GOES-16/ABI Thermal Emissive Band Assessments Using GEO-LEO-GEO Double Difference

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Abstract Geostationary satellite (GOES)-16/Advanced Baseline Imager (ABI) and Himawari-8/Advanced Himawari Imager (AHI) represent a significant improvement over the imagers on board previous GOES. Their bands 7–16 are infrared channels covering the 3.9- to 13.3-μm spectral range and with a 2-km spatial resolution. Their spectral coverage of the thermal emissive bands (TEBs) is almost identical, and both instruments employ similar calibration strategies using an onboard blackbody and a space look. The intercomparison between the two instruments will be very helpful for their calibration assessments and their product quality enhancements. GOES-16 was launched on 19 November 2016, initially to a test position at 89.5° east and reached its operational position (longitude of 75.2° west) on 11 December 2017. The Himawari-8 spacecraft was launched on 7 October 2014 and the observation focuses on the Asia-Pacific region. In this work, an intercomparison of their TEB measurement is performed using double difference with Aqua Moderate Resolution Imaging Spectroradiometer (MODIS). The same type of scenes are selected for the two instruments, and their measurements with the closest observation times are compared with Aqua MODIS matching bands. The view angle effect is corrected and their spectral mismatching effect is estimated. The dependence on the scene uniformity is analyzed. The ABI-AHI differences are within 0.3K for bands 10 (7.35 μm), 11 (8.44 μm), 12 (9.64 μm), and 14 (11.24 μm), and up to 0.8K difference for bands 15 (12.38 μm) and 16 (13.28 μm). The ABI precision is better than AHI for all TEB and their image navigation and registration precisions are comparable. In general, the ABI performances before and after relocation are consistent.

1. Introduction

Advanced Baseline Imager (ABI) on board geostationary satellite (GOES)-16(GOES-R) launched on 19 November 2016 and the Advanced Himawari Imager (AHI) on board Himawari-8 launched on 7 October 2014 were designed and built by Harris Corporation (formerly ITT Exelis Geospatial Systems) and represent a significant improvement over the imager onboard previous GOES (Schmit et al., 2017; Schmit et al., 2018; Kalluri et al., 2018; Goodman et al., 2018; Bessho et al., 2016, and Griffith, 2015). ABI and AHI are the primary instruments on the satellites for imaging Earth’s weather and environment. They track and monitor cloud formation, atmospheric motion, convection, land surface temperature, ocean dynamics, and other applications for environment. The two instruments use the same on-board calibrators and similar on-orbit calibration algorithms. The instrument calibration and uncertainty assessments are very useful for their calibration improvements and their product consistency enhancements. Their thermal emissive bands (TEB) have near-identical relative spectral response, spatial resolution, and dynamic range, which provide advantages for comparison.

The methods for sensor intercomparisons have been overviewed in the literatures (Chander et al., 2013; Xiong et al., 2010). The intersatellite sensor comparisons for thermal bands have been performed using simultaneous nadir overpasses (SNO) and calibration sites such Dome Concordia (Dome C) site in Antarctica, Lake Tahoe, ocean buoys, and various land sites (Cao et al., 2004; Xiong et al., 2008; Gunshor et al., 2009; Shrestha et al., 2018; Madhavan et al., 2015; Hook et al., 2007; Tobin et al., 2006; Moeller et al., 2014, and Veglio et al., 2016). The SNO method has also been applied to ABI TEB assessment using Infrared Atmospheric Sounding Interferometer (IASI) on MetOp-B and the Cross-track Infrared Sounder (CrIS) on S-NPP (Yu et al., 2017). The GOES sensors image the full disk of Earth and provide near-continuous observations, which is advantageous for intercomparison with other satellite sensors. GOES-16 and Himawari-8 satellites are positioned on nearly opposite sides of Earth, meaning that a direct
comparison using calibration sites is not applicable. A double difference method using a low earth orbit (LEO) satellite sensor can be applied to achieve their comparison. In this work, measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board the Aqua satellite are used as a near-simultaneous reference over selected scenes (Xiong et al., 2015; Xiong et al., 2017). The double difference has been demonstrated in the application to Terra-Aqua MODIS TEB comparison using Himawari-8/AHI as a bridge (Chang et al., 2019). This method provides enormous number of samples that further enhance the comparison precision. This method can also be extended for a consistency assessment of GOES-16/ABI before and after its re-location on 30 November 2017. In addition, this paper also analyzes the uniformity impact on comparison and uses the uniformity dependency to compare ABI and AHI image navigation and registration (INR) uncertainties and to assess ABI performance consistency before and after spacecraft re-location.

