Using the Moon as a Common Reference for Inter-calibration

Thomas C. Stone
U.S. Geological Survey, Flagstaff, AZ USA

CALCON Technical Conference
22-25 August 2016

calcon
www.calcon.sdl.usu.edu

The Moon as a calibration reference

The Moon is available for viewing by all sensors in LEO and GEO.

Advantages:

- exceptionally stable diffuse reflecting surface
- no atmosphere between the sensor and the target

Disadvantages:

- non-uniform appearance — distribution of lunar terrain = albedo
- continuously changing brightness, due to illumination/phase angle and non-Lambertian BRDF
- observability can be limited by line-of-sight constraints
  - examples: VIIRS rotating telescope cross-track scanner
    - ➢ lunar views employ roll maneuvers and Earth-view sector rotation
    - ➢ several months each year the Moon does not cross the view field
  - Landsat-8 OLI nadir-viewing pushbroom sensor
    - ➢ lunar views are done with 3-axis attitude maneuvers, slewing across the Moon with all 14 focal plane arrays in a raster pattern

USGS

Accommodating different lunar views by sensors

No two observations of the Moon are completely identical, but the lunar reflecting surface is effectively invariant.

- the solution: a numerical model that predicts the lunar brightness spectrally for specific conditions of illumination and viewing

This capability enables calibration against a common standard for any solar-band radiometer instruments that view the Moon.

- consistent calibration over time, *i.e.* temporal response trending
- cross-calibration without needing near-simultaneous observations
- back-calibration, including sensors that may no longer be operating

Different Moon observations by the same or different sensors can be compared by normalizing using the model results.

USGS

USGS-ROLO lunar model

Lunar model development and operation is done in terms of the lunar disk-equivalent reflectance ***A***

Empirical formulation, a function of only the geometric variables of phase angle (g) and the lunar librations (φ,θ,Φ):

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\phi + c_2\theta + c_3\Phi\phi + c_4\Phi\theta$$

$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

g = phase angle
ϕ = observer selenographic longitude
θ = observer selenographic latitude
Φ = selenographic longitude of the Sun

- coefficients derived by fitting ~1200 ROLO observations in 32 bands
- mean absolute residual ≈1%

