Assessment of the NPP VIIRS RVS for the Thermal Emissive Bands Using the First Pitch Maneuver Observations

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ABSTRACT

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a key sensor carried on Suomi NPP (National Polar-orbiting Partnership) satellite (http://npp.gsfc.nasa.gov/viirs.html) (launched in October 2011). VIIRS sensor design draws on heritage instruments including AVHRR, OLS, SeaWiFS and MODIS. It has on-board calibration components including a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) for the reflective solar bands (RSB), a V-groove blackbody for the thermal emissive bands (TEB), and a space view (SV) port for background subtraction. These on-board calibrators are located at fixed scan angles. The VIIRS response versus scan angle (RVS) was characterized prelaunch in lab ambient conditions and is currently used to characterize the on-orbit response for all scan angles relative to the calibrator scan angle (SD for RSB and blackbody for TEB). Since the RVS is vitally important to the quality of calibrated radiance products, several independent studies were performed to analyze the prelaunch RVS measurement data. A spacecraft level pitch maneuver was scheduled during the first three months of intensive Cal/Val. The NPP pitch maneuver provided a rare opportunity for VIIRS to make observations of deep space over the entire range of scan angles, which can be used to characterize the TEB RVS. This study will provide our analysis of the pitch maneuver data and assessment of the derived TEB RVS. A comparison between the RVS determined by the pitch maneuver observations and prelaunch lab tests will be conducted for each band, detector, and half angle mirror (HAM) side.

Keywords: VIIRS, calibration, response versus scan angle, pitch maneuver, prelaunch

1. INTRODUCTION

Following the successful launch of Suomi NPP (National Polar-orbiting Partnership) satellite (http://npp.gsfc.nasa.gov/viirs.html) [1] on October 28, 2011, the Visible Infrared Imaging Radiometer Suite (VIIRS), a key sensor carried on Suomi NPP, has gone though a number of scheduled spacecraft activities during the first several months in support of calibration related issues. The pitch maneuver is one of these activities, scheduled on Feb 20, 2012, the purpose of which is to characterize the response versus scan angle (RVS) for the VIIRS thermal emissive bands (TEB). Figure 1 provides a schematic of the spacecraft orientation in normal orbit and during the pitch maneuver and Figure 2 gives a snapshot of two Earth view images at the beginning and near the end of the pitch, respectively. During the normal orbit, the nadir side of the satellite always faces the earth, which is achieved by a continuously pitching of the spacecraft in the forward direction. During the pitch maneuver, however, the spacecraft stops its pitching, resulting in the spacecraft being in a constant pointing orientation. This provides a complete view of deep space for VIIRS during the middle course of the maneuver. Since the radiance from cold space is nearly zero, the remaining radiance received by the detectors is from the thermal emission of the scan mirror. Thus, analysis of detector responses during the pitch maneuver can provide an initial checkout of the TEB RVS.

VIIRS sensor design draws on heritage instruments including AVHRR (Advanced Very High Resolution Radiometer), OLS (Operational Linescan System), MODIS (Moderate Resolution Imaging Spectroradiometer), and SeaWiFS (Sea-viewing Wide Field-of-view). It uses a constant-rate rotating telescope assembly (RTA) and a double sided half angle mirror (HAM) rotating at half the speed of the RTA. VIIRS has 22 bands with a spectral range from 0.4 to 12.0 µm (see Table 1). The Earth view swath covers a distance of ~3000 km over scan angles of ± 56.0^o off nadir. Observations by VIIRS cover the entire earth's surface every one or two days and the derived products provide high quality environmental and climate information for land, ocean, and atmosphere.

