An Overview of Inter-comparison Methodologies for Terra and Aqua MODIS Calibration

X. Xiong[a], A. Wu[b], J. Sun[b], and B Wenny[b]

[a]*Sciences and Exploration Directorate, NASA/GSFC, Greenbelt, MD 20771;*
[b]*Science Systems and Applications, Inc., 10210 Greenbelt Road, Lanham, MD 20706*

ABSTRACT

With increasing efforts on data fusion and long-term climate data records (CDR) using observations made by multiple sensors on the same or different platforms, sensor cross-calibration has become increasingly important. It is known that the uncertainty of climate models or science data records depends not only on the calibration quality of individual sensors but also on their calibration consistency. This paper provides an overview of inter-comparison methodologies applied by the MODIS Characterization Support Team (MCST) at NASA/GSFC for the studies of Terra and Aqua MODIS on-orbit calibration consistency. Improved over heritage sensors, MODIS was built with a set of on-board calibrators (OBC) that include a blackbody (BB), a space view (SV) port, a solar diffuser (SD), and a solar diffuser stability monitor (SDSM). The BB is primarily used for the thermal emissive bands (TEB) calibration and the SD/SDSM system for the reflective solar bands (RSB) calibration. Detector responses to the SV provide measurements for the instrument background. Although instrument design requirements and calibration approaches are nearly identical for both Terra and Aqua MODIS and they all went through extensive and similar pre-launch calibration and characterization activities, their on-orbit calibration consistency still has to be carefully examined and validated as many science products are generated from observations made by both instruments. Methodologies discussed in this paper include inter-comparison studies using the Moon, a third sensor, and ground targets. Our results show that Terra and Aqua reflective solar bands and thermal emissive bands have been calibrated consistently to within their combined uncertainty requirements. For the 11μm and 12μm bands used for surface temperature measurements, the calibration differences between Terra and Aqua MODIS are less than ±0.15K at scene temperatures from 240-280K and less than ±0.50K at cold scene temperatures from 190 to 230K (before corrections). For most reflective solar bands, their reflectance calibration differences are typically less than ±2%.

Keywords: Terra, Aqua, MODIS, sensor, calibration, inter-comparison, Moon, AVHRR

1. BACKGROUND

Accurate global observations from space via Earth-observing sensors provide useful and critical information to monitor long-term global climate change and to address environmental and geopolitical issues. Sensor calibration accuracy and consistency are extremely important to assure the quality of the data products derived from their on-orbit observations. About a decade ago in May 1995, a Workshop on Strategies for Calibration and Validation of Global Change and Measurements was hosted by NASA/GSFC on behalf of the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration / Validation, the Global Change Observing System (GCOS), and the US Committee on Environment and Natural Resources (CENR) [1]. Recommendations were made from this workshop based on 19 key findings in the categories that include programmatic support, preflight and in-flight calibration, data set continuity and consistency, and combining remotely sensed and in-situ data. A few years later in November 2002, a similar Workshop on Satellite Instrument Calibration for Measuring Global Climate Change was organized by agencies that include the National Institute of Standards and Technology (NIST), National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Office (IPO), National Oceanic and Atmospheric Administration (NOAA), and National

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Aeronautics and Space Administration (NASA) [2]. This workshop addressed issues and challenges of measuring small changes associated with long-term global climate change. A follow on Workshop to this, Achieving Satellite Instrument Calibration for Climate Change ($ASIC^3$), was held recently in April 2006 [3]. A primary objective of the latest workshop is to formulate a national roadmap for a calibration system that will allow scientists and researchers to achieve the requirements associated with the measurements of long-term global climate change. With increasing efforts on data fusion and existing challenges of producing high quality long-term climate data records (CDR) using observations made by multiple sensors either on the same or different platforms, including sensors of the same or different generation of instruments and technologies, cross-sensor calibration and validation work has become more important and demanding. It has been known that the uncertainty of the climate models and data records depends not only on the calibration quality (accuracy and stability) of individual sensors but also on their calibration consistency.

