Radiometric Calibration Stability and Inter-calibration of Solar-band Instruments in Orbit Using the Moon

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ABSTRACT

With the increased emphasis on monitoring the Earth's climate from space, more stringent calibration requirements are being placed on the data products from remote sensing satellite instruments. Among these are stability over decade-length time scales and consistency across sensors and platforms. For radiometer instruments in the solar reflectance wavelength range (visible to shortwave infrared), maintaining calibration on orbit is difficult due to the lack of absolute radiometric standards suitable for flight use. The Moon presents a luminous source that can be viewed by all instruments in Earth orbit. Considered as a solar diffuser, the lunar surface is exceedingly stable. The chief difficulty with using the Moon is the strong variations in the Moon's brightness with illumination and viewing geometry. This mandates the use of a photometric model to compare lunar observations, either over time by the same instrument or between instruments. The U.S. Geological Survey in Flagstaff, Arizona, under NASA sponsorship, has acquired an extensive set of lunar radiance measurements using the RObotic Lunar Observatory (ROLO), and developed a model for the lunar spectral irradiance that explicitly accounts for the effects of phase, the lunar librations, and the lunar surface reflectance properties. The model predicts variations in the Moon's brightness with precision of ∼1% over a continuous phase range from lunar eclipse to the quarter lunar phases. Given a time series of Moon observations taken by an instrument, the geometric prediction capability of the lunar irradiance model enables sensor calibration stability with sub-percent per year precision. Cross-calibration of instruments with similar passbands can be achieved with precision comparable to the model precision. Although the Moon observations used for intercomparison can be widely separated in phase angle and/or time, SeaWiFS and MODIS have acquired lunar views closely spaced in time. The near-simultaneous SeaWiFS and MODIS data provide an example to assess inter-calibration biases between these two instruments.

Keywords: On-orbit calibration, Calibration stability, Cross-calibration, Moon, Irradiance

1. INTRODUCTION

Remote sensing data products from satellites in Earth orbit have been used for many years for terrestrial environmental monitoring, and have an increasingly important role in measuring climate change. The climate task imposes stringent quality requirements on the data products from space-based instruments. For example, radiometric measurement of the surface albedo for climate change detection requires stability on the order of 0.1% per decade.[1] The decade-length time scale of climate measurements means that data records must be compiled from multiple sources, i.e., instruments on different space platforms. The implications of this requirement for sensor calibration include the needs for long-term stability and accurate assessment of biases between instruments.

Maintaining calibration on orbit is a challenge for radiometer instruments in the solar reflectance wavelength range, ∼300 to 2500 nm, due in part to the lack of absolute reference standards suitable for flight use. Typical onboard calibration systems utilize solar diffusing panels and/or lamps, either of which requires careful monitoring to track the degradation that occurs with operation in the space environment.

The Earth's Moon presents a luminous source that is available to all Earth-orbiting instruments. As a calibration target, the Moon has the advantageous property that the "diffuser" is exceedingly stable — at the spatial resolution of Earth Observing (EO) imaging sensors, the Moon is considered photometrically stable at a

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level of 10^{-8} per year.[2] The chief difficulty with using the Moon is its widely varying brightness, primarily the familiar lunar phases, but also the lunar librations and its non-uniform albedo and non-Lambertian reflectance. However, the inherent stability of the lunar surface reflectance enables these cyclic variations to be characterized with high precision, and thus durable models to be developed, given sufficient measurement coverage. Because lunar views are acquired from spacecraft with particular geometric circumstances, use of such models is the only practical means to utilize these instruments' observations of the Moon for calibration.

A program to develop the Moon as a calibration source has been established at the U.S. Geological Survey in Flagstaff, AZ.[3] The requisite set of lunar measurements for characterizing the Moon's brightness variations was collected by the ground-based RObotic Lunar Observatory (ROLO)[4] through an observational program spanning more than 6 years. The ROLO database forms the basis for an empirical model that predicts the lunar spectral irradiance for arbitrary illumination and viewing geometry with high precision.[5] The efforts of the USGS program have shown irradiance to be the useful quantity for calibration of instruments in Earth orbit using the Moon. The lunar irradiance model explicitly accounts for phase, lunar librations, and the lunar surface reflectance properties. The relative precision is $\sim$1% over a continuous range in phase from lunar eclipse to the quarter lunar phases.

