Radiometric Calibration Performance of GOES-17 Advanced Baseline Imager (ABI)

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ABSTRACT

GOES-17 (G17), the second NOAA's latest generation weather geostationary GOES-R series satellites, was declared as the operational GOES-West satellite at 137.2°W longitude on February 12, 2019. The Advanced Baseline Imager (ABI) onboard is the primary instrument which is now paired with the GOES-16 (GOES-East) ABI to provide faster, more detailed and accurate measurements for the weather phenomena over the Western Hemisphere compared to the legacy GOES Imagers. Yet right at the beginning of the G17 ABI post-launch test and post-launch product test (PLT/PLPT) in late April 2018, the malfunctioning of Loop Heat Pipe (LHP) on the spacecraft was detected. This anomaly leads to degraded data quality for all the infrared (IR) bands and no useful data for some IR bands during some hours at night of one some days in the year. Despite all the adversities, significant improvements in the L1b radiance have been made. This study reported the radiometric calibration performance for all the G17 ABI bands and the comparison with that of GOES-16 (G16) ABI. During the time when the IR focal plane module (FPM) is controlled, the G17 IR radiometric calibration is generally well calibrated and very stable. The radiometric calibration difference to G16 IR data is within 0.1K for all the IR bands except for B09 at 0.22K and B16 at 0.57K. The predictive calibration algorithm (pCal) which was operationally implemented on July 25, 2019 significantly improves the radiometric calibration accuracy during the time when the IR FPM temperature is unstable. The radiometric calibration accuracy for the visible and near-infrared (VNIR) bands at both G16 and G17 is within 5% using the SNPP/VIIRS as the reference, except for G16 and G17 B02 and G17 B05. With the recent updates of the B02 solar calibration look-up tables, the G16 and G17 B02 radiance are also significantly reduced and comparable to the common reference. Continuous efforts to improve the G17 radiance quality are still ongoing.

Keywords: GOES-17 ABI, GOES-16, post-launch test and post-launch product test (PLT/PLPT), radiometric calibration accuracy, Loop-heat pipe anomaly, focal plane module temperature, predictive calibration algorithm, calibration and validation.

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1. INTRODUCTION

GOES-S, the second latest generation geostationary satellites of GOES-R series operated by NOAA, was launched on March 1, 2018. It was re-named as GOES-17 (G17) after reaching at the geostationary orbit on March 12, 2018. After the intensive post-launch test (PLT) and post-launch product test (PLPT) at 89.5°W longitude location, it drifted to 137.2°W position in November 2018 and was officially declaimed as GOES-West on February 12, 2019. It now joins its sister geostationary satellite GOES-16 (G16), the first GOES-R series geostationary satellite which was launched on November 16, 2016 and became as GOES-East at 75.2W since December 18, 2017 to provide the high resolution visible and infrared imagery and other observations from the Western Hemisphere.

The Advanced Baseline Imager (ABI) is the primary payload onboard the GOES-R series of satellites. Right at the beginning of the G17 ABI PLT/PLPT tests in late April 2018, the anomaly of the loop-heat pipe (LHP) was detected

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which caused the malfunctioning of the ABI instrument cooling system. This anomaly results in degraded data quality for all the IR bands compared to the designed and G16 [1]. Radiance at some IR bands can be saturated and not applicable at some hours at night on some days of the year (Figure 1). Great progress has been made to optimize the G17 ABI performance and to improve its data quality which enabled G17 to join GOES-16 (G16) as providers of visible and infrared imagery with high spatial, temporal, spectral, radiometric, and geometric quality in the Western Hemisphere for the weather forecast and environmental change studies. This paper is to summarize the G17 ABI radiometric calibration performance since after the PLT/PLPT started and compare the results with G16.

