Use of the Moon to support on-orbit sensor calibration for climate change measurements

Thomas C. Stone[a] and Hugh H. Kieffer[b]

[a] US Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ, 86001
[b] Celestial Reasonings, 2256 Christmas Tree Lane, Carson City, NV 89703

ABSTRACT

Production of reliable climate datasets from multiple observational measurements acquired by remote sensing satellite systems available now and in the future places stringent requirements on the stability of sensors and consistency among the instruments and platforms. Detecting trends in environmental parameters measured at solar reflectance wavelengths (0.3 to 2.5 microns) requires on-orbit instrument stability at a level of 1% over a decade. This benchmark can be attained using the Moon as a radiometric reference. The lunar calibration program at the U.S. Geological Survey has an operational model to predict the lunar spectral irradiance with precision ∼1%, explicitly accounting for the effects of phase, lunar librations, and the lunar surface photometric function. A system for utilization of the Moon by on-orbit instruments has been established. With multiple lunar views taken by a spacecraft instrument, sensor response characterization with sub-percent precision over several years has been achieved. Meteorological satellites in geostationary Earth orbit (GEO) capture the Moon in operational images; applying lunar calibration to GEO visible-channel image archives has the potential to develop a climate record extending decades into the past. The USGS model and system can provide reliable transfer of calibration among instruments that have viewed the Moon as a common source. This capability will be enhanced with improvements to the USGS model absolute scale. Lunar calibration may prove essential to the critical calibration needs to cover a potential gap in observational capabilities prior to deployment of NPP/NPOESS. A key requirement is that current and future instruments observe the Moon.

Keywords: On-orbit calibration, Climate Change, Moon, Irradiance

1. INTRODUCTION

The increasing awareness of the Earth's changing climate has led to increased reliance on global observations from space-based remote sensing systems to provide monitoring of the environmental variables that constitute the basis for climate modeling and the prediction of climate variability. Earth-viewing instruments aboard spacecraft such as the NASA EOS research satellites have produced multi-year datasets of environmental parameter measurements. Developing the ensemble of these data products into climate records requires consistency of the data between instruments, and calibration stability of the sensors over long time scales.

Substantial efforts have been dedicated to maintaining stable calibrations for instruments in orbit. For sensors in the solar reflectance wavelength range, 350–2500 nm, major challenges arise from degradation of on-board calibration hardware and a lack of practical absolute radiance standards suitable for flight use. The need for spacecraft instruments to periodically view a calibrated multispectral source has driven interest in using the Moon as a calibration target. An operational system to utilize the Moon's reflected light[1] has been established at the U.S. Geological Survey in Flagstaff, AZ under NASA sponsorship.

The lunar calibration development work conducted at USGS has shown that practical use of the Moon involves a photometric model of the lunar disk that covers the geometry of the Moon's illumination and viewing virtually without restriction, to accommodate typical spacecraft lunar observations. The focus of USGS modeling efforts

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Further author information: (Send correspondence to T.C.S.)
e-mail: tstone@usgs.gov, telephone: 928-556-7381
H.H.K. e-mail: hkieffer@charter.net

has been on the spatially integrated lunar irradiance[2]; the capability now exists to predict this quantity with precision ~1% over the full range of geometry covered: phase angles from eclipse to 90°, and all lunar librations visible from Flagstaff. This level of precision enables relative sensor response trending for on-orbit instruments with sub-percent per year precision, meeting the stability requirement for climate specified in the NIST report on Satellite Instrument Calibration for Measuring Global Climate Change, NISTIR 7047.[3] Additionally, the current and future capability of lunar calibration enables multiple sensors to view the same source, the Moon, to provide a consistent radiometric scale for the data products derived from the instruments.

