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Cross-calibration of Terra and Aqua MODIS using Radcalnet

Abstract-- **The twin MODIS instruments onboard the Terra and Aqua spacecraft have been successfully operating for nearly two decades and providing complementary observations of the Earth's land, ocean, and atmosphere. Although the two MODIS instruments view the entire Earth's surface once every 2-3 days, simultaneous views between them are limited due to their varying orbits. Therefore, the intercomparison between these two instruments has been previously performed using a transfer instrument (such as AVHRR) or using lunar measurements normalized using a common model such as the USGS ROLO. In recent years RadCalNet, a CEOS initiative, has provided SI-traceable Top-of-Atmosphere (TOA) reflectances from a coordinated network of instrumented land-based sites. RadCalNet facilitates a unique mechanism to perform cross-calibration of instruments by minimizing the uncertainties associated with overpass time differences. In this work, the near-simultaneous TOA reflectance measurements from the Railroad Valley, US (RVUS) are used as a transfer to compare the on-orbit observations for the Terra and Aqua MODIS RSB. Near-nadir overpasses from January 2013 to January 2019 are processed and matched up with near-simultaneous RadCalNet measurements. Results show that the VIS/NIR bands agree to within 2% and the SWIR bands agree to within 5%. Also, discussed in this work are the future efforts that will be undertaken to expand this comparison to include other instruments, other sites, and both nadir- and off-nadir views after compensation for BRDF effects.**

Index Terms—**MODIS, RadCalNet, RVUS, Terra, Aqua, vicarious calibration**

I. INTRODUCTION

OVER the last three decades vicarious calibration has been widely adopted as the means to provide an independent assessment of the accuracy of the remotely sensed data from spaceborne sensors. The Remote Sensing Group (RSG), University of Arizona demonstrated the use of high altitude dry lake beds such as Railroad Valley and Lunar Lake, Nevada and White Sands Missile Range, New Mexico as effective vicarious calibration targets in the reflective solar range. The post-launch radiometric calibration of various Earth observing instruments was assessed by simulating the top-of-atmosphere (TOA) signals from in-situ surface and atmospheric measurements collected over these targets at the time of the satellite overpass [1], [2]. However, a practical limitation of this technique is the complexity involved with the deployment of the equipment for each field collect and the possible biases associated with the individual site or the associated instrumentation.

To overcome these deficiencies, the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) initiated the Radiometric Calibration Network (RadCalNet) effort that prototyped the methodology that seeks to minimize the calibration biases by creating a standardized network of sites and post-processing techniques. Furthermore, this also enhanced the temporal frequency at which the Earth observing sensor's radiometric accuracy can be assessed. The RadCalNet currently consists of four instrumented sites located in Railroad Valley Playa in the United States (RVUS), the LaCrau site in France (LCFR), the Gobabeb site in Namibia (GONA) and the Baotou site in China (BTCN). Automated measurements including the surface reflectance and atmospheric measurements are acquired every 30 minutes between 09:00 and 15:00 local time. After post-processing that also involves radiative transfer calculations, this data is available through the RadCalNet portal as SI-traceable at nadir TOA reflectance between 0.4 to 2.5 µm at 10 nm spectral resolution [3].

The twin Moderate Resolution Imaging Spectroradiometer (MODIS) instruments onboard the Terra and Aqua spacecraft have successfully operated for nearly two decades, providing complimentary observations of the Earth's land, ocean, and atmosphere [4]. Terra is in the morning orbit with a 10:30 am equatorial crossing time, whereas Aqua is in the afternoon orbit with a 1:30 pm equatorial crossing time, resulting in limited simultaneous views between the two instruments. Therefore, the cross-calibration of the two instruments has often been performed using a transfer instrument (such as AVHRR and VIIRS in more recent years) or using lunar measurements normalized via a common model such as USGS ROLO [5], [6]. More recently, the pseudo-invariant calibration sites (PICS), such as the widely used Libya 4 site, have been employed to perform a cross-calibration between multiple instruments [7], [8]. In this work, we demonstrate the use of RadCalNet to facilitate a SI-traceable cross-calibration of the two MODIS instruments by minimizing the uncertainties associated with the differences in their overpass times.

