Results and Lessons from MODIS Reflective Solar Bands Calibration: Pre-launch to On-orbit

X. Xiong[a], N. Che[b], C. Pan[b], X. Xie[b], J. Sun[b], W.L. Barnes[c], and B. Guenther[c]

[a]*Earth Sciences Directorate, NASA/GSFC, Greenbelt, MD 20771;*
[b]*Science Systems and Applications, Inc., 10210 Greenbelt Road, Lanham, MD 20706;*
[c]*University of Maryland, Baltimore County, Baltimore, MD 21250*

ABSTRACT

MODIS is a major instrument for NASA's EOS missions, currently operating aboard the EOS Terra and Aqua spacecraft launched in December 1999 and May 2002, respectively. It was designed to extend heritage sensor measurements and data records and to enable new research studies of the Earth's land, oceans, and atmosphere. MODIS has 36 spectral bands (0.41 - 14.4μm) located on four focal plane assemblies (FPA). It makes measurements at three nadir spatial resolutions: 0.25km, 0.5km, and 1km. Because of instrument design complexity and more stringent calibration requirements, extensive calibration and characterization activities were conducted pre-launch by the sensor vendor for both Terra and Aqua MODIS. For the 20 reflective solar bands (RSB) with wavelengths below 2.2μm, these activities include detector noise characterization, radiometric response at different instrument temperatures and at different scan angles, and relative spectral response. On-orbit RSB calibration is performed using a solar diffuser (SD) and a solar diffuser stability monitor (SDSM). In addition, regular lunar observations are made to track RSB radiometric stability. This paper provides a summary of Terra and Aqua MODIS RSB pre-launch and on-orbit calibration and characterization activities, methodologies, data analysis results, and lessons learned. It focuses on major issues that could impact MODIS RSB calibration and data product quality. Results presented in this paper include RSB detector noise characterization, response versus scan angle and instrument temperature, SD bi-directional reflectance factors characterization, and on-orbit calibration stability. Similar discussions on MODIS thermal emissive bands (TEB) are presented in a separate paper in these proceedings (Xiong *et. al*).

Keywords: Terra, Aqua, MODIS, reflective solar bands, solar diffuser, calibration

1. INTRODUCTION

MODIS is a major instrument for NASA's EOS Terra and Aqua missions, designed to extend and improve heritage sensor measurements and data records, and to provide a broad range of applications for the studies of Earth's land, oceans, and atmosphere. Two MODIS instruments were built for NASA's EOS by Raytheon / Santa Barbara Remote Sensing (SBRS) in Goleta, California. MODIS proto-flight model (PFM) on-board the EOS Terra satellite has operated for more than 6.5 years since its launch in December 1999. MODIS flight model (FM1) on-board the EOS Aqua satellite has operated for more than 4 years since it launch in May 2002. Together they have collected more than 10.5 years of Earth-observing data sets and produced about 40 science data products for operational applications and research studies of short- and long-term changes of the Earth system environment and climate [1-3].

Compared to its heritage sensors, MODIS was developed with improved spectral, spatial, and temporal scales, and therefore with more stringent calibration requirements [1,4]. It is a scanning radiometer that uses a double-sided scan mirror. Each scan of 1.478 seconds, the sensor collects data from the Earth view (EV) over a scan angle range of ±55° about instrument nadir and from its on-board calibrators (OBC). MODIS makes observations in 36 spectral bands from

Earth Observing Systems XI, edited by James J. Butler, Jack Xiong,
Proc. of SPIE Vol. 6296, 629607, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.679144

0.41μm to 14.4μm and at three nadir spatial resolutions: 0.25km for bands 1-2 with 40 detectors each, 0.5km for bands 3-7 with 20 detectors each, and 1km for the remaining 29 bands with 10 detectors each. MODIS bands 1-19 and 26 are the reflective solar bands (RSB) covering wavelengths from 0.41 to 2.2μm. MODIS RSB detectors are located on the visible (VIS) focal plane assembly (FPA), near infrared (NIR) FPA, short- and mid-wave infrared (SMIR) FPA. The other 16 spectral bands are the thermal emissive bands (TEB). Key MODIS RSB design specifications are summarized in Table 1, which includes each RSB band center wavelength (CW), bandwidth (BW), typical and maximum scene radiance (Ltpy and Lmax), noise equivalent difference radiance (NEdL) and signal-to-noise ratio (SNR). Also included in this table are RSB primary science applications.

TABLE 1 MODIS REFLECTIVE SOLAR BANDS SPECIFICATION

Band	CW	BW	Ltyp	Lmax	NEdL	SNR	Primary Use
1	0.645	50	21.8	685	0.1703	128	Land/Cloud/Aerosols Boundaries
2	0.858	35	24.7	285	0.1229	201	
3	0.469	20	35.3	593	0.1453	243	Land/Cloud/Aerosols Properties
4	0.555	20	29.0	518	0.1272	228	
5	1.240	20	5.4	110	0.0730	74	
6	1.640	24	7.3	70	0.0265	275	
7	2.130	50	1.0	22	0.0091	110	
8	0.412	15	44.9	175	0.0510	880	Ocean Color/Phytoplankton/ Biogeochemistry
9	0.443	10	41.9	133	0.0500	838	
10	0.488	10	32.1	101	0.0400	802	
11	0.531	10	27.9	82	0.0370	754	
12	0.551	10	21.0	64	0.0280	750	
13	0.667	10	9.5	32	0.0104	910	
14	0.678	10	8.7	31	0.0080	1087	
15	0.748	10	10.2	26	0.0174	586	
16	0.869	15	6.2	16	0.0120	516	
17	0.905	30	10.0	185	0.0599	167	Atmospheric Water Vapor
18	0.936	10	3.6	256	0.0632	57	
19	0.940	50	15.0	189	0.0600	250	
26	1.375	30	6.0	90	0.0400	150	Cirrus Clouds Water Vapor

