Prelaunch and On-orbit Electronic Calibration for Earth Observing Instruments

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ABSTRACT

The Electronic Calibration (Ecal) tests are performed during various stages of instrument development to examine the linearity of the instrument electronics. During this process, charges with stepwise increments are injected in the analog electronics circuitry to generate a ramp signal that can be used to characterize any nonlinearities in the electronics. The prelaunch characterization of MODIS (on the Terra and Aqua platforms) and VIIRS (on SNPP, JPSS-1 and JPSS-2) involved a regular evaluation of the electronics linearity using the Ecal tests. On orbit, the Ecal tests have been regularly performed over the mission for both the MODIS instruments to derive the electronics gain and linearity. Unlike MODIS, the Ecal tests on the VIIRS instruments are performed on an as-needed basis. To date, no Ecal tests were performed for S-NPP VIIRS on orbit. The VIIRS instrument on JPSS-1 (now NOAA 20) was launched on November 18, 2017. An Ecal test was performed to support the instruments initial post-launch performance assessment. Shortly after the first on-orbit emissive band calibration, degradation in the instrument gain was observed for the LWIR bands (M15, M16 and I5). As a part of the investigation related to this anomaly, a second Ecal test was performed and results were compared with the prelaunch results. In this paper, we discuss the prelaunch Ecal tests and representative results from MODIS and VIIRS prelaunch characterization. Also, discussed are the on-orbit results from the two MODIS instruments as well as from the recently launched VIIRS instrument.

Keywords: MODIS, VIIRS, Electronic calibration, ECAL, prelaunch

1. INTRODUCTION

Over the last two decades, scientific measurements from the two MODIS instruments (on the Terra and Aqua spacecraft), SeaWiFS, and the Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) have been widely used.[1–4] The MODIS instruments extend the heritage of its predecessor, the AVHRR instruments.[5] The VIIRS instruments (on the SNPP and JPSS-1 platforms) were designed and built to carry forward the legacy of the MODIS instruments.[6] With the exception of the latest VIIRS instrument on the JPSS-1 (now NOAA 20) platform and the Landsat 8 OLI, the rest of the instruments were built by the same instrument vendor, Santa Barbara Research Center (SBRC) in Goleta, CA. As a result, the pre- and post-launch calibration methodologies have been interoperable. Prelaunch calibration is the starting point to successfully implement an end-to-end calibration strategy for Earth observing sensors. The gain of the electronics, the amplifier, and the analog to digital converter (ADC) is tested extensively at various stages of the prelaunch characterization. This is commonly achieved via a test, called Electronic Calibration (Ecal) that involves injecting a voltage ramp when all detectors are disconnected from the electronics, and recording the output counts. Sensor-specific design features such as multiple gain settings, different detector types, etc. require modifications to this approach as necessary. The AVHRR/3 series of instruments has two electronic calibration functions: continuous ramp calibration mode (RAMP-CAL) and voltage calibration mode (VOLT-CAL, not used frequently on-orbit). The RAMP-CAL is used to verify the linearity and gain of the instruments ADC and amplified electronics using a ramp signal. The VOLT-CAL mode eliminates the detector signals and provides a three-point voltage calibration of the ADC and amplifier electronics.[7] The SeaWiFS on-orbit gain calibration uses a constant voltage source (a calibration pulse)injected into the post-detector electronics to monitor the output of electronic gains over time.[8] Some of the sources of non-linearities in Earth observing instruments include those

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associated with the electronics [ReadOut Integrated Circuit (ROIC), ADC] and the detectors.[7] The electronics non-linearities can be characterized by varying the integration time of the electronics when viewing a constant source,as is performed on the Landsat 8 OLI and Thermal Infrared Sensor (TIRS) instruments. The detector non-linearities need to be characterized by varying the input radiance in a very well controlled manner. For the thermal emissive bands, this can be achieved by periodically warming up and cooling down the on-board blackbody, but it is challenging to achieve this for the reflective solar bands (RSB) that continue to rely on the prelaunch Spectral Integrating Sphere (SIS) based calibration.[9] In this paper, we discuss the prelaunch and on-orbit Ecal operations for the MODIS and VIIRS instruments. Ecal operation in MODIS was designed to check the linearity of the on-board electronics for both the photovoltaic (PV) and the photoconductive (PC) bands.[10–13] While the Ecal operation was performed extensively prelaunch, only two instances of on-orbit Ecal operations have been performed for NOAA 20 VIIRS (and none for SNPP).[14,15]The results of comparing prelaunch Ecal with on-orbit Ecal, along with long-term electronic gain trends from on-orbit measurements of the two MODIS instruments are discussed Finally, a summary of the observed measurements and recommendations for future missions is also provided.

