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GOES-16 ABI solar reflective channel validation for earth science application
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ABSTRACT
This paper presents the validation results of GOES-16 Satellite's Advanced Baseline Imager (ABI) obtained from a reflectance-based field campaign undertaken at the Salar de Uyuni in Bolivia in June 2017. In situ ground measurements are used to characterize the surface reflectance and the atmosphere in order to constrain the radiative transfer code and predict at-sensor reflectance (also referred to as top-of-atmosphere (TOA) reflectance) to compare with concurrent GOES-16 ABI measurements. The five-day field campaign provided repeated TOA reflectance estimates, allowing assessment not only of the calibration accuracy of the ABI reflective channels 1, 2, 3, 5 and 6, but also of its stability over the duration of the campaign. The results show that the accuracy of the ABI reflective channels calibration is within specification for channels 1, 3, 5, and 6 - average biases within 2%; for channel 2 the bias is 5%. The estimated uncertainty on the derived biases is 2–2.4%. Some calibration stability issues were present in the ABI calibration at the time of the campaign: (i) a jump on the order of 2% in channels 1 and 6, coincident with an ABI solar calibration event, reflects an instability of the ABI gains in these channels, and (ii) short-term variability in channels 1 and 2 is due to striping (ABI detector-to-detector calibration differences). Continued validation and subsequent reprocessing of ABI reflectance imagery would allow Earth scientists to fully benefit from the high spatial and spectral fidelity of the GOES-16 ABI diurnal measurements at the continental scale.

1. Introduction
Following a successful launch in November 2016, the Geostationary Operational Environmental Satellite R (GOES-R) satellite was renamed GOES-16. Initially GOES-16 was positioned at the non-operational test position at 89.5° west for check out and validation. In December 2017, GOES-16 was stationed to its operational location at 75.2° west, and began operations as GOES-East. The Advanced Baseline Imager (ABI) – a 16-channel passive imaging radiometer – is the primary sensor onboard GOES-16. The ABI, with its substantial improvement over predecessor sensors in temporal, spectral, spatial, and radiometric fidelity, supplies a new data stream to greatly improve weather and environmental intelligence gathering. ABI data can also be used for earth science and climate studies given the data has a reliable calibration over time.

In addition to the standard pre-launch calibration and on-board calibration protocols, vicarious radiometric validation and calibration using natural targets as reference standards, provides a third method for validating the calibration or calibrating instruments. Vicarious calibration can be used to correct for the effects of post-launch instrument degradation over time caused by thermal, mechanical, or electrical effects, as well as exposure to ultraviolet radiation (Muller, 2014).

In this paper we present vicarious validation of the ABI reflective channels 1, 2, 3, 5, and 6 using the salt flats at Salar de Uyuni in Bolivia as a reflectance reference. The field data were collected in June 2017, when ABI was at its test position at ~89.5° longitude above the Equator, at an azimuthal angle of about 311° from North, and satellite zenith angle of 34° at the Salar de Uyuni test site.

The paper is organized as follows. Section 2 describes the ABI instrument, its modes of operation, and calibration overview. Section 3 describes the test site measured in this work and summarizes the vicarious calibration technique used to provide a reflectance reference for ABI. Section 4 presents the methodology used to compare predicted signal to ABI measurements, associated uncertainties, and the results. Section 5 provides a summary and discussion.

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The advanced baseline imager

The ABI’s large focal plane detector array allows for scanning of Earth scenes with a very high temporal resolution. The ABI is capable of completing a full hemisphere scan (full-disk scan) within 5 min and rapid frames are completed in 30 s. This increase in scanning speed from the previous instruments permits better monitoring of atmospheric conditions such as wind motion, and significantly improves severe weather forecasting. The GOES-16 ABI has several scene types: full disk, mesoscale, and continental United States. Full disk (FD) mode provides a scan of the full hemispheric at 83° local zenith angle, with a temporal resolution of 5, 10 or 15 min, depending on the instrument mode of operation, at spatial resolution at nadir of 0.5–2.0 km, depending on the channel. Mesoscale mode gives coverage over a 1000 km by 1000 km square with a temporal resolution of 30 s. Continental U.S. mode (CONUS) scans a 5000 km (E/W) and 3000 km (N/S) rectangle over the United States every 5 min. Flex mode (Mode 3) scans the full hemisphere disk every 15 min, a CONUS scan every 5 min, and two mesoscale scans every 60 s (or the option of one sub-region every 30 s). A more comprehensive description of the ABI instrument, operations, and products can be found in Schmit et at, 2017.

From an earth science standpoint, ABI’s high temporal frequency of full disk acquisitions yields benefits such as increased probability of cloud-free imagery and the ability to study diurnal phenomena. It provides a great improvement over GOES 8–15 imagers which could capture several full-disk images per day, at one visible and four infrared channels. The ABI has six solar reflective channels and ten thermal emissive channels. The central wavelengths and nadir resolutions of the six reflective channels are listed in Table 1; channels 1–3 cover the visible and near infrared (VNIR) spectral region, and channels 4–6 the short-wave infrared (SWIR). Fig. 1 shows the six solar reflective channels of ABI on the same plot as Landsat 8 Operation Land Imager (OLI) and MODIS (Terra). The common spectral selection of these sensors is optimized for characterizing atmospheric and land surface parameters – ideal for weather prediction and disaster detection and assessment in addition to the scope of traditional science sensors.

