MODIS cross-talk effects and areas of potential performance differences for Terra from Aqua characteristics

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ABSTRACT

Optical and electronic cross-talk effects are present in the Terra MODIS sensor. Those effects are reviewed and the physical (engineering) characteristics that give rise to the effects are described when they are known. The potential for performance degradation also is assessed for each effect. The long-term consequence of these effects is to give rise to Terra MODIS to Aqua MODIS performance trend differences and researchers are cautioned to use care in interpretation of these trend differences as potential diurnal environmental effects.

Keywords: MODIS, electronic cross-talk, optical cross-talk, sub-frame differences

1. INTRODUCTION

The NASA Earth Observing System (EOS) MODIS instruments are major sources of environmental science and operational data. The Terra MODIS is operating in the 1030 local time orbit beginning in 1999 and the Aqua MODIS is operating in the 1330 local time orbit beginning in 2002. The sensors have a common design, and are operated by a common research team. The characteristics generally are the same for the two sensors. Certain features in signal purity in sensor development were discovered, and largely mitigated, and have not yet been described and discussed in the open scientific literature. Other characteristics are just now being documented in current research publications and are finding their way into the operational MODIS calibration algorithm. Additionally signal purity issues revealed late in development of the first MODIS on Terra have been mitigated with on-orbit operations strategies, followed by improved design implementation for the second MODIS sensor on Aqua. The signal purity characteristics that are discussed in this paper fall into the category of optical and electronic cross-talk. All of these effects are known to be characteristics of the MODIS. Specific topics for this paper are a 5 µm leak in the Short-wave spectral bands (SWIR), an electronics offset phenomenon that came to be known as sub-frame differences in the SWIR- and Mid-wave spectral bands (MWIR), and electronic cross-talk in the MWIR bands and in the Long-wave spectral bands (LWIR) observed on orbit from lunar maneuvers to track sensor responses to the moon. The two sets of MODIS observations are set-apart in time by 3 hours (90 minutes before and 90 minutes after local noon) and suggest the opportunity to perform studies of sensitivity of environmental phenomena over a daytime cycle. We will extend these cross-talk discussions to introduce effects that operate differently on the morning and afternoon MODIS missions with the intent to caution research users in co-mingling the two data sets into a common single data set without care to some effects that have resulted from matters described in this paper. The key design characteristics of MODIS are reviewed in Section 2. Each of the four cross-talk effects will be treated in separate sections, Sections 3 – 7. The expected differences in Terra and Aqua MODIS are summarized in Section 8, Discussion of potential on-orbit differences. A Conclusion section that restates the primary findings is provided in Section 9.

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Earth Observing Systems XXIII, edited by James J. Butler, Xiaoxiong (Jack) Xiong, Xingfa Gu, Proc. of SPIE Vol. 10764, 1076411 · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2320325

2. MODIS DESIGN CHARACTERISTICS

The Moderate Resolution Imaging Spectral-radiometer (MODIS) [1,2] is a 36-band device which achieves spatial coverage by the forward motion of the host spacecraft (called track direction) and cross-track coverage as a result of a scanning mirror (called scan or cross-track direction). Light from the earth-atmosphere scene reflects off the scan mirror into the fixed optics. The fixed optics are designed to achieve a specified spatial field of view, and the several spectral observing ranges are defined by dichroic and interference filters in front of the focal planes. The shorter wave portion of the spectrum is reflected by each dichroic and the longer wave portion is transmitted by the dichroic. Dichroic 1 separates the incident light about 1 µm. Dichroic 2 separates the light reflected from Dichroic 1 into VIS below 0.6 µm and the NIR. Dichroic 3 separates the light transmitted by Dichroic 1 in the SWIR/MWIR below 8 µm from the LWIR. Band 1 and 2 on the NIR have a footprint of approximately 250 m square at NADIR. Bands 3 and 4 on the Vis and Bands 5, 6 and 7 on the SWIR have a footprint of approximately 500 m square at NADIR. The remaining 29 bands have approximately 1000 m square footprint at NADIR.

