Sentinel-2A MSI and Landsat-8 OLI radiometric cross comparison over desert sites

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ABSTRACT

The Sentinel-2A and Landsat-8 satellites carry on-board moderate resolution multispectral imagers for the purpose of documenting the Earth’s changing surface. Though they are independently built and managed, users will certainly take advantage of the opportunity to have higher temporal coverage by combining the datasets. Thus it is important for the radiometric and geometric calibration of the MultiSpectral Instrument (MSI) and the Operational Land Imager (OLI) to be compatible. Cross-calibration of MSI to OLI has been accomplished using multiple techniques involving the use of pseudo-invariant calibration sites (PICS) using direct comparisons as well as through use of PICS models predicting top-of-atmosphere reflectance. A team from the University of Arizona is acquiring field data under both instruments for vicarious calibration of the sensors. This paper shows that the work done to date by the Landsat and Sentinel-2 calibration teams has resulted in stable radiometric calibration for each instrument and consistency to ~2.5% between the instruments for all the spectral bands that the instruments have in common.

ARTICLE HISTORY

Received 29 June 2017
Revised 11 May 2018
Accepted 30 July 2018

KEYWORDS

Landsat; Sentinel-2A; OLI; MSI; radiometric calibration

Introduction

The Sentinel-2A MultiSpectral Instrument (MSI) and Landsat-8 Operational Land Imager (OLI) are on-orbit as part of larger programs to provide systematic global coverage of terrestrial surfaces and coastal regions. These instruments cover the visible, near- and shortwave infrared regions. Landsat-8, with OLI and the Thermal Infrared Sensor (TIRS), continues the 40+ year history of the Landsat program. Sentinel-2, with MSI, builds on the success of the Landsat program with a specific mission objective to provide continuity with Landsat and SPOT, within the context of the European Union’s Copernicus program (ESA, 2017a).

Both the Landsat and Sentinel calibration teams are working to ensure that the instruments are radiometrically calibrated and provide data that are comparable for users. The teams are working independently, with their own methods and tools, but the effort to ensure that OLI and MSI data are compatible is a joint one.

Sentinel-2 MSI

Sentinel-2A was launched on 23 June 2015 from Kourou, French Guiana. The Sentinel-2A orbit has a mean local solar time (10:30 am) close to the local overpass time of Landsat-8 (10:13 am) and that of SPOT-5 (10:30 am), permitting the integration of Sentinel-2 data with existing and historical missions, and contributing to long-term time series data collection. Sentinel-2A’s revisit period is 10 days. Fully operational in combination with Sentinel-2B, launched on 7 March 2017, Sentinel-2 provides a 5-day repeat coverage.

MSI is a 13-spectral band push-broom imager with 12 individual arrays of detectors that cover the 295 km swath width (Table 1). Two of the bands’ relative spectral response curves are shown in Figure 1, along with the corresponding Landsat-8 OLI bands. The spatial resolution of the 13 bands varies between 10 and 60 m. MSI carries a full field-of-view solar diffuser panel that is deployed approximately monthly. The diffuser calibrations provide updates of the absolute gain coefficients for each spectral band and relative gain coefficients for detectors in each array. Complementary vicarious calibration methods are used to validate the estimated absolute gain coefficients.

The visible through near-infrared (VNIR) bands, which are on the warm focal plane, have been stable to within 1% since launch, and within 0.1% since April 2016 (Gascon et al., 2017). The shortwave infrared (SWIR) bands, which are on the cold focal plane, have been affected by icing on the cold optics. The
build-up of ice causes a decrease in the responsivity over time. It is corrected by regular decontamination operations, where the cold focal plane is warmed to melt off the ice. In the worst case, responsivity decreased by as much as 2.5% before a decontamination operation was performed. Over time, the water vapor has dispersed and the ice now builds up more slowly on the focal plane. The changes in the SWIR bands’ responsivities are accounted for in the MSI processing system by a monthly update of absolute gain coefficients.

**Landsat-8 OLI**

Landsat-8 was launched on 11 February 2013 from Vandenberg Air Force Base, California. The revisit period is 16 days; it is 8 days out of phase with Landsat-7, providing 8-day repeat coverage between the two.

OLI is a nine spectral band push-broom imager with 14 individual arrays of detectors to cover the 185 km swath width (Table 1). The spatial resolution of most bands is 30 m; the exception is the 15-m panchromatic (Pan) band. The OLI on-orbit calibration capabilities include: three pairs of "stim" lamps, two full-aperture solar diffuser panels and lunar scanning, achieved by maneuvering the spacecraft to view the moon through the telescope. The three lamp pairs, used at different intervals, along with the monthly acquisitions of the moon are used for stability monitoring; the two diffusers are used weekly and semi-annually for absolute gain determination for each spectral band and relative gain determination for the detectors of each array. Additionally, two university teams regularly (weather permitting) acquire surface and atmospheric measurements in conjunction with the instrument measurements for a vicarious calibration.

Over 4 years on orbit, OLI has been shown to be radiometrically stable to better than 1.5% (Markham & Barsi, 2017). The coastal/aerosol (CA) band has exhibited degradation in radiometric sensitivity over the lifetime (USGS, 2017a), though the degradation has been tracked and was corrected for in the Collection-1 reprocessing effort in February–May 2017 (USGS, 2017b). The other OLI bands were corrected for a small change in sensitivity in September/October 2013 but since then have all remained stable (USGS, 2017a). Validation of the absolute radiometric calibration of OLI has shown the instrument within ±5% in radiance and ±3% in reflectance (Markham et al., 2014).

