GOES-16 ABI Level 1b and Cloud and Moisture Imagery (CMI) Release Full Validation Data Quality

Product Performance Guide for Data Users

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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 resolution of 0.5 km to 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, and so on.

This document summarizes the key performance and existing issues of GOES-16 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 June 1, 2018. The product performance and issues may also be carried over to the downstream Sectorized Cloud and Moisture Imagery (SCMI) products. Additional material that relevant to the ABI L1b and CMI products and their quality include the Product 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 utilize the embedded data quality flags (as listed 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.

The rest of Section 1 introduces some of the key characteristics of ABI and a timeline of the ABI product validation process. Section 2 is provides the 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.

Figure 1: Photo of the Advanced Baseline Imager (ABI). Courtesy of Exelis (now Harris).

Table 1: Spectral Allocation of GOES-R ABI

ABI Band	**Band Central Wavelength and Range[1] (µm)**	**Nominal IGFOV (km)**	**Sample Objective(s)**
1	**0.47** (0.45-0.49)	1	Daytime aerosol over land, coastal water mapping
2	**0.64** (0.59-0.69)	0.5	Daytime clouds fog, insolation, winds
3	**0.865** (0.846-0.885)	1	Daytime vegetation/burn scar and aerosol over water, winds
4	**1.378** (1.371-1.386)	2	Daytime cirrus cloud
5	**1.61** (1.58-1.64)	1	Daytime cloud-top phase and particle size, snow
6	**2.25** (2.225-2.275)	2	Daytime land/cloud properties, particle size, vegetation, snow
7	**3.90** (3.80-4.00)	2	Surface and cloud, fog at night, fire, winds
8	**6.19** (5.77-6.60)	2	High-level atmospheric water vapor, winds, rainfall
9	**6.95** (6.75-7.15)	2	Mid-level atmospheric water vapor, winds, rainfall
10	**7.34** (7.24-7.44)	2	Lower-level water vapor, winds & SO_2
11	**8.50** (8.30-8.70)	2	Total water for stability, cloud phase, dust, SO_2, rainfall
12	**9.61** (9.42-9.80)	2	Total ozone, turbulence, and winds
13	**10.35** (10.1-10.6)	2	Surface and cloud
14	**11.2** (10.8-11.6)	2	Imagery, SST, clouds, rainfall
15	**12.3** (11.8-12.8)	2	Total water, ash, and SST
16	**13.3** (13.0-13.6)	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-16 flight model ABI bands.

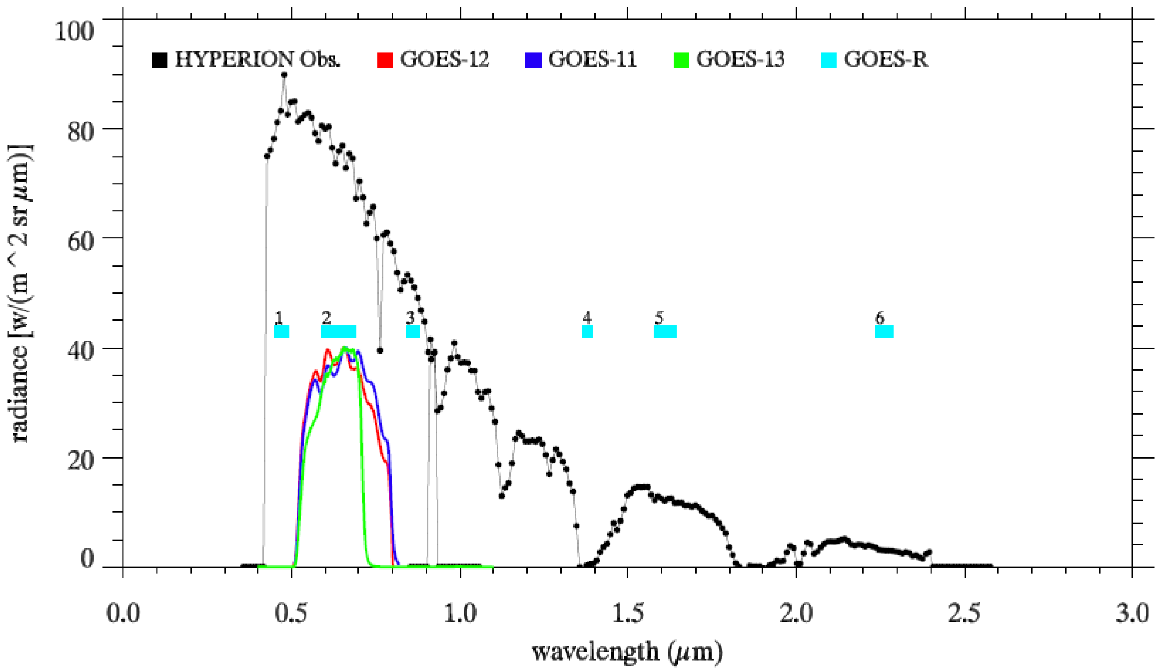

Figure 2: Spectral allocation of ABI visible and near infrared (VNIR) channels (marked in cyan). The color curves are the spectral response function (SRF) of some of legacy GOES Imager. The black curve is the spectral radiance from a high albedo target observed by Hyperion on the Earth-Observer One (EO-1)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

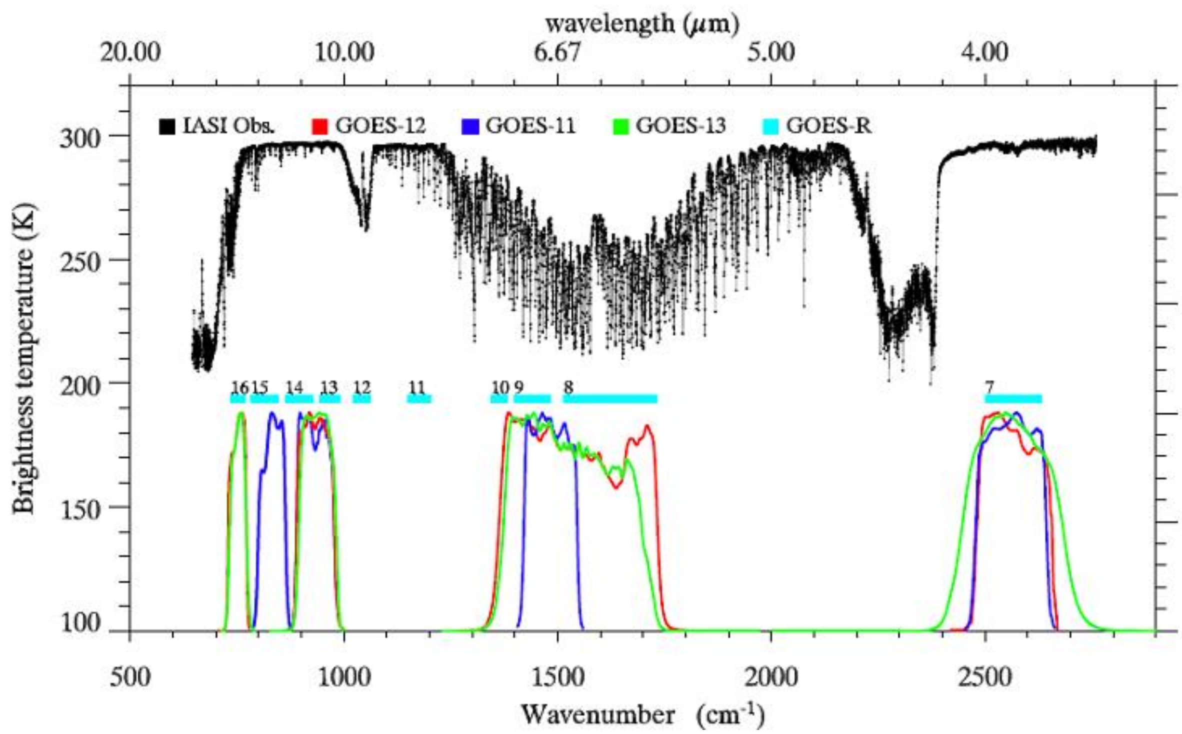

Figure 3: Spectral allocation of ABI infrared (IR) channels (marked in cyan). The color curves are the spectral response function (SRF) of some of legacy GOES Imager. The black curve is a sample spectral radiance (expressed as brightness temperature) from the Infrared Atmospheric Sounding Interferometer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

1.1 ABI Product Description

The ABI has two operational scanning routines or "timelines": Mode-3 and Mode-4. The Mode-3 timeline (Figure 4), also referred to as "Flex Mode," acquires one full disk image (FD), three CONtiguous United States images (CONUS), and 30 1000 km by 1000 km mesoscale (MESO) images in 15 minutes. The Mode-4 timeline (Figure 5) acquires one FD image every five minutes and is called the "Continuous Full Disk Mode". Besides scanning the Earth, both timelines include periodic measurements of blackbody, solar diffuser, space, and star scenes to maintain radiometric and geometric calibration accuracy. With its high temporal coverage capability and uninterrupted operations through eclipse, ABI provides continuous and timely monitoring of rapidly changing weather phenomena.

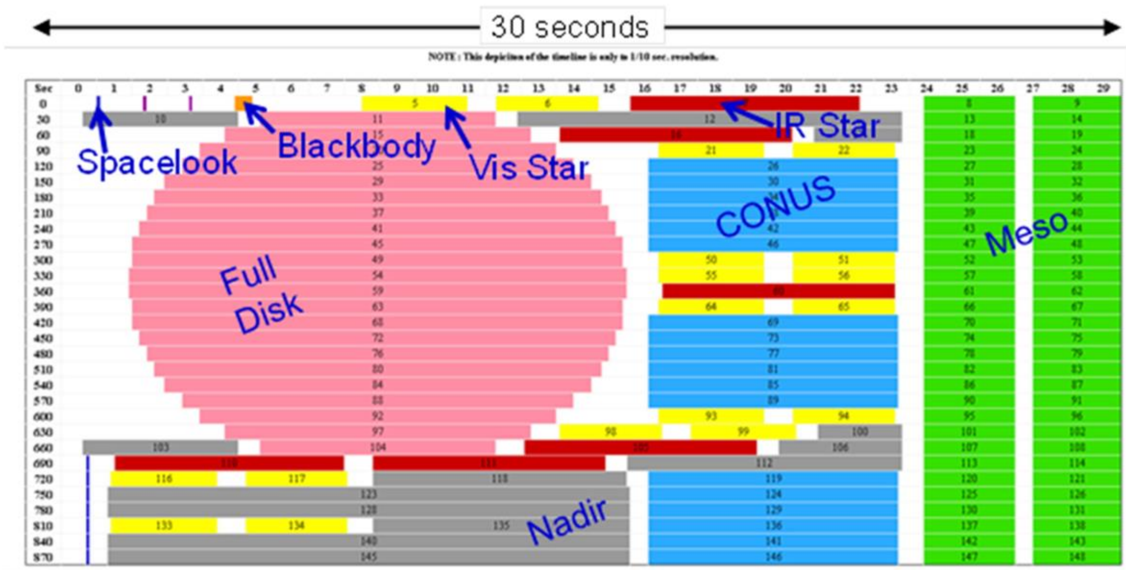

Figure 4: ABI Flex Mode (scan mode 3) timeline diagram. Timeline diagrams (often called "time-time diagrams") like this one depict the observations of ABI over 30 sections for each line, starting at the top. The numbers along the left are the starting times of each line, in seconds, from the beginning of the timeline. This timeline, for example, covers 15 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.

