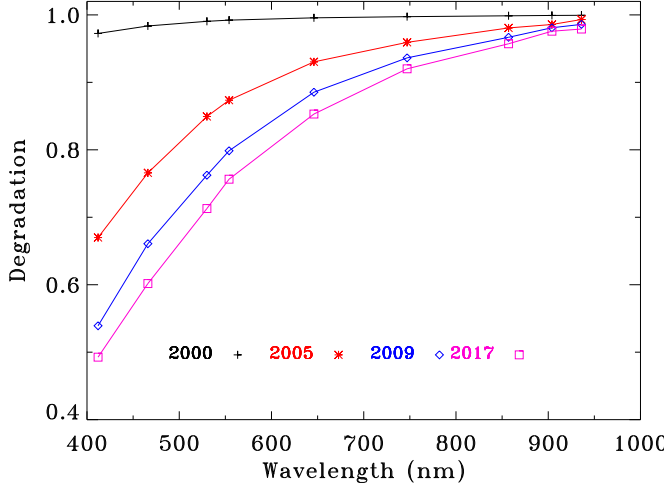
SDSM D1 ($0.412 \mu\text{m}$) shows about 50% degradation over the course of the Terra MODIS mission. The vertical dotted line in Figure 3a denotes the SD door anomaly after which the door was left open for the remainder of the mission. The rate of SD degradation increased after the door anomaly due to increased solar exposure. Aqua MODIS SD degradation, shown in Figure 4a, shows a lower rate of degradation, around 20% degradation at the shortest wavelengths. Figures 3b and 4b show the yearly-averaged degradation for select years, showing a well-defined behavior as a function of wavelength.

B. Spectral band (detector) response trending

The long-term changes in the gains determined from the SD measurements for select VIS bands of Terra MODIS are shown in Figure 5a. The responses are averaged over the detectors for each spectral band and normalized to their first on-orbit measurement (day 55 of the year 2000). The VIS and NIR bands of both MODIS instruments do not have any inoperable or noisy detectors. As of September 2018, the gain has decreased to 48.5% for band 8 ($0.412 \mu\text{m}$), 50% for band 9 ($0.443 \mu\text{m}$), and about 56% for bands 3 and 12 relative to the values at the mission beginning. This wavelength-dependent

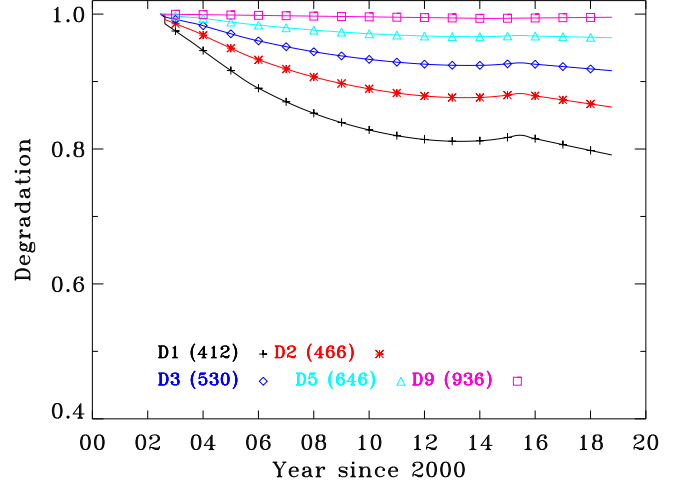


(a)

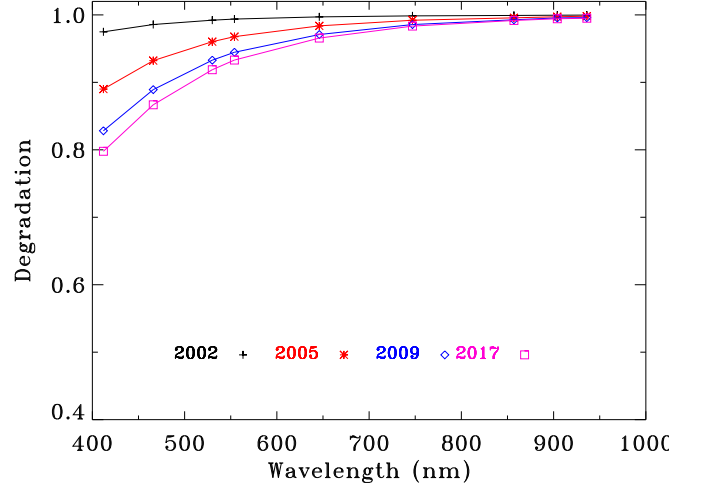


(b)

Fig. 3. (a) Terra MODIS SD degradation as measured by the SDSM at selected wavelengths. (b) Cumulative Terra MODIS SD degradation at different times in the mission.



(a)



(b)

Fig. 4. (a) Aqua MODIS SD degradation as measured by the SDSM at selected wavelengths. (b) Cumulative Aqua MODIS SD degradation at different times in the mission.

degradation in the VIS spectral region is also mirror side dependent as shown by the ratios of gains between the two mirror sides in Figure 5d. Both the normalized gains and the mirror side differences exhibit a scan angle dependence, particularly for the short wavelength bands, therefore warranting a need for a careful RVS characterization on-orbit.

Figure 5 plots 5b and 5e show similar trends for select NIR bands of Terra MODIS. Band 14 follows the decreasing trend seen in the VIS-band results, while band 16 shows less change over time. Bands 1 and 2 show a noticeably different trending behavior. A 5% increase in the gain is observed for the first ten years of the mission, followed by a decrease, with the current gain being relatively close to its early mission value. The lunar measurements, as well as response trends from the desert sites, show a similar behavior (of different magnitudes) for bands 1 and 2. As discussed earlier, bands 13 and 14 have both low and high gain. The on-orbit gain changes for the high gain bands are derived using a scaling from the low gain due to saturation issues during SD and lunar calibrations. Overall,

the trending results of the 13hi and 14hi bands are nearly identical to the 13low and 14low bands. It should be noted that the mirror side differences between the gains for Terra NIR bands are generally less than 0.5%, with the most change observed in band 1. The response trends shown in these figures are a system-level gain, which is a measure of the changes in optical, detector, and electronic gains. The increase in the gains for bands 1 and 2 are likely due to the varying contributions from electronic and detector gain changes.