2. MODIS PRELAUNCH AND ON-ORBIT ELECTRONIC CALIBRATION

The MODIS instruments on the Terra and Aqua platforms underwent intensive prelaunch characterization at the vendor facility in Goleta, CA. The MODIS Focal Plane Assembly (FPA) design includes 36 distinct spectral bands placed on four separate FPAs (VIS, NIR, SW/MWIR, and LWIR) covering the wavelength range from 0.4 to 14.5 μm. Photo-Voltaic (PV) silicon hybrid detectors are used on the VIS/NIR FPAs (0.4 to 1 μm); the HgCdTe PV hybrid detectors are used on the SW/MWIR FPA (1.2 to 4.5 μm) and in four bands on the LWIR FPA. The LWIR FPA also includes six bands using HgCdTe photo-conductive (PC) hybrid detectors covering wavelengths beyond 10 μm. The signal processing of the output for each channel in the PV bands (1-30) consists of a detector on the FPA feeding into a capacitive transimpedance amplifier (CTIA), a multiplexer selecting channel, an integrator on the input to the analog electronics module (AEM) to remove the multiplexer transient effects, a programmable gain and offset, and a 12-bit ADC. Ecal for the PV bands consists of electronically inserting a programmed amount of charge into the CTIA instead of reading in the detector input. At the end of the multiplexer read-out interval, the CTIA is not reset which results in an increase of charge, thus forming a stair-step of output with a programmable number of steps (typically set to be FPA dependent, 25 for VIS, NIR, SMIR, MWIR and 8 for PV-LWIR). For the PC bands 31 through 36, it is not possible to disconnect the detectors from the signal process. Ecal for these bands is implemented by inserting charge in addition to the detector output. The Ecal process is only performed when the channels are looking at the low signals from the Space View (SV) port, thus allowing the full range of the Ecal to be exercised. The PC Ecal has been performed using 10 steps. The full set of Ecal data is saved by taking 50 frames of data for the SV sector.

The Ecal, commonly known as MF-10L from the MODIS prelaunch testing perspective, was performed several times for both MODIS instruments at various test environments (ambient, Thermal Vacuum (TVAC), post TVAC). The left panels of Figure 1 show a typical Ecal ramp from a performance test (Hot Plateau) for bands 8 and 29 on Terra MODIS. The center (right) panels of Figure 1 show the Ecal tests that were performed in the first year of Terra MODIS operation on July 31, 2000 (October 20, 2000). The injected voltage values for the prelaunch and on-orbit Ecal for the VIS bands (band 8) and PV LWIR bands (band 29) were set to 52 and 65, respectively. Due to the lower number of programmable steps in the PV LWIR bands, the shape of the ramp in band 29 was of a shorter duration than that observed in band 8. The Ecal gain for every detector is calculated as the slope of this ramp and a comparison between the prelaunch and early on-orbit gain is provided in Table I. Only the results for a middle detector are included for clarity. For the VIS, NIR and MWIR bands, the agreement between prelaunch and on-orbit measurements is generally within 7%. For the SWIR bands (5-7) and band 27, several gain changes were performed in the first year which resulted in greater disagreement between the prelaunch and on-orbit Ecal gains.