CW: Center Wavelengths in μm;
BW: Bandwidth in nm;
Ltyp: Specified Typical Scene Radiance in W/m^2/sr/μm;
Lmax: Specified Maximum Scene Radiance in W/m^2/sr/μm;
NEdL: Noise Equivalent Difference Radiance in W/m^2/sr/μm;
SNR: Signal-to-Noise Ratio (SNR)

Both Terra and Aqua MODIS went through extensive pre-launch calibration and characterization activities. Key RSB radiometric calibrations were performed in a thermal vacuum (TV) environment at three instrument temperature plateaus. MODIS RSB on-orbit calibration is reflectance based and the specified (reflectance) calibration requirements are ±2% at their typical scene radiances (Table 1). RSB on-orbit calibration is performed using an on-board solar diffuser (SD) and a solar diffuser stability monitor (SDSM). The SDSM is operated to track on-orbit changes of SD bi-directional reflectance factors (BRF). Lunar observations are also regularly scheduled to monitor RSB radiometric stability [5-7]. This paper provides an overview of MODIS RSB pre-launch and on-orbit radiometric calibration and characterization activities, calibration methodologies, data analysis results, and lessons learned. Discussions are focused on major issues that could have significant impact on RSB calibration and data product quality, such as detector noise characterization, response versus scan angle (RVS), SD BRF characterization, response versus instrument temperature, and on-orbit calibration stability. Similar discussions for the MODIS TEB are presented in a separate paper in these proceedings (Xiong *et. al*). Sensor spectral and spatial characterization activities and results, such as relative spectral response (RSR) and spectral band-to-band registration (BBR), have been reported elsewhere [8-10].

2. MODIS RSB CALIBRATION AND CHARACTERIZATION ACTIVITIES

2.1 Pre-launch calibration and characterization activities

MODIS RSB pre-launch calibration and characterization activities include spatial, spectral, radiometric, and polarization sensitivity measurements. This paper focuses on RSB radiometric calibration issues including measurements made in ambient as well as the thermal vacuum (TV) environment. The primary calibration source for the RSB is a 100cm diameter spherical integrating source (SIS-100) traceable to NIST irradiance standards. RSB system level radiometric calibration was performed at cold, nominal, and hot instrument temperature plateaus with either primary (A-side) or redundant (B-side) electronics. The "primary" and "redundant" were arbitrarily designated since both consist of near-identical components or sub-systems. Only initial parameter settings, such as gain and offset, focal plane voltage bias, and sub-system location, could have some minor differences.

At TV nominal plateau, RSB calibration was performed using a complete set of SIS levels and primary electronics. This is referred to as a comprehensive (COM) test. At other instrument temperatures and with different electronic configurations, including different DC restores (DCR), MODIS RSB radiometric calibrations were also made using a subset of SIS levels. This is referred to as a limited (LIM) test. Table 2 summarizes the measurements performed in TV environment for Terra MODIS RSB radiometric calibration.

TABLE 2 TERRA MODIS RSB PRE-LAUNCH THERMAL VACUUM CALIBRATION

Instrument Plateau	Cold (256K)	Nominal (273K)	Hot (283K)
Primary Electronics	LIM (1), LIM (2)	COM (1), COM (2)	LIM (1), LIM (2)
Redundant Electronics	LIM	LIM	LIM, LIM (DCR-1) LIM (DCR-2)

For both Terra and Aqua MODIS, the RSB response versus scan angle (RVS) was characterized pre-launch at ambient environment with MODIS mounted on a rotating table so that a fixed calibration source (SIS-100) could be viewed at different angles of incidence (AOI). Different SIS levels were used at each scan angle in order to optimize RSB detector response.

MODIS RSB on-orbit calibration is performed using an on-board solar diffuser (SD) panel, a near-Lambertian diffuser plate comprised of space-grade Spectralon. Its bi-directional reflectance factors (BRF) were measured with reference to diffuser samples traceable to NIST reflectance standard. For both Terra and Aqua MODIS, The SD BRF characterization was made at 6 different wavelengths (0.4μm, 0.5μm, 0.6μm, 0.7μm, 0.9μm, and 1.7μm) and at 9 different illuminating directions that could cover the viewing angles to be used during on-orbit calibration. A linear interpolation of the polynomial fitting to the SD BRF was made to match the wavelengths for MODIS spectral bands.

2.2 On-orbit calibration and characterization activities

On-orbit SD calibration is normally performed on a bi-weekly basis (weekly first year). This has been the most critical and demanding on-orbit calibration activity for MODIS RSB. Normally when there is no SD calibration, a solar diffuser door is closed to prevent the SD panel from being illuminated by direct sunlight. During each scheduled SD calibration, the SDSM is operated so that on-orbit changes of SD BRF can be monitored. The SD calibration system also includes an optional SD screen (SDS), a metal plate with uniformly distributed pinholes. It is placed in front of the SD for calibrating RSB high gain bands (8-16) whose response saturate when the SD is illuminated by the direct sunlight.

