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On-orbit Calibration and Characterization of MODIS Reflective Solar Bands

This paper summarizes the NASA experiences calibrating the MODIS reflective solar bands. It is submitted in response to Action 30.19.

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On-orbit Calibration and Characterization of MODIS Reflective Solar Bands

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ABSTRACT:

The MODerate Resolution Imaging Spectroradiometer (MODIS) has 36 spectral bands with wavelengths ranging from 0.41 to 14.5μm and three nadir spatial resolutions of 250m (2 bands), 500m (5 bands), and 1km (29 bands). Bands 1-19 and 26 are the reflective solar bands (RSB) covering the visible, near infrared, and short wave infrared spectral regions from 0.41 to 2.1μm. All the reflective solar bands are calibrated on-orbit by a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) system. In addition, on-orbit lunar observations are used to monitor the sensor's RSB radiometric stability. In this paper, we describe on-orbit calibration and characterization of the MODIS reflective solar bands and provide examples of RSB long-term response trending. We discuss the methodology of inter-calibration of different sensors via lunar observations. We also present an approach for using satellite orbital intersections for inter-comparison and/or calibration and the application of this technique to the Terra and Aqua MODIS (bands 1 and 2) and the latest Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA-17 (channels 1 and 2).

1. IntroduCtion

The MODerate Resolution Imaging Spectroradiometer (MODIS) is one of the key instruments for the NASA's Earth Observing System (EOS). Its ProtoFlight Model (PFM) was launched on-board the EOS Terra spacecraft on December 18, 1999 in a near sun-synchronous polar orbit at an altitude of 705km, descending southwards across the equator at 10:30 AM local time. The MODIS Flight Model 1 (FM 1) was launched on-board the EOS Aqua spacecraft on May 04, 2002. The Aqua spacecraft is also in a polar orbit at the same altitude of 705km, but ascends northwards with a 1:30 PM equatorial crossing time. Together they have been providing continuous data sets for the global studies of the Earth's land, oceans, and atmosphere with both morning and afternoon observations (Barnes, Xiong, and Salomonson 2002; Salomonson et. al., 2002).

MODIS has 36 spectral bands with wavelengths from 0.41 to 14.5μm and nadir spatial resolutions of 250m (bands 1-2), 500m (bands 3-7), and 1km (bands 8-36). The sensor's 20 reflective solar bands (RSB), bands 1-19 and 26, from 0.41 to 2.1μm are calibrated on-orbit by a solar diffuser (SD) with its degradation measured by a solar diffuser stability monitor (SDSM). In addition to using the on-board calibrators for the sensor's radiometric calibration, regularly scheduled lunar observations are used to track the MODIS RSB response stability. The Moon is a common calibration source with good radiometric stability that can be used for the inter-calibration of different sensors. In this paper, we report MODIS on-orbit/post-launch calibration and characterization methods and related results, including inter-comparison of two MODIS instruments through their lunar observations. The broad spectral range and the extensive calibration and characterization of the MODIS instruments make them ideal candidates for inter-calibration and comparison with other sensors.

The latest model of the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA-15/16/17 is a six-channel visible and infrared imaging radiometer (0.55 to 12.5μm). Channel 1 is in the VIS region (0.58-0.68μm) and channel 2 is in the NIR region (0.73-1.00μm). In this paper, we present an approach and show examples of using satellites' orbit intersections for the inter-comparison of Terra/Aqua MODIS bands 1 and 2 through the use of NOAA-17 AVHRR channels 1 and 2.

2. MODIS RSB On-oRBIT CALIBRATION

MODIS is a cross track scanning radiometer using a two sided paddle wheel scan mirror that produces a swath of 10km (nadir) along track by 2330km along scan every scan of 1.478 seconds. MODIS has 20 reflective solar bands with wavelengths ranging through the visible (VIS), near infrared (NIR), and short wave infrared (SWIR). Some key specifications of the RSBs are given in Table 1, including the spectral band center wavelengths, typical scene radiances, corresponding signal-to-noise ratios (SNRs), and primary applications. Previous reports (Barnes and Salomonson 1993; Barnes, Pagano, and Salomonson 1998) have provided detailed descriptions of the MODIS instrument and its pre-launch characterization. On-orbit MODIS reflective solar bands are calibrated using instrument's on-board solar diffuser and the solar diffuser stability monitor. The calibration is performed on each band, detector, sub-frame (for sub-km resolution bands), and mirror side (Xiong et. al., 2002 and 2003). Figure1 shows the schematic of the MODIS scan cavity and its on-board calibrators, including a solar diffuser (SD)/solar diffuser stability monitor (SDSM) system for calibration of the reflective solar bands (RSBs) and a blackbody (BB) for calibration of the thermal emissive bands (TEB).