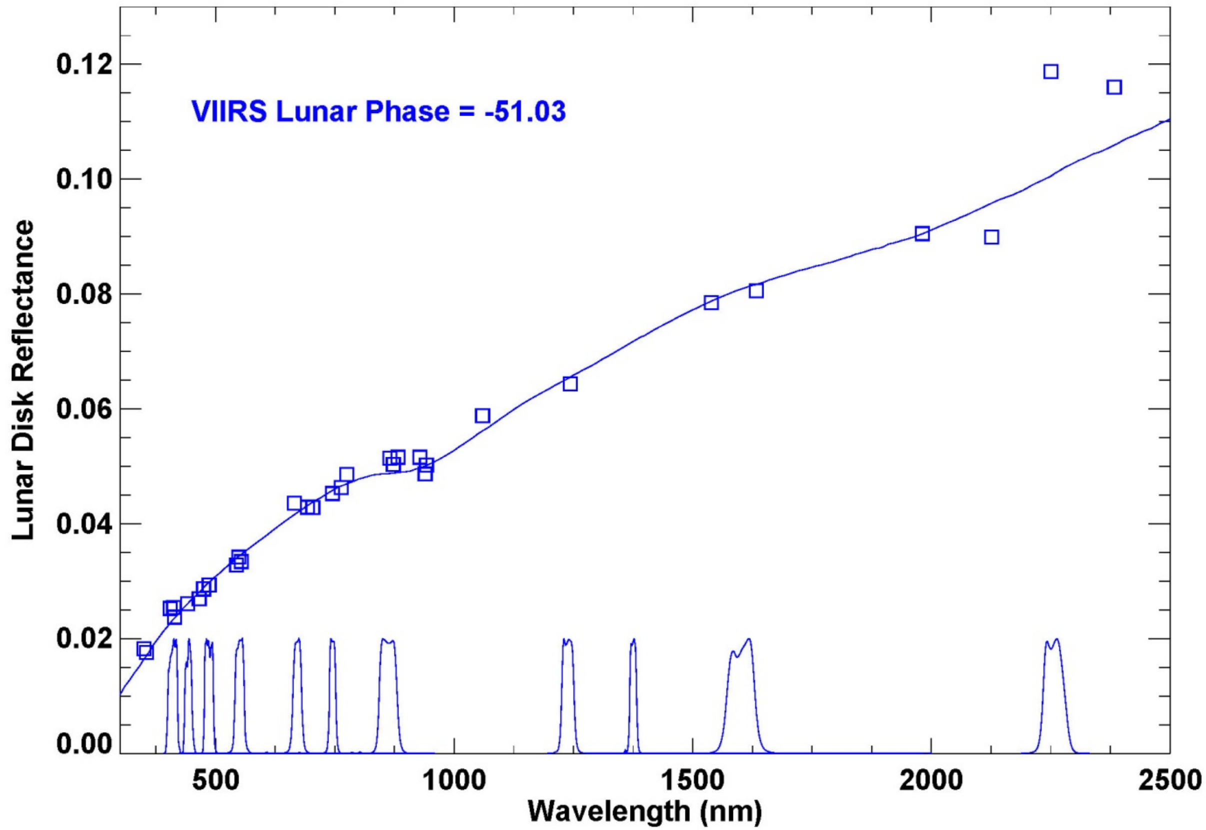
USGS

Lunar model outputs processing

Computing the model equation gives the lunar disk reflectance (A_k) at the 32 ROLO wavelengths. A representative lunar reflectance spectrum is then fitted to these A_k values.

Symbols □ are A_k from the lunar model computation

Solid line is the reference lunar reflectance spectrum, fitted to the A_k values.



USGS

Lunar model outputs processing (2)

The fitted reflectance spectrum is convolved with the instrument band spectral response functions and the solar spectrum to give the lunar irradiance ($\boldsymbol{E}_{\mathrm{M}}$) at the sensor band wavelengths:

$$\boldsymbol{E}_{\mathrm{M}} = \frac{\Omega_{\mathrm{M}}}{\pi} \frac{\int A_{\mathrm{fit}}(\lambda)\, E_{\mathrm{Sun}}(\lambda)\, S(\lambda)\, d\lambda}{\int S(\lambda)\, d\lambda}$$

A_{fit} = lunar reflectance spectrum
E_{Sun} = Solar spectral irradiance
S = spectral response function
$\Omega_{\mathrm{M}} = 6.418 \times 10^{-5}$ sterad

The model computations ($\boldsymbol{A}_{\mathrm{fit}}$) and Ω_{M} are for standard Sun–Moon and Moon–Observer distances of 1 AU and 384400 km

Apply distance corrections:

$$E'_{\mathrm{M}} = E_{\mathrm{M}} \left(\frac{1\,\mathrm{AU}}{d_{\mathrm{Sun-Moon}}} \right)^2 \left(\frac{384\,400\,\mathrm{km}}{d_{\mathrm{Moon-Obs}}} \right)^2$$

The final output $\boldsymbol{E'}_{\mathrm{M}}$ is the lunar irradiance present at the instrument location at the time of the observation, in each sensor spectral band.