For Terra MODIS, a SD door operational anomaly occurred in May 2003. Consequently a decision was made to keep the SD door in the "open" position and the SDS permanently in front of the SD so that all the RSB bands could be calibrated without SD door and SDS operations. This has been the SD door and screen configuration since July 2, 2003.

Meanwhile the SDSM operation still remains on a bi-weekly basis. Based on instrument design there is a limit (design life) on the number of SD door movements. For Aqua MODIS, many SD door movements were made during pre-launch functional testing. In order to support an option of extending Aqua mission beyond its initial 6-year design life and ensuring MODIS on-orbit SD calibration capability, Aqua SD/SDSM calibration schedule has been change to a tri-weekly basis, started from early 2006.

A number of MODIS RSB on-orbit calibration and characterization activities were performed using observations made during carefully planned spacecraft maneuvers. Near-monthly spacecraft (both Terra and Aqua) roll maneuvers are scheduled for lunar observations. The lunar observations are used independently to track RSB calibration stability [11]. Two sets of yaw maneuvers (each consists of two series of 8 consecutive yaws, one with SDS and one without SDS) by Terra spacecraft and one set by Aqua spacecraft have been executed. Data collected during these maneuvers have been utilized to derive the SDS transmission since no pre-launch measurements were made, and to validate SD BRF spatial uniformity [12-13]. To this date Terra spacecraft has made two pitch maneuvers: one on March 26, 2003 and the other on April 14, 2003.

SWIR bands (5-7 and 26) thermal leak and electronic crosstalk problems were identified in both Terra and Aqua MODIS during pre-launch sensor characterization. The effects are much smaller in Aqua MODIS as based on the experience gained from Terra MODIS, efforts were made to reduce the effects and improve the sensor performance. A special on-orbit operation has been designed and implemented to collect nighttime Earth view (EV) RSB data using day mode since normally RSB only collect daytime data. The observations made during this special operation are used to characterize the SWIR thermal leak and the electronic crosstalk. A set of correction coefficients are derived and used for the L1B correction algorithm [14].

3. MODIS RSB CALIBRATION METHODOLOGIES

MODIS RSB calibration is reflectance based using a solar diffuser. The calibration is made for each band, detector, sub-sample (for sub-kilometer bands 1-7), and mirror side (BDSM) using a simple linear algorithm. Details of MODIS RSB pre-launch and on-orbit calibration methodologies have been reported in references [5-7, 15]. We provide in this section a brief description of the RSB on-orbit calibration approach of using SD observations to calculate EV observations. MODIS L1B RSB primary data product is the EV reflectance factor, $\rho_{EV}\cos(\theta_{EV})$, computed using a linear algorithm,

$$\rho_{EV}\cos(\theta_{EV}) = m_1 \cdot dn^*_{EV} \cdot d^2_{ES(EV)} \tag{1}$$

where

θ_{EV} is the EV solar zenith angle
m_1 is the calibration coefficient related to each detector's gain
$dn_{EV}*$ is EV response corrected for instrument background, temperature, and viewing angle
$d_{ES(EV)}$ is the Earth-Sun distance in AU at the time of the EV observation.

Applying Eqn. 1 to SD observations yields a similar reflectance factor, $\rho_{SD}\cos(\theta_{SD})$, for the SD,

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

where

θ_{SD} is the SD solar zenith angle,
$dn_{SD}*$ is SD response with the same corrections for the EV response,
$d_{ES(SD)}$ is the Earth-Sun distance in AU at the time of the SD observation.

Since SD BRF changes slowly on-orbit and a SDS is used for calibrating RSB high gain bands, two additional terms, one correcting for SD degradation (Δ_{SD}) and the other for the SDS transmission or vignetting function (Γ_{SDS}), are needed in SD calibration. Thus,

$$m_1 = \frac{\rho_{SD} \cos(\theta_{SD})}{dn^*_{SD} \cdot d^2_{ES(SD)}} \cdot \Gamma_{SDS} \cdot \Delta_{SD} \tag{3}$$

where, $\Gamma_{SDS} = 1$ if the SDS is not used in the calibration. The SD degradation (Δ_{SD}) factor is measured during each SD calibration using the SDSM. MODIS RSB calibration coefficients are updated if necessary via time dependent look-up tables (LUT). Similar calibration equations can be written for MODIS lunar observations in which the geometric factors will include lunar phase angles, libration angles, Sun-Moon and Moon-Satellite distances, and an over-sampling factor.

4. MODIS RSB CALIBRATION AND CHARACTERIZATION RESULTS AND DISCUSSIONS

In this section we present results derived from MODIS RSB pre-launch and on-orbit measurements on detector noise characterization, response versus scan-angle (RVS) and instrument temperature, SD BRF characterization, SD BRF degradation and on-orbit calibration stability. It should be pointed out that it is impossible to cover all RSB calibration results that have been produced by the MODIS Characterization Support Team (MCST) at NASA/GSFC on various topics.