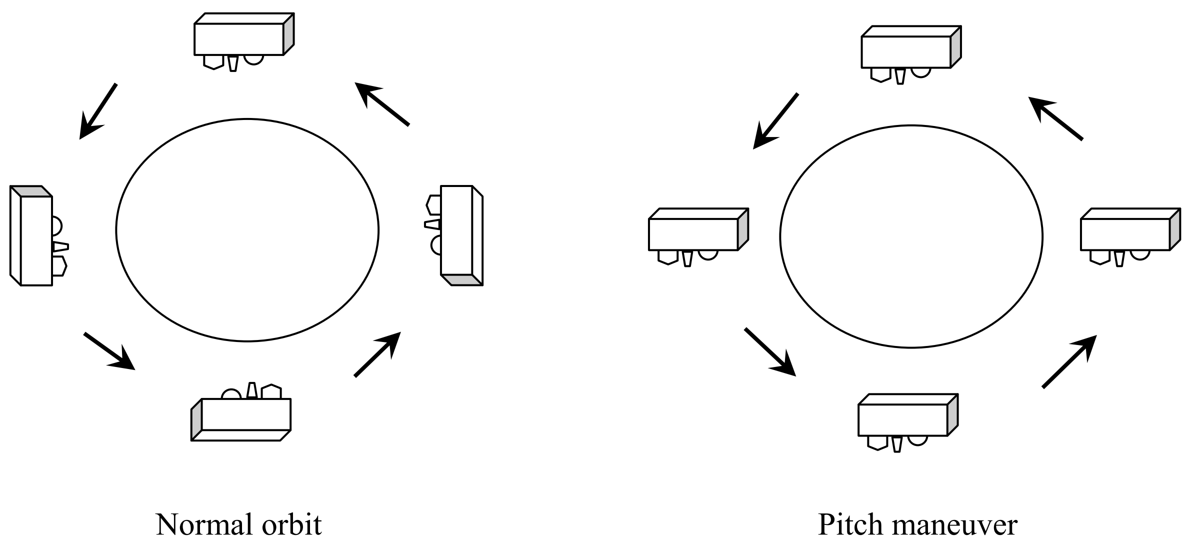

Figure 1. Schematic diagram of spacecraft orientation in normal orbit and during the pitch maneuver.

The on-board calibration components are a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) for the reflective solar bands (RSB), a V-groove blackbody for the TEB, and a space view (SV) port used to remove background signals from both RSB and TEB raw responses. The SD and blackbody provide absolute calibration with standards traceable to those provided by the National Institute of Standards and Technology (NIST). Since both the SD and blackbody are located at fixed angles of incidence (AOI), the calibration at other AOIs is dependent upon the RVS that describes relative changes to those obtained at the on-board calibrator AOI. Thus, how well the RVS is characterized is vitally important to ensure the quality of the calibrated radiance product.

The VIIRS RSB/TEB RVS was characterized prelaunch in lab ambient conditions [2-10]. These tests were conducted at a number of different scan angles to ensure a good description of the RVS over the valid scan angles. The purpose of this document is to describe the methodology of determining the VIIRS TEB RVS from the pitch maneuver and provide the first post-launch RVS results and the associated uncertainties. The derived RVS results are compared with those obtained from prelaunch to validate the TEB RVS using the two independent sources. It is expected that the TEB RVS is very stable and the post-launch results should be in good agreement with those from prelaunch tests.

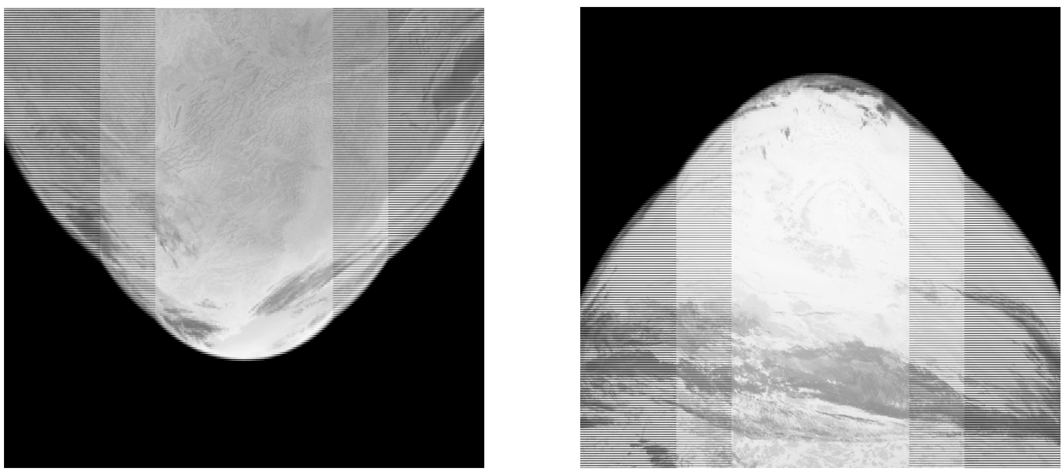

Figure 2. Images of I05 brightness temperature obtained at the beginning (left) and near the end (right) of the pitch maneuver. The entire pitch maneuver period was from 18:15:34 GMT to 18:59:19 GMT on Feb 20, 2012. The left image was taken using scans collected for a period of 18:22:02 to 18:27:44 GMT and the right image was for a period of 18:47:39 to 18:53:20 GMT.