This paper presents the initial efforts to compare the radiometric response of MSI to OLI. Several techniques are used by the calibration teams represented by the authors. These techniques involve direct comparison of

| Table 1. MSI and OLI spectral band characteristics. |
|-----------------------------------------------|
| Landsat band | MSI band | MSI center wavelength [nm] | MSI spatial resolution [m] | MSI active detectors (#) | OLI band | OLI center wavelength [nm] | OLI spatial resolution [m] | OLI active detectors (#) |
|---------------|-------|--------------------------|-----------------------------|-----------------------|--------|---------------------------|-----------------------------|-----------------------|
| CA            | 1     | 443                      | 60                          | 15552                 | 1      | 443                       | 30                          | 6916                  |
| Blue          | 2     | 490                      | 10                          | 31104                 | 2      | 492                       | 30                          | 6916                  |
| Green         | 3     | 560                      | 10                          | 31104                 | 3      | 561                       | 30                          | 6916                  |
| Red           | 4     | 665                      | 10                          | 31104                 | 4      | 654                       | 30                          | 6916                  |
|               | 5     | 705                      | 20                          | 15552                 |        |                           |                             |                       |
|               | 6     | 740                      | 20                          | 15552                 |        |                           |                             |                       |
|               | 7     | 783                      | 20                          | 15552                 |        |                           |                             |                       |
|               | 8     | 842                      | 10                          | 31104                 |        |                           |                             |                       |
| NIR           | 8A    | 865                      | 20                          | 15552                 | 5      | 865                       | 30                          | 6916                  |
|               | 9     | 945                      | 60                          | 15552                 | 9      | 937                       | 30                          | 6916                  |
| Cirrus        | 10    | 1375                     | 60                          | 15552                 | 9      | 1373                      | 30                          | 6916                  |
| SWIR1         | 11    | 1610                     | 20                          | 15552                 | 6      | 1609                      | 30                          | 6916                  |
| SWIR2         | 12    | 2190                     | 20                          | 15552                 | 7      | 2201                      | 30                          | 6916                  |
| Pan           | 8     | 590                      | 15                          | 13832                 |        |                           |                             |                       |

Figure 1. Relative spectral response curves for two sample common bands of Landsat-8 OLI and Sentinel-2A MSI. The MSI RSRs have been updated to the version 3 release, which has improved the spectral overlap between the Blue bands.
the response to the same targets as well as comparisons between independent absolute calibrations of the two sensors using the same techniques. Pseudo-invariant calibration sites (PICS) in the Sahara Desert are a primary tool for these analyses. They are used here (1) to evaluate the long-term stability, as was done previously for prior Landsat instruments (Barsi, Markham, & Helder, 2012) (stability here being a prerequisite for cross-calibration), (2) to validate the absolute calibration through two different radiometric models, as done by Bouvet (2014) and Mishra, Helder, Angal, Choi, and Xiong (2014) and (3) to directly compare MSI to OLI. Independent vicarious calibrations by the Landsat calibration team of MSI and OLI using the same sites and methods also allow comparison of the two sensors (Czapla-Myers et al., 2015; Thome, Helder, Aaron, & Dewald, 2004). This paper only addresses MSI spectral bands that MSI and OLI have in common and will generally refer to the bands as their spectral “color” or Landsat-8 band number.

An effort to characterize the geometric and alignment differences between MSI and OLI was published by Storey et al. (2016).

Data sources

Sentinel-2A MSI

The standard MSI data product is a radiometrically and geometrically corrected image referred to as Level-1C (L1C). The L1C product contains ortho-rectified scaled top-of-atmosphere (TOA) reflectance. The wide swath image data are subset into tiles of 110 x 110 km based on the Military Grid Reference System and are projected into Universal Transverse Mercator (UTM) space (Gascon et al., 2017). Sentinel-2 L1C products are Standard Archive Format for Europe (SAFE) format, which contains geolocated JPEG2000 images for each spectral band, metadata in XML format and auxiliary data in Geographic Mark-up Language format. Sensor viewing as well as solar illumination angles (zenith/azimuth) for each spectral band are provided on a 5-km grid ((Fletcher, 2015); https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi). Sentinel-2A data are available from the Copernicus Open Access Hub (https://scihub.copernicus.eu), the USGS Earth Explorer (https://earthexplorer.usgs.gov) and the Amazon S3 service (http://sentinel-pds.s3-western-central-1.amazonaws.com). There have been several increments of the processing system but all data used here have been processed with processing baseline 2.00 or higher.

In December 2017, an updated version of the Sentinel-2A MSI relative spectral responses was released to correct some errors in the prelaunch analysis of the spectral data (ESA., 2017b). This paper makes use of the corrected curves, referred to as version 3 (v3) per the spreadsheet version number.

Landsat-8 OLI

The standard Landsat-8 OLI data product is a radiometrically and geometrically corrected image referred to as Level-1TP (L1TP). The L1TP products are digital numbers with coefficients provided to convert the data to either radiance or reflectance. The image data are subset into frames of about 185 x 185 km based on the second World Reference System (WRS2) and are projected into UTM space. The L1TP consists of GeoTIFF images for each spectral band, a quality band and a metadata text file (USGS, 2016). The data are available from the USGS Earth Explorer. The calibration of OLI was updated in early 2017, and the entire archive was reprocessed into Collection-1. All of the OLI results presented here were generated with Collection-1 data.

Pseudo-invariant calibration sites

PICS are spatially and temporally uniform locations on Earth which can be monitored easily from space. Based on an analysis of Meteosat-4 data from July 1989 to January 1990, Cosnefroy, Leroy and Briottet (1996) identified a set of twenty 100 x 100 km locations across the Sahara Desert and the Arabian peninsula that met specific criteria: “good spatial uniformity [of about ~3% from the table] and temporal stability, minimal directional variations, minimal cloud cover and minimal atmospheric variability associated with changes of aerosols and water vapor amounts” (Cosnefroy, 1996, 103).

Much more data have become available since that initial study based on six years of Meteosat data. Additional characterization was done on four years of MERIS data, which further confirmed the spatial and temporal stability of the sites but also suggested that the defined sites were too large for most higher resolution imagers (Lacherade, Fougnie, Henry, & Gamet, 2013). An optimized 20 x 20 km region was defined for each site; these region boundaries are referred to as the Committee on Earth Observation Satellites (CEOS) sites.

The three sites used for the OLI and MSI comparison are a subset of the CEOS sites (Table 2). Within the Landsat team, only a subset of CEOS sites have been regularly used for analysis; these were based on historical site coverage and early assessment using Landsat-7 (using only two years of data). For example, the only one of the original list that was regularly acquired by Landsat-5 was Libya-4, so Libya-4 plays an important role in the long-term continuity of the Landsat archive (Markham & Helder, 2012).

Due to the orbital properties of the Landsat-8 and Sentinel-2A, the imagers acquire coincident images of
specific locations on Earth every 80 days. Two of these locations happen to be two of the PICS regions used in the analysis, Libya-4 and Algeria-3. The satellites overpass the two sites within 20 min of each other. Table 3 lists the coincident overpass details.