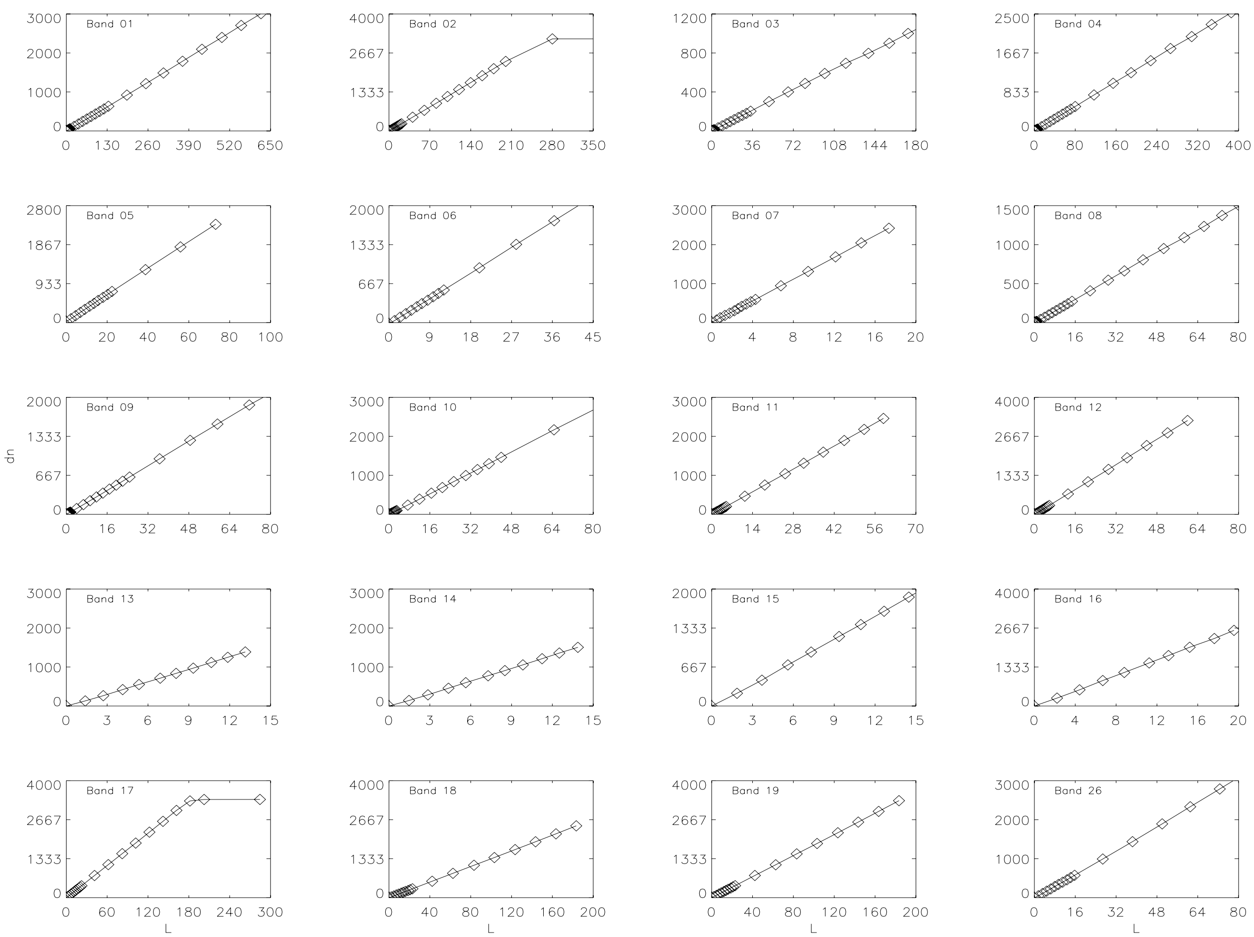

Figure 1. Terra MODIS RSB (middle detector, mirror side 1) response in digital numbers (y-axis) versus SIS-100 spectral radiance in W/m^2/sr/μm (x-axis): pre-launch thermal vacuum comprehensive test with primary electronics at nominal plateau.

4.1 Noise characterization

Figure 1 illustrates an example of Terra MODIS RSB response in digital numbers versus input SIS-100 radiance. In addition to detector dynamic range and nonlinearity, noise characterization was determined at all non-saturation SIS levels. The results, pre-launch and on-orbit, for both Terra and Aqua MODIS current operating configurations are summarized in Table 3. They are reported in terms of SNR at typical radiance (Table 1) for each band (middle detector). For Terra MODIS RSB, SNR of all 20 detectors in band 7 were found to be below the design requirement since pre-launch. Currently (after more than 6 years of on-orbit operation), only 2 additional noisy detectors were identified. For Aqua MODIS, band 6 detectors that were identified as inoperable pre-launch and shortly after launch, nearly all other RSB detectors have been performing well on-orbit.

TABLE 3 MODIS RSB NOISE CHARACTERIZATION RESULTS (SNR)

Band	Spec	Pre-launch		On-orbit	
		Terra-A	Aqua-B	Terra-A	Aqua-B
1	128	170	176	194	200
2	201	383	437	507	507
3	243	296	302	322	304
4	228	302	311	329	313
5	74	121	156	91	132
6	275	406	400	378	245
7	110	65	143	102	156
8	880	958	977	1005	912
9	838	1134	1374	1450	1078
10	802	1097	1180	1410	1037
11	754	1166	1328	1600	990
12	750	989	1160	1250	994
13	910	677	1149	1200	937
14	910	692	1063	1200	937
15	1087	715	1149	1350	994
16	1087	737	1157	1350	994
17	586	752	1063	1250	871
18	516	701	968	1050	828
19	167	352	256	363	376
26	57	88	88	94	92

