Potential for calibration of geostationary meteorological satellite imagers using the Moon

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ABSTRACT

Solar-band imagery from geostationary meteorological satellites has been utilized in a number of important applications in Earth Science that require radiometric calibration. Because these satellite systems typically lack on-board calibrators, various techniques have been employed to establish "ground truth", including observations of stable ground sites and oceans, and cross-calibrating with coincident observations made by instruments with on-board calibration systems. The Moon appears regularly in the margins and corners of full-disk operational images of the Earth acquired by meteorological instruments with a rectangular field of regard, typically several times each month, which provides an excellent opportunity for radiometric calibration. The USGS RObotic Lunar Observatory (ROLO) project has developed the capability for on-orbit calibration using the Moon via a model for lunar spectral irradiance that accommodates the geometries of illumination and viewing by a spacecraft. The ROLO model has been used to determine on-orbit response characteristics for several NASA EOS instruments in low Earth orbit. Relative response trending with precision approaching 0.1% per year has been achieved for SeaWiFS as a result of the long time-series of lunar observations collected by that instrument. The method has a demonstrated capability for cross-calibration of different instruments that have viewed the Moon. The Moon appears skewed in high-resolution meteorological images, primarily due to satellite orbital motion during acquisition; however, the geometric correction for this is straightforward. By integrating the lunar disk image to an equivalent irradiance, and using knowledge of the sensor's spectral response, a calibration can be developed through comparison against the ROLO lunar model. The inherent stability of the lunar surface means that lunar calibration can be applied to observations made at any time, including retroactively. Archived geostationary imager data that contains the Moon can be used to develop response histories for these instruments, regardless of their current operational status.

Keywords: On-orbit calibration, Geostationary imagers, Moon, Irradiance

1. INTRODUCTION

The Earth's surface and clouds have been observed for many years by meteorological satellites operating in geostationary Earth orbit (GEO), distributed in longitude around the globe. Images from solar-band channels (visible and shortwave infrared, ∼0.4–2.5 μm) have been used to monitor important climate variables such as surface insolation, surface albedo, aerosol optical depth, and cloud optical properties. Quantitative analyses using GEO imagery require that the instruments be calibrated, and monitoring of long-term changes requires accurate assessment of sensor system response changes over time. Because the solar channels of meteorological instruments typically lack on-board calibration systems, a number of methods have been employed to establish calibrations, including use of pre-launch laboratory measurements,[11] vicarious techniques using observations of desert sites[8] and oceans,[5] and statistical analysis of star observations for relative response trending.[2] Techniques have been developed for cross-calibrating GEO imagers against well-calibrated research instruments on scenes matched closely in location and geometry.[6,7]

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Full-disk operational images of the Earth from GEO instruments having a rectangular field of regard include margins and corners that view deep space. The Moon appears regularly in these areas, typically several times each month. Use of the Moon as a calibration reference source is complicated by its complex photometric behavior and by the periodic variations in the face of the Moon that is presented to an observer on Earth or in orbit, i.e. lunar libration. However, the reflectance properties of the lunar surface are extremely stable,[3] thus these geometric effects can be expressed analytically with a photometric model for the Moon. Such a model, once established, can be applied to spacecraft observations made at any time, including in the past.

The US Geological Survey RObotic Lunar Observatory (ROLO) project has developed a model for the lunar spectral irradiance that accounts for phase and libration explicitly. The stability of the ROLO model over its operational range of geometries currently is better than 1%. If the Moon in a GEO image is not significantly clipped on an edge, a calibration can be realized through comparison of the lunar disk-integrated irradiance against the ROLO model predictions. With a long-term set of observations, ROLO lunar calibration has demonstrated the capability for relative sensor response trending with precision approaching 0.1% yr^{-1}.[1] Applying ROLO lunar calibration to GEO imagery has the potential to generate global data sets with the level of precision necessary for long-term climate data records.

2. ROLO LUNAR CALIBRATION

ROLO is a NASA-sponsored program established to enhance the capabilities for on-orbit calibration of solar-band imaging instruments on NASA EOS satellites. The approach is an accurate radiometric characterization of the Moon that allows construction of photometric models to predict the lunar irradiance and radiance for the specific geometry of a spacecraft observation of the Moon. Recent ROLO efforts have produced a model for the spatially integrated lunar disk-equivalent irradiance.[4,9] This model is now mature, although the current version is based on a subset of the full ROLO observational database.

