

# Intercalibration of the reflective solar bands of MODIS and MISR instruments on the Terra platform

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## ABSTRACT

The multispectral imaging sensors on the Terra platform have been operating for over two decades facilitating a variety of scientific applications. The MODIS sensor provides the largest spectral coverage of 0.41 to 14.2  $\mu\text{m}$ , acquiring data at three different spatial resolutions, 250 m, 500 m, and 1 km. The MISR instrument views the Earth using nine discrete cameras pointed at fixed angles including viewing the nadir direction at a spatial resolution of 275 m and covering a wavelength range from 0.44 to 0.86  $\mu\text{m}$ . Being on the same platform, the two sensors complement each other in terms of spatial coverage (and target viewing geometry) and facilitate synergistic applications using multispectral data. A consistent radiometric calibration between these sensors is a prerequisite for creating high quality science products from their observations. Both instruments underwent intensive prelaunch characterization, with calibration monitored on-orbit using their onboard calibrators. In this paper, we perform a calibration inter-comparison of the spectrally matching bands of the two instruments using vicarious techniques. Vicarious techniques include multiyear simultaneous views of the North African desert, North Atlantic Ocean and Dome Concordia, thereby covering the different parts of the dynamic range. Also included in this work are the near-simultaneous top-of-atmosphere (TOA) reflectance measurements from Railroad Valley, USA, as provided by the RadCalNet (converted to TOA), that are used as a calibration reference to compare the on-orbit observations between MODIS and MISR.

## 1. Introduction

On December 18, 1999, the Terra spacecraft, carrying a payload of five remote sensing instruments, was successfully launched. The Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectroradiometer (MISR) are the two key instruments on Terra that facilitate a wide variety of scientific applications in the reflective solar region. Both instruments have been operating successfully over the last two decades making high-quality scientific measurements. More importantly, several scientific applications and products involve a synergy of measurements from these two instruments therefore highlighting the need for a consistent and accurate data record. In addition to the intensive prelaunch characterization, both instruments are regularly calibrated on-orbit using a combination of solar, lunar and vicarious measurements. [1-4] In this paper, we use the at-sensor reflectances from their simultaneous Earth view observations and evaluate the calibration consistency between the spectrally matching bands of the two instruments.

Simultaneous nadir-viewing scenes from the two instruments over the North African desert, North Atlantic Ocean, Dome Concordia in Antarctica and the Railroad Valley Playa, Nevada, USA (RRV) are chosen to compute the at-sensor reflectance from the two instruments. A set of common geolocation points are identified over a pre-defined region of interest to compute the at-sensor reflectance and other statistics. A correction for relative spectral response mismatch is applied based on representative hyperspectral reflectance profiles. In the case of RRV, the hyperspectral at-sensor reflectance profile as provided by the RadCalNet is used to achieve this correction. The results from the four ground targets are compared for consistency. A general agreement to within 2% is observed between the spectrally matching MODIS and MISR bands over desert, Dome C and RRV. Results reveal bias greater than 2% for the red and near-infrared band pairs for the low radiance ocean scenes. In addition to the discussion of these results, future work has also been identified.

## 2. Sensor Overview and Methodology

A unique feature of the MISR instrument is the nine cameras pointed at fixed angles, one viewing the nadir and four each viewing the forward and the aftward directions along the spacecraft ground track, providing measurements across a large number of scattering angles. In this analysis, we only consider the results from the nadir (An) camera. [5] The key characteristics of the MODIS and MISR instruments pertaining to this intercalibration, are summarized in Table I. The MODIS bands 1 and 2 acquire data at 250 m, band 4 at 500 m, and band 9 at 1 km spatial resolution at nadir. However, in this work, we use the aggregated 1 km products for MODIS in which all the bands are available at the same spatial resolution. MISR is capable of acquiring imagery at two different spatial resolution modes. In the Local Mode, select targets are observed at 250 m across track spatial resolution from the nadir camera. However, due to limitations with the data transmission rates, the instrument is largely operated in a lower resolution Global mode, achieved by averaging the adjacent samples in the cross-track and along-track direction. The MISR Level 1B2 Ellipsoid data version 3 product chosen for this work contains ellipsoid-projected top-of-atmosphere (TOA) radiance, resampled at the surface and topographically and geometrically corrected. This product reflects the latest calibration version employed on-orbit.

