Twenty years of Terra MODIS spectral performance using the Spectro-Radiometric Calibration Assembly

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ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on-board the Terra spacecraft has provided valuable Earth data to the science community for the last 20 years. Equipped with several on-board calibrators (OBCs), MODIS has continued to operate nominally since its launch in December 1999. The Spectro-Radiometric Calibration Assembly (SRCA) is one such OBC that is able to provide on-orbit measurements of the MODIS reflective solar bands (RSBs) in radiometric, spatial and spectral modes. While the SRCA is operating in spectral mode, it is able to monitor the center wavelength (CW), bandwidth (BW) and in-band relative spectral response (RSR) of most RSBs. Prelaunch measurements of the CWs, BWs and RSRs of the RSBs were performed at the system level using the Spectral measurement Assembly (SpMA). Using both the prelaunch measurements and the measurements obtained on-orbit using the SRCA, the changes in the spectral response of the MODIS reflective bands can be monitored throughout the mission. This paper will provide a brief description of the spectral calibration approach and report on-orbit changes in these spectral performance parameters and their uncertainties over the last 20 years. It will also address changes to the SRCA operation on-orbit and their impact on measured spectral calibration results. Despite two decades in orbit, the spectral responses for most Terra MODIS reflective bands continue to remain within their design specifications.

Keywords: MODIS, Terra, relative spectral response, on-orbit, reflective solar bands

1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on-board NASA's Earth Observing System (EOS) Terra spacecraft, which was launched on December 18, 1999, has provided high-quality data to the science community over the last 20 years.[1] It is equipped with 36 spectral bands in the visible (VIS), near-infrared (NIR), short-wave infrared (SWIR), mid-wave infrared (MWIR) and long-wave infrared (LWIR) wavelengths. The 20 reflective solar bands (RSBs) cover a range of 0.41 - 2.2 μm, while the 16 thermal emissive bands (TEBs) cover a range of 3.7 - 14.4 μm.[2] The MODIS instrument includes a set of on-board calibrators (OBCs) to monitor the on-orbit performance of these spectral bands throughout the mission. A solar diffuser (SD) and solar diffuser stability monitor (SDSM) are used for the on-orbit calibration of the RSBs, while a blackbody (BB) is used to monitor the TEBs. MODIS is also equipped with a unique OBC, a Spectro-Radiometric Calibration Assembly (SRCA), which was designed to provide supplementary radiometric measurements,[3] along with on-orbit spatial and spectral characterizations.[4]

While the SRCA is a unique OBC to MODIS, it is not considered an absolute calibrator since its signal only fills 1/5 of the MODIS aperture. To monitor the on-orbit characterization of the MODIS bands, the SRCA is run in three modes: spatial, radiometric and spectral. When in spatial mode, the SRCA is used to measure the on-orbit shifts in the along-scan and along-track directions through the position shifts of the detectors and the shifts in the centroids of each band.[5–7] The data obtained in radiometric mode is used to monitor the radiometric changes of the RSBs from prelaunch, which were obtained at multiple radiance levels. While this radiometric data was used in the calculation of the on-board response-verses-scan angle (RVS) of the RSBs in previous Level-1B (L1B) collections, it is no longer used in an official sense due to the SRCA lamp failures throughout the

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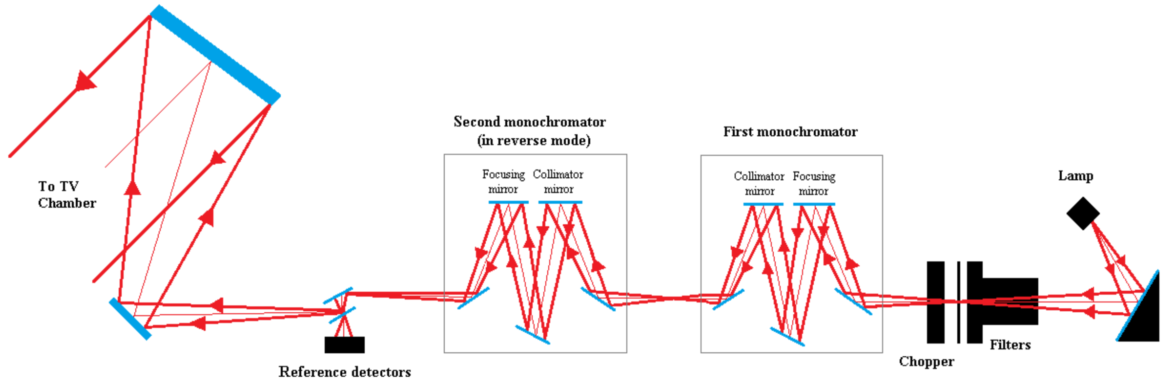


Figure 1: Schematic of the SpMA.[10]

mission. The SRCA is also capable of monitoring the on-orbit changes in the relative spectral response (RSR) profiles, the bandwidth (BW) and center wavelength (CW) of each RSB while operating in spectral mode, which is currently only scheduled bi-annually in order to preserve the remaining functional lamps.[8] Due to the higher frequency of the SRCA spectral calibrations in the past, the on-orbit spectral performance of the RSBs have been closely monitored over the life of the mission and will continue to be monitored in the future, contingent upon the SRCA lamps.