TABLE 4 MODIS RSB TEMPERATURE COEFFICIENTS

Band	Terra MODIS		Aqua MODIS	
	A-side	B-side	A-side	B-side
1	0.0014	0.0009	0.0030	0.0020
2	0.0022	0.0017	0.0029	0.0018
3	0.0008	0.0004	0.0015	0.0013
4	0.0008	0.0003	0.0016	0.0013
5	0.0005	0.0018	-0.0049	0.0009
6	0.0001	0.0002	0.0007	0.0009
7	0.0006	0.0000	-0.0008	0.0006
8	0.0018	0.0019	0.0029	0.0029
9	0.0008	0.0005	0.0016	0.0015
10	0.0006	0.0002	0.0013	0.0011
11	0.0006	0.0000	0.0014	0.0011
12	0.0006	0.0001	0.0013	0.0010
13	0.0008	0.0004	0.0027	0.0014
14	0.0008	0.0003	0.0027	0.0004
15	0.0007	0.0003	0.0028	0.0018
16	0.0007	0.0003	0.0028	0.0003
17	0.0009	0.0005	0.0031	0.0020
18	0.0008	0.0003	0.0037	0.0026
19	0.0005	0.0004	0.0016	0.0012
26	0.0007	-0.0002	0.0020	0.0010

4.2 Response versus instrument temperature and versus scan-angles

From RSB pre-launch TV radiometric calibration at different instrument plateaus (cold, nominal, and hot), detector temperature coefficients (changes per degree) were determined for both Terra and Aqua MODIS, for both primary and redundant electronic configurations. The band-averaged results are summarized in Table 4. In general the changes for most bands are less than 0.3 %/K. The calibration coefficients were computed for each band, detector, mirror side, and sub-sample and used in the L1B on-orbit calibration algorithm as well as in the SD on-orbit calibration.

As mentioned earlier, both Terra and Aqua MODIS RSB response versus scan angle (RVS) measurements at sensor system level were performed. The RSB RVS was characterized at ambient environment using different SIS radiance levels. For a given SIS illumination level, detector response at different angles of incidence (AOI) were analyzed and applied to derive the relative response versus scan-angle (normalized to on-orbit SD calibration AOI at about 50.2°). RSB RVS is spectral band dependent and mirror side dependent. The results of Terra MODIS RSB pre-launch RVS are presented in Figure 2. On-orbit, the RSB RVS has been regularly updated, primarily for spectral bands in the VIS spectral region.

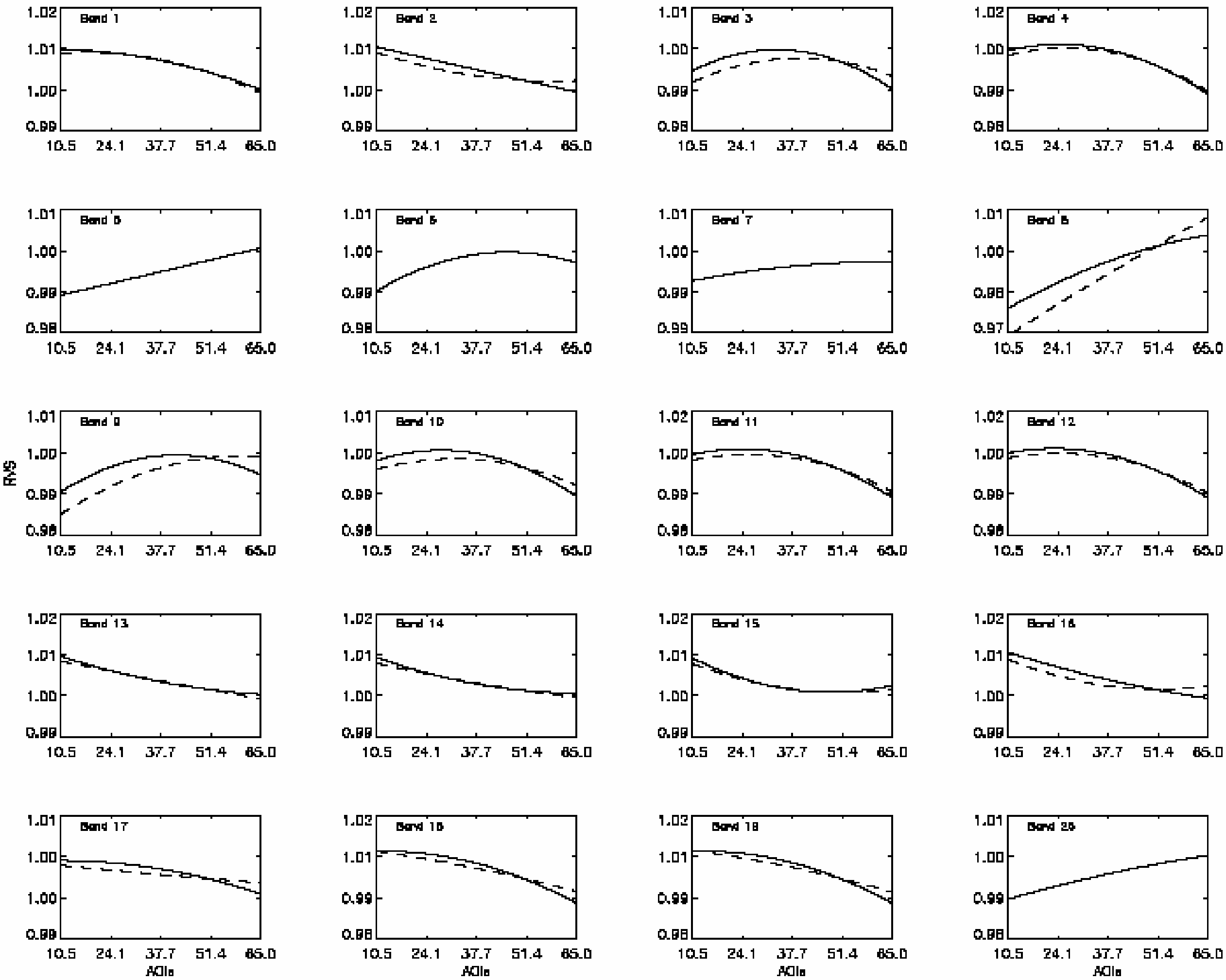

Figure 2. Terra MODIS RSB relative response versus scan angle (RVS): solid line for mirror side 1 and dashed line for mirror side 2.