Prelaunch characterization, using SI-traceable standards in a controlled laboratory environment, provides a unique opportunity to characterize the instrument performance and calibrate its response before launch into space (e.g. Datla et al., 2011). Once in orbit, onboard calibrators are used to trend and correct for any instrument response changes due to exposure to the space environment so the sensor remains well calibrated throughout its lifetime. The ABI solar reflective imagery bases its calibration on intermittent updates from measurements of its solar diffuser (e.g. Datla et al., 2016). As the on-board calibrators may be a subject to degradation themselves, there remains a need to independently validate the on-orbit instrument calibration. One validation approach used early in the GOES-16 mission was to compare the ABI-measured radiance with a well-calibrated imaging spectrometer flying on a high-altitude ER2 aircraft at a geometry designed to match the view angles of both instruments (Padula et al., 2018; Bartlett et al., 2018). Other approaches used for validation and calibration of the reflective channels on geostationary instruments include sensor inter-calibration with low earth orbit instruments using ray-matching measurements, as well as vicarious techniques including collocated measurements of Deep Convective Clouds (DCC) (Yu and Wu, 2016), intercalibration over stable earth targets (deserts) (Yoo et al., 2017; Yu et al., 2014), and Rayleigh scattering calibration. This work uses a type

Table 1
ABI solar reflective channels with their central wavelengths and pixel sizes at nadir on the ABI fixed grid.

<table>
<thead>
<tr>
<th>ABI Channel</th>
<th>Central Wavelength [μm]</th>
<th>Nadir Pixel Size [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.470</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.640</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.865</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1.378</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>1.610</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>2.250</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 1. Spectral response functions of the ABI solar reflective channels and other earth science sensors, Landsat 8 OLI and MODIS (Terra).
of vicarious calibration based on ground site characterization detailed in the next section.

3. Reflectance-based approach of vicarious calibration and validation

The reflectance-based approach is among the calibration techniques developed in the 1980s at the Remote Sensing Group at the University of Arizona along with irradiance- and radiance-based methods (Slater et al., 1987; Thome, 2001). This section describes the calibration technique as applied to GOES-16 ABI, provides an overview of the Salar de Uyuni field campaign, and details the reflectance and atmospheric measurements and subsequent derivations.

3.1. Reflectance-based approach overview

The reflectance-based approach of vicarious validation uses surface reflectance and atmospheric parameters to constrain radiative transfer code to predict spectral reflectance at the sensor. The method works best for atmospheric window channels - in the case of ABI for channels 1, 2, 3, 5, and 6 (see Table 1 for central wavelengths). ABI channel 4, situated near the center of a strong water vapor absorption, receives little radiation reflected off the ground, and is very sensitive to the atmospheric water vapor content, which results in large uncertainty on the estimated TOA reflectance. The measurements in channel 4 are only shown for reference.

The reflectance-based approach has historically been used for low earth orbit sensors such as Landsat (Thome, 2001; Czapla-Myers et al., 2015) and MODIS (Thome et al., 2003) which only have one near-nadir acquisition during a 16-day period. In such case, the ground-based reflectance and atmospheric measurements have to be coordinated to best match the time when the satellite sensor measures the ground.

In the case of geostationary sensor like ABI the instrument observes the in situ collection site continuously (at 15-min cadence for ABI Mode 3), and a campaign spanning several days can be used to study the day-to-day repeatability of the measurements. In addition, as the reflectance measurements of the test site take about 100 min, and provided that the test site has high spatial uniformity, the measurements can be averaged over segments of approximately 5-min duration as described the next section. Thus, the ground measurements can be treated as time series, and compared to the time series of the sensor measurements. In this study we show the time series to illustrate the bidirectional reflectance factor (BRF) of the site, but the conclusions on ABI performance are based on the average values over each day, in order to minimize effects of site nonuniformity and uncertainty. The results are further averaged over all days of the campaign to derive average biases. A flow chart illustrating the validation process adopted in this paper is shown in Fig. 2.

Fig. 2. Flow chart illustrating the reflectance-based validation of ABI reflective channel.

Fig. 3. Location of the six sun photometers and the reflectance test site indicated on a Landsat 8 OLI image (10 June 2017) of Salar de Uyuni.
3.2. Salar de Uyuni campaign

The ABI vicarious validation campaign took place in the salt desert Salar de Uyuni in Bolivia in June 2017. The desert was selected because it provides a stable reflectance source during the dry season, with mostly clear skies - cloud fraction <0.2, (June 2017, the number is from neo.sci.gsfc.nasa.gov), at an advantageous view geometry – the GOES-16 zenith angle is 34°. The high elevation of the desert (3.64 km) provides the additional advantage of it being above the densest layers of the troposphere thus decreasing the uncertainty due to propagation of the ground measurements through the atmosphere. The test site location (-20.0617°, -67.5894°) within the Salar de Uyuni was selected by studying the uniformity of the desert on about 16-km scale using Landsat 8 OLI imagery from May 2017. The standard deviation over the pixels covering the area of interest was assessed at several locations. The location with high reflectance and best uniformity was selected as...
our field campaign site. Imagery from the same season was used for the assessment, as the desert floods annually during the rainy season (typically December through March) creating a new surface and as such, there is little season-to-season uniformity repeatability. Once the surface dries however, the uniformity doesn’t change significantly until the next rainy season.

