Comparison of MODIS solar diffuser stability monitor calibration results for different operational configurations

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ABSTRACT

The MODIS instruments on the Terra and Aqua spacecraft use a sunlit solar diffuser (SD), with an optional SD attenuation screen (SDS), to calibrate the reflective solar bands. A solar diffuser stability monitor (SDSM) is used to track the SD reflectance degradation on orbit, by taking a ratio of the detector response when viewing the SD compared to the response when viewing the sun. The MODIS SDSMs have been operated both with and without the SDS in place. The SDSMs have also been operated in both a fixed and an alternating mode. In the alternating mode, the SDSM detectors view the SD, sun, and a dark background in an alternating pattern with the view changing on every MODIS scan within a single orbit. In the fixed mode, the SDSM detectors are fixed on the sun view for one orbit, and then are fixed on the SD view for the following orbit. This paper reviews the history of the SDSM operational configurations used throughout the MODIS missions and discusses the differences in the SD degradation results, which may be due to differences in sun-satellite geometry, SD signal level, and stray light effects. We highlight Aqua SDSM results from two recent dates in October 2017 and July 2019, where both the fixed and alternating mode calibrations were run on the same day, providing clear examples of the calibration differences. Additionally, we show how mixing the results from calibrations done with and without the SDS for Aqua MODIS can provide more stable results.

1. INTRODUCTION

The MODIS instruments on board the Terra and Aqua spacecraft have 20 reflective solar bands (RSB) with wavelengths spanning from 412 nm to 2130 nm. A reflectance-based calibration is used for the MODIS RSB on-orbit, relying primarily on the observations of an on-board solar diffuser (SD). The SD is exposed to the sun through an optional SD attenuation screen (SDS) at regular intervals throughout the mission. The diffuse light reflecting off the SD is observed by the MODIS RSB in order to track the on-orbit change in the gain of each detector. MODIS is equipped with a solar diffuser door (SDD) that is designed to only be opened during a scheduled SD calibration event and kept closed at other times in order to limit the exposure of the SD to solar radiation. But the SD reflectance has been observed to degrade on orbit, primarily due to the solar UV exposure of the SD.

In order for the SD to continue to be a useful calibration source for the MODIS RSB, the on-orbit change in the SD reflectance must be tracked. Each MODIS instrument is equipped with a solar diffuser stability monitor (SDSM) that can track the degradation of the SD reflectance on-orbit.[1–5] The SDSM is a ratioing radiometer that measures the SD reflectance by taking a ratio of the SDSM detector signals when viewing the SD to the detector signals when viewing the sun. A solar attenuation screen, separated from the SD attenuation screen, is fixed in place to attenuate the light from the sun view such that it is approximately the same level as the signal from the SD view.

The MODIS SDSMs have been operated in several different configurations since launch. The moveable SD attenuation screen means that the SDSM measurements can be made in configurations with the SDS either up (open) or down (closed). The SDSMs have also been operated in both a fixed and an alternating mode. In the alternating mode, the SDSM detectors view the SD, the sun, and a dark background in an alternating pattern with the view changing on every MODIS scan within a single orbit. In the fixed mode, the SDSM detectors are fixed on the sun view for one orbit, and then are fixed on the SD view for the following orbit. For most of the Aqua and Terra missions, the SD reflectance degradation used for calibration has been derived from SDSM data from a consistent configuration: alternating mode with SDS closed for Terra and alternating mode with SDS open for Aqua.

The SD observations, combined with the SD degradation measured by the SDSM, continue to be the primary calibration source for most of the MODIS RSB.[6] In the current version of the MODIS Collection 6.1 Level 1B (C6.1 L1B) products,

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the SD calibrations are supplemented with data from near-monthly lunar observations and regular observations of pseudo-invariant calibration sites in the Libyan Desert. But particularly for the high-gain ocean near-infrared (NIR) bands, and also the short-wave infrared (SWIR) bands,[7] the on-orbit SD reflectance changes measured by the SDSM translate directly into the on-orbit RSB gain changes, so accurate knowledge of this degradation is critically important to the long-term accuracy of the MODIS L1B product.

Evaluating the differences between the results from different SDSM operational configurations can provide insight into the possible systematic errors involved that may be influencing the SD degradation measurements. In addition to MODIS calibration, this information could also be useful for other remote sensing missions. For example, the VIIRS instruments on the SNPP and NOAA-20 satellites (and planned JPSS missions) also carry an SDSM with a similar design to the MODIS SDSM; however, in the case of VIIRS there is no SD door and the SDSM has only been operated in a consistent configuration throughout the missions.[8–10]

This paper reviews the history of the MODIS SDSM operational configurations used throughout the MODIS missions, and the specific SDSM data that is used to monitor the SD's degradation on-orbit. We discuss the differences in the SD degradation results from different configurations, which may be due to differences in sun-satellite geometry, SD signal level, instrument temperature, and stray light effects. We highlight Aqua SDSM results from two recent dates in October 2017 and July 2019, where both the fixed and alternating mode calibrations were run on the same day, providing clear examples of the calibration differences. We show how mixing the results from calibrations done with and without the SDS for Aqua MODIS can provide more stable results.

2. SDSM OPERATION

The SDSM is a ratioing radiometer designed to monitor the degradation of the reflectance of the SD on orbit. A schematic of the SDSM design is shown in Fig. 1. Light from the sun takes two paths into the SDSM system. For the sun view, the sunlight passes through the solar attenuation screen with a transmittance of approximately 1.44%, and for the SD view the sunlight passes optionally through the SD screen and then off of the SD. A mirror can be placed in three different positions to direct light to the SDSM detectors: sun view, SD view, and dark view. The SDSM has nine narrow band detectors embedded in a solar integration sphere (SIS) to detect light from 412 nm to 936 nm.

