

Orbital Path and Spacecraft Attitude Correction for the MODIS Lunar Spatial Characterization

Truman Wilson, Amit Angal, and Xiaoxiong Xiong

Abstract—For the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua platforms, regularly scheduled lunar observations using spacecraft roll maneuvers have been used extensively for sensor characterization. While the primary purpose of these observations is for radiometric calibration of the reflective solar bands, they have also been leveraged for a number of other sensor performance assessments, such as the band-to-band (BBR) and detector-to-detector (DDR) spatial registration. The spatial registration calculations are complicated by the fact that the Moon does not move in a straight path across the sensor field-of-view (FOV). This path is determined by the relative orbital motion between the spacecraft and the Moon and the instrument attitude error that results from the roll maneuver. In this work, we develop a correction for the MODIS lunar spatial characterization measurements by calculating the predicted path of the Moon across the sensor FOV using spacecraft and lunar ephemeris data to model the relative orbital motion between the spacecraft and the Moon along with spacecraft attitude error data acquired during the roll maneuver. The difference between measured and predicted positions of the Moon in the MODIS FOV can be used to calculate the BBR and DDR results. Since the predicted path across the FOV will be the same for each band, the BBR results will be minimally affected. However, we will show that the along-scan spread in the DDR can be significantly reduced, which results in a much greater consistency throughout the full mission for both Aqua and Terra MODIS.

Index Terms—MODIS, BBR, DDR, lunar calibration, Aqua, Terra.

I. INTRODUCTION

THE Moderate Resolution Imaging Spectroradiometer (MODIS) has been in operation on board the Aqua and Terra platforms for over 17 and 19 years respectively [1]. MODIS is a whisk-broom, scanning radiometer with 36 spectral bands that range in wavelength from 0.4 to 14.2 μm . Each spectral band consists of a linear array of detectors at 3 nadir spatial resolutions: 250 m for bands 1 and 2 (40 detectors/band), 500 m for bands 3 – 7 (20 detectors/band), and 1 km for bands 8 – 36 (10 detectors/band). The bands are separated by wavelength onto 4 focal plane assemblies (FPA). On the FPAs, each band's detectors are aligned perpendicular to the direction of the image scan and parallel to the apparent direction of spacecraft motion, as seen in Figure 1. To create the MODIS images, a double-sided rotating scan mirror directs light towards the FPA and moves the image across each band

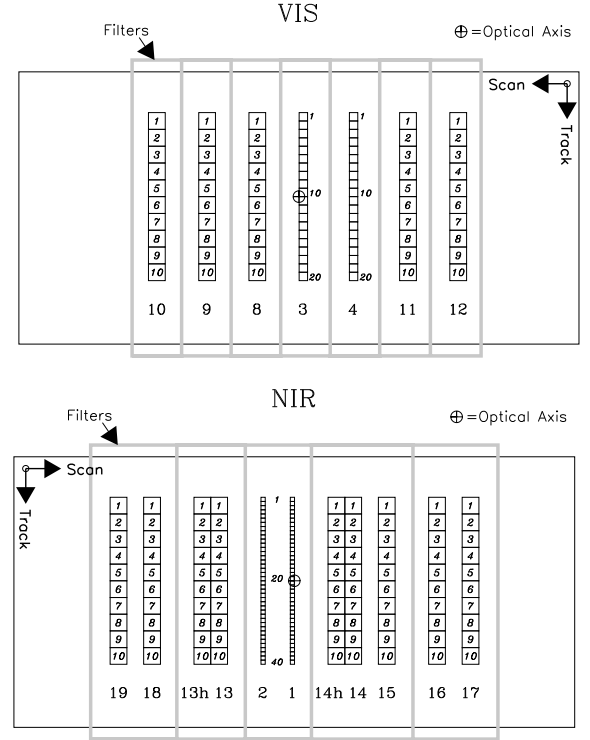


Fig. 1. A diagram of the band/detector layout on the visible (VIS) and near-infrared (NIR) FPAs.

in the scan direction. The images are constructed through timed sampling of the detectors as the scan mirror rotates, with each sample producing one column of pixels in the image. Each image swath is 10 km wide in the track direction at nadir and 2330 km wide in the scan direction. The rate of the scan mirror rotation is such that the satellite track moves on the Earth's surface by 10 km per scan, producing continuous scan-by-scan imagery at nadir.

The MODIS bands are calibrated on orbit using a set of on-board calibrators (OBC), which include a solar diffuser (SD) and its associated SD stability monitor (SDSM) for the reflective solar bands (RSB), a blackbody (BB) for the thermal emissive bands (TEB), and a spectroradiometric calibration assembly (SRCA) for spatial, spectral, and radiometric characterization of the bands [2]–[4]. For the RSB, the Moon provides an independent calibration reference at a different angle-of-incidence on the scan mirror than the SD [5]. This provides a method for the derivation of the scan mirror response-versus-scan angle (RVS), which is necessary for an

T. Wilson and A. Angal are with Science Systems and Applications, Inc., Lanham, MD 20706 USA (e-mail: truman.wilson@ssaiahq.com; amit.angal@ssaiahq.com).

X. Xiong is with the Science and Exploration Directorate, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: xiaoxiong.xiong-1@nasa.gov).

accurate characterization of the instrument's gain on-orbit.

For the MODIS lunar calibration, the phase angle of the observations is restricted to a narrow range throughout the mission in order to reduce the residual variations associated with a changing phase angle. These phase angles are from -56° to -55° for Aqua (waxing phase) and from 55° to 56° for Terra (waning phase), since the instruments are in opposite orbits [5]. Geometric correction factors from the USGS ROLO model are also used in order to account for the precise phase of the Moon, lunar libration angles, and the spectral response function for each MODIS band [6]. Alignment of the orbital position of the Moon and the MODIS space-view port (SV) at the desired phase angle is rare during normal operation, and therefore a spacecraft roll maneuver is used in order to bring the Moon into view at the selected time [7]. For MODIS, these instrument roll maneuvers can range between -20° and 0° during the nighttime portion of the orbit. A negative roll angle moves the SV further away from the Earth limb. As of the beginning of 2019, there have been 170 and 186 scheduled lunar observations for Aqua and Terra MODIS respectively.

While the primary use for lunar observations has been for radiometric calibration, they have also been leveraged for a number of other sensor performance characterizations. For MODIS, these observations have been used extensively throughout the mission for the characterization of electronic crosstalk between the bands [8], [9]. An implementation of this correction can be found for bands 27 – 30 in Terra MODIS Collection 6.1 [10]. Lunar observations have also been used to characterize and implement a correction to an optical leak in bands 32 – 36 in Terra MODIS since early in the mission [11]. Additionally, the Moon can be used to measure the modulation transfer function of the instrument optics owing to its sharp contrast with the dark background of space [12], [13]. As we will show in this work, lunar observations can be used for sensor spatial characterization assessments, which include the band-to-band and detector-to-detector registration (BBR/DDR) [13]–[16].

For MODIS science products, accurate geolocation of the imagery of each band is critical. Since the bands are spatially separated on the different FPAs as shown in Figure 1, the time in which each band views the same target differs according to their relative locations. While the nominal spatial offsets are known based on the instrument design specifications, the SRCA measurements have shown offsets to the nominal positions that can change over time [17]. In particular, the BBR and DDR for Aqua MODIS shows a shift between the cold and warm FPAs that is a result of pre-launch vibration testing of the instrument. While the BBR for the bands on the cold FPAs in Aqua MODIS are outside of the instrument specifications, they have been stable on orbit.

