Impact of satellite orbit drift on MODIS Earth scene observations used in calibration of the reflective solar bands

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ABSTRACT

After more than 20 years in orbit, NASA's Terra and Aqua satellites have both started drifting away from their historically maintained orbits. The MODIS instruments on Terra and Aqua continue to collect valuable Earth observation data, but the changing orbits present a challenge for maintaining accurate calibration. The MODIS reflective solar bands (RSB), spanning the wavelength range from 412 nm to 2130 nm, are calibrated on orbit using a combination of regular data collections from an on-board solar diffuser, the Moon, and pseudo-invariant Earth scenes. Starting in the Collection 6 Level 1B (L1B) data products, the RSB calibration began using data from desert targets for a few of the visible bands to better track changes in the response versus scan angle that could not be captured by the on-board calibration. The use of Earth scene data has been extended recently for Terra MODIS calibration in Collection 6.1 (C6.1) and the upcoming Collection 7 (C7) L1B to also include data from ocean scenes and deep convective clouds (DCC). Drifts in both the orbit inclination and ground track of Terra and Aqua lead to changes in the solar illumination angles and satellite view angles of the Earth scenes. We discuss how these orbital changes impact the desert and DCC targets used for MODIS RSB calibration and present the accompanying changes made to our C6.1 and C7 calibration algorithms. We also discuss remaining future challenges, such as better characterization of bi-directional reflectance distribution functions, and possible alternative calibration strategies.

Keywords: MODIS, Terra, Aqua, calibration, reflective solar bands

1. INTRODUCTION

After their launches in 1999 and 2002, NASA's Terra and Aqua satellites maintained stable sun-synchronous orbits with consistent local equator crossing times and solar inclination angles, and a ground track that was regularly repeated, for approximately two decades each. The stable orbits were maintained over the mission by two primary types of spacecraft maneuvers: inclination adjustment maneuvers (IAM) and drag make-up maneuvers (DMU). The IAMs were performed on a roughly yearly basis for both satellites and served the purpose of keeping the inclination of the orbital plan relative to the Sun within a narrow window and keeping the local mean equatorial crossing time stable to within a few minutes (at 10:30 for Terra and 13:30 for Aqua). The DMUs made up for varying atmospheric drag and were performed as needed, typically once every month or two, as well as ensuring the satellites maintained a consistent ground track that repeated on a roughly 16-day cycle to within ±20 km.

Over the past three years, due to fuel limitations, the regular orbit maintenance (IAMs and DMUs) for both Terra and Aqua has ended and the orbits have begun to drift. The last dates of the maneuvers are listed in Table 1. In addition, for Terra only, a pair of constellation exit maneuvers (CEM) were performed in October 2022 to lower the satellite altitude by approximately 5.5 km and begin the free drift of the orbit.

Table 1. List of important dates related to orbit drift of Terra and Aqua satellites.

Terra		**Aqua**	
February 27, 2020	Last IAM	March 18, 2021	Last IAM
July 28, 2022	Last DMU	December 1, 2021	Last DMU
October 12 and 19, 2022	CEMs		

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After the final IAMs were performed, the inclination of the orbital planes relative to the Sun began to drift. Figure 1 shows the solar beta angles – the angle between the solar vector and the satellite's orbital plane – for both Terra and Aqua from 2018 through the predicted end of the missions at the end of 2026. The beta angle has a characteristic seasonal wobble of a few degrees that has repeated yearly from the start of the mission through the end of regular IAMs. After this time, the yearly-average beta angle begins to increase, slowly at first but accelerating steadily with time. The predicted future values shown here and throughout this paper are from simulated satellite ephemerides provided by the flight operations teams. Similarly, the local mean equator crossing times drift, with Terra moving toward earlier morning and Aqua moving toward later afternoon. After the final DMUs were performed, the ground track which had previously been repeated about every 16 days began to drift. In this case, the impact is comparatively quick, with the ground track moving outside of its historic ±20 km box within a few months.

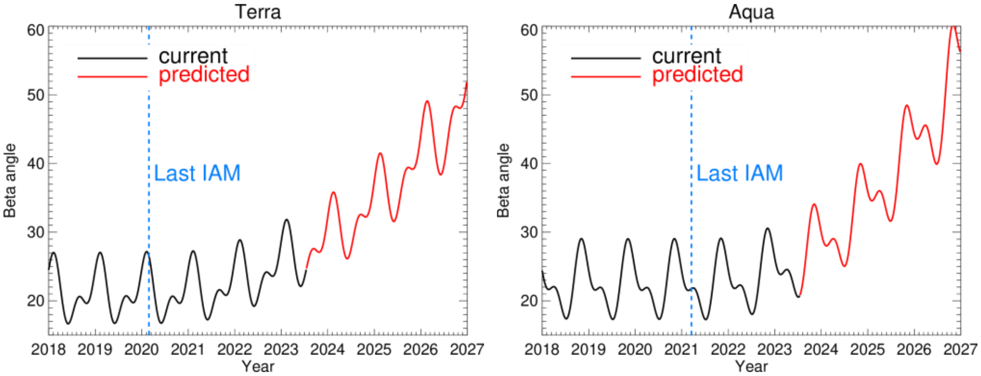


Figure 1. Past and predicted trends of solar beta angle for (left) Terra and (right) Aqua.

