Improvement of MODIS RSB Calibration by Minimizing the Earthshine Impact on Solar Diffuser Observations

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ABSTRACT

The MODerate Resolution Imaging Spectroraiometer (MODIS) reflective solar bands (RSB) are calibrated on-orbit using solar illuminations reflected from its onboard solar diffuser (SD) plate. The specified calibration uncertainty requirements for MODIS RSB are ±2% in reflectance and ±5% in radiance at their typical top of atmosphere (TOA) radiances. The onboard SD bi-directional reflectance factor (BRF) was characterized pre-launch by the instrument vendor using reference samples traceable to NIST reflectance standard. The SD on-orbit degradation is monitored using a solar diffuser stability monitor (SDSM). One of contributors to the RSB calibration uncertainty is the earthshine (ES) illumination on the SD plate during SD calibration. This effect was estimated pre-launch by the instrument vendor to be of 0.5% for all RSB bands. Analyses of on-orbit observations show that some of the SD calibration data sets have indeed been contaminated due to extra ES illumination and the degree of ES impact on the SD calibration is spectrally dependent and varies with geo-location and atmospheric conditions (ground surface type and cloudiness). This paper illustrates the observed ES impacts on the MODIS RSB calibration quality and compare them with the effects derived from an ES model based on the viewing geometry of MODIS SD aperture door and likelihood atmospheric conditions. It also describes an approach developed to minimize the ES impact on MODIS RSB calibration.

Keywords: Terra, Aqua, MODIS, sensor, calibration, solar diffuser, earthshine, uncertainty

I. INTRODUCTION

Terra and Aqua MODIS, launched on December 18, 1999 and May 4, 2000 respectively, have made major contributions to NASA's Earth Observing System (EOS) missions. One of the primary design objectives of MODIS instruments is to collect continuous multi-year global data sets for the studies of both short- and long-term changes in of the Earth system, including its land, oceans, and atmosphere. MODIS collects data using 36 discrete spectral bands that consists of 490 detetors located on four focal plane assemblies (FPAs). There are 20 reflective solar bands (RSB) with wavelengths from 0.41 to 2.2 μm and 16 thermal emissive bands (TEB) with wavelengths from 3.7 to 14.4 μm. The nadir spatial resolutions are 0.25km for bands 1 and 2, 0.5km for bands 3-7, and 1.0km for the remaining 29 bands. In order to maintain sensor's on-orbit calibration and date product quality, MODIS was built with a complete set of on-board calibrators that include a blackbody (BB), a solar diffuser (SD), a solar diffuser stability monitor (SDSM), a spectro-radiometric calibration assembly (SRCA), and a space view (SV) port. Since launch Terra and Aqua MODIS have been regularly performing comprehensive spatial, spectral, and radiometric calibration and characterization activities [1-5].

For MODIS RSB the specified calibration uncertainty requirements are ±2% in reflectance and ±5% in radiance at their typical top of atmosphere (TOA) radiances. MODIS RSB Level 1B (L1B) radiometric calibration uses a simple linear algorithm that relies on the calibration coefficients derived from sensor's responses to the sunlight

Earth Observing Systems XI, edited by James J. Butler, Jack Xiong,
Proc. of SPIE Vol. 6296, 629608, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.679081

diffusely reflected from the SD panel of known bi-directional reflectance factor (BRF). The SD on-orbit degradation is tracked by the SDSM on a bi-weekly basis. Obviously, MODIS RSB calibration uncertainty strongly depends on the quality of SD BRF characterization. It has been known that some of the SD calibration data could be contaminated due to small, but non-negligible, earthshine (ES) illuminations on the SD plate. This ES impact on the RSB calibration uncertainty was estimated pre-launch by the instrument vendor to be of 0.5% and included as a contributor to the SD calibration uncertainty, equally applied to all RSB bands for both Terra and Aqua MODIS [6]. Analyses of on-orbit observations clearly show that the degree of contamination due to extra ES illumination or its impact on the SD calibration uncertainty is spectrally dependent. In addition it varies with geo-locations and atmospheric conditions, such as ground surface type and cloudiness, and differs between Terra and Aqua instruments. In general these observations have also been consistent with simulated effects derived from an ES model built based on the viewing geometry of MODIS SD aperture door and likelihood atmospheric conditions during SD calibration [7].