This paper focuses on ABI-AHI comparison for their TEB. Section 2 presents the background of ABI and AHI instruments on the GEO satellites and their spectral band matching with MODIS. Section 3 presents the data processing and double difference procedure in this work. Section 4.1 presents the ABI-AHI comparison with corrections applied, such as view angle effect correction, uniformity consideration, and ABI-AHI spectral mismatch effect correction. Section 4.2 presents ABI consistency assessment before and after the spacecraft re-location.

2. Background

2.1. GOES-16/ABI and Himawari-8/AHI

GOES-16 is the first satellite of the GOES-R series and was launched on 19 November 2016 (Schmit et al., 2017; Kalluri et al., 2018, and Goodman et al., 2018). The spacecraft was initially positioned in a nonoperational test position at 89.5° west. It was moved to its operational position beginning on 30 November 2017 and reached the GOES East position (longitude of 75.2° west) by 11 December 2017. GOES-16 was declared fully operational on 18 December 2017. GOES-16 ABI provides high spatial and temporal resolution imagery of the Earth through 16 spectral bands at visible, near-infrared (IR), and IR wavelengths. The Himawari-8 spacecraft was launched on 7 October 2014 to the longitude of 140.7° east, covering the East Asia and Western Pacific regions (Bessho et al., 2016; Griffith, 2015). The primary instrument aboard Himawari-8, AHI, is a similar 16-channel multispectral imager that captures visible, near-IR, and IR images of the Asia-Pacific region.

Among their 16 spectral bands, ABI has two visible channels and four near-IR channels covering 0.47- to 2.2-μm range with subpoint spatial resolution 0.5–2 km, while AHI has three visible, three near-IR. For both instruments, bands 7 to 16 are IR channels covering 3.9- to 13.3-μm range. For these thermal IR channels, their spatial resolutions are 2 km in their full-disk image products. Both AHI and ABI produce full-disk images of the Earth every 10 min (ABI produces full-disk image every 15 min before 2 April 2019). The spectral coverages of their thermal IR bands are almost identical, and similar calibration algorithms are applied using data from an on-board BB and space-look. The TEB shows a significant nonlinear response, and a quadratic response function is used for the calibration. The linear coefficient of the response function for each channel is derived using an onboard BB, while the nonlinear coefficients were derived during pre-launch testing. ABI calibration accuracy specification for TEB is ±1 K for 300 K scene (GOES-R Series Data Book, 2019). The field campaign and intercomparison with reference sensors are helpful for the assessments of the calibration accuracy.

GOES-16 field campaign conducted sixteen validation missions during March to May 2017. Three of the campaigns served as the primary ABI validation conducted over ideal Earth targets with an integrated set of well characterized hyperspectral reference sensors aboard a high-altitude National Aeronautics and Space Administration (NASA) ER-2 aircraft. The ABI TEB performance was found to have biases within 1 K for all bands (Bartlett et al., 2018). However, these data are preliminary and nonoperational. Radiometric quality assessment of GOES-16 ABI L1b images shows that the general criterion for product maturity have been largely met. The GOES-R ABI TEB performance assessment using SNO method with respect to IASI on MetOp-B and CrIS on S-NPP shows less than 0.3 K bias in full-disk image mean brightness temperature (Yu et al., 2017).
2.2. ABI-MODIS and AHI-MODIS Spectral Matching Bands

The reference sensor used in this work is Aqua MODIS, which was launched in 2002 and demonstrated reliable performance, providing 17 years of continuous global observations (Xiong et al., 2017). ABI/AHI bands 10–12 and 14–16 have close spectral matching to MODIS bands 28–33. For most of the matching bands, ABI/AHI TEBs have broader spectral response functions than MODIS. Although spectral matching is imperfect, the effects of the differences are insignificant to the first order for the ABI-AHI comparison using the double difference method. The MODIS and ABI/AHI matching bands are listed in Table 1, and their relative spectral response (RSR) functions are shown in Figure 1 in section 3.1. As shown in the figure, there are slight differences between the matching pairs of ABI and AHI TEB. The impacts of these slight differences on their comparison, also listed in Table 1, are discussed in section 3.1.

3. Data Processing and Comparison Procedure

The comparison is performed for the measurements of GOES-16/ABI and Himawari-8/AHI full-disk images during nighttime with Aqua MODIS Collection 6.1 (C6.1) L1B data as a bridge. The MODIS, ABI, and AHI L1B data are downloaded from NASA LAADS/DAAC, NOAA CLASS, and JAXA data distribution systems. Since ABI and AHI acquire a full-disk image every 15 and 10 minutes respectively, we are guaranteed an observation time difference with MODIS of less than 7.5 min. With sufficient long period of duration, the time differences are approximate evenly distributed and its impact on ABI-MODIS and AHI-MODIS comparisons can be averaged out. Besides the MODIS granule and ABI (AHI) full-disk image selection, the site selection, MODIS data resampling, and cloud filtering are also applied and will be described in the following sections. This work uses the statistical analysis for implementation of empirical modeling of view angle effect, Gaussian fitting of ABI-MODIS and AHI-MODIS difference, and uniformity dependency assessments. Sufficient number of sample is required and some random effects can be reduced from the statistical analysis.