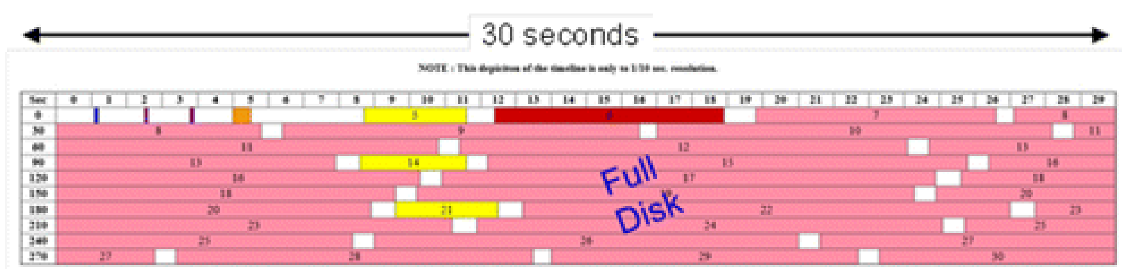

Figure 5: ABI Continuous Full Disk (scan mode 4) timeline diagram. This timeline covers 5 min. Colors same as Figure 4. There are no CONUS or mesoscale scenes in this timeline.

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 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 documents does not describe the quality of these products, although all the L2+ products are derived from the L1b/CMI products, so this document may be useful to users of the L2+ products.

1.2 GOES-16 ABI Product Validation Timeline

GOES-R, the first satellite of the series, was launched on November 19, 2016, and became GOES-16 on November 30, 2016, after successful orbit insertion. 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. At the end of the PLT activity for ABI, the first of a series of reviews was held to access the status of the GOES-16 ABI L1b and CMI data products. The result of this first Peer Stakeholder–Product Validation Review (PS-PVR), held on February 28, 2017, was that the review chair declared that the GOES-16 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-16 ABI L1b and CMI products, this led to PS-PVR for the Provisional Maturity on June 1, 2017. 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.

Many PLPTs continued during a period of Extended Validation to evaluate the products more comprehensively in all intended environment of applications. During this period, GOES-16 drifted from its check-out location of 89.3° W (89.5° W before August 8, 2017) to the GOES-E orbital position of 75.2° W. GOES 16 was declared operational as GOES-East on December 19, 2017. On June 1, 2018, the final GOES-16 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-16 ABI performance requirements are summarized in GOES-R Series Mission Requirements Document (MRD, currently version 3.26, June 22, 2018, [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-16 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 testing is 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.

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[2]. The MRD requirement, the Performance Baseline result, and the GOES-16 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. All performance measurements are better than the MRD requirements and the predicted Performance Baseline.

[2] Before computing resources became adequate in June 2017, evaluation was limited to the FD image at noon of Satellite Local Time (SLT).

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**	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64	28.0	28.0	10.4	10.1	6.6	6.0	3.9	0.7
0.86	28.0	28.0	10.5	10.3	17.1	16.9	2.7	1.9
1.38	28.0	28.0	11.0	10.3	S[1]	S	S	S
2.25	28.0	28.0	10.6	10.4	56.2	46.3	5.5	3.2
3.90	28.0	28.0	11.4	11.3	70.0	62.3	8.2	4.5
6.95	28.0	28.0	11.6	12.1	S	S	S	S
10.35	28.0	28.0	11.9	12.5	76.6	65.6	9.4	5.1

[1]"S" denotes "Sounding channels". Landmarking methods are unreliable at these wavelengths.

For MRD523, the FD image at satellite local time (SLT) midnight on March 22, 2018 was used for evaluation. MRD requirement, Performance Baseline, and measured on-orbit GOES-16 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 EW navigation results reported are slightly worse than the MRD requirement. These values were computed over the duration of the eclipse only; however, the PB reflects performance computed over the specified 24 hours period. These results will be addressed in Section 3.

Table 4. Navigation errors for selected channels during eclipse

MRD523: Navigation Errors For Selected Channels During Eclipse (µrad)								
Channel	**MRD**		**Performance Baseline**		**Provisional**		**Full**	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
3.90	42.0	42.0	11.4	11.3	103.4	87.8	**43.0**	**17.3**
6.95	42.0	42.0	11.6	12.1	S[1]	S	S	S
10.35	42.0	42.0	11.9	12.5	116.2	104.9	**52.9**	**22.8**

[1]"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[3].

The MRD requirement, the Performance Baseline result, and the GOES-16 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, however the NS co-registration between the 0.64 µm and 3.90 µm channels and co-registration between 3.90 µm and 13.3 µm channels in both directions did not meet the PB. CCR was initially problematic for GOES-16 ABI L1b processing, especially for channels in different focal planes – Bands 1-6 (0.64 – 2.25 µm), 7-11 (3.90 – 8.50 µm), and 12-16 (10.35 - 13.30 µm) until changes in both the processing parameters and INR star observation methodology were made to alleviate the issues. The errors were reduced to 2-3 times larger than required at the Provisional Maturity, and further reduced

[3] Before computing resources became adequate in June 2017, only pairs of window channels were evaluated.

further to 2-3 times smaller than required at the Full Validation Maturity. The performance predicted by the PB indicates potential improvements in 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	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64-3.90	11.2	11.2	6.6	5.5	26.1	31.1	5.4	5.9
0.64-6.95	11.2	11.2	7.8	6.5	S[1]	S	S	S
0.64-8.50	11.2	11.2	7.4	6.3	S	S	S	S
0.86-1.61	7.0	7.0	4.9	4.4	154.3	37.5	1.4	1.2
1.38-2.25	11.2	11.2	7.6	6.1	S	S	S	S
1.38-8.50	11.2	11.2	7.7	8.2	S	S	S	S
1.38-9.61	11.2	11.2	8.3	8.6	S	S	S	S
2.25-6.95	11.2	11.2	7.7	7.1	S	S	S	S
3.90-13.30	11.2	11.2	5.8	4.6	32.8	58.4	6.7	7.2
6.95-8.50	11.2	11.2	7.3	6.8	S	S	S	S
9.61-10.35	11.2	11.2	7.0	6.8	11.6	18.1	2.5	2.9

[1]"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, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 6. Test results for channels with central wavelengths shorter than 2 µm are better than MRD requirements and the predicted PB values. Performance results for channels with central wavelengths longer than 2 µm are better than MRD requirements, but are worse than the predicted PB. As seen in Table 6, between the Provisional and Full Validation maturity reviews, this error has been stable for the 3.9 µm and 10.35 µm channels, but increased for others, in particular the 0.64 µm and 0.86 µm channels. Both of the visible channels had large performance margins at the Provisional review.

These changes are likely the results of some trade-offs made to improve some of the more critical performance metrics at the expense of this performance measurement. On August 2, 2018, after the Full Validation review, the default timelines for GOES-16 were modified to add additional star look scenes to improve the WFIR performance.

Table 6. Pixel-to-pixel registration errors

MRD 535: Pixel-to-Pixel Registration Error Within Frame (µrad)								
Channel	MRD		Baseline		Provisional		Full	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64	28.0	28.0	12.6	12.6	1.9	1.9	4.4	3.8
0.86	28.0	28.0	12.6	12.6	3.9	3.9	7.4	7.1
1.38	28.0	28.0	12.6	12.6	S[1]	S	S	S
2.25	28.0	28.0	12.6	12.6	15.2	15.2	**25.2**	**24.1**
3.90	28.0	28.0	12.6	12.6	23.6	23.6	**24.1**	**23.8**
6.95	28.0	28.0	13.2	13.2	S	S	S	S
10.35	28.0	28.0	13.2	13.2	25.7	25.7	**26.5**	**25.3**

[1]"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, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 7. The performance measurements for channels with wavelength longer than 2 µm were worse than the MRD requirements and Performance Baseline prediction. These results will be addressed in Section 3.

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	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64	7.80	7.80	4.60	6.00	3.00	1.50	1.4	0.9
0.86	7.80	7.80	4.70	6.10	3.60	10.00	4.3	2.3
1.38	7.80	7.80	4.60	6.10	S[1]	S	S	S
2.25	7.80	7.80	4.70	6.10	50.00	17.20	**12.5**	**10.1**
3.9	7.80	7.80	5.40	6.90	68.90	36.00	**12.9**	**9.7**
6.95	7.80	7.80	5.40	7.10	S	S	S	S
10.35	7.80	7.80	5.50	7.20	11.20	35.70	**18.1**	**9.1**

[1]"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, the Performance Baseline result, and the GOES-16 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.

Table 8. Frame-to-frame registration

MRD 538 and 539: Frame-to-Frame Registration (µrad)								
Channel	MRD		Performance Baseline		Provisional		Full	
(µm)	EW	NS	EW	NS	EW	NS	EW	NS
0.64	21.0	21.0	13.7	13.5	3.3	5.7	0.8	1.6
0.86	21.0	21.0	13.8	13.5	0.5	3.1	0.8	1.4
1.38	21.0	21.0	13.8	13.7	S[1]	S	S	S
2.25	21.0	21.0	13.7	13.6	2.7	7.8	2.2	3.2
3.9	21.0	21.0	13.8	14.8	3.8	4.1	2.9	3.5
6.95	21.0	21.0	13.8	15.0	S	S	S	S
10.35	21.0	21.0	13.7	15.0	12.2	6.1	3.6	4.2

[1]"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), computing μ/σ as detector SNR, and the minimum of all detector SNR as channel SNR. The channel mean SNR is also reported, which sometimes relates more closely to user experience.

The MRD requirement, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 9. The requirements are for the detector with the minimum SNR among all detectors of the channel, whereas user experience is often related to the mean SNR of the channel, so both values are reported. 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. The Full Validation on-orbit performance measurement is that the lowest SNR for a Band 2 detector is 266, and the SNR for the detector of the 15th lowest SNR value is 350. Therefore, the measurement of the on-orbit performance is better than both the MRD requirement and the Performance Baseline prediction for Band 2.