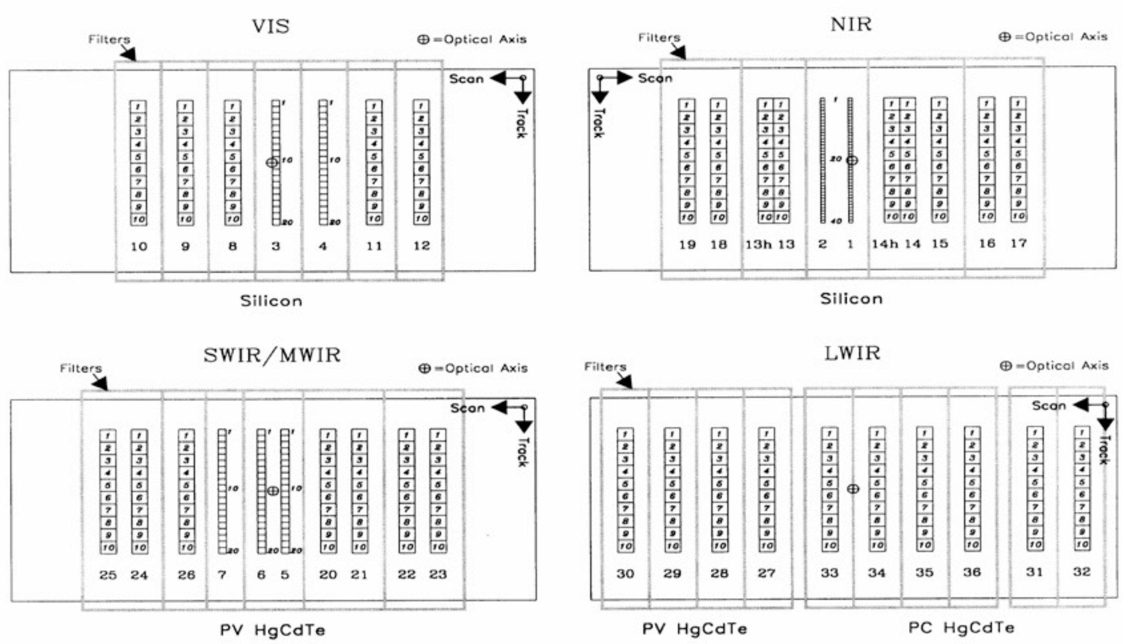

Fig 1. Layout of the MODIS focal planes. SWIR bands are Bands 5, 6, 7 and 26. The longest wavelength LWIR Bands, Bands 31 – 36 are PhotoConductive HgCdTe. All other SWIR. MWIR and LWIR bands are PhotoVoltaic Bands. These 20 bands all are cooled on-orbit for operations.

The 1000 m bands have 10 detectors in track direction. 500 m bands have 20 detectors in track, and are sampled twice in scan for each sample obtained with the 1000 m bands. The Vis and NIR focal planes are silicon and have analog-to-digital readouts tied to electronic ground. The HgCdTe (Mer-cad-telluride) detectors have a digital readout that is not tied to electronic ground, but "floats". Fig. 1 provides the arrangement of the 36 bands, arranged by positions on the focal planes.

3. SWIR CROSS-TALK

The center wavelengths for the SWIR bands range from 1.24 to 2.1 µm [3]. Spectral band center and band width, and spectral near and far out of band testing on the Engineering Design Unit (EDU) verified the spectral design of the MODIS. The filter specifications were very stringent for then current manufacturing standards, and the filter builder agreed to provide best effort against the filters, including band centers, filter shape, out of range bandpass and spectral bandpass. The intent was to provide Science Team review of the delivered filters and decide if any of the actual filters would hinder desired science performance of each band. Only one filter was rejected by "science" in the 0.93 µm NIR region, because of the original filter proximity to an atmospheric molecular absorption feature. This filter was rebuilt to more stringent specifications. The SWIR band spectral characteristics were acceptable in the EDU. Spectral sensitivity is a combination of both the spectral shaping filter characteristics as well as the detector characteristics. The SWIR focal planes delivered for Terra and Aqua MODIS had an enhanced sensitivity beyond 5 µm compared to that present on the EDU. In particular the flight SWIR detectors were sensitive beyond 5 µm, out to about 5.5 µm and the out of band blocking filter characteristics on the EDU were not verified beyond 5 µm. Additionally, the 5 µm spectral region is twice the wavelength of the longest SWIR center band, and out of band blocking on this specific design implementation did not block the 5 µm light. We characterized the MWIR out of band signals out to the spectral cut-off of the MWIR detectors (5.5 µm) for the flight models. Consequently, we learned in Terra MODIS flight unit spectral characterization that the SWIR bands have a light leak (cross-talk) for photons in the spectral range surrounding 5.3 µm.

In typical light leak conditions, (as will be seen in Section 7 on LWIR Band 31 leak) the sending signal is measured somewhere else on the system and a correction algorithm is constructed based on measured signal of the sending band and susceptibility of the receiving band to the light leak. In this case, the sending signal at 5.3 µm is not measured directly by any MODIS band. Our approach to identify a reliable on-orbit characterization of the sending signal at 5.3 µm was to use the Line-by-Line-Radiative-Transfer-Model (LBLRTM) to compute the contribution function at 5.3 µm. A global set of over 250,000 radiosondes from 1996 were used to define the atmospheric conditions for the contribution function. The MODIS Airborne Simulator (MAS) [4] band 40 spectral response was used as a proxy for the 5.3 µm response, and was convolved with each of the radiosonde spectra by means of the LBLRTM. Measured MODIS MWIR and LWIR band spectral response were also convolved with each radiosonde spectra and then compared to the (MAS band 40) 5.3 µm signal. The study indicated that MODIS Band 28 signal correlated well with the 5.3 µm signal (Fig. 2), and thus Band 28 was selected as the at-launch proxy for the on-orbit cross-talk correction for the SWIR leak. This correction was known to be reliable for all observations except where the atmospheric water vapor is very low, allowing surface emission to become a large component of the Band 28 integrated signal. In the situation for low atmospheric water vapor the MODIS SWIR crosstalk correction algorithm based on Band 28 is less reliable. Radiosonde test data showed us the distinction for performance with low atmospheric water vapor (where Band 28 is signal source is seen with surface features present).

SWIR out-of-band blocking to 5.3 µm was improved on MODIS Aqua, and the effect is not expected to change significantly with time on orbit.

