Status of Aqua MODIS Spatial Characterization and Performance

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Abstract

NASA's EOS Aqua spacecraft was launched on May 04, 2002. The Moderate Resolution Imaging Spectroradiometer (MODIS) is one of the six Earth-observing sensors aboard the EOS Aqua spacecraft. MODIS is the highest spatial resolution instrument on the Aqua platform with data products generated in 250m, 500m, and 1000m resolutions (nadir). It has 36 spectral bands, a total of 490 detectors, located on four focal plane assemblies (FPAs) with two of them controlled during operation at 83K by a passive radiative cooler. In addition to radiometric calibration and spectral characterization, MODIS spatial performance was extensively characterized pre-launch, including measurements of band-to-band registration (BBR), FPA to FPA registration (FFR), line spread function (LSF), modulation transfer function (MTF), and instantaneous field-of-view (IFOV). The sensor's spatial characterization is monitored by an on-board calibrator, the spectro-radiometric calibration assembly (SRCA). In this paper, we will briefly describe MODIS SRCA spatial characterization methodologies and operational activities. We will focus on the sensor's spatial performance using four years of on-orbit observations and, consequently, evaluate the SRCA's performance. On-orbit results of key spatial characterization parameters (BBR, FFR, and MTF) will be examined and compared to pre-launch measurements and design requirements.

1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) was designed to make improved measurements compared to heritage sensors, in spatial, spectral, and temporal scales for the NASA Earth Observing System (EOS)[1-2]. It has 36 spectral bands with wavelengths from 0.41 to 14.4μm and spatial resolutions of 250m (bands 1-2), 500m (bands 3-7), and 1km (bands 8-36) at nadir. The MODIS proto-flight model (PFM) on the EOS Terra spacecraft was launched on December 18, 1999. Flight model 1 (FM1) aboard the EOS Aqua spacecraft was launched on May 4, 2002. Since launch, both MODIS instruments, with Terra operated in a 10:30am (morning) orbit and Aqua in a 1:30pm (afternoon) orbit, have been producing continuous and complementary global data sets for a broad range of applications. MODIS observations in both the reflective solar region and thermal emissive region have successfully extended the data records from heritage sensors and greatly enhanced our understanding of the Earth system and its changes with many new science data products.

The 250m, 500m, and 1km spatial resolution bands each have 40, 20, and 10 detectors, respectively, aligned in the along-track direction. Bands 13 and 14 each use a pair of 10 detectors to collect data with both high and low gains through time-delay and integration (TDI). Thus MODIS has a total of 490 detectors. MODIS spectral bands and detectors are located on four focal plane assemblies (FPAs): visible (VIS), near infrared (NIR), short- and mid-wave infrared (SMIR), and long-wave infrared (LWIR) as shown in Figure 1. The VIS and NIR are operated at instrument ambient while the SMIR and LWIR are controlled at 83K via a passive radiative cooler. Bands 1-19 and 26, with wavelengths from 0.41 to 2.2μm, are the reflective solar bands (RSB) and bands 20-25 and 27-36, with wavelengths from 3.5 to 14.4μm, are the thermal emissive bands (TEB). In addition to radiometric calibration and spectral characterization, MODIS spatial characterization was extensively conducted pre-launch, including measurements of band-to-band registration (BBR), FPA to FPA registration (FFR), line spread function (LSF), modulation transfer function (MTF), and instantaneous field-of-view (IFOV). On orbit, the sensor's spatial characterization is monitored by an on-board calibrator, the spectro-radiometric calibration assembly (SRCA).

