Product Performance Guide for Data Users of GOES-17 ABI Level 1b and Cloud and Moisture Imagery (CMI) Products Released for Full Validation Data Quality

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1. Introduction

The Advanced Baseline Imager (ABI, see Figure 1) is the key instrument on the Geostationary Operational Environmental Satellite R Series (GOES-R). ABI is an imaging radiometer with sixteen spectral channels (Table 1, Figures 2 and 3; note the terms “channel” and “band” are used interchangeably). These channels have spatial resolutions of 0.5 km, 1 km, and 2 km, covering visible and infrared wavelength regions that allow the generation of dozens of critical weather and climate products such as cloud and moisture imagery, atmospheric instability, precipitation, aerosol concentration, cloud properties, sea and land surface temperature, fire, volcanic ash, vegetation, snow and ice, etc.

Figure 1: Photo of the Advanced Baseline Imager (ABI). Courtesy of L3Harris.

This document summarizes the key performance and existing issues of GOES-17 ABI Level 1b (L1b) and Cloud and Moisture Imagery (CMI) to allow users of these products to be familiar with the product performance and existing issues as found at the time of the Full Validation Peer/Stakeholder-Product Validation Review (PS-PVR) on February 19, 2020. The product performance and issues may also be carried over to the downstream Sectorized Cloud and Moisture Imagery (SCMI) products. Additional material that are relevant to the ABI L1b and CMI products and their quality include the Product Definition and User’s Guide (PUG; see [1] and [2]) and the presentations and supporting documents from the PS-PVR [3]. In order to obtain most satisfactory outcomes from these data products, users are also expected to utilize the embedded data quality flags (DQFs, as described in the PUG), and be informed of the announced improvements and anomalies that occur occasionally (see [4] and [5]). Users are encouraged to contact the NOAA ABI calibration scientist and CMI developer (the authors of this document) to report an anomaly or suggest improvements.

Table 1: Spectral Allocation of GOES-R ABI

ABI Band	Band Central Wavelength[1] (µm)	Nominal IGFOV (km)	Sample Objective(s)
1	**0.47**	1	Daytime aerosol over land, coastal water mapping
2	**0.64**	0.5	Daytime clouds, fog, insolation, winds
3	**0.865**	1	Daytime vegetation/burn scar and aerosol over water, winds
4	**1.378**	2	Daytime cirrus cloud
5	**1.61**	1	Daytime cloud-top phase and particle size, snow
6	**2.25**	2	Daytime land/cloud properties, particle size, vegetation, snow
7	**3.90**	2	Surface and cloud, fog at night, fire, winds
8	**6.19**	2	High-level atmospheric water vapor, winds, rainfall
9	**6.95**	2	Mid-level atmospheric water vapor, winds, rainfall
10	**7.34**	2	Lower-level water vapor, winds & SO_2
11	**8.50**	2	Total water for stability, cloud phase, dust, SO_2, rainfall
12	**9.61**	2	Total ozone, turbulence, and winds
13	**10.35**	2	Surface and cloud
14	**11.2**	2	Imagery, SST, clouds, rainfall
15	**12.3**	2	Total water, ash, and SST
16	**13.3**	2	Air temperature, cloud heights and amounts

[1]Band central wavelength approximate. These are taken from the Mission Requirements Document. See Table 1 of Schmit (2017) [6] for more values of the spectral attributes of GOES-17 flight model ABI bands.

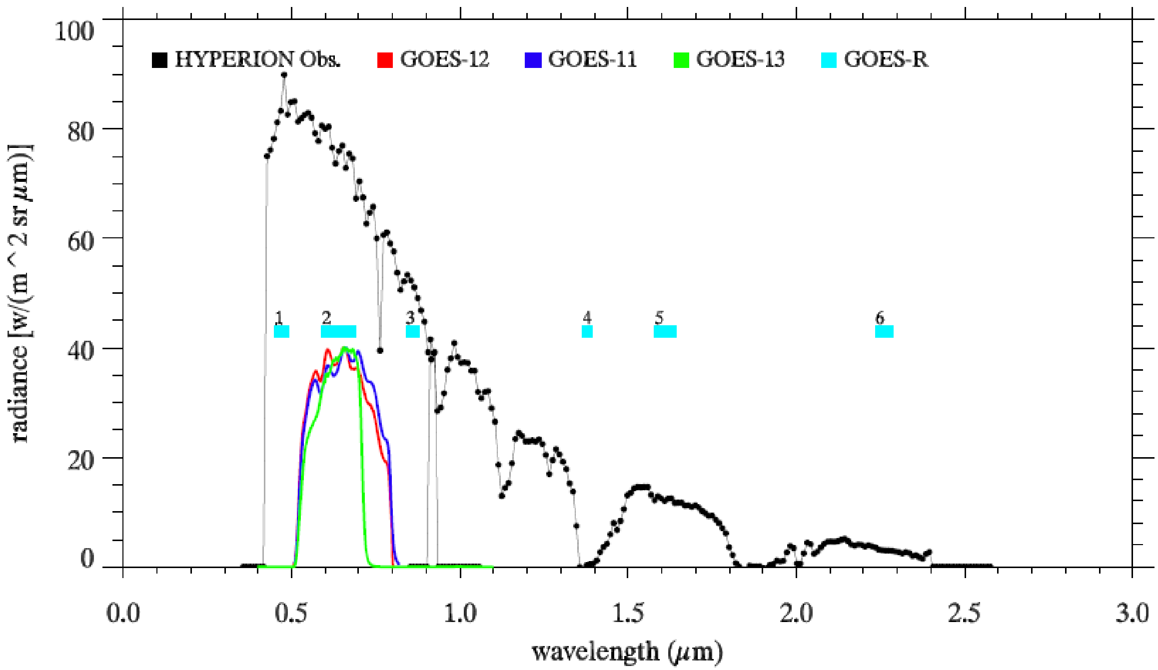

Figure 2: Spectral allocation of ABI visible and near infrared (VNIR) channels (marked in cyan). The color curves are the spectral response function (SRF) of some of legacy GOES Imager. The black curve is the spectral radiance from a high albedo target observed by Hyperion on the Earth-Observer One (EO-1) satellite.

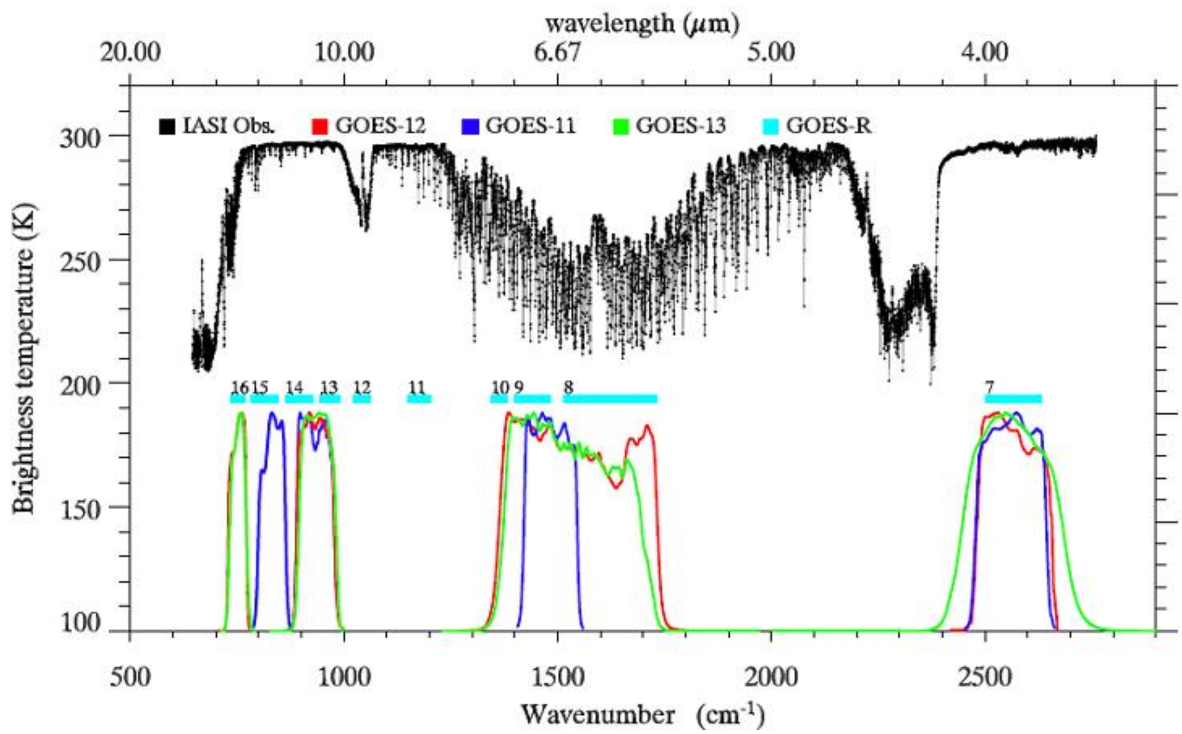

Figure 3: Spectral allocation of ABI infrared (IR) channels (marked in cyan). The color curves are the spectral response function (SRF) of some of legacy GOES Imager. The black curve is a sample spectral radiance (expressed as brightness temperature) from the Infrared Atmospheric Sounding Interferometer (IASI) on METOP-A.

