MODIS on-orbit spatial characterization results using ground measurements

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Abstract

MODerate resolution Imaging Spectro-radiometer (MODIS), as part of NASA's Earth Observe System (EOS) mission, is widely utilized in diversified scientific research areas. Both Terra and Aqua MODIS observe the earth in sun-synchronous orbit at three nadir spatial resolutions. MODIS has thirty-six bands that are located in four Focal Plane Assembles (FPAs) by wavelength: Visible (VIS), Near-Infrared (NIR), Short-and Middle-wavelength IR (SMIR), and Long wavelength IR (LWIR). MODIS Band-to-Band Registration (BBR) was measured pre-launch at the instrument vendor. Mis-registration exists between bands and FPAs. The spatial characterization could change in storage, at launch, and years on-orbit. In this study, a special ground scene with unique features has been selected as our study area to calculate the spatial registration in both along-scan and along-track for bands 2 - 7 relative to band 1. The results from the earth scene targets have been compared with on-board calibrator, the Spectro-Radiometric Calibration Assembly (SRCA), with good agreement. The measured differences between the SRCA and our ground scene approach are less than 20m on average for VIS/NIR bands both along-scan and along-track. The differences for SMIR bands are 20m along-scan and 0.1 – 0.18 km for along track. The SMIR FPA crosstalk could be a contributor to the difference. For Aqua MODIS instruments, the spatial deviation is very small between the bands located on the same FPA or between VIS and NIR FPAs but is relatively large between warm (VIS and NIR) and cold (SMIR and LWIR) FPAs. The spatial deviation for MODIS/Terra can be ignorable but not for MODIS/Aqua. The results from this study show that the spatial deviation of Aqua MODIS may impact on the science data when multi-band data from both warm and cold FPAs is combined.

Keyword: MODIS, spatial characterization, BBR, SRCA,

INTRODUCTION

MODerate resolution Imaging Spectro-radiometer, one of the sensors for NASA's EOS mission, is of great importance in diversified scientific research areas, such as land, ocean, and atmosphere. The MODIS on board Terra spacecraft was launched on December 18, 1999 and the MODIS on Aqua spacecraft was launched on May 4, 2002. The Terra spacecraft crosses the equator at 10:30 AM and the Aqua spacecraft crosses the equator at 1:30 PM. Both Terra and Aqua MODIS are operated at a sun-synchronous orbit with the altitude of 705km, observing the earth with thirty-six spectral bands at three different nadir spatial resolutions: 250m, 500m, and l000m [1, 2].

MODIS has been widely used for land, ocean, atmosphere area, devoted in observing the globe climate change, land cover change, detecting the fires, hurricane, dust storm, generating a set of indices, such as NDVI (Normalized Difference Vegetation Index), NDSI (Normalized Difference Snow Index), NDWI (Normalized Difference Water Index) and so on. Because of MODIS wide application areas, the accuracy of measurements is the most critical specification that the scientists and researchers typically pay great attention to.

MODIS has a set of On-Board Calibrators (OBCs) designed for instrument on-orbit characterization including solar

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diffuser (SD), solar diffuser stability monitor (SDSM), blackbody (BB), Space-view (SV) and the Spectro-Radiometric Calibration Assembly (SRCA) [3, 4]. The SD and SDSM are used for radiometric calibration of reflective solar bands (RSB) and the blackbody is for thermal emissive bands (TEB). SV provides the back ground signal, a data point with zero radiance. The SRCA, as an independent device within MODIS instrument, can work at three calibration modes: radiometric, spatial, and spectral. It has the capability of tracking the Band-to-Band Registration (BBR) shift during MODIS entire mission. With the operation of MOIDS/Terra for more than 6 years and MODIS/Aqua for about four and half years, the substantial spatial deviation exists between cold and warm FPAs for Aqua MODIS but is negligible for Terra MODIS.