The Salar de Uyuni ground campaign took place 12–18 June 2017 with several days on each side used for travel and shipping equipment. The 12 June was the first day at the test site and the team began by navigating to the planned site location. The salt surface appeared uniform except for sparse locations of soft salt that were typically evenly-distributed, oval-shaped, and 2 m–15 m in diameter. These features account for less than one percent of the test site surface area and do not have substantially different brightness than the rest of the surface.

Six sun photometers were distributed in a high-density grid upon arrival (Holben et al., 2018), to oversample the atmosphere at the test site. One photometer “SDU1” was deployed adjacent to the reflectance test site to best measure the atmospheric conditions in the ABI line of sight to the test site. Three additional units, SDU2, SDU3, and SDU4, were deployed in a 20-km radius surrounding the test site in order to assess spatial variability of atmospheric conditions. Two more sun photometers were deployed on the center and eastern perimeters of the salt flat for additional spatial extent of atmospheric measurements. Positions of the sun photometers are indicated on the map in Fig. 3. The team remained at the site to begin to layout the test site by defining four 1-km transects separated by 333 m and oriented at 311°. Along each transect flags were placed every 250 m.

![Fig. 6. Mean Salar de Uyuni test site BRF based on measurements taken 16:45–18:25 UTC on 17 June 2017. The percent standard deviation of the mean is shown in the dashed line and its scale in on the right vertical axis.](image)

![Fig. 7. Time series of the interpolated AOT at 550 nm of SDU1-4, as well as the average over the four instruments, at the time of ground reflectance measurements for all days of the Salar de Uyuni campaign.](image)
3.3. Reflectance measurements and calculations

Reflectance is the most important characteristic input for the radiative transfer code since it is the most heavily weighted input that predicts at-sensor reflectance as well as carrying traceability to national standards. A spectroradiometer (ASD FieldSpec 4) was used to take reflectance measurements of the surface of the Salar de Uyuni and a reference target. The ASD spectral resolution is 3 nm (1.4 nm spectral sampling) in the 350–1000 nm range and 10 nm (2 nm spectral sampling) in the 1000–2500 nm range. The instrument control software resamples and saves these data to a 1-nm grid. The ASD has a fiber optic that couples the spectrometer to a foreoptic that defines the field of view of the measurement. A foreoptic with eight-degree field of view was used throughout this work. The ASD operator holds the foreoptic assembly at approximately 1-m to the side of his or her body at waist height, in order to minimize operator-related effects on the measurement. Two ASDs were used throughout the campaign: the primary unit had serial number 18188 and the secondary unit serial number was 18555. Throughout the campaign, the ASD-18188 was oriented so that its foreoptic was pointed 34° from nadir, in a plane parallel to the direction of travel (311° azimuthal angle), to match the ABI view geometry. The ASD-18555 switched between two foreoptic zenith geometries, 34° and nadir, depending on satellite sensor overpass schedule. There were several low-earth orbiting sensors that acquired near-nadir acquisitions of the test site during the campaign. When one of these overpasses coincided with reflectance measurements, the ASD-18555 foreoptic view was switched to nadir position for a single transect of the four-transect test site. The 34-degree geometry was used for all other transects. The orientations of both ASDs throughout the campaign are reported in Table 2.

The surface reflectance is calculated by transferring the BRF of the Spectralon reference panel to the test site surface. The ASD measures upwelling radiance of the test site in between measurements of the reference panel as shown in Fig. 4 where the red squares represent locations of reference panel measurements and blue points represent locations of measurements of the salt surface. The collection of the test site begins at location ‘0’ by initiating an optimization function on the ASD while the foreoptic is pointed at the reference panel. The optimization function sets the integration time for the ASD’s silicon spectrometer (350–1000 nm), the gains for the ASD’s two shortwave infrared spectrometers (1000–1830, 1830–2500 nm), and measures dark signals for all channels. The reference panel is brighter than the salt surface so the integration time and gain levels are appropriate for both targets. The optimization function is run before the reference panel measurement at the beginning of each transect, specifically locations, ‘0’, ‘5’, ‘10’, and ‘15’. The time between optimizations are 24–27 min and are sufficient to account for instrument instabilities and changing illumination conditions.

Once the ASD optimization function is complete, the measurement of a transect begins with the reference panel at location ‘0’ when the 8-degree foreoptic is held about 10-inches above the 12-inch square reference panel. ASD measurements are initiated by pressing the spacebar on the control computer and its duration was about 27 s with the configuration used during this campaign. Twenty individual files are saved during this measurement period, each with an associated time-stamp and GPS-based location. Once the reference panel measurement is complete, the ASD operator walks towards the next reference panel measurement location that is 250-m away and indicated by a survey flag. There were consistently seven-to-eight 27-s measurement periods, or 140–160 saved measurements files, between each reference panel measurement.

Fig. 8. Surface BRF based on in situ measurements and spectrally averaged to the ABI channels. Results are shown for each day of the field campaign and each marker represents the mean of a 250-m segment of the test site.
location. Upon arriving at the next reference panel location, support personnel had removed the panel from the previous location, drove to the next panel location, and deployed and leveled the panel to prepare it for measurement. This process was repeated until the end of the transect. The ASD operator then rode in the support vehicle for the 333-m transit to the next transect where the optimization and measurement process begins again. Measurement of the complete four-transect site took about approximately 100 min to complete.

