IMPROVING VIIRS THERMAL EMISSIVE BAND CALIBRATION DURING LUNAR INTRUSION INTO SPACE VIEW EVENTS

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ABSTRACT

In the NOAA operational processing, the Thermal Emissive Band (TEB) data from the VIIRS onboard the NOAA-20 and S-NPP satellites are not calibrated if all scans in a granule are flagged as lunar intrusion into space view (SV). As a result, more than 100 NOAA-20 and S-NPP VIIRS single-gain TEB granules are un-calibrated each year. For M13 (dual-gain fire detection band), the number of un-calibrated granules due to lunar intrusion is doubled because of an additional bug in the operational processing software. This study presents a Lowest N Algorithm for calibrating VIIRS TEB during lunar intrusions. It takes advantage of the fact that the extent of the full moon image is smaller than the field of view of VIIRS SV. Moreover, the bug that affects M13 calibration was also fixed. A VIIRS SDR algorithm code change package has been implemented in the NOAA operational processing since March 30, 2021.

***Index Terms*—** VIIRS, NOAA-20, S-NPP, lunar intrusion, space view (SV), Thermal Emissive Bands (TEB), Lowest N Algorithm, operational processing.

1. INTRODUCTION

The Visible Infrared Imaging Radiometer Suite (VIIRS), onboard the National Oceanic and Atmospheric Administration - 20 (NOAA-20) and the Suomi National Polar-orbiting Partnership (S-NPP) satellites were launched on November 18, 2017 and October 28, 2011, respectively [1, 2]. VIIRS has 5 imagery resolution bands (I-bands, I1-I5, 375 m), 16 moderate resolution bands (M-bands, M1-M16, 750 m) and 1 Day/Nigh Band (DNB, 750 m). Among the 22 spectral bands, there are seven Thermal Emissive Bands (TEB) including six single-gain TEBs (M12, M14-M16, and I4-I5) and one dual-gain TEB (M13, for fire detection). S-NPP and NOAA-20 VIIRS TEB Sensor Data Records (SDR) have widely been used for monitoring severe weather events and deriving a wide variety of environmental products, such as sea/land/ice surface temperature, active fires, and cloud properties.

VIIRS TEB on-orbit radiometric calibration relies on blackbody and deep space (SV) view. SV observations are used as background reference for calculating on-orbit degradation factors (F-factor) and Earth View (EV) radiance. Lunar intrusion into SV events (will be referred to as lunar intrusion in the rest of the text) occur occasionally. In the NOAA operational processing, lunar intrusion is detected and flagged in the SDR products. However, a long-standing issue exists in the TEB SDRs, i.e., a TEB granule is not calibrated if all scans are flagged as lunar intrusion. Each year, more than 100 NOAA-20 and S-NPP TEB granules are un-calibration due to lunar intrusion. As a result, downstream products, such as active fire and sea/ice/land surface temperatures, cannot be retrieved. For M13 (fire detection band), the number of un-calibrated granules due to lunar intrusion are doubled because of an additional bug in the operational processing software. Anderson et al. [3] developed an alternative lunar intrusion detection method for the NASA processing system, based on thresholds of the standard deviation and the first lag of autocorrelation of SV samples. Isaacson et al. [4] proposed another threshold-based lunar intrusion detection approach, however, this approach was not designed for operational processing.

This paper presents a Lowest N Algorithm for calibrating VIIRS TEBs during lunar intrusion. The algorithm is designed for operational processing. Compared to the Anderson et al. method [3], it requires less code change and does not require any new threshold. Moreover, the root cause of the bug that affect M13 calibration during lunar intrusion was also analyzed and corrected. NOAA-20 and S-NPP VIIRS lunar intrusion event and its impacts on the NOAA operational TEB SDRs will be given in Section 2. Section 3 presents the Lowest N Algorithm and the bug fix (for M13) for improving TEB calibration during lunar intrusion. Section 4 evaluates improvements in TEB SDRs. Section 5 summaries this study.