The rest of Section 1 introduces some of the key characteristics of ABI and a timeline of the ABI product validation process. Section 2 provides comparison of the measured on-orbit ABI Level 1b (L1b) product performance to mission requirements and the predicted Performance Baseline. The Performance Baseline is a prediction of the on-orbit product performance compiled by a team at MIT/Lincoln Labs based on vendor reports and pre-launch test data. Section 3 and 4 contain descriptions of some remaining issues within the L1b and CMI products, respectively, and the process toward mitigating them.

1.1 ABI Product Description

The GOES-17 ABI has several operational scanning routines or "timelines". The Mode 6 timeline (Figure 4), also referred to as "10-Minute Flex Mode," acquires one full disk image (FD), two PACific United States images (PACUS) of 3000 km by 50000 km, and 20 mesoscale (MESO) images of 1000 km by 1000 km in 10 minutes.

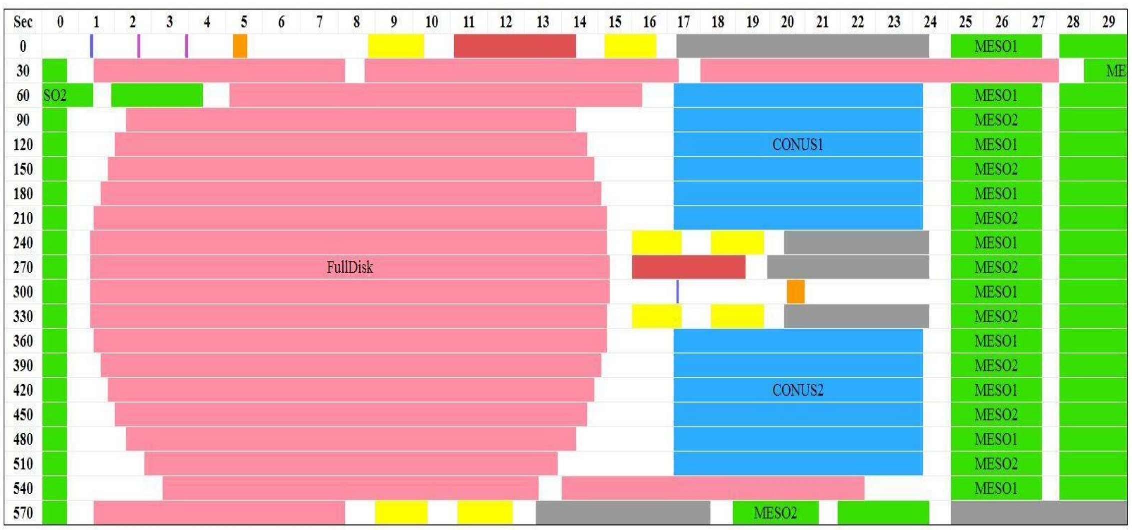

Figure 4: ABI 10-Minute Flex Mode (scan Mode 6) timeline diagram. Timeline diagrams (often called "time-time diagrams") like this one depict the observations of ABI over 30 seconds for each line, starting at the top. The numbers along the left are the starting times of each line, in seconds, from the beginning of the timeline. This timeline, for example, covers 10 min. Pink, blue, and green represent the time scanning the FD, CONUS, and mesoscale sectors, respectively. Autonomous space looks are also included as part of each pink FD swath. White represents the time when ABI slews the line-of-sight (LOS) between observations. Gray represents the time when ABI points at nadir, collecting no data.

The Mode 4 timeline (Figure 5) acquires one FD image every five minutes and is called the “Continuous Full Disk Mode”.

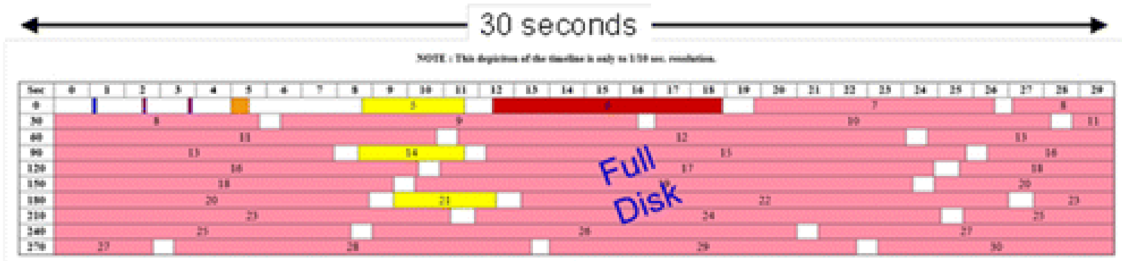

Figure 5: ABI Continuous Full Disk (scan mode 4) timeline diagram. This timeline covers 5 min. Colors same as Figure 4. There are no PACUS or mesoscale scenes in this timeline.

The Mode 3 “Cooling timeline” (Figure 6) is used during the peak hours in peak heating seasons for GOES-17 to slow down the rising of ABI Focal Plane Module (FPM) temperature. This consists of one Full Disk and 15 meso scenes in 15 min, and there is no PACUS sector in the cooling version of Mode 3. This timeline is put into use from 0600-1200 UTC each day the focal plane module temperatures, assuming Mode 6 is utilized, are predicted to be over 100 K; this corresponds to four approximately 25 day periods per year (mostly falling in the months of February, April, August, and October).

During the April 2020 Cooling Timeline operations (April 9 to May 1, 2020), the peak focal plane module temperatures were reduced by 3-5 K against the predicted values if Mode 6 was utilized full-time. The cooler temperatures reduced the time in saturation from 30 to 130 minute each day, depending on band and the expected peak temperature for a given day.

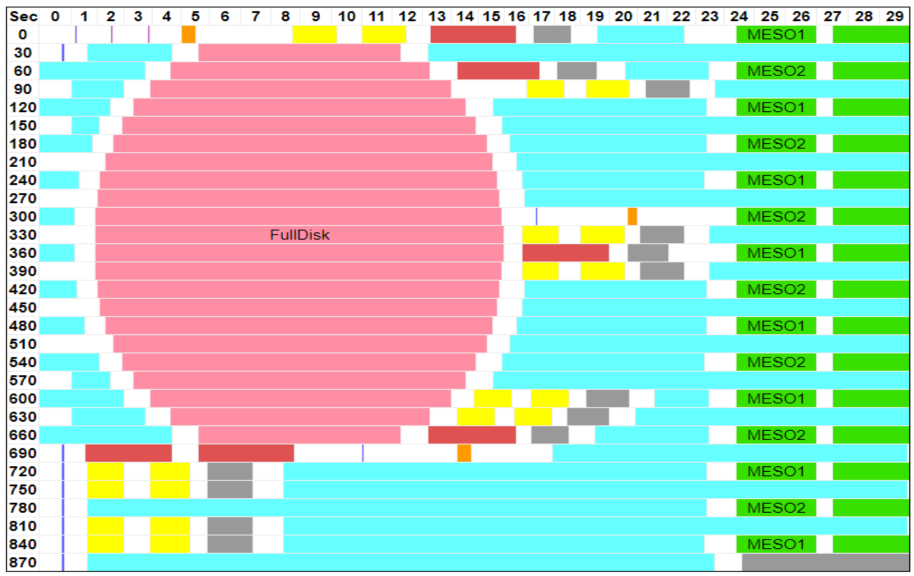

Figure 6: ABI Cooling Timeline (a version of Mode 3) diagram. This timeline covers 15 min. Colors are the same as Figure 4, with the addition of cold space scenes (light blue). There are no PACUS and reduced number of mesoscale scenes in this timeline.

Besides scanning the Earth, these timelines include periodic measurements of blackbody, solar diffuser, space, and star scenes to maintain radiometric and geometric calibration accuracy. Additionally, there are other timelines for calibration and diagnosis. With its high temporal coverage capability and uninterrupted operations through eclipse, ABI provides continuous and timely monitoring of rapidly changing weather phenomena.

The ABI L1b products are the calibrated, geo-located, and resampled radiances of the 16 ABI channels over the FD, CONUS, and MESO regions. In addition to these Earth view data, L1b products also include certain instrument calibration and engineering data. The ABI CMI products are the ABI L1b Earth view data expressed in terms of reflectance factor for the VNIR channels (Bands 1-6) and brightness temperature for the IR channels (Bands 7-16), and can be displayed as color-enhanced images. The CMI products use the L1b products as the main inputs, along with metadata for the conversions. The ABI Level 2+ (L2+) products include the clear sky mask, cloud top properties, sea and land surface temperatures, etc. This document does not describe the quality of the L2+ products, but to the extent that all the L2+ products are derived from the L1b/CMI products, this document is also beneficial to users of the L2+ products.

1.2 GOES-17 ABI Product Validation Timeline

GOES-S was launched on March 1, 2018, and became GOES-17 on March 12, 2018, when it was successfully inserted into the geostationary orbit. After outgassing, the ABI instrument was turned on and started a series of Post-Launch Tests (PLT) to verify that the instrument works and the products are produced as expected.

In May 2018, it was determined that the instrument cryocooler loop heat pipe (LHP) had suffered an anomaly, and it would not be possible to cool the IR focal plane module (FPM) temperatures down to the nominal operating temperature of 60 K. This anomaly and the mitigation steps taken to improve the situation have been described previously [14, 15]. After extensive work by the instrument vendor (L3Harris), GOES-R Flight Team, and others, a mitigation plan was implemented that allows the IR focal plane temperatures to stay around 81 K for most of the year. However, under intense solar heating around satellite midnight on certain days of year, these FPM temperatures can rise up to over 105 K, peaking around 1300 UTC (0400 satellite local time). More details of the effects of this anomaly are given below, especially in Section 3.