Table 1. VIIRS TEB sensor spectral bands (units in nm)

Band	M12	M13	M14	M15	M16	I04	I05
CW	3700	4050	8550	10763	12013	3740	11450
BW	180	155	300	1000	950	380	1900

2. METHODOLOGY

With the pitch maneuver data, the RVS is determined using detector responses measured at two separate sources: the deep space and onboard blackbody. At a given earth view (EV) scan angle, the measured radiance, ΔL_{EV}, can be written as [11]

$$\Delta L_{EV} = RVS_{EV} L_{EV} + (RVS_{EV} - RVS_{SV}) \frac{(1-\rho_{RTA})L_{RTA} - L_{HAM}}{\rho_{RTA}} \quad (1)$$

$$\Delta L_{EV} = C_0 + C_1 dn_{EV} + C_2 dn_{EV}^2 \quad (2)$$

where RVS_{EV} and RVS_{SV} are the RVS at a given EV and the SV scan angle, respectively, L_{EV} is the EV radiance, L_{RTA} and L_{HAM} are the radiances from the RTA and HAM, ρ_{RTA} is the reflectance of RTA, and dn_{EV} is the background subtracted digital count at the EV scan angle. Coefficients C_0, C_1 and C_2 are band, detector, HAM and instrument temperature dependent.

By setting

$$L^{\wedge}_{RTA\_HAM} = \frac{(1-\rho_{RTA})L_{RTA} - L_{HAM}}{\rho_{RTA}} \quad (3)$$

equation (1) becomes after combining with equation (2)

$$C_0 + C_1 dn_{EV} + C_2 dn_{EV}^2 = RVS_{EV} L_{EV} + (RVS_{EV} - RVS_{SV}) L^{\wedge}_{RTA\_HAM} \quad (4)$$

By applying equation (4) to the deep space during the pitch maneuver (in this case, $L_{EV} = 0$) and onboard blackbody (BB), respectively, the following two equations are derived

$$C_0 + C_1 dn_{EV} + C_2 dn_{EV}^2 = (RVS_{EV} - RVS_{SV}) L^{\wedge}_{RTA\_HAM} \quad (5)$$

$$C_0 + C_1 dn_{BB} + C_2 dn_{BB}^2 = RVS_{BB} L_{BB} + (RVS_{BB} - RVS_{SV}) L^{\wedge}_{RTA\_HAM} \quad (6)$$

Taking a ratio between equations (5) and (6) and neglecting the offset and nonlinear terms of the left-hand side of the two equations yields

$$\frac{dn_{EV}}{dn_{BB}} = \frac{(RVS_{EV} - RVS_{SV}) L^{\wedge}_{RTA\_HAM}}{RVS_{BB} L_{BB} + (RVS_{BB} - RVS_{SV}) L^{\wedge}_{RTA\_HAM}} \quad (7)$$

By setting $RVS_{BB} = 1.0$, then RVS_{SV} can be derived from equation (7), given dn_{EV} at the viewing angle of the blackbody AOI, i.e., $dn_{EV=BB}$. In this case, $RVS_{EV=BB} = 1.0$.

$$RVS_{SV} = 1 - \frac{L_{BB}}{\hat{L}_{RTA\_HAM}} \frac{dn_{EV=BB}}{(dn_{BB} - dn_{EV=BB})} \tag{8}$$

By combining equation (7) and (8), RVS_{EV} can be derived

$$RVS_{EV} = 1 + \frac{L_{BB}}{\hat{L}_{RTA\_HAM}} \frac{(dn_{EV} - dn_{EV=BB})}{(dn_{BB} - dn_{EV=BB})} \tag{9}$$

A second order polynomial is used to fit the RVS versus AOI, or

$$RVS_{EV} = a_0 + a_1 AOI + a_2 AOI^2 \tag{10}$$

Once the coefficients a_0, a_1, and a_2 are produced by the fitting, equation (10) is used to characterize the RVS. These RVS coefficients should be band, detector, HAM side, and sub-sample dependent as determined in prelaunch tests. The VIIRS earth view AOI range is from 29.0^{o} to 56.47^{o}. Since the RVS is characterized relative to the reference, equation (10) is generally normalized to the AOI of the onboard calibrator. For the RSB, the normalization point is the AOI of solar diffuser (SD) at 60.18^{o}; for the TEB, the RVS is normalized to the same AOI as the RSB to be consistent.