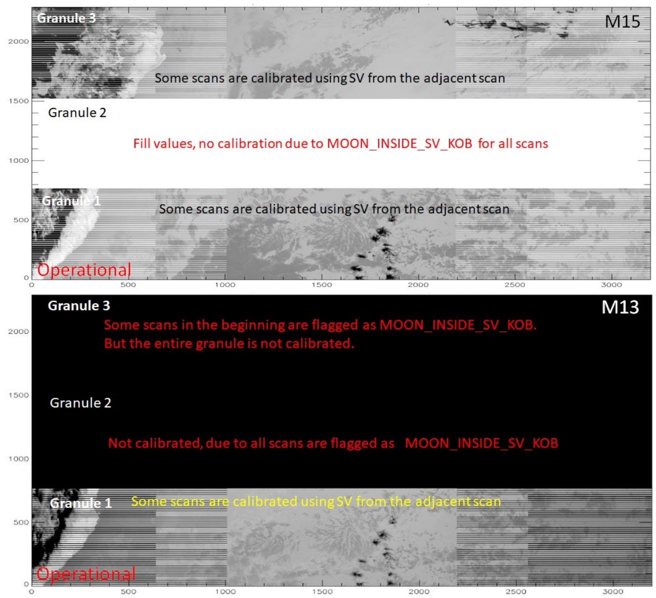

Fig. 1. NOAA-20 VIIRS M15 (top) and M13 (bottom) operational SDRs during the April 15, 2019 19:19-19:24 UTC lunar intrusion into SV event. All scans in granule #2, as well as some scans in granules #1 and #3, are flagged as lunar intrusion.

2. NOAA-20 AND S-NPP VIIRS LUNAR INTRUSION INTO SV EVENTS AND ITS IMPACTS ON TEB SDRS

VIIRS is a scanning radiometer with a Rotating Telescope Assembly that rotates 360° to collect signals from the EV port and the onboard calibrators, including solar diffuser, blackbody, and SV port. SV observations provide the instrument background reference. In the NOAA operational processing, lunar intrusion in SV events are detected at scan level, using lunar vectors calculated by the geometric calibration algorithm [5]. Scan level quality flag (moon inside SV keep-out-box, or MOON_INSIDE_SV_KOB) in the SDR products is triggered and pixel level radiance quality is set to poor or un-calibrated, if the lunar angles are within the predefined angular limits of SV. The moon inside SV keep-out-box is defined conservatively, i.e., with additional scans flagged before and after the scans that are actual affected by lunar intrusion [4].

For a TEB granule with at least one moon-free scan, the scans flagged as lunar intrusion are calibrated using substituted SV counts from the moon-free scan. However, radiance and brightness temperature (BT) products in a TEB SDR granule are fill values (un-calibrated) if all scans in the granule are flagged as MOON_INSIDE_SV_KOB. Fig. 1 (top) shows 3 consecutive granules of NOAA-20 M15 SDRs during the April 15, 2019 lunar intrusion event. Granule #2 is not calibrated because all scans are flagged as MOON_INSIDE_SV_KOB. Some scans in granule #1 and #3 are also flagged as MOON_INSIDE_SV_KOB, and therefore SV counts from adjacent moon-free scans within the same granule are used for calibration. Similar patterns

	S-NPP		NOAA-20	
	M12, M14-M15, I4-I5	M13	M12, M14-M15, I4-I5	M13
2017	100	200	-	-
2018	75	150	67	134
2019	72	144	63	126
2020	58	116	55	110

Table 1. Statistics of the number of un-calibrated S-NPP and NOAA-20 TEB granules in the NOAA operational products due to lunar intrusion into SV from 2017 to 2020.

were observed in other NOAA-20 and S-NPP single-gain TEBs (M12, M14, M16, and I4-I5), as well as during other lunar intrusion events.

For NOAA-20 and S-NPP M13 (dual-gain band for fire detection), the impact of lunar intrusion is relatively more sever. Besides the un-calibrated granule with all scans flagged as lunar intrusion, a granule with first scan flagged as lunar intrusion is also un-calibrated because of a bug in the NOAA operational processing code. Fig. 1 (bottom) shows the 3 granules of M13 SDRs during the same time period as that of Fig. 1 (top). It can be observed that both granules #2 and #3 are un-calibrated in the NOAA operational processing. Similar issues were observed during other lunar intrusion events.