In order to validate the spatial characterization results for the SRCA and serves as the complement for real time measurement, we calculated the spatial deviation using ground measurements (GM) at a particular site. Additionally, using GM to track the spatial characterization is helpful for the sensors which have no on-board spatial characterization capability. For example, two targets including berms between agricultural fields at the Maricopa Agricultural Center, Arizona and the Lake Pontchartrain Causeway, Louisiana are applied for spatial characterization of the NASA EO-1 Advanced Land Imager sensor [5].

Since MODIS has daily global coverage, the approximate real time spatial deviation can be calculated if the measurement is qualified. The specific site chosen for MODIS spatial characterization is located at the Libya desert in Africa, where a series of dark circular targets are arranged regularly. The spatial deviation results computed from the ground measurements are consistent with the results derived by the SRCA. The maximum spatial deviation of MODIS/Aqua is up to one pixel (500m spatial resolution) between warm and cold FPAs.

In this paper, the instrument background and the SRCA is briefly introduced in section two. In section three, we illustrated the approach used for calculating the spatial deviation both along-track and along-scan using ground targets in details. The spatial deviation impact on current MODIS products is discussed in section four.

Our calculation demonstrates that the careful selected ground targets can be utilized to determine band to band registration in both along-scan and along-track. This is important for majority of remote sensing instruments without on-board devices for BBR measurements. Evident band to band mis-registration can be detected and to be considered for correction in the products of data application.

INSTRUMENT BACKGROUND

MODIS instrument has 36 spectral bands located on four FPAs: Visible (bands 3-4, 8-12), Near Infrared (bands 1-2, 13-19), Short-and Middle-Wavelength Infrared (bands 5-7, 20-26), and Long-Wavelength Infrared (bands 27-36). Figure 1 is the MODIS optical system. The dichroics separate the incoming beam to different FPAs. The four FPAs are carefully aligned prelaunch using high-precision theodolite. In along-scan direction, the electronic phase-delay can be applied to each FPA to adjust the sampling starting time by a step size equivalent to one tenth of 1km Instant Field-Of-View (IFOV) so that the FPA in along-scan direction can be electronically shifted instead of physically shifting the FPAs for registration.

The BBR was measured by a ground calibration device called Integration Alignment Calibrator, IAC, at the instrument vendor. At near the same time and test environment, the SRCA was operated in spatial mode. Because the SRCA fills only 1/5 of the MODIS aperture size, the measurement results from IAC and the SRCA have some difference. The difference is served as bias and is assumed unchanged. On-orbit, the SRCA is operated at a designed time period which allows measurement of BBR change from pre-launch to on-orbit and throughout the MODIS life-time.
In pre-launch measurement, the SRCA measured Band-to-Band Registration (BBR) in both along-scan and along-track direction. The SRCA has a rectangular reticle covering 5km IFOV along-scan and 12km IOFV along-track to measure BBR along-scan. The illuminated reticle is sharply imaged onto four FPAs and is scanned across all MODIS bands/detectors. Several illumination levels are available so that the best SNR can be obtained from one of the illumination level for each band. The along-track reticle is formed by four small rectangular reticles. When the reticle scans across the detectors, different detectors are illuminated fully or partially [6]. The band centroid position along-track can be determined. Table 1 listed the average BBR shift of band 1-7 for two MODIS instruments in both along-track and along-scan directions. The left side listed the results of Terra MODIS and the results of Aqua MODIS displayed on the

right side.