For MODIS, lunar observations have been used as an additional method for measuring the BBR and DDR of the MODIS bands [15], [16]. During the observations, the Moon is viewed by each MODIS detector over multiple scans, allowing us to construct lunar images for each detector individually. The Moon's position in each of the detector images is compared in order to produce the BBR and DDR results. To improve the accuracy of the BBR and DDR measurements, it is important

to account for the apparent motion of the Moon across the sensor field-of-view (FOV) during the observation. The two major factors that influence this apparent motion are the relative orbital motion of the spacecraft and the Moon, and the instrument attitude error caused by the spacecraft maneuver. In Wang *et. al.* (2015) [13], the relative orbital motion was computed for Moon-based DDR measurements for the Suomi-NPP VIIRS instrument using a set of analytical equations based on the orbital parameters. However, this method did not account for instrument attitude errors associated with spacecraft maneuvers.

In recent years, the instrument attitude effect on the MODIS DDR has been of particular importance for Aqua MODIS. During the lunar roll maneuvers, the instrument pointing settles to the desired position over the course of several minutes, as seen in Figure 2. Starting in 2018, the total dwell time during the maneuvers for Aqua was reduced from 6 minutes and 46 seconds to 3 minutes and 46 seconds, with the observation taking place in the center of the dwell time. For Terra MODIS, the instrument dwell time has been 3 minutes and 46 seconds for the entire mission. In Figure 2, we show the attitude offset versus time for two Aqua MODIS lunar observations, one before and one after this change. The dashed lines in this figure show the times where the Moon can be observed during each event. While the settling of the attitude offset for each event is nearly the same, the difference in the observation time can have a significant impact on the apparent motion of the Moon across the FOV, as we will show in the text.

In this work, we will detail the development of an orbital path and spacecraft attitude correction to the MODIS spatial registration results. For the orbital path correction, we will compute the relative positions of the Moon and spacecraft directly using ephemeris data. For the Moon, we use the NASA JPL Developmental Ephemeris 430, DE430 [18], along with the SPICE Toolkit, which was developed by the Navigation and Ancillary Information Facility at JPL [19]. For the satellite orbital data, we use Two-Line Element (TLE) sets for both Aqua and Terra provided by CelesTrak [20]. The instrument attitude data is provided by the Aqua and Terra Flight Operations Teams out of NASA Goddard Space Flight Center. We will show that this correction provides a significant improvement to the spatial registration results, particularly for the DDR measurement in the scan direction. In Section II, we will discuss the relevant geometry of lunar observations as it relates to the spatial characterization measurements, and the implementation of the attitude data to correct the spacecraft reference frame orientation. Then, in Section III, we will discuss the methodology used to compute the predicted Moon path through the MODIS FOV during the observation and our measurements of the Moon's position in the detector images. Finally, in Section IV, we will discuss the results of the correction on the BBR and DDR calculations.

II. OBSERVATION GEOMETRY

A. Coordinate System Definitions

To perform the spatial characterization measurements using lunar observations, we first need to understand the relative

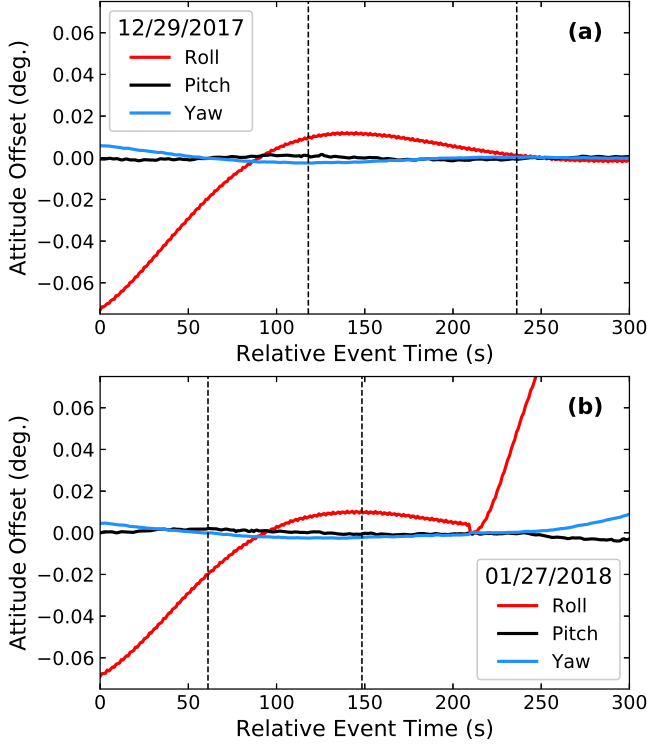


Fig. 2. Example data for the instrument attitude offsets for Aqua MODIS for two events before (a) and after (b) the change in the instrument dwell time during the observation. The vertical, dashed lines show the time when the Moon is visible on the instrument FPA (a) Roll, pitch, and yaw attitude offsets for the lunar observation on December 29, 2017. (b) Roll, pitch, and yaw attitude offsets for the lunar observation on January 27, 2018.

geometry of the spacecraft and Moon. For Earth-observing satellites in low-Earth orbit, such as MODIS, it is convenient to define the instrument coordinate system (ICS) in the following way [21]. Since the spacecraft pointing direction rotates at a rate equal to its orbital period, the z -axis is defined along the Earth-view port at nadir, which points from the instrument to the center of the Earth. The x -axis is defined as pointing perpendicular to z in the direction of orbital motion. The y -axis is normal to the spacecraft orbital plane. These axes can be defined in terms of the spacecraft (instrument) position ($\vec{r}_I$) and velocity ($\vec{v}_I$) in the Earth-centered inertial (ECI) J2000 reference frame using the following equations:

$$\begin{aligned}\hat{x} &= \frac{-\vec{r}_I \times (\vec{r}_I \times \vec{v}_I)}{|\vec{r}_I \times (\vec{r}_I \times \vec{v}_I)|} \\ \hat{y} &= \hat{z} \times \hat{x} \\ \hat{z} &= -\frac{\vec{r}_I}{|\vec{r}_I|}\end{aligned}\quad (1)$$

A diagram of the ICS can be seen in Figure 3. In this figure, we also show the location of the MODIS SV port in red, which is located at an angle of $\delta = -8.425^\circ$ from the y -axis in the yz -plane. For this work, it is convenient to define a new coordinate system for the observations with one of the principle axes aligned with the SV port, through which we observe the Moon. We call this coordinate system

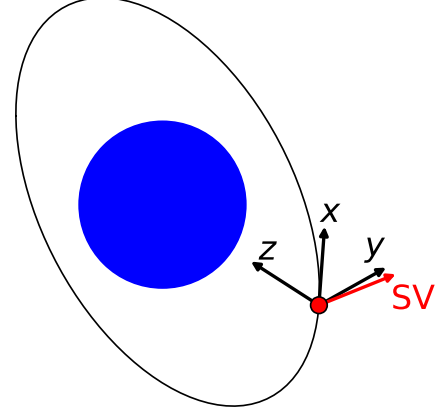


Fig. 3. A diagram of the MODIS instrument coordinate system (ICS). The SV is indicated by the red vector.

the observation coordinate system, or OCS, which will be defined by the principle axes x' , y' , and z' . These axes are aligned along the scan direction, space-view port, and track direction, respectively. In order to calculate vectors in the OCS, we must perform a set of rotations on the ICS that account for the following factors: the instrument roll about the x -axis to the ideal instrument pointing configuration after the spacecraft maneuver, the attitude error relative to the ideal pointing configuration while the spacecraft attitude settles, and the SV port offset. These rotations are summarized in Equation 2 and are shown in Figure 4.

