Four-years On-orbit Spectral Characterization Results for Aqua MODIS Reflective Solar Bands

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ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) flight model 1 (FM-1) was launched on-board NASA's EOS Aqua spacecraft on May 04, 2002. MODIS has 20 reflective solar bands (RSB) with wavelengths from 0.41 to 2.2μm and 16 thermal emissive bands (TEB) with wavelengths from 3.7 to 14.4μm. Typical sensor spectral characterization includes measurements of in-band (IB) and out-of-band (OOB) relative spectral responses (RSR) or spectral response functions (SRF), center wavelengths (CW) and bandwidths (BW). During MODIS instrument pre-launch calibration and characterization, these parameters were measured using a spectral measurement assembly (SpMA) by the instrument vendor. In addition to its on-orbit radiometric calibration capability, MODIS has a unique on-board calibrator - spectro-radiometric calibration assembly (SRCA) that can be used to monitor RSB on-orbit spectral performance. This paper presents an overview of MODIS spectral characterization methodologies, from pre-launch to on-orbit. It describes Aqua MODIS SRCA operational activities in spectral mode, summarizes the results from its four-years of on-orbit spectral measurements, and discusses lessons learned for future sensor design and development. The results show that on-orbit changes of Aqua MODIS RSB center wavelengths and bandwidths have been very small, typically less than 0.5nm for the CW and less than 1nm for the BW.

Keywords: MODIS, relative spectral response, center wavelength, bandwidth

1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) proto-flight model (PFM) was launched aboard NASA's Earth Observing System (EOS) Terra spacecraft on December 18, 1999 and flight model 1 (FM1) was launched on May 4, 2002 aboard the EOS Aqua spacecraft. Together they have provided the user community more than 10 years of calibrated data and science products for studies of climate and environmental changes[1-4].

MODIS is a comprehensive EOS sensor designed to extend and enhance its heritage sensors' global observations and climate data records. It collects data in 36 spectral bands covering wavelengths from 0.41 to 14.4μm. Bands 1-19 and 26 with wavelengths from 0.41 to 2.2μm are the reflective solar bands (RSB) and bands 20-25 and 27-36 with wavelengths from 3.7 to 14.4μm are the thermal emissive bands (TEB). Observations are made at three different spatial resolutions (nadir): 250m (bands 1-2), 500m (bands 3-7) and 1km (bands 8-36). In addition to the improvements made in spatial and spectral resolutions, MODIS was also designed with more stringent calibration requirements than heritage sensors. Because of this, both Terra and Aqua MODIS went through extensive radiometric, spatial, and spectral calibration and characterization activities pre-launch in either ambient condition or a thermal vacuum environment. In order to maintain and monitor sensor spatial, spectral, and radiometric characteristics during its on-orbit operation, each MODIS has a

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complete set of on-board calibrators. They include a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) for RSB radiometric calibration, a blackbody (BB) for TEB radiometric calibration, and a spectro-radiometric calibration assembly (SRCA) for spatial (RSB and TEB) and spectral (RSB) characterization.

This paper presents an overview of MODIS spectral characterization methodologies, from pre-launch to on-orbit. It focuses on Aqua MODIS SRCA on-orbit spectral characterization activities for the RSB and summarizes the results from four-years of on-orbit spectral measurements. Lessons learned and performance issues are discussed for the benefit of future sensor designs and development. The results show that on-orbit changes of Aqua MODIS RSB center wavelengths and bandwidths have been very small, typically less than 0.5nm for the CW and less than 1nm for the BW, therefore meeting the sensor design requirements. Except for the small shifts that occurred shortly after launch, the on-orbit spectral performance of Aqua MODIS has been very stable. Radiometric calibration and spatial characterization performance of Aqua MODIS are presented in separate papers in these proceedings.