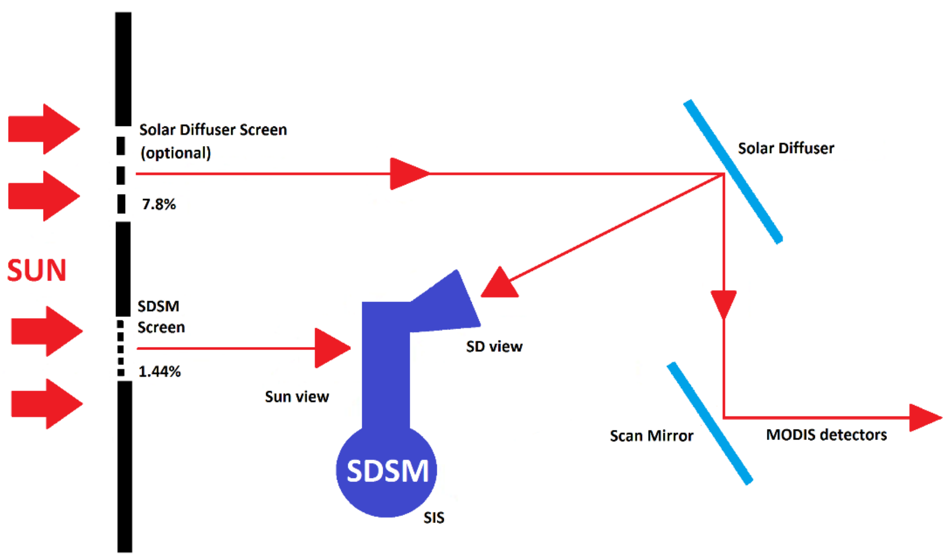

Figure 1. Schematic of the MODIS SDSM.

The SDSM has been operated regularly since launch for both MODIS instruments. During a typical SD calibration event, the SDSM collects data during the sweet spot of the SD calibration when the SD is fully illuminated by the sun. Three samples of data are collected for each MODIS scan. The SDSM has operated in two different modes which are described as alternating (alt) mode or fixed (fix) mode and refer to the action of the SDSM mirror for successive scans of the MODIS scan mirror. In alternating mode, the SDSM mirror changes its position on each scan of the scan mirror, alternating between the three views in a repeating pattern (sun view, dark view, SD view, dark view) through the entire SD calibration. Data is collected over one orbit during the SD calibration (North Pole for Terra MODIS and South Pole for Aqua MODIS) with the SDS either open (alt-open mode) or the SDS closed (alt-close mode). In fix mode, data for the SDSM calibration is taken over two orbits. In one orbit, the SDSM mirror is held fixed in the sun view for all scans over the sweet spot of the calibration, and then in another orbit the SDSM mirror is held fixed in the SD view. Several scans of data with the SDSM mirror fixed at the dark view are taken at the beginning and end of the data collection in each orbit to give the dark background reference for the data. Regardless of operating mode, three samples of data are taken during each MODIS scan.

The SDSM for both Aqua and Terra has been operated in both the fix and the alt modes at different times during the mission. Table 1 lists the dates over which the different modes were operated. For Terra MODIS, the first calibrations of the mission were done using alt mode, with calibrations being done with both the SDS open and closed in nearby orbits each time. After approximately the first two years of operation, Terra SDSM switched to operating solely with the fix mode configuration. In mid-2003, there was an anomaly during operation of the SDD that resulted in the decision to permanently leave the SDD in the open position with the SDS in the closed position. After this time, only the alt mode with SDS closed has been run. For Aqua MODIS, the first several calibrations after launch were performed in fix mode. After this initial period, Aqua SDSM has primarily used alt mode calibrations, with both SDS open and SDS closed being scheduled on a regular basis. There have been four additional fix mode calibrations for Aqua, one each in 2003, 2004, 2017, and 2019. The frequency at which the SDSM calibrations have been run has also been adjusted multiple times since launch for both instruments.[2] For both instruments, the SDSM was also operated in fix mode for every orbit of the early mission yaw maneuvers.

Table 1. List of SDSM operational configurations and the dates (in year/day-of-year format) when these configurations were used for both Terra and Aqua MODIS.

Configuration	Dates for Terra	Dates for Aqua
Alt mode; SDS open	2000/055 – 2002/006	2002/243 – present
Alt mode; SDS closed	2000/055 – 2002/006 2003/183 – present	2002/243 – present
Fix mode	2002/007 – 2003/112	2002/164 – 2002/240 2003/300, 2004/337, 2017/296, 2019/196

The two different modes each have their relative advantages. For example, the fix mode calibrations collect the SD view and sun view data from different orbits, which may make the data more susceptible to systematic error from changes in solar angle or instrument temperature between the two orbits. On the other hand, the collection of every scan of data from the same view in the fix mode allows for clearer visualization of how the in-scan change in solar angle affects the results, which is useful for evaluating the effect of the screen transmission. We elaborate more on these differences when discussing the results in Section 4.

3. SD DEGRADATION ALGORITHM

Here we review the algorithm used to calculate the SD degradation from the SDSM measurements. The degradation of the SD reflectance, denoted as Δ in Eq. 1, is calculated from the SDSM measurements by taking the ratio of the SD view signal to the sun view signal for each of the nine detectors:

$$\Delta_{\mathrm{i}} = \frac{dc_{SD,i}\Gamma_{Sun}}{dc_{Sun,i}\Gamma_{SDS}\rho_{SD,i}\cos(\theta_{SD})}, \qquad i = 1 \ldots 9 \tag{1}$$

where dc_{SD} and dc_{Sun} are the background subtracted digital signals of each detector for the SD and sun views, respectively, Γ_{Sun} is the transmittance of the sun view screen, Γ_{SDS} is the transmittance of the SD screen, ρ_{SD} is the bi-directional reflectance factor of the SD (from the SDSM-view), θ_{SD} is the angle between the solar vector and the SD surface, and the subscript i indicates the SDSM detector number.

The transmittance of the sun view screen is particularly hard to characterize for the MODIS instruments due to a misalignment in the SDSM design. The SDSM detector signals for the sun view vary by up to 10% with different values of the solar vector direction.[11] This happens both as the solar zenith angle changes within an orbit and as the solar azimuth angle changes over the course of a yearly cycle. The result is that the values of Δ calculated using Eq. 1 vary greatly over time and cannot be used directly to characterize the SD reflectance degradation.