$$\begin{aligned}R_1 &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\rho & -s\rho \\ 0 & s\rho & c\rho \end{bmatrix} \\ R_2 &= \begin{bmatrix} c\phi c\psi + s\phi s\theta s\psi & c\theta s\psi & -s\phi c\psi + c\phi s\theta s\psi \\ -c\phi s\psi + s\phi s\theta c\psi & c\theta c\psi & s\phi s\psi + c\phi s\theta c\psi \\ s\phi c\theta & -s\theta & c\phi c\theta \end{bmatrix} \\ R_3 &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\delta & -s\delta \\ 0 & s\delta & c\delta \end{bmatrix}\end{aligned}\quad (2)$$

Here, the c and s symbols represent the sine and cosine functions, respectively. For the first rotation, R_1 , the spacecraft is rolled about the x -axis by an angle ρ , creating an intermediate frame defined by x_R , y_R , and z_R as seen in Figure 4(a). The second rotation, R_2 , is then applied to this intermediate frame using a 2-1-3 Euler rotation of angles ϕ , θ , and ψ representing the pitch, roll, and yaw attitude offsets, respectively [22]. Using the provided attitude offsets shown in Figure 2 for each event, the first two rotations move our coordinate system from the simple definition based on orbital parameters in Equation 1 to the actual spacecraft pointing configuration during the lunar observation. This frame is defined by the axes x_A , y_A , and z_A in Figure 4(b). The final rotation, R_3 , rotates about x_A by the SV port offset, δ , which generates the OCS as seen in Figure 4(c).

An OCS reference frame kernel can be defined in SPICE using the 3 rotations described above with the time-dependent attitude data. The OCS is defined over a range of times which

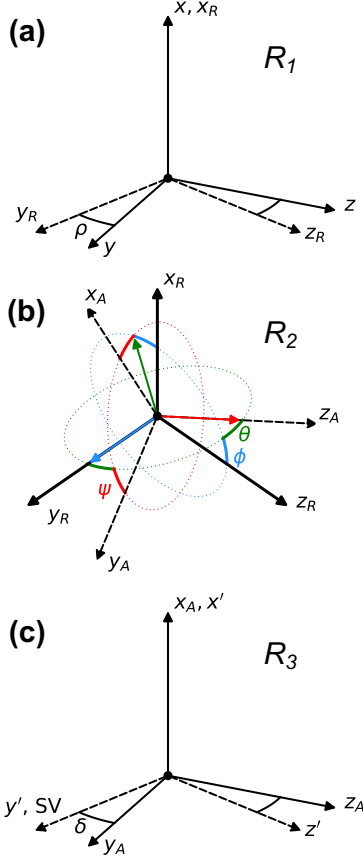


Fig. 4. A diagram of the three coordinate system rotations described by Equation 2 from the ICS to the OCS. (a) The initial rotation of the spacecraft roll by an angle ρ . (b) The attitude correction rotation using the Euler angles ϕ , θ , and ψ . The rotation axes and planes are marked in blue, green, and red, respectively. (c) The final rotation to align the y' -axis with the SV port by the SV offset δ . The rotations shown in (a) and (c) are for negative angles, which are used for MODIS lunar observations through the SV port.

encapsulates the entire lunar observation. With this reference frame definition, the computed position of the Moon at any input time will already account for the spacecraft attitude offsets. This will be discussed further in Section III-B.

B. Oversampling

Another important consideration for MODIS lunar observations is pixel oversampling. For MODIS, the Moon is viewed over multiple scans owing to the greater distance between the spacecraft and the Moon compared to Earth observations, where each successive scan is designed to produce a continuous image at the Earth-view nadir. In Sun *et al.* (2007) [5], the oversampling factor, f_{os} , is defined as the ratio of the MODIS pixel size on the Moon, P , and rate of the pixel movement on the lunar surface, d . It can be computed using the following equation:

$$f_{os} = \frac{P}{d} = \frac{\left(\frac{|\vec{r}_{IM}| R}{h} \right)}{|\vec{v}_t| s} \quad (3)$$

Here, $|\vec{r}_{IM}|$ is the instrument-Moon distance, R is the spatial resolution of the band at the Earth-view nadir, h is the nominal

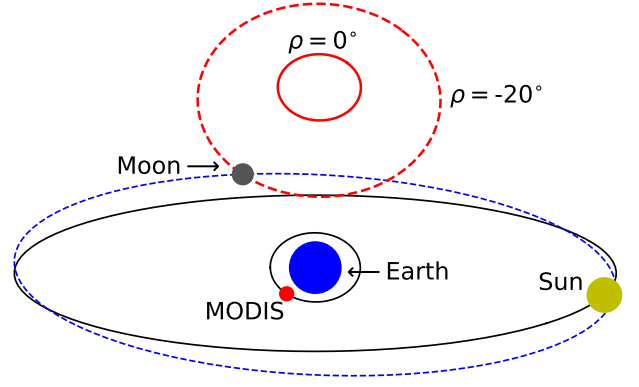


Fig. 5. A plot of the relative orbits of the Sun, Earth, Moon, and spacecraft. The orbital trace of the SV FOV is shown in red for the nominal pointing direction (solid) and at a roll angle of approximately -20° (dashed). The relative positions of the objects are not to scale.

altitude (705 km for MODIS), $|\vec{v}_t|$ is the speed of a MODIS pixel on the Moon's surface relative to the instrument in the track direction, and s is the scan time (1.477 seconds for MODIS). From Sun *et al.* (2007) [5], we can simplify the equation for $\vec{v}_t$ as follows:

$$\vec{v}_t = \vec{v}_I \left(1 - \frac{|\vec{r}_{IM}|}{|\vec{r}_I|} \sin(\rho + \delta) - \frac{\vec{v}_I \cdot \vec{v}_M}{|\vec{v}_I|^2} \right) \quad (4)$$

where $\vec{r}_I$ and $\vec{v}_I$ are the position and velocity of the instrument in the ECI J2000 reference frame, respectively, $\vec{v}_M$ is the velocity of the Moon in ECI J2000, ρ is the roll angle of the instrument and δ is the SV offset (-8.425° for MODIS). The relative track velocity for the MODIS pixel on the Moon is proportional to the direction of the instrument velocity with correction factors associated with the orbital motion of the spacecraft (second term of Equation 4) and the relative motion between the spacecraft and the Moon (third term of Equation 4).

From Equations 3 and 4, we can see that the magnitude of the oversampling factor will be dependent on the roll angle used during the observation. To understand this, we can consider the following. During each orbit, the FOV of the SV traces out an annulus in space at the distance of the Moon, as seen in Figure 5. For MODIS, if a roll maneuver is performed, the size of the annulus increases, but the orbital period of the spacecraft remains the same. This means that if the Moon is viewed with a large roll angle, then it is observed over fewer scans, resulting in a smaller oversampling factor. For MODIS lunar observations, the Moon shifts in the image each scan by less than a single MODIS 1-km pixel, with oversampling factors that vary between 1.8 and 5.4 scans per 1-km pixel shift for both Aqua and Terra MODIS during scheduled lunar observations.

The oversampling effect has two main consequences for the MODIS spatial characterization. First, with small shifts in the lunar position in between successive scans, an image of the Moon can be constructed for each individual detector using data from multiple scans. The relative position of the

Moon in each of the detector images can then be compared for the spatial registration assessment as will be discussed in Section III. Second, the observed motion of the Moon across the FPA will vary based on the total time of the observation and the relative curvature of the SV annulus during the observation. For observations with small roll angles (large oversampling factors), there is an increased curvature in the apparent motion of the Moon from scan-to-scan. Accounting for this motion will allow us to make better comparisons of the spatial registration results between events.