In contrast, the Terra MODIS SWIR bands shown in Figure 5 have experienced less than 12% change in the instrument gains. In the early mission, the changes in instrument configuration resulted in a sudden gain increase for all the SWIR bands. Unlike the VIS and NIR bands, the SWIR bands do have a noisy detector in band 5 (detector 4 product order) that has been excluded from the band-average trend. The mirror side ratio in the gain for band 5 trends in the opposite direction (downward) compared to the other SWIR bands, likely due to the uncertainties associated with the

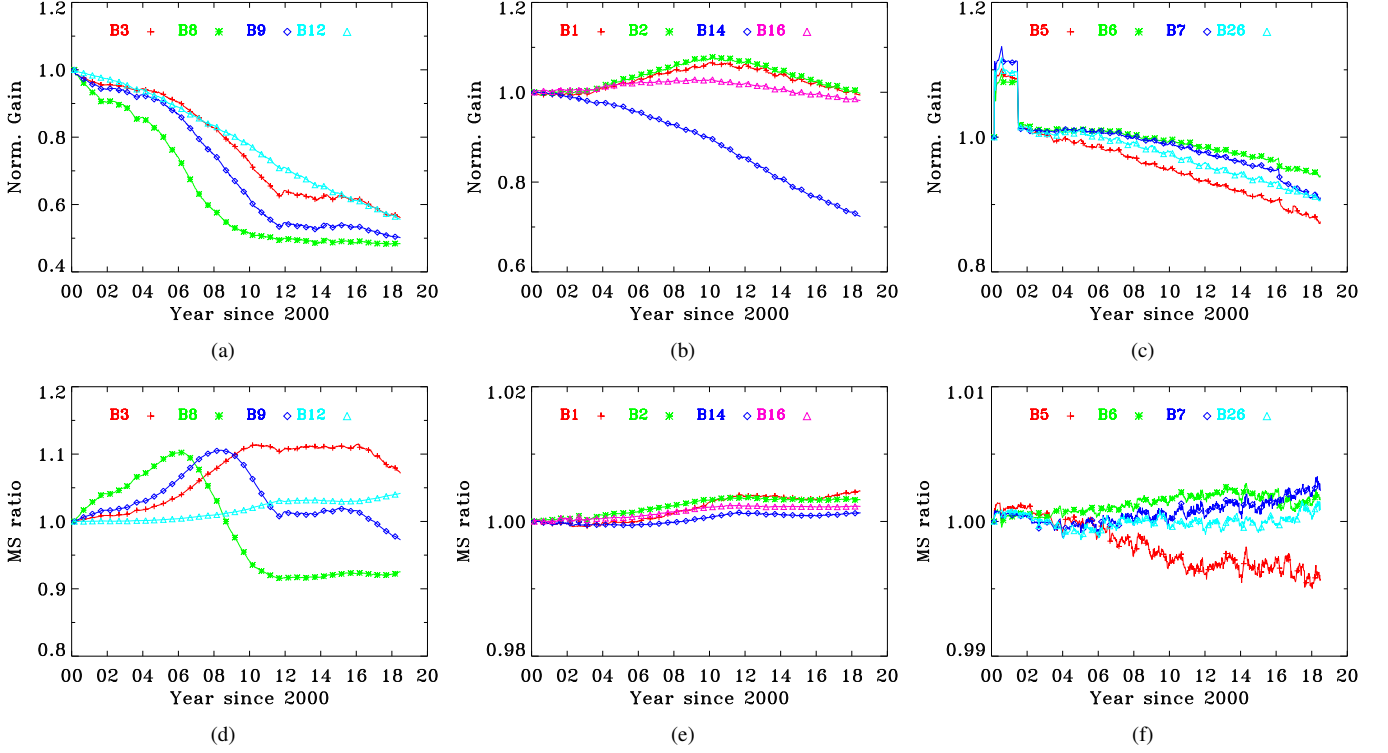


Fig. 5. Terra MODIS RSB on-orbit gain changes from SD observations (band-averaged, mirror side 1 only) for select (a) VIS bands, (b) NIR bands, and (c) SWIR bands. Bottom row plots show the mirror side ratios of RSB gains from SD observations for (d) VIS bands, (e) NIR bands, and (f) SWIR bands.

SWIR crosstalk correction. As discussed earlier, the safe-mode anomaly that occurred in Feb 2016 did impact the TEB crosstalk and in turn the performance of the SWIR bands. More details about these impacts and mitigation strategies are discussed in Section VI.

Figure 6 shows similar plots of the normalized gains and mirror side ratios from the SD calibration data for Aqua MODIS VIS, NIR, and SWIR bands. In general, the gains for Aqua have had smaller on-orbit changes compared to Terra, but show some similar patterns. The largest changes in gain happen for the short wavelength VIS bands, with band 8 and band 9 gains dropping to 67% and 78%, respectively, by September 2018 compared to the values at mission start. Also similar to Terra MODIS, bands 1 and 2 both show an increase in gain of more than 10% over the mission, but all other NIR and SWIR bands have experienced very minimal gain changes. The mirror side ratios for Aqua MODIS have been much more stable than for Terra MODIS, with all bands changing less than 3% on-orbit and most bands changing by much less than 1%.

C. RVS performance

The variation of the gain as a function of AOI on the scan mirror, the RVS, was characterized prelaunch for all RSB and is band and mirror side dependent, with some short wavelength bands also exhibiting detector dependence. On-orbit changes are monitored primarily using measurements from SD and the Moon acquired at two different AOI. A linear approximation for the response change between these two AOIs is used to estimate the on-orbit RVS. Figure 7

compares the gains as measured from the SD observations and the lunar observations for two representative bands of Terra MODIS, bands 3 and 8. Also shown for reference is the change in gain derived from Earth-view data from pseudo-invariant calibration sites (PICS) in the Libyan desert at one example AOI near nadir. The divergence of the SD and lunar trends with time indicates that the RVS is not constant on orbit. Bands 8 and 3, in addition to band 9, are the shortest wavelength RSB on MODIS and in addition to showing the largest changes in SD reflectance and instrument gain, they show the largest changes in RVS. Figure 8 shows similar trends for these bands on Aqua MODIS.

A majority of RSB continue to perform reasonably using the on-orbit RVS derived solely based on the on-board SD and lunar calibrations. However, as the instruments continue to operate over a decade beyond their designed life, some short wavelength RSB have required supplemental inputs from desert PICS. In Figures 7 and 8, it is clear that a linear approximation of the RVS from the SD and Moon is not adequate for bands 3 and 8, as the EV-based gain trends at nadir are not consistent between the SD and Moon trends. This approach, used for bands 1-4, 8, and 9 of both instruments as well as band 10 of Terra MODIS, tracks the instrument gain change at multiple AOIs using the response trends from the Libya 4, Libya 2, and Libya 1 sites [25], [26]. Figures 9 and 10 show the normalized gains for bands 8 and 3 as a function of AOI at different times throughout the mission. The gains (RVS/m_1) are normalized to their values at the SD AOI (50.2°) at mission start. The shape of the RVS curves change along with the overall gain levels as the missions progress.