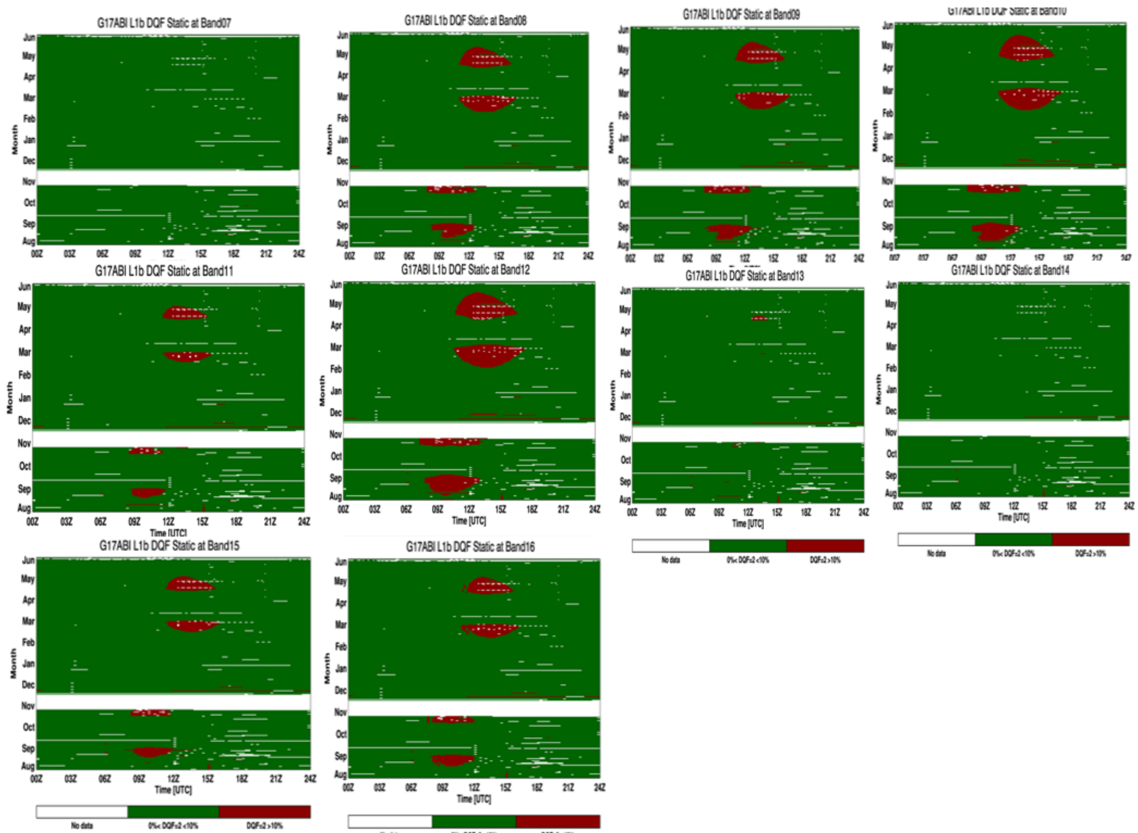

Figure 1.Data availability for the 10 G17 IR bands from August 2018 through June 2019. The x-axis is the 24 hours in a day, and the y-axis is the month from August 2018 to June 2019. Green: valid data with data quality flag (DQF) set to 0 or 1, Red: saturated L1B data with DQF set to 2, White: no data or data missing.

2. IMPACTS OF THE LHP ANOMALY AND MITIGATION EFFORTS

The ABI IR detectors need to be cold in order to accurately measure the thermal energy from the Earth. The LHP transports the heat from the ABI electronics to the external radiator which rejects excess energy into space. Right at the beginning of the G17 ABI PLT/PLPT in late April 2018, it was discovered that the LHP didn't work properly, resulting in the malfunctioning of the cooling system. This anomaly leads to warmer focal plane module (FPM) temperature as designed. At some hours at night the IR FPM temperature can be so high that certain IR bands can get saturated to provide useful data (Figure 1, 2). When the data are available, the detector noise is larger than G16 due to the much warmer FPM operational temperature. Despite of all these adversities, great progress has been made to optimize the ABI performance and improve the radiance quality. The main efforts implemented by NOAA can be summarized as follows:

- Changes of the FPM operational temperature: While the visible and near-infrared (VNIR) FPM is set floating, the IR FPMs are controlled at an elevated temperature at 81K until the power of the cryocooler reaches certain limit and turned off [2]. This leads to stable IR FPM temperature at day-time and unstable IR FPM temperature at night (Figure 2). The duration and magnitude of the "warm" FPM temperature varies day by day, depending on the solar beta angle and the spacecraft orientation.

- Gain-set switches as needed: Two gain-set configurations are applied for the radiometric calibration for some of the IR bands to optimize the IR performance during the unstable FPM period [2]. The gainset I is applied when the IR FPM is stable, while the gainset III is used when the unstable IR FPM temperature reaches certain threshold. Currently the two gainsets are switched at the fixed time in the day (Figure 2). The timing can be varied at the different spacecraft orientation position. The occurrence and timing of the gainset switches are available at the NOAA GOES-R Calibration Working Group (CWG) website at: https://www.star.nesdis.noaa.gov/GOESCal/goes_SatelliteAnomalies.php.
- Adjustments of operational procedures: (1) The operational timelines are modified to minimize the impact of dark current variation, and at the meanwhile to maintain the sufficient geometrical calibration accuracy to meet the image navigation and registration (INR) requirements; and (2) application of more frequency in the blackbody calibration. The G17 blackbody calibration is conducted at an interval of every five minutes instead of every 5, 10 or 15 minutes as G16.
- Yaw-flip for the spacecraft semi-annually.
- Algorithm changes: 1). Updates of the calibration look-up tables (LUTs) to reduce the striping; 2) Application of the predictive calibration algorithm (pCal) for Band 8-16 when the FPM temperature reaches certain thresholds [3]. This pCal algorithm was operationally implemented since 25 July 2019.
- Update of the best-detector-selected (BDS) table to reduce the IR image striping [4]
- Ongoing effect to reduce the FPM temperature dependent solar calibration accuracy for the VNIR bands.