2. MODIS PRE-LAUNCH SPECTRAL CHARACTERIZATION

Using a spectral measurement assembly (SpMA), a comprehensive pre-launch spectral characterization was conducted for each MODIS instrument by the instrument vendor, Raytheon Santa Barbara Remote Sensing (SBRS), Goleta, CA (US). The relative spectral response (RSR) measurements, performed for all 36 bands, were used to calculate the center wavelengths and bandwidths. The latter were compared to the specification to determine whether the sensor spectral characterization meets the instrument design requirements. Table 1 lists the MODIS RSB specifications and tolerances for the center wavelengths and bandwidths. The center wavelengths and bandwidths (band averaged) which were measured by the SpMA are also included for comparison. The shaded (colored) boxes contain parameters that are out of specification. It was noted pre-launch that Aqua MODIS bands 6, 7, 19, and 26 are slightly off their specified center wavelengths (CW), however, all RSB met the bandwidth (BW) requirements.

	Center wavelength (nm)			Bandwidth (nm)		
Band	Specification	$\Delta\lambda$	SpMA measured	Specification	$\Delta\lambda$	SpMA measured
1	645	±4	645.8	50.0	±4	47.2
2	858	±2.2	856.9	35.0	±4.3	37.8
3	469	±4	466.1	20.0	±2.8	18.8
4	555	±4	553.9	20.0	±3.3	19.6
5	1240	±5	1241.5	20.0	±7.4	22.8
6	1640	±7	1628.1	24.6	±9.8	26.9
7	2130	±8	2113.9	50.0	±12.8	52.3
8	412	±2	412.4	15.0	±1.5	14.3
9	443	±1.1	442.2	10.0	±1.6	9.6
10	488	±1.2	487.4	10.0	±1.7	10.5
11	531	±2	530.1	10.0	±1.9	11.9
12	551	±5	547.2	10.0	±1.4	10.3
13	667	-2, +1	666.0	10.0	±1.7	10.0
14	678	±1	677.6	10.0	±1.7	11.2
15	748	±2	746.8	10.0	±1.9	9.8
16	869	±5	866.9	15.0	±4.3	15.5
17	905	±2.3	904.4	30.0	±5.4	34.6
18	936	±2.3	936.4	10.0	±5.6	13.5
19	940	±2.4	936.3	50.0	±5.6	46.1
26	1375	±6	1382.3	30.0	±8	36.4

Table 1: Summary of Aqua MODIS RSB center wavelengths (CW) and bandwidths (BW): design specification versus pre-launch characterization results.

The SpMA relative spectral responses (RSR) measurements have been used by the MODIS Characterization Support Team (MCST) for sensor on-orbit calibration. They have also been distributed for user applications. The Aqua MODIS RSR data (in text format) can be obtained from the MCST website[†] for all 36 bands. During MODIS RSR characterization, the measurement accuracy for the spectral band CW was carefully examined by the instrument vendor. Factors evaluated included the accuracy and precision of the SpMA double-monochromator, SpMA source short-term and long-term repeatability and stability, the repeatability or consistency when the wavelength was measured using different grating orders, the monochromator slit width effects, and the uncertainty in the reference detectors used for source illumination corrections. It was concluded that the CW uncertainty (RSS) was 0.25nm for the VIS bands, 0.3nm for NIR bands, and 0.5nm for the SWIR bands. Pre-launch spectral characterization also included measurements of out-of-band (OOB) spectral responses.

3. SPECTRO-RADIOMETRIC CALIBRATION ASSEMBLY (SRCA)

The SRCA is one of the MODIS on-board calibrators. It can be operated in three calibration modes: spatial, spectral, and radiometric. The spatial mode tracks the band-to-band registration (BBR) of all 36 spectral bands in the along-scan and along-track directions, the spectral mode measures the RSB center wavelength and bandwidth shifts, and the radiometric mode monitors the RSB calibration (response) stability. When the SRCA is configured into the spectral mode, a grating monochromator is located between the lamp source and the output collimator as shown in Figure 1.