The lunar radiometry program at USGS has established an operational system for providing lunar calibration support for spacecraft instruments, with a number of instruments supported.[6] Access to the system currently involves interfacing with the USGS team using formalized protocols; detailed descriptions can be found on the lunar calibration website: `www.moon-cal.org` → **Spacecraft Calibration**. Current users of the lunar calibration system have shown that a time series of Moon observations taken by a given instrument can be analyzed to achieve sensor calibration stability with sub-percent per year precision.[7] Lunar calibration also enables cross-calibration of instruments having similar bandpasses, with precision comparable to the model precision. This paper discusses these two applications of instrument observations of the Moon.

2. THE MOON AS A CALIBRATION SOURCE

The key component to using the Moon for calibration purposes is the capability to predict the target brightness for the precise geometric circumstances and band wavelengths of an instrument that observes it. The geometry of a Moon observation involves not only the phase angle but also the lunar libration state, i.e. the particular hemisphere of the Moon that is viewed. Although in general the same side of the Moon always faces the Earth, viewing from different vantage points (on the Earth or on orbit) and actual physical rotations of the Moon result in a slightly different hemisphere presented to a viewer at any given time.

To accommodate lunar observations taken by a given instrument, the USGS lunar calibration system provides a continuous geometric prediction capability, limited only by the valid range of coverage, eclipse to 90° phase. The lunar irradiance model at the core of the system is an analytic function of the geometric variables of phase and libration, and thus can be queried for any values of these variables corresponding to an instrument Moon observation geometry. In operation, the phase and libration angles are found using a double precision ephemeris to determine the locations of the Sun and Moon and the orientation of the Moon, and the spacecraft location provided by the instrument team.

A photometric model of the Moon based solely on geometry is valid for any given time (within the current geologic era), deriving this validity from the inherent stability of the lunar surface reflectance. In the context of a radiometric target for EO sensor systems, the Moon is considered photometrically stable at a level of 10^{-8} per year. Such a metric cannot be measured directly; this value is determined from analysis of cratering events on the Moon and weathering of lunar soils.[2]

The predictive capability of the lunar model derives from fitting thousands of ROLO irradiance measurements to the model kernel equation (Eqn. 10 in ref. 5) to generate a best-fit set of coefficients (listed in Table 4 of ref. 5; these are provided in electronic form to scientists wishing to replicate the model by contacting the author). The ROLO observational dataset spans 6+ years, covering enough of the lunar Saros cycle to sufficiently capture the libration behavior for modeling.[3] The mean absolute residual of the fit is about 1%; this is a measure of the model relative precision for predicting the variation in lunar irradiance with geometry.

Although instrument measurements and model results are compared in terms of irradiance, the model operates in lunar disk-equivalent reflectance. For development, data for the model were processed from spatially resolved ROLO telescope images, corrected for atmospheric transmission and calibrated to exoatmospheric radiance, and summed to irradiance:

$$I = \Omega_p \sum_{i=1}^{N_p} L_i \tag{1}$$

where L_i = pixel value (radiance), Ω_p = pixel solid angle, and N_p = number of pixels on the Moon. This process is similar for imaging instruments that view the Moon. A key consideration directly affecting the consistency of irradiance measurements is the determination of which pixels comprise the lunar disk. The effects of stray light contamination, imaging quality (MTF), etc. are contributing factors to specifying N_p. The ROLO irradiances were converted to reflectance A by:

$$I = A \cdot \Omega_M E_s / \pi \tag{2}$$

where Ω_M = solid angle of the Moon, and E_s is the solar flux in a particular ROLO (or instrument) band.

Model results get interpolated to instrument wavelengths in terms of reflectance. For narrow-band instruments, interpolation between the ROLO band wavelengths is linear, but includes a scaling factor that preserves the shape of a reference lunar reflectance spectrum. This reference spectrum was developed from spectral reflectance data of Apollo returned samples, using a mix of 95% soil[8] (Apollo 16 sample 62231) and 5% breccia[9] (Apollo 16 sample 67455), where these proportions were determined by fitting the lunar model results at a nominal geometry of 7° phase and zero libration. For wide-band instruments, a set of weightings of ROLO bands is generated to simulate the instrument band(s), rather than using a single effective wavelength. The weights are used to scale the model outputs (in reflectance). Modeled reflectances are converted back to irradiance using Equation 2.