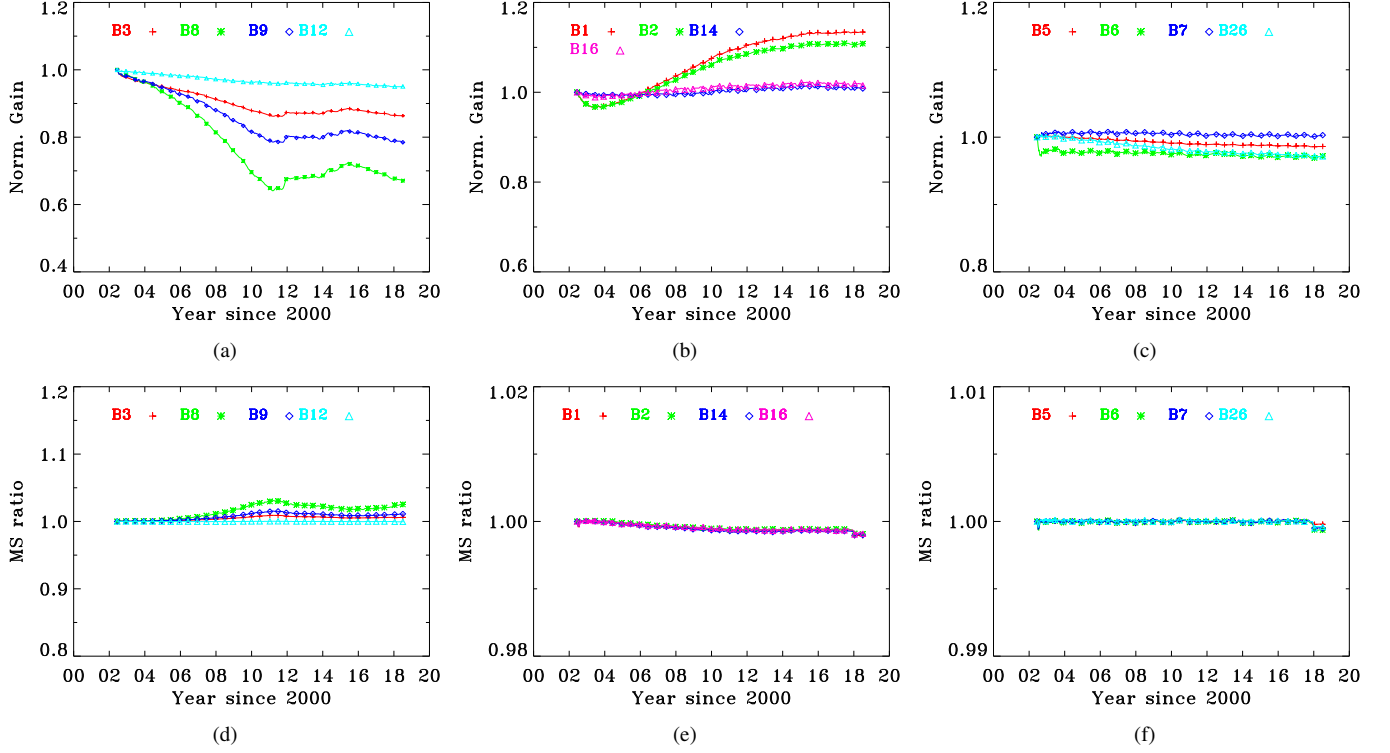


Fig. 6. Aqua MODIS RSB on-orbit gains from SD observations (band-averaged, mirror side 1 only) for select (a) VIS bands, (b) NIR bands, and (c) SWIR bands. Bottom row plots show the mirror side ratios of RSB gains from SD observations for (d) VIS bands, (e) NIR bands, and (f) SWIR bands.

These representative RVS curves are taken at a similar time of each year to mitigate changes due to seasonal fluctuations. Note that for bands 8 and 3 in Figures 9 and 10, the on-orbit gains derived from the desert PICS trends at the SD AOI deviate from the long-term trends from the SD observations shown in Figures 7 and 8. This discrepancy, in addition to the non-linear change in gain with AOI seen in Figures 9 and 10, demonstrates the need for the Earth-view based calibration approach for these bands.

For some bands, particularly bands 8-12, the on-orbit RVS has exhibited a detector-dependence, therefore the detector differences in the gain from SD and lunar measurements are used to derive on-orbit detector-dependent RVS. Implementation of a detector-dependent RVS has resulted in reduced striping in the calibrated Earth-view products.

D. Detector noise characterization

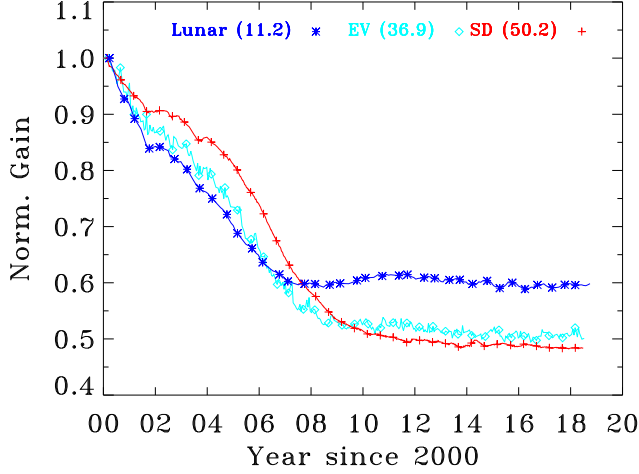
Figures 11 and 12 present the band-averaged prelaunch and on-orbit SNR values at L_{typ} compared against the SNR specification for Terra and Aqua MODIS RSB, respectively. Each figure shows the yearly-averaged results for select years as compared to the SNR specification for each band, with both instruments having the same specifications. Tables III and IV provide the band-averaged prelaunch SNR values along with two on-orbit SNRs performed early and late in the mission for the Terra and Aqua RSB, respectively. Due to the Terra MODIS SDD anomaly in 2003, the SNR values shown in Figure 11 and Table III are calculated using the SD calibration events performed with the screen in the closed position, while the Aqua SNR values shown in Figure 12 and Table IV are

calculated using the SD calibration events performed with the screen in the open position.

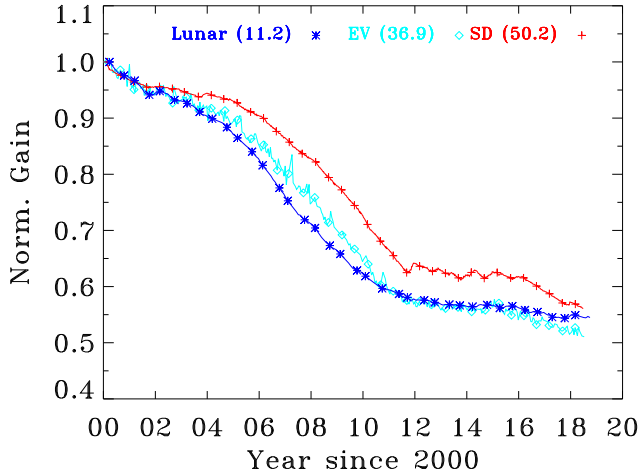
TABLE III
SNR SPECIFICATION AND SELECTED RESULTS FOR TERRA MODIS RSB.