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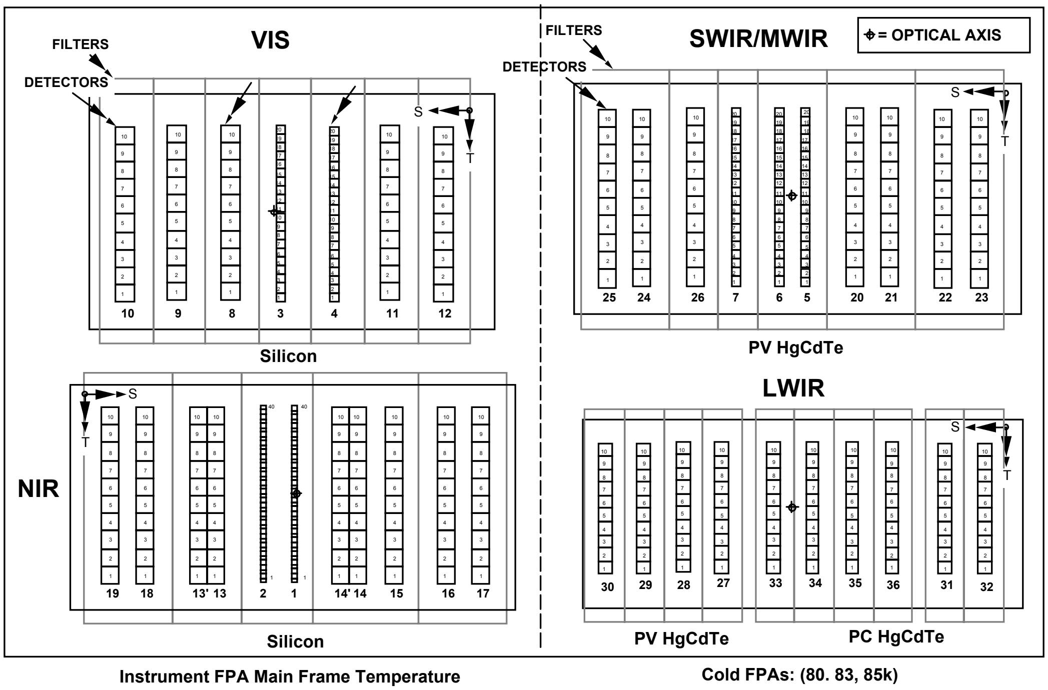


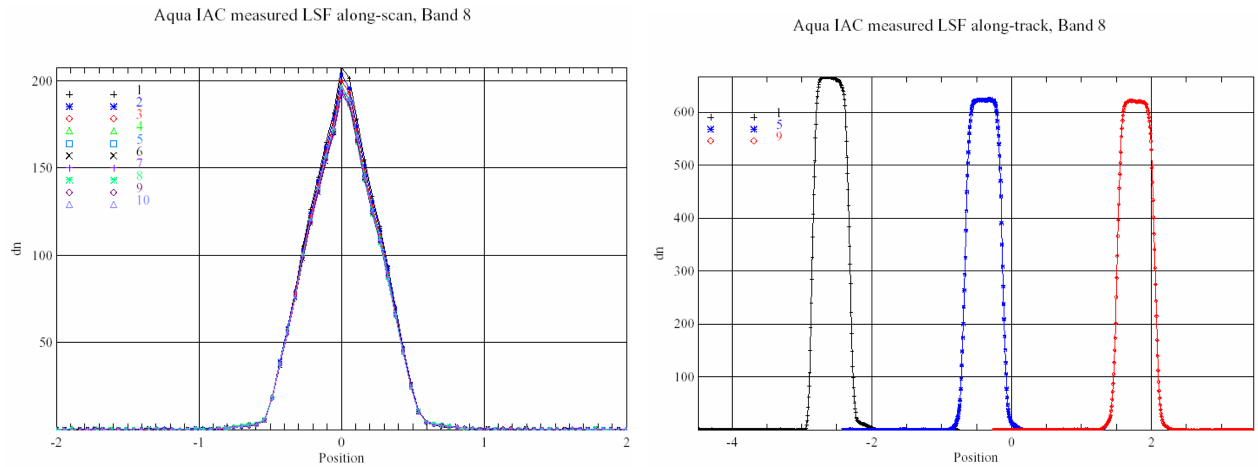
Figure 1: MODIS focal plane assemblies (FPAs): visible (VIS), near infrared (NIR), short- and mid-wave infrared (SMIR), and long-wave infrared (LWIR).

This paper briefly describes the MODIS pre-launch spatial characterization activities. It also presents on-orbit spatial characterization methodologies with a focus on Aqua MODIS SRCA operational activities and spatial characterization performance using four–years of on-orbit observations. On-orbit measurements of key spatial characterization parameters, such as BBR, FFR, and MTF, will be evaluated and compared to pre-launch measurements and design requirements. The BBR is an important parameter needed for the images and data products derived from multiple spectral bands. It was found from pre-launch spatial characterization that Aqua MODIS had large band-to-band mis-registration between bands on the warm FPAs (VIS and NIR) and cold FPAs (LWIR). Therefore this problem has been carefully examined in this paper in terms of the BBR magnitudes and stability using Aqua MODIS SRCA on-orbit observations over the last four years.

2. MODIS SPATIAL CHARACTERIZATION PRELAUNCH

MODIS spatial characterization was measured prelaunch by a ground calibration source named the Integration and Alignment Collimator (IAC) at the instrument vendor. The characterization tests covered the entire 36 MODIS bands. A set of reticles were utilized for measuring Band-to-Band Registration (BBR) in both the along-scan and along-track directions, Focal plane to Focal plane Registration (FFR), Linear Spread Function (LSF), and Instant Field of View (IFOV) of the detectors.