III. METHODOLOGY

In order to perform the spatial characterization measurements using lunar observations, there are several calculations in addition to those presented in Section II that need to be implemented which will be detailed in this section. A flow chart of the algorithm can be seen in Figure 6. The spatial characterization will mainly consist of a comparison between the predicted and measured Moon path across the MODIS FOV during the observation. To predict the Moon path, we combined data from 3 sources: JPL's DE430 dataset for the orbit of the Moon [18], CelesTrak TLE datasets for the orbit of the spacecraft [20], and instrument attitude error data from the MODIS Flight Operations Teams. Combining these datasets requires an accurate time reference for the event, which can be measured using the observation data with accurate timestamps that come from the spacecraft. With the event timing, we can compute the expected Moon path across the FOV, and then compare it with measurements of the Moon's position for each detector in order to calculate the spatial registration offsets in both the scan and track directions.

A. Measuring the Event Time

To accurately compute the relative geometry of the Moon and spacecraft, the timing of the observation needs to be

determined on the sub-scan level. During the observation, the data collect start time is recorded for each scan. When the full disk of the Moon is on the FPA, we can use edge fitting on the band 1 images of the Moon (because it is at the highest resolution, along with band 2) in order to calculate the center position of the Moon in the track direction for each scan, as seen in Figure 7. We can then calculate the fractional scan number when the Moon's position is centered in the track direction, which for band 1, corresponds to a track pixel number of 19.5 (the track pixel numbers range between 0 – 39 for the 40 detectors in the track direction). Finally, we interpolate the scan times to find the event center time.

As an additional correction to the event center time, we can use the Moon's position in the scan direction to determine the event time offset. The recorded scan times are associated with the start of the data collect, however, the Moon is typically not viewed until the later part of the scan during MODIS lunar observations. The observation center frame is typically 1127 out of 1354 total frames, with 1354 frames corresponding to 110° of a scan mirror rotation, which is 180° per scan since the scan mirror is double-sided. With a scan time of 1.477 seconds, the offset time is generally around 0.75 seconds from the scan start time.

B. Calculating the Moon Path

With the center time for the lunar observation calculated from the previous section, we can now compute the expected Moon path across the MODIS FOV during the observation. First, we generate a SPICE kernel for the OCS using the event time and attitude offset data as described in Section II. Next, given a range input times, the Moon's position in the OCS, $\vec{r}$, can be converted into the equivalent pixel position in units of 1-km instantaneous-FOV (IFOV), d_p , using the following equation:

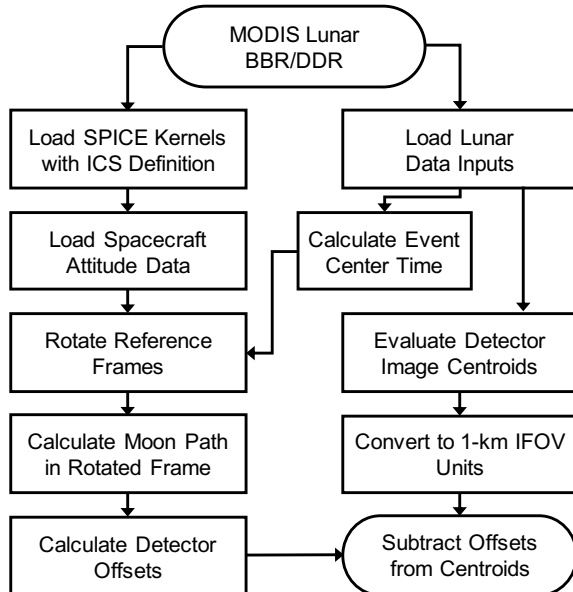


Fig. 6. Algorithm flow chart for the MODIS Lunar BBR/DDR calculation.

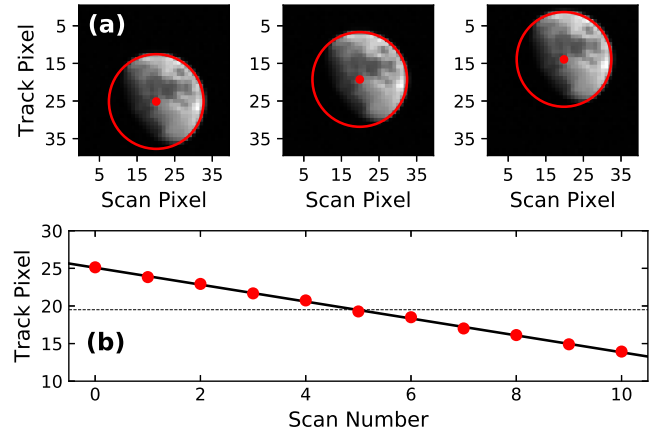


Fig. 7. An example of the observation center time calculation. (a) Edge-fitting for 3 example scans of a lunar image from Aqua MODIS band 1. The center of the Moon is marked with a red dot. (b) The measured track position as a function of scan. A linear fit to the data is shown as the black, solid line. The center time is computed by interpolating the scan times to when the Moon position is in the center of the FPA (dotted line).

$$d_{p,i} = \frac{r_i}{r_{y'}} \cdot h \quad (5)$$

where $i \in \{x', z'\}$ representing the track and scan directions of the OCS, respectively, and h is the nominal altitude of the spacecraft, which for Aqua and Terra is 705 km. In Figure 8, we show the calculated Moon path across the FOV for two events in Aqua MODIS, corresponding to those shown in Figure 2. The relative position of the Moon is set to zero in both the scan and track directions at the event center time. By setting the attitude offsets equal to zero, we can separate the components of the Moon path into those of the orbital path and attitude contributions, shown in blue and green respectively. When comparing the events from Figure 8(a) and (b), we can see that the change in the dwell time has significantly changed the attitude contribution, while the nature of the orbital path correction is similar between events. The majority of the attitude contribution comes from the roll offset as shown in Figure 2, and setting the pitch and yaw offsets to zero shows a negligible impact to the overall path correction. However, the current implementation allows for the general application of the instrument attitude correction which could be useful for other satellite missions with more complex maneuvers.

C. Measuring the Moon Position

While the edge-fitting method used to calculate the event time works well to find the Moon's center position for the

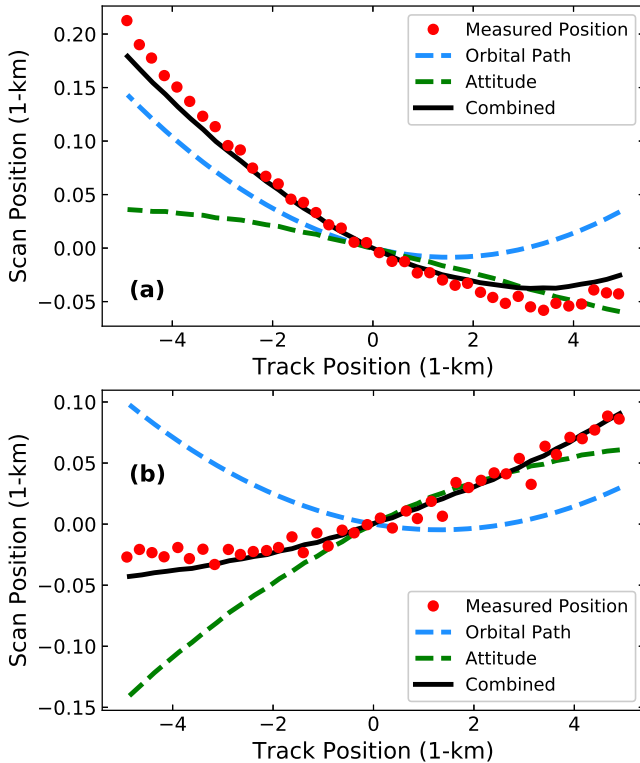


Fig. 8. Example orbital path and spacecraft attitude corrections for Aqua MODIS. (a) Data from December 29, 2017 with an oversampling factor of 4.8. (b) Data from January 27, 2018 with an oversampling factor of 3.5. Starting in 2018, the instrument dwell time before the observation was decreased (see Figure 2), resulting in a change to the instrument attitude correction.