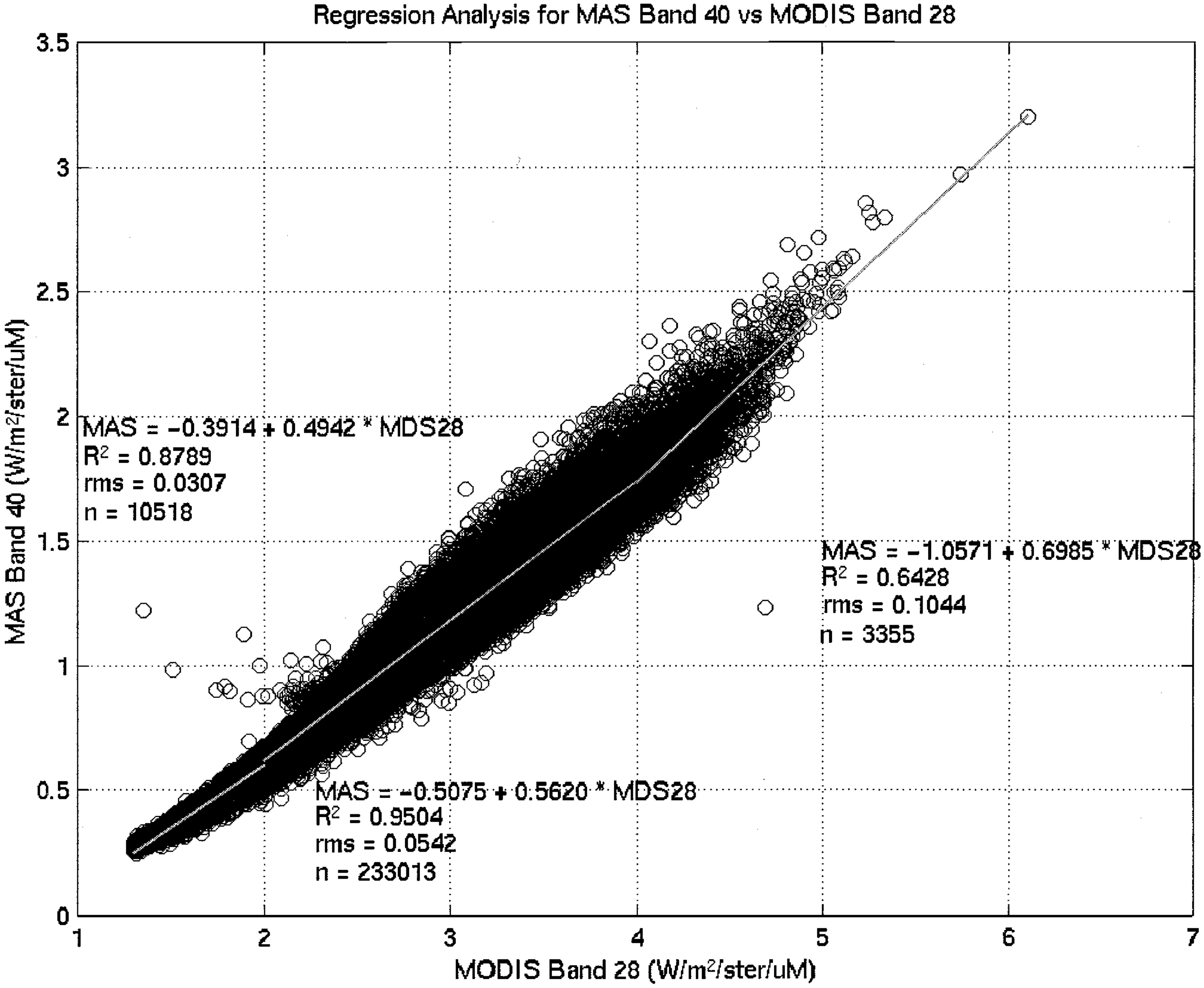

Fig 2 Relationship between MODIS band 28 and 5.3µm radiance as represented by MAS band 40. The data used in the chart are simulated radiances for one year of global radiosonde data. Very cold to very warm conditions are represented in the global sample. A 3-part linear regression relationship minimized residuals of cold, moderate, and warm scene temperatures.

Fig 3 depicts a Band 26 spectral leak in the short wavelength blocking. The leak largely corresponds to the signal seen in Band 5, and Band 5 is used to correct for this leak. The middle frame of Fig 3 shows a day scene where surface features are present as ghosts in this atmosphere band. The correction of Band 26 by Band 5 is shown in the third frame and the ghost of the surface feature has been suppressed with this correction. This effect is not expected to change on Terra MODIS over lifetime of the mission, and also is seen on Aqua MODIS.