3.1. Spectral Mismatching Effect Correction

Since the same type of scenes are used for ABI-MODIS and AHI-MODIS comparisons, the spectral differences between ABI and MODIS and between AHI-MODIS can be generally canceled by using the double difference method.
difference. ABI and AHI TEB were designed to have the same spectral bands. However, slight differences between their RSR exist and impact their BT measurement comparison. The BT difference due to their RSR mismatch is estimated using the modeled radiance spectrum for each band for typical ocean scene using MODTRAN (Berk et al., 2008). Figure 1 shows the BT spectrum from MODTRAN modeling for a typical ocean site plotted on top of their matching band pairs. The impacts estimated from the modeling on the comparison are listed in Table 1. The ABI and AHI sites are expected to have slight difference and are not as same as the typical ocean scene used in the modeling. This spectral mismatching correction is applied to the ABI-AHI comparison. For band 16, the spectral difference is small. However, the BT spectrum in that spectral range is sensitive to the spectral difference due to the large change in the BT across that band. The ABI (AHI) and MODIS band mismatching effect has insigneificant impact on the double difference. The impact on ABI-MODIS difference is also estimated and listed in Table 1 for reference.

### 3.2. Site Selection

In order to make a comparison between GOES-16/ABI and Himawari-8/AHI using MODIS as a reference, the same type of scene should be used to reduce the scene dependent and BT dependent biases. The areas around 89.5° west and 140.7° east along the equator are both primarily ocean, which are used for comparison. The selected ABI nadir site is slightly shifted to avoid a set of islands. These sites are near nadir and therefore the measurements will not be affected by the view angle of each instrument.

After GOES-16 was re-located to 75.2° west, the site under its nadir is land. Two ocean sites are selected for assessment of ABI calibration consistence before and after relocation. One is the nadir site before re-location (around longitude 89.5° west) and the second site is an ocean site (around longitude 82.35° west), the middle region before and after re-location. Using the first site, the view angle effect on ABI product, radiometric uncertainty, and INR uncertainty can be assessed. The ABI measurements over the second site have identical view angle before and after re-location. It can be used for assessment of calibration consistence and mirror response versus scan angle (RVS) in addition to the precision assessments. The three sites, one for AHI and two for ABI, are listed in Table 2. The over-pass time for Aqua MODIS is during the night time. Aqua crosses the equator at about 1:30am local time. The three selected sites are at equator and the local time of all the comparisons are very close. The date range of L1B data is also listed for each site and comparison. The date range is limited due to the GOES-16 re-location.

### 3.3. Resampling

The L1B data from Aqua MODIS C6.1 and ABI/AHI are processed for ABI-MODIS and AHI-MODIS comparisons. This work employs pixel-to-pixel comparisons between MODIS and ABI and between MODIS and AHI. However, the ABI and AHI TEB pixel size is 2 km at the sub-point and the MODIS TEB pixel size at nadir is 1 km. The MODIS data are resampled and interpolated to the ABI (AHI) grid over the selected areas. The pixel-to-pixel comparison after resampling enhances the comparison accuracy and also allows the comparison to be performed over a broad range of BTs. Since ABI and AHI use the same kind of grid, the assessments are comparable for ABI and AHI and the uniformity impact on the comparisons can also be assessed.
The resampling can contribute extra uncertainty in pixel-matching. This effect is random and can propagate to the uncertainty in the comparison for nonuniform scenes, as presented in section 4.1.2.

3.4. Cloud Filtering

The observation time difference also has effects if there are clouds present or the atmospheric conditions change between the MODIS and ABI (AHI) measurements. MODIS C6.1 level 2 products (MOD35 for Terra and MYD35 for Aqua) are used for identifying clear sky measurements for both ABI-MODIS comparison and AHI-MODIS comparison (Platnick et al., 2003). The cloud mask has four values indicating cloudy, partially cloudy, partially clear, and clear. The pixels selected for comparison are totally clear sky. The clear sky filtering can reduce the observation time difference effect. In addition, the time difference is randomly distributed on both positive and negative sides. The time difference may have effect on the scene BT. However, its effects on the comparison due to clouds movements can be averaged out and the impact on the comparison will be greatly reduced.