At the end of the PLT activity for ABI, the first of a series of reviews was held to assess the status of the GOES-17 ABI L1b and CMI data products. The result of this first Peer Stakeholder–Product Validation Review (PS-PVR), held on July 28, 2018, led to the declaration that the GOES-17 ABI L1b and CMI products reached the Beta Maturity, which means that:

- Product is made available to users to gain familiarity with data formats and parameters (via GRB)
- Product has been minimally validated and may still contain significant errors
- Product is not optimized for operational use.

Post-Launch Product Tests (PLPT) followed the PLTs to evaluate the products generated from the ABI data. For GOES-17 ABI L1b and CMI products, this led to the PS-PVR for the Provisional Maturity on November 28, 2018. The focus of this review was on the period of the year when the IR focal plane module temperatures were stable around 81 K, which covers the majority of the time. Provisional Maturity means that:

- Product performance has been demonstrated through analysis of a small number of independent measurements obtained from select locations, periods, and associated ground truth or field campaign efforts.
- Product analysis is sufficient to communicate product performance to users relative to expectations (Performance Baseline).

- Documentation of product performance exists that includes recommended remediation strategies for all anomalies and weaknesses. Any algorithm changes associated with severe anomalies have been documented, implemented, tested, and shared with the user community.
- Product is ready for operational use and for use in comprehensive cal/val activities and product optimization.

Prior to the Provisional PS-PVR, GOES-17 drifted from its check-out location of 89.3°W to the GOES-W orbital position of 137.2° W in November 2018. Many PLPTs continued during a period of Extended Validation to evaluate the products more comprehensively in all intended environment of applications. GOES 17 was declared operational as GOES-West on February 12, 2019. On February 19, 2020, the final GOES-17 ABI L1b/CMI PS-PVR concluded that the ABI L1b and CMI products have reached the Full Validation Maturity per GOES-R Program, which means that:

- Product performance for all products is defined and documented over a wide range of representative conditions via ongoing ground-truth and validation efforts.
- Products are operationally optimized, as necessary, considering mission parameters of cost, schedule, and technical competence as compared to user expectations.
- All known product anomalies are documented and shared with the user community.
- Product is operational.

2. Key Performance

2.1. Overview

Top level GOES-17 ABI performance requirements are summarized in GOES-R Series Mission Requirements Document (MRD, currently version 3.30, June 2020, [7]). An earlier version (version 3.21, May 2016) has been amended with several performance waivers. Several requirements are shown in Table 2, which was taken from Section 3.4.8.1.2 of MRD and is intended as a quick reference. Many of the MRD requirements are quoted here with their identification numbers.

These MRD requirements were then flowed down to lower level Product Requirements, Instrument Requirements, and so forth, and verified and accepted at those levels before launch. Lower level requirements and verifications are not released to the public. Additionally, GOES-17 ABI post-launch performance has been predicted and documented before launch in the Performance Baseline (PB), drawing upon the verified performance by the as-built instrument.

Table-2 includes the MRD radiometric requirements for the GOES-R series ABI channels. For channels with central wavelengths less than 3 μm, these requirements pertain to accuracy at maximum scene radiance and short-term pixel-to-pixel repeatability when viewing a uniform target. For channels with center wavelengths longer than 3 μm, there are requirements for radiometric accuracy and repeatability, as well as IR channel linearity. Meanwhile, the geometric calibration has several requirements that relate to navigation residuals, within frame registration, image-to-image registration, and channel-to-channel co-registration. There are also requirements on the lifetime of each ABI unit.

Reported in this document are post-launch instrument performance, using both the MRD and PB as reference. The post-launch tests are not meant to verify instrument compliance with requirements. That verification was performed before launch with pre-defined equipment, methods, analyses, etc. Post-launch validation, on the other hand, is often subject to potential operation defficiencies, instrument degradation, sub-optimal collection of test data, etc. Post-launch validation is useful in its own right, particularly for tracking the performance over time, and may supplement to the pre-launch verification. Post-launch testing also allows for the re-certification that the products fulfill the intended role while the satellite is in its intended environment. Readers of this document need to understand that while this document may contain language such as "this on-orbit measurement meets requirements", this is shorthand for more precise, but unwieldy, language that would not add to the usability of this document.

Table 2: Summary of ABI radiometric and geometric calibration and instrument lifetime requirements [1].

Spectral Bands, Radiometric Sensitivity, Dynamic Range		
Navigation		≤ 1.0 km (≤ 28 μrad)
Registration within Frame		≤ 1.0 km (≤ 28 μrad)
Line-to-Line Registration		≤ 0.25 km (at SSP) or ≤ 7 μrad
Registration Image to Image		≤ 0.75 km (at SSP) or ≤ 21 μrad for 0.5 km bands and 1.0 km bands ≤ 1.0 km (at SSP) or 28 μrad for 2.0 km bands
Band to Band Co-Registration (pre-margining)	0.5 km to 2.0 km bands	≤ 0.3 km (at SSP) or ≤ 8.4 μrad
	2.0 km to 2.0 km bands	≤ 0.3 km (at SSP) or ≤ 8.4 μrad
	0.5 km to 1.0 km bands	≤ 0.3 km (at SSP) or ≤ 7 μrad
	1.0 km to 1.0 km bands	≤ 0.25 km (at SSP) or ≤ 7 μrad
	1.0 km to 2.0 km bands	≤ 0.3 km (at SSP) or ≤ 8.4 μrad
On-Orbit Calibration	Visible and reflected solar < 3 μm	Pre-launch to ± 5% On-board to ± 3% 0.2% short-term repeatability
	Emissive IR	0.2 K repeatability 1.0 K abs. Accuracy
IR Band Linearity		± 1%
Lifetime	Ground Storage	5 years
	On-Orbit Storage	5 years is max possible
	Mean Mission Duration (MMD)	8.4 years
	Instrument On life	10 years with R=0.6

In the subsections that follow, the results provided at the Full Validation PS-PVR are reported, together with the relevant requirements in MRD and prediction in the Performance Baseline. The method of validation and the related Post-Launch Test (PLT) and Post-Launch Product Test (PLPT) can be found in "Geostationary Operational Environmental Satellite (GOES) – R Series ABI L1b Beta, Provisional and Full Validation Readiness, Implementation and Management Plan (RIMP)", which is available to approved users upon request (for CMI, see [2]). Four performance test results at the Full Validation did not find evidence that the on-orbit performance meets corresponding requirements in the MRD; those are marked in **red and bold** in the tables and are addressed later in the report. More test results did not find evidence that the on-orbit performance meets the prediction in the Performance Baseline; those are marked in orange in the tables and are addressed where they appear.

The GOES-17 ABI suffers from reduced cooling due to the Loop Heat Pipe (LHP) anomaly [14]. Instead of operating at 60 K all the time as GOES-16 ABI, GOES-17 ABI operates at elevated FPM temperature of 81 K part time of the day, and changes to higher temperatures at other times.

The duration and peak FPM temperature varies, depending on the solar heating at satellite midnight, which varies seasonally. The greatest heating is about 20 days before and after the equinoxes, when the Sun appears to travel above or below the poles (once the Sun enters eclipse behind the Earth, the shadowing effect greatly decreases the maximum daily FPM temperatures). The revised performance requirements apply to the period when the FPM temperature is stable near 81 K. There are reduced performance requirements when the FPM temperature fluctuates, since the measurements for many channels saturate around midnight for the hotter days.

2.2. Navigation Error

MRD522 states that "The GOES-R System **shall** navigate Radiance product observations with errors not to exceed 1.0 kilometer (3-σ) at SSP, except during eclipse."

MRD523 states that "The GOES-R System **shall** navigate Radiance product observations with errors not to exceed 1.5 kilometer (3-σ) at SSP during eclipse."

These are fundamental requirements, necessary for any application of the ABI data. These requirements were evaluated by calculating the North-South (NS) and East-West (EW) components of navigation errors at various landmarks in terms of angle, finding their average μ and standard deviation σ, and reporting max[abs($\mu \pm 3\sigma$)] for both the NS and EW components as error. The required Ground Sample Distances (GSD) have been converted to angles as 1 km = 28 µrad at the sub-satellite point (SSP). Full Disk images were used to achieve the best statistics. Eclipse is defined as when the Sun is eclipsed by the Earth.

For MRD522, evaluation was performed hourly and the 24-hour average is reported. The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 3. Evaluations for the 1.38 µm and 6.95 µm channels (so-called "sounding channels) are not available due to atmospheric absorption in those spectral regions. For Provisional, performance measurements were better than the MRD requirements but four out of ten were worse than the predicted Performance Baseline. For Full Validation, all performance measurements are better than the MRD requirements and the predicted Performance Baseline.

Table 3. Navigation errors for selected channels not during eclipse

MRD522: Navigation Errors For Selected Channels Not During Eclipse (µrad)								
Channel	MRD		Performance Baseline		Provisional		Full[1]	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64	28.0	28.0	10.4	10.1	3.4	2.9	1.4	1.4
0.86	28.0	28.0	10.5	10.3	6.0	3.0	2.0	1.6
1.38	28.0	28.0	11.0	10.3	S[2]	S[2]	S[2]	S[2]
2.25	28.0	28.0	10.6	10.4	11.0	9.4	5.0	5.5
3.90	28.0	28.0	11.4	11.3	10.1	12.8	5.9	7.8
6.95	28.0	28.0	11.6	12.1	S[2]	S[2]	S[2]	S[2]
10.35	28.0	28.0	11.9	12.5	15.4	16.2	7.3	6.4

[1] Performance for M6 is reported here. M3 & M4 (not reported) were similar.
[2] "S" denotes "Sounding channels". Landmarking methods are unreliable at these wavelengths.