The objective of this letter is to establish a method that will: 1) assess the Terra and Aqua MODIS calibration consistency using their repeated nadir observations over the RVUS and the RadCalNet as a reference, and 2) identify the challenges involved with extending this technique to perform off-nadir comparisons at the RVUS and other RadCalNet sites.

II. METHODOLOGY

The 20 reflective solar bands covering the wavelength range from 0.4 to 2.2 µm collect Earth scene data at three different spatial resolutions (250 m, 500 m and 1 km). Table I lists the MODIS spectral design specifications (nearly identical for the two instruments) along with the spatial resolution for the land-viewing bands considered in this work. With the suite of its on-board calibrators (solar diffuser and solar diffuser stability monitor) supplemented with regular lunar observations and Earth scene measurements, the reflective bands of both MODIS instruments continue to provide accurate at-sensor reflectance products that meet its uncertainty specification of 2%. The design, on-orbit calibration and performance of the two MODIS instruments is extensively documented [4], [9], [10].

Table I. MODIS spectral band design specifications

	B1	B2	B3	B4	B5	B6	B7
λ (μm)	0.645	0.858	0.469	0.555	1.240	1.640	2.130
Res. (m)	250	250	500	500	500	500	500

The RVUS site, maintained and operated by the RSG includes four multi-spectral ground viewing radiometers (GVRs) to determine the surface reflectance in an 1 km x 1 km area centered at 38.497°N and 115.690°W. The deployed nadir-viewing GVRs have eight spectral channels from 400 to 1550 nm. The calibrated radiance data from the GVRs is combined with data from an AErosol RObotic NETwork (AERONET) network Cimel sun photometer to derive the surface reflectance via radiative transfer computations [11]. These surface reflectance measurements are submitted to RadCalNet for processing to TOA reflectance.

(a) (b)

Fig. 1(a). Terra MODIS B1 image of RVUS from October 26, 2018, 18:45 GMT (b) Ground instrumentation at RVUS.

With its wide swath of 2330 km, each MODIS sensor views the RVUS site at least once every 2-3 days and the nadir-view of the site is repeated once every 16 days. Using the 1 km x 1km region of interest of the GVRs to determine the surface reflectance, the TOA reflectance for each MODIS spectral band in Table I is computed at its native spatial resolution. As expected, it yields a 2x2 pixel region for the 500 m resolution bands and 4x4 pixel region for the 250 m bands. The latest version of the MODIS Level 1B Collection 6.1 data is used in this analysis. Due to the limited amount of pixels available from this site, any overpasses with a bad pixel are flagged and not used from further analysis. Also, the B6 of Aqua MODIS has a known issue with inoperable and noisy detectors and therefore is not considered in this analysis. The B5 of Terra MODIS has an inoperable detector that manifests as a fill value in the L1B product and is subsequently excluded.

The participating RadCalNet sites submit their surface reflectance data and are converted to TOA reflectance using a common processing methodology. Supplemental atmospheric parameters are included in the data submission. Each site owner is responsible for QA of submitted surface reflectance data as well as the uncertainty on the BOA reflectance. Radiative transfer calculations using MODTRAN convert the BOA reflectance combined with known atmospheric parameters to a predicted TOA reflectance. RadCalNet data production is detailed by Bouvet et al [3].

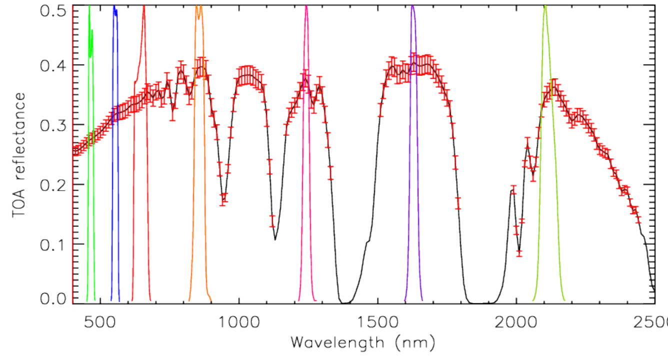

Fig. 2 TOA reflectance (black) from RVUS October 12, 2015 overlayed with the Terra MODIS relative spectral responses and the reflectance uncertainty provided with the Radcalnet outputs

