

Measuring crosstalk in MODIS spectral bands on-orbit using the SRCA

Daniel O. Link^a, Emily J. Aldoretta^a, Truman Wilson^a, and Xiaoxiong Xiong^b

^aScience Systems and Applications, Inc., 10210 Greenbelt Road, Lanham, MD 20706, USA

^bSciences and Exploration Directorate, NASA/GSFC, Greenbelt, MD 20771, USA

ABSTRACT

Near-identical MODIS instruments launched on-board the Terra and Aqua spacecraft in 1999 and 2002, respectively. Each MODIS instrument has 36 spectral bands covering 0.41 to 14.2 μm mounted among four focal plane assemblies, along with a series of on-board calibrators (OBCs) used to characterize the instrument performance on-orbit. One such OBC is the Spectro-radiometric Calibration Assembly (SRCA), which is a multi-function calibrator, able to provide calibration sources to measure spatial, spectral, or radiometric properties of the MODIS bands depending on its configuration. The MODIS instrument performance, including measurements of the signal cross-contamination (crosstalk) between bands, was measured on-orbit during early-mission characterization for both instruments. This crosstalk test used the SRCA in its spatial mode while utilizing the thin slit, which is normally used for spectral calibrations. A similar crosstalk test was recently performed for Terra MODIS. Since the Terra safe mode event in 2016, the PV LWIR bands specifically (6.7-9.7 μm) have shown increased influence from crosstalk. The process involved in preparing and performing this crosstalk test is included in this work, as well as the findings from the recent and previous SRCA-based crosstalk characterizations.

1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument continues to operate on the NASA Earth's Observing System (EOS) Terra spacecraft since its launch in late 1999. Continuing to operate well beyond its six-year design life, the Terra MODIS has performed nearly constant observations of the Earth using its 36 spectral bands with center wavelengths ranging from 0.41 to 14.2 μm . These bands are made up of a linear array of detectors aligned in the spacecraft track direction and are spatially co-registered to provide high-fidelity composite images and data products. A rotating, dual-sided scan mirror directs signal from the instrument's Earth view (EV) port towards the instrument telescope along its way to the detectors. As the scan mirror rotates, the detectors are also able to sample other areas within the instrument. Situated about the scan mirror are several on-board calibrators (OBCs). These OBCs are used in the calibration of the MODIS detectors. The solar diffuser (SD) and solar diffuser stability monitor (SDSM) are used in tandem to calibrate the performance of the reflective solar bands (RSB) ($\lambda < 2.2 \mu\text{m}$). The blackbody (BB) source provides a thermal reference for the thermal emissive bands (TEB) ($\lambda > 3.7 \mu\text{m}$). To aid in measuring a dark background signal, there is also a porthole in the side of the instrument known as the space view (SV) port. The SV port also allows the near-monthly observation of the Moon by utilizing a spacecraft roll maneuver. Finally, MODIS is equipped with the Spectro-radiometric Calibration Assembly (SRCA). This unique calibrator contains its own light source and can be used in the radiometric, spectral, and spatial calibration of the MODIS bands.

The MODIS bands are mounted among four focal plane assemblies (FPAs) according to spectral wavelengths (see Table 1). Bands 1 and 2 are 250 m resolution bands and are made up of 40 detectors each. Bands 3-7 are 500 m resolution bands, made up of 20 detectors each. The remaining bands are 1 km resolution bands with 10 detectors. In order to achieve equal resolution in the scan and track directions at nadir for all bands, the higher resolution bands are measured more often. The 500 m resolution bands are sampled twice as often as the 1 km bands and the 250 m resolution bands 4 times as often. Each 1-km measurement from a detector is referred to as a frame of data as it is equivalent to a 1 km by 1 km measurement of the Earth for that detector. These bands therefore record multiple sub-frames of information for every 1-km frame. The sampling of frames and sub-frames is consistent between measurements of the Earth through the MODIS earth view (EV) port as well as for all of the OBCs.

Table 1: Terra MODIS Bands and center wavelengths on each FPA. Bands are presented according to the order each band is illuminated each scan.

FPA	MODIS Bands (center wavelength in micrometers)									
VIS	10	9	8	3	4	11	12			
	(0.485)	(0.445)	(0.412)	(0.469)	(0.555)	(0.531)	(0.551)			
NIR	17	16	15	14	1	2	13	18	19	
	(0.905)	(0.869)	(0.748)	(0.678)	(0.645)	(0.858)	(0.667)	(0.936)	(0.940)	
SMIR	25	24	26	7	6	5	20	21	22	23
	(4.515)	(4.465)	(1.375)	(2.130)	(1.640)	(1.240)	(3.750)	(3.959)	(3.959)	(4.050)
LWIR	30	29	28	27	33	34	35	36	31	32
	(9.730)	(8.550)	(7.325)	(6.715)	(13.335)	(13.635)	(13.935)	(14.235)	(11.030)	(12.020)

Crosstalk among MODIS bands was characterized during pre-launch testing and assessed once on orbit [1]. Increased effects of crosstalk were observed in the Terra MODIS TEB, specifically in band 27 [2]. On February 18, 2016, the Terra spacecraft was autonomously commanded into safe mode. As part of the internal spacecraft commanding, Terra MODIS was also commanded into its safe mode configuration. As part of this configuration, the SV and EV doors closed and heaters and motors turned off. Over the next 4 days, instrument component temperatures drifted to ambient conditions. After spacecraft recovery, MODIS commanding opened the doors and performed an outgas procedure before returning to nominal science configuration. As part of the post-safe mode analysis, the short- and long-term performance of the MODIS instrument and its calibration were monitored. A significant increase in the crosstalk among bands 27-30, the photo-voltaic bands on the LWIR FPA (PV LWIR bands) was identified due to the safe mode event. The performance of these bands (specifically bands 27-29) is of particular importance due to their use in the cloud mask product (MOD35_L2), which is not only important in its own right, but also a key input to many downstream data products [3].