Table 1. Prelaunch (PL) and on-orbit Ecal gain for Terra MODIS PV bands

Band	PL	PL/OO-I	PL/OO-II	Band	PL	PL/OO-I	PL/OO-II
1	412.21	0.98	0.98	16	547.83	0.99	0.98
2	93.93	0.97	0.96	17	453.32	0.99	0.99
3	304.65	0.97	0.97	18	476.43	0.99	0.99
4	245.00	0.97	0.97	19	659.07	0.99	0.99
5	81.48	0.87	0.94	20	468.43	0.93	0.97
6	99.07	0.90	0.96	21	493.43	0.93	0.97
7	475.36	0.90	0.97	22	469.09	0.93	0.97
8	370.33	0.97	0.97	23	453.78	0.92	0.97
9	217.35	0.96	0.96	24	799.92	0.93	1.02
10	212.47	0.96	0.96	25	893.3	0.93	1.02
11	169.93	0.96	0.97	26	526.65	0.92	0.96
12	189.28	0.96	0.96	27	640.97	1.05	1.05
13	714.79	0.98	0.98	28	438.03	1.006	1.008
14	622.44	0.98	0.96	29	383.33	1.005	1.005
15	431.57	0.98	0.98	30	671.5	0.98	0.98

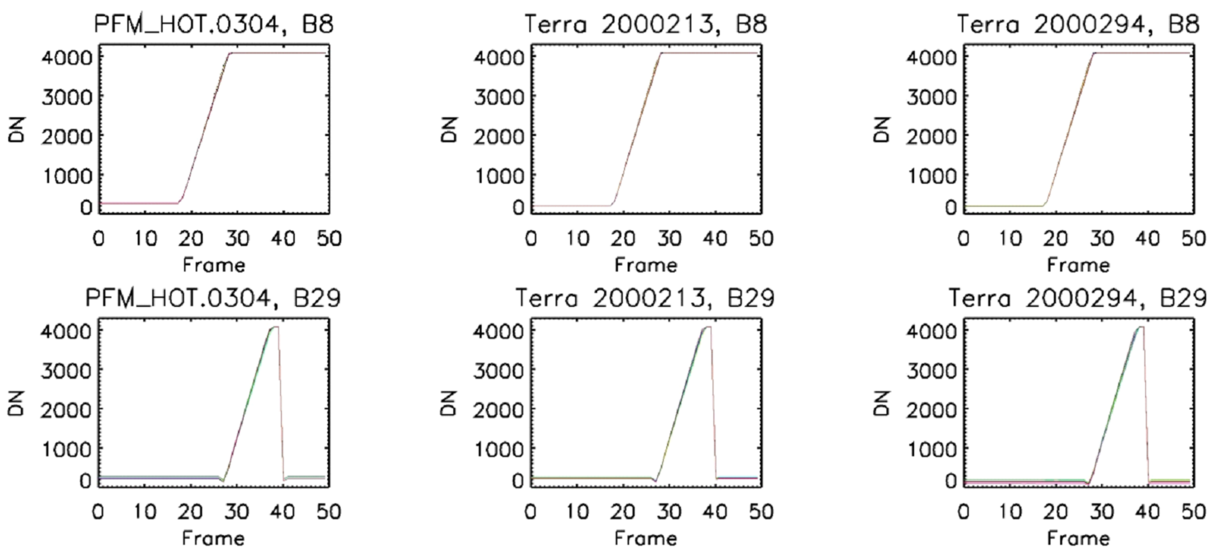

Figure 1. Ecal ramp from prelaunch and early on-orbit calibrations for Terra MODIS

On-orbit, the PV Ecal operation for both MODIS instruments has been performed on a quarterly basis, until recently (January 2018) where it was decided to reduce the frequency of these events compared to previous years. The PC Ecal operation was only performed in the initial year and has not been performed since. As discussed earlier, the PV Ecal detectors are disconnected from the digitization electronics and voltage is injected into the circuit (after the ROICs/pre-amplification stage),therefore facilitating an evaluation of the linearity of the ADC.[16] As multiple bands use the same ADC, the on-orbit Ecal gain trends are ADC specific; in other words, all of the bands sharing an ADC show similar on-orbit gain degradation. As a result, the changes in the detector non-linearity on-orbit are not monitored. Figures 2 and 3 show the normalized Ecal gain for representative Terra and Aqua bands (center detector). Each PV band shown in Figures 2 and 3 represent the trends from a unique ADC which is representative of the trend for other bands sharing the same ADC. For both MODIS instruments, the PV VIS, NIR and SMIR bands show a gain increase whereas the PV LWIR bands show a gain decrease over the entire mission. The exact reason behind the divergence of this trend is not completely understood at this time. It was also observed that bands 1 and 2 show seasonal oscillations in the Ecal trends that correlate with instrument temperature variations. All RSB exhibit a correlation between the Ecal trend and instrument temperature of varying magnitudes.