The MODIS instruments on Terra and Aqua continue to collect valuable Earth observation data even as the missions near their ends. The changing observation conditions will likely even enable new scientific studies with MODIS data that were not previously accessible. But the changing orbits present a challenge for maintaining accurate calibration, particularly for the reflective solar bands (RSB). The MODIS RSB, spanning the wavelength range from 412 nm to 2130 nm, are calibrated on orbit using a combination of regular data collections from an on-board solar diffuser (SD), the Moon, and pseudo-invariant Earth scenes,[1–3] all of which are affected by the orbital changes. While the question of how to maintain RSB calibration during satellite orbit drift has been addressed before for previous satellite remote sensing instruments such as AVHRR[4] and others,[5,6] MODIS is unique compared to its predecessors in its stringent calibration and uncertainty requirements and in its use of a mix of on-board and ground targets in calibration.

This paper focuses on the impact of the satellite orbit drift on the Earth scene data that is used in the calibration of MODIS RSB by the MODIS Characterization Support Team (MCST), particularly for the North African desert sites and the deep convective clouds (DCC). The impacts of the orbit drift on the solar diffuser calibration and lunar calibration are not discussed here but the strategies have been introduced previously[7,8] and will continue to be developed and improved. In Section 2, we review the calibration algorithms used to generate the Collection 6.1 (C6.1) and Collection 7 (C7) Level 1B (L1B) data products, focusing on how the Earth scene data are used. We also highlight some recent changes made to incorporate additional Earth scene data into the C6.1 calibration for forward production. In Section 3, we provide details for how the drifts in the orbit inclination and ground track, and the corresponding changes in solar illumination and sensor viewing angles, impact the Earth scenes used in our calibration. Section 4 provides an outlook on some remaining challenges, such as better characterization of bi-directional reflectance distribution functions (BRDF), and Section 5 provides a summary.

2. RSB CALIBRATION REVIEW

2.1 Collection 6.1 RSB algorithm

The MODIS RSB calibration relies on a combination of data from the on-board solar diffuser, near-monthly observations of the Moon, and long-term trends from various pseudo-invariant Earth scenes.[1] For all RSB, the solar diffuser is the primary on-orbit calibration source, used to track the time-dependent gain changes, with the degradation of the SD reflectance determined using measurements from the SD stability monitor. Since the SD is only able to track the gain at one angle of incidence (AOI) off the MODIS scan mirror, data from additional calibration sources must be used to track the response versus scan angle (RVS) of the mirror. For all RSB except the short-wave infrared (SWIR) bands, near-monthly observations of the Moon are used to track long-term changes in the gain at a different AOI than the SD. The lunar and SD data are combined using a linear function to determine the gain at all scan angles for each band.

Starting in Collection 6, data from three pseudo-invariant calibration sites in the Libya desert – Libya 1, 2 and 4 – began to be used for a few RSB where the linear RVS model from the SD and Moon was insufficient to track the RVS changes.[2] The observed top-of-atmosphere (TOA) desert signals are tracked at several different view angles (equivalently expressed in terms of AOI or MODIS instrument frame numbers) and are corrected using a semi-empirical BRDF model to reduce seasonal variations in the trends prior to using them to derive the on-orbit RVS changes. In addition to providing better characterization of the RVS, the desert data are also used to correct long-term errors in the SD-based gain, which are largest for the shortest visible wavelength bands. The desert data was initially applied to Terra bands 1-4 and 8-9 and Aqua bands 8-9 in Collection 6 and was later extended to Terra band 10. In Collection 6.1, the method was also extended to Aqua bands 1-4.[9]

2.2 Collection 7 RSB algorithm

Several improvements were made to the MODIS calibration for the upcoming Collection 7 algorithm, the details of which have been presented before.[3] Most of the changes from C6.1 to C7 involved the extended use of pseudo-invariant Earth scene data to aid in correcting long-term drifts in the calibration as both the MODIS sensors and the performance of their on-board calibrators continue to degrade. The C7 calibration uses data from three different types of Earth targets: desert sites, ocean, and DCC. The same Libya desert sites used in C6/C6.1 are also used in the C7 algorithm for the same bands of both Terra and Aqua, though there are some differences in the processing of the data. In part to deal with the expected challenges of upcoming orbit drift, the desert observations were fit differently for C7, by first binning the observations into monthly bins and then fitting the data over frame first and then over time. Importantly, the Terra desert observations in C7 are also corrected for polarization impacts before being used to derive the RVS. The desert data processing details and how they differ between C6.1 and C7 will be discussed in more detail in Section 3.1. The DCC data are used to correct long-term drifts in the gain and RVS observed in the C6.1 products for the Terra SWIR bands 5, 6, 7, and 26. The ocean scene data is used only for Terra bands 11 and 12 in an inter-band calibration algorithm with the nearly spectrally matched band 4 as a reference. Together, these algorithm enhancements will result in more accurate and stable reflectance trends in the C7 L1B products. The C7 RSB algorithm was finalized, and the calibration look-up-tables (LUT) were released for initial testing in March 2021. Testing of the C7 LUTs by science teams is underway, and production of the C7 L1B is expected to begin by the end of 2023.