250-m resolution bands in MODIS, the 1-km bands have too few pixels for consistent fitting in this way. Therefore, a different method must be used in order to generate comparable spatial registration results between the bands. For MODIS, there have been multiple methods used historically for these calculations. In Xiong *et. al.* (2002) [14], the location of the lunar limb was used to compare the BBR in the scan direction. In order to compute the relative differences in both the scan and track directions, Xiong *et. al.* (2004) [15] developed a method which uses minimization between two normalized lunar radiance profiles with an applied spatial offset. Another method, described in Xiong *et. al.* (2011) [16] and Wang *et. al.* (2015) [13], calculates the centroid position of integrated line profiles over the scan and track directions. The centroid calculation has the advantage of generating position measurements for each detector independently. In principle, the orbital path and attitude correction can be applied to any spatial characterization results. Here, we choose the centroid method for calculating the Moon's position for each band and detector, which will allow us to compare the measured results to the predicted position as described in Section III-B.

For each MODIS detector, the Moon is viewed over many scans owing to the oversampling effect discussed previously. Therefore, by taking data for a single detector over multiple scans, we can construct an image of the Moon for every detector, as seen in Figure 9. Since the Moon moves slowly across the FPA, each detector is able to construct a nearly complete image of the Moon. For these detector images, the aspect ratio of the images is not necessarily 1:1, as the Moon image will be scaled in the track direction to an aspect ratio equal to the oversampling factor. In comparison to individual scan images, where the pixel number in the track direction corresponds to a particular detector, the track pixel for the detector images corresponds to a particular scan number. Further, the scan number corresponds to a particular time as given by the instrument data.

When comparing the detector images in Figure 9, we crop each image to the same set of pixels in the scan and track directions. For the higher resolution bands at 250-m and 500-m nadir resolution, 4 and 2 additional subpixels are added for each 1-km pixel in the scan direction, respectively. These bands sample at a higher rate during the scan and the inclusion of these subpixels will be necessary for proper

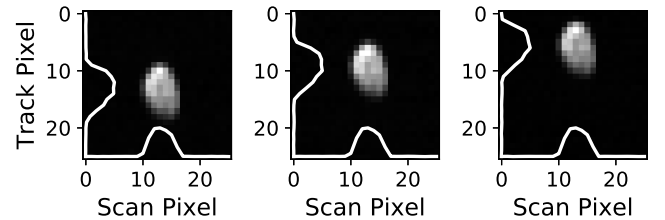


Fig. 9. Example Moon position measurements for Terra MODIS band 8 on April 16, 2017 for detectors 6, 8, and 10. The images are constructed for each detector using multiple scans. The sum of the image over each dimension creates a distribution seen in white overlaid on each image. The centroid positions are calculated from these distributions.

spatial registration between bands at different resolutions. In Figure 9, we can see that the Moon moves in the image for different detectors, with the majority of the motion in the track direction. To compute the position of the Moon in the detector images, we first integrate each detector image over the scan and track directions to produce line profiles, as seen in Figure 9. We then calculate the centroid, μ , of each line distribution using the following equation:

$$\mu = \frac{\sum_i \left(\sum_j dn_{i,j} \right) \cdot i}{\sum_{i,j} dn_{i,j}} \quad (6)$$

where i and j represent the location of a pixel in either the scan or the track direction and $dn_{i,j}$ is the background-subtracted image pixel value. For the first comparisons we make, we set a reference position in both the scan and track directions using the interpolated location of the Moon in band 1 at the calculated event center time. To compare this data with the predicted Moon path discussed in Section III-B, we need to first convert the position measurements into equivalent units of 1-km IFOV for each detector. In the scan direction, we simply divide by the number of subpixels at a given resolution. In the track direction, we divide by the calculated oversampling factor at the event center time. The consequence of this conversion of the position in the track direction means that our comparisons in Section IV will be between using a constant oversampling factor for the motion in the track direction versus one that changes with time.

A comparison of the measured path of the Moon versus the predicted path with the combined orbital and attitude data can be seen in Figure 8. We can see that the combined orbital and attitude path correction matches the measured data well, and that the orbital data alone is not sufficient for this prediction. However, to calculate the spatial registration results, we need to be able to determine where along the predicted path each detectors' measurement will be. We will show this along with the BBR and DDR results in the following section.

IV. CALCULATING THE BBR AND DDR

The orbital path and attitude correction terms described in Sections II-A and III-B combine to give us a prediction of the Moon path across the FOV as a function of time. To make use of these predictions when comparing to the measured data, we must first calculate the expected position of the Moon in the FOV for each detector. In the track direction, each band's IFOV is 10 km at the Earth-view nadir and split evenly among each detector within the band. Since the number of detectors in each band is even, the nominal center positions of the detectors at each resolution will be at half-integer pixel distances away from the track center, as shown in Figure 10. Therefore, the expected position of the Moon in the track direction will be fixed based on each band's resolution. To compute the position in the scan direction for each detector, we first compute the Moon position in the FOV from our predicted path data over a range of times. We can then interpolate the position of the Moon versus time onto the detector track positions in order to

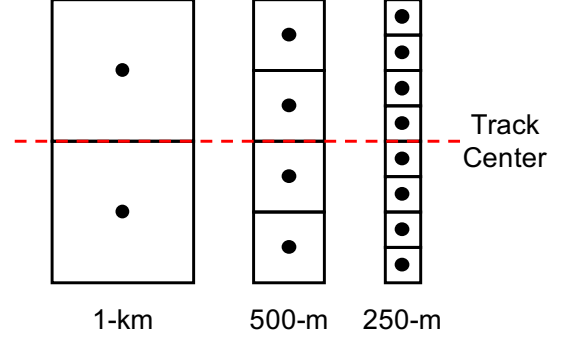


Fig. 10. A diagram of the nominal detector positions in the track direction for MODIS bands at each resolution about the track center position. The dots represent the center position of the detector IFOV, which are at half-integer distances away from the track center for each resolution.

get the expected observation times. From these times, we can then calculate the predicted position of the Moon in the scan direction. The detector position predictions are shown with the measured data in Figure 11(a).

Subtracting the prediction from the measured data gives us the scan and track offsets for each detector from their expected position, as shown in Figure 11(b). We can do this subtraction for each band to determine both the BBR and DDR. The mean value of the detector offset data in both directions will give a measurement of the BBR relative to a given reference. The spread in the values relative to the mean represents the in-band DDR measurement. For our BBR reference in both directions, we use the mean values for band 1, which are subtracted from the shifts for every detector in each band.

The Moon path correction shows a large reduction in the detector spread, particularly in the scan direction. As discussed previously in Section II-B, events with large oversampling factors are expected to have a larger spread in the scan direction because of the curvature of the path of the FOV. In Figure 12(a), we show that there is a strong correlation in the maximum difference between detector positions in the scan direction with the oversampling factor before the path correction is applied. In the track direction, the spread is relatively flat over the full range of oversampling factors as seen in Figure 12(b). When we apply the path correction to the data, we see that detector spread in the scan direction is reduced to being approximately flat over the entire range of oversampling factors. For the data in the track direction, the results are relatively unaffected by the path correction.