2. USGS LUNAR CALIBRATION

A facility to establish the Moon as a radiometric standard for on-orbit instrument calibration was developed at the U.S. Geological Survey Flagstaff Science Center as a NASA-funded project in support of the EOS space-based program.[1, 4, 5] A detailed description of the USGS lunar calibration facility, models, and methods is given in Ref. 2. The USGS work has determined that accommodating the photometric geometry (illumination and viewing) of a lunar observation from a spacecraft requires a model to provide continuous coverage of the geometric variables. Further, the most useful quantity for calibration purposes is found to be the lunar irradiance, derived for an imaging sensor by spatial integration of all pixels on the Moon. The USGS lunar irradiance model explicitly accounts for the effects of phase, the spatial variegation of the lunar surface, the changes in the hemisphere of the Moon presented to an observer (the lunar librations), and the strong backscatter enhancement at low phase angles (the "opposition effect"), as well as the straightforward distance dependencies.

The basis for the USGS lunar models is an extensive database of radiance images of the Moon acquired by a purpose-built ground-based observatory located on the USGS Flagstaff campus, called the RObotic Lunar Observatory (ROLO). ROLO was in operation for more than 6 years, acquiring over 85,000 lunar images in 32 wavelength bands from 350 to 2450 nm. Figure 1 shows the filter passbands for the dual ROLO telescopes, covering the VNIR (350–950 nm) and SWIR (950–2450 nm) ranges. These bands include several commonly found in terrestrial remote sensing applications, and also traditional stellar photometry bands. Observations were made on clear nights during the bright half of each month, First Quarter to Last Quarter lunar phase. The 6+ year time span provides coverage of the 18.6-year lunar libration cycle sufficient for modeling, although libration coverage is limited to visibility from Flagstaff and may be sparse for narrow ranges of phase angles. The majority of observing time was dedicated to imaging stars, for the purpose of determining atmospheric opacity for correcting the lunar images. The ROLO database contains several hundred thousand calibrated stellar images.

Data inputs for the irradiance model are derived from processed ROLO lunar images, calibrated to exoatmospheric radiance and summed over all pixels on the lunar disk (including the unilluminated portions) to give the disk-equivalent irradiance I_k:

$$I_k = \Omega_p \sum_{i=1}^{N_p} L_{i,k} \tag{1}$$

where $L_{i,k}$ is an individual radiance measurement (i.e. pixel) on the Moon in band k, Ω_p is the solid angle of one pixel, and N_p is the total number of pixels in the lunar disk image. Development of the model terms and coefficients, and actual model operation, is done in dimensionless reflectance, converted from the summed irradiance values by:

$$I_k = A_k \cdot \Omega_M E_k / \pi \tag{2}$$

where A_k is the disk-equivalent reflectance (albedo), Ω_M is the solid angle of the Moon at standard distance (=6.4236x10-5 steradian) and E_k is the solar spectral irradiance at the effective wavelength $\lambda_{S,k}$ of a band for a lunar spectrum. The analytic form of the disk reflectance model is a function in the primary geometric variables of illumination and viewing of the Moon; for wavelength band k:

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\theta + c_2\phi + c_3\Phi\theta_+ c_4\Phi\phi + d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4) \tag{3}$$

where g is the absolute phase angle, θ and ϕ are the selenographic latitude and longitude of the observer, and Φ is the selenographic longitude of the Sun. In a multi-step fitting process, ~1200 data points are fitted for each of