Various methods have been used to investigate and mitigate the problem of the SDSM sun screen alignment. An optical model was developed that took into account the misalignment and was able to reproduce the observed oscillations in the data fairly well.[11] Fortunately, by design, the nine SDSM detectors contained inside the SIS all see about the same solar illumination. As the solar illumination incident into the SIS changes with the solar vector direction due to the screen misalignment, the variations in radiance are highly correlated between the detectors. In addition, the degradation of the SD at the longest SDSM detector wavelength (detector 9, 936 nm) is very small over most of the mission. Thus, it is very useful to calculate the normalized degradation, denoted as Δ_n in Eq. 2, for detectors 1-8 (D1-D8) by dividing by the degradation of detector 9 (D9):

$$\Delta_{\mathrm{n,i}} = \frac{\Delta_i}{\Delta_9} \qquad (2)$$

The normalized degradation for D1-D8 has a much smoother trend with time compared to the degradation calculated directly with Eq. 1. This has been well documented previously and has been in use in MODIS RSB calibration since shortly after launch.[1] By utilizing this ratio, we assume that both the SD screen and SDSM screen transmittance functions are independent of wavelength, so they cancel out in the ratio and are effectively not considered.

The total SD degradation at each SDSM detector wavelength is finally computed by multiplying the normalized degradation by the degradation at the D9 wavelength (936 nm). Early in the MODIS missions, it was reasonable to assume that the degradation at D9 was negligibly small and could be ignored, but after several years on orbit the D9 degradation became large enough that it could no longer be ignored, particularly for Terra MODIS. To derive an accurate degradation for D9, an empirical correction was developed based on early mission on-orbit SDSM measurements to mitigate the effect of the large variations in the SDSM sun screen transmittance.[12,13] This is the method used to derive the D9 degradation, and by extension the total SD degradation at all SDSM and MODIS RSB wavelengths, in the current C6.1 L1B product for both Terra and Aqua MODIS. For Terra MODIS, the D9 degradation has exceeded 2% in recent years, whereas for Aqua MODIS it is only around 0.5%. Finally, the SD degradation is calculated at the wavelengths of the MODIS SWIR bands using a power law fitting of the SDSM measurements and extrapolating the fit to the SWIR wavelengths.[7] We note that a different approach for calculating the degradation at the D9 wavelength was recently presented that assumes a power-law dependence of the SD degradation together with the normalized degradation measurements.[4] This approach is applied in the calibration of the Aqua MODIS ocean color products.

4. RESULTS

4.1 Normalized degradation trends

In this paper, we focus on examining the trends in D9-normalized degradation (and other quantities) for the different operational configurations of MODIS. Figure 2 plots the measured normalized degradation, $\Delta_{n,i}$, for detectors 1-8 of the Terra MODIS SDSM for all SDSM calibration events since the mission start. Different operational configurations are plotted with different colors and symbols, with the periods of operation for each configuration corresponding to the lists of dates in Table 1. Figure 3 shows the same plots for the Aqua MODIS SDSM.

There are several features in the data that are common to both instruments. Clearly Fig. 2 depicts that more degradation is observed for shorter wavelength detectors. The alt-close mode data has significantly higher variance in the time trend than the alt-open and fix mode data. This is because the signal level of the SDSM detectors when viewing the SD view with the SDS closed is roughly a factor of 10 lower and the measurement signal-to-noise ratio is correspondingly increased. There is also a clear offset between the data from different modes, most significantly when comparing alt-open to alt-close modes. For Aqua MODIS, there is also an offset between the alt-open and fix mode data that is not as apparent for Terra. The trends of the normalized degradation in time from alt-open vs alt-close modes are also significantly different in the first several years of each mission. Further discussion of the reasons for these differences among modes is the focus of the following sub-sections.

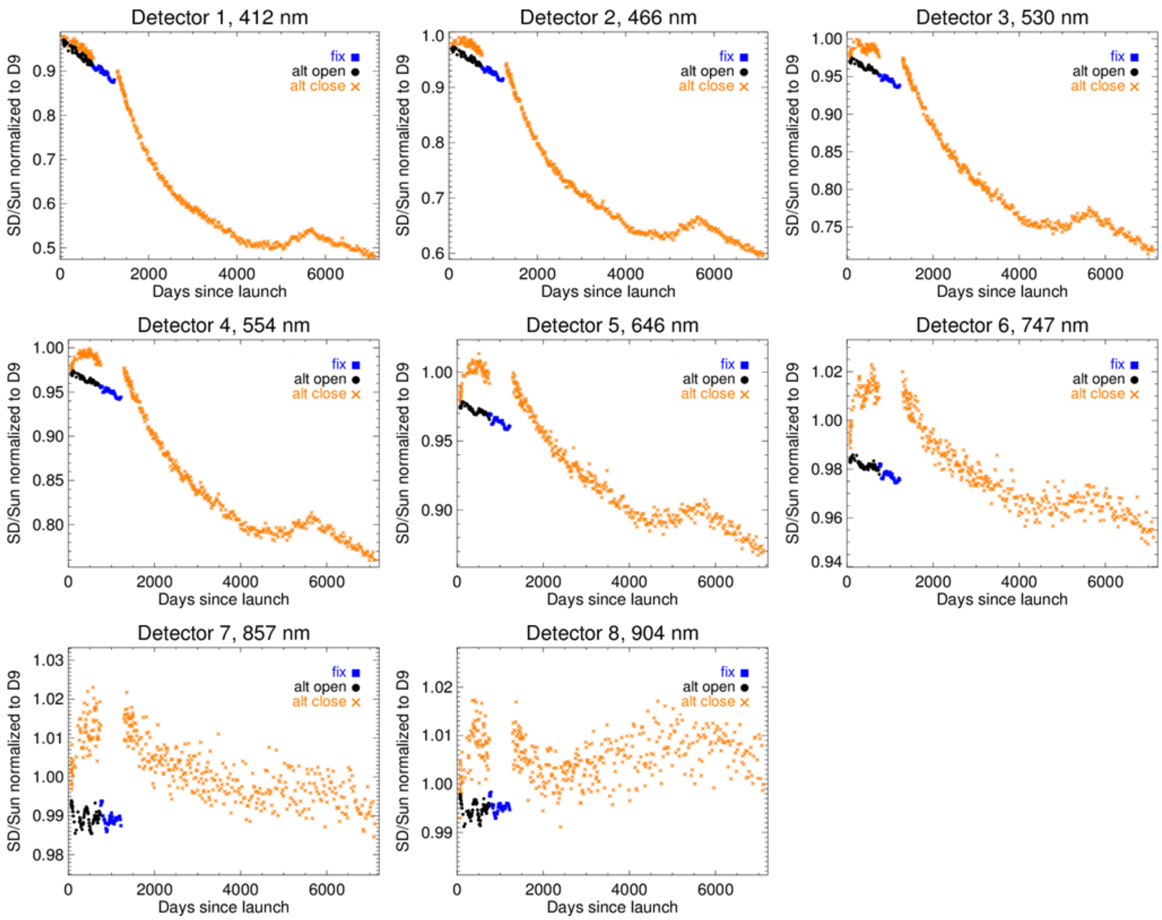

Figure 2. Plots of normalized degradation, $\Delta_{n,i}$, for Terra MODIS. The different modes are highlighted with different symbols and colors.

