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Abstract. The Moderate Resolution Imaging Spectroradiometer (MODIS), launched on the Terra and Aqua spacecrafts, was designed to collect complementary and comprehensive measurements of the Earth's properties on a global scale. The 20 reflective solar bands (RSBs), covering a wavelength range from 0.41 to 2.1 μm, are calibrated on-orbit using regularly scheduled solar diffuser (SD) observations. Although primarily used for on-orbit gain derivation, the SD observations also facilitate the characterization of the detector signal-to-noise ratio (SNR). In addition to the calibration requirement of 2% for the reflectance factors and 5% for the radiances, the required SNRs are also specified for all RSB at their typical scene radiances. A methodology to characterize the on-orbit SNR for the MODIS RSB is presented. Overall performance shows that a majority of the RSB continue to meet the specification, therefore performing well. A temporal decrease in the SNR, observed in the short-wavelength bands, is attributed primarily to the decrease in their detector responses. With the exception of the inoperable and noisy detectors in band 6 identified prelaunch, the detectors of Aqua MODIS RSB perform better than Terra MODIS. The approach formulated for on-orbit SNR characterization can also be used by other sensors that use on-board SDs for their on-orbit calibration (e.g., Suomi National Polar-Orbiting Partnership [SNPP]-Visible Infrared Imaging Radiometer Suite). [DOI: 10.1117/1.JRS.9.094092]

Keywords: Moderate Resolution Imaging Spectroradiometer; radiometer; calibration; solar diffuser; signal-to-noise ratio; solar diffuser degradation.

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1 Introduction

The sensitivity of satellite sensors, both prelaunch and on-orbit, is commonly expressed via its signal-to-noise ratio (SNR). Prior to their launch in December 1999 and May 2002, both Moderate Resolution Imaging Spectroradiometer (MODIS) instruments were extensively characterized at Raytheon Santa Barbara Remote Sensing, Goleta, California. The SNR for the reflective solar bands (RSB) is a key sensor performance metric, which since its prelaunch characterization has been regularly monitored to ensure the fidelity of the on-orbit calibration to the prelaunch measurement.[1] The SNR measures the intrinsic detector variations in its digital number output for a stable input radiance source. Although maximizing the SNR is a fundamental goal of remote sensing, on-orbit degradation of optical systems, electronic systems, and detectors presents a significant challenge. The SNR is one of the key parameters to determine the precision of the ocean color products, such as surface chlorophyll-a concentration.[2] Although it is always desirable to achieve a high SNR, a limited dynamic range of sensors may result in lower saturation radiances as a result. One of the primary radiometric drivers of the MODIS design was the high-SNR requirement for the ocean color and ocean fluorescence visible (VIS) and

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near-infrared (NIR) solar channels.[2] Table 1 provides a summary of the key design specifications for the MODIS RSB including the center wavelengths, bandwidth, detector's nadir instantaneous field of view, typical scene radiance (L_{typ}), and SNR.[3]

The RSB on both MODIS instruments, covering a wavelength range from 0.41 to 2.1 μm, has been collecting data on a nearly continuous basis since launch. The MODIS RSB employs a reflectance-based calibration, using a solar diffuser (SD) and the solar diffuser stability monitor (SDSM) to monitor the SD's on-orbit degradation.[3] Given the large scan-angle range of MODIS (± 55 deg), the response variation as a function of scan angle needs to be considered. The correction for response versus scan-angle (RVS) is derived using near-monthly lunar measurements and regular SD measurements, supplemented by earth-view response trends for some short-wavelength bands.[4–8] Since launch, the short-wavelength MODIS RSB has experienced large scan-angle dependent gain changes. In the case of Terra MODIS bands 1 to 4, 8 to 10, and Aqua MODIS bands 8, 9, the earth-view responses from pseudoinvariant North African desert sites are used to supplement the on-orbit measurements from the SD and the moon.[9] The calibration requirements for the MODIS Level 1B (L1B) products are 2% for reflectance and 5% for radiance in the ± 45 deg scan-angle range.[7]

Prior to launch, most sensors undergo intensive prelaunch characterization, and the SNR is one of the most important parameters to be considered.[6] The response of the sensor to a known input radiance in a controlled environment is used to characterize the SNR. However,

Table 1 Key design specifications for the Moderate Resolution Imaging Spectroradiometer (MODIS) reflective solar band.

Band	CW (μm)	IFOV (km)	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	
17	0.905	1.0	10.0	167	Atmospheric water vapor
18	0.936	1.0	3.6	57	
19	0.940	1.0	15.0	250	
26	1.375	1.0	6.0	150	Cirrus clouds water vapor

Note: CW, center wavelength; IFOV, instantaneous field of view; SNR, signal-to-noise ratio.

transferring this ability on-orbit presents a great challenge. Sensors, such as MODIS or SeaWIFS, have an advantage of being equipped with an on-board SD, the responses of which to the observed solar irradiances can be used to characterize the on-orbit SNR.[10] In the case of Operational Land Imager aboard the Landsat-8 spacecraft, the total sensor noise is determined at the dark level of the instrument as well as at the various illumination levels provided by the lamps and on-board SD.[11]

Algorithms to evaluate the performance of the MODIS RSB, in terms of compliance with the specification, have been implemented since launch.[1–6] This paper provides a brief overview of RSB on-orbit calibration approach and in-depth description of SNR characterization methodology, along with the on-orbit SNR performance. Section 2 revisits the prelaunch characterization for MODIS, with the focus on SNR. Also, a brief description of the on-orbit calibration mechanism is presented. The formulation of the on-orbit approach to characterize the MODIS RSB SNR is presented in Sec. 3, with the results and related discussion in subsequent sections. Results from Terra MODIS (15 years on orbit) and Aqua MODIS (12.5 years) show that both sensors and their onboard calibrators have been performing well and, with the exception of a few short-wavelength RSB bands later in the mission, have met their overall design specifications.