Every acquisition of the three PICS in Table 2 is considered for use for both MSI and OLI, though cloudy data are removed from the dataset. TOA reflectance is calculated from MSI L1C products or OLI L1TP product. TOA reflectance is calculated slightly differently for the two sensors as the processing systems treat the solar zenith angle differently. The MSI processing system accounts for the per-pixel solar zenith angle, while the OLI processing system does not apply a correction for solar zenith angle at all (USGS, 2016).

Thus, the OLI TOA reflectance is given as

\[
\rho_{\text{OLI}} = \frac{M \times Q_{\text{cal,OLI}} + A}{\cos(\theta_s)}
\]  

(1)

where \(Q_{\text{cal,OLI}}\) is the average count over the OLI region of interest (ROI), \(M\) and \(A\) are reflectance scaling factors found in the OLI metadata\(^1\) and \(\theta_s\) is the solar zenith angle for the ROI as extracted for the solar angle band. The MSI TOA reflectance is given as

\[
\rho_{\text{MSI}} = \frac{Q_{\text{cal,MSI}}}{Q_{\text{QUANTIFICATION_VALUE}}}
\]  

(2)

where \(Q_{\text{cal,MSI}}\) is the average count over the MSI ROI and \(Q_{\text{QUANTIFICATION_VALUE}}\) is the reflectance scaling factors found in the accompanying XML file.

In order to compare the MSI TOA reflectance to the OLI TOA reflectance directly, the spectral band differences must be accounted for. As shown in Figure 1, the spectral bands can be very similar though the differences in spectral response can cause significant differences in the reflectance detected by the two instruments. Teillet, Fedosejevs, Thome and Barker (2007) proposed a

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**Table 2.** Selected PICS used for MSI and OLI comparison. Those listed in parenthesis are used by the DIMITRI analysis.

| Site       | Center (latitude, longitude) | CEOS site corners (latitude, longitude) | Team            | Landsat path/row | Sentinel tile |
|------------|------------------------------|------------------------------------------|-----------------|------------------|--------------|
| Libya-4    | 28.55, 23.39 (28.54, 22.91)  | 28.65, 23.29 28.65, 23.49 28.45, 23.49 28.45, 23.29 | Landsat, Sentinel | 181/40          | 34RGS        |
|            |                              |                                          |                 | (182/40)        | (34RFS)      |
| Sudan-1    | 21.9, 28.0                   | 22.00, 27.90 22.00, 28.10 21.80, 28.10 21.80, 27.90 | Landsat         | 177/45          | 3SQNE, 3SQPE |
| Algeria-3  | 30.32,7.66                   | 30.42, 7.56 30.42, 7.76 30.22, 7.76 30.22, 7.56 | Landsat, Sentinel | 192/39          | 32RLU        |

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**Table 3.** Coincident dates for Libya-4 and Algeria-3 acquisitions. The dates listed are all coincident opportunities since the Sentinel-2A launch though not all are available for comparison; dates listed in bold were acquired by both instruments and are cloud-free. The OLI imaging time is an average of multiple acquisitions. The MSI imaging time is predicted from an orbital model. The view angles were extracted from both instruments’ angle bands.

| Site    | Coincident dates (yyyy.mm.dd) | Approximate OLI acquisition time (GMT) | Approximate MSI acquisition time (GMT) | MSI view angles (average Blue band) | OLI view angles (average Blue band) |
|---------|-----------------------------|----------------------------------------|---------------------------------------|------------------------------------|------------------------------------|
|         |                             |                                        |                                       | Zenith/ Azimuth                    | Zenith/ Azimuth                    |
| Libya-4 | 2015.08.12 2015.10.31 2016.01.19 2016.04.08 2016.06.27 2016.09.15 2016.12.04 2017.02.22 2017.05.13 2015.07.24 2015.10.12 2015.12.31 2016.03.20 2016.06.08 2016.08.27 2016.11.15 2017.02.03 2017.04.24 | 08:54 09:12 | 5.73/97.63 3.25/102.06 |                                    |                                    |
| Algeria-3 | 2015.07.24 2015.10.12 2015.12.31 2016.03.20 2016.06.08 2016.08.27 2016.11.15 2017.02.03 | 10:02 10:22 | 5.56/277.72 3.72/277.96 |                                    |                                    |

\(^1M\) and \(A\) are called REFLECTANCE_MULT_BAND_N and REFLECTANCE_ADD_BAND_N in the L1TP product MTL file, where N is the band number.
method for generating equivalent reflectances using the spectral band adjustment factor (SBAF). The SBAF is target-specific and requires a source of hyperspectral image data to calculate, in this case Hyperion:

\[
SBAF = \frac{\hat{\rho}_{\text{OLI}}}{\hat{\rho}_{\text{MSI}}} = \frac{\int \rho_{\text{h}}(\lambda) RSR_{\text{OLI}}(\lambda) \, d\lambda}{\int \rho_{\text{h}}(\lambda) RSR_{\text{MSI}}(\lambda) \, d\lambda}
\]

where \(\rho_{\text{h}}(\lambda)\) is the per-wavelength reflectance over the ROI from a hyperspectral imager, \(RSR_{\text{OLI}}\) and \(RSR_{\text{MSI}}\) are the per-wavelength relative spectral response curves from OLI and MSI and \(\hat{\rho}_{\text{OLI}}\) and \(\hat{\rho}_{\text{MSI}}\) are the predicted OLI and MSI TOA reflectances based on the integration of the hyperspectral data. Using the SBAF, the MSI TOA reflectance is converted to an OLI-equivalent reflectance (\(\rho_{\text{OLI}}\)).

\[
\rho_{\text{OLI}} = \rho_{\text{MSI}} \times SBAF
\]

The SBAF were calculated using the best available Hyperion acquisitions, attempting to use data acquired close in time to the OLI and MSI acquisitions. A study of the stability of the OLI-to-MSI SBAF over 10 years of Libya-4 data (2004–2014) shows that the seasonal variability is a 0.25% (1-sigma) effect in the worst-case band (Blue). The consistency of the SBAFs across regions for the different sample sizes and acquisition dates suggests that over the Sahara Desert, the spectral differences are independent of season and location.