In order to derive a smooth trend of the SD reflectance degradation over the full mission, the results of the different operation modes must be combined. For times when both close and open data are available, the open data are preferred since the signal-to-noise ratio is higher and because the SDSM detector signal level of the SD view with screen open is closer to the signal level of the sun view data. For Terra, the alt-open and fix mode data through the time of the SD door anomaly (day 1279) are fit together and the data are normalized so that the value of $\Delta_{n,i}$ is equal to one for each detector at the time of the first SD calibration. After the time of the door anomaly, the alt-close mode data is fit with an exponential decay function and normalized such that the fitted value from the alt-close mode degradation matches the fitted value from the initial degradation period at the time of the SD door anomaly. The alt-close mode data for the remainder of the mission are fit to a piecewise exponential polynomial function. The combined normalized data set and fit curves are shown in the left panel of Fig. 4 for a few select detectors.

For Aqua, the alt-open and alt-close calibrations have both been operated consistently for the entire mission, with the exception of the first 80 days of the mission when only fix mode calibrations were run. Since the rate of SD degradation is most significant in these early mission times, it is important to include the early mission fix mode results if possible. Since there is an apparent offset between the fix and alt-open mode data, the data from these two modes over the first 1000 days are fit separately, but with the constraint that the slope of degradation with time be the same. The fit parameters are used to separately normalize the fix and alt-open mode data sets such that the normalized ratio is equal to one at the time of the first calibration. Very early in the Aqua mission, there was also a period of five days where the SD door was accidentally left in the open position and the SD experienced rapid degradation. This is seen as the sharp drop in the data just after mission start and was also considered when performing the initial data fitting and normalization. The remainder of the alt-open mode data is fit to a piecewise function and the results are shown in the right panel of Fig. 4.

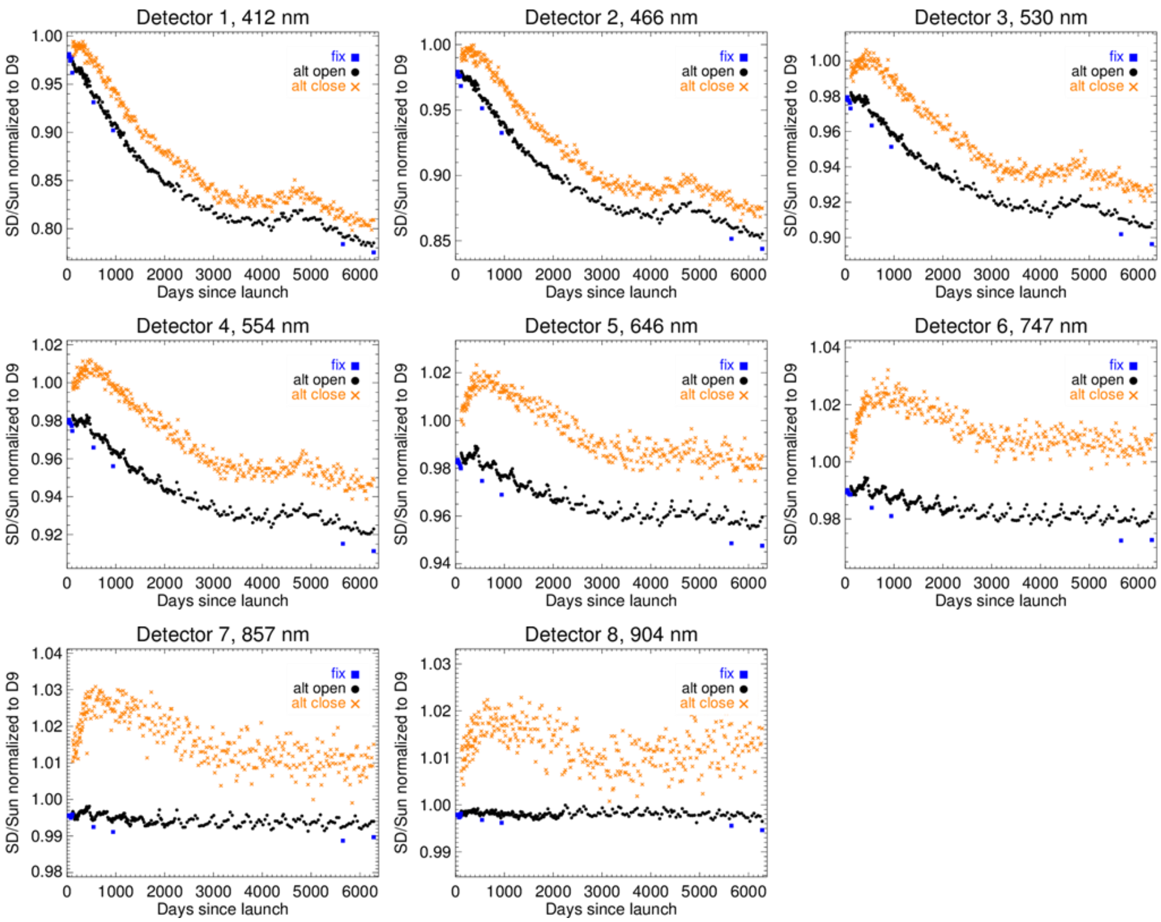

Figure 3. Plots of normalized degradation, $\Delta_{n,i}$, for Aqua MODIS. The different modes are highlighted with different symbols and colors.