This paper will provide an overview of the current spectral performance of the reflective bands on-board Terra MODIS. Section 2 will discuss the prelaunch CWs, BWs, and RSRs of the reflective bands measured with the Spectral Measurement Assembly (SpMA), along with their tolerances and on-orbit specifications. A detailed description of the SRCA in spectral mode and the algorithms used to determine the on-orbit RSR, CW and BW characterizations of the RSBs will be presented in Section 3. The trends of these spectral characterizations and their uncertainties over the last twenty years of the Terra MODIS mission will be discussed in Section 4. Section 5 will include a general summary of the total on-orbit spectral response changes over the last 20 years and a discussion of future challenges, including changes in the spectral calibration activities with future lamp failures.[8]

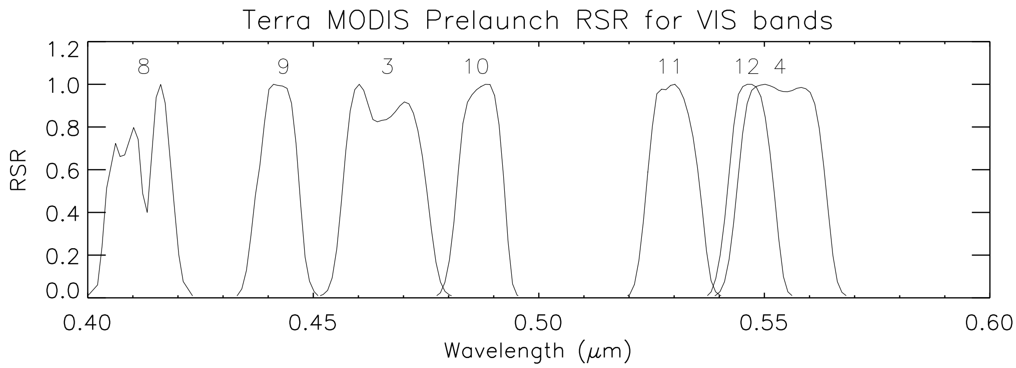
2. PRELAUNCH SPECTRAL CHARACTERIZATION

The spectral characterization of Terra MODIS was measured by the instrument vendor, Santa Barbara Remote Sensing (SBRS), Goleta, CA in both an ambient and Thermal Vacuum (TV) environment, with the ambient data used for characterizing the RSBs. The primary device used for these characterizations was the SpMA, which consisted of a light source (lamps for reflective bands, ceramic rod for thermal bands), a double monochromator, a source spectrum measurement device and a collimator. A simple schematic of the SpMA can be seen in Figure 1. In order to provide the most accurate measurements, several inter-changable gratings were used to cover multiple wavelength ranges. Unlike the SRCA, the SpMA was capable of filling the entire MODIS aperture during the pre-launch tests. The SRCA was also used for pre-launch measurements under the same operational conditions for the ground to on-orbit calibration transfer.[9] In order to calculate the normalized MODIS RSRs, the SpMA reference detector signal and the digital number of the MODIS spectral response were used per band, detector and wavelength. The RSR profile of each band and detector was calculated by normalizing the spectral response (R) to the peak response (R_{max}):

$$RSR(b,d,\lambda) = \frac{R(b,d,\lambda)}{R_{max}(b,d)} \ . \tag{1}$$

The pre-launch, in-band (IB) RSRs for the Terra MODIS VIS, NIR and SWIR bands measured by the SpMA for the center detectors are shown in Figure 2.

Before the pre-launch measured RSRs could be used to calculate the CW and BW of each RSB, two corrections needed to be applied to the response profiles. Each of the MODIS bands has an array of detectors in the along-track direction, ranging from 10-40 per band. During the pre-launch spectral measurements using the SpMA,



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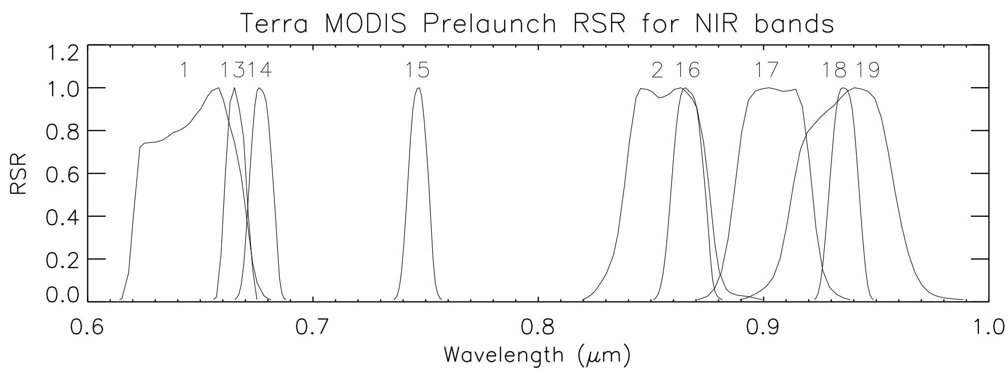

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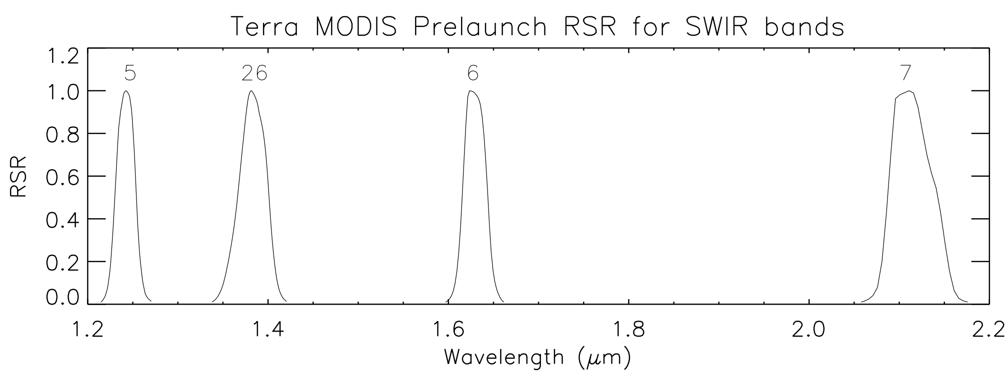

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Figure 2: The pre-launch, in-band RSR profiles for Terra MODIS (a) VIS, (b) NIR and (c) SWIR bands' center detector.

each band (and subsequent array of detectors) was illuminated by a narrow slit image. Due to wavelength variations of this beam through the exit slit and the consequent non-uniform illumination across the detectors in each band, the measured CW patterns inherently had a curved shape; this effect caused the center detector in each band to have a lower CW measurement than the detectors on either side. In order to mitigate this effect, a model which calculates the along-track wavelength differences was applied, with the CW of each detector in the corresponding band forced to the modeled value. An atmospheric correction was also applied to bands 19 and 26 to accommodate for any atmospheric absorption. This was performed by environmental parameters controlled during the pre-launch tests and corrects for any water vapor and CO_2 absorption features. However, due to the pre-launch testing conditions, residual absorption peaks appeared in several atmospheric bands. These residuals are corrected for by applying the absorption curve calculated from the MODTRAN atmospheric radiative transfer model.[11–14]