Band	CW (nm)	Ltyp (W/m^2/sr/μ)	SNR (spec.)	Primary Application
1	645	21.8	128	Land/Cloud/Aerosols Boundaries
2	858	24.7	201	
3	469	35.3	243	Land/Cloud/Aerosols Properties
4	555	29.0	228	
5	1240	5.4	74	
6	1640	7.3	275	
7	2130	1.0	110	
8	412	44.9	880	Ocean Color/ Phytoplankton/ Biogeochemistry
9	443	41.9	838	
10	488	32.1	802	
11	531	27.9	754	
12	551	21.0	750	
13L	667	9.5	910	
14L	678	8.7	1087	
15	748	10.2	586	
16	869	6.2	516	
17	905	10.0	167	Atmospheric Water Vapor
18	936	3.6	57	
19	940	15.0	250	
26	1375	6.0	150	Cirrus Clouds Water Vapor

Table 1: MODIS reflective solar bands (RSB) key specifications (center wavelength, typical scene radiance, and signal-to-noise ratio, and primary applications).

The MODIS solar diffuser (SD), shown in Figure 2, is made of space grade spectralon. It provides full aperture calibration for the MODIS RSB with the same optical path used for the Earth scene observations. For the high gain ocean color bands (B8-16), direct solar irradiance on the SD causes detector saturation. Thus a retractable metal pinhole attenuation screen with nominal 7.8% transmission is added in front of the SD during the calibration. Pre-launch, the solar diffusers of both MODIS/Terra and MODIS/Aqua were characterized using reference samples traceable to the NIST reflectance standard. The SD on-orbit degradation is measured using the solar diffuser stability monitor (SDSM), also shown in Figure 2. The SDSM functions as a ratioing radiometer. During each scheduled SD calibration, the SDSM alternately measures the response of the SD view and the response of the direct Sun view. The ratio of the two responses tracks the SD time dependent degradation (Xiong et. al., 2001). The SDSM consists of a solar integrating sphere with 9 detectors that can monitor the SD degradation from 0.41 to 0.94□m.

The MODIS L1B RSB primary data product is the earth reflectance factor □$_{EV}$cos(□$_{EV}$),

$$\rho_{EV}\cos(\theta_{EV}) = m_1 \cdot dn_{EV}^{*} \cdot d_{ES}^{2} \qquad (1)$$

where □□ is the solar zenith angle, m_1 is the SD calibration coefficient, d_{ES} is the Earth-Sun distance in AU at the observation time, and dn_{EV}^{*} is the background subtracted, scan mirror angle response corrected, and instrumental temperature effect corrected digital signal. The calibration coefficients are determined from SD observations,

$$m_1 = \frac{\rho_{SD} \cos(\theta_{SD})}{dn_{SD}^{*} \cdot d_{ES}^{2}} \cdot \Gamma_{SDS} \cdot \Delta_{SD} \tag{2}$$

where ρ_{SD} is the initial SD bi-directional reflectance factor (BRF), Γ_{SDS} is the SDS vignetting function, and Δ is the SD degradation factor determined from the SDSM. Figure 3 shows Terra MODIS bands 1 and 2 (middle detector) calibration coefficient trending for more than three years of on-orbit SD calibration. The detector response for Band 1 has changed less than 1% each year. The Band 2 response change is even smaller. The deviation of the measured calibration coefficients from the long-term trending curves is less than $\pm$0.5%. All the reflective solar bands, from the VIS to NIR and SWIR, are calibrated by the SD/SDS system.