Table 1. The average BBR shift measured by the SRCA for band 1-7 in both along-track and along-scan directions

Terra/MODIS	Along-scan(m)	Along-track(m)	Aqua/MODIS	Along-scan(m)	Along-track(m)
Band 1	0	0	Band 1	0	0
Band 2	20	0	Band 2	-4	0
Band 3	-28	4	Band 3	30	-9
Band 4	-40	16	Band 4	4	-38
Band 5	40	52	Band 5	-246	366
Band 6	46	18	Band 6	-285	382
Band 7	33	86	Band 7	-223	409

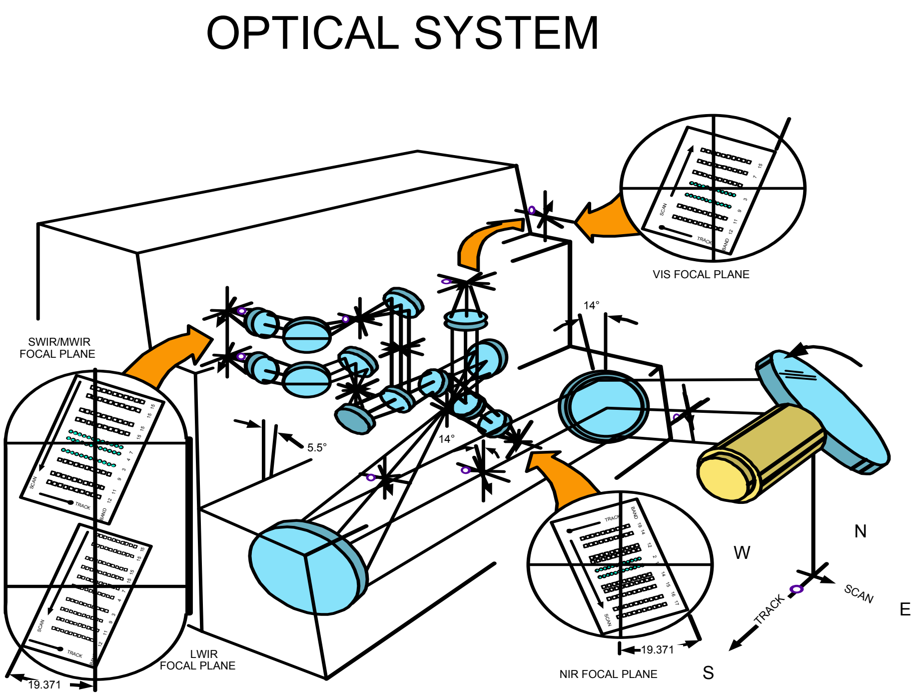

Figure 1. MODIS optical system

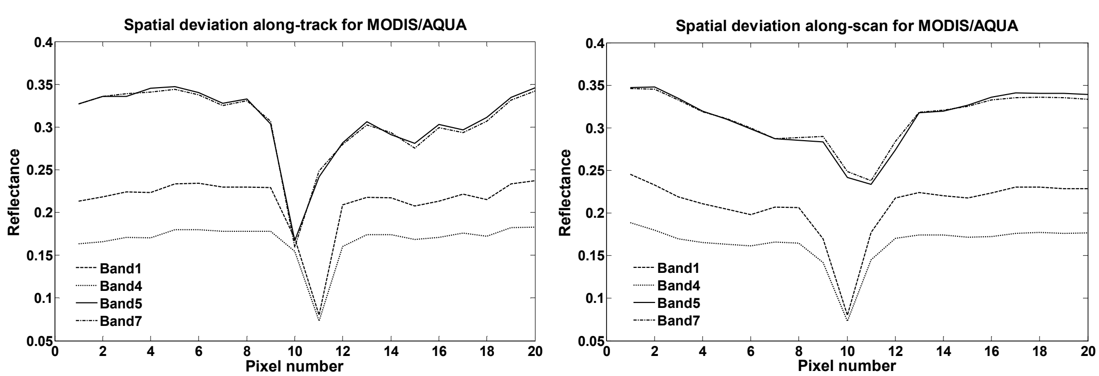

Figure 2 (a) Spatial deviation between VIS and SMIR FPAs along-track for Aqua MODIS
(b) Spatial deviation between VIS and SMIR FPAs along-scan for Aqua MODIS

For Aqua MODIS, it was detected a major shift between VIS/NIR and SMIR/LWIR FPAs after a second vibration test of the MODIS instrument pre-launch. No adjustment was made to the instrument. The mis-registration of these two FPA groups has been remained since. After Aqua MODIS was launched, it has been detected that the BBR of the four FPAs had some relative shifts. The BBR was then stabilized after MODIS was on-orbit for three months. Aqua MODIS BBR mis-registration becomes a petty to the science applications.