The leading method of characterizing the PV LWIR band crosstalk is to use data obtained through the regular Terra spacecraft rolls for MODIS lunar calibration [2]. Coefficients derived from these observations are now used to mitigate the electronic crosstalk effects in the MODIS collection 6.1 calibrated data product [4]. Continued work has extended the characterization of the crosstalk to include other MODIS bands, such as the mid-wave infrared [5] and near infrared [6].

As part of early mission testing, the SRCA was given special commanding to test the crosstalk in the SWIR bands (bands 5-7, and 26). A similar test was performed in the summer of 2019 to assess the state of Terra MODIS crosstalk, particularly the PV LWIR bands (bands 27-30). The early mission test was effective in determining the SWIR band crosstalk, but the thermal band results did not show notable crosstalk contamination. In addition, these early mission tests were performed in February and April 2001, after Terra MODIS was commanded to use the backup (B-side) electronics [7]. In 2002, MODIS was commanded back to primary electronics cross-strapped with the B-side formatter. The calibration factors, including gain, differ depending on electronics side, so the results from these tests are not directly comparable with recent tests. In this work, we will focus on the recent test by presenting the background behind the commanding used for this special SRCA crosstalk test, the methodology of analyzing the data, and present the results, with comparisons against the lunar-based method discussed above. We end with our conclusions and thoughts for continuing work moving forward.

2. SRCA CROSSTALK TEST

The SRCA, when commanded to its spatial calibration mode, involves using its internal light source with a series of optics and masks to create well-characterized signal in either a 5 km instantaneous field-of-view (IFOV) wide slit or step-pattern [8]. For spectral calibrations, the SRCA uses a thinner slit (0.5 km IFOV wide) and a diffraction grating to produce calibrated monochromatic light over the spectral range of bands on the VIS and NIR FPAs [9]. The light source used in these calibrations involves six halogen lamps mounted within a 2-inch diameter spherical integration source (SIS). Four of the lamps are 10W lamps and the remaining two are 1W lamps. This allows light from a combination of lamps to be combined and output uniformly. However, due to instrument aging, two of the 10W lamps are no longer operational. These lamps are used primarily for characterizing the RSB. A thermal glow bar is also within the SRCA for characterizing the TEB in SRCA spatial calibrations. These signals are combined using a beam combining optical filter to send all outgoing light along the same optical path. Aside from the ‘beam combiner’, other optical filters can be actuated in the

path of the outgoing signal. Of primary note is a neutral density filter with a transmittance of 0.25 in the range of MODIS RSB wavelengths [10].

For our special SRCA crosstalk test, the SRCA was commanded to its nominal spatial calibration configuration with several adjustments. First, instead of the wider slit or step optical mask used for spatial calibration, the thin slit, nominally used for spectral calibrations, was used. This provides the most discrete signal the SRCA can generate. During a nominal spatial calibration, the IR thermal source is turned on and measured in combination with one and then two 10W halogen lamps. For this test, we operated the SRCA with a variety of lamp and filter combinations (see Table 2). The goal was to obtain as much valid data as possible for this and potential future applications. Although there are two 1W lamps in the SRCA SIS, due to design constraints, they cannot both be used simultaneously. In order to facilitate additional data points in the along-scan spatial calibration, electronic phase delays are introduced into the SRCA data sector to adjust when the detectors are read. This allows sub-pixel measurements in between those recorded nominally and gives greater resolution of determining spatial co-registration. These phase delays are also used in the crosstalk test to provide additional data points in a similar way. These delays are adjusted for the second set of IR On observations (data sets 12-14) with intermittent delays.

Table 2: SRCA crosstalk test configurations

Data Set	Day	Orbit	Lamp Setting	IR Setting	Filter Wheel Setting	Phase Delays
1	1	1	OFF	OFF	Neutral Density (ND)	0, 0.2, 0.4, 0.6, 0.8, 1.0
2	1	1	1W	OFF	ND	0, 0.2, 0.4, 0.6, 0.8, 1.0
3	1	1	10W	OFF	ND	0, 0.2, 0.4, 0.6, 0.8, 1.0
4	1	1	20W	OFF	ND	0, 0.2, 0.4, 0.6, 0.8, 1.0
5	1	2	OFF	OFF	Beam Combiner (BC)	0, 0.2, 0.4, 0.6, 0.8, 1.0
6	1	2	OFF	ON	BC	0, 0.2, 0.4, 0.6, 0.8, 1.0
7	1	2	10W	ON	BC	0, 0.2, 0.4, 0.6, 0.8, 1.0
8	2	1	OFF	OFF	Open (no filter)	0, 0.2, 0.4, 0.6, 0.8, 1.0
9	2	1	1W	OFF	Open	0, 0.2, 0.4, 0.6, 0.8, 1.0
10	2	1	10W	OFF	Open	0, 0.2, 0.4, 0.6, 0.8, 1.0
11	2	1	10W	OFF	BC	0, 0.2, 0.4, 0.6, 0.8, 1.0
12	2	2	OFF	OFF	BC	0, 0.1, 0.3, 0.5, 0.7, 0.9
13	2	2	OFF	ON	BC	0, 0.1, 0.3, 0.5, 0.7, 0.9
14	2	2	10W	ON	BC	0, 0.1, 0.3, 0.5, 0.7, 0.9