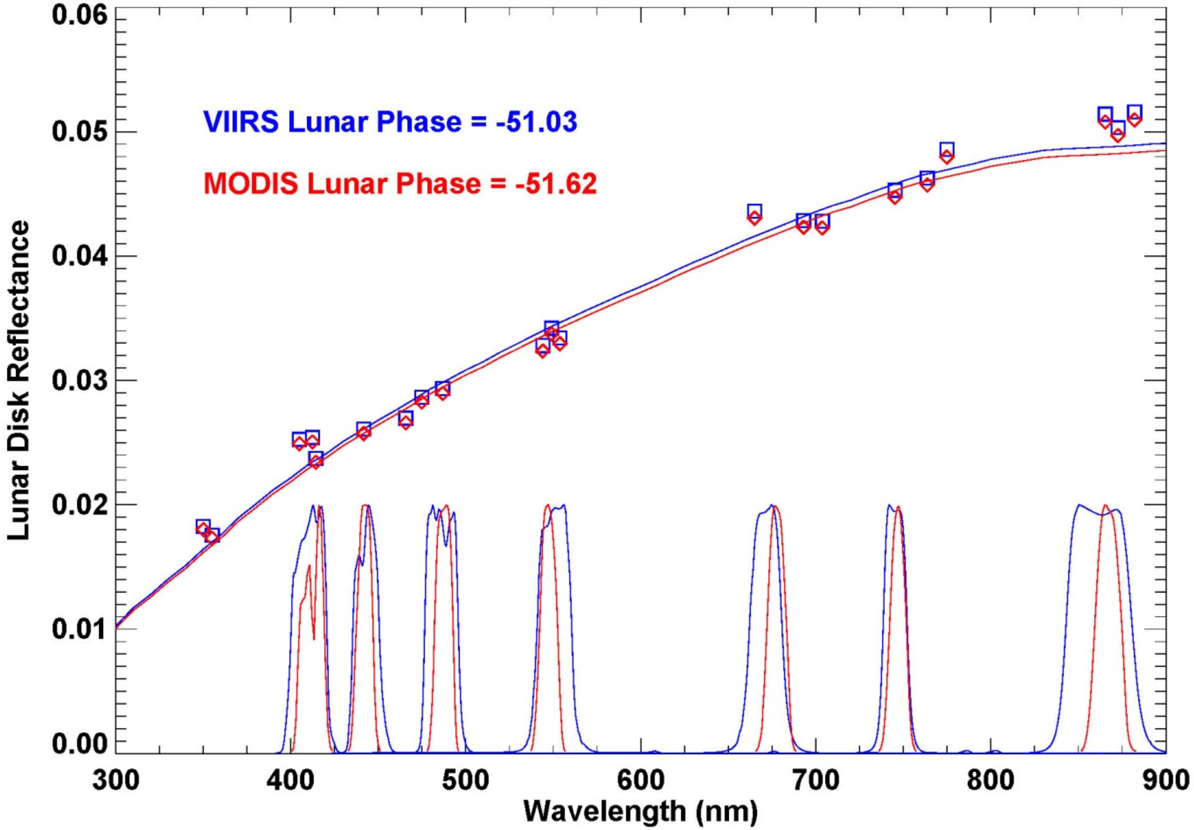
USGS

Lunar cross-comparison: MODIS and VIIRS

	Observation date	Phase angle	Sub-solar longitude	Sub-solar latitude	Sub-satellite longitude	Sub-satellite latitude
NPP-VIIRS	2014-02-10	−51.03	55.32	1.488	4.328	5.159
MODIS-Aqua	2002-10-16	−51.62	56.55	1.171	5.024	5.774

Seven MODIS ocean color bands coincide with VIIRS bands M1–M7.

The similar geometry of the observations means the lunar disk reflectance spectra are nearly the same.



