Results and Lessons from MODIS Thermal Emissive Bands Calibration: Pre-launch to On-orbit

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ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a major instrument for NASA's Earth Observing System (EOS), currently operating on-board the EOS Terra spacecraft, launched in December 1999, and Aqua spacecraft, launched in May 2002. MODIS is a whiskbroom scanning radiometer using a double-sided paddle wheel scan mirror. It makes measurements in 36 spectral bands with wavelengths from visible (VIS) to long-wave infrared (LWIR). Bands 20-25 and 27-36 are the thermal emissive bands (TEB) covering wavelengths from 3.5 to 14.4μm. During pre-launch thermal vacuum measurements, a laboratory blackbody calibration source (BCS) was used as the primary calibration source for the TEB. For on-orbit operation, an on-board blackbody (BB) source and a space view (SV) port are used together for the TEB calibration on a scan-by-scan basis. This paper provides an overview of Terra and Aqua MODIS pre-launch and on-orbit calibration and characterization activities, methodologies, data analysis results, and lessons learned for the thermal emissive bands. It focuses on major issues that could impact MODIS TEB calibration and data quality. Results presented in this paper include detector noise characterization, response versus scan angle (RVS), and response versus instrument and focal plane temperatures. Similar discussions for the MODIS reflective solar bands (RSB) are presented in a separate paper in these proceedings (Xiong *et. al*).

Keywords: Terra, Aqua, MODIS, thermal emissive bands, blackbody, calibration, noise characterization

1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a major instrument for NASA's Earth Observing System (EOS). Two nearly identical MODIS instruments were built by Raytheon / Santa Barbara Remote Sensing (SBRS), Goleta, California. MODIS proto-flight model (PFM) has been in operation on-board EOS Terra satellite (formerly EOS AM-1) since its launch in December 1999 in a morning orbit (10:30 a.m. descending southwards). The flight model (FM1) has been in operation on-board the EOS Aqua satellite (formerly EOS PM-1) since it launch in May 2002 in an afternoon orbit (1:30 p.m. ascending northwards). Together they have collected more than 10.5 years of Earth-observing data sets and generated many science products used by science communities for their research studies of environment and climate and for monitoring changes of the Earth's land, oceans, and atmosphere [1-3].

MODIS is a whiskbroom scanning radiometer using a double-sided paddle wheel scan mirror. It makes measurements in 36 spectral bands with wavelengths from 0.41μm to 14.4μm and at three nadir spatial resolutions of 0.25km (bands 1-2), 0.5km (bands 3-7), and 1km (bands 8-36). MODIS bands 20-25 and 27-36 are the thermal emissive bands (TEB) covering wavelengths from 3.5 to 14.4μm. The other 20 spectral bands are the reflective solar bands (RSB). Table 1 summarizes MODIS TEB design specifications, including center wavelength, bandwidth, typical and maximum scene radiance and corresponding temperature, noise equivalent difference radiance (NEdL) and temperature (NEdT) at typical radiance, and primary science application. All TEB bands are of 1km spatial resolutions with 10 detectors each. The

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TEB detectors are located on two cold focal plane assemblies (FPAs): short- and mid-wave infrared (SMIR) FPA and long-wave infrared (LWIR) FPA. MODIS was designed and built in order to extend and enhance a number of heritage sensor measurement capabilities and data records with improved spectral, spatial, and temporal resolutions (or scales), and consequently with more stringent calibration requirements [4]. Because of this, extensive calibration and characterization activities were conducted pre-launch by the sensor vendor for both Terra and Aqua MODIS instruments. During pre-launch thermal vacuum measurements, a large aperture blackbody calibration source (BCS) with high spectral emissivity was used for the TEB radiometric calibration and characterization. After launch an on-board calibrator (OBC), a v-grooved blackbody (BB), is used for TEB on-orbit calibration. The OBC BB is used together with the sensor's space view (SV) on a scan-by-scan basis [5-7].

TABLE 1 MODIS THERMAL EMISSIVE BANDS SPECIFICATION

Band	CW	BW	Ltyp	Lmax	Ttyp	Tmax	NEdL	NEdT	Primary Use
20	3.75	0.18	0.45	1.71	300	335	0.0010	0.05	Surface/Cloud Temperature
21	3.96	0.06	2.38	85.44	335	500	0.0154	0.20	
22	3.96	0.06	0.67	1.89	300	328	0.0019	0.07	
23	4.05	0.06	0.79	2.16	300	328	0.0022	0.07	
24	4.47	0.07	0.17	0.34	250	264	0.0022	0.25	Atmospheric Temperature
25	4.52	0.07	0.59	0.88	275	285	0.0062	0.25	
27	6.72	0.36	1.16	3.21	240	271	0.0108	0.25	Water Vapor
28	7.33	0.30	2.19	4.47	250	275	0.0172	0.25	
29	8.55	0.30	9.59	14.55	300	324	0.0090	0.05	
30	9.73	0.30	3.70	6.34	250	275	0.0219	0.25	Ozone
31	11.03	0.50	9.56	13.26	300	324	0.0070	0.05	Surface/Cloud Temperature
32	12.02	0.50	8.95	12.10	300	324	0.0061	0.05	
33	13.34	0.30	4.53	6.56	260	285	0.0183	0.25	Cloud Top Altitude
34	13.64	0.30	3.77	5.03	250	268	0.0161	0.25	
35	13.94	0.30	3.11	4.42	240	261	0.0141	0.25	
36	14.24	0.30	2.08	2.96	220	238	0.0154	0.35	

CW: Center Wavelength in μm;
BW: Bandwidth in μm;
Ltyp: Specified Typical Scene Radiance in W/m^2/sr/μm;
Lmax: Specified Maximum Scene Radiance in W/m^2/sr/μm;
Ttyp: Specified Typical Scene Temperature in Kelvin (K);
Tmax: Specified Maximum Scene Temperature in Kelvin (K);
NEdL: Noise Equivalent Difference Radiance in W/m^2/sr/μm;
NEdT: Noise Equivalent Difference Temperature in Kelvin (K)