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 21. At the Provisional review, the method to evaluate this performance metric was not yet available. The data used to derive the results that were reported at Full Validation were collected before the Provisional review. 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 48, and the minimum value cannot be derived from available validation measurements. The low-light SNR for the worst detector would be 29 if taking the ratio of mean to minimum (430/261) at 100% albedo as a first-order estimate. This estimate for the low-light SNR meets MRD and PB levels.

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	650	1141	532	1144
0.64	300/150	247	261	427	266/350	430
0.64 at 5% albedo	20	21	Not Reported	Not Reported	30 (est.)	48
0.86	300	470	563	767	503	770
1.38	300	937	876	1057	870	1058
1.61	300	564	447	607	352	610
2.25	300	1008	886	1050	728	1056

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 channel NEdT. The channel mean NEdT is also reported, which sometimes relates more closely to user experience.

The MRD requirement, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 10. The measured performance is better than the MRD requirements for all channels and is better than the Performance Baseline prediction for all but the 3.90 µm channel (Band 7). One possible contributing factor to this discrepancy is that the on-orbit evaluation was based on measurements of the Internal Calibration Target (ICT) which may not be as stable temporarily or homogeneous spatially as the External Calibration Target (ECT) used in the pre-launch testing. The main factor, however, is likely related to the relatively weak signal for on-orbit calibration of this channel. For example, due to the nature of the Planck function and the required dynamic range, the ABI ICT radiates about 40% and 3% of the maximum radiance values for the 11.2 µm and 3.9 µm channels, respectively. Consequently, one count of noise is equivalent to 9 mK and 49 mK of NEdT for the 11.2 µm and the 3.9 µm channels, respectively.

Table 10. Noise Equivalent delta temperature (NEdT)

MRD506: Noise Equivalent delta Temperature (NEdT, mK @300°K)				
Channel (µm)	MRD	Performance Baseline	Provisional	Full
3.90	100	70	80	74
6.19	100	20	13	13
6.95	100	19	15	15
7.34	100	31	25	23
8.50	100	24	18	19
9.61	100	30	20	18
10.3	100	58	28	28
11.2	100	33	25	19
12.3	100	37	22	22
13.3	300	107	29	34

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 consecutive CONUS images for the first 144 images (12 hours of data) on May 28, 2017 (for Provisional maturity) and on May 3, 2018 (for Full Validation maturity). Images for the rest of these days were not used because some data in the 145th image on May 28, 2018 were corrupted, and because the used data were deemed sufficient. 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, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 11. The measured performance is better than the MRD requirements for all channels, and is better than the Performance Baseline predictions for the 6.19 µm channel (Band 8), the 6.95 µm channel (Band 9), 7.34 µm channel (Band 10), and the 9.61 µm channel (Band 12). Note that all of these channels are subject to strong atmospheric absorption (by water vapor for Bands 8-10 and by ozone for Band 12), which makes them less sensitive to surface and cloud radiation that generally are more variable in space and time. Also note that because of the presence of the Periodic Infrared Calibration Anomaly (PICA, see below) at the time of the Provisional review evaluation, the results at that time are worse in general than at the time of the Full Validation review. Good results for this test hinge on the assumption that the underlying scene does not change much over time, which is closer to what is observed for some channels more than others.

Table 11. IR radiance precision

MRD2158: IR Radiance Precision (mK)				
Channel (µm)	MRD	Performance Baseline	Provisional	Full
3.90	200	< 1	64	**46**
6.19	200	7	29	2
6.95	200	7	32	3
7.34	200	7	33	4
8.50	200	< 1	58	**19**
9.61	200	28	63	10
10.3	200	10	80	**25**
11.2	200	7	83	**25**
12.3	200	7	92	**23**
13.3	200	10	98	**16**

Compared to the performance at the Provisional maturity, the IR precision for all channels (except perhaps for the 3.90 µm channel) was substantially improved at Full Validation. This is largely due to the correction of Periodic Infrared Calibration Anomaly (PICA), as shown in Figure 6.

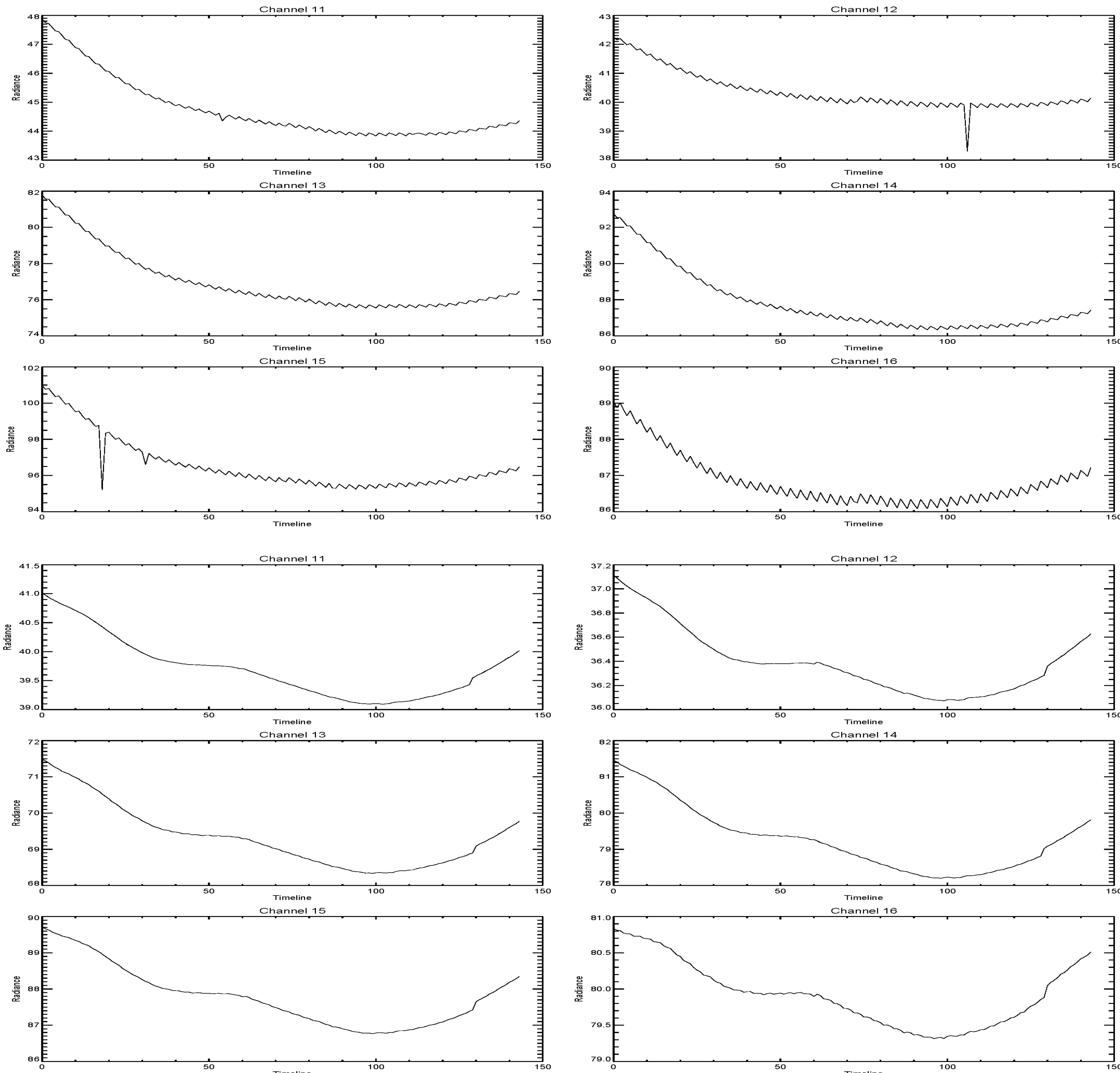

Figure 6: Time series of GOES-16 ABI CONUS mean radiances for Bands 11-6 on May 28, 2017 (upper 6 panels) and on May 3, 2018 (lower 6 panels). Note the zig-zag features in 2017 before the PICA correction.

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 ground 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, the Moon, the Airborne Visual Imaging Infrared Spectrometer Next Generation (AVIRIS-NG), and the ground-based measurements.

The MRD requirement, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 12. Additionally the standard deviation of the differences are reported with the Full Validation result. These values provide a "1-*k* uncertainty" for the accuracy measurements. Uncertainties were not reported at the Provisional Review because there was not sufficient quality data collected before the review. Performance measurements for the 0.64 µm channel (Band 2) are worse than the MRD requirement; this will be discussed in more detail in Section 3. Performance results for the 0.47 µm channel (Band 1) and 1.61 µm channel (Band 5) are better than the MRD requirements, but are worse than the Performance Baseline predictions; the reason is attributed to uncertainties within the validation method.

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 satellite, the Cross-track Infrared Sounder (CrIS) on S-NPP, and the Scanning High-resolution Interferometer Sounder (S-HIS).

The MRD requirement, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 13. Additionally the standard deviation of the differences are reported with the Full Validation result. These values provide a "1-*k* uncertainty" for the accuracy measurements. Uncertainties were not reported at the Provisional Review because there was not sufficient quality data collected before the review. The measured performance for all channels at the time of both PS-PVRs are better than both the MRD requirements and the Performance Baseline predictions.

Table 12. Radiometric accuracy for VNIR channels

MRD2120: Radiometric Accuracy - VNIR (Percent Difference)					
Channel (µm)	MRD	Performance Baseline	Provisional Mean	Full Mean	Full Stdev
0.47	5.00	2.71	4.20	**4.70**	3.30
0.64	5.00	2.53	7.30	**6.70**	4.50
0.86	5.00	2.39	1.70	1.50	3.20
1.38	5.00	3.77	-5.00	-0.50	7.50
1.61	5.00	2.74	4.50	**3.80**	5.70
2.25	5.00	2.71	-0.20	0.50	3.80

Table 13. Radiometric accuracy for IR channels

MRD 1493, 1503 and 1513: Radiometric Accuracy – Infrared (mK)					
Channel (µm)	MRD	Performance Baseline	Provisional Mean	Full Mean	Full Stdv
3.9	1000	869	-190	-180	11
6.19	1000	644	-320	-210	50
6.95	1000	662	-320	-250	40
7.34	1000	649	-240	-190	20
8.5	1000	612	-240	-220	20
9.61	1000	607	-210	-230	25
10.3	1000	617	-210	-220	20
11.2	1000	641	-140	-150	26
12.3	1000	677	-120	-160	28
13.3	1000	709	-280	-290	87

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 therefore 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, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 14. The measured performance is better than the MRD requirements for all channels and, with the exception of the 1.38 µm channel (Band 4), is also better than the Performance Baseline predictions. While the source of this difference has not yet been identified, the maximum radiance corresponds to nearly 300% albedo and is certainly more than adequate for any known applications.