An example of the signal collected throughout the measurement of the test site is shown in Fig. 5 where the normalized signal of one spectral channel from each of the three spectrometers is plotted, in this case, the black line is 500 nm, blue line is 1600 nm, and red line is 2250 nm. The thick red line segments at 1.05 on the vertical axis indicate measurements of the reference panel. The black circles indicate when the ASD optimization function was executed and these coincide with the beginning of each transect. The signal in between the reference panel measurements represents the test site.

There is a total of 20 reference panel measurements during the collection of the test site and each of these is a set of 20 measurement files. The mean signal of each group is found along with mean measurement time in UTC and mean solar illumination geometry in these 27-s measurement periods. The solar illumination angle changes during the 5-to-6 minutes in between reference panel measurements so adjacent mean reference panel signals are interpolated to predict what the

<table>
<thead>
<tr>
<th>Date</th>
<th>Water [g/cm²]</th>
<th>AOT 550 nm</th>
<th>Angstrom Exp.</th>
<th>Ozone [ATM cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017-06-14</td>
<td>0.069</td>
<td>0.011</td>
<td>0.0156</td>
<td>0.0022</td>
</tr>
<tr>
<td>2017-06-15</td>
<td>0.084</td>
<td>0.008</td>
<td>0.0139</td>
<td>0.0012</td>
</tr>
<tr>
<td>2017-06-16</td>
<td>0.080</td>
<td>0.007</td>
<td>0.0122</td>
<td>0.0006</td>
</tr>
<tr>
<td>2017-06-17</td>
<td>0.070</td>
<td>0.008</td>
<td>0.0121</td>
<td>0.0005</td>
</tr>
<tr>
<td>2017-06-18</td>
<td>0.054</td>
<td>0.008</td>
<td>0.0109</td>
<td>0.0011</td>
</tr>
</tbody>
</table>

Fig. 9. Predicted top-of-atmosphere (TOA) reflectance. In situ measurements propagated to TOA using MODTRAN with aerosol and water parameters as measured by AERONET photometers SDU1-4 at the time of the in situ observations.
reference panel would be for each of the salt surface measurements. This results in a predicted reference panel measurement for each salt surface measurement. Next, the BRF of the panel is transferred from the panel to the salt surface using

$$\text{BRF}_{\text{test site}} = \frac{\text{BRF}_{\text{reference panel}}(\lambda, \theta) \cdot S_{\text{test site}}(\lambda, \theta)}{S_{\text{predicted reference panel}}(\lambda, \theta)}$$

where \(\text{BRF}_{\text{reference panel}}\) is the spectrally and angularly dependent bidirectional reflectance function of the reference panel, \(S_{\text{test site}}\) are the ASD signals measured over the salt test site, and \(S_{\text{predicted reference panel}}\) is the signal that has been interpolated from the ASD reference panel measurements before and after the \(S_{\text{test site}}\) measurements were acquired. BRF of the reference panel was characterized using the same methodology and goniometric laboratory at University of Arizona that characterized the solar diffuser used by the Landsat 8 Operational Land Imager (N. Anderson, personal communication). The method first measures at 45-degrees a normally illuminated Spectralon panel that has been characterized by NIST with the same geometry. The reference panel replaces the NIST-traceable panel in the experimental setup and is measured in 21 discrete wavebands that span the 400–2400 nm spectral region every 5° in the 15–75° view range. The NIST-traceable BRF is transferred to each of the spectral and angular measurement points of the reference panel. A continuous BRF spectrum is constructed using values from these 21 spectral measurements and knowledge of the intrinsic spectral shape of the reference panel material. Finally, \(\text{BRF}_{\text{reference panel}}\) is calculated by interpolating to the exact illumination angle of the salt test site measurement. The mean site BRF of 17 June is shown in Fig. 6 to illustrate the spectral shape of the salt surface. The dashed line in the figure shows the combined site uniformity and variability of the measurement itself in units of percent standard deviation.

### 3.4. Atmospheric measurements and derivations

In order to propagate the surface reflectance measurements to the TOA, the atmosphere above the test site needs to be characterized and accounted for using radiative transfer code – in this study MODTRAN.
5v2 (Berk 2005) was used. Measurements by four AERONET sun photometers deployed in the Salar de Uyuni (SDU1-4) during the field campaign (see Fig. 3) were used to obtain the aerosol distribution and properties, precipitable water, and to estimate the uncertainty on these parameters.

The photometers collected daily measurements from approximately 12:00 to 21:00 UTC. The field data, processed as AERONET Level 2.0 products (quality assured) using AERONET Version 3.0 algorithms (Giles et al., 2017), were obtained from https://aeronet.gsfc.nasa.gov/. The AERONET Level 2.0 product provides aerosol optical thickness (AOT) at various wavelengths, as well as Angstrom parameters (the negative slope of AOT with wavelength), computed over several wavelength ranges. The data products used in this study are: the AOT at 500 nm and 675 nm, the Angstrom parameter as derived from the 440–870 nm spectral interval, the precipitable water (cm), and ozone (atm-cm) and NO2 corrections from OMI climatology. The MODTRAN

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Fig. 12. A uniformity assessment was made using Landsat 7 ETM + imagery. Plot (a) shows the signal difference between regions of various sizes and Plot (b) shows how the variability of the signal changes with increasing site size.