This paper provides an overview of MODIS pre-launch and on-orbit radiometric calibration and characterization activities, methodologies, data analysis results, and lessons learned for TEB, with focusing on major issues that could impact MODIS TEB calibration and data product quality. Results presented in this paper include, but are not limited to, TEB detector noise characterization, response versus scan angle (RVS), response versus instrument and focal plane temperature, and on-orbit calibration stability. Similar discussions on MODIS reflective solar bands (RSB) calibration and characterization are presented in a separate paper in these proceedings (Xiong *et. al*). MODIS TEB (and RSB) spectral and spatial characterization activities and results (pre-launch and on-orbit), such as relative spectral response (RSR) characterization and spectral band-to-band registration (BBR) measurements, have been reported previously and therefore are not discussed in this paper [8-10].

2. MODIS TEB CALIBRATION AND CHARACTERIZATION ACTIVITIES

2.1 Pre-launch calibration and characterization activities

MODIS thermal emissive bands (TEB) pre-launch calibration and characterization activities include spatial, spectral, and radiometric measurements. This paper focuses on radiometric calibration issues, including measurements made in the ambient and thermal vacuum (TV) environment. During pre-launch thermal vacuum measurements, a laboratory blackbody calibration source (BCS) and a space view source (SVS) were used for MODIS TEB calibration and characterization. The BCS is a large aperture source using a buried first bounce design with high emissivity (believed to be better than 0.9999). It was operated in thermal vacuum with temperature settings ranging from 170K to 340K. The BCS temperatures were measured using thermistors with traceability to NIST temperature scales. The SVS, having nearly the same design as the BCS, was operated at an extremely low temperature (with liquid helium cooling) for measurements of instrument background.

System level TEB calibration was performed at three instrument temperature plateaus (cold, nominal, and hot) and at three focal plane assembly (FPA) temperatures, using either primary (A-side) or redundant (B-side) electronics. It should be pointed out that the "primary" and "redundant" were arbitrarily assigned since they were made of nearly identical electronics (component and sub-system). Initial gain and offset settings, focal plane biases, and sub-system locations could have some minor differences between primary and redundant electronic configurations. For a given configuration, radiometric calibration was performed using either 21 BCS temperatures (called comprehensive measurements) or 11 BCS temperatures (called limited measurements). Some tests only used a fixed BCS temperature. Table 2 summarizes the measurements performed for Terra MODIS TEB pre-launch radiometric calibration. The BCS temperature settings for both comprehensive and limited measurements are listed in Table 3. Two primary comprehensive tests at nominal plateaus were designed to examine short-term stability and two primary limited measurements at nominal plateaus were made using different FPA biases.

TABLE 2 TERRA MODIS TEB PRE-LAUNCH THERMAL VACUUM CALIBRATION

Instrument Plateau		Cold (256K)	Nominal (273K)	Hot (283K)
Focal Plane Temperature (K)	77		PRI/LIM	
	83	PRI/COM; RDT/LIM	(2) PRI/COM; RDT/LIM (2) PRI/LIM	PRI/COM; RDT/LIM
	85		PRI/LIM	

Each electronic configuration (primary or redundant) includes a power supply (PS), a control processor (CP), a timing generator (TG), analog-to-digital converters (ADC), a data formatter engine (FE), and a PFA heater. To better characterize and understand sensor performance under different configurations and help select the best on-orbit operational configuration, Aqua MODIS (FM-1) performed more completed TEB calibration including uses of different combinations of the electronic sub-systems. In addition more frames of data were collected for TEB detector responses to the BCS. Another change made in Aqua MODIS TEB pre-launch calibration was to modify BCS temperature settings for better coverage of detector dynamic range and to assure that enough temperature settings are within their response fitting range, normally from 0.3 typical radiance (or temperature) to 0.9 maximum radiance (or temperature). The modified BCS temperature settings (comprehensive and limited levels) used for Aqua MODIS TEB calibration, as a comparison to Terra MODIS, are also listed in Table 3.

MODIS is a scanning radiometer making observations over a scan angle range of ±55° about nadir using a continuously rotating double-sided scan mirror. The sensor's response versus scan angle (RVS) was characterized pre-launch at ambient environment with MODIS on a rotary table so that a fixed blackbody source could be viewed at different angles of incidence (AOI) to the scan mirror. Due to test difficulties, only Aqua MODIS made a successful TEB RVS characterization. For Terra MODIS, the TEB RVS was initially constructed using parameters derived from Aqua MODIS RVS and reflectance of the scan mirror witness samples measured by the National Physical Laboratory (NPL). It was improved after launch using on-orbit observations.

TABLE 3 BCS TEMPERATURE SETTINGS FOR COMPREHENSIVE AND LIMITED MEASUREMENTS

Terra MODIS			Aqua MODIS		
Comprehensive	**T_BCS(K)**	**Limited**	**Comprehensive**	**T_BCS(K)**	**Limited**
1	170		1	170	1
2	190		2	190	2
3	210	1	3	200	
4	220		4	210	3
5	230	2	5	220	
6	240		6	230	4
7	250	3	7	240	
8	260	4	8	247	5
9	270	5	9	255	
10	280	6	10	262	6
11	290	7	11	270	
12	295		12	278	7
13	300	8	13	285	
14	305		14	292	8
15	310	9	15	300	
16	315		16	307	9
17	320	10	17	315	
18	325		18	321	10
19	330	11	19	328	
20	335		20	334	11
21	340		21	340	