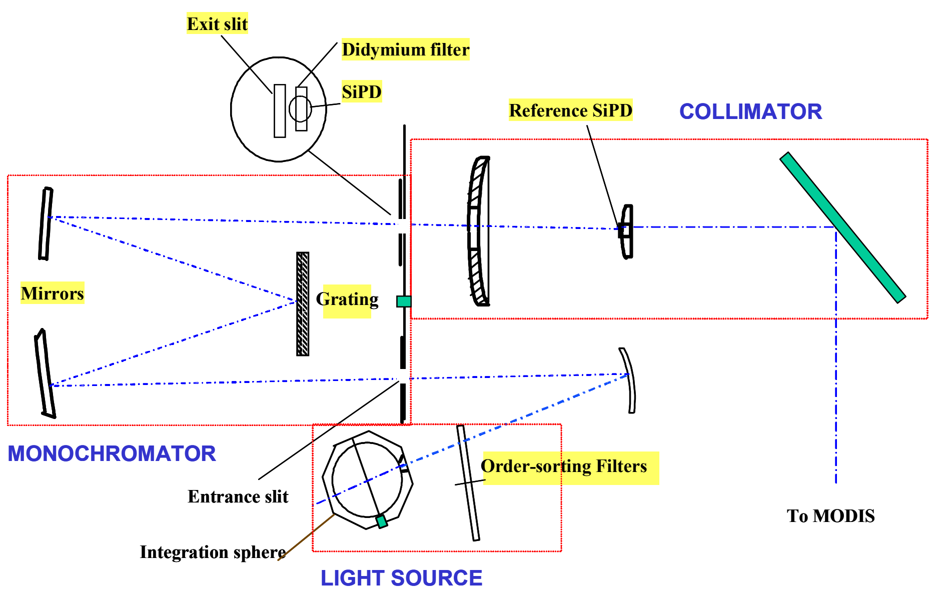

Figure 1: MODIS spectro-radiometric calibration assembly (SRCA) configured in spectral characterization mode.

The light source is a small integration sphere (25.4mm in diameter) with four 10W lamps and two 1W lamps embedded (one 10W and one 1W are the backup lamps). Two lamp configurations (combinations) are used for the spectral mode: 30W and 10W. The 30W lamp configuration is utilized for the shorter wavelength spectral bands while the 10W lamp is used for the others. The grating of the monochromator is used together with the order-sorting filters in spectral characterization. One important SRCA feature is its capability for wavelength self-calibration via an off-axis silicon photo-diode (SiPD) and a didymium filter. This filter has many absorption features (high contrast peaks and valleys). When the SRCA monochromatic beam illuminates RSB detectors, it also illuminates the SiPD. Because the center wavelengths of the didymium peaks are well known and extremely stable, the relationship between the center

[a] ftp://ftp.mcst.ssai.biz/pub/permanent/MCST/FM1_RSR_LUT_07_10_01/

wavelengths of the didymium peaks and the grating step numbers can be determined. This enables the monochromator to be spectrally calibrated during each SRCA operation, thus providing wavelength calibrations for the MODIS spectral bands. To eliminate the source spectrum impact on RSR characterization, a reference SiPD is embedded near center of the collimator. It provides information to remove source spectrum from RSR measurements made by the SRCA. Since the SiPD spectral response is cutoff at wavelengths above 1.05μm, no on-orbit spectral characterization has been made for the SWIR bands (5, 6, 7, and 26). Details of the SRCA spectral characterization algorithm can be found in our previous publications[5-7].

In order to transfer spectral band center wavelengths or, in general, the RSRs derived from pre-launch SpMA measurements to the on-board SRCA so that these parameters can be continuously tracked on-orbit, the SRCA was operated pre-launch together with the SpMA under the same laboratory environment. The measured differences between the SpMA and the SRCA have been considered as an offset and used for on-orbit reference (assumed to be fixed). On-orbit SRCA measurements can be used directly to track the RSB center wavelength shifts. Figures 2 and 3 illustrate the RSB spectral band locations in terms of SRCA monochromator grating step numbers: one from a 30W lamp configuration and the other from a 10W lamp configuration (different grating orders are used).