The BBR and DDR data for Terra and Aqua MODIS are shown in both the scan and track directions in Figures 13–16 for selected MODIS RSB. The results for bands 5 – 7 and 26 (short-wave infrared bands) are not shown because the lunar signals are significantly contaminated by electronic crosstalk and an out-of-band optical leak [23], [24]. For bands 13 – 16, the lunar signal saturates which impacts the centroid measurements. The black line in Figures 13–16 represent the BBR for each band relative to band 1. The error bars show the minimum and maximum deviation from the mean for each event for the uncorrected data (blue) and corrected data (red),

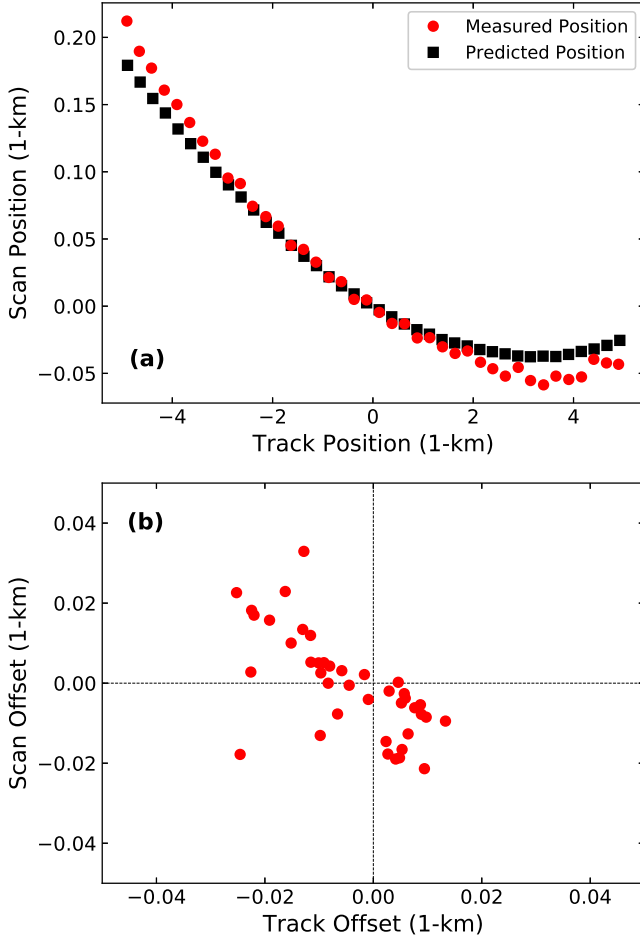


Fig. 11. (a) A comparison of the predicted Moon positions (black) and the measured Moon positions (red) for the Aqua MODIS band 1 lunar observation on December 29, 2017. (b) A plot of the detector offsets which are computed by subtracting the predicted positions from the measured positions.

which we use as a representation of the DDR results.

Since the orbital path and attitude correction affects all of the bands, the BBR results are minimally impacted by the correction. The results for both instruments in both directions are stable over time and are in good agreement with measurements from the SRCA [3], [17]. For some of the bands, small oscillations can be seen in the BBR results which can differ in both the scan and the track directions. In previous work on the VIIRS instrument, these oscillations were found to correlate with the relative rotation of the Moon image on the FPA, which is also the case in our work [25]. Because the centroid calculation adds weight to each pixel value based on the signal level, differences in the pixel level spectral reflectance can result in slight offsets in the measured position for each band depending on the particular orientation of the Moon during the observation. It is possible to remove these oscillations if an edge fitting approach were developed to measure the Moon's position, since this does not use any data from the lunar surface. However, as stated in Section III-C, for MODIS, edge fitting does not produce consistent results for the 1-km bands, and therefore we opt for the centroid method in this work. The empirical method developed to correct these oscillations

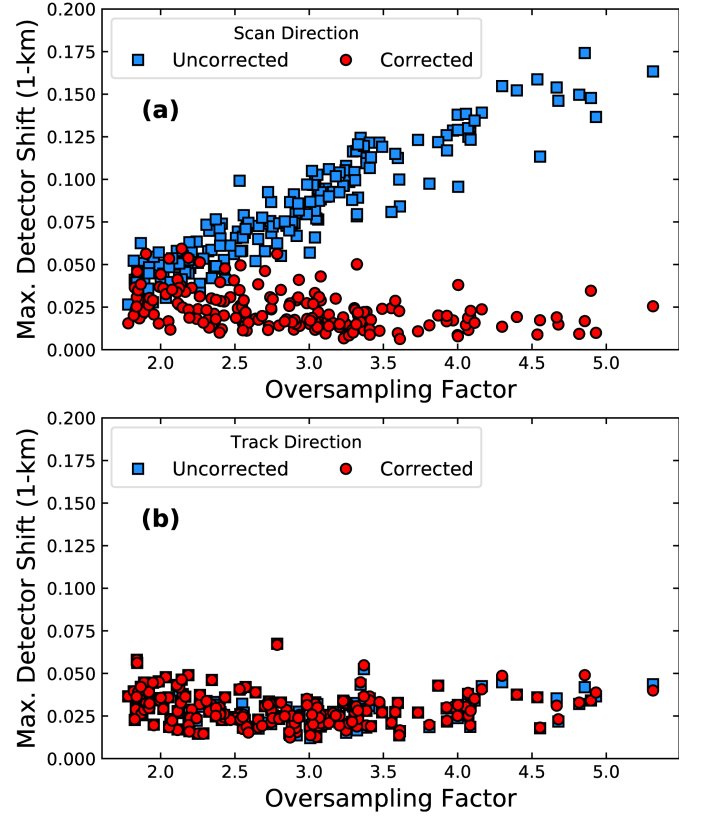


Fig. 12. Plots of the maximum differences in the detector positions as a function of oversampling factor for Terra MODIS band 8. (a) A comparison of the uncorrected and corrected data in the scan direction. (b) A comparison of the uncorrected and corrected data in the track direction.

in Reference 25 was not applied for this work.

For Terra, the BBR is within 50 m of the band 1 reference for each band in both directions. For Aqua, the BBR has larger shifts for some bands, particularly in the track direction. These shifts have been known since pre-launch and are the results of a vibration test of the instrument [17]. The BBR results for the bands analyzed in this work are well within the 0.2 km specification for both instruments.

The DDR results show a significant change in the scan direction for both Aqua and Terra MODIS as a result of the Moon path correction. Before the correction is applied, the maximum difference in the detector positions can be as high as 200 m. The correction shows a significant reduction in this difference to the range of 50 – 100 m for most bands and events. In the track direction the change in the DDR is minimal, which means that the use of a constant oversampling factor models the motion of the Moon across the FPA well for MODIS lunar observations. The maximum difference in the track direction is also on the order of 50 – 100 m with the exception of Terra MODIS band 2, which shows a larger difference across all events. This is because several detectors in band 2 have a small amount of electronic crosstalk contamination, which can affect the centroid results for these detectors [26]. The impact of this contamination can be reduced by applying a mask to the integrated line profiles used to calculate the centroid away from the peak signal. However, the effect is not mitigated completely, as some contamination exists close to or within

the peak signal.

V. CONCLUSION

The MODIS spatial characterization from lunar observations is significantly impacted by the apparent motion of the Moon across the MODIS FOV. The two main sources of this apparent motion are from the relative orbital motion of the Moon and spacecraft and the spacecraft attitude error that is introduced during the roll maneuver. In this work, we developed a method for predicting the path of the Moon across the MODIS FOV using Moon and spacecraft ephemeris data combined with attitude data provided by the Aqua and Terra Flight Operations Teams. Using this data, we calculated the expected position of the Moon for individual detector images based on the measured event time and the resolution of each band. The measured position of the Moon in the detector images was calculated by using the centroid of integrated line profiles in both the scan and the track directions. By subtracting the predictions from the measurements, we were able to compute the BBR and DDR results for each band relative to a band 1 reference. While the BBR results were unaffected by the path correction, the spread in the DDR along-scan was significantly reduced for all bands for both Aqua and Terra MODIS. The events that were most impacted occurred at large values of the oversampling factor, where the relative curvature of the apparent lunar motion was greatest. The results of the Moon-based spatial characterization for MODIS are in good agreement with previous results obtained from the SRCA, which is the primary method for performing the spatial characterization for both MODIS instruments. This work shows that with the application of the orbital path and attitude correction, the Moon can be used to generate accurate spatial characterization results on instruments that do not have specialized instruments such as the SRCA on board.