The procedure for providing modeled lunar irradiances for comparison with instrument observations currently involves interfacing with the USGS lunar calibration program through established protocols. The lunar calibration web site `www.moon-cal.org` provides details of this interface; briefly, the instrument team provides the relative spectral response for all instrument bands (done once), and for each Moon observation: the time, the spacecraft location, and the lunar irradiance measured by each sensor. The operations of the lunar calibration system include: consulting the ephemeris to generate the photometric geometry, querying the lunar model and interpolating the outputs to the instrument bands, and applying distance corrections to correspond to the instrument location. Results are provided as the percent discrepancy of the instrument-measured irradiance against the model; for each instrument band:

$$\left(\frac{\text{inst}}{\text{model}} - 1\right) \times 100\%$$

Reporting results in this way effectively compares the instrument radiometric calibration against the lunar model absolute scale. Uncertainty in the model scale currently remains ∼5–10% referenced to absolute radiometric standards;[5] however, any bias in scale will be consistent for a particular wavelength, or instrument band.

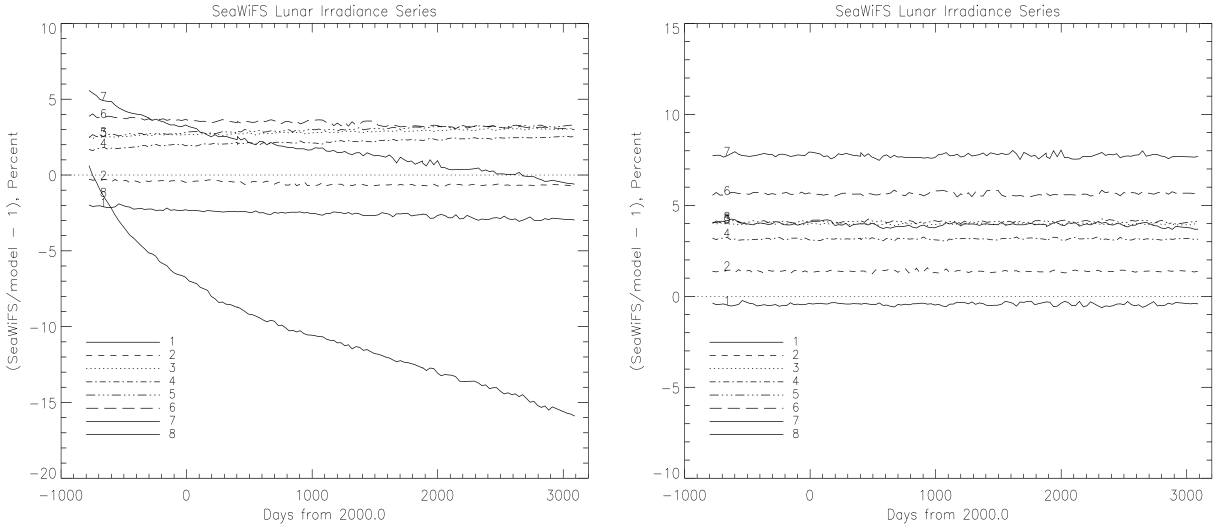
3. CAPABILITY FOR CALIBRATION STABILITY MONITORING

Maintaining calibration on orbit can be difficult for solar-band radiometer instruments, since reliable absolute standards at these wavelengths suitable for flight use have not reached mature development. Typical on-board calibration systems consist of solar diffusing panels and/or lamps, both of which are known to degrade with exposure and operation in the space environment. To achieve calibration accuracy in flight, the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments, for example, employ a radiometric Solar Diffuser Stability Monitor.[10] Using the Moon as a calibration target has the advantage that the "solar diffuser" has stabilized to an extreme degree from eons of exposure to the degrading effects of space.

Tracking sensor response changes over time can be accomplished using a series of Moon observations taken by an instrument compared using lunar model predictions. As explained earlier, the model results offset the variations in irradiance due to geometric effects with high precision. An extended series of measurements not only discerns trends, but also smooths any uncertainties in processing the instrument observations to irradiance.