For MRD523, the FD image at satellite local time (SLT) midnight was used for evaluation. MRD requirement, Performance Baseline, and measured on-orbit GOES-17 ABI L1b performance at the Provisional and Full Validation PS-PVRs are reported in Table 4. Evaluations for channels less than 3 µm (e.g., those channels dominated by reflected solar light) are not available because eclipse is always at night. Evaluation for the 6.95 µm channels is not available due to atmospheric absorption. The results are substantially better than requirements and comparable (slightly worse) than the PB. This performance is actually a remarkable achievement, considering that the GOES-17 ABI temperature is not only elevated for all optical parts during eclipse but also subject to tremendous change from the design specification.

Table 4. Navigation errors for selected channels during eclipse

MRD523: Navigation Errors For Selected Channels During Eclipse (µrad)								
Channel	MRD		Performance Baseline		Provisional		Full[1]	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
3.90	42.0	42.0	11.4	11.3	22.1	14.7	11.8	13.7
6.95	42.0	42.0	11.6	12.1	S[2]	S[2]	S[2]	S[2]
10.35	42.0	42.0	11.9	12.5	25.4	18.9	12.3	13.5

[1] Performance for M6 is reported here. M3 & M4 (not reported) were similar.
[2]"S" denotes "Sounding channels". Landmarking methods are unreliable at these wavelengths.

2.3. Channel-to-Channel Registration (CCR)

MRD529 states that "The GOES-R System **shall** co-register Radiance product observations between spectral channels having 2.0 km spatial resolution with 99.73% absolute error of 0.4 km at SSP."

MRD530 states that "The GOES-R System **shall** co-register Radiance product observations between spectral channels having 2.0 km and 0.5 km spatial resolution with 99.73% absolute error of 0.4 km at SSP."

MRD531 states that "The GOES-R System **shall** co-register Radiance product observations between spectral channels having 2.0 km and 1.0 km spatial resolution with 99.73% absolute error of 0.4 km at SSP."

MRD532 states that "The GOES-R System **shall** co-register Radiance product observations between spectral channels having 1.0 km spatial resolution with 99.73% absolute error of 0.25 km at SSP."

MRD533 states that "The GOES-R System **shall** co-register Radiance product observations between spectral channels having 1.0 km and 0.5 km spatial resolution with 99.73% absolute error of 0.25 km at SSP."

These requirements are critical for downstream products using multiple channels data. These requirements were evaluated by calculating the relative differences of navigation errors for the pair of participating channels in both the NS and EW directions. The required ground distances have been converted to angles as 1 km = 28 μrad at SSP. Pairs involving sounding channels were evaluated via image-to-image navigation.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 5. At the time of the Full Validation PS-PVR, all performance metrics meet the MRD, and performance between channels on the same FPM also meet the PB. However, performance between channels on different FPMs (0.64 μm – 3.90 μm, 3.9 μm – 13.3 μm) is often worse than PB. This is similar to GOES-16 ABI. The performance predicted by the PB indicates potential improvements in the future as the operation teams continue to tune the navigation algorithm and other key components of navigation.

Table 5. Channel-to-channel registration errors

MRD529-533: Channel-to-Channel Registration (CCR) Errors (μrad)								
Channels Compared	MRD		Performance Baseline		Provisional		Full[1]	
(μm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64-3.90	11.2	11.2	6.6	5.5	7.8	10.4	7.8	10.2
0.64-6.95	11.2	11.2	7.8	6.5	S[2]	S[2]	S[2]	S[2]
0.64-8.50	11.2	11.2	7.4	6.3	S[2]	S[2]	S[2]	S[2]
0.86-1.61	7.0	7.0	4.9	4.4	3.7	5.4	1.8	3.1
1.38-2.25	11.2	11.2	7.6	6.1	S[2]	S[2]	S[2]	S[2]
1.38-8.50	11.2	11.2	7.7	8.2	S[2]	S[2]	S[2]	S[2]
1.38-9.61	11.2	11.2	8.3	8.6	S[2]	S[2]	S[2]	S[2]
2.25-6.95	11.2	11.2	7.7	7.1	S[2]	S[2]	S[2]	S[2]
3.90-13.30	11.2	11.2	5.8	4.6	**21.5**	**29.0**	5.8	5.0
6.95-8.50	11.2	11.2	7.3	6.8	S[2]	S[2]	S[2]	S[2]
9.61-10.35	11.2	11.2	7.0	6.8	10.1	7.7	2.0	1.9

[1] Performance for M6 is reported here. M3 & M4 (not reported) were similar.
[2]"S" denotes "Sounding channels". Landmarking methods are unreliable at these wavelengths.

2.4. Pixel-to-Pixel Registration Within Frame (WIFR)

MRD535 states that "The GOES-R System **shall** separate two Radiance product navigated data samples in the same channel by a known fixed distance not to exceed 1.0 km at SSP (28 μrad)."

This requirement prevents the existence of regions with large local navigation errors, which may vary in time to remain invisible in the average measures of the image. This requirement is evaluated by the standard deviation of a large number of navigation errors in FD images to homogeneity of image navigation.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 6. Test results for the 0.64 μm and 0.86 μm channels are better than MRD requirements and the predicted PB values. For other channels, the performance are better than MRD requirements but worse than the predicted PB. These performance results are comparable to GOES-16 ABI and consistent between Provisional and Full Validation.

Table 6. Pixel-to-pixel registration errors

MRD 535: Pixel-to-Pixel Registration Error Within Frame (μrad)								
Channel	**MRD**		**Baseline**		**Provisional**		**Full[1]**	
(μm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64	28.0	28.0	12.6	12.6	5.3	4.5	5.0	3.9
0.86	28.0	28.0	12.6	12.6	7.1	6.8	9.2	12.2
1.38	28.0	28.0	12.6	12.6	S[2]	S[2]	S[2]	S[2]
2.25	28.0	28.0	12.6	12.6	26.3	24.3	17.4	18.9
3.90	28.0	28.0	12.6	12.6	22.7	23.9	23.8	26.7
6.95	28.0	28.0	13.2	13.2	S[2]	S[2]	S[2]	S[2]
10.35	28.0	28.0	13.2	13.2	24.1	24.1	23.8	27.5

[1] Performance for M6 is reported here. M3 & M4 (not reported) were similar.
[2]"S" denotes "Sounding channels". Landmarking methods are unreliable at these wavelengths.

2.5. Swath-to-Swath Registration (SSR)

MRD536 states that "The GOES-R System **shall** register to 99.73% absolute error two adjacent Radiance product lines/swaths of navigated data samples by a known fixed distance of 0.28 km at SSP."

This requirement is to ensure homogeneity of image navigation, specifically near the scan swath boundaries. It is of particular concern for ABI because of unprecedented large separation in time between swaths (up to 30 seconds, compared to 2.2 seconds or less previously) at higher spatial resolution, and the less-restrictive requirement that the adjacent swaths be in parallel. SSR errors also provide a fine temporal resolution to monitor and diagnose complex navigation processes. As a fine and delicate instrument, ABI may be subject to subtle external disturbance.

These requirements were evaluated by calculating the relative differences of navigation errors for adjacent swaths in both the NS and EW directions. The required ground distances have been converted to angles as 1 km = 28 μrad at SSP.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 7. The performance had difficulties in meeting the MRD requirements at the Provisional review, however significant improvements were made thereafter such that all performance for all channels tested meet the MRD and Performance Baseline prediction with substantial margin.

Table 7. Swath-to-swath registration

MRD 536: Pixel-to-Pixel Registration Error Within Frame – Register Two Adjacent Lines/Swaths (SSR; µrad)								
Channel	**MRD**		**Performance Baseline**		**Provisional**		**Full[1]**	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64	7.80	7.80	4.60	6.00	4.0	4.8	0.1	0.2
0.86	7.80	7.80	4.70	6.10	7.4	5.0	0.1	0.1
1.38	7.80	7.80	4.60	6.10	S[2]	S[2]	S[2]	S[2]
2.25	7.80	7.80	4.70	6.10	**9.7**	5.7	0.8	0.7
3.9	7.80	7.80	5.40	6.90	**38.9**	**13.0**	1.6	1.7
6.95	7.80	7.80	5.40	7.10	S[2]	S[2]	S[2]	S[2]
10.35	7.80	7.80	5.50	7.20	**20.4**	**11.7**	0.6	2.5

[1] Performance for M6 is reported here. M3 & M4 (not reported) were similar.
[2] "S" denotes "Sounding channels". Landmarking methods are unreliable at these wavelengths.

2.6. Frame-to-Frame Registration (FFR)

MRD538 states that "The GOES-R System **shall** register the same Radiance product sample location in two consecutive products ("frame-to-frame registration") within 0.75 km at SSP (21 µrad) for spectral channels with 0.5 km and 1.0 km spatial resolution."

MRD539 states that "The GOES-R System **shall** register the same Radiance product sample location in two consecutive products ("frame-to-frame registration") within 1.0 km at SSP (28 µrad) for spectral channels with 2.0 km spatial resolution."

These requirements are critical for products using radiance in time sequence, for example the atmospheric motion vectors (AMV). These MRD's were evaluated by calculating the relative differences of navigation errors for two consecutive images of the channel in question, in both the NS and EW directions. Only window channels were evaluated. The required ground distances have been converted to angles as 1 km = 28 µrad at SSP.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 8. The on-orbit performance measurements for all channels are better than both the MRD requirements and Performance Baseline predictions. This is consistent with GOES-16 ABI performance.