Band	Specification	Prelaunch	2002/02/24	2018/07/10
1	128	172	192	198
2	201	418	485	521
3	243	309	337	206
4	228	310	340	228
5	74	114	89	81
6	275	393	363	343
7	110	70	103	91
8	880	906	1008	634
9	838	1148	1220	822
10	802	1099	1106	978
11	754	1154	1074	1119
12	750	983	963	754
13	910	1064	1012	1127
14	1087	1253	1091	958
15	586	756	972	1057
16	516	712	890	942
17	167	359	368	314
18	57	92	98	99
19	250	465	524	473
26	150	213	252	239

A majority of the RSB on both MODIS instruments continue to meet their design specifications, with the exception of some short-wavelength bands. The SNR of band 8 for both instruments is seen to be below the specification during recent years due to the decrease in the detector response. A similar behavior is also observed in the case of bands 3 and 9 on Terra MODIS. The noisy and inoperable detectors are excluded from the band-average RSB SNR characterization for both

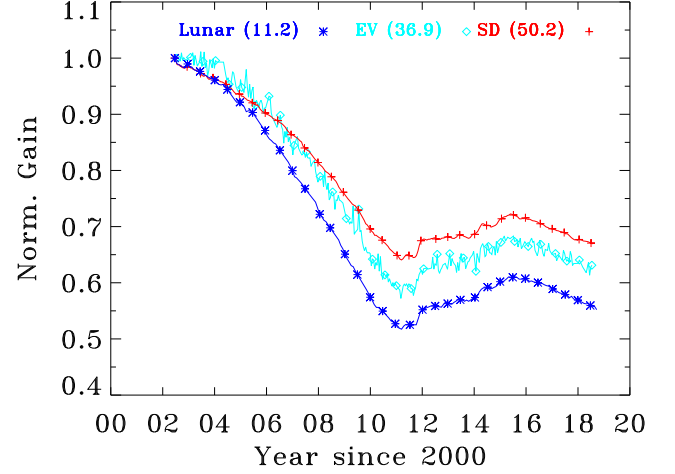


(a)

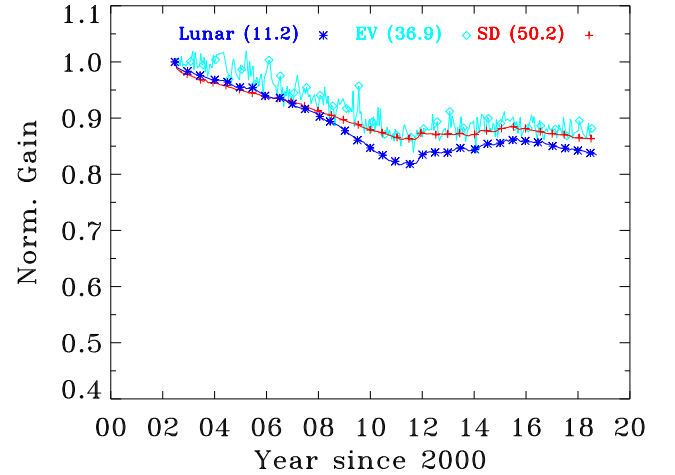


(b)

Fig. 7. Normalized on-orbit gains from the SD, lunar and EV observations used in the on-orbit RVS characterization for Terra MODIS (a) band 8 and (b) band 3.



(a)



(b)

Fig. 8. Normalized on-orbit gains from the SD, lunar and EV observations used in the on-orbit RVS characterization for Aqua MODIS (a) band 8 and (b) band 3.

MODIS instruments. However, Terra band 7 is an exception, since all twenty detectors have been classified as noisy since pre-launch measurements as the SNR was seen to be below the specification. In the case of Aqua MODIS, only one noisy detector in band 6 was identified prelaunch. However, eight detectors in band 6 and one detector in band 5 were identified as inoperable during the prelaunch characterization. The inoperable Aqua detectors in band 6 have a significant impact on the MODIS snow products, which use the band 6 response for snow detection. Therefore, Aqua band 7 has been used in these downstream products for global detection of snow coverage [27].

E. Long-term reflectance trending

The long-term accuracy of the calibrated gains of the MODIS RSB can be evaluated using a variety of Earth targets. Analyses have previously been presented using desert PICS [25], [26], deep convective clouds (DCC) [28],[29] [30] and inter-comparison with other remote sensing instruments, [31],

[32], [33] all of which generally show stable performance for the C6.1 L1B product. Figure 13 shows examples of long-term normalized reflectance trends from Libyan desert PICS for a few different AOI of Terra and Aqua MODIS band 8. The reflectance is calculated using Eq. 1 with dn averaged over a small area of the desert site and the m_1 and $RV S_{EV}$ from the C6.1 L1B, and then normalized to mission start. For AOI near the beginning of scan (10.5°) and near nadir (38°), the normalized reflectance is constant throughout the mission for both instruments, to within the noise of the measurements. For AOI near the end of scan (65.5°), there is larger noise in the reflectance trend, particularly for Terra MODIS where there are significant seasonal fluctuations.

These fluctuations are due to changing polarization sensitivity of the Terra MODIS scan mirror with time. They are most significant for the short wavelength VIS bands 8, 9, and 3 due to the larger impact of atmospheric Rayleigh scattering at these wavelengths and at large scan angles. Prelaunch analysis showed that the MODIS RSB are sensitive to the polariza-

