Multiple-instrument-based spectral irradiance of the Moon

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Abstract. A model of lunar spectral irradiance incorporates data from multiple spacecraft and surface telescopic observations. Using 12 data sources derived from 90,000 lunar images, models that are smooth across both geometry and wavelength and involve only about 35 derived coefficients are found with a mean weighted residual of <0.5%. An irradiance libration model derived from lunar orbiter observations is used to reduce the number of coefficients required. Derivation uses iterative assignment of a single scaling factor for each band in each instrument, which is effectively the long-term lunar calibration coefficient for that band. Calibration of 26 instruments and two other published models reveals that although eight instruments agree within about 3% over 400 to 840 nm, some large biases exist. The model provides a sensitive assessment of instrument response trends. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.JRS.16.038502]

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1 Introduction

Spacecraft instruments are calibrated in laboratory conditions against traceable standards, but their on-orbit response is often different and may continue to change for years. The Moon’s surface is available to Earth-orbiters and is an extraordinarily stable diffuse reflector, 10⁻⁸ per annum.¹ However, what is needed for calibration is the spectral irradiance from this surface as illuminated by the Sun and viewed by spacecraft over a range of geometries, i.e., a lunar model. Lunar calibration,² which compares an instrument-reported irradiance of the Moon to the “actual” irradiance, has been based largely on the Robotic Lunar Observatory (ROLO) model,³ or its later implementation by the Global Space-based Inter-Calibration System (GSICS) as GIRO.⁴,⁵ The ROLO model, however, has several known issues. Its uncertainty is thought to be about 5%⁶,⁷ or more [Ref. 8, Fig. 9(b)], the libration terms are constant over wavelength, and it requires 328 coefficients to generate results at 32 quite irregularly spaced wavelengths, which are then interpolated or convolved to the desired band. Conceptually, one could calibrate using radiance for a specific part of the Moon, but this is challenging due to the variegation of the Moon; radiance calibration has been used for lunar orbiters with ~100-m resolution.⁹

There have been several efforts to improve knowledge of lunar irradiance. Miller and Turner¹⁰ developed a model to provide an estimate of lunar illumination of Earth scenes; however, it does not consider waxing/waning differences or libration. In a three-color mapping of lunar reflectance from 2593-m elevation based on calibration against the Sun, Velikodsky et al.⁸ found the average ROLO albedo 13% lower than their observations. Wang et al.¹¹ have acquired lunar irradiance measurements over 400 to 1000 nm at a few phase angles with a calibrated imaging spectrometer from a high-altitude site; comparison indicates that the ROLO model is about 8% low. The lunar irradiance model of the European Space Agency (LIME) is based on six-band CIMEL observations from Tenerife.¹² At least three flight investigations are planned or active.¹³

The objective here of the spectral lunar irradiance model (SLIM) system is to utilize many data sources and a new methodology (SLIMED) to generate a significantly improved lunar

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spectral irradiance model over the Solar-reflectance range, 350 to 2400 nm. Data for 25 instruments have been accumulated, more sources exist but were not available. From calibration using the ROLO model, it was known that gain differences were significant. Thus, the ability to apply an empirical gain to each instrument band is essential in combining many sources. Calibration by operating the resulting model allows an improved sensitivity and reliability in the measure of trends.

1.1 Radiometric Nature of the Moon

The Moon’s surface has been in virtually the same environment since formation; the last major volcanic eruptions appear to have been in late Eratosthenian, \( \sim 1.2 \) billion years ago.\(^{14,15}\) Its global photometric stability, based on cratering rates and the associated local albedo change, is \( 10^{-8} \) per annum.\(^{1}\) The Moon appears gray to the eye, but its reflectance increases about a factor of 3 from 400 to 2500 nm. Its spectral reflectance is smooth apart from weak broad bands associated with FeO near 950 and 2000 nm.

In addition to the obvious change in brightness associated with the fractional illumination change through the month, the surface photometric function is near Lomell–Seeliger with a small mix of Lambertian. The albedo increases sharply at small phase angles, called “the opposition effect” associated with coherent back-scattering and shadow-hiding [Ref. 16, Chap. 9]. From the Earth, the study of the opposition effect is limited by onset of lunar eclipse near 1.6 deg but lunar orbiters can measure this to 0 deg. Using lunar reconnaissance orbiter data in a study of small phase angles, Velikodsky et al.\(^{17}\) found that the width of the coherent-backscattering opposition effect ranges from 1.2 deg to 3.9 deg, dependent on wavelength and surface type. Thus, phase angle \(< \sim 4\) deg remains a region to be avoided for calibration.

Lunar soil reflectance is weakly dependent upon temperature, <1% per 100 K relative reflectance, particularly near the FeO bands.\(^{18}\) This is not treated explicitly in SLIM but is indirectly addressed through terms involving subsolar longitude and wavelength; the degree in wavelength would need to be five or more to isolate the FeO bands. Light reflected from the Moon is weakly polarized [Ref. 19, Fig. 8]. Lunar irradiance polarization is negative at small phase angle \( g \), with a minimum \( \sim 1.2\% \) near 10 deg, zero near \( g \approx 25\) deg (wavelength dependent\(^{20}\)), positive thereafter with a maximum beyond 90 deg of 6.6% (waxing), and 8.8% (waning). Modern measurements of the polarization of lunar light have been discussed extensively by Shkuratov et al.\(^{21}\)

The impact of lunar light polarization on calibration depends upon the polarization sensitivity of the instrument. The ROLO and NIST telescopes were designed to be polarization insensitive, but spacecraft instruments can have significant polarization sensitivity, particularly those using scan mirrors. SLIM models do not currently consider polarization.

1.2 Terminology

For lunar modeling, the direction from the center of the Moon to the spacecraft vehicle or viewer is the sub-viewer selenographic longitude “\( V_{\lambda} \)” or \( x \) and latitude “\( V_{\phi} \)” or \( y \); together called “libration.” The abbreviations and symbols are specific to this work. The direction to the Sun is expressed as the subsolar selenographic longitude “\( H_{\lambda} \)” or \( h \) and latitude “\( H_{\phi} \)” or \( z \). The key parameter is the signed phase angle \( p \), this increases in time through a lunation, becoming positive discontinuously at full Moon. The absolute value of phase angle, \( g \), is used in most equations, as is \( q \equiv 1/g \). Wavelength \( \lambda \), is usually shown in nanometers, however a value called “wave” or \( w \) based on micrometers, \( \mu m \), is used in calculations.

2 Method and Materials

Within SLIM, all spectra are resampled onto a set of points starting at 300 nm and spaced by \( \lambda/1000 \), the last point is 2481.8 nm. For example, the reference solar spectrum \( S_0(\lambda) \) (25,281 points, see Sec. 2.3), and the lunar albedo reference spectrum (LARS) \( R_0(\lambda) \) (221 points, see Sec. 2.1) are put on this 2115 point system; their product times the geometric factor \( \Omega/\pi \) is the lunar irradiance reference spectrum (LIRS), see Fig. 1. \( \Omega \) is the solid angle of the Moon at
standard distance, illuminated or not; \( \Omega = 6.41780 \times 10^{-5} \) steradian. The system-level relative spectral response \( T(\lambda) \) of each instrument band \( j \) is put on this point set and then combined with the LIRS to determine the equivalent width and the effective wavelength for the Moon

\[
\lambda_{eq} = \frac{\int_{\lambda_1}^{\lambda_2} \lambda \cdot S_{0}(\lambda) R_{0}(\lambda) T_{j}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S_{0}(\lambda) R_{0}(\lambda) T_{j}(\lambda) d\lambda},
\]

which is used throughout SLIMED models and calibration. The use of an effective wavelength is a rough approximation for panchromatic bands. Because of this, bands with an equivalent width/effective wavelength ratio of >0.2 are not used in model development. For calibration, wide bands can easily use a few weighted effective wavelengths spread across the band, which has not been done here. For practicality and to reduce noise, spectrometer data are averaged onto 27 flat-topped synthetic bands aligned with common spacecraft bands and intervening gaps.

### 2.1 Theory

The SLIMED model treats the effective spectral reflectance of the lunar disk \( R(\lambda) \) viewed from the region of the Earth (out to geosynchronous orbit) as represented by \( R_0(\lambda) \) multiplied by some continuous function of wavelength and photometric angles. The SLIM system allows a general dependence upon “wave” \( w \), which may be wavelength in micrometers \( \lambda_1 \), or its inverse \( \lambda_2 \equiv 1/\lambda_1 \) or its natural log \( \lambda_3 \equiv \ln \lambda_1 \). Here, the log form is used unless explicitly stated otherwise.

Although the core of lunar models is lunar reflectance, the product is a lunar spectral irradiance \( E \) in the form

\[
E_{\odot}(\lambda) = S_{\odot}(\lambda, t) \frac{\Omega}{\pi D} R_0(P, \lambda) L(P, w) B(P, w).
\]

![Fig. 1](Fig1.png) The SLIMED Base model (see Sec. 4) at the effective wavelength of the 27 synthetic bands wavelengths (solid line), although the SLIMED models are continuous over wave. Phase angles 7 deg, 28 deg, and 55 deg are shown (color legend) for both waxing (negative) and waning Moon. Diamonds are the reference Moon at these wavelengths. Orange dots are the reference Moon on the SLIM uniform proportional resolution system, showing its full resolution.
Here, $S_\odot(\lambda, t)$ is the solar spectral irradiance at 1 astronomical unit (AU); this may be treated as constant or variable, as discussed in Sec. 2.3. $D$ is the “distance factor” $d_v d_H^2$, where $d_v$ is the distance from the Moon’s center to the viewer normalized to a standard distance of 384,400 km, near the mean Earth:Moon separation; and $d_H$ is the Sun:Moon distance in AU. The distance factor used is based on $1/r^2$ irradiance, which ignores the small potential effect due to seeing less of the Moon when it is closer. Numerical simulation using the lunar orbiter laser altimeter (LOLA) map (Sec. 2.2) shows this approximation to be good at 0.044% for $g \leq 65$ deg.

The last three terms together constitute $R_\odot(\lambda, P)$, the SLIM model of lunar disk-equivalent-reflectance (DER), which is a function of wavelength and photometric angles represented by $P$. Five angles, $p, x, y, z, \text{ and } h$ with four independencies, comprise $P$; only odd powers of $h$ are allowed to avoid near-degeneracy with even powers of $p$. $R_\odot(\lambda)$ is the high-resolution nominal lunar reflection spectrum based on laboratory measurements of returned Apollo samples; the 5% breccia mix used by ROLO$^2$ has been retained to make the LARS. Errors in the LARS that are higher in frequency than the wave polynomials will propagate into the mean calibration spectrum of each instrument.

$L$ is a libration model (MapLib) derived here based on global lunar maps of spectral reflectance made from observations by spacecraft orbiting the Moon, see Sec. 2.2. It has the form

$$L(P_i, w_j) = \sum_k d_k[l_1, l_2, l_3, l_4, l_5] \cdot [x, y, z, x^2, y^2, xz, yz, xy] + \sum_d d_i w_i$$

and

$$L(P_i, w_j) = \exp L(P_i, w_j),$$

(3)

where $\mathcal{L}$ represents the 54 cross-terms of the two sets in brackets. Any subset of the 108 terms can be selected to include in a fit, see Table 3. For increased numerical stability of the fit, all the independent variables are scaled to the order of 1; $p$ is in radians, $x$ and $y$ are degrees/10 and $z$ is in degrees. These maps were made at photometric geometries particular to each lunar mission and are quite different from the geometry of Earth-orbiting observations in avoiding the strong slope emphasis near the limb.

$B$ carries the variation of the lunar irradiance over angles and wavelength in the form

$$B_{ij}(P_i, w_j) = \sum_k^{K} F_k(P_i) \sum_{m=0}^{M_k} c_{km} w_j^m$$

and

$$B(P_i, w_j) = \exp B_{ij}(P_i, w_j),$$

(4)

where $i$ is an observation index, $j$ is a band index, $k$ runs over the selected geometric basis functions (BF) $F$. The $F_k$ terms involve the angles comprising $P$ and some cross-products; each may be polynomials of low degree. $M_k$ is the degree in wave for each of the $k$ terms and $c_{km}$ are the model coefficients. $p$ and $h$ are expressed in radians; $x, y,$ and $z$ are in degrees.

Model generation requires finding the coefficients $c_{km}$ of $B$ [Eq. (4)] for the least-squares best fit to the instrument observations adjusted to standard distances

$$E_\odot(\lambda_j) = S_\odot(\lambda_j) \frac{\Omega}{\pi} R_\odot(P_0, \lambda_j) [1 + \mathcal{H}(\lambda_j, t)] L(P_i, w_j) B(P_i, w_j) G_j,$$

(5)

where $t$ is the time of observation. Uncertainties are assigned to all measurements $E_{ij}$. Everything else is known except the empirical gains $G_j$, which are found from the residuals by iteration. Once $G$ is incorporated, each instrument can contribute to filling in the sparsely populated illumination-observation geometry space. Once the $L$ and $B$ coefficients are known, Eq. (5) without the $G$ term can be used to compute irradiances at standard distance for any observation; this is the SLIMED model. To adjust the desired total weight of an instrument, e.g., to avoid one instrument dominating a SLIMED model, a “heft” term is included, which multiplies all the weights (1/$\sigma^2$) of an instrument.
Judgment choices include which instruments to use, the heft assignments, which geometric BFs to include, and the wave-degree for each. Empirical gains are initially set to unity and a set of three least-squares fits are done, rejecting points with residuals outside 3σ after each of the first two fits. The resulting mean weighted residual for each band is the basis for the gains applied for the next iteration, at the start of which the rejected points are reincluded.

A potential problem is finding the global minimum in a 168-dimensional space, the number of bands fit. To aid in this, the gain change at each iteration is limited based on a probability that is scaled to the average uncertainty of valid points for the band, typically significant only for the first iteration. For a band mean residual $r$, the change of ln gain is

$$\Delta = r\left[f_1 < 2\left(1 - P\left(\frac{|r|}{U}\right)\right) < f_2\right].$$

$P(x) \equiv \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-t^2/2} \, dt$ is the Gaussian probability function, [Ref. 25, Sec. 26.2.2]. The function between limit signs is a monotonic decreasing positive function near 1 for small $r$. $f_2$ provides a general damping factor on changes for all steps, initially 0.7; after three iterations, it is set to 0.9. $f_1$ is arbitrarily set at $\frac{1}{3}$. A large number of iterations is done to converge on the minimum.