We analyzed all NOAA-20 and S-NPP VIIRS TEB SDR products from January 1, 2017 to December 31, 2020. Table 1 summarizes the number of un-calibrated granules for TEBs. For M12, M14-M16, and I4-I5, more than 100 NOAA-20 and S-NPP TEB granules are un-calibrated each year. For M13, the number of un-calibrated granules is more than 200.

3 IMPROVING VIIRS TEB CALIBRATION DURING LUNAR INTRUSION INTO SV EVENTS

3.1 VIIRS SV Observations during Lunar Intrusions

For each VIIRS scan, there are 48 (for M-bands) or 96 (for I-bands) frames (or samples) of SV observations. Fig. 2 shows an example of TEB SV images for one granule during the April 15, 2019 18:30-18:31 UTC NOAA-20 VIIRS lunar intrusion event. All scans are flagged as MOON_INSIDE_SV_KOB in this granule for all TEBs (SDRs are fill values, see Fig. 1 granule #2). It can be observed that only a portion of SV frames are contaminated by the moon, while some scans are actually moon free. For example, less than one third of M13 SV frames and less than half of M14-M16 and I4-I5 SV frames are affected by the moon. This can be explained by the angular diameter of the Moon and the field of view (FOV) of the VIIRS SV. The VIIRS SV FOV is about 0.85°, derived using VIIRS scan pattern (see Figure 6 in [6]). The angular diameter of the Moon is about 0.52°-0.57°, which can be estimated using the angular diameter equation and the distances from the moon to the VIIRS instruments over time [2, 7, 8]. Therefore, only about 67% of SV frames are contaminated by the moon in the

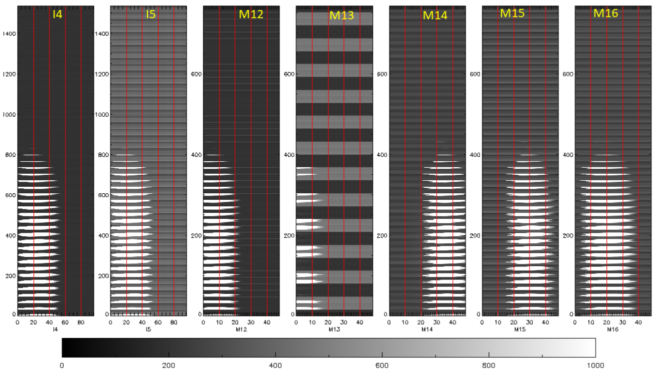

Fig. 2. S-NPP VIIRS TEB SV images for bands I1-I4 and M12-M16 during the April 15, 2019 18:30-18:31 UTC lunar intrusion into SV event.

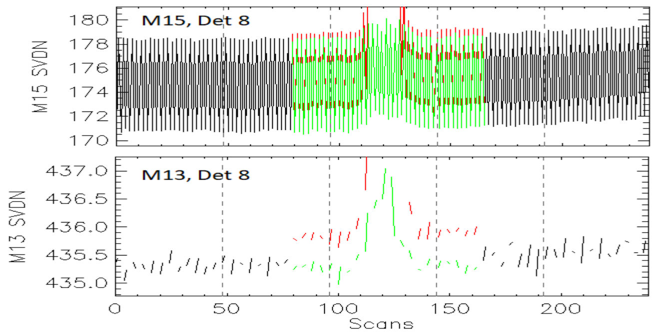

Fig. 3 Examples of scan-averaged SV DNs for M15 and M13 during the April 15, 2019 18:30-18:31 UTC lunar intrusion into SV event. For the scans flagged as lunar intrusion, unfiltered SV DNs were shown in red color, while those calculated using the Lowest N Algorithm were shown in green color. Normal scans were plotted by black color.

worst case. The algorithm proposed in this study will take advantage of this feature to calibrate TEBs during lunar intrusion (see next Subsection).