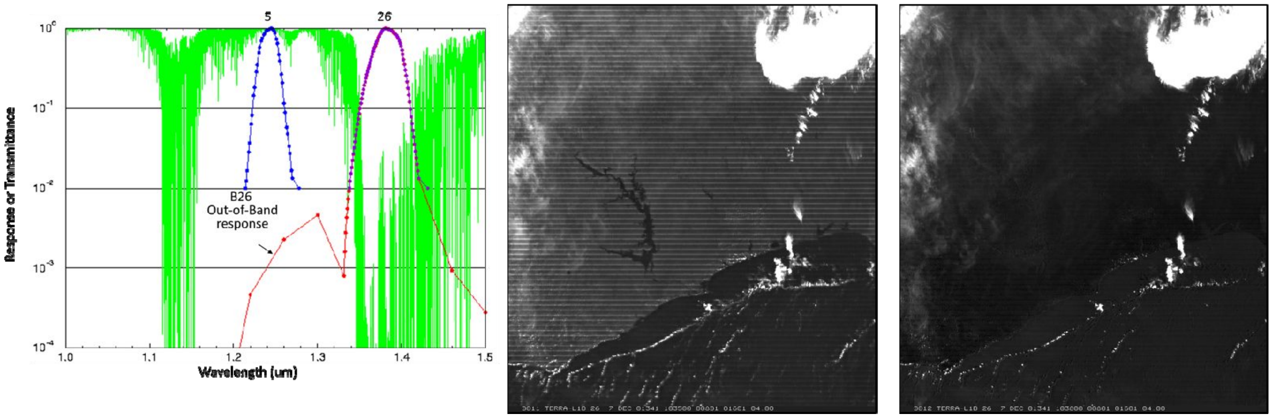

Fig 3. Band 26 also had a short wave light leak in the out-of-band characteristics that largely corresponded to signals on Band 5. Band 26 is an atmosphere band, and is not sensitive to the surface features.

4. SUB-FRAME GAIN DIFFERENCES

Three SWIR bands on the SW/MWIR focal plane have a field of view at NADIR of approximately 500 m X 500 m, with a focal plane photosensitive area dimensions half the size in both track and scan direction of the focal plane dimensions of the 1000 m bands. Image contiguity of observations in track direction is achieved by 20 pixels in the track direction for the 500 m bands compared to 10 pixels in track direction for the 1000 m pixels. Contiguity of observations in the scan direction is achieved with two samples, called sub-frame one and sub-frame two for the 500 m bands, for each 1000 m band sample. The data readout uses identical analog to digital conversions, and of course the same detector elements for each 500 m band in the SWIR. The data readout is achieved with a signal read and reset for all pixels on the SW/MWIR for one of the sub-frame observations (sub-frame two) and perform read and reset for only the 500 m SWIR bands on the other, sub-frame one, observations. The read and reset for sub-frame one involves action on the 60 500 m pixels, and read and reset for sub-frame two involves action on 130 pixels for three 500 m bands, and seven 1000 m SWIR bands. Reset of 40 PV MCT detectors on the LWIR focal plane also are performed with the reset of the 1000 m bands on the SWIR focal plane on sub-frame two. Calibration is achieved separately for each detector, each pixel, each sub-frame for sub-1000 m bands, and even each mirror side for the scan mirror. All together on only the SW/MWIR focal plane, we treat this as 380 equivalent radiometers with potentially different calibration coefficients for each equivalent radiometer.

We apply quality control standards though so that independent calibration coefficients will not produce irregular scene radiance values in observations for low contrast scenes. A quality standard we apply to the 500 m bands is that calibrated observations for each pixel must be consistent for the two sub-frame observations. Our pre-launch testing demonstrated that the 500 m SWIR bands had large sub-frame differences, more than 30% differences, for a static scene. Static, largely low contrast or flat field scenes are present in Ground testing with use of a large aperture integration sphere. The flat-field scene on-orbit for the 500 m sub-frame observations is solar reflectance off the flight diffuser. The detector readout for each sub-frame may be set independently, but those differences would be captured in the calibration coefficients. Even so, these differences could be handled with an additional, ad hoc, calibration coefficient if the sub-frame differences were stable.

Unfortunately, our observations are that the sub-frame differences were not stable, and not linear. We consider this effect to be an electronic cross-talk effect. We demonstrate this effect in pre-launch by looking at the ground blackbody and a cold, dark space view (SVC) source. The ground blackbody calibration source (BCS) temperature range varies between sensor ambient and 350K maximum. We do not expect to see significant signals in the SWIR bands looking at the BCS when that source is at or below 350K. This observed sub-frame behavior is displayed in Fig 4, and shows a sensitivity to BCS temperature that is not expected, and was not observed with the EDU build of MODIS.