In the BBR tests, a set of reticles were placed at the focus of the IAC and illuminated. The reticles had a rectangular pattern (along-scan) and a stair-step pattern (along-track). With the MODIS scan mirror rotating, the reticle images were scanned across all bands and detectors. Sample delays of 0.1km IFOV were applied to along-scan BBR test to improve the precision of the test. The along-scan BBR was measured for each detector but the along-track BBR was only measured for three 1-km IFOV detectors because only three stair-step reticle bars were available. The BBR of the other detectors along-track was interpolated from the measured detectors. Figure 2 shows the LSF along-scan (left) and detector response along-track (right) for band 8. All tested detectors are plotted. For along-scan, the centroid value of each LSF determines the detector position. The Full Width Half Maximum (FWHM), which corresponds to the LSF width at half-maximum response, determines the apparent detector size along-scan. The IFOV is calculated by the detector size (mm) divided by the system magnification. The along-track figure shows data for detectors 1, 5, and 9. The centroids of the signals are compared with their ideal detector locations to determine the BBR along-track. Considering the width of the reticle, the LSF is calculated by taking the derivative of the along-track signal profile to eliminate any reticle width impact.



(a) Along-scan reticle response

(b) Along-track reticle response

Figure 2. Aqua MODIS BBR measured by the IAC

After Aqua MODIS had a second vibration test, a shift of the SMIR/LWIR FPAs was detected relative to the VIS/NIR FPAs in both the along-scan and along-track directions. The SMIR/LWIR FPAs had a shift of 0.2 – 0.35km IFOV (fraction of a 1 km IFOV) opposite the along-scan direction and had a shift of 0.2 – 0.4km in the along-track direction. Therefore, the Aqua BBR failed its specification of ±0.1km co-registration in both directions.

3. SRCA AS A TRANSFER DEVICE FROM PRELAUNCH TO ON-ORBIT

The Spectro-Radiometric Calibration Assembly (SRCA) is a unique device. It is a simplified calibration/characterization laboratory within MODIS. The main functions of this device are (1) measuring the BBR and tracking BBR changes for all MODIS bands; (2) measuring the center wavelength shifts and tracking their changes for the Reflective Solar Bands (RSB) ; and (3) tracking changes in the radiometric gain, mirror-side ratio, and subsample ratio (bands 1 – 7) between the RSB detectors. Tracking the spatial and spectral performance changes is unique because there was previously no device on remote-sensing instruments to monitor these parameters over such a long period of time. This tracking provides valuable information to the remote sensing community and is beneficial for the development of future remote-sensing systems.

Figure 3 is a layout of the SRCA. It consists of three subassemblies: a light source, a monochromator/optical relay, and a collimator. The light source includes an integrating sphere for the RSB and a glow bar for the Thermal Emissive Bands (TEB). Four 10W lamps and two 1W lamps are provided so that multi-lamp configurations can be used. The multi-lamp configurations allow each band to be operated at a good SNR level. The SRCA can be operated in constant radiance mode or constant current mode. When operated in constant radiance mode, the output from the integration sphere is measured by a Silicon Photo-Diode to control the broadband output constant. In constant current mode, the lamp current is controlled to be constant by adjusting the lamp voltage. The beam is focused to the entrance opening by merging both the VIR/NIR and SMIR/LWIR illuminations though a beam-combiner. In spatial mode, the grating is replaced by a plain mirror (located on the back side of the grating) and the monochromator becomes an optical relay. The along-scan and along-track reticles are mounted in a wheel and are located at the focus of the SRCA collimator. The reticles are imaged onto the MODIS FPAs. To improve the precision of the tests, the SRCA spatial measurement utilizes sampling via phase-delay in the along-scan BBR measurements. The sampling is delayed by an increasing interval of 0.2 IFOV between scans and the data from the five delays is combined.

The SRCA does not fill the MODIS aperture but only 1/5 of its area. Hence, the SRCA is a transfer device to determine changes between measurements. The SRCA measured the BBR both along-scan and along-track at three temperature plateaus during Thermal Vacuum (TV) pre-launch testing at the instrument vendor. The BBR was measured by the SRCA and IAC in the same test environment and at nearly the same time. The difference in BBR from the two devices is a bias. This bias anchors the SRCA measured BBR results to the IAC results.