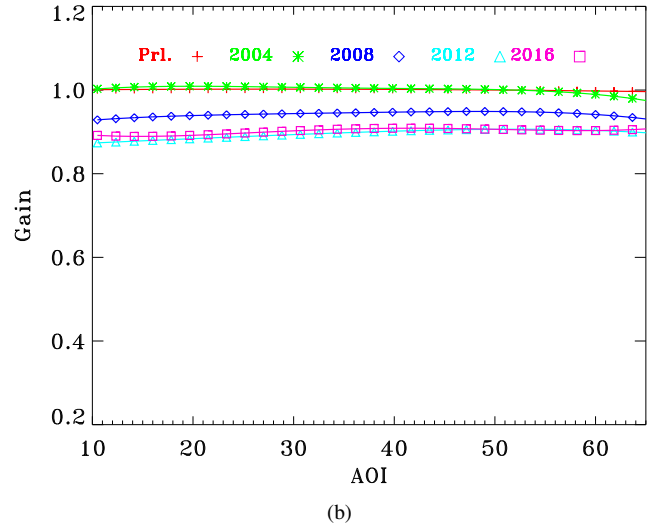
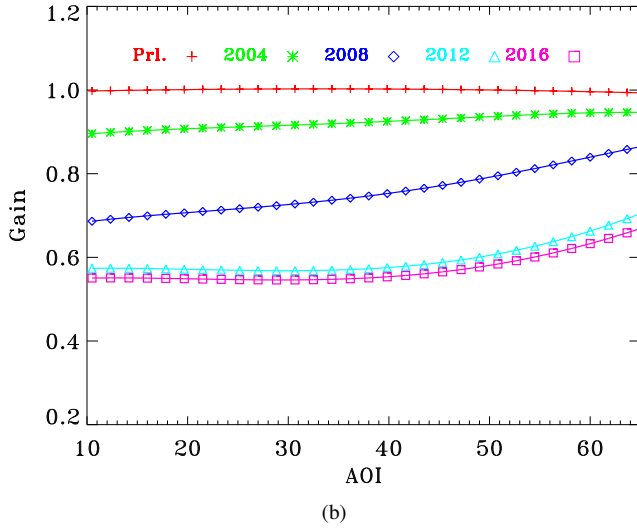
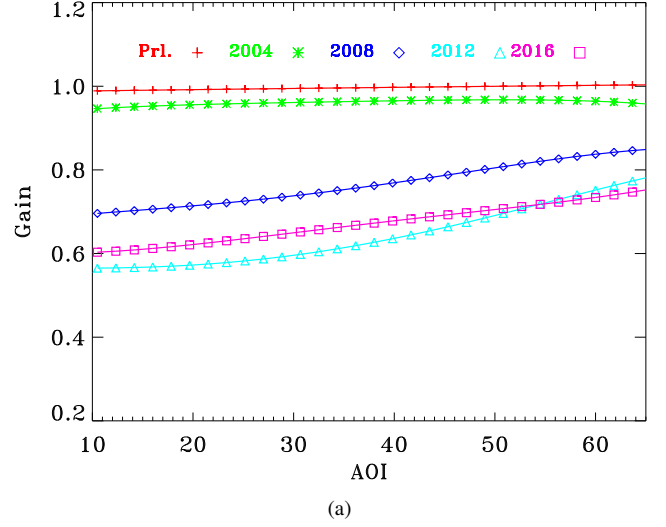
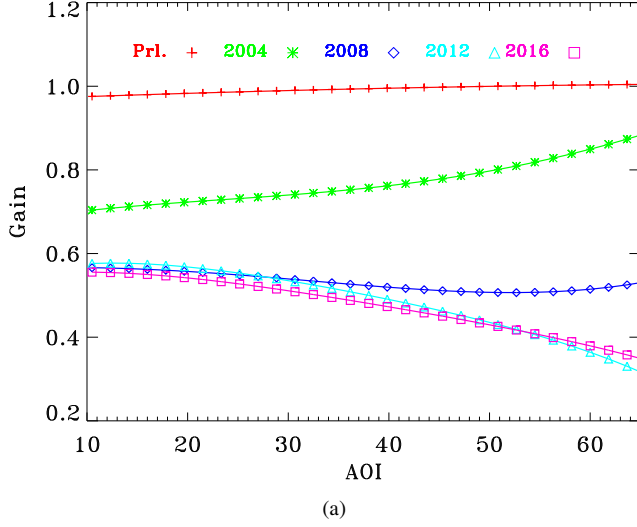


Fig. 9. Normalized gains vs AOI from representative timelines in the mission for Terra MODIS (a) band 8 and (b) band 3.

Fig. 10. Normalized gains vs AOI from representative timelines in the mission for Aqua MODIS (a) band 8 and (b) band 3.

TABLE IV
SNR SPECIFICATION AND SELECTED RESULTS FOR AQUA MODIS RSB.

Band	Specification	Prelaunch	2002/06/13	2018/07/02
1	128	182	202	227
2	201	446	515	565
3	243	316	326	289
4	228	308	327	323
5	74	149	151	145
6	275	132	502	489
7	110	141	152	156
8	880	977	1137	780
9	838	1391	1587	1293
10	802	1307	1583	1423
11	754	1282	1757	1701
12	750	1185	1550	1505
13	910	1210	1432	1527
14	1087	1207	1557	1618
15	586	1078	1581	1604
16	516	944	1464	1484
17	167	251	370	371
18	57	88	90	94
19	250	381	506	512
26	150	224	279	279

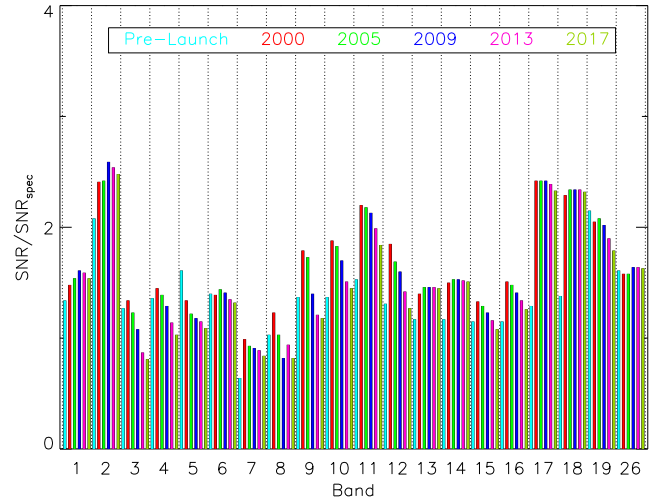


Fig. 11. On-orbit SNR for Terra MODIS RSB.

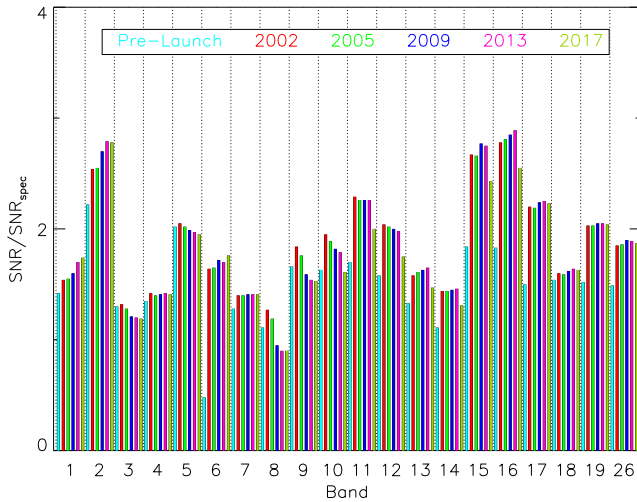


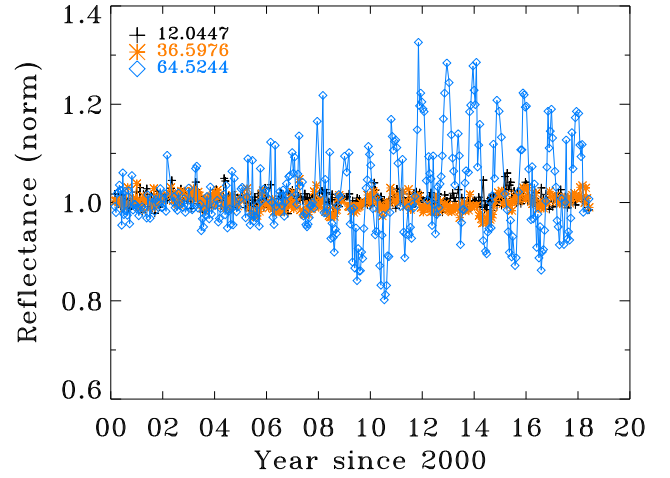
Fig. 12. On-orbit SNR for Aqua MODIS RSB.

tion of the incident light, particularly at short wavelengths. Furthermore, it was evident that the polarization sensitivity increases with the AOI on the scan mirror with expected impacts up to $\pm 5\%$ on the observed TOA radiance radiance for the shortest wavelength band 8 [34]. A significant difference in the polarization sensitivity between the two mirror sides was also observed. Although the results from the polarization sensitivity observed prelaunch were consistent between the two MODIS instruments, considerable evidence on-orbit shows that the polarization sensitivity for Terra MODIS has changed significantly, whereas Aqua MODIS continues to show a stable behavior. Due to severe impacts on the dark ocean scene measurements, the Ocean Biology Processing Group (OBPG) at NASA Goddard Space Flight Center has developed a vicarious calibration approach using SeaWiFS and Aqua MODIS as a reference to isolate the impacts due to changes in the polarization sensitivity [35], [36]. Methods for improving the calibration to correct for the polarization impact are discussed more in Section VI.