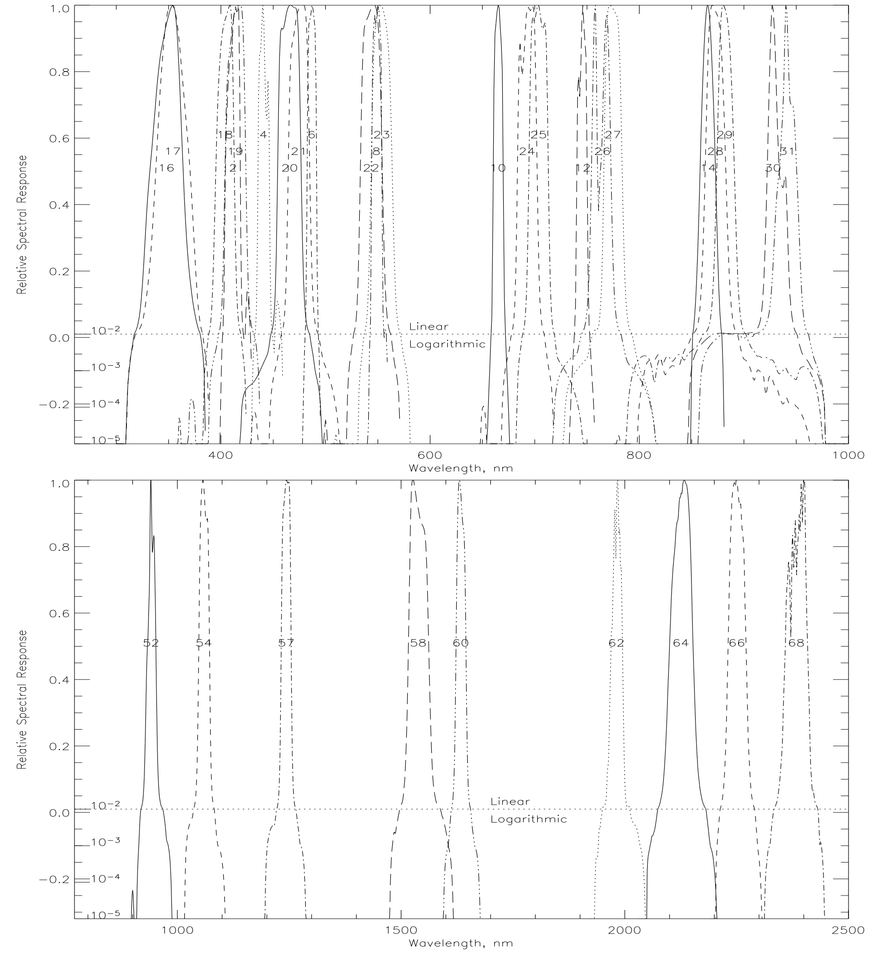


Figure 1. Spectral response of the ROLO bands, normalized to 1.0 maximum. The ordinate is linear in the upper portion of the plot to display the shape of the primary response. In the lower portion, the wings are displayed on a logarithmic scale. Outside of response above 0.002, the raw measurement values have been filtered with a Gaussian of sigma 8 nm. The integers near half maximum response are the ROLO filter numbers.

the 32 ROLO bands. The band-averaged absolute residual for the final fit is 0.0096 in $\ln A$, or $\sim$1% in irradiance. This value represents a measure of the model's capability to predict in-band variations in the lunar irradiance over the full range of the geometric variables. For a recent set of 7 dedicated lunar observations acquired by the Hyperion instrument on EO-1 during November 2005, comparisons against the lunar model agree within 0.74% over nearly the entire Hyperion spectral range, where the phase angles ranged from 7.4° to 81.0° and included observations both before and after Full Moon.

Uncertainty in the lunar model absolute accuracy, scaled against SI radiometric units, remains at the 5–10% level. Inter-band irregularities in the model outputs require an adjustment to produce a smooth reflectance spectrum that is expected for the Moon. Thus the model's reliability for prediction of irradiance variation with geometry far exceeds the absolute accuracy. Reducing this uncertainty is a high priority for improving the utility of the Moon as a transfer standard for inter-calibration of instruments which have dissimilar bands.

Spacecraft instrument teams access USGS lunar calibration through a largely formalized set of information and data exchanges. A detailed guide to this process can be found on the lunar calibration website:

www.moon-cal.org → Spacecraft Calibration

Along with other data items specific to each lunar observation, the spacecraft team must provide their measured lunar irradiance, computed with the usual instrument calibration coefficients. Model results generated by USGS are reported to spacecraft teams as the discrepancy between the instrument and the model, expressed as a percentage difference from unity:

$$P = \left(\frac{I_{\text{instrument}}}{I_{\text{model}}} - 1 \right) \times 100\% \tag{4}$$

3. APPLICATION FOR SENSOR CALIBRATION STABILITY — SeaWiFS

The reliability of the USGS model for predicting the lunar irradiance over a wide range of geometry means that a set of multiple observations of the Moon taken by a spacecraft instrument can reveal trends in the sensors' radiometric response with high precision. The prime example for this has been SeaWiFS. SeaWiFS has viewed the Moon roughly monthly since November 1997, having acquired more than 100 lunar observations to date.