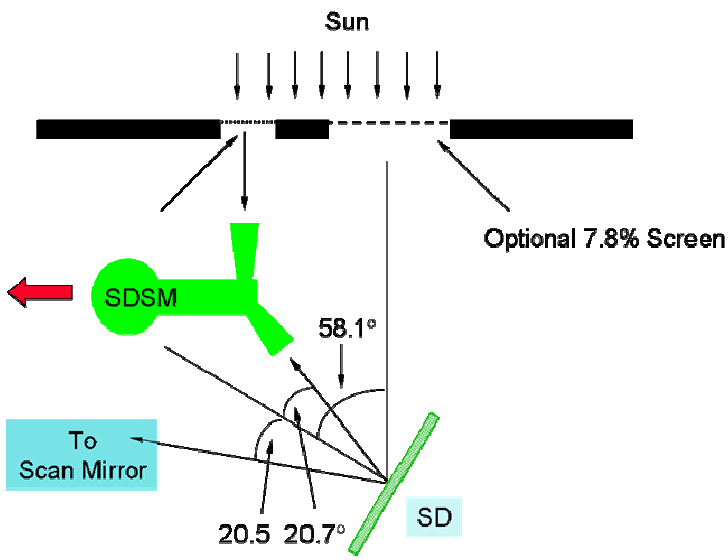


Figure 1, MODIS RSB calibration schematic drawing

In this paper we first provide a short description of MODIS RSB calibration algorithm and then illustrate the observed ES effects on the MODIS RSB calibration data sets and compare them with the modeling results. In general, MODIS longer wavelength reflective solar bands have more earthshine contamination than the shorter wavelength bands albeit that the shorter wavelengths may have more atmospheric scattering contamination. We also describe an approach developed to minimize the ES impact on MODIS RSB calibration and use examples to demonstrate the effectiveness of this approach.

II. MODIS RSB CALIBRATION

MODIS RSB calibration generates the on-orbit calibration coefficients, m_1, and update them in the Level 1B (L1B) algorithm to retrieve the earth scene reflectance factor product, $\rho_{EV}\cos(\theta_{EV})$, which is given by the following expression [2,3],

$$\rho_{EV}\cos(\theta_{EV}) = m_1 \cdot dn^*_{EV} \cdot d^2_{Earth-Sun(EV)} \qquad (1)$$

where dn^*_{EV} is the sensor's earth view (EV) response (digital number) with corrections for the instrument background recorded via sensor's response to the space view (SV), instrument temperature effect, and the sensor's response versus scan angle (RVS). For the short-wave infrared (SWIR) bands, an optical leak correction algorithm is also applied. $d^2_{Earth-Sun(EV)}$ is the Earth-Sun distance in units of AU at the time of EV observations.

The on-orbit MODIS RSB calibration is performed using the SD while its degradation is tracked by the SDSM. Figure 1 shows the diagram of the MODIS SD/SDSM combined calibration system. The SDSM is operated during its regularly scheduled SD calibration events. The following equation shows how to derive the RSB calibration scaling coefficient m_1 from on-board SD calibration data [2.3],

$$m_1(B,D,S,M) = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{dn^*_{SD} \cdot d^2_{Earth-Sun(SD)}} \Delta_{SD} \cdot \Gamma_{SDS} \qquad (2)$$

where B, D, S, and M denote band, detector, sub-frame (for the sub-kilometer resolution bands), and mirror side respectively, $\rho_{SD}(\theta,\varphi)$ is SD bidirectional reflectance factor (BRF) characterized pre-launch at sensor vendor (Raytheon Santa Barbara Remote Sensing) using reference materials traceable to NIST (National Institute of Standard and Technology) reflectance standard, $d^2_{Earth-Sun(SD)}$ is the Earth-Sun distance during SD calibration, dn^*_{SD} is the digital number of the SD response with the same corrections applied as the earth view response in Eqn. (1), Δ_{SD} is the SD degradation factor obtained from the SDSM at the time of each SD calibration, and Γ_{SDS} is SD screen vignetting function. The derivation of the SD degradation and screen Vignetting function can be found in [8, 9].

