VIIRS On-Orbit Spatial Characterization Using the Moon

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Abstract—The VIIRS instrument onboard the Suomi-NPP satellite was launched in October 2011. The design and operation of its on-orbit calibration system are strongly based on MODIS heritage. However, VIIRS has no onboard calibrator similar to the spectro-radiometric calibration assembly (SRCA) on MODIS to perform the sensor on-orbit spatial characterization of band-to-band registration (BBR) and modulation transfer function (MTF). The Moon has been known as a spectrally, radiometrically, and geometrically stable source that can be used for sensor on-orbit calibration and characterization. In this letter, the algorithms developed and validated for MODIS spatial characterization using the Moon are briefly summarized and extended to VIIRS. The BBR in both along-scan and along-track directions and the MTF in the along-track direction are calculated with the scheduled VIIRS lunar observations and presented. These early results confirm that the VIIRS spatial characterization parameters have been stable since launch and are within the performance specification. As part of the VIIRS on-orbit calibration and validation effort, the BBR and MTF parameters will be continuously monitored and evaluated throughout its mission lifetime.

Index Terms—Band-to-band registration (BBR), modulation transfer function (MTF), spatial characterization, visible infrared imaging radiometer suite (VIIRS).

I. INTRODUCTION

T
HE Visible Infrared Imaging Radiometer Suite (VIIRS) is a key instrument aboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite to provide information of large-scale global dynamics in the oceans, on land, and in the lower atmosphere. It is a passive whiskbroom scanning imaging spectro-radiometer, performing measurements in the wavelength range from 0.4 to 12.2 \( \mu \text{m} \) in 14 reflective solar bands (RSB) and seven thermal emissive bands (TEB) [1]. The instantaneous fields of view (IFOVs) of VIIRS detectors are band dependent: the nominal ground pixel sizes at nadir are 375 m for the imaging (I) bands I1–I5 and 750 m for the moderate (M) resolution bands M1–M16, respectively. Designed and built by the same instrument vendor, VIIRS is a follow-on instrument to the MODerate resolution Imaging Spectroradiometer (MODIS), currently operating onboard the NASA’s Earth observation system (EOS) satellites, Terra and Aqua [2].

The VIIRS spectral bands are located on three separate focal plane assemblies (FPA): visible/near-infrared (VIS/NIR), short-wave and mid-wave infrared (S/MWIR), and long-wave infrared (LWIR). These spectral bands are spread in the along-scan direction and the detectors within a band are assembled in the along-track direction. Fig. 1 is a sketch of the detector layout on the VIS/NIR FPA. The matching detectors, or the detectors in the same along-track positions, between bands are spatially coregistered in both the along-scan and along-track directions and the accuracy of the band-to-band coregistration (BBR) can be quantified by either the overlapping fraction of corresponding pixels of the two bands or the offset \( \Delta \) between the pixels in these directions. As with other remote sensing systems, the modulation transfer function (MTF) of VIIRS is a measure of the image sharpness. Both BBR and MTF are key performance parameters of the VIIRS spatial characterization [3], [4].

Unlike its heritage sensor-MODIS, which has an onboard spectro-radiometric calibration assembly (SRCA) that can perform sensor spectral and spatial characterization, VIIRS does not have an onboard device to characterize the BBR and MTF [5]. Therefore, alternative approaches have been developed by
the MODIS characterization support team (MCST) to calculate the BBR offset \( \Delta \) and the MTF of MODIS RSB using the lunar images captured during the scheduled lunar calibration. The results have been compared and verified with those derived from the onboard SRCA [6]–[8]. Because of the similarity in the design between MODIS and VIIRS, the approaches are conveniently extended to VIIRS RSB.