2.2 On-orbit calibration and characterization activities

MODIS TEB on-orbit calibration and characterization activities include spatial characterization (not covered in this paper) and radiometric calibration using the OBC BB. The BB is normally set at a fixed temperature and periodically operated from instrument ambient of about 270K to 315K via electric heaters. The nominal setting is 290K and 285K for Terra and Aqua MODIS, respectively. These temperatures correspond to the OBC-BB temperatures extensively used during Terra and Aqua MODIS pre-launch TV TEB measurements. During BB warm-up operation (from ambient to 315K), the BB is also controlled at several intermediate temperature plateaus. The cool-down operation is a passive process without BB heating. OBC BB warm-up and cool-down data sets are normally used to examine and update sensor nonlinear calibration coefficients. In addition to calibration and characterization activities using on-board calibrators, regular lunar observations and special spacecraft maneuvers have been used to support TEB on-orbit calibration. Other activities applied to examine Terra and Aqua MODIS TEB calibration consistency are presented in a separate paper in these proceedings (Xiong *et. al*).

Bands 31-36 use photoconductive (PC) detectors. Thus they are referred to as MODIS PC bands. For Terra MODIS an optical leak from band 31 to other PC bands (32-36) was identified during pre-launch characterization. On-orbit lunar observations, initially designed to monitor RSB calibration stability, have been used to characterize Terra MODIS PC optical leak and track its stability, and to derive the correction coefficients [11]. As previously mentioned that Terra MODIS TEB pre-launch RVS characterization was not successful due to test difficulties, such as calibration source stability, focal plane temperature stability at ambient environment, and large thermal loading (background) on the TEB detectors. Consequently many efforts have been made to improve Terra MODIS TEB RVS via on-orbit observations. One approach applied sensor's responses to its nadir aperture door (NAD) when it was closed. This approach assumes one mirror side RVS is correct and apply it to derive the RVS for the other mirror side since both mirror sides view the same aperture door. A complete characterization of Terra MODIS TEB RVS was not accomplished until March 26, 2003 when Terra spacecraft executed its first deep space maneuvers (DSM). The second Terra DSM was performed on April 14, 2003. It was specially planned to include the Moon in the spacecraft nadir view for cross-sensor calibration and inter-comparison purposes [12].

3. MODIS TEB CALIBRATION METHODOLOGIES

Details of MODIS TEB pre-launch and on-orbit calibration methodologies have been reported previously [5-7, 13]. The TEB calibration was performed for each band, detector, and mirror side using a quadratic calibration algorithm. For pre-launch calibration, the source contribution includes calibration source (BCS) and scan mirror (SM) emission difference at different angle of incidence (AOI) to the scan mirror [13]. Thus,

$$RVS_{BCS} \cdot L_{BCS} + (RVS_{SV} - RVS_{BCS}) \cdot L_{SM} = a_0 + a_1 \cdot dn_{BCS} + a_2 \cdot dn_{BCS}^2 \ , \qquad (1)$$

where

L_{BCS} is the spectral radiance of the BCS at temperature T_{BCS}
L_{SM} is the spectral radiance of the scan mirror at temperature T_{SM}
RVS_{SV} is the RVS at SV AOI
RVS_{BCS} is the RVS at BCS AOI
$a_0, a_1,$ and a_2 are the quadratic calibration coefficients
dn_{BCS} is detector response (in digital number) to calibration source SV measurements subtracted.

The spectral radiance terms are computed using Planck's equation weighted by the detectors' relative spectral response (RSR). For on-orbit calibration, the source contribution (in Eqn. 1) also includes scan cavity emission reflected from the on-board BB [6]. Equation 1 can be directly applied to Earth view (EV) scene radiance retrieval, simply replacing the BCS subscript with EV. Thus,

$$RVS_{EV} \cdot L_{EV} + (RVS_{SV} - RVS_{EV}) \cdot L_{SM} = a_0 + b_1 \cdot dn_{EV} + a_2 \cdot dn_{EV}^2 . \qquad (2)$$

Equation 2 uses b_1, instead of a_1, for the linear calibration coefficients to emphasize that they are derived form on-orbit calibration. B21, designed for fire detection with low gains, is an exception. Its linear calibration coefficients are fixed using values provided by the look-up table (LUT). The LUT is updated, if necessary, using data from regularly scheduled BB warm-up and cool-down activity. For Terra MODIS, a PC optical correction is implemented in the level 1B (L1B) calibration algorithm.

4. MODIS TEB CALIBRATION AND CHARACTERIZATION RESULTS AND DISCUSSIONS

MODIS Characterization Support Team (MCST) at NASA/GSFC has been responsible for MODIS instrument pre-launch and on-orbit calibration and characterization. Over the years, the team has analyzed many test data sets and generated many results, covering instrument spatial, spectral, and radiometric calibration and characterization. Obviously it's impossible to cover all calibration results for both Terra and Aqua MODIS in one paper. However we present in this section a few key calibration and characterization results for MODIS thermal emissive bands (TEB), some derived from pre-launch measurements and some from on-orbit observations. The results presented here focus on sensor radiometric calibration, including TEB detectors responses versus instrument temperature, responses versus cold FPA temperature, response versus scan angle (RVS), and detector noise characterization. These results have provided useful information for on-orbit calibration algorithm design and development, calibration quality assessment, and instrument performance.

4.1 Pre-launch calibration and characterization results

Figure 1 illustrates Terra MODIS TEB (middle detector, mirror side 1) response, dn_{BCS}, versus radiance from BCS and scan mirror (see Eqn. 1). At each L_{BCS} or T_{BCS}, dn_{BCS} was computed with frame (50) and scan (20 for each mirror side) average. Because band 21 is used for fire detection with low setting, it has much smaller dn response. Saturations in several bands at high BCS temperatures are expected (see Table 1 for their specified maximum temperatures). A quadratic fitting (Eqn. 1) was applied to all radiometric calibration data sets for Terra MODIS (Table 2) and Aqua MODIS. From each data set (comprehensive or limited), a set of calibration coefficients (a_0, a_1, and a_2) could be derived and analyzed.