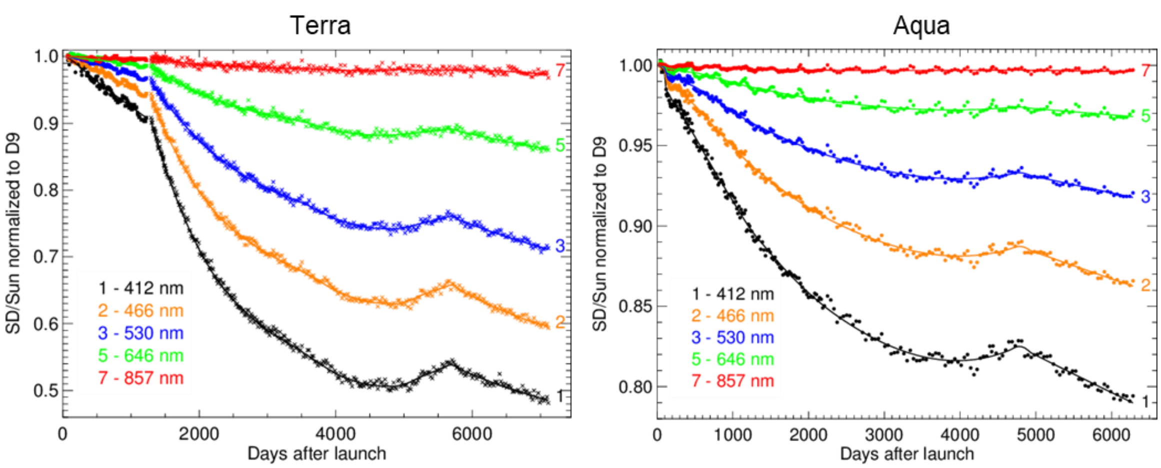

Figure 4. Normalized SD degradation calculated by combining the results of multiple operating modes and normalizing to mission start for select SDSM detectors of Terra (left) and Aqua (right). Symbols are the degradation data points after normalization with the same symbol scheme that was used in Figs 2 and 3. Lines are a piecewise fit to the data in time. Note: the vertical scale is different in the two plots, as Terra has had significantly more degradation than Aqua.

These degradation curves, combined with the separately calculated D9 degradation, determine the total SD degradation used in the calibration of MODIS RSB in C6/C6.1 L1B products. In the following sub-sections, we analyze the differences between the different SDSM calibration modes and assess the potential impact these differences have on the calibration.

4.2 Comparison of alt-open and fix mode results

On October 23, 2017 and July 15, 2019, the Aqua MODIS SDSM was operated in both fix and alt mode configurations on the same day. On both dates, the fix mode calibration was run over two orbits around 01:00 – 04:00 UTC, and the usual alt-close and alt-open calibrations were run around 20:00 – 23:00 UTC. The near-coincidence of the two sets of calibrations gives a unique opportunity to evaluate the differences between the two calibration modes, as the sun-satellite geometry is very similar.

Figure 5 shows the raw SD view signal (DC_{SD}, before background subtraction) for the alt-open and fix mode calibrations on October 23, 2017 for SDSM detectors 1, 5, and 9. A point is shown for every SDSM sample (three per scan) for all scans in the sweet-spot of the calibration. The signal decreases with increasing solar zenith angle due to the changing angle of incidence of the solar vector on the SD surface. The data from the different modes are in good agreement: the average difference between the SD view signals in the two sets of calibrations is within 0.3% for all detectors. Similarly, Fig. 6 shows the sun view signal for all three calibration modes over the calibration sweet spot. In fix mode, the sun view signal is collected every scan, so the large undulations in the signal due to the misalignment of the solar attenuation screen are clearly visible. The difference between the sun view signals for the alt-open vs fix mode calibrations is larger than was seen for the SD view – up to 1.5% for detector 9. There is also clear wavelength dependence, with longer wavelengths having a larger difference between the alt-open and fix mode results. On the other hand, the alt-close mode data is in relatively good agreement with the fix mode data. In the fix mode calibration, the sun view data is taken during the orbit where the SD screen is closed, so it should not be surprising that the alt-close mode data is in better agreement with the fix mode data. The results for the SD and sun view signals for the calibration pair on July 15, 2016 are very similar and are also shown in Figs. 5 and 6.

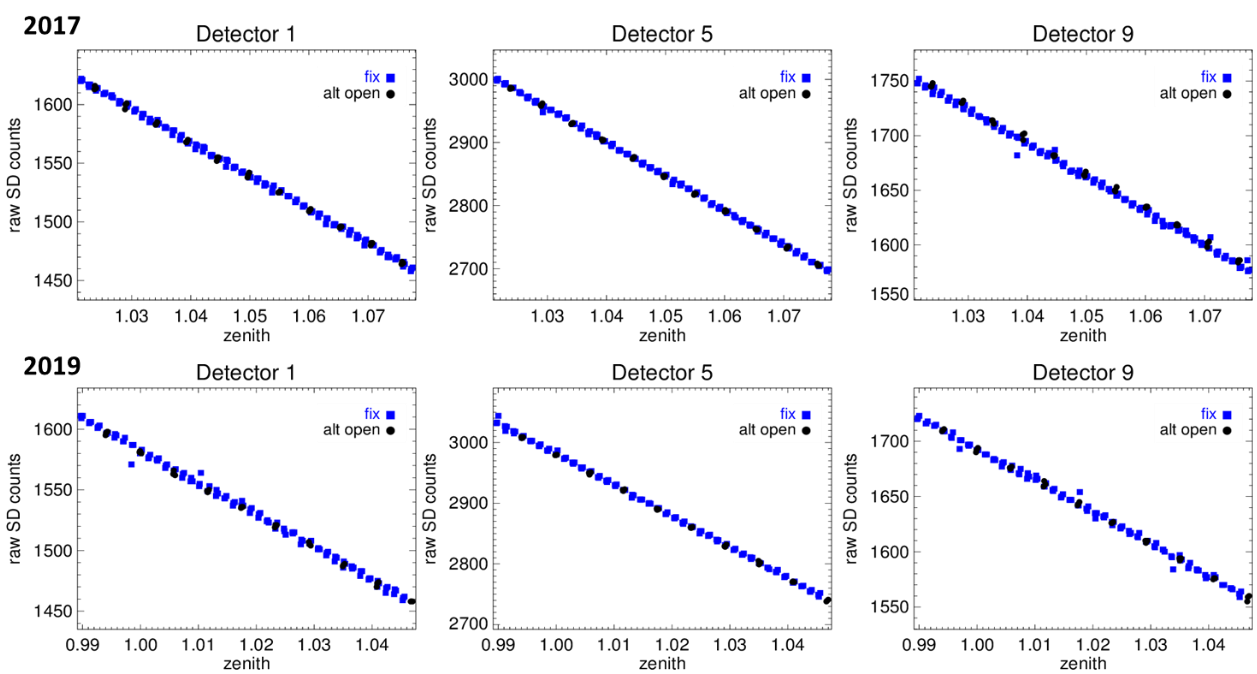

Figure 5. The SD view signal levels for alt-open and fix mode calibrations on October 23, 2017 (top row) and July 15, 2019 (bottom row). Results are shown for detectors 1 (left), 5 (middle), and 9 (right).