The most extensive set of observations of the Moon taken by an EO instrument in orbit has been collected by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), with over 180 lunar views to date. Using a pitch-over attitude maneuver in combination with an ability to roll the spacecraft up to 20°, SeaWiFS captures the Moon through its nadir-view optics during the shadowed part of its orbit. Moon observations have been acquired at least once per month since November 1997, with a typical phase angle near 7°, although numerous views at higher phase angles have been collected in the later years of the mission. The wide field of view of SeaWiFS results in a Moon image size of ∼6×24 pixels. Because spacecraft attitude telemetry is not available, the oversampling rate for SeaWiFS Moon observations must be determined from measurement of the along-track spatial extent of the Moon image itself. This contributes a source of uncertainty in the SeaWiFS lunar irradiance measurements; however, these are correlated among all SeaWiFS bands. Nonetheless, the substantial SeaWiFS Moon observation dataset has been utilized for calibration stability purposes with great effect, and lunar analysis results are incorporated into the standard processing of SeaWiFS data products.[7,11]

Figure 1 shows the series of SeaWiFS low-phase angle lunar observations acquired from November 1997 to June 2008, numbering 124 altogether. The plots show the SeaWiFS measurements of lunar irradiance effectively normalized by the model results, expressed as discrepancy with the model as described in §2 above. These measurements exhibit a band-correlated temporal jitter, which has been averaged over all bands and removed for the plots. The instrument/model comparisons provide a measure of the sensor response for each observation, and the series shows the response trend over time. The data in Figure 1(a) show degradations in all eight SeaWiFS bands, most noticeably in bands 7 and 8, where sensor response has decreased ∼8% and ∼19%, respectively.



(a) (b)

Figure 1. Time series of SeaWiFS lunar irradiance measurements, as compared against corresponding results of the USGS lunar irradiance model. The ordinate is the discrepancy of the instrument measurements to the model, given as $\left(\frac{\text{inst}}{\text{model}} - 1\right) \times 100\%$. A band-correlated temporal jitter has been averaged over all bands and removed. (a) Uncorrected SeaWiFS lunar measurements, showing response degradation trends; (b) with temporal response correction applied, resulting in calibration stability at better than 0.1% over the 10+ year series for all eight SeaWiFS bands. The offsets of the bands show the difference in calibration between SeaWiFS and the lunar model.

The trends shown in Figure 1(a) were modeled by the SeaWiFS calibration team to develop temporal sensor response corrections as analytic functions of time.[11] Applying these corrections to the lunar series gives the trends shown in Figure 1(b). The corrected sensor response for each SeaWiFS band exhibits calibration stability at a level better than 0.1% over the 10+ year span of lunar series, and thus the instrument lifetime.

4. INSTRUMENT INTER-COMPARISON CAPABILITY

Lunar calibration enables inter-comparison of instruments, using the Moon as a common calibration target. The lunar irradiance variations resulting from different geometries of the instruments' views of the Moon are offset by normalization to the lunar model results. For sensors with similar spectral responses, the current uncertainty in the model absolute scale is not a factor, and rigorous comparison of lunar irradiance responses can be realized.

Multispectral sensors of the current generation of EO instruments often have several bands in common, used for various remote sensing purposes. Two instruments that have viewed the Moon, SeaWiFS and MODIS, have several common bands. Figure 2 shows the relative spectral response of all eight SeaWiFS bands, and six MODIS bands that coalign with SeaWiFS bands. The MODIS bandpasses are generally narrower than SeaWiFS.