Using a pitch-over attitude maneuver in combination with an ability to roll the spacecraft up to 20° from nadir, SeaWiFS views the Moon at $\sim 7^\circ$ phase angle, either before or after Full Moon. This provides high signal strength while avoiding the opposition effect backscatter enhancement. The pitch maneuver starts when the spacecraft passes into the Earth's shadow after a South polar crossing (SeaWiFS is in a Sun-synchronous orbit with a N–S equator crossing time at local noon), and is timed such that the instrument FOV scans past the Moon as the spacecraft passes the sub-lunar point on the orbit ground track. The pitch rate is $\sim 0.15^\circ$ per second, thus SeaWiFS oversamples the Moon by a factor of about 4. The SeaWiFS IFOV is 1.6×1.6 mrad per pixel, resulting in a lunar image size of about 6×24 pixels.

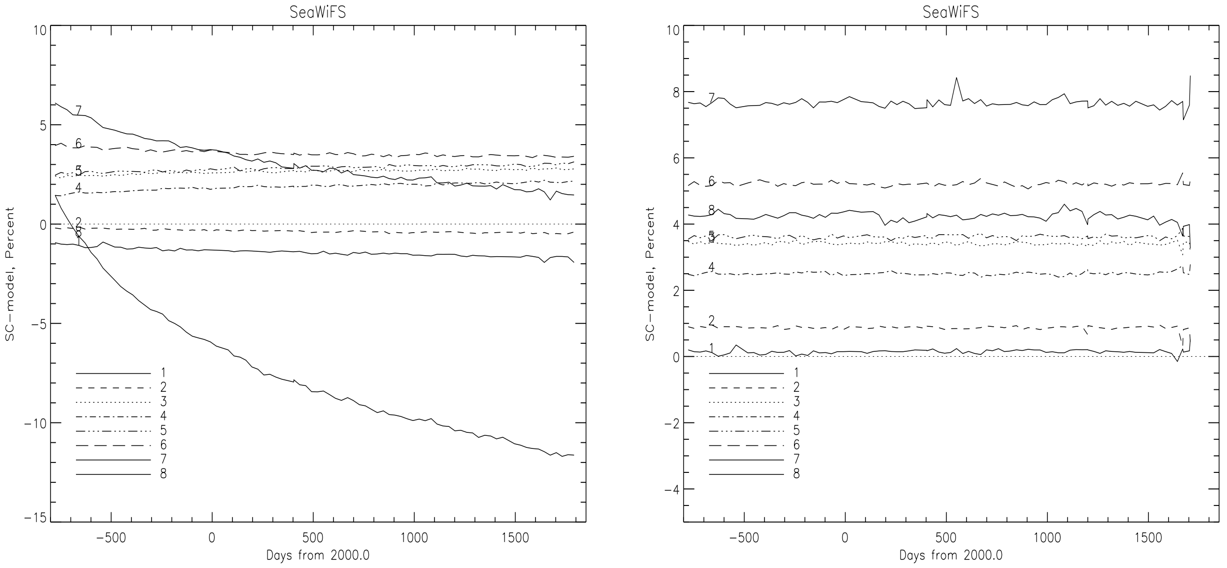
The SeaWiFS instrument team has utilized the lunar views to develop a correction for time-dependent sensor response degradations. Figure 2 shows lunar irradiance comparisons for 85 SeaWiFS observations, given as a percentage discrepancy between SeaWiFS measurements and the USGS model, as per Eq. 4. Because spacecraft attitude telemetry is not available to the SeaWiFS team, the oversampling of the Moon must be determined from measurement of the down-track spatial extent of the Moon in a SeaWiFS image. This measurement process is suspected of producing a correlated temporal jitter in the time series of lunar irradiance comparisons; the correlated jitter has been averaged over several SeaWiFS bands and removed for the plots shown here. In Figure 2(a), changes in sensor response are visible in most bands, with noticeable decreases in bands 7 and 8. Figure 2(b) shows the results of applying the temporal response correction developed by the SeaWiFS team from the first 66 lunar views. There is some residual, largely uncorrelated jitter at the 1% level, but the corrected long-term response trends are less than 0.1% per thousand days.[6]

The sensor response corrections developed for SeaWiFS have been vital to efforts in ocean color monitoring conducted using SeaWiFS data. The level of calibration precision achieved for SeaWiFS using the Moon meets the criteria for visible-band instrument stability for climate change specified in the NISTIR 7047 report.[3] The SeaWiFS example demonstrates the utility of a long-term set of regular observations of the Moon acquired by remote sensing satellite instruments.