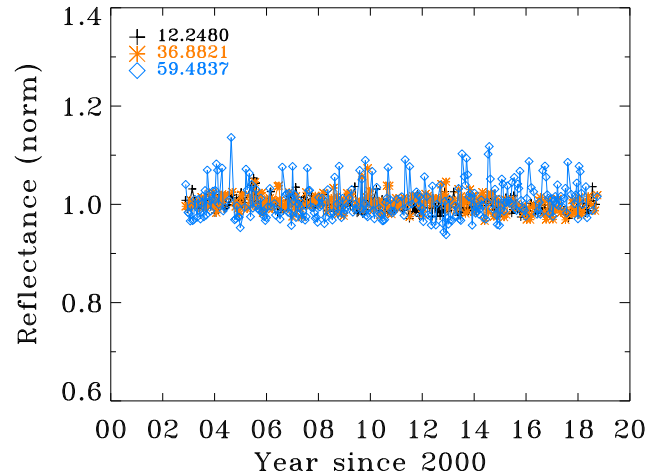
Since the mission beginning, ground-based test sites have also been used to validate the MODIS reflectance data products. The Remote Sensing Group at University of Arizona has employed a reflectance-based calibration approach at the Railroad Valley Playa, Nevada site and results from this method shows agreement between the two MODIS sensors to better than 5% [37].

V. CALIBRATION UNCERTAINTY

As stated earlier, the accuracy requirements for the MODIS RSB are $\pm 2\%$ in reflectance and $\pm 5\%$ in radiance for angles within $\pm 45^\circ$ and radiance near the typical radiance. An additional 1% uncertainty is allowed for scan angles outside this range and for radiance levels from 0.3 times the typical radiance to 0.9 times the maximum radiance. To meet these requirements, the uncertainty in each component of the MODIS calibration algorithm was measured in prelaunch testing and continues to be assessed on-orbit [38]. The changes in the calculation of the calibration uncertainty have to be



(a)



(b)

Fig. 13. Long-term reflectance trending for (a) Terra and (b) Aqua MODIS band 8 at representative AOI from Libyan desert PICS.

made every time there is an update to the calibration algorithm. A recent publication gave a comprehensive review of the calculation of MODIS RSB uncertainty from prelaunch measurements through the latest on-orbit calibration strategies, and a summary of the MODIS uncertainty performance [39]. Most MODIS bands calibration accuracy is below the $\pm 2\%$ requirement throughout the mission, though there are some exceptions, particularly for the short-wavelength bands that currently rely on desert targets for calibration. This section summarizes the MODIS RSB uncertainty performance.

The solar diffuser calibration provides the baseline reflectance measurement that is used to derive the absolute reflectance of the MODIS RSB. Even for the bands where the on-orbit changes in gain at the SD AOI are tracked by the desert site observations, in place of the SD, the initial on-orbit SD measurements are still used as the absolute reference. Thus, the uncertainty calculation is generally split into terms relating to the uncertainty in the initial SD measurement and terms relating to the uncertainty in the relative on-orbit trends.

The EV reflectance, Eq. 1, can be rewritten as

$$\rho_{EV}(t, AOI) \cdot \cos(\theta_{EV}) = \frac{dn_{EV} \cdot (1 + k_{Inst}(T_{Inst_EV} - T_{Ref}))}{d_{ES_EV}^2 \cdot \frac{m_1(t=0)}{RV S_{pl}(AOI)} \cdot \frac{m_1^{oo}(t)}{RV S^{oo}(t, AOI)}}, \quad (7)$$

where $m_1(t=0)$ is from the initial on-orbit SD calibration, $RV S_{pl}$ is the prelaunch RVS, and m_1^{oo} and $RV S^{oo}$ are the on-orbit changes. For all RSB and all of the calibration algorithms described in Section III, the first four terms on the right hand side of Eq. 7 are calculated in the same way, and only the last term describing the on-orbit change is calculated differently.

To determine the relative uncertainty in the EV reflectance factor, a standard uncertainty analysis is performed considering every term in Eq. 7. The dominant factor for most RSB throughout the missions is the uncertainty in $m_1(t=0)$, which is in turn dominated by the uncertainty in the prelaunch measured SD BRF, ρ_{SD} . The SD was characterized extensively in prelaunch measurements in order to have a calibrated reflectance measurement traceable to NIST standards with a well understood uncertainty. The prelaunch SD BRF measurement was determined to have an uncertainty of 1.37% ($k=1$) for all RSB.

The uncertainty in the on-orbit change of m_1 and RVS is different for bands that use the algorithm based on on-board calibrators (SD and lunar observations) compared to bands that use the EV-based calibration algorithm. The uncertainty in the on-orbit trends of the SD and lunar measurements are generally quite small, much less than 1%, and are relatively stable on-orbit. The data from the desert sites used to derive the on-orbit gains of the short-wavelength bands are considerably noisier than the OBC data, and thus the uncertainty in the on-orbit trends is higher, in the range of 1% to 3% depending on band, AOI, and time during the mission. The uncertainty contributions from the temperature correction term are generally very small, as the instrument temperature typically varies by only about 1 K over a yearly cycle and even less on orbital and daily timescales (see Ref. [12] for MODIS temperature performance data). The uncertainty in the Earth-Sun distance is negligible.

Lastly, the scene-dependent uncertainty in the measured EV signal, dn_{EV} , must be included. This term is simply the inverse of the instrument SNR as described in Section IV. This uncertainty term is calculated separately for each individual pixel based on the measured dn_{EV} and a set of coefficients, derived from the SD calibrations, to relate the dn_{EV} to the instrument noise.