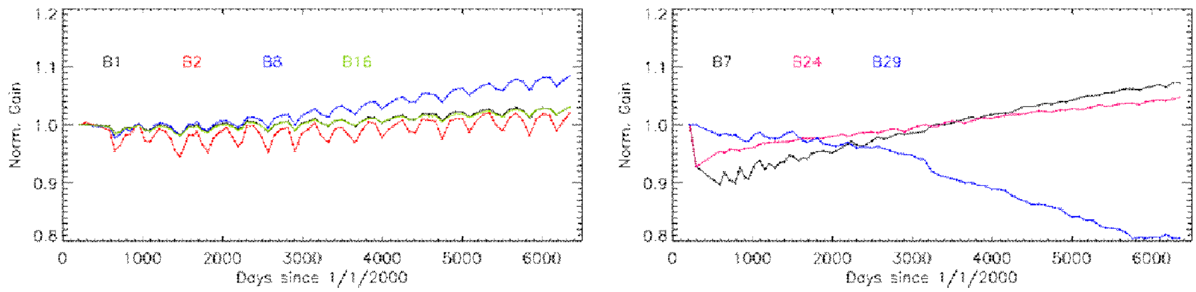

Figure 2. Normalized Ecal Gain trending for select Terra MODIS bands

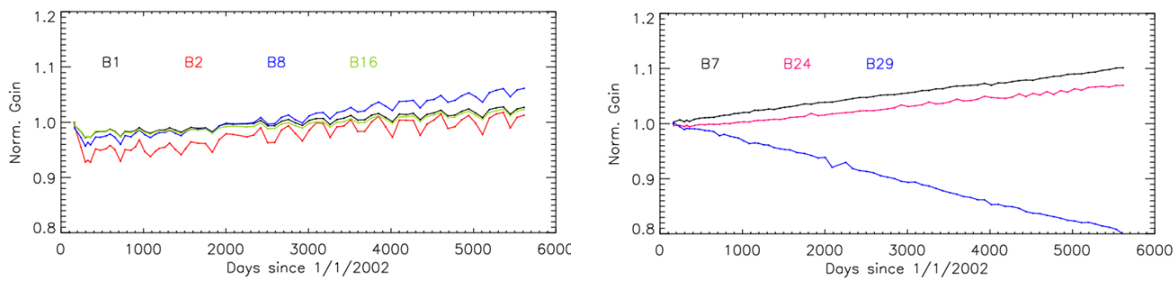

Figure 3. Normalized Ecal Gain trending for select Aqua MODIS bands

3. VIIRS PRELAUNCH AND ON-ORBIT ELECTRONIC CALIBRATION

The VIIRS instruments, built with a strong MODIS heritage, have 22 spectral bands that include 16 moderate (M) resolution bands, 5 imaging (I) bands, and a day/night band (DNB). The M and I band detectors are located on three focal planes: VIS/NIR, SMIR, and LWIR. The DNB is located on a separate FPA. Among the M-bands, M1-M5, M7, and M13 are the dual gain bands where the gain transitions between high and low based on the measured radiance. Similar to MODIS, the VIIRS instrument also underwent an intensive prelaunch characterization. The Ecal, commonly known as SI-5 from the VIIRS prelaunch testing perspective, was performed several times for NOAA 20 (or JPSS-1) VIIRS at various test environments (ambient, TVAC, post TVAC). Extensive SI-5 tests were also conducted prior to launch for SNPP VIIRS, but no on-orbit Ecal was performed.[14,15] The purpose of the test is to characterize the response of the electrical signal path (ROIC to digital output) using an internally generated step ramp at the input of each detector channels unit cell. During the prelaunch testing, a complete SI-5 Part 1.1 (comprehensive option) contains eight data collects. Each collect corresponds to one of the four ramp settings (Full Ramp, Lower Ramp, Upper Ramp, and Saturation) in combination with a timing synchronization input signal either targeted for the I-bands or M-bands. The test is performed with the detectors disconnected and rotating telescope with minimal illumination. The Day-Night Band (DNB) is not tested as a part of this procedure.[14]