4. POTENTIAL CLIMATE APPLICATION — GEOSTATIONARY METEOROLOGICAL IMAGERS

Archives of visible-channel images from meteorological satellites in geostationary Earth orbit (GEO) represent a potential climate record extending decades into the past. However, because the weather mission does not require high levels of calibration for visible-wavelength data, most meteorological instruments lack on-board calibration systems for these channels. Operational scans of the Earth from GEO imagers typically sample space in the margins and corners of a rectangular field-of-regard (FOR). The Moon appears regularly in these regions, offering an opportunity to apply lunar calibration to the visible-channel sensors.

Figure 3 shows an example of a GOES-12 image that has captured the Moon in a corner of the FOR. An initial comparison of the lunar irradiance generated for this GOES-12 image is described in detail in Ref. 7. Ongoing collaborative efforts between USGS and NOAA are developing time-series lunar calibrations for the



(a) (b)

Figure 2. Lunar irradiance comparisons for 85 SeaWiFS views of the Moon. The ordinate is the difference between SeaWiFS measurements and the USGS model, expressed as percent discrepancy. A band-correlated temporal jitter has been averaged and removed from these series. (a) Sensor response changes with time are clearly visible at levels of ∼5% in band 7 and ∼13% in band 8. (b) Results of applying a temporal correction developed by the SeaWiFS team – response trends are less than ∼0.1% per thousand days for all bands. The vertical distribution of individual band plots shows the difference in absolute scale between SeaWiFS and the lunar model.

visible channel imagers on GOES-10 and GOES-12; preliminary results are reported by Wu et al. in these Proceedings.[9]

The simultaneous presence of the Moon in an Earth disk image shows the range of radiances compared between the Moon and Earth scenes. Extracts from the GOES-12 image of Figure 3 are given in Figure 4. Both subsamples are identical in size, for comparison of their histograms. The Moon image appears skewed due to the orbital motion of the GOES satellite during image acquisition; full-field scanning over the lunar disk area takes about 42 seconds. The Moon histogram shows the zero-radiance level ("space clamp") at 29 DN, clipped by the plot scale. The brightness range of the Moon, here for lunar phase 9.6°, coincides with that of clear land.

The task of processing the series of GOES-10 and GOES-12 lunar images has revealed some hindrances to the application of lunar calibration to archived GEO images. Capture of the Moon by fortuitous coincidence with the GOES operational schedule has yielded a lower frequency of observations than what is needed to extract the level of precision in sensor response trending achievable with the lunar model, such as demonstrated for SeaWiFS. A significant fraction (∼40%) of the GOES Moon images were found to be clipped on an edge, either by the Earth or the edge of the image frame. Clipped images can be utilized with the USGS system, however deriving reliable irradiance comparisons will require implementation of a more robust spatial modeling method for handling them. This task has been proposed as part of a plan for development of a climatology from GEO archives. An unexpected result that demands closer scrutiny involves several instances where the GOES archive contains two images with Moon captures that were acquired ∼1 hour apart. The differences in the lunar irradiance comparisons for these pairs exceeds the formal model uncertainty by at least a factor of 2, possibly indicating a spatial dependency of the sensor response (the Moon appears on opposite sides of the Earth disk), such as a scan mirror angle effect. However, it must be emphasized that the GOES lunar image processing is still preliminary; the irradiance values are subject to revision.