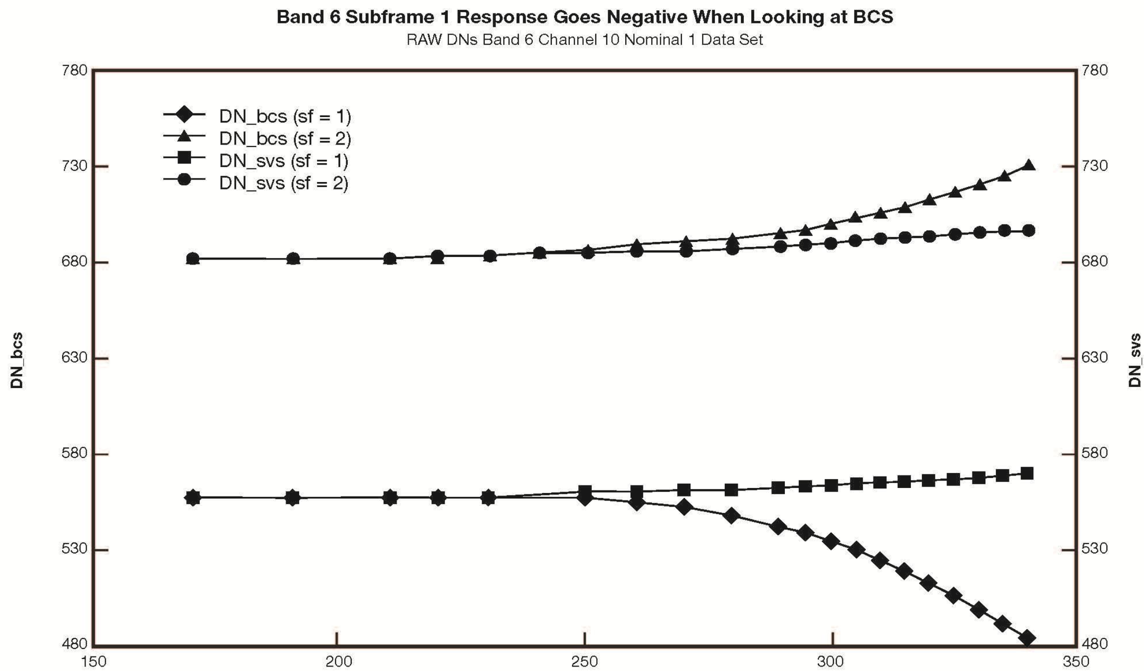

Fig 4. Response in the SWIR for Band 6 (centered at 1.4 µm) to the Ground Blackbody Calibration Source (BCS) with view to space view source (SVS) for multiple BCS temperatures of the BCS. The data are distinguished by sub-frame 1 (electronics resetting 60 detectors and sub-frame 2 (electronics resetting 170 detectors).

The behavior is anomalous. The Response (R) is characterized by Eq. (1) where DN is the digital number for a detector for a single observation. The two sub-frames are observing identical sources, and have significant different characteristics. The BSC is considered the signal and the SVC is the zero offset. Notice that the sub-frame 1 response goes negative as sub-frame 2 response is positive. The behavior is consistent with incomplete readout offset effects for sub-frame 2. The trends are non-linear and are identified as electronic cross-talk.

$$R = DN_{BCS} - DN_{SVC} \tag{1}$$

We learned from the instrument builder that the focal plane provider reduced the "in-rush current" on the Terra flight focal plane compared to the EDU design due to a concern that the in-rush current set on the EDU device may lead to a long-term fatigue of the focal plane and provide degraded performance late in mission lifetime. The cadence of spacecraft altitude (and velocity), along with scan mirror rotation, combined with requirement for contiguity of successive scans on the surface leads to a specific and limited reset interval for each pixel between readout and reset to collect the next signal. Lower limits to the in-rush current in this case translated to reduced capability in the detector analog circuit getting reset to baseline voltage (-1V), and was dependent on the integrated current needed to reset the ensemble detector elements being reset with each action. The total current depends on number of detectors getting reset as well as the amount of signal (electrons) in the detector element at the previous observation. On some instances this electronic offset appeared to be a positive effect and some instanced the effect appeared to be a negative effect. The situation impacted all observations for the SW/MWIR focal plane (10 bands), and the 4 PV bands on the LWIR focal plane. Analysis of synthesized scenes that would be half uniform vegetated surface at 300K and half uniform cloud at 240K were found to have an error nearing 80% for Band 24 and 10% or greater for each SWIR sub-frame 2. Errors (variable depending on signal of previous observations) were found to invalidate most of the MODIS Level 2 product requirements for products using the SWIR and MWIR bands. Results of this analysis are provided in Fig 5.