The configuration of the MODIS data collection is also adjusted for this special SRCA crosstalk test. Nominally, the MODIS scan mirror records 10 frames of data while observing the SRCA sector. However, in order to obtain information farther away from the peak sending signal, additional frames of data were needed. To accommodate this, data tables in the MODIS formatter were changed to provide 55 frames of data instead, adjusted to remain centered on the SRCA port. The MODIS data engine is hard-set to only transmit a specific data size. To maintain a constant size in the data output, 45 frames were ‘borrowed’ from the SD sector, leaving it with 5 instead of its nominal 50 frames. These tables were set back to their nominal values after testing was completed for that day (after the second orbit of data collection).

3. METHODOLOGY

SRCA data was collected over four orbits on August 21 and 22, 2019. Data was averaged over the number of scans with a 3-sigma standard deviation error rejection with average SV background signal removed. Each filter wheel configuration was measured without any output signal (lamps and IR source off) to provide a configuration dark measurement that was then removed from each measured profile of the same configuration. The dark measurements were collected as data sets 1, 5, 8, and 12. The configuration order was chosen to allow as many configurations to be measured over four spacecraft nighttime orbits. Special attention was paid to allow the IR source time to reach a stable temperature before taking measurements. The plots in Figure 1 show an example signal from band 27, data set 13 with its corresponding background signal from data set 12 (left) and the resultant signal with the background data removed (right). The peak centered at frame 39 is the expected signal from illuminating band 27 using the thin slit and the smaller negative dn (digital number) features near frames 30, 33, and 36 are due to electronic crosstalk from neighboring bands 30, 29, and 28, respectively.

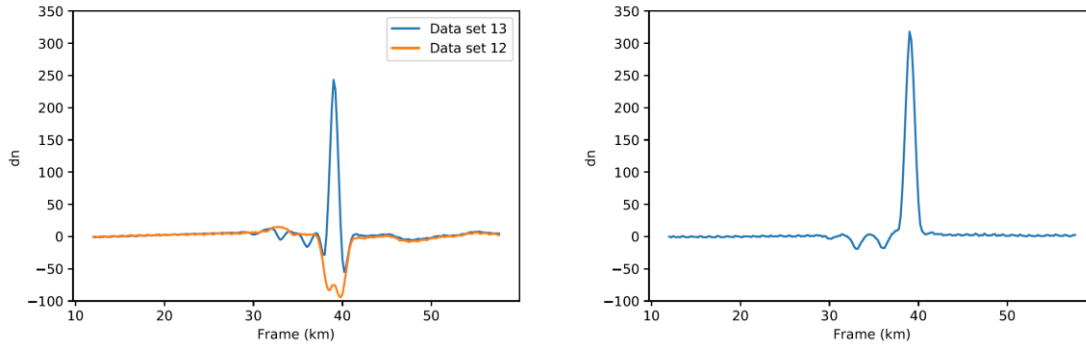


Figure 1: Example SRCA signal for Band 27, with IR source on (data set 13) and IR source off (data set 12) in the left plot. The plot on the right shows the signal once data set 12 is subtracted from data set 13.

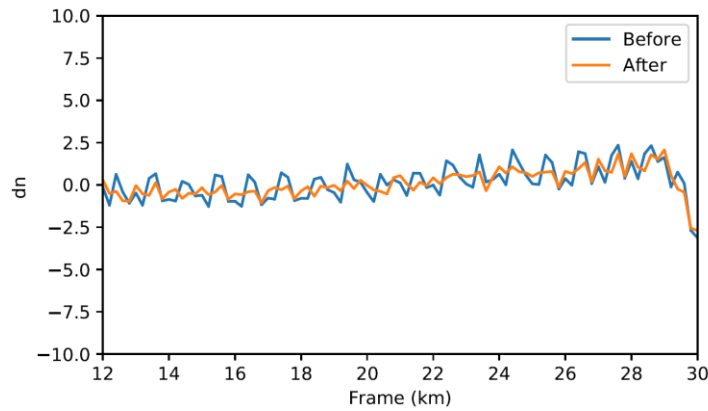


Figure 2: Example SRCA signal for Band 27 with IR source on and dark signal removed before and after correcting for phase-delay differences.

While the combination of SV and dark signals should be sufficient to render a valid SRCA crosstalk profile, there are additional artifacts seen caused by the phase delays. Measurements for each phase delay are taken sequentially and then the signal is stitched together in frame-space. This causes slight differences in where the background level is measured for each phase delay. A final correction is performed to zero-out the difference in phase delay. Figure 2 shows the same profile as shown in Figure 1 (right plot), in blue, but focusing on the first series of frames. The blue trend shows a jagged signal level due to the different background measured using each phase delay. The corrected signal is over plotted in orange to show a smaller, consistent background level. A well-characterized background, distinct from the contaminated signal, aids the determination of crosstalk coefficients.

When comparing the signal from different bands, a frame shift is applied. The electronic timing within MODIS presents the output signal to be co-registered with time. However, when investigating crosstalk, the fact that each band ‘sees’ the light at a different time is important and needs to be preserved. To account for that, we adjust each signal in frame-space, where we note where each spectral band of detectors is mounted on its FPA and where each band is mounted in relation to the other. When we apply the frame-shift, we can more easily see when each band is illuminated and the impacts on other bands (see Figure 3).