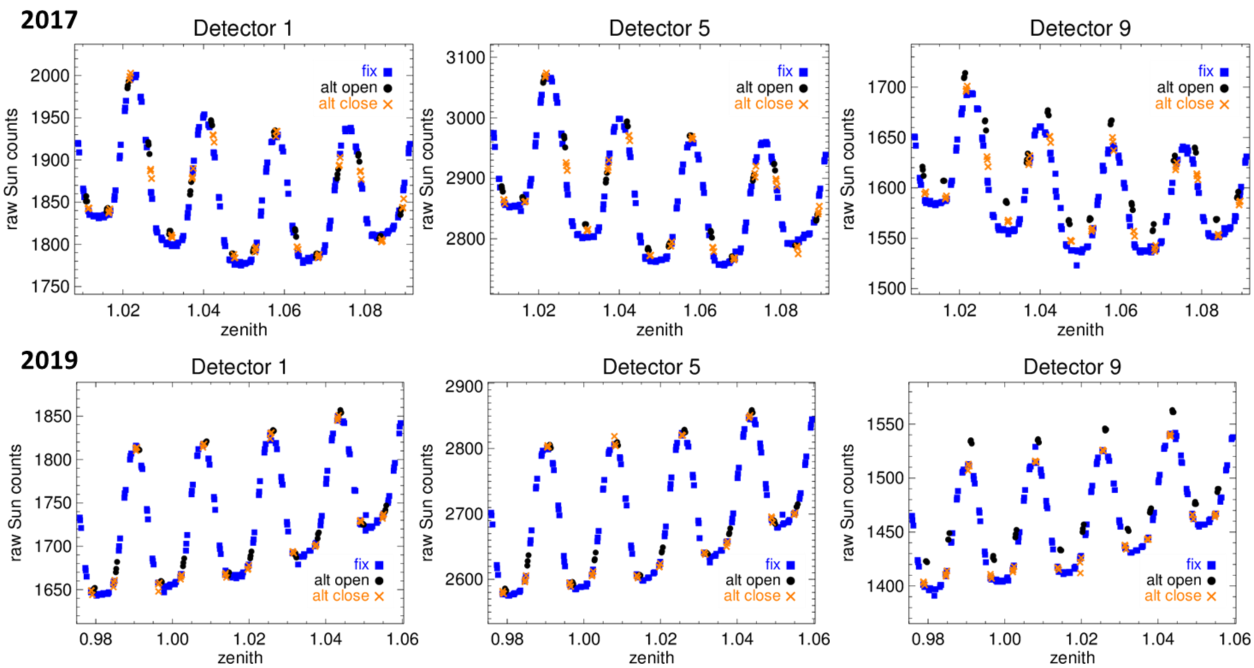

Figure 6. The sun view signal levels for alt-open, alt-close, and fix mode calibrations on October 23, 2017 (top row) and July 15, 2019 (bottom row). Results are shown for detectors 1 (left), 5 (middle), and 9 (right).

The reason for the offset in the sun view signal when the SD screen is open vs closed may be due to any of a number of possible factors, such as differences in sun-satellite geometry, presence of stray light, or differences in instrument temperature. Changes in sun-satellite geometry are known to have a large impact on the sun view data as evidenced by the large undulations in the sun view signal. However, the relatively good agreement between the fix mode and alt-close mode sun view data indicates that the change in solar azimuth angle over the 18-hour separation between the calibrations is not a significant factor. Another possibility is the presence of stray light in the sun view signal when the SDS is open that increases the value of the sun view signal. This is a realistic possibility since the light coming from the SD view into the SDSM system is about ten times larger when the SDS is open compared to when it is closed. If there is any available optical path for this light to reach the SDSM detectors when the mirror is facing the sun view (reflecting off the back of the sun view attenuation screen, for example), then the sun view signal could be contaminated. We note that the dark view signal does not appear to be affected, as the dark view measurements are within 1 DN on average for all configurations on this date. If stray light is the cause, the effect is apparently larger for longer wavelength detectors.

Yet another possibility is a difference in instrument temperature between the three sun view measurements, as the SDSM detector signals are not corrected for instrument temperature. Throughout the Aqua mission, there is a consistent difference in temperature, measured using a telemetry point within the SDSM, of around 1 K between the first orbit (usually with SDS closed) and the second orbit (usually with SDS open) of the calibration. For the usual alt mode calibrations, the temperature difference should not matter since the SD view and sun view data are taken on alternating scans and thus will see smaller temperature variations. For the fix mode, the SD and sun view data come from different orbits and thus the SDSM detectors are at different temperatures. For the sun view data in Fig. 6, the alt-close and fix mode data are both from the SDS closed orbit and the SDSM detectors are at similar temperature, but the alt-open mode data are from the SDS open orbit, which has a slightly different temperature. For reference, the VIIRS SDSM has observed clear changes in the SD and sun view signals as a result of instrument temperature changes during blackbody warm-up cool-down calibrations.[8] It is likely that the MODIS SDSM detectors experience similar temperature dependence, though there is not sufficient data for MODIS to say whether or not the magnitude of the temperature difference can explain the magnitude of observed signal differences in the sun view data in Fig. 6.