4.3 SD BRF characterization and on-orbit degradation

MODIS solar diffuser (SD) bi-directional reflectance factors (BRF) were characterized pre-launch with reference to a NIST reflectance standard. It was made at a fixed viewing direction with the 9 different illuminating directions used for on-orbit operation. A polynomial fit was applied to SD BRF measurements at all six wavelengths: 0.4μm, 0.5μm, 0.6μm, 0.7μm, 0.9μm, and 1.7μm. The pre-launch BRF results at 0.4μm and 0.5μm are shown in Figure 3 as a function of azimuth angle and elevation angle. During on-orbit operation, the SD BRF degradation has been monitored by the SDSM. The SDSM is a ratioing radiometer that has 9 filtered detectors with wavelengths from 0.41 to 0.94μm. It makes alternate measurements of direct sunlight and sunlight diffusely reflected from the SD. The time series of these ratios determines SD degradation.

Since SD on-orbit degradation at 0.94μm is extremely small, the SDSM measurements at this wavelength (D9) are often used for normalization purposes to remove data noise due to SDSM screen modulation at other wavelengths. Terra MODIS SD degradation results after each year of on-orbit operation are presented in Figure 4. Noticeable increases of the SD degradation rate after the third year are primarily due to the SD door operational anomaly described in the previous section. This anomaly led to a decision to keep the SD door in the "open" position thus causing more solar exposure onto the SD panel. The results in Figure 4 also clearly show a strong wavelength dependent degradation. After 6 years of on-orbit operation, the SD degradation is about 35% at 0.41μm.

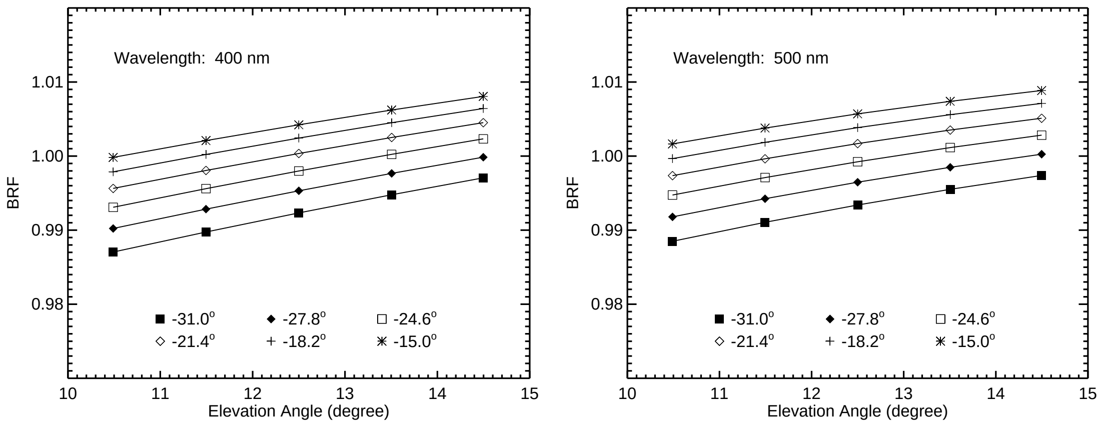

Figure 3. Examples of Terra MODIS SD bi-directional reflectance factor (BRF) at 400nm (left) and 500nm (right) presented at six fixed azimuth angles from -31° to -15°.

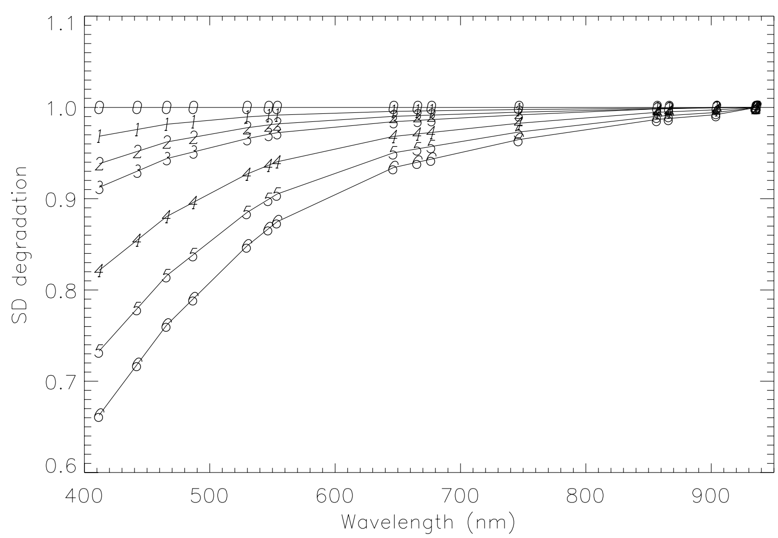

Figure 4. Terra MODIS solar diffuser on-orbit degradation (annually accumulated) as a function of wavelength.