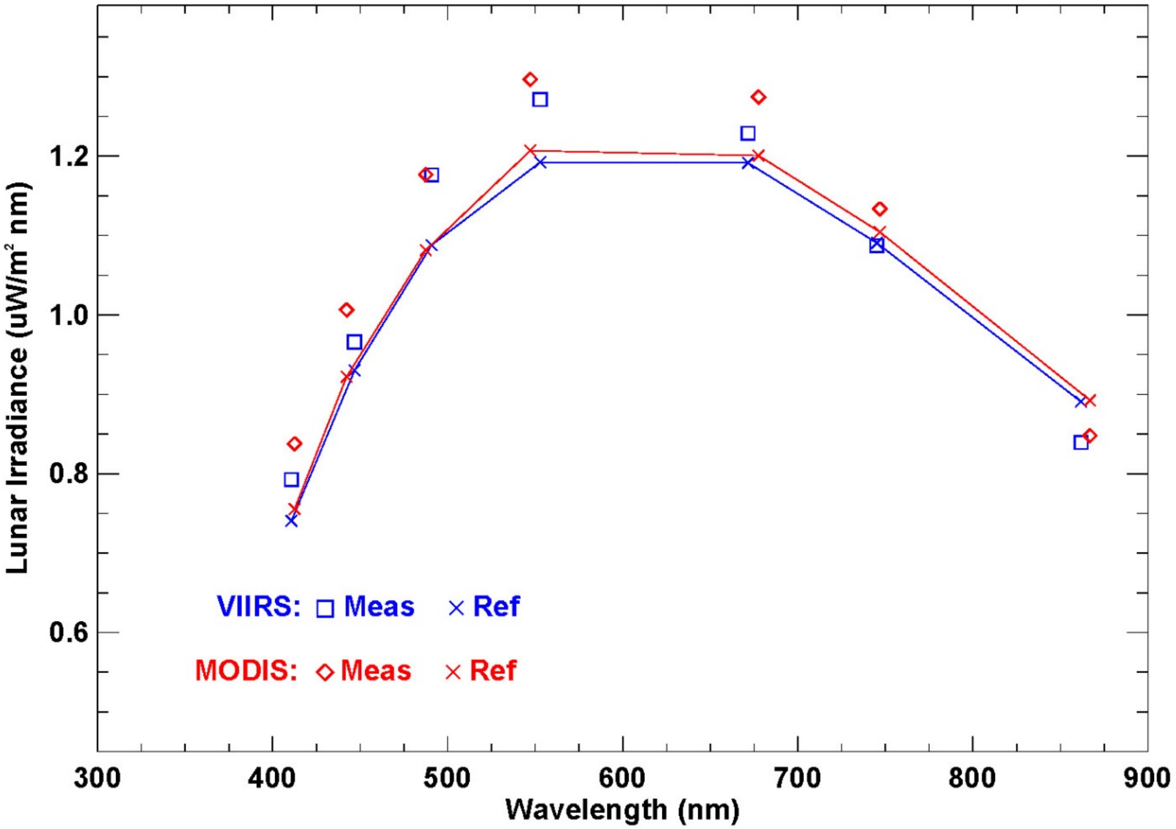
Lunar irradiance cross-comparison

MODIS-Aqua and VIIRS Moon observations with similar geometry, but more than 11 years apart

□ and ◊ symbols are lunar irradiance measurements from VIIRS and MODIS images.

The reference lunar irradiance is nearly identical for both instruments.

The measurements show the sensor responses to the same lunar target.



VIIRS calibration: IDPS
MODIS calibration: Collection 6

USGS

Lunar inter-calibration uncertainty sources

For sensors with different spectral responses, and Moon observations with different geometries, the accuracy of lunar inter-calibration is directly dependent on **uncertainties in the lunar model reference**:

- spectral specification of the lunar reflectance (and solar irradiance)
- geometric specification of the lunar surface reflectance (BRDF, albedo distribution)

The current reference standard for lunar calibration is the USGS-ROLO lunar spectral irradiance model[1]

- lunar disk-equivalent reflectance, computed for Sun-Moon-Observer geometry and converted to irradiance at the sensor spectral bands
- irradiance absolute accuracy is ~5%
  - this uncertainty enters into risk assessments for satellite maneuvers to view the Moon
  - it is a limitation of the lunar model, not of the Moon as a reference
- future model improvements can be applied to past Moon observations

USGS

[1]Astronom. J. 129, 2887-2901 (2005)

Lunar inter-calibration uncertainty sources

Accuracy is also dependent on **uncertainties in the lunar irradiance measurements** by instruments, by summation of radiance pixels:

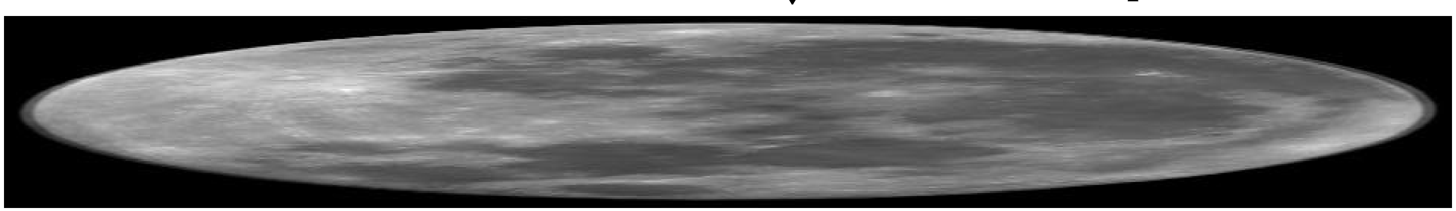
$$I = \Omega_{\mathrm{p}} \sum_{i=1}^{N_{\mathrm{p}}} L_i$$