3.2 The Lowest-N Algorithm

In this study, a Lowest N Algorithm was developed to calibrate VIIRS TEBs during lunar intrusion. The existing TEB SDR algorithm uses a lower and an upper digital number (DN) limits for quality control when scan-averaged SV (and blackbody) DNs are calculated. Zero and 4095 are set for the lower and upper limits, respectively. The Lowest N Algorithm modifies the upper limit during lunar intrusion so that the moon free SV frames within a scan can be identified and used for calibration (the lower limit is not changed). The algorithm first searches all SV frames within a scan and identifies N SV samples with lowest DN values $(DN_1, DN_2, \dots, DN_N)$. Then the upper limit is modified using the following equation:

$$DN_{upper\_limit} = DN_N + 1.0 + 3 \cdot \sigma(DN_1, DN_2, \dots, DN_N)$$

where DN_{upper_limit} is the modified SV DN upper limit calculated using the Lowest N Algorithm; DN_1 is the first SV frame with the lowest value; DN_N is the Nth SV frame with lowest values $(DN_1 \leq DN_2, \dots, \leq DN_N)$; $\sigma(DN_1, DN_2, \dots, DN_N)$ is the standard deviation of the N SV samples identified. The purpose of the $1.0 + 3 \cdot \sigma(DN_1, DN_2, \dots, DN_N)$ term is to add a margin to the modified SV DN upper limit for more stable calibration. Note that the same function is used for calculating SV and blackbody view scan-averaged DNs in the existing code. The modified upper limit is used for calculating scan-averaged SV DN during lunar intrusion only.

Fig. 3 shows examples of M15 and M13 detector 8 scan averaged SV DNs before (red) and after (green) applying the Lowest N Algorithm. Results for other detectors and TEBs are similar. Our analysis results indicate that the algorithm performs well, with errors in scan-averaged DNs less than 3 counts in all cases. For the scans that are flagged as lunar intrusion but not actual affected by the moon, the errors can be ignored in most of cases.

The Lowest N algorithm is a localized method that applies only during lunar intrusion. VIIRS SDR calibration for the moon-free scans are not affected. Moreover, no LUT format change is required. There is a reserved field (SV_DN_moon_include_frames) in the existing VIIRS SDR Emissive LUT. This field and VIIRS SDR code are modified to configure how many SV samples are used for calculating the upper limit during lunar intrusion.

Theoretically, a maximum value of N=7 may be used for M-band TEBs, estimated using the angular diameter of the moon and the FOV of the SV. Note that the existing code calculates TEB scan-averaged SV DNs for even and odd frames separately. The Lowest-N algorithm modifies the upper limits for even and odd frames accordingly. Currently, N is set conservatively, with a value of 5 specified for both NOAA-20 and S-NPP VIIRS, which means that 5 even and 5 odd SV frames are used for M-band TEBs, while 10 even and 10 odd SV frames are used for I-band TEBs. Compared to the Anderson et al. [3] method, the Lowest N Algorithm requires less code change and no LUT format change. In addition, it is also less computationally expensive.

3.3 Code Change to Resolve the M13 Calibration Issue

Besides the Lowest N Algorithm, the M13 calibration issue (see Section 2) during lunar intrusion was also addressed. Our analysis indicated that this issue is caused by a scan index error in the existing code. After correcting this error, all M13 SDR granules during lunar intrusion can be calibrated successfully using the Lowest N Algorithm, similar to other TEBs. A VIIRS SDR algorithm code change package has been implemented in the in the NOAA operational processing software since March 30, 2021.