SPATIAL CALIBRATION WITH GROUND MEASUREMENTS

The SRCA onboard both MODIS/Terra and MODIS/Aqua works very well on-orbit, so far, measuring the on-orbit BBR shift of the detectors/bands in cross-track and cross-scan directions. Using ground measurements at the specific site to calculate the spatial deviation is one of the appropriate approaches for validating the results of SRCA and serving as the complementary for real time measurements. In this study, we only compute the spatial deviation for band 2-7 relative to band 1 with MODIS L1B 500 meter spatial resolution measurements. This approach is also useful to track the BBR for the sensors which have no on-board spatial characterization capability and provide the experience for the design of next generation sensors.

1. Examples of spatial deviation

Figure 2 is an example showing that the spatial deviation exists between different FPAs in both along-track and along-scan direction on 11:50am, Jan 4th 2003. There is one dark target located at the center of selected area, which has lower reflectance than its neighboring pixels. The view angle (order of pixel number) that the sensor observes the same target should be identical for all bands if there is no BBR shift. In figure 2(a), band 1 and band 4, located at the warm FPA, scan the dark target at pixel number 11 in along-track direction but band 5 and band 7, located at the cold FPA, observe the same target about one pixel early. Similarly, in figure 2(b), band 1 and band 4 scan the dark pixel at pixel number 10 but band 5 and band 7 observe the dark target about one pixel later in along-scan direction. Approximate one pixel (500 meter at the nadir area) difference between cold and warm FPAs demonstrates the existence of spatial deviation which can be found in both two directions using ground measurements.

2. The site used for spatial calibration

With the observation and filtering, a specific site located at the Sahara desert in Libya, Africa is appropriate for spatial characterization, in which more than one hundred dark targets are arranged regularly. The latitude of this site covers from 26.5 North to 28.0 North and the longitude is from 21.5 East to 22.5 East. The RGB (Red, Green, and Blue) image of this site with remote sensing measurements is shown in top left of figure. The left images in figure 3 displays the Google images of this site with three different spatial resolutions. A series of orderly arranged dark targets in this site can be recognized. If the spatial deviation exists, all bands observe the same target in different view angle. The difference of view angle between two bands is defined as the spatial deviation.

3. Data

As mentioned, MODIS observes the Earth at the 705km sun-synchronous orbit in three kinds of moderate spatial resolutions, providing almost daily global coverage except some gaps in equatorial area. We can have two pictures per day for the specified site for our spatial characterization study: one is the measurement in the unit of reflectance or radiance in daytime for all thirty-six bands and the other is the measurement in the unit of brightness temperature (BT) in nighttime only for thermal emissive bands (band 20-36). Based on the daily GM, we can track approximately real time BBR shifts. Not all the measurements, however, are qualified for spatial characterization. Only the measurements that satisfied two basic requirements are considered and selected for calculating the spatial deviation. One requirement is that the measurements are clear scene in which there are no cloud, dust storm, snow and so on. The other is that the selected site (the area shown in figure 3) must be located at the nadir area (sensor view angle less than ±15 degrees).

The MODIS Level 1B (L1B) data are used broadly, which are well-calibrated and geo-located from Level 1A (L1A) data. Each granule of MODIS L1B data is comprised of the measurements in 5 minutes, coving the area with 2030 (along-track) multiplies 1354 (along-scan) pixels for 1km spatial resolution. Therefore, there are 8120×5146 pixels for 250m spatial resolution bands and 4060×2708 pixels for 500m spatial resolution bands. Since all selected measurements meet our requirement two, only the pixels located at nadir range in each qualified granule are selected for computing the spatial deviation.