The complications of using the Moon as a radiometric calibration target primarily stem from its complex photometric behavior, the spatial variegation of the surface, and the variation in the particular hemispheric area of the Moon that is viewed at a given time and location, i.e. lunar libration. Although in general the same face of the Moon is always turned toward Earth, the optical librations result in about 59% of the lunar surface being viewable from Earth. ROLO modeling results have found that the variation in lunar irradiance due to librations are on the order of 5% over the range of observed angles.[4,9]

While it may be possible to construct an analytic photometric function for the Moon based on physical principles, this becomes untenable for dealing with libration. The Moon's orbit is inclined 5.1° to the ecliptic, and its spin axis is tilted 6.7° from the normal to its orbital plane. The orbit precesses with a node-to-node repeat time of about 18.6 years. The combination of the lunar orbit orientation, eccentricity, tilt of the lunar spin axis, and the 23.5° tilt in the Earth's spin axis result in variations in the hemisphere of lunar surface that is presented to an observer on Earth or in orbit, both in longitude and latitude, as well as in the lunar disk diameter. The limits of apparent motion (optical librations) are ±8.1° in longitude and ±6.7° in selenographic latitude for an Earth-based observer. The diurnal, monthly, and seasonal variations describe a longitude/latitude pattern similar to a Lissajous figure, with a repeat time equal to the period of the precession of nodes, roughly 18.6 years.

The ROLO observational program and development of the empirical irradiance model are described in detail in Ref. 4. Briefly, lunar image observations have been acquired over a period of 6+ years, covering phase angles from near-eclipse up to 90° and a wide range of libration angles (although not both simultaneously) in 32 wavelength bands from 350 to 2500 nm. Corrections for the atmosphere are generated for each observing night from nightly multiple stellar extinction measurements. For irradiance model inputs, the spatially resolved image data are calibrated to exoatmospheric radiance, then integrated over the entire lunar disk, regardless of illuminated fraction. These quantities function as irradiances, and follow the one-over-R-squared law for distances. The data are corrected to standard distances: Moon–observer = 384,400 km, Sun–Moon = 1 A.U. Model development and fitting of the irradiance data has been done in the natural log of reflectance, converted by

$$I_k = A_k \cdot \Omega_M E_k / \pi \tag{1}$$

where I_k is the distance-corrected irradiance sum and A_k the disk-equivalent albedo for band k, Ω_M is the solid angle of the Moon (=6.4177×10^{-5} steradian) and E_k is the solar spectral irradiance at the effective wavelength $\lambda_{S,k}$ of a band for solar radiation. The model analytic form is an empirically-derived function in the primary geometric variables, and includes terms for the opposition effect:

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

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. There are 8 coefficients that are constant over wavelength (c_n and p_n), plus 10 values for each band for a total of 324 coefficients. A complete list of coefficients for model version 311g is given in Ref. 4.

The mean absolute fit residual over all 32 ROLO bands after fitting ∼1200 data points in each band is 0.0096 in $\ln A$. The fitting process utilized a subset of the extensive ROLO observational database, currently containing over 85000 individual lunar images and several hundred thousand star images. The subset that was used spanned about one quarter of the orbit precession repeat cycle. Improvements in the geometric specification of lunar irradiance are expected from utilizing the full database, and would be enhanced further with acquisition of additional observations (although the observatory is still functional, lack of funding halted regular telescope operations in September 2003). Refinements to the data reduction system are ongoing.

A formal protocol has been developed for the interface between ROLO and spacecraft instrument teams participating in ROLO lunar calibration. A description is available online at:
www.moon-cal.org → Spacecraft Calibration → Information Exchange Items
Although this system has been developed for use with NASA EOS instruments, it can readily accommodate almost any solar-band imager. An amount of image processing and data formatting is required of the participating instrument teams, but ROLO typically provides preliminary assistance with the standard formats for lunar calibration information exchange. The process requires the Relative Spectral Response (RSR) for each of the spacecraft instrument bands, then for each lunar observation: the time in UTC and spacecraft location in J2000 coordinates at the middle of the image acquisition, the scan-rate information necessary for determining oversampling factors, and the lunar irradiance computed using the normal instrument calibration coefficients. ROLO computes all ephemeris and geometric parameters and corrects to standard distances, then queries the lunar model and interpolates the output to the instrument band wavelengths. Results are reported as comparisons: the percent discrepancy between the modeled and instrument-generated irradiances.

