The Moon as a Common Reference for Sensor Cross-Comparison

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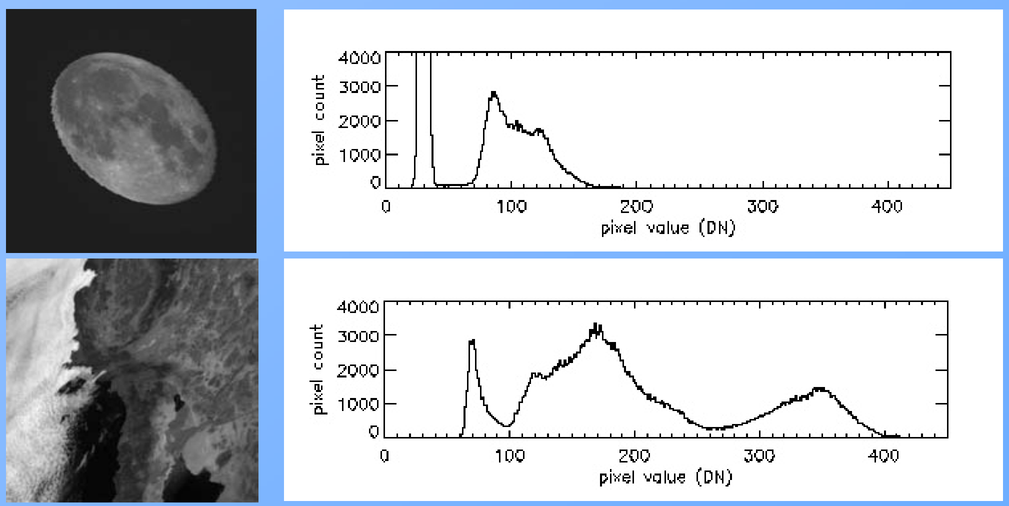
The Moon as a source — lunar calibration

The Moon can be considered a “solar diffuser” with exceptional stability — invariant to <10^{-8}per year (Icarus 130, 323-327 (1997))

- accessible in all Earth orbits
- no intervening atmosphere
- suitable dynamic range →



The apparent brightness of the Moon changes continuously with illumination and view angles, thus an analytic model is required to enable radiometric comparisons from any spacecraft viewpoint

- direct comparisons, using the Moon as a stable standard
- spacecraft–to–spacecraft, using the Moon as a common reference

Modeling the Moon

The Lunar Calibration program at USGS has developed a model for the spatially-integrated spectral irradiance of the Moon (Astron. J. 129, 2887-2901 (2005))

- developed from fitting 6+ years of ground-based observations (ROLO facility)
  - multiple years required to sufficiently capture the cyclic brightness variations
- operates on the spatially integrated full lunar disk
  - fractional illumination is contained in the model
  - for imaging instruments, accommodates different spatial resolutions, and has S/N advantage from sampling multiple pixels
  - requires that instruments acquire the entire Moon in some manner
- contains only geometric variables, thus valid for any time
  - enabled by the inherent stability of the lunar surface reflectance
  - allows cross-comparison of any Moon observations within range constraints
- capability for predicting lunar irradiance with relative precision ~1% over the full range of geometric variables, in 32 spectral bands 350−2450 nm

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

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

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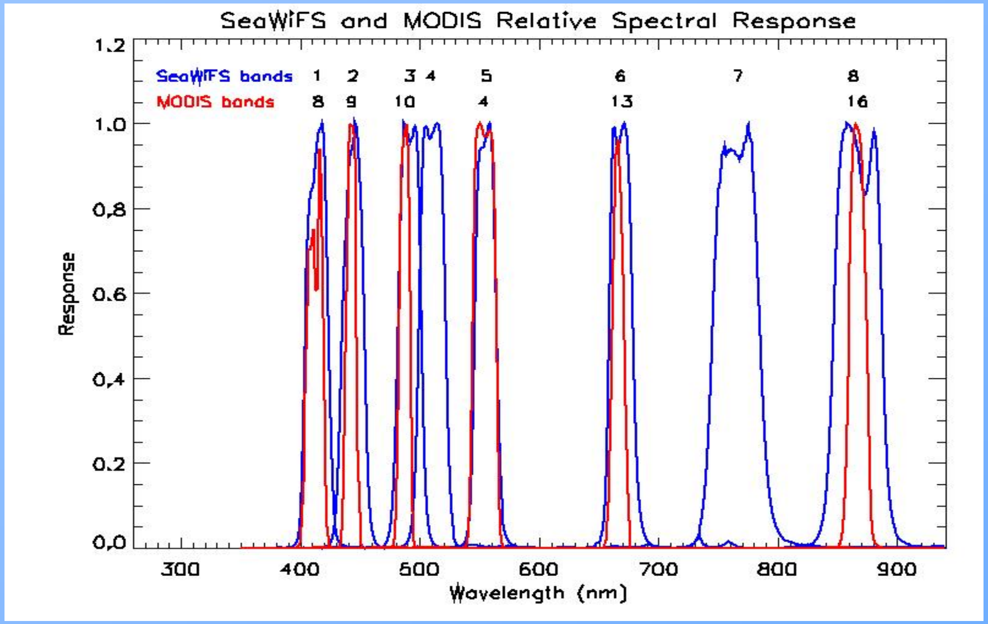
Sensor cross-comparison using the Moon

Many Earth-observing instruments have common spectral bands. SeaWiFS and MODIS (both Terra and Aqua) also have viewed the Moon often.