2 MODIS Reflective Solar Bands Calibration

Due to the stringent calibration requirements, extensive calibration and characterization activities were conducted prelaunch for both MODIS instruments. In the case of MODIS RSB, these activities included characterizing the radiometric response at different instrument temperatures and scan angles, detector noise characterization, and relative spectral response measurements. A system-level radiometric calibration was performed for all RSB at cold, nominal, and hot instrument temperature plateaus using a 100-cm diameter spherical integrating source (SIS 100). The measurements were performed with both primary (A-side) and redundant (B-side) electronic configurations. Contrary to Terra MODIS, which has operated in both A- and B-side configurations, Aqua MODIS has been operated in B-side configuration since launch.[12] It can be seen from Table 2 that while a majority of the RSB detectors meet or exceed the specification, the SNR values of Terra MODIS band 7 detectors are slightly below the specified requirement.[12] In the case of Aqua MODIS, with the exception of the inoperable and noisy detectors in the short-wave infrared (SWIR) bands, the SNR for all RSB detectors exceeds the specification. A noticeable discrepancy is observed between the prelaunch and on-orbit results in Aqua band 6. This is caused due to the discrepancy in the operability status (noisy, inoperable, and out-of-family) of the band 6 detectors during prelaunch and on-orbit characterization.

The on-orbit measurement of the MODIS SNR is tracked using regularly scheduled SD observations. The SD and SDSM operate together as a system to calibrate the 20 MODIS RSB on-orbit. In the absence of an SD calibration event, the SD aperture door is normally closed to avoid unnecessary exposure of the SD to solar illumination. A deployable 7.8% transmission screen provides 2 illumination levels for SD calibration, with the low SD radiance values facilitating the calibration of the 9 high-gain ocean color bands (0.41 to 0.86 μm, bands 8 to 16). The remaining RSBs (land and atmosphere) are calibrated using the unscreened SD measurements. The SDSM, acting as a ratioing radiometer, is also operated with every scheduled SD calibration, to provide an estimate of the on-orbit degradation of the SD. Since July 2, 2003, the SD screen for Terra MODIS has been in place and the aperture door open on a permanent basis. While this allows an SD calibration every orbit, it also leads to increased solar exposure and, in turn, an accelerated degradation of the SD. The Aqua SD calibration continues to operate nominally at a triweekly frequency with the SD screen calibration performed once in every 6 weeks. Similar to the prelaunch results, the on-orbit SNR for RSB is specified at the typical scene radiances (Table 1) and is monitored using regular SD observations. The detailed algorithm for the SNR computation is discussed in the next section.

3 On-Orbit Signal-to-Noise Ratio Characterization Algorithm

The two essential quantities required to calculate the on-orbit SNR are the input signals (i.e., solar irradiance in the case of MODIS) and the measured noise. Although the noise in modern-day imaging systems arises from various sources (photon noise, dark noise, readout electronics

Table 2 Summary of the on-orbit MODIS SNR performance.

		Aqua MODIS				Terra MODIS			
Band	Spec.	Prelaunch	2002	2007	2015	Prelaunch	2000	2007	2015
1	128	197	202	203	223	171	186	205	203
2	201	525	515	527	569	418	478	506	512
3	243	331	326	301	292	309	319	292	211
4	228	333	327	321	325	309	324	308	256
5	74	158	151	146	145	114	93	85	81
6	275	114	502	474	487	394	298	391	375
7	110	145	152	155	157	71	102	101	97
8	880	1092	1137	941	826	902	1048	699	704
9	838	1506	1587	1423	1301	1147	1476	1372	1053
10	802	1528	1583	1488	1466	1100	1485	1482	1249
11	754	1607	1757	1729	1730	1152	1640	1704	1540
12	750	1436	1550	1506	1496	983	1373	1270	1071
13L	910	1405	1435	1472	1506	1173	1278	1371	1375
13H	910	1551	1632	1677	1758	1187	1365	1428	1431
14L	1087	1507	1557	1595	1564	1315	1441	1390	1265
14H	1087	1885	2008	2017	1932	1337	1646	1614	1477
15	586	1519	1580	1581	1623	754	1412	1466	1438
16	516	1380	1464	1487	1480	713	1170	1249	1250
17	167	391	370	365	373	360	338	342	313
18	57	93	90	91	95	92	89	91	94
19	250	504	506	512	519	464	497	502	470
26	150	229	279	283	285	212	244	249	237

noise), the dominant source still remains the photon noise, which can be approximated to the square root of the signal.[2] Over the dynamic range of the SD measurements used in these SNR calculations, the square root dependence of the response can be approximated by a linear dependence. Given this linear dependence, a gain or response change would in turn impact the derived SNR.