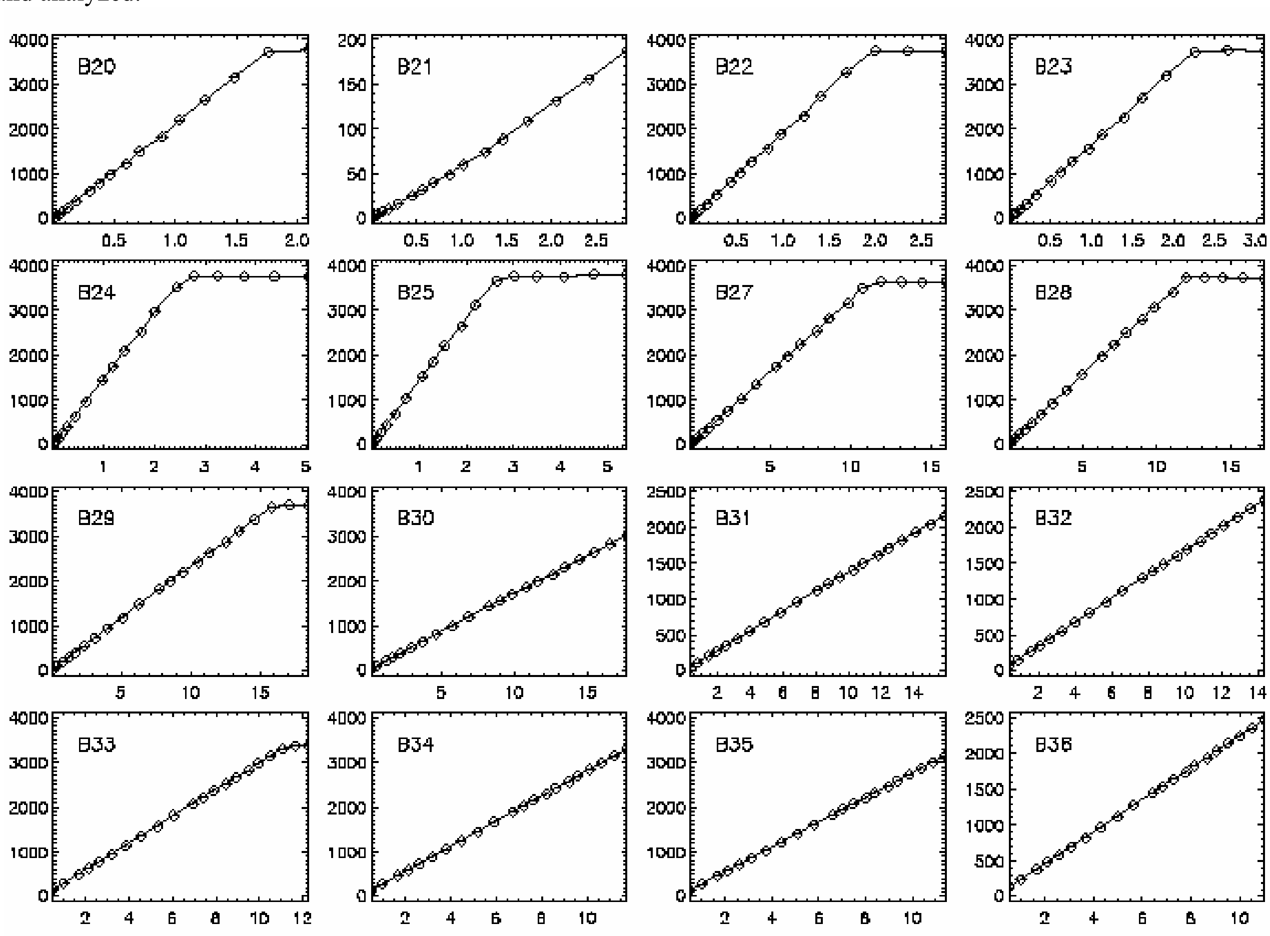

Figure 1. Terra MODIS thermal emissive bands (middle detector, mirror side 1) responses in digital numbers (y-axis) versus spectral radiances in W/m^2/sr/µm (x-axis): pre-launch thermal vacuum comprehensive test with primary electronics at nominal plateau and 83K FPA temperature.

As listed in Table 2, Terra MODIS TEB pre-launch calibration in thermal vacuum was performed at three instrument plateaus (cold, nominal, and hot) with primary electronic configuration. At the same temperature plateau (nominal), TEB was also calibrated at three different FPA temperatures (77K, 83K, and 85K). Figure 2 presents calibration coefficients versus instrument temperature (primary electronic configuration with FPA at 83K) and Figure 3 shows calibration coefficients versus FPA temperature (primary electronic configuration at nominal plateau). The changes in detector response with instrument temperature are less than 0.5% /K. On the other hand, the changes with FPA temperatures are about 1-2%/K for PV bands (20-25, 27-30) and 4-6%/K for PC bands (31-36). Similar data analyses were also performed by MCST for Aqua MODIS thermal vacuum measurements over various operational configurations.