The Ecal was performed during the initial days (December 8, 2018) after JPSS-1 launch as a part of the instrument health check. The goal of this test was to compare the results (electronic gain and non-linearity) with the last data set collected in prelaunch testing, which was performed during the Spacecraft-level testing in June 2017. The gain results from the on-orbit test are compared with those obtained from prelaunch for all the M and I bands. Another Ecal test, not originally planned, was performed in support of the LWIR response

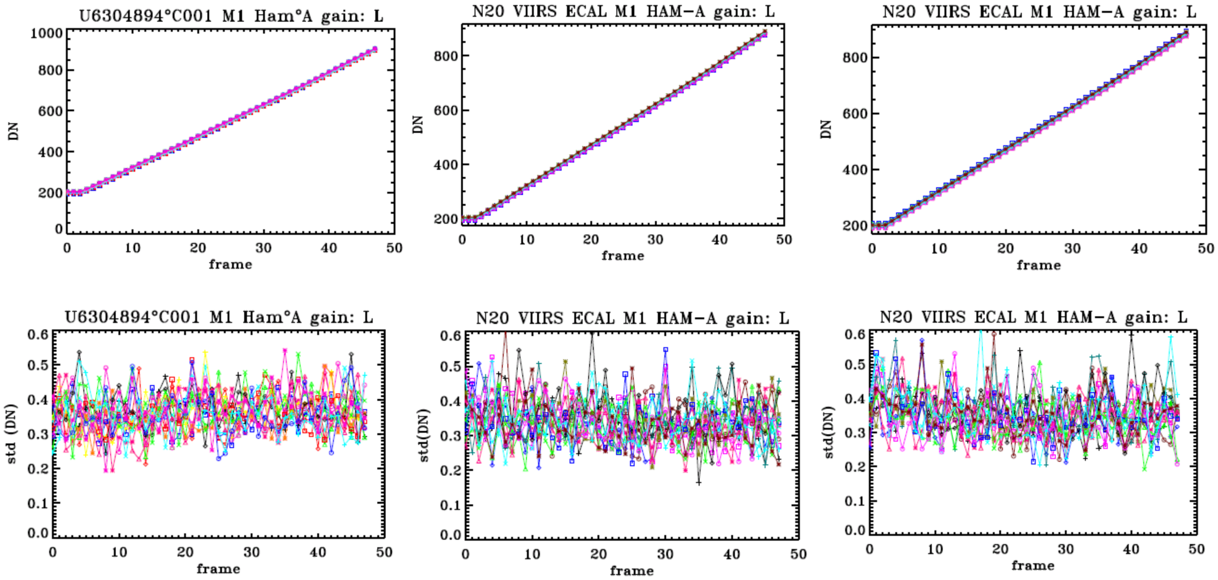

Figure 4. E-Cal ramp from prelaunch and early on-orbit calibrations for NOAA 20 VIIRS band M1