2.3 Recent changes to Collection 6.1 RSB algorithm

Since the initial release of the C7 LUTs, some of the same algorithm enhancements developed for C7 have also begun to be implemented in the forward production of the C6.1 L1B. Starting in March 2023, several C7-based algorithm improvements began to be gradually phased in to the C6.1 LUTs, most importantly the changes in the use of Earth scene data described in the previous section. The primary goal for making these relatively significant changes in the middle of the C6.1 production is to improve the long-term stability and prevent further drifts of the continuing C6.1 L1B reflectance data. Part of the motivation is also to improve the handling of the desert data to be more prepared for the challenges presented by orbit drift.

Figure 2 shows the expected change in reflectance of the C6.1 Terra and Aqua MODIS RSB due to these algorithm changes for every RSB and at three different view angles: near beginning of scan (-45°), nadir, and near end of scan (45°). For Aqua MODIS, the differences between the C6.1 and C7 algorithms at the time of C7 development were minimal, with the only major change being the method for processing the desert data, and there is no notable impact to the L1B reflectance at the current time. These minor changes were implemented between March and May 2023 into the Aqua C6.1 LUTs.

For Terra MODIS, the visible bands and SWIR bands have some significant differences between the two Collections, so a gradual phase-in period of about one year was chosen to avoid any sharp changes in the forward C6.1 LUTs. During this phase-in period, we calculate the difference between the gain (m_1) and RVS LUTs with and without the algorithm improvements for every band, as shown in Fig. 2, and reduce them linearly in time until only the new algorithm is used. By March 2024, the forward C6.1 LUTs will include the enhanced use of Earth scene data (DCC and ocean data and improved processing of desert data) and will be very similar, but not identical, to the forward C7 LUTs. For a few bands, there are slight (<1%) mission-long offsets in the reflectance and radiance values between the C6.1 and C7 L1B and this will continue to be true even after phasing-in the enhanced Earth-based calibration data into C6.1. The goal of the recent C6.1 changes is to stabilize or correct existing drifts in the C6.1 reflectance values, not to make them identical to the C7 values. We also emphasize that the C6.1 reflectance changes noted in Fig. 2 are for the L1B reflectance and radiance products only. Higher level MODIS science products in C6.1 already have extra mitigation strategies in place for correcting the errors in the C6.1 L1B,[10–13] for example for the impact of polarization. These strategies should be able to be adopted to handle the above changes in L1B reflectance so that any impact to the end users will be minimized.

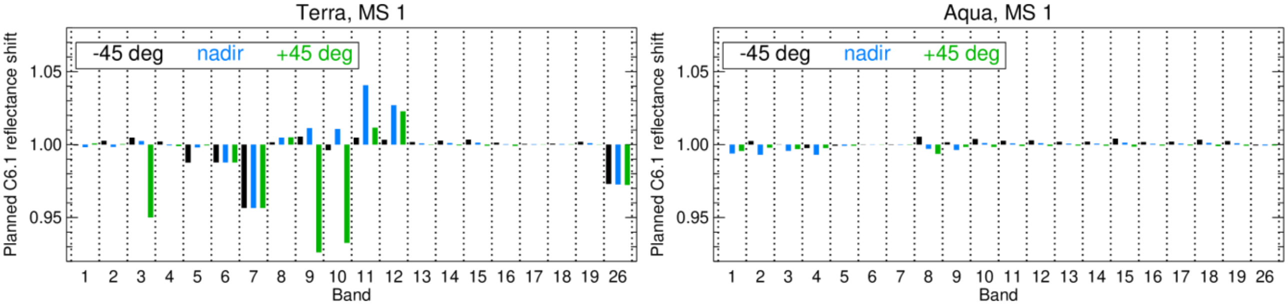


Figure 2. Change in (left) Terra and (right) Aqua C6.1 reflectance due to several algorithm changes applied in 2023.