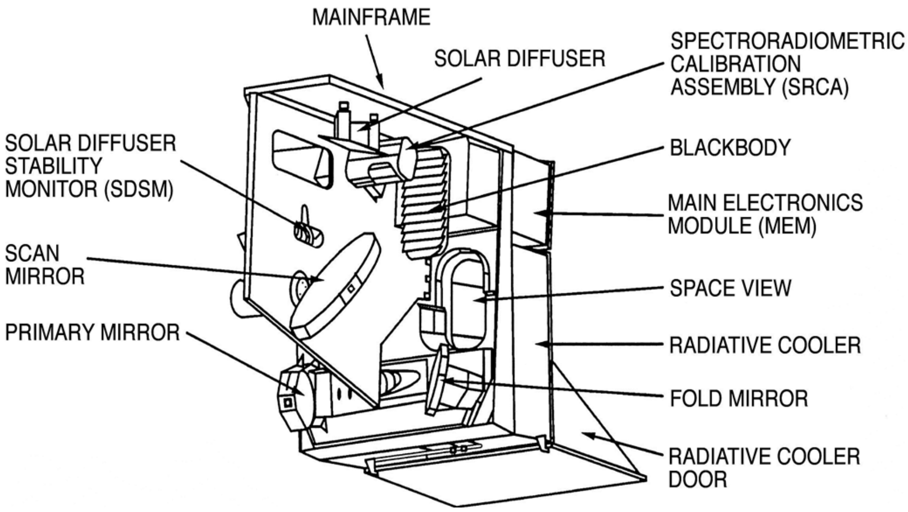

Figure 1: MODIS scan cavity and on-board calibrators: solar diffuser (SD), solar diffuser stability monitor (SDSM), Blackbody (BB), and spectroradiometric calibration assembly (SRCA)

Figure 2: MODIS RSB calibrators: solar diffuser (Left) and solar diffuser stability monitor (Right)

The MODIS RSB required reflectance factor uncertainty is $\pm$2%. The major contributing factors to the calibration uncertainty include SD BRF characterization, reflectance standard transfer, SD uniformity, and SD degradation uncertainty. Errors in the pre-launch measured response versus scan angle also contribute. Except for the SWIR bands (5-7 and 26), that have electronic crosstalk and a thermal leak, most of the reflective bands are calibrated to within the required uncertainty limits. The MODIS RSB radiance product uncertainty is ±5% including the solar irradiance error contribution.