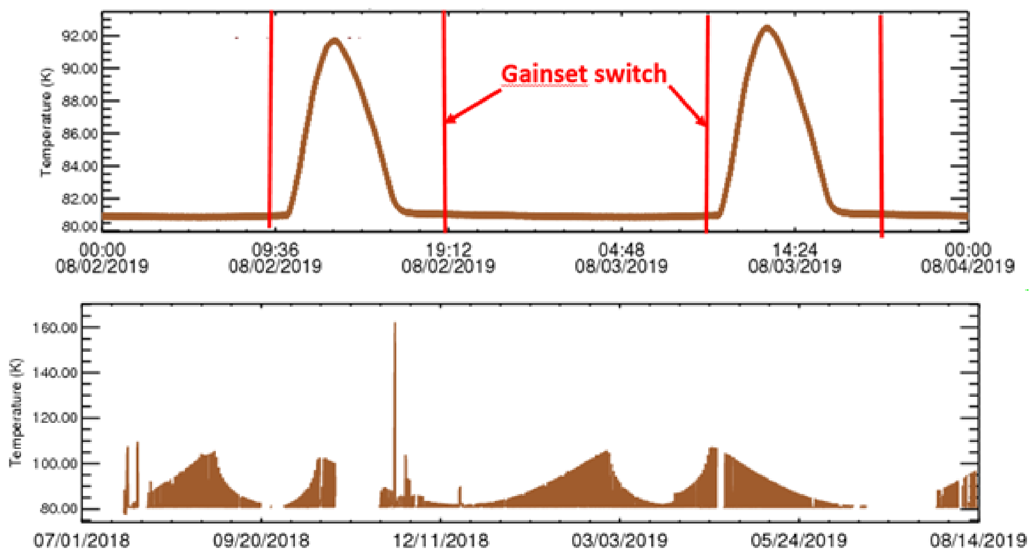

Figure 2. G17 Long-wavelength IR (LWIR) FPM temperature. Upper: time-series of the FPM temperature for continuous two days on 08/02/2019 – 08/03/2019. Gainset switch between gainset I and gainset III occurred at 0900 and 1900UTC. Bottom: Long-term monitoring of the daily maximum FPM temperature. Note that some of the Product Distribution and Access (PDA) engineering temperature data were empirically corrected.

3. VALIDATIONS OF THE IR RADIOMETRIC CALIBRATION ACCURACY

The IR radiometric calibration accuracy is validated and monitored using the GEO-LEO inter-calibration and GEO-GEO inter-comparison methods. The GEO-LEO inter-calibration uses the well-calibrated hyperspectral radiometers at low earth orbit (LEO) satellites, including the CrIS on-board SNPP and NOAA-20 (N20) satellites and the IASI instruments onboard EUMETSAT Metop-A and Metop-B satellites. The standard procedure proposed by the Global Satellite Inter-Calibration System (GSICS) community was applied to calculate the radiometric calibration difference between G17 and the four references [5,6]. The radiance difference between G16 and G17 is estimated with the double difference using the IASI on Metop-B (IASI-B) as the reference. The GEO-GEO method was long-time used to validate the radiometric calibration performance between two geostationary satellites since the GOES-14/15 PLPT tests [7]. While the GEO-LEO can provide the absolute calibration difference, the GEO-GEO inter-comparison can provide the relative calibration variation at high temporal resolution. In this study, the GEO-LEO method is used to assess the radiometric calibration accuracy during the gain-set I period, and GEO-GEO result is applied to evaluate the pCal performance, as well as the possible diurnal variation for the two geostationary instruments.

3.1 IR Calibration accuracy during the stable FPM temperature period

Figure 3 is the GEO-LEO inter-calibration results for all the G16 and G17 IR bands. The inter-calibration results with SNPP/CrIS and Metop-B/IASI are also listed in Table 1. Data from G17 is the gain-set I data at night-time, and night-time data for G16. As the CrIS spectra has large spectral gaps over the ABI B07 and B11 spectral response functions (SRF), the ABI vs. CrIS inter-calibration was not applied for these two bands. The relatively large bias between ABI vs. CrIS at B08 shown in Figure 3 is because CrIS does not fully cover the foot-tail SRF at this band (Figure 4). As shown in Figure 3, G17 IR radiance are well-calibrated with the mean Tb bias to all the LEO reference instruments within about 0.15K except for G17 B16, which is about 0.45K warmer than the CrIS/IASI measurements (Table 1).

Table 1. The mean Tb bias to SNPP CrIS and metop-B IASI for G16 and G17 IR bands (night time collocations for G16, gainset I night time collocations for G17) .