Moderate Resolution Imaging Spectroradiometer (MODIS) is a major and critical instrument for NASA's Earth Observing System (EOS) missions, developed based on a number of heritage sensors with improved features and calibration requirements. MODIS collects data using 36 spectral bands covering visible (VIS), near-infrared (NIR), short- and mid-wave infrared (SMIR), and long-wave infrared (LWIR) spectral regions. Currently there are two nearly identical MODIS instruments operated in space, making continuous observations and producing science data products that have been used for the studies of short- and long-term changes, natural and human-induced, of the Earth's land, oceans, and atmosphere [4,5]. MODIS proto-flight model (PFM) was launched in December 1999 aboard the NASA EOS Terra satellite (formerly EOS AM-1) in a morning orbit (10:30 a.m. descending southwards). Its flight model 1 (FM1) was launched in May 2002 aboard the EOS Aqua satellite (formerly EOS PM-1) in an afternoon orbit (1:30 p.m. ascending northwards). Although both Terra and Aqua MODIS instruments are of the same design requirements and calibration approaches and both went through extensive pre-launch calibration and characterization activities [6,7], their on-orbit calibration consistency still needs to be carefully examined and validated as many science products are generated from observations made by both instruments. For this reason MODIS calibration and validation scientists and MODIS Characterization Support Team (MCST) have made significant efforts to accurately calibrate and characterize both Terra and Aqua MODIS instruments and to inter-compare and validate their calibration consistency [8-12]. Although much progress has been made in recent years, significant challenges still exist due to increasing demands for high quality climate observations.

This paper provides an overview of methodologies applied by MCST at NASA/GSFC for inter-comparison studies of Terra and Aqua MODIS on-orbit calibration consistency. Methodologies discussed in this paper include: (1) using the Moon as a reference source, (2) using a third sensor as a transfer radiometer, and (3) using ground targets for long-term calibration stability monitoring. Our results, derived from different approaches, show that Terra and Aqua reflective solar bands and thermal emissive bands have been calibrated consistently with excellent long-term stabilities. The differences between the two sensors are within their combined uncertainty. Approaches and techniques adopted and developed in our inter-comparison studies will have many potential applications for validating and characterizing future sensors' calibration consistency.

2. MODIS ON-ORBIT CALIBRATION METHODOLOGIES

MODIS was developed to continue and enhance heritage sensor observations and data records with improved calibration requirements. It makes measurements using 36 spectral bands from 0.41μm to 14.4μm and at three nadir spatial resolutions: 0.25km, 0.5km, and 1km. MODIS bands 1-19 and 26, collecting daytime reflected solar radiation in the wavelength range from 0.41 to 2.2μm, are the reflective solar bands (RSB). Bands 20-25 and 27-36, measuring both daytime and nighttime thermal emissions from 3.5 to 14.4μm, are the thermal emissive bands (TEB). In order to track changes of sensor responses and to maintain calibration and data product quality, MODIS was built with a complete set of on-board calibrators (OBC), that include a blackbody (BB), a space view (SV) port, a solar diffuser (SD), and a solar diffuser stability monitor (SDSM). The BB is primarily used for the TEB calibration and the SD and SDSM system for the RSB calibration. The SV port provides measurements for instrument background. In addition, both Terra and Aqua

MODIS have been making regular lunar observations since launch through the SV port, thus enabling an independent monitoring of RSB radiometric calibration stability [13-16].

Table 1 summarizes MODIS design specifications, including each bands center wavelength, typical scene radiance, signal to noise ratio (SNR) for RSB, and noise equivalent difference temperature (NEdT) for TEB. The 2% uncertainty is specified for RSB reflectance calibration. For RSB radiance calibration, the uncertainty requirements are 5%. The TEB uncertainty is specified for radiance calibration, ranging from 0.5 to 1.0% (except for band 21). The calibration uncertainty and noise characterization requirements listed in Table 1 are specified at typical scene radiances and for observations made within ±45º viewing angles. For TEB, an additional 1% uncertainty is applied for observations made at other radiance levels from 0.3 typical to 0.9 maximum radiances.

TABLE 1 MODIS DESIGN SPECIFICATIONS AND CALIBRATION UNCERTAINTY (UC) REQUIREMENTS

RSB	CW	Ltyp	SNR	UC
1	0.645	21.8	128	2%
2	0.858	24.7	201	2%
3	0.469	35.3	243	2%
4	0.555	29.0	228	2%
5	1.240	5.4	74	2%
6	1.640	7.3	275	2%
7	2.130	1.0	110	2%
8	0.412	44.9	880	2%
9	0.443	41.9	838	2%
10	0.488	32.1	802	2%
11	0.531	27.9	754	2%
12	0.551	21.0	750	2%
13	0.667	9.5	910	2%
14	0.678	8.7	1087	2%
15	0.748	10.2	586	2%
16	0.869	6.2	516	2%
17	0.905	10.0	167	2%
18	0.936	3.6	57	2%
19	0.940	15.0	250	2%
26	1.375	6.0	150	2%