Fig. 13. GOES-16 ABI measured TOA reflectance over 2.28 × 2.28 km² area centered on the ground campaign site over a time interval coinciding with the ground reflectance measurements. Each marker on the plot represents data from full-disk ABI scans taken at 15-min intervals.
code requires the AOT at 550 nm, which is not provided by AERONET, and was calculated using linear interpolation of \( \log(AOT) \) as function of \( \log(\lambda) \) between the AERONET-derived values at the nearest two wavelengths of \( \lambda = 500 \text{ nm} \) and \( \lambda = 675 \text{ nm} \).

The parameters derived by the six deployed sun photometers SDU1-6 were compared as an average and as a time series; the photometers situated within the Salar de Uyuni (SDU1-4) were found to have largely similar daily trends and some offsets in absolute value. The time series of the interpolated AOT at 550 nm at the time of ground reflectance measurements are shown in Fig. 7.

The AOT at 500 nm reported by AERONET photometer at the reflectance test site (SDU1) has campaign-average value (average over the 14–18 June date range) of 0.015, with a standard deviation of 0.002. Photometers SDU2-4 report similar values with a minimum of campaign-average value of 0.012 at SDU3.

The campaign-average precipitable water reported by photometers SDU1-5 was between 0.06 and 0.08 cm, with a standard deviation of 0.01. The campaign-average Angstrom parameter from photometers SDU1-4 is about 1.0, with a standard deviation 0.1–0.3. Note that SDU5 and 6 are not quality assured (Level 1.5) as they are without a post field calibration, however the quality is commensurate with the SDU1-4. Thus we use the average of the four photometers SDU1-4 deployed in the Salar de Uyuni to specify the atmospheric properties in the radiative transfer model. By comparison the Railroad Valley Nevada calibration site winter time minimum climatologies reported by AERONET (aeronet.gsfc.nasa.gov/new_web/V3/climo_new/LEV20/Railroad_Valley_500_interpolated.html) are AOT500 of 0.03 (0.018) and precipitable water of 0.48 (0.21) adding perspective to the excellent optical clarity of atmosphere over Salar de Uyuni.

3.5. At-sensor reflectance prediction

The MODTRAN 5v2 radiative transfer code (Berk, 2005) was used to account for the Earth atmosphere by propagating the measured ground reflectance to the top of the atmosphere. In order to compare with the ABI-measured TOA reflectance, the ground-measured reflectance was first averaged temporally. The test site measurements, acquired between reference panel measurements, were averaged over approximately 5-min intervals during which a 250-m segment of the test site was measured. The result, averaged spectrally over the six ABI reflective channels, is shown in Fig. 8.

Generally, the reflectance measurements follow the same trend for each day sampling the BRF of the test site. Some high frequency (point to point) variations are present and likely represent a combination of observer geometry errors combined with actual reflectance variation on 500-m to 1-km scale.

For each of the averaged ground reflectance measurements, a MODTRAN model was computed to propagate the ground reflectance value to the TOA, using input geometry and atmospheric parameters specific for each ground measurement time and location. MODTRAN has an extensive set of input parameters, the description of which is beyond the scope of this paper. A summary of the input parameters which differ from the default or recommended MODTRAN values, or input parameters with time dependences, are provided in Table 3.

![Fig. 14. At-sensor reflectance normalized at the average predicted value is shown as a time series for each measurement day of the campaign, from 14 June in panel a) through 18 June in panel e). Values derived from GOES-16 ABI imagery 2.28 x 2.28 km² area, centered on the test site, are indicated with red diamond markers. The mean surface reflectance of each 250-m transect segment are shown with open circles. The solid black circles show the predicted at-sensor reflectance. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)](image-url)
The satellite–ground target–sun geometry is computed for each average ground reflectance point using JPL SPICE software (Acton, 1996). The atmospheric model is the standard tropical atmosphere scaled using the AERONET-derived parameters summarized in Table 3. The average of SDU1-4 values for columnar water, AOT at 550 nm, Angstrom parameter, and ozone are listed, further averaged over the ground-reflectance measurements time interval. The standard deviation provided in the second column for each parameter illustrates its daily variability. In the actual MODTRAN input, the time series of each parameter are interpolated at the average time of the ground reflectance measurement for each point (see the AOT at 550 nm time series illustrated in Section 3.4 Fig. 8). The third column for each parameter provides the standard deviation between the different photometers (average over each day) which is used as an error estimate of each parameter.

In Fig. 9, the predicted TOA reflectance is shown versus time of day for the five days of the field campaign. Each point is computed using the average ground reflectance illustrated in Section 3.3 Fig. 7 and propagating it to TOA using a MODTRAN model with time specific geometry and atmospheric parameters.

TOA reflectance results from each day follow the same trend except for the spectral region of channel 4, which is very sensitive to the water vapor content. The reflectance within the VNIR channels generally increases throughout the day and the reflectance within SWIR channels 5 and 6 reach a minimum before local noon.

The day-to-day repeatability is very good for all channels except channel 4, as expected given the surface reflectance stability and clear sky conditions.