Once these instrumental and environmental impacts were corrected for, the RSRs measured by the SpMA were then used to calculate the pre-launch CW for each band and detector by

$$\lambda_c(b,d) = \frac{\int_{\lambda_1}^{\lambda_2} \lambda \cdot RSR(b,d,\lambda) \cdot d\lambda}{\int_{\lambda_1}^{\lambda_2} RSR(b,d,\lambda) \cdot d\lambda} , \tag{2}$$

where λ_1 and λ_2 are the wavelengths at which the $RSR(b,d,\lambda)$ is 1% of its peak value. The BWs for each band and detector are calculated by $\lambda_U - \lambda_L$, in which the lower and upper wavelengths correspond to where the RSR is 50% of its peak value, or full-width at half-maximum (FWHM). The final, pre-launch measured CW and BW values for each of the Terra MODIS reflective bands are shown in Table 1. The majority of the bands show CW values within their design specifications, with the exception of Bands 6, 7, 19 and 26, which are marked red in the table. However, all of the pre-launch measured BW values were found to be within their specifications. The out-of-band (OOB) spectral characterizations of the RSBs were also performed pre-launch but are not discussed due to the inability of the SRCA to measured the OOB profiles. All of the pre-launch IB and OOB RSR tables for both Terra and Aqua MODIS RSBs and TEBs are available on the MODIS Characterization Support Team (MCST) website, as well as several other pre-launch MODIS instrument parameters*.

3. ON-ORBIT SPECTRAL CHARACTERIZATION

When the SRCA is run in spectral mode on-orbit, it is configured as a monochromator, which can be seen in Figure 3. In order to accurately characterize the spectral response of the RSBs, the SRCA is equipped with 6 lamps (four 10 W and two 1 W) for multiple radiance levels, three diffraction order sorting filters within the filter wheel and a diffraction grating, which is adjusted using a step motor. Two silicon photodiodes (SiPDs) reside within the SRCA chamber to monitor the generated beam and are located on the secondary mirror of the Cassegrain telescope (reference SiPD) and behind a didymium filter (calibration SiPD) next to the exit slit, as seen in Figure 3. The didymium filter, along with the two SiPDs, are used for self-wavelength calibration during a SRCA spectral calibration. The didymium filter, which was well characterized pre-launch and known to have minimal degradation over time, is assumed to have no on-orbit changes. Within the didymium spectral response, three of its spectral peaks are utilized in finding the half-included angle (β) and the grating motor offset angle (θ_{off}) of the monochromator using the basic grating equation:

$$\overline{\lambda}_n = \frac{2A}{m} \sin(\overline{\theta}_{didy\_pk,n} + \theta_{off}) \cos(\beta) , \tag{3}$$

where A is the grating spacing, m is the grating order, and $\overline{\lambda}$ and $\overline{\theta}_{didy\_pk}$ are the centroid wavelength and respective grating angle for peak n, respectively. A least-squares fit technique is used to adjust the two monochromator angles in Eq. 3 until the on-orbit CW of the three didymium peaks match the pre-launch values.[15,16] For the MODIS SRCA, the θ_{off} and β angles would be 0° and 15°, respectively, under perfect conditions. Due to on-orbit instrumental factors, however, these angles do not remain constant and must be determined for every spectral calibration event before the spectral characterizations of the reflective bands can be analyzed. The on-orbit β and

*https://mcst.gsfc.nasa.gov/calibration/parameters

Table 1: The center wavelength and bandwidth specifications, tolerances and prelaunch SpMA measurements for the Terra MODIS reflective bands' center detector.[10]

	Center Wavelength (nm)			Bandwidth (nm)		
Band	**Spec.**	**Tol.**	**Meas.**	**Spec.**	**Tol.**	**Meas.**
1	645	±4.0	646.3	50.0	±4.0	47.8
2	858	±2.2	856.5	35.0	±4.3	37.7
3	469	±4.0	465.7	20.0	±2.8	18.6
4	555	±4.0	553.7	20.0	±3.3	19.7
5	1240	±5.0	1242.3	20.0	±7.4	23.5
6	1640	±7.0	1629.4	24.6	±9.8	28.4
7	2130	±8.0	2114.2	50.0	±12.8	52.4
8	412	±2.0	411.8	15.0	±1.5	14.7
9	443	±1.1	442.1	10.0	±1.6	9.6
10	488	±1.2	487.0	10.0	±1.7	10.5
11	531	±2.0	529.7	10.0	±1.9	11.9
12	551	±5.0	546.9	10.0	±1.4	10.2
13	667	-2.0, +1.0	665.6	10.0	±1.7	10.0
14	678	±1.0	677.0	10.0	±1.7	11.3
15	748	±2.0	746.6	10.0	±1.9	9.9
16	869	±5.0	866.3	15.0	±4.3	15.5
17	905	±2.3	904.2	30.0	±5.4	34.7
18	936	±2.3	935.7	10.0	±5.6	13.5
19	940	±2.4	936.2	50.0	±5.6	45.7
26	1375	±6.0	1382.3	30.0	±8.0	34.6

θ_{off} angles for the SRCA on-board Terra MODIS can be seen in Figure 4. These angles are known to experience fluctuations over the mission, along with having a correlation to the background correction of the SiPDs.[17] Due to this sensitivity, the mission-averaged dark signal of the SiPDs are now used when calculating these angles to more accurately characterize the spectral responses of the RSBs. More information on the self-wavelength calibration process for the SRCA can be found in [15].