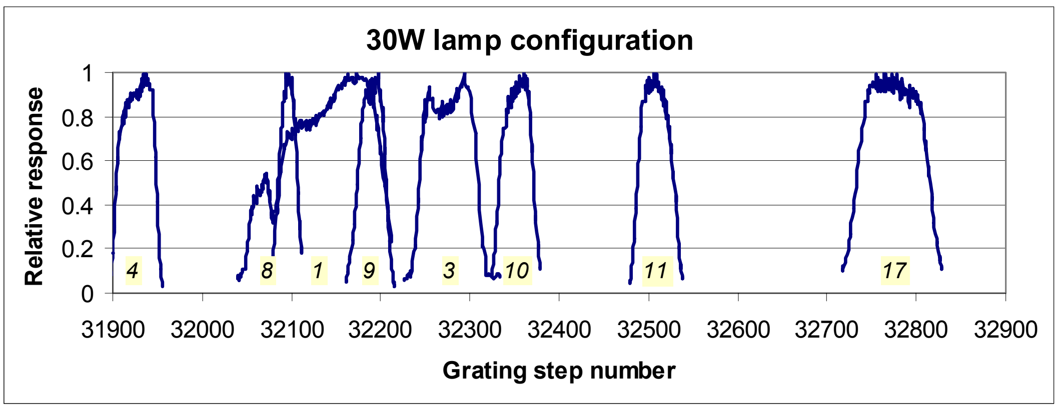

Figure 2: Aqua MODIS RSB relative spectral response (RSR) from SRCA 30W lamp configuration.

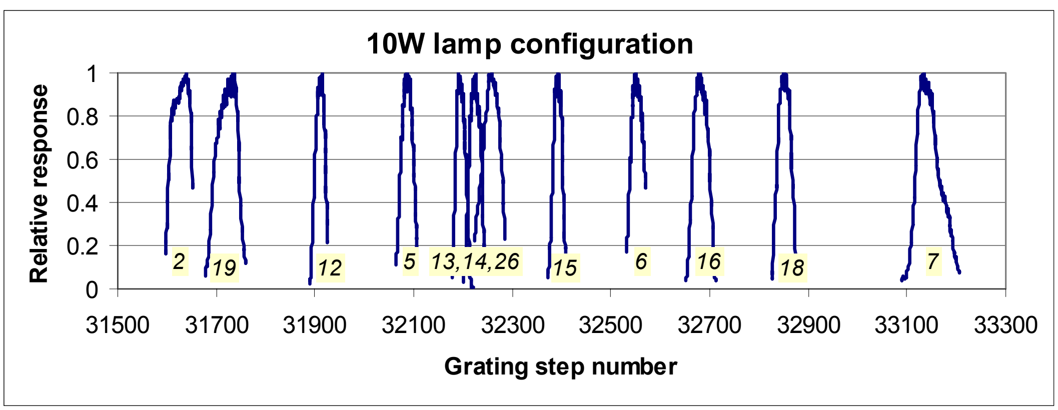

Figure 3: Aqua MODIS RSB relative spectral response (RSR) from SRCA 10W lamp configuration.

On-orbit the daytime stray light from the Earth view (EV) port can severely affect the response of the SRCA reference SiPD used for wavelength calibration. Thus on-orbit SRCA spectral characterization is performed during nighttime. The duration of the space dark varies seasonally from 33.5 to 35.2 minutes. A complete SRCA spectral calibration needs approximately 140 minutes and thus has to be divided into four consecutive orbits. By carefully arranging the measurement sequence of RSB spectral bands and didymium peaks, 99% of the spectral calibration is gathered in space dark. The remaining 1% with contaminated signals is corrected using the pre-launch SiPD response profile.

4. AQUA MODIS ON-ORBIT SPECTRAL CHARACTERIZATION

Normally the SRCA spectral characterization is performed on a quarterly basis with 30W and 10W configurations. During its first year of Aqua MODIS SRCA on-orbit operation, one of the 10W lamps in the 30W configuration became noisy (day 2003104) and was replaced with the backup lamp. On day 2005137, another 10W lamp became inoperable. Therefore, the original 30W configuration has to be changed to a 20W configuration and new flight software and SRCA operational scripts have to be designed and tested. Since the signal-to-noise ratio (SNR) under 20W lamp illumination is lower than for 30W, this change has slightly affected SRCA spectral characterization uncertainty. The Aqua MODIS SRCA lamp problem could be related to extra lamp usage during pre-launch characterization. Since launch a total of 14 spectral calibrations have been performed.