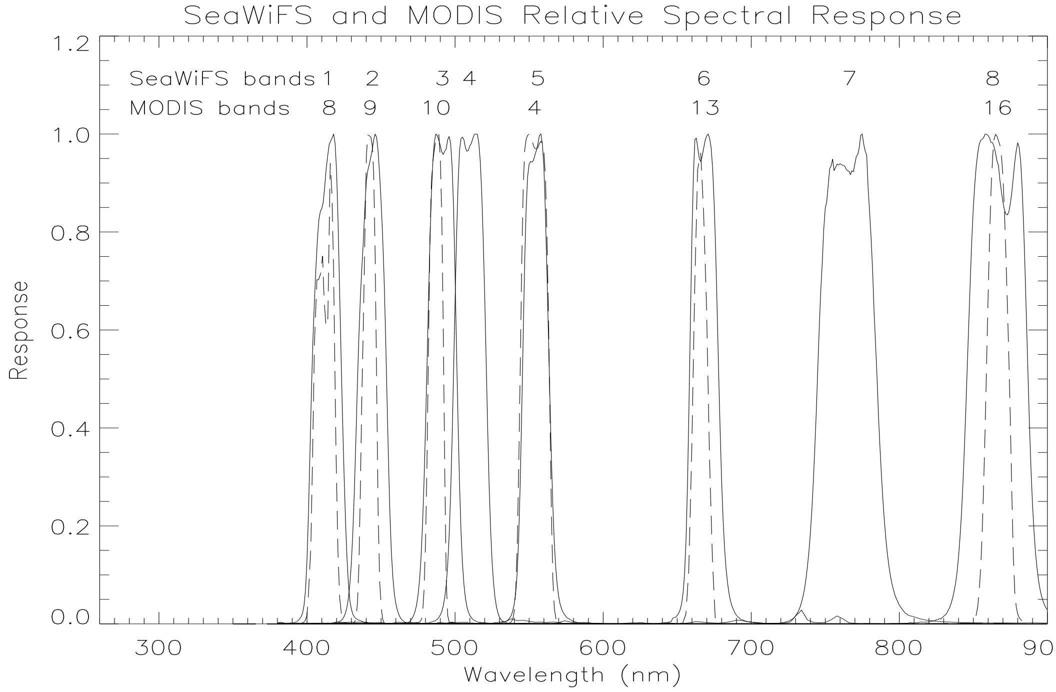


Figure 2. Relative spectral response of the eight SeaWiFS bands and six selected MODIS bands, normalized to 1.0 maximum. The MODIS bands, shown as dashed lines, have narrower bandpasses than SeaWiFS, and largely fall within the SeaWiFS response curves.

The MODIS instruments on both the NASA Terra and Aqua spacecraft have viewed the Moon numerous times. MODIS observes the Moon through a space-view port, normally used to measure the instrument dark response. These views utilize a different scan mirror angle than the nadir observations, which contributes some uncertainty to the sensor response determination. Analysis of MODIS response versus scan mirror angle characteristics based on lunar views is the topic of ongoing research efforts.[12] Both the Terra and Aqua spacecraft execute roll maneuvers to capture the Moon with the MODIS instruments at very nearly the same phase angle, $\sim 55°$. This can be accomplished about 9 months of the year.

Since 2006, SeaWiFS has supplemented its lunar observations with views having similar phase geometry to the MODIS regular lunar observations. Often the acquisitions happen within several hours of each other. Table 1 gives specifications of two such contemporaneous Moon observations. The Observation Geometry section of the table is derived from the spacecraft location (provided by the instrument teams) and the ephemeris of the Moon at the times of the observations. The distance corrections are used to convert from standard Sun-Moon and Moon-spacecraft distances to the actual spacecraft locations. The wavelengths are effective center wavelengths determined from the spectral response functions for each instrument band. The instrument-measured irradiances were provided by the SeaWiFS and MODIS teams, and include the SeaWiFS calibration stability corrections described in §3 above. The model irradiances have been interpolated to the instrument bands and corrected to the spacecraft distances, allowing direct comparison of the values.

Observation Geometry, Angles in Degrees

	Time	Phase Angle	Sub-lunar Longitude	Sub-lunar Latitude	Distance Correction
Observation date:	2006-12-09				
SeaWiFS	08:27:51	54.490	6.39	-4.29	0.988136
MODIS	09:34:11	55.119	6.47	-3.62	1.005660
Observation date:	2007-01-08				
SeaWiFS	03:56:20	53.992	3.44	-1.11	1.025943
MODIS	06:14:21	55.306	3.59	-1.12	1.047375

Lunar Irradiances in μWatt/m^2·nm

SeaWiFS band	1	2	3	4	5	6	7	8
wavelength	414.2	444.1	491.9	510.3	556.6	668.5	767.8	864.9
MODIS band	8	9	10		4	13		16
wavelength	414.9	443.3	487.3		554.4	670.3		866.6
Observation date: 2006-12-09								
SeaWiFS	0.7282	0.9030	1.073	1.078	1.169	1.170	1.067	0.8614
model	0.7323	0.8898	1.025	1.037	1.115	1.102	0.9841	0.8304
MODIS	0.7660	0.9080	1.063		1.154	1.134		0.8623
model	0.7075	0.8435	0.9704		1.077	1.063		0.7945
Observation date: 2007-01-08								
SeaWiFS	0.7031	0.8724	1.037	1.040	1.126	1.126	1.029	0.8318
model	0.7099	0.8621	0.9928	1.004	1.080	1.067	0.9522	0.8037
MODIS	0.7199	0.8561	1.002		1.094	1.076		0.8171
model	0.6718	0.7998	0.9211		1.023	1.009		0.7542

Table 1. Lunar measurement data for two SeaWiFS and MODIS observations closely spaced in time

The plots of Figure 3 show the lunar irradiance data given in Table 1. There is a noticeable difference in the modeled irradiances for the two instruments, despite the similarities of the observations. This is due entirely to geometry, including the effects of Sun-Moon and Moon-spacecraft distances, and the slightly higher phase angles of the MODIS observations.