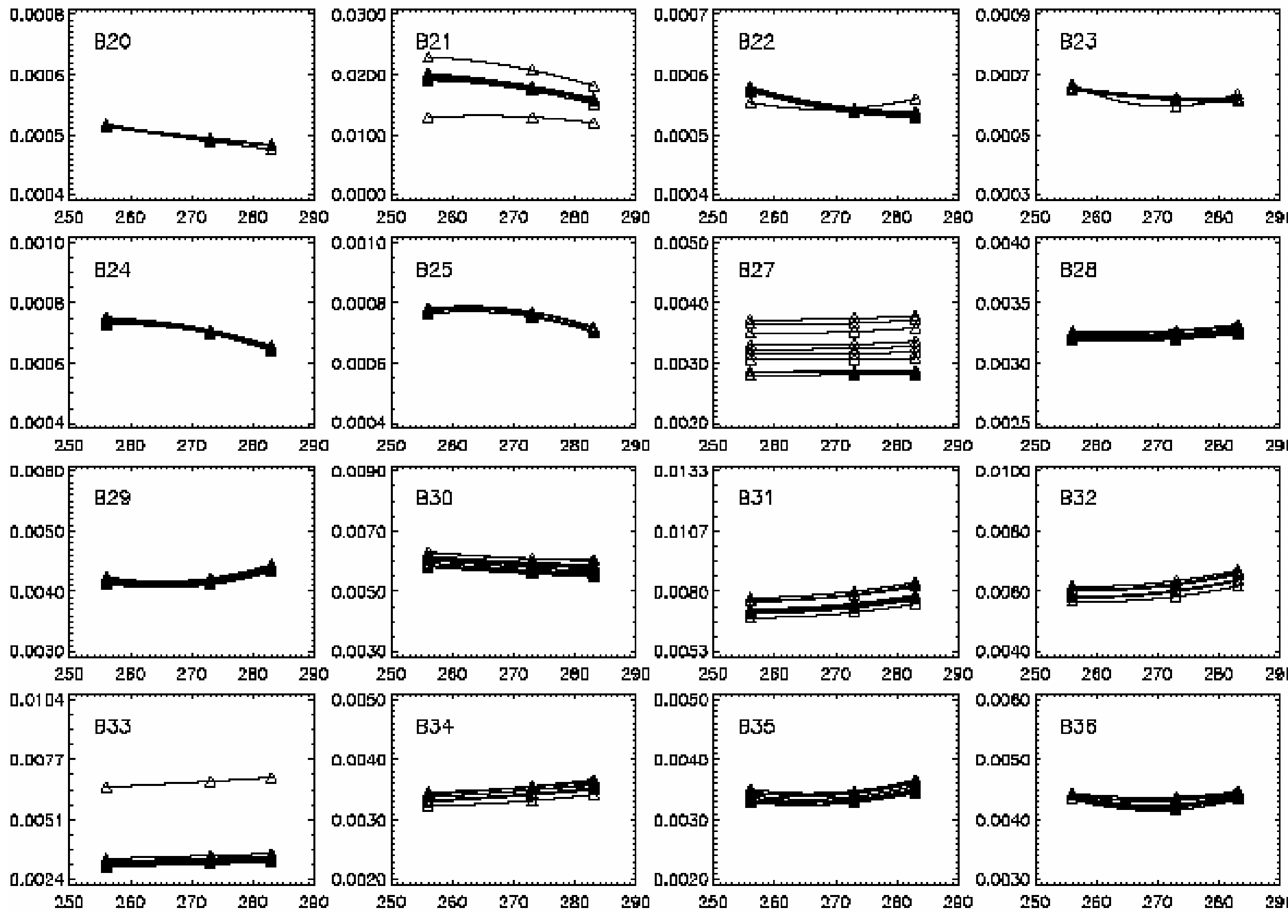

Figure 2. Terra MODIS thermal emissive bands linear calibration coefficient (a_1) versus instrument temperature [K].

As shown in Figure 2, nearly all detectors within a spectral band have a similar dependence on instrument temperature, with the exceptions of 2 detectors in band 21, 1 in band 22, and 1 in band 33. Although band 27 detectors' gains are quite different, they still have similar instrument temperature dependence. This is also the case for the FPA temperature dependence in Figure 3. There were a few out-of-family (OOF) TEB detectors identified from Terra MODIS pre-launch calibration and characterization in term of their gain, non-linearity, and noise characterization behavior. The 2 detectors in band 21 and 1 in band 33 were among those OOF detectors. The standard deviation of dn_{BCS} at constant L_{BCS} or T_{BCS} was a measure of detector noise characterization. At each BCS level, a set of NEdL or NEdT was calculated for all spectral bands and detectors. Table 4 summarizes Terra and Aqua MODIS TEB pre-launch noise characterization results at different operational configurations (middle detector only). On-orbit noise characterization results are also included for comparison. All the results in Table 4 are computed at typical radiance or temperature in order to compare with design specifications. Notice detectors in band 34 and band 36 have NEdT higher than the specifications.

As shown in Equations 1 and 2, the RVS plays an important role in TEB calibration. It corrects for response differences at different AOI (including mirror emission difference at different AOI) since calibration coefficients are derived at a fixed AOI. MODIS TEB RVS was characterized pre-launch in an ambient environment with temperatures of the calibration source set above the ambient temperature. Due to pre-launch measurement difficulties and limitations, only Aqua MODIS successfully performed a system level RVS measurement [12]. The results are presented in Figure 4 for bands 29-36. The other bands (20-25 and 27-28) have much smaller RVS effects, typically less than 1% over all the scan angles used for observations.