3. Results

3.1. Data selection and treatment

As shown in Figures 1 and 2, the pitch maneuver started at 18:15:34 GMT and ended at 18:59:19 GMT. Since a complete view of deep space occurred at the middle point of the maneuver, one might be expected to use data collected around 18:37:00 GMT. However, at around 18:30:00 GMT, temperatures of the cold focal planes started to rise rapidly (Figure 3) as a result of the thermal infrared absorption of earth's radiation due to the pitch maneuver. Thus, data collected slightly earlier than 18:30:00 GMT is selected to avoid any possible impact due to the rapid rise in the cold focal plane temperatures. As shown in Figure 3, the exact starting time of the data collection is at 18:26:19 GMT.

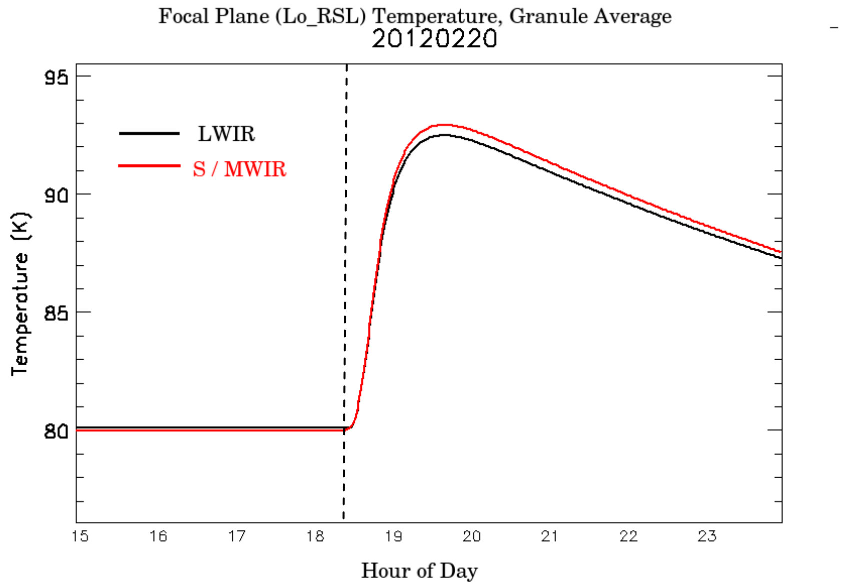

Figure 3. Variations of the cold focal plane (LWIR and S/MWIR) temperatures throughout the course of the pitch maneuver. The vertical line is at 18:26:19 GMT when scan by scan data is collected for the RVS analysis.

A total of 40 consecutive scans (20 for each HAM side) of data samples are collected from the pitch maneuver. Each scan covers the entire earth view with 3200 pixels for M bands with exception for M13 (6304 pixels) and 6400 pixels for I bands. Figure 4 plots the raw response versus sample number based on multiple scans at HAM-A side for M12, M14 and I05. These responses are from the background contribution because the sensor is viewing deep space during the pitch maneuver. The fact that the response is not flat (i.e., M14 and I05) crossing the entire earth view range indicates that the reflectivity of the scan mirror changes with the scan angle. Thus, use of the data collected from the pitch maneuver can provide useful information to assess the RVS. Figure 4 also shows that the response of I05 has a discontinuity at sample number 1280 and 5120, respectively. The discontinuity happens between the aggregation zones where an average of the two or three sub-samples is performed between sample number 1280 and 5120. To remove the discontinuity, an additional average of the two sub-samples between sample number 1 to 1279 and 5121 to 6400 is performed. Thus, our sampled data is consistent throughout the entire sample range.

According to equations (1) through (9), the background subtracted response, i.e., dn_{EV}, is used to determine the RVS. The background signal can be taken either from the response obtained at the space view port or from the earth view sector obtained at a particular AOI. In this study, we use an average of the last ten samples of the earth view as the background. Figure 5 plots dn_{EV} versus AOI using the same data shown in Figure 4. The conversion from the sample number to AOI is based on a Raytheon provided method.