A complete MODIS RSB calibration should include measurements taken in two consecutive orbits. In one calibration event, bands for land and atmospheric applications (bands 1-7 and 17-26) are calibrated using SD observations without the SD screen in place. Another calibration with incident sunlight intensity reduced by the SD screen is performed for the ocean color bands 8-16 that normally have higher gains. For each calibration event, MODIS opens its SD door when the satellite crosses from nighttime to daytime orbit. During a short period of time MODIS SD is fully illuminated by the incident sunlight. RSB calibration coefficients are computed by averaging results of 20 scans (for each mirror side) taken within the so-called "sweet spot range" (MODIS elevation angle from 12.8° to 14.2°).

EARTSHINE IMPACTS ON RSB CALIBRATION

There are two possible ports in the MODIS that may introduce earthshine contaminations into the process of RSB calibration. The first one is the NADIR door since it remains open all the time even during the regular RSB calibration. The second one is the SD view port. Sunlight reflected from the earth can also illuminate the SD through the SD view port if the incident angle and the earth terrain satisfy certain view conditions. In this paper, we are only concerned the contaminations within the sweet spot range during the regular SD calibration process since the contaminations outside of the sweet spot range have no impacts on calibration quality.

To investigate if sweet spot is contaminated by earthshine from the NADIR door, Figure 2 shows a typical plot of Terra MODIS calibration dn (band 2) vs. elevation angle when its SD door open (a) and closed (b). Dashed lines in the figure indicate the sweet spot range and daytime start-point. Sweet spot range is, as indicated in the figure, far away from the day mode. This choice of sweet spot range greatly reduces the impacts on the RSB calibration of earthshine contaminations (i.e. scattering light) from the NADIR door. As shown in figure 2 (b), the SD door is closed and MODIS sensors actually record the scattering light from the NADIR door if any. The plot clearly indicates that the contamination caused by the earthshine from NADIR on MODIS RSB calibration within the sweet spot range is extremely small and can be ignored.

It is not easy to separate earthshine contamination through the SD view port from regular calibration sunlight within the sweet spot range. Figure 3 shows an example of earthshine contamination on Terra RSB calibrations by plotting one-year band averaged m1 trending curve for band 2, 3, 9, and 16 taken from year 2001 day 199 to year 2002 day

198. For comparison purposes, m1s are normalized to the first point of each individual band itself. The reason to choose these bands is that for each measurement, both band 2 and 3 were calibrated using the calibration data with no SD screen while band 9 and 16 were calibrated using the data sets with the SD screen closed. Furthermore, the corresponding central wavelength for band 2 and 16 (860 μm) are almost the same and much longer than that of band 3 and 9 (450 μm), which have less earthshine impacts as described in [7] and are used as references in our analysis for band 2 and 16 respectively. In figure 3(a), it is noticed that band 2 and band 16 have one outlier point (marked with larger symbol) by 0.4% which does not appear for bands 3 and 9 at the same time as shown in figure 3(b). This indicates that this contamination is strongly dependent on the wavelength. A further investigation can be taken by looking into the digital response of signals from the SD view port along track direction. In figure 4, dns (corrected by cosine factor) of the calibration sweet spot range are plotted against scan number for band 2 and 16 using the calibration data in the same time range of figure 3. The dns for the outlier shown in Figure 3 are indicated with diamonds in Figure 4. The plot shows dn increases along track direction for these two measurements, especially in the last part of the sweet spot range. Both band 2 and band 16 show a similar pattern. For those regular measurements not contaminated by earthshine in figure 3, no significant increases along track direction are observed.