The resulting average SBAFs for each site are shown in Figure 2 and Table 4. The largest SBAFs are in the Blue and Red bands, where the OLI and MSI RSRs are shifted relative to each other. There is more difference in the Green band across sites; presumably, this is due to the difference in the width of the bandpasses between the two bands.

**Long-term stability**

In order to trend the three PICS together, several additional steps need to be taken to remove systematic differences. The TOA reflectances have some seasonal dependence; an empirical fit to the solar zenith angle is used to normalize the lifetime data for an individual site to a standard reference angle of 52.5° (Barsi et al., 2012). Also, each site has a different brightness, so the corrected TOA reflectances are normalized to 1 by the average of the dataset. Figure 3 shows the trended data for two sample MSI bands for all the three sites.

To assess instrument stability, the slope over time is determined along with a 2-sigma uncertainty on the slope; Table 5 provides the slopes for Libya-4. The MSI change over time is plotted in Figure 4 for all the three sites. The three sites show general agreement within the 2-sigma uncertainty that there is little to no change over the MSI lifetime. The exception is the SWIR2 band which has a positive slope over time. However, the data over the same period of time (June 2015–May 2017) for OLI and Landsat-7 ETM+ indicate similar increases in the SWIR2 band (Figure 5). As a result, it seems more likely that there is a residual seasonal effect due to the short time period than an unaccounted for change in multiple sensors.

While these results indicate that MSI has been stable over its ~2-year lifetime, it has been shown that the PICS stability results are relatively unstable until there are at least 3 years of data (E. Micijevic, personal communication, 8 December 2015). The seasonal variability affects the regression enough that the dataset should include at least three annual cycles. Until then, the regression can be skewed by more or less data in any one season.
Coincident acquisitions

Table 3 lists all the dates for which OLI and MSI could have acquired data within 20 min of each other over Libya-4 and Algeria-3. The dates listed in bold are the cloud-free acquisitions for which the reflectances can be compared directly once the SBAF is accounted for. The reflectance ratio \((R_c)\) is given by

\[
R_c = \frac{\rho_{\text{MSI}}}{\rho_{\text{OLI}}} \quad (5)
\]

Figure 6 shows the reflectance ratio between OLI and MSI for the CA and Green bands. Figure 7 shows the lifetime average reflectance ratios for all the suitable coincident image pairs for all the common OLI and MSI bands. In general, the instruments agree to within 1%. There is less agreement in the CA and Blue bands; though the instruments agree to within 1.5%, the differences between the sites are larger than between the other bands. In the CA and Blue, the reflectances are consistent to within 0.7% (1-sigma) for a given site. This suggests there may be some spectral differences that are not accounted for in the SBAF correction.

The stability of the PICS regions is also evident by the comparison of OLI and MSI image pairs that were acquired up to 6 days apart. There were five coincident image pairs and 28 near-coincident image pairs of Libya-4 between August 2015 and March 2017. Figure 8 shows the trend of MSI with SBAF correction and OLI reflectance over time including both the coincident images and near-coincident images for the VNIR bands. Figure 9 shows the average TOA reflectance ratios for the Libya-4 image pairs. Comparing the results from the coincident to the near-coincident pairs, the lifetime

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Table 3. The OLI to MSI SBAF for three PICS. Different numbers of Hyperion acquisitions were available for each site due to cloud coverage and Hyperion's acquisition schedule.

| Band | Libya-4 \((n = 17)\) | Sudan-1 \((n = 1)\) | Algeria-3 \((n = 2)\) |
|------|----------------|----------------|----------------|
| CA   | 0.995          | 0.996          | 0.994          |
| Blue | 0.964          | 0.967          | 0.966          |
| Green| 1.003          | 1.008          | 1.016          |
| Red  | 0.966          | 0.968          | 0.965          |
| NIR  | 0.996          | 0.996          | 0.997          |
| SWIR1| 0.999          | 0.999          | 0.999          |
| SWIR2| 0.998          | 1.000          | 1.000          |

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Table 5. The PICS-estimated Libya-4 change over time for MSI and OLI as derived from the CEOS small site.

| Band  | OLI change over time ±2-sigma [%/year] | MSI change over time ±2-sigma [%/year] |
|-------|---------------------------------------|---------------------------------------|
| CA    | −0.06 ± 0.51                          | −0.14 ± 0.73                          |
| Blue  | 0.06 ± 0.49                           | 0.27 ± 0.64                           |
| Green | 0.63 ± 0.50                           | 0.60 ± 0.44                           |
| Red   | 0.86 ± 0.52                           | 0.50 ± 0.40                           |
| NIR   | 0.56 ± 0.39                           | 0.04 ± 0.37                           |
| SWIR1 | 0.51 ± 0.36                           | −0.02 ± 0.47                          |
| SWIR2 | 1.96 ± 1.31                           | 1.56 ± 1.31                           |

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Figure 3. The lifetime trends for all three PICS for two MSI bands. The lack of significant slope over time indicates the processed image data are stable.
averages are within 0.5%. This shows that Libya-4 is in fact very stable over the 6-day time period for cloud-free conditions and that given a stable instrument, image pairs do not necessarily need to be acquired on the same date to be used for calibration validation.

**PICS absolute calibration**

The PICS regions are generally inhospitable places that are not easy to access to acquire field data in the traditional mode of vicarious calibration. Two different models are being used to predict the TOA reflectance of the PICS regions using hyperspectral satellite data as the source of the “field” data. This method does not rely on OLI and MSI being coincident, but the same process can be run for both OLI and MSI independently so the model results provide another comparison of the two instruments’ radiometric calibration and consistency.

**South Dakota State University (SDSU) absolute PICS model**

As developed by Mishra (2014), Terra MODIS can be used as a transfer radiometer for the absolute calibration of Libya-4. With a spectral model from Hyperion, a Bidirectional Reflectance Distribution Function (BRDF) model of the site from MODIS and an atmospheric model derived from residual analysis of the seasonal reflectance patterns, the absolute calibration model can be used to predict a TOA reflectance for an area around the Libya-4 region (this analysis uses a custom-defined area around the CEOS Libya-4). The model was validated to ~2% with Terra MODIS, Aqua MODIS, Landsat-7 ETM+, UK-2 DMC and MERIS.
Five pairs of simultaneous Hyperion and Terra MODIS images were used to derive per-band scale factors to adjust the Hyperion radiance integrated over the MODIS bandpass to match the MODIS radiance, in a technique developed by Helder et al. (2013). The scale factors agree to within 3% for each MODIS band for the limited viewing and solar geometries considered. The scale factors for MSI are calculated by a linear interpolation using the values provided by Mishra (2014), and the results are provided in Table 6.