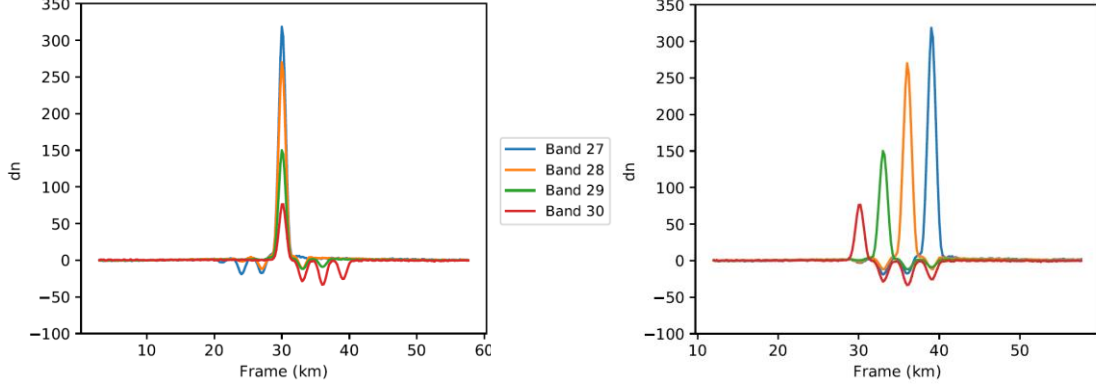


Figure 3: PV LWIR band signals for data set 7 before (left) and after (right) the frame-shift is applied. The influence of one band on another appears as one sending peak aligned in frame-space to a receiving trough measured in another band.

4. CROSSTALK CALCULATION

In assessing the crosstalk, we have based our approach on the method first explored by Sun et al. [2] and applied to the Terra Collection 6.1 data by Wilson et al. [4] using lunar observations to determine crosstalk contamination and correction coefficients. This method involves a single linear coefficient relating the sending signal of a single detector to the receiving signal of a separate detector. An adjustment is made for the SRCA results as the SRCA measurements illuminate all detectors on a band simultaneously, as compared to the lunar images, which have more variability in detector illumination throughout a lunar observation. With that in mind, we have simplified the crosstalk calculation to determine the receiving signal by band average. This still takes into account the variation in each detectors sending response (the difference in each sending detectors gain response). Even with that restriction, there is still a significant amount of data to process and is used as input to the coefficient calibration equation:

$$dn_i(S, F) = dn_i^*(S, F) - \sum_j c_{i,j} \cdot dn_j^*(S, F + \Delta F_j) \quad (1)$$

where dn^* is contaminated signal corrected for background signal, and i and j are the indices for receiving detector and sending band, respectively. S and F are the scan and frame of each measurement and $c_{i,j}$ is the correction coefficient. ΔF notes the relative frame shift. To derive the coefficients, we perform a least squares minimization to Equation 1 for a single receiving signal and multiple band-average sending signals. The main peak in the receiving signal is ignored to prevent correcting for the expected signal. The main peak is assumed to be in its expected location and uniform due to the shape of the spectral slit and known properties of the MODIS band spatial performance [8].

Depending on the bands in question, the number of receiving bands can be adjusted. With the PV LWIR bands, for example, we restrict the sending/receiving bands to other PV LWIR bands as these are the areas in frame-space where crosstalk is observed. This same logic is applied when looking at other band sets, where only the bands appearing to be of influence are considered and a sufficient correction is obtained. This reduces the computation time and the complexity of the coefficients, should it be needed for application to calibration data. While all bands and lamp configurations were investigated, many did not provide sufficient signal levels to gain correction coefficients. Most of the crosstalk has been observed in the longer wavelength bands, which are mostly reliant on the IR thermal source to provide sufficient signal. Unfortunately, because the IR source signal level cannot be adjusted there is essentially only a single signal level for all thermal band results.

5. RESULTS

5.1 PV LWIR bands (Bands 27-30)

Early mission data supports the understanding that the crosstalk among these bands was small in the early mission time period compared to the operation after February 2016. As noted earlier, data from the tests performed in 2001 are not

directly comparable to 2019 data due to the difference in MODIS electronic configuration. In addition, issues with the test format led some of the data collections to be less useful in generating an applicable crosstalk signal. These shortcomings were reviewed as part of the test planning and were mitigated in the 2019 tests. The measured profiles from one of these early mission test configurations shown in Figure 4 show little to no influence of contamination for bands 27-30, especially when compared against results from the recent test shown in Figure 3, right.

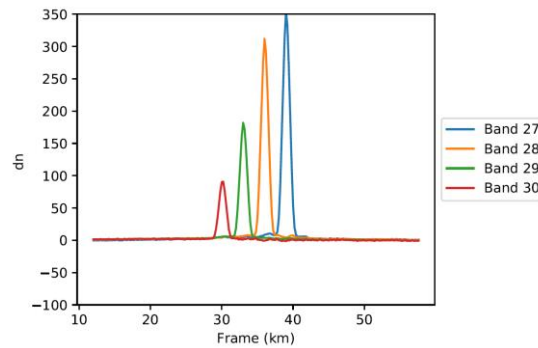


Figure 4: PV LWIR band signals from early mission (February 2001) SRCA crosstalk calibration.