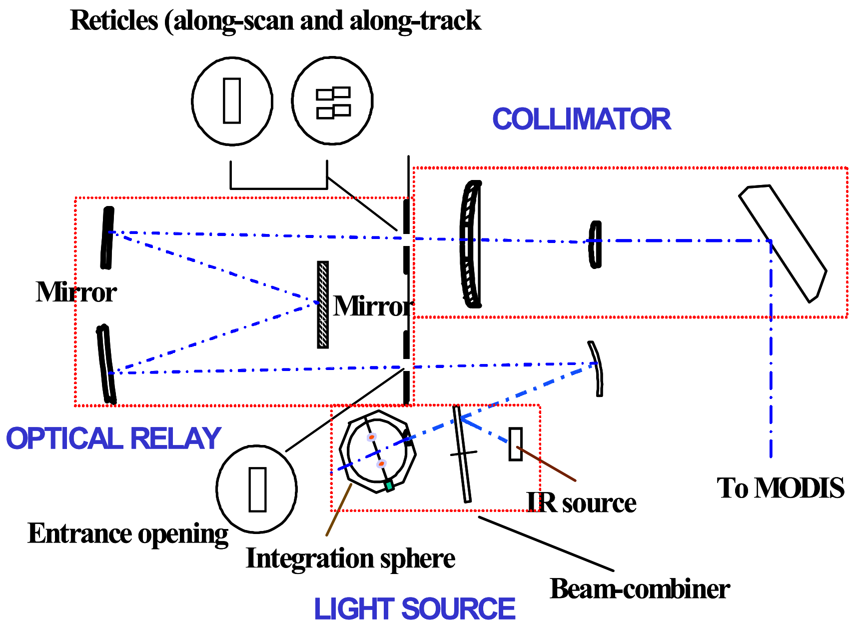


Figure 3. The SRCA layout in spatial mode

The SRCA along-scan and along-track signals are shown in Figure 4. The measurement takes 10 frames. In the along-scan measurement , five phase-delays in steps of 0.2km IFOV are applied so that a total of 50 data points are available. The X-axis value is the frame# + phase-delay# × 0.2. The along-track signal is slightly more complicated. A 2×2 rectangular openings is arranged in step shapes (see Figure 3). When the reticle scans across the detectors, four peaks are formed. Their position along the track direction determines the band position along-track. The detailed algorithms are described in the references[3-5].

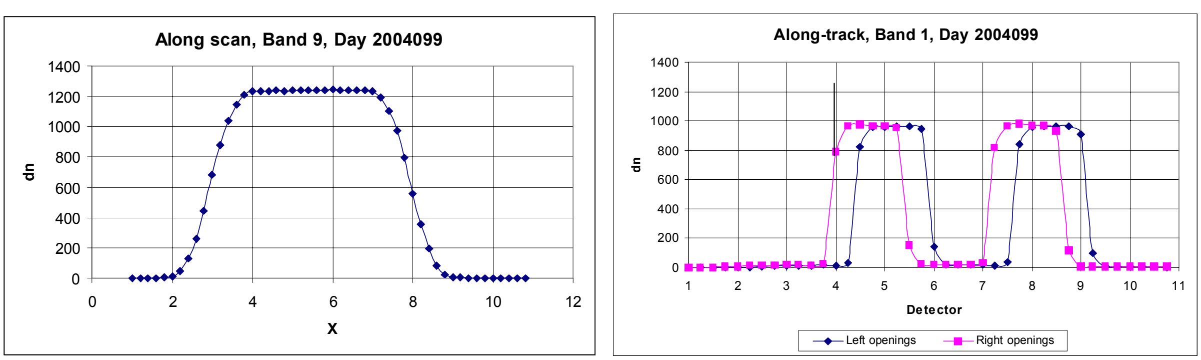


Figure 4. The SRCA measured signal in spatial mode

4. SPATIAL CHARACTERIZATION TRENDING

The SRCA spatial mode was originally performed bi-monthly. When the scan mirror is viewing the SRCA, the Earth scene illumination can pass through the MODIS system and interfere with the measurement. In order to minimize this effect, the SRCA is only operated in the night portion of the orbit.

The along-scan signal profile is named the Combined Aperture Response Function (CARF). Useful information can be obtained from the CARF profile. The centroid values of the CARFs provide the detector position along-scan. The difference in the centroid value, X, from the two mirror sides demonstrates the mirror inclination angle. The centroid X of all detectors in a FPA shows the FPA rotation angle and any changes. The FWHM of the CARF can be utilized to monitor the MODIS-SRCA system change in magnification. If the magnification in one of the FPAs remains unchanged, then the change for the other FPAs can be attributed to magnification changes in the MODIS optical sub-systems. The derivatives of the CARF on both left and right sides give the LSF from which the MTF can be monitored. In the following, we introduce FFR and MTF trending on-orbit.