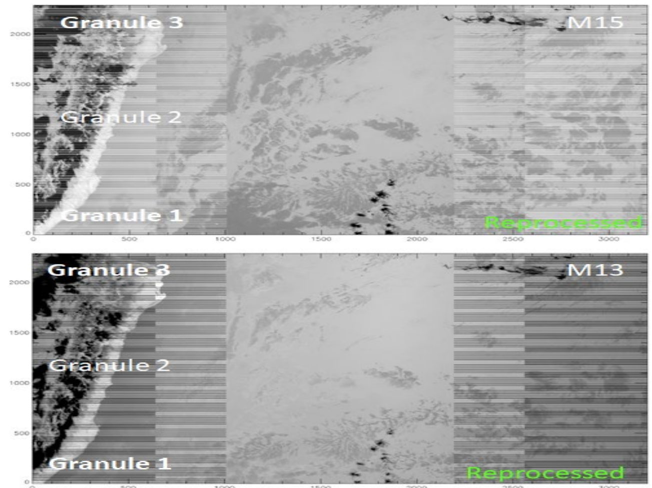

Fig. 4 Reprocessed NOAA-20 VIIRS M15 (top) and M13 (bottom) SDRs during the April 15, 2019 19:19-19:24 UTC lunar intrusion event.

4. EVALUATION OF TEB CALIBRATION IMPROVEMENTS DURING LUNAR INTRUSION

The Lowest-N algorithm and the bug fix for M13 were evaluated using the reprocessed VIIRS SDRs during multiple lunar instrument events from January 2017 to June 2020, for both NOAA-20 and S-NPP. Fig. 4 shows the NOAA-20 M15 (top) and M13 (bottom) granules during the same lunar intrusion event as that of Fig. 1, using reprocessed SDRs. It can be observed that granule #2 for M15, as well as granules #2 and # 3 for M13, were successfully calibrated. At typical scene temperatures, estimated calibration errors for scans flagged as lunar intrusion are about -0.1 K or less for M14-M16, -0.3 K or less for I5, and -0.5 K or less for the mid-wave infrared bands (M12-M13 and I4).

Fig. 5 shows three reprocessed S-NPP bands I5 and M13 granules during the April 15, 2019 18:28 – 18:31 UTC lunar intrusion event. Similar to Fig. 4 (for NOAA-20), granule #2 for I5 and granules #2 and #3 for M13 were un-calibrated in the NOAA operational processing (not shown). After reprocessing, all granules were calibrated as expected, with calibration errors during lunar intrusion similar to those of NOAA-20 TEBs. We also verified the Lowest N algorithm and the bug fix for M13 using on-orbit data during the April 20 and April 23, 2021 NOAA-20 and S-NPP lunar intrusion events. Results show that the code change has performed as expected.

5. SUMMARY

This paper presents the Lowest N Algorithm for improving NOAA-20 and S-NPP VIIRS TEB calibration during lunar intrusion into SV events. The Algorithm is designed for operational implementation. It takes advantage of the fact that less than 67% of SV frames at any scan are contaminated during the worst lunar intrusion cases. Moreover, the bug that affect M13 calibration during lunar intrusion was also fixed. A VIIRS SDR algorithm code and LUT change package has been implemented in the NOAA operational processing system since March 30, 2021. Evaluation results using processed and on-orbit data indicate that the code change has been performed well.

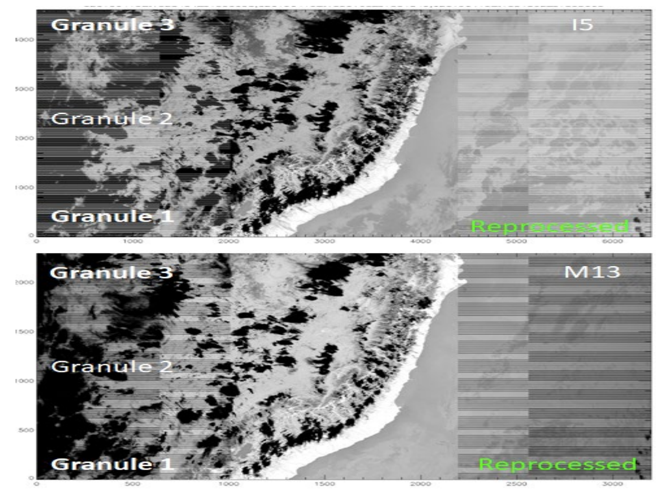

Fig. 5 Reprocessed S-NPP I5 (top) and M13 (bottom) SDRs during the April 15, 2019 18:28 – 18:31 UTC lunar intrusion event.

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