4.4 Response short-term stability and long-term changes

Terra MODIS RSB response short-term stability is illustrated in Figure 5 using scan-by-scan SD calibration coefficients (middle detector, mirror side 1, sub-sample 1) derived using Equation 3. For the bands (1-7, 17-19, and 26) that are calibrated without SDS, the variations are typically less than ±0.15%. For bands (8-16) that are calibrated with SDS, the variations are typically on the order of ±0.30%, mainly due to SDS effects. Aqua MODIS RSB response shows similar behavior. The final calibration coefficients are averaged over all scans to further reduce the random noise and SDS impact.

The changes of RSB response are tracked using the SD calibration with its degradation removed using SDSM measurements. Sensor response appears to be largely dependent on wavelength. Visible bands such as band 8, 9, 3 and 10 have experienced the largest gain changes since launch. For 6 years of Terra MODIS operation, the gain decreases (mirror side 1) are about 28%, 14%, 10%, and 8% respectively for these bands. While for Aqua band 8, 9, 3 and 10, the gain changes are around 12%, 8%, 6.5%, and 5% respectively over 4 years of operation. These changes are primarily due to mirror reflective degradation.

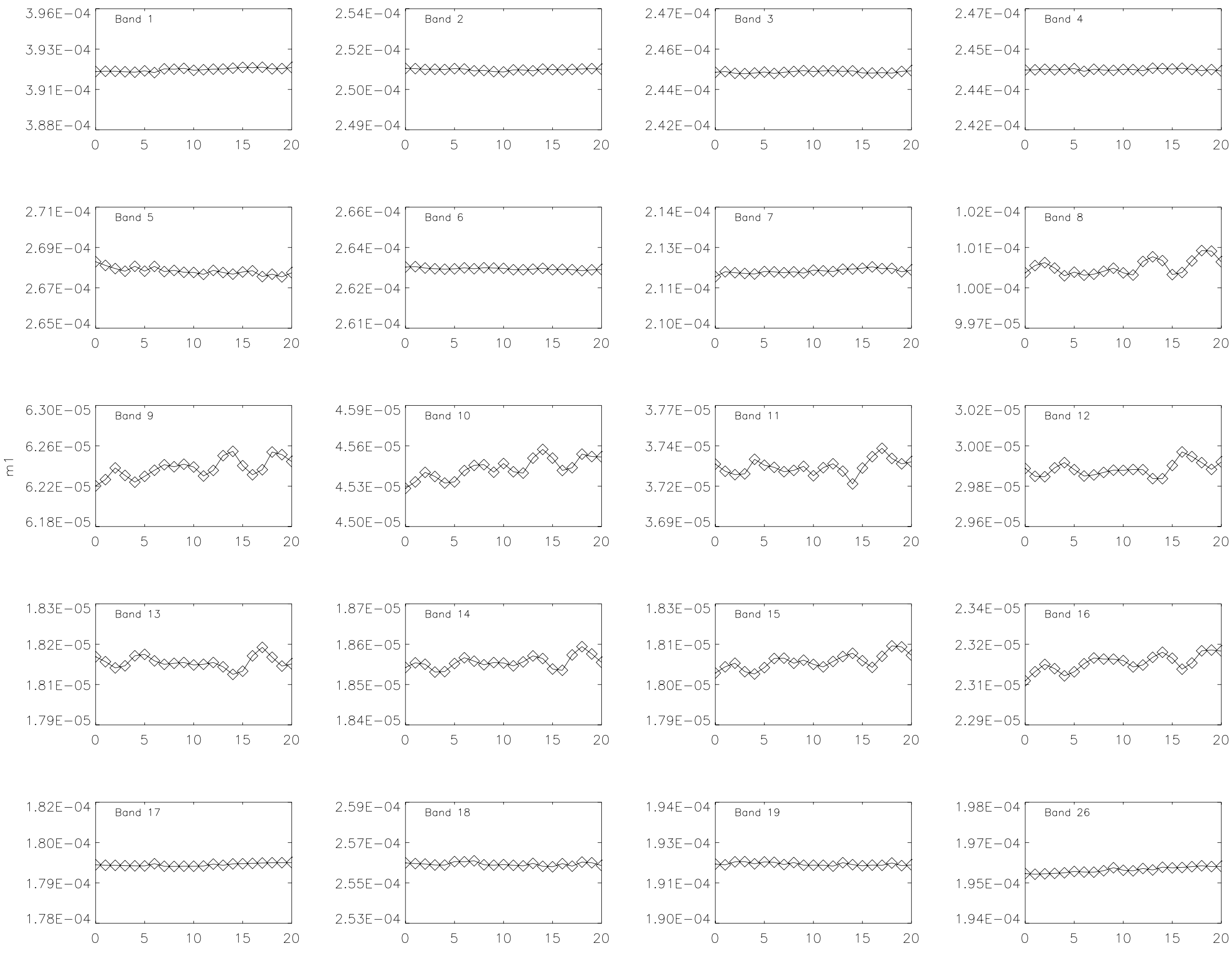

Figure 5. Terra MODIS RSB short-term stability: scan-by-scan calibration coefficients during a compete set of SD calibration. Bands 1-7, 17-19, and 26 are calibrated without SDS and bands 8-16 are calibrated with SDS.

5. LESSONS FROM PRE-LAUNCH AND ON-ORBIT CALIBRATION

From sensor design and development phase to pre-launch calibration and characterization activities and on-orbit performance, many lessons have been learned for Terra and Aqua MODIS reflective solar bands (RSB). Due to limited space we provide the following abbreviated list of lessons learned based on MODIS RSB calibration experience for future reference. Some of the requirements and recommendations can also be applied to the thermal emissive bands as we presented in a separate paper in these proceedings (Xiong *et. al*).