### 2.2 Libration Terms from Spacecraft Maps

High-resolution simple-cylindrical maps of the Moon at several wavelengths have been derived from spacecraft orbiting the Moon and can be used to derive a libration model. The Clementine UV-VIS imager has bands at 415, 700, 600, 950, and 1000 nm and the maps are pole-to-pole. The NIR imager has bands at 1000, 1250, 1500, 2000, 2600, and 2780, the maps cover $\pm 70$ deg. These maps have increasing shadows toward the poles; Gores constitute <1% in these maps and tend to elongate in latitude; they were filled by linear interpolation along line. The maps were then resampled by averaging to 8 pixel/deg resolution. Clementine map longitude averages start to increase beyond 56 deg from the equator and become noisy starting near 75 deg. The 2600- and 2780-nm bands are distinctly different, may be influenced by thermal radiation, and were not included in the libration fits. For irradiance analysis, Clementine maps pole-ward of 69 deg were set to be uniform with the average over both hemispheres over 64 deg: 69 deg; this represents $\sim 6.6\%$ of the disk.

The LOLA returned signal strength at 1084 nm was converted into a surface zenith, zero-phase, albedo map with global coverage at 8 pixels/deg. Contrast related to topography is typically small near zero phase; applying LOLA to Earth-view libration assumes that the local relation of the reflectance of slopes (particularly equator-ward) to reflectance of adjacent flat terrain is reasonably consistent over the near-side.

A study of possible libration angles for geocentric [as surrogate for low earth orbit (LEO)] and geosynchronous Earth orbit (GEO) locations indicated that a grid extending to $\pm 8$ deg in Vlat and Vlon ($\pm 12$ deg for GEO) would cover nearly all possibilities. The irradiance using the 8 pixel/deg maps was computed for a “GEO” geometric grid covering this range with 4-deg spacing, Hlat $\pm 1.5$ deg, and phase $\pm [3, 8, 14, 20, 30, 40, 50, 60, 70, 80, 90]$ deg for a total of 1540 points for each band. The subsolar longitude (Hlon) is computed to strictly maintain phase angle; points where the phase angle is smaller than the difference between viewer and solar latitude are not used.

The simple and colorless Lomell–Seeliger photometric function, $P = \frac{\mu_0}{\mu + \mu'}$, was used to compute the reflected radiance at each map point, $\mu_0$ and $\mu$ are cosine of the incidence and emergence angles. The Lunar–Lambert photometric relation was tried for $P$, this has a proportion of Lambertian reflectance that increases with $g$. The fractional difference in the resulting normalized irradiance between these two functions is small, for $g$ up to 60 deg, the mean difference is 0.018% with StdDev is 0.19%, the extreme of 1.5% is at large negative phase and Vlat. More recent photometric relations are available but these involve 448 to 2172 coefficients. Some derivation of these complex relations may be useful for later versions of SLIMED.
Irradiance is linear with the summation over the map where both illuminated and visible

\[ E = \sum_j \cos \theta_j \sum_i (\mu_{ij} > 0) A_{ij} P_{ij}(\mu_0, \mu, g), \]  

(6)

where \( i \) is the sample, \( j \) is the line, \( \theta \) is the map latitude, and \( A \) is the mapped reflectance. This result is equivalent to summing over an orthographic projection for the same illumination and viewing geometry, an example image is Fig. 2. The irradiances for each phase are normalized to the \((x, y, z) = (0, 0, 0)\) libration point. The libration effect is about 2% except near the waning half-Moon where it reaches 6% for the lowest \( \text{Vlon} \). The Moon is on average about 0.35% dimmer at the northern subsolar limit than at the southern limit.

### 2.3 Solar Spectral Irradiance and Its Variation

The 0.025-nm resolution version of the TSIS-1 hybrid solar reference spectrum (HSRS)\textsuperscript{34} was used as \( S_0(\lambda) \), the constant solar spectrum. Variation of both total and spectral solar irradiance are small but well-known. Total solar irradiance (TSI) \( H(t) \) has been measured with a precision of about 1/10,000 over the period of lunar observations considered here. The TSI measurements from several sources were merged onto a consensus scale covering November 17, 1978, to December 31, 2015, by de Wit et al.\textsuperscript{35} This dataset was extended using the same methodology to May 15, 2019, by Kopp\textsuperscript{36} and here further extended to February 16, 2021, using TSIS data\textsuperscript{37,38} and adjusting for the small bias in the time overlap with the consensus record. Over this 42.3-year daily record, the standard deviation (StDev) is 0.36 ppt, the range is \(-2.87: +1.58\) ppt, and the fraction of time the magnitude exceeds 1 ppt is 1.1%. The relative variation with wavelength is based on a quadratic fit in log/log space over 290:2412 nm to the ratio \( f \) of solar spectral irradiance variation (high-pass filtered) to TSI variation provided by Kopp, yielding

\[ f(\lambda) = \exp(-0.338752 - 0.785894 \ln \lambda + 0.202152(\ln \lambda)^2), \]  

(7)

where \( \lambda \) is in micrometers; the mean weighted absolute residual is 2% of the mean weighted value. Solar variation is implemented in SLIM as...
\[ S_0(t, \lambda) = S_0(\lambda) \left[ 1 + f(\lambda) \left( \frac{H(t)}{H_0} - 1 \right) \right], \] 

(8)

where \( S(t, \lambda) \) is the solar spectral irradiance and \( H_0 \) is the average of \( H(t) \) over the dataset, \( 1361.62 \, \text{W/m}^2 \). \( \mathcal{N}(t, \lambda) \) is the solar variation model. It can optionally be applied to the irradiiances going into a model fit and/or a calibration, normally both.

### 2.4 Available Lunar Irradiance Observations

With the exception of the NIST surface observations, all lunar observation data were supplied by representatives of the instrument teams, see Table 1 and Table 8 in Appendix C. Teams provide the time of observation, location of the instrument at that time, and the measured spectral irradiance in each band. The time and location are converted into distances and angles using the JPL DE430 ephemeris. Relative spectral response data are largely from instrument websites. Although team assessment of uncertainties is desirable, these were rarely provided. Some supplied datasets have points that are clearly outliers in calibration; these points are assigned huge uncertainties. LEO instruments usually point at or near geocentric nadir and require something special to view the Moon, commonly an attitude maneuver to point at the Moon, or use of a scan mirror at an unusual angle, or some combination of these. GEO instruments observe the Moon off the limb of the Earth in their field of regard as part of normal operations; some have special sequences to track the Moon. More details are in Appendix A.

### 2.5 Photometric Geometry

Of the five photometric angles used in the irradiance model, phase angle has by far the major effect on irradiance; there is a few percent difference between waxing (−) and waning (+) phases. Strictly, there are only four independent geometric variables. With the addition of wavelength, there are six dimensions, making display challenging. Generally, Hlon is close to the negative phase, and Hlat has a small range ±1.6 deg, leaving three prime geometric dimensions, plus wavelength.

The nine LEO instruments and three observatory instruments used in SLIMED fits are listed in Table 2. Coverage of these three angles for the spacecraft instruments is shown versus the cumulative time index in Fig. 3. Each instrument has a limited phase range except ROLO, AeroNet, and both PLEIADES. For these four, the distribution in libration is similar and generally well spread in both axes apart from PLEIADES concentrations near ±40 deg. SeaWiFS is largely near ±7 deg, with a few spread out at larger phases of both signs. OLI is largely near +8 deg, with a few negative. Moderate-resolution imaging spectroradiometer (MODIS) are largely near 55 deg with one-fourth to one-third spread out to 80 deg; Terra are all positive and Aqua are all negative. Both VIIRS are all near −50 deg. Both PLEIADES are spread over ±100 deg with concentrations at ±40 deg.

### 3 Data and Parameter Selection

The geometric BFs available in SLIM are listed below, these are the same as for the ROLO model. Each of these (except constant) can independently be made polynomial and each of those may independently be multiplied by a polynomial in wave to generate the full set of SLIMED BFs

- **constant**: 1
- **phase**: \( g \), absolute phase angle in radians, polynomial;
- \( 1/g \): inverse absolute phase angle in radians, polynomial;
- **Hlon**: \( h \), subsolar longitude in radians; polynomial of odd powers;
- **Hlat**: \( z \), subsolar latitude in degrees; polynomial (only first degree used);
- **Vlon** and **Vlat**: \( x, y \), subviewer longitude and latitude in degrees; polynomial, same degree for both;
Table 1  Available data, grouped by type. “Band” is the number of useful bands, “Lun” is the number of distinct lunations covered; “Time” is the number of observation times, “Points” is the number of observations points with useful uncertainty. The three phase-angle columns are the minimum, the smallest absolute, and the maximum. The last column is the percent of observations before full-Moon. ROLOG is ROLO 311-g dataset. AerN is AeroNet on Mauna Loa. Description in Appendix A.

| Instrument | Acronym | Number of | Phase | % |
|------------|---------|-----------|-------|---|
|            |         | Band Lun Times Points Min Abs Max Wax |
| LEO        | —       | — — — — | LEO — — — | |
| SeaWIFS    | SeaW    | 8 144 204 1632 | −48.9 5.1 65.5 | 57 |
| EO1-Hyperion| HypM    | 26 18 20 520 | −28.3 6.9 29.4 | 15 |
| Terra-MODIS| MODT    | 20 192 993 19,798 | 47.9 47.9 81.5 | 0 |
| Aqua-MODIS | MODA    | 19 175 743 14,117 | −79.9 36.9 −36.9 | 100 |
| Suomi-VIIRS| VIIRS   | 14 70 71 966 | −56.2 49.8 −49.8 | 100 |
| NOAA20-VIIRS| VIIRN  | 14 28 28 387 | −52.0 50.1 −50.1 | 100 |
| Landsat-8  | OLI     | 9 70 1080 9720 | −8.4 5.4 9.7 | 3 |
| PLEIADES-A | PleA    | 5 61 141 698 | −94.5 2.1 111.9 | 47 |
| PLEIADES-B | PleB    | 5 42 339 1669 | −101.5 1.4 101.6 | 50 |
| GEO        | —       | — — — — | GEO — — — | |
| GOES-8     | GS8     | 1 38 44 44 | −91.1 4.3 84.1 | 43 |
| GOES-9     | GS9     | 1 7 9 9 | −70.4 10.0 82.5 | 56 |
| GOES-10    | GS10    | 1 40 49 49 | −89.3 7.3 89.6 | 53 |
| GOES-11    | GS11    | 1 49 77 77 | −87.6 4.5 89.9 | 61 |
| GOES-12    | GS12    | 1 38 49 49 | −83.4 6.8 66.5 | 51 |
| GOES-13    | GS13    | 1 26 47 47 | −76.9 6.4 74.3 | 53 |
| GOES-15    | GS15    | 1 14 28 28 | −52.8 2.6 69.0 | 57 |
| MSG-1-SEVIRI | SEV1  | 4 183 1190 3669 | −153.0 1.5 156.1 | 52 |
| MSG-2-SEVIRI | SEV2  | 4 162 1313 3645 | −158.1 1.3 158.7 | 50 |
| MSG-3-SEVIRI | SEV3  | 4 82 630 1744 | −155.7 1.6 157.2 | 51 |
| MSG-4-SEVIRI | SEV4  | 4 31 225 655 | −155.4 3.6 147.6 | 52 |
| GOES-16-ABI | ABI16  | 6 15 115 690 | −76.0 5.6 69.9 | 58 |
| GOES-17-ABI | ABI17  | 6 15 121 726 | −73.6 5.0 72.3 | 57 |
| Other      | —       | — — — — | Other — — — | |
| Obs. @2148 m | ROLOG  | 32 30 1249 39,007 | −124.7 1.4 109.3 | 39 |
| Obs. @2367 m | NIST   | 9 1 2 18 | 19.8 19.8 19.8 | 0 |
| Obs. @3402 m | AerN   | 7 20 50 350 | −73.9 4.3 86.8 | 52 |
| HiRISE-Mars | HiRIS  | 3 1 4 12 | 69.6 69.6 69.6 | 0 |
Table 2  Uncertainties, heft and net weights for the instruments fit by SLIMED. The first three columns apply to all models and list the instrument acronym, how many observations were made and the nominal uncertainty assigned to the instrument. The central columns list the “Heft” assigned and the right five columns lists the resulting percentage weight each instrument contributed to the final fit; “Hu” is uniform weight for each instrument, “H1” is all heft equal 1, and “Bal” includes only instruments that are roughly balanced between waxing and waning phases. ~B is the Base model rounded for clarity.

| Inst acro | Num. times | Ave. Uncert. | Heft Base | Heft Hu | Heft bal | Total weight ~B Base | Total weight Hu | Total weight H1 | Total weight bal |
|-----------|-----------|--------------|-----------|---------|----------|---------------------|----------------|----------------|-----------------|
| SeaW      | 1632      | 0.030        | 1.644     | 2.10    | 1.64     | 10                  | 9.99           | 8.45           | 4.02            | 8.78            |
| HypM      | 520       | 0.100        | 5.936     | 73.0    | 1.00     | 8                   | 8.12           | 0.11           |                 |
| MODT      | 19,860    | 0.050        | 0.379     | 0.48    | 0.38     | 10                  | 9.96           | 8.36           | 17.38           | 14.78           |
| MODA      | 14,117    | 0.050        | 0.432     | 0.69    | 0.43     | 8                   | 7.95           | 8.42           | 12.09           | 11.98           |
| VIIRS     | 994       | 0.050        | 3.856     | 9.70    |           | 5                   | 4.99           | 8.32           | 0.86            |                 |
| VIIRN     | 392       | 0.050        | 19.250    | 24.0    |           | 10                  | 9.98           | 8.25           | 0.34            |                 |
| OLI       | 9720      | 0.030        | 0.310     | 0.39    |           | 10                  | 9.97           | 8.34           | 21.30           |                 |
| PleA      | 705       | 0.050        | 10.974    | 17.3    | 10.97    | 8                   | 7.99           | 8.34           | 0.48            | 15.19           |
| PleB      | 1695      | 0.050        | 4.777     | 7.60    | 4.78     | 8                   | 7.99           | 8.42           | 1.10            | 15.90           |
| ROLOG     | 39,968    | 0.050        | 0.335     | 0.21    | 0.34     | 20                  | 20.0           | 8.34           | 39.53           | 28.79           |
| NIST      | 18        | 0.006        | 1.722     | 4.30    |           | 5                   | 4.99           | 8.26           | 1.92            |                 |
| AerN      | 350       | 0.030        | 4.000     | 9.70    | 4.0      | 5                   | 5.21           | 8.38           | 0.86            | 4.58            |

Fig. 3  Geometry coverage over cumulative time index for the nine spacecraft instruments used in SLIMED fits. Each angle and its range are shown at the left. Data for each instrument begins at the abscissa of the left edge of its acronym (in green). PleB did a dense sweep in phase angle covering the bright half of a single lunation.
Several other terms used in the ROLO model are available; these are all nonlinear, involve additional fitting loops, and were rarely used in SLIM development. Because the goal is a calibration model, the absolute phase angle in SLIMED fits here is restricted to $3 \leq g \leq 95$ deg, and terms addressing the opposition effect are less important.