The MRD requirement, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 15. The performance exceeds the MRD requirements for all channels and, with the exception of the 12.3 µm channel (Band 15), is also better than the Performance Baseline predictions. For Band 15, all detectors surpass the PB predictions except for one out-of-family detector, as shown in Figure 7. It is possible that this detector changed after launch, although the performance still has large margin compared to MRD requirement.

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	16.77	16.73
0.64	21.1	38.3	45.91	45.82
0.86	22.8	47.7	49.07	49.15
1.38	21.7	73.7	60.61	62.57
1.61	20	40.2	40.08	40.42
2.25	12.1	21.7	22.02	22.24

Table 15. Maximum brightness temperature

MRD506: Maximum Brightness Temperature (Dynamic Range, °K)				
Channel (µm)	MRD	Performance Baseline	Provisional	Full
3.90	400	409	420	420
6.19	300	333	337	335
6.95	300	333	336	336
7.34	320	365	369	368
8.50	330	391	394	394
9.61	330	341	347	346
10.3	400	410	424	424
11.2	330	359	379	378
12.3	330	405	403	402
13.3	305	410	487	486

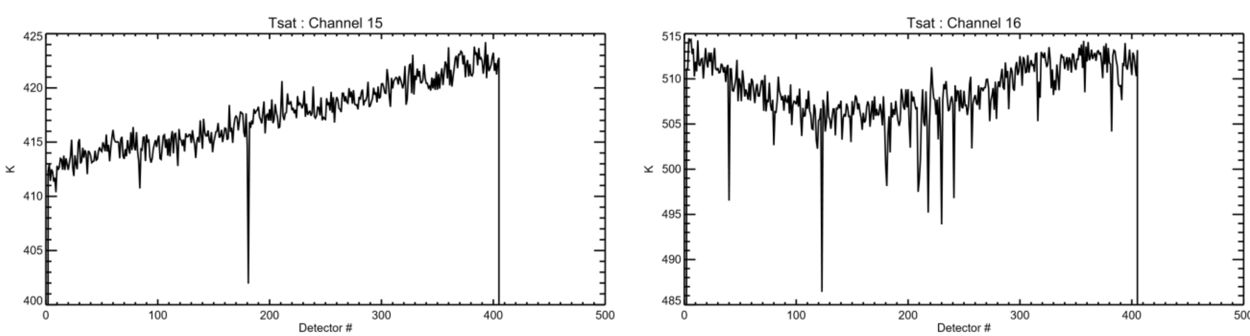

Figure 7: Dynamic range, expressed as maximum brightness temperature, for every detector in Band 15 (12.3 µm, left panel) and Band 16 (13.3 µm, right panel).

2.11. Linearity

Table 2 (from Section 3.4.8.1.2 of the MRD) includes a 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, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Table 16. Note that the measured performance is better than the MRD requirements for all channels, but the 3.90 µm, 6.2 µm, 7.3 µm, 9.6 µm, 12.3 µm, and 13.3 µm channels (Bands 7, 8, 10, 12, 15, and 16) are worse than the PB prediction at the time of the Full Validation PS-PVR. For the IR channels, this performance was evaluated pre-launch using the External Calibration Target (ECT) at varying temperature, which is more stable and homogeneous than using the Internal Calibration Target (ICT) that is available for post-launch evaluation with varying integrating time.

Table 16. Radiometric linearity

MRD502: Linearity (Percent)				
Channel (µm)	MRD	Performance Baseline	Provisional	Full
0.47	1.00	0.6	0.7	0.1
0.64	1.00	1.4	2.0	0.1
0.86	1.00	0.4	0.9	0.1
1.38	1.00	0.9	2.8	0.2
1.61	1.00	0.8	1.0	0.2
2.25	1.00	0.4	0.9	0.1
3.90	1.00	0.07	0.35	**0.09**
6.19	1.00	0.14	0.93	**0.44**
6.95	1.00	0.26	0.46	0.22
7.34	1.00	0.07	0.20	**0.08**
8.50	1.00	0.08	0.15	0.08
9.61	1.00	0.13	0.33	**0.18**
10.30	1.00	0.10	0.20	0.10
11.20	1.00	0.56	0.16	0.10
12.30	1.00	0.07	0.17	**0.12**
13.30	1.00	0.10	1.38	**0.12**

2.12. Modulation Transfer Function (MTF)

After 2011, the Modulation Transfer Function is considered part of the spatial resolution requirements for MRD and were specified only at lower requirements level. However, since this performance is critical for image quality, it is evaluated using the method described in [11]. Briefly, the sharp edge of lunar image is corrected for curvature, then fitted to the Ferma function, whose derivative in direction cross the lunar edge is the Line Spread Function (LSF). Fast Fourier Transform (FFT) is applied to LSF that leads to MTF.

The MRD requirement, the Performance Baseline result, and the GOES-16 ABI L1b performance reported at the Provisional and Full Validation PS-PVRs are given in Tables 17-20. MTF in the NS direction is not available for some channels (indicated by blanks for some IR channels in Tables 17 and 18) due to measurement noise. In summary:

- Six of the 200 performance metrics were worse than the MRD requirements:
    - Five were at the Nyquist frequency where the signals are too noisy to be trusted
    - One was at the ¾ Nyquist frequency that is less important
- 46 of the 200 performance metrics were worse than the PB predictions:
    - 32 were at the Nyquist frequency where the signals are too noisy to be trusted
    - Five were at the ¾ Nyquist frequency that is less important
    - Seven were from lunar NS scans, for which the data quality is of concern due to low signal levels
    - Two remaining discrepancies for the MTF at ½ Nyquist frequency for the EW scan of the 1.61 µm channel indicate that the performance is slightly worse (0.76 and 0.77 vs. 0.78) than the PB, but it is still better than the MRD requirements within comfortable margins.

Table 17. Spatial resolution (MTF), NS-Falling

MRD527: Spatial Resolution (Modulation Transfer Function), NS Falling																
Channel	MRD				Performance Baseline				Provisional				Full			
(µm)	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq
0.47	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.94	0.79	0.59	0.39	0.94	0.79	0.59	0.39
0.64	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.93	0.77	0.58	0.39	0.93	0.77	0.58	0.39
0.86	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.93	0.78	0.59	0.40	0.93	0.78	0.59	0.40
1.38	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.95	0.81	0.63	0.43	0.95	0.81	0.63	0.43
1.61	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.95	0.82	0.64	0.44	0.95	0.82	0.64	0.44
2.25	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.95	0.81	0.61	0.41	0.95	0.81	0.61	0.41
3.90	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
6.19	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
6.95	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
7.34	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
8.50	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
9.61	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
10.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
11.20	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
12.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
13.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								

Table 18. Spatial Resolution (MTF), NS Rising

MRD527: Spatial Resolution (Modulation Transfer Function), NS Rising																
Channel	MRD				Performance Baseline				Provisional				Full			
(µm)	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq
0.47	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.93	0.77	0.56	0.36	0.93	0.77	0.56	0.36
0.64	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.93	0.75	0.51	0.29	0.93	0.75	0.51	0.29
0.86	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.92	0.75	0.57	0.38	0.92	0.75	0.57	0.38
1.38	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.95	0.82	0.63	0.44	0.95	0.82	0.63	0.44
1.61	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.93	0.77	0.56	0.36	0.93	0.77	0.56	0.36
2.25	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.96	0.84	0.68	0.50	0.96	0.84	0.68	0.50
3.90	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.91	0.70	0.48	0.30	0.91	0.70	0.48	0.30
6.19	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.72	0.49	0.28	0.92	0.72	0.49	0.28
6.95	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.71	0.45	0.21	0.92	0.71	0.45	0.21
7.34	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.93	0.75	0.52	0.31	0.93	0.75	0.52	0.31
8.50	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.93	0.74	0.51	0.29	0.93	0.74	0.51	0.29
9.61	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.93	0.76	0.53	0.32	0.93	0.76	0.53	0.32
10.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
11.20	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
12.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								
13.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30								

Table 199. Spatial Resolution (MTF), EW Falling

MRD527: Spatial Resolution (Modulation Transfer Function, MTF), EW Falling																
Channel	MRD				Performance Baseline				Provisional				Full			
(µm)	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq
0.47	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.94	0.79	0.59	0.38	0.95	0.81	0.62	0.42
0.64	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.93	0.75	0.52	0.29	0.94	0.79	0.58	0.37
0.86	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.94	0.78	0.57	0.37	0.95	0.80	0.61	0.41
1.38	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.94	0.78	0.56	0.35	0.94	0.80	0.60	0.39
1.61	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.93	0.74	0.50	0.27	0.93	0.76	0.53	0.31
2.25	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.94	0.76	0.54	0.33	0.94	0.78	0.57	0.37
3.90	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.73	0.49	0.28	0.94	0.76	0.54	0.33
6.19	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.72	0.48	0.27	0.93	0.75	0.50	0.27
6.95	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.71	0.45	0.24	0.94	0.78	0.56	0.34
7.34	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.71	0.46	0.25	0.93	0.75	0.51	0.29
8.50	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.72	0.47	0.24	0.93	0.74	0.50	0.28
9.61	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.72	0.47	0.24	0.92	0.72	0.46	0.22
10.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.72	0.47	0.25	0.93	0.74	0.50	0.28
11.20	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.72	0.47	0.24	0.93	0.74	0.50	0.27
12.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.71	0.45	0.22	0.92	0.73	0.48	0.25
13.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.70	0.43	0.20	0.92	0.71	0.45	0.22

Table 20. Spatial Resolution (MTF), EW Rising

MRD527: Spatial Resolution (Modulation Transfer Function), EW Rising																
Channel	MRD				Performance Baseline				Provisional				Full			
(µm)	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq	1/4 Nyq	1/2 Nyq	3/4 Nyq	Nyq
0.47	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.96	0.83	0.66	0.47	0.95	0.80	0.60	0.39
0.64	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.94	0.79	0.58	0.37	0.94	0.78	0.56	0.35
0.86	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.95	0.83	0.65	0.46	0.95	0.83	0.66	0.46
1.38	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.95	0.83	0.65	0.46	0.95	0.82	0.63	0.43
1.61	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.94	0.78	0.56	0.35	0.94	0.77	0.56	0.34
2.25	0.90	0.73	0.53	0.32	0.93	0.78	0.57	0.42	0.95	0.81	0.62	0.42	0.95	0.80	0.61	0.41
3.90	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.93	0.74	0.50	0.29	0.93	0.74	0.51	0.30
6.19	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.73	0.49	0.29	0.92	0.71	0.45	0.22
6.95	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.72	0.47	0.27	0.93	0.75	0.52	0.29
7.34	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.72	0.48	0.27	0.93	0.74	0.50	0.28
8.50	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.73	0.48	0.26	0.93	0.74	0.49	0.27
9.61	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.73	0.48	0.26	0.92	0.71	0.44	0.20
10.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.73	0.48	0.26	0.93	0.74	0.50	0.28
11.20	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.73	0.48	0.26	0.92	0.72	0.47	0.24
12.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.71	0.44	0.21	0.92	0.72	0.47	0.24
13.30	0.84	0.62	0.39	0.22	0.91	0.71	0.47	0.30	0.92	0.70	0.44	0.21	0.92	0.70	0.43	0.19