During a nominal SD calibration, the solar illumination angle to the SD panel changes continuously with spacecraft movement. This variation of the detector response to the SD, even within a scan, facilitates SNR characterization at different signal levels.[13] The SNR is commonly defined as follows:

$$\mathrm{SNR} = \frac{\mathrm{dn}}{\sigma}, \tag{1}$$

where dn denotes the net SD response signal after background correction, as observed by a MODIS detector and σ is the associated standard deviation at that dn level. Since the primary focus, as specified, and computed in prelaunch is the evaluation of SNR at typical radiance, Eq. (1) can be rewritten as follows:

$$\mathrm{SNR}_{\mathrm{typ}} = \frac{\mathrm{dn}_{\mathrm{typ}}}{\sigma_{\mathrm{typ}}}. \tag{2}$$

The $\mathrm{dn}_{\mathrm{typ}}$ in the above expression can be expressed as follows:

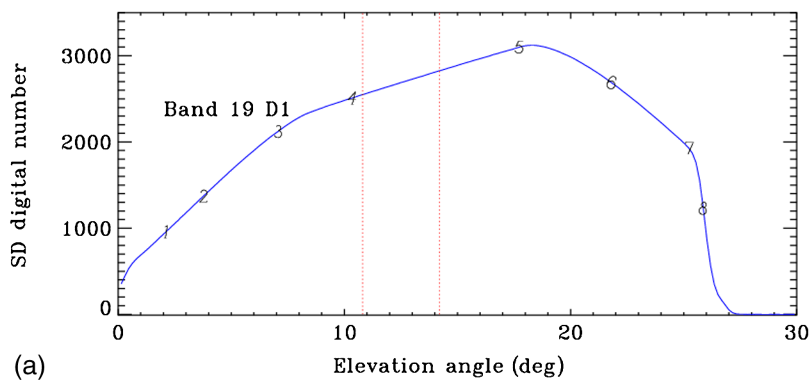
$$\mathrm{dn}_{\mathrm{typ}} = \frac{L_{\mathrm{typ}}\pi}{m_1 E_{\mathrm{sun}}}, \tag{3}$$

where L_{typ} denotes the typical scene spectral radiance (as specified in Table 1), $1/m_1$ denotes the instrument gain derived from the regular SD calibration, and E_{sun} is the solar spectral irradiance.[4,5] Although varying response levels are available during each SD calibration, the σ_{typ} may not be obtained directly from the measurement. An interpolated value from the fit of standard deviations across different signal levels is effectively used. Assuming a linear dependence of SDs on dn, the function of the linear fit can be expressed as follows:

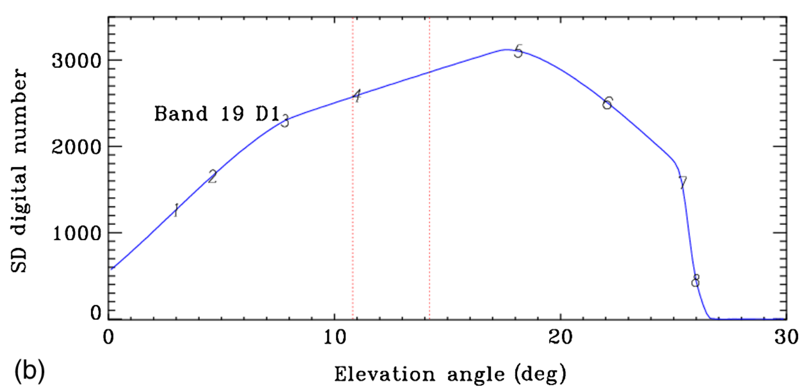
$$\sigma = \sigma_{\mathrm{SV}} + A\mathrm{dn}, \tag{4}$$

where σ_{SV} is SD of the space view (SV) signal, i.e., noise at zero signal level. After obtaining the slope A, the σ_{typ} can be calculated using the $\mathrm{dn}_{\mathrm{typ}}$ from Eq. (3).

Figure 1(a) shows the SD response of Aqua MODIS band 19 detector 1 during a nominal calibration event from day 19 of the year 2015. It should be noted that the SD calibration for Aqua band 19 is performed without the screen. The RSB calibration coefficients are derived from the scans within the sweet-spot range, marked by vertical dotted lines. The sweet-spot scans correspond to the time when the SD panel is fully illuminated. Although the SNR can be characterized using the different response levels within the sweet-spot scans, the range of the detector responses is still very limited and deviates significantly from its typical earth-view radiance. In order to provide a more meaningful estimate of the on-orbit SNR,



(a)



(b)

Fig. 1 (a) Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) solar diffuser (SD) response (background corrected) for detector 1 of band 19 derived from the unscreened SD calibration from January 19, 2015. Vertical lines show the sweet spot. (b) Terra MODIS SD response (background corrected) for detector 1 of band 19 derived from the unscreened SD calibration from January 30, 2003. Vertical lines show the sweet spot.

the scans outside the sweet-spot range are also considered, to provide a wider range of SD responses even though the SD is only partially illuminated. Fifty data samples (frames) are recorded by the SD sector for each scan (sun elevation angle) and the detector responses are nearly constant over the 50 frames in the case of sweet-spot scans. However, in the case of scans beyond the sweet-spot range, significant variation can be observed within the 50 frames due to varying solar elevation angles and a special consideration needs to be made to account for this behavior. Also marked in Fig. 1(a) via numbers is 8 representative scans, which will be used to illustrate the SNR computation. Similarly, Fig. 1(b) shows the SD response of Terra MODIS band 19 detector 1 during an unscreened calibration event from day 30 of the year 2003.

Figure 2(a) shows the Aqua MODIS SD response across 50 frames for the scans marked in Fig. 1(a). The scans include cases with both partial and full illumination of the SD. The scan-to-scan variation is the dominant feature seen in the figure; however, the variations along the frames also exist, especially in the case of the scans where the SD is partially illuminated. The corresponding Terra MODIS results are shown in Fig. 2(b).