Band (μm)	**G16 (K)**		**G17 (K)**	
	SNPP/CrIS	Metop-B/IASI	SNPP/CrIS	Metop-B/IASI
B07 (3.9μm)	-	0.00(0.18)	-	-0.02(0.17)
B08(6.2μm)	-	-0.12(0.13)	-	-0.10(0.21)
B09(6.9μm)	-0.14(0.03)	-0.14(0.08)	0.05(0.17)	0.05(0.19)
B10(7.3μm)	-0.09(0.04)	-0.07(0.09)	-0.04(0.16)	-0.03(0.19)
B11(8.5μm))	-	-0.04(0.19)	-	-0.02(0.22)
B12(9.6μm)	-0.05(0.04)	-0.10(0.13)	-0.08(0.20)	-0.12(0.25)
B13(10.3μm)	-0.07(0.06)	-0.02(0.21)	-0.12(0.21)	-0.07(0.28)
B14(11.2μm)	-0.01(0.06)	0.05(0.21)	-0.15(0.22)	-0.08(0.31)
B15(12.3μm)	-0.03(0.07)	0.03(0.22)	0.02(0.24)	0.05(0.32)
B16(13.3μm)	-0.15(0.06)	-0.12(0.20)	0.45(0.31)	0.41(0.35)

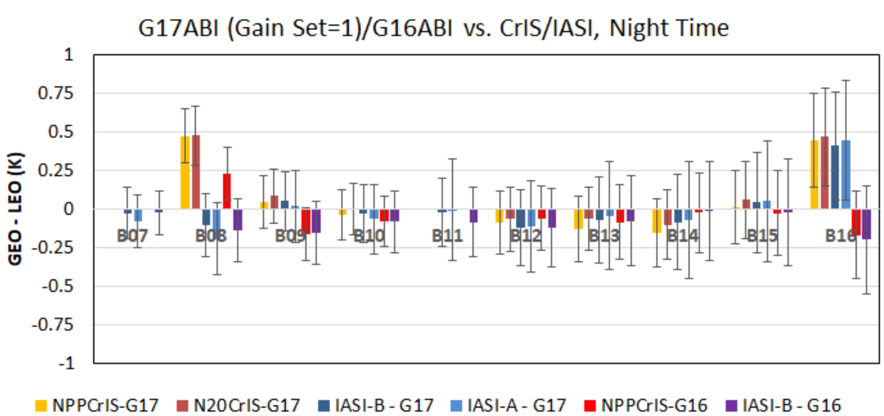

Figure 3. GEO-LEO inter-calibration results for G17 and G16 at their best performance time.

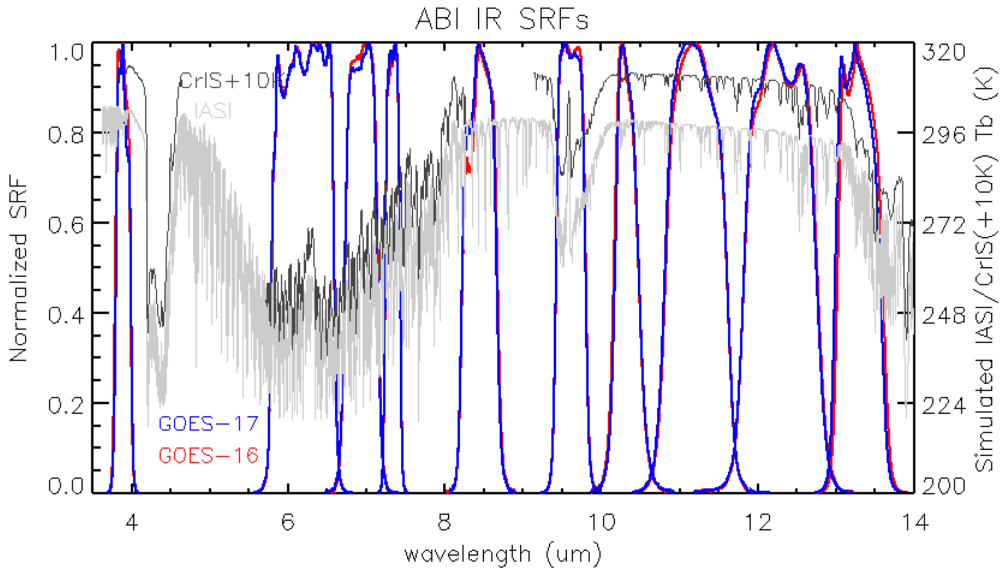

Figure 4. SRFs for the G16 and G17 IR bands, overpotted with the CrIS and IASI spectra simulated over the clear tropical atmosphere. The CrIS Tb is shifted with +10K for the plotting purpose.

No strong Tb (or radiance) dependent GEO-LEO bias can be observed at the all the G17 IR bands. Figure 5 shows the examples for the two channels – B10 and B16. It suggests that the mean Tb bias to CrIS/IASI reported in Table 1 and Figure 3 are consistent across a large range of radiance for all the IR bands.