Table 8. Frame-to-frame registration

MRD 538 and 539: Frame-to-Frame Registration (µrad)								
Channel	MRD		Performance Baseline		Provisional		Full[1]	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64	21.0	21.0	13.7	13.5	1.7	2.3	0.6	0.5
0.86	21.0	21.0	13.8	13.5	3.0	3.8	1.3	2.1
1.38	21.0	21.0	13.8	13.7	S[2]	S[2]	S[2]	S[2]
2.25	21.0	21.0	13.7	13.6	7.4	9.0	3.8	3.9
3.9	21.0	21.0	13.8	14.8	11.3	9.3	5.4	6.1
6.95	21.0	21.0	13.8	15.0	S[2]	S[2]	S[2]	S[2]
10.35	21.0	21.0	13.7	15.0	13.5	11.4	5.4	6.5

[1] Performance for M6 is reported here. M3 & M4 (not reported) were similar.
[2]"S" denotes "Sounding channels". Landmarking methods are unreliable at these wavelengths.

2.7. Radiometric Sensitivity

MRD506 sets requirements for ABI radiometric sensitivity and dynamic range for all channels. These are fundamental requirements that defines the upper limit of ABI measurement precision. For VNIR channels, these requirements are expressed in terms of signal-to-noise ratio (SNR). It is evaluated by calculating, for individual detectors, the mean μ and standard deviation σ of radiances from on-orbit calibration scans of the Solar Calibration Target (SCT), and computing μ/σ as detector SNR. Normally, the minimum of all detector SNR is designated as channel SNR. For GOES-17 ABI, the channel SNR is relaxed to be the mean of all detector SNR.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs for the VNIR channels are given in Table 9. Overall, the on-orbit performance measurements are better than the MRD requirements and the Performance Baseline predictions for all channels.

Channel 2 deserves extra attention for two reasons. First, the SNR requirement for the 0.64 µm channel (Band 2) is "300:1, except < 1% [of the detectors can have SNR] smaller than 300:1 and greater than 150:1". As Band 2 has 1460 detectors, this means that the lowest SNR measured for any detector should be greater than 150, and the SNR for the detector with the 15th lowest SNR shall be larger than 300. The PB predicts that the lowest detector SNR should be larger than 247, and the 99 percentile SNR is 311. The Full Validation on-orbit performance measurement is better than both the MRD requirement and the Performance Baseline prediction for Band 2.

Second, an additional requirement for Band 2 under MRD 506 is that the SNR for scenes of 5% albedo (low light scenes) **shall** be larger than 20. The Performance Baseline estimate for this value is 44. This test requires special data that have been collected only once; this performance is not expected to change significantly over time. At Full Validation, the measured mean SNR for this channel is 41. The minimum value cannot be derived directly from available validation measurements, but can be estimated. The ratio of the mean and minimum SNR at 100% albedo is 411 / 324 = 1.27. Assuming this ratio does not change at low light, the low-light SNR for the worst detector would be 41 / 1.27 = 32. This estimate for the low-light SNR meets MRD, is consistent with GOES-16 ABI performance of 30, but does not meet the PB prediction of 44 that is much higher than 21, the prediction for GOES-16 ABI.

The performance for the three channels of longer wavelength does not meet the PB, even not the MRD in some cases. The performance is consistent between Provisional and Full Validation, and is consistently worse than GOES-16 ABI. Unlike Channels 1-3 that use a silicon detector, these channels use HgCdTe detectors whose noise performance is more sensitive to temperature, and thus the elevated FPM temperature of GOES-17 ABI may have slightly compromised this performance.

Table 9. Signal-to-noise ratio

MRD506: Signal-to-Noise Ratio – 100% Albedo						
Channel (µm)	**MRD**	**Performance Baseline**	**Provisional Minimum**	**Provisional Mean**	**Full Minimum**	**Full Mean**
0.47	300	349	970	1164	1004	1135
0.64[1]	150	247	373	473	324	411
0.64[2]	300	311	393	489	331	412
0.64[3]	20	44			*32*	41
0.86	300	470	658	774	632	751
1.38	300	937	**267**	1082	725	1019
1.61	300	564	333	619	**248**	605
2.25	300	1008	604	1088	933	1043

[1] For all detectors at 100% albedo.
[2] For 99% of detectors at 100% albedo.
[3] For all detectors at 5% albedo.

For the IR channels, the radiometric sensitivity requirements are expressed in terms of Noise Equivalent differential Temperature (NEdT) at 300K. It is evaluated by calculating, for individual detectors, the standard deviation σ of radiances from the Internal Calibration Target (ICT) as measured by ABI, and converting the σ as δR to brightness temperature perturbation δT at the specified scene temperature using $\partial B^{-1}/\partial R$, the partial differentiation of reverse Planck's function B^{-1}. The maximum (worst) value of all detector NEdT measurement for a channel is then reported as the channel NEdT. The channel mean NEdT is also reported, which sometimes relates more closely to user experience.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs for the IR channels are given in Table 10. In consideration of the elevated FPM temperature for GOES-17 ABI, all requirements apply to mean instead of the maximum NEdT. Even so, only channels 11 (8.5 µm), 13 (10.3 µm), and 14 (11.2 µm) meet the PB predictions, and Channels 15 (12.3 µm) and 16 (13.3 µm) does not even meet the MRD. For reference, performance with Gain Set III[2] is also provided (no requirement). It was derived when the Gain Set is III but the FPM temperature is close to that for Gain Set I (81 K).With Gain Set III, the noise changed little for Channel 7 and increased by 50% – 100% for other channels.

Table 10. Noise Equivalent delta Temperature (NEdT)

MRD506: Noise Equivalent delta Temperature (NEdT, mK @300°K)								
Channel (µm)	**MRD**	**Performance Baseline**	**Provisional Max**	**Provisional Mean**	**Full Max**	**Full Mean**	**GS III Max**	**GS III Mean**
3.90	100	70	107	88	102	86	106	88
6.19	100	20	95	23	58	22	68	32
6.95	100	19	84	22	270	22	402	29
7.34	100	31	152	43	295	43	372	64
8.50	100	24	121	23	78	22	90	41
9.61	100	30	368	110	400	111	449	183
10.3	100	58	93	37	89	39	111	72
11.2	100	33	73	30	69	33	120	69
12.3	100	37	138	94	149	**109**	217	166
13.3	300	107	1107	350	788	**402**	1097	808

[2] An early mitigation step has been the utilization of an alternative detector settings (effective integration time and detector bias levels) to prevent detector saturation until higher FPM temperatures. These detector settings are colloquially called "gain sets". At this time, two gain sets are employed for all days when the maximum FPM temperatures are expected to rise over 85 K: a nominal set ("Gain Set I") for when the FPM temperatures stay near 81 K, and another set ("Gain Set III") for the hotter part of days. For operational simplicity, the time of the two gain set switches (GSI to GSIII and GSIII to GSI) are fixed in time depending on the satellite orientation.

2.8. IR Channel Radiometric Precision

MRD2158 states that "The GOES-R System **shall** provide calibrated Radiances product measurements for the emissive infrared channels to within a precision of 0.2 K."

This requirement provides an estimate of the lower limit of ABI measurements precision for IR channels. This requirement was evaluated by calculating the standard deviation of radiance differences for each fixed grid between 144 consecutive CONUS images (12 hours of data). The results of these evaluations would be a measure of ABI precision if the underlying scenes do not change with time. Since that is approximately true at best, the results offer a "no-worse-than" estimate of the precision.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 11. All channels meet the MRD easily but are challenged by the PB.

Table 11. IR radiance precision

MRD2158: IR Radiance Precision (mK)				
Channel (µm)	**MRD**	**Performance Baseline**	**Provisional**	**Full**
3.90	200	< 1	32	34
6.19	200	7	11	7
6.95	200	7	7	7
7.34	200	7	29	7
8.50	200	< 1	19	14
9.61	200	28	86	9
10.3	200	10	17	18
11.2	200	7	18	19
12.3	200	7	34	23
13.3	200	10	60	31

2.9. Radiometric Accuracy

MRD2120 states that "The GOES-R System **shall** provide calibrated Radiances product measurements for the solar reflective channels to within an absolute accuracy of 5%."

In 3.4.8.1.2 of the MRD, "A summary of the imager requirements is provided in the ABI Performance Summary Table below and is intended as a quick reference guide only", gives the requirement that the absolute accuracy of on-orbit calibration for emissive IR channels be 1.0 K.

Radiometric accuracy is critical for all applications of ABI measurements. Accuracy in this context measures the proximity of ABI radiance to truth. In reality, since the truth is often not known, accepted with consensus, or readily available, these requirements are evaluated using comparable measurements by a well-calibrated radiometer.

For VNIR channels, the primary validation is direct comparison with the Visible and Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite. Additional references include radiances from the targets in Sonora Desert and Uyuni Desert, Deep Convective Clouds, and the Moon.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 12, together with the standard deviation of the differences that provide a "1-*k* uncertainty" for the accuracy measurements. Performance measurements for Channels 2 (0.64 µm) and 5 (1.61 µm) were worse than the MRD requirement at the Provisional because two known deficiencies were not corrected then. At Full Validation, performance of all channels is better than PB.