3.6. Uncertainty of the at-sensor (TOA) reflectance prediction

To assess the uncertainties of the predicted ABI TOA reflectance, the following sources of error were taken into account:

(i) Uncertainty on the ground-measured surface reflectance: Absolute uncertainty: The NIST-traceability of the reference panel is 1.1–1.7% in the VNIR and 1.4–1.9% in the SWIR (Anderson et al., Personal communication). Repeatability: As described in Section 3.3 two ASDs were used in the Salar de Uyuni campaign, with the primary ASD 18188 always observing at ABI view geometry (34-degree zenith angle), and the secondary ASD 18555 switching between nadir and 34-degree zenith angle. The repeatability of the measurements between the two instruments at 34-degree zenith angle is used as an estimate of the error due to observer dependent biases such as measurement geometry differences, small-scale spatial uniformity differences between the tracks of the two observers, and other errors not captured in the standard deviation of the 5-min averaged observations (which does include spatial nonuniformity on 250 m scale). Measurements from both instruments are available for three days of the campaign (15, 16, and 17 June 2017). The comparison of the 5-min time-averaged ground reflectance, further averaged over the ABI spectral channels for 16 June, is shown in Fig. 14.

We also attempted using location specific atmospheric profiles from the National Centers for Environmental Prediction (NCEP) analysis data to compute the TOA reflectance. As in the case of tropical atmosphere the profiles were scaled by the AERONET-derived column quantities. As expected, the reflective window channels, which are the subject of this paper, are not affected by the profile used. The change in reflectance propagated to the TOA using the NCEP atmospheric profiles is within 0.05% for channels 1,2,3, 5, and 6.
Generally, the observations agree within the standard deviation of the averaged data, which is about 1% in the VNIR (Channels 1–3) and closer to 2% in the SWIR (Channels 4–6). There is a small, <1% on average, bias between the two ASDs for this day. The average bias over all days of simultaneous observations is on the order of 1%.

(ii) Uncertainty in the atmospheric parameters: The standard deviation of the measurements of the sun photometers SDU1-4 is used as an uncertainty estimate of the atmospheric parameter (see Table 3).

(iii) Uncertainty propagation of ground measurements to TOA reflectance: The accuracy of the MODTRAN model (<1% for atmospheric transmittance) is low compared to the atmospheric parameters and ground reflectance uncertainty. To assess the effect of the input atmospheric and aerosol parameters uncertainty, a grid of models was computed for one representative location and time by varying the atmospheric parameters within their uncertainty and, in the case, of the AOT and Angstrom parameter above the measurement uncertainty. The typical AOT at 550 nm measured during the Salar de Uyuni campaign is 0.01 with a standard deviation of 0.002. The AERONET AOT calibration uncertainty was estimated to be ~0.01 (Eck et al., [1999]) and is comparable to our measured value, thus we varied the AOT by 50%–100% - from 0.005 to 0.02. The Angstrom parameter was also varied by 50% from 0.5 to 1.5. The columnar water was varied within its standard deviation, and the total ozone column by 5 DU.

The resulting grid of models shows very low dependence on the atmospheric parameters in the ABI channels, with the exception of the strong dependence of the cirrus channel 4 (1.38 μm) on the columnar water – the 0.01 g/cm² water uncertainty yields about 10% change in the TOA reflectance at channel 4. For the rest of the reflective channels the contribution of the atmospheric parameters described above to the TOA uncertainty adds up to less than <0.2%. Further, we allocate 1% uncertainty on the propagation of the ground reflectance to TOA to allow for biases and using some default modeling parameters. The calibration uncertainty of the surface reflectance measurement has the highest contribution to the uncertainty of the predicted TOA reflectance.

Combining the ground reflectance measurement uncertainty (standard deviation of the mean of the 5-min average ground reflectance ±1%; bias between the two observers – 1%; reference panel characterization uncertainty – 1.4%/1.7% for VNIR/SWIR respectively) with the propagation to TOA uncertainty gives uncertainty of the predicted TOA reflectance on the order of 2% for channels 1, 2, 3, about 2.2% for channels 5 and 6, and about 15–20% for channel 4.

4. ABI-measured to predicted at-sensor reflectance comparison

Over the duration of the Salar de Uyuni campaign the GOES-16 ABI was operating in Mode 3 taking full disk imagery every 15 min. The TOA reflectance measured in the six ABI reflective channels was derived from the Level 1b radiance product after accounting for the sun-ground-satellite geometry. The data were then spatially matched to the ground measurements site. The limitations of the spatial matching are largely compensated by the excellent uniformity of the area surrounding the ground measurements site as described below in Section 4.1.
4.1. Site uniformity assessment and spatial matching

When comparing the predicted TOA reflectance to ABI-measured reflectance the different spatial scales of the measurements need to be taken into account. The ABI Level 1b imagery products are resampled to the ABI fixed grid – a projection relative to the ideal location of a satellite in geostationary orbit – allowing the same data points in every product to be at the same location on the earth. The fixed grid pixel sizes of the ABI reflective channels at zenith angle of 34° are about 0.57 km (channel 2), 1.14 km (channels 1, 3, 5) and 2.28 km (channel 6) (the nadir resolution for each channel is given in Table 1). Thus, uncertainty arises due to the imperfect matchup of the ABI 2.28×2.28 km² pixel with the 1×1 km² ground measurements site. The higher the site uniformity the lower this additional uncertainty would be, to the limit of zero additional uncertainty due to this mismatch if the site were perfectly uniform. The site uniformity and the associated comparison uncertainty can be estimated using high-resolution imagery, such as the 30 m resolution Landsat 7 ETM+. An ETM + channel 2 (0.56 μm) reflectance image, acquired on June 18, 2018, is shown in Fig. 11, where the color scale is normalized to the mean of the center 1×1 km² area. It shows that the area within approximately 4 km of the center is within 1% of the ground measurements site that was sampled.