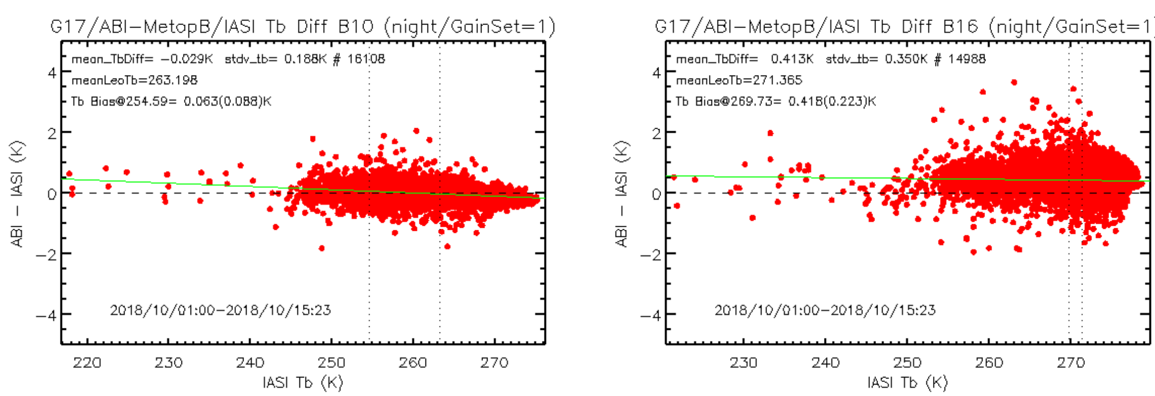

Figure 5. Examples of the scatterplot of the Tb difference between ABI and IASI versus the scene Tb for G17 B10 (left) and B16 (right). Similar results with the other IR bands.

The double difference of the GEO-LEO inter-calibration results using IASI-B as the reference indicates that the radiometric calibration difference between G16 and G17 is within about 0.10K, except for B09 at 0.22K and B16 at 0.57K (Figure 6). The relatively large difference between these two sounding channels is due to the warmer FPM operational temperature for G17. Currently the G17 IR SRFs implemented operationally were measured at the designed temperature of 60K. As the FPM changes to 81K, it is expected that the SRF at 81K should differ from those measured at 60K [7].

Figure 7 is the daily mean Tb bias for the radiance at night-time during the gain-set I period. Consistent daily Tb bias among the four LEO reference indicates: 1) G17 ABI IR radiometric calibration has been very stable during the gain-set I period since late July 2018, 2) The four LEO instruments are all well-calibrated and comparable to each other, and 3) Impact of the G17 IR scan-mirror emissivity look-up-table (LUT) on August 10, 2019 can be detected with the GEO-

LEO inter-calibration. Again, the CrIS instruments do not fully cover the G17 IR B08 SRF range, which results in large bias to both SNPP/CrIS and N20/CrIS measurements.

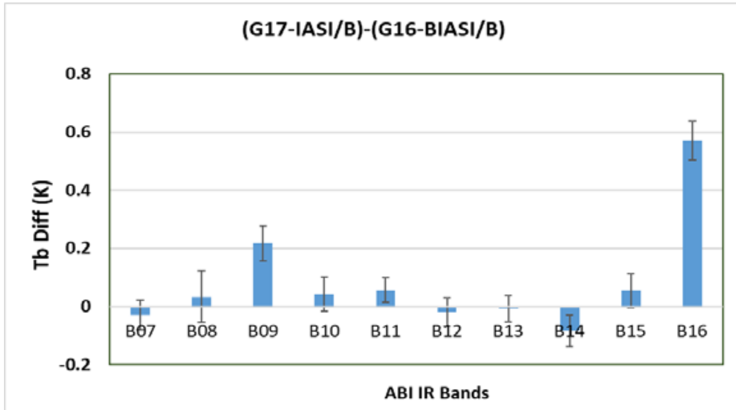

Figure 6. G16 and G17 IR radiometric calibration difference (G17 – G16) using the GEO-LEO double difference with IASI-B as the reference.