A total of 22 SRCA operations in spatial mode have been executed over four years. The SRCA lamp was operated in constant radiance mode after launch. To examine the SRCA's health, detector digital counts are tracked to observe if there is any unexpected change between each detector/band. Signal-to-Noise Ratios (SNR) are calculated to check source stability. The most fragile elements are the lamps, especially the 10W lamps, due to their warmer temperature. The lamp current and power are monitored during each measurement. Figure 5 is the SRCA lamp current trending. Vertical lines mark lamp replacement and the time period where the failed lamp was under investigation.

During four measurements between days 316 - 385, it was discovered that one of 10W lamps in the 20W lamp configuration (2-10W lamps) was unstable The four 10W lamps were then lit one by one to find the bad lamp and replace it with the back-up 10W lamp. After day 2005-76, it was found that another lamp in the 20W lamp configuration had failed. A Failure Review Board was established to investigate the problem. A decision was made to change the lamp control mode from constant radiance to constant current mode.Since then, the Aqua SRCA spatial mode has been performed every three months instead of every two months as originally planned.

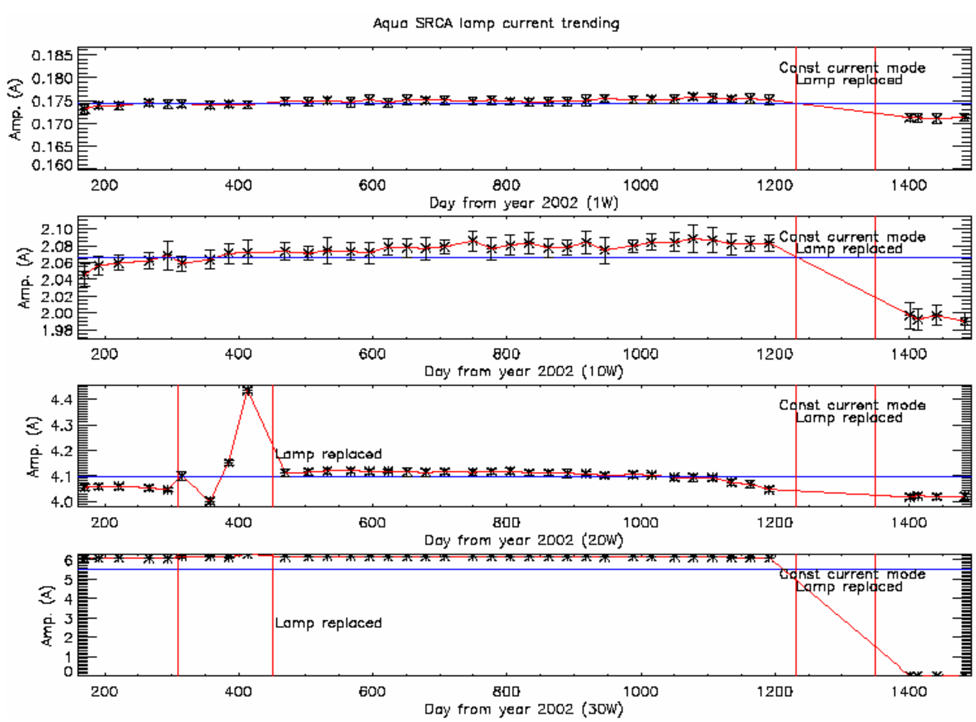


Figure 5. SRCA Lamp current trending

4.1 Band to Band Registration trending

Figure 6 depicts the four-year trending of Aqua MODIS FPA to FPA Registration (FFR) for both along-scan and along-track. The pre-launch value is plotted at day zero for comparison. The first data point is day 170 with the Aqua MODIS nadir door closed (the nadir door was opened on 2002175). All data is normalized to band 1 on the NIR FPA. Hence, the NIR FFR is zero. The VIS FPA variation is within 0.05km. Note that the temperature of the VIS FPA is not controlled. The temperature of the VIS FPA is the instrument temperature. Hence, a temperature dependent variation is shown. This variation is due to an annual instrument temperature variation of ±1K and a slow increase in instrument temperature over time (about 1.7K in four years). The fourth annual cycle should be between days 1200 – 1300. It is not visible due to a failure of a 10W lamp which caused a data gap during the failure investigation.