3. IMPACT OF ORBIT DRIFT ON EARTH SCENE OBSERVATIONS

3.1 Desert

For observations of specific ground targets, both the changes in the satellite ground track and the solar inclination angle affect how the sites are observed by MODIS. Figure 3 shows the view angle of all observations recorded by Aqua MODIS of the Libya 4 site for the past several years and extending into the future. In this case, the view angle is expressed in the instrument frame which ranges from 0 at beginning of scan to 1354 at end of scan, with frame 677 at nadir. For the entire mission before the start of ground track drift, each observation came at one of a set of 16 frames, with only slight deviations. This is consistent with the well-maintained ground track of ±20 km which repeated itself on a 16-day period. But after the end of DMUs (December 2021) and the loss of the historic ground track, the observations quickly drifted away from their historic frames within a few months. The future observations (red points in Fig. 3) are from a simulated ephemeris which was generated in November 2022. The exact ground track cannot be accurately predicted far into the future due to changing impacts of atmospheric drag, as can be seen by the divergence of the measured and predicted points in the plot, but the future observations should follow a similar general pattern to what is shown here. Figure 4 shows a similar plot for Terra MODIS over Libya 4. For Terra, the historic ground track is well maintained until the CEMs in October 2022, after which the observations immediately diverge from their historic frames.

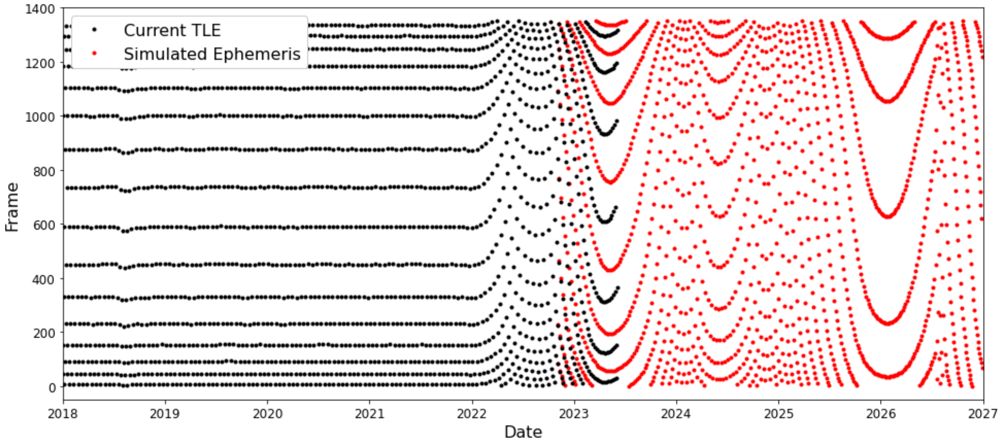


Figure 3. Frames of every Libya 4 site observation made by Aqua MODIS from 2018 through 2026. The black points represent real observations, and the red points are predicted observations based on a simulated ephemeris from November 2022.

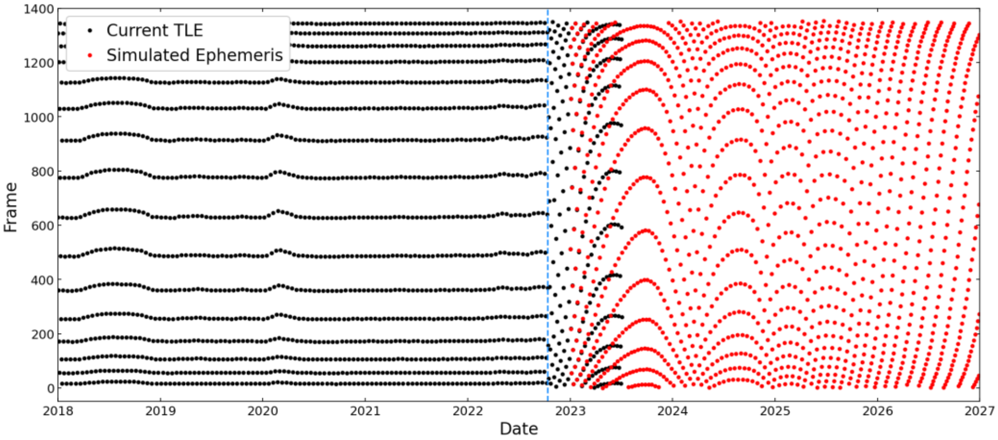


Figure 4. Frames of every Libya 4 site observation made by Terra MODIS from 2018 through 2026. The black points represent real observations, and the red points are predicted observations based on a simulated ephemeris from November 2022. The vertical blue line represents the CEMs in October 2022.

Figure 5a shows a zoomed-in horizontal slice of the plot in Fig. 4: only the observations that come within ±20 frames of frame 640, near nadir, are analyzed. For the entire Tera mission prior to the CEMs, an observation was available within this narrow frame window about once every 16 days. After the ground track drift, the observations are spread out across all view angles and a significantly smaller number are observed in this same 640±20 frame window, as indicated in Fig. 5b. Also plotted in Fig. 5 are the historic and predicted solar zenith, solar azimuth, sensor zenith, and sensor azimuth angles for the same set of observations. The solar illumination and sensor view angles exhibit a gradual drift over several years, following the change in solar beta angle shown in Fig. 1. Results for other parts of the frame range are similar. Both the change in ground track and the change in the solar inclination have implications for our use of the desert observations in the RSB calibration algorithms for both C6.1 and C7 (both Collections use a similar algorithm going forward, as described in the previous section). The loss of ground track changes the frequency of observations within specific frame windows, whereas the change in the inclination changes the solar zenith, sensor zenith, and relative azimuth angles, and thus the observed BRDF of the site.