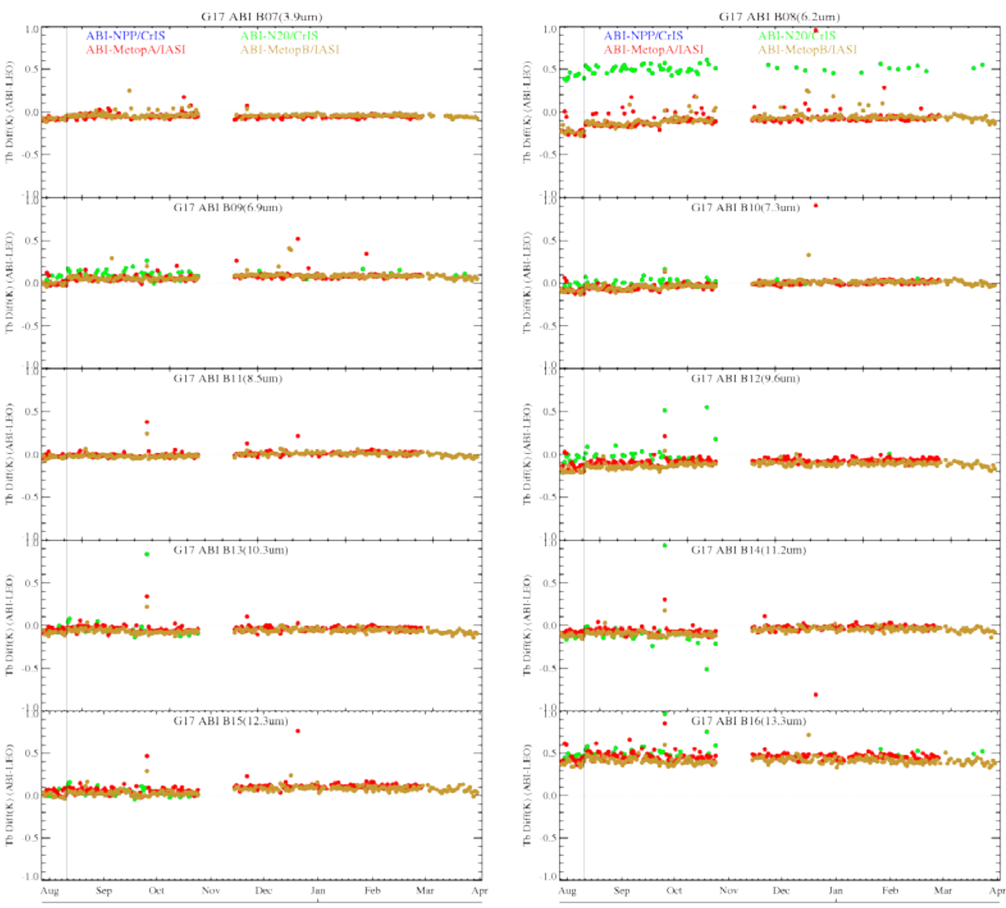

Figure 7. Time-series of daily mean Tb bias to CrIS/IASI for G17 ABI during the night-time gainset I period. There was a Ground system scan-mirror emissivity look-up table (LUT) update for G17 IR bands on 08/10/2019.

3.2 IR Radiometric Calibration accuracy with the pCal Correction

Inter-comparison between two similar spectral bands at different GEO satellites has been long-time used to validate and monitor the radiometric calibration performance for the NOAA GOES Imager data [7]. While the GEO-LEO inter-calibration with the hyperspectral measurements provides the absolute calibration accuracy at certain time in a day, the GEO-GEO inter-comparison provides the relative calibration variation at high temporal resolution. In this study, the GEO-GEO collocated paired pixels are identified as: 1) same geo-location (same lat/lon), 2) cosine of the viewing zenith angle difference is less than 2%, and 3) time difference is less than one minute. The spatial distribution of the collocations are shown in Figure 8.

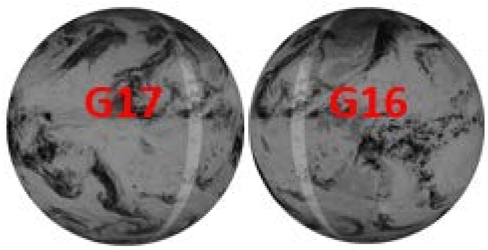

Figure 8. Collocation between GOES-16 and GOES-17 shown with brighter grayness.

The predictive calibration (pCal) algorithm was delivered by the Vendor to mitigate the impact of the rapid change of the FPM temperature on the radiance accuracy for G17 B08 through B16. It was operationally implemented at the Operational Environment (OE) at the Ground on 25 July 2019. Before this operational implementation, the pCal algorithm was intensively tested and validated at the Integration and Test Environment (ITE) at the Ground. Figure 9 displays the GEO-GEO inter-comparison result. The pCal algorithm significantly reduce the GEO-GEO variation when the FPM temperature was not controlled. The small residual variation at B16 is most likely due to the noisy detectors at this band for G17. Effort for the optimal implementation of the pCal performance is still ongoing. The daily monitoring of the GEO-GEO inter-comparison can also be available at: http://cimss.ssec.wisc.edu/goes-r/abi-/band_statistics_imagery.html and https://www.star.nesdis.noaa.gov/GOESCal/G17_ABI_GEO_GEO_IR_daily.php.

Table 2. The mean and standard deviation difference between ABI and VIIRS collocated radiance, calculated as (ABI/VIIRS – 1)%.