In this study, we selected the L1B measurements at the site from January 1st 2003 to January 16th 2003 for calculating the sixteen-day averaged spatial deviation for 500m spatial resolution bands (band 1-7) because the high spatial resolution measurement can provide more accurate results than using 1km spatial resolution measurements. For band 1 and band 2, the 500 meter spatial resolution measurements are aggregated from the 250m spatial resolution measurements.

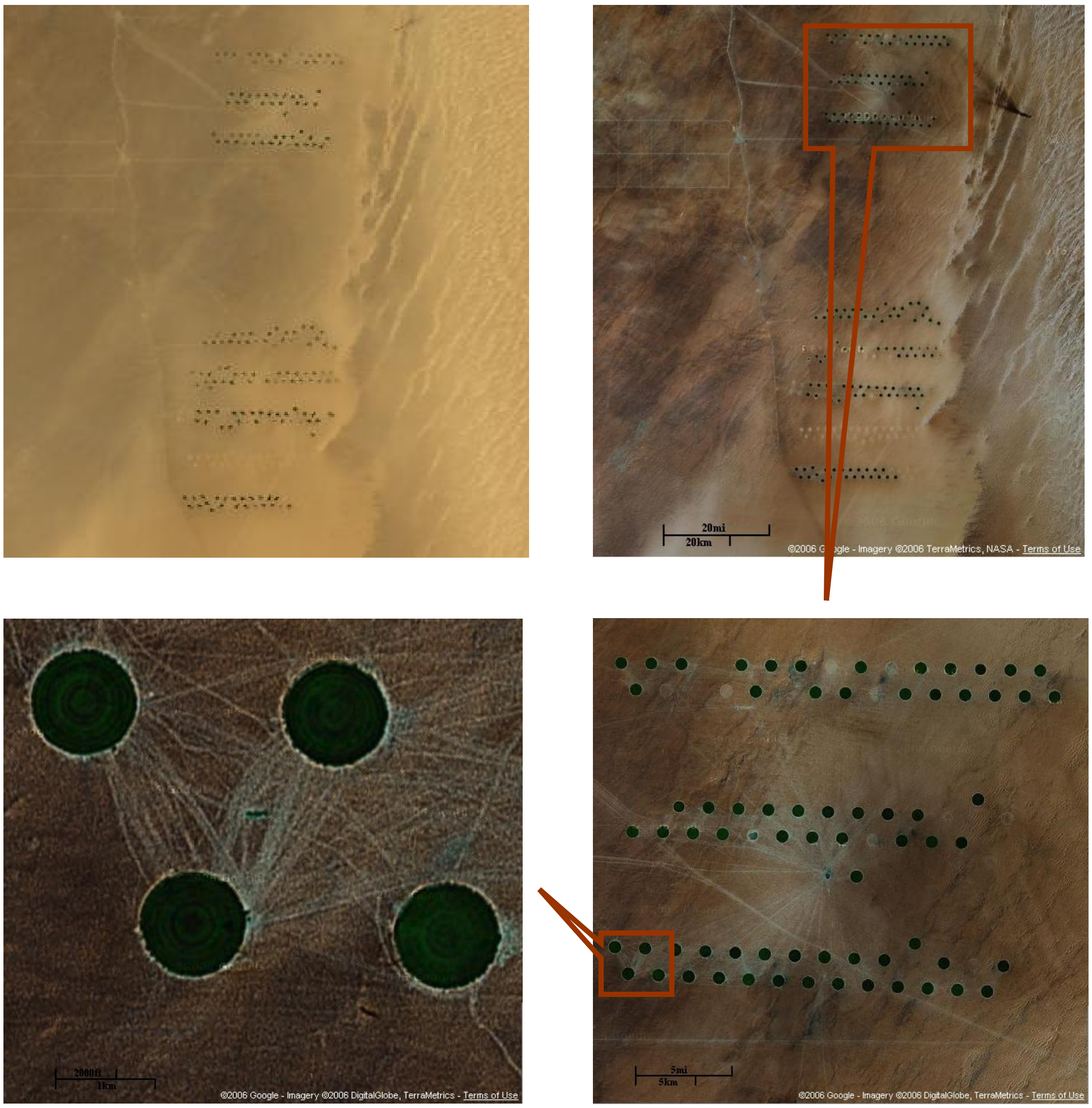

Figure 3. The image in the top left is MODIS RGB image for the select area (Latitude: 26.5N-28.0N, Longitude: 21.5E-22.5E) generated by the software ENVI in 500 meter spatial resolution. The left images are Google's images with difference enlargements for the same site (Courtesy of Google).

4. Algorithm for spatial calibration