2.13. Summary

Overall, the measured on-orbit performance of the GOES-16 ABI L1b products is excellent, exceeding mission requirements in nearly all cases and often with large margins. The following three exceptions will be further addressed in Section 3:

1. Navigation errors during eclipse in EW direction are 43 µrad and 54 µrad, respectively, for the 3.9 µm (Band 7) and 10.4 µm (Band 12) channels, which are worse than the requirements of 42 µrad.
2. Within frame pixel-to-pixel registration errors (WIFR) (adjacent lines/swaths) for the 2.25 µm channel (Band 6, 12.5 µrad / 10.1 µrad for EW / NS), the 3.9 µm channel (Band 7, 12.9 µrad / 9.7 µrad), and the 10.4 µm channel (Band 12, 18.1 µrad / 9.1 µrad) are worse than the requirement of 7.8 µrad / 7.8 µrad.
3. The 0.64 µm channel (Band 2) is 6.7% brighter than commonly accepted values, which is worse than the requirement on radiometric accuracy that bias be less than 5%.

As mentioned above, MTF is no longer part of MRD, however evaluation of this performance indicates 6 of 200 (3%) of the performance metrics are worse than an older version of MRD requirements, and more measurements are worse than the PB.

In addition, the following performance measurements are better than the MRD requirements, but are worse than the Performance Baseline predictions:

1. Navigation error during eclipse in NS direction.
2. The NS co-registration between the 0.64 µm and 3.9 µm channels and co-registration in both directions between 3.9 µm and 13.3 µm channels.
3. WIFR (separate samples) for channels with wavelength longer than 2 µm.
4. NEdT for the 3.9 µm channel (Band 7).
5. IR Precision for all channels except for the 6.95 µm and 7.34 µm channels (Bands 9 and 10).
4. Accuracy for the 0.47 µm and 1.61 µm channels (Bands 1 and 5).
6. Dynamic range for the 1.38 µm and 12.3 µm channels (Bands 4 and 15).
7. Linearity for the 3.9 µm, 6.2 µm, 7.3 µm, 9.6 µm, 12.3 µm, and 13.3 µm channels (Bands 7, 8, 10, 12, 15, and 16).

3. Existing Issues in ABI L1b Products for User Awareness

3.1. B02 Bias

The 0.64 µm channel (Band 2) is ~7% brighter than commonly accepted values. This happens for all Band 2 pixels at all times. This is a bias relative to the measurement, not the absolute bias in reflectance (albedo). For example, if the target reflectance is 20%, ABI measurement would be 21.4%, not 27%. Users may notice this anomaly when properly comparing with MODIS, VIIRS, and virtually all validated space- and ground-based and airborne measurements, in other words the commonly accepted values. 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.

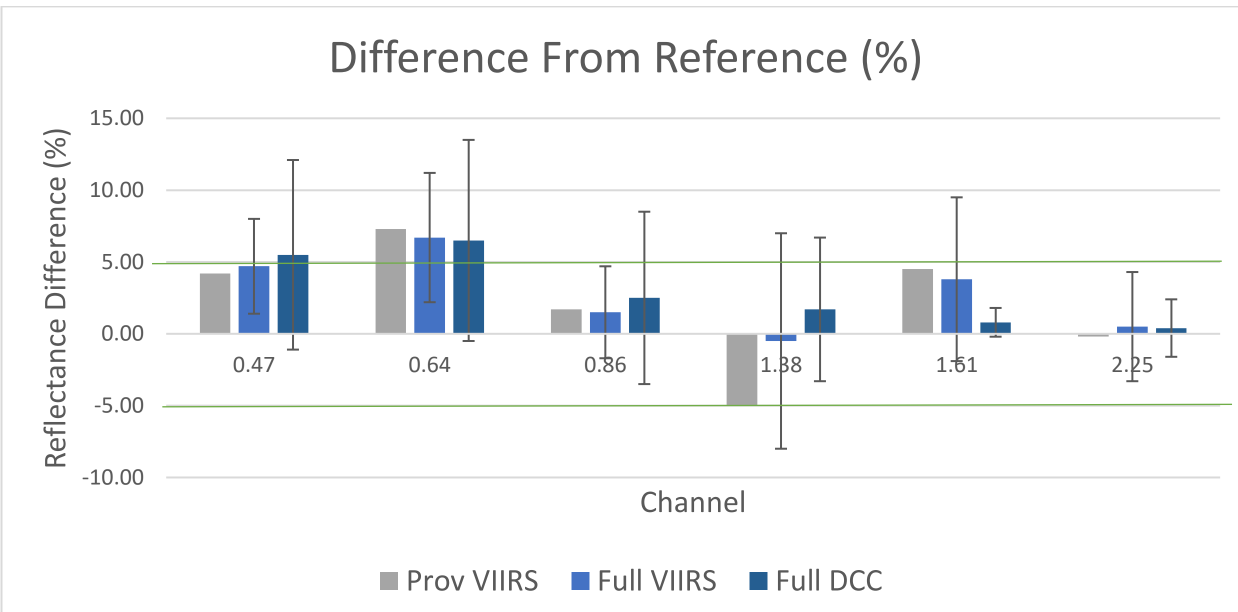

Figure 8: Comparison of ABI VNIR channels with corresponding VIIRS channels and DCC at the Provisional and Full Validation review.

This anomaly exceeds the MRD requirement of 5% accuracy. The root cause of this anomaly is still being investigated, meanwhile effort is being made to bring the radiance closer to the commonly accepted value. A mitigation was submitted in July 2018 and preliminary testing shows that the Band 2 gains can be corrected to remove the bias. However further testing is requires to ensure the Level 2+ algorithms are ready to accept the change. If the final change is approved, the fix will be implemented in a future Ground System update.

3.2. **B14-16 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 following sections will describe three cases of striping due to three different root causes.

Another definition refers to lower-level radiance variations between detectors and is noticeable when viewing largely uniform scenes, like bright cloud tops, or in some derived products, like sea surface temperatures. Significant striping of this type has been seen for some of the VNIR channels. A correction for Bands 1-3 was implemented in early 2018, and the Band 5 correction is in-work. CWG monitors this type of striping and additional correction methodologies are available if striping of this type becomes problematic as the instrument degrades on-orbit.

Finally, another type of striping, often called "banding" occurs if the detector-detector calibration is good over neighboring detectors, but there's a slope in the calibration over the length of the focal plane array. For ABI this would lead to noticeable swath boundaries in the data. This has not been seen in the ABI products for GOES-16, but is included here for clarity.

Returning to the first definition described above, some IR channel image have displayed stripes, especially the 11.2 µm channel (Band 14) and, to lesser extent, the 12.0 µm channel (Band 15) and 13.3 µm channel (Band 16). These stripes may exist all the time, but become weaker for scenes with brightness temperature closer to 300°K. Users may notice this anomaly when viewing the relevant images or use the data quantitatively. This anomaly was characterized from user feedback, through visual inspection of the relevant images, and monitoring of striping index.

This anomaly exceeds the requirements of 0.2°K repeatability. The root cause of three most offending stripes, as well as one each for the 12.0 µm channel (Band 15) and 13.3 µm channel (Band 16) was discovered to be the application of incorrect coefficients for the affected detectors. A correction was submitted in July 2018, was tested, approved, and, implemented on the Ground System. The time and date of the implementation of the correction for distributed products was 20:18 UTC on August 7, 2018.

3.3. **Failed Detector Effects**

Due to the large size of each ABI swath, each channel utilizes hundreds of detector rows. For each detector row, there are three to six (depending on the channel) backup detectors to act as a replacement in case of failure. If the performance of a detector degrades severely the affected pixels in the L1b products will have invalid data that would lead to severe stripes in the affected channel images. These stripes appear suddenly and persistently when the anomaly occurs and disappear suddenly when the failed detector is replaced. Since occasional detector failure is expected, caution has to be made to prevent the data from such detectors from being used in subsequent processing, such as in the image resampling, until the failed detector is replaced. Unfortunately a deficiency was found in the implementation of the rejection mechanism, meaning data from a failed detector sometimes escaped the data quality checks and created stripes. In the DO.07.00.00 ground system build (brought into operations on October 15, 2018), a stopgap mechanism has been implemented to all operators to temporarily remove stripes cosmetically until a new detector is put into operation.

This anomaly can happen in any channel at any time and has twice in the past year for Bands 10 and 12, and were corrected within a few days. Since ABI L1b products are the basis for any downstream ABI products (KPP included), this anomaly will propagate to those products. Therefore, it is important that these detector failures are caught and remedied quickly. ABI operators have been trained to accelerate the detection and replacement of failed detectors.