The four spectrally matching bands chosen for this work are also summarized in Table I. Among the chosen MODIS bands, band 9 is a high-gain band designed for ocean applications and is therefore prone to saturation over high radiance targets such as Dome C. In addition to bands listed here, there are other MODIS ocean bands that also spectrally overlap with MISR red and NIR bands, but are not considered here as they are affected by saturation.

The solar diffuser (SD) together with the solar diffuser stability monitor (SDSM), provide a reflectance-based on-orbit calibration for the MODIS reflective solar bands (RSB). In addition to the solar observations, measurements from the Moon as well as response trending from the desert sites is used to characterize the evolution of the scan-angle dependence on-orbit, also referred to as response-versus-scan angle (RVS). The on-orbit performance of the MODIS RSB continues to be stable and compliant with the 2% uncertainty requirement (in reflectance) with a few exceptions. Recent publications by Xiong et.al, summarizes the on-orbit calibration performance of the MODIS RSB in great detail. [6-7]

MISR also employs regular on-board calibration to track the radiometric response changes. On a monthly basis, the panels are deployed to reflect diffuser sunlight into the standard detectors and MISR CCD cameras simultaneously to compute the gain coefficients for each of the 1504 pixels. The MISR on-orbit performance is summarized in detail by Bruegge et.al. [5]

Table I. Summary of key characteristics of the MODIS and MISR RSB

	<b>MODIS</b>	<b>MISR</b>
<b>Swath</b>	2330 km	360 km
<b>Spatial Resolution (at nadir)</b>	250 m, 500 m, 1km	250 m (averaged to 1.1 km in Global mode)
<b>Spectral Coverage</b>	band 9 (0.442 $\mu\text{m}$ )	Blue (0.446 $\mu\text{m}$ )
<b>Band (Center Wavelength)</b>	band 4 (0.555 $\mu\text{m}$ )	Green (0.558 $\mu\text{m}$ )
	band 1 (0.645 $\mu\text{m}$ )	Red (0.672 $\mu\text{m}$ )
	Band 2 (0.858 $\mu\text{m}$ )	NIR (0.867 $\mu\text{m}$ )

Being on the same spacecraft, continuous simultaneous observations of the Earth's surface at nadir are acquired by the MODIS and MISR RSB. Therefore, the intercalibration between the two instruments can be performed using any given target on the Earth. While a scene-independent approach can provide a reliable long-term stability assessment of the reflectance ratios between the two instruments, applying a correction for the spectral response mismatch can be challenging without prior knowledge of the spectral signature of the ground target that is being imaged. To overcome this limitation, three ground targets, North African desert, North Atlantic Ocean and Dome Concordia that have a known spectral signature are chosen for this study. Each MISR L1B2 Ellipsoid product covers an entire orbit and is subdivided into 180 equally-sized blocks. A fixed number of blocks are selected from every overpass of these sites over the mission lifetime and the details are summarized in Table II.

Table II. MISR Block selection

Site	North African desert	North Atlantic Ocean	Dome C
Blocks	75-80	65-70	150-153

The MODIS L1B granules cover a 5-minute interval with swath of 2330 km (cross track) x 2030 km (along track at nadir). To retrieve the MODIS geolocated pixels at 1 km resolution, the MODIS L1A geolocation product (MOD03) is used to extract a per-pixel latitude and longitude values. The distance between a MODIS and a MISR pixel is computed based on these latitude and longitude values and pixel pairs with distance less than 250 m are retained for subsequent processing. Typically, about 20,000 co-located pixels are retained for each overpass over the North African desert and North Atlantic Ocean, each consisting of 6 MISR blocks. The TOA reflectance from these co-located pixels is computed for both instruments on a per-band basis. In the case of MODIS, additional information such as mirror side, frame (scan angle) and detector is also retained. This information has previously been used to monitor the MODIS RSB detector and mirror side differences and is summarized in detail in Angal. et.al, 2018. Finally, a reflectance ratio for each spectrally matching band is computed and an average of all the ratios for a given event are computed. [8]