All three wave modes were tried. The effect of wave-mode is most easily seen as the variation of the sum of the BF with wavelength, $b_{jk}$ in Eq. (4). In SLIMED models, this term has a relatively low value at extreme wavelengths. This drop is greatest at short wavelengths for $w = \lambda$ and at long wavelengths for $w = 1/\lambda$. This led to adopting $w = \ln \lambda$ for the Base model (Sec. 4).

Starting with all gains equal unity, after 19 iterations the largest change of gain was 0.076%, the average was 0.023%; see Fig. 13. With the $c_{km}$ determined, the model irradiance $E_m$ for any wavelength and geometry can be calculated, applying MapLib and solar variation consistent with model generation. The lunar calibration ratio is $R_C = E_d/E_m$ where $E_d$ is the irradiance reported by the team, adjusted to standard distance; optionally, the current trend model (Sec. 3.1) for a band can be applied to $E_d$. The weighted average over date of $R_C$ for a band is its empirical gain.

Differences between SLIMED models or other published models were assessed using the GEO geometry grid, Sec. 2.2. For wavelength, the eight bands chosen by the GSICS lunar calibration group were used: centered on 442, 550, 670, 765, 870, 1380, 1640, and 2350 nm and with trapezoidal response, 10-nm wide at top and 30-nm wide at zero response.

Estimates of many potential errors in lunar calibration are listed in Appendix B. The values are generally not precise, but their magnitude indicates areas that need effort. Any bias in radiometric calibration that is systematic across the data sources would propagate invisibly into the model.

### 3.1 Trends

Changes in instrument gain over time are usually decreasing and continuous. Smooth fits to gain changes are called “trends.” Derivation of gain trends in SLIM is based on calibration ratios and are not normalized. However, in application, trends are normalized to their values at the first lunar observation for that instrument, separating the empirical gain from the trend effect. Instruments with obvious trends included SNPP-VIIRS and most of the GOES series through GOES-15 (panchromatic bands).

The independent variable $x$ in SLIMED trends is years after launch. Five forms were studied; any $c$ in the exponent is $-1/\tau$. (1) $y = c_0 + c_1 x$, (2) $y = c_0 e^{c_1 x}$, (3) $y = c_0 + c_2 e^{c_3 x}$, (4) $y = c_0 + c_2 e^{c_3 x} + c_3 x$, and (5) $y = c_0 + c_2 e^{c_3 x} + c_3 e^{c_4 x}$.

For form 5: First, solve form 3 for its $\tau_3$ and then constrain $0 < \tau_1 \leq \tau_3$ and $\tau_4 > \tau_3$. Simply to avoid more complexity, the trend form is constrained to be the same for all bands of an instrument. The quality metric (QM) for trend fits is the normalized decrease of the StDev $\sigma$ of the calibration ratio weighted by $1/U^2$

$$Q_j = \frac{\sigma(R_j)}{\langle R_j \rangle} - \frac{\sigma(R_j/y_j)}{\langle R_j/y_j \rangle}.$$  

where $R_j$ is the set of calibration ratios in band $j$ and $y_j$ are the fit points to those data. QM can be small negative. For an instrument, QM is averaged over all bands. For instruments with significant change, it was found that form 4 is generally the best or close to it. Form 1 is used for instruments with little change. An example of QM for the bands of SNPP-VIIRS for each of the five forms is shown in Fig. 4; for SNPP-VIIRS, form 4 is generally significantly better and never worse than the lower forms, form 5 is fragile (can yield very large $\tau$), and was never a significant improvement over form 4.
A performance metric for MapLib libration models (PML) was defined as the ratio of the StDev of the fit residuals to the StDev of the data; basically, the fraction of the variation that is not captured. The terms can be ranked by a measure of effective magnitude, defined as $|d_i|/\sigma_i$, where $d_i$ is the coefficient and $\sigma_i$ is the StDev of BF $j$. Libration models were derived using each of the three wave modes, with similar results. The $\ln \lambda$ mode is used for consistency with the SLIMED model fit. From an initial fit with all 108 terms of Eq. (3) and $PML = 0.1075$, the smallest terms were progressively dropped until the PML started to rise significantly; a model with 24 terms was chosen, listed in Table 3, with $PML = 0.1219$.

Decisions on which instruments to fit, hefts to use, BFs to include and values for several convergence parameters are largely a matter of reducing residuals versus increasing complexity. Modestly different choices yield similar models, with the relative empirical gains between instruments being little changed. The SLIMED models are currently based on data from nine LEO instruments and three surface observatories. GEO instruments, apart from ABI16, were found to have more "noisy" calibrations, see Fig. 8. Panchromatic bands, $\Delta \lambda \geq 0.2$, were omitted from the fit. For the Base model, only SNPP-VIIRS uses trend-correction before fit. Including an instrument with trend corrections involve iterations to generate a model, calibrate the observations, develop trends, and apply them to observations to be included in fitting the next model.

The spectral irradiance models discussed here are listed in Table 4. The Base model uses MapLib, includes solar variation for all data, uses $\ln \lambda$ as “wave” and includes all the terms listed in Table 5, which lists the resulting coefficients. The Heft terms used for this model are in Table 2. Including MapLib means that the libration terms, lines 22 to 33 in Table 5, need to deal only with MapLib deficiencies. For the Base model, there are 168 bands with initially a total of 89,971 points. After rejection of outliers and within the phase angle limits, 85,924 are used in the final fit; these values are similar for all models incorporating 12 instruments. The “Balan” model includes only instruments for which the wax and wane points roughly balance; ROLO and AeroNet, SeaWiFS, both PLEIADES, and the pair of MODIS instruments that balance each other; a total of 96 bands and 74,730 points are used in the final fit. The last stage was to generate
a model including the trends derived using the Base model and using the version of the ROLO dataset based on the HSRS solar spectrum (see Appendix A); the result is the V1 model.

The fractional difference between the Base model and all others is shown for zero libration and the GEO phase-angle set in Fig. 5. Models that change the weighting of input data result in brightness differences of roughly 2%; up to 8% for extreme geometries at the longest wavelength. Changes to the fitting parameters yield normalized brightness differences mostly <1%.

Statistics on the differences between models, based both on irradiances on the GEO grid and on calibration results, show that changes related to instrument set, heft, or wave mode are on the order of 1% while those related to the other fit options here are on the order of 0.1%.

Quantitative lunar calibration is the ratio of the instrument measured irradiance (adjusted to standard distances) to the model irradiance, often expressed as a percentage difference from one.

Table 3  Coefficients of the map-based libration model with 24 terms; coefficients and formal uncertainty multiplied by 1000. Fit based on Eq. (3) and variables scaled as described there. $p$ is signed phase angle in radians, $x$ is Vlon/10 deg, $y$ is Vlat/10 deg, $z$ is Hlat in degrees, $w$ is in wavelength in $\mu$m.

| Term   | Coef $\times 10^3$ | sig $\times 10^3$ |
|--------|--------------------|--------------------|
| $x$    | 11.827             | 0.176              |
| $y$    | −7.031             | 0.148              |
| $z$    | −0.916             | 0.080              |
| $x^2$  | 3.642              | 0.211              |
| $y^2$  | −2.254             | 0.405              |
| $yz$   | 0.920              | 0.101              |
| $px$   | −22.691            | 0.484              |
| $p^2x$ | 1.096              | 0.445              |
| $p^3x$ | 13.967             | 0.719              |
| $p^4x$ | −3.576             | 0.189              |
| $p^5x$ | −4.166             | 0.236              |
| $py$   | −8.709             | 0.689              |
| $p^3y$ | 2.742              | 1.023              |
| $p^5y$ | −0.826             | 0.336              |
| $pxy$  | −3.428             | 0.200              |
| $p^2z$ | −0.536             | 0.068              |
| $px^2$ | 4.410              | 0.131              |
| $p^2x^2$ | −3.413            | 0.427              |
| $p^4x^2$ | 2.216             | 0.178              |
| $py^2$ | 5.732              | 0.944              |
| $p^2y^2$ | 2.474             | 0.303              |
| $p^3y^2$ | −6.290            | 1.383              |
| $p^5y^2$ | 1.845             | 0.454              |
| $wpx$  | −3.418             | 0.285              |

Kieffer: Multiple-instrument-based spectral irradiance of the Moon
The final empirical gain for each band is the average of this over date weighted by 1/uncertainty; points with \( g \) outside the range for model fit have 1.0 added to their uncertainty, decreasing their weight by a factor of about 400. For instruments used in a fit, this differs negligibly from the final gain computed in the fit process, \( G_j \) in Eq. (5). For convenience in displaying calibration results for OLI, the calibration was averaged over the 15 observations obtained within 2 h on each date, covering the 14 identical blocks of detector arrays.

The Base model was used to calibrate all instruments, then look for trends in instruments (except those with a single date) and select a trend form. The results are summarized for all instruments and bands in Table 7, including the mean calibration ratio (col. 4), the StDev over time (col. 5), the magnitude of trends (cols 9:11), and the extent to which the trend model fits the gain history (col. 14).

Calibrating many instruments against one model reveals both similarities and large differences, Figs. 6 and 7. Some of the LEO and surface instruments have offsets fairly consistent over wavelength, Fig. 6: SeaWiFS \(-4\%\), ROLO using HSRS \(-7\%\), Hyperion \(+22\%\). The offset for the two versions of ROLO are similar, but the new version has less scatter. Both PLEIADES, both MODIS, ABI16, AerN, and NIST cluster below 1000 nm near \(+1\%\), see also Fig. 14.

### 5 Discussion

The SLIMED formulation represents the Moon by its disk-equivalent-reflectance and isolates this from the complex spectrum of the Sun and its variability. With a library of many instruments and a model generation system with many parameters, the SLIM system can produce many spectral irradiance models. The Base model presented here represents individual judgment on the weights assigned to instruments and BFs to be included. Application of this irradiance model reveals that over 400 to 870 nm, the group of OLI, both MODIS, both PLEIADES, GOES-16 ABI and two surface observatories calibrated against laboratory standards rather than
Table 5 Coefficients for all BFs of the Base model and the V1 model. The symbols are described in Sec. 1.2, \( w \) is natural log of wavelength in \( \mu \)m. In the right six numerical columns all values are multiplied by 1000. The third column is the coefficient; fourth column is the formal uncertainty of the coefficient in the SVD fit. The fifth column is the “importance” of the BF as measured by the absolute value of the coefficient times the StDev of the BF. Columns 6 to 8 are the values for the final model discussed here, V1.