Figure 2. shows the hyperspectral TOA reflectance profile from October 2015 obtained via RadCalNet overplotted with the Terra MODIS relative spectral response (RSR) of the bands chosen for this analysis. The error bars on the RadCalNet profile are the reflectance uncertainties. This hyperspectral RadCalNet profile is convolved with the RSR of each band to produce a predicted TOA reflectance that is compared with the measured TOA reflectance obtained from the L1B product as shown in equation (1) where ρ_{RadCal} represents the hyperspectral RadCalNet profile such as shown in Fig. 2, $\rho_{TOA\text{-}measured}$ represents the per-band at-sensor reflectance calculated from the MODIS L1B product and RSR(λ) indicates the in-band RSR for each MODIS band. Since RadCalNet provides a measurement once every 30 minutes, the nearest matchup in time is used to generate the banded TOA reflectance values for each band. Ideally, the deviation of the sensor-measured TOA reflectance from the RadCalNet predicted reflectance represents a calibration bias.

$$\Delta_{bias-MODIS} = \frac{\int \dfrac{\rho_{RadCal} RSR(\lambda) d\lambda}{RSR(\lambda) d\lambda}}{\rho(\lambda)_{TOA-measured}} \quad \textbf{(1)}$$

To assess the calibration consistency between the RSB of Terra and Aqua MODIS, the RadCalNet measurements are used to track the relative bias between the two sensors. In this manner, the contribution of the absolute uncertainties associated with the RadCalNet measurements is also mitigated. Assuming minimal impact of diurnal cycles on the Terra and Aqua MODIS overpass, the RadCalNet can be successfully used as a proxy to also track any temporal trends in the relative bias.

III. RESULTS AND DISCUSSIONS

Among the four RadCalNet sites, RVUS has the most temporal coverage therefore resulting in the most overlapping overpass matchups with the two MODIS instruments. Over 700 matchups between each MODIS instrument and corresponding RadCalNet data were identified from the 2013-2019 time-period. The focus of this work is nadir (±15° view zenith) as more effort is involved in converting the RadCalNet predicted reflectances at off-nadir view angles associated with the MODIS overpasses. After restricting the matchups to nadir and eliminating the scenes contaminated with clouds, the number of RadCalNet matchups with Aqua and Terra MODIS comes out to be 45 and 47 respectively.

Figure 3 shows the MODIS B1 TOA reflectance as well as the RadCalNet predicted TOA reflectance for all nadir overpasses of Aqua MODIS. The temporal variations as a function of time of year can also be seen with the lowest reflectance in the winter months due to a rising water table. In some years, fewer matchups are observed in winter months due to cloud contamination. Similar behavior is also observed for Terra MODIS.

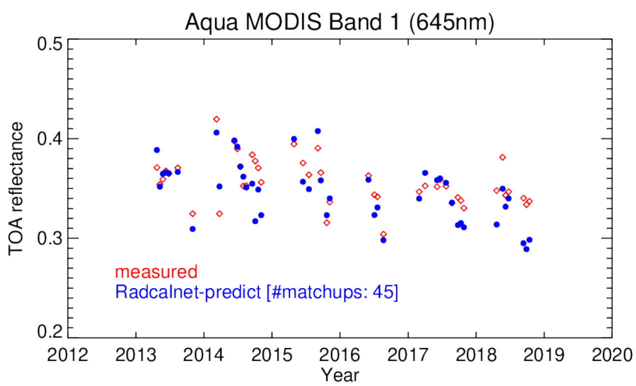

Fig. 3. TOA reflectance and RadCalNet predicted TOA reflectance at nadir for Aqua MODIS band 1 over RVUS.

Figure 4 shows a similar result for a SWIR B5 of Terra MODIS. In comparison with B1, more variations in the at-sensor measured TOA reflectances are observed in B5, likely due to atmospheric effects. The B5 of Terra MODIS has an inoperable detector (excluded from the processing) and two out-of-family detectors that might also contribute to the large scatter observed in the measured TOA reflectances.