Using the spectral-band adjustment factor (SBAF) tool developed by NASA Langley, a correction for relative spectral response mismatch is applied based on representative hyperspectral reflectance profiles from SCIAMACHY observations. The correction factors used in this study are site and band-dependent, but are time-independent, primarily due to unavailability of simultaneous SCIAMACHY hyperspectral observations. [9]

In addition to the three sites chosen above, an additional instrumented site is also chosen. The RadCalNet, a Committee on Earth Observation Satellites (CEOS) initiative, has provided SI-traceable TOA reflectances from a network of instrumented land-based sites. One such site is the RRV which is a high altitude dry lake bed. In addition to RRV, the RadCalNet currently consists of instrumented sites located in the LaCrau, France, Gobabeb in Namibia, and Baotou in China. [10] Among the four sites, the RRV has the most coincident measurements and subsequently at-sensor predicted TOA reflectances that can be used as transfer to compare MODIS and MISR. Automated measurements, including surface reflectance and other atmospheric measurements are available, from the RadCalNet portal, every 30 minutes between 09:00 and 15:00 local time and post-processed products include TOA reflectance at nadir between 0.4 to 2.5  $\mu\text{m}$ , after radiative transfer calculations. The MODIS and MISR overpass, obtained once every 16 days, at around 10:30 am local standard time is used to extract the TOA reflectance on a 1km x 1km area surrounding the ground viewing radiometers. The RadCalNet reflectances are band-weighted by the MODIS and MISR Relative Spectral Response (RSR) to derive an at-sensor predicted TOA reflectance that is used to normalize the measured TOA reflectance, effectively cancelling out the spectral differences and atmospheric variations on the MODIS/MISR reflectance ratios. In the next section, the results from all the four ground targets are presented and discussed. [11]

A total of 147 simultaneous overpasses between MODIS and MISR over RRV were processed from January 1, 2013 to January 1, 2021. These were further reduced to 57 after excluding the overpasses that did not have corresponding Radcalnet data. As these are simultaneous views of the site, no further filtering for potentially cloudy or partially cloudy scenes is applied.

### 3. Results and Discussions

Using the methodology described in the previous section, at-sensor reflectance ratios over the co-located MODIS and MISR pixels is computed. Figure 1 shows the TOA reflectance ratios for the spectrally matching MODIS and MISR bands over the north African desert site, with MODIS data shown in green and MISR in red. The yearly-averaged TOA reflectance is shown in circles along with a quadratic exponential model fit to estimate the long-term drift. The seasonal oscillations vary in the individual measurements, an expected behavior attributed to the view-geometry variations. In short wavelength band-pair (0.442  $\mu\text{m}$ ), noticeable variations in the TOA reflectance trends can be seen that are likely believed to be caused due to the Rayleigh scattering. Since these are simultaneous observations, these effects are absent from the at-sensor reflectance ratios, as will be shown in the later results. A multi-year reflectance drift is observed in the red and NIR bands of MISR. This was also earlier noted by Bruegge et.al. and is expected to be addressed in a future mission-reprocess of the MISR data-record.[12]