### II. VIIRS Lunar Calibration and Data

Regular VIIRS lunar observations are scheduled primarily for tracking its RSB radiometric calibration stability, given the inherent stability of the lunar reflecting surface. Lunar irradiance strongly depends on the illuminating and viewing geometry, primarily the lunar phase. To maintain a nearly constant irradiance level, the phase angle at the time of lunar calibration is set to be within a small range from \(-51^\circ\) to \(-50^\circ\). The observation can only be scheduled approximately monthly because of limitations created by the orbits of the Earth and the Moon [9]. Table I lists the 13 scheduled lunar calibrations that have been performed since launch. A spacecraft roll maneuver is usually implemented for each lunar calibration to ensure the Moon is viewed through the space view (SV) port of the instrument. VIIRS can also view the Moon through its SV port at different lunar phases without scheduling. The BBR and MTF results presented here are calculated from the scheduled lunar calibrations.

VIIRS has a rotating telescope assembly (RTA) scanning across its track direction. At a nominal altitude of 824 km, the double-sided half angle mirror (HAM) rotates at half the speed of the RTA and captures a swath of 3000 km in the along-scan (cross-track) direction by 12 km in the along-track direction at nadir. Each I band has 32 detectors and each M band has 16 detectors. In the along-scan direction, the I band is sampled at twice the frequency as the M band. The shapes of the detectors of the RSB are rectangular, as is indicated in Fig. 1. Among a series of operational products produced for VIIRS, the raw data record (RDR) is used as the input of our calculation. During the scheduled lunar calibration, a data sector rotation is applied so the Moon image captured through the SV port is actually read out from the earth view sector. Every three samples of the I bands (I1–I5) and the single gain M bands (M6, M8–M12, M14–16) are spatially aggregated in the along-scan direction onboard by the instrument. For the dual gain M bands, their data saved in the RDR are unaggregated so that the previous aggregation strategy is applied on the ground for consistency. After aggregation, the detector IFOV is nearly of a square shape. The diameters of the lunar images are approximately 20 pixels for I bands and 10 pixels for M bands. The actual numbers change from event to event, depending on the VIIRS-Moon distances.

At a phase of approximately \(-50^\circ\), the illuminated portion of the Moon is not a full circular disk but a little more than half of it. The orientations of the lunar images captured by VIIRS change with calibration events, depending on the position and pointing direction of VIIRS relative to the Moon. The change of the orientation can be observed from the lunar images in Fig. 2 for a few events. Each single plot in Fig. 2 is the lunar image of the center scan of that event. The horizontal direction is the along-scan direction and the vertical direction is the along-track direction. During each calibration, the Moon moves from the bottom to the top along the track direction while its movement along the scan direction is less than one pixel. The swaths of VIIRS scans on the lunar surface are overlapping and the amounts of overlap change from calibration event to calibration event, depending on the view geometry. The oversampling factor \( \beta \) is defined as the number of scans taken for the VIIRS swatch to move one detector IFOV. The factor can be calculated from the ephemeris data of the VIIRS and the Moon. Because of oversampling, the numbers of scans taken to image the whole Moon also vary from event to event. For the scheduled lunar calibrations to date, the numbers range from approximately 30 to 46. Data of all these scans are used as the input for the following BBR and MTF calculation.

The data readout from the EV sector of RDR is 12-bit digital number (DN). The background DN is nonzero and thus needs to be subtracted from the total signal. The subtraction is performed on a scan basis with the background DN calculated by averaging the DNs of samples away from both sides of the lunar image. With the instrument temperature-dependent coefficient (prelaunch values), the F-factor calibrated on-orbit, and the response versus scan (RVS) angle, the background subtracted DN is further corrected to remove the detector-to-detector gain difference [10]. The data after all these corrections are denoted as \( dn^* \), which represents the actual spatial profile of the lunar surface radiance.