In order to further quantify the variations across the frame range, the response of each frame is subtracted from the first frame, on a scan-by-scan basis. Figures 3(a) and 3(b) show the SD dn difference (response of each frame – response of first frame) for the scans selected in Figs. 2(a) and 2(b) for Aqua and Terra MODIS, respectively. It is evident that a significant bias exists for the scans where the SD is partially illuminated. Hence, in addition to the scan-based characterization of the SNR, each scan is also divided into 2 segments containing 30 frames each, with the middle 10 frames included in both segments. A linear fitting is applied to each segment, and the ratio of the detector's average signal to the linear fitting's SD represents the SNR. Hence, in the case of a fully illuminated scan, the SNR values are derived from 2 similar signal levels, whereas in the case of a partially illuminated scan, these SNR values can be derived from significantly different signal levels.

As discussed previously, in order to evaluate the compliance with the sensor design requirements, the SNR at scene typical radiances is computed. Figures 4(a) and 4(b) show the variation of the σ in Eq. (4) as a function of SD dn for Aqua and Terra MODIS, respectively. Each

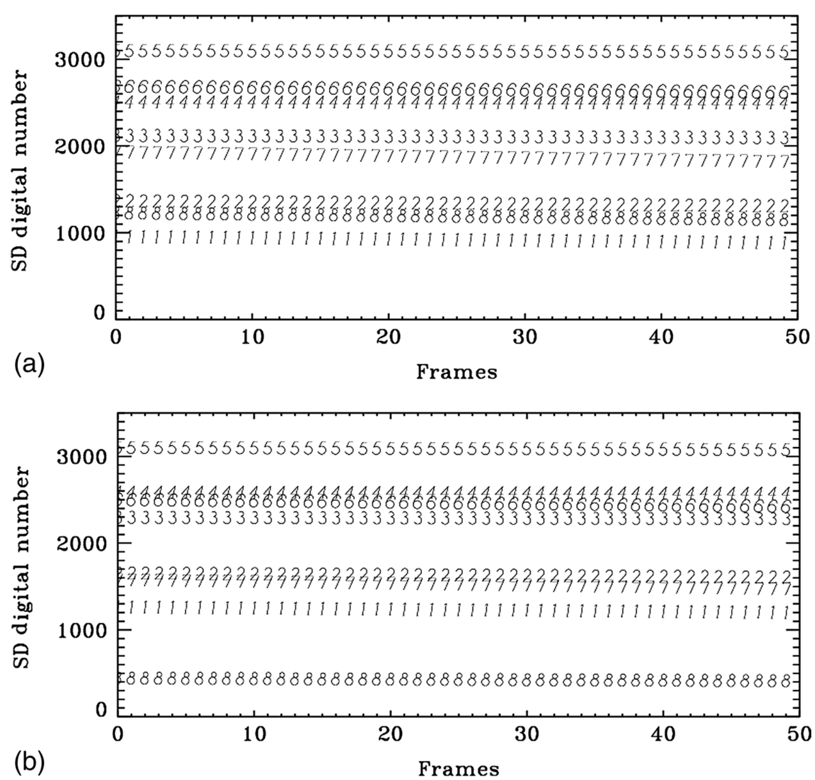


Fig. 2 (a) Aqua MODIS SD response for detector 1 of band 19 as a function of frame for select scans, as marked in Fig. 1(a). (b) Terra MODIS SD response for detector 1 of band 19 as a function of frame for select scans, as marked in Fig. 1(b).

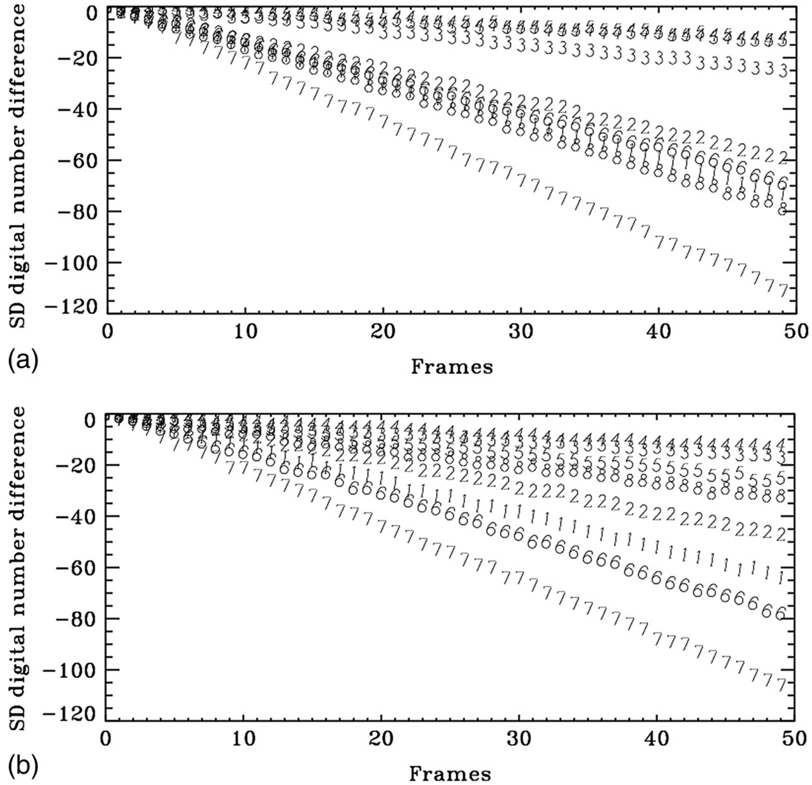


Fig. 3 (a) Frame dependence of the SD response for Aqua MODIS detector 1 of band 19, with the difference relative to the first frame plotted for the selected scans and (b) frame dependence of the SD response for Terra MODIS detector 1 of band 19, with the difference relative to the first frame plotted for the selected scans.

measurement shown in Fig. 4(a) is derived from multiple SD scan and frame illumination levels. The vertical dotted line denotes the typical dn derived from Eq. (3). Finally, using Eq. (2), the SNR value at typical scene radiance is computed.