Band (µm)	**G16 (%)**		**G17 (%)**	
	Mean	Standard Deviation	Mean	Standard Deviation
B01 (0.47µm)	4.7	3.3	-0.66	2.65
B02 (0.64 µm) before the LUT update in April 2019	6.7	4.5	8.85	3.67
B02 (0.64 µm) after the LUT update in April 2019	-0.01	2.52	-0.01	4.95
B03 (0.86 µm)	1.5	3.2	0.42	3.80
B04 (1.38 µm)	-0.5	7.5	-3.18	6.96
B05 (1.61 µm)	3.8	5.7	5.45	3.51
B06 (2.25 µm)	0.5	3.8	-2.80	3.49

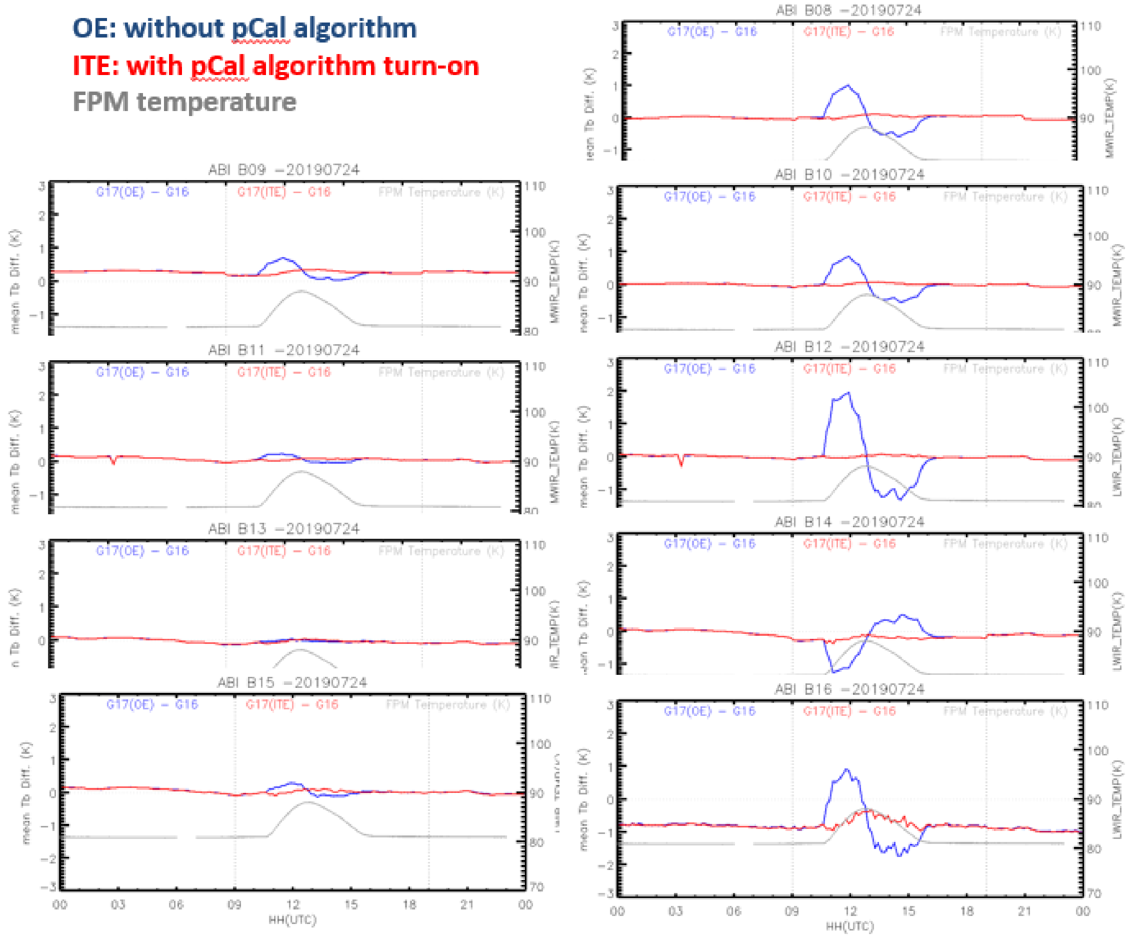

Figure 9. Time-series of the GEO-GEO IR inter-comparison for the IR bands with the G17 IR FPM temperature on 07/24/2019. Blue: G17 radiance without pCal correction, Red: G17 radiance with pCal correction.

4. RADIOMETRIC CALIBRATION ACCURACY FOR THE VNIR BANDS

The radiometric calibration accuracy of the VNIR bands are validated and monitored with a series of vicarious calibration methods, including inter-calibration with SNPP/VIIRS and NOAA-20/VIIRS using the Ray-matching method [9,10], Deep Convective Cloud (DCC) [11], lunar irradiance trending [12], and desert methods [13]. The ray-matching method was applied as the primary method to assess the ABI VNIR calibration accuracy.