The cloud products from ABI and AHI are not used in this study to avoid in-equallity effect in the double difference. For example, the ABI cloud mask was considered Beta-maturity for most of the time of this study and would have a constant offset in INR from the TEB data. The use of MODIS level 2 cloud mask may have effect on the comparison due to MODIS cloud uncertainty and pixel mismatching. However, these effects are the same for both ABI-MODIS and AHI-MODIS comparisons.

3.5. Comparison Procedure

Our previous work on Terra-Aqua MODIS TEB comparison using Himawari-8/AHI as reference has demonstrated the LEO-GEO-LEO double difference method (Chang et al., 2019). This work extends and improves this method for the application to the comparison between GOES-16/ABI and Himawari-8/AHI. Figure 2 shows a flow chart for the ABI-AHI comparison using Aqua MODIS as a bridge. For the two selected ocean sites under ABI and AHI nadirs, the overpass time for Aqua and L1B granule data are

![Figure 2. Flow chart for the Advanced Baseline Imager-Advanced Himawari Imager (ABI-AHI) comparison using Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) as a bridge. The rectangular shape indicates data or results, and the diamond indicates the processing.](image-url)
processed. From the passing time during night, the ABI (AHI) full-disk images at closest observation time are also processed. For each pair of matching bands, the ABI (AHI) BT measurements and MODIS BT measurements as well as the MODIS cloud mask are processed for the selected area. Based on the ABI (AHI) grid, the MODIS BT and cloud mask are resampled. After clear sky and uniformity filtering, the pixel-to-pixel ABI-MODIS and AHI-MODIS differences are calculated. The view angle dependence is corrected using the empirical model presented in Section 4.1.1. The comparison dependence on the uniformity is then analyzed to determine the threshold for uniformity filter. The uniformity dependence analysis is also used for INR precision comparison between ABI and AHI and between ABI before and after re-location. Using the double difference, the ABI-AHI differences are derived. Using statistical analysis, their measurement precision is also compared. Finally, the correction for ABI-AHI spectral mismatching over typical ocean scene using MODTRAN modeling is applied.

4. Comparison and Assessment

4.1. ABI-AHI Comparison

4.1.1. View Angle Effect Correction

While the sites selected for comparison for ABI/AHI are near nadir for those instruments, MODIS can view these sites over a wide range of view angles. This introduces a view angle dependence to the comparison between MODIS and ABI/AHI for these sites. For ABI non-nadir site, the view angle dependence of ABI measurements is negligible since it has the same view angle before and after GOES-16 re-location. The bias is then removed in the double difference for the Aqua-MODIS comparison. The view angle effect is empirically modeled and corrected to achieve an improved ABI-MODIS and AHI-MODIS differences. A few different functions with view angle symmetry have been tested for the regression with the measurements and one function is selected as an empirical model.

\[ T(\theta_{\text{view}}) = c_0 + c_1 [1 - \cos(\theta_{\text{view}})] + c_2 [1 - \cos(\theta_{\text{view}})]^2 \]  

where \( T \) is the ABI-MODIS or AHI-MODIS BT differences, \( \theta_{\text{view}} \) is the view angle of MODIS measurement, and the coefficients \( c_{0,1,2} \) are fitting parameters. Figure 3 (left column) shows the ABI-MODIS and AHI-MODIS difference as a function MODIS view angle, respectively. The red symbols are the AHI-MODIS difference and the blue symbols are ABI-MODIS difference. The view angle in the plot is the absolute angle from the two sides around the nadir.

The view angle correction is applied to the measurement data for each of the paired bands. The lines in the figures are the regression using the empirical model. It can be attributed to the slight differences in the ocean scenes which cause slight absorption difference in MODIS measurements. The view angle effect is relative to the MODIS measurement with zero view angle, the spectral differences between ABI, AHI, and MODIS have no contribution on the view angle effect. The coefficients can be obtained from regression of the model using all the comparison data. Then the correction for the comparison for each pixel can be derived using

\[ T_c(\theta_{\text{view}}(i)) = T(\theta_{\text{view}}(i)) - c_1 [1 - \cos(\theta_{\text{view}}(i))] - c_2 [1 - \cos(\theta_{\text{view}}(i))]^2, \ i = 0, 1, ..., N, \]

where \( i \) is the index of pixel with total \( N \) pixels. The same model and correction are applied to both ABI-MODIS and AHI-MODIS difference and the corrected differences are used for ABI-AHI comparison. For each site, the MODIS measurements at different view angles are used for the comparison with ABI and AHI respectively. Figure 3 middle column shows the corrected BT differences as function of the MODIS view angle. It exhibits that, in general, the comparison uncertainty increases with view angle. The MODIS spatial resolution is 1 km for the pixels around nadir and the pixels with large view angle have large pixel size. It increases the uncertainty of geo-location of resampled pixel and then the uncertainty propagates to the uncertainty of the brightness difference. However, this effect is random and can be averaged out using sufficiently large number of samples in the comparison.