TEB	CW	Ttyp	NEdT	UC
20	3.75	300	0.05	0.75%
21	3.96	335	0.20	10%
22	3.96	300	0.07	1%
23	4.05	300	0.07	1%
24	4.47	250	0.25	1%
25	4.52	275	0.25	1%
27	6.72	240	0.25	1%
28	7.33	250	0.25	1%
29	8.55	300	0.05	1%
30	9.73	250	0.25	1%
31	11.03	300	0.05	0.5%
32	12.02	300	0.05	0.5%
33	13.34	260	0.25	1%
34	13.64	250	0.25	1%
35	13.94	240	0.25	1%
36	14.24	220	0.35	1%

CW: Center Wavelengths in μm
Ltyp: Typical Spectral Radiance in $W/m^2/\mu m/sr$
SNR: Signal to Noise Ratio
NEdT: Noise Equivalent difference Temperature (K)

For reflective solar bands, MODIS Level 1B (L1B) primary data product is a top of atmosphere (TOA) reflectance factor. It is calculated using a simple linear algorithm with calibration coefficients derived and updated regularly from SD observations for all the bands, detectors, sub-samples, and mirror sides. MODIS RSB calibration is reflectance based using a solar diffuser (SD). The SD bi-directional reflectance factor (BRF) was characterized pre-launch by the sensor vendor at component level using references traceable to NIST reflectance standards. On-orbit changes of the SD BRF are measured by the SDSM. The SDSM is operated during each scheduled SD calibration. Lunar observations are regularly made via spacecraft roll maneuvers so that the lunar phase angles are nearly identical. MODIS thermal emissive bands use a quadratic calibration algorithm with coefficients computed each scan from OBC BB. The OBC BB can be operated from instrument ambient of about 270K to 315K. The temperature of the BB is measured on a scan-by-scan basis using a set of 12 thermistors.

3. INTER-COMPARISON METHODOLGIES FOR TERRA AND AQUA MODIS

3.1 Inter-comparison using the Moon

In order to independently track RSB radiometric calibration stability, both Terra and Aqua MODIS have been making regular lunar observations since launch. MODIS bands 1-2 each have 40 detectors, bands 3-7 20 detectors, and all others

10 detectors. For a given spectral band that does not saturate during lunar observations, an integrated lunar spectral irradiance can be computed from responses of (1) a single detector with multiple scans, (2) all detectors in one scan, and (3) all detectors with multiple scans. Approaches 1 and 3 require additional corrections for over-sampling effect. Figure 1 illustrates Terra MODIS band 1 lunar responses (in digital numbers) from all detectors in one scan (left) and that using one detector of multiple scans (right). Similar responses from Aqua MODIS band 1 are presented in Figure 2 for comparison purposes. The lunar irradiance results computed from observations by each MODIS are first normalized to the corresponding values derived from a lunar model [17]. The results (with normalization) for both Terra and Aqua MODIS are then compared to examine their calibration consistency. To reduce the impacts due to lunar viewing geometry differences, each MODIS schedules its lunar observations at nearly the same phase angles of 55.5º (Terra: waning phase and Aqua: waxing phase). Table 2 lists total number of lunar observations scheduled each year for Terra MODIS (March 3, 2000 - June 25 2006) and Aqua MODIS (July 9, 2002 - June 25 2006).

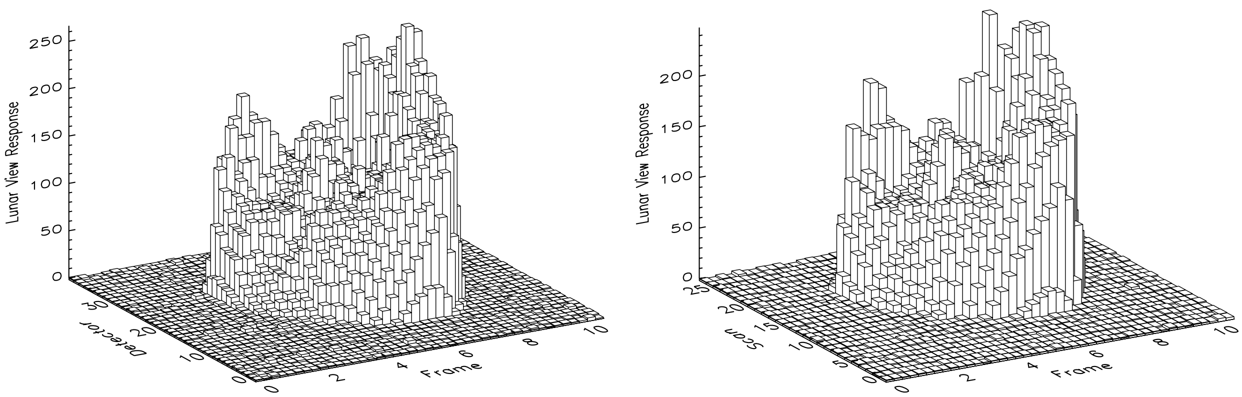

Figure 1. Terra MODIS band 1 lunar response (November 05, 2001). Left: all detectors in one scan; Right: one detector with multiple scans.