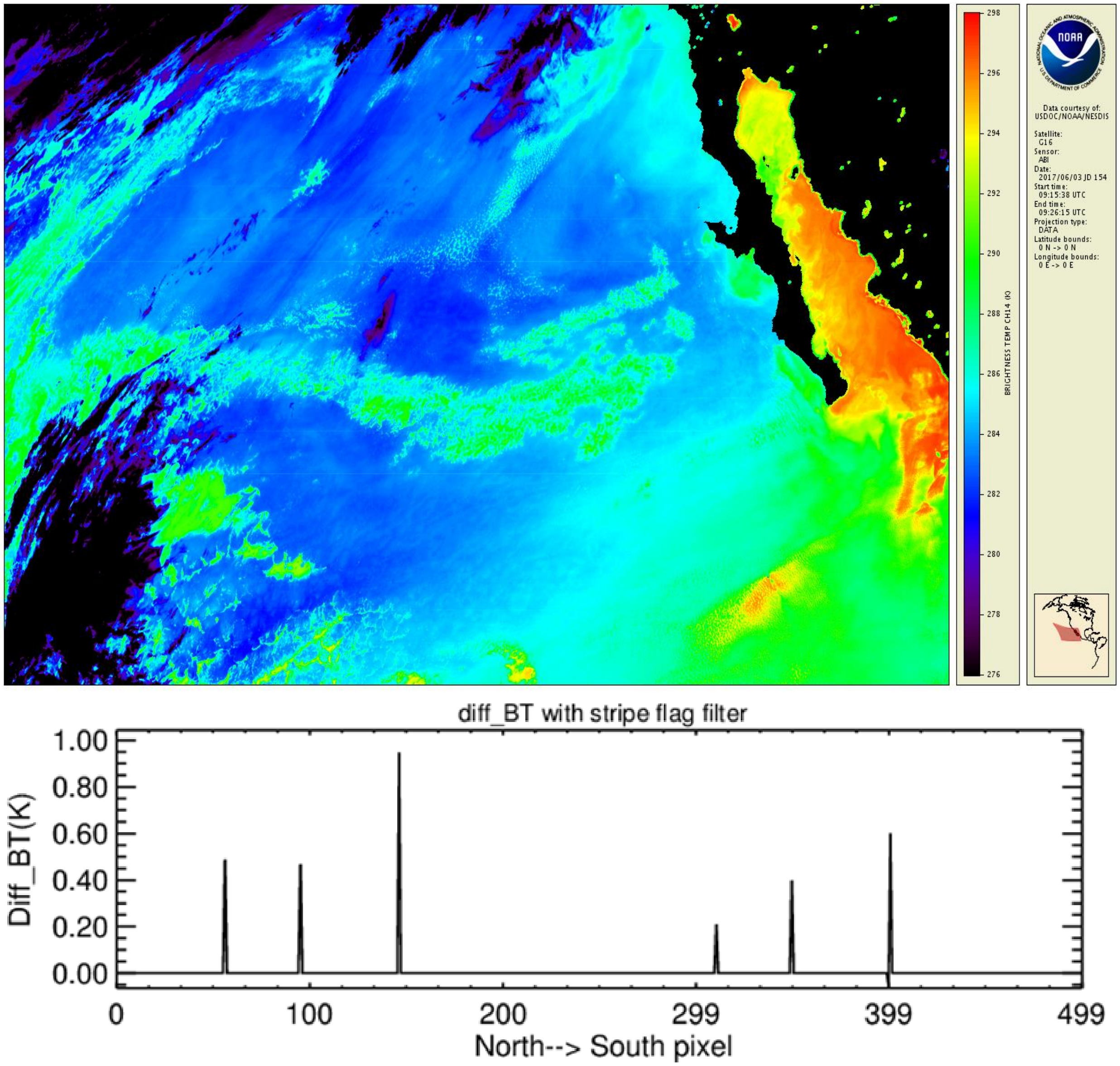

Figure 9: Example of GOES-16 ABI 11.2µm channel (B14) striping from users (Sea Surface Temperature team, top panel) and Calibration Working Group (Striping Index, bottom panel).

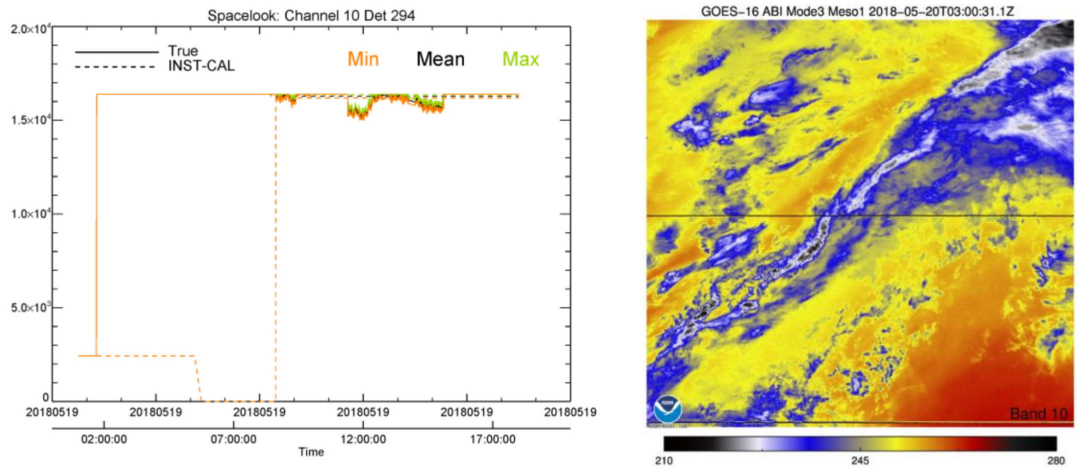

Figure 10: Time series of ABI Band 10 Detector 294 (zero-based) space look counts statistics (minimum, mean, and maximum) on May 19, 2018 (left panel), both the actual values computed by the CWG (solid lines) and the values used in operational calibration (dashed lines). This detector failed shortly before 0200 UTC, and the measurements became saturated. The operational algorithm considered the sudden jump in measurements as due to lunar intrusion so the measurements became "latched" thereafter. Right panel shows the stripes due to this failed detector in ABI Band 10 mesoscale image on May 20, 2018, before the failed detector was replaced.

3.4. **Latched Detector Response**

ABI detectors can experience sudden changes in their characteristics during normal operation, commonly referred to as "level shift". These detectors remain useful; however, the calibration algorithm can mistake elevated space look data by these detectors as the result of lunar intrusion into the field of view. This means the post-level shift space look data are not used, and the previous space look data, which is now invalid, are used instead. This continues, leading to the so-called "latched detector response". Sometimes the latch is released automatically when the space look count is reduced during the diurnal cycle; other times the latch remains until human intervention. A few examples are given in Figure 11.

This anomaly can happen to any detector of any channel. It has happened multiple times in the past year, approximately once a month on average. It leads to a subtle stripe that appears suddenly and often noticeable only with image enhancement such as differencing in time and/or spectral channel. These stripes often vary diurnally, appearing and disappearing over the course of an orbit. Currently, the Bright Object Avoidance (BOA) algorithm is disabled so this anomaly should not occur because no space look values are rejected due to the suspicion a bright object (e.g., the Moon) being in the space look field of view. An improved BOA algorithm is in analysis to be implemented to prevent lunar intrusion without triggering this anomaly.

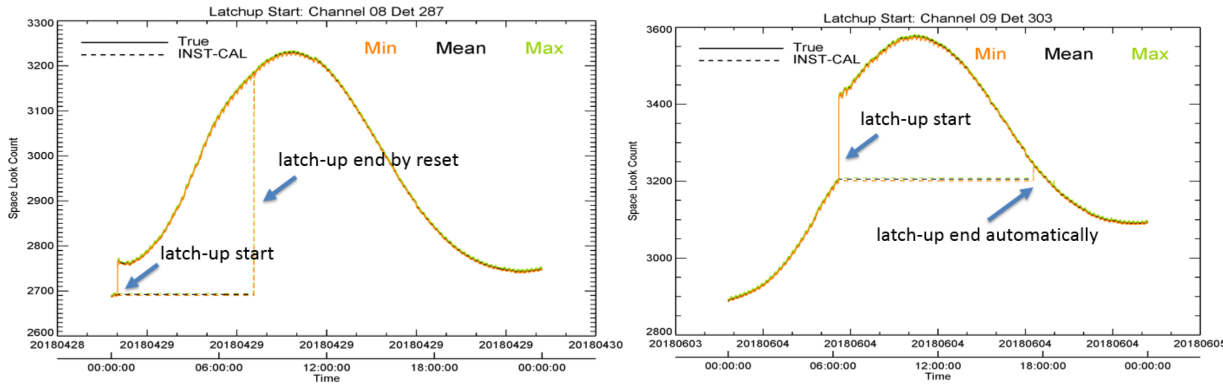

Figure 11: Time series of ABI Band 8 Detector 287 (counting from zero) space look counts on April 29, 2018 (left panel) and Band 9 Detector 303 on June 3, 2018 (right panel). Both detectors experienced a "level shift", as shown by the sudden jumps in all statistics (minimum, mean, and maximum) computed by the CWG (solid lines). The operational processing at the Ground Segment, shown as dashed lines, considered these as lunar intrusions and discarded all the measurements thereafter. The measurement is therefore "latched", which can be corrected either by a manual reset by operator on April 29, 2018 (left) or, on June 3, 2018, when the measurement returned close to the latched value (right). The calibrated radiance for this detector during the affected period had warm bias.

3.5. **IR Channels Bias**

The ABI IR channels have a cold bias of about 0.2°K for all channels and at all times until a correction was implemented on June 19, 2018. This anomaly was characterized by monitoring instrument performance and comparing with data from hyperspectral instruments and the GOES-16 Airborne Field Campaign. This anomaly does not exceed the accuracy requirement of 1°K, however its correction will reduce the bias further. Figures 11 and 12 illustrate this anomaly and its correction.

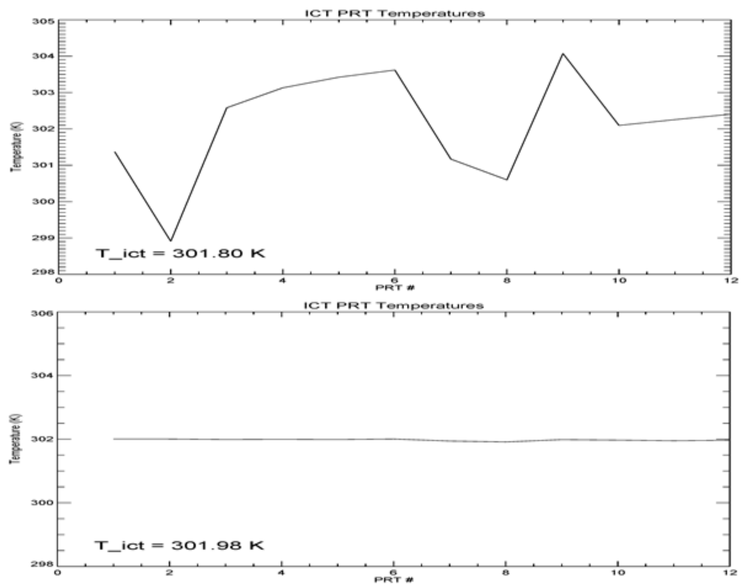

Figure 12: Temperatures measured by the 12 Platinum Resistance Thermistors (PRT) embedded in the Internal Calibration Target (ICT) on ABI. The upper panel is the PRT counts converted to temperature using the incorrect coefficients showing the variation of up to 0.5 K. The lower panel is the PRT temperature values after correction.