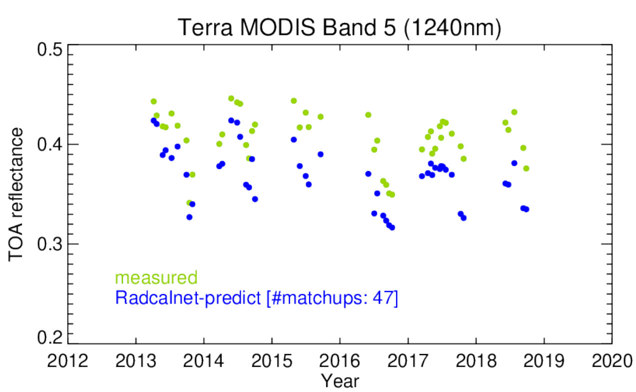

Fig. 4. TOA reflectance and RadCalNet predicted TOA reflectance at nadir for Terra MODIS band 5 over RVUS.

Figure 5 shows the reflectance ratios between the TOA values calculated from the MODIS L1B and the near-simultaneous RadCalNet predicted reflectance for Terra (green) and Aqua (red) MODIS B1 plotted as a function of time. Similar trends are also obtained for each band. Some of the deviations (> ~10%) observed in the case of Aqua MODIS are days where the values of the Angstrom exponent were beyond the nominal range of 0.7 to 1.4 (typical for RVUS).

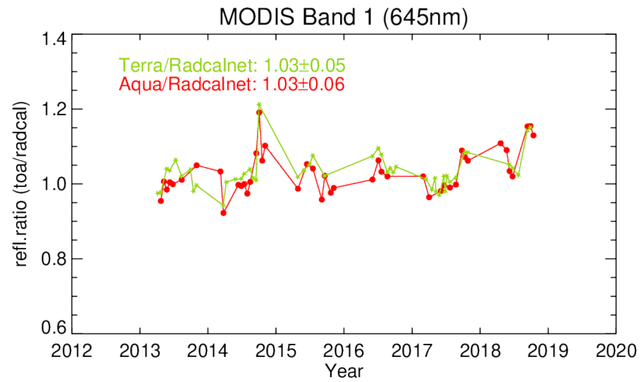

Fig. 5. TOA reflectance normalized by RadCalNet reflectance for MODIS band 1 over RVUS

The corresponding RadCalNet normalized TOA reflectances for Terra and Aqua MODIS B5 are shown in Figure 6. A noticeable deviation (~5%) is observed between the two MODIS instruments at this wavelength. Although more effort is required to fully understand the deviation observed in band 5, the recent improvements (since June 2019) in the SWIR crosstalk correction for Terra MODIS, when used in the mission reprocess is expected to lower the TOA measured reflectance for this band by about 1% therefore agreeing better with the RadCalNet predicted reflectance. The Angstrom exponent threshold is further used to reduce the number of matchups before performing a quantitative comparison between the two instruments.

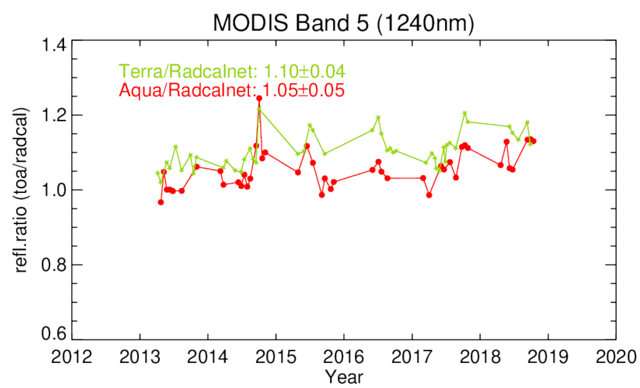

Fig. 6. TOA reflectance normalized by RadCalNet reflectance for MODIS band 5 over RVUS

Table II summarizes the results for all the MODIS bands of both instruments relative to RadCalNet. The **μ** represents the average of the MODIS/RadCalNet ratios over the time-series and the σ/μ represents the standard deviation around this mean. As discussed earlier, the results for Aqua band 6 could not be obtained due to inoperable and noisy detectors. Overall, the visible and near-infrared bands (1-4) show an agreement to within 5% between the sensor-measured and RadCalNet predicted reflectance values. The large deviation observed in Terra MODIS B5 is attributed to the noisy detectors and inadequate data (due to an inoperable detector) in the band. Using RadCalNet as a transfer, a cross-calibration between Terra and Aqua MODIS can be performed using a double difference technique. The last two columns of the Table II show the results of Terra/Aqua MODIS ratio with RadCalNet as a common transfer. With the exception of B5, the two instruments show an agreement to within 3%.