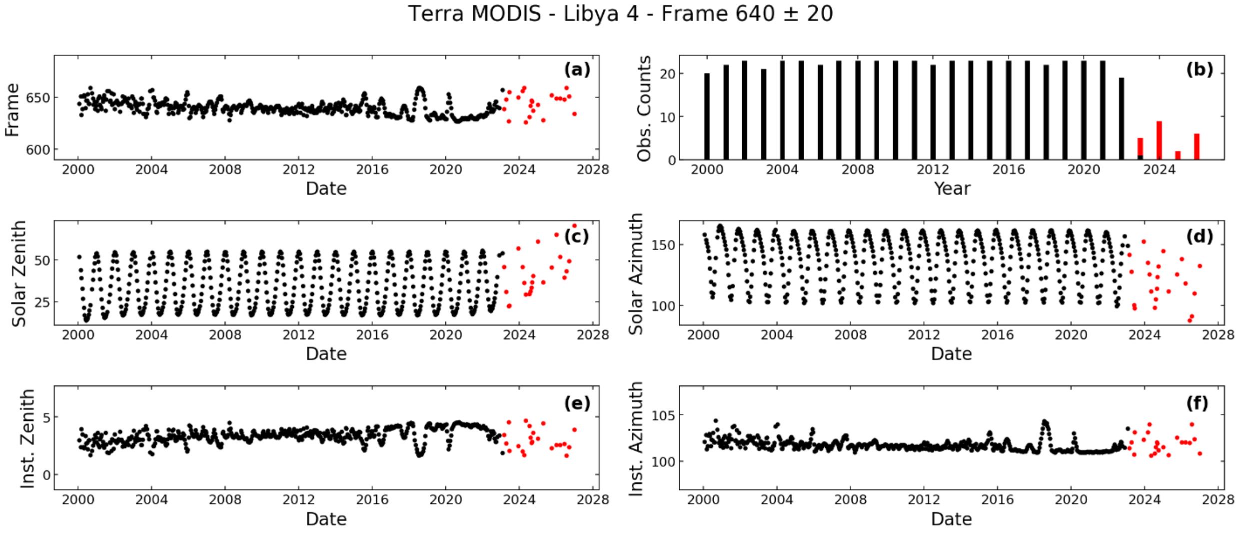


Figure 5. (a) Frames of Libya 4 site observations made by Terra MODIS through the entire mission, extended into the future through 2026 for a ±20 frame window around near-nadir frame 640. (b) Number of observations made within this frame window for each year of the mission. (c-f) Solar zenith, solar azimuth, sensor zenith, and sensor azimuth angles for each observation. The black points represent real observations, and the red points are predicted observations based on a simulated ephemeris from November 2022.

For the Collection 6/6.1 algorithms, the data from the desert sites used in deriving RVS calibration are processed in a similar way as shown in Fig. 5a. The observations are separated into the 15 or 16 different frame windows where reliably consistent views occurred over the whole mission prior to orbit drift. A semi-empirical kernel-driven BRDF model was derived,[2,14] with the coefficients determined separately for each of these frame windows using MODIS data from early mission when the reflectance was well characterized by the on-board calibrators alone. Trends of the desert signals for each of the frame windows are fit or smoothed over time to remove noise and then are fit over frame (or AOI) to derive the gain and RVS corrections used in the L1B calibration. The initial challenge presented by the orbit drift is the sharp reduction in the frequency of observations within these narrow frame windows that happens when the ground track drift begins. The left panel of Fig. 6 shows the C7 normalized reflectance trending of a single frame window of Aqua MODIS band 1 observations over Libya 4 near nadir (frame 731 ± 20). There have only been a handful of observations in this frame window over more than 1.5 years since the start of ground track drift in December 2021. The infrequent observations make it impractical to use this data to track real-time changes in the instrument gain and RVS for calibration purposes.

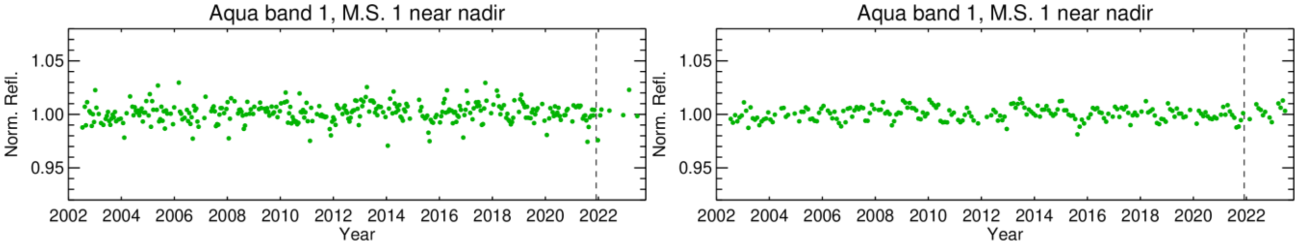


Figure 6. (left) Aqua MODIS band 1 mirror side 1 C7 reflectance trend with every individual desert observation of Libya 4 made in the frame window 731 ± 20. (right) Reflectance trend at the same frame with one point per month generated using the frame-first processing strategy. The vertical dashed line is the time of the final Aqua DMU on December 1, 2021.