On-orbit center wavelength shift is a key indicator of spectral performance and stability. The changes in relative spectral response (and, therefore, of CW and BW) are primarily due to changes in environmental temperature and changes in the thin-film transmittance, including changes during sensor storage, changes in laboratory to space environment, and on-orbit variations in temperature. Figure 4 presents the center wavelength shifts for the Aqua MODIS VIS/NIR spectral bands derived from over four-years of on-orbit measurements. The x-axis is wavelength in nanometers and the y-axis is center wavelength shift in nanometers. The diamond symbols are initial on-orbit shifts. Among the VIS/NIR spectral bands, bands 1 and 19 have relatively broad bandwidths and their on-orbit center wavelength shifts are relatively large. Shift in band 2 is not included due to the change of its spectral characterization configuration on-orbit (see the end of this section). Table 2 also summarizes the center wavelength shifts on an annual basis (SWIR bands and band 2 are not included). In general the center wavelength shifts have been very small (less than 0.5nm) for most bands.

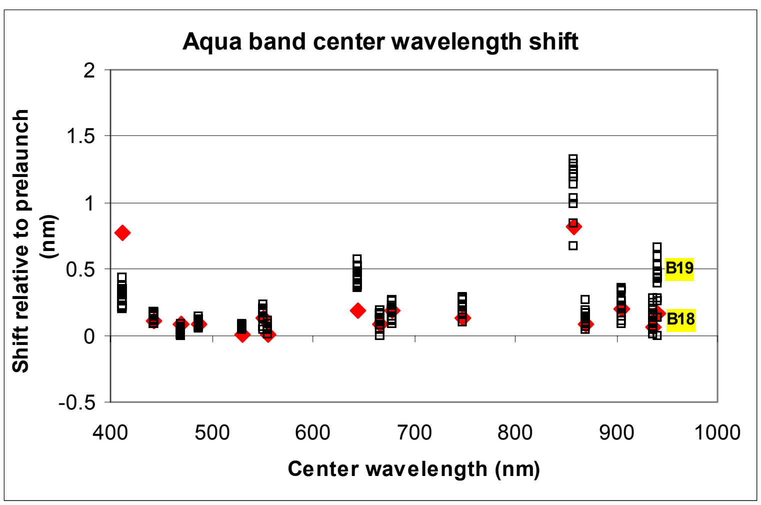

Figure 4: Aqua MODIS VIS/NIR RSB on-orbit center wavelength shifts (nm) since launch. Diamond symbols represent initial on-orbit shifts

To track the RSR profiles and their changes on-orbit, an approach has been developed to recover the RSRs from the SRCA observations. The RSR profiles from SRCA observations are the convolution of the sensor RSRs with the SRCA slit. The finite SRCA slit width causes the SRCA measured RSR to be slightly shifted towards longer wavelengths. Consequently the SRCA slit effect has to be removed from the RSR profiles. However the center wavelength shift trends are not affected. The algorithm applied to correct the RSR from the SRCA to the MODIS RSR (from SpMA) uses the SRCA measured RSR at nominal plateau (a pre-launch thermal vacuum environment that was closest to the on-orbit condition) divided by the SpMA measured RSR in frequency domain to derive the SRCA slit function. On-orbit the RSR from the SRCA is divided by the slit function in frequency domain followed by a reversed Fourier transform. Figures 5-7 show examples of on-orbit recovered RSRs for bands 3, 9, and 11. The SpMA measured RSRs are also included in these figures (hard to tell as they overlap closely with on-orbit results). It is clear that RSR changes for these bands are very small. Only band 8 (not included here) has shown small noticeable variations. This band has the shortest wavelength and its signal level is very low (less than 20 digital counts).

Band	Wavelength (nm)	2002	2003	2004	2005	2006
1	645	0.4	0.4	0.4	0.5	0.6
3	469	0.0	0.0	0.0	0.0	0.1
4	555	0.0	0.1	0.1	0.0	0.1
8	412	0.4	0.3	0.3	0.3	0.2
9	443	0.1	0.1	0.2	0.1	0.2
10	488	0.1	0.1	0.1	0.1	0.1
11	531	0.0	0.1	0.1	0.1	0.1
12	551	0.1	0.2	0.2	0.2	0.2
13	667	0.0	0.1	0.1	0.1	0.2
14	678	0.1	0.2	0.2	0.2	0.3
15	748	-0.1	0.2	0.2	0.2	0.3
16	869	0.1	0.1	0.1	0.1	0.3
17	905	0.2	0.2	0.2	0.3	0.4
18	936	0.1	0.1	0.1	0.2	0.2
19	940	0.1	0.4	0.4	0.6	0.7

Table 2: Aqua MODIS VIS/NIR spectral bands (band 2 excluded) annual on-orbit center wavelength shifts (nm).