The current lamp status for the Terra MODIS SRCA can be found in Table 2. Because the SRCA on-board Terra MODIS has had two 10W lamps fail, the spectral calibrations (along with radiometric and spatial) have undergone two configuration changes. After the initial 10W lamp failure in 2004, the back-up 10W lamp became used during the 30W spectral calibrations in order to continue the 30W radiance level. However, after the second lamp failure in 2006, the 30W calibrations were forced to use only two 10W lamps. At this point in time, it was decided to a) reduce the frequency of all SRCA calibrations and b) begin using the lamps in constant current mode rather than constant radiance mode. Both of these actions were taken to preserve the life of the remaining lamps and have had an impact on the monochromator angles, as seen in Fig. 4. These lamp configuration changes have also had an impact on the noise of the RSR profiles for certain wavelength bands, which will be discussed in further detail in Section 4.

Table 2: The lamp status for the Terra MODIS SRCA as of December 2019. The two inoperable 10W lamps are indicated in the table as red, with lamp #2 failing on 11/20/2004 and lamp #3 failing on 02/18/2006.

Lamp Power	**10W**				**1W**	
Lamp #	1	2	3	4	1	2
Usage (hr)	383.2	172.1	190.3	142.0	591.1	314.0
Life (hr)	500	500	500	500	4000	4000
%	76.6	34.4	38.1	28.4	14.8	7.9

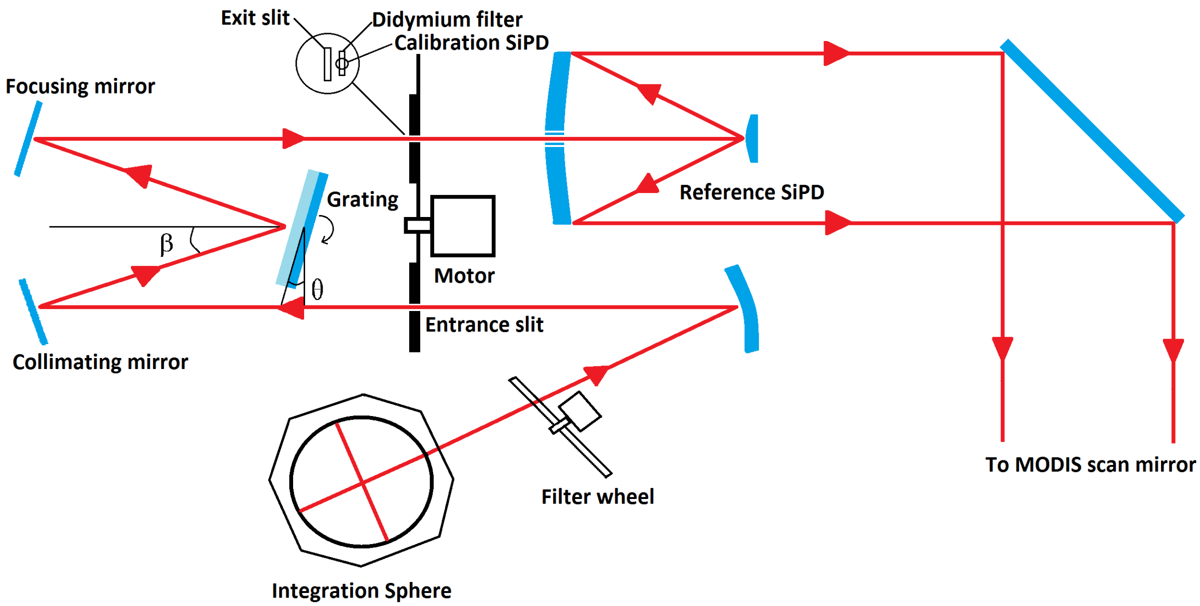


Figure 3: Schematic of the SRCA in spectral mode.

Each of the reflective band/detector's illuminated response from the SRCA during spectral mode is directly proportional to the SRCA source spectrum and its RSR. To calculate the RSR of each band/detector, the source spectrum detected by the reference SiPD must be removed from the RSB signal:

$$RSR(b,d,\lambda) = \frac{dn(b,d,\lambda) \cdot RSR_{SiPD\_ref}(\lambda)}{dn_{SiPD\_ref}(\lambda)} , \tag{4}$$

where $dn(b,d,\lambda)$ is the response to the SRCA illumination source for each band/detector, $RSR_{SiPD\_ref}(\lambda)$ is the RSR of the reference SiPD and $dn_{SiPD\_ref}(\lambda)$ is the reference SiPD's response to the SRCA illumination. Before a direct comparison can be made between the pre-launch SpMA measurements and the on-orbit SRCA measurements, a small shift is applied to the SRCA RSR profiles to account for the difference in aperture sizes. Once the corrected RSRs have been determined, the CW (λ_c) measured by the SRCA can be found by:

$$\lambda_c(b,d) = \frac{\Sigma_\lambda RSR(b,d,\lambda) \cdot \lambda \cdot d\lambda}{\Sigma_\lambda RSR(b,d,\lambda) \cdot d\lambda} . \tag{5}$$

The CW uncertainties in the RSBs caused by the β and θ_{off} angles can also be calculated on-orbit by differentiating the monochromator grating equation with resepect to both β and θ_{off}, as described in [17]:

$$\sigma_\lambda(cal) \approx \sqrt{\left(\frac{\delta\lambda_\beta(cal)}{\delta\beta(cal)}\right)^2 \cdot \sigma_\beta^2 + \left(\frac{\delta\lambda_{\theta_{off}}(cal)}{\delta\theta_{off}(cal)}\right)^2 \cdot \sigma_{\theta_{off}}^2 + 2 \cdot \left(\frac{\delta\lambda(cal)}{\delta\beta(cal)}\right) \cdot \left(\frac{\delta\lambda(cal)}{\delta\theta_{off}(cal)}\right) \cdot \sigma_{\beta,\theta_{off}}} . \tag{6}$$

The on-orbit BWs of the RSBs are determined using the same method as the pre-launch BWs by calculating the FWHM of the normalized RSR profile. Due to the wavelength limitations of the didymium filter, only reflective bands that have a spectral response less than 1 μm have an on-orbit wavelength characterization requirement. This excludes the SWIR bands (Bands 5-7, 26).