For Collection 7 (and forward C6.1), we instead process the desert data by first aggregating all site observations from each month – a vertical slice of the data in Figs. 3 and 4 – and then fitting the measured signals to a polynomial function of frame.[3] The values from the fitted curves can then be monitored over time at any arbitrary frame to track and correct any changes in gain and RVS. The right panel of Fig. 6 shows the reflectance trending for Aqua band 1 near nadir using this algorithm, where there is one point per month over the entire mission. In contrast to the previous method in the left panel, the trend in the right panel has no interruption of data frequency when the ground track drift begins. In this way, we avoid any concerns from the loss of ground track experienced already by both Aqua and Terra.

On a longer timescale, there remains a concern for how the gradual drift in solar inclination will impact the desert observations. Due to the BRDF, which is different for each desert site, the changes in solar angles can have a notable effect on the observed reflectance of the site. Our current BRDF model for all the desert sites used in our calibration was based on a few years of early mission MODIS data where the solar angles fell within a consistent range. As the angles drift out of this range, it is unclear how well the BRDF kernel model functions and the previously derived coefficients will be able to track the true site BRDF over the next few years.

3.2 DCC

The DCC data used in our calibration cover a box in the eastern Indian and western Pacific oceans: from 30° S to 30° N latitude and 95° E to 175° E longitude. The DCC pixels are identified using a brightness temperature threshold of 205 K in the 11 μm channel (MODIS band 31) and a scene uniformity criterion.[15] The pixels are split into 13 different zones based on the MODIS frame number and aggregated into monthly bins. The mean value of all valid DCC pixels for each zone is the DCC reflectance for that month. The trends of DCC signals over time are used to apply adjustments to the Terra MODIS SWIR bands calibration so that the DCC reflectance trends in C7 will be stable over the entire mission.[16] For Aqua MODIS, the DCC are processed in the same way and are used to evaluate the performance of both C6.1 and C7 calibration for the RSB, but are not used directly in the calibration.

Since the DCC reflectance values are aggregated over a large number of pixels covering a wide region of the globe, rather than a specific site, the loss of the repeatable ground track that happened in 2022 for both Aqua and Terra did not have any impact on the data collection or the DCC reflectance trends. However, the gradual changes in the solar illumination angles remain a concern and have already begun to have an impact for Terra MODIS. Figure 7 shows the mean solar zenith angle for each month of DCC data over the mission alongside some examples of DCC reflectance trends. The mean solar zenith angle and the min-max range of solar zenith angles over which DCC pixels are observed varies over a yearly cycle but was repeatably consistent throughout most of the Terra mission. In the last about two years, there is a clear upward trend in the DCC solar zenith angle range.

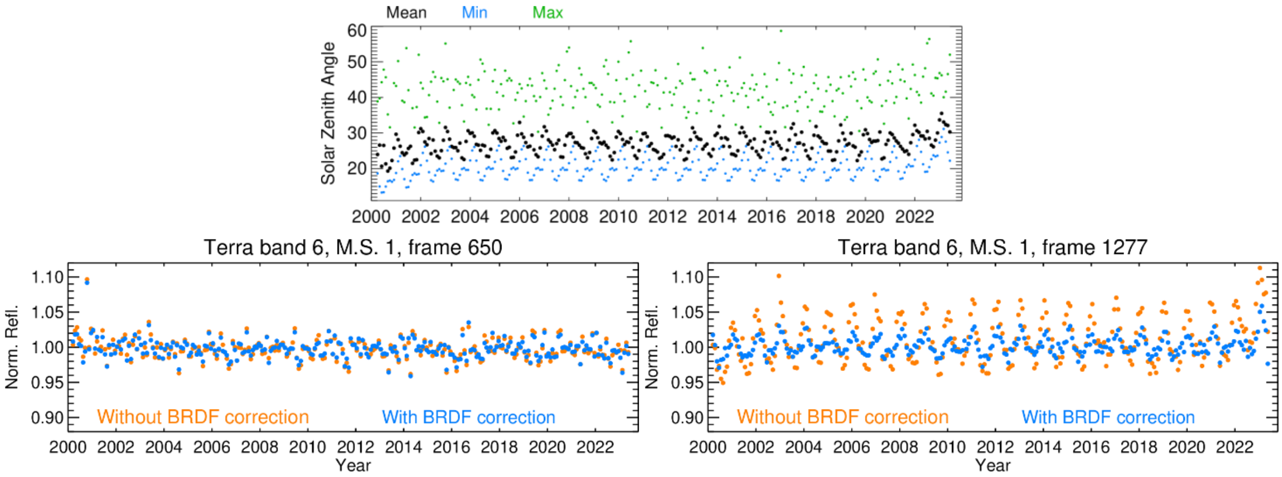


Figure 7. (top) Trend of min (blue), mean (black), and max (green) solar zenith angle of the DCC pixels for each month over the mission. (bottom left) Reflectance trends of Terra C7 band 6 near nadir with and without BRDF correction. (bottom right) Reflectance trends of Terra band 6 near end of scan with and without BRDF correction.