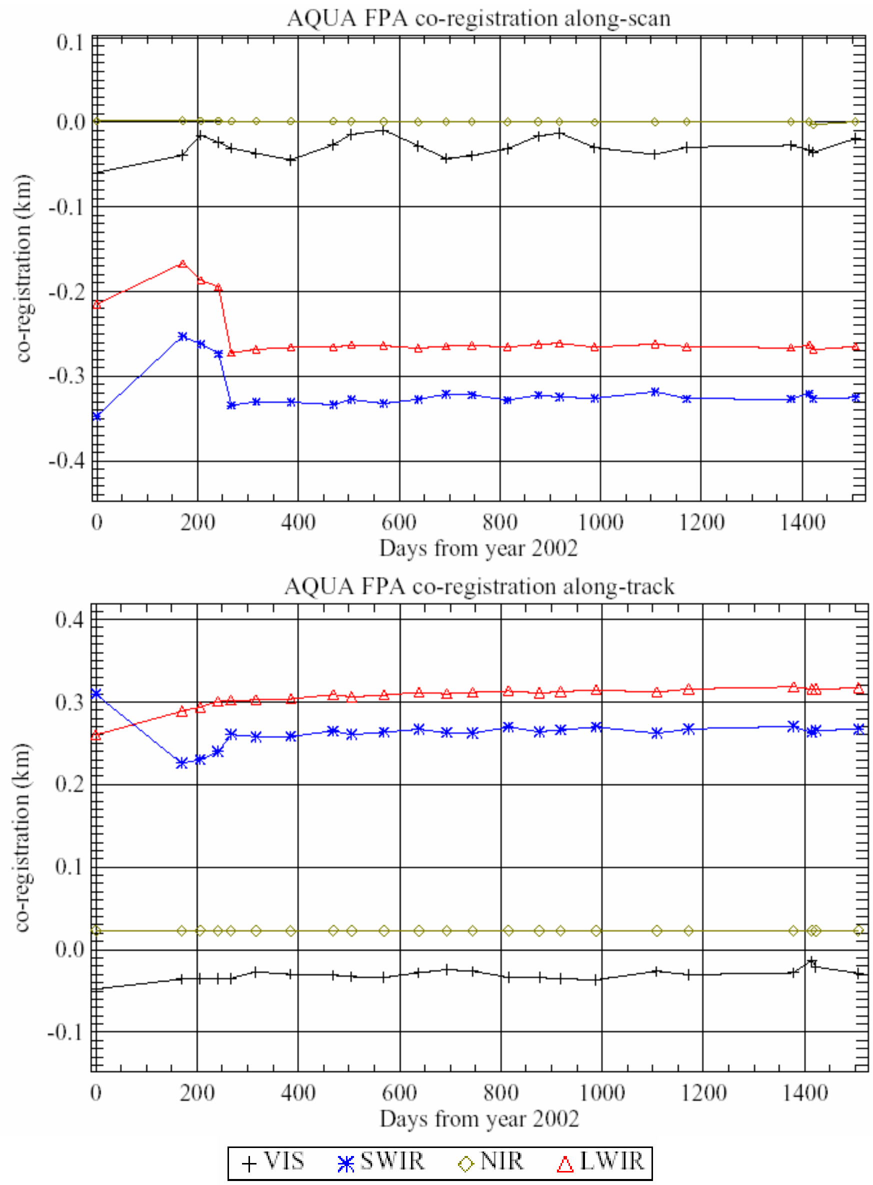


Figure 6. Aqua Focal plane to focal plane co-registration along-scan and along-track

Note that the first three data points after launch differ from the remaining trend for the SMIR and LWIR FPAs. The duration of 90 days is the period during which the instrument was becoming stable. The VIS FPA does not have a noticeable transition time. Over the four-year trending, the BBR change between FPAs is very consistent which demonstrates that the SRCA measurement is stable and precise. The SMIR and LWIR FPAs were shifted prelaunch in the along-scan direction by -0.35 and -0.21km IFOV, respectively. On orbit, the four FPAs have shifted by 0.02km (VIS), 0.11 km (SMIR), and 0.05km (LWIR). After the instrument stabilized, they have remained at their new positions which differ by only a limited amount from their pre-launch positions: 0.04km (VIS), 0.03km (SMIR) and 0.05km (LWIR) relative to the NIR FPA.

The along-track VIS FPA also has an annual variation. The temperature coefficient is about 0.005km IFOV/K. The SMIR and LWIR had a mis-registration of 0.31km and 0.26km pre-launch. After the instrument stabilized, the VIS FPA shifted 0.01km, the SMIR FPA -0.05 km and the LWIR 0.04km in comparison with the pre-launch data. Figure 7 shows yearly-averaged BBR for MODIS' 36 bands along-scan and along-track. The units are 1km IFOV.