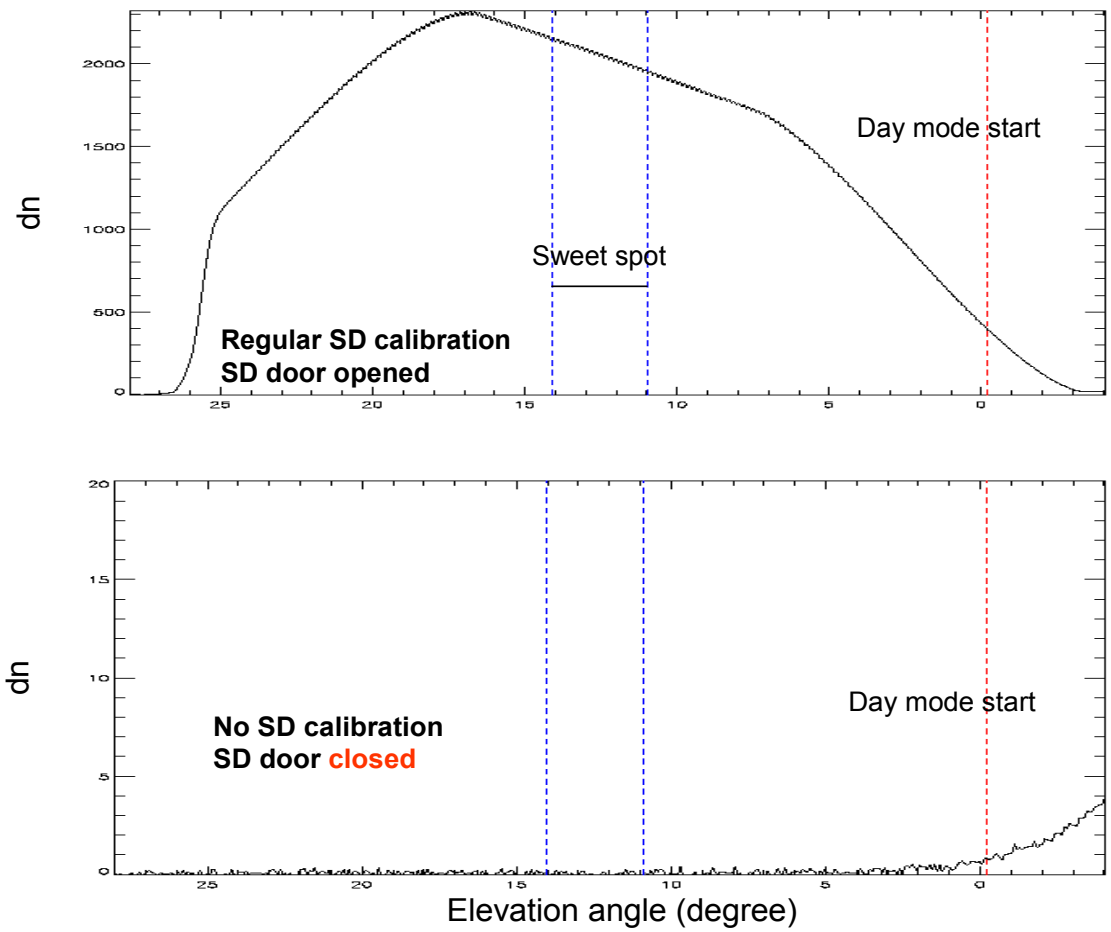


Figure 2, Terra MODIS SD calibration dn vs elevation angle

The results from figure 4 suggest a new scheme can be applied to calibrate MODIS RSB bands with earthshine impacts minimized. A simple model also shows that the earthshine contamination is relatively small at the early stage of RSB calibration due to the small reflection area. To do this, the sweet spot range used in RSB calibration is moved 20 scans (10 scans for each mirror side) ahead to avoid increasing earthshine impacts along the track

direction. RSB calibration coefficients in figure 3 (a) were reprocessed using the new scheme and re-plotted in the figure 3(c). The results show noticeable improvements to those m1s contaminated by earthshine and no impacts for calibration coefficients not affected by the earthshine.