3. THE MOON IN GEO OPERATIONAL IMAGES

Full-disk operational images of the Earth taken by GEO imagers typically have a rectangular field of regard (FOR) with margins around the Earth disk, scanning past the limb and viewing deep space. For GOES imagers, the nominal scan FOR for full-disk imaging is 20.8° E–W × 19° N–S, while the Earth disk diameter is about 17.4° from geostationary orbit, resulting in margins of 1.7° and 0.8° respectively. From geostationary orbit the Moon's diameter ranges between 0.44° and 0.51°, thus for the GOES visible imagers, whose detectors have an instantaneous field of view of 28μrad on a side and an effective E–W sample size of 16μrad, the full Moon at perigee will be imaged in ∼318 N–S lines by ∼556 E–W pixels. The declination of the Moon varies along its phase cycle due to the inclination of the lunar orbit between limits of ±18° and ±29°, depending on the point in the precession cycle. During normal GOES operations in which full-disk images are acquired every three hours, the Moon will appear unoccluded in the image margins or corners of the FOR several times each month.

Figure 1 shows a GOES-12 image taken 30 August 2004, 17:45 UTC, that has captured the Moon at phase angle of about 9° and declination –9.3°. This image has been corrected for oversampling, however the Moon still appears elongated due to the motion of the satellite during the image acquisition time. A GOES full-disk scan nominally takes 26 minutes to complete; the lunar disk is scanned in about 42 seconds. During this latter time the apparent motion of the Moon across the FOR is ∼0.17°. A subsample of Figure 1 of the region containing the Moon is shown in Figure 2(a). The sawtooth pattern of scan line offsets seen at the East and West limbs has two amplitudes, resulting from the boustrophedonic raster acquisition sequence and the Moon being off-center in the full image. These offsets can be corrected by straightforward repositioning of scan lines; such a correction is discussed in the next section.