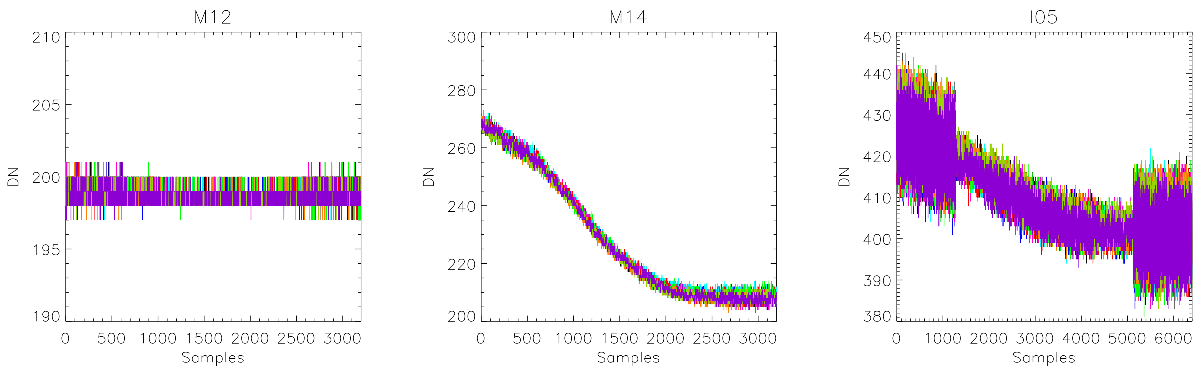

Figure 4. Raw responses (DN) of M12, M14 and I05 versus sample number during the pitch maneuver. Different detectors are represented by different color.

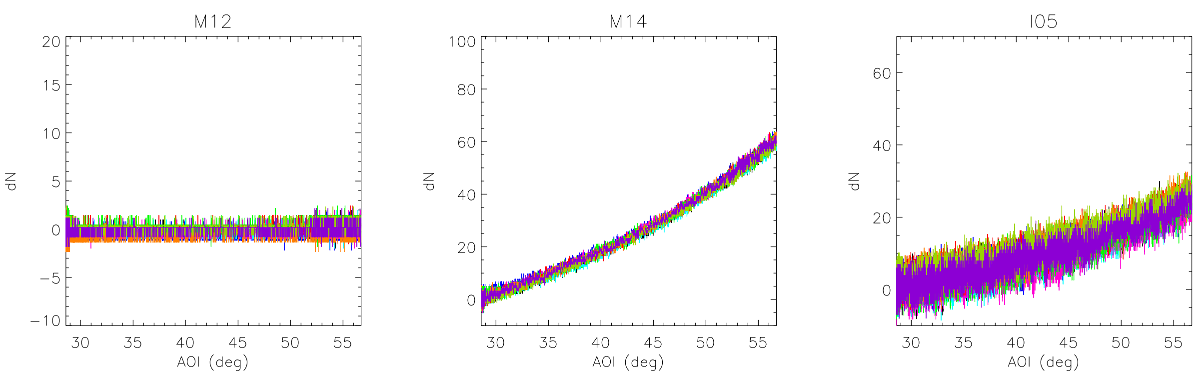

Figure 5. Background subtracted responses (dn) versus AOI for M12, M14 and I05 during the pitch maneuver. Different detectors are represented by different color.

3.2. Determination of RVS

After an average of the two sub-samples for I bands and the background subtraction, dn_{EV}, along with dn_{BB}, is applied to equation (9) to determine RVS_{EV}. Examination of the 40 scans of the pitch maneuver data indicates that the temperatures of the two cold focal planes (S/MWIR and LWIR) were well controlled at around 80 K (between 80.004 and 80.010 K for S/MWIR and between 80.089 and 80.095 K for LWIR). Thus, it is not necessary to correct for any possible impacts of cold focal plane temperature variations on the detector response. HAM temperatures change from 262.017 to 261.999 K. Values of ρ_{RTA} are taken from the auxiliary calibration data provided by Raytheon. There are two reported temperatures for RTA: 1) mainframe bulkhead temperature and 2) mainframe –X scan cavity panel PZ temperature. An average of the two RTA temperatures is used, which is 264.18 K.

In additional to the direct use of the averaged RTA temperature, a small temperature offset should be applied according to simulations provided by Raytheon's thermal calibration model. Various values of the offset were suggested during the pre-launch tests. Currently, the latest suggested offset is 6.0 K. To examine how sensitive our retrieved RVS to the offset is, we used three different offsets in this study, which are 0.0, 6.0 and 12.0 K.