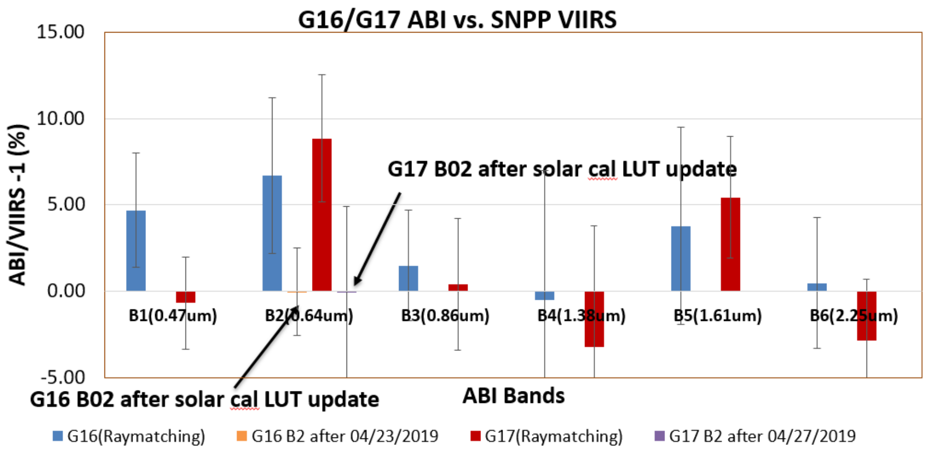

Figure 10. Radiance difference between ABI and SNPP/VIIRS with the Ray-matching method.

The difference to SNPP/VIIRS is in generally within 5% for most of the ABI VNIR bands, except for B02 at both satellites, and for B05 at G17 (Figure 10 and Table 2). Since the first day of the G16 and G17 ABI solar calibrations, it was found that B02 at these two satellites have larger in-orbit solar calibration coefficients than the pre-launch measurements by about 6.2% and 6.9% for G16 and G17, respectively. The inter-calibration results with the collocated SNPP/VIIRS showed that ABI was brighter than SNPP/VIIRS by about 6.7% and 8.9% at these two channels. The brighter ABI B02 measurements were confirmed later by the inter-calibration with Himawari-8 AHI data using the lunar observations [15] and in-situ measurements at the Uyuni desert [16]. To mitigate the impact, the new solar-calibration look-up tables, which was revised based on the integrating sphere measurements before the launches, were implemented operationally on 23 April 2019 for G16 and 27 April 2019 for G17, respectively. The initial assessments of the G16 and G17 B02 data indicated that the radiance after the LUT updates were in well agreement with the SNPP/VIIRS measurements.

The ABI L1B data are available to the public in the NOAA Comprehensive Large Array-Data Stewardship System (CLASS) since after their reaches the provisional validation mature levels on June 1, 2017 for G16 and November 28, 2018 for GOES-17. Several versions of ABI operational algorithms for the VNIR bands were updated at both satellites over the past years. Also some operational calibration anomalies happened at both satellites. Details of the operational updates and the calibration anomalies are available at the webpage maintained by the NOAA GOES-R calibration working group at: https://www.star.nesdis.noaa.gov/GOESCal/goes_SatelliteAnomalies.php.

5. SUMMARY

GOES-17 was declared as GOES-West at 137.2°W on Feb. 12, 2019. The LHP anomaly was detected right at the beginning of the post-launch test at the check-out point at 89.5°W in late April 2018. This anomaly leads to the malfunction of the ABI cooling system and fails to maintain the FPM temperature at the designed temperature. As the results, the image quality of all the IR bands are degraded compared to GOES-16 ABI. However, great progress has been achieved to optimize the instrument performance and to improve the image quality. Inter-calibration and inter-comparison with the other satellites show that during the period when the FPM temperature is stable, the G17 IR data are well calibrated and very stable. The overall difference to the reference hyperspectral sounding instruments is less than 0.15K, except for B16 which is warmer by less than 0.5K. The radiometric calibration difference between G16 and G17 is also very small within 0.1K for most of the IR bands except for B09 at 0.22K and B16 at 0.57K. This difference is most likely due to the warmer FPM temperature for G17 ABI. The recently implemented pCal algorithm also significantly improves the radiometric calibration accuracy at the time when FPM temperature are unstable. The calibration difference to SNPP/VIIRS is less than 5% for most G16/G17 VNIR bands, except for G16 and G17 B02 and G17 B05. The new solar calibration LUTs were successfully implemented at G16 and G17 on April 23, 2019 and April 27, 2019, respectively, which greatly reduced the bias to the reference measurements. Continuous efforts are still ongoing to improve the data quality for the G17 VNIR and IR bands.

Acknowledgements: We would like to thank the ABI instrument engineers and calibration scientists from the Vendor, NASA GOES-R Flight, MIT/LL and contractor companies for all the efforts to improve the G17 ABI radiometric calibration performance, data users for the feedback, and the GOES-R Program Office for the coordination.

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