A series of dark targets arranged regularly in selected area is specially helpful for spatial calibration with ground measurements. When sensor scans the surface in along-track or along-scan direction, several signal valleys were observed in which the reflectance changes dramatically from bright pixel to dark one then to bright one again. Figure 4 and figure 5 are examples of reflectance curve in both scan and track directions for two the MODIS instruments.

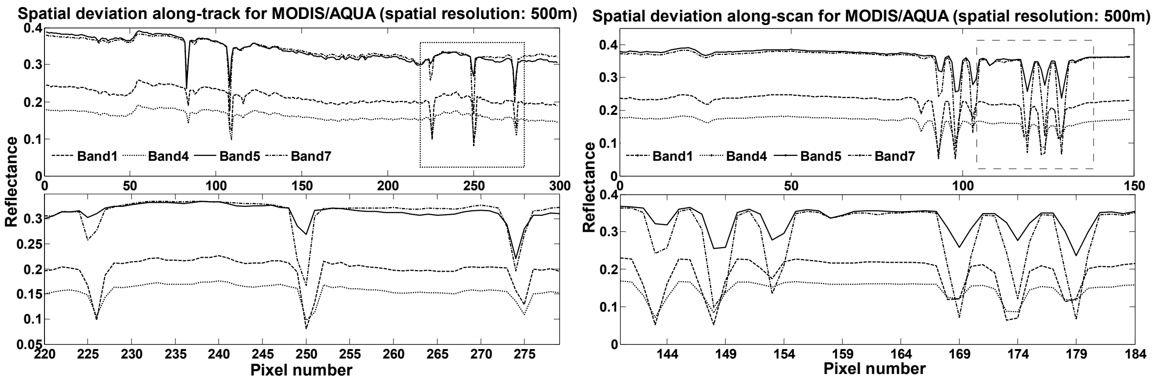

Figure 4. Spatial deviation for MODIS/Aqua
Left: reflectance curve in along-track direction. Right: reflectance curve in along-scan directions

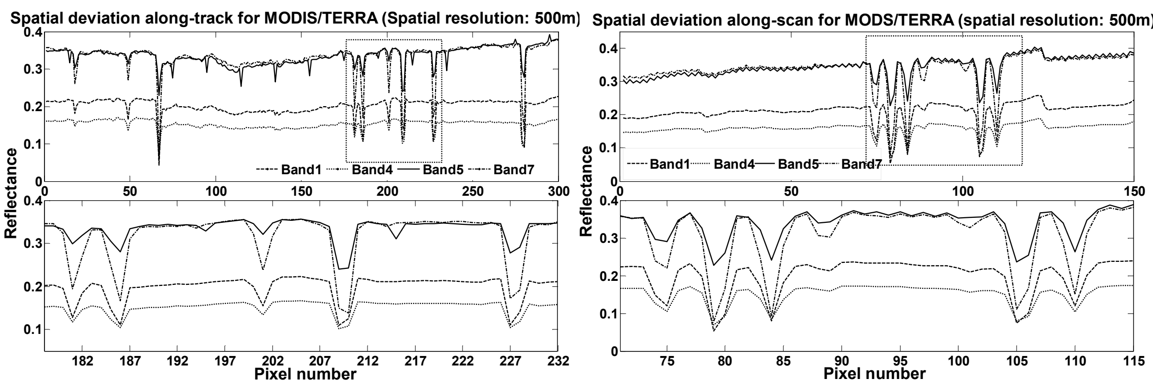

Figure 5. Spatial deviation for MODIS/Aqua
Left: reflectance curve in along-track direction. Right: reflectance curve in along-scan directions