The RVS determined from equation (9) is fitted versus AOI by a second order polynomial, i.e., equation (10). Figure 6 plots the HAM-A RVS as a function of AOI for the three RTA temperature offsets (0.0, 6.0 and 12.0 K). The RVS used in current SDR lookup tables (LUT) is also plotted as a function of AOI. The LUT RVS is provided by Raytheon, which is based on prelaunch tests in lab ambient conditions [5, 6]. The prelaunch RVS results were compared and validated among three independent studies of the NPP Instrument Calibration Support Team (NICST) funded by NASA, Raytheon, and the Aerospace Corporation [2]. It should be noted that the results shown in Figure 6 are band and HAM side dependent. The RVS from the pitch maneuver is not detector dependent. This is because samples at beginning and end of the scan are filled with default value of 65534 for detectors 1-2 and 15-16 of M bands and detectors 1-4 and 29-32 of I bands. Therefore, the derived RVS from the pitch maneuver cannot cover all detectors. The RVS from the pitch maneuver shown in Figure 6 is the average over middle detectors. For M bands, the average is over detectors 4 to 13 and for I bands, the average is over detectors 8 to 26. Table 2 lists the detector averaged RVS coefficients and fitting uncertainties using equation (10) with the current RTA offset of 6.0 K.

The results in Figure 6 show that the three different RTA temperature offsets have negligible impact on the derived RVS for almost all bands except for M14. For M14, the three offsets cause up to 0.30% differences at the end of scan (AOI = 29^o). Comparison of the pitch maneuver and prelaunch (used in LUT) RVS results shows good agreement. With the current offset of 6.0 K, the differences between the two RVS results are within 0.4% on average (Table 3), which is generally within the requirement of 0.3% allowed for the characterization of the prelaunch RVS [12]. Similar agreement is shown for both HAM sides. It is believed that errors in additional parameters except for the RTA temperature offset used to determine $\hat{L}_{RTA\_HAM}$, i.e., equation (3), are the reason for the existing small RVS differences between the prelaunch and pitch maneuver results. Nevertheless, it is believed that the prelaunch based RVS is well characterized based on the comparison with the results obtained from the pitch maneuver.