4.1.2. Measurement Precision Comparison

Figure 3 right column shows distributions of ABI-MODIS and AHI-MODIS comparisons for the selected bands over the nadir ocean sites. The distribution is normalized to the peak sample number. For both comparisons, the distributions of the difference are close to a Gaussian shape, \( \exp \left[ -\frac{(x-x_0)^2}{2\sigma^2} \right] \), where \( x \) is the scene
Figure 3. (left) The Advanced Baseline Imager-Moderate Resolution Imaging Spectroradiometer (ABI-MODIS) and Advanced Himawari Imager (AHI)-MODIS differences as a function MODIS view angle over the ocean sites under AHI or ABI nadir, respectively. The lines in the figures are the regression using the empirical model. The view angle in the plot is the absolute angle from the two sides around the nadir. (middle) The corrected MODIS-AHI difference as a function MODIS view angle. (right) ABI-MODIS and AHI-MODIS BT difference distribution. The red symbols are the AHI-MODIS difference and blue symbols are ABI-MODIS difference.
BT, \(x_0\) is the BT difference corresponding to the Gaussian peak, \(\sigma\) is the Gaussian width representing the comparison uncertainty. This Gaussian profile is used to estimate the comparison precision. The width of the distribution of ABI-MODIS or AHI-MODIS difference, including uncertainties in the MODIS measurements, ABI and AHI measurements, and the effects of comparison method presented in section 4.1.2, can be expressed as

\[
\sigma_{\text{ABI-AHI}}^2 = \sigma_{\text{ABI}}^2 + \sigma_{\text{MODIS}}^2 + \sigma_{\text{comparison}}^2
\]  

The MODIS measurement uncertainty and comparison method uncertainty are almost the same for ABI-MODIS and AHI-MODIS comparisons. Therefore, the width can be used to compare ABI and AHI measurement precision. The Gaussian widths for ABI-MODIS and AHI-MODIS comparison are listed in Table 3. The analysis shows that ABI precision is better than AHI for all TEB.

### 4.1.3. Uniformity Effect Consideration

For ideal case without ABI (AHI) INR error, MODIS geo-location error, and pixel mismatching, the comparison results should have no dependency on the scene uniformity. However, these errors exist and propagate to the comparison bias. The scene uniformity is assessed using the brightness temperature of surrounding pixels. A pixel selected for comparison should have the same cloud mask status (clear sky) over the 3x3 resampled ABI (AHI) pixels. The uniformity is estimated using the standard deviation of the brightness temperature of the 9 pixels. Since ABI and AHI use the same grid and same spatial resolution, the uniformity is an appropriate factor and the assessments of their INR precisions are comparable. Since the uniformity is estimated for surrounding area of 3x3 pixels, the analysis is valid only if the INR uncertainty is within 1 ABI (AHI) pixel. If the INR uncertainty is much larger than 1 pixel, such as ABI data from the early-mission check-out period, there is no dependency of comparison on the uniformity and the INR uncertainty contributes random noise in the comparison.

The ABI-MODIS and AHI-MODIS comparison dependencies on the uniformity are analyzed using the plot of their BT difference as the function uniformity. The uniformity effect analysis can be used for two purposes. One is for the determination of threshold for filtering uniform pixels with certain tolerance on the impact on comparison. The second is for the assessment of INR uncertainty. Even if it is very challenging to derive the INR uncertainty quantity, it still can be compared between ABI and AHI or between ABI before and after re-location. The scene uniformity impacts the ABI-MODIS and AHI-MODIS comparisons in three ways. In addition, MODIS and ABI (AHI) have different pixel sizes and orientations. AHI and ABI grid is lined up with east-west and north-south direction while the MODIS orbit is tilted to an inclination angle of approximately 98°, meaning that the scan is not exactly along east-west direction. The pixel size of AHI and ABI is 2km for TEB while MODIS has a 1km pixel size for TEB, with the pixel size for both increasing with view angle away from nadir. These effects will propagate to resampling uncertainty \(\sigma_{\text{rs}}\). The three uncertainties are independent and the combined uncertainty due to pixel mismatch can be expressed as