The system settings of the first two calibrations (Table I) differ from follow-on event. No data sector rotation was not applied for these calibrations so the lunar images are read-out

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**TABLE I**

<table>
<thead>
<tr>
<th>Calibration Time</th>
<th>Data Sector</th>
<th>BBR Scan I2</th>
<th>BBR-Track I2</th>
<th>MTF-Track I2</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/04/2012</td>
<td>Space View</td>
<td>-0.0098a</td>
<td>-0.0112</td>
<td>Not Processed</td>
</tr>
<tr>
<td>02/03/2012</td>
<td>Space View</td>
<td>-0.0072</td>
<td>-0.0088</td>
<td>Not Processed</td>
</tr>
<tr>
<td>04/02/2012</td>
<td>Earth View</td>
<td>-0.0095</td>
<td>-0.0101</td>
<td>0.599</td>
</tr>
<tr>
<td>05/02/2012</td>
<td>Earth View</td>
<td>-0.0098</td>
<td>-0.0057</td>
<td>0.567</td>
</tr>
<tr>
<td>05/31/2012</td>
<td>Earth View</td>
<td>-0.0077</td>
<td>0.0005</td>
<td>N/A</td>
</tr>
<tr>
<td>10/25/2012</td>
<td>Earth View</td>
<td>-0.0042</td>
<td>0.0029</td>
<td>0.595</td>
</tr>
<tr>
<td>11/23/2012</td>
<td>Earth View</td>
<td>-0.0077</td>
<td>0.0069</td>
<td>N/A</td>
</tr>
<tr>
<td>12/23/2012</td>
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<td>-0.0088</td>
<td>-0.0010</td>
<td>0.603</td>
</tr>
<tr>
<td>02/22/2013</td>
<td>Earth View</td>
<td>-0.0078</td>
<td>-0.0081</td>
<td>0.603</td>
</tr>
<tr>
<td>02/21/2013</td>
<td>Earth View</td>
<td>-0.0073</td>
<td>-0.0149</td>
<td>0.561</td>
</tr>
<tr>
<td>03/23/2013</td>
<td>Earth View</td>
<td>-0.0089</td>
<td>-0.0080</td>
<td>0.574</td>
</tr>
<tr>
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<td>0.0001</td>
<td>0.541</td>
</tr>
<tr>
<td>05/21/2013</td>
<td>Earth View</td>
<td>-0.0093</td>
<td>-0.0053</td>
<td>0.593</td>
</tr>
</tbody>
</table>

* unit: M band pixel after aggregation

![Fig. 2. VIIRS lunar images at the center scans of various lunar calibration events.](image)
The centroid in the along-track direction can be calculated by

\[ f_{B,D} = \frac{\sum_s \left( \sum_f \delta_{n,B,D,f} \right) \cdot f}{\sum_f \sum_s \delta_{n,B,D,f}} \]  

where \( f \) is the sample number and \( s \) is the scan number. The subscripts \( B \) and \( D \) represent band and detector, respectively. The centroid in the along-scan direction can be calculated by

\[ s_{B,D} = \frac{\sum_s \left( \sum_f \delta_{n,B,D,f} \right) \cdot s}{\sum_f \sum_s \delta_{n,B,D,f}} \]  

The band-averaged differences of \( f_{B,D} \) between all matching detectors are thus the BBR in the along-scan direction. The band-averaged differences of \( s_{B,D} \), however, have to be divided by the oversampling factor to get the BBR in the along-scan direction

\[ \Delta_{\text{scan}} = \frac{f_{B1,D} - f_{B2,D}}{} \quad \Delta_{\text{track}} = \frac{s_{B1,D} - s_{B2,D}}{\beta} \]  

The key of success of the edge method is finding an object with high contrast edges. The Moon has high-contrast edges that can serve as the target. The lunar MTF calculation algorithm has been developed for MODIS to calculate the MTF in the along-scan and along-track directions and the results agree with the MTF measured by the onboard SRCA very well [7], [8]. The first step of the algorithm is selecting an appropriate lunar edge. When measuring the MTF in one direction, the edge perpendicular to the direction is selected to minimize the interference of the MTF components between the along-scan and along-track directions. Actual lunar edges should be selected for the calculation, instead of the boundaries between the illuminated and unilluminated portions of the Moon due to partial illumination. It is found that the left edge of the lunar image is always the actual lunar edge. For the along-track MTF calculation, either the top edge or the bottom edge could be selected (see Fig. 2). For convenience, we name the row of data that contains the left edge of the lunar image “center row” and the column of the data that contains the upper or lower edge “center column.” The \( \delta_{n} \) of the center row is used for along-scan MTF calculation and the \( \delta_{n} \) of the center column is used for along-track MTF calculation.