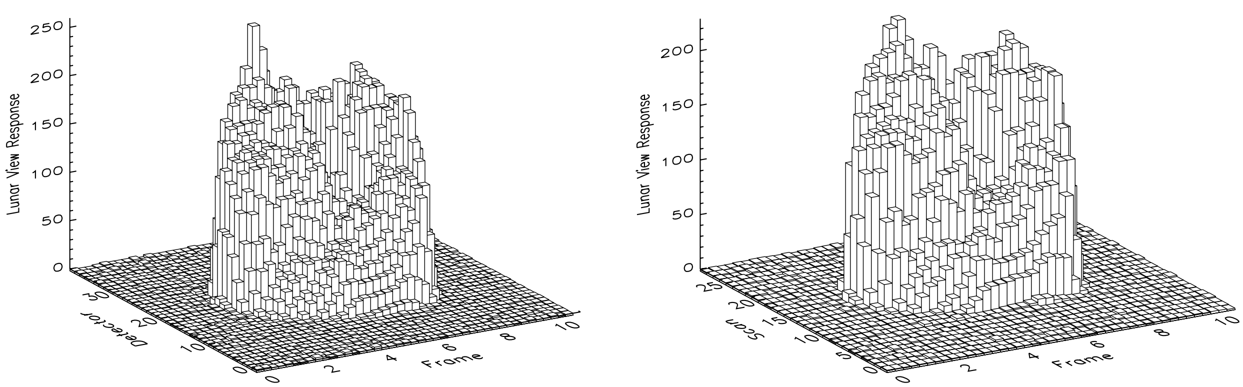

Figure 2. Aqua MODIS band 1 lunar response (November 15, 2002). Left: all detectors in one scan; Right: one detector with multiple scans.

TABLE 2 LUNAR OBSERVATIONS SCHEDULED FOR TERRA AND AQUA MODIS

Year	2000	2001	2002	2003	2004	2005	2006
Terra MODIS Lunar Observations	6	10	10	9	10	8	3

Aqua MODIS Lunar Observations	N/A	N/A	5	9	10	9	5

3.2 Inter-comparison using other sensors

One of the methods often used to inter-compare two sensors' calibration is to use their simultaneous nadir observations [11,18]. This is also known as the simultaneous nadir overpasses (SNO) approach. Since both Terra and Aqua MODIS are operated at the same altitude, there is no simultaneous nadir overpasses. Consequently the SNO approach cannot be directly applied to inter-compare Terra and Aqua MODIS calibration. Because of this, an indirect approach was developed and used by MCST. In this approach a third sensor that can be directly compared with both Terra and Aqua MODIS (via SNO) is selected. The difference between its comparison with Terra MODIS and that with Aqua MODIS provides useful information on the calibration difference between the two sensors.

To assure inter-comparison quality the selected sensor should be stable during the time between its comparisons with both MODIS instruments. In this approach the third sensor serves as a transfer radiometer. We use AVHRR/NOAA-16 as an example to serve as a transfer radiometer. Table 3 lists its SNO cases with both Terra and Aqua MODIS from July 2002 to June 2006 using a crossing window (time) of less than 15 seconds and less than 45 seconds. Obviously when the "simultaneous" observation window (time) is relaxed from 15 seconds to 45 seconds, the number of cases significantly increases. AVHRR channels 1, 2, 4, and 5 are closely matched with MODIS spectral bands 1, 2, 31, and 32. For reflective solar bands the top of atmosphere (TOA) reflectance factor is used in the comparison. For thermal emissive bands the comparison is made using TOA scene brightness temperature (BT).

TABLE 3 NUMBER OF SIMULTANEOUS NADIR OBSERVATIONS OF AVHRR/NOAA-16 WITH TERRA AND AQUA MODIS

Year	2002	2003	2004	2005	2006
AVHRR-16 and Terra MODIS SNO (15 sec.)	33	56	63	43	18
AVHRR-16 and Aqua MODIS SNO (15 sec.)	44	75	77	87	18
AVHRR-16 and Terra MODIS SNO (45 sec.)	173	342	306	307	87
AVHRR-16 and Aqua MODIS SNO (45 sec.)	279	452	362	288	78