### Table 3

| ABI (AHI) band | 10 | 11 | 12 | 14 | 15 | 16 |
|---------------|----|----|----|----|----|----|
| MODIS band    |    |    |    |    |    |    |
| ABI           |    |    |    |    |    |    |
| Average BT (K)| 260.54 | 289.34 | 272.16 | 291.70 | 288.80 | 275.71 |
| ABI-MODIS (K) | -0.10 | -1.00 | -3.16 | -0.39 | -1.84 | 5.46 |
| Gaussian width (K) | 0.20 | 0.18 | 0.18 | 0.08 | 0.11 | 0.23 |
| AHI           |    |    |    |    |    |    |
| Average BT (K)| 258.00 | 293.12 | 275.68 | 294.24 | 289.63 | 275.75 |
| AHI-MODIS (K) | 0.26 | -0.35 | -3.24 | -0.58 | -3.04 | 5.66 |
| Gaussian width (K) | 0.22 | 0.21 | 0.22 | 0.20 | 0.26 | 0.28 |
| ABI-AHI (K)   | -0.36 | -0.65 | 0.07 | 0.19 | 1.20 | -0.20 |
| ABI-AHI after spectral correction (K) | -0.17 | -0.04 | 0.32 | 0.20 | 0.77 | -0.68 |

Note: The correction for ABI-AHI spectral mismatching is applied for reference. The Gaussian width for ABI-MODIS and AHI-MODIS comparison are also listed for their precision comparison.

Abbreviations: ABI: Advanced Baseline Imager; AHI: Advanced Himawari Imager; MODIS: Moderate Resolution Imaging Spectroradiometer.
\[ \sigma_{\text{geo}} = \sqrt{\sigma_{rs}^2 + \sigma_{\text{MODIS geo}}^2 + \sigma_{\text{ABI/AHI INR}}^2} \]  

(4)

where \( \sigma_{\text{ABI INR}} \) and \( \sigma_{\text{AHI INR}} \) are ABI and AHI INR uncertainties and \( \sigma_{\text{MODIS geo}} \) is Aqua MODIS geo-location uncertainty in their L1B products. The impacts from resampling uncertainty (\( \sigma_{rs} \)) and MODIS geo uncertainty \( \sigma_{\text{MODIS geo}} \) cannot be estimated from this analysis. However, they are the same on the comparisons between ABI-MODIS and between AHI-MODIS. Then we can have

\[ \sigma_{\text{ABI/AHI INR}} = \frac{1}{\sigma_{\text{geo}}} \left( \sigma_{rs}^2 + \sigma_{\text{MODIS geo}}^2 \right) \]  

(5)

From the comparison dependency on the uniformity, the ABI and AHI INR uncertainty can be qualitatively compared.

Figure 4 shows the impact on the differences between ABI and MODIS and between AHI and MODIS as function of the scene uniformity. The dependence is related to pixel-matching uncertainty calculated using Eq. (5). The impacts are compared for ABI-MODIS and AHI-MODIS, as shown in the figure. The impact is calculated as the difference between nonuniform scene (nonzero standard deviation of 9 neighboring pixels) and uniform scene (the lowest standard deviation of 9 neighboring pixels). The error bars are for each bin and plotted in the figure. It is obvious that the comparisons have dependence on the scene uniformity. For ABI/AHI bands 11, 12, 14, and 15, the dependences are consistent for both ABI-MODIS and AHI-MODIS comparisons, which mean that the INR uncertainties for ABI and AHI are comparable. For bands 10 and 16, it shows that ABI has larger INR uncertainty than AHI. In addition to use these results to assess the instrument INR uncertainty effect, they are also useful for the determination of the criteria of uniform scene for comparison samples. For the statistical analysis in the following sections, the samples with scene uniformity less than 0.3 K are used. The clear dependence also allows the use of projection of ABI-MODIS and AHI-MODIS differences to uniform scene for reducing the impact of pixel-matching uncertainty.

### 4.1.4. ABI-AHI Difference

Table 3 lists the ABI and AHI BT, ABI-MODIS and AHI-MODIS difference, and derived ABI-AHI difference over the ocean sites respectively. The scene BT from ABI and AHI measurements over their nadir sites have less than 4K difference. To avoid the effect of ABI test data on the comparison results, the Gaussian peak from the fitting is used. The Gaussian widths for ABI-MODIS and AHI-MODIS comparison are also listed for their precision comparison. These widths show that ABI has a slightly better measurement precision than AHI. The ABI-AHI BT differences impact their averaged scene measurements and their actual scene.
BT should be closer than those in Table 3. Since the sites are both ocean and the scene BT difference is insignificant, the double difference method should be valid and useable for ABI-AHI radiometric comparison. As described in methodology section 4.1.3, the ABI-AHI spectral mismatching impacts on their comparison and the impacts are estimated using MODTRAN modeling for typical ocean scene. The correction for ABI-AHI spectral mismatching is applied for reference.

