Using the Moon as a Radiometric Calibration Source for Earth-observing Satellite Instruments

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1 Background and Motivation

The importance of satellite-based Earth observations to global climate monitoring and climate change detection is well known. Assembling long-term environmental records from the observational data products of many different radiometric instruments and platforms requires consistency in the calibration of the sensors and stability of their response over time. In cases where gaps exist in the observational record, the sensors must be calibrated against internationally recognized absolute standards.

In the solar-reflectance spectral region, near-UV through Visible and Shortwave Infrared (UV-Vis-SWIR), measurements of environmental variables such as cloud abundance and optical properties, aerosol optical depth and global distribution, snow and ice cover and reflectance properties, ocean color, and vegetation are essential to understanding the radiation balance of the Earth. Data products generated from different solar-band radiometers utilize independent pre-launch calibrations, on-board calibration hardware when available, and on-orbit vicarious calibration methods using terrestrial reference sites. Each has its limitations: the disconnect between pre-launch and flight operations, a lack of absolute standards suitable for flight use, degradation of on-board systems in the space environment, and the need for characterization and monitoring of calibration sites.

A novel approach to on-orbit calibration has been developed that utilizes the Earth's Moon as a source of UV-Vis-SWIR radiation. The Moon's brightness range is similar to clear land. Calibrating on the Moon can employ an instrument's full optical train, although spacecraft in low-Earth orbit (LEO) usually require an attitude maneuver to view it. The foremost challenge to using the Moon is accounting for the variations in its brightness with illumination and viewing geometry, primarily the familiar lunar phase changes, resulting from the Moon and spacecraft orbits around the Earth. However, the Moon's reflectance is extremely stable[1], the result of eons of existence in the space environment. Therefore, with adequate characterization of the geometric variations, the lunar brightness can be predicted with high precision. This capability currently exists. Through comparison of a time series of Moon observations collected by an instrument against these predictions, sensor response trending is possible with climate-level precision. Since the Moon is accessible to all Earth-orbiting satellites, lunar calibration has the potential to put all instruments that view it on consistent radiometric scale.

2 Lunar Calibration Program

Analysis of lunar observations acquired by a spacecraft instrument requires accommodation of the lunar illumination and view geometry without restriction. Thus the standard for comparison is a photometric model of the Moon. A successful model and methodology for lunar calibration has been developed under a unique program at the U.S. Geological Survey (USGS) in Flagstaff, AZ, through NASA sponsorship. The USGS efforts have focused on the radiometric quantity of spatially integrated irradiance; a detailed description of the lunar spectral irradiance database and model is found in reference [2].

Modeling the lunar brightness requires a database of radiometric measurements of sufficient extent to capture the variational behaviors of lunar phase, spatial non-uniformity, the hemisphere of lunar surface presented to an observer (the lunar librations), and the complex surface reflectance phase function. The physical librations resulting from precession of the Moon's orbit have a repeat period of 18.6 years; however, analysis of the libration periodicities shows that coverage sufficient for modeling can be achieved in about one-fourth that amount of time[3].

2.1 Observational database

Radiometric measurements of the Moon have been acquired from a dedicated facility called the RObotic Lunar Observatory (ROLO), developed as part of the USGS lunar calibration program. Twin telescopes (20 cm diameter, f/5, Ritchey-Chrétien) comprise an imaging system with 23 bands from 350 nm to 950 nm, and 9 SWIR bands from 950 nm to 2450 nm. In 6+ years of operation, ROLO acquired over 85000 images of the Moon with geometric coverage in phase angle from eclipse ($\sim$1.5°) to 90° before and after Full Moon, and a substantial range of the librations viewable from Flagstaff. Additionally, several hundred thousand star images were acquired for determining atmospheric extinction for each observing night. Atmospheric correction of the lunar data remains one of the largest sources of uncertainty in the database.

2.2 Irradiance model

A photometric model has been developed for the lunar spectral irradiance, taking advantage of the increased signal to noise that comes with spatial integration of resolved images. This approach requires that spacecraft instruments capture the entire lunar disk in some fashion, but the field of regard (FOR) of typical Earth-viewing instruments can usually accommodate the angular extent of the Moon, $\sim$0.5°.

The analytic form of the irradiance model was developed empirically, fitting the ROLO lunar data with a function in the geometric variables of phase and libration. The lunar images are calibrated to exoatmospheric radiance and spatially integrated to irradiance, normalized to standard distances (Sun–Moon = 1 AU, Moon–Observer = 384400 km), then converted to reflectance for fitting. The 32 ROLO bands are fitted with 18 adjustable coefficients for each band, 8 of which are constant across all bands. Currently there are $\sim$1200 data points fitted for each band, thus the model system of equations is highly overdetermined. A multiple-step fitting process is employed for culling outlier data points. The final fit has a mean absolute residual ∼1%. This value is a measure of the precision with which the model predicts the variations in lunar irradiance with observational geometry.