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Truman Wilson received the B.S. and Ph.D degrees in Physics from Colorado State University, Fort Collins, CO, USA, in 2007 and 2013, respectively.

He is currently a Senior Research Scientist for the MODIS Characterization Support Team and the VIIRS Characterization Support Team at Science Systems and Applications, Inc., Lanham, MD, USA.

Dr. Wilson was awarded a National Research Council Postdoctoral Fellowship at the National Institute of Standards and Technology, Gaithersburg, MD, USA, in 2013.

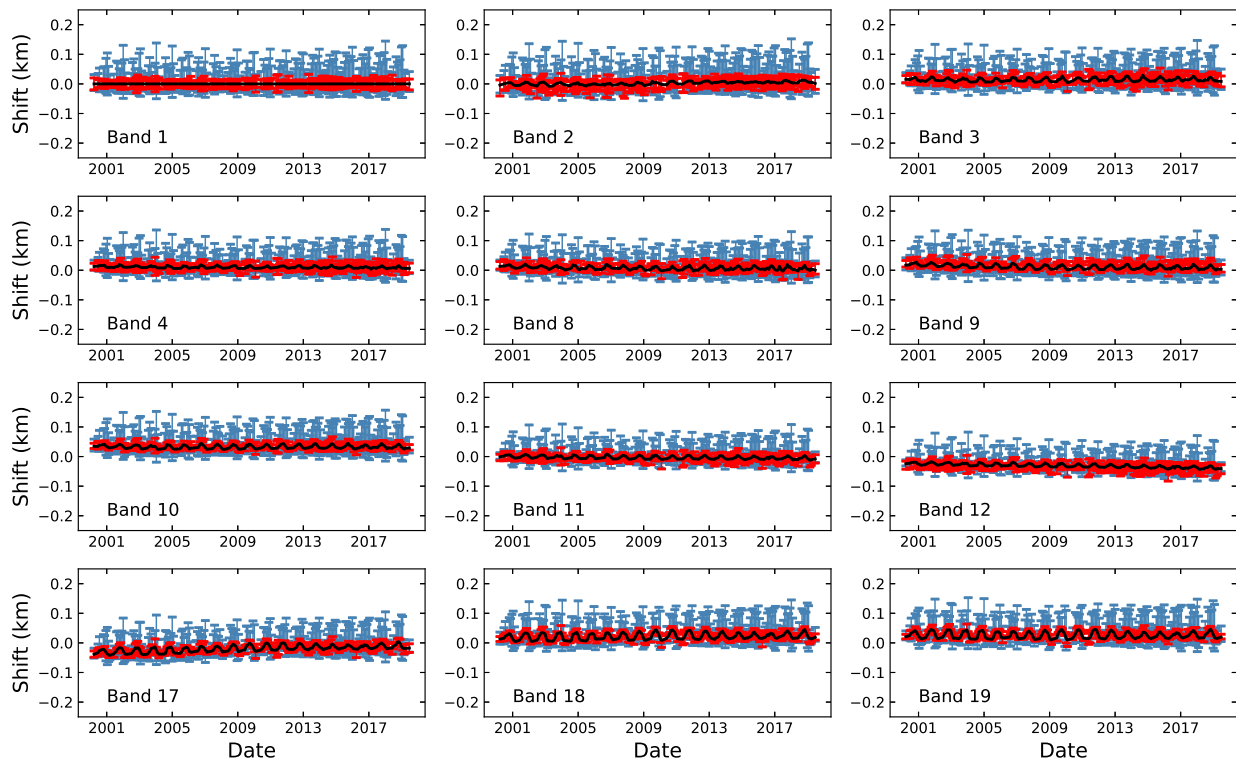


Fig. 13. Terra MODIS along-scan BBR and DDR. The black data represents the mean value of the detectors offsets (BBR), which is unaffected by the path and attitude correction. The error bars represent the maximum deviation of the detector offsets from the mean before correction (blue) and after correction (red).

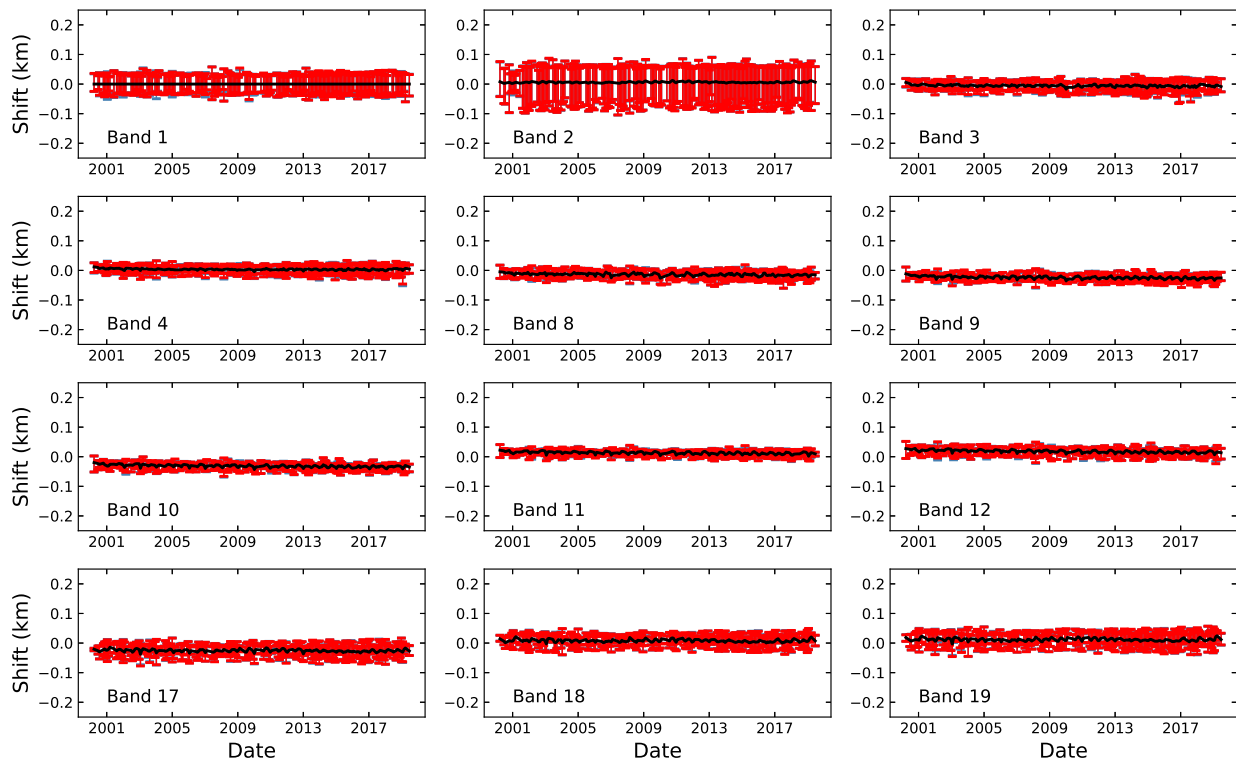


Fig. 14. Terra MODIS along-track BBR and DDR. The black data represents the mean value of the detectors offsets (BBR), which is unaffected by the path and attitude correction. The error bars represent the maximum deviation of the detector offsets from the mean before correction (blue) and after correction (red).