Table II. Summary of the Terra and Aqua MODIS reflectance ratios using RadCalNet as an transfer.

Band	Terra/Radcalnet		Aqua/Radcalnet		Terra/Aqua	
	μ	σ/μ	μ	σ/μ	μ	σ/μ
1	1.03	0.05	1.03	0.06	1.00	0.08
2	1.05	0.05	1.04	0.05	1.02	0.07
3	1.03	0.05	1.01	0.07	1.02	0.09
4	1.03	0.06	1.03	0.07	1.01	0.09
5	1.10	0.05	1.05	0.05	1.05	0.07
6	1.08	0.05	N/A	N/A	N/A	N/A
7	1.06	0.07	1.03	0.07	1.03	0.10

Figure 6 evaluates the temporal dependence of the Terra/Aqua reflectance ratios after RadCalNet normalization. Yearly-averaged results from the six years since 2013 have been plotted in different colors for each MODIS band. While no clear temporal trend is observed in the yearly averaged reflectance ratios, some years, such as 2018 in purple show large standard deviations due to very few (<4) valid matchups.

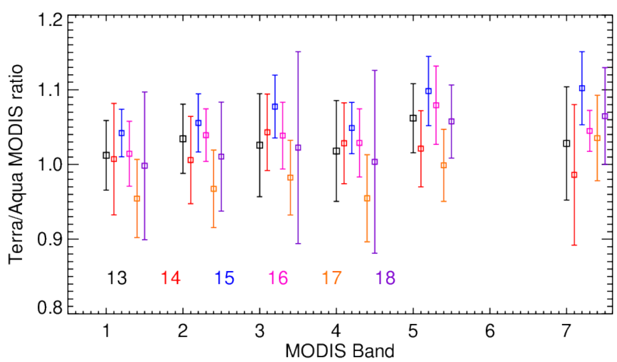

Fig. 7. Terra/Aqua double difference from 2013-2018 as a function of wavelength.

IV. FUTURE WORK

In the earlier section, only the results from near-nadir overpasses were presented to minimize the uncertainties associated with the BRDF effects associated with the site and the atmosphere. However, with the high repeatability of the MODIS overpasses over the site, multiple off-nadir matchups with RadCalNet are also available. Figure 8 shows the TOA reflectance from MODIS B1 normalized by the RadCalNet reflectance as a function of view zenith angle with Terra MODIS overpasses shown in green and Aqua MODIS shown in red. Since the RadCalNet provides at-nadir reflectance measurements, large deviations, between 15-20 % are observed at the either end of the scan angle range. As expected, a similar behavior with varying magnitudes of deviation is observed for the other MODIS bands [12].

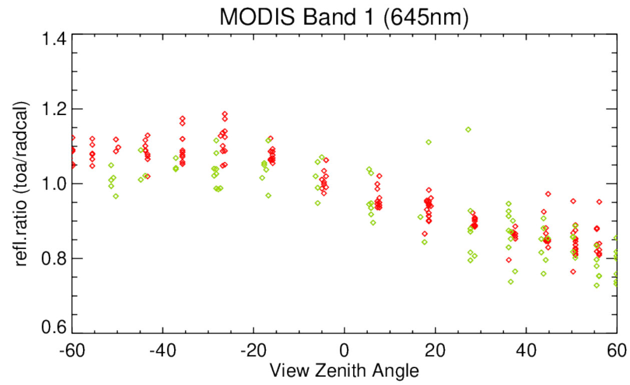

Fig. 8. TOA reflectance ratio for Terra and Aqua MODIS as a function of view zenith angle.