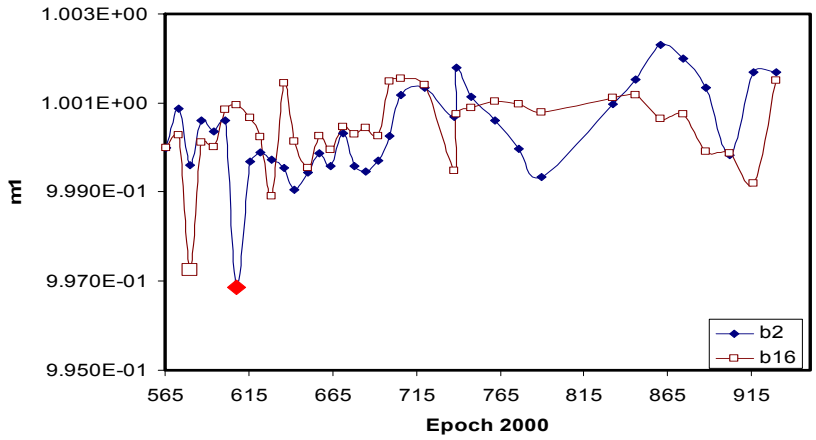
RESULTS AND DISCUSSION

Following a SD door operational anomaly in May 2003, Terra MODIS SD door has remained open to avoid further malfunction since July 2nd 2003. Nearly three years of continuous orbit-by-orbit calibration data have been accumulated for Terra MODIS since then. It has provided us an opportunity of using these measurements to test statistically our new calibration scheme. Figure 5 shows the percentage deviations of m1s from the mean value of the measurement each day. The maximum upper deviations shown in the figure is around 0.2%. If we assume symmetric deviations resulted from regular measurement errors, it is most likely that deviations below –0.2% are caused by the earthshine contamination. It needs to be pointed out that most of these contaminations occurred in summer time, probably due to the non-frozen ocean surface. To clearly illustrate the improvements by the new calibration scheme, for those measurements whose deviations below –0.2%, m1 residues calculated by both the old method and new method were plotted together in figure 5(b). It is clearly shown that the earthshine contaminations in RSB calibration were reduced for most points.

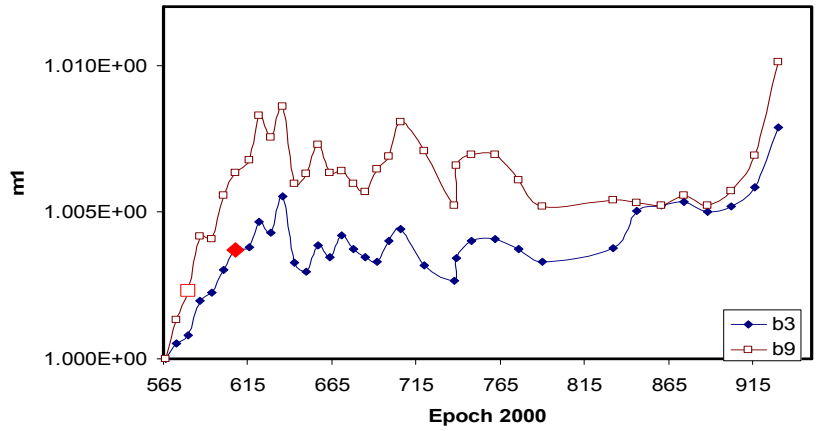
The new scheme was also applied to Aqua MODIS RSB calibration. No significant changes have been observed. One reason for this is that there are not enough measurements available to validate our new scheme. Another reason may be that the earthshine impacts on Aqua RSB calibration itself are relatively smaller compared to Terra MODIS. Figure 6 shows the geo-locations of RSB calibration spots for both Terra and Aqua MODIS. The RSB calibrations have been performed when Terra satellite flies over the North Pole and Aqua over the South Pole. The arrows in the figure show the geo-locations of the start point of the sweet spot to the end point of the sweet spot. Black arrows indicate measurements during summer and autumn, while gray arrows represent spring and winter measurements. The figure shows that Terra MODIS is over the ocean for most of calibrations during summer and autumn, during which time it is unlikely to be ice-covered. This increases the chances for Terra MODIS RSB calibration to be contaminated by earthshine from ocean surface as modeled in [7]. For Aqua, MODIS faces lands (Antarctica) most of time during summer, which indicates fewer chances to be contaminated by earthshine. It gives us hints that in order to minimize earthshine contamination the calibration spot should be carefully selected to avoid ocean surfaces.