In these figures, the left column is for along-track direction and the right column is for cross-track direction. In both directions, we observe several signal valleys appeared in the reflectance curve because of existence of dark pixels. These valleys, met our threshold, are selected to calculate the centroid location of this valleys. Therefore, the difference of the centroid location of certain valleys between two bands is considered as spatial deviation. According to these two figures, the reflectance curve of band 2 is almost same as that of band 1 for both MODIS/Terra and MODIS/Aqua.

The centroid location value of certain valleys, A_{ij}, can be derived with the normalization, expressed in equation (1),

$$A_{ij} = \frac{\sum_{a_{ijk_1}}^{a_{ijk_2}} a_{ijk} \cdot R_{ijk}(a_{ijk})}{\sum_{a_{ijk_1}}^{a_{ijk_2}} a_{ijk}} \tag{1}$$

where a_{ijk} is the pixel number (the observed pixel of the sample area or view angle) of valley j, band i and R_{ijk} is the reflectance value of the pixel a_{ijk}. The data points in the range between a_{ijk1}, and a_{ijk2} are resampled to calculate the centroid location value, A_{ij}. Five pixels of each valley are computed in our algorithm.

The centroid location of a certain band I, A_i, is the average of all the centroid location values, A_{ij}, given by equation (2). n is the total number of the valleys in qualified L1B measurement in sixteen days. The n is equal to 7.

$$A_i = \frac{\sum_{j=1}^{n} A_{ij}}{n} \quad (2)$$

Thus, the spatial deviation of band i relative to band k can be calculated by equation (3).

$$\Delta A_i = A_i - A_k \quad (i \neq k) \quad (3)$$

5. Results

The sixteen-day (from January 1st 2003 to January 16th 2003) averaged spatial deviation for both MODIS/Terra and MODIS/Aqua is calculated with qualified L1B measurements and the results are given in Table 2 (Aqua MODIS) and Table 3 (Terra MOIDS). In these two tables, the results in lower left triangle are for along-track direction and those in the upper right triangle are for along-scan direction. All the results are the spatial deviation between two bands. For an instance, the spatial deviation of band 2 relative to band 1 in along-track direction for Aqua MODIS is -2 meters (column two, row 2 in Table 2). The spatial deviation band 6 relative to band 3 in along-scan direction for Terra MODIS is 41 meters (column 7, row 4 in Table 3).

Table 2. The spatial deviation for band 1-7 of MODIS/Aqua

Band	1	2	3	4	5	6	7
1		0	1	-13	-261	-217	-219
2	-2		1	-13	-261	-217	-219
3	-46	-44		-14	-262	-218	-220
4	-55	-53	-9		-248	-204	-206
5	244	246	290	299		44	42
6	167	169	213	222	-77		-2
7	219	221	265	274	-25	52	

Table 3. The spatial deviation for band 1-7 of MODIS/Terra

Band	1	2	3	4	5	6	7
1		0	-27	-15	2	14	13
2	-6		-27	-15	2	14	13
3	-11	-5		12	29	41	40
4	-6	-0	5		17	29	278
5	-45	-39	-34	-39		12	11
6	-41	-35	-30	-35	4		-1
7	-44	-38	-33	-38	1	-3	

Table 4. The comparison between the spatial deviation from the ground measurements and that from the SRCA for MODIS Terra and Aqua in both along-track and along-scan directions.