In summary, the BBR on-orbit changes over more than four years are within 0.05km both along-scan and along-track.

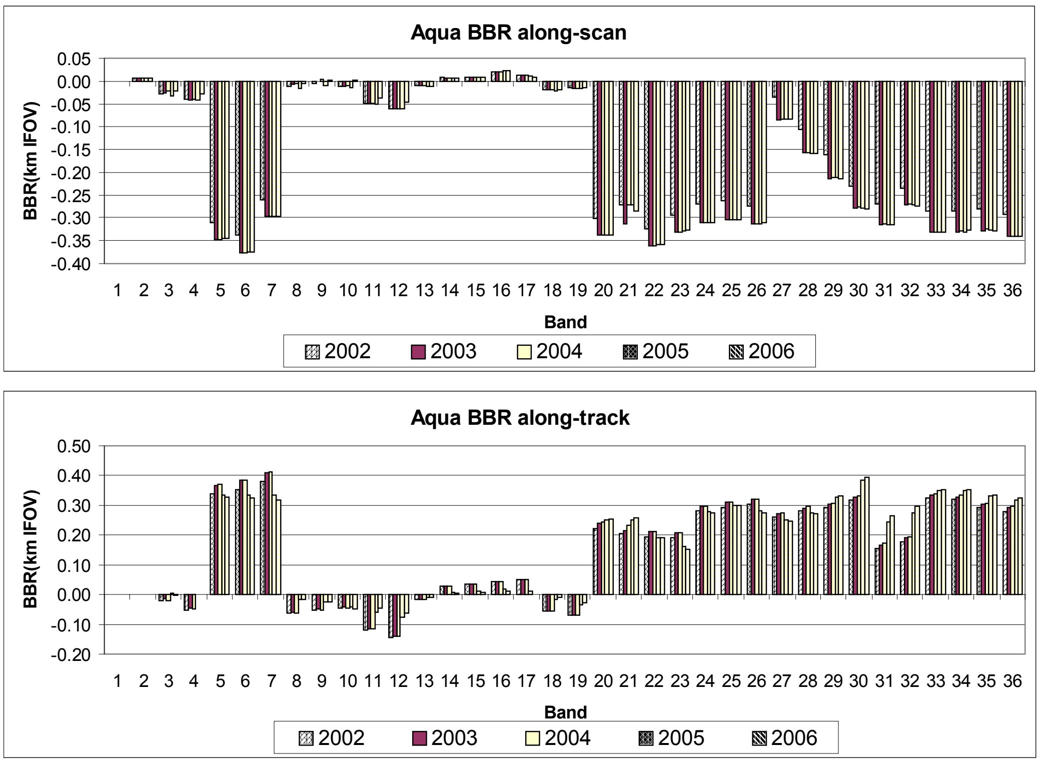


Figure 7. BBR trending (year average) along-scan and along-track

4.2 MTF trending

The LSF of Aqua MODIS was measured pre-launch both along-scan and along-track. The measurements were performed with the scan mirror rotating. Hence, the along-scan LSFs contain blur effects due to the mirror rotation during the signal integration time. Narrow slits (0.2km IFOV for the 1km IFOV bands and 0.1km IFOV for the smaller resolution bands) were illuminated and scanned across all detectors of the 36 bands. Phase-delay was utilized to measure the LSF at 0.1 IFOV spacing. The measurement was at ambient condition with the SMIR/LWIR FPAs cooled by a bench-cooler.

The Fourier Transform of the LSF is the Modular-Transfer Function (MTF). The specification require that the MTF along track and along scan be greater than 0.9 $@f/f_{NYQ} = 0.25$, 0.7 $@f/f_{NYQ} = 0.50$, 0.5 $@f/f_{NYQ} = 0.75$, 0.3 $@f/f_{NYQ} = 1.00$, where f_{NYQ} is the Nyquist frequency.

The Nyquist frequency is calculated by

$$f_{NYQ} = \frac{1}{2 \cdot dis} \tag{1}$$

where dis is the detector size. A knife-edge reticle was utilized in the SRCA LSF measurements. The LSF is the derivative of the knife-edge response. The reticle image scans across the detector solely in the scan direction. Hence, the along-track MTF is not available. Because the SRCA spatial characterization was conducted in thermal vacuum, the test conditions were close to the on-orbit environment.