Figure 14 and Figure 15 show the relative EV reflectance uncertainty for each RSB of Terra and Aqua MODIS, respectively, for mirror side 1 at nadir and at typical radiance. For most RSB, the uncertainties are stable over the mission and below the 2% requirement. Exceptions are the bands that use EV-based calibration of the on-orbit gain (Terra and Aqua bands 1-4, 8, and 9, and Terra band 10) due to the noise in the EV measurements. Terra bands 5 and 7 also exceed the specification due to their relatively low SNR. The uncertainties

for all bands decrease for higher radiances and increase for lower radiances due to the impact of the instrument SNR. The uncertainties are fairly stable across AOI for most bands; though some of the bands that use EV-based calibration show increased uncertainty at large AOI due to increased noise from atmospheric effects in the EV data. In the case of Terra bands 3, 8, and 9, an increase in noise due to changes in polarization sensitivity also increases the uncertainty at large AOI. Results at other AOI and radiance levels and other special uncertainty considerations are discussed in [39].

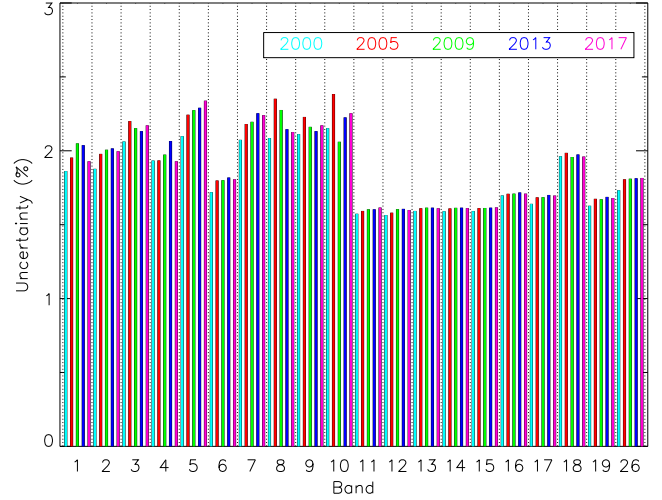


Fig. 14. Uncertainty of Terra MODIS reflectance for mirror side 1 at nadir at typical radiance.

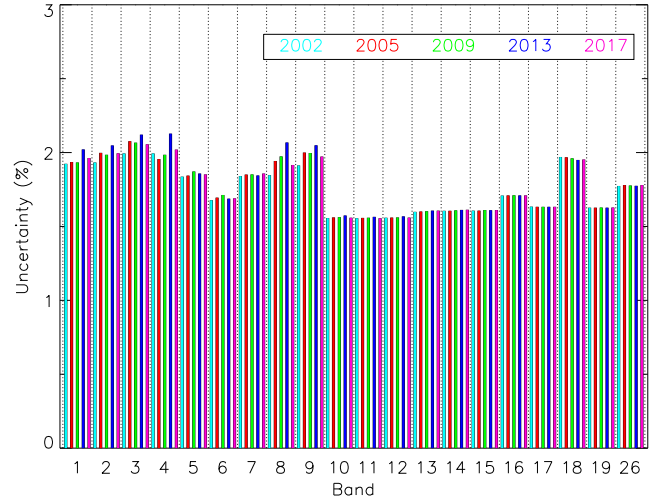


Fig. 15. Uncertainty of Aqua MODIS reflectance for mirror side 1 at nadir at typical radiance.

VI. CHALLENGING ISSUES AND FUTURE IMPROVEMENTS

Many lessons have been learned from the prelaunch and on-orbit calibration and characterization activities of the two MODIS instruments. Various challenging issues, their mitigation strategies and future improvements are discussed in this section. The SD BRF is characterized as a function of solar

illumination and sensor viewing angles. Studies evaluating the SD degradation uniformity (within the sweet spot) revealed an angular dependence in the degradation particularly for the short wavelength bands. The SDSM, designed to track the on-orbit changes in the SD's BRF, views the backward-scattered sunlight from the SD. In contrast, the MODIS detectors via the scan mirror, observe forward-scattered sunlight from the SD. Terra MODIS has been on-orbit for nearly two decades and its SD has experienced significant degradation at short wavelengths, particularly after the SD door anomaly from July 2003. The issue is further complicated by the presence of the fixed SDS in the case of Terra MODIS. A long-term drift in the EV reflectance trending from the desert sites at the SD AOI points to a likely difference in the SD degradation as observed by the SDSM (backscatter direction) and by the MODIS detectors (forward scatter direction). As pointed out earlier, this has significant impact only at short wavelengths and the issue is mitigated by the use of Earth-view response trending at the SD AOI. Nevertheless, a careful inspection of this issue is warranted to further enhance the RSB calibration algorithm.

The primary cause of the SD degradation is due to exposure to UV radiation. Laboratory testing of Spectralon diffuse reflectance material confirmed this behavior, also showing that the short wavelengths are more prone to degradation. The analysis also showed that minimal degradation was observed for wavelengths greater than $1\ \mu\text{m}$ for over 100 hours of solar exposure [40]. As discussed earlier, the MODIS SDSM's spectral coverage limits it from tracking the degradation at wavelengths greater than $0.94\ \mu\text{m}$ (SDSM D9 wavelength). In the case of Terra MODIS, where the rate of solar exposure increased after the 2003 SD door anomaly, the degradation at wavelengths beyond $1\ \mu\text{m}$ needs to be carefully monitored. From the SDSM measurements, the Terra SD showed a degradation of up to 2% at $0.94\ \mu\text{m}$ by twelve years after launch [41]. Therefore, unaccounted SD degradation at SWIR wavelengths, particularly for band 5, is expected and needs to be corrected. Similar to the short-wavelength bands, the Libyan Desert sites were used to monitor the long-term reflectance trends from bands 5, 6 and 7. An upward drift of about 1.2% for Terra band 5 confirmed the inadequate SD degradation applied at these wavelengths. However, due to the noisy response of the desert sites observed in bands 6 and 7 and the inability to monitor band 26 (cirrus band, $1.3\ \mu\text{m}$) using desert sites, DCC were also adopted as a source to monitor the long-term performance of the MODIS SWIR bands [42]. In recent years, significant efforts have been undertaken to characterize the DCC as an effective and viable alternative to the desert sites. The DCC are the coldest natural targets in the tropics that are identified using a brightness temperature (BT) threshold from an infrared band. Their long-term trends, that also showed an upward drift, reaffirmed the unaccounted degradation for the SWIR bands. As a result, an empirical approach that predicts the SD degradation for the SWIR bands using the degradation estimates from the NIR bands has now been employed for both instruments. Unlike Terra MODIS, Aqua MODIS shows minimal degradation at SWIR wavelengths [24].

The bands on the Terra MODIS VIS FPA that share a

common Analog to Digital Converter (ADC) (bands 3, 4, 8-12) have shown a tendency to exhibit uneven distribution of the ADC bins. Prelaunch testing showed uneven distribution of the ADC bins when measuring the responses from these bands. Particularly, the output from the ADC favors odd multiples of 64 over values within the neighboring bit (8 DN). This artifact bears an impact on all the sectors (i.e. EV, SD, SV), but noticeable impact has been observed as the response of the instrument continues to degrade, particularly for the on-board calibrator response (SD and SV) for these bands. An update to the on-board tables was made in December 2017 and March 2018 to raise the minimum DN level or to move away from the most serious uneven bins for these bands therefore resulting in an improved short-term stability of the gain characterization. The Earth-view calibrated products did not show any impacts due to this update.