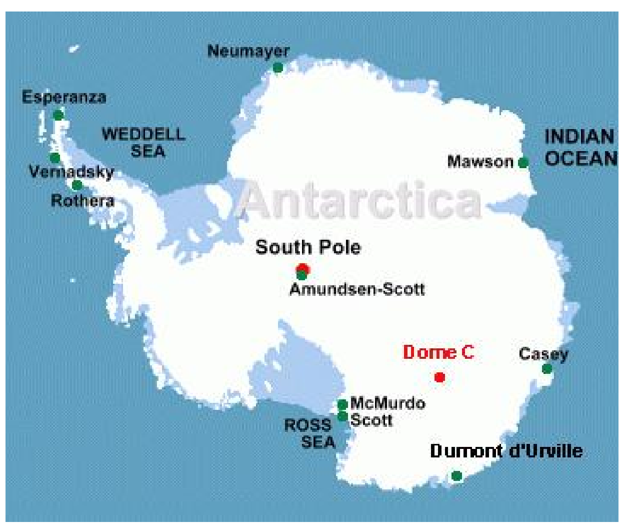

Figure 3. Ground target (surrounding area of Dome Concordia, Antarctica) used for Terra and Aqua MODIS TEB response trending and inter-comparison studies.

3.3 Inter-comparison using ground targets

A number of ground targets (Earth view observations) have been used by MCST to support MODIS on-orbit calibration and characterization. This paper discusses an approach designed to track the performance of MODIS TEB and its on-board calibrator. It studies potential calibration drift over time for each instrument and can be applied to evaluate calibration consistency between both Terra and Aqua MODIS TEB. In this study the area surrounding Dome Concordia, Antarctica (75.1 S, 123.4 E), as shown in Figure 3, is used as a cold target to track the long-term stability of MODIS bands 31 and 32 (11 and 12 μm, respectively). Dome Concordia is a very flat (slope ~0.0004%) high altitude (~3200 m) area located on the Antarctic plateau and is one of the most homogeneous land surfaces on Earth in terms of surface temperature and emissivity. The atmosphere overlying the site is extremely dry, cold and rarefied, with a seasonal temperature range of 190 to 250 K and less than 5 g/cm^2 of snow accumulation per year. The manned Concordia research station provides a record of climate variables and the opportunities for satellite validation field campaigns.

4. RESULTS AND DISCUSSIONS

4.1 Results from lunar observations

Figure 4 illustrates the integrated lunar irradiances measured using Terra and Aqua MODIS band 1. The variations in the time series are due to lunar viewing geometry differences, such as the Sun-Moon and Moon-Sensor distance, the phase angle, and the libration angle at the time of the lunar observations. For comparison purposes, the integrated lunar irradiances computed using a lunar model [17] are also presented for the same time series. Although the lunar model's absolute accuracy of derived irradiances is still being studied and validated, the lunar model results at any given phase angle provide very useful and extremely stable information to track sensor long-term calibration stability. It is clear that the results obtained from on-orbit observations track well with the results predicated using the lunar model.

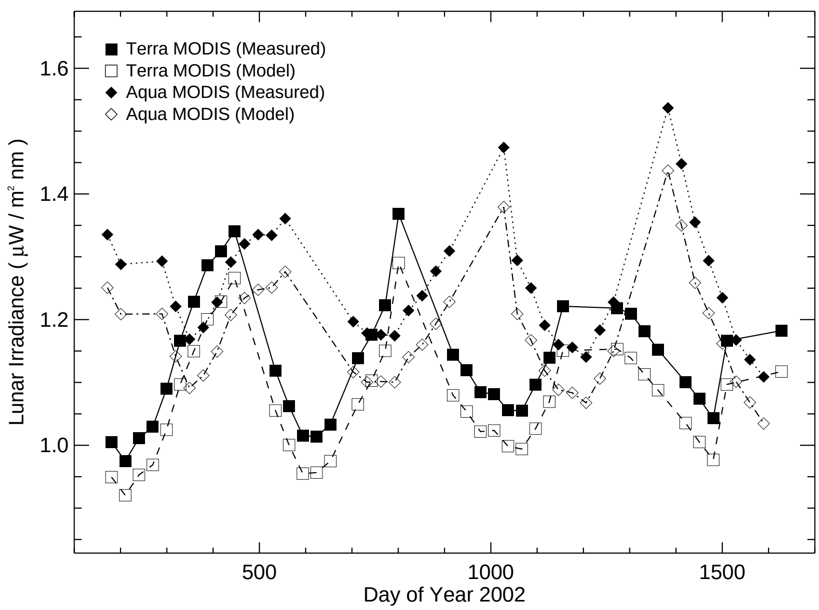

Figure 4. Integrated lunar irradiances from Terra and Aqua MODIS band 1 observations and lunar model.