Therefore, we will focus on results from the recent tests moving forward. Crosstalk coefficients have been calculated for each configuration of the 2019 tests for the PV LWIR bands. Not every data set yielded significant signal to view crosstalk effects or calculate crosstalk coefficients mostly due to the limited signal levels available from SRCA configurations in the desired wavelength ranges. A plot showing the derived coefficients from data set 6 and their comparison against coefficients derived from lunar observations are shown in Figure 5. The lunar coefficients were generated for the lunar observation on August 20, 2019, which was a day before the SRCA test began. The lunar calibration coefficients are viewed as the standard to which the SRCA-based results are compared. One note is that the coefficients derived from lunar observations are calculated with a coefficient for each receiving detector from each sending detector. This allows individual detector interactions to be characterized and is a more comprehensive correction. Because the SRCA results use a band-average for sending signal, the lunar coefficients are averaged for each sending band to allow for a likewise comparison. This is different than deriving the coefficients on a band-average basis, but should provide a sufficient side-by-side comparison. When compared against coefficients derived using lunar observations, we see some interesting factors. Firstly, the shape and influence of sending bands on receiving detectors is quite similar with edge detectors (1, 2, 9, and 10) of Band 27 having the largest coefficients derived from both sources. We see the coefficients grouped together between calibration sources. Overall, the Moon-based coefficients are larger in magnitude than the SRCA-based coefficients. In addition, the inability to determine self-sending signals for a given band resulted in a coefficient of zero for SRCA-based coefficients among the same band.

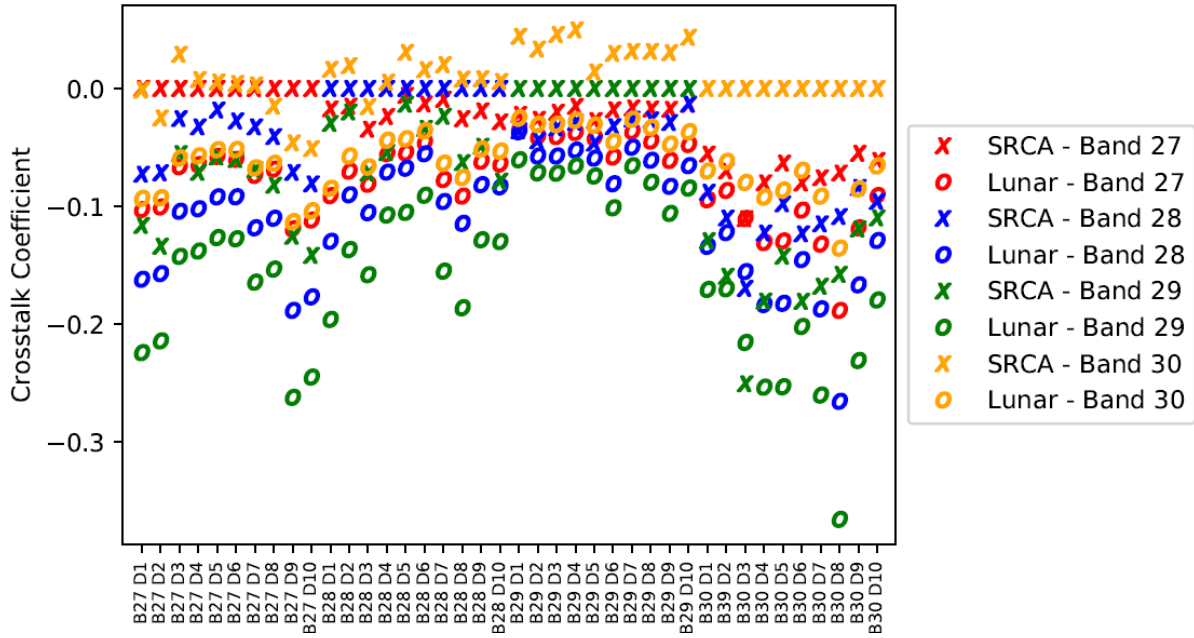


Figure 5: Calculated crosstalk correction coefficients for MODIS PV LWIR bands. Coefficients derived using the SRCA crosstalk test on August 21, 2019 are shown with crosses and the coefficients from lunar observations on August 20, 2019 are shown as circles. Bands are color matched for easier comparison.

Presented in Figure 6 are the recovered signals from each of the PV LWIR bands. Each plot shows the measured signal from the middle detector of the band from data set 7 (using data set 5 as background) in red and the corrected signal after applying the correction coefficients over-plotted, derived using the data set 6. The lack of adjustment in the SRCA thermal source prevents any change in the measured signal among other data sets. Because of this, all data sets with the thermal source ON show similar results with only small changes in the noise/background present. The correction does show significant improvement in the profiles, particularly for band 30, which had the most contamination. The sending signal from band 30 is low however (less than 80 dn) and therefore the correction from contamination due to band 30 is not corrected as well as that from other bands. This can be viewed in the positive coefficients derived for all detectors of band 29 from band 30 and the lack of significant correction in the frame space near band 30 (around frame 30).

When compared against the correction based on lunar observations, the 2019 SRCA crosstalk test does not provide the same thermal signal level diversity and has added complexity in performing the test itself. However, this test does verify the methodology used in the lunar assessment can be applied to other measurements with some success and proves expanded potential of using the SRCA for calibrations beyond its regularly planned calibrations, as Terra continues in its extended mission. Continued analysis of these results and assessment of the test procedure will aid in planning of any potential, future SRCA crosstalk tests. As our test provided results for all MODIS bands, we continue our analysis beyond the PV LWIR bands. The remaining bands on the LWIR FPA, bands 31-36 were investigated but insufficient signal was observed to note any crosstalk or correction coefficients.