The average reflectance of regions of increasing size relative to the 1×1 km² site, with variability of <1% in the VNIR on up to 6-km scale. Even considering a worst-case scenario of a 1.14-km geodetic error, the differences shown at the 3.4-km point in Fig. 12-a are less than 1% for the VNIR spectral region and about 1% for the SWIR spectral region. Similar results were obtained using imagery on different days during the same season prior to the field campaign, indicating that the surface uniformity remains unchanged on time scales longer than the field campaign.

Further in this study we evaluate the ABI measurements in the same 2.28×2.28 km² area for all channels. Using this larger area also for the higher-resolution channels is justified by the high uniformity of the site. In addition, the higher-resolution channels 1 and 2 had significant striping at the time of the Salar de Uyuni campaign, the effect of which is mitigated by averaging several pixels – 16 pixels are averaged at for the high-resolution (channel 2), and 4 pixels for the medium resolution (channels 1, 3, and 5).

The rest of this section is dedicated to the comparison of the ABI-measured to the predicted at-sensor reflectance.

4.2. ABI TOA reflectance

The TOA reflectance in the six ABI reflective channels, over a 2.28×2.28 km² area and during the time interval of the ground reflectance measurements, is shown in Fig. 13. The daily trends and the day-to-day variability can be compared between the predicted (Fig. 9) and ABI-measured (Fig. 13) reflectance. The day-to-day repeatability in channels 3 and 5 is very good and as expected given the stability of the surface reflectance and the clear sky conditions. The channel 4 variability is due to the changes in atmospheric column water and, aside
from a large ~30% bias, it is qualitatively following the prediction – both as daily trends and day-to-day variations. The day-to-day variability observed in channels 1, 2, and 6 is not seen in the predicted TOA reflectance and is due to the ABI stability as described further in this section.

4.3. ABI TOA reflectance comparison to predicted TOA reflectance

The comparison of the daily reflectance trends is shown for each day of the campaign in Fig. 14. The TOA reflectance trends, normalized to the average predicted TOA reflectance, are shown in red for the ABI-measured reflectance, and in black solid circles for the ground-based predicted TOA reflectance. The differences between the in situ (open circles) and predicted TOA reflectance illustrate the contribution of the atmospheric transmission and scattering to the TOA reflectance prediction. The objective of this validation work is the assessment of the differences between the predicted TOA reflectance and the ABI-measured reflectance.

There is a good agreement between the daily trendsof the predicted and ABI-measured at-sensor reflectance suggesting that the daily trends indicate actual surface BRF and atmospheric effects rather than ABI stability issues. One notable exception is the channel 2 trend, where the ABI-measured reflectance shows jumps and very different standard deviations from one observation to the next – see, for example, the channel 2 trend for 18 June in Fig. 14 (last panel). Visual inspection of the ABI L1b images shows that channel 2 has prominent striping at the time of the Salar de Uyuni campaign and both the jumps in reflectance (see also the B2 panel in Fig. 13) and the large standard deviation of the average for some observations are due to a very bright (~10%) stripe falling in and out of the region of interest considered in this study. Some high frequency variability in the in situ-based TOA reflectance measurement present in channels 5 and 6 is likely due to a combination of observer geometry errors combined with actual reflectance variation on 500 m to 1 km scale. As described below the ABI-to-in situ ratio is further averaged over the whole day to reduce any nonuniformity effects and geometry uncertainty.

A summary of the daily TOA reflectance comparison is given in Fig. 15; the ABI data was interpolated at the times of in situ observations and the ratio of ABI to predicted reflectance was averaged for each day. The error bars (the standard deviation of the averaged results) represent the variability of the reflectance ratio for each day, which is smaller in the VNIR and increases in the SWIR, consistent with the higher ground measurement uncertainty in the SWIR. Channel 2 (and for some days channel 1) has larger variability due to striping in the ABI L1b imagery as described above. From Fig. 15 it is evident that the daily average of the reflectance ratios in channels 1 and 6, shows a jump between the 14–16th of June and 17–18th of June values. The predicted TOA reflectance in channels 1 and 6 is stable (Fig. 9), while the ABI-measured reflectance (Fig. 13) changes by ~2%. In order to address this day-to-day variability in channels 1 and 6, the on-orbit calibration coefficient applied over the duration of the field campaign (as reported by the GOES-16 ground system) is shown in Fig. 16. Note that the calibration coefficient is derived at solar calibration events and remains constant from one calibration event to the next. During the Salar de Uyuni campaign there was one solar calibration which took place at 12:12 UTC on 17 June. After the calibration, the gains of
Channels 1 and 6 change by ~1.8% and ~2.5% respectively — values consistent with the reflectance jumps of ~2% in these channels seen in Figs. 13 and 15. The gains derived on 17 June for the rest of the reflective channels are within 1% of the previous values. Given the change of ABI-derived gains on 17 June, and the day-to-day stability of the in situ measurements, the jump in the daily ABI vs in situ TOA reflectance comparison for channels 1 and 6 is attributable to instability in the ABI solar calibration.