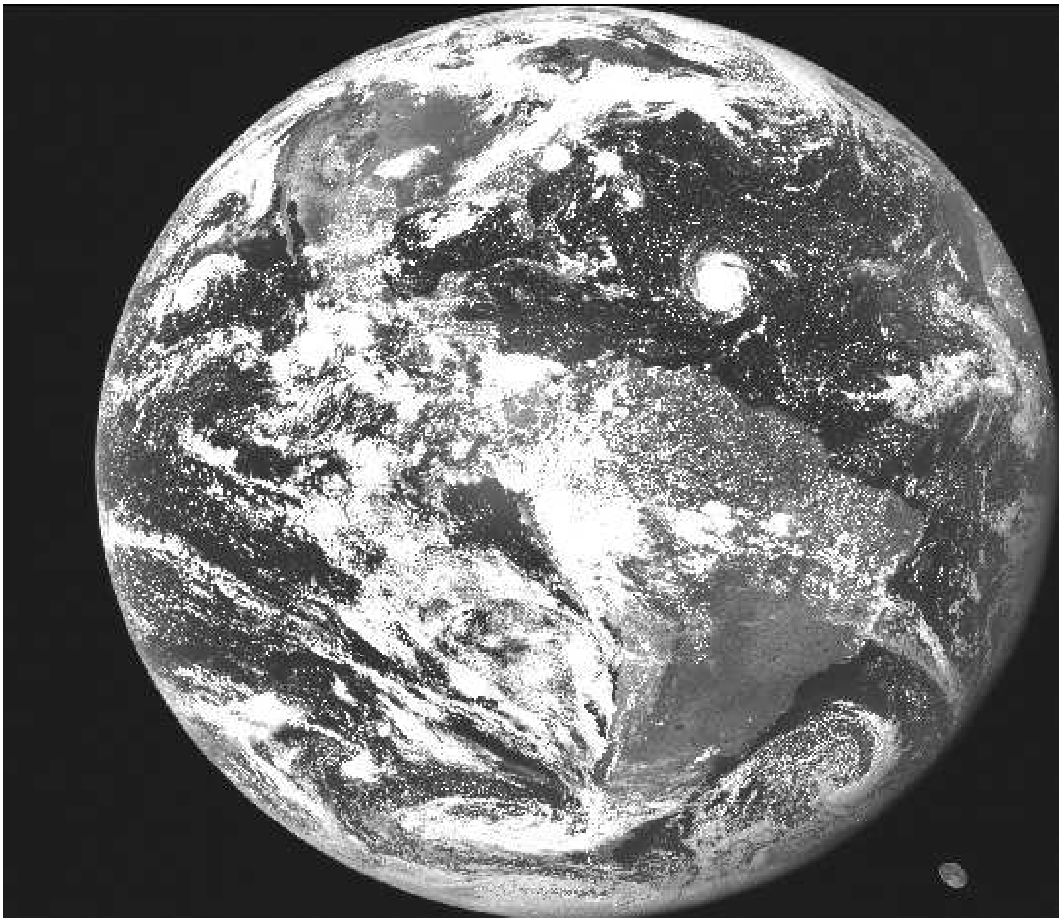
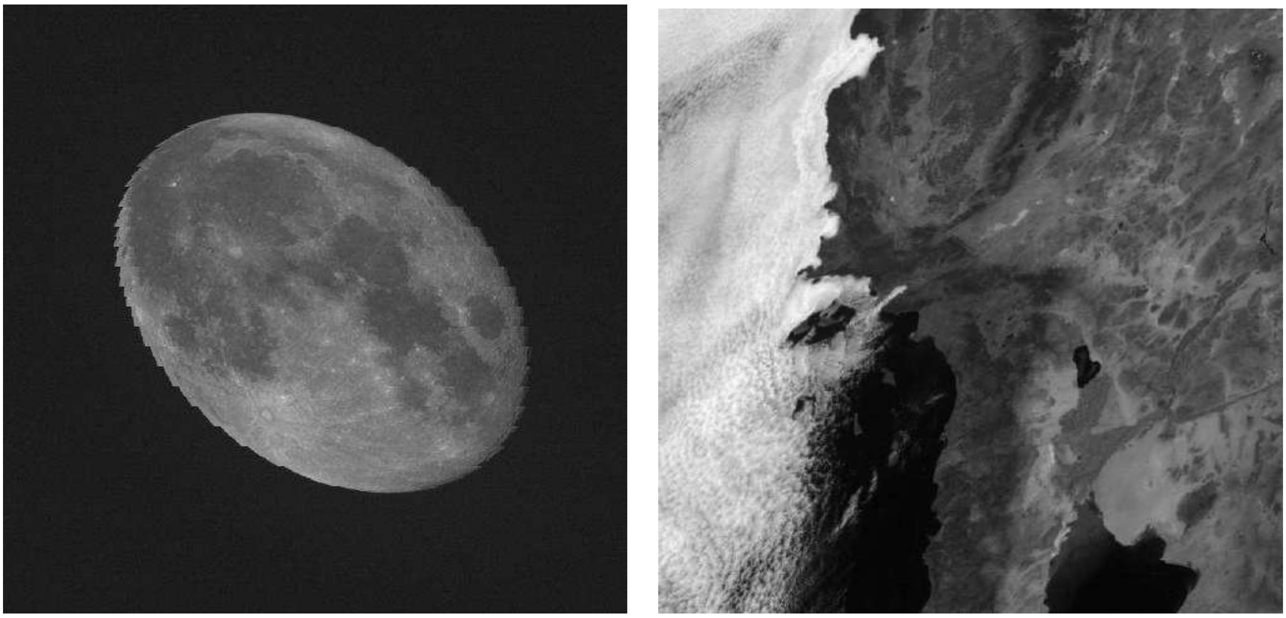


Figure 1. GOES-12 visible channel full-disk image acquired 2004 August 30, 17:45:14 UTC. The nearly full Moon is captured in the southeast corner.