| I | Symbol | Base = 22Apr16T1827 | V1 = 22May28T1548 |
|---|--------|---------------------|---------------------|
|   |        | value \( \times 10^3 \) | uncert \( \times 10^3 \) | val \( \times \text{StD} \times 10^3 \) | value \( \times 10^3 \) | uncert \( \times 10^3 \) | val \( \times \text{StD} \times 10^3 \) |
| 0 | 1      | 165.933             | 2.82187             | 0.000               | 160.471             | 2.86976             | 0.000               |
| 1 | \( w \) | 2.361               | 2.48288             | 1.026               | −95.600             | 3.07038             | 23.997               |
| 2 | \( w^2 \) | −95.281             | 3.02417             | 24.203              | 95.281              | 3.02417             | 24.203              |
| 3 | \( g \) | −1243.839           | 1.73058             | 515.531             | −1234.935           | 1.71108             | 509.973             |
| 4 | \( g^2 \) | 151.422             | 3.26420             | 88.952              | 139.370             | 3.37072             | 81.269              |
| 5 | \( g^3 \) | −154.345            | 4.20604             | 122.599             | −149.600            | 4.33973             | 117.620             |
| 6 | \( gw \) | 279.268             | 1.85148             | 98.557              | 250.609             | 1.78433             | 87.556              |
| 7 | \( gw^2 \) | −29.627             | 2.94323             | 6.525               | −24.373             | 2.79679             | 5.260               |
| 8 | \( g^3w \) | −89.973             | 9.14530             | 35.644              | −78.435             | 9.39848             | 30.637              |
| 9 | \( q \) | 4.816               | 10.87541            | 14.459              | 5.146               | 11.15408            | 15.449              |
|10 | \( q^2 \) | 0.306               | 9.70104             | 9.634               | 0.301               | 10.10182            | 9.466               |
|11 | \( qw \) | −8.662              | 1.77229             | 19.535              | −12.735             | 1.66997             | 28.769              |
|12 | \( qw^2 \) | 0.738               | 9.98481             | 1.141               | 0.427               | 10.37717            | 0.660               |
|13 | \( q^2w \) | 0.309               | 23.20380            | 6.227               | 0.538               | 22.67480            | 10.835              |
|14 | \( h \) | 49.458              | 28.01185            | 37.971              | 48.971              | 28.87266            | 37.469              |
|15 | \( h^3 \) | 11.279              | 3.13963             | 11.016              | 12.558              | 4.20469             | 12.150              |
|16 | \( h^5 \) | −4.722              | 0.40499             | 7.858               | −5.171              | 0.37757             | 8.480               |
|17 | \( hw \) | 4.606               | 1.16928             | 1.849               | 3.820               | 0.97497             | 1.522               |
|18 | \( hw^2 \) | −8.007              | 0.97728             | 2.273               | −7.464              | 0.99700             | 2.088               |
|19 | \( h^3w \) | −0.824              | 0.67489             | 0.418               | 0.334               | 0.64279             | 0.167               |
|20 | \( z \) | −0.024              | 0.89116             | 0.026               | 0.204               | 0.79356             | 0.218               |
|21 | \( zw \) | −0.307              | 0.82406             | 0.181               | 0.043               | 0.77641             | 0.025               |
|22 | \( x \) | −0.808              | 0.54739             | 3.562               | −0.750              | 0.54813             | 3.300               |
|23 | \( y \) | −0.340              | 0.47219             | 1.639               | −0.383              | 0.48505             | 1.847               |
|24 | \( x^2 \) | −0.002              | 0.12142             | 0.038               | −0.004              | 0.12132             | 0.061               |
|25 | \( y^2 \) | −0.009              | 0.12752             | 0.158               | 0.006               | 0.13697             | 0.109               |
|26 | \( xw \) | 0.053               | 0.24935             | 0.126               | 0.020               | 0.25262             | 0.046               |
|27 | \( yw \) | 0.253               | 0.22680             | 0.674               | 0.143               | 0.22894             | 0.380               |
|28 | \( \langle hx \rangle \) | −0.429          | 0.16818             | 1.609               | −0.450              | 0.17355             | 1.683               |
|29 | \( \langle hy \rangle \) | 0.032          | 0.11829             | 0.123               | 0.063               | 0.12172             | 0.242               |
|30 | \( \langle hx \rangle^2 \) | 0.008          | 0.04717             | 0.177               | 0.006               | 0.05016             | 0.135               |
|31 | \( \langle hy \rangle^2 \) | 0.004          | 0.03287             | 0.080               | −0.010              | 0.03345             | 0.222               |
|32 | \( \langle hx \rangle w \) | −0.115          | 0.01492             | 0.227               | −0.062              | 0.01519             | 0.121               |
|33 | \( \langle hy \rangle w \) | −0.158          | 0.03187             | 0.322               | −0.044              | 0.03224             | 0.088               |
Fig. 5 Average change in DER from the Base model at zero libration over the GEO grid. In each panel phase angle increases from left to right. Models left of the legend involve different instrument sets, wave-mode or heft; those at or to the right involve change of fit parameters. “+trend” is the V1 model.

Fig. 6 Calibration of LEO (lines) and surface instruments (dashed) with the Base model showing the average over time for each band, with two versions of the ROLO dataset.
stars, NIST and AeroNet, agree within a few percent, averaging about 1% above the model; Fig. 14. Considering the gain-adjustment used in SLIMED models, it is plausible that the real Moon lies in this cluster and that the Base model is about 1% low in this wavelength region. Although the LIME model is traceable to a cryogenic radiometer and has an expanded (k = 2) absolute radiometric uncertainty of ∼2%,

it is 4 to 7% below this group. The ROLO/GIRO model is 5% to 10% lower than this group, Fig. 7. These relative values are consistent across SLIMED models resulting from modest changes in model inputs.

The scatter (standard deviation) of calibration over time for each band is a measure of the consistency of the instrument’s lunar observations, shown in Fig. 8. All GEO instruments except ABI16 show more scatter than LEO instruments. The GOES 8 to 15 series, after correction for trends, have a few percent scatter but no clear dependence on phase angle. The calibration ratio including trend corrections (forms listed in Table 7) for the bands of each fit instruments and GOES-ABI’s were normalized to average one, then the average over band for each instrument was plotted versus time, Fig. 9. While there are some seasonal oscillations near the 1% level, there is no apparent phase coherence across instruments, which if present would suggest a problem with the model. However, the bjk in Eq. (4) are relatively low at both ends of the spectral range overall phase angles, suggesting that the lunar reference spectrum, based on disturbed lunar soil samples, is too bright at both ends.

Both PLEIADES made frequent observations during one lunation, see Fig. 3. In particular, PleB made 227 observations in 15.8 days centered on full Moon, covering −101.5 deg to +101.6 deg phase. The calibration results (including trend correction, which is small) for this phase-angle sweep, Fig. 10, provide a test of the model. For 10 deg < g < 60 deg deviations are <0.5%. However, under g = 5 deg the calibration drops sharply indicating a model of the opposition effect more sophisticated than the simple polynomial in 1/g used here is needed for calibration at such small phase angles.

5.1 Examples of Trends

Table 7 has the calibration trend results for all bands of instruments with more than one date. The trend form used is the simplest that captures the instrument behavior. These continuous
Fig. 8 Standard deviation of the calibration ratio for most instruments with trend correction using the Base model. GEO instruments are shown dashed; single-band GOES are single diamonds near 650 nm. SEVIRI are largely above 10%, suggesting problems in processing images to irradiance; a couple MODIS bands are also high, as are ROLO version 3 SWIR bands. There are two curves for OLI, the lower one is for data averaged over the 15 observations on one date.

Fig. 9 Instrument calibration versus date using the trend forms listed in Table 7. Average calibration ratio over instrument bands for each date, then normalize each instrument to a grand average of one. Each symbol is one date. Instruments are offset by 2%. Dotted lines at the beginning of each year.
forms do not deal with the many styles of events that can cause offsets in response or their rates of change.

OLI was calibrated and trended using both the Base and the V1 model, results are nearly identical. Only the coastal aerosol band (443 nm) has discernible early decrease, Fig. 11.

Fig. 10 Calibration using the V1 model of PleB during its dense coverage of one lunation. The small correlated jumps in both waxing and waning phase are when observations were spaced by >0.3 deg phase (36 min of time) and may be related to location of the spacecraft along its 98.7-min orbit.

Fig. 11 Calibration of OLI using the V1 model. The first two lunations (during commissioning) had two raster sets. Dashed lines are the form 4 trend fit.

Fig. 11 Calibration of OLI using the V1 model. The first two lunations (during commissioning) had two raster sets. Dashed lines are the form 4 trend fit.
The pan, green, and red bands show a small initial rise of about 0.02%, probably due to inconsistencies in procedure or processing during commissioning. After the first two or three years, there is a clear annual variation in all bands of about 0.4%. For OLI, except for Coastal Aerosol (Aer), QM for all forms and bands is small, <0.02%; Aer reaches 0.1% for forms 4 and 5, which capture the early drop in response. However, the low QM does not justify any form above 3 for the other bands. All OLI bands drop about $\frac{1}{2}\%$ over 6 years, fairly small compared to the scatter. The OLI full-resolution calibration data would support a study of the gain history of all 126 detector arrays in OLI.

Calibration for SNPP-VIIRS using the Base model shows an initial asymptotic drop and a continuing linear trend, well fit by form 4, Fig. 12. The StDev of residuals from the trend-fit is 0.30% and there is an indication of an about 0.02% annual or semiannual oscillation on top of the much larger trend. NOAA20-VIIRS (VIIRN) shows little trend, form 1 has a linear coefficient of about 0.1%/year or less.

As ROLO data are calibrated against stars every night, trends were not expected. However, the band near 2250 nm has a linear trend of +3.2% per year and the other bands average +1%. One possibility is a gradual increase in scattering in the telescopes that led to a drift in the calibration of point sources relative to the lunar integration.

Among GEO instruments, lunar calibration for all except GOES-16 ABI is noisier than operational LEO instruments, see Fig. 8. The early GOES series generally have strong trends; Table 7. For both ABI’s, trends are small for all bands, but there is about 1% to 2% scatter at each lunation. Also, both ABI’s show an increase in calibration ratio with an absolute phase angle of about 2%; the reason for this is unknown.

6 Conclusions

A methodology for incorporating multiple sources of information on lunar spectral irradiance has been developed and applied to generate an improved lunar model useful for instrument radiometric calibration. This addresses the major known issues with the ROLO model, listed in the introduction. SLIMED models are continuous in wavelength and all geometry parameters,
as must be the actual Moon, and the full prescription is given here. The “V1” model, resulting
from using the trends derived with the Base model, is thought to be closest to the actual Moon;
V1 supports trending at the 0.1% level. SLIMED models are based on 12 times the number of
instruments and three times the amount of data as the ROLO/GIRO model, have 1/10 the
number of coefficients and 1/2 the magnitude residuals. Applying the SLIMED Base model
to 25 instruments and two other models reveals some encouraging consistencies and some
large differences.

It seems implausible that the geophysical products of these instruments, used by the world’s
scientific community, can have differences as large as indicated by lunar calibration. Thus, some-
thing is amiss in the lunar calibration of at least some of the instruments, either in the observ-
ations or the processing to irradiance. The realities of comparisons based on a single model of
the Moon need to be examined and resolved before the full potential of lunar calibration can be
realized. Observing the Moon with the same optical configuration as science targets should help,
especially for absolute calibration. There is no barrier to a lunar model, and even lunar calibra-
tion, eventually achieving accuracy at the 0.1% level.

SLIMED was developed in IDL, which is a proprietary language but is common within
NASA. When implemented in an open language, the SLIMED concept can be used to generate
an up-gradable reference model for the lunar calibration community. The methodology could
weigh heavily accurate, traceable, above-the-atmosphere measurements of lunar irradiance; such
measurements do not yet exist. In the future, the lunar calibration community could be involved
in setting the weights assigned to the source data and in other decisions, leading to a “consen-
sus” model.

7 Appendix A: Instrument Data

MODIS, Terra, and Aqua. On MODIS-Aqua (MODA), the 1630-nm band is noisy and
was omitted. Description of Lunar observations and comparison with PLEIADES is in
Refs. 41–43.

Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was the first operational instrument
to do regular lunar calibrations. SeaWiFS did reverse-pitch attitude maneuvers to view the
Moon directly on most months for 13 years, concentrated near \( p = \pm 7 \) deg; there are also
about 60 early observations at large phase angles. Its 1.16-mrad resolution yields about
6 pixels across the Moon. Lunar calibration was used extensively in developing the final
response history for SeaWiFS. All the lunar observations described in Ref. 44 are included
here.

Operational Land Imager, Landsat 8 (OLI) is a push-broom imager with 14 blocks of detec-
tors cross-track. OLI did reverse-pitch attitude maneuvers to view the Moon directly,45 scanning
in a raster pattern so the Moon passed through the center of 7 or 8 of its 14 focal-plane-modules.
OLI data are available for 72 lunations at similar phase angle; each raster pair was acquired on
successive orbits in 113 min, within which the optical libration variation is largely due to
N–S spacecraft motion. For convenience in displaying calibration results, these were averaged
over each raster-pair for each band to form a virtual instrument assigned the acronym OLIa;
the full-resolution data are always used in the model generation.

Visible Infrared Imaging Radiometer Suite; Suomi NPP (VIIRS). SNPP VIIRS showed a
significant drop in response over the first 400 days on orbit.46 Lunar views are obtained through
a spaceport during spacecraft day, using scan-mirror angles different from ground scenes.46
Lunar observations are described by Refs. 47 and 48. The team analyzed these data using the
ROLO model.48 Suomi-VIIRS has a known problem of degradation of scan-mirror coatings,
which has been monitored by its solar diffuser. Eplee et al.50 analyze this in detail using both the
on-board solar diffuser and lunar calibration with the ROLO model; their Fig. 4 shows most
months from January 2012 to June 2019. They fit \( A_0 - A_1(1 - e^{-\tau(t-t_0)}) \) with \( \tau = 1/2000 \) days
with roughly 0.5% annual residual. Here, trends are based only on lunar calibration using
SLIMED models. The scan mirror degradation has a spectral component, which would result
in small changes to the equivalent wavelength of some bands; this is not addressed in the SLIM
system.
Visible infrared imaging radiometer suite; NOAA-20 (VIRRN). Similar to VIIRS, but this second instrument avoided the mirror-coating issues; bands have little trend.

The PLEIADES spacecraft are agile and point directly at the Moon from many places along their orbits. PLEIADES 1A and 1B made observations over a wide range of phase angles, including dense sets in a single lunation,\textsuperscript{51} 1B made additional dense lunation sweeps but these were not provided. The team provided trend information as calibration factors for each band every 3 months. These factors are close to linear with time and were treated as piece-wise-linear in application to the measured irradiances.

Hyperion is a spectrometer on the EO-1 spacecraft with VIS and near-IR focal planes, which have overlapping wavelengths.\textsuperscript{52} Each section has bands of negligible response at its low and high wavelength ends. Omitting these bands and the less-responsive bands in the overlap region leaves 204 bands of about 10.5-nm resolution covering 427 to 2400 nm with crossover near 916 nm. The level 0 ancillary data and level 1 images were processed by the author to lunar irradiance values, independent of the lunar calibration of Ref. 53 but with similar results. Hyperion did attitude maneuvers to scan across the Moon; the cross-track width was barely larger than the Moon and incomplete coverage scans are not included.

The first eight Geostationary Operational Environmental Satellites, GOES-8 to -15, had a single broad band in the solar-reflectance regions, 0.5:0.8 \(\mu m\); no data was available for GOES-14.

GOES-16 and 17 carry the advanced baseline imager (ABI), which has six solar-reflective bands.

The Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instruments are on four Meteosat second generation (MSG) geostationary spacecraft; descriptions of lunar observations are in Refs. 4 and 54. The instruments have four solar-reflective bands, one of which is very wide, 0.4:1.1 \(\mu m\). Various bands were listed as valid as a function of date and some of these were calibration outliers. About 28% of the total points were rejected for each instrument.

The ROLO ran during the bright half of each month on clear nights for nearly 7 years. The version 3 dataset, source of the 311g model,\textsuperscript{3} was used with the acronym ROLOG. Formal uncertainties were provided for each point; these do not include the much larger absolute scale uncertainty of about 5%;\textsuperscript{55} thus the provided uncertainties were scaled to average 5%. A second version of the irradiances, developed using the recent HSRS\textsuperscript{34} was provided by Tom Stone and is assigned the acronym ROLOH.