The full validation the ABI TEB BT data using SNO method shows approximate 0.2 K cooler than the reference instruments, such as VIIRS and CrIS on S-NPP and IASI on MetOp-B (Yu et al., 2017). The GOES-16 post-launch airborne science field campaign also shows that the ABI TEB performance was found to have biases within 1 K for all bands (Bartlett et al., 2018). The ABI-AHI comparison using this double difference shows insignificant difference for bands 10, 11, 12, and 14, while bands 15 and 16 have up to 0.8K difference. As shown in Figure 1, band 16 is located on a slope of BT spectrum on typical ocean scene, and the band mismatches between ABI-MODIS and ABI-AHI may have large impact on the comparisons. The relatively large ABI-MODIS and AHI-MODIS differences due to their band mismatching for band 15 may also impact on the double difference. As ABI calibration accuracy specification for TEB is ±1 K for 300 K scene, the comparison shows the performances are much better than the specification (GOES-R Series Data Book, 2019).

4.2. ABI Consistency Assessment

The two ocean sites are used for consistency assessment before and after GOES-16 re-location on 30 November 2017. ABI uses two scan mirrors (north-south and east-west scan mirrors) for producing a full-disk image. ABI measurements over the selected ocean sites in Table 2 have different scan angles for the east-west mirror, while the scan angle of north-south mirror is the same. Before the re-location, the first ocean site is under ABI nadir and its view angle is zero. After re-location, the view angle is nonzero and the BT should have a slight difference. In general, the INR uncertainty is also different, while INR characterization is better for nadir comparison with no-nadir area.

The uniformity impact analysis and BT distribution analysis reference to Aqua MODIS can be used for radiometric uncertainty and INR uncertainty comparisons. The ABI measurements over the second ocean site have the same view angle, which is on its east side to nadir before re-location and the on its west side after. The analysis using double difference with Aqua MODIS is used for a consistency assessment. The ABI-MODIS and AHI-MODIS differences showing in this section has been corrected for MODIS view angle effects. As mentioned in section 4.1.3, the scene uniformity is estimated using the standard deviation of surrounding area of 3x3 pixels. The uniformity dependency assessment is valid only for the measurements with INR uncertainty within 1 pixel. The larger INR uncertainty may only contribute random noise in the comparison.

4.2.1. ABI View Angle Effect Assessment

The ocean site under the ABI nadir before the re-location is used for assessing the ABI view angle effect. It is expected that the ABI-MODIS BT measurements are different, similar to that of MODIS presented in section 4.1.1. The ABI-MODIS is shown in left column in Figure 5. The comparison is used for ABI precision assessment for the measurement with different view angle. Figure 5 middle column shows the distribution of ABI-MODIS difference before and after the re-location. The distribution is close to a Gaussian shape. Before the re-location, the Gaussian width is less than after re-location for these 6 bands. The width is the combination of radiometric uncertainty and INR uncertainty. ABI bands 14 and 15 (MODIS bands 31 and 32) are longwave window bands and have less atmospheric impact. Their view angle effect is less than those of other bands, as shown in Figure 3 left column for view angle effect of MODIS bands 31 and 32. The comparison of the width before and after re-location is for qualitative assessment for the measurement precision, including both the radiometric uncertainty and INR uncertainty.

Figure 5 right column shows the uniformity impact on the ABI-MODIS comparison. Before re-location, the impact of scene uniformity is much less than after re-location for all 6 bands. The dependence of the difference with uniformity is due to the INR uncertainty difference between nadir and non nadir areas. ABI bands 10 and 16 are less sensitive to the uniformity for the pixels with uniformity better than 0.1 K. For the other bands, the comparison have approximately linear dependence on the uniformity. The INR uncertainty comparison is qualitative, while quantitative assessment requires a modeling and good understanding of view angle effect for different spectral band.
Figure 5. (left) The Advanced Baseline Imager–Moderate Resolution Imaging Spectroradiometer (ABI-MODIS) difference after view effect correction as a function MODIS view angle over the ocean sites under the first ABI ocean site before and after re-location, respectively. The MODIS view angle in the plot is the absolute angle from the two sides around the nadir. (middle) The distribution of ABI-MODIS difference over the first ocean site before and after re-location. (right) The uniformity impact on the ABI-MODIS comparison over the first ocean site before and after re-location. The blue symbols are for the comparison before re-location and the red symbols are for after re-location.
Figure 6. (left) The Advanced Baseline Imager-Moderate Resolution Imaging Spectroradiometer (ABI-MODIS) difference after view effect correction as a function of MODIS view angle over the ocean sites under the second ABI ocean site before and after re-location, respectively. The MODIS view angle in the plot is the absolute angle from the two sides around the nadir. (middle) The distribution of ABI-MODIS difference over the second ocean site before and after re-location. (right) The uniformity impact on the ABI-MODIS comparison over the second ocean site before and after re-location. The blue symbols are for the comparison before re-location and the red symbols are for after re-location.
Table 4
The ABI Measurement BT, the Comparison With Aqua MODIS, and the Double Difference Over the Second Ocean Site Before and After Re-location