Images of the Moon acquired with line-array sensors are assembled from e.g. cross-track scans (VIIRS, MODIS), pushbroom scans (OLI, PLEIADES) or raster scans (3-axis stabilized geostationary imagers)

← GOES-12
8 pixels/frame
1.75x oversampled

SNPP-VIIRS →
16 pixels/frame
critically sampled

OLI 494 pixels/frame (Moon dia. ~230)
↓ 8.25x oversampled



Lunar irradiance measurements from images: critical parameters

<u>Oversampling factor</u>

- a direct dependency of irradiance measurements by pixel summation
- requires frame sampling stability and consistency
- must account for the orbital motions of the spacecraft and the Moon

Example cross-track scanner: VIIRS

- ~30 frames (unaggregated) across the Moon diameter, acquired in ~2.6 ms
- critically sampled, based on nadir-view acquisition scheme
  - ➢ when translated to Moon view, may impose a constant scale factor

Example pushbroom scanner: Landsat-8 OLI

- dedicated attitude maneuvers, scan across the Moon diameter in ~8 sec
- detailed telemetry shows stable slew rates → excellent lunar radiometry

Example raster scanner: GOES-8 and later

- bi-directional E-W scanning means different <u>lunar</u> sampling rates each way

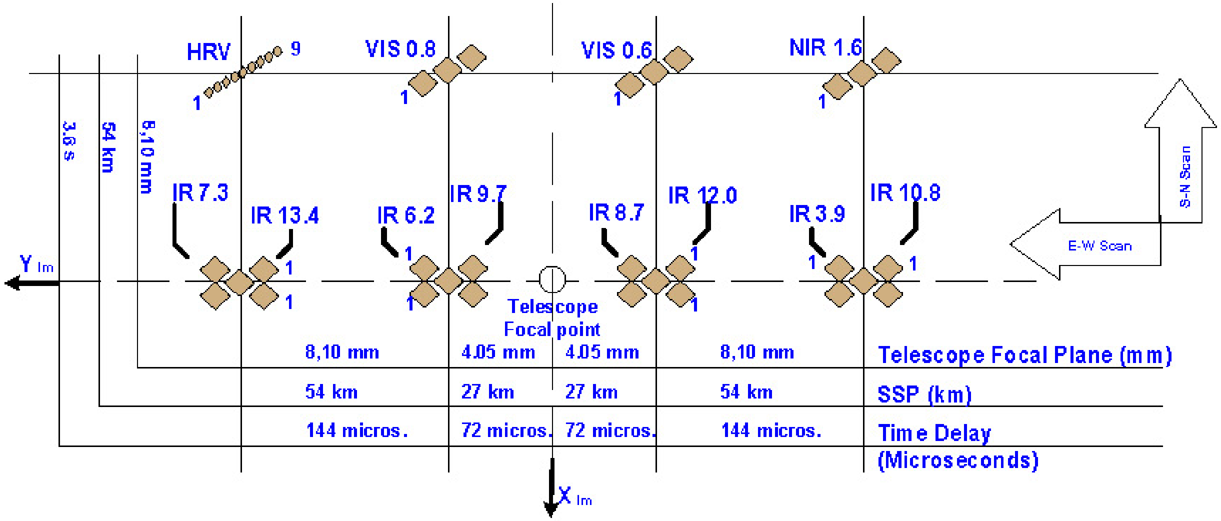
USGS

Lunar irradiance measurements from images: critical parameters

Oversampling factor

Example spin-scanner: Meteosat 2nd Gen SEVIRI

- E-W scanning rate determined by satellite spin rate = 100 rpm ±1%
- diagonal detector arrangement
  - vertical alignment is obtained by time-delayed acquisition
  - N-S overlap contributes to oversampling (constant for each channel)



USGS

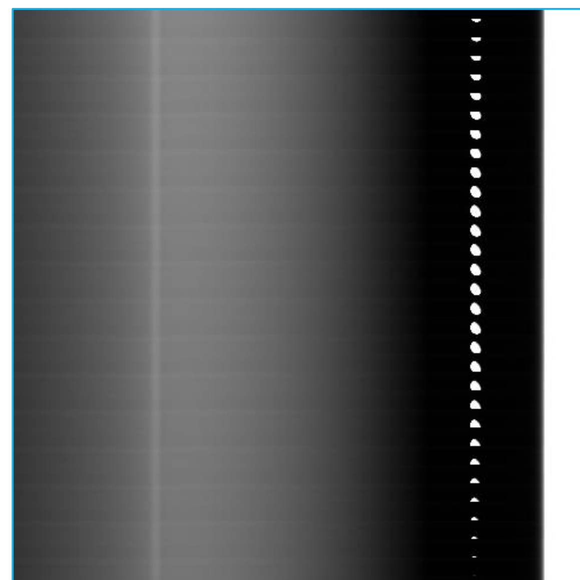
Lunar irradiance measurements from images: critical parameters