4. RESULTS

The on-orbit RSR profiles for Terra MODIS VIS bands 8, 3 and 4 for select calibrations throughout the mission can be seen in Figure 5, with the pre-launch SpMA profiles of each band included as a reference. While the

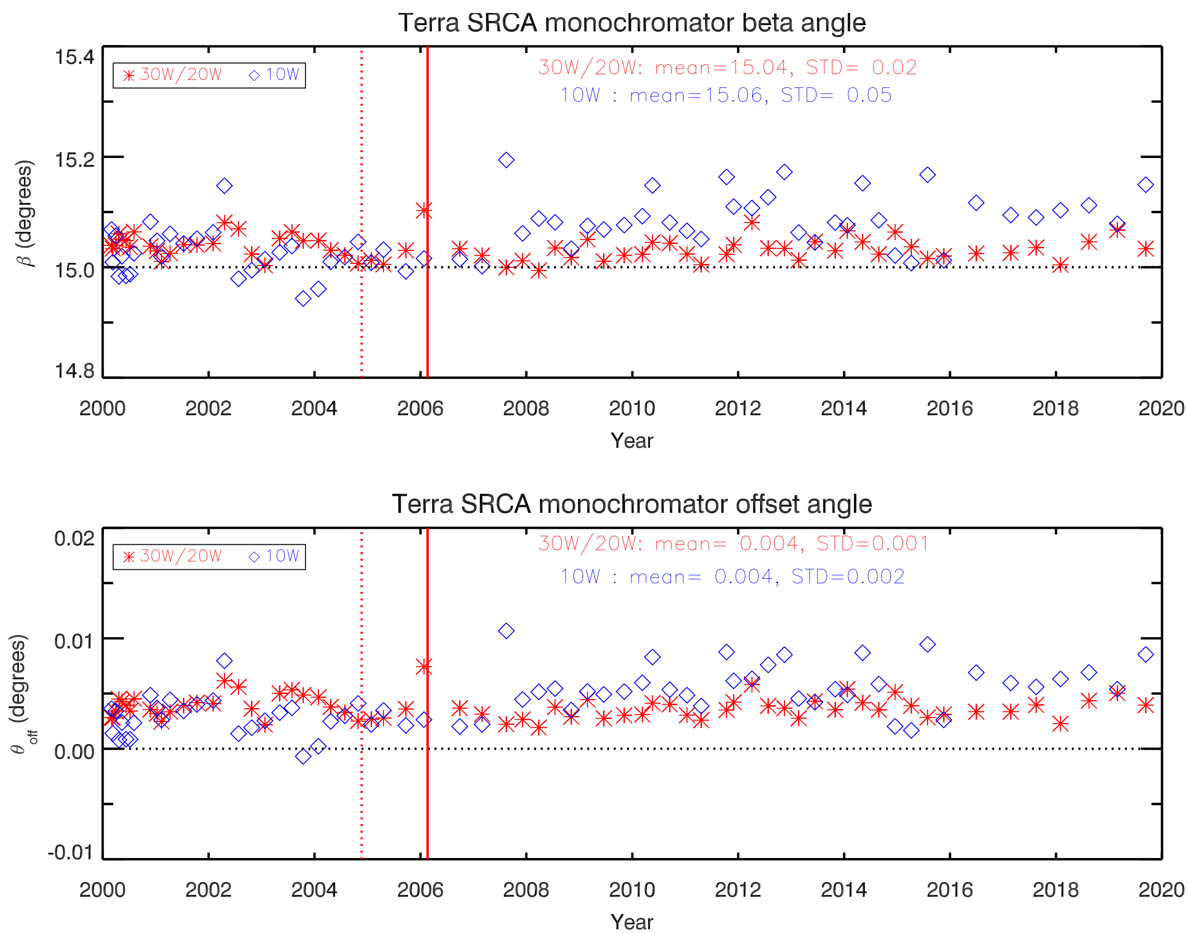


Figure 4: The on-board half-included angle (*top*) and the grating offset angle (*bottom*) trending for the Terra MODIS SRCA grating for both 30W (*red stars*) and 10W (*blue diamonds*) calibrations. The black, horizontal dashed lines represent the angle values under perfect conditions. The red vertical lines represent the on-orbit lamp failures, with the dashed line representing a lamp failure with no configuration change and the solid line representing a lamp failure and configuration change.

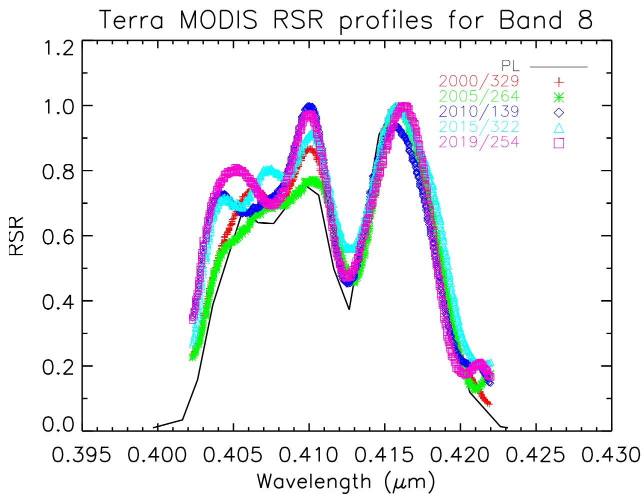
band-averaged values are shown in Fig. 5, the RSRs for each RSB detector are generally consistent with the results shown. Overall, the RSRs of the VIS bands have remained relatively stable over the last 20 years, with a few exceptions. The signal to noise ratio of the RSR measurements has decreased noticeably for some bands due to changes to the SRCA calibrations, as well as degradation of the MODIS scan mirror at these wavelengths.[18] After the second 10W lamp failure in February 2006, the 30W spectral calibrations were reduced to 20W. The profiles of Bands 8 and 3 experienced the largest impact from the reduction in signal, shown in Figs. 5a and 5b. These two bands, along with Band 9, are expected to show larger variations in their RSR profiles with more reduction in the signal level, which has been seen in Aqua MODIS after the most recent 10W lamp failure in 2016.[8] Band 4 shows the largest change in the RSR profile over the mission for the VIS bands, with a significant spectral response change of ∼25% on the left side of the profile peak since 2000. Bands 10 and 11 also show small changes in the peaks of their profiles, less than 10%.