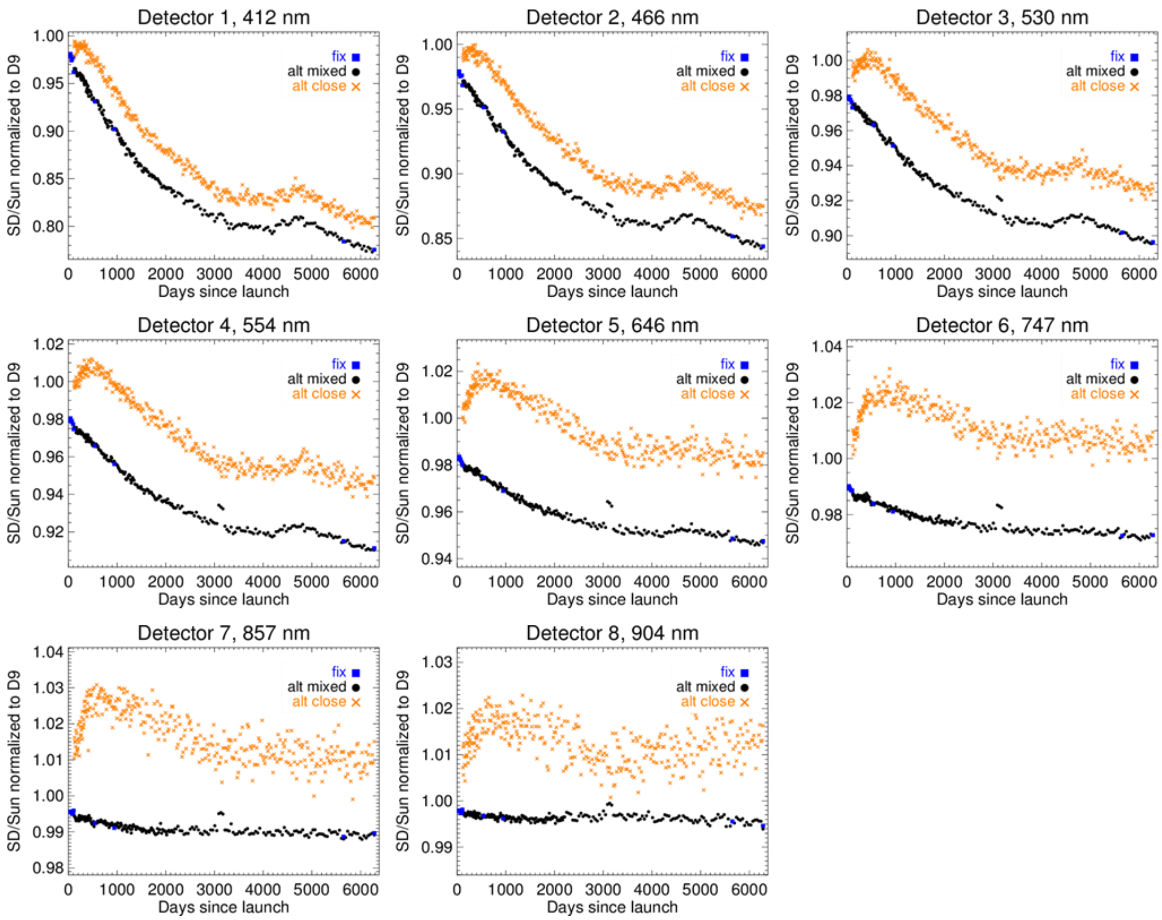

Figure 7. Mixed mode results of normalized degradation, $\Delta_{n,i}$, for Aqua MODIS.

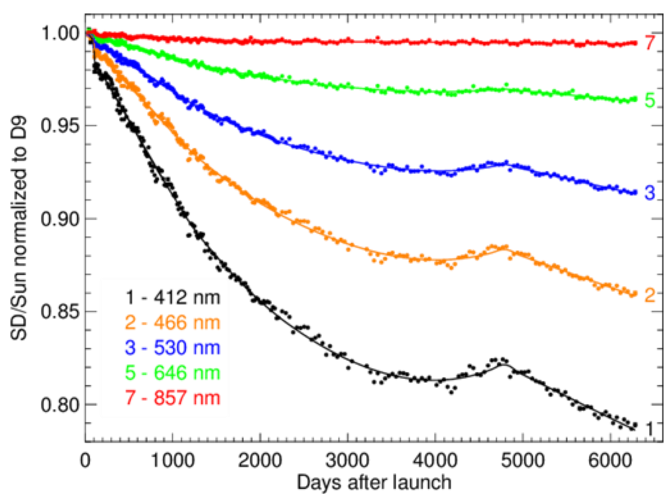

Figure 8. Normalized SD degradation calculated by combining the results of fix mode and alt-mixed mode and normalizing to mission start for select SDSM detectors of Aqua, similar to Fig. 4. Symbols are the degradation data points after normalization. Lines are a piecewise fit to the data in time.

Regardless of the cause, we can use these observations to re-evaluate the Aqua SD degradation data. If the behavior observed for the October 23, 2017 and July 15, 2019 calibrations is consistent throughout the mission, then the observed difference in sun view signal for detector 9 is likely the main reason for the offset between the alt-open and fix mode calibration $\Delta_{n,i}$ results depicted in Fig. 3. Since the SD/sun ratio for all detectors is normalized to that of detector 9, a systematic deviation in the detector 9 data will affect all detectors. To test this, we process all the alt mode calibrations by mixing the data from the SDS open and SDS closed orbits, similar to fix mode. We take the SD view response, dc_{SD} in Eq. 1, as the average signal from the SD view scans during the SDS open orbit as usual, but we take the sun view response, dc_{Sun}, to be the average of the sun view scans during the SDS closed orbit. The resulting values of $\Delta_{n,i}$ for this "alt-mixed" mode calibration approach are shown in Fig. 7 compared to the fix mode and alt-close mode data, similar to Fig. 3.

The alt-mixed mode results show much better agreement with the fix mode calibration and also show elimination of the yearly oscillations in the data. This suggests that the bias in the sun view signals from the alt-open mode data has seasonal variation. There are three calibration dates around day 3200 that are significantly out of trend: 2010/291, 2010/333, and 2011/010. For these three calibrations, the two-orbit calibration sequence was run with SDS open on the first orbit followed by SDS closed on the second orbit, whereas all of the other fix and alt mode calibrations for Aqua were run with SDS closed followed by SDS open. The orbit order may be important because of how the instrument temperature is affected.