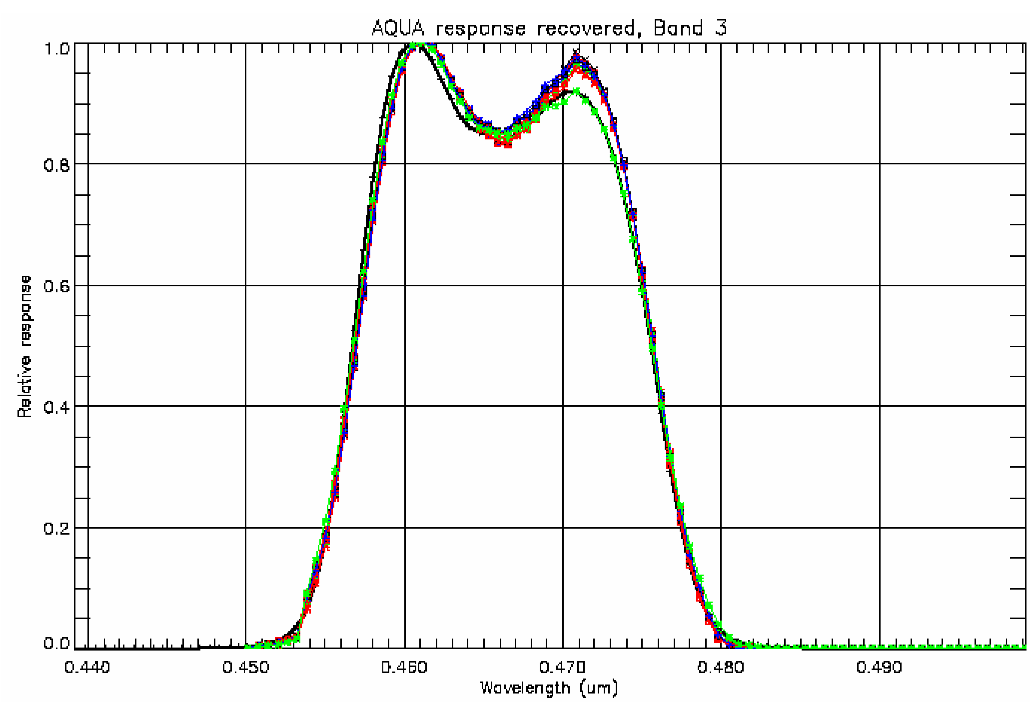

Figure 5: Aqua MODIS on-orbit recovered relative spectral response (RSR) for band 3.