Lunar images of multiple scans are available for VIIRS. For each scan, there is one center row or one center column of data, which is not enough for ESF construction. However, because of the lunar movement among scans, the relative positions of the lunar edges to the pixel grid change from scan to scan. The superposition of the lunar images of multiple scans could provide enough shifts to construct a complete ESF. The superposition requires accurate lunar position information of each scan. For VIIRS, the \((x, y, z)\) component of a unit vector toward the Moon in the instrument coordinate system is generated by the VIIRS geolocation algorithm on a scan-by-scan basis. With the Moon-VIIRS distance at the time of lunar calibration, the lunar vectors can be converted into lunar image positions in the SV in unit of image pixels. Then, the left edge position for the center row of each scan can be calculated by

\[ X = X_0 - \sqrt{r^2 - (d - Y_0)^2} \]  

where \( X_0 \) and \( Y_0 \) are the moon center positions in the along-scan and along-track directions. \( d \) is the detector number of the center row. \( r \) is the radius of the Moon in pixels. For the along-track MTF calculation, the top or bottom edge position for the center column of each scan can be calculated by

\[ Y = Y_0 \pm \sqrt{r^2 - (f - X_0)^2} \]
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Fig. 3. Procedure of the along-track MTF derivation.

where \( f \) is the sample number of the center column. One detector and each sample in (4) or (5) are equivalent to one image pixel. The choice of using plus or minus sign depends on whether the top edge or the bottom edge is used for ESF derivation. Using one scheduled lunar calibration as an example, the data profiles in the along-track direction of multiple scans during a calibration are plotted side-by-side with their calculated edge positions in Fig. 3 (top panel).

With the edges accurately located scan-by-scan, the \( dn^* \) profiles from multiple scans can be shifted accordingly so that the edges from multiple scans are aligned by their subpixel edge locations. The process is illustrated in Fig. 3 (middle panel). The shifted \( dn^* \) is then normalized to the maximum \( dn^* \) value to get the ESF. The X-coordinates of the ESF are determined by the actual edge positions of the Moon and thus are unevenly spaced. The ESF data points need to be resampled at a constant interval to perform the discrete FT. The resampling is done by the least-squares method interpolation. We then differentiate the ESF to get the LSF and take the FT of the LSF to get the MTF. The process is illustrated in Fig. 3 (bottom panel). The VIIRS MTF is specified to be greater than 0.9, 0.7, 0.5 and 0.3 at 0.25, 0.5, 0.75, and 1 Nyquist frequency, respectively, as indicated in Fig. 3. Since the ESF is constructed with lunar images of multiple scans and captured by all detectors within a band, only one band-averaged MTF is derived for each band.

IV. RESULTS AND DISCUSSION

With the algorithms introduced above, the lunar BBR in both the along-scan and along-track directions are calculated for all scheduled lunar calibrations for VIIRS RSB. The results are shown in Fig. 4, using band I1 as the reference. The unit of BBR in the plot is M band pixel after aggregation, roughly corresponding to a nominal ground IFOV of 750 m at nadir. The top panel of Fig. 4 shows the temporal trending of the BBR between band I2 and band I1 with the values provided in Table I. Overall, the BBR trending is stable over time, which is also true for all RSB. The bottom panels show the mean (curves), the maximum and the minimum values (error bars).

If the actual BBR is stable, the error bars here indicate the uncertainty of the lunar BBR algorithm.

The VIIRS BBR specification is that the overlapping fraction of the pixel sizes of the matching detectors between two bands shall be greater than a band-pair-dependent threshold, or

\[
(1 - \Delta_{\text{scan}}) \cdot (1 - \Delta_{\text{track}}) > T_{B1,B2}.
\]

The thresholds are 0.80 between I bands and between LWIR M bands. For the rest of the band pairs, the thresholds are mostly 0.64 [3]. If the BBR offsets between the two bands are 0.1 pixels in both directions, the overlapping fraction of the two IFOVs will be 0.81; if offsets are 0.2 pixels, the overlapping fraction of the IFOVs will be 0.64. The lunar BBR results show the actual offsets between all RSB band pairs are less than 0.05 pixels in both along-scan and along-track directions, so the performance specification is met.