In the case of Aqua MODIS, the SD calibration was performed on a weekly basis in the first year after launch. Since then, the frequency of SD calibration has been gradually reduced in order to conserve the SD door movements and prolong the operability of SD calibrations. During each nominal calibration event, the screened (SD door open and SD screen down) measurement is performed in the first orbit, and the unscreened (SD door open and SD screen up) measurement is performed in the next orbit. Since May 2008, the SD screened calibration for Aqua MODIS is performed on a triweekly basis, and the SD unscreened calibration is performed once every 6 weeks. The SD calibration for Terra MODIS RSB was also performed on a weekly basis in the first year, with a gradual reduction thereafter. Since July 2, 2003, due to an SD door anomaly, the SD screen is permanently in the down position and the SD door is left permanently open. This allows an SD calibration every orbit, with a downside of increased exposure of the SD panel. In this paper, all the Aqua MODIS unscreened calibrations are used to derive the on-orbit SNR. In case of Terra MODIS, unscreened measurements are used in the SNR computation before the SD door anomaly (July 2, 2003) and screened measurements are used thereafter. Section 4 describes the on-orbit SNR performance of the MODIS RSB detectors.

4 Results and Discussions

4.1 *Visible Band Performance*

The MODIS bands from 0.41 to 0.55 μm, (bands 3, 4, 8–12) are located on the visible focal plane. Most of the on-orbit lifetime gain change for MODIS RSB is observed in these bands, with the shortest-wavelength band 8 (0.41 μm) experiencing around 50% gain degradation for

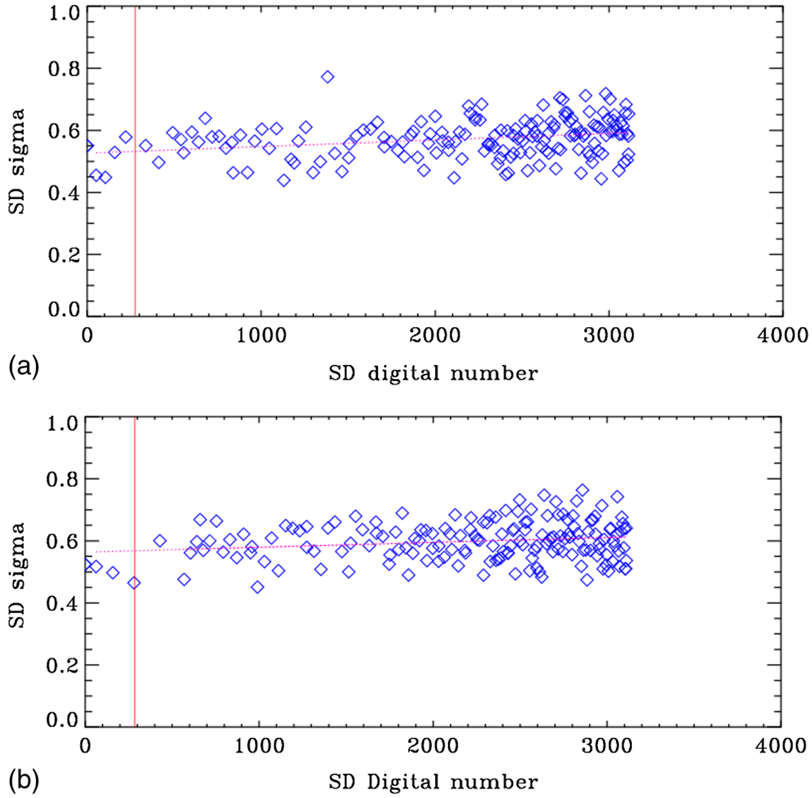


Fig. 4 (a) The standard deviation (SD sigma) for Aqua MODIS detector 1 of band 19 plotted as a function of SD response. The vertical line (in pink) denotes the typical dn levels (derived from the typical radiance specified for all MODIS reflective solar band). (b) The standard deviation (SD sigma) for Aqua MODIS detector 1 of band 19 plotted as a function of SD response. The vertical line (in pink) denotes the typical dn levels (derived from the typical radiance specified for all MODIS RSB).

Terra MODIS and about 30% gain degradation for Aqua MODIS. This gain change will impact the on-orbit SNR. The derived SNR values are normalized to the specification (from Table 1) so that the performance of both sensors across multiple wavelengths can be evaluated consistently. Using the approach described earlier, the on-orbit SNR for the Aqua VIS bands, normalized to the specification, at typical earth view (EV) radiance level, is plotted in Fig. 5. The SNR of each band is the average across all operable detectors. The various VIS bands are shown in different colors, with each symbol representing a yearly average value. The SNR computation for Aqua MODIS is performed using screen-open measurements, therefore eliminating the impact of screen vignetting effect. A variation of up to 4%, within a year, is observed between the SNR values derived with screened measurements, as compared to the 2% variation observed with the unscreened measurements. With the exception of bands 8 and 9, the SNR values for the VIS bands do not exhibit a temporal decrease and continue to exceed the specification. In the case of bands 8 and 9, a temporal decrease is observed between years 2007 and 2010 with a flattening trend thereafter. This behavior is consistent with the gain curve derived from the SD measurements, therefore reaffirming the impact of response degradation on the derived SNR measurements. Figure 6 shows the VIS band SNR results for Terra MODIS. In the case of Terra MODIS, the results before July 2, 2003, are derived using unscreened measurements, but thereafter, due to the SD screen anomaly, the results had to be derived from the screened measurements. A temporal degradation in the SNR, similar to as seen in the Aqua MODIS bands 8 and 9, is observed across all the VIS bands of Terra MODIS. The Terra SNR trend also agrees with its SD derived gain, with increased rate of degradation seen after 2003. It should be noted that all the detectors of the MODIS VIS bands (both Terra and Aqua) have been operational throughout the prelaunch testing and on-orbit operations. A similar trend is also seen in band 3, where the on-orbit SNR normalized by the specification, is less than unity starting