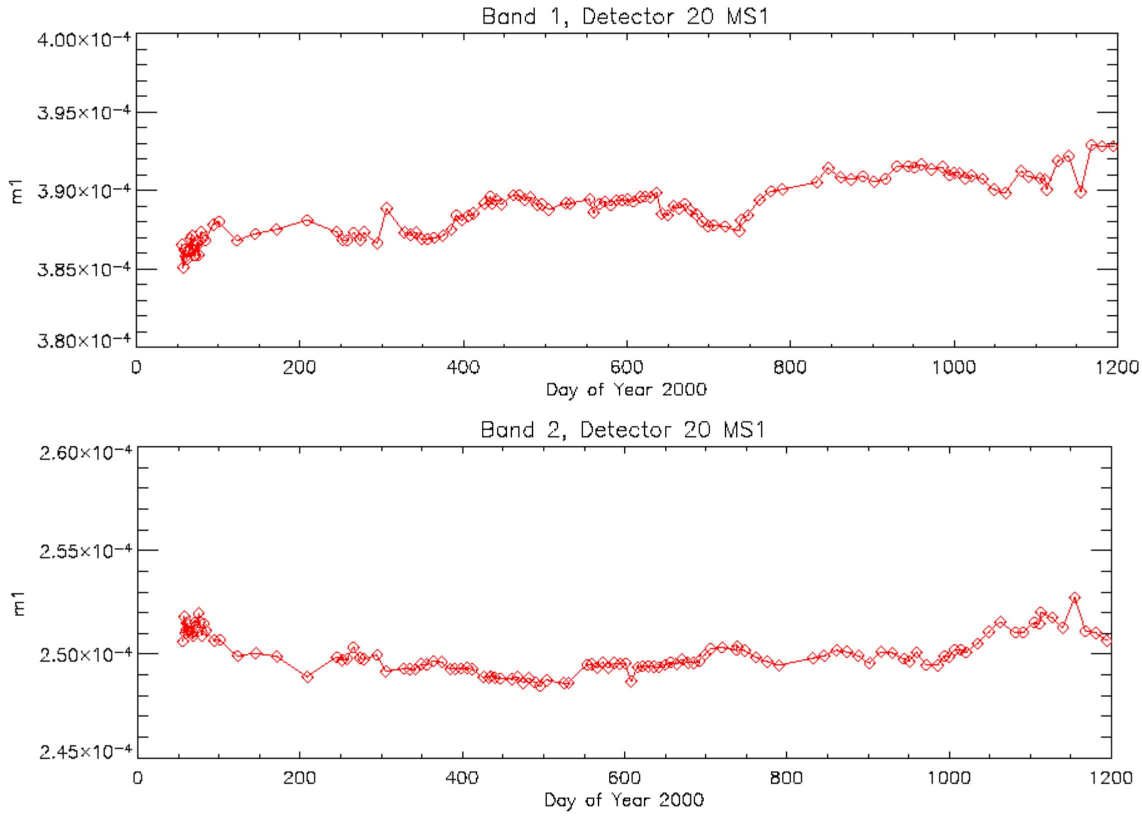

Figure 3: Terra MODIS long-term response trending results (top: band 1, middle detector, mirror side 1; bottom: band 2, middle detector, mirror side 1)

3. Inter-comparison Using the moon

Each MODIS performs monthly lunar observations through the instrument's space view (SV) port. MODIS lunar observations are being used to monitor the sensor's RSB response stability (Sun et. al., 2003; Xiong et. al., 2002). The Moon is a very stable radiometric source that can be used for calibrating Earth-orbiting sensors. Lunar viewing geometric factors that must be corrected when using the Moon for inter-comparison or calibration among different sensors include the lunar phase angle, libration angle, and the distances between the Sun, the Moon, and the MODIS during each observation. Additionally, the instrument's lunar-view's over-sampling effect must be considered. To minimize the phase angle correction in the response stability trending, the MODIS lunar observations are scheduled for nearly the same phase angle (55.5°).

Recently, the lunar observations have also been used to compare the RSB calibration between Terra and Aqua MODIS. Figure 4 shows the Terra MODIS measured lunar irradiances from bands 1 and 2 for over three years of on-orbit lunar observations with comparisons to the modeling values (Stone and Kieffer 2003). The nearly constant trend for each band indicates the detectors' calibration stability. The offset between the model and the measurements is still under investigation. Likely sources include calibration and measurement uncertainties, the modeling uncertainty, and the solar irradiance model used. Same comparisons have also been performed for the Aqua MODIS using its existing on-orbit lunar observations. The percent differences between the model and measured values are nearly identical for both Terra and Aqua MODIS (less than 1%), a clear demonstration of their consistent calibration.