| ABI band | 10   | 11   | 12   | 14   | 15   | 16   |
|----------|------|------|------|------|------|------|
| MODIS band | | | | | | |
| Before | Average BT (K) | 259.38 | 289.62 | 272.35 | 291.65 | 288.30 | 275.08 |
|        | ABI-MODIS (K)  | −0.15  | −1.33  | −3.44  | −0.60  | −2.17  | 5.38  |
|        | Gaussian width (K) | 0.21  | 0.24  | 0.23  | 0.20  | 0.21  | 0.21  |
| After  | Average BT (K) | 260.24 | 289.71 | 273.24 | 291.91 | 288.73 | 275.28 |
|        | ABI-MODIS (K)  | −0.25  | −1.17  | −3.22  | −0.46  | −2.03  | 5.42  |
|        | Gaussian width (K) | 0.24  | 0.20  | 0.23  | 0.14  | 0.18  | 0.25  |
| ABI before-after (K) | 0.10  | −0.16  | −0.22  | −0.14  | −0.14  | −0.05  |

Abbreviations: ABI: Advanced Baseline Imager; MODIS: Moderate Resolution Imaging Spectroradiometer.

4.2.2. Consistency Assessment
The second ocean site in Table 2 is used for an ABI consistency assessment before and after re-location using the measurements with same view angle. The only difference is that it is one the east side of nadir before re-location and is west side after re-location. In other word, the mirror scan angle has slight difference. The ABI-MODIS BT difference is shown in left column in Figure 6. Figure 6 middle column shows the distribution of ABI-MODIS difference before and after the re-location. The distribution is close to Gaussian shape. Figure 6 right column shows the uniformity impact on the ABI-MODIS comparison before and after re-location. Similar to the analyses using the first ocean site, the uniformity impact on ABI-MODIS comparison and the distribution of the BT difference are used for the assessment. The impact are consistent before and after re-location. However, this analysis is only valid for INR uncertainty is within 1 pixel. The large INR uncertainty such as during the early-mission check-out period, does not have dependency of comparison on the uniformity.

Table 4 lists the ABI measurement BT, the comparison with Aqua MODIS, and the double difference over the second ocean site before and after re-location. The average scene temperature is less than 1K before and after re-location, which is due to the seasonal variation. The ABI-MODIS difference has been corrected for MODIS view angle effect and the scene nonuniformity effect. The double difference shows the radiometric consistence before and after re-location, with a maximum difference of 0.2K. The Gaussian widths before and after re-location are also comparable, around 0.2K, while bands 11, 14, and 15 shows better performance for after re-location and bands 10 and 16 show better performance before the re-location. It is noted that, the measurements are from different season for before and after re-location and the seasonal effect may affect the assessments. In addition, the measurements over this site before and after re-location have different mirror scan angles and the difference also includes the RVS effect. As shown in the table, the differences are insignificant and the RVS effect should be unimportant for ABI. These results show that the ABI calibration performance is consistent before and after re-location.

5. Summary
ABI on board GOES-16 and AHI on Himawari-8 have a similar design and their spectral coverages of their TEB are almost identical. A similar calibration strategy is applied post-launch using an on-board BB and a space look. The intercomparison between the TEB of two instruments will be very helpful for their calibration assessments. Due to their nonoverlapping coverage, the intercomparison for their TEB is performed using double difference with Aqua MODIS as a reference. The ocean sites under their nadir are selected for intercomparison with Aqua MODIS respectively. The selected sites are around equator and Aqua crosses the equator at about 1:30am local time. The diurnal variation effect is not included in the analysis. The comparison uses clear sky measurements which limits the BT measurements to a narrow range. The ABI-AHI comparison is for ABI pre-operational measurements. The view angle effect correction and uniformity consideration reduce their impact on the pixel-to-pixel comparison. The spectral mismatching effect is also considered and estimated. The ABI-AHI comparison using this double difference shows insignificant difference (within 0.3K) for bands 10, 11, 12, and 14, while bands 15 and 16 have up to 0.8K difference. ABI calibration accuracy specification for TEB is ±1 K for 300 K scene and this assessment using ocean scene shows the post-
launch calibration meets the requirement. The analysis shows that ABI precision is slightly better than AHI for all TEB. Their INR precision are comparable from the statistical analyses. In general, the ABI performance is consistent before and after its re-location.

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Earth and Space Science
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2316