The relative brightness of the Moon is somewhat less than typical Earth scenes. Figure 2(b) shows a subsample from the same GOES-12 image, matched in size to the Moon image of Figure 2(a). The histograms of Figure 3 were generated from the regions of Figure 2 using the full-disk raw image data, without oversampling corrections. For both image subsamples, the histogram salient features are contained within a range maximum of 400 DN (out of the 10-bit full dynamic range, 0–1023). The phase angle of the Earth view in Figure 2(b) is about 8.7°. The lunar image histogram shows the space clamp level at $\sim$10.6 DN, and the distribution of highlands and maria in a contiguous grouping, expected for a bright target with a sharp edge against the dark background of space. Three major peaks are seen in the Earth scene histogram, corresponding to the brightness levels of the oceans, landmasses, and clouds in the scene. The dynamic range of the near-full moon covers somewhat less than half that of the Earth scene, although it spans the full range of ocean and almost all of the range of the clear arid lands of the southwestern US and northern Mexico. Thus the Moon is particularly well-suited for calibration of GEO imagers for cloud-free applications such as the estimation of atmospheric aerosol abundances and land surface albedo.



(a) (b)

Figure 2. Subsamples of Figure 1 showing: (a) the Moon, (b) the southwestern United States and northern Mexico, Pacific Ocean, and Gulf of California. The subsample sizes are identical for both images.

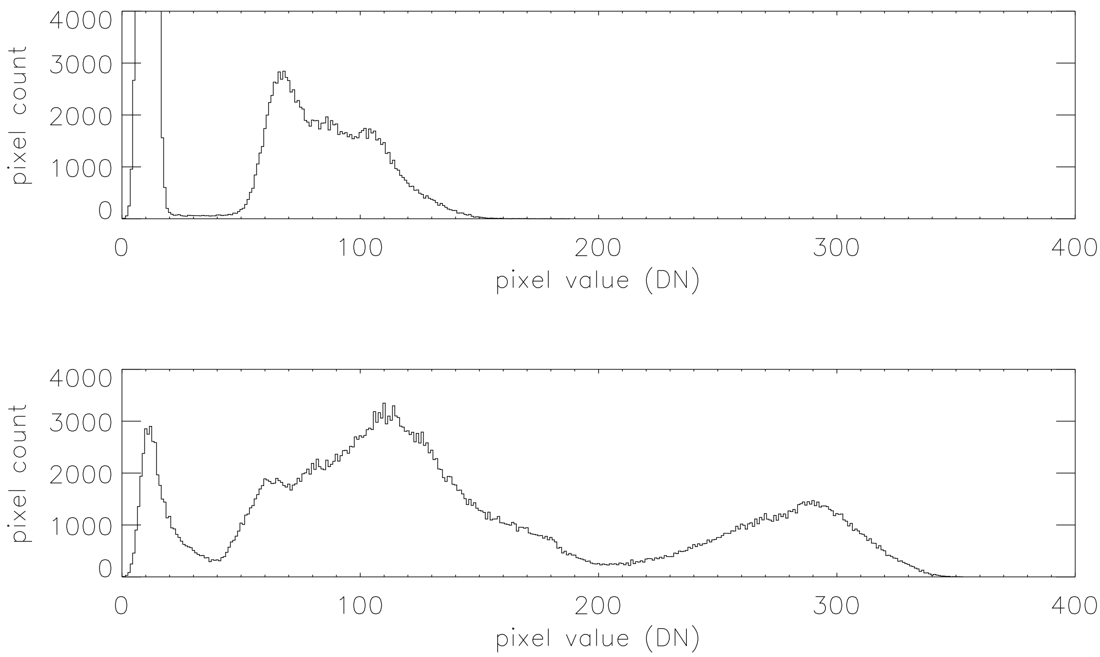


Figure 3. Histograms of raw pixel counts for the two subsampled regions. *Top*: for the Moon image of Figure 2(a), *Bottom*: for the Earth scene of Figure 2(b). Both histograms were generated using full-disk image data, uncorrected for oversampling.

4. APPLICATION OF ROLO LUNAR CALIBRATION TO GOES IMAGES

The ROLO method for on-orbit calibration using the lunar spectral irradiance is established and is actively being applied to several spacecraft instruments. Capabilities have been developed to assist instrument teams with prediction of lunar observation opportunities and the maximum radiance levels expected for a particular observation geometry. These tools can be readily adapted for use with archived GOES visible-channel image data.