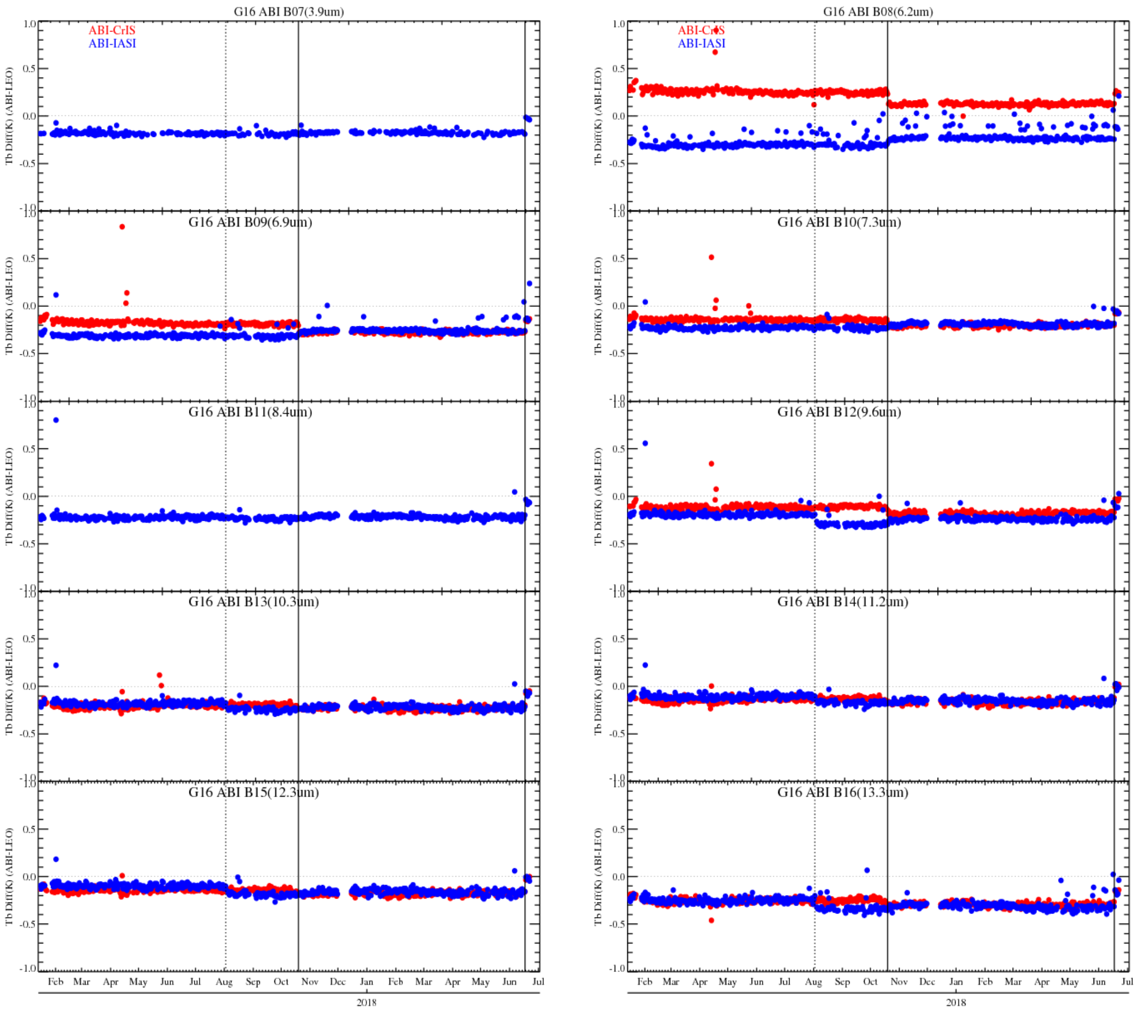

Figure 13. Time series of radiance differences between ten ABI IR channels and hyperspectral radiometers, converted to brightness temperature at 300 K, for ABI - CrIS (red) and ABI - IASI (blue). The effects of PRT temperature correction on ABI calibration accuracy are shown towards the end of the time series as a 0.2 K rise, often bringing the differences closer to zero. There are also interesting but unrelated features in this time series. In early August 2017, an update of IASI nonlinearity led to a change (blue symbols) in many (but not all) channels. Note that the comparison with CrIS did not change, which is expected, and relative differences between IASI and CrIS increased, which is somehow puzzling. In middle October, an update of ABI scan mirror emissivity changed the comparison with both IASI and CrIS, which is expected, and reduced their relative differences in general, which is indirect validation of the emissivity update.

3.6. **Cold Bias Around Fire (CBAF)**

For the 3.9 µm channel (Band 7), some pixels around target 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 believed that cold bias of varying degree often exists for pixels nearby a hot region.

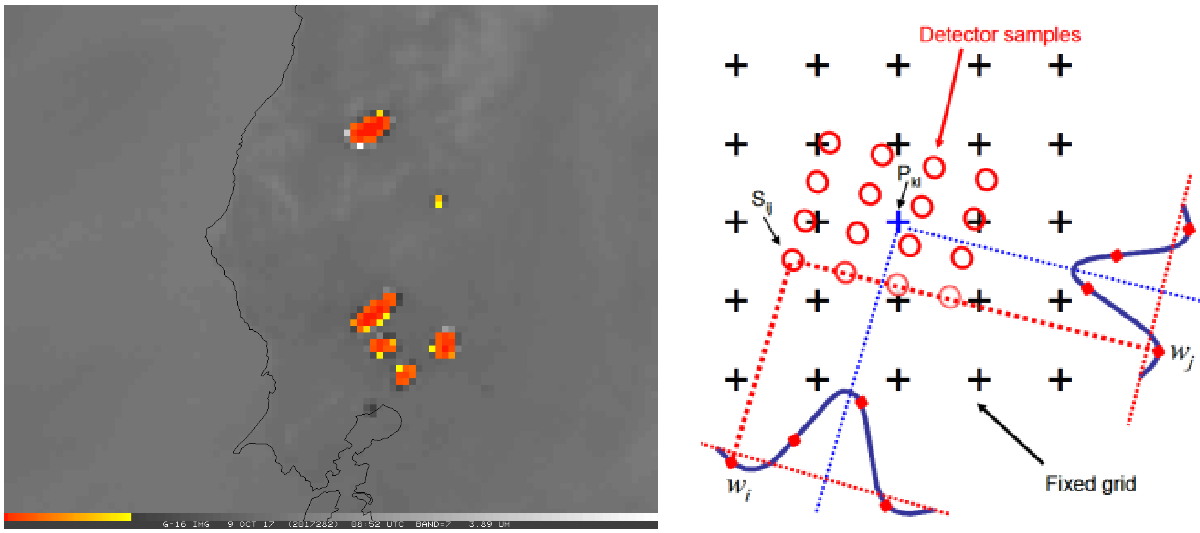

Figure 14: Left panel is an ABI 3.9 µm channel (Band 7) image of the October 2017 Northern California fire (red pixels). Cold pixels are found in yellow and black, and in an extreme case, a white pixel south to the fire in the upper part of this image. One of the two factors contributing to this phenomenon is that radiance of fire pixels can be up to 70 times of those from a nearby pixel of typical temperature (about two times for other window channels). The other factor is that, during resampling (right panel), small negative weight can be assigned to samples (red circles) one sample away from the pixel in question (blue cross). This combination of small negative weight and very large value leads to the negative bias.

This bias was reported by users. This bias is expected and the root cause is well understood. For the severe cases, the pixels have been properly flagged as required. In order to improve users’ experience, correction to this bias is being investigated. Current options of correction may involve compromises of other aspects of instrument performance. CWG will evaluate the merits, impacts, and viability of these options, communicate the results with users, and optimize their overall experience.

3.7. **Refraction Induced Stray Light**

ABI has been designed and operates to avoid direct solar imaging. When the Sun is close to the edge of the Earth, for example, ABI will be commanded not to scan too close to the Sun. When the Sun is behind the Earth, however, ABI should be able to scan the full disk of the Earth.

In rare cases, when the Sun is barely blocked by the Earth, sunlight can reach to ABI by refraction of sunlight through the Earth's atmosphere, even though the Sun at the time is geometrically behind the Earth. An example of this is shown in Figure 6. This occurs rarely, only once in the past year because it is possible only during certain days of the year, certain time of the day, for less than one minutes, when ABI scans the area in question. When it occurs it affects all channels.

This anomaly was reported by users. This anomaly temporarily violates the requirement on IR accuracy. The root cause was discovered and a correction was submitted in July 2018 and implemented before the next eclipse season that began in late August 2018.

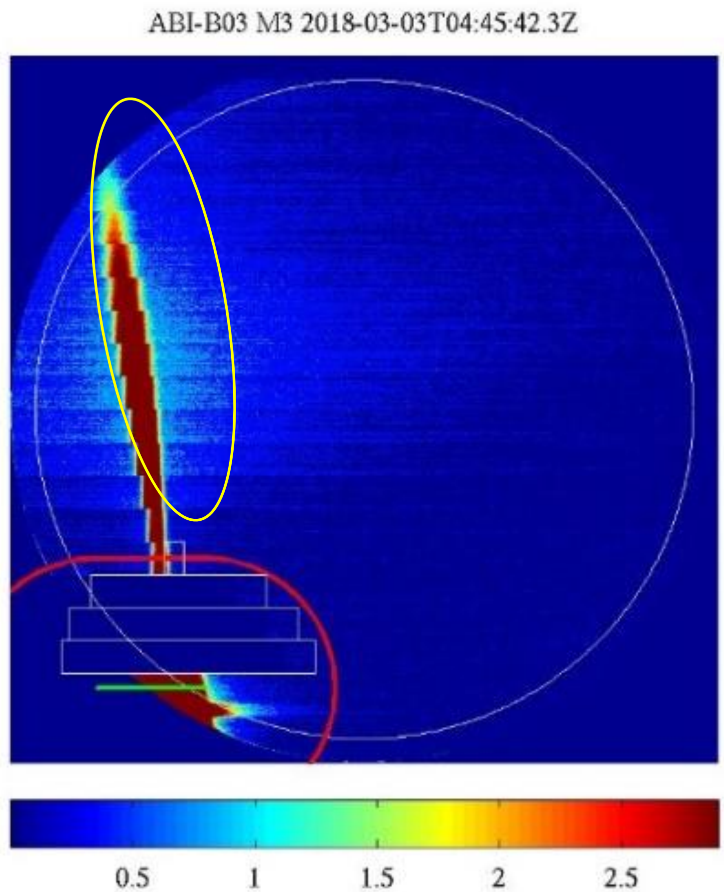

Figure 15: Sunlight in the lower left (in red oval) was induced by atmospheric refraction as discussed in Section 3.7. This Band 3 image also exhibits an example of VNIR stray light at night, shown in the yellow oval (see Section 3.8).

3.8. **VNIR 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 VNIR channels in the form of a vertical beam that is more intense toward the end closer to the Sun for Bands 1-5, and somehow differently for Band 6. Figure 15 shows an example.