National Institute of Standards and Technology (NIST). Surface observations from an observatory in Arizona. Data are extracted from Table 1 of Ref. 39, which is for a single time and includes uncertainties (data were duplicated to avoid processing complications). Initial analysis suggested that the longest wavelength irradiance is errant, and its published uncertainty was arbitrarily tripled.

AeroNet lunar observations using CIMEL photometers on Mauna Loa at 3402-m elevation used a NIST-traceable calibration, with nightly Langley plots to determine atmospheric attenuation.

High Resolution Imaging Science Experiment (HiRISE). An instrument of extraordinary angular resolution and calibration challenges made a few observations of the Moon from Mars. The Moon is resolved with about 8 pixels across the lunar diameter (similar to SeaWiFS).

8 Appendix B: Error Estimates

Estimates of possible errors are listed in Table 6. There are uncertainty values for typical current practice and after potential improvements over the next decade or so. Some can be calculated based on an image time error or spacecraft location error, some are rough estimates, and some are known to be so small that at worst they are negligible.
Table 6  Estimates of sources of error in lunar calibration. “Value” is the current or typical value; “est.” = estimated. Last two columns are effect on an irradiance calibration in ppt. Typical: Magnitude if ignored or an estimate at current practice. Best: Rough forecast considering best practice perhaps a decade in the future.

| Item:                              | Value       | Typical | Best |
|-----------------------------------|-------------|---------|------|
| Model: absolute                   | est. 3%     | 30      | 5    |
| Model: relative                   | est. 0.5%   | 5       | 1    |
| Maneuver from Nadir: hardware     | est. 2%     | 20      | 1    |
| Image artifacts: ghosts, flare    | est. 1%     | 10      | 1    |
| Oversampling factor (now commonly poorly known) | 1%     | 10      | 0.1  |
| Pixel scale change cross-track, e.g., for OLI | 0.5% | 5.8 | 0.01 |
| Scan uniformity: $\varepsilon \cdot \nabla I$ | est. 1/200 | 5       | 0.5  |
| Frame image distortion, residual: $\sim \propto \theta^3$, use 2 deg | $4 \times 10^{-5}$ | 0.04 | 0.04 |
| Polarization: lunar times instrument$^a$ | Moon max. is 9% | 25      | 1    |
| Image processing to irradiance, corrected for above | 0.1% to 3% | 1 to 30 | 0.1 |
| Solar variability, most in UV     | $\sim 1 \text{ W/m}^2$ | 0.7 | 0.1 |
| Image time: distance and libration: 1 s $\sim 7.6 \text{ km}$ | $5.2 \times 10^{-4}$ | 0.4 | 0.04 |
| $1/r^2$ approximation, out to GEO | $5 \times 10^{-4}$ | 0.5 | 0.05 |
| Moon not a sphere: $\Delta h/R \sim 1/1737$ local$^a$ | $2 \times 10^{-4}$ | 2 | $<1$ |
| Below are negligible at worst      | —           | —       | —    |
| Spacecraft ephemeris: one axis    | est. 0.1 km | $2.6 \times 10^{-4}$ | $<1$ |
| Lunar surface global reflectance change$^b$ | $1 \times 10^{-8}$/year | 2 $\times 10^{-4}$ | $<1$ |
| Relativity: time$^b$             | $d/c \sim 1.3$ s | $1.4 \times 10^{-8}$ | $<1$ |
| Relativity: Aberration            | $v/c \sim 2 \times 10^{-5}$ radian | $3 \times 10^{-6}$ | $<1$ |
| Lunar ephemeris                   | 10 cm       | $2.6 \times 10^{-8}$ | $<1$ |

$^a$May vary widely between instruments.
$^b$Fractional rate change while crossing the Moon, e.g., change in mean scan rate over first 1/2 Moon to second 1/2.
$^c$Depends upon scan direction. Typical proportional radiance difference between two halves of a lunar image may be 10%.
$^d$Variables with phase angle and wavelength.
$^e$Nonlinearity in $1/\cos \theta$ over 7 deg $[1.2 \times 10^{-3}]$ for LEO; times the fractional circumference. Arbitrarily set at $\frac{1}{2}$ topography/radius. It is covered by libration terms.
$^f$Accounted for in libration terms in model.
$^g$Barring major human activity on the Moon.
$^h$Maximum effect on $d$ is 0.11 km.

9 Appendix C: Supporting Figures
The gain adjustment factors $G_j$ converge asymptotically with each iteration of Eq. 5; the change in $G_j$ typically decreases with each iteration, an example is shown in Fig. 13. By iteration 19, most bands are changing less than 0.01%. The empirical gain, which for instruments fit in the model is almost the same as the final $G_j$, shown in Fig. 6 is displayed in more detail in Fig. 14. The trends derived with the Base model for all instruments are listed in Table 7. The calendar dates for each instrument are listed in Table 8.
Fig. 13 Convergence of the empirical gain factor for all bands used in the Base model fit. The change in the natural logarithm of the gain factor between successive iteration is shown. The iteration index is indicated in the color legend. Low value in early iterations usually indicate a change of sign. Small triangles indicate the value was negative.

Fig. 14 Calibration of some LEO and surface instruments, both ABI’s, two versions of the ROLO dataset, and two models. This enlarges the “cluster” of Fig. 6 omitting the instruments that deviate considerably from 1.
Table 7  Calibration and trends. The instrument title lines contain the acronym followed by the trend form used and the number of dates. All other lines are: Col. (1) is band index within instrument in SLIM; (2) band name; (3) nominal wavelength in nm; (4) mean calibration ratio as % above 1; (5) standard deviation of calibration over time ×10^4; (6) range of calibration, minimum – mean, ×10^3; (7) range of calibration, maximum – mean, ×10^3; (8) fit coefficient c_0; (9) For form 1, fit coefficient c_1, for form 2: τ in years; (10 and 11) fit coefficient c_2 and c_3; (12) normalized (σ/mean) weighted standard deviation of the calibration ×10^3; (13) similar to col. 12 but with the trend removed, weighted mean absolute residual from the fit, ×10^3; (14) improvement (decrease) in the normalised standard deviation by applying the trend, ×10^5.

| Band index | Band name | Wave nm. | Calibration | Trend coefficient | Normalized SD |
|------------|-----------|----------|-------------|--------------------|--------------|
|            | ROLOG     | 1249     | 1245        | 1245               |              |
| 0          | 16        | 345      | -1.5 197 -658 230 | 0.97622 0.0044 | 42.7 42.4 26 |
| 1          | 17        | 355      | -7.9 189 -729 221 | 0.91826 0.0033 | 31.8 31.6 21 |
| 2          | 18        | 405      | 1.4 128 -82 196 1.00737 0.00602 | 16.1 15.5 57 |
| 3          | 2         | 412      | -0.8 112 -62 192 | 0.99614 0.00144 | 11.2 11.1 4 |
| 4          | 19        | 415      | -8.6 148 -540 164 | 0.91213 0.00376 | 18.6 18.3 29 |
| 5          | 4         | 443      | -7.3 96 -52 159 | 0.92333 0.00329 | 19.2 19.0 19 |
| 6          | 20        | 465      | -12.1 99 -65 130 | 0.87721 0.00307 | 18.2 18.0 25 |
| 7          | 21        | 475      | -9.8 101 -70 119 | 0.89693 0.00496 | 23.5 23.1 45 |
| 8          | 6         | 488      | -9.3 89 -55 111 | 0.90064 0.00470 | 20.1 19.7 34 |
| 9          | 22        | 545      | -10.7 140 -292 93 | 0.89361 0.00393 | 13.5 13.0 50 |
| 10         | 8         | 551      | -7.7 93 -74 87 0.92055 0.00452 | 9.8 8.9 90 |
| 11         | 23        | 555      | -10.5 106 -80 93 | 0.89743 0.00328 | 11.0 10.6 40 |
| 12         | 10        | 667      | -2.9 94 -74 73 | 0.97675 0.00216 | 9.0 8.8 20 |
| 13         | 24        | 695      | -9.0 103 -89 51 | 0.91296 0.00359 | 11.1 10.7 44 |
| 14         | 25        | 705      | -10.0 101 -90 52 | 0.90649 0.00132 | 12.3 12.1 12 |
| 15         | 12        | 748      | -8.0 85 -63 53 | 0.92803 -0.00016 | 8.4 8.4 0 |
| 16         | 26        | 765      | -9.3 154 -87 60 | 0.90926 0.00208 | 17.9 17.8 19 |
| 17         | 27        | 775      | -5.3 102 -93 49 | 0.95324 0.00179 | 10.5 10.3 15 |
| 18         | 14        | 869      | -2.1 98 -65 58 | 0.99406 -0.00172 | 9.0 8.9 12 |
| 19         | 28        | 875      | -4.5 123 -92 45 | 0.96565 0.00149 | 12.3 12.2 5 |
| 20         | 29        | 885      | -2.3 123 -96 53 | 0.98851 0.00153 | 11.9 11.8 7 |
| 21         | 30        | 935      | -8.5 157 -86 67 | 0.92138 0.00071 | 17.8 17.8 2 |
| 22         | 31        | 944      | -15.5 179 -80 86 | 0.85726 -0.00026 | 23.3 23.3 -1 |
| 23         | 52        | 945      | -13.3 303 -157 151 | 0.87290 0.00222 | 48.6 48.5 6 |
| 24         | 54        | 1060     | -5.4 269 -181 101 | 0.95192 0.00279 | 31.8 31.7 13 |
| 25         | 57        | 1250     | -7.2 251 -157 81 | 0.93715 0.00032 | 41.2 41.2 1 |
| 26         | 58        | 1550     | -7.9 207 -875 81 | 0.94109 -0.00211 | 27.1 27.1 1 |
| Band index | Band name | Wave nm. | Calibration Mean | Calibration SD | Δ min | Δ max | Trend coefficient | Normalized SD | Cal | Trend | Imp |
|-----------|----------|----------|-----------------|----------------|-------|-------|------------------|--------------|-----|-------|-----|
| 27        | 60       | 1640     | -7.8            | 232            | -573  | 65    | 0.94939          | -0.00331     | :   | :     | 30.2 30.2 2 |
| 28        | 62       | 1990     | -5.2            | 232            | -826  | 80    | 0.97785          | -0.000367    | :   | :     | 31.3 31.3 0 |
| 29        | 64       | 2140     | -15.0           | 202            | -452  | 101   | 0.84363          | 0.000724     | :   | :     | 22.1 22.5 -41 |
| 30        | 66       | 2260     | -0.6            | 204            | -96   | 157   | 0.97695          | 0.01620      | :   | :     | 28.3 25.3 298 |
| 31        | 68       | 2390     | -2.3            | 215            | -347  | 67    | 0.98723          | 0.00144      | :   | :     | 22.8 22.8 3 |
|           |          |          |                 |                |       |       |                  |              |     |        |     |
|           |          | 0        | 2               |                |       |       |                  |              |     |        |     |
| 0         | 450      | 450      | 2.4             | 0              | 0     | 0     | :                | :            | :   | :     | :     |
| 1         | 500      | 500      | -1.8            | 0              | 0     | 0     | :                | :            | :   | :     | :     |
| 2         | 550      | 550      | 0.4             | 0              | 0     | 0     | :                | :            | :   | :     | :     |
| 3         | 600      | 600      | 0.7             | 0              | 0     | 0     | :                | :            | :   | :     | :     |
| 4         | 650      | 650      | 2.1             | 0              | 0     | 0     | :                | :            | :   | :     | :     |
| 5         | 703      | 703      | 2.0             | 0              | 0     | 0     | :                | :            | :   | :     | :     |
| 6         | 750      | 750      | 1.2             | 0              | 0     | 0     | :                | :            | :   | :     | :     |
| 7         | 850      | 850      | 0.4             | 0              | 0     | 0     | :                | :            | :   | :     | :     |
| 8         | 1000     | 1000     | -8.5            | 0              | 0     | 0     | :                | :            | :   | :     | :     |
|           |          |          |                 |                |       |       |                  |              |     |        |     |
|           |          | 1        | 1249            |                |       |       |                  |              |     |        |     |
| 0         | 16       | 345      | -6.3            | 201            | -82   | 32    | 0.92782          | 0.00322      | :   | :     | 29.8 29.7 7 |
| 1         | 17       | 355      | -6.4            | 184            | -84   | 29    | 0.92654          | 0.00322      | :   | :     | 28.7 28.6 7 |
| 2         | 18       | 405      | -4.5            | 79             | -102  | 11    | 0.94518          | 0.00340      | :   | :     | 25.0 25.0 8 |
| 3         | 2        | 412      | -6.3            | 72             | -101  | 10    | 0.92698          | 0.00331      | :   | :     | 25.1 25.0 8 |
| 4         | 19       | 415      | -6.4            | 71             | -101  | 10    | 0.92577          | 0.00333      | :   | :     | 25.2 25.1 8 |
| 5         | 4        | 443      | -5.9            | 61             | -104  | 9     | 0.93162          | 0.00334      | :   | :     | 25.7 25.6 7 |
| 6         | 20       | 465      | -6.3            | 59             | -104  | 9     | 0.92701          | 0.00334      | :   | :     | 26.3 26.2 7 |
| 7         | 21       | 475      | -6.9            | 58             | -103  | 9     | 0.92077          | 0.00332      | :   | :     | 26.5 26.4 7 |
| 8         | 6        | 488      | -6.9            | 58             | -103  | 10    | 0.92112          | 0.00331      | :   | :     | 26.8 26.7 7 |
| 9         | 22       | 545      | -7.1            | 57             | -102  | 11    | 0.91917          | 0.00334      | :   | :     | 27.9 27.8 6 |
| 10        | 8        | 551      | -7.1            | 58             | -101  | 12    | 0.91891          | 0.00331      | :   | :     | 28.0 28.0 6 |
| 11        | 23       | 555      | -7.2            | 57             | -101  | 11    | 0.91786          | 0.00334      | :   | :     | 28.1 28.0 6 |
| 12        | 10       | 667      | -7.9            | 58             | -95   | 11    | 0.91129          | 0.00331      | :   | :     | 29.8 29.8 5 |
| 13        | 24       | 695      | -8.1            | 57             | -94   | 10    | 0.90892          | 0.00334      | :   | :     | 30.2 30.1 5 |
| 14        | 25       | 705      | -8.2            | 57             | -93   | 10    | 0.90808          | 0.00334      | :   | :     | 30.3 30.3 5 |
| 15        | 12       | 748      | -7.8            | 61             | -92   | 10    | 0.91268          | 0.00336      | :   | :     | 30.9 30.9 4 |
| 16        | 26       | 765      | -7.9            | 60             | -91   | 9     | 0.91111          | 0.00339      | :   | :     | 31.1 31.1 4 |
| Band index | Band name | Wave nm. | Calibration | Trend coefficient | Normalized SD |
|------------|-----------|----------|-------------|-------------------|--------------|
|            |           |          | Mean SD Δ min Δ max | c₀ | c₁ \( r₁ \) | c₂ | c₃ | Cal −Trend Imp |
| 17         | 27        | 775      | -7.7 61 | 9 | 0.91352 | 0.00340 | : | : | 31.3 31.2 4 |
| 18         | 14        | 869      | -8.0 76 | -84 15 | 0.91055 | 0.00341 | : | : | 32.5 32.4 4 |
| 19         | 28        | 875      | -7.8 77 | -83 15 | 0.91170 | 0.00344 | : | : | 32.6 32.5 4 |
| 20         | 29        | 885      | -8.0 80 | -82 16 | 0.91006 | 0.00344 | : | : | 32.7 32.7 4 |
| 21         | 30        | 935      | -8.0 87 | -80 18 | 0.90989 | 0.00348 | : | : | 33.4 33.3 4 |
| 22         | 31        | 944      | -7.9 88 | -80 19 | 0.91051 | 0.00349 | : | : | 33.5 33.5 4 |
| 23         | 52        | 945      | -8.2 87 | -80 18 | 0.90800 | 0.00348 | : | : | 33.5 33.5 4 |
| 24         | 54        | 1060     | -7.8 87 | -79 19 | 0.91200 | 0.00364 | : | : | 34.9 34.9 4 |
| 25         | 57        | 1250     | -7.4 84 | -80 18 | 0.91488 | 0.00389 | : | : | 36.9 36.9 3 |
| 26         | 58        | 1550     | -6.3 75 | -83 14 | 0.92499 | 0.00457 | : | : | 39.7 39.7 3 |
| 27         | 60        | 1640     | -6.0 73 | -85 13 | 0.92716 | 0.00455 | : | : | 40.6 40.6 3 |
| 28         | 62        | 1990     | -4.2 71 | -93 19 | 0.94311 | 0.00524 | : | : | 43.7 43.7 4 |
| 29         | 64        | 2140     | -3.7 77 | -98 25 | 0.94765 | 0.00553 | : | : | 45.1 45.1 4 |
| 30         | 66        | 2260     | -3.2 88 | -102 30 | 0.95225 | 0.00579 | : | : | 46.5 46.4 4 |
| 31         | 68        | 2390     | -2.6 104 | -107 35 | 0.95742 | 0.00608 | : | : | 48.0 47.9 4 |
| —          | AerN      | 1        | 50      | — | — | — | — | — | — | — | — | — | — | — |
| 0          | B440      | 440      | 1.5 118 | -33 36 | 1.01491 | -0.0212 | : | : | 12.3 11.7 59 |
| 1          | B500      | 500      | 1.5 90  | -27 25 | 1.01532 | -0.0164 | : | : | 9.4 8.9 45 |
| 2          | B675      | 675      | -0.6 75 | -15 19 | 0.99434 | -0.00130 | : | : | 8.0 7.6 34 |
| 3          | B870      | 870      | 0.6 48  | -11 11 | 1.00614 | -0.00156 | : | : | 5.5 4.8 73 |
| 4          | B1020     | 1020     | -3.4 61 | -16 11 | 0.96636 | -0.00166 | : | : | 7.1 6.4 68 |
| 5          | B1021     | 1021     | -1.6 46 | -12 10 | 0.98416 | -0.00048 | : | : | 4.8 4.7 8 |
| 6          | B1640     | 1640     | 4.1 102 | -18 29 | 1.04089 | -0.00107 | : | : | 10.0 9.9 16 |
| —          | HiRIS     | 0        | 4       | — | — | — | — | — | — | — | — | — | — | — |
| 0          | BluGm     | 501      | -21.9 449 | -61 44 | : | : | : | : | : | : | : |
| 1          | Red       | 677      | -29.8 407 | -49 34 | : | : | : | : | : | : | : |
| 2          | nIR       | 859      | -35.7 332 | -49 20 | : | : | : | : | : | : | : |
| —          | OLI       | 1        | 1080    | — | — | — | — | — | — | — | — | — | — | — |
| 0          | Aer       | 443      | 3.8 41  | -10 11 | 1.03644 | -0.00090 | : | : | 4.3 4.0 28 |
| 1          | Blu       | 482      | 1.3 22  | -8 6 | 1.01231 | -0.00035 | : | : | 2.2 2.1 8 |
| 2          | Gm        | 562      | 0.8 33  | -10 7 | 1.00594 | -0.00022 | : | : | 3.2 3.2 2 |
| 3          | Pan       | 590      | 1.4 27  | -8 7 | 1.01309 | -0.00020 | : | : | 2.6 2.6 2 |
| 4          | Red       | 655      | 0.8 32  | -10 7 | 1.00654 | -0.00017 | : | : | 3.1 3.1 1 |
Table 7 (Continued).