The spectral response profiles for the MODIS NIR bands 1, 2, 17 and 19 are shown in Figure 6. During the pre-launch testing, the spectral characterizations for Band 2 were measured using a 30W lamp configuration. However, due to a time constraint for the on-orbit calibrations, Band 2 was switched to using the 10W lamp configuration. Therefore, the on-orbit spectral characterizations for this band can now only be monitored for change since the pre-launch measurements are no longer applicable. To monitor the on-orbit changes in this band, the first SRCA spectral calibration (03/01/2000) is used as a reference for all spectral characterizations.[19] While none of the NIR bands displayed an increase in noise after the lamp reduction in 2006, Bands 1 (Fig. 6a), 17 (Fig. 6c) and 19 (Fig. 6d) all have significant spectral response changes on the left side of their profiles, similar to Band 4. Of these three bands, Band 1 has the largest profile change on-orbit, around 35%, while Band 17 has a 30% change. Band 19 shows the smallest change of these three bands, less than 10%. All of the remaining NIR bands show stability in their spectral responses over the last twenty years. Band 2 also shows a change in the left and center of its RSR profile on-orbit when compared to the first on-orbit calibration, with differences up to 20%.

The on-orbit CW and BW shifts for the Terra MODIS VIS and NIR bands are shown in Figure 7 and Table 3, respectively. While the majority of the reflective bands continue to behave normally, the CW and BW results for Bands 1 and 8 are currently only monitored and no longer reported in an official capacity. The out-of-family RSR profile of Band 8 caused by the 2006 signal reduction, which can be seen in Fig. 5a, has made the CW and BW calculations unreliable since that time. Over the last several years, the RSR changes in Band 1 have made it difficult to accurately characterize the on-orbit CW and BW. Therefore, these values for Band 1 are no longer reported after 2015 due to the left side of the profile falling below the half maximum (0.5). The remaining VIS and NIR bands have not been impacted by any on-orbit changes. Bands 1, 17 and 19 show the largest CW shifts of +1.7 nm, +1.3 nm and +1.1 nm from their pre-launch SpMA values, respectively. All other bands show CW shifts less than 1 nm over the last twenty years. Taking into account the measured CW values and the on-orbit CW uncertainties caused by the β and θ_{off} angles shown in Figure 8, all of the on-orbit VIS/NIR CW values for the Terra MODIS reflective bands remain within their pre-launch specifications listed in Table 1. Bands 1 and 19 have shown the largest BW shifts over the life of the mission. Up to 2015, Band 1 had a BW shift of -2.8 nm from its pre-launch values caused by the large change in the RSR profile. Band 19 has had a significantly large BW shift of -6.1 nm due to the narrowing of the RSR profile over time (see Fig. 6d) and has now fallen out of the pre-launch specification values.

5. SUMMARY AND FUTURE WORK

Over the last twenty years, the SRCA on-board Terra MODIS has provided accurate spectral characterizations of the VIS and NIR reflective bands. Due to the wavelength range of the didymium filter within the SRCA chamber, the spectral characterizations of the Terra SWIR bands are only monitored on-orbit. The on-orbit spectral characterizations of Band 2 must be compared to the initial on-orbit spectral calibration rather than pre-launch due to a time constraint within the 30W orbit, and therefore cannot be accurately tracked from pre-launch. The spectral characterizations for Terra MODIS Bands 8, 3 and 9 are expected to become more unreliable with any further drops in signal level.[8] While the 1W lamps are not currently utilized for spectral calibrations on either MODIS instrument, using one of the 1W lamps along with the 10W lamp(s) may be taken



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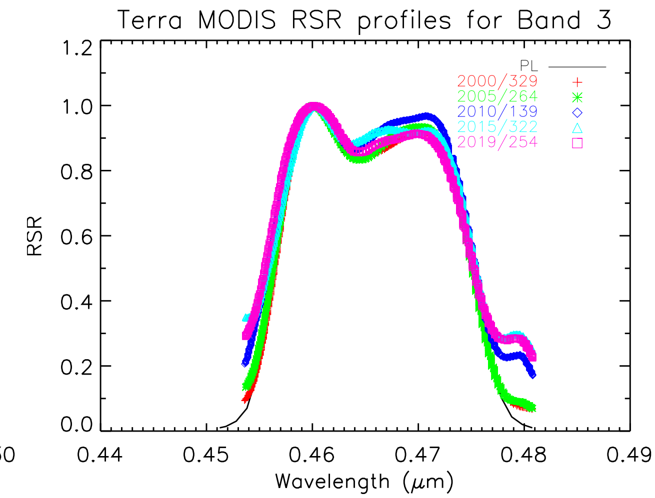

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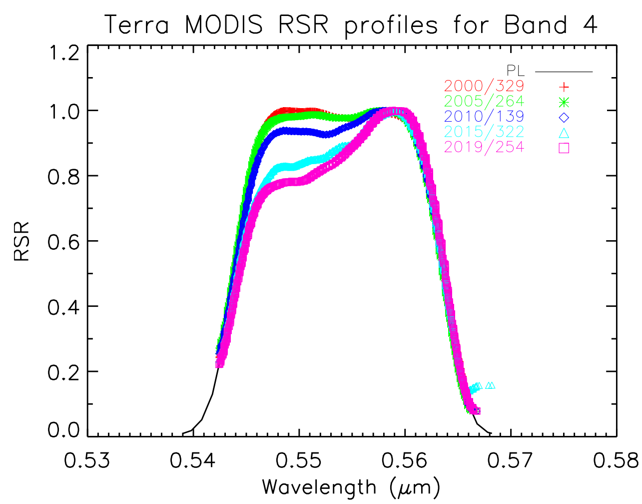