Fig. 16. Linear coefficients used to calibrate ABI channels 1 (left panel) and 6 (right panel) over the duration of the Salar Uyuni field campaign. The average value over all detectors is shown for each day. The coefficients are normalized at the first day of the campaign — 14 June 2017. The calibration coefficients are derived at ABI solar calibration events and remain constant until the next calibration event occurs. The jump in the coefficients trend is due to a calibration event on 17 June 2017. The calibration coefficient for the rest of the solar channels (not shown) experience little <1% to no change at the 17 June calibration event. The channels 1 and 6 calibration coefficient change of ~1.8% and ~2.5% respectively is consistent with the ABI to in situ comparison jumps in these channels seen in Fig. 15.
5. Summary and discussion

A campaign to collect in situ measurements for the validation of the GOES-16 ABI solar reflective spectral channels was held 14–18 June 2017 at the Salar de Uyuni salt flat in Bolivia. The results show that the accuracy of the ABI reflective channels calibration is within specification for channels 1, 3, 5, and 6 – average biases within 2%. Channel 2 shows large positive bias of ~5%. The estimated uncertainty on the derived biases is 2–2.4%. The bias in Channel 2 reported in this paper is in the same direction as found by other groups over different time periods. A positive bias of 8% in GOES-16 ABI channel 2 is reported by the NOAA GOES-R Calibration working Group (CWG) in an early radiometric performance assessment (Yu et al., 2017); a 7% positive bias is also estimated by airborne field campaign (Bartlett et al., 2018). Currently (April 2019) a radiance correction of 6.9% to the channel 2 radiance is being implemented in the GOES16 ABI operational processing (see www.ospo.noaa.gov/Operations/messages.html).

The results indicate also some stability issues in the ABI calibration at the time of the campaign: (i) a jump on the order of 2% in channels 1 and 6, coincident with an ABI solar calibration event, reflects an instability of the ABI gains in these channels, and (ii) short-term varia-

cility in channels 1 and 2 measurements is due to striping (ABI detector-to-detector calibration differences). These and other imagery issues have been studied and improved since this campaign took place, however, these improvements are only applied forward in time.

Calibration improvements resulting from instrument performance studies can be applied to historical data to improve the accuracy of the time series of ABI. Flagship Earth science sensors such as SeaWIFS, MODIS, Landsat, and VIIRS use historical calibration data and sensor telemetry to derive a high-fidelity time series of accurate and consistent model of instrument response, so the entire data base of sensor data is reprocessed with the most current set of instrument calibration parameters. For example, the MODIS data set is currently in its sixth iteration called “Collection 6” (Toller et al., 2013) and the Landsat data archive was recently baseline to “Collection 1” (Micijevic et al., 2017) using a consistent instrument calibration time series. Also, downstream data products leverage this more accurate calibration time series in addition to implementing algorithm improvements (Levy et al., 2013). The GOES-R series ABI data however is not reprocessed after the initial distribution.

The radiometric, spatial, and spectral improvements of ABI relative to previous geostationary imagers make its performance comparable to the performance of low earth orbit environmental satellite sensors, with the advantage of capturing the diurnal signal with its temporal persistence. The ABI data set will continue through the mid-2030s or further, and, if reliably calibrated, can potentially provide a decades-long environmental record. Reprocessing ABI data would require sensor model development, and data processing resources – which can be acquired at

Table 4
Summary of daily comparisons of ABI-measured TOA reflectance in channels 1, 2, 3, 5, and 6, and predictions based on in situ measurements in units of percent difference (ABI – predicted). The standard deviation presented in the second column for each channel is over all points averaged for a given day. The average percent difference over the five days is also provided in the last row. The standard deviation of the mean over the five days, characterizing the statistical uncertainty of the derived average biases is also listed.

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<th>Channel</th>
<th>B1</th>
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<th>(ABI-predicted [%])</th>
<th>std</th>
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<th>(ABI-predicted [%])</th>
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Fig. 17. Average ABI validation results using the reflectance-based approach of vicarious calibration. The error bars show the standard deviation of the mean over the five campaign days.

4.4. Campaign average reflectance comparison

In this section the temporal results are averaged to provide an assessment of solar reflective channel radiometric validation based on the Salar de Uyuni field campaign. The average over all days of the ABI-measured to ground-based at-sensor reflectance comparison result is shown in Fig. 17 (except channel 4). Each point is the average of the daily average ratios shown in Fig. 15. The standard deviation of the mean, shown as error bars, can be used as an estimate of the random error on the average bias derived in this comparison. The results are also tabulated in Table 4, which summarizes the ABI-measured to predicted TOA reflectance biases for each day (rows 1–5) of the campaign, as well as the average biases over the five days (row 6).

The average biases between the ABI measurements and the predicted TOA reflectance, over all days, are within 2% for channels 1, 3, 5, and 6. Channel 2 shows about 5% positive bias. Channel 4 is not discussed due to the large uncertainty in the in situ-based TOA prediction at 1.38 μm.

The statistical uncertainty of the derived biases between ABI-measured and predicted TOA reflectance is small (see the last row of Table 4) due to the extensive data set. Combining the statistical uncertainty with the estimated 1% observer-dependent bias in the surface reflectance measurement (see Section 3.6), 1% uncertainty of the surface reflectance measurement propagation through the atmosphere, and the 1.1–1.9% uncertainty of the reflectance reference characterization, yields an uncertainty of about 2–2.4% on the derived biases.

Table 4

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a small fraction of the cost of sensor development, launch, and operation of the GOES-R series of satellites – and would provide a unique signal complementary to current observation fleet of sensors for accurate Earth science studies.

Declarations of interest

None.

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