degradation anomaly. A major difference between this test (performed on February 15, 2018), and the first test, is that the cyroradiator door was open, therefore facilitating in the cooling of the Cold Focal Plane Assemblies (CFPAs). Although this should not have had a major impact on the results from the Ecal test (detectors disconnected), some differences between the gains for the CFPA bands were observed. Table II summarizes the on-orbit Ecal tests for NOAA 20 VIIRS that were performed during the initial months of operation. The results from these two tests will be compared with the last Ecal performed during the second Spacecraft post-Thermal Vacuum Testing (SC-TV2) on June 18, 2017. As discussed earlier, the goal of this test is to verify the stability of the analog processing within the ROIC/ASP sub-system, by comparing results to the last pre-launch measurements. This newly collected data may be used as a reference point in the event any questions arise regarding the health of the analog on-board processing over the life of the mission. For all the collects, the space-view data over the duration of the test was used. The slope of the ramp (after excluding the first few low quality samples) is compared for each case to evaluate the consistency. Figure 4 (top panel) shows the response of M1 detectors (low gain) during the Ecal test. The different colors represent different detectors. For every frame, the response (DN) is averaged over the scans during the Ecal. For the on-orbit calibrations, two scans at the beginning and the end of the Ecal are excluded from the calculation. The bottom panel plots show the standard deviation associated with the average response across the multiple scans. The levels of standard deviation have stayed fairly consistent from prelaunch to the two on-orbit Ecal measurements. Figure 5 shows a similar plot for the thermal emissive band (TEB) M14. Although the December Ecal event was scheduled before the opening of the cyroradiator door (CFPA temperatures not near their operational levels), no noticeable difference in the Ecal ramp or the standard deviations is observed as the detectors are disconnected during this operation. Similar performance is also observed for other TEBs. However, minor variations between the two on-orbit events for the TEBs are expected due to variations in the instrument and operational temperatures. After excluding the first four samples and samples beyond 95% of the peak value (saturation in most cases), a linear fit is performed to estimate the linear gain on a per-detector basis. Table III shows a comparison between the prelaunch and on-orbit linear gain for a center detector of each band. In the case of the dual-gain bands, only the results from the low gain stage are presented. While only the results from a center detector are shown, similar behavior is observed from other detectors, as expected. In column 2 of the Table III, the actual value of the linear gain from prelaunch is presented and columns 3 and 4 provide the ratio of the two on-orbit measurements with the prelaunch gains respectively. Columns 5-8 provide similar information for the remaining VIIRS bands. The ratios between 0.99 to 1.01 represent the difference between prelaunch and first on-orbit measurement to be within 1%. A systematic 3-4% difference is observed for the VIS/NIR bands (M1-M7, I1 and I2). The reasons for this disagreement are not fully understood at this time. After the stabilization of the CPFA temperatures, the SWIR bands show better agreement using the second Ecal measurement with the prelaunch measurement. Most TEB on-orbit gains agree to within 0.5% (except I4). As discussed earlier, the second on-orbit Ecal was scheduled in support of the LWIR degradation anomaly, where the gains for the LWIR bands M15, M16 and I5 started changing at a faster rate (greater than 1% per month). One of the possible causes of the degradation anomaly was the change in the electronic gain for these bands during the first couple months on-orbit. However, the results from Table III confirm that the electronic gain for these bands did not change significantly, therefore eliminating this as a possible cause for the observed degradation. Further analysis revealed that the reason behind the response degradation was ice-buildup, predominantly impacting the LWIR bands.

Table 2. Summary of the on-orbit Ecal Test for NOAA 20 VIIRS

Sr. No	Test Description	Start Time	End Time	Orbit Number
1	Ecal (Warm CFPA)	12/08/2017 14:04	12/08/2017 20:23	287-290
2	Ecal (Cold CFPA)	02/15/2018 22:22	02/15/2018 22:29	1271

Table 3. Comparison of the prelaunch and on-orbit linear gain for NOAA 20 VIIRS

Band	PL	PL/OO-I	PL/OO-II	Band	PL	PL/OO-I	PL/OO-II
M1	66.769	1.03	1.03	M12	102.124	0.993	0.995
M2	74.53	1.03	1.03	M13	70.11	1.006	0.994
M3	67.66	1.03	1.03	M14	144.16	1.008	1.002
M4	71.38	1.02	1.02	M15	95.73	1.006	1.001
M5	69.35	1.03	1.03	M16A	160.84	1.01	1.002
M6	82.59	1.02	1.02	M16B	161.27	1.01	1.001
M7	70.993	1.033	1.032	I1	48.55	1.041	1.041
M8	81.59	0.996	0.989	I2	52.20	1.041	1.04
M9	80.371	1.002	0.994	I3	99.076	1.005	1.001
M10	81.436	1.001	0.993	I4	119.535	1.014	0.993
M11	96.653	0.992	0.990	I5	353.00	1.001	0.999