Table 12. Radiometric accuracy for VNIR channels

MRD2120: Radiometric Accuracy - VNIR (Percent Difference)						
Channel (µm)	MRD	Performance Baseline	Provisional Mean	Provisional Stdev	Full Mean	Full Stdev
0.47	5.00	2.71	-0.66	2.65	1.52	3.24
0.64	5.00	2.53	**8.85**	3.67	0.99	4.45
0.86	5.00	2.39	0.42	3.80	0.00	3.60
1.38	5.00	3.77	-1.17	7.97	-3.18	6.96
1.61	5.00	2.74	**5.45**	3.51	-0.97	3.36
2.25	5.00	2.71	-2.80	3.49	-2.61	2.86

For IR channels, the primary reference is the Infrared Atmospheric Sounding Interferometer (IASI) onboard the METOP-B satellite. Additional references include the IASI on METOP-A/C satellite, and the Cross-track Infrared Sounder (CrIS) on S-NPP and NOAA-20.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 12, together with the standard deviation of the differences that provide a "1-*k* uncertainty" for the accuracy measurements. The measured performance for all channels at both PS-PVRs are better than both the MRD requirements and the Performance Baseline predictions.

Table 13. Radiometric accuracy for IR channels

MRD 1493, 1503 and 1513: Radiometric Accuracy – Infrared (mK)						
Channel (µm)	MRD	Performance Baseline	Provisional Mean	Provisional Stdev	Full Mean	Full Stdv
3.9	1000	869	-18	124	-29	102
6.19	1000	644	-31	53	-23	47
6.95	1000	662	19	73	34	69
7.34	1000	649	-23	98	6	184
8.5	1000	612	-16	179	-6	87
9.61	1000	607	-84	160	-82	164
10.3	1000	617	-67	247	-46	253
11.2	1000	641	-77	284	-33	287
12.3	1000	677	39	297	77	305
13.3	1000	709	333	288	347	280

2.10. Dynamic Range

MRD506 sets requirements for the maximum radiance for each channel that ABI must be able to measure. These are fundamental requirements for ABI to perform in its expected applications. The ABI data are collected and processed on-board as 14-bit numbers, so these requirements are evaluated by calculating the maximum radiance for each channel:

$$R_{\max} = (2^{14} - 1 - C_{\text{space}}) * S$$

where C_{space} is the space-look counts, and S is slope, the linear calibration coefficient. The values for R_{max} vary among detectors and, especially for the IR channels, also change over time. The minimum measured values for all detectors for a given channel in a given day is reported as measured value of the channel maximum radiance.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs for the VNIR channels are given in Table 14. The dynamic range was not quantitatively characterized during Provisional PS-PVR. At the Full Validation, the measured performance is better than the MRD requirements for all channels and is also better than the Performance Baseline predictions for five of the six channels. The only exception is Channel 4 (1.38 µm), for which the PB is substantially higher than the MRD. It is unclear why, but the maximum radiance corresponds to nearly 300% albedo and is certainly more than adequate for any known applications.

Table 14. Maximum radiance

MRD506: Maximum Radiance (Dynamic Range, ($mW/m^2/sr/cm^{-1}$))				
Channel (µm)	**MRD**	**Performance Baseline**	**Provisional**	**Full**
0.47	14.4	16.2	Meet the MRD	17.2
0.64	21.1	38.3	Meet the MRD	43.1
0.86	22.8	47.7	Meet the MRD	49.0
1.38	21.7	73.7	Meet the MRD	61.5
1.61	20	40.2	Meet the MRD	39.8
2.25	12.1	21.7	Meet the MRD	21.1

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs for the IR channels are given in Table 15. The performance exceeds the MRD requirements for nine of the ten channels, but Channel 13 (10.3 µm) did not meet the requirement. The MRD for this channel is rather challenging compared to other IR channels (except for the 3.9 µm channel that requires special attention). It can be reached when the ABI functions normally, such as the case for GOES-16 ABI, but is out of reach for GOES-17 ABI operated at elevated temperature. Of the nine channels that passed MRD, eight also meet the PB. Elevated FPM temperature and excessively high PB prediction (as in the case for Channel 4) may also be part of the reason. Nevertheless, these exceptions are not expected to affect most applications, if any at all.

Note that the dynamic range for Channels 15 (12.3 µm) and 16 (13.3 µm) is, respectively, two and four times higher than MRD and PB. However, as long as instrument noise and dynamic range compete for the limited resource of bit depth allocated to the channel, excessive achievement in one is often at the expense of the other (see Table 10).

Table 15. Maximum brightness temperature

MRD506: Maximum Brightness Temperature (Dynamic Range, °K)				
Channel (µm)	**MRD**	**Performance Baseline**	**Provisional**	**Full**
3.90	400	409	419	418
6.19	300	333	352	354
6.95	300	333	363	361
7.34	320	365	386	391
8.50	330	391	355	356
9.61	330	341	570	580
10.3	400	410	**368**	**370**
11.2	330	359	396	397
12.3	330	405	705	708
13.3	305	410	1666	1794

2.11. Linearity

Table 2 in Section 3.4.8.1.2 of the MRD includes the requirement that the IR Channel Linearity be ±1%. This requirement is relevant to radiometric calibration accuracy at the low and high ends of the dynamic range. It is evaluated using the Electronic Calibration (ECAL) data and the standard procedure [9] & [10]. Measurements were plotted as a function of integration time. Deviation of the measurements from linear regression indicates the system nonlinearity.

The MRD requirement, Performance Baseline result, and GOES-17 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 16. The special data for this test was collected and analyzed only once before Provisional. Originally, the MRD and PB are specified for the worst detector of the channel. Because of the LHP anomaly, they were relaxed for the channel mean. Both values are listed for reference. All channels meet the relaxed MRD. The FPM temperature apparently has no impact on the linearity of VNIR channels, which also meet the PB. However, six of the ten IR channels performed worse than PB. To adapt to the elevated FPM temperature, gain set has been changed for the IR channels that can have substantial implications to the nonlinearity. It has been noticed that, for Channels 8-12, detectors behave very differently when signal count exceeds around 14,000.

Table 16. Radiometric linearity

MRD502: Linearity (Percent)				
Channel (µm)	MRD (%)	Performance Baseline (%)	Provisional Maximum (%)	Provisional Mean (%)
0.47	1.00	0.58	0.07	0.07
0.64	1.00	1.38	0.11	0.11
0.86	1.00	0.43	0.10	0.10
1.38	1.00	0.87	0.13	0.13
1.61	1.00	0.77	0.19	0.19
2.25	1.00	0.42	0.14	0.14
3.90	1.00	0.07	0.09	0.06
6.19	1.00	0.14	18.20	0.12
6.95	1.00	0.26	0.38	0.05
7.34	1.00	0.07	0.43	0.08
8.50	1.00	0.08	31.70	0.24
9.61	1.00	0.13	0.53	0.23
10.30	1.00	0.10	32.70	0.53
11.20	1.00	0.56	16.10	0.12
12.30	1.00	0.07	0.18	0.11
13.30	1.00	0.10	0.74	0.36

2.12. Summary of Key Performance

Table 17 is a summary of GOES-17 ABI L1b key performance. For geometric calibration (INR), it is all-time performance. Compared to GOES-16 ABI, the LHP anomaly has little impact on INR performance (the "worse-than-PB" performance will be discussed later). For radiometric calibration, it is the performance when the FPM temperature is stable at 81 K. Compared to GOES-16 ABI, the most significant impact of the LHP anomaly is on radiometric noise, especially for the IR channels, for which two channels do not meet the relaxed requirements. These impacts also have the most implications in related applications. Other performances that were not as good as the PB (including the dynamic range of Channel 13 that failed the MRD) are not likely to affect most applications.

Table 17: Summary of Key Performance

Performance	Better Than MRD?	Better Than PB?
Navigation Residual – Not Eclipse	Yes	Yes
Navigation Residual – Eclipse	Yes	No
Channel-to-Channel Registration	Yes	2/4[1]
Pioxel-to-Pixel Registration	Yes	2/5[2]
Swath-to-Swath Registration	Yes	Yes
Frame-to-Frame Registration	Yes	Yes
VNIR Noise[3]	Yes	7/8[4]
IR Noise[3]	**8/10**	3/10
IR Precision	Yes	No
VNIR Accuracy	Yes	Yes
IR Accuracy	Yes	Yes
VNIR Dynamic Range	Yes	5/6
IR Dynamic Range	**9/10**	8/10
Linearity	Yes	10/16

[1]: Not for channels in different FPM.

[2]: Not for the channels with HCT detectors.

[3]: Mean, not the worst, of all detectors for the channel.

[4]: Not for low light SNR (Channel 2).

GOES-17 ABI FPM temperature becomes unstable on most days of the year for a period that depends on the season. There are reduced/no requirements for performance during this period (the MRD was updated in March 2020 with the full list of performance requirement waivers), in fact the FPM temperature can be so high on many days for a short period of time that no measurements are useful at all. Nevertheless, the Calibration Working Group (CWG) has characterized the performance during this period for reference. For INR, performance during this period is always better than the MRD and is better than the PB in most cases. The few exceptions are likely related to the elevated FPM temperature but unlikely to cause degraded products. For IR noise, the best performance during this period is reported in Table 10 for comparison. A more comprehensive summary is provided in Figure 7.

