A Model of the Spectral Irradiance of the Moon for Calibration of Earth-orbiting Spacecraft Instruments

H. Kieffer
Celestial Reasonings

T. Stone
US Geological Survey

Abstract. Observations of the Moon from an observatory designed and operated specifically for determination of absolute lunar photometry have been used to develop a spectral irradiance model of the Moon covering 340-2430 nm appropriate for calibration of Earth-orbiting spacecraft. An empirical model of irradiance has been developed that treats phase and libration explicitly, with absolute scale founded on photometry of the star Vega and the spectra of returned Apollo samples. This model has the same form at each wavelength, with 18 coefficients, 8 of which are constant across wavelength, for a total of 328 coefficients. Over 1000 lunar observations are fitted at each wavelength; the average residual is less than 1%. The irradiance model is actively being used in lunar calibration of several spacecraft instruments, and can track sensor response changes at the 0.1% level.

Introduction and Observational Data Although the brightness of the Moon varies strongly with time, the surface of the Moon has reflectance properties that are virtually invariant over time{Kieffer 1997} and the lunar irradiance is strictly a function of wavelength and geometry.

The RObotic Lunar Observatory (ROLO) project was established to accurately determine the irradiance and radiance of the Moon. Routine observations were made on every clear night during the bright half of each month for several years{Kieffer 1998, Stone 2002, Kieffer 2005}. Lunar images were acquired in 32 bandpasses covering 340-2430 nm approximately every half hour when the Moon was at least 30° above the horizon. The remainder of observing time was dedicated to stellar observations for use in determining atmospheric extinction and instrument absolute response. Stellar targets are a subset of 190 “standard” stars selected by the ROLO project specifically for their invariant properties. The same stars were imaged repeatedly through the night. The database currently contains over 85000 individual images of the Moon and several hundred thousand star images.

Model Development The ROLO irradiance model is based on 1249 observation sequences, each including all 32 ROLO bands, acquired over more than 3 years. These observations have a relatively uniform distribution over phase angle, but have some correlation with libration due to coverage of only about 1/4 of a Saros cycle. These data support modeling for phase angles from 1.5 to 90°.

It was found that no existing physically-based irradiance model supports the accuracy of the ROLO observations. Hence, we developed an empirical analytic model of the equivalent reflectance of the entire lunar disk (regardless of illuminated fraction) based on the primary geometric variables:
$\ln A_k = \sum_{i=0,3} a_{ik} g^i + \sum_{j=1,3} b_{jk} \Phi^{2j-1} + c_1\theta + c_2\varphi + c_3\Phi\theta + c_4\Phi\varphi + d_1\exp(-g/p_1) + d_2\exp(-g/p_2) + d_{3k}\cos[(g-p_3)/p_4]$
where A_k is the disk-equivalent reflectance, 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.

The first polynomial represents the basic photometric function dependence upon phase angle, disregarding any opposition effect. The second polynomial approximates the dependence upon the face of the Moon that is illuminated, primarily representing the distribution of maria and highlands. The four terms with coefficients c_n represent the face of the Moon that is seen (topocentric libration), with a consideration of how that is illuminated. The next two represent the opposition effect and the last one simply addresses a correlation seen in the irradiance residuals, possibly associated with mare/highland distribution not covered by the second polynomial.

The fitting process yields 8 values that are constant over wavelength (4 for libration and the 4 nonlinear parameters) and 10 additional values for each filter, for a total of 328 coefficients. The mean absolute residual over all observations fitted is 0.0096 in the natural logarithm of reflectance. Test runs of this model show that the extreme effects of libration (the c_x terms) could exceed 7% over a full Saros cycle.

Model Performance Uncertainty in the Vega-based radiance calibration can be no less than the absolute flux measurements on which it is based{Hayes 1985, Strecker 1979}. Hayes(1985) cites a measurement uncertainty of 1.5% for the absolute flux at 555.6 nm, the scaling point for the visible-wavelength flux spectrum. The reported experimental error for the IR measurements of Strecker(1979) is ~4% absolute. Both sets of absolute flux data rely on an assumed energy distribution for Vega.

The model based upon Vega calibration yields reflectance spectra which have modest excursions in wavelength between bands, whereas the reflectance spectrum of the Moon has only weak, broad features{McCord 1970, Lucey 1986}. An adjustment to the model absolute scale for each wavelength is based on fitting the ROLO model reflectance spectrum for g=7°, Φ=7°, θ=0, φ=0, to a composite of laboratory reflectance spectra of returned Apollo samples of soil (95%) and breccia (5%) multiplied by a linear scaling ($a+b\lambda$); this adjustment averaged 3.5%

over all bands.

ROLO Lunar Calibration Current knowledge of lunar photometry resulting from the ROLO program is adequate to support precise determination of the responsivity history of imaging instruments in orbit around the Earth. The spatially integrated radiance derived from the nominal calibration of spacecraft lunar images can be compared directly with models of the lunar irradiance to determine instrument gain factors. Descriptions of the lunar calibration technique applied to spacecraft can be found in the literature (e.g., Barnes 2001, Kieffer 1999, Kieffer 2002, Barnes 2004).

The Moon is available to all Earth-orbiting spacecraft at least once per month, and thus can be used to tie together the at-sensor radiance scales of all instruments participating in lunar calibration without requiring near-simultaneous observations. A corollary, resulting from the intrinsic stability of the lunar surface, is that any future improvements to radiometric knowledge of the Moon could be applied retroactively to instrument calibration.

Several instruments have now viewed the Moon while in orbit, and observations have been compared with the ROLO model. Typically, the spacecraft will execute a pitch maneuver while in the Earth's shadow to scan past the Moon. For instruments in a Landsat-like orbit (705 km altitude), the Moon's diameter corresponds to roughly 6.3 km on the ground, and lunar image acquisition takes only a few seconds. The lunar calibration technique can be employed for geosynchronous satellites without special attitude maneuvers, since the Moon periodically passes through the corners of the rectangular field of regard for full-disk images of the Earth.

The spacecraft instrument team supplies to ROLO the spacecraft location and time at the mid-point of the lunar observation, along with the apparent size of the Moon in the scan direction. The ROLO team then computes the relative positions of the spacecraft and the Sun in selenographic coordinates using the high-precision ephemeris of the Moon and planets{Standish 1990} and the IAU orientation of the Moon. The lunar irradiance model is computed for this geometry, and corrected for the actual Moon-Sun and Moon-spacecraft distances for comparison with the spacecraft observation.

This work has demonstrated that the lunar spectral irradiance can be modeled with a precision that enables a significant advancement in on-orbit monitoring of spacecraft instrument performance. Comparison between several spacecraft reveal substantial differences in the radiance scales of their standard imagery products. The most extensive set of spacecraft lunar observations, the six-year record of SeaWiFS, suggests that instrument response trending can be determined approaching the 0.1% level on a monthly basis over any longer time period{Barnes04}. This level of long-term stability meets the goals for radiometric calibration of decade-scale climate observations set for the upcoming National Polar-orbiting Operational Environmental Satellite System. However, this level of precision indicates that it will be useful to incorporate treatment of the variation in solar irradiance, which is at this level, to generate appropriate lunar irradiances using the lunar disk reflectance model.

Acknowledgments This work was supported by the NASA EOS Project Science Office at the Goddard Space Flight Center under contract S-41359-F.

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