SUMMARY

In conclusion, we investigated the impacts of Earthshine on Terra and Aqua MODIS RSB SD calibration. And the impacts on Terra MODIS and Aqua MODIS are compared. Based on our results, a new solution is proposed to minimize this undesired impact. The results indicate that a large improvement in minimizing earthshine impacts could be achieved by the new calibration scheme.



(a)



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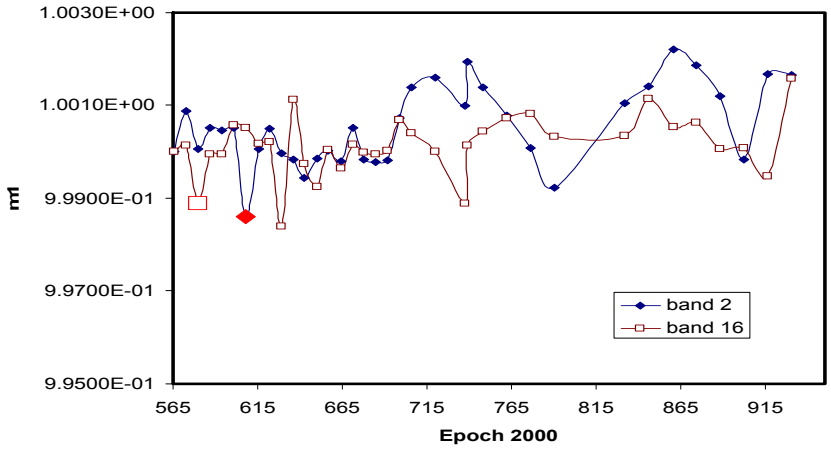
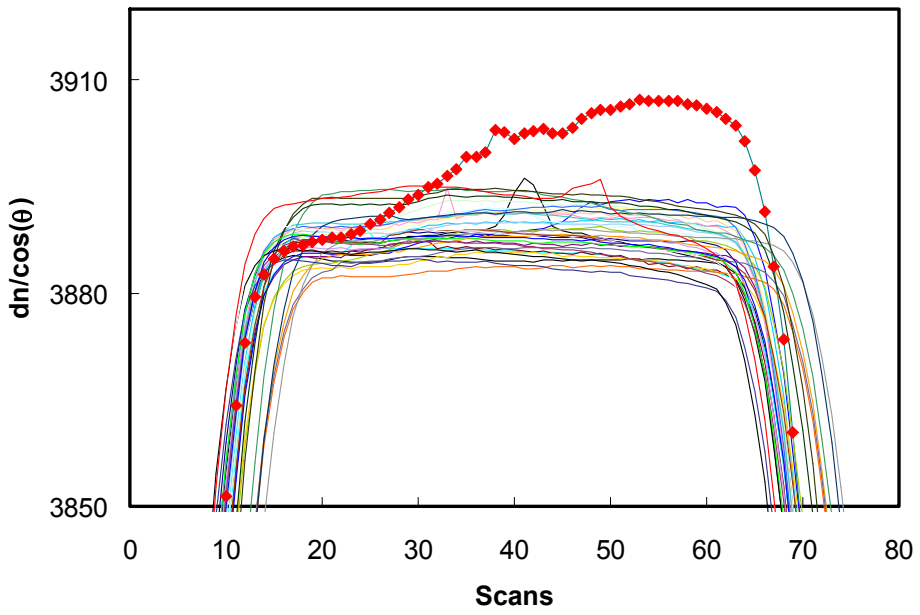
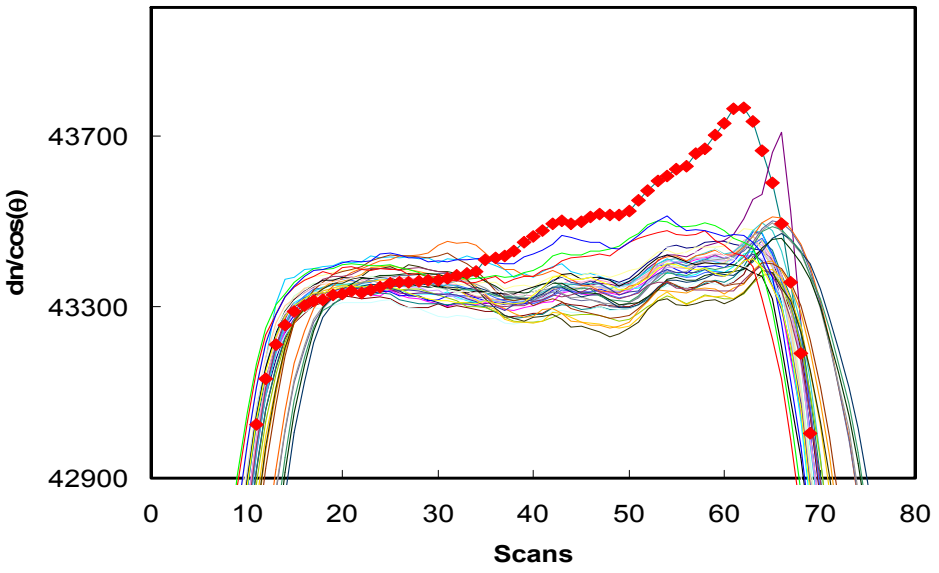