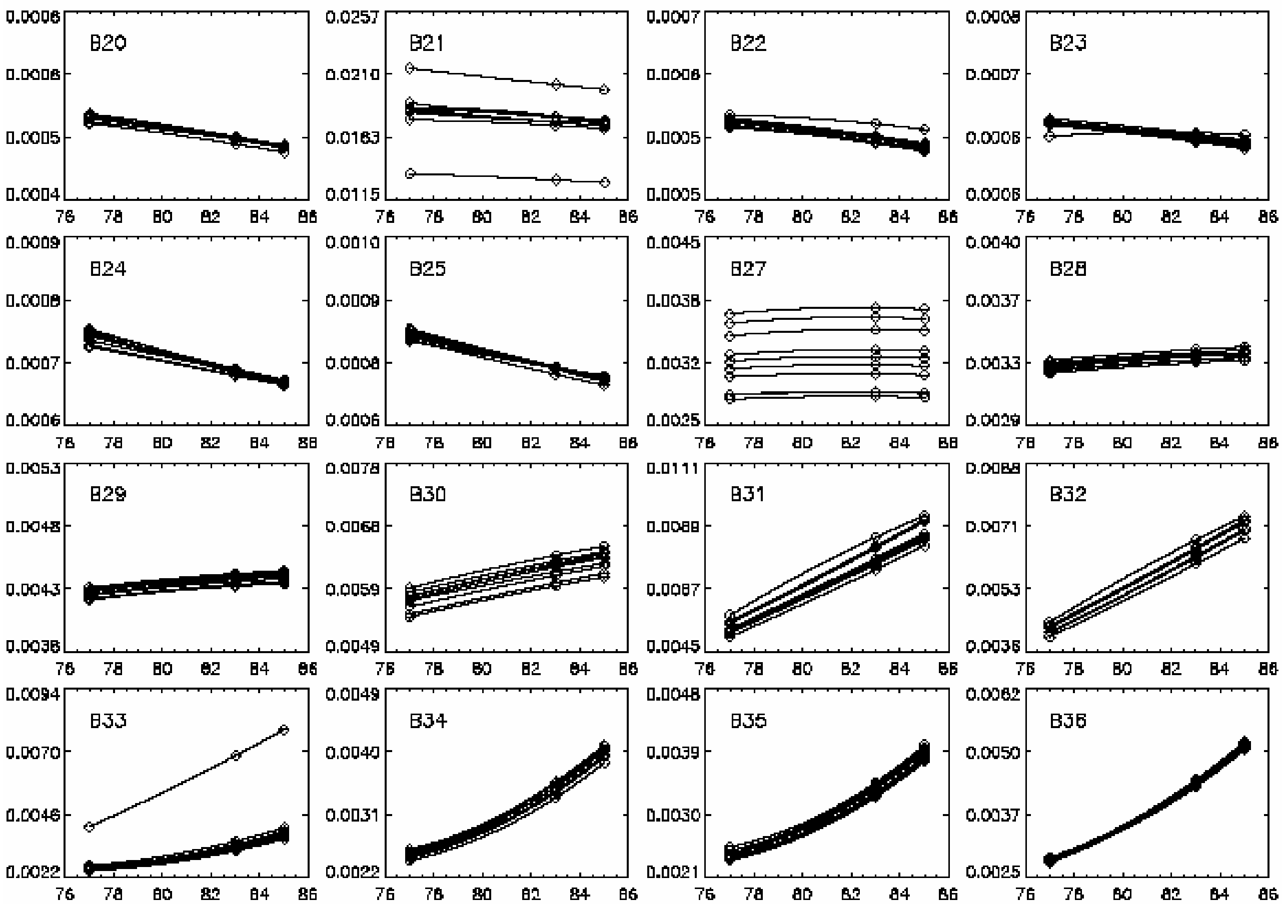

Figure 3. Terra MODIS thermal emissive bands linear calibration coefficient (a_1) versus cold focal plane temperature [K].

TABLE 4 MODIS TEB DETECTORS NOISE CHARACTERIZATION (PRE-LAUNCH)

Band	Specification		Terra Pre-launch		Aqua Pre-launch		Terra On-orbit		Aqua On-orbit	
	Ttyp	NEdT	PRI	RDT	PRI	RDT	PRI	RDT	PRI	RDT
20	300	0.05	0.02	0.03	0.02	0.02	0.03	0.03	NA	0.02
21	335	0.20	0.15	**0.28**	0.19	0.21	0.18	0.14	NA	0.20
22	300	0.07	0.03	0.03	0.02	0.02	0.03	0.03	NA	0.02
23	300	0.07	0.02	0.02	0.02	0.02	0.02	0.03	NA	0.02
24	250	0.25	0.12	0.14	0.14	0.12	0.13	0.13	NA	0.10
25	275	0.25	0.06	0.05	0.05	0.03	0.05	0.05	NA	0.04
27	240	0.25	0.11	0.09	0.10	0.08	0.10	0.11	NA	0.16
28	250	0.25	0.05	0.04	0.05	0.05	0.14	0.07	NA	0.05
29	300	0.05	0.02	0.02	0.02	0.02	0.02	0.03	NA	0.02
30	250	0.25	0.10	0.10	0.07	0.08	0.17	0.14	NA	0.09
31	300	0.05	0.03	0.03	0.03	0.02	0.03	0.02	NA	0.02
32	300	0.05	0.03	0.03	0.01	0.03	0.04	0.03	NA	0.03
33	260	0.25	0.14	0.13	0.08	0.08	0.13	0.13	NA	0.08
34	250	0.25	0.20	0.19	0.12	0.12	0.19	0.19	NA	0.12
35	240	0.25	**0.33**	0.23	0.14	0.14	0.23	0.23	NA	0.15
36	220	0.35	**0.44**	**0.43**	0.22	0.26	**0.45**	**0.43**	NA	0.23