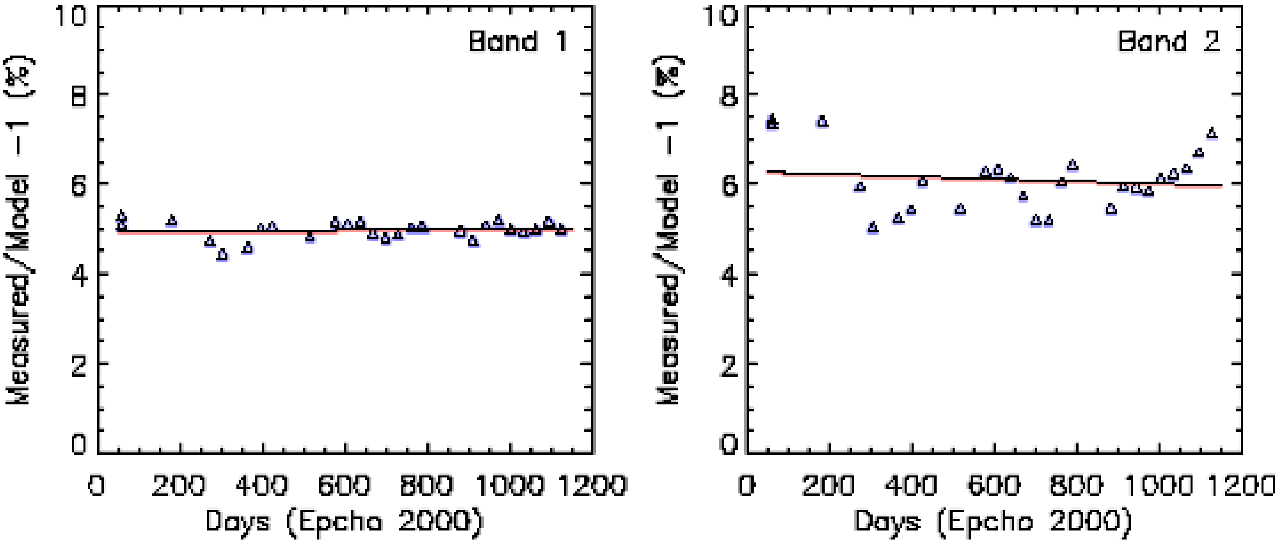

Figure 4: Terra MODIS bands 1 (left) and 2 (right) measured lunar irradiances and the modeling results.

The MODIS lunar observations have also been used to compare with other sensors like SeaWiFS and MISR in the visible and near IR regions. Some of these comparisons use nearly simultaneous lunar observations.

4. Inter-comparisons using satellite orbit intersections

In this section, we discuss an inter-comparison of the Terra and Aqua MODIS (bands 1 and 2) using the NOAA-17 AVHRR (channels 1 and 2). The AVHRR channels serve as intermediate transfer bands since Terra and Aqua are at the same altitude, which makes direct inter-comparisons difficult. On the other hand, inter-comparison between the AVHRR and MODIS using simultaneous nadir observations at their orbital intersections can be made about every three days because they operate at different orbital altitudes. To compare or inter-calibrate the two MODIS instruments, we examine the relative difference between each of the MODIS instruments and the AVHRR.

This approach was developed and used for Terra MODIS and the AVHRR onboard the NOAA-16 (Heidinger Cao, and Sullivan 2002, Cao and Heidinger 2002). This approach has been extended and applied to the inter-comparison of Terra and Aqua MODIS IR bands with corresponding AVHRR IR channels serving as intermediate transfer references (Wu, Xiong, and Cao 2003) and to the Geostationary Operational Satellite (GOES) Imager visible channel's calibration using Terra MODIS (Wu 2003).

If one wants to directly compare MODIS bands and AVHRR channels, the relative spectral response (RSR) differences, including spectral bandwidth differences, between the MODIS bands and AVHRR channels must be considered. Since the spectral difference between the two MODIS sensors is very small, we do not apply additional corrections in this preliminary study. The differences with the AVHRR will be the same for both MODIS instruments. Figure 5 shows the RSRs of Aqua and Terra MODIS bands 1 and 2 and AVHRR channels 1 and 2.