The correction for BRDF is a two-step process; one is the correction for solar zenith angle and the other for viewing zenith angle. A large sample of MODIS image data, limited to sensor view angles of ± 20°, are used to build a linear model of reflectance vs. solar zenith angle and a quadratic model of reflectance vs. viewing zenith angle. An exponential model was fit to the slope of the linear regressions over wavelength to express BRDF as a function of solar zenith angle. The BRDF model for viewing angles required a quadratic model. An exponential model was fit to the quadratic term over wavelengths. The details of these two BRDF models can be found in the work by Mishra (2014).

Figure 6. The ratio between OLI and MSI TOA reflectance for the collection of Libya-4 and Algeria-3 coincident acquisitions for two sample bands. Though the CA results show differences, the individual site results are very consistent.

Figure 7. The average lifetime ratios between coincident acquisitions for the common spectral bands with 1-sigma error bars.
Table 6. The scale factor to convert integrated Hyperion spectral bands to MODIS spectral radiances that correspond to MSI spectral bands. The CA band is extrapolated from the other VNIR band results.

| Spectral band | MODIS band | MSI scale factor (K) | OLI scale factor (K) |
|---------------|------------|----------------------|----------------------|
| CA            | N/A        | 0.9802               | 0.9794               |
| Blue          | 3          | 0.9960               | 0.9911               |
| Green         | 4          | 1.0100               | 1.0082               |
| Red           | 1          | 1.0098               | 1.0163               |
| NIR           | 2          | 0.9900               | 0.9844               |
| SWIR1         | 6          | 0.9900               | 0.9923               |
| SWIR2         | 7          | 0.9700               | 0.9681               |

Table 7. The solar zenith angle and viewing zenith angle corrections for the MODIS radiances.

| Spectral band | Solar zenith angle BRDF model | Viewing zenith angle BRDF model |
|---------------|------------------------------|--------------------------------|
|               | (m1(λ))                     | (m2(λ))                        | (m3(λ))                        |
| CA            | 0.000065                     | -0.000082                       | 0.0000035                      |
| Blue          | -0.000017                    | -0.0000816                      | 0.0000054                      |
| Green         | -0.0000380                   | -0.0000811                      | 0.0000072                      |
| Red           | -0.0000588                   | -0.0000803                      | 0.0000093                      |
| NIR           | -0.0000789                   | -0.0000788                      | 0.0000114                      |
| SWIR1         | -0.0001090                   | -0.0000760                      | 0.0000122                      |
| SWIR2         | -0.001331                    | -0.0001190                      | 0.0000116                      |

Figure 8. The temporal trends of MSI SBAF-corrected reflectance and OLI TOA reflectance for the collected subset of coincident and near-coincident images for a sample of bands.

Figure 9. The average lifetime difference between acquisitions collected on the same day and those collected up to 6 days apart.

Table 7 provides the solar and viewing zenith angle BRDFs as generated by the exponential per-wavelength models for the Sentinel-2A MSI analysis.

The SDSU Absolute PICS (APICS)-model-predicted TOA radiance is

$$ \rho_{\text{model}}(\lambda, \text{SZA}, \text{VZA}) = \frac{K(\lambda) \times \rho_h(\lambda) \times f_a(t)}{1 - (\theta_s - 30°) \times m_1(\lambda) - \theta_v(\lambda) \times m_2(\lambda) - \theta_v^2 \times m_3(\lambda)} $$

where $\theta_s$ is the solar zenith angle, $\theta_v$ is the view zenith angle, $K$ is a scaling factor from Table 6, $\rho_h$ is the simulated spectral reflectance of the scene derived from Hyperion, $m_1$ is the BRDF coefficient for the solar zenith angle derived using Terra and scaled to 30° solar zenith angle and $m_2$ and $m_3$ are the BRDF coefficients for the view zenith angle using Hyperion measurements, and each parameter is specific to an individual sensor’s bandpasses ($\lambda$). The model includes a correction for atmosphere, $f_a(t)$ for day $t$, but the effect is negligible in this study and therefore will not be used.

Table 8 lists some details of the MSI and OLI datasets. Figure 10 illustrates the lifetime results for the common bands for both instruments; the
simulated TOA reflectance is compared to the reflectance extracted from the image data. Figure 11 provides the lifetime average ratios \( R_{\text{APICS}} \) between the image-derived TOA reflectance \( \rho_{\text{image}} \) and APICS-predicted TOA reflectance \( \rho_{\text{model}} \):

\[
R_{\text{APICS}} = \frac{\rho_{\text{image}}}{\rho_{\text{model}}} (7)
\]

The OLI calibration is within about 0.5% of the model prediction for all bands, except CA at 2%. The MSI calibration is within 0.5% except for the Red band, which is within 3%.

**DIMITRI desert absolute calibration model**

The Database for Imaging Multi-spectral Instruments and Tools for Radiometric Intercomparison (DIMITRI; https://dimitri.argans.co.uk) consists of a software package and a database containing remote sensing radiometrically and geometrically corrected products (Level-1) from 2002 until present day for various sensors and is continuously being populated with the latest image data. The DIMITRI software consists of a suite of routines for the comparison of TOA reflectance from Earth observation sensors either sensor-to-sensor or sensor-to-simulation. The DIMITRI database contains Level-1 data from about 10 sensors (among them are

**Table 8. Summary of data used in the SDSU APICS comparison.** The region of interest is a larger area that includes the CEOS Libya-4 site.

| Sensor | Time range  | Number of scenes | Region of interest: size, region corners (latitude/longitude) |
|--------|-------------|------------------|---------------------------------------------------------------|
| OLI    | June 2015–May 2017 | 39              | 65 km by 46 km (28.80, 23.09), (28.37, 23.83) |
| MSI    | Aug 2015–May 2017  | 49              |                                                             |

Figure 10. The APICS results over time for the expanded Libya-4 region for the CA and SWIR1 bands of OLI and MSI.