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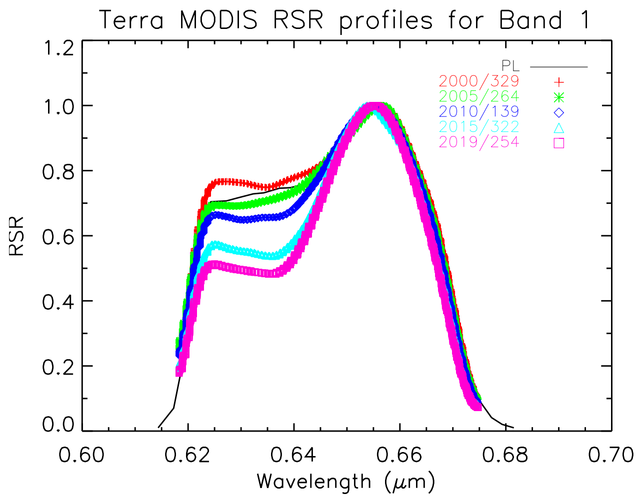
Figure 5: The band-averaged on-orbit RSR profiles for the Terra MODIS VIS bands (a) 8, (b) 3 and (c) 4 for select dates throughout the mission; 2000/329 (*red plus*), 2005/264 (*green star*), 2010/139 (*dark blue diamond*), 2015/322 (*light blue triangle*), 2019/254 (*magenta square*). The band-averaged pre-launch RSR profiles measured with the SpMA are shown for reference (*black*).

under consideration to increase the signal level of these RSR profiles. This could provide useful measurements and bring the noise down for the current bands impacted by the lamp reduction on-board Terra MODIS.

Beginning in 2006, Bands 8 and 3 have shown an increase in noise in their RSR profiles due to the lamp configuration changes and decreased signal level. The majority of the remaining VIS and NIR bands have shown minimal changes in their RSR profiles, with the exception of Bands 1, 17 , 4 and 19 showing changes of 35%, 30%, 25% and 10%, respectively. Due to these RSR changes over the mission, these four bands also show the most significant changes in the CW and BW shifts. As of 2019, Band 1 has a shift of +1.7 nm, while Bands 17 and 19 have shifts of +1.3 nm and +1.1 nm, respectively. When taking the on-orbit CW shifts and uncertainties into consideration, all of the CWs for the Terra MODIS RSBs remain within their pre-launch specifications. For the bands where a BW can still be reliably calculated, the current BW of Band 19 is the only spectral characterization



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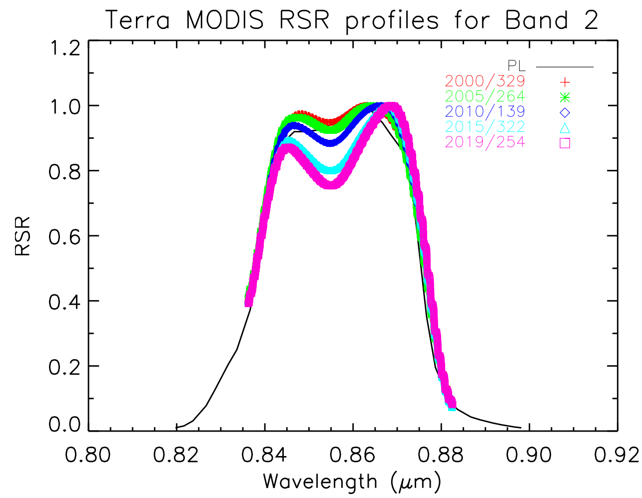

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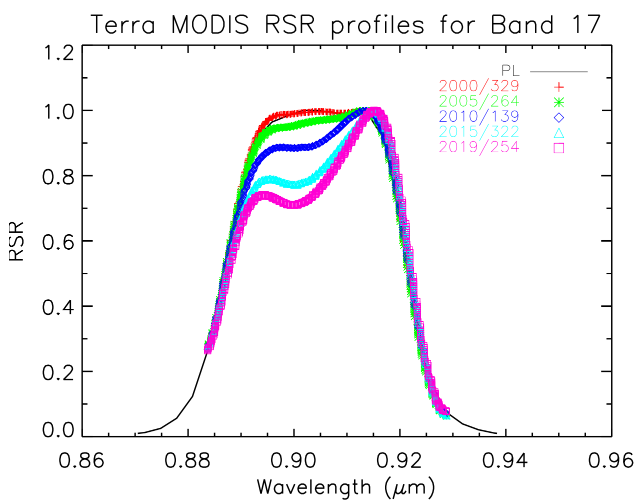

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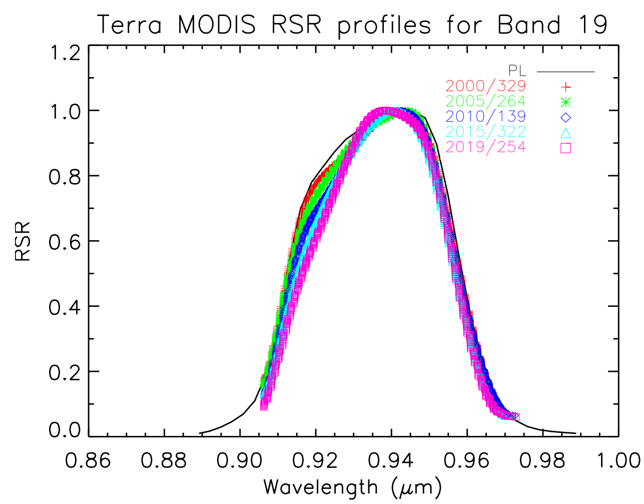