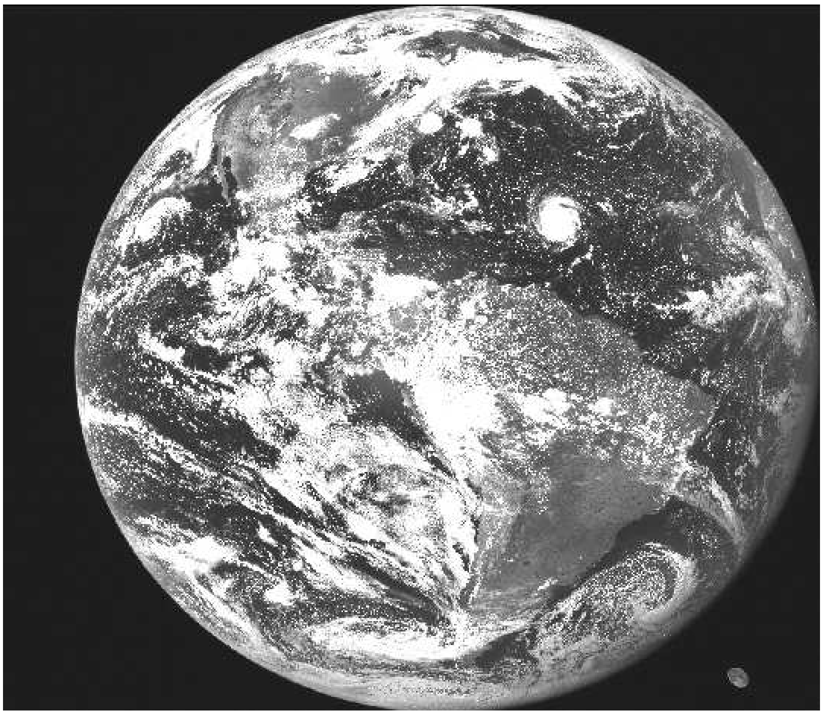


Figure 3. GOES-12 visible channel full-disk image acquired 2004 August 30, 17:45:14 UTC. The nearly full Moon is captured in the southeast corner.