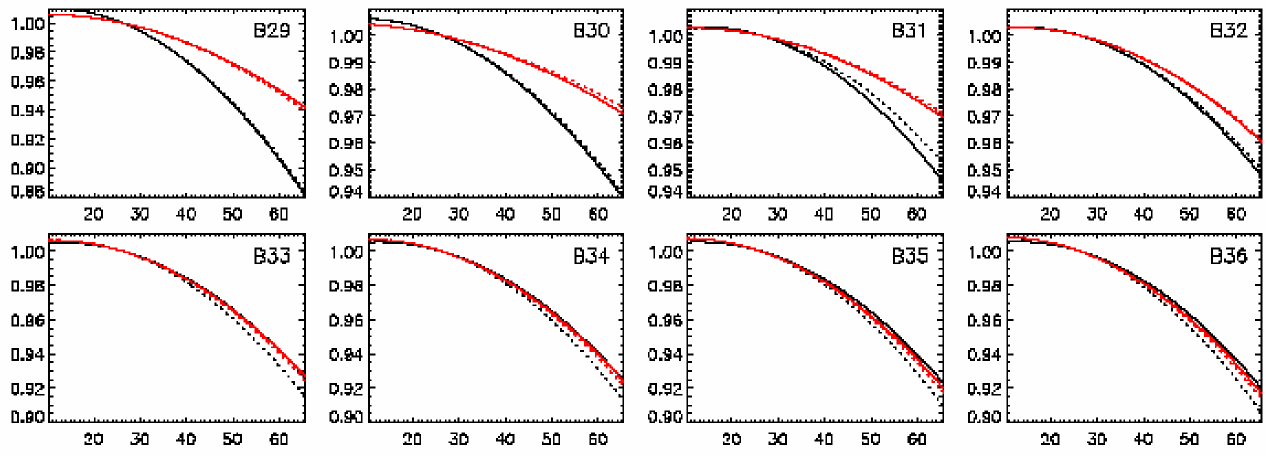

Figure 4. MODIS TEB (bands 29-36) responses versus scan angles (RVS): Terra MODIS (black or dark color) from on-orbit measurements and Aqua MODIS (red or light color) from pre-launch characterization (solid line for mirror side 1, dashed line for mirror side 2)

4.2 On-orbit calibration and characterization results

MODIS TEB on-orbit calibration is performed on a scan-by-scan basis using the OBC BB and SV. The BB temperature is measured using a set of 12 thermistors traceable to NIST temperature scales. The cold FPAs (SMIR and LWIR) were set at 83K for both Terra and Aqua MODIS. Normally the OBC BB is set to 290K for Terra MODIS and 285K for Aqua MODIS. Regular BB warm-up and cool-down operation is used to track TEB nonlinear calibration coefficients. It also allows detector noise characterization to be made at different temperatures (or radiances). Since launch in December 1999, Terra MODIS has been in operation for more than 6 years and with both primary and redundant electronics. On the other hand, Aqua MODIS has been operated using the same redundant electronics. Their on-orbit noise characterization results are also included in Table 4.

Figure 5 illustrates Terra MODIS TEB on-orbit scan-by-scan calibration coefficients (detector 3) derived from a 5 min granule data (mid detector). The short-term stability is presented in Figure 6 for all detectors using one granule (5 min) and one orbit (98 min) calibration data set (2006180). Excluding band 21 (low gain) and noisy detectors identified pre-launch and on-orbit, the Terra MODIS TEB short-term stability is better than 0.2-0.4%. To reduce the impact of gain variations (due to noise), MODIS L1B TEB calibration algorithm uses a running average of the scan-by-scan calibration coefficients over 20 scans.

The time series of the linear calibration coefficients (the dominant terms in quadratic calibration algorithm) has been used to track MODIS TEB on-orbit long-term stability. From over 6-year on-orbit observations (excluding primary and redundant electronics difference), the gains (inversely proportional to linear calibration coefficients, b_1) of Terra MODIS TEB have changed, annually on average, less than 0.4% for the MWIR PV bands (except for B21), less than 1% for LWIR PV bands, and less than 0.5% for LWIR PC bands.

Using data (observations through nadir aperture) acquired during Terra spacecraft deep space maneuvers (DSM) on March 26 and April 14, 2003, the MODIS (Terra) TEB RVS was finally characterized at sensor system level. The results derived from both maneuvers are identical and they are also presented in Figure 4 for bands 29-36 together with Aqua MODIS RSV (pre-launch results). There are some noticeable differences between Terra and Aqua MODIS TEB RVS, especially at large AOI. For both Terra and Aqua MODIS, bands 20-25 RVS variations are less than 1% and bands 27-28 are less than 2% over all AOI. The DSM RVS is currently used in the Terra MODIS L1B algorithm. MODIS lunar observations have also been used to support TEB on-orbit calibration and characterization. For example, the Terra MODIS PC bands optical leak has been tracked using nearly monthly lunar observations [11]. There is no optical leak in Aqua MODIS PC bands.