4.1. Lunar Irradiance Comparison

Measurement of lunar irradiance from a calibrated radiance image requires accurate knowledge of the oversampling factor. For GOES, this can be determined from the mirror scan rates if these are known with high accuracy. Alternatively, it can be computed by fitting an ellipse to the illuminated edge of the lunar disk (avoiding the terminator) after applying sample offset corrections for the apparent motion of the Moon across the image field. For the lunar image of Figure 2(a), an average 9.31 pixels offset was applied cumulatively to groups of 16 image lines, with an additional 2 pixels offset for alternating groups of 8 lines. Results of the steps in this process are shown in Figure 4.

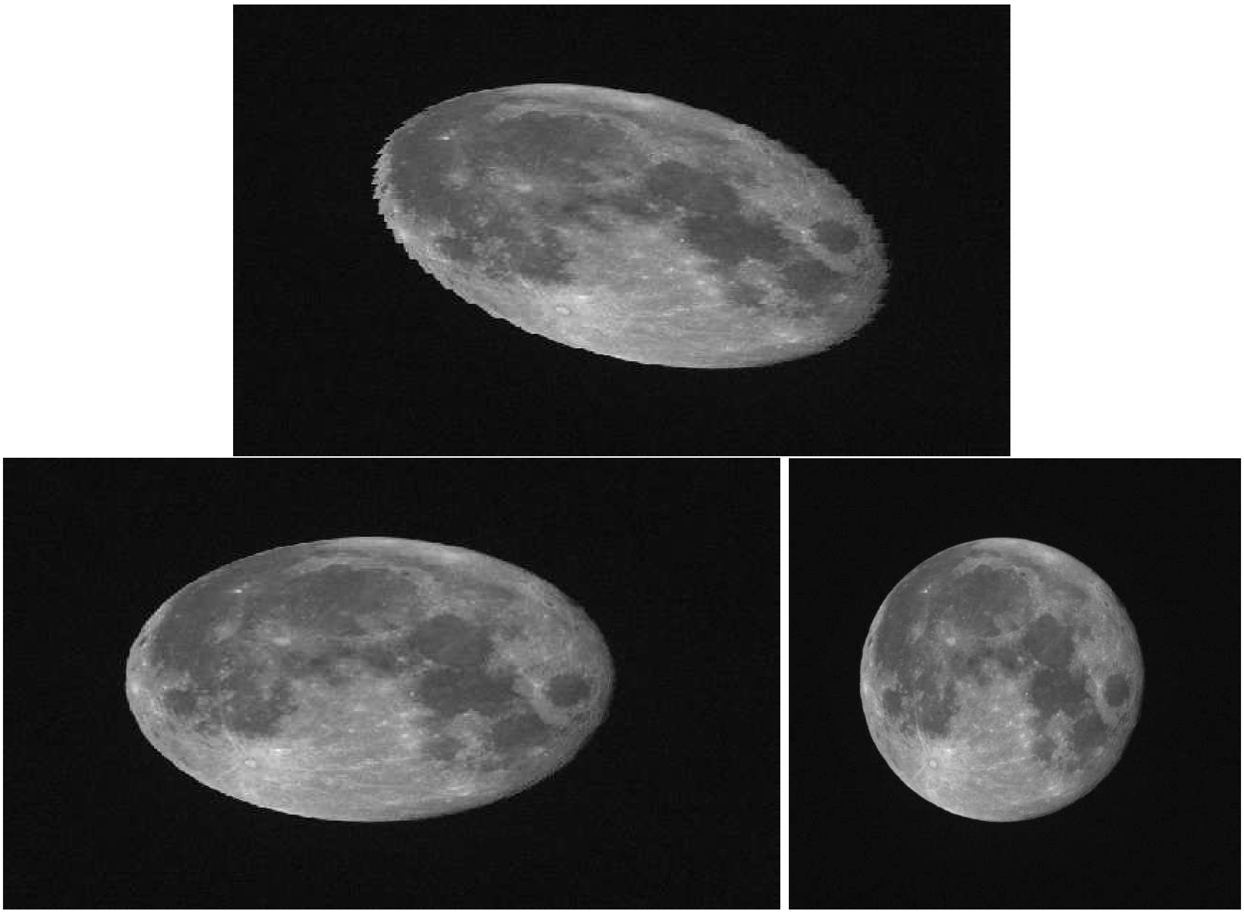


Figure 4. Steps in GOES-12 lunar image processing. *Top:* subsample of the full-disk image, uncorrected for oversampling. *Lower left:* with scan line offset correction to remove the apparent motion of the Moon across the FOR. *Lower right:* with oversampling correction based on an elliptical limb fit.