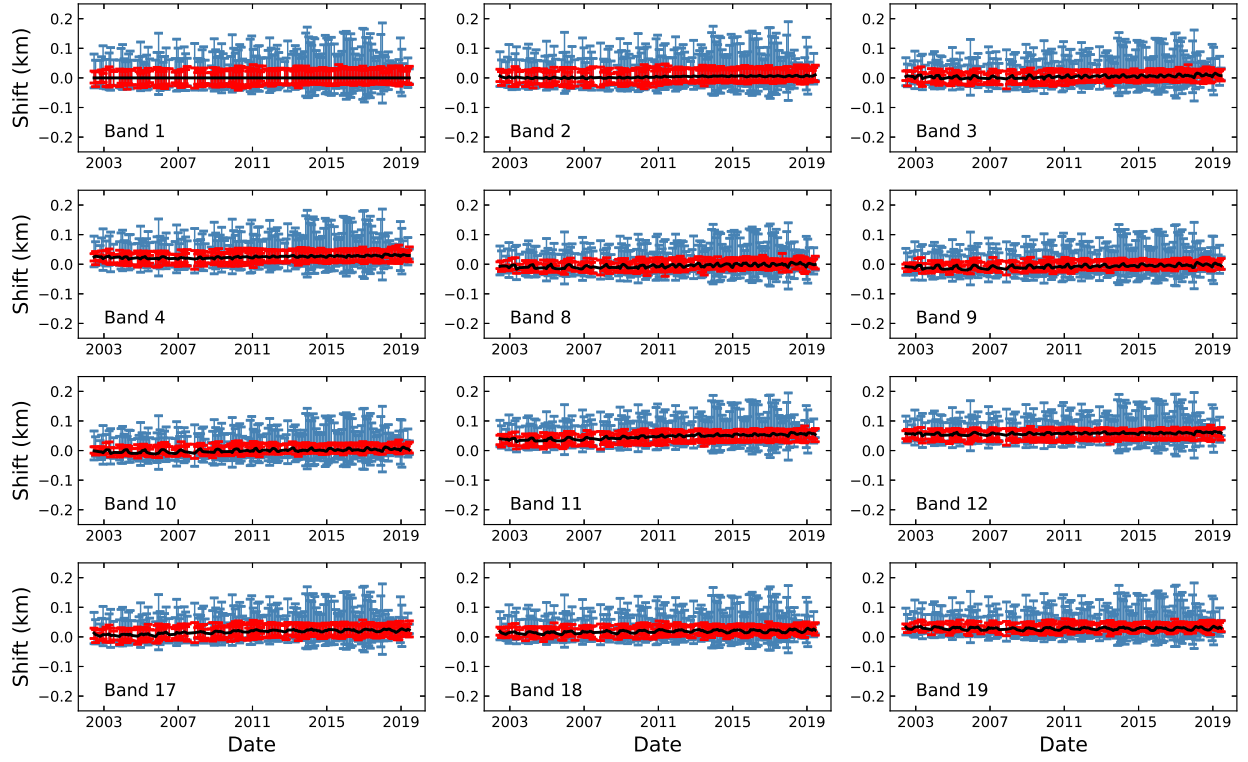


Fig. 15. Aqua MODIS along-scan BBR and DDR. The black data represents the mean value of the detectors offsets (BBR), which is unaffected by the path and attitude correction. The error bars represent the maximum deviation of the detector offsets from the mean before correction (blue) and after correction (red).

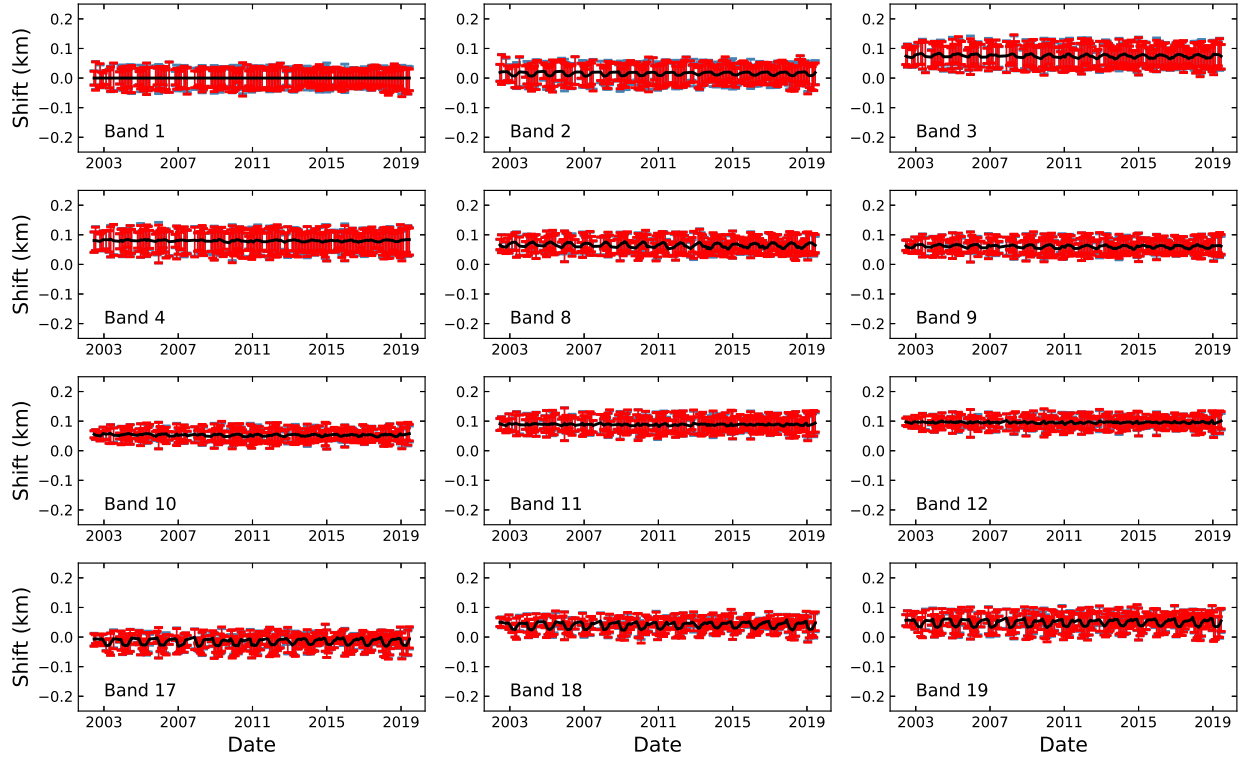


Fig. 16. Aqua MODIS along-track BBR and DDR. The black data represents the mean value of the detectors offsets (BBR), which is unaffected by the path and attitude correction. The error bars represent the maximum deviation of the detector offsets from the mean before correction (blue) and after correction (red).

Amit Angal is currently a Lead Optical Engineer and a Supervisor with Science Systems and Applications, Inc., Lanham, MD, USA, where he is involved in the radiometric characterization and calibration of remote sensing instruments. He is primarily involved in the on-orbit calibration of the reflective solar bands of the MODIS instruments on-board the Terra and Aqua spacecraft. He has also supported the CLARREO Mission Preformulation activities in the reflective solar spectrum. In addition, he supports the preflight calibration of the JPSS VIIRS instruments and is involved in the on-orbit calibration and validation of the SNPP and NOAA-20 VIIRS instrument. His research interests include cross-calibration between Landsat and MODIS instruments.



Xiaoxiong Xiong received the B.S. degree in optical engineering from the Beijing Institute of Technology, Beijing, China, and the Ph.D. degree in Physics from the University of Maryland at College Park, College Park, MD, USA.

He is an Optical Physicist at NASA/GSFC, Greenbelt, MD, USA, currently serving as the MODIS Project Scientist and the MODIS and VIIRS Calibration Scientist. In addition to remote sensing, he had also worked in the fields of optical instrumentation, nonlinear optics, laser/atomic spectroscopy, and mass spectrometry. See <http://science.gsfc.nasa.gov/sed/bio/xiaoxiong.xiong-1> for more details.

Dr. Xiong is a fellow of SPIE.