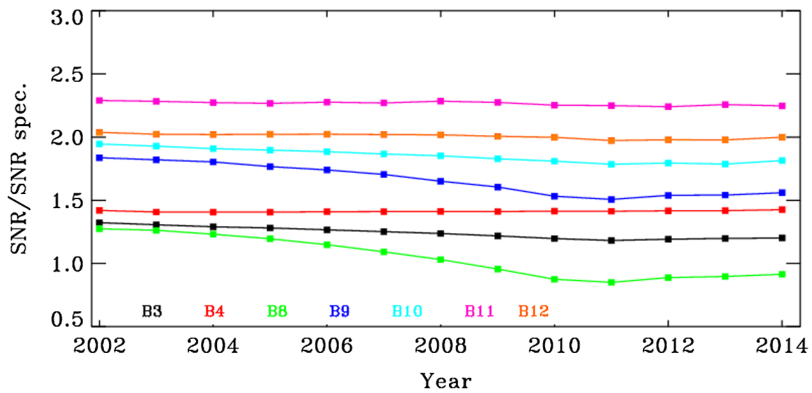


Fig. 5 Yearly averaged on-orbit SNR for the VIS bands of Aqua MODIS normalized to the specification. The values of the SNR/SNR specification that are greater than unity represent that the MODIS detectors of that band meet or exceed the specification.

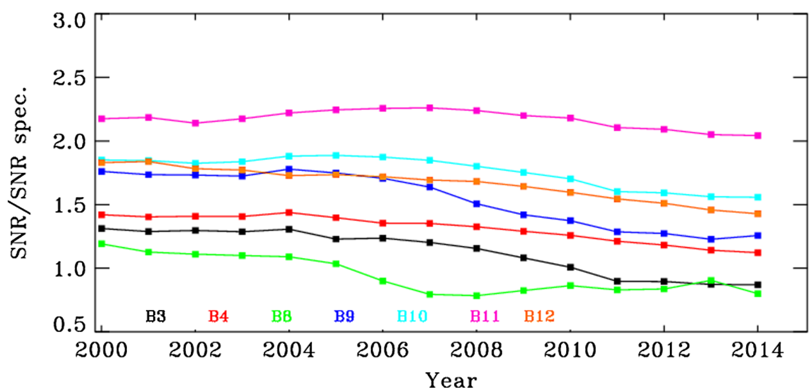


Fig. 6 Yearly averaged on-orbit SNR for the VIS bands of Terra MODIS, normalized to the specification. The values of the SNR/SNR specification that are greater than unity represent that the MODIS detectors of that band meet or exceed the specification. Note that the measurements after 2003 are derived from screened calibrations.

in 2010. The SNR for band 9 of Terra MODIS also continues to degrade but still exceeds the specification. As the gain of more VIS bands continues to degrade, a temporal degradation in the SNR for all VIS bands is expected.

4.2 *Near Infrared Band Performance*

The MODIS bands 1, 2, 13–19, covering the wavelength range from 0.64 to 0.94 μm, are located on the NIR focal plane. Given the wavelength dependence of the MODIS SD gain and degradation, the NIR bands have experienced a lesser degradation as compared to the VIS bands. With the exception of Terra MODIS band 14, the gain change for all MODIS NIR bands is generally within 10% after 15 years of Terra operation and 12 years of Aqua MODIS operation. Figures 7 and 8 show the yearly averaged SNR (normalized to the specification value) for the NIR bands of Terra and Aqua MODIS, respectively. It can be seen that the Aqua NIR band detectors perform better than the corresponding Terra MODIS detectors. However, the SNR for all NIR band detectors continue to exceed the specification value, with a very minimal temporal dependence in its trend. It is also worth mentioning that all the detectors in the NIR bands of both MODIS instruments have been operational over the entire mission and continue to produce valuable scientific measurements.

4.3 *Short-Wave Infrared Bands Performance*

The MODIS bands 5, 6, 7, and 26, covering the wavelength range from 1.2 to 2.1 μm, are colocated with other thermal emissive bands on the short- and mid-wave infrared focal plane.

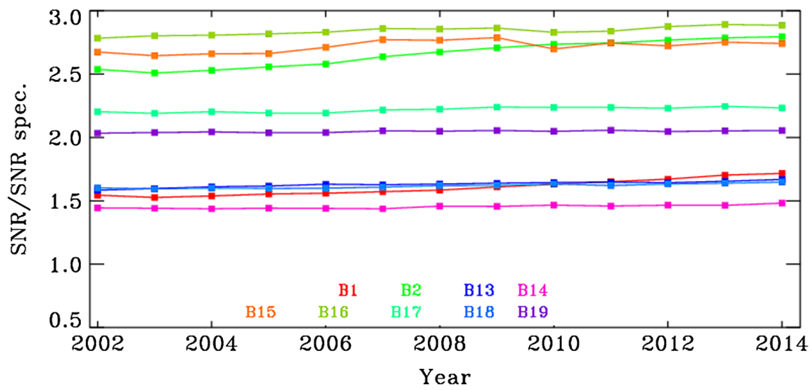


Fig. 7 Yearly averaged on-orbit SNR for the near-infrared (NIR) bands of Aqua MODIS, normalized to the specification.