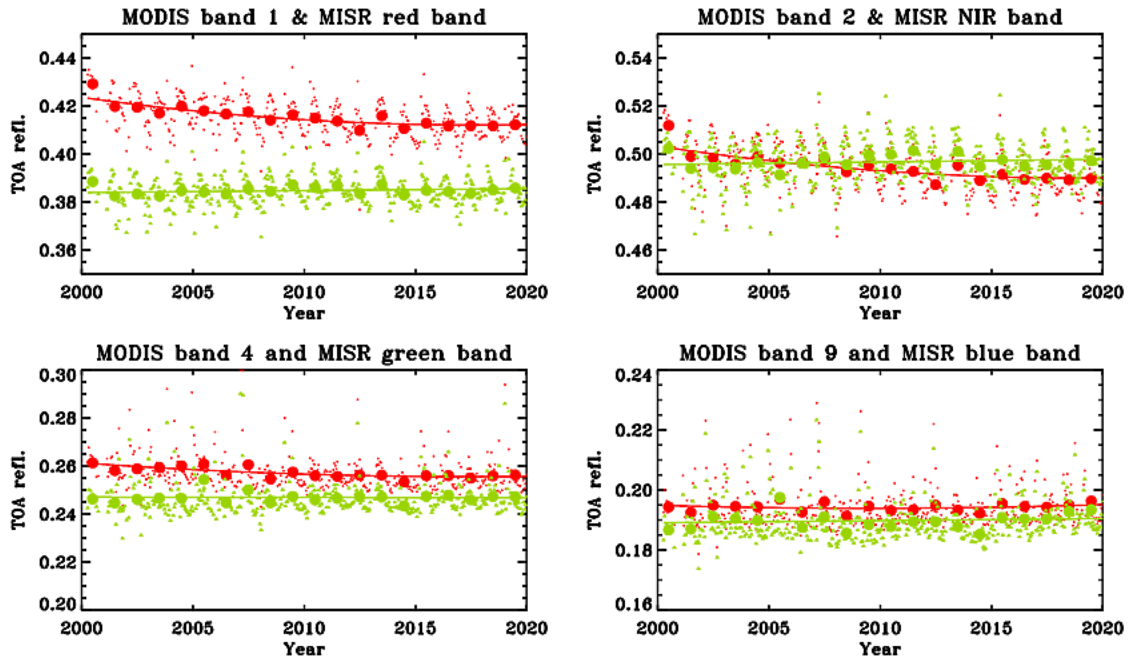


Figure 1. At-sensor reflectance trending over the North African desert target for the spectrally matching MODIS and MISR bands.

Figure 2 shows the per-year reflectance ratios for the spectrally matching bands including the trends from the three sites chosen for this study. The correction for the RSR mismatch has already been applied to these results. The reflectance drift in the MISR red and NIR bands shown in Figure 1 is reaffirmed in Figure 2 with the results from the desert and Dome C showing up to 2% drift over the two decades of operation.