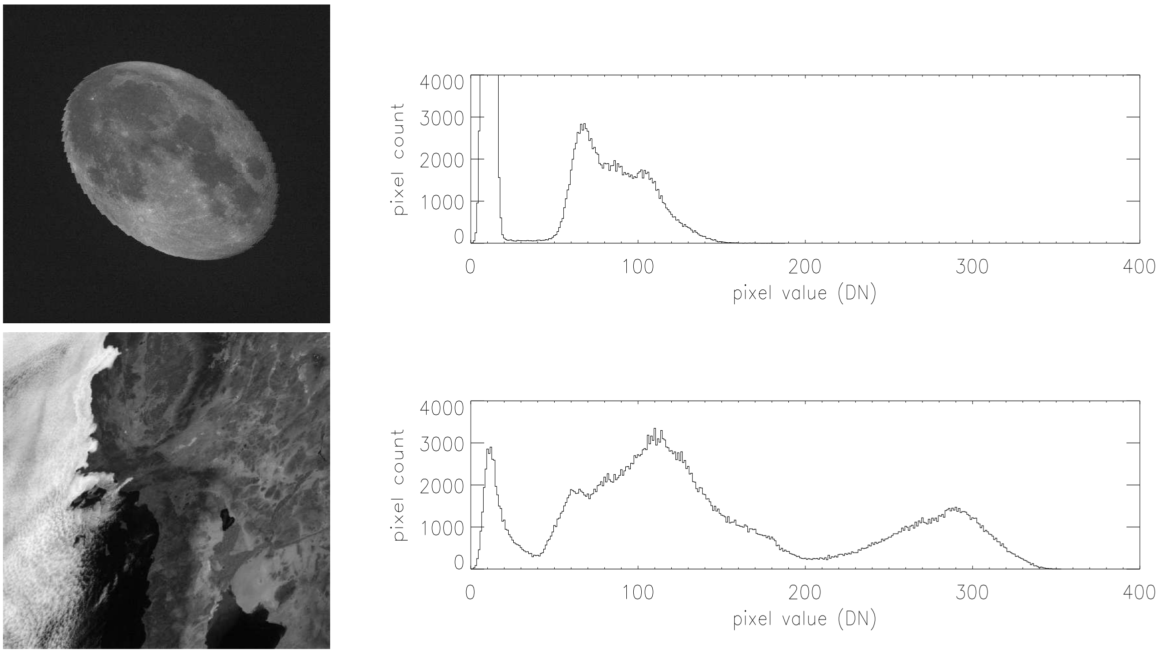


Figure 4. Subsamples of Figure 3 and corresponding histograms. *Top*: the Moon; *Bottom*: Southwestern United States and northwestern Mexico. The 3 distinct modes seen in the Earth histogram correspond to ocean, land, and cloud.

The above issues notwithstanding, lunar calibration of GOES has been successful in showing sensor response trends that are consistent with other methods of vicarious calibration.[9] The infrequent chance lunar image captures has prompted NOAA to institute monthly dedicated scans of the Moon for both GOES-10 and GOES-12. This is strongly recommended for all Earth-viewing sensors. The USGS program has developed a software tool for predicting the appearance of the Moon in a GEO imager FOR based on the satellite two-line-element orbit parameters. This tool can be used to locate possible Moon captures in a data archive, or for planning future dedicated observations.

5. THE MOON AS A COMMON CALIBRATION SOURCE FOR SPACECRAFT INSTRUMENTS

The circumstance of the Moon being available to all Earth-orbiting spacecraft, combined with the applicability of the lunar irradiance model to observations of the Moon made at any time, means that the Moon can serve as a common radiometric standard for Earth-observing sensor systems. Although the absolute accuracy of the current USGS model remains uncertain at the 5–10% level, the capability for in-band comparisons of lunar irradiance measurements is under 1%. Thus multiple lunar views by an individual instrument, or by different instruments with similar bands deployed on the same or different platforms, can be inter-compared with this level of precision.

Figure 5 shows lunar irradiance comparisons plotted as the spectrum of P in Eq. 4 (percent disagreement between the instrument and the USGS lunar model) for 7 on-orbit imaging instruments. The plots represent averages of a number of observations taken by each instrument, ranging from 1 for ASTER to 70 for SeaWiFS. The difference between instruments is ∼6% in the silicon detector range (<950 nm). Part of this discrepancy may be explained by the use of different solar spectral irradiance models for on-board solar diffuser-based references. But the inconsistency among instruments at comparable wavelengths displayed in Figure 5 exceeds the formal uncertainty in the lunar model for relative comparisons.