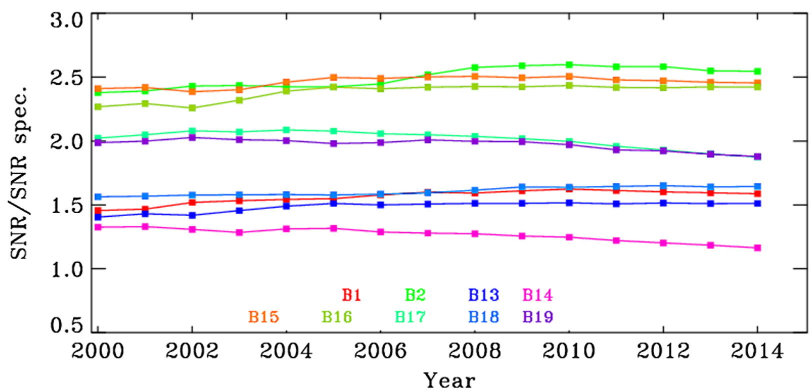


Fig. 8 Yearly averaged on-orbit SNR for the NIR bands of Terra MODIS, normalized to the specification.

Figure 9 shows the on-orbit SNR (normalized to its specification) for the SWIR bands of Aqua MODIS. A total of 8, out of 20 Aqua band 6 detectors, were identified as inoperable during the prelaunch characterization due to the focal plane delamination.[3] An additional 5 detectors were deemed inoperable based on on-orbit measurements. Also, 3 detectors in Aqua band 6 have exhibited noisy behavior throughout the mission lifetime, and therefore have a major impact on the downstream science products. Consequently, the SNR results for band 6 derived from 4 operational detectors, shown in Fig. 9, exhibit more fluctuations but continue to meet the specification. In comparison, the band 5 of Aqua MODIS has only one inoperable

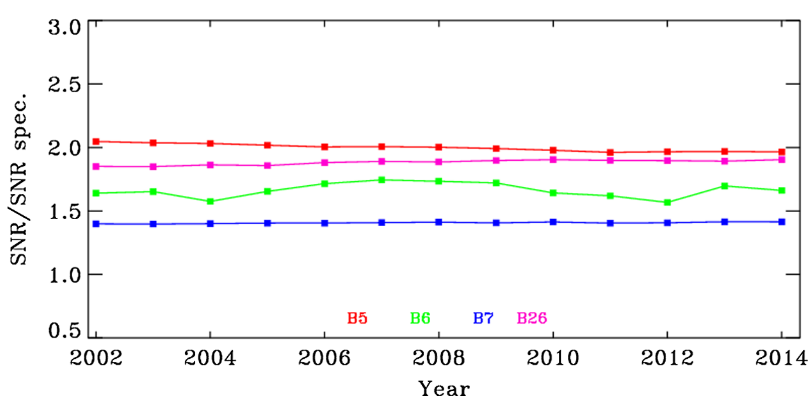


Fig. 9 Yearly averaged on-orbit SNR for the short-wave infrared (SWIR) bands of Aqua MODIS normalized to the specification.

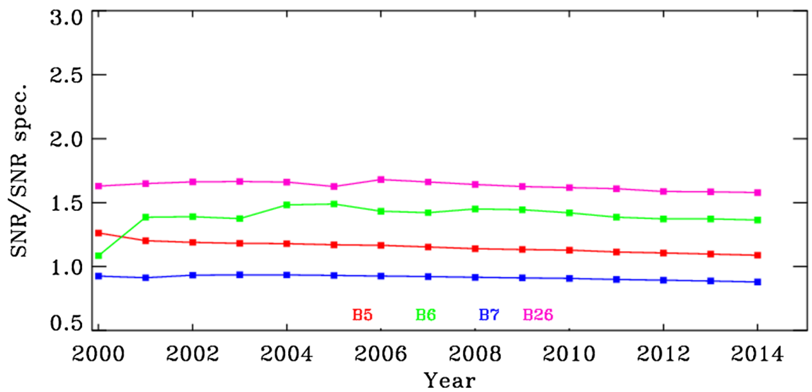


Fig. 10 Yearly averaged on-orbit SNR for the SWIR bands of Terra MODIS normalized to the specification.

detector, and no inoperable or noisy detectors can be found in band 7. During the initial on-orbit testing, different voltage biases were used for short periods of time, resulting in several inoperable or noisy detectors. After the settings were reverted back to the original biases, the detectors also mirrored their at-launch performance. In the computation of SNR trends, shown in Fig. 9, these periods of on-orbit testing were excluded. All SWIR bands of Aqua MODIS continue to exceed the specification. In comparison, the Terra MODIS SNR trends, shown in Fig. 10, do not match the performance of the Aqua MODIS detectors. While bands 5, 6, and 26 continue to exceed the specification, the band 7 detectors continue to perform below the specification. Additionally, one detector in Terra band 5 has been exhibiting noisy behavior over the entire mission. To eliminate the impact of noisy and inoperable detectors in the L1B product, a quality assurance look-up-table is maintained to flag and remove the contributions from these detectors in the native resolution, as well as aggregated L1B products.[3–5]