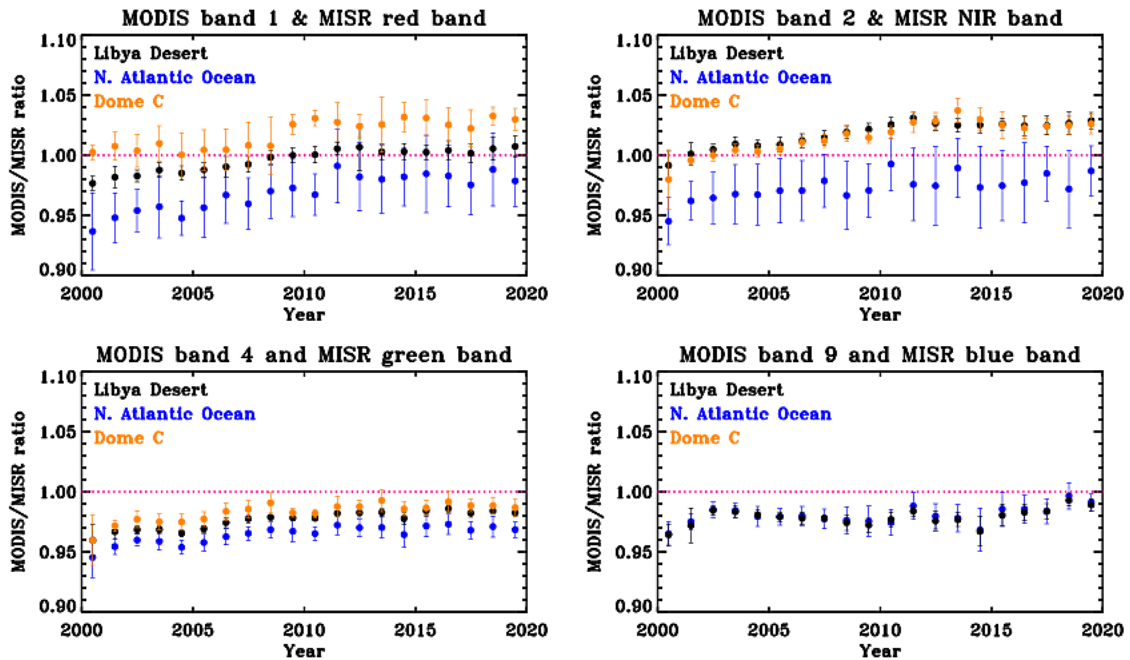
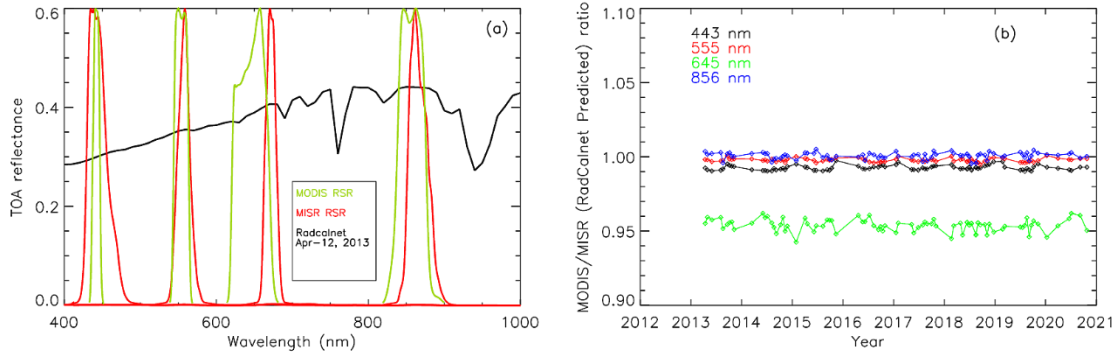
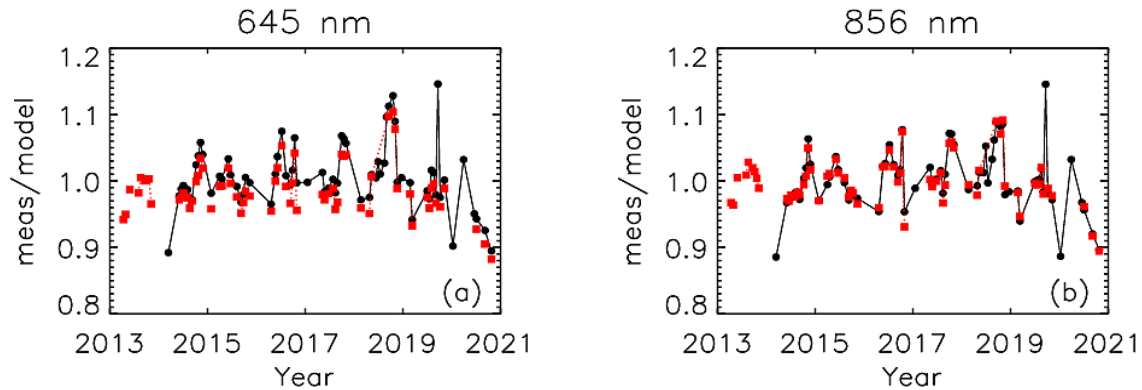


Figure 2. At-sensor reflectance ratios over multiple targets for the spectrally matching MODIS and MISR bands.

Figure 3a shows the TOA reflectance profile over RRV site from April 12, 2013 (sampled at 18:30 UTC) plotted along with the MODIS and MISR RSRs. For every measurement, the band-integrated RadcalNet TOA reflectance for each MODIS and MISR band is used to compute the RadcalNet predicted TOA reflectance. In Figure 3b, the TOA reflectance ratio from the RadcalNet predicted reflectances for the spectrally matching MODIS and MISR bands. These ratios represent the differences in the TOA reflectance over RRV caused due to the RSR mismatch between the two sensors. With the exception of the red bands (MODIS band 1 and MISR red), the observed agreement is within 2% with no apparent temporal drift over the 7 years of available data series.