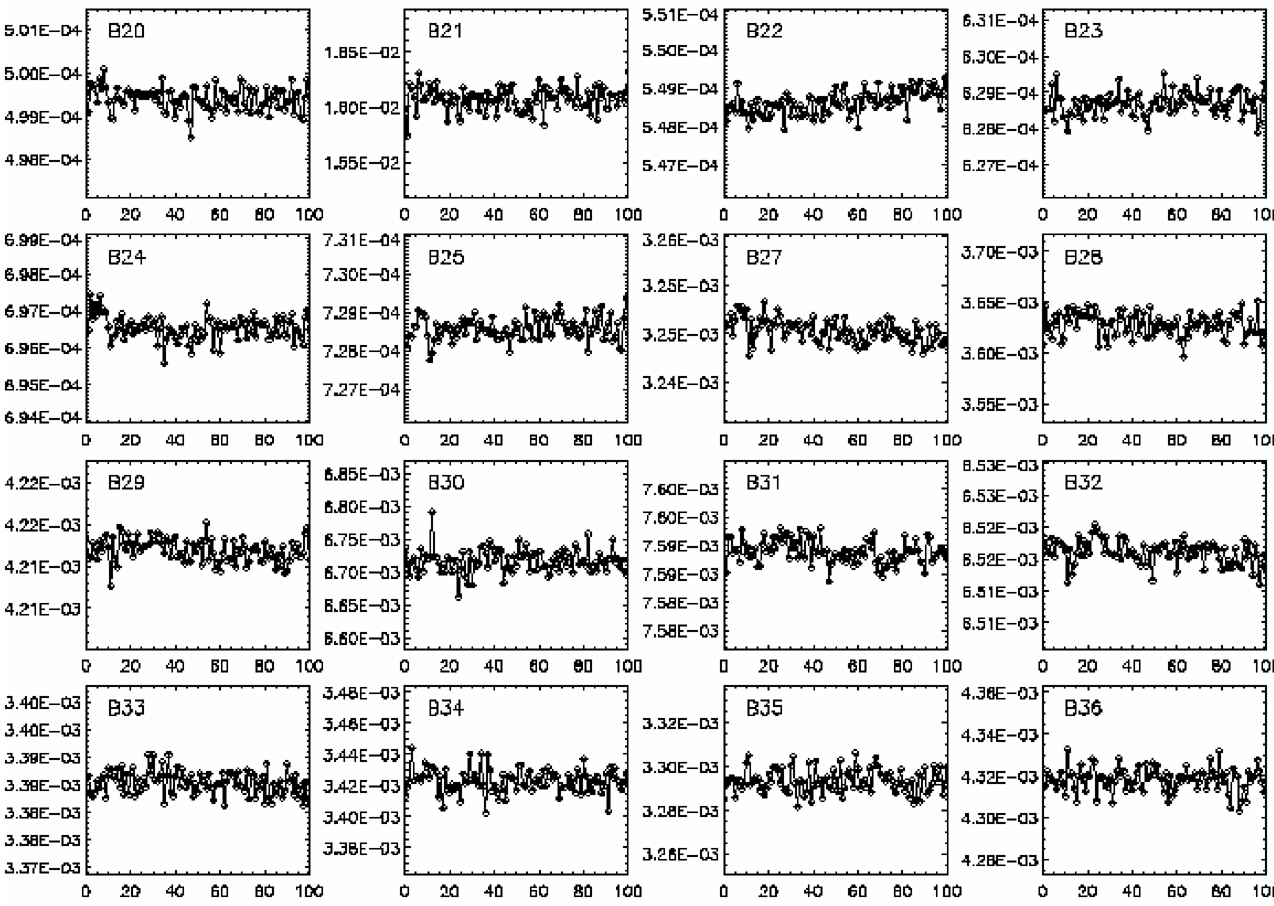

Figure 5. Terra MODIS thermal emissive bands (middle detector, mirror side 1) scan-by-scan calibration coefficients (b_1).

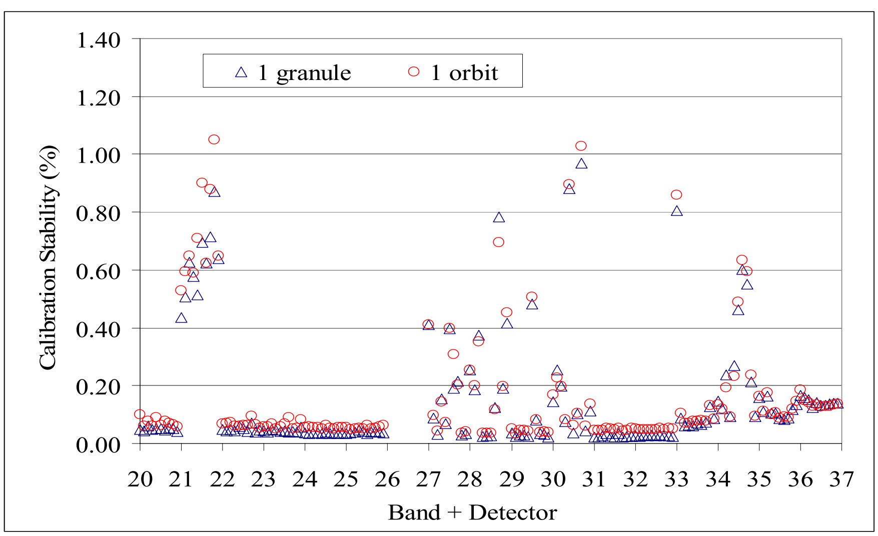

Figure 6. Terra MODIS thermal emissive bands calibration short-term stability (%) computed from one granule (5 min) and one orbit (98 min) calibration data sets (2006180).

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

Many lessons have been learned from Terra and Aqua MODIS pre-launch and on-orbit calibration and characterization activities and from sensor on-orbit performance. Due to space limits we provide the following short list based on MODIS experience for future missions/instruments.

- Full radiometric calibration is necessary at different instrument temperature, focal plane temperature, possibly electronic temperature if it can be independently controlled, and at different combination of sensor operational configurations.
- Characterization using high-contrast scenes or targets should be included.
- On-board BB with capability of controlling its temperature is useful so that the calibration and characterization can be made at different temperatures.
- Independent characterization of BB emissivity is important (only effective emissivity retrieved from MODIS pre-launch measurements)
- Spacecraft maneuvers and lunar observations can provide additional and important information for sensor calibration and characterization.
- Calibration source stability and traceability are critical for high quality measurements and uncertainty assessments.
- Continuous efforts on sensor calibration and characterization from pre-launch characterization to on-orbit operation are necessary for better understanding and predicting sensor performance.

6. SUMMARY

This paper presented an overview of MODIS thermal emissive bands calibration and characterization activities and calibration algorithms. It discussed the results derived from pre-launch and on-orbit calibration and characterization and offered many lessons learned. Since the launch, both Terra and Aqua MODIS TEB have performed well with excellent noise characteristics, and short-term and long-term stability. Excluding noisy detectors identified pre-launch and on-orbit, the on-orbit calibration short-term stability is better than 0.2-0.4%. 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 that high quality calibration and validation work, including data analyses, should be done independently and possibly with different approaches. In addition to on-board calibrators, the observations of the Moon and ground targets could provide sensor calibration and validation support.

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