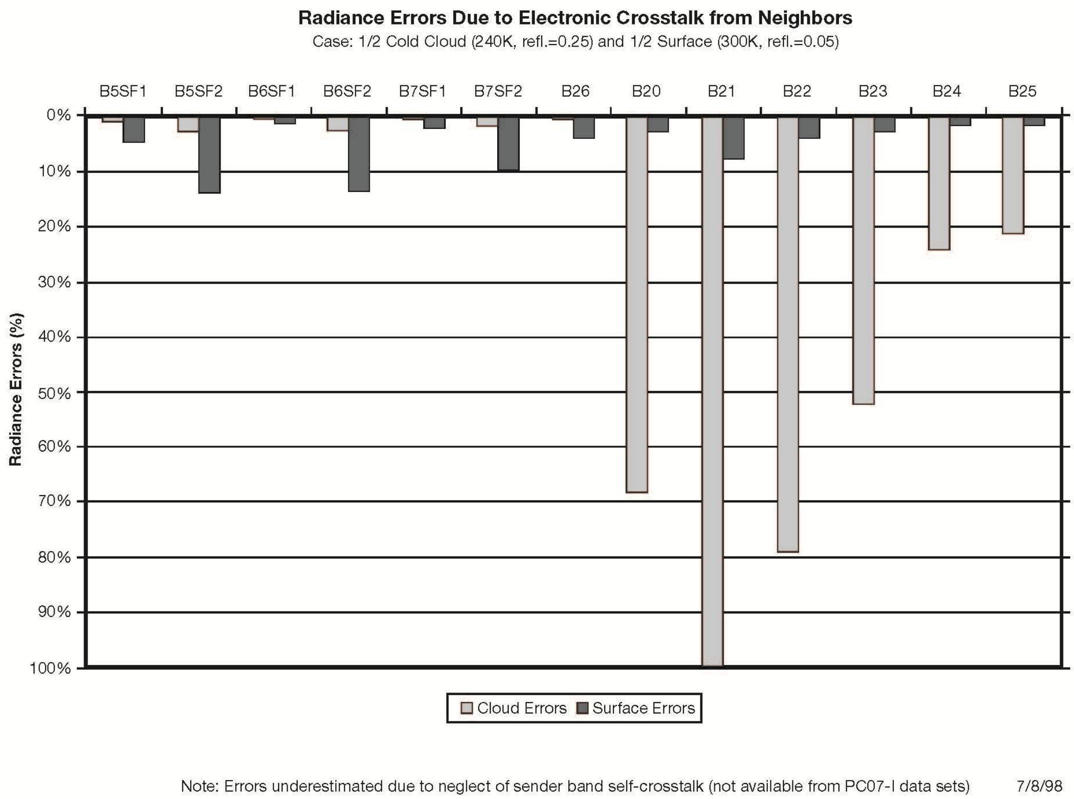

Fig 5 Errors predicted for the SWIR/MWIR bands due to sub-frame gain differences for a scene which is half cloudy and half clear on the focal plane at the time of observation. This effect is for a scene about 26 km in track and 10 km in scan direction at Nadir, and grows significantly for scan angles away from Nadir

Changes to the reset time were not possible, and hardware improvement involved increasing the upper limit of inrush current. The "tools" available for reducing electronic cross-talk became the commandable in-rush current (known as I_{twk}) and the detector operating bias voltage (known as V_{det}). Hardware correction involved removal of focal plane control electronics board and replacement of components controlling in-rush current. This engineering step was performed after the completion of all Terra MODIS system characterization tests, and change of this component also had effect of invalidating per-launch characterization (calibration) testing of 14 thermal bands. The repair was performed on the launch critical path schedule so no further testing to verify optimum focal plane operations occurred on the ground.

In the early Terra MODIS on-orbit operations the engineering performance for the focal planes are impacted by two commandable quantities, Vdet and Itwek. Further, our launch schedule was driven by a requirement to get to orbit in the 20th Century, before any so-called Y2K (Year 2000) effects may occur. The early operations for Terra MODIS were largely dictated by adjustments of Vdet and Itwek adjusted to provide the minimum sub-frame differences in the

SWIR bands. The Vdet and Itwek were control knobs for the 10 bands on the SW/MWIR focal plane, and 4 bands on the LWIR focal plane, and not just on the SWIR bands. Our testing demonstrated that the electronic cross-talk from these effects were minimized, based on minimizing the differences in response between the two sub-frames for on-board blackbody observations. Routine on-orbit calibration with full aperture calibration devices (Solar Diffuser and Dark Space for SWIR reflected solar bands, and On-Board Blackbody and Cold Space for the MWIR bands) are used to recover the radiometric calibration for these 14 bands.

The focal plane in-rush current effects were minimized for the MODIS Aqua sensor. The concern for potential long-term fatigue of the SWIR/MWIR focal plane need to be heeded, and we anticipate that the MODIS Terra focal plane may demonstrate long-term fatigue behaviors based on the considerations described in this Section.

5. MWIR ELECTRONIC CROSS-TALK

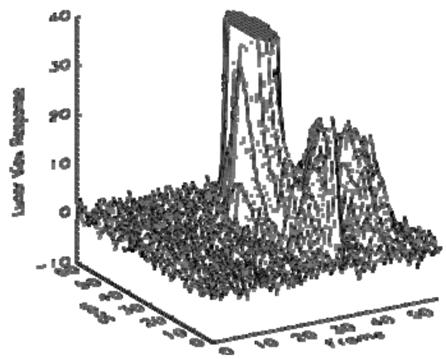

Fig 6. Band 24 three dimensional representation of a scan of the moon. Lunar calibrations are baselined for reflected band calibration long term trending, and have provided essential information of electronic (or optical) cross-talk in the thermal bands where the lunar edge represents a sharp demarcation between hot and cold target scene. The IR bands saturate and the lower signals away from the saturation peak is a cross-talk signal.

Fig 6, shows the MODIS response to lunar observations for a MWIR band, Band 24 in this case. The central peak signal is truncated to emphasize the peaks to the right of the peak. These minor peaks are electronic cross-talk signals due to signals in adjacent bands. A linear model has been developed by Sun et al. [5, 6]_to describe the crosstalk contamination from each sending band and the overall contribution is assumed to be a linear sum of the crosstalk magnitude from each sending band,

$$dn_{B_rD_r}^{xtalk}(F) = \sum_{B_sD_s} c(B_r, D_r, B_s, D_s) dn_{B_sD_s}^{msr}(F + \Delta F_{rs}) , \qquad (2)$$

where B_r, D_r, B_s, and D_s represent the receiving band, receiving detector, sending band, and sending detector, respectively, $c(B_r, D_r, B_s, D_s)$ is the crosstalk coefficient for the crosstalk contamination from detector D_s of the sending band B_s to detector D_r of the receiving band B_r. F is the pixel number along scan of band B_r, ΔF_{rs} is the frame shift between band B_r and band B_s for viewing same target. The observations must be corrected for both the calibration views of the on-board blackbody as well as for earth-observations. The differences between uncorrected and corrected signals for this apparent cross-talk effect may be up to 10K.