Figure 11. Average MSI and OLI absolute calibration results for the expanded Libya-4 region over the lifetime of MSI (June 2015–June 2017). Error bars indicate the estimated uncertainty for the SDSU APICS method.
MERIS, Aqua MODIS, Landsat-8 OLI, Sentinel-2A MSI, Sentinel-3 OLCI, Sentinel-3 SLSTR and recently Sentinel-2B MSI) over more than 15 fixed test sites (including desert, ice, ocean and salt flats). Several cloud-screening modules are implemented for an automatic cloud screening of the database. In addition, one can screen for clouds manually. Currently, three vicarious calibration/validation methods using simulated TOA reflectances are implemented into the DIMITRI software – Rayleigh scattering, sun-glint and desert PICS methods. In this study, only the desert PICS method will be used.

The DIMITRI-PICS algorithm can be divided into two steps that aim to simulate the TOA reflectance in the VNIR spectral range over predefined desert sites. The first step consists of building a reference reflectance model for the selected site. TOA measurements from a reference sensor, MERIS in this case, are used for the model calibration (Bouvet, 2014). A database of bottom-of-atmosphere (BOA) reflectance measurements with various acquisition geometries is built using an inverse radiative transfer simulation of the TOA measurements (LibRadtran code; http://www.libradtran.org). This BOA reflectance database is then used to fit a four-parameter BRDF model (so-called RPV-model; Rahman, Pinty, & Verstraete, 1993) for each spectral band. Finally, a hyperspectral model with 1-nm spectral resolution is generated using spectral interpolation.

The second step of the algorithm simulates the observed TOA measurements of the targeted sensor (e.g. MSI) using the reference BRDF model and with consideration for the observation geometry. The atmospheric water vapor and ozone content are provided by the European Centre for Medium-range for Weather Forecasts. Note that a constant aerosol optical thickness is assumed (AOT = 0.2 at 550 nm). Finally, the resulting hyperspectral signal is convolved with the spectral response of the sensor to simulate the TOA reflectance of the sensor under test. The BRDF model is “calibrated” over each PICS site using 4 years of MERIS observations between 2006 and 2009 (inclusive). Then the whole archive of the MERIS third reprocessing campaign (2002–2012) has been used to validate the model (Bouvet, 2014). This method has been used to perform the multi-temporal analysis and intercomparison of multiple sensors over the same site (Francesconi et al., 2017).

Note that the BRDF model is generated for a 1 × 1° area of the CEOS-defined test site. The impact of the site size on the BRDF model has been assessed over the subsampled CEOS region, and correction is applied when needed over the VNIR spectral range. All available MSI L1C products over the PICS acquired between July 2015 and May 2017 were ingested to the DIMITRI database. More than 140 Landsat-8 L1TP products over six PICS (among them 29 products over Libya-4) between July 2015 and May 2017 were ingested into the DIMITRI database. Then, the data from both sensors are automatically cloud-screened by DIMITRI and manually verified.

In order to perform the intercomparison between MSI and OLI, only the clear scenes have been selected over PICS sites (Table 2), and only results for Libya-4 are presented here. Note that MERIS only has spectral bands through the NIR, so the SWIR bands cannot be assessed with this method.

The ratio of the observed reflectance \( (\rho_{\text{image}}) \) to DIMITRI-PICS simulated reflectance \( (\rho_{\text{model}}) \) is computed as

\[
R_{\text{DIMITRI}} = \frac{\rho_{\text{image}}}{\rho_{\text{model}}} \quad (8)
\]

The ratio can be trended over time to monitor the stability of both sensors. Figure 12 exhibits the ratios of CA, Red and NIR bands over time for both instruments. The time series of the MSI CA band is stable at a ratio value of 0.997 with a slight scattering reflected by a standard deviation of about 1.14%. The time series of the OLI CA band is similar at about 0.991 and a standard deviation of 1.2%. Red and NIR bands time series from both sensors show the similar patterns (Figure 12) though the OLI Red band standard deviation is higher than MSI by ~0.4%.

Figure 13 summarizes the temporal average of the ratios over the common VNIR bands from both sensors over Libya-4 test site. The results from both sensors are consistent within 1.5% for OLI and 0.5% for MSI. The results illustrate good consistency between the sensors in terms of radiometric calibration and image qualities.

Vicarious calibration

In spite of the value of the PICS analysis to provide an assessment about the long-term stability and absolute calibration of a sensor, it is still valuable to have measurements at accessible sites, where the entire radiometric chain can be considered without assumptions about stability of the site or the atmosphere. The University of Arizona (UAz) is making surface measurements under OLI and MSI at Railroad Valley (RRV) Playa, Nevada.

UAz radiometric calibration test site (RadCaTS)

The remote sensing group (RSG) of the College of Optical Sciences at the UAz has designed and developed an automated approach to the traditional ground-based vicarious radiometric calibration. The RadCaTS was established at RRV, Nevada, to acquire suitable data for ground-based vicarious calibration without the need for on-site personnel
The current RadCaTS configuration consists of instruments that are used to measure the surface reflectance and also the atmosphere. Surface reflectance measurements are made using multispectral ground-viewing radiometers (GVRs), which collect data throughout the day and night (Anderson et al., 2013). A representative sample of the RRV surface reflectance is shown in Figure 14. There are currently five GVRs at RadCaTS, four of which view the ground in a nadir configuration. The fifth GVR views the ground.
in a GOES 16 configuration for RSG’s calibration work with the advanced baseline imager (ABI) sensor (Figure 15). Atmospheric measurements are made using a Cimel sun photometer, which is part of the Aerosol Robotic Network (AERONET) (Holben et al., 1998). In the spring of 2017, RSG deployed a new Cimel CE318-T. A meteorological station is also present at RadCaTS to measure air temperature, wind speed and direction, barometric pressure and precipitation. All of the GVRs and the meteorological station use WiFi to connect to a central base station that relays the data to the UAz via a satellite uplink. Data are uploaded on a daily basis for processing. The surface reflectance and atmospheric quantities are used as inputs in a radiative transfer code and, with a solar irradiance model, are converted to TOA quantities of interest (e.g. spectral radiance or reflectance). Currently, RadCaTS uses the MODTRAN radiative transfer code and can use either the ChKur or the Thuillier solar irradiance models.