This issue was identified from a dedicated test and by users. This issue is well understood and expected. User desire for VNIR stray light rejection at night was not captured in requirement, and no current product depends on the use of the additional information that can appear in Band 6 and the dark ABI VNIR Bands 1-5. Effort will be made, where possible, to characterize stray light in hope to alert users to the impacts.

3.9. **IR Stray Light At Night**

Approximately 45 minutes before and after satellite local midnight 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 IR channels, especially for the 3.9 μm channel (Band 7). Figure 10 gives an example.

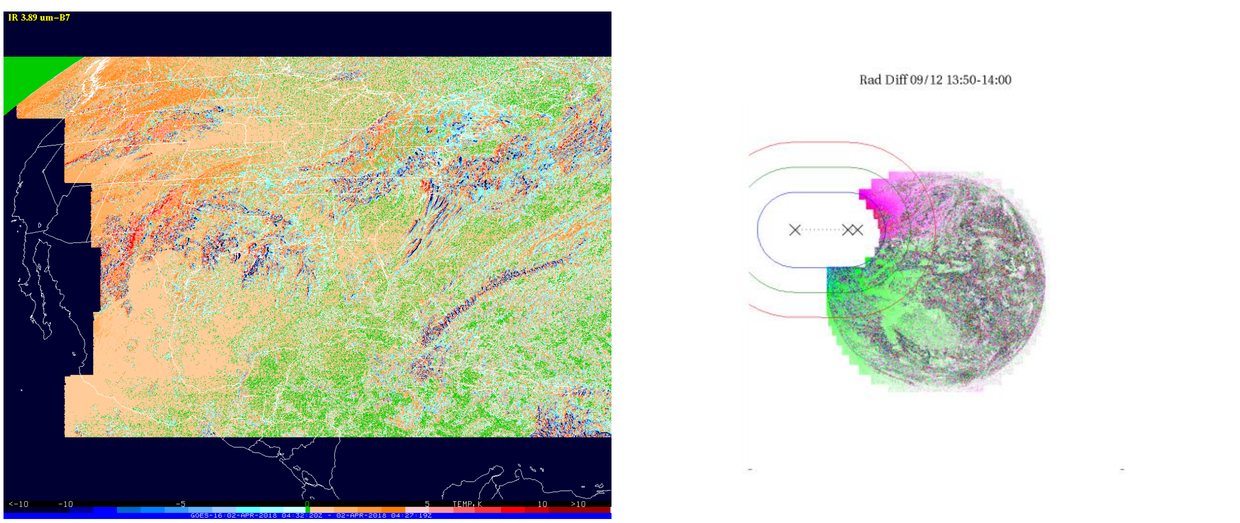

Figure 16: Example of IR stray light at night. The left panel shows the T_B (3.9 μm) change in five minutes, the closer to the Sun, the larger the T_B change. Note also that the colder the scene, the larger the T_B change, even for scene fairly far away from the Sun. The right panel illustrates the size of Restricted Zone (blue) and the Zone of Reduced Data Quality (ZRDQ, red).

This issue was identified by a dedicated test during PLPT and by users. This issue is well understood and expected. Stray light is allowed for ABI within 5° from the Sun ("Restricted Zone") for the 3.9 µm channel (Band 7), and within 3° for other IR channels. In reality, stray light in the Restricted Zone is often excessive for the 3.9 µm channel (Band 7), small for the 6.2 µm channel (Band 8), and negligible for other channels.

Outside of the Restricted Zone, but within 7.5° from the Sun is the Zone of Reduced Data Quality (ZRDQ), where requirements is relaxed by a factor of two than in "Operational Zone". In reality, stray light in ZRDQ is smaller than the required for the 3.9 µm channel (Band 7) and negligible for other channels.

Note that the requirement is defined in radiance, so stray light may appear excessive in terms of brightness temperature T_B, especially for 3.9 µm at low scene radiance (and T_B). For example, let B and B^{-1} be Planck and inverse Planck function, and omit the radiance unit of W/(m^2 sr µm) in the following discussion, then B(300°K) = 0.6025. In the ZRDQ, the requirement is 2°K at 300°K. Since B(302) = 0.6537, the allowed radiance error is 0.6537 - 0.6025 = 0.0512. This means that T_B error must be less than 2°K for scenes with T_B of 300°K or warmer, but since B(250) = 0.0515 and B^{-1}(0.0515+0.0512) = 262.3°K, T_B error of up to 12°K is allowed for scenes with T_B of 250°K or colder. Users should beware of these stray light characteristics and their potential impacts on certain applications.

3.10. **Navigation Error During Eclipse**

Navigation errors during eclipse in EW direction are 43 µrad and 54 µrad, respectively, for the 3.9 µm (Band 7) and 10.4 µm (Band 12) channels. These did not meet the MRD requirements of 42 µrad for these channels by 1 µrad and 12 µrad, respectively, after being improved from 103 µrad and 116 µrad at the time of the Provisional PS-PVR. The errors in NS direction were also non-compliant at that time.

Users have not complained about this performance. The procedure to correct the issues requires some fundamental changes in ABI operations. At the core of the improvement is the need to optimize star observations (the basis of ABI navigation), by taking star looks more frequently at the preferred time. The Mode 3 and Mode 6 operational timelines are being modified, taking advantage of faster slew of scan mirror, to squeeze in more and more evenly-distributed star observations within the 15- or 10-minutes timeline execution period. Ground processing is also being modified to accommodate shorter time for star looks. Tests have been planned for GOES-17 (now in post-launch testing), then expanded, if successful, to GOES-16. It is expected that performance will become compliant after the modified timelines are implemented.

3.11. **WIFR**

WIFR (WithIn Frame pixel-to-pixel Registration errors, see also Section 2.4) is not to be confused with the frame-to-frame registration (FFR), which is critical to wind product, and the channel-to-channel registration (CCR), which is critical to many multiple channel products. The impact of the WIFR anomaly, if exaggerated, can lead to distorted (sheared or warped) images.

Within frame pixel-to-pixel registration errors (adjacent lines/swaths) for the 2.25 µm channel (Band 6, 12.5 µrad / 10.1 µrad for EW / NS), 3.9 µm channel (Band 7, 12.9 µrad / 9.7 µrad), and 10.4 µm channel (Band 12, 18.1 µrad / 9.1 µrad) exceed the requirement of 7.8 µrad / 7.8 µrad, after being improved from 50 µrad / 17.2 µrad, 69 µrad / 36 µrad, and 11.2 µrad / 35.7 µrad for these channels at the time of Provisional PS-PVR.

Users have not complained about this performance. This non-compliance results reflect one of fundamental challenges of ABI geometric calibration based on the ABI L1b navigation algorithm, namely to assemble a consistent image from multiple swaths collected over time. The modified Mode 3 and Mode 6 timelines described above, and the tuning of the navigation parameters, are expected to bring this performance into compliance.

3.12. **Imaging Quality**

Evaluation of modulation transfer function (MTF) has been attempted for 16 channels at four values of Nyquist frequency in four cases, totaling 256 attempts. Due to the lack of quality data, 56 of the 256 evaluations were not available. Of the remaining 200 evaluations, six were worse than the requirement marginally by 0.02, 0.03, 0.01, 0.01, 0.02, and 0.03. Five of the six are at the Nyquist frequency.

Since the lunar data used for post-launch evaluation are far less optimal than the pre-launch data collected in well controlled lab, the apparent non-compliances are marginal, and most are at the least important Nyquist frequency, this is not a serious non-compliance.

4. <u>Existing Issues for ABI CMI</u>

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.

4.3. **Start Time Drift**

When ABI is in routine operations, a new timeline starts as soon as the last timeline ends. At this time the default timeline is Mode 3 ("Flex Mode") which is approximately 15 minutes long. If the actual time elapsed by a timeline is slightly more or less than the expected time, even by a few milliseconds, the drift in the start time can build up. After long periods of continuous Mode 3 scanning, it has been shown the Mode 3 start time drifts about 3.9 milliseconds per timeline, or roughly 0.38 seconds/day.

This was corrected on September 20, 2018 by changing the length of the Mode 3 by 4 milliseconds. Over 90 days, the longest likely period of time before a calibration or other command re-synchronizes timeline starts to the wall clock, the remaining drift will be less than a second. However, there is not enough data on any possible drift caused by Mode 4 or Mode 6 timelines, so users need to be aware that start time drift may occur after extended use of those timelines until a similar correction for those timelines can be performed.

4.4. 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.

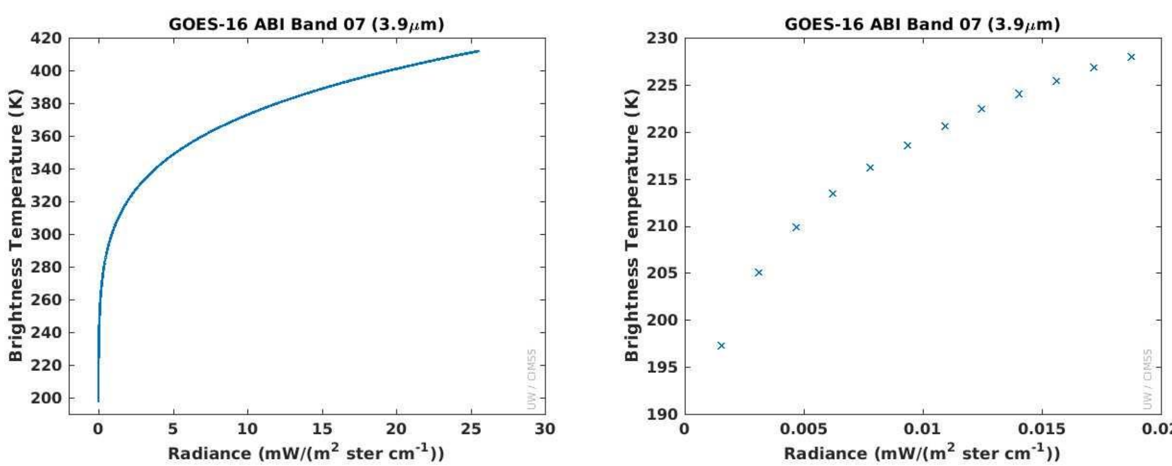

Figure 17: Planck relationship between brightness temperature and radiance for Band 7 (3.90 µm), displayed over the full dynamic range of the ABI band (left) and zoomed in to show the large discrete steps in brightness temperature at the cold (low radiance) end of the ABI L1b radiance range. A small 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-16 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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ABI CMI AWG Team Lead: Tim Schmit (tim.j.schmit@noaa.gov)

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

[9] 821404 test description document EM channel CAL, CDRL No. 0067-19 (2010).

[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