Early work performed by the RSG employed the use of a BRF camera that included a silicon CCD array and interference filters at four wavelengths in the VIS/NIR [13]. More recently, the Univ. of Lethbridge deployed their Goniometer system during a field campaign in the summer of 2018 to measure the directional effects at RVUS. Results from select VIS/NIR wavelengths over a range of 0° to 60° view zenith angle ranges indicated a strong anisotropic behavior at longer wavelengths [14]. Recently (September, 2019), an RRV field campaign was conducted to build on the previous modelling efforts and additional data was collected in support of a RadCalNet BRDF correction as well as supplementing and verifying more extensive BRDF data collected previously. Work is underway to apply a BRDF correction factor from these efforts to the current RadCalNet results.

Any cross-calibration efforts between the two instruments needs to account for the impacts of the various water-vapor absorption features. Figure 9 shows the band 5 TOA reflectance of the two MODIS instruments normalized by the RadCalNet TOA reflectance plotted as a function of total water vapor column provided as a part of the RadCalNet outputs. The uncertainty of RadCalNet TOA reflectance near strong atmospheric absorption regions can exceed 10%. These wavelength regions are assigned large uncertainties in the data files during processing as a caveat to the users. Future improvements in the RadCalNet algorithms is expected to reduce these uncertainties.

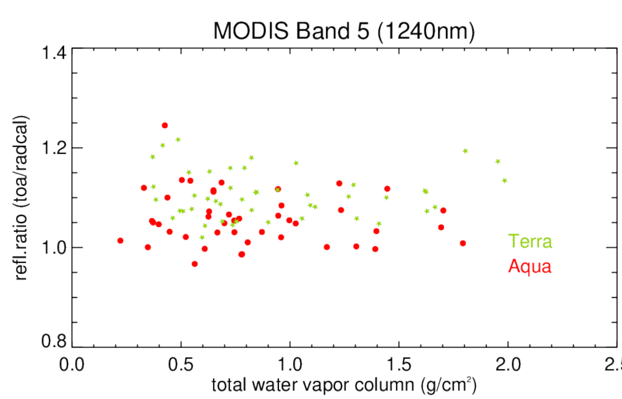

Fig. 9. TOA reflectance ratio for Terra and Aqua MODIS as a function of total water vapor column.

Over the two decades of successful MODIS operations, its data together with that from other scientific instruments aboard the Terra and Aqua platforms have provided one of the longest running data records. An important aspect to facilitate a synergistic use of the multi-instrument data is the characterization and calibration of these instruments and validation of their data products. RadCalNet provides an excellent medium to cross-calibrate the instruments with different characteristics and also minimizes the uncertainties associated with differences in overpass times and variations in the atmospheric profiles. The results from other Terra instruments such as MISR and ASTER over RVUS have been analyzed using the similar methodology and preliminary results indicate a good agreement with the MODIS instruments. Results from the RadCalNet based comparison are evaluated against those obtained from a PICS-based and Moon-based cross-calibration.

As introduced earlier, the methodology formulated here is to be extended to other RadCalNet sites, in particular the GONA. Due to the coarse MODIS spatial resolution, an extension of this work to the LaCrau and Baotou sites presents significant challenges.

V. SUMMARY

In this work, we have demonstrated the use of RadCalNet to perform a cross-calibration between the two MODIS instruments. The visible and near-infrared bands (1-4) show an agreement to within 5% between the sensor-measured and RadCalNet predicted reflectance values. Furthermore this RadCalNet based comparison has indicated that both instruments are performing well and show an agreement to within between 2-5% using the measurements analyzed between the years 2013 to 2018. The comparison focusses on nadir-overpasses to avoid the BRDF-related challenges associated with the off-nadir overpasses. However, work is underway to predict off-nadir RadCalNet TOA reflectance using recently collected field measurements. Work is also underway to expand this comparison to other RadCalNet sites such as GONA and LaCrau as well as to include other Earth observing instruments such as MISR, ASTER, Landsat OLI, and VIIRS.

VI. ACKNOWLEDGEMENTS

The authors would like to thank the Bureau of Land Management (BLM) Tonopah, Nevada, office for their assistance and permission in using Railroad Valley and Dr. Jeff Czapla Myers for technical discussions related to this work.

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