RadCaTS is being used for a variety of Earth-observing sensors such as Landsat-7 ETM+, Landsat-8 OLI, Sentinel-2A MSI, MODIS, ASTER, Suomi NPP VIIRS, RapidEye and most recently, ABI. Currently, each GVR takes a measurement every 2 min throughout the day, but the thermoelectric cooler that controls the focal plane temperature is only on when clear-sky conditions exist. This is done to conserve power, since the system is charged completely by a solar charging system. The Cimel makes measurements throughout the day using the standard AERONET collection protocol, and the data are uploaded to NASA Goddard Space Flight Center for processing and distribution through the AERONET web portal.

RadCaTS has been operational in its current form since 2012, which means that it has been available for both Landsat-8 OLI and Sentinel-2A MSI since their launches. Landsat-8 passes over RRV with a nadir view angle every 16 days in path/row 40/33, while Sentinel-2A has near-nadir overpasses at RRV.
approximately six times per month in tile 11SPC (~6° and ~11° view angles). Clouds at the site are the primary reason for unsuccessful collects, but water or snow on the surface also constitutes a bad day. There were various times throughout this work when not all GVRs were available to measure the 1-km² ROI at RadCaTS. In these cases, the ROI in the satellite imagery was reduced accordingly to reflect the number of GVR measurements available.

The summary of results presented here are from the period of March 2013 to May 2017 in the case of Landsat-8 OLI and from August 2015 to May 2017 in the case of Sentinel-2A MSI. During these periods, there were 13 successful RadCaTS collects for OLI and 25 for MSI. For this analysis, the ChKur solar irradiance model was used for both instruments. In both cases, the image-derived reflectance \( \rho_{\text{image}} \) was compared to the TOA reflectance determined using RadCaTS \( \rho_{\text{model}} \):

\[
R_{RRV} = \frac{\rho_{\text{image}}}{\rho_{\text{model}}}
\]

Figure 16 shows the lifetime average TOA reflectance ratios for the common OLI and MSI bands. Across all bands in both instruments, the image-derived reflectance agrees with the RadCaTS predicted reflectance within 4%. But the more significant result is that OLI and MSI agree within ~2.5% across all common bands.

### Summary of results

The Landsat and Sentinel calibration teams have used multiple methods and datasets to assess the radiometric stability, the radiometric calibration of MSI relative to OLI and the absolute calibration of both instruments relative to several different models. There are some residual differences with some bands and some techniques, but the instruments generally agree.

Monitoring the TOA reflectance with selected PICS reveals that the processed MSI data are stable in all bands with possible exception of SWIR2, which may indicate some brightening (Figure 4). However, the same increase shows up for the OLI SWIR2 band (Figure 5), suggesting the sensors are not changing (to within the sensitivity of the analysis) but rather there is some residual effect that has not been modeled out of the data. Neither instruments’ calibration over time should be changed based on this assessment.

The OLI and MSI TOA reflectances were compared directly (after correcting for sun angle and spectral differences) over PICS regions for coincident image pairs (~20 min apart) and for image pairs acquired up to 6 days apart. These comparisons indicate how consistently MSI is calibrated relative to OLI. The Green, Red, NIR, SWIR1 and SWIR2 bands show very good agreement, within 1.5% for the worst of these bands (Figure 7). There are larger differences in the CA and Blue than in the other bands, though within specific PICS the variation is small, which may indicate some residual spectral or atmospheric difference that is not being corrected.

The absolute calibration of the sensors is validated by several different models that predict TOA reflectance based on sources external to the sensors: the SDSU APICS model, DIMITRI-PICS and the field efforts at RRV. The DIMITRI-PICS absolute calibration model only functions in the VNIR bands, whereas the SDSU and UAz models work over all spectral bands. Using DIMITRI-PICS, the results for both sensors are calibrated to within 2% for all bands (Figure 13). The SDSU APICS model estimates indicate both instruments are calibrated.
within 0.5% except for the MSI Red band (3%) and OLI CA band (2%) (Figure 11). The RadCaTS RRV estimates that OLI and MSI are calibrated to within 4% across all bands (Figure 16).

In order to isolate the possible differences between the sensors and neglect systematic errors in the absolute calibration models, consider the ratio between the ratios:

\[ R_d = \frac{R_n_{\text{MSI}}}{R_n_{\text{OLI}}} \]  

(10)

where \( R_n \) is the per-band instrument result from one of the absolute calibration models from Equations 7, 8 and 9. Figure 17 shows the ratio differences for the four absolute calibration models with error bars indicating the uncertainty in terms of a standard deviation of the mean in each method (so they do not include all model uncertainties, e.g. those in the adjustments for the differences in the spectral bands between the sensors). With few exceptions, all models agree across all common bands that the instruments are calibrated to within ~2.5% of each other.

While each method is independent, taken as a whole, there is no overwhelming evidence that MSI is miscalibrated within the levels of uncertainties in the methods. Where there are results that indicate a miscalibration (i.e. SDSU APICS of MSI Red at 3%), the other methods do not generally support it. And comparing the instruments directly suggests there may be some systematic errors still present in the models, rather than there being issues with OLI or MSI. At this point, with 2 years on orbit, MSI appears to be stable and calibrated across all bands in common with OLI to within ~2.5%.

**Conclusions**

The Sentinel-2A MSI sensor and the Landsat-8 OLI sensor are continuing the mission of providing a moderate resolution, multispectral record of the Earth. The Landsat and Sentinel calibration teams are working to verify that the OLI and MSI data can be used together, to provide higher temporal resolution for users who want to combine the datasets. The stability of both instruments is monitored using PICS regions, and the data suggest that both instruments are stable once the data are processed with the time-appropriate processing parameters (i.e. to account for the MSI contaminant in the SWIR bands and the OLI CA band degradation). The collection of relative and absolute calibration efforts indicates differences between the two instruments generally smaller than the uncertainties in the processes, and therefore not significant, indicating that an adjustment of either of the sensor’s calibrations is not warranted.