The offsets, or discrepancies, between instrument-measured and modeled irradiances are the standard outputs of the lunar calibration system. These results show the difference in calibration between instruments that have viewed the Moon, considering the Moon as a common source, where consistency has been realized through the normalizing effects of the lunar model. Figure 4 plots these standard outputs for the pair of SeaWiFS and MODIS observations. The discrepancies to the model track spectrally within ∼1% for both instruments, and by extension, the discrepancies between the instruments also closely track each other. The table below lists the measured/model discrepancies and the ratio of these discrepancies, as [MODIS/SeaWiFS]. The ratios show the level of consistency attained for this pair of observations. SeaWiFS has conducted a number of extra Moon views since 2006 December, to correlate with MODIS observations.

Irradiance Discrepancy: Instrument Measured to Modeled (%)

SeaWiFS band	1	2	3	4	5	6	7	8
wavelength	414.2	444.1	491.9	510.3	556.6	668.5	767.8	864.9
2006-12-09	-0.33	1.58	4.63	3.91	4.83	6.22	8.46	3.71
2007-01-08	-0.71	1.29	4.37	3.52	4.22	5.61	8.06	3.48
MODIS band	8	9	10		4	13		16
wavelength	414.9	443.3	487.3		554.4	670.3		866.6
2006-12-09	8.26	7.77	9.50		7.16	6.67		8.53
2007-01-08	7.15	7.03	8.76		7.00	6.63		8.34
Ratio of Discrepancies: MODIS/SeaWiFS								
2006-12-09	-0.040	0.204	0.487		0.674	0.933		0.435
2007-01-08	-0.100	0.184	0.499		0.603	0.846		0.417

The example given here involves a pair of Moon observations closely matched in geometry and time between MODIS and SeaWiFS. The lunar calibration system does not require such near-simultaneous observations for inter-comparison of instruments, although the similar geometries helps reduce uncertainties, both in the lunar model results and in the processing of instrument observations to irradiances.

5. SUMMARY

A methodology has been developed to utilize the Moon for calibration of solar-band radiometer instruments in orbit. The lunar calibration system established at the U.S. Geological Survey has the capability to predict variations in the brightness of the Moon using an empirical model for the lunar spectral irradiance, the (spatially integrated) disk-equivalent quantity. The lunar model predictions have relative precision ∼1% over the range of phase angles from eclipse to 90°. These predictions can be used to effectively normalize the variation in lunar irradiance measurements taken by instruments that view the Moon, providing a consistent measure of instrument sensor response.

The predictability of the Moon's brightness, and thus the ability to model its variations, derives from the inherent stability of the lunar surface reflectance, considered stable to better than one part in 10^8 per year. Capturing the Moon's variational behavior for modeling requires an extended set of measurements to cover a