Assuming the results from the lunar model are self-consistent at the phase angles MODIS uses regularly then the calibration difference between the two MODIS instruments can be examined by comparing their measured lunar irradiances with normalization to the lunar model. The normalization removes the differences due to viewing geometry differences. Table 4 presents Terra and Aqua MODIS bands 1-4 calibration differences derived from lunar observations, including the differences between the lunar model and lunar observations by each MODIS instrument. Since RSB calibration uncertainty requirements for each MODIS instrument are 2%. The results in Table 4 show that the two

MODIS instruments have been calibrated consistently to within their combined uncertainty requirements. The small deviations in the comparison results indicate excellent long-term stability for both sensors.

TABLE 4 TERRA AND AQUA MODIS RSB CALIBRATION DIFFERENCES FROM LUNAR OBSERVATIONS

Band	Center λ (μm)	Terra Observations/Model		Aqua Observations/Model		Terra and Aqua Comparison
		Ratio	RMS	Ratio	RMS	Ratio
1	0.645	1.062	0.004	1.068	0.003	0.994
2	0.858	1.082	0.004	1.084	0.003	0.998
3	0.469	1.095	0.005	1.073	0.003	1.020
4	0.555	1.071	0.003	1.067	0.003	1.004

4.2 Results from a third sensor (AVHRR-16)

Examples of inter-comparison results for Terra and Aqua MODIS calibration consistency using a third sensor (AVHRR/NOAA-16) are illustrated in Figures 5 and 6. Figure 5 shows the relationship between Terra and Aqua MODIS (bands 1 and 2) reflectance and AVHRR-16 reflectance (channels 1 and 2) using their near-simultaneous nadir observations. The data points plotted here are accumulated from a number of near-simultaneous nadir observation cases in 2004. For reflective solar bands (RSB), the comparisons are very sensitive to the scene types, the surface bi-directional reflectance properties, and the sensors' view geometry differences. Consequently the comparison results vary over a large range. To improve the quality of the inter-comparison, corrections must be made to reduce the errors caused by these effects. Obviously it is important that the comparisons must be made within a time frame that the third sensor is stable enough. Otherwise, additional errors will be introduced in the Terra and Aqua calibration inter-comparison.

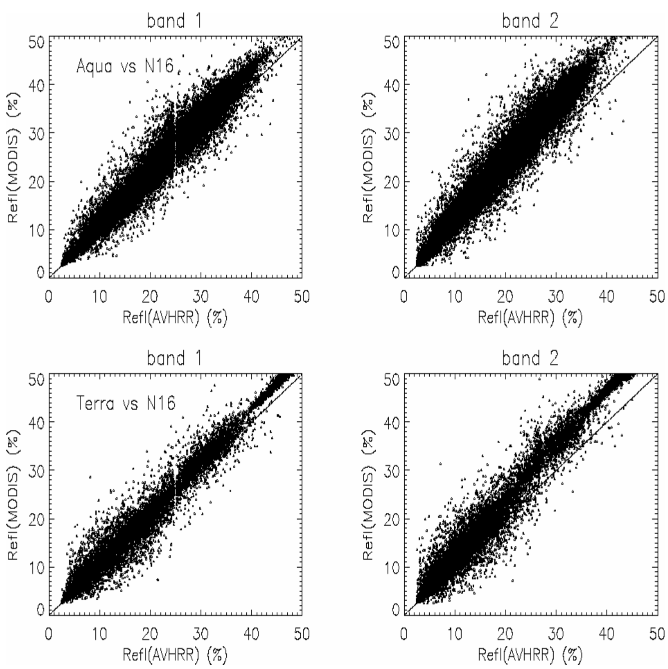

Figure 5. Terra and Aqua MODIS bands 1 and 2 reflectance versus AVHRR-16 channels 1 and 2 reflectance (data from near simultaneous observations in 2004).

Figure 6 shows the inter-comparison examples for Terra and Aqua MODIS thermal emissive bands (TEB). The brightness temperatures of MODIS bands 31 and 32 are compared with that from AVHRR matching channels 4 and 5 at 11μm and 12μm. The number of near-simultaneous nadir observation events in Figure 5 is the same as that in Figure 6. Table 5 provides a summary of inter-comparison results of Terra and Aqua MODIS via AVHRR/NOAA-16 obtained by averaging all SNO cases from 2002 to 2006.