2.3 Comparison with spacecraft observations

Comparison of lunar irradiance measurements from spacecraft observations against model results is conducted through a largely formalized set of data exchanges with the USGS lunar calibration team. The model accommodates any illumination and viewing geometry of an Earth-orbiting instrument. It is queried for the particular circumstances of a spacecraft observation — geometry derived from the time and satellite location. Intermediate results give the disk-equivalent reflectance at the 32 ROLO bands; these are interpolated to the spacecraft instrument bands along a smooth lunar reflectance spectrum. For wide-band instruments, a weighted combination of the ROLO bands is used. The modeled reflectance is converted back to irradiance using the same solar spectrum as the forward conversion, thus uncertainties in the solar model used impose only second-order effects. The spacecraft irradiance measurements are corrected for oversampling and normalized to standard distances. The quantities of spacecraft and model irradiances can then be compared directly.

3 Capability for Sensor Response Trending

Temporal changes in the radiometric response of a sensor system can be monitored on-orbit using a series of Moon observations compared against model results. The lunar model predicts the variations in irradiance with observation geometry with precision better than 1%. Acquiring spacecraft lunar views at similar phase angles lowers the uncertainty in the model predictions, although this is not a requirement for lunar calibration. With a large number of observations taken by an instrument, temporal trends in sensor response emerge from the typical scatter associated with uncertainties in reducing the spacecraft observations to irradiance. This trending capability derives solely from the lunar model precision in predicting the geometric brightness variations; it does not require high accuracy irradiance predictions on an absolute scale.

A leading demonstration of sensor response trending and calibration stabilization using the Moon is demonstrated by SeaWiFS[4]. Since 1997 November, SeaWiFS has viewed the Moon roughly once per month, with more than 100 observations acquired to date. Analysis of 66 SeaWiFS lunar measurements taken over a $5\frac{1}{2}$ year period revealed response trends in all 8 instrument bands, with degradations up to 13% seen. Based on the results of lunar model comparisons, calibration corrections were developed for each SeaWiFS band. The corrected sensor response trends are flat to within 0.01% per year. This level of calibration stability meets the requirements for UV-Vis radiometers for measuring global climate change[5].

4 Capability for Instrument Inter-calibration

An absolutely calibrated Moon can serve as a standard for all radiometric instruments that view it. The continuously changing, but predictable, brightness characteristic of the Moon means that the standard must be a model, rather than the physical artifact. The current lunar irradiance model has an uncertainty in absolute scale ∼5–10%, not yet sufficient to be considered an absolute standard. Nonetheless, valuable inter-comparisons of spacecraft instruments can be realized through observations of the Moon using the current lunar model.

Key to instrument inter-comparison using the Moon is that the lunar irradiance model operates in reflectance, and the reflectance spectrum of the Moon is smooth, with only broad, shallow absorption features. Thus the modeled disk-equivalent reflectance for two instruments having slightly different passband spectra will be very nearly the same for a given observation geometry. This is almost entirely independent of the model absolute scale — comparisons of lunar views at similar wavelengths are unaffected by a global bias in the model, if any exists, regardless of the view geometries.

Several band wavelengths in the solar range are common to multispectral instruments used for Earth observations; the 8 SeaWiFS bands are typical. A comparison study of lunar observations acquired by a number of EOS instruments[6] shows differences up to ±5% from the lunar model results, despite similarities among many bands. Some of this discrepancy may be attributed to the use of different solar irradiance models in the independent calibration of the instruments, but these differences are within the lunar model precision. The predictive capability of the model is ∼1%, significantly less than the magnitude of the discrepancies seen.

5 Imperatives for Earth Observing Missions

The capability currently exists to track response changes of remote sensing instruments in orbit using the Moon. The lunar technique has the advantage that the vicarious calibration observations do not need corrections for the atmosphere, which can be a significant source of uncertainty. Precise sensor response trending requires a time series of lunar views, thus regular observations of the Moon are recommended over the lifetime of Earth observing satellite missions, including during post-launch check-out, and particularly straddling an absolute calibration measurement such as viewing a pristine solar diffuser. The precision in response trending currently available enables detection of climate change from space-based instruments. Because the Earth's environment is undergoing certain, possibly rapid, change, instituting regular lunar observations should be expedited.

Improved absolute radiometry of the Moon can address the apparent discrepancy in calibration of Earth observing instruments. A new program has been proposed to measure the absolute irradiance of the Moon with accuracy at the limit of current best practices. The LUnar Spectral Irradiance (LUSI) project is based with NIST, and involves verifiable traceability to primary radiance standards. The resulting high-accuracy lunar irradiance scale can be transferred to the existing lunar model and applied to spacecraft observations of the Moon made at any time, including in the past. An absolute lunar standard can provide a consistent radiometric scale for all Earth observing instruments that view the Moon, with the accuracy needed for climate monitoring. This is particularly important for tying together non-overlapping missions, e.g. a gap in observing capabilities. The essential element is observations of the Moon acquired by the satellite instruments.

References

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