The correction involves ΔF_{rs}, the frame offset. The MODIS L1B calibration product is published with observations adjusted so that all frames observing one point on the earth are registered. This strategy is best for implying environmental parameters from the observations. The actual observations for two bands in VIIRS for a specific point on the earth do not occur simultaneously but are delayed in time by separation of the bands for the sensor optical axis and the scan rate of the scan mirror. Cross-talk effects of the nature of the MWIR Electronic Cross-talk must be adjusted for "moment of observation' rather than in the earth registered space. This difference is called frame offset and is congruent to the separation of bands on the MODIS focal planes shown in Fig 1.

MODIS infrared scenes show striping in the imagery. The above correction algorithm is applied on a detector by detector basis, and the corrected scenes show reduced striping effects compared to the uncorrected scenes. We infer that these differences obtained with this approach to electronic cross-talk effects provide an actual improvement in thermal MWIR radiometry because we know that stripes in the observations are measurement artifacts and we infer that reducing the size of the artifact is moving to a more correct radiometric observation. Verification of this inference has been provided by other research results [7]. The MODIS MWIR electronic cross-talk corrections are firstly applied in MODIS Collection 6 processing. The MWIR electronic cross-talk corrections using this approach should be applied to all bands between Bands 20 and Band 25, except for the "Fire Band", Band 21, which has a high saturation radiance and must be treated separately. The effect is strongest in the MWIR in Band 24. Characterization of cross-talk effects for Band 21 also are beyond the scope of this paper.

6. LWIR ELECTRONIC CROSS-TALK

Electronic cross-talk also is present in the photovoltaic infrared long wavelength bands, Band 27 – Band 30 [5-7]. (Bands 31 to 36 are photoconductive bands, with significantly different analog to digital signal processing techniques and do not show the electronic cross-talk.) The strategy to observe PV LWIR electronic cross-talk, and the analysis techniques are nearly identical to those used in Section 5, MWIR electronic cross-talk. The within band detector-to-detector differences are as large as 15K for Band 27 uncorrected, that appear as ghosts and image striping. Band 27 drifts of 6K also are seen. Some of the LWIR electronic cross-talk effects are negative, as seen in Fig 3 in SWIR too. A PV LWIR electronic crosstalk correction has been implemented in MODIS Collection 6.1 [8, 9]. The electronic cross-talk is shown to remove striping effects in the product and also shown to remove performance drift and improve product performance [10].

The presence of LWIR electronic cross-talk may be related to sub-frame gain differences, as described in Section 4. Consequently the effects may be larger in MODIS Terra than MODIS Aqua, and the long-term trends for MODIS Terra for this electronic cross-talk are anticipated to be greater than any trends of this behavior on MODIS Aqua.

7. LWIR OPTICAL CROSS-TALK

The LWIR light leak from Band 31 leaking (optical cross-talk) into the other Photo-conductive LWIR bands (Bands 32 – 36) is well described in the MODIS Level 1B Calibration ATBD [2]. That ATBD is hyperlinked here. MOD5S ATBD, see page 16. The SWIR optical cross-talk (Section 3) is the consequence of a design characteristic for the interference filters for these bands. This LWIR PC Bands effect is the consequence of light scattering between the interference filter stack and the detectors. The thinking is that light is scattered from an edge of the filter assembly at the bottom of the Band 31 filter. Consequently one characteristic of this cross-talk is that the magnitude of the effect decreases with physical distance from Band 31. Another characteristic is that the correction must be executed with frame offset observations. The cross talk of Band 31 into Band 33 is shown in Fig 7.

This effect is not expected to change on Terra MODIS with time on orbit, and was corrected in the Aqua MODIS design.

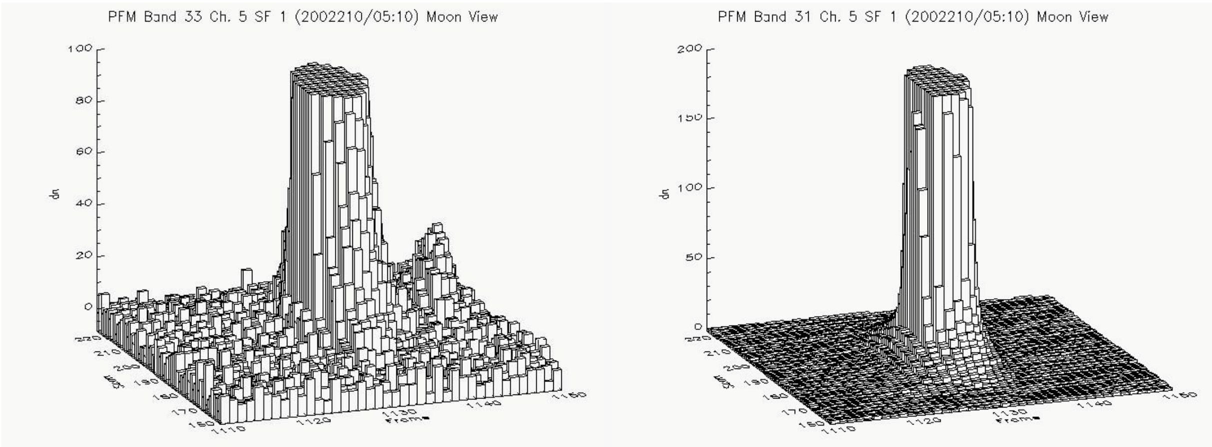

Figure 7: The Terra MODIS lunar response for B33 (left figure) and B31 (middle detectors only). The X-axis represents the data frame number, the Y-axis is the scan number, and the Z-axis is the response (dn). Fig from MODIS Algorithm Theoretical Basis Document, Figure 10, used by permission.