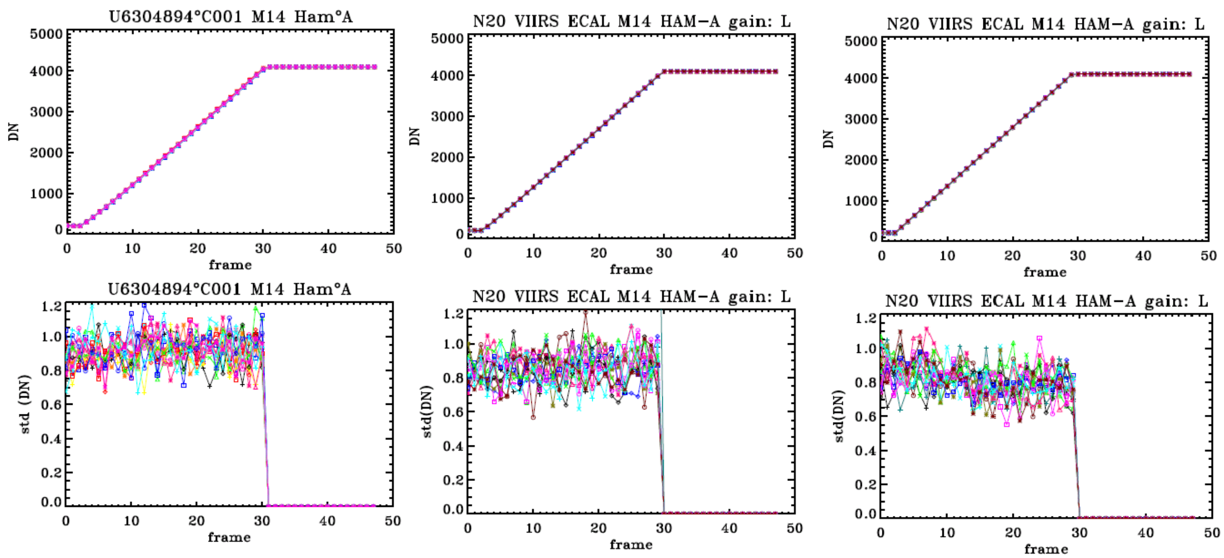

Figure 5. E-Cal ramp from prelaunch and early on-orbit calibrations for NOAA 20 VIIRS band M14

4. SUMMARY AND LESSONS LEARNED

A key factor influencing the radiometric accuracy of Earth observing sensors is the stability and linearity of the electronics and the ADC. The MODIS and VIIRS instruments underwent extensive testing for electronic gain and linearity during their prelaunch characterizations. While the MODIS instruments continue regular on-orbit Ecal operations, VIIRS on the NOAA 20 spacecraft has performed only a limited number of tests in support of a LWIR degradation anomaly. In the case of the MODIS instruments, the system gain for the RSB is characterized using the regular observations of the solar diffuser (SD), including degradation of the optical throughput as well as changes in the electronic gain. Regular on-orbit Ecal operations facilitate decoupling of the electronic gain from the system gain. As discussed in this paper, the on-orbit Ecal operation for MODIS is performed by injecting a voltage after the ROIC/pre-amplification stage and therefore does not include any possible nonlinearities within the detector. In the case of SNPP VIIRS, no Ecal operations have been performed on-orbit so far and only two on-orbit Ecal operations were performed for NOAA20 VIIRS. As observed from the MODIS on-orbit trends, the electronic gain shows likely dependence on instrument temperature variations which might also explain the differences between the prelaunch and early on-orbit electronic gain for the VIS/NIR bands. Unlike MODIS, VIIRS (SNPP and JPSS-1) is not expected to perform regular on-orbit Ecal operations, but special calibrations may be scheduled in the event of an instrument anomaly or reset. After multiple years in orbit, Earth observing instruments are expected to experience measurable optical throughput degradation, and decoupling of the electronic gain will help in reaffirming the accuracy of the estimated on-orbit system gain.

ACKNOWLEDGMENTS

Authors in this paper would like to acknowledge MODIS and VIIRS instrument vendor (Raytheon) and other MCST and VCST members (previous and current) for their contributions in support of pre-launch and on-orbit ECAL data analyses. The authors would also like to thank Emily Aldoretta, MCST for technical review of this manuscript.

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