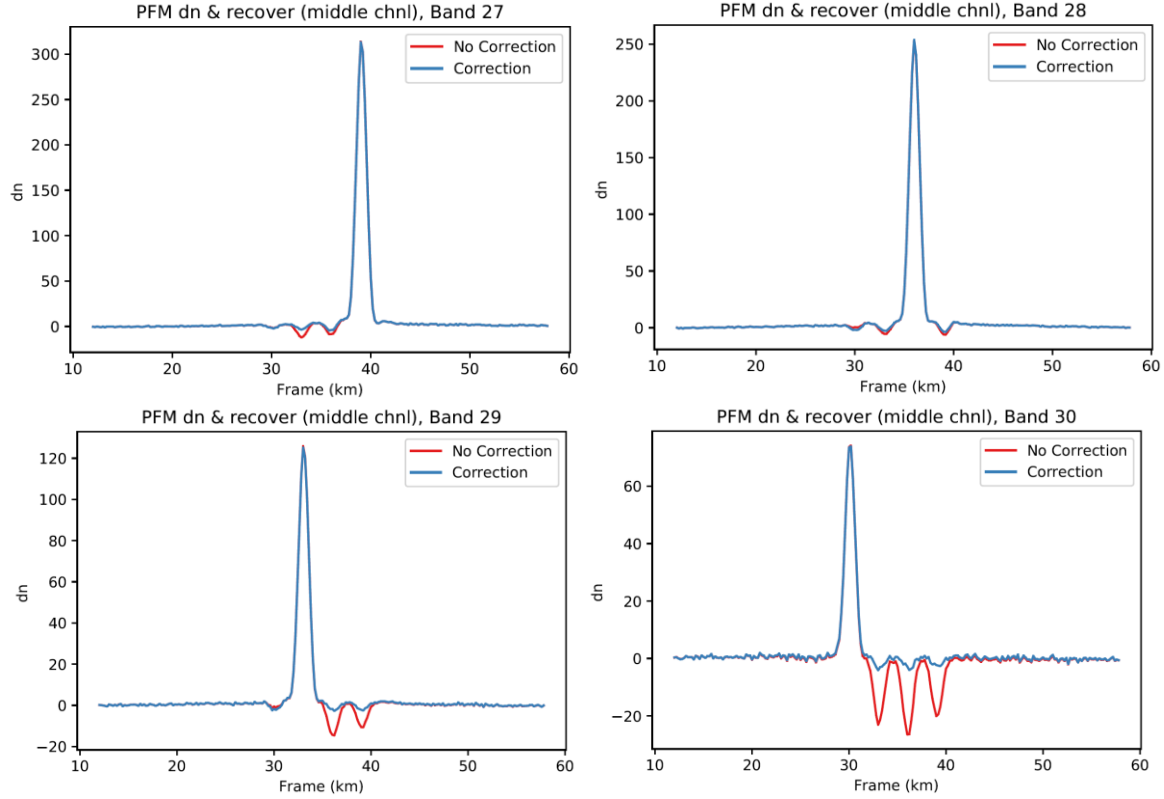


Figure 6: Crosstalk coefficients derived from data set 6 are applied to data set 7 to remove crosstalk signal.

5.2 SMIR Bands

The crosstalk measured for the SWIR bands (bands 5-7, 26) has been studied and corrected in MODIS L1B calibrated data products [11] [12]. There is not a clear sending/receiving relationship with these bands as is seen in the PV LWIR bands, as these bands are also influenced by a large out-of-band thermal leak around $5.3 \mu\text{m}$ in addition to the electronic crosstalk. Without a MODIS band at that wavelength, the signal from band 25 is used and a linear correction is applied to SWIR band data. The relationship between band 25 and the thermal leak is monitored using spacecraft night observations [13]. To mimic the spacecraft night observations in this study, we investigated data sets 6 and 13 for the SWIR bands. In these data sets, the IR source is ON but the lamps are not. In this way, we expect no native signal for the SWIR bands and any signal seen would be due to thermal leak. Our tests show less than 5 dn due to thermal leak, which were too low to determine coefficients. Further analysis of these bands is on-going and may yield more fruitful results. The remainder of the bands on the SMIR FPA were investigated separately for crosstalk signal, the mid-wave infrared bands (MWIR): bands 20-25. With these bands, there is less interaction between each other, as seen in the PV LWIR bands, but instead the majority of the contamination can be linked to individual bands, specifically band 21 and 26. This is most likely due to their relative signal in this test, limited to the only available IR source signal, as this relationship has not been observed using lunar observations. As noted in [5], in addition to the expected band-to-band crosstalk signal, there is also an unexpected crosstalk signal that can be explained by investigating the sampling electronics. In their work, the authors describe how the MODIS detectors are sampled according to a specified order and the sampling electronics show contamination from the last detector of a given band and the first detector of the band sampled next. The degree of contamination was measured to be larger than from other detectors in the same band. Our current analysis uses band-averaged receiving signal, so it is not able to determine this factor directly. However, we see the impacts of this contamination when we apply the crosstalk algorithm as described for the LWIR bands. When applied in the same way, the largest contamination signals cannot be fully corrected. By shifting the sending signal by a full frame, however, we are able to determine an approximate, appropriate correction. The shift in frame space corresponds to a shift in time, to account for the time difference when these detectors are sampled.