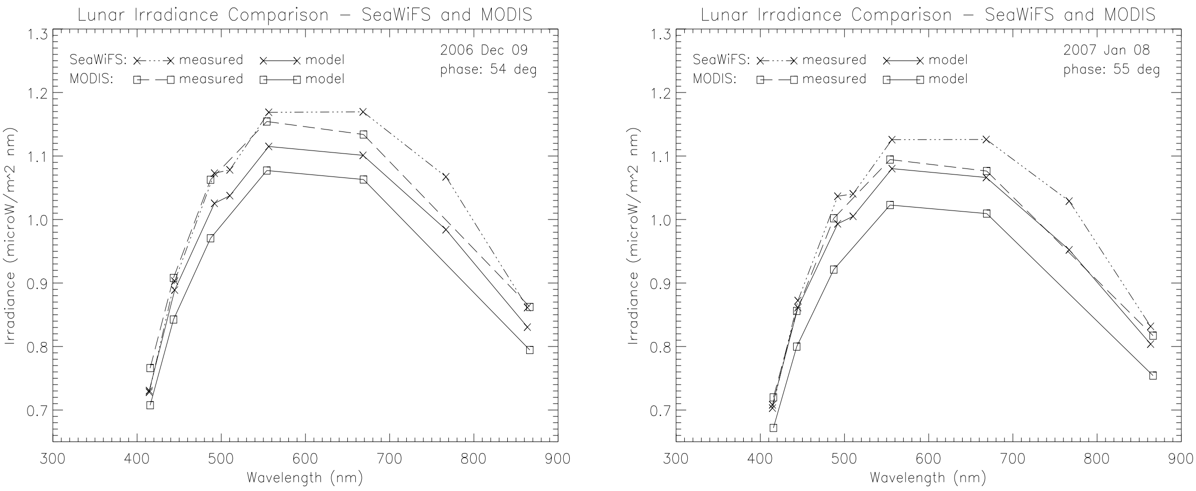


Figure 3. Lunar irradiance spectra for SeaWiFS and MODIS observations of 2006 Dec 09 and 2007 Jan 08. The modeled irradiances (solid lines) have been interpolated to the instrument wavelengths and corrected from standard distances to the actual Sun-Moon and Moon-spacecraft distances, to correspond directly to the instrument observations.

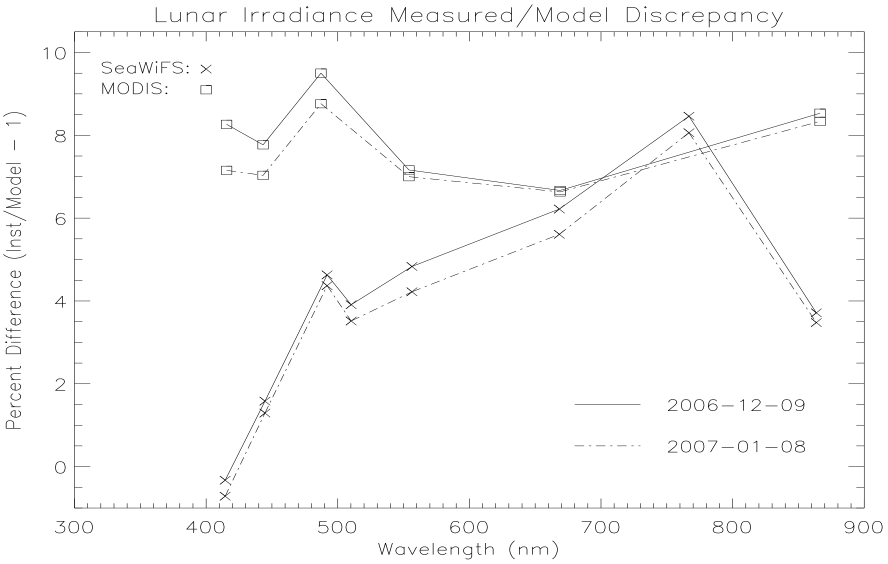


Figure 4. Lunar irradiance comparisons for two SeaWiFS and MODIS observations closely spaced in time. The ordinate is the standard lunar calibration product: discrepancy $= \left(\frac{\text{inst}}{\text{model}} - 1\right) \times 100\%$. Results for the two observations track closely for both instruments.

sufficient portion of the lunar libration cycle, ∼4–5 years minimum.[3] The dataset underlying the USGS lunar model was collected over 6+ years by the ROLO facility.

A time-series of Moon observations taken by an instrument, processed to irradiance and compared using lunar calibration results, can reveal trends in sensor performance over time with high precision. Uncertainties in such trending analyses can be reduced by viewing the Moon at similar phase angles, due to improved accuracy of the lunar model results and consistency in processing the instrument observations to irradiance. However, restriction to a narrow phase range is not a requirement for lunar calibration. The capability for sensor performance trending has been successfully demonstrated for the SeaWiFS instrument, which has viewed the Moon at least monthly for more than 10 years, usually close to 7° phase. Using this set of lunar irradiance measurements, sensor response corrections were developed for all eight SeaWiFS bands that provide calibration stability at a level better than 0.1% over the series of ∼120 observations.

The similar spectral bands on many Earth-observing instruments enables inter-comparison of sensor calibration for instruments, viewing the Moon as a common calibration source. Six MODIS visible-solar bands are closely aligned with SeaWiFS bands, and both MODIS instruments regularly view the Moon. An example of MODIS-Terra and SeaWiFS Moon observations taken a few hours apart, compared using the lunar calibration results, shows consistency in the calibration differences between the two instruments.

Observations of the Moon taken by remote sensing instruments can meet calibration stability requirements for climate change measurements. The ability to view the Moon may be an important consideration for future instrument designs and EO mission planning.

ACKNOWLEDGMENTS

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