(c)

Figure 3, Terra MODIS band averaged m1 trending (normalized to the first point) for (a) band 2 and band 16, (b) band 3 and band 9, (c) band 2 and ban 16 calibrated by the new approach

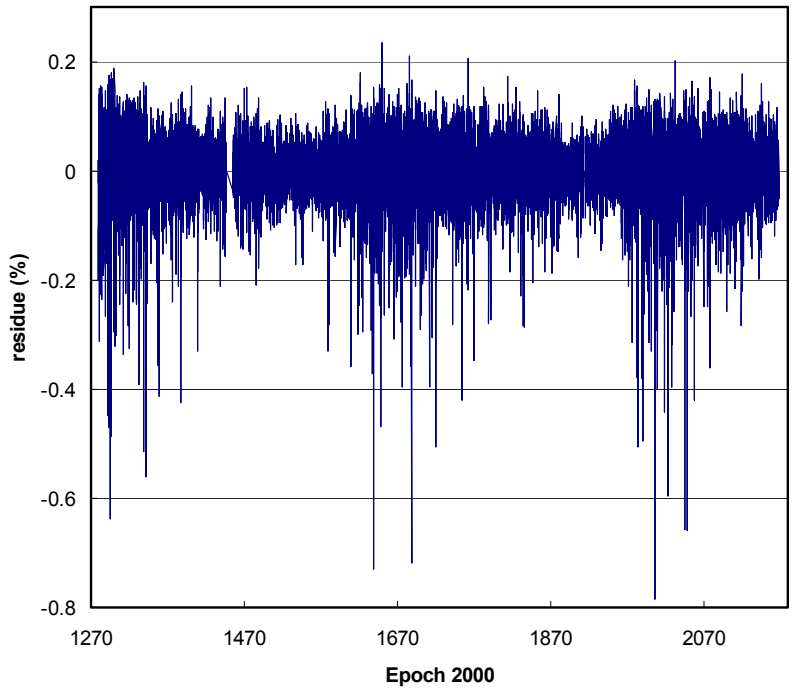


(a)



(b)

Figure 4, Terra MODIS dn (mirror side 1) corrected by cos factor vs. scans for (a) band 2 and (b) band 16