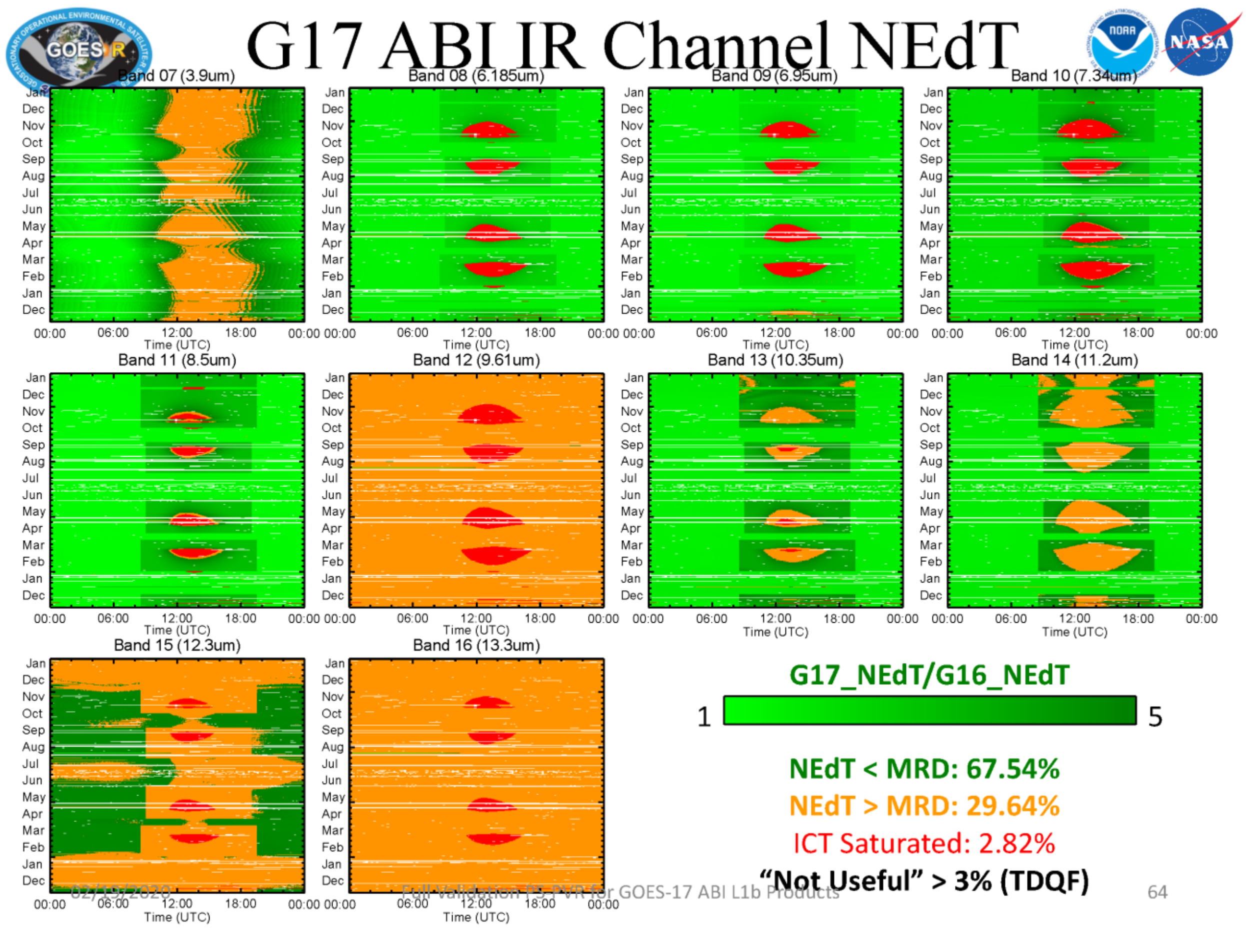

Figure 7: Noise of the ten GOES-17 ABI IR channels (one in each panel) for the 24 hours in a day (horizontal) and 365 days in a year (vertical). The green color is when the performance meets the MRD requirements, with the shade reflecting the comparison with corresponding GOES-16 ABI performance. The orange color is when the performance does not meet the MRD requirements. The red color is when the data cannot be used. The FPM temperature is stable for about 14 hours a day, when the performance meets the MRD (light green) for most channels and has been reported in detail in this section. For the other ten hours around satellite midnight, the FPM temperature is unstable in most (but not all) days and the performance is deteriorated.

3. Existing Issues in ABI L1b Products for User Awareness

1. An anomaly with the GOES-17 ABI Loop Heat Pipe (LHP) prevents the instrument cooling system from maintaining the desired operating temperature at all times of the year. In addition, the thermal stability is not maintained for some parts of the instrument during certain periods of the day and year.
   a. For 13-14 hours a day, the Focal Plane Module (FPM) is maintained at a stable but elevated temperature of 81K (compared to 60K for GOES-17). During this period of time:
      i. The Imager Navigation and Registration (INR) performance for all channels is not affected.
      ii. The accuracy of radiometric calibration performance for Channels 1-6 is affected, but probably within the requirements, especially for channel 4-6.
      iii. The accuracy of radiometric calibration performance for Channels 7-15 is not affected.
      iv. Caused a warm bias of up to 0.4 K for Channel 16, which is expected to be corrected by the pending update of the spectral response function (SRF) for the operating temperature of 81K.
      v. Does not increase noise in Channels 1-6.
      vi. Led to higher noise in Channels 7-16 when compared to GOES-17 but meet the waived requirements.
   b. For the other 10-11 hours a day, the FPM temperature rises each night. During the roughly 100 days centered on the vernal and autumnal equinoxes:
      i. INR performance may remain nominal.
      ii. Radiometric calibration performance is further degraded and sometimes unusable for Channels 8-16.
      iii. The peak of the FPM temperatures occurs about 20 days before and after the equinox as shown in Figure 1. The "valleys" in Figure 1 result from the spacecraft being eclipsed by the Earth. The small discontinuities at the bottom of each "valley" results from spacecraft yaw-flip maneuvers which are executed to reduce FPM temperatures.
      iv. Several changes were made to improve GOES-17 ABI performance when its FPM temperature is unstable. Among them is the Predictive Calibration (pCal) that was implemented at 1721 UTC on 25 July 2019. pCal accounts for the effects of rapid change in FPM temperature between acquisitions of calibration data. While it reduces biases when a channel is not saturated, it does not change the time period when a channel is saturated.

   v. The predicted times of band saturation effects for 2020 (expect updated links for future years) can be found at: http://cimss.ssec.wisc.edu/goes/GOES-17_ABI_Saturation_Prediction_Reference_Tools_v8.pdf

   c. The review in November 2018 covered the ABI performance during the times of the day when the FPM temperature is stable. The update in October 2019 covers some improvements of ABI performance, especially during the times of the day when the FPM temperature is unstable.

2. Stray light exists for Visible and Near IR (VNIR) bands approximately one hour before and after satellite local midnight during the eclipse season before the vernal (spring) equinox and after the autumnal (fall) equinox, and may exist in other days of the year. Effects include:
   a. Significant stray light for Channels 1-6 (VNIR) approximately one hour before and after satellite local midnight for approximately forty days before and after the vernal (spring) and autumnal (fall) equinox, and may exist in other days of the year.
   b. Stray light for Channel 7 approximately one hour before and after satellite local midnight for approximately forty days before and after the vernal (spring) and autumnal (fall) equinox within the Zone of Reduced Data Quality (ZRDQ).
3. Lunar contamination of space view may compromise many (not all) detectors of several (not all) channels of any channels for one swath in all sectors (up to 30 second), or more rarely many detectors of several IR channels for up to 300 seconds.
4. Gyro rate drop may occasionally cause short lived but sharp navigation anomalies.
5. Channel 16 will have warm bias of up to 0.4K before the SRF update.
6. Channel 3 (0.86 µm) radiance may vary slowly by up to 5%. For example, an object with reflectance of 80% may appear as 78% at one time and 82% some months later. This may also happen to Channels 2 & 1 (0.64 µm & 0.47 µm) but to a much lesser degree (~1%). The root cause of this anomaly has been identified; the correction has not been implemented.
7. For the channels that saturate on selected days, the performance shortly before and after saturation may be improved.
8. Calibration discontinuity can be noticed for some IR channels at the time of semi-annual yaw flip, daily change of Gain Set switch and space look side, and more frequently after star looks. The magnitudes are well within the requirements.
9. There seems to be increased frequency of the occurrence of certain type of data drops, commonly referred to as “Caterpillar Tracks” and “Shark Fins”.

https://www.star.nesdis.noaa.gov/GOESCal/goes_SatelliteAnomalies.php has more calibration updates.

For CMI, all the issues noted above for the radiances are valid, in addition to the following:

1. Originally, there were no data quality flags based on focal plane temperatures.

a. There are now data quality flags based on focal plane temperatures (including the maximum temperature value). The summary flags include: DQF:percent_good_pixel_qf = 0.9999929f ;

b. DQF:percent_conditionally_usable_pixel_qf = 0.f ;

c. DQF:percent_out_of_range_pixel_qf = 0.f ;

d. DQF:percent_no_value_pixel_qf = 7.1e-06f ;

e. DQF:percent_focal_plane_temperature_threshold_exceeded_qf = 0.f ;

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3.1. L1b, CMI, and SCMI Product Changes

Several changes have been made to the ABI L1b and CMI product files to help users identify when the increased focal plane temperatures may be degrading the products. For more details on each, please consult the Product Users Guide (PUG):

- The Focal Plane Module temperatures for each band have been added to the L1b and SCMI (the latter available September 3, 2020) files of every scene. These are maximum values of the temperature measured over the observation of the scene in the given file.
- Pixel-level Data Quality flags trigged by the FPM temperatures have been added at the pixel level to the L1b and SCMI (the latter available September 3, 2020). Metadata describing the rising or falling temperatures that trigger these flags are included as well.
- (Available September 3, 2020): Metadata describing the detector settings will be added to the L1b and CMI files. This will help users identify which of the two “gain sets” the band is utilizing. Information on the meaning of these settings is in the PUG.
- (Available September 3, 2020): A flag indicating whether the “Predictive Calibration” algorithm is active has been added to the INST-CAL files.