The changing range of solar angles has the potential to impact the reflectance trends. Figure 7 also shows example Terra C7 reflectance trends over DCC for band 6 near nadir and near end of scan. In both cases, the trends are shown with and without a BRDF correction applied. The BRDF correction is an empirical model based on early mission MODIS data.[15] For the near-nadir data in Fig. 7, the reflectance trends with and without BRDF are stable and the BRDF correction imparts only a slight reduction in the variance of the data. For the reflectance trends near end of scan, the uncorrected reflectance has very large seasonal oscillations that are significantly reduced by the BRDF model. However, in both the uncorrected and corrected trends, the data from 2022 into 2023 has a clear upward undulation due to the impact of the changing solar angles.

For most bands and frame ranges, the impact of the solar inclination drift in Terra MODIS is not yet clearly visible; the impact is only clearly visible for bands 6 and 7 near the end of scan, like the example shown in Fig. 7. For bands 6 and 7, we do not apply any RVS correction in the C7 algorithm and use the DCC data only to apply a gain correction. For this gain correction, only the data from beginning of scan through frame 850 is currently used, to avoid any impacts of orbit drift on the end of scan data. For bands 5 and 26, the DCC data is used to derive both a gain and RVS correction in the C7 algorithm, but we have not yet seen any major impact of orbit drift for these bands.

3.3 Ocean

For the ocean data used for Terra bands 11 and 12 in C7, there is less concern about the impact of orbit drift. The calibration is based on using the band 4 calibrated reflectance as a reference, and taking the ratio of the band 11 or 12 signal to the band 4 signal to derive an equivalent reflectance trend with relatively low noise or seasonal variation for bands 11 and 12. Since our analysis uses ocean data over a wide area rather than a specific site, the changes in the satellite ground track should not have any impact. Likewise, while changes in the solar angles would certainly change the observed TOA ocean reflectance, the changes should have similar impact on bands 4, 11, and 12, so that the inter-band ratio is not significantly affected. However, the accuracy of bands 11 and 12 calibration is tied to the accuracy of the band 4 calibration (including use of desert data) and any associated orbit drift effects.

4. FUTURE IMPROVEMENTS

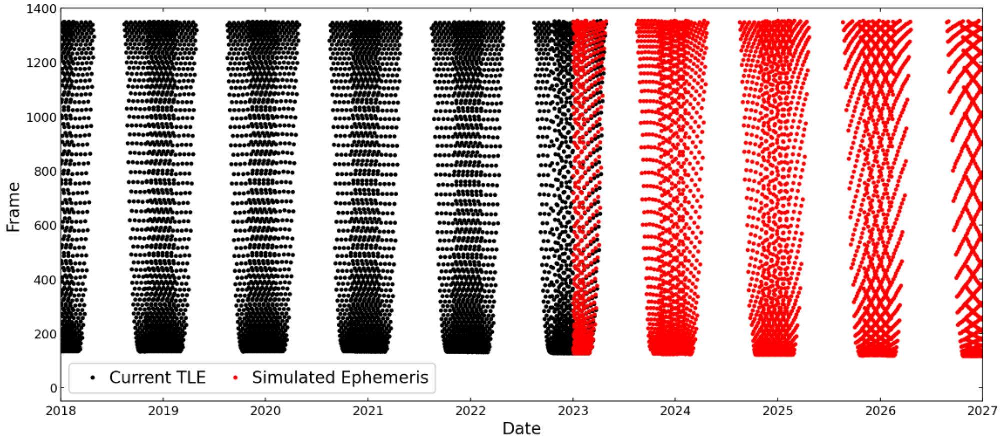
4.1 BRDF models

Improvements in the semi-empirical BRDF models currently used for the desert and DCC data sets will be important for ensuring continued accuracy of these sites as calibration references through the orbit drift periods. For the desert data, we have not yet seen any clear evidence that our current semi-empirical BRDF model is failing to describe the data for the VIS/NIR bands for which the desert data is used in calibration. However, we are investigating alternative options, such as using the 6SV radiative transfer software[17] and various ground BRDF models to develop a less empirical and more physics-based model of the desert sites which may have a better chance of accurately modeling the changes in TOA reflectance viewed by MODIS at the future solar angles. For the DCC, there are different models of BRDF correction that have been presented in the literature[18,19] which may do a better job of tracking the changes during orbit drift, though we note that the SWIR bands in particular have been a challenge for previous BRDF models of DCC. We are also investigating how the pixel selection criteria impact the performance of our current BRDF model. It remains to be seen how accurately any of these different BRDF models for the desert and DCC could characterize the MODIS TOA reflectance over the next few years.