MODIS	Direction/Measurement	Band2	Band3	Band4	Band 5	Band 6	Band 7
Aqua	Along-track/GM[1]	-2	-46	-55	244	167	219
	Along-track/SRCA	0	-9	-38	366	382	409
	Along-scan/GM	0	1	-13	-261	-217	-219
	Along-scan/SRCA	-40	30	4	-246	-285	-223
Terra	Along-track/GM	-6	-11	-6	-45	-41	-44
	Along-track/SRCA	0	4	16	52	18	86
	Along-scan/GM	0	-27	-15	2	14	13
	Along-scan/SRCA	20	-28	-40	40	46	33

1: GM is the abbreviation of Ground Measurement

Table 4 gives the comparison between the spatial deviation from the ground measurements and that from the SRCA for MODIS Terra and Aqua in along-track and along-scan directions. For Aqua MODIS, the average differences between the SRCA and GM are: 2m (scan) and 19m (track) for VIS/NIR FPAs; 19m (scan) and 176 m (track) for SWIR FPA. For

Terra MODIS, the average differences between the SRCA and GM are: 2m (scan) and 14m (track) for VIS/NIR FPAs; 30m (scan) and 95m (track) for SWIR FPA. The difference in along-scan is smaller than along-track especially the along-track for SWIR FPA. The biggest difference is 0.1km for Terra and 0.18km for Aqua.

The MODIS/Aqua spatial deviation between the bands at the same FPA and that between the VIS and NIR is so small that its impact on the scientific data can be neglected but the deviation between warm FPA and cold FPA is large, up to one pixel. The shift for MODIS/Aqua along-track has the opposite sign from the along-scan deviation.

POTENTIAL APPLICATION

The results from Table 2 and Table 3 illustrate the existence of the substantial spatial deviation between warm FPA and cold FPA for Aqua MODIS, which will cause impact on the science data when multi-band measurements from these two FPAs are combined. For example, NDSI (Normalized Difference Snow Index) is an index to describe the snow covering. For Aqua MODIS, NDSI is defined as the normalized ratio of band 4 and band 7, (Band 4-Bang7)/(Band 4+Band7). Band 6 data is not in use because it has more than half of non-functional detectors. About one pixel mis-registration between these two bands will bring the uncertainty to the final snow index especially for the margin of snow area. With the preliminary results validated by the Terra MODIS measurements, the NDSI will be improved with shifting one pixel along-track direction to eliminate the mis-registration.

SUMMARY

Using the ground measurements is one of effective approaches for validating the results and serving as the complement of the on-board calibrator, the SRCA. With the observation and filtering, a specific site located at Sahara desert in Libya, Africa is selected for spatial characterization, where more than one hundred dark targets are regularly arranged. All the measurements of this site that satisfied two basic requirements are considered as qualified measurements and used for calculating the sixteen-day average spatial deviation.

The spatial deviation averaged over 16 days of 500 meter spatial resolution bands are calculated. The results are compared with that measured by the SRCA with good agreement of <30m for both Terra/Aqua in along-scan direction and the along-track direction for Terra. The agreement is not as good for SMIR FPA in along-track direction. The difference between the SRCA and the ground approach is 95m for Terra and 176m for Aqua.

The spatial deviation of MODIS/Terra is small with negligible impact on the science data. That is not the case for MODIS/Aqua, however, where the spatial mis-registration is relatively large and its impact on the science data should be evaluated. The spatial deviation among the bands located at the same FPA and that between VIS FPA and NIR FPA is relatively small. The spatial deviation between warm FPA (VIS and NIR) and cold FPA (SWIR) is relative large for Aqua MODIS. Therefore, the uncertainty caused by the spatial deviation to the science data may need correction when multi-band data is combined if high accuracy is required.

The success of our proposed approach provides an effective way for the sensor without on-orbit calibrators to track the spatial characterization during mission lifetime. This approach is useful for the further remote-sensed satellite imagers.

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