| Band index | Band name | Wave nm. | Mean | SD | Δ min | Δ max | $c_0$ | $c_1 \lor r_1$ | $c_2$ | $c_3$ | Cal | Trend | Imp |
|------------|-----------|----------|------|----|-------|-------|------|----------------|------|------|-----|-------|-----|
| 5          | NIR       | 865      | 1.9  | 28 | -8    | 7     | 1.01840 | -0.00034     | :   | :   | :   | :     | 2.8 | 2.8 |
| 6          | Cir       | 1375     | 3.5  | 55 | -14   | 12    | 1.03318 | -0.00025     | :   | :   | :   | :     | 5.3 | 5.3 |
| 7          | SW1       | 1610     | -1.1 | 32 | -9    | 7     | 0.98811 | -0.00016     | :   | :   | :   | :     | 3.3 | 3.2 |
| 8          | SW2       | 2200     | -1.5 | 28 | -8    | 6     | 0.98457 | -0.00015     | :   | :   | :   | :     | 2.9 | 2.9 |
|            | OLIR      |          |      |    |       |       |      |               |     |     |     |       |     |     |
| 0          | Aer       | 443      | 4.3  | 15 | -3    | 3     | 1.03570 | 0.25          | 0.01136 | -0.0006 | 2.3 | 1.4 |
| 1          | Blu       | 482      | 1.3  | 14 | -3    | 2     | 1.01731 | 4.95          | -0.00488 | -0.0009 | 1.5 | 1.4 |
| 2          | Gm        | 562      | 0.5  | 13 | -3    | 2     | 1.00764 | 0.51          | -0.00392 | -0.0005 | 1.5 | 1.4 |
| 3          | Pan       | 590      | 1.3  | 15 | -3    | 3     | 1.01536 | 1.35          | -0.00293 | -0.0006 | 1.6 | 1.5 |
| 4          | Red       | 655      | 0.6  | 13 | -3    | 2     | 1.00846 | 0.73          | -0.00353 | -0.0005 | 1.5 | 1.4 |
| 5          | NIR       | 865      | 1.8  | 13 | -2    | 2     | 1.02086 | 1.84          | -0.00284 | -0.0007 | 1.5 | 1.3 |
| 6          | Cir       | 1375     | 3.4  | 15 | -3    | 3     | 1.03208 | 19.62         | 0.00148 | -0.0002 | 1.6 | 1.5 |
| 7          | SW1       | 1610     | -1.2 | 13 | -4    | 2     | 0.98918 | 1.28          | -0.00121 | -0.0003 | 1.4 | 1.4 |
| 8          | SW2       | 2200     | -1.5 | 15 | -4    | 2     | 0.98490 | 500.00        | 0.00000 | 0.00001 | 1.6 | 1.6 |
|            | HypM      |          |      |    |       |       |      |               |     |     |     |       |     |     |
| 0          | HM2       | 415      | 28.2 | 387| -125  | 56    | 1.44107 | -0.01298     | :   | :   | :   | :     | 31.7 | 30.2 |
| 1          | HM3       | 443      | 14.2 | 121| -23   | 23    | 1.19754 | -0.00451     | :   | :   | :   | :     | 11.3 | 10.6 |
| 2          | HM4       | 468      | 16.4 | 83 | -14   | 11    | 1.19988 | -0.00294     | :   | :   | :   | :     | 7.6  | 7.2  |
| 3          | HM5       | 490      | 22.7 | 80 | -14   | 10    | 1.25083 | -0.00194     | :   | :   | :   | :     | 6.8  | 6.6  |
| 4          | HM6       | 512      | 27.2 | 78 | -14   | 10    | 1.29449 | -0.00183     | :   | :   | :   | :     | 6.4  | 6.2  |
| 5          | HM7       | 532      | 26.7 | 78 | -14   | 10    | 1.28447 | -0.00146     | :   | :   | :   | :     | 6.3  | 6.2  |
| 6          | HM8       | 553      | 27.2 | 77 | -14   | 10    | 1.29029 | -0.00148     | :   | :   | :   | :     | 6.2  | 6.1  |
| 7          | HM9       | 578      | 28.0 | 80 | -15   | 10    | 1.29949 | -0.00163     | :   | :   | :   | :     | 6.4  | 6.3  |
| 8          | HM10      | 613      | 30.1 | 88 | -15   | 12    | 1.32288 | -0.00176     | :   | :   | :   | :     | 7.0  | 6.8  |
| 9          | HM11      | 648      | 29.8 | 85 | -15   | 11    | 1.31520 | -0.00140     | :   | :   | :   | :     | 6.7  | 6.6  |
| 10         | HM12      | 666      | 26.0 | 79 | -15   | 10    | 1.26986 | -0.00079     | :   | :   | :   | :     | 6.4  | 6.3  |
| 11         | HM13      | 680      | 26.8 | 80 | -15   | 10    | 1.28327 | -0.00129     | :   | :   | :   | :     | 6.4  | 6.4  |
| 12         | HM14      | 704      | 27.2 | 83 | -15   | 11    | 1.28328 | -0.00177     | :   | :   | :   | :     | 6.7  | 6.6  |
| 13         | HM15      | 730      | 24.6 | 82 | -15   | 11    | 1.27272 | -0.00216     | :   | :   | :   | :     | 6.8  | 6.6  |
| 14         | HM16      | 750      | 24.5 | 84 | -16   | 11    | 1.27808 | -0.00274     | :   | :   | :   | :     | 7.2  | 6.8  |
| 15         | HM17      | 775      | 25.2 | 91 | -17   | 12    | 1.29638 | -0.00362     | :   | :   | :   | :     | 7.8  | 7.3  |
| 16         | HM18      | 850      | 28.1 | 82 | -16   | 11    | 1.33239 | -0.00425     | :   | :   | :   | :     | 7.3  | 6.5  |
| 17         | HM19      | 870      | 26.2 | 84 | -16   | 11    | 1.32864 | -0.00543     | :   | :   | :   | :     | 8.0  | 6.7  |
Table 7 (Continued).