As stated before, for the fix (and alt-mixed) mode data, the SD view and sun view data are taken at slightly different temperatures since they are collected during different orbits. Since both the orbit order (SDS closed followed by SDS open) and the temperature bias between the two orbits have been quite consistent over the mission, this bias should not affect the long-term trends after they are normalized to mission beginning. However, for the cases where the two orbits were run in opposite order, the temperature bias is reversed and this could translate to the observed bias in the SD/sun ratio for these three points.

Figure 8 shows a plot of the Aqua SD degradation normalized to mission start and fitted in time for several detectors, similar to Fig. 4, but in this case the fix mode data are combined with the alt-mixed mode data and the three outlier calibrations are removed. The procedure to combine the data from different modes and do the fitting and normalization to mission start is the same as the procedure that was used to generate the fit lines in Fig. 4. Compared to the final fitted results shown in Fig. 4, the curves in Fig. 8 show slightly more degradation in the first 1000 days of the mission, up to 0.5% for D1-D6 and less for D7 and D8, and then maintain this consistent bias for the rest of the mission. Since the alt-mixed mode results have smoother trending between the fix and alt mode data sets in the early mission, the normalization to mission start and fitting of the first few years of data can be calculated more reliably. This would imply that the SD degradation used in the current calibration is underestimated by up to 0.5% for most of the visible and NIR bands. While the oscillations in the original data (Fig. 4, right panel) could also be removed using empirical correction methods as has been demonstrated before,[3,4] those methods use only the alt-open mode data and may not be able to derive the early mission trends, including the fix mode data, as reliably as the approach presented here.

A similar analysis comparing the fix and alt-open mode results for Terra MODIS is more challenging. The alt-open mode and fix mode calibrations for Terra were taken in separate time intervals with no overlap, so it is difficult to compare relative trends in time. Additionally, the calibrations for Terra MODIS in the first few years of the mission were not run as consistently as they were for Aqua; the calibration orbit order (open-then-close vs close-then-open) was not done consistently and the calibrations were not always run in consecutive orbits, leading to larger uncertainties from the influence of different sun-satellite geometry or instrument temperature differences. Note that the variance of the alt-open and fix mode time trends of $\Delta_{n,i}$ in the early mission for Terra MODIS is clearly higher than for Aqua MODIS (compare for example the D7 plot in Fig. 2 vs Fig. 7).

4.3 Comparison of alt-open and alt-close results

Examining the plots in Figs. 2, 3, and 7, it is clear that there is a significant difference between the alt-open and alt-close mode time trends of the normalized degradation for all detectors. For all detectors across both instruments, there is a similar pattern where the alt-close data increases relative to the alt-open data over the first 1000 days after launch, decreases until about day 3000, and then trends steadily with the alt-open data after day 3000 (see D7 of Fig. 7 for example). The increase and subsequent decrease in the alt-close results relative to the alt-open results over the first 3000 days has a magnitude of approximately 2%, varying slightly among detectors. The common trend in the normalized degradation among all detectors 1-8 suggests that there may be a systematic problem with the D9 data that is being transferred to the other detectors by the D9 normalization.

The cause for the difference in the open vs close results is not known at this time. One possibility could be differences in the SDSM detector response at different signal levels. The SDSM detector signal level for the SD view data with SDS open is at a similar magnitude (see Figs. 5 and 6) to the sun view data. But the SD view signal level with SDS closed is much lower, so non-linearities in the SDSM detector response could introduce a bias into the SD/sun ratios. Once again, if the bias is consistent on orbit, then it would not pose a problem for the calibration since the data trends are always normalized to the start of mission. However, if a bias exists that is changing in time, it would become a problem. The SDSM detectors are known to have significant gain degradation on-orbit. The gain degradation is generally larger for the NIR wavelengths, with D9 being affected the most. If the gain degradation has a signal level dependence, i.e. if the gain degradation is different for high incident radiance compared to low incident radiance, then it could potentially explain the feature seen in the alt-close mode data in the early mission.

For Aqua MODIS, this discussion has no impact on the RSB calibration, since the SDSM alt-close mode data is not used. For Terra MODIS, however, the alt-close mode data is used exclusively after the SD door anomaly in 2003, so a bias in the alt-close mode time trend will directly impact the RSB calibration. We can use the Aqua data as a reference to estimate the potential magnitude of the bias. As a test, we derive mission-long SD degradation curves using the fix mode and alt-mixed mode data for the first 1300 days of the mission and the alt-close mode data only for the remainder of the mission. The alt-close mode data is scaled at the time of the switch, similar to the explanation of our fitting of the Terra MODIS data in Sec. 4.1, as depicted in the left panel of Fig. 4. The fitted SD degradation calculated in this way overestimates the SD degradation (i.e. smaller values of $\Delta_{n,i}$) compared to the fitting of the mixed mode data shown in Fig. 8. The magnitude of the overestimation grows from day 1300 to day 3500 up to maximum differences between 0.9% and 1.4% depending on the detector. From day 3500 to the end of mission the overestimation bias remains fairly stable. Assuming the difference between the alt-close and alt-open mode data for Terra MODIS would follow a similar trend as Aqua, the current SD degradation (Fig. 4, left panel) is likely overestimating the degradation by as much as 1.5%. While this is clearly a concern, further investigation will be required to understand and appropriately model the open-close differences before any potential correction to the Terra SD degradation can be considered.

5. CONCLUSIONS

We have reviewed the operation of the Terra and Aqua MODIS SDSM over the missions and showed the results of the SD degradation as measured with all of the available SDSM operational configurations. We have used the results of two recent sets of SDSM calibrations for Aqua MODIS taken on October 23, 2017 and July 15, 2019 to improve our understanding of the differences between the alternating and fixed operating modes of the SDSM. We re-calculated the SD degradation for Aqua using a pseudo-fixed mode, or mixed mode, which combines the alternating mode SD view data from the SDS open orbit with the alternating mode sun view data from the SDS closed orbit. The resulting degradation trend agrees much better with the fixed mode results and has lower variance and no seasonal oscillations compared to the trend derived using the alternating mode SDS open data only. This mixed mode method allows for more accurate fitting of the data, especially in the early mission, and will be considered for inclusion in a future version of calibrated Aqua MODIS L1B products. We also discussed the differences between the SDSM data taken with SDS closed compared to SDS open. We identified a possible bias of up to 1.5% in the mid-mission time trends of the Terra MODIS SD degradation, however more investigation of this data is needed before any improvement to the current calibration can be proposed.

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