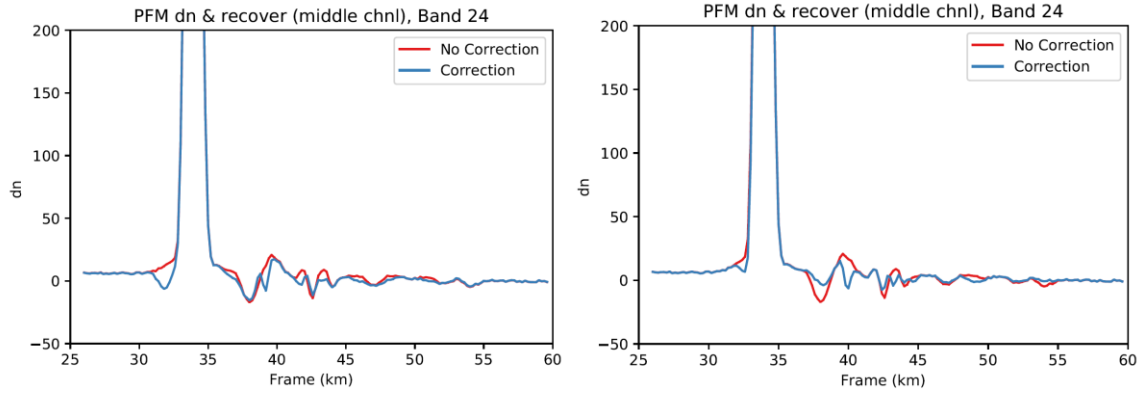


Figure 7: Middle detector of Band 24 measured profile (red) and corrected profile (blue) with largest contamination due to Band 26, shown as a trough centered on frame 37. The signal peak is cut-off to show contamination signal in detail. The left plot shows the unsuccessful attempt to correct contamination. The right plot shows an improved correction after applying a 1 km frame shift to sending signal.

5.3 NIR bands (bands 1 and 2)

Additionally, the SRCA crosstalk test was able to identify crosstalk signal in MODIS bands 1 and 2. These are the 250 m resolution bands and are sampled at 4 times the rate of the 1 km resolution bands. As such, evidence of crosstalk can be seen during measurement of a particular sub-frame and not for another. The sub-frame differences of these bands have been investigated previously [14]. The crosstalk of specific detectors in band 2 was investigated using lunar observations [15] and more recently to include band 1 [16]. As with the MWIR bands, crosstalk contamination has been linked to the timing and order of when the MODIS electronics sample each detector. For these 250-m resolution bands, detectors are sampled in order from 1-40, sub-frame 1 to 4 throughout each frame of data collection. With that, each detector takes the same amount of time to sample, regardless of its size. So while 40 detectors of band 1, sub-frame 1 are sampled, all 10 detectors of bands 15, 16, and 17 are also sampled. The analysis performed in [16] shows contamination for specific detectors and sub-frames in bands 1 and 2 and the cause can be tied directly to the other detectors sampled. Either the sending detectors can be read at the same time or there can be a latency effect from the detector sampled just before. As presented in Figure 8, contamination is shown for band 2, sub-frame 1, detectors 22 and 23. Not shown is the measured signal for detectors 21 and 24, which show no contamination. As shown with Moon data, the contamination can be directly linked to sampling, where detector 22 is sampled in between the end of band 16 and the start of band 15. Band 2 detector 23 corresponds with the timing of the start of band 15. The correction shows a good ability to characterize the contamination, but that it is not able to remove the signal at the edges of each feature. This could be due to potential non-linearity in the crosstalk correction. Non-linear crosstalk has been investigated using lunar data for bands 1 and 2 [16].

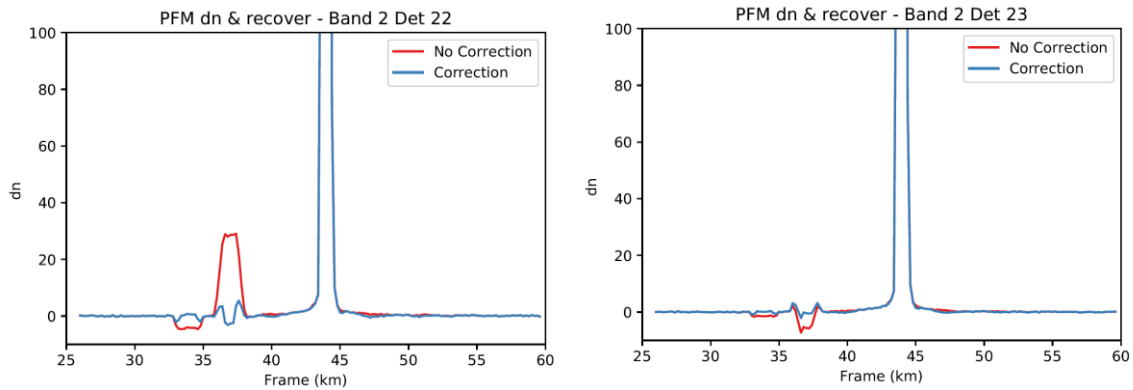


Figure 8: Measured signal (red) and correction (blue) signal for detector 22 (left) and detector 23 (right) of band 2. Contamination from band 16 is seen centered at frame 34 and contamination from band 15 is seen near frame 37.

5.4 VIS Bands

The results for MODIS VIS bands (bands 3, 4, 8-12) did not show any contamination due to crosstalk. This is expected, as there have not been any reported evidence of crosstalk in these bands from outside sources or determined using lunar observations.