The disk-equivalent lunar irradiance I' is derived from integration of the radiance image:

$$I' = \Omega_p \sum_{i=1}^{N_p} L_i \qquad (3)$$

where L_i is an individual radiance measurement (i.e. pixel) on the Moon, Ω_p is the solid angle of one pixel in the scan-corrected image, and N_p is the total number of pixels on the lunar disk. In practice the space background level should have zero average radiance, and the actual summation could extend beyond the disk. Hence if the oversample factor is known *a priori*, the summation can be performed on the calibrated image without a scan line offset correction.

Using GVAR data processing tools, the lunar subsample region of Figure 1 (uncorrected for oversampling) was output in radiance units, W m^{-2} sr^{-1} μm^{-1}. After applying the pixel offset correction described above, a multiple-point elliptical fitting routine was used to determine the extent of the Moon in the image. Pixel radiances were summed over this elliptical area, but extending slightly past the limb edges. From these processes and ephemeris calculations for the Moon and GOES-12, the following values were found:

semi-major (down-scan) axis	262.0	pixel
semi-minor axis	152.1	line
oversample factor	1.722	
summed radiance	5.551×10^{6}	W/(m^2 sr μm)
number of pixels summed	126300	
Moon–GOES-12 distance	414213.	km
pixel solid angle	4.380×10^{-10}	steradian
GOES-12 lunar irradiance	2.4315	μW/(m^2 nm)

The irradiance, down-scan size of the Moon, and the GOES-12 satellite location at the center of the lunar image acquisition time, estimated to be 18:06:05 UTC, were given as inputs to a test run of the ROLO lunar irradiance model. Output was generated for a narrow passband centered at ~650 nm, a proxy for the GOES visible channel. The results show the instrument irradiance to be 10.52% lower than the ROLO model. Although this is a single observation comparison and the actual instrument spectral response function was not modeled directly, the result is consistent with GOES-12 visible-channel degradation over time (e.g. Ref. 7).

4.2. Capabilities for Long-term Response Characterization

The current ROLO irradiance model (version 311g) has fitted the calibrated exoatmospheric irradiance data with residuals under 1% over the full range of geometric variables, which includes the effects of lunar libration and opposition effect backscatter. The inherent stability of the lunar surface reflectance is estimated at better than one part in 10^8 per year.[3] With this level of stability, a time-series of lunar observations compared against the ROLO model can determine sensor response trends with sub-percent precision.[1] Lunar model comparisons can also support cross-calibration of satellite instruments, using the Moon as a common target.

In support of spacecraft teams using lunar calibration, ROLO has developed tools for prediction of Moon observation opportunities. A test run using GOES satellite orbital parameters and the nominal full-disk acquisition schedule of every three hours shows that the Moon will appear unoccluded in the corners of GOES images with a phase angle within the ROLO operational range of $\leq 90°$ at least once per month. This prediction capability can be used as a selection method for archived GOES data. Because the lunar irradiance model can be applied to observations made at any time, response histories could be developed for any of the GOES satellites, including those that have been decommissioned.

An additional capability is to estimate the detailed spatial response (line-spread function and MTF) from the response profile crossing the bright limb of the Moon into space. Because the radiance off the Moon is virtually zero, the apparent brightness profile in space adjacent to the bright limb of the Moon is an extremely sensitive measure of scattering, related to possible degradation in quality of optical surfaces. This is especially important for applications that use the contrast of small features.

4.3. Limitations

The method for ROLO irradiance comparisons was developed primarily to support multispectral imagers with relatively narrow channel band widths, ∼10–30 nm, whereas the spectral response of geostationary visible channels is typically much wider. A recent effort has been initiated to accommodate wide-band instruments with a more rigorous band interpolation scheme, utilizing a weighted complement of the ROLO bands to cover the spectral range. For an imager that has no prior radiance calibration, the accuracy of the ROLO irradiance comparisons will be constrained by the uncertainty in the ROLO model absolute scale. The current model version derives its absolute scale from observations of the star Vega; uncertainty estimates are ∼5–10%. An effort to tie ROLO to the NIST radiometric scale is current work in progress.[10]