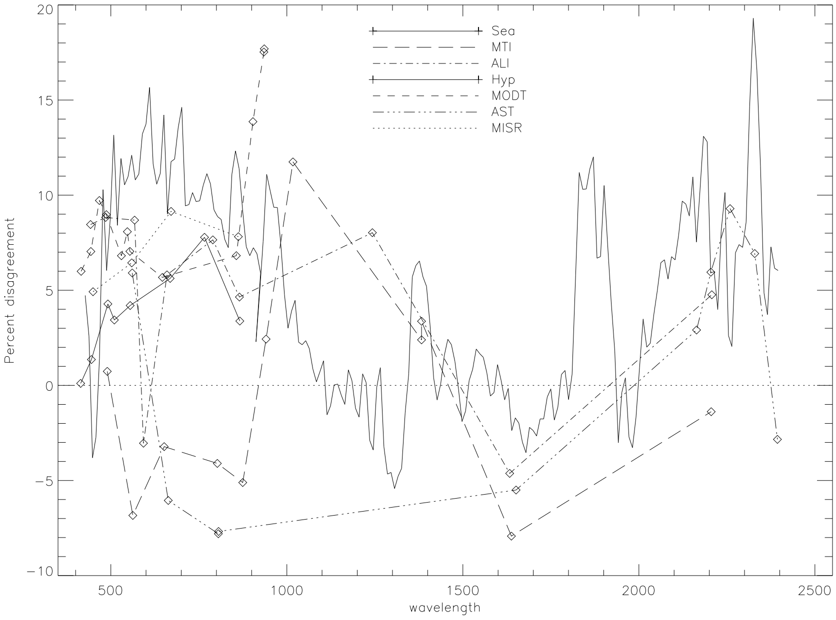


Figure 5. Lunar calibration comparison of 7 on-orbit imaging instruments. The ordinate is the spacecraft reported irradiance ratioed to the USGS model, expressed as a percentage difference from unity. Sea = SeaWiFS, on SeaStar; MTI = Multiband Thermal Imager (DOE spacecraft); ALI = Advanced Land Imager on EO-1; Hyp = Hyperion on EO-1; MODT = Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra; AST = Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) on Terra; MISR = Multiangle Imaging SpectroRadiometer on Terra.

Within similar wavelength bands, the current USGS lunar model enables using the Moon as a known source for transfer of calibration between spacecraft instruments. Anticipated refinements to the model absolute accuracy will extend the capability of lunar calibration to providing a consistent radiometric scale for all instruments that view the Moon. This is important for establishing calibration consistency among instruments that are used for climate measurements, particularly where the operational time spans do not overlap, thus precluding simultaneous observations of other vicarious calibration targets. The possibility of the EOS instruments' end-of-life occurring prior to deployment of the NPOESS Preparatory Project (NPP) is an example.

Although USGS efforts toward improving lunar model absolute accuracy are ongoing,[8] there is a recognized need for high-accuracy lunar irradiance measurements to affirm traceability of the model absolute scale to SI radiometric units. Proposed methods include development of a hyperspectral irradiance radiometer, calibrated at NIST, flown as a high-altitude balloon payload.[10]

Light reflected from the Moon exhibits weak linear polarization, which may affect the irradiance measurements of some spacecraft instruments. The ROLO telescopes are entirely on-axis in optical design, and hence insensitive to polarization. For the integrated Moon, polarization is negative at low phase angles, with a minimum ~1.2% at $g = \pm 11°$ (negative phase angle indicating before Full Moon). Polarization passes through zero near 24°, with two positive branches reaching maxima at $g = -94°$ and $+105°$,[11] the degree depending upon the distribution of highlands and maria (and hence libration) and wavelength, up to about 9% and 12%, respectively, in blue light.[12]

6. SUMMARY

The task of formulating a climate-quality database of environmental measurements from the many diverse data products generated by multiple space-based Earth observing missions requires rigorous calibration and inter-calibration of the remote sensing instruments that acquired the observations. Calibration stability for sensor systems and consistency among instruments are key. At solar-reflectance wavelengths, meeting the stability and accuracy goals for climate are particularly challenging, typically utilizing multiple calibration pathways, including on-board spectral sources and/or solar diffusers, and viewing vicarious targets, often by several instruments closely spaced in time.

The Moon is attractive as a calibration target – it is an extended, far-field source that is observable by any Earth-orbiting spacecraft. The variations in lunar brightness have been modeled with high precision by the lunar calibration program at USGS, and an operational system for using the Moon has been established. This system works with the spatially integrated lunar irradiance. The USGS model can predict the lunar irradiance with precision ~1% over its full range of geometric coverage. With a time series of lunar views collected by a spacecraft instrument, sensor response characterization with sub-percent precision is achievable. Temporal response corrections for the sensors on SeaWiFS, developed from multiple lunar views, have demonstrated the capability to meet the stability requirements for climate specified by NISTIR 7047.[3]

Using the Moon, inter-calibration of instruments with similar wavelength bands currently can be realized at the level of precision of the USGS model, ~1%. This is irrespective of the observation geometry (within the range of coverage, e.g. phase angles up to 90°), and largely independent of the model absolute calibration. The absolute scale of the lunar model is undergoing refinement; current uncertainties are ~5–10%. With improvement of the absolute scale, lunar calibration can enable a consistent radiometric scale for Earth-observing sensors that view the Moon as a common source.

The utility of lunar calibration can only be realized if current and future instruments view the Moon. Visible-channel imagers on geostationary meteorological satellites capture the Moon in normal operational images. The value of regular lunar views has been recognized; NOAA has recently instituted monthly scans of the Moon for both GOES-10 and GOES-12.

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