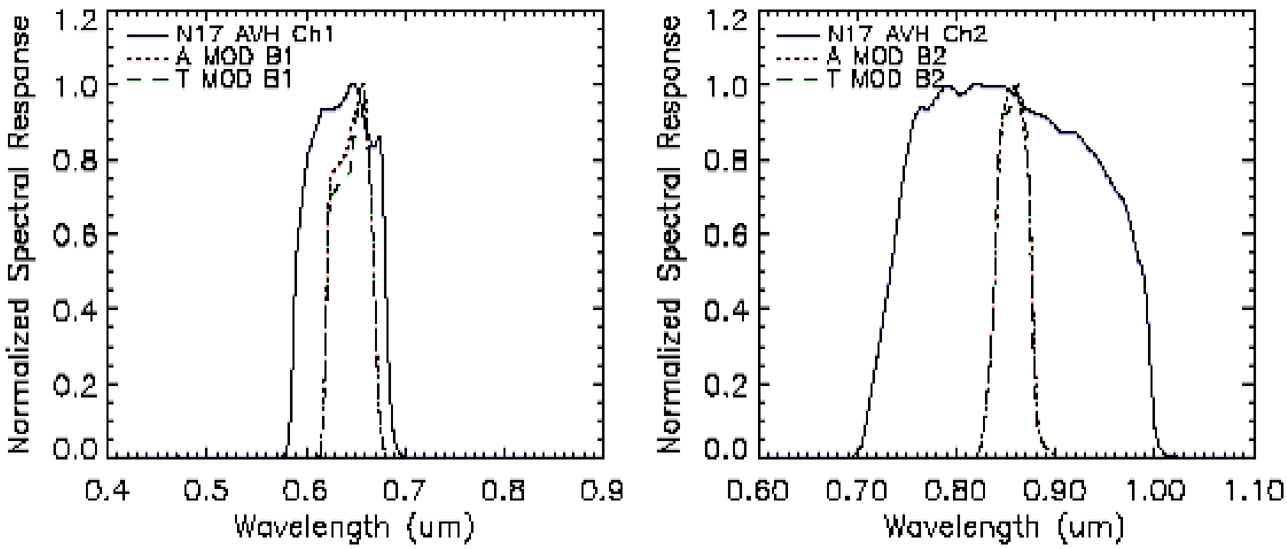

Figure 5: Relative spectral response (RSR) comparison between Terra and Aqua MODIS and N-17 AVHRR

The inter-comparison data sets from the MODIS and AVHRR sensors are selected from nearly simultaneous near-nadir views with pixel-by-pixel matches. The Aqua MODIS and N-17 AVHRR data are from day 157 of 2003. The reflectance values between the corresponding band and channel of MODIS and AVHRR are plotted against each other. The results are presented in Figure 6. The large difference between MODIS band 2 and AVHRR channel 2 is due to their large RSR differences. The same comparison is made using Terra MODIS and N-17 AVHRR data from day 180 of 2003. The results are presented in Figure 7.

The fitted slopes are 0.933 and 0.719 for the VIS and NIR comparison in Figure 6 and 0.936 and 0.713 in Figure 7. From these numbers, the difference between Terra and Aqua MODIS calibration is about 0.3% and 0.7% for bands 1 and 2. This type of observation form satellite orbital intersections provides high quality inter-calibration data sets with small temporal and spatial uncertainties.

5. Summary

In this paper, we describe the methodologies and illustrate the results of MODIS reflective solar bands' (RSB) on-orbit calibration and characterization using its on-board calibrators and the lunar observations. We also discuss an approach for using satellite orbital intersections for spectral band inter-comparisons. The examples shown represent various opportunities for inter-calibration between different sensors. MODIS is a good inter-comparison candidate because of its broad spectral coverage and the two nearly identical copies currently operating on the EOS Terra and Aqua satellites. The use of MODIS with the Visible/Infrared Imaging Radiometer Suite (VIIRS) in the National Polar-Orbiting Operational Environment Satellite System (NPOESS) will be even more attractive in providing high quality inter-comparisons because of their similar design characteristics including some of the same on-board calibrators and many similar spectral bands.