Detector dark level

- represents an offset to image radiance
- typically evaluated from space-view, then subtracted from image data
- the space region surrounding a lunar disk image should average zero radiance, *except:*
  - stars may be detected if the sensor has sufficient dynamic range
  - stray light can be an issue, especially scattering from the Earthlimb

Example: SNPP-VIIRS

- Moon scans acquired in Earth-view sector using spacecraft roll maneuvers
- consistent scattered light signal off the limb
- uniform dark level close to the Moon



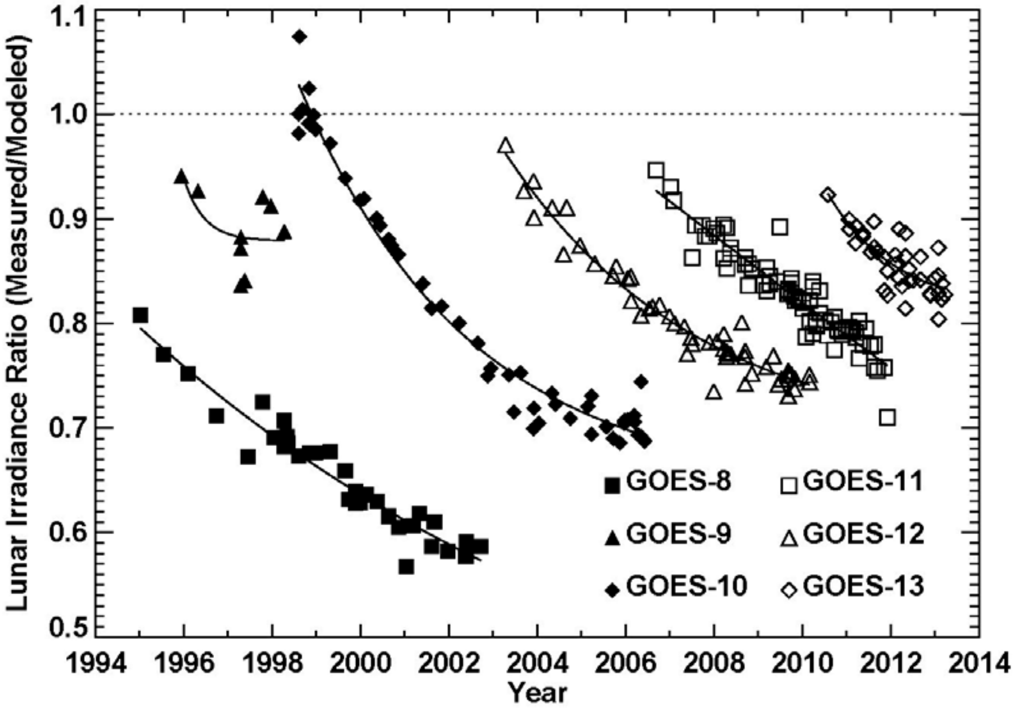
USGS

Application of lunar inter-calibration: GOES series

Images of the Moon captured in the space-view regions of operational GOES visible-channel images were used in lunar calibration analysis

- presumed constant oversampling = 1.75x
- used constant, pre-launch calibration coefficients

- dividing the lunar irradiance measurements by reference values normalizes the variation due to different phase angles
- for the GOES-8 to13 series shown, the phase angle range is 4.3° to 91°; the irradiance range is 3.77 to 0.296 µW/(m² nm)
- time series of measurement/ reference ratios reveal sensor response changes in orbit