5. CONCLUSION

The ROLO program has developed the techniques and tools to allow use of the Moon for on-orbit characterization of imaging system radiometric response utilizing the lunar disk-integrated equivalent irradiance. An empirical model for the lunar spectral irradiance was built from an extensive set of ground-based radiance measurements of the Moon, corrected for the atmosphere and calibrated using the star Vega. The ROLO data set spans a sufficient portion of the lunar orbit precession cycle such that the model treats the effects of libration explicitly, as well as the basic dependence on phase angle, including the enhanced backscatter "opposition effect". Model fit residuals are at the 1% level, indicative of its stability over the range of geometric variables. Comparisons of on-orbit lunar irradiance measurements against ROLO model results have been conducted for several instruments, and are utilized in-line to data products for one (SeaWiFS). The SeaWiFS work has shown that the ROLO lunar calibration method is capable of determining sensor response trending with sub-percent precision.

Full-disk images of Earth acquired by geostationary instruments will capture the Moon at phase angles useful for lunar calibration at least once per month. The Moon in GEO images appears skewed due to the satellite orbital motion during the image acquisition time, but this does not exclude their use with ROLO lunar calibration. The brightness of the Moon spans roughly half the dynamic range of a typical Earth scene, but covers all of the range of clear ocean and most of that of clear land.

The stability of the ROLO irradiance model means that it can be applied to observations made at any time without loss of precision. The tools developed to assist spacecraft teams with lunar observation opportunities can be used to find images that contain the Moon in a GEO imager archive. With a long time series of observations to compare against ROLO lunar irradiance predictions, response trending with a precision level of a fraction of a percent can be achieved. A potential additional benefit of analyzing lunar images is the ability to observe degradation of the imager optics over time by examining the sharp edge of the Moon against the black background of space.

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REFERENCES

1. R. A. Barnes, R. E. Eplee Jr., F. S. Patt, H. H. Kieffer, T. C. Stone, G. Meister, and J. J. Butler C. R. McClain. Comparison of SeaWiFS measurements of the Moon with the USGS lunar model. *Applied Optics*, 43(30):5838–5854, 2004.
2. J. C. Bremer, J. G. Baucom, H. Vu, M. P. Weinreb, and N. Pinkine. Estimation of long-term throughput degradation of GOES 8 & 9 visible channels by statistical analysis of star measurements. *Proc. SPIE*, 3439:145–154, 1998.
3. H. H. Kieffer. Photometric stability of the lunar surface. *Icarus*, 130:323–327, 1997.
4. H. H. Kieffer and T. C. Stone. The spectral irradiance of the Moon. *Astronom. J.*, 129(6):2887–2901, 2005.
5. K. R. Knapp and T. H. Vonder Haar. Calibration of the eighth Geostationary Observational Environmental Satellite (GOES-8) imager visible sensor. *J. Atmos. and Ocn. Tech.*, 17(12):1639–1644, 2000.

6. P. Minnis, L. Nguyen, D. R. Doelling, D. F. Young, W. F. Miller, and D. P. Kratz. Rapid calibration of operational and research meteorological satellite imagers. Part I: Evaluation of research satellite visible channels as references. *J. Atmos. and Ocn. Tech.*, 19(9):1233–1249, 2002.
7. L. L. Nguyen, D. R. Doelling, P. Minnis, and J. K. Ayers. Rapid technique to cross calibrate satellite imager visible channels. *Proc. SPIE*, 5542:227–235, 2004.
8. C. R. Nagaraja Rao. Implementation of the post-launch vicarious calibration of the GOES imager visible channel. http://www.oso.noaa.gov/goes/goes-calibration/vicarious-calibration.htm, 2001.
9. T. C. Stone and H. H. Kieffer. Absolute irradiance of the Moon for on-orbit calibration. *Proc. SPIE*, 4814:211–221, 2002.
10. T. C. Stone and H. H. Kieffer. Assessment of uncertainty in ROLO lunar irradiance for on-orbit calibration. *Proc. SPIE*, 5542:300–310, 2004.
11. M. P. Weinreb, M. Jamieson, N. Fulton, Y. Chen, J. X. Johnson, J. Bremer, C. Smith, and J. Baucom. Operational calibration of Geostationary Operational Environmental Satellite-8 and -9 imagers and sounders. *Applied Optics*, 36:6895–6904, 1997.