- Full radiometric calibration is necessary at different instrument temperatures and electronics temperatures if they can be independently controlled, and at different combinations of sensor operational configurations.

- Characterization using high-contrast scenes or targets is needed.
- End-to-end pre-launch characterization is recommended for on-board solar diffuser (SD) calibration and for the pre-launch system level measurements using solar diffuser stability monitor (SDSM).
- A calibration transfer from pre-launch to on-orbit must be carefully designed and implemented.
- Improvements (accuracy, wavelength intervals, and uniformity) are needed for SD BRF characterization, as it is a major contributor for future RSB calibration uncertainty.
- Spacecraft maneuvers and lunar observations can provide additional sensor calibration and characterization information.
- Calibration source stability and traceablility are critical for high quality measurements and uncertainty assessments.
- Continuous calibration efforts have to be made from pre-launch characterization to on-orbit operation.

6. SUMMARY

This paper presented an overview of the MODIS reflective solar band calibration and characterization activities. Results derived from pre-launch and on-orbit calibration and characterization are discussed as well as lessons learned. Since launch both Terra and Aqua MODIS have performed well and exceeded design specifications for SNR characteristics for all RSB bands except for detectors in Terra band 7 and Aqua band 6 which were identified as noisy or inoperable during pre-launch testing. The RVS is tracked on-orbit and regularly updated. The SD is a key component of the MODIS on-orbit calibration system and its BRF and degradation performance is tracked using the SDSM. A SD door anomaly occurred for Terra in May 2003, and the door is currently kept in the open position, thus causing a higher SD degradation rate. After six years of operation the Terra SD degradation is about 35% at 0.41 μm. The short-term stability in RSB response is within ±0.15% for bands 1-7, 17-19, and 26, and ±0.30%, for bands 8-16 for both Terra and Aqua. Examples in the paper have illustrated the importance of pre-launch calibration and characterization activities for better understanding of sensor characteristics and performance. They have also demonstrated the need for constant and/or continuous on-orbit calibration efforts. We firmly believe that the high quality calibration and validation work, including data analyses, should be done independently and possibly with different approaches.

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 and V.V. Salomonson, "Status of Terra MODIS and Aqua MODIS," *Proceedings of IGARSS*, 2002.
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, V.V. Salomonson, and X. Xiong, "Development, Characterization, and Performance of the EOS MODIS Sensors," *Proceedings of SPIE – Earth Observing Systems VIII*, 5151, 337-345, 2003.
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. X. Xiong and W.L. Barnes, "An Overview of MODIS Radiometric Calibration and Characterization," *Advances in Atmospheric Sciences*, 23 (1), 69-79, 2006.
7. X. Xiong, J. Sun, J. Esposito, B. Guenther, and W. L. Barnes, "MODIS Reflective Solar Bands Calibration Algorithm and On-orbit Performance," *Proceedings of SPIE – Optical Remote Sensing of the Atmosphere and Clouds III*, 4891, 2002.
8. W.L. Barnes, T.S. Pagano, and V.V. Salomonson, "Prelaunch characteristics of the Moderate Resolution Imaging Sectroradiometer (MODIS) on EOS-AM1," *IEEE Trans. Geosci. Remote Sensing* 36, pp.1088-1100, 1998.
9. X. Xiong, N. Che, B. Guenther, W.L. Barnes, and V.V. Salomonson, "Five Years of Terra MODIS On-orbit Spectral Characterization," *Proceedings of SPIE – Earth Observing Systems X*, Vol. 5882, 2005.
10. N. Che, X. Xiong, B. Guenther, W.L. Barnes, and V.V. Salomonson, "Five Years of Terra MODIS On-orbit Spatial Characterization," *Proceedings of SPIE – Earth Observing Systems X*, Vol. 5882, 2005.

11. X. Xiong, J. Sun, K. Chiang, S. Xiong, and W. Barnes, "MODIS On-orbit Characterization Using the Moon," *Proceedings of SPIE – Sensors, Systems, and Next Generation Satellites VI*, 4881, 2002.
12. X. Xiong, J. Sun, J. Esposito, X. Liu, W.L. Barnes, and B. Guenther, "On-orbit Characterization of a Solar Diffuser's Bi-directional Reflectance Factor Using Spacecraft Maneuvers," *Proceedings of SPIE – Earth Observing Systems VIII*, 5151, 375-383, 2003.
13. X. Xie, X. Xiong, D. Moyer, J. Sun, X. Liu, and W.L. Barnes, "Analysis of MODIS Solar Diffuser Screen Vignetting Function," *Proceedings of SPIE – Earth Observing Systems X*, Vol. 5882, 58820T, doi:10.1117/12.615394, 2005.
14. Xiong X., K. Chiang, F. Adimi, W. Li, H. Yatagai, and W.L. Barnes, "MODIS Correction Algorithm for Out-of-band Response in the Short-wave IR Bands," *Proceedings of SPIE – Sensors, Systems, and Next Generation of Satellites VII*, 5234, 605-613, 2004.
15. B. Guenther, G. Godden, X. Xiong, E. Knight, H. Montgomery, M. Khayat, and Z. Hao, "Pre-Launch Algorithm and Data Format for the Level 1 Calibration Products for the EOS AM-1 MODerate Resolution Imaging Spectroradiometer (MODIS)," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 36, No. 4, 1142-1151, 1998.