6. CONCLUSIONS AND FUTURE WORK

By commanding its SRCA into a non-standard configuration and adjusting the MODIS sector reporting allocation, the SRCA crosstalk test was able to view crosstalk contamination among the MODIS bands. Application of a band-averaged signal to the crosstalk correction algorithm, which has already been used to characterize crosstalk using lunar observation data and applied to the MODIS Collection 6.1 calibrated data product, has shown improved results. Moving forward, additional analysis can be performed to determine if there is evidence in non-linear contamination that can be determined using SRCA data for bands 1 and 2. Expanding the test configuration to allow for additional phase delays would give greater fidelity to the results, currently only spacing of 0.2 frames was used, but the SRCA is able to sample at frame intervals of 0.01. This would require longer calibration times and potentially several orbits on one configuration. The NASA EOS Aqua spacecraft performed early mission crosstalk tests using its own MODIS SRCA. Lessons learned from this analysis could also be applied to future tests using the Aqua SRCA.

7. ACKNOWLEDGEMENTS

The authors would like to thank and acknowledge the planning and operations efforts made by the MODIS Instrument Operations Team, including Michael Lucci, Daniel Todaro, and Sarah Schwenger. We would also like to thank Joseph Auchter, MODIS software design engineer, currently of Raytheon Systems, for his continued technical guidance. Thanks to Amit Angal for his efforts to review this manuscript.

8. REFERENCES

- [1] B. Guenther, X. Xiong, V. V. Salomonson, W. L. Barnes and J. Young, "On-orbit performance of the Earth Observing System Moderate Resolution Imaging Spectroradiometer; first year of data," *Remote Sensing of Environment*, vol. 83, pp. 16-30, 2002.
- [2] J. Sun, X. Xiong, S. Madhavan and B. N. Wenny, "Terra MODIS Band 27 Electronic Crosstalk Effect and Its Removal," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 52, no. 3, pp. 1551-1561, 2014.
- [3] C. Moeller, R. Frey, E. Borbas, W. P. Menzel, T. Wilson, A. Wu and X. Geng, "Improvements to Terra MODIS L1B, L2, and L3 science products through using crosstalk corrected L1B radiances," in *Proc. of SPIE - Earth Observing Systems XXII*, 2017.
- [4] T. Wilson, A. Wu, A. Shrestha, X. Geng, Z. Wang, C. Moeller, R. Frey and X. Xiaoxiong, "Development and Implementation of an Electronic Crosstalk Correction for Bands 27-30 in Terra MODIS Collection 6," *Remote Sensing*, vol. 9, no. 569, 2017.
- [5] T. Wilson, A. Shrestha and X. Xiong, "Electronic crosstalk impact assessment in the Terra MODIS mid-wave infrared bands," in *Proc. of SPIE - Sensors, Systems, and Next-Generation Satellites XXI*, 2017.
- [6] T. Wilson, A. Angal, A. Shrestha and X. Xiong, "Lunar calibration improvements for the short-wave infrared bands in Aqua and Terra MODIS," in *Proc. of SPIE - Sensors, Systems, and Next-Generation Satellites XXI*, 2017.
- [7] X. Xiong, B. N. Wenny and W. L. Barnes, "Overview of NASA Earth Observing Systems Terra and Aqua moderate resolution spectroradiometer instrument calibration algorithms and on-orbit performance," *Journal of Applied Remote Sensing*, vol. 3, p. 032501, 2009.

- [8] X. Xiong, N. Che and W. Barnes, "Terra MODIS On-Orbit Spatial Characterization and Performance," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 43, no. 2, pp. 355-365, 2005.
- [9] X. Xiong, N. Che and W. Barnes, "Terra MODIS On-Orbit Spectral Characterization and Performance," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 44, no. 8, pp. 2198-2206, 2006.
- [10] H. Montgomery, N. Che and J. Bowser, "Determination of the spatial characteristics by using the Spectro-Radiometric Calibration Assembly (SRCA) of MODIS (Part 1. Along-scan)," in *Proc. of SPIE - Earth Observing Systems III*, San Diego, California, 1998.
- [11] X. Xiong, K. Chiang, F. Adimi, W. Li, H. Yatagai and W. Barnes, "MODIS Correction Algorithm for Out-of-band Response in the Short-wave IR bands," in *Proc. of SPIE - Sensors, Systems, and Next-Generation Satellites VII*, 2004.
- [12] X. Xiong, A. Angal, J. Fulbright, N. Lei, Q. Mu, Z. Wang and A. Wu, "Calibration Improvements for MODIS and VIIRS SWIR Spectral Bands," in *Proc. of SPIE - Earth Observing Systems XX*, 2015.
- [13] X. Xiong, A. Angal and Y. Li, "Improvements in the on-orbit calibration of the Terra MODIS short-wave infrared spectral bands," in *Proc. of SPIE - Earth Observing Missions and Sensors: Development, Implementation, and Characterization V*, 2018.
- [14] Y. Li, A. Angal, N. Chen, X. Geng, D. Link, Z. Wang, A. Wu and X. Xiong, "Improvement in the Characterization of MODIS Subframe Difference," in *Proc. of SPIE - Earth Observing Systems XXI*, San Deigo, California, 2016.
- [15] J. Sun, X. Xiong, N. Che and A. Angal, "Terra MODIS Band 2 Electronic Crosstalk," in *Proc. of SPIE - Sensors, Systems, and Next-Generation Satellites XIV*, 2010.
- [16] T. Wilson and X. Xiong, "Electronic crosstalk characterization and correction for MODIS bands 1 and 2 using lunar observations," in *Proc. of SPIE - Earth Observing Systems XXIV*, 2019.