Alternatively, a more empirical approach could be pursued. Since the changes in the solar angles will be gradual over the next few years, there is a significant amount of overlap from one year to the next in the ranges of BRDF values for the expected site observations, for example in the solar zenith angle plot in Fig. 5. In principle, it is straightforward to use the year-to-year overlap along with an assumption of short-term stability to extend the existing BRDF models as each new year of data is received, though this approach would come with increased uncertainty.

4.2 Dome-C

Lastly, the Dome Concordia (Dome-C) site in Antarctica may be another option for aiding MODIS RSB calibration going forward. Dome-C is another ground target with stable and well-characterized reflectance that has been used for characterization of satellite sensors in the RSB wavelengths.[20,21] Since daytime observations of the site are limited to only about six months per year, the data are best used for tracking long-term year-over-year characterization of the instrument. The lack of data for half of the year is a serious drawback when considering potential use in calibration, where adjustments to the instrument gain parameters need to be made as close to real time as possible. However, there are potential advantages to the Dome-C site, particularly during the era of drifting satellite orbits. Figure 8 shows every daytime observation of the Dome-C site made by Terra MODIS from 2018 through 2026. Through the mission history, there are several observations of Dome-C made per day for the daytime portions of the year. These observations come over most of the MODIS view angle range, missing only about the first 150 frames, and they cover a solar zenith angle range of about 52° to 90°. As the orbits drift through the end of the Terra and Aqua missions, these ranges of view angles and, importantly, the ranges of solar zenith angles of the observations remain about the same. This contrasts with the North African desert sites, which show a steady drift in the range of solar zenith angles in the next few years. Therefore, good characterization of the Dome-C site BRDF using historic MODIS data can in principle be reliably applied to the future without concerns about limitations in the range of the BRDF model. We are currently investigating BRDF models for the Dome-C site that could make it useful for real-time characterization of the MODIS RSB through the end of the mission.[21]



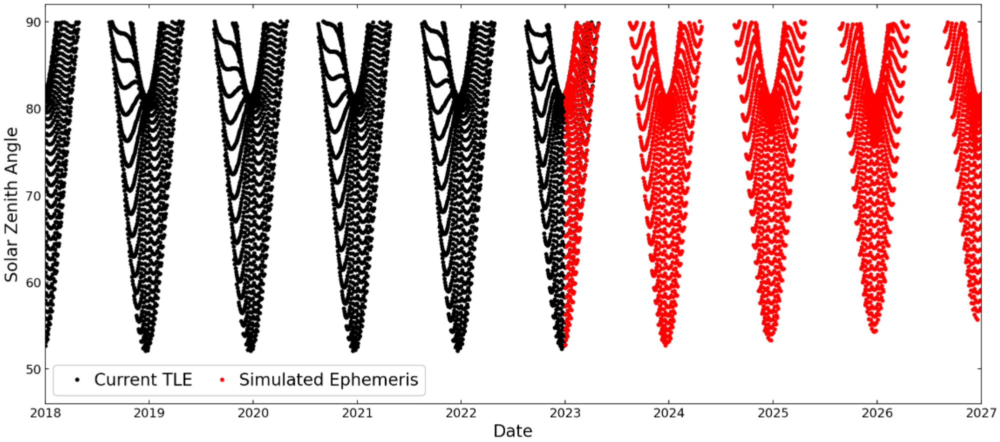


Figure 8. (top) Frames and (bottom) solar zenith angles of every Dome-C site observation made by Terra MODIS from 2018 through 2026. The black points represent real observations, and the red points are predicted observations based on a simulated ephemeris from November 2022.

5. SUMMARY

Current and future drifts in the orbits of the Terra and Aqua spacecrafts will add significant challenges to the continued calibration of the MODIS reflective solar bands, as all on-board, Moon-based, and Earth-based calibration sources will be observed by MODIS under different conditions than they have been throughout the previous two decades. This paper summarizes the current state of MCST's efforts to understand and correct the impact of the orbit drift on the Earth scenes currently used in MODIS RSB calibration. For the first few years of orbit drift, from the start up through the current time, the primary impact on the Earth data was the loss of the repeatable ground track which happened in early 2022 for Aqua and in late 2022 for Terra. The algorithms for processing the desert site data were previously adjusted in preparation for the ground track loss and the aggregated DCC data is not affected; thus, the calibration impact from the loss of ground track has been minimal. The more significant impact of orbit drift is the gradual and increasing change in the solar zenith angles which changes the observed TOA reflectance of both the desert and DCC data outside of the range where our current BRDF models are well characterized. We describe our efforts to develop improved BRDF models or to empirically extend the present models, as well as the potential use of the Dome-C site in calibration, since it is less sensitive to the orbit drifts. Combined with improved strategies for the solar diffuser and lunar calibrations, these methods should enable us to continue to provide an L1B product that meets the science community's high accuracy and precision expectations for MODIS.

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