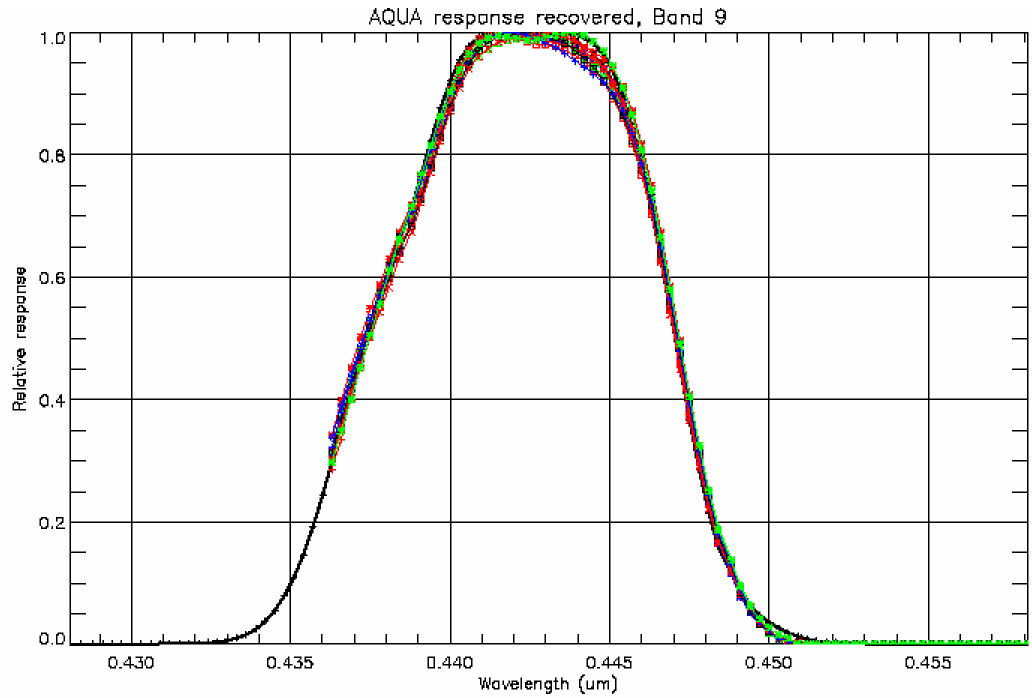

Figure 6: Aqua MODIS on-orbit recovered relative spectral response (RSR) for band 9.

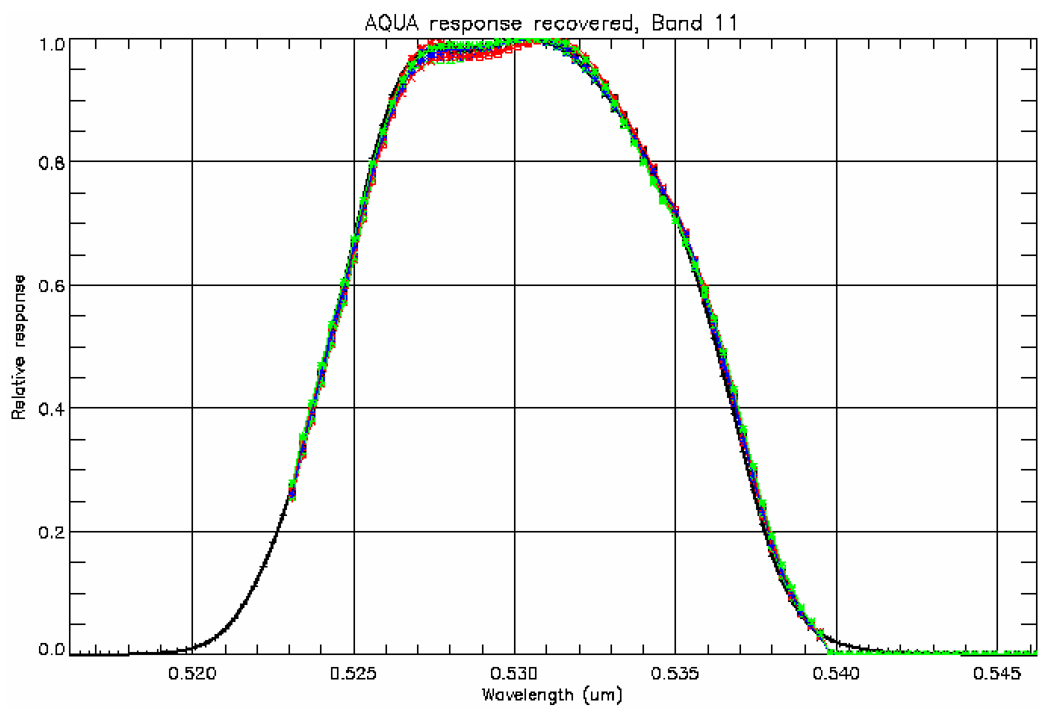

Figure 7: Aqua MODIS on-orbit recovered relative spectral response (RSR) for band 11.