Note that the SRCA only partially fills the MODIS aperture and that the focal length of the SRCA is shorter than that of MODIS. A question is raised as to whether the SRCA measured MTF is of sufficient quality to be comparable to that from the IAC. Although the SRCA measured MTF may not be as precise as the IAC measurement, the SRCA is capable of accurately tracking changes in MTF. Ground measurement has demonstrated that the SRCA does track the MODIS MTF. Four–years of on-orbit operation of the SRCA has proven that the SRCA is very stable. Hence, the MTF trending can be trusted.

Figure 8 shows the SRCA measured initial on-orbit MTF at and the MTF four years later. All detectors are marked and the specifications are shown as horizontal lines. Data from Bands 5-7 was contaminated by crosstalk and is not shown. Band 21 has very low signal so its MTF is low. There are only four plots to compare with the specification since the f/f_{NYQ} equals one when the MTF is normalized to the calculation at zero frequency. For the VIS/NIR bands, the MTF change is tiny. The bands on the NIR FPA have not changed while the bands on the VIS FPA show a small improvement. We have mentioned that the BBR for the SMIR/LWIR was not stabilized in the first three months. The MTF was in the same situation. The MTF gradually improved during this period and then stabilized. The figure shows that the MTF has improved on-orbit for the SMIR/LWIR bands.

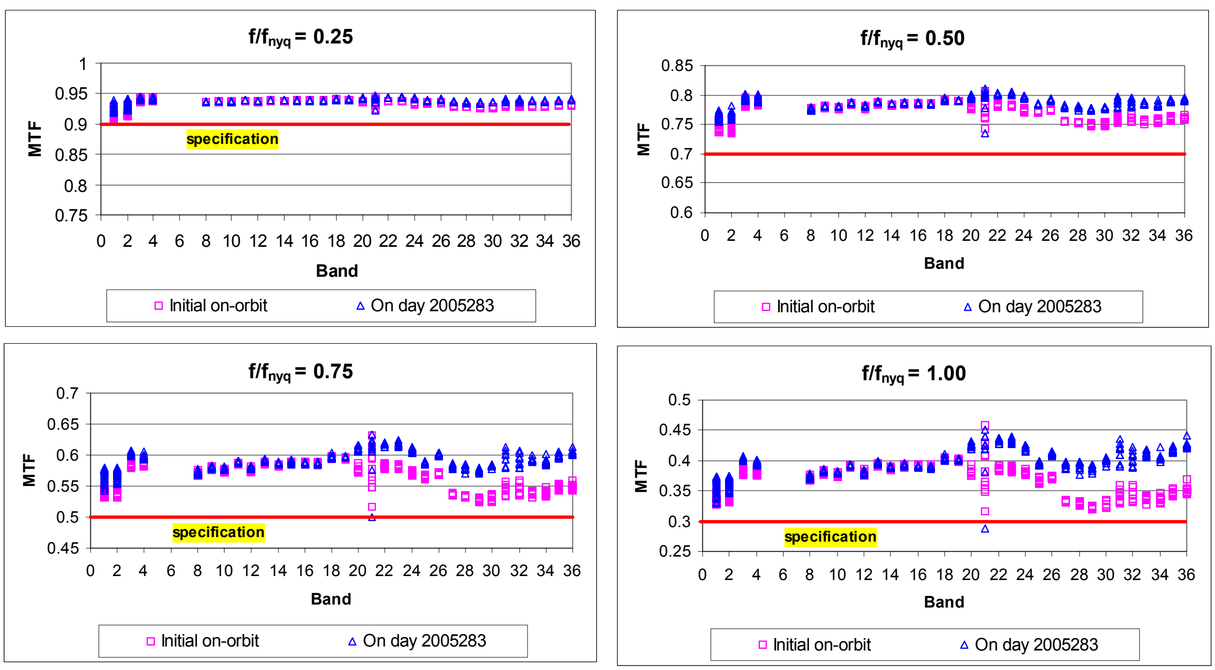


Figure 8. Aqua MODIS MTF comparison of initial on-orbit and day 2005283

5. CONCLUSIONS

The Aqua MODIS band-to-band registration does not meet the specification. The SMIR and LWIR FPAs are shifted, relative to the VIS/NIR FPAs, by -0.32 and -0.26km along-scan; 0.27km and 0.32km along-track, respectively. This occurred prelaunch. On-orbit, the BBR has shown some minor changes. After the instrument stabilized, the BBR has been very stable except for a seasonal variation of the VIS FPA

The Aqua SRCA is deemed stable based on four–years of on-orbit operation. The SRCA spatial response has tracked the MTF from pre-launch to on-orbit. Its on-orbit results show that the Aqua MODIS MTF has improved for both the SMIR and LWIR FPAs and remains unchanged for both the VIS and NIR FPAs.

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