Although the RSB are primarily calibrated using an unpolarized source (the SD), supplemental inputs like the Earth-view response trends used in the RVS characterization are impacted by the Earth scene polarization. In C6.1, the EV desert trends are uncorrected for polarization and therefore result in additional uncertainties in the characterization of the RVS, particularly at large AOIs for short wavelength bands. An approach that uses the standard polarization correction equation in combination with simulated at-sensor radiances using the 6SV [43] code is used to derive the correction for the response trends from the EV desert sites before RVS characterization. The correction parameters derived from this approach are in reasonable agreement with those provided by NASA OBPG. Although the corrected response trends show improved trending, along with reduced uncertainties in the forward prediction, a careful assessment of its impact on the radiometric accuracy of the calibrated product is warranted before adopting this approach in forward production [44].

The on-orbit RVS characterization for the short wavelength RSB employs the use of desert PICS to supplement the on-board calibrator measurements. The initial on-orbit SD calibration continues to provide the absolute reference, and the gain derived from lunar and EV measurements tracks the on-orbit changes in the gain at different AOI. The current EV-based RVS approach relies on the temporal fitting of the EV data from different sites/AOI and an AOI-based fitting thereafter. Hence, a large emphasis is placed on the temporal stability of the ground sites used in the characterization. The TOA reflectance from the calibrated products (C6.1), which uses this approach, continues to show excellent long-term stability, therefore confirming the validity of this assumption. However, with the stringent requirements on the RSB calibration uncertainty budgets, a close examination of alternative RVS characterization strategies is warranted. One such approach, which has been developed in recent years, uses a site-independent approach to derive the EV-based RVS. In this approach, response trends from a single site (Libya 4) are modeled as a function of AOI on a monthly basis, with the modeled profile from the same month over multiple years used to derive the time-dependence of the RVS. Currently, this approach has been shown to produce comparable results with the existing C6.1 algorithm [45], [46].

Some of the high-gain ocean bands (bands 11-16) pose an additional complexity in the EV-based RVS characterization, as they typically saturate while viewing a high-radiance desert target. Consequently, an alternative interband-calibration approach has been developed to overcome this limitation. In this approach, a spectrally-matching stable reference band is chosen to track the long-term stability of these high-gain ocean bands over non-saturated ocean sites. Results show that the on-board calibrator based approach continues to be sufficiently accurate in characterizing the on-orbit RVS changes for a majority of bands. Of notable exception are bands 11 and 12 of Terra MODIS that see a long-term reflectance drift (1-2%) at nadir and SD AOI. The EV-based approach using the measurements from this interband-calibration has already been formulated and implemented. The improvements from this approach were confirmed after comparison with the NASA OBPGs cross-calibration coefficients and will be considered for a future implementation.

The MODIS RSB performance trends presented in Section IV are the average performance of all detectors within a band. But it is also important to accurately calculate the gains and evaluate the calibration at the individual detector level, as errors in the gain differences between detectors can lead to unwanted striping in the L1B images and downstream products. For all RSB, the gain differences between detectors are initially calculated from the SD calibration. This is true even for bands that use desert sites trends to adjust the average gain of the band; the gain differences between detectors are still based on the SD calibration. But the SD may not be a reliably uniform calibration source, due to incomplete characterization of the screen vignetting function or spatially dependent degradation of the SD surface, for example. For some bands (Terra 3,8-12; Aqua 8-12), we apply a time-independent correction based on analysis of uniform ocean scenes to help improve the detector level calibration. As already noted in Section IV, we also apply a detector-dependent RVS for some bands. These corrections help to reduce the observed L1B image striping. For the short-wavelength VIS bands, the polarization characterization from prelaunch showed strong detector dependence that is most evident at large AOIS [34]. Furthermore, some detector-detector differences in the Earth-view imagery at large AOI are expected due to the solar illumination geometry. A more comprehensive evaluation for all bands, using multiple Earth and calibrator scenes, could further improve the detector level calibration in the future.

Prelaunch measurements of both MODIS instruments showed non-negligible OOB response in the SWIR bands. The OOB response is known to be a combination of optical leak at $5.3\ \mu\text{m}$ and electronic crosstalk from the MWIR bands. The electronic crosstalk in the Terra LWIR PV bands, which includes band 28, has increased in magnitude over the mission lifetime, with a significant increase after the Feb 2016 safe mode event. This also bears an impact on the SWIR band calibration that uses band 28 as a representative crosstalk sending band. A crosstalk correction algorithm based on lunar observations has been successfully implemented in C6.1 to mitigate the impacts on the LWIR bands caused by the crosstalk. Work is underway to mitigate these impacts by (1)

correcting the representative sending band (band 28) response for electronic crosstalk before the SWIR band radiometric calibration process is performed, and (2) choosing band 25 as the representative sending band (similar configuration as Aqua). Preliminary results show both approaches can effectively reduce the impact due to LWIR crosstalk. The approach with band 25 as a representative crosstalk sending band presents a more simplistic implementation due to the absence of any major electronic crosstalk impacts in the MWIR bands and will be considered for implementation in the next L1B version[47].

VII. SUMMARY

The MODIS L1B employs a reflectance-based calibration for the RSB using a SD with its BRF characterized prior to launch, and monitored on-orbit using a SDSM. Since launch, the MODIS RSB calibration performance has been satisfactory, meeting the 2% specification for reflectance uncertainty in most cases. Measurements from regular solar and lunar observations have provided necessary information to track the on-orbit changes in the response (gain) and RVS for a majority of RSB, therefore allowing high-quality LUTs to be continuously derived and updated. As the missions have operated over a decade beyond their design life, supplemental information from some pseudo-invariant desert sites is required for accurate characterization of gain and RVS for the short wavelength spectral bands. The degradation of the SD and the changes in the scan mirror reflectance have been primarily in the VIS spectral region with Terra MODIS bands showing more degradation than Aqua MODIS. The VIS and NIR band detectors of both instruments continue to perform well, with no detectors identified as noisy or inoperable. There also have been no new noisy or inoperable detectors identified in the SWIR bands since launch, with the exception of Aqua band 6. The detector SNRs of the RSB remain above specification, except for some of the short wavelength RSB in recent years due to the continued optical degradation at these wavelengths. Several potential improvements to the RSB calibration have been identified and will be considered for future L1B versions. These include applying a polarization correction to Terra data from desert PICS to improve the accuracy of gain trends derived from these sites, improving the OOB/crosstalk correction applied to the SWIR bands, and extending the use of EV data for calibration to some of the ocean color bands, as necessary, via an interband calibration approach. The calibration efforts made by the MODIS Characterization Support Team (MCST) at NASA Goddard Space Flight Center is instrumental to continuously maintain the data product quality via regular LUT updates that correct for various instrumental effects.

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