8. DISCUSSION, ONE OF THESE SENSORS IS NOT LIKE THE OTHER

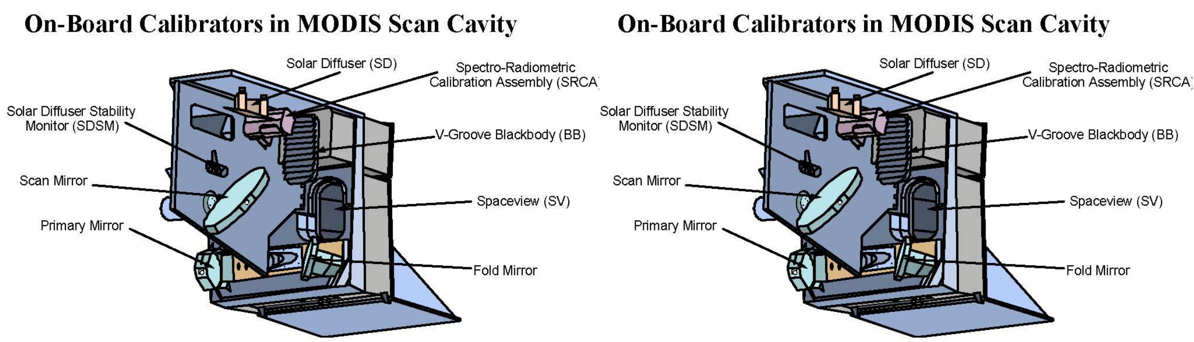

Fig. 8 Terra MODIS on left side and Aqua MDIS on right side.

The sensors are identical to the external view, and are built to identical specifications, as shown in Fig. 8. We describe several effects here that are present in Terra MODIS and do not occur in Aqua MODIS, or appear weaker on Aqua. The differences are considered sufficiently significant that we will address some aspects of them here. The caution identified in Section 4, for sub-frame differences that was shown by the detector manufacturer must be respected. Our adjustments to limit sub-frame differences were necessary to provide high fidelity performance for the 14 bands on the SW/MWIR and LWIR focal plane. And our adjustments for V_{det} and I_{twk} were near the best that can be achieved with our coarse controls at the system level, while the sensor is operating in space without an external calibration source to carefully verify sub-frame differences. The second flight build was set with a better compromise between reset performance in in-rush current and long-term detector fatigue. We observe long-term drift in MWIR electronic cross-talk on Terra MODIS and we do not expect to observe on MWIR Aqua MODIS electronic cross-talk. Consequently we must anticipate that the 14 MODIS Terra PV infrared bands will age more significantly than will the MODIS Aqua PV infrared bands. We do not anticipate that the Terra LWIR PC bands will be less stable than will be those bands on Aqua.

Terra MODIS also experienced a before launch test mishap that caused a contamination of the Terra Solar Diffuser and the scan mirror. Publications elsewhere adequately describe the accelerated Terra Solar Diffuser and scan mirror degradation, and we have added the references here to highlight that we also see differences in Terra MODIS long-term stability performance in the VisNIR bands too. These effects are thought to be limited to reflected solar bands, Vis and NIR mainly. Technical description of this VisNIR mishap and details on the effects for MODIS are beyond the scope of this paper.

9. CONCLUSIONS

The Terra MODIS Cross-talk effects are described. The corrections for these effects are described in the MODIS Level 1B Algorithm Theoretical Basis Document. The background for the SWIR cross-talk and SWIR 500 m band sub-frame differences are presented for the first time. Strategies for pre-launch and on-orbit mitigation of SWIR cross-talk are presented. The strategies for tracking MWIR and LWIR electronic cross-talk are presented and a correction equation for these effects also is provided. Finally, data users are cautioned for the comparison of long-term trends from Aqua MODIS with Terra MODIS. Specific features of Terra MODIS suggest that device may be vulnerable to lower resilience in long term performance than will be the Aqua MODIS.

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ACKNOWLEDGEMENTS

The MODIS Level 1B Algorithm Theoretical Basis Document is the *primary* reference for all MODIS characteristics. The MODIS Characterization Support Team (MCST) is led by Jack Xiong, and Jack and the MCST folks are extraordinarily supportive. Vince Salomonson and Michael King have provided MODIS Science Team Leadership support for more than 3 decades. Two slides were redrawn by the Exhibits Team at the NASA-Goddard Mission Science Directorate from 2 decade old paper charts. Financial support for this work has come from NASA's MODIS and Earth Observing System and NOAA and NASA's VIIRS and the Joint Polar Satellite System