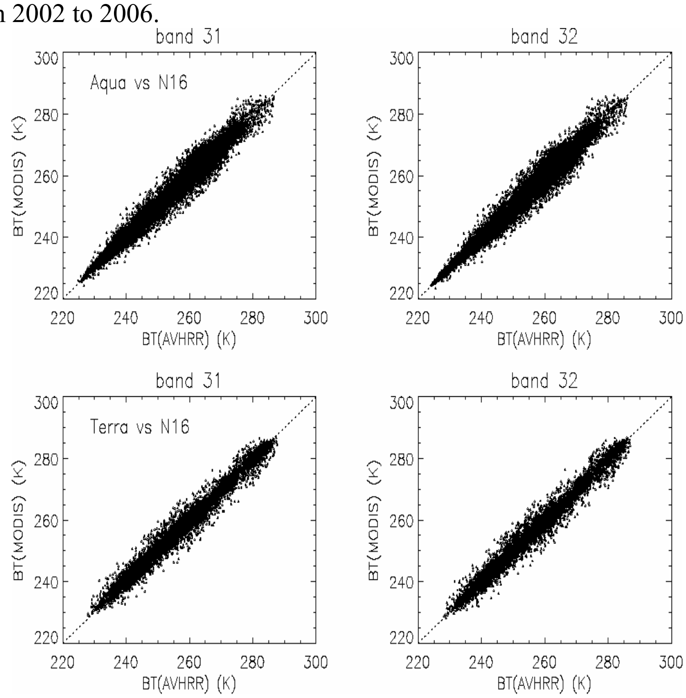

Figure 6. Terra and Aqua MODIS bands 31 and 32 brightness temperature versus AVHRR-16 channels 4 and 5 brightness temperature (data from near simultaneous observations in 2004).

For bands 1 and 2, the calibration consistency between the two MODIS sensors is about 0.8% and 0.3%, respectively. For 11μm and 12μm spectral bands, the calibration differences between Terra and Aqua MODIS are less than 0.2K. In general the calibration difference is smaller at temperatures above 270K and somewhat higher at temperatures below 240K. We have also applied this approach using other Earth observing sensors, including the AVHRR on NOAA-15, NOAA-17, and NOAA-18, VIRS on TRAM, and GLI on ADEOS II. Terra and Aqua MODIS calibration consistency results determined from using different sensors are in good agreement to within their combined uncertainties. Again, each high quality inter-comparison of Terra and Aqua MODIS should be made during the time when the third sensor is very stable.

TABLE 5 INTER-COMPARISON RESULTS OF TERRA AND AQUA MODIS CALIBRATION USING AVHRR/NOAA-16

Band	Center λ (μm)	Terra and Aqua MODIS		Band	Center λ (μm)	Terra and Aqua MODIS	
		Ref. Ratio	RMS			BT Difference (K)	RMS (K)
1	0.645	1.008	0.022	31	11.03	-0.19	0.20
2	0.858	1.003	0.035	32	12.02	-0.18	0.20

4.3 Results from ground targets

The ground target (Figure 3) selected in this study is the area surrounding Dome Concordia, Antarctica. This is a cold target with a seasonal temperature varying from 190 to 250 K. This study was initially designed to track Terra and Aqua MODIS thermal emissive bands calibration long-term stability and therefore their on-board blackbody performance since the TEB calibration is very sensitive at very low temperature. In addition, both sensors overpass this area multiple times each day and can provide measurements over a range of scan angles. Figure 7 shows Terra and Aqua MODIS band 31 (11μm) brightness temperatures retrieved at Dome C area over time. Both time series show similar seasonal variations. No atmospheric corrections are applied in this preliminary trending. To illustrate the behavior of seasonal variations, Figure 8 provides the surface temperatures for the Dome C area as reported by the Automated Weather Station (AWS). This station has been in operation since 1995 (data available from http://amrc.ssec.wisc.edu/index.html), providing a long-term temperature record.

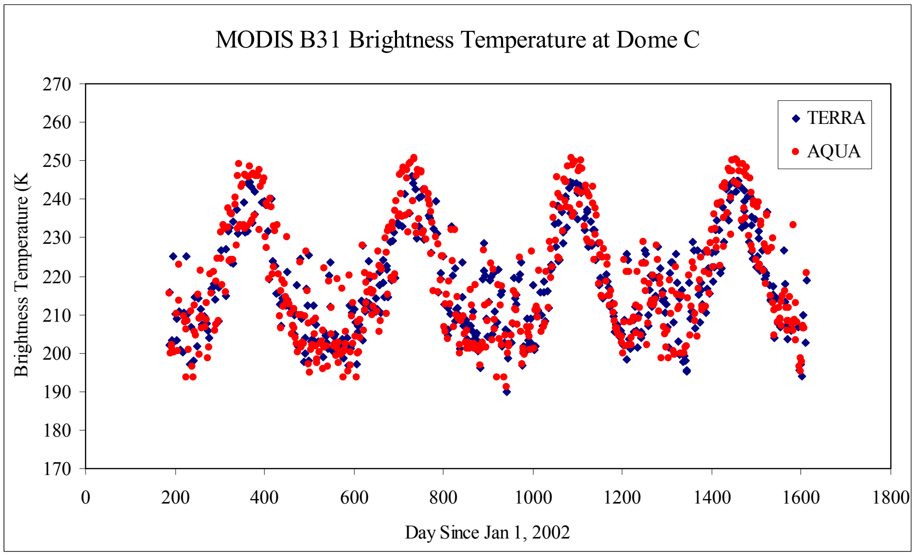

Figure 7. Terra and Aqua MODIS bands 31 surface brightness temperatures at Dome C area.