**Figure 3 (a). MODIS and MISR RSR + sample RVPN Radcalnet profile (b) Radcalnet predicted reflectance ratios**



**Figure 4 (a) Red and (b) NIR bands (measured/model of all available RadCalNet matchups). MODIS data is shown in red and MISR in black.**

Figure 4. shows the measured TOA reflectances over RRV normalized by the RadCalNet predicted reflectances for the red and NIR bands. All the TOA reflectances that have corresponding RadCalNet matchups are shown here. In general, the MODIS TOA reflectance measurements after normalization are seen to be about 1-2% lower than the corresponding MISR measurements. The fluctuations in the time-series of the normalized TOA reflectances of either instrument can be attributed to the uncertainties associated with the RadCalNet TOA reflectances, but the effects of this are significantly diminished when considering the double difference  $\left(\frac{\rho_{MODIS-TOA}}{\rho_{MODIS-RadCalpredict}}\right) / \left(\frac{\rho_{MISR-TOA}}{\rho_{MISR-RadCalpredict}}\right)$ .

Table III provides a summary of the MODIS/MISR ratios from the four different ground targets over a common 6-year period. The results from desert, ocean and Dome C sites are corrected for RSR mismatch using SCIAMACHY observations whereas RadCalNet provides real-time information of the spectral signature of the RRV site that is used to correct the at-sensor reflectance ratios. The results over Dome C and RRV for the 443 nm channel were unavailable due to the saturation of the high-gain MODIS band 9. The results from multiple sites are seen to agree within  $\pm 2\%$  except for the ocean site where 645 nm and 856 nm bands show larger disagreement compared with desert and Dome C.

**Table III. Summary of MODIS/MISR ratios (2014-2020) over multiple targets**

Band	desert		ocean		Dome C		RadCalNet	
	mean	std.dev	mean	std.dev	mean	std.dev	mean	std.dev
645 nm	1.004	0.008	0.982	0.027	1.028	0.013	0.983	0.007
856 nm	1.026	0.007	0.978	0.029	1.027	0.008	0.997	0.008
555 nm	0.983	0.004	0.970	0.008	0.989	0.007	0.988	0.007
443 nm	0.982	0.007	0.983	0.012	N/A	N/A	N/A	N/A

#### 4. Summary and Future Work

The Terra mission continues to operate successfully providing valuable scientific measurements serving various land, atmosphere, ocean and cryosphere products. An intercalibration between the reflective solar bands of the two key instruments on the Terra platform, MODIS and MISR, has been performed in this work using vicarious ground targets. Simultaneous overpasses from desert, ocean, Dome C, and RadCalNet reveal that the agreement between the four spectrally matching bands is within 3% for the time-period between 2014 and 2020. Also, observed are some long-term drifts in the TOA reflectance time-series from MISR for the red and NIR band that are expected to be corrected in a future calibration reprocess.

Recently, the MODIS Characterization Support Team (MCST) delivered a set of entire mission LUTs for Collection 7 L1B processing. These LUTs include various algorithm enhancements with noticeable changes in band 9 (443 nm). Minor improvements are also expected for the other bands shown in this comparison. The Terra MODIS instrument's polarization sensitivity at short wavelengths has experienced significant changes on-orbit. The effects due to Earth scene polarization needs to be considered for an accurate cross-calibration, particularly for the short wavelength band pairs. Another intercomparison technique involves the use of the Moon as a stable reference to compare the calibration performance of satellite instruments. While MODIS observes the Moon via a roll maneuver on a near-monthly basis, MISR has only viewed the Moon, together with MODIS, twice via a pitch maneuver in its mission, once in 2003 and 2017. Future work involves the comparison of the lunar irradiance measured by the spectrally matching bands of MODIS and MISR normalized by a common reference such as the USGS ROLO model.

#### 5. Acknowledgement

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