3.2. Band 2 Radiometric Bias

Prior to a correction applied on April 23, 2019, the radiances derived post-launch for the GOES-17 ABI 0.64 µm channel (Band 2) were found to be 6.9% brighter than commonly accepted values. This happens for all Band 2 pixels at all times. A 6.2% radiometric bias was observed for Band 2 for GOES-16 as well. This anomaly was confirmed through comparisons with pre-launch data, VIIRS data, desert data, lunar measurements, deep convective cloud (DCC) observations, and Airborne Visible/Infrared Imaging Spectrometer – Next Generation (AVIRIS-NG) data airborne field campaign data.

This issue is described in more detail within the GOES-16 ABI Product Performance Guide. A correction was applied on April 23, 2019 that resolved this issue for both GOES-16 and GOES-17.

3.3. Stripes, Banding, and Striping

The term "stripes" and "striping" can be used to describe a number of imagery phenomena, each with different root causes. One definition refers to when radiance values derived from one or more detectors are out of specification, or at least out-of-family, as compared to the other detectors from that channel. The result is the appearance of a strong line for each bad detector across each swath of ABI data. The GOES-16 ABI Product Performance Guide describes three cases of striping found in ABI L1b data due to three different root causes.

The GOES-17 Loop Heat Pipe anomaly leads to additional causes of stripes. For example, due to normal variations in the individual detectors, some detectors may saturate at high FPM temperatures before the majority of the other detectors for that band, causing stripes. More examples of striping evident in GOES-17 ABI data can be found in Gunshor et al. 2020 [13].

3.4. Cold Bias Around Fires (CPAF)

Prior to a correction placed into operation in April 2019, some pixels for the 3.9 µm channel (Band 7) around targets of high radiance (such as hot fire) often have cold bias. These affected pixels are often one pixel away from the hot target, and the bias is loosely proportional to the target radiance. For pixels saturated by fire, for example, some affected pixels adjacent may report zero or negative radiance (this effect is also called "cold pixels around fire" or "CPAF" for this reason). Although the severe (saturated) cases are rare, it is thought that cold bias of varying degree often exists for pixels nearby a hot region.

This behavior was also seen in GOES-16 ABI data and a more detailed description is included in the GOES-16 ABI Product Performance Guide. A correction Band 7 resampler kernel was approved and went into effect for GOES-16 on April 23, 2019 at 1820 UTC. For GOES-17, the update occurred on April 18, 2019 at 1840 UTC.

3.5. VNIR and IR Stray Light at Night

Approximately 45 minutes before and after satellite local midnight (e.g., when the Sun is opposite of the Earth from ABI) during eclipse season, which is approximately 40 days before and after the vernal (March 21) and autumnal (September 21) equinoxes, stray light may exist for both VNIR and IR channels. These phenomena were described in the GOES-16 ABI Product Performance Guide, and the description given for GOES-16 holds for GOES-17 ABI data as well. There is no requirement on VNIR stray light, and the residual IR stray light is well within requirements.

4. Existing Issues for ABI CMI

For CMI, all the issues noted above in Section 3 for the radiances are valid, in addition to the following:

4.1. Inconsistent Spatial Coverage

ABI utilizes on-board flight software to avoid direct observations of the Sun. The software prevents the ABI mirrors to direct light from within a specified angular region around the Sun onto the detectors. Some of the aspects of this Bright Object Avoidance (BOA) are evident in Sections 3.7 and 3.9 above. Due to the physical layout of the detectors for each channel on the multiple focal planes, the region of the field of regard seen by each channel is different for a fixed set of mirror angles. When a swath is truncated to avoid pointing too close to the Sun, the actual position seen on the Earth at the swath truncation point is different for every channel, shifted East-West depending on the channel detector position on the focal planes. That is, the "chunk" of the Earth not scanned during BOA varies channel-by-channel (see Figures 14 and 15 above for examples).

Early in the design of the ground processing algorithms it was decided to process each channel independently and set data quality flags (DQFs) for the BOA region for each channel. Developers of products that use multiple channels need to carefully scrub their input data to ensure they are not missing one or more channels around the BOA region, resulting in degraded or misleading products.

4.2. Metadata Timing

When the metadata arrives for an ABI file via GOES-R ReBroadcast (GRB), that is supposed to be the indicator that the entire file has been delivered. Yet, in some cases this metadata is sent too soon. To address this issue, some users have inserted a "sleep" command to wait for extra time. In general, this is effective, but adds latency, for example 10 sec. Yet, there are infrequent situations where the added time isn't enough and hence part of an image is missed. Most of the time the latency is less than 4 sec, but it can be larger as well. As of September 2019, a correction has been found, but it may be early 2021 before the correction is implemented. Once the correction is applied, GRB users should be able to remove or reduce the duration of the "sleep" command.

4.3. T_B(3.9) For Cold Target

Cold targets (< 230 K) produce very little light at 3.9 µm (Band 7). Due to the nature of the Planck relationship each step in the quantized radiance values for cold targets converts into large brightness temperature steps (see Figure 16). Care should be taken for enhanced visual representation of cold clouds, so that the noise in these low light levels is not amplified. For example, during the nighttime a high cloud can be very cold, resulting in small (near zero) radiance values observed by the satellite. Hence, if a color mapping is applied that varies over many colors on the cold end, the image may appear noisier. More on this issue can be found on the CIMSS Satellite Blog: http://cimss.ssec.wisc.edu/goes/blog/archives/28030.

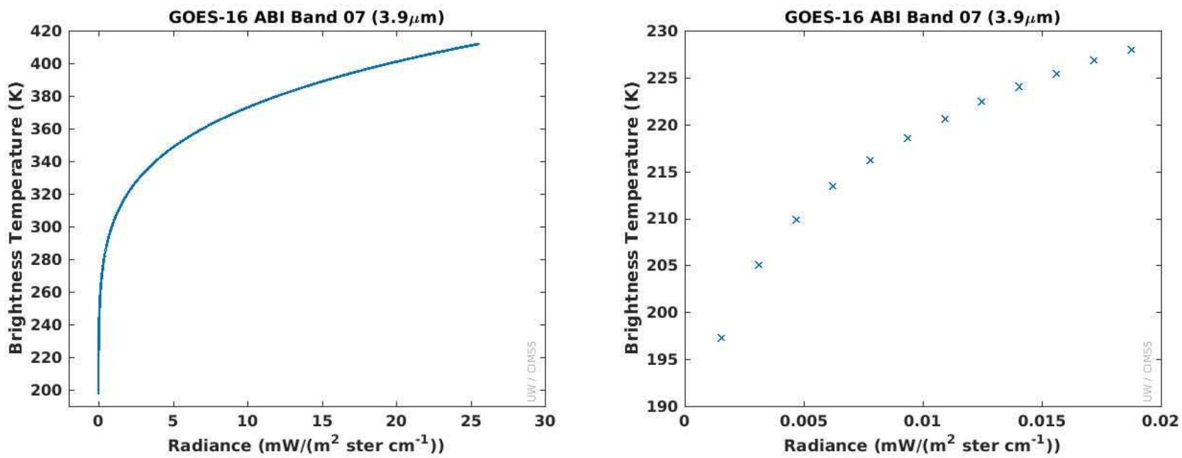

Figure 8: Planck relationship between brightness temperature and radiance for Band 7 (3.90 μm), displayed over the full dynamic range of the ABI band (left) and zoomed in to show the large discrete steps in brightness temperature at the cold (low radiance) end of the ABI L1b radiance range. A small amount of noise in the radiance values can be exaggerated into very large brightness temperature noise (plots courtesy UW/CIMSS Satellite Blog liked in the text).

5. Summary

The GOES-17 ABI instrument and the ground processing work well to create high quality L1b and CMI products. The performance and existing issues have been described, including how users will be affected, channel-by-channel. Results from the testing of ABI L1b performance, product compliance with the expected performance, and mitigation plans have been presented. More information on the calibration and navigation performance can be found at: https://www.star.nesdis.noaa.gov/GOESCal/index.php#

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6. References

[1] GOES-R Product Definition and Users Guide (PUG) Volume 3 (L1b Products): https://www.goes-r.gov/users/docs/PUG-L1b-vol3.pdf

[2] GOES-R Product Definition and Users Guide (PUG) Volume 5 (L2+ Products): https://www.goes-r.gov/products/docs/PUG-L2+-vol5.pdf

[3] ABI L1b/CMI PS-PVR Materials: No official website hosts the materials at the time of writing, but they are available from the authors upon request.

[4] CWG Event Log: https://www.star.nesdis.noaa.gov/GOESCal/goes_SatelliteAnomalies.php

[5] ESPC Notifications for satellite operations (including GOES-16): https://www.ospo.noaa.gov/Operations/messages.html

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[8] ABI Cloud and Moisture Imagery RIMP: https://www.goes-r.gov/products/RIMPs/RIMP_ABI-L2_CMI_v1.0.pdf

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[10] Post launch test report: ABI system linearity characterization (ABI-E-014), CDRL No. 0121-8 (2017).

[11] Additional technical documents for test design and results will be available through: https://www.star.nesdis.noaa.gov/GOESCal/goes_presentations.php

[12] GOES-R Series Data Book: https://www.goes-r.gov/downloads/resources/documents/GOES-RSeriesDataBook.pdf

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