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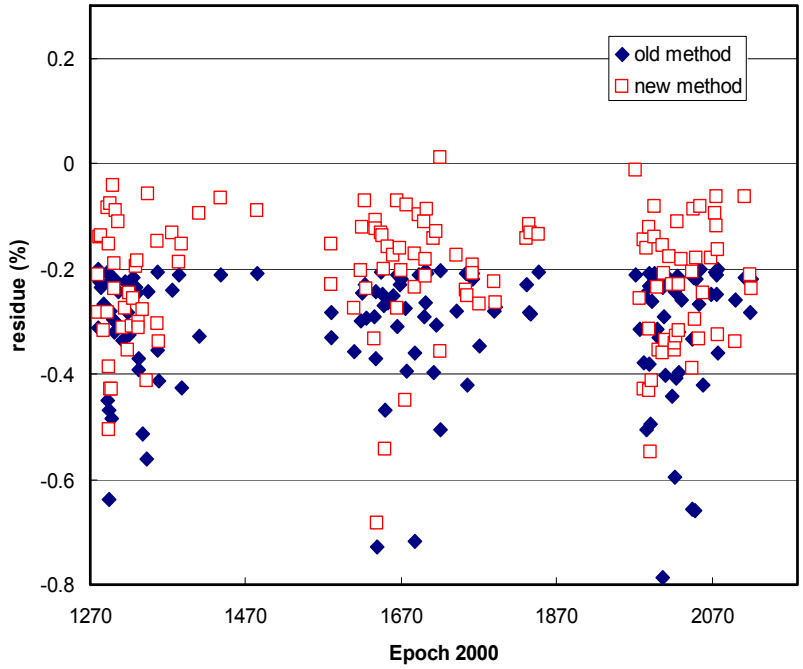
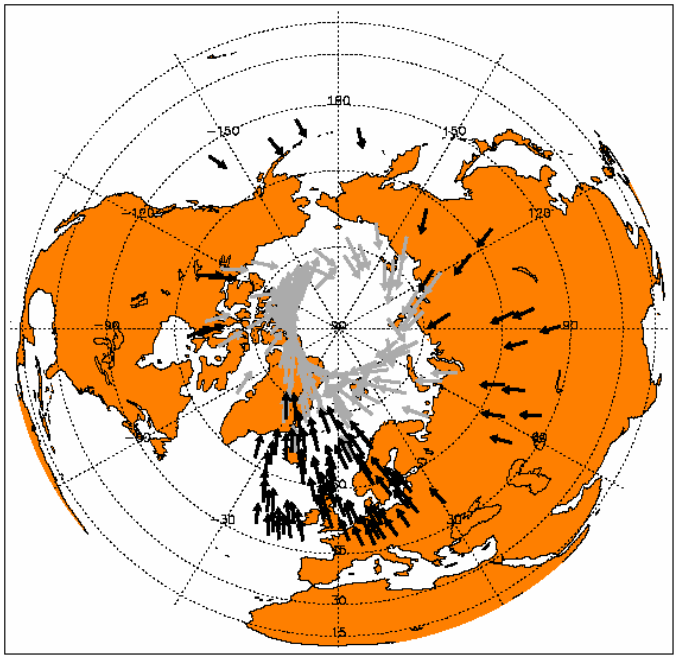
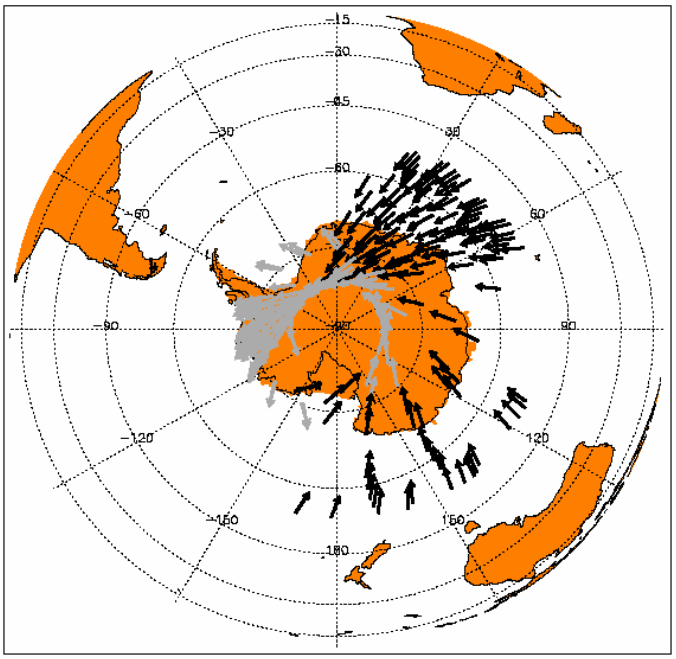


(b)

Figure 5, (a) Terra orbit m1 residues. (b) The improvement of new approach on the residues less then –0.3%



(a)



(b)

Figure 6, (a) Terra RSB calibration spots on North Pole, (b) Aqua RSB calibration spots on South Pole.

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