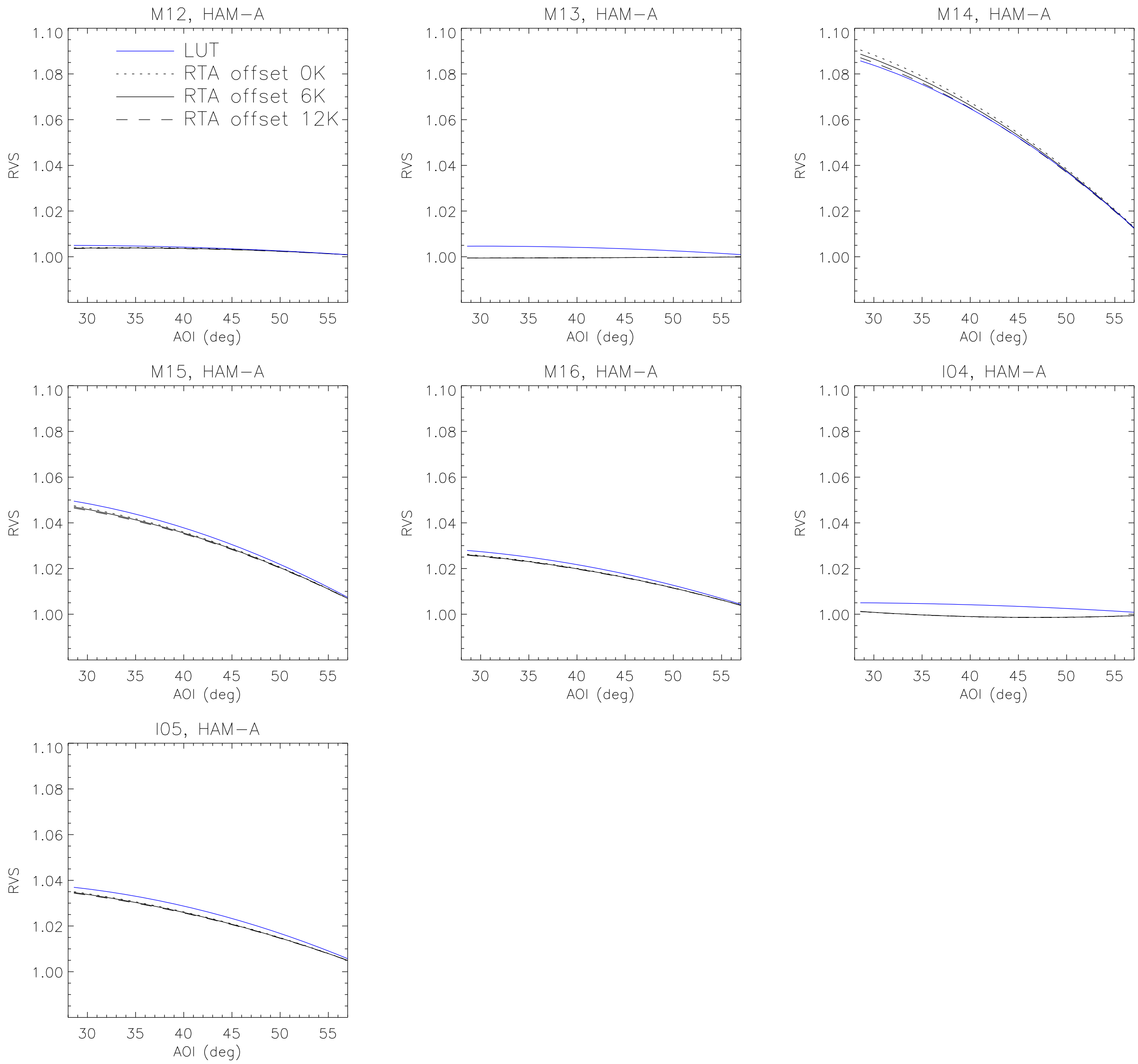

Figure 6. RVS of HAM-A determined from the pitch maneuver with three different RTA temperature offsets (0.0, 6.0 and 12.0 K). Values of the RVS are detector averaged. Also shown is the RVS used in LUT.

Table 2. Detector averaged RVS coefficients a0, a1 and a2 at each HAM side determined using equations (1) – (10). Also listed are the average percent fitting errors (%).

	HAM-A				HAM-B			
Band	a0	a1	a2	Error (%)	a0	a1	a2	Error (%)
M12	0.9974	3.902E-4	-5.779E-6	0.04	0.9977	4.018E-4	-6.048E-6	0.04

M13	0.9996	-1.937E-5	4.241E-7	0.04	0.9978	9.384E-5	-9.687E-7	0.04
M14	1.0996	8.914E-4	-4.232E-5	0.03	1.1166	9.369E-4	-4.775E-5	0.04
M15	1.0485	6.603E-4	-2.437E-5	0.02	1.0595	7.538E-4	-2.894E-5	0.02
M16	1.0253	4.431E-4	-1.435E-5	0.01	1.0296	4.823E-4	-1.619E-5	0.02
I04	1.0165	-7.669E-4	8.187E-6	0.13	1.0159	-7.276E-4	7.711E-6	0.13
I05	1.0381	3.657E-4	-1.661E-5	0.03	1.0461	3.537E-4	-1.861E-5	0.03

Table 3. RVS Differences between the pitch maneuver and prelaunch results for three different RTA temperature offsets. The differences are provided in percentage (%) on average and maximum.

	HAM-A						HAM-B					
Band	Offset at 0K		Offset at 6K		Offset at 12K		Offset at 0K		Offset at 6K		Offset at 12K	
	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
M12	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.2
M13	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5	0.3	0.5
M14	-0.2	-0.4	-0.1	-0.3	-0.0	-0.1	-0.3	-0.6	-0.2	-0.4	-0.1	-0.2
M15	0.1	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.2	0.3
M16	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.2	0.2	0.2	0.3
I04	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
I05	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3

4. Summary

The pitch maneuver is one of the scheduled early mission activities in support of Suomi NPP instrument and calibration related issues, performed on Feb 20, 2012. The maneuver provided a good opportunity to examine the VIIRS TEB RVS. This study provided a detailed description of algorithm to derive the RVS and compared the results with those derived from prelaunch tests. Results show that the pitch maneuver based RVS agrees with the prelaunch values to within 0.4%. Such differences are likely caused by uncertainties in input parameters used in the algorithm. In conclusion, the results of this study indicate that the prelaunch RVS is well characterized and there is no need to make any adjustment for current on-orbit use.

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