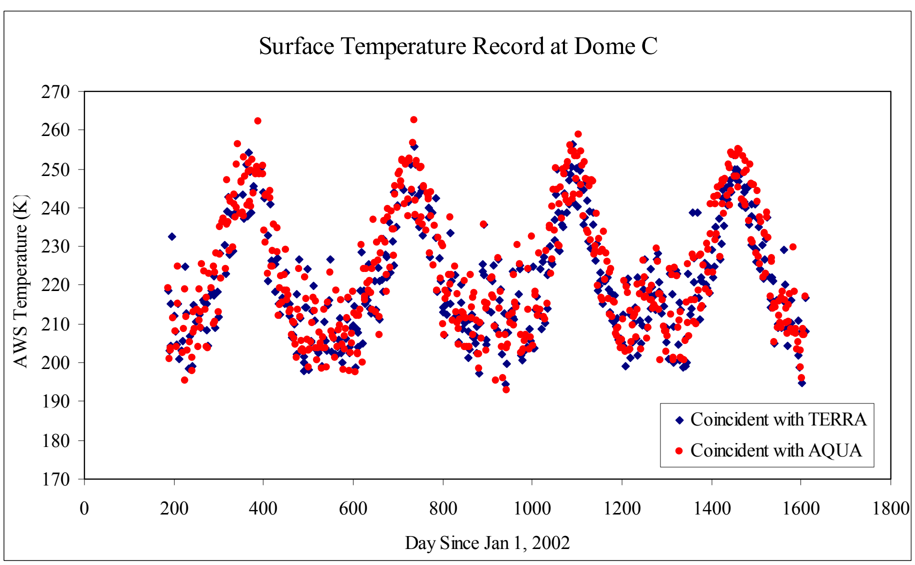

Figure 8. Surface temperature recorded at Dome C from an Automated Weather Station (AWS). Data selected to match the observation time by both Terra and Aqua MODIS.

In addition to applications of tracking individual sensor's calibration stability, a simple and quick inter-comparison study for Terra and Aqua MODIS TEB can be performed using data sets shown in Figures 7 and 8. The observation time difference from two satellites, thus their retrieved temperature difference, can be corrected (on average over long term) by normalizing the temperatures measured by satellites to that recorded by the AWS. Since the atmosphere overlying the site is extremely dry, no correction is made in this preliminary investigation that focuses on the two window channels at 11μm and 12μm designed for MODIS surface temperature measurements. Our results from this simple approach show the calibration difference between Terra and Aqua MODIS is within 0.53K at 11μm within 0.46K at 12μm. MCST is currently studying Terra and Aqua MODIS calibration difference at low temperatures and working on improvements of this approach.

5. SUMMARY

In this paper we have provided an overview of methodologies applied by the MODIS Characterization Support Team (MCST) at NASA/GSFC for inter-comparison studies of Terra and Aqua MODIS calibration consistency. The approaches presented in this paper include using the Moon, a third Earth-observing sensor, and ground targets. Since recent efforts and demands on the quality of long-term climate data records (CDR) using observations made by multiple sensors have been significantly increased, our approaches and results for MODIS inter-comparison study should provide useful insight into other sensors and missions/flight programs. Our results show that Terra and Aqua RSB and TEB have been calibrated consistently to within their combined uncertainty requirements with excellent long-term stabilities. When the Moon is used as a calibration reference, the agreement between Terra and Aqua MODIS calibration is better than ±1% for most reflective solar bands. Using ground targets or a third sensor as a transfer radiometer, the RSB calibration differences are typical better than ±2% (this is the specified calibration requirement for each MODIS sensor). Normally the approach using ground targets requires a large amount of data samples for comparison studies. For the 11μm and 12μm surface temperature bands, the calibration differences between Terra and Aqua MODIS are less than ±0.15K at scene temperatures from 240-280K and less than ±0.50K at cold scene temperatures from 190 to 230K. Improvements and refinements of these approaches have been in progress at MCST in order to further enhance the quality of tracking Terra and Aqua MODIS long-term stability and monitoring their calibration consistency. Our studies and results have provided and will continue to provide valuable experiences and lessons for other sensors (past, present, and future) and their inter-comparison studies.

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