Application of lunar inter-calibration: GOES series

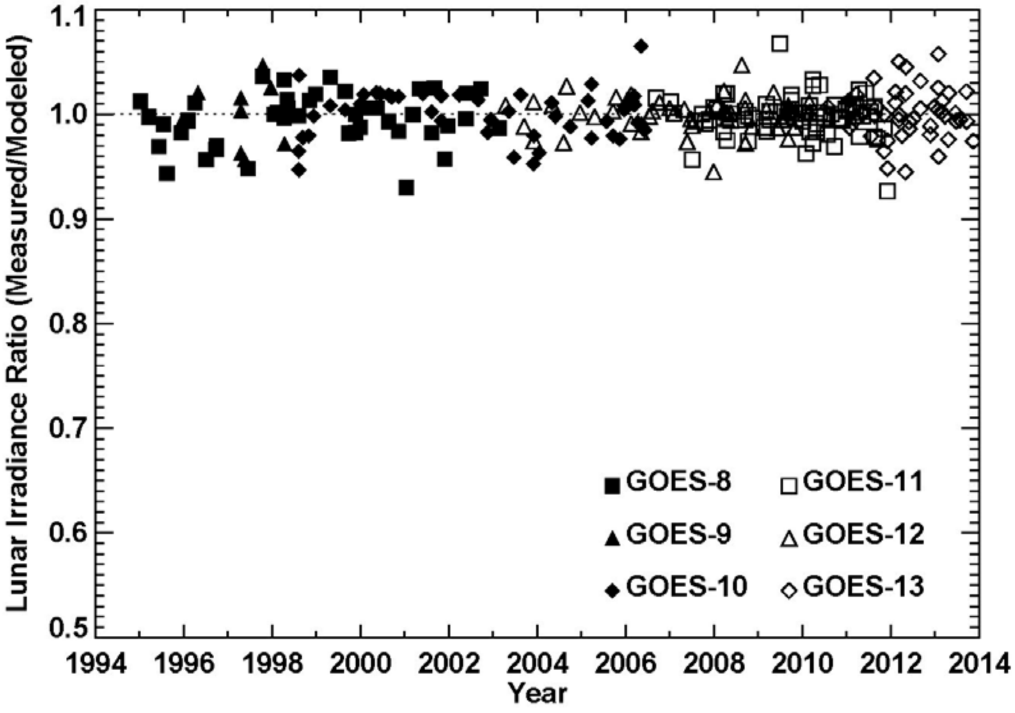
Time-dependent radiance conversions for the GOES visible channels were developed to correct the measurements to the lunar reference:

$$L_{\mathrm{pix}} = C_t(\mathrm{DN} - \mathrm{DN}_{\mathrm{space}})$$

$$C_t = C_0\left[a_0 + a_1(t - t_0) + a_2(t - t_0)^2\right]$$

	C_0	t_0	a_0	a_1	a_2
GOES-8	0.5502	1995-04-10	1.269	1.755E-4	0.0
GOES-9	0.5492	1995-08-07	0.996	5.088E-4	-4.166E-7
GOES-10	0.5582	1998-03-21	0.923	3.044E-4	-4.480E-8
GOES-11	0.5562	2006-06-21	1.063	1.213E-4	0.0
GOES-12	0.5771	2003-04-01	1.036	1.902E-4	-2.657E-8
GOES-13	0.6118	2010-04-14	1.098	1.507E-4	-2.904E-8

- applying these expressions to the lunar time series removes the degradation trends and places these sensors on the same radiometric scale
- provides a consistent 20-year record of Earth observations from GOES imagery



USGS

Summary and Conclusions

- The Moon is an extremely stable solar reflectance target, available to all Earth-orbiting sensors
  – potentially an exceptional calibration reference
  – its most significant limitation is a relatively low albedo: avg. 0.11 @ 500nm
- The operational lunar calibration reference is an analytic model
  – provides a common standard for sensor inter-calibration, by generating self-consistent reference values for individual Moon observations
  – lunar inter-calibration can be applied sensors no longer operating, with implications for climate measurements from archived image datasets
- Improvements to the lunar calibration reference are feasible
  – efforts are ongoing to acquire new lunar radiometric characterization data
- For lunar irradiance measurements from images, oversampling is a critical parameter
  – this factor must be known precisely to achieve accurate lunar calibrations
  – its evaluation requires accurate knowledge of sampling and scan rates, and accounting for the orbital motions of the spacecraft and the Moon

USGS