From the recovered RSR profiles, the bandwidths (FWHM of RSR) and their on-orbit changes can be calculated. Figure 8 is the time series of bandwidth variations for Aqua MODIS VIS/NIR bands. Since the band 2 calibration reference cannot be tracked due to a change in grating order used pre-launch and on-orbit, its spectral characterization results are not included. Like center wavelength changes on-orbit, bands 1 and 19 show more variations than the other bands. In general the changes of BW have been less than 0.5nm.

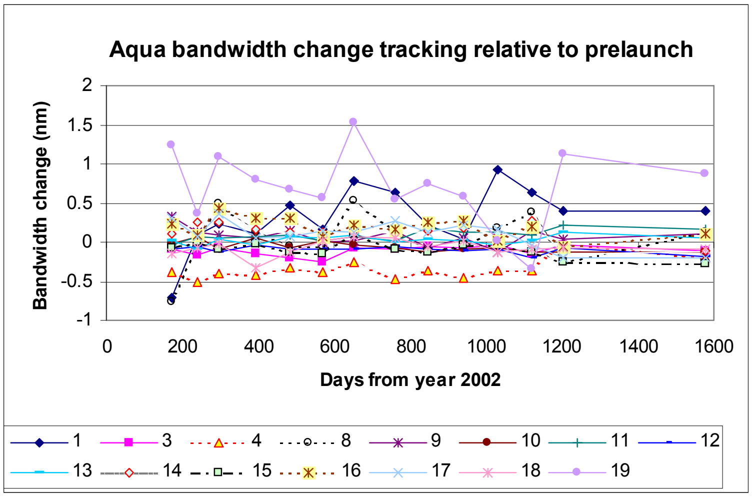

Figure 8: Aqua MODIS RSB bandwidth changes over more than four years.

5. SUMMARY

This paper has presented an overview of MODIS pre-launch and on-orbit spectral characterization activities and methodologies with focus on Aqua MODIS SRCA on-orbit spectral characterization performance. On-orbit results clearly show that changes of Aqua MODIS RSB center wavelengths and bandwidths have been very small, typically less than 0.5nm. Bands 1 and 19 have relatively broad bandwidths and have experienced larger on-orbit changes in both center wavelengths (CW) and bandwidths (BW). Except for the small shifts occurred shortly after launch, Aqua MODIS four-year on-orbit spectral characterization results have demonstrated that the Aqua MODIS sensor spectral performance has been very stable and that the on-board SRCA has achieved its design objective. In addition to CW and BW, the changes of VIS/NIR RSR profiles are also very small. On-orbit stable spectral performance of MODIS instrument can be attributable to the use of ion-assisted deposition (IAD) technique for VIS/NIR optics that has significantly improved the optical coatings stability against on-orbit environmental variations. Obviously the MODIS on-orbit spectral characterization performance has provided useful information for future sensor design, developed, and characterization.

REFERENCES

1. W.L. Barnes and V.V. Salomonson, "MODIS: A global image spectroradiometer for the Earth Observing System", *Critical Reviews of Optical Science and Technology*, CR47, 285-307, 1993
2. W.L. Barnes, X. Xiong, B. Guenther, and V.V. Salomonson, "Development, Characterization, and Performance of the EOS MODIS Sensors', *Proceedings of SPIE – Earth Observing Systems VIII*, 5151, 337-345, 2003
3. V. V. Salomonson, W. L. Barnes, X. Xiong, S. Kempler, and E. Masuoka, "An Overview of the Earth Observing System MODIS Instrument and Associated Data Systems Performance", *Proceedings of IGARSS*, 2002
4. W. L. Barnes, X. Xiong, and V.V. Salomonson, "Status of Terra MODIS and Aqua MODIS", *Proceedings of IGARSS*, 2002

5. X. Xiong, K. Chiang, J. Esposito, B. Guenther, and W.L. Barnes, “MODIS On-orbit Calibration and Characterization,” *Metrologia* 40 89-92, 2003
6. H. Montgomery, N. Che, K. Parker, and J. Bowser, “The algorithm for MODIS wavelength on-orbit calibration using the SRCA”, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, 877-884, 2000
7. X. Xiong, N. Che, and W.L. Barnes, “Terra MODIS On-orbit Spectral Characterization and Performance”, *IEEE Transactions on Geoscience and Remote Sensing*, in press 2006