| Band index | Band name | Wave nm. | Mean | SD | Δ min | Δ max | c₀ | c₁ \lor τ₁ | c₂ | c₃ | Cal | Trend | Imp |
|------------|-----------|----------|------|----|-------|-------|----|------------|----|----|-----|-------|-----|
| 18         | HM20      | 915      | 18.4 | 101 | -24   | 14    | 1.27893 | -0.00779 | :  | :  | 10.9 | 8.6   | 230 |
| 19         | HM21      | 1060     | 20.8 | 95  | -17   | 21    | 1.26311 | -0.00455 | :  | :  | 8.8  | 7.9   | 89  |
| 20         | HM22      | 1245     | 17.4 | 80  | -17   | 12    | 1.22406 | -0.00410 | :  | :  | 7.7  | 6.8   | 86  |
| 21         | HM23      | 1383     | 23.9 | 104 | -23   | 18    | 1.29797 | -0.00483 | :  | :  | 9.3  | 8.4   | 87  |
| 22         | HM24      | 1608     | 19.0 | 93  | -17   | 16    | 1.20704 | -0.00144 | :  | :  | 7.9  | 7.8   | 10  |
| 23         | HM25      | 2160     | 23.2 | 111 | -21   | 16    | 1.27287 | -0.00336 | :  | :  | 9.5  | 9.1   | 41  |
| 24         | HM26      | 2255     | 20.5 | 84  | -15   | 14    | 1.23298 | -0.00232 | :  | :  | 7.3  | 7.0   | 27  |
| 25         | HM27      | 2383     | 28.0 | 109 | -18   | 22    | 1.26865 | 0.00089  | :  | :  | 8.6  | 8.5   | 3   |
| MODT       | 1         | 993      | —    | —   | —     | —     | —  | —          | —  | —  | —   | —     | —   |
| 0          | b8        | 412      | 1.2  | 86  | -22   | 31    | 1.01283 | 0.00014  | :  | :  | 8.6  | 8.5   | 3   |
| 1          | b9        | 443      | 1.4  | 66  | -20   | 22    | 1.01513 | -0.00002 | :  | :  | 6.5  | 6.5   | 0   |
| 2          | b3        | 469      | 1.3  | 79  | -25   | 32    | 1.01425 | 0.00034  | :  | :  | 8.1  | 7.8   | 21  |
| 3          | b10       | 488      | 1.7  | 47  | -14   | 12    | 1.01751 | -0.00025 | :  | :  | 4.8  | 4.6   | 20  |
| 4          | b11       | 531      | -0.1 | 38  | -12   | 12    | 0.99962 | -0.00003 | :  | :  | 3.8  | 3.8   | 0   |
| 5          | b12       | 551      | 1.1  | 39  | -15   | 9     | 1.01185 | 0.00003  | :  | :  | 3.9  | 3.9   | 0   |
| 6          | b4        | 555      | -0.5 | 52  | -17   | 13    | 0.99552 | 0.00002  | :  | :  | 5.3  | 5.3   | 0   |
| 7          | b1        | 645      | -2.2 | 88  | -22   | 23    | 0.97828 | 0.00129  | :  | :  | 11.5 | 9.0   | 251 |
| 8          | b13       | 666      | 0.4  | 41  | -11   | 12    | 1.00509 | 0.00011  | :  | :  | 4.2  | 4.1   | 4   |
| 9          | b14       | 678      | -0.2 | 52  | -15   | 16    | 0.99868 | 0.00003  | :  | :  | 5.2  | 5.2   | 0   |
| 10         | b15       | 748      | 0.7  | 50  | -18   | 13    | 1.00799 | 0.00009  | :  | :  | 5.0  | 5.0   | 2   |
| 11         | b2        | 858      | -0.4 | 83  | -19   | 26    | 0.99681 | 0.00146  | :  | :  | 11.5 | 8.4   | 317 |
| 12         | b16       | 868      | 1.4  | 41  | -13   | 13    | 1.01513 | -0.00003 | :  | :  | 4.1  | 4.1   | 0   |
| 13         | b17       | 905      | 4.2  | 42  | -11   | 12    | 1.04313 | -0.00004 | :  | :  | 4.0  | 4.0   | 0   |
| 14         | b18       | 936      | 3.4  | 47  | -12   | 13    | 1.03453 | 0.00001  | :  | :  | 4.6  | 4.6   | 0   |
| 15         | b19       | 940      | 4.1  | 39  | -10   | 12    | 1.04130 | -0.00005 | :  | :  | 3.8  | 3.8   | 1   |
| 16         | b5        | 1240     | 30.3 | 321 | -86   | 159   | 1.30417 | 0.00214  | :  | :  | 26.1 | 24.7  | 146 |
| 17         | b26       | 1375     | 9.5  | 150 | -42   | 75    | 1.09575 | 0.00053  | :  | :  | 13.9 | 13.7  | 23  |
| 18         | b6        | 1640     | 9.8  | 117 | -47   | 66    | 1.09927 | 0.00053  | :  | :  | 11.0 | 10.7  | 30  |
| 19         | b7        | 2130     | -4.3 | 151 | -39   | 64    | 0.95749 | 0.00087  | :  | :  | 16.5 | 15.8  | 73  |
| MODA       | 1         | 743      | —    | —   | —     | —     | —  | —          | —  | —  | —   | —     | —   |
| 0          | b8        | 412      | 3.1  | 74  | -24   | 22    | 1.03146 | -0.00041 | :  | :  | 7.5  | 7.3   | 24  |
| 1          | b9        | 443      | 2.0  | 42  | -13   | 12    | 1.01980 | -0.00028 | :  | :  | 4.4  | 4.2   | 20  |
| 2          | b3        | 469      | 0.3  | 47  | -15   | 11    | 1.00262 | -0.00010 | :  | :  | 4.8  | 4.7   | 2   |
Table 7 (Continued).

| Band index | Band name | Wave nm. | Calibration | Trend coefficient | Normalized SD |
|------------|-----------|----------|-------------|-------------------|---------------|
|            |           |          | Cal         | $c_0$             |               | $c_1$ $\tau_1$ | $c_2$ | $c_3$ | Cal | Trend | Imp |
| 3          | b10       | 488      | 1.2 33 -10 11 | 1.01177 -0.00014 |               |               | 3.4   | 3.4   | 7   |
| 4          | b11       | 531      | -1.2 28 -10 8 | 0.98851 -0.00014 |               |               | 3.0   | 2.9   | 7   |
| 5          | b12       | 551      | 0.3 31 -11 6  | 1.00321 -0.00013 |               |               | 3.2   | 3.1   | 6   |
| 6          | b4        | 555      | -1.6 32 -12 7 | 0.98426 -0.00005 |               |               | 3.4   | 3.3   | 1   |
| 7          | b1        | 645      | -1.3 55 -17 13 | 0.98655 0.00054  |               |               | 6.2   | 5.6   | 57  |
| 8          | b13       | 666      | 1.1 52 -13 15 | 1.01119 -0.00035 |               |               | 5.5   | 5.2   | 25  |
| 9          | b14       | 678      | 1.2 61 -14 17 | 1.01213 -0.00033 |               |               | 6.2   | 6.1   | 20  |
| 10         | b15       | 748      | 1.2 159 -53 29 | 1.0171 -0.00046  |               |               | 15.9  | 15.7  | 14  |
| 11         | b2        | 858      | -0.1 51 -14 12 | 0.99920 0.00116  |               |               | 7.4   | 5.1   | 233 |
| 12         | b16       | 868      | -1.1 359 -96 52 | 0.98913 -0.00036 |               |               | 36.4  | 36.4  | 4   |
| 13         | b17       | 905      | 3.7 31 -10 12 | 1.03670 -0.00009 |               |               | 3.0   | 3.0   | 3   |
| 14         | b18       | 936      | 3.3 35 -12 13 | 1.03330 -0.00004 |               |               | 3.5   | 3.5   | 0   |
| 15         | b19       | 940      | 3.7 30 -9 12  | 1.03756 -0.00005 |               |               | 2.9   | 2.9   | 1   |
| 16         | b5        | 1240     | 15.3 294 -69 69 | 1.15346 -0.00105 |               |               | 25.9  | 25.5  | 36  |
| 17         | b26       | 1375     | 4.3 143 -32 21 | 1.04324 -0.00016 |               |               | 13.8  | 13.8  | 2   |
| 18         | b7        | 2130     | -3.0 74 -18 21 | 0.96995 -0.00008 |               |               | 7.7   | 7.7   | 1   |
|            | SeaW 4    | 204      | —          | —              | —              | —              | —     | —     | —   |
| 0          | M1        | 421      | -2.1 67 -20 28 | 0.96506 10.21 | 0.01523 0.0010 | 6.9   | 6.9   | 5   |
| 1          | M2        | 446      | -2.2 67 -21 28 | 0.97577 5.55  | 0.00209 0.0003 | 6.9   | 6.9   | 3   |
| 2          | M3        | 491      | -3.1 68 -18 30 | 0.98932 232.10 | -0.02034 0.002 | 7.1   | 7.1   | 8   |
| 3          | M4        | 510      | -3.9 69 -18 31 | 0.98449 140.01 | -0.02308 0.0001 | 7.3  | 7.2   | 9   |
| 4          | M5        | 555      | -4.8 72 -19 33 | 0.97685 26.90  | -0.02457 -0.0003 | 7.7  | 7.6   | 11  |
| 5          | M6        | 670      | -5.2 74 -19 33 | 0.97798 17.81  | -0.03010 -0.0007 | 8.0  | 7.8   | 15  |
| 6          | M7        | 765      | -3.6 75 -18 31 | 0.99452 15.82  | -0.03073 -0.0008 | 8.0  | 7.8   | 20  |
| 7          | M8        | 865      | -5.3 69 -21 28 | 0.95580 -804.76 | -0.00924 -0.0000 | 7.3  | 7.3   | 1   |
|            | VIIRS 4   | 71       | —          | —              | —              | —              | —     | —     | —   |
| 0          | I1        | 421      | -21.3 13 -6 4  | 0.77805 1.74  | 0.01185 -0.0052 | 19.0  | 1.7   | 1731 |
| 1          | I2        | 446      | 6.9 10 -2 2  | 1.06656 1.06  | 0.00592 -0.0035 | 8.6  | 0.9   | 775  |
| 2          | I3        | 489      | 11.4 26 -14 2 | 1.09614 402.94 | 0.01779 -0.0039 | 8.9  | 2.3   | 653  |
| 3          | I4        | 552      | 10.8 13 -2 3  | 1.09489 9.90  | 0.01332 -0.0030 | 8.7  | 1.1   | 762  |
| 4          | I5        | 638      | 3.9 19 -4 4  | 0.99893 0.49  | 0.06211 -0.0063 | 20.9 | 1.8   | 1906 |
| 5          | I6        | 671      | 3.6 16 -3 2  | 0.97414 0.46  | 0.09531 -0.0079 | 28.2 | 1.5   | 2763 |
| 6          | I7        | 745      | -5.3 23 -4 4  | 0.82935 0.43  | 0.18470 -0.0114 | 53.7 | 2.4   | 5126 |

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| Band index | Band name | Wave nm. | Calibration | Trend coefficient | Normalized SD |
|------------|-----------|----------|-------------|--------------------|---------------|
|            |           | Mean     | SD          | Δ min | Δ max | c₀   | c₁ \( \tau₁ \) | c₂   | c₃ | Cal | Trend | Imp |
| 7          | I2        | 861      | -7.0       | 40    | -8    | 8    | 0.72892       | 0.42  | 0.32007       | -0.0164 | 97.2 | 4.3 | 9283 |
| 8          | M7        | 862      | -6.9       | 40    | -7    | 8    | 0.72832       | 0.41  | 0.32383       | -0.0160 | 96.0 | 4.3 | 9166 |
| 9          | M8        | 1241     | -8.7       | 33    | -9    | 6    | 0.73163       | 0.44  | 0.27973       | -0.0153 | 80.1 | 3.7 | 7649 |
| 10         | M9        | 1375     | -3.1       | 29    | -8    | 4    | 0.83374       | 0.49  | 0.20174       | -0.0132 | 52.2 | 3.0 | 4921 |
| 11         | I3        | 1601     | -1.4       | 26    | -7    | 4    | 0.89505       | 0.43  | 0.14266       | -0.0092 | 37.8 | 2.7 | 3518 |
| 12         | M10       | 1602     | -2.2       | 25    | -8    | 3    | 0.88750       | 0.44  | 0.14024       | -0.0091 | 35.2 | 2.6 | 3254 |
| 13         | M11       | 2257     | 3.6        | 17    | -5    | 2    | 1.01018       | 0.47  | 0.03992       | -0.0030 | 9.8  | 1.7 | 818  |
|            |           |          |            |       |       |      |              |       |                |        |      |      |      |
|            | VIIRN     |          |            |       |       |      |              |       |                |        |      |      |      |
| 0          | M1        | 421      | 17.5       | 14    | -2    | 2    | 1.17464       | -0.00012 | :     | :     | 1.2  | 1.2 | 0   |
| 1          | M2        | 446      | 12.9       | 10    | -1    | 2    | 1.12898       | -0.00107 | :     | :     | 1.3  | 0.9 | 43  |
| 2          | M3        | 489      | 12.7       | 8     | -1    | 1    | 1.12686       | -0.00093 | :     | :     | 1.1  | 0.7 | 40  |
| 3          | M4        | 552      | 13.5       | 7     | -1    | 1    | 1.13504       | -0.00109 | :     | :     | 1.2  | 0.6 | 53  |
| 4          | I1        | 638      | 10.5       | 10    | -2    | 2    | 1.10496       | -0.00136 | :     | :     | 1.6  | 1.0 | 62  |
| 5          | M5        | 671      | 14.6       | 8     | -1    | 2    | 1.14575       | -0.00080 | :     | :     | 1.0  | 0.7 | 30  |
| 6          | M6        | 745      | 12.9       | 10    | -1    | 1    | 1.12901       | -0.00059 | :     | :     | 1.0  | 0.9 | 15  |
| 7          | I2        | 861      | 11.7       | 12    | -1    | 2    | 1.11644       | -0.00019 | :     | :     | 1.1  | 1.1 | 1   |
| 8          | M7        | 862      | 14.0       | 19    | -3    | 2    | 1.13959       | -0.00006 | :     | :     | 1.7  | 1.7 | 0   |
| 9          | M8        | 1241     | 1.9        | 12    | -2    | 1    | 1.01850       | -0.00008 | :     | :     | 1.2  | 1.2 | 0   |
| 10         | M9        | 1375     | -1.3       | 15    | -2    | 2    | 0.98629       | 0.00034  | :     | :     | 1.6  | 1.6 | 4   |
| 11         | I3        | 1601     | -0.5       | 16    | -2    | 3    | 0.99443       | 0.00001  | :     | :     | 1.7  | 1.7 | 0   |
| 12         | M10       | 1602     | -2.5       | 13    | -3    | 1    | 0.97495       | -0.00008 | :     | :     | 1.3  | 1.3 | 0   |
| 13         | M11       | 2257     | 4.7        | 12    | -2    | 2    | 1.04671       | -0.00038 | :     | :     | 1.3  | 1.2 | 5   |
|            | PleA      | 1        | 141        | —     | —     | —    | —             | —     | —     | —    | —   | —   | —   |
| 0          | Blue      | 490      | -0.8       | 50    | -12   | 16   | 0.99157       | 0.00125 | :     | :     | 11.1 | 10.8 | 24  |
| 1          | Green     | 560      | 2.4        | 76    | -29   | 20   | 1.02370       | 0.00286 | :     | :     | 13.1 | 12.2 | 96  |
| 2          | Red       | 650      | 0.4        | 61    | -49   | 9    | 1.00282       | 0.00056 | :     | :     | 12.4 | 12.3 | 2   |
| 3          | Pan       | 655      | -0.2       | 62    | -37   | 10   | 0.99976       | 0.00142 | :     | :     | 28.8 | 28.6 | 19  |
| 4          | NIR       | 840      | 1.9        | 50    | -44   | 8    | 1.01820       | 0.00132 | :     | :     | 13.2 | 13.0 | 15  |
|            | PleB      | 4        | 339        | —     | —     | —    | —             | —     | —     | —    | —   | —   | —   |
| 0          | Blue      | 490      | -0.2       | 43    | -33   | 14   | 0.52231       | 11.70  | 0.47284       | 0.0318 | 41.0 | 40.8 | 13  |
| 1          | Green     | 560      | 1.9        | 40    | -21   | 8    | 0.52922       | 16.87  | 0.48537       | 0.0236 | 42.3 | 42.2 | 8   |
| 2          | Red       | 650      | 1.4        | 34    | -22   | 8    | 0.51132       | -46.63 | 0.49567       | -0.0100 | 44.5 | 44.5 | -2  |
| 3          | Pan       | 655      | 0.2        | 48    | -16   | 9    | 0.50892       | 144.60 | 0.48729       | 0.0038 | 44.1 | 44.1 | -1  |
| 4          | NIR       | 840      | 2.5        | 42    | -18   | 13   | 0.50242       | 76.19  | 0.51649       | 0.0076 | 47.3 | 47.3 | -1  |
### Table 7 (Continued)