Users of Landsat-8 OLI and Sentinel-2A can use the products together, though need to take care to account for differences in spectral reflectances due to the differences in the spectral response curves of the instruments.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

The University of Arizona work was supported by NASA under grant number NNX16AH44G and USGS under grant
number G14AC00371. The South Dakota State University work was supported by NASA under grant number NNX15AP36A and USGS EROS under grant number G14AC00370. The ARGANS work was supported by ESA via the Sentinel-2 Mission Performance Centre under the contract number 4000108650/13/I-LG and via DIMITRI project under the contract number 4000114544/15/I-SBo.

References

Anderson, N., Czapla-Myers, J., Leisso, N., Biggar, S., Burkhart, C., Kingston, R., & Thome, K. (2013). Design and calibration of field deployable ground-viewing radiometers. Applied Optics, 52, 231–240.

Barsi, J.A., Markham, B.L., & Helder, D.L. (2012). Continued monitoring of Landsat reflective band calibration using pseudo-invariant calibration sites. IEEE International Symposium on Geoscience and Remote Sensing (IGARSS) (pp. 7007–7010). doi: 10.1109/IGARSS.2012.6351958

Bouvet, M. (2014). Radiometric comparison of multispectral imagers over a pseudo-invariant calibration site using a reference radiometric model. Remote Sensing of Environment, 140, 141–154.

Cosnefroy, H., Leroy, M., & Briottet, X. (1996). Selection of a reference instrument to characterize of Saharan and Arabian desert sites for the calibration of optical satellite sensors. Remote Sensing Environment, 58, 101–114.

Czapla-Myers, J., McCorkel, J., Anderson, N., & Biggar, S. (2017). Earth-observing satellite intercomparison using the Radiometric Calibration Test Site at Railroad Valley. Journal Applications Rem Sensing, 12. doi:10.1117/1.JRS.12.012004

Czapla-Myers, J., McCorkel, J., Anderson, N., Thome, K., Biggar, S., Helder, D., ... Mishra, N. (2015). The ground-based absolute radiometric calibration of Landsat 8 OLI. Remote Sensing, 7, 600–626.

ESA. (2017a). Retrieved June 22, 2017, from. https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-2/mission-objectives.

ESA. (2017b). Retrieved January 15, 2018, from https://sentinels.copernicus.eu/web/sentinel/news/-/asset_publisher/xR9e/content/new-sentinel-2a-spectral-response-functions.

Fletcher, K. (2015). Sentinel-2: ESA’s optical high-resolution mission for GMES operational services. AG Noordwijk, The Netherlands: ESA Communications. ISBN:978-92-9221-419-7.

Francescon, B., Neveu-VanMalle, M., Espesset, A., Alhammoud, B., Viallefont, F., Bouzinac, C., ... Gascon, F. (2017). Image quality validation of Sentinel 2 Level-1 products: Performance status at the beginning of the constellation routine phase. Proceedings Volume 10423, Sensors, Systems, and Next-Generation Satellites XXI. doi:10.1117/12.2276847

Gascon, F., Bouzinac, C., Thépaut, O., Jung, M., Francescon, B., Louis, J., ... Fernandez, V. (2017). Copernicus Sentinel-2A calibration and products validation status. Remote Sensing, 9, 584.

Helder, D., Thome, K.J., Mishra, N., Chander, G., Xiong, X., Angal, A., & Choi, T. (2013). Absolute radiometric calibration of Landsat using a pseudo invariant calibration site. IEEE Transactions Geosci Remote Sensing, 51, 1360–1369.

Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., & Smirnov, A. (1998). AERONET—a federated instrument network and data archive for aerosol characterization. Remote Sensing Environment, 66, 1–16.

Lacherade, S., Fougnie, B., Henry, P., & Gamet, P. (2013). Cross calibration over desert sites: Description, methodology, and operational implementation. IEEE Transactions on Geoscience and Remote Sensing, 51, 1098–1113.

Markham, B.L., & Barsi, J.A. (2017). Landsat-8 operational land imager on-orbit radiometric calibration. In: IEEE International Symposium on Geoscience and Remote Sensing (IGARSS) (pp. 4205–4207). Fort Worth, TX. doi: 10.1109/IGARSS.2017.8127929.

Markham, B.L., Barsi, J.A., Kvaran, G., Ong, L., Kaita, E., Biggar, S., ... Helder, D.L. (2014). Landsat-8 operational land imager radiometric calibration and stability. Remote Sensing, 6, 12275–12308.

Markham, B.L., & Helder, D.L. (2012). Forty-year calibrated record of earth-reflected radiance from Landsat: A review. Remote Sensing of Environment, 122, 30–40.

Mishra, N., Helder, D.L., Angal, A., Choi, J., & Xiong, X. (2014). Absolute calibration of optical satellite sensors using Libya 4 pseudo invariant calibration site. Remote Sensing, 6, 1327–1346.

Rahman, H., Pinty, B., & Verstraete, M.M. (1993). Coupled surface-atmosphere reflectance (CSAR) model 2, semi empirical surface model usable with NOAA advanced very high resolution radiometer data. Journal of Geophysical Research, 98, 20791–20801.

Storey, J., Roy, D.P., Masek, J., Gascon, F., Dwyer, J., & Choate, M. (2016). A note on the temporary misregistration of Landsat-8 operational land imager (OLI) and Sentinel-2 multi spectral instrument (MSI) imagery. Remote Sensing of Environment, 186, 121–122.

Teillet, P.M., Fedosejevs, G., Thome, K.J., & Barker, J.L. (2007). Impacts of spectral band difference effects on radiometric cross-calibration between satellite sensors in the solar-reflective spectral domain. Remote Sensing of Environment, 110, 393–409.

Thome, K.J., Helder, D.L., Aaron, D., & Dewald, J.D. (2004). Landsat-5 TM and Landsat-7 ETM+ absolute radiometric calibration using the reflectance-based method. IEEE Transactions on Geoscience and Remote Sensing, 42, 2777–2785.

USGS. (2016). Landsat 8 (L8) data users handbook. Retrieved June 22, 2017, from https://landsat.usgs.gov/sites/default/files/documents/Landsat8DataUsers HandBook.pdf.

USGS. (2017a). Retrieved June 22, 2017, from https://landsat.usgs.gov/april-25-2017-oli-radiometric-calibration-updates-collection-1-processing.

USGS. (2017b). Retrieved June 22, 2017, from https://landsat.usgs.gov/may-10-2017-landsat-4-8-collection-1-processing-complete.