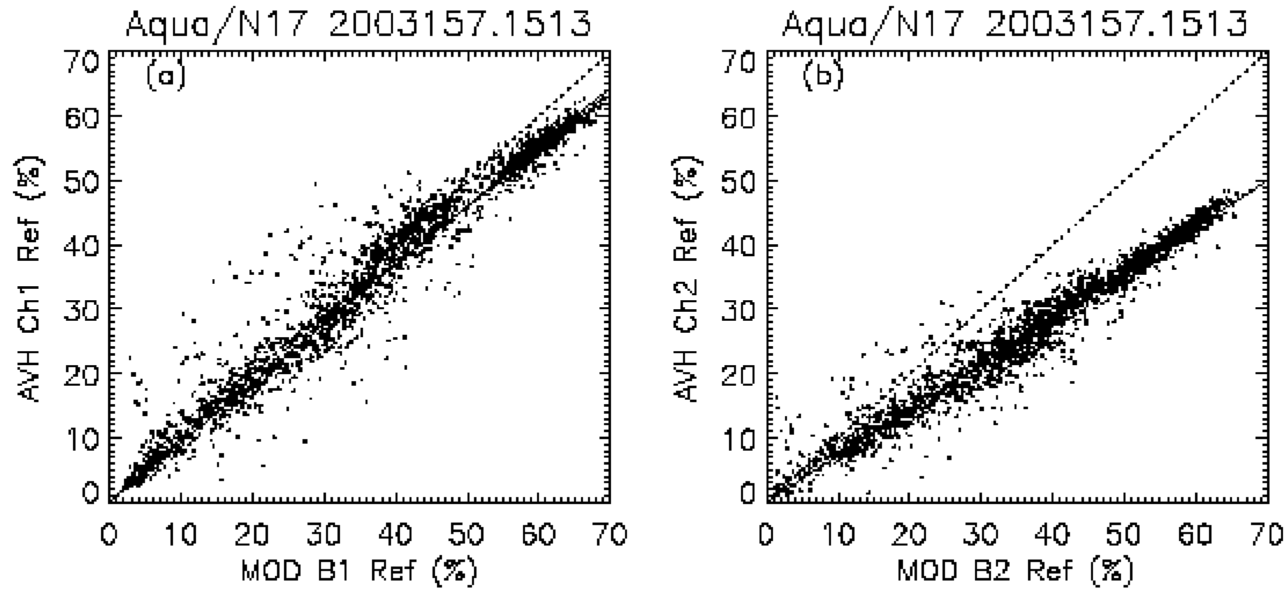

Figure 6: Aqua MODIS and N-17 AVHRR VIS and NIR reflectance comparison (left: MODIS band 1 and AVHRR channel 1; right: MODIS band 2 and AVHRR channel 2).

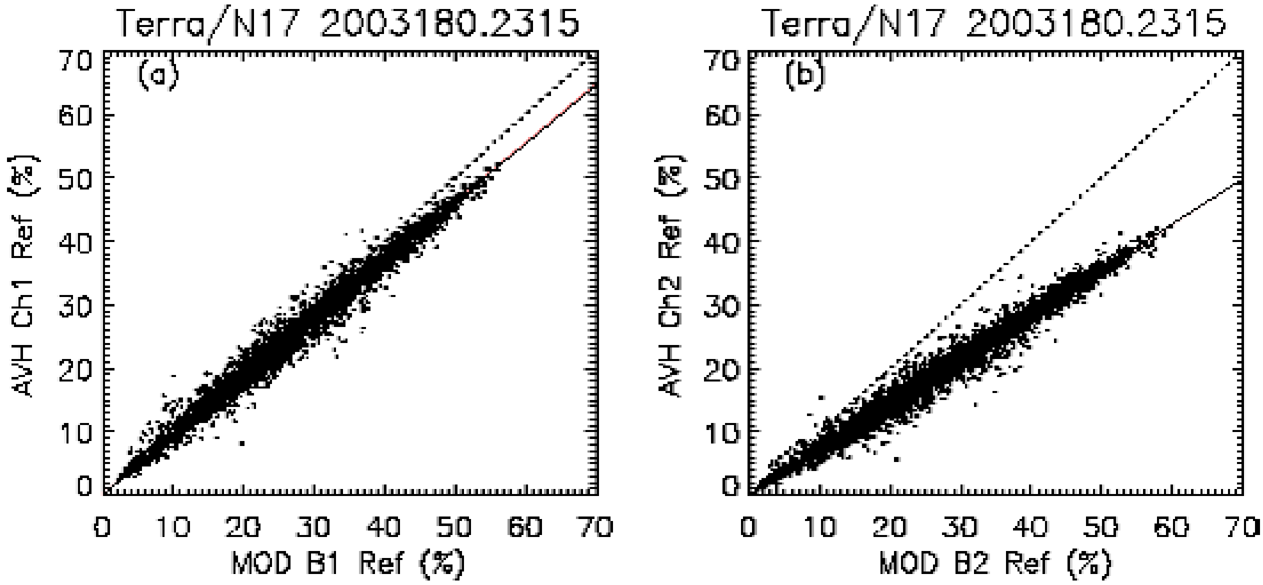

Figure 7: Terra MODIS and N-17 AVHRR VIS and NIR reflectance comparison (left: MODIS band 1 and AVHRR channel 1; right: MODIS band 2 and AVHRR channel 2).

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