| Band index | Band name | Wave nm. | Calibration | Trend coefficient | Normalized SD |
|------------|-----------|----------|-------------|--------------------|---------------|
|            |           |                      | Mean SD   |  \( \Delta_{\text{min}} \) |  \( \Delta_{\text{max}} \) |
| 0          | GS8       | 2        | 44         | 0.73719             | 24.34         |
|            | GS9       | 1        | 9          | 0.84159             | -0.01461      |
| 0          | GS10      | 3        | 49         | 0.59258             | 3.66          |
| 0          | GS11      | 1        | 77         | 1.03576             | -0.02952      |
| 0          | GS12      | 3        | 49         | 0.94222             | -0.02705      |
| 0          | GS13      | 1        | 47         | 0.93312             | 0.00030       |
| 0          | GS14      | 1        | 11209      | 0.90315             | -0.04376      |
| 0          | VISO06    | 34       | 9          | 0.91468             | -0.00064      |
| 1          | HRVIS     | 1        | 202        | 0.91189             | -0.00375      |
| 2          | VISO08    | 810      | -40        | 0.93352             | -0.00051      |
| 3          | NIR016    | 1640     | 5.8        | 1.03312             | 0.000030      |
| 0          | VISO06    | 34       | 9          | 0.92446             | -0.00164      |
| 1          | HRVIS     | 1        | 202        | 0.98007             | -0.00375      |
| 2          | VISO08    | 810      | -35        | 0.94527             | -0.00043      |
| 3          | NIR016    | 1640     | 6.4        | 1.03075             | 0.00145       |
| 0          | VISO06    | 34       | 9          | 0.88916             | 0.000025      |
| 1          | HRVIS     | 1        | 202        | 0.86576             | 0.00448       |
| 2          | VISO08    | 810      | -34        | 0.94402             | -0.00067      |
| 3          | NIR016    | 1640     | 6.4        | 1.04214             | 0.00162       |
| 0          | VISO06    | 34       | 9          | 0.8734              | 0.00419       |
| 1          | HRVIS     | 1        | 202        | 0.84669             | 0.01821       |
| 2          | VISO08    | 810      | -28        | 0.94692             | 0.00436       |
| 3          | NIR016    | 1640     | 7.2        | 1.04134             | 0.00738       |
| Band index | Band name | Wave nm. | Calibration | Trend coefficient | Normalized SD | Cal | Trend | Imp |
|------------|-----------|----------|-------------|-------------------|---------------|-----|-------|-----|
|            |           |          | Mean SD   | Δ min Δ max c₀  c₁ β₁ c₂  c₃ |               |     |       |     |
| 0          | B01       | 470      | 2.9 117   | -18 54          | 1.00235 0.01025 : : 12.0 11.4 59 |
| 1          | B02       | 640      | -0.5 66   | -14 14         | 0.99570 -0.00045 : : 6.7 6.7 0 |
| 2          | B03       | 865      | 1.8 38    | -7 12         | 1.01684 0.00014 : : 3.7 3.7 0 |
| 3          | B04       | 1378     | 1.1 48    | -8 13        | 1.00827 0.00080 : : 4.8 4.8 1 |
| 4          | B05       | 1610     | 2.3 68    | -13 16       | 1.01300 0.00341 : : 6.8 6.7 11 |
| 5          | B06       | 2250     | 1.4 90    | -17 20       | 0.99958 0.00521 : : 9.1 8.9 20 |
| 0          | ABI16     | 470      | 4.2 169   | -21 62       | 1.02900 0.01036 : : 16.6 16.2 41 |
| 1          | B02       | 640      | 3.9 224   | -208 32      | 1.02798 0.00851 : : 21.8 21.6 21 |
| 2          | B03       | 865      | 2.5 86    | -18 22      | 1.00872 0.01314 : : 9.6 8.4 117 |
| 3          | B04       | 1378     | 5.5 89    | -15 23      | 1.05313 0.00129 : : 8.5 8.5 1 |
| 4          | B05       | 1610     | 6.6 100   | -16 27     | 1.05741 0.00652 : : 9.7 9.4 26 |
| 5          | B06       | 2250     | 3.1 111   | -20 27     | 1.02469 0.00515 : : 10.9 10.8 16 |
| 0          | GIRO      | 1610     | -        |          |               |     |       |     |
| 1          | 16        | 345      | -1.3 113  | -46 13     |               |     |       |     |
| 2          | 17        | 355      | -1.4 100  | -41 13     |               |     |       |     |
| 3          | 18        | 405      | -3.1 68   | -30 10     |               |     |       |     |
| 4          | 2         | 412      | -3.1 67   | -32 10     |               |     |       |     |
| 5          | 19        | 415      | -3.2 64   | -30 10     |               |     |       |     |
| 6          | 4         | 443      | -3.9 49   | -24 10     |               |     |       |     |
| 7          | 20        | 465      | -4.7 52   | -26 11     |               |     |       |     |
| 8          | 21        | 475      | -4.8 46   | -24 11     |               |     |       |     |
| 9          | 6         | 488      | -5.0 45   | -23 12     |               |     |       |     |
| 10         | 22        | 545      | -6.2 54   | -26 8      |               |     |       |     |
| 11         | 8         | 551      | -6.0 49   | -25 8      |               |     |       |     |
| 12         | 23        | 555      | -6.4 55   | -28 8      |               |     |       |     |
| 13         | 10        | 667      | -7.7 49   | -24 8      |               |     |       |     |
| 14         | 24        | 695      | -7.8 45   | -23 8      |               |     |       |     |
| 15         | 25        | 705      | -7.9 48   | -23 9      |               |     |       |     |
| 16         | 12        | 748      | -8.1 48   | -24 7      |               |     |       |     |
| 17         | 26        | 765      | -8.1 42   | -22 16     |               |     |       |     |
| Band index | Band name | Wave nm. | Calibration | Trend coefficient | Normalized SD |
|------------|-----------|----------|-------------|-------------------|---------------|
|            |           |          | Mean | SD | Δ min | Δ max | c₀ | c₁ | γ₀ | c₂ | c₃ | Cal | Δ Trend | Imp |
| 17         | 27        | 775      | -8.3 | 45 | -24   | 9     | :  | :  | :  | :  | :  | :   | :      |     |
| 18         | 14        | 869      | -8.9 | 63 | -27   | 10    | :  | :  | :  | :  | :  | :   | :      |     |
| 19         | 28        | 875      | -8.9 | 67 | -30   | 10    | :  | :  | :  | :  | :  | :   | :      |     |
| 20         | 29        | 885      | -9.0 | 70 | -31   | 10    | :  | :  | :  | :  | :  | :   | :      |     |
| 21         | 30        | 935      | -9.2 | 83 | -39   | 14    | :  | :  | :  | :  | :  | :   | :      |     |
| 22         | 31        | 944      | -9.9 | 166 | -50   | 25    | :  | :  | :  | :  | :  | :   | :      |     |
| 23         | 52        | 945      | -9.8 | 159 | -49   | 24    | :  | :  | :  | :  | :  | :   | :      |     |
| 24         | 54        | 1060     | -9.6 | 167 | -60   | 20    | :  | :  | :  | :  | :  | :   | :      |     |
| 25         | 57        | 1250     | -8.3 | 106 | -36   | 14    | :  | :  | :  | :  | :  | :   | :      |     |
| 26         | 58        | 1550     | -6.6 | 68 | -25   | 12    | :  | :  | :  | :  | :  | :   | :      |     |
| 27         | 60        | 1640     | -5.6 | 60 | -21   | 12    | :  | :  | :  | :  | :  | :   | :      |     |
| 28         | 62        | 1990     | -3.4 | 42 | -21   | 10    | :  | :  | :  | :  | :  | :   | :      |     |
| 29         | 64        | 2140     | -3.0 | 191 | -48   | 52    | :  | :  | :  | :  | :  | :   | :      |     |
| 30         | 66        | 2260     | -1.6 | 58 | -23   | 16    | :  | :  | :  | :  | :  | :   | :      |     |
| 31         | 68        | 2390     | -0.3 | 72 | -16   | 17    | :  | :  | :  | :  | :  | :   | :      |     |
|            | LIIMO     |          |      |    |       |       | :  | :  | :  | :  | :  | :   | :      |     |
| 0          | band_1    | 440      | -3.1 | 102 | -22   | 28    | :  | :  | :  | :  | :  | :   | :      |     |
| 1          | band_2    | 500      | -3.3 | 89 | -20   | 27    | :  | :  | :  | :  | :  | :   | :      |     |
| 2          | band_3    | 675      | -4.9 | 81 | -19   | 24    | :  | :  | :  | :  | :  | :   | :      |     |
| 3          | band_4    | 870      | -6.1 | 94 | -21   | 25    | :  | :  | :  | :  | :  | :   | :      |     |
| 4          | band_5    | 1020     | -6.1 | 110 | -24   | 26    | :  | :  | :  | :  | :  | :   | :      |     |
| 5          | band_6    | 1640     | -6.9 | 88 | -22   | 23    | :  | :  | :  | :  | :  | :   | :      |     |
|            | SLIMO     |          |      |    |       |       | :  | :  | :  | :  | :  | :   | :      |     |
| 0          | G1        | 442      | -0.0 | 19 | -6    | 5     | :  | :  | :  | :  | :  | :   | :      |     |
| 1          | G2        | 550      | 0.1  | 20 | -6    | 4     | :  | :  | :  | :  | :  | :   | :      |     |
| 2          | G3        | 670      | 0.1  | 21 | -7    | 4     | :  | :  | :  | :  | :  | :   | :      |     |
| 3          | G4        | 765      | 0.2  | 22 | -7    | 5     | :  | :  | :  | :  | :  | :   | :      |     |
| 4          | G5        | 870      | 0.2  | 23 | -7    | 5     | :  | :  | :  | :  | :  | :   | :      |     |
| 5          | G6        | 1380     | 0.1  | 25 | -7    | 6     | :  | :  | :  | :  | :  | :   | :      |     |
| 6          | G7        | 1640     | 0.1  | 26 | -8    | 6     | :  | :  | :  | :  | :  | :   | :      |     |
| 7          | G8        | 2350     | -0.1 | 27 | -8    | 7     | :  | :  | :  | :  | :  | :   | :      |     |
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Table 8  Instrument dates, grouped by type. Date of launch and date range covered by data on hand.

| Instrument | Acronym | Launch Dates | First Observation Dates | Last Observation Dates |
|------------|---------|--------------|-------------------------|------------------------|
| SeaWIFS    | SeaW   | September 20, 1997 | November 14, 1997  | November 22, 2010 |
| EO1-Hyperion | HypM  | November 21, 2000 | February 26, 2013 | February 23, 2016 |
| Terra-MODIS | MODT   | December 18, 1999 | March 24, 2000 | February 23, 1999 |
| Aqua-MODIS  | MODA   | May 04, 2002 | June 20, 2002 | February 15, 2019 |
| Suomi-VIIRS | VIIRS  | October 28, 2011 | January 04, 2012 | March 05, 2020 |
| NOAA-20-VIIRS | VIIRN | November 18, 2017 | December 29, 2017 | March 24, 2021 |
| Landsat-8-OLI | OLI    | February 11, 2013 | March 26, 2013 | January 21, 2019 |
| PLEIADES-A | PleA   | December 17, 2011 | January 02, 2012 | April 07, 2017 |
| PLEIADES-B | PleB   | December 02, 2012 | February 17, 2013 | April 07, 2017 |
| GOES-8     | GS8    | April 13, 1994 | January 08, 1995 | February 20, 2003 |
| GOES-9     | GS9    | May 23, 1995 | December 12, 1995 | April 12, 1998 |
| GOES-10    | GS10   | April 25, 1997 | August 09, 1998 | June 06, 2006 |
| GOES-11    | GS11   | May 03, 2000 | September 08, 2006 | December 04, 2011 |
| GOES-12    | GS12   | July 23, 2001 | April 14, 2003 | March 02, 2010 |
| GOES-13    | GS13   | May 24, 2006 | July 30, 2010 | November 14, 2013 |
| GOES-15    | GS15   | February 05, 2010 | March 06, 2012 | November 14, 2013 |
| MSG-1-SEVIRI | SEV1  | August 28, 2002 | November 04, 2003 | December 31, 2019 |
| MSG-2-SEVIRI | SEV2  | December 22, 2005 | July 04, 2006 | December 31, 2019 |
| MSG-3-SEVIRI | SEV3  | July 5, 2012 | January 01, 2013 | December 19, 2019 |
| MSG-4-SEVIRI | SEV4  | July 05, 2015 | August 29, 2015 | December 21, 2019 |
| GOES-16-ABI | ABI16 | November 03, 2016 | May 14, 2019 | July 10, 2020 |
| GOES-17-ABI | ABI17 | March 01, 2018 | May 14, 2019 | June 11, 2020 |
| Observ.@2148m | ROLOG | February 29, 1996 | July 03, 1998 | December 17, 2000 |
| Observ.@2367m | NIST | November 30, 2012 | November 30, 2012 | November 30, 2012 |
| Observ.@3402m | AerN | February 26, 2016 | March 27, 2016 | June 27, 2021 |
| HiRISE-Mars | HiRIS | August 12, 2002 | November 20, 2016 | November 20, 2016 |
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Data, Materials, and Code Availability

The Base and V1 models can be implemented from information in this article. A full set of IDL code to do an instrument calibration using a SLIMED model is available by contacting the author. Hopefully, some organization will convert this to a common computer language. The JPL DE430 ephemeris and FORTRAN code to run that is also required. Source code for all IDL routines called at any level by the SLIM system is archived at an academic institution and currently available only to two younger colleagues. It includes 252 routines, about 38,000 lines of high-level executable code, and totals about 4 Mb. Also archived there are all nonembargoed data files and SLIMED output files, descriptions of all file contents, and a user guide to running the SLIM system, about 400 Mb. This is intended to be transferred to a US government institution. Public access is unresolved.

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