A quantitative summary of the on-orbit SNR performance for MODIS RSB is provided in Table 2. For every MODIS band, the prelaunch, the first-year SNR (year 2000 for Terra and year 2002 for Aqua), mid-mission SNR (year 2007), and current day SNR (year 2015) have been provided. The SNR specification value has also been listed for completeness. In the case of Terra MODIS, the prelaunch values are from A-side electronics configuration, whereas in the case of Aqua MODIS, the values are from B-side electronics configuration. Since the current electronics configuration of Terra MODIS operation is A-side, the values from B-side prelaunch were not used for comparison. With the exception of VIS bands 8, 9, and 3 in later years and Terra MODIS band 7, the detectors of remaining MODIS bands continue to exceed the specification in terms of SNR. In the case of bands 3, 8, and 9 of Terra MODIS and band 8 of Aqua MODIS, there has been around 30% change in the SNR over 15 years on-orbit. As discussed earlier, this is primarily caused by the response degradation at short wavelengths. Contrary to the VIS bands, most NIR bands have exhibited a gain increase over time for both MODIS instruments.

The SNRs presented in Table 2 are calculated using the fitted function of the typical response corresponding to the typical earth-view scene radiance, as listed in Table 1. The inverse of this SNR (noise equivalent change in response, $Nedn_{EV}$) represents the fractional uncertainty associated with the earth-view scene response, at typical radiance levels. Table 3 lists the percent $Nedn_{EV}$ for all MODIS RSB, for the 3 representative years. It should be noted that the data presented in Table 3 are in fact derived from Table 2. The $Nedn_{EV}$ parameter is one of the key contributors in the calculation of the net RSB calibration uncertainty, also available in the MODIS L1B product, on a per-EV pixel basis. The lower uncertainties (<0.1%) seen across the high-gain ocean bands (8 to 16) of both instruments are reflective of the higher SNR values seen in these bands with the notable exception of band 8. In comparison, the bands with lowest SNR, band 18 (and Terra band 5) exhibits values of percent $Nedn_{EV}$ exceeding 1%. In addition to the values listed in Table 2, the net RSB uncertainty is computed using various other parameters including uncertainty associated with the SD calibration and RVS on-orbit changes.[7]

Table 3 Summary of the on-orbit MODIS noise equivalent change in response (Nedn_{EV}) performance. All the numbers in this table are in percent (%).

	Aqua Nedn_{EV} at L_{EV}			Terra Nedn_{EV} at L_{EV}		
Band	2002	2007	2015	2000	2007	2015
1	0.50	0.49	0.45	0.54	0.49	0.49
2	0.19	0.19	0.18	0.21	0.20	0.20
3	0.31	0.33	0.34	0.31	0.34	0.47
4	0.31	0.31	0.31	0.31	0.32	0.39
5	0.66	0.68	0.69	1.07	1.17	1.24
6	0.20	0.21	0.21	0.34	0.26	0.27
7	0.66	0.64	0.64	0.98	0.99	1.03
8	0.09	0.11	0.12	0.10	0.14	0.14
9	0.06	0.07	0.08	0.07	0.07	0.09
10	0.06	0.07	0.07	0.07	0.07	0.08
11	0.06	0.06	0.06	0.06	0.06	0.06
12	0.06	0.07	0.07	0.07	0.08	0.09
13L	0.07	0.07	0.07	0.08	0.07	0.07
13H	0.06	0.06	0.06	0.07	0.07	0.07
14L	0.06	0.06	0.06	0.07	0.07	0.08
14H	0.05	0.05	0.05	0.06	0.06	0.07
15	0.06	0.06	0.06	0.07	0.07	0.07
16	0.07	0.07	0.07	0.09	0.08	0.08
17	0.27	0.27	0.27	0.30	0.29	0.32
18	1.11	1.10	1.05	1.12	1.10	1.07
19	0.20	0.20	0.19	0.20	0.20	0.21
26	0.36	0.35	0.35	0.41	0.40	0.42

The on-orbit SNR estimates discussed above represent the detector's performance at the typical radiance level. However, the SD sigma versus dn (equivalent radiance after gain conversion), can be used to estimate the SNR at different radiance levels. Although this dependence is seen to be linear in the case of MODIS bands, it is a vital piece of information that can be used by other satellite sensors to compare their on-orbit performance with the MODIS instruments.

5 Summary

As both the MODIS instruments continue to operate well beyond their prime lifetime of 6 years, monitoring the on-orbit performance of the detectors is vital in maintaining the quality of the calibrated product. An important metric providing a quantitative assessment of the detector performance is the instruments' SNRs, which were derived prelaunch and monitored on-orbit to provide valuable information on the instrument performance. The SNR for MODIS RSB detectors was characterized prelaunch and an algorithm to derive the on-orbit SNR is described. Regularly scheduled SD calibrations are used to derive the SNR at all levels of the dynamic range, with the results compared to the specification at typical radiance ranges. Overall, a majority of the MODIS RSB detectors continue to exceed the specification. A temporal degradation in the SNR is observed in the case of VIS bands of both instruments, which is primarily attributed to the response degradation over time. Since 2010, band 8 of both instruments has yielded an SNR that is below the specification. In comparison, the NIR bands have performed exceedingly well, with the SNR exceeding specification in every band of both instruments. Unlike the VIS and NIR bands, which do not have any inoperable or noisy detectors, the SWIR bands are impacted by some inoperable and noisy detectors. Contributions of the on-orbit SNR change to the MODIS L1B product are also summarized for both instruments. The Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on the S-NPP platform, launched in October 2011, is a follow-on mission to the MODIS instrument. Similar on-orbit SNR characterization algorithms using the SD response are being implemented to derive the VIIRS SNR on-orbit.[14]

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