The lunar images of the TEB always contain saturated pixels. The saturated pixels distort the shapes of the spatial profiles and thus the actual centroid positions, so the BBR related to TEB cannot be calculated the same way as RSB.

Fig. 5 shows the MTF values at Nyquist frequency\(^1\) for VIIRS RSB. The top panel is the temporal trending, using the results of band I1 and M1 as examples. The MTF values of band I2 are provided in Table I. The MTF trends look similar for all RSB. The bottom panel shows the mean (curves), the

\(^1\)Nyquist frequency is defined as 1/2 of the sampling frequency. For VIIRS detectors, the spatial sampling frequency is 1 cycle per IFOV.
maximum and the minimum values (bars). Overall, the on-orbit MTF trending has been stable over time. According to the plot, the MTF values at Nyquist frequency are consistent with the prelaunch measurement result of approximately 0.6 [3] and are well above the specification value of 0.3. The uncertainty in the MTF calculation detector dependency can be partly explained by the MTF’s detector dependency. The maximum and the minimum MTF values measured prelaunch for band 11 detectors, for example, are 0.601 and 0.579. The weight of different detectors in the MTF derivation changes from event to event, so the band-averaged lunar MTF is expected to vary between the two extremes.

The MTF is not calculated for a few calibration events due to various reasons. The first two calibrations are excluded because their data are not aggregated. While manual aggregation works well for BBR, its impact to MTF has not been analyzed and further evaluation is required. The MTF result for 11/23/2012 is not available because of an intrinsic limitation of the algorithm. In this algorithm, the ESF is constructed by shifting the lunar images of multiple scans in reference to the calculated lunar edges. The shift for each scan is based on the distances between the pixel grid and the edge. The distances should spread from zero to one pixel, so that the dn* of the adjacent pixels are continuously connected after the shifting to construct a complete ESF (Fig. 3). However, the distance is determined by the movement of the Moon relative to the instrument during the lunar calibration, which is not a controllable parameter in our algorithm. For the 11/23/2012 calibration, the oversampling factor is 1.01 for I bands, meaning that the lunar images move almost exactly one pixel per scan. The distances between the pixel grid and the edge barely change for all scans. The resultant ESF is thus incomplete and unsuitable for MTF calculation.

For the same reason, the along-scan MTF calculation is more difficult because lunar movement in the direction is usually less than 0.2 pixels for I bands and 0.1 pixels for M bands for the scheduled lunar calibration events, which are insufficient to build a complete ESF.

V. CONCLUSION

The on-orbit BBR and MTF of VIIRS RSB in both the along-scan and along-track directions are calculated using the scheduled lunar observations. The early results presented here show that these spatial characterization parameters have been stable since launch. Their values are in good agreement with the prelaunch measurements and meet the performance specification. The results also confirm that the lunar BBR and MTF algorithms developed and validated for MODIS can be conveniently extended to VIIRS and future instruments with similar designs.

The lunar BBR and MTF will be continuously monitored and evaluated throughout VIIRS lifetime, as part of the on-orbit calibration effort. The BBR algorithm and the along-track MTF algorithm are proved robust. Further improvement will focus on the along-scan MTF calculation. The key of success of the MTF algorithm is accurately locating the edge positions of lunar images for each scan with the aid of lunar positions calculated by the geolocation algorithm. The accuracy of these lunar positions will be further evaluated. Also, the current along-track MTF calculation only uses the center dn* column and the constructed ESF is proved to be accurate and complete enough. Because of the limitation of the lunar movement in the along-scan direction, using more than one dn* rows could provide additional shift to build a more complete ESF for along-scan MTF calculation.

REFERENCES