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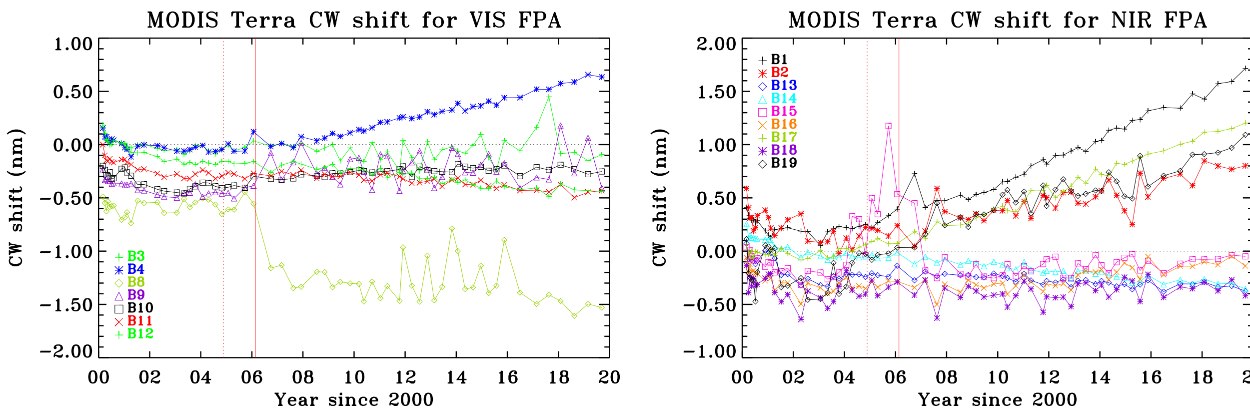
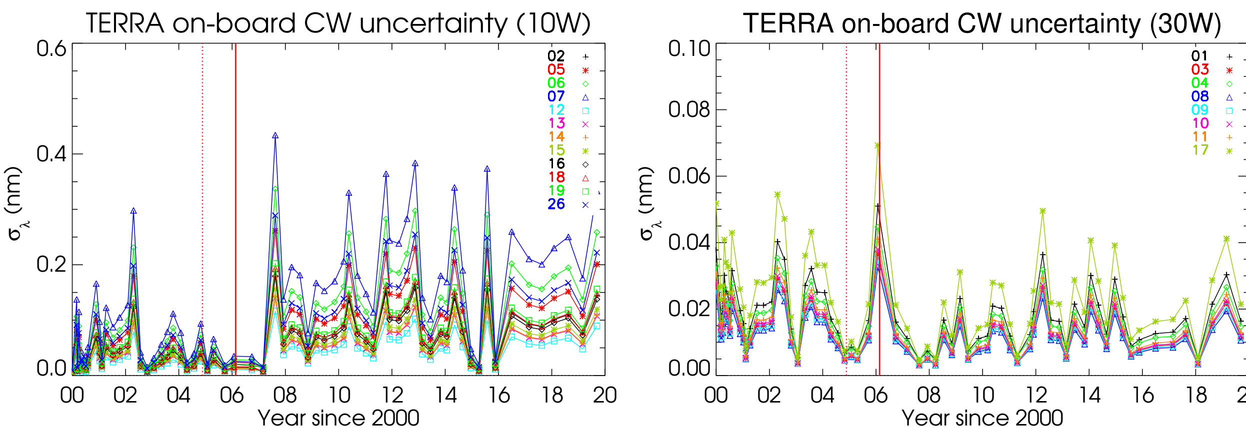
Figure 6: The band-averaged on-orbit RSR profiles for the Terra MODIS NIR bands (a) 1, (b) 2, (c) 17 and (d) 19 for select dates throughout the mission; 2000/329 (*red plus*), 2005/264 (*green star*), 2010/139 (*dark blue diamond*), 2015/322 (*light blue triangle*), 2019/254 (*magenta square*). The band-averaged pre-launch RSR profiles measured with the SpMA are shown for reference (*black*).

out of its specification, with a BW shift of -6.1 nm over the mission. The lack of any wavelength-dependence or common SRCA configuration[17] for these bands indicates that these are in fact real, on-orbit RSR changes over the last twenty years and not an artifact of the SRCA optical components. These time-varying RSR profiles are not currently used in the derivation of the C6/6.1 L1B products. The impact of the time-varying RSR on the calculation of calibrated instrument gain has been discussed in depth in [20] and generally found to be small, less than 0.5% even for the bands with significant on-orbit RSR changes. The impact on the retrieved Earth scene radiance may be larger though, depending on the spectral properties of the scene. The MCST will continue monitoring the on-orbit spectral characterizations of these bands for the remaining life of the SRCA instrument.



(a) (b)

Figure 7: The on-orbit CW changes for the Terra MODIS (a) VIS and (b) NIR bands. The red vertical lines represent the on-orbit lamp failures, with the dashed line representing a lamp failure with no configuration change and the solid line representing a lamp failure and configuration change.



(a) (b)

Figure 8: The on-orbit CW uncertainty trends caused by the β and θ_{off} angles for the Terra MODIS RSBs using the (a) 10W and (b) 30W lamp configurations. The red vertical lines represent the on-orbit lamp failures, with the dashed line representing a lamp failure with no configuration change and the solid line representing a lamp failure and configuration change.

Table 3: The yearly-averaged BW shifts for the Terra MODIS VIS and NIR bands (excluding Band 2) for 2000, 2005, 2010, 2015 and 2019. The unreliable BW values for Bands 1 (after 2017) and 8 (after 2004) are indicated as red.

	On-orbit BW shift (nm)													
Band	**1**	**3**	**4**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
2000	0.8	-0.5	0.1	0.2	-0.3	-0.1	-0.5	0.3	-0.3	0.6	0.1	0.2	-0.3	-0.2	0.2
2005	-0.8	-0.3	0.1	0.3	-0.6	-0.2	-0.6	0.3	-0.2	0.6	-1.3	0.1	-0.3	-0.1	-2.1
2010	-1.3	0.8	-0.2	0.7	-0.8	-0.3	-0.6	0.1	-0.1	0.7	-0.1	-0.2	-0.2	-0.1	-3.6
2015	-2.8	0.7	-0.3	1.0	-0.8	-0.2	-0.6	0.2	-0.2	0.8	-0.2	-0.4	-0.3	-0.1	-5.7
2019	-14.3	0.7	-0.6	1.4	-0.9	-0.3	-0.7	0.2	-0.2	0.8	-0.2	-0.5	-0.2	-0.1	-6.1

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