Inter-comparison of lunar observations *in similar spectral bands* minimizes the effects of absolute scale uncertainty in the lunar model.



Six MODIS reflective solar bands (red) overlap SeaWiFS bands (blue)

The MODIS instruments view the Moon through a space-view port, typically near 55° phase angle. Since 2006, SeaWiFS has collected additional Moon views to complement MODIS observations, often within hours of each other.

MODIS and SeaWiFS lunar cross-comparison

Two near-simultaneous Moon views: 09 December 2006 and 08 January 2007

	Time	Phase Angle	Sub-lunar Longitude	Sub-lunar Latitude	Distance Correction
Observation date: 2006-12-09					
SeaWiFS	08:27:51	54.490	6.39	-4.29	0.988136
MODIS	09:34:11	55.119	6.47	-3.62	1.005660
Observation date: 2007-01-08					
SeaWiFS	03:56:20	53.992	3.44	-1.11	1.025943
MODIS	06:14:21	55.306	3.59	-1.12	1.047375

- Similar phase angles are NOT a requirement for lunar calibration, but can reduce errors, including processing instrument Moon images to irradiance

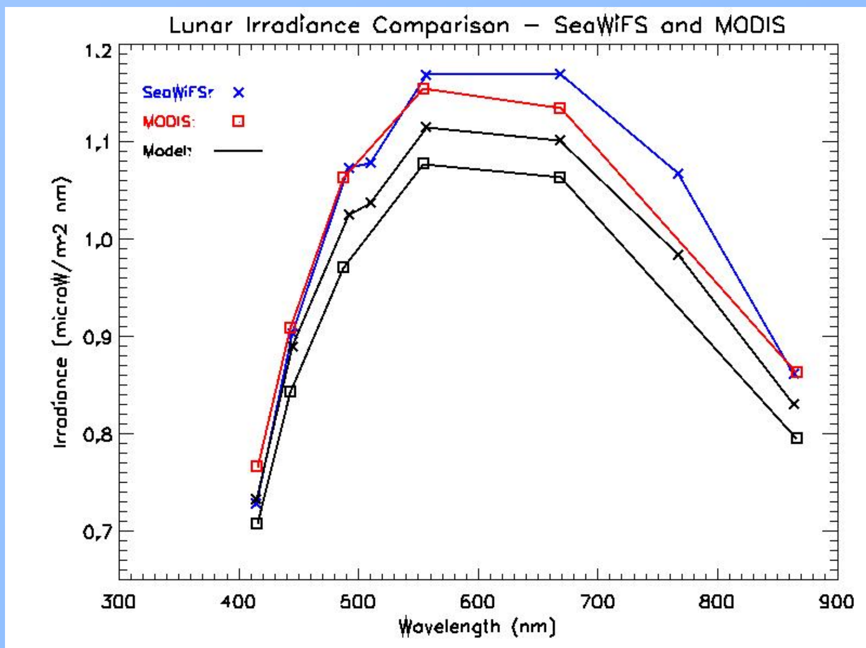
Lunar model inputs: observation geometry

- satellite position @ observation time — provided by the spacecraft teams
- selenographic variable parameters — computed by the lunar calibration system

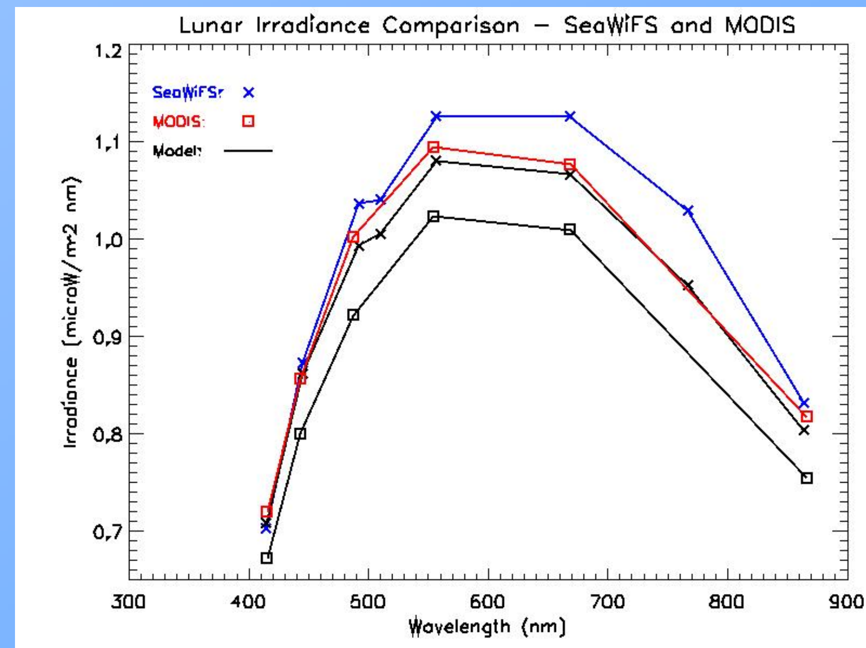
MODIS and SeaWiFS Moon Observations — Irradiances

Instrument-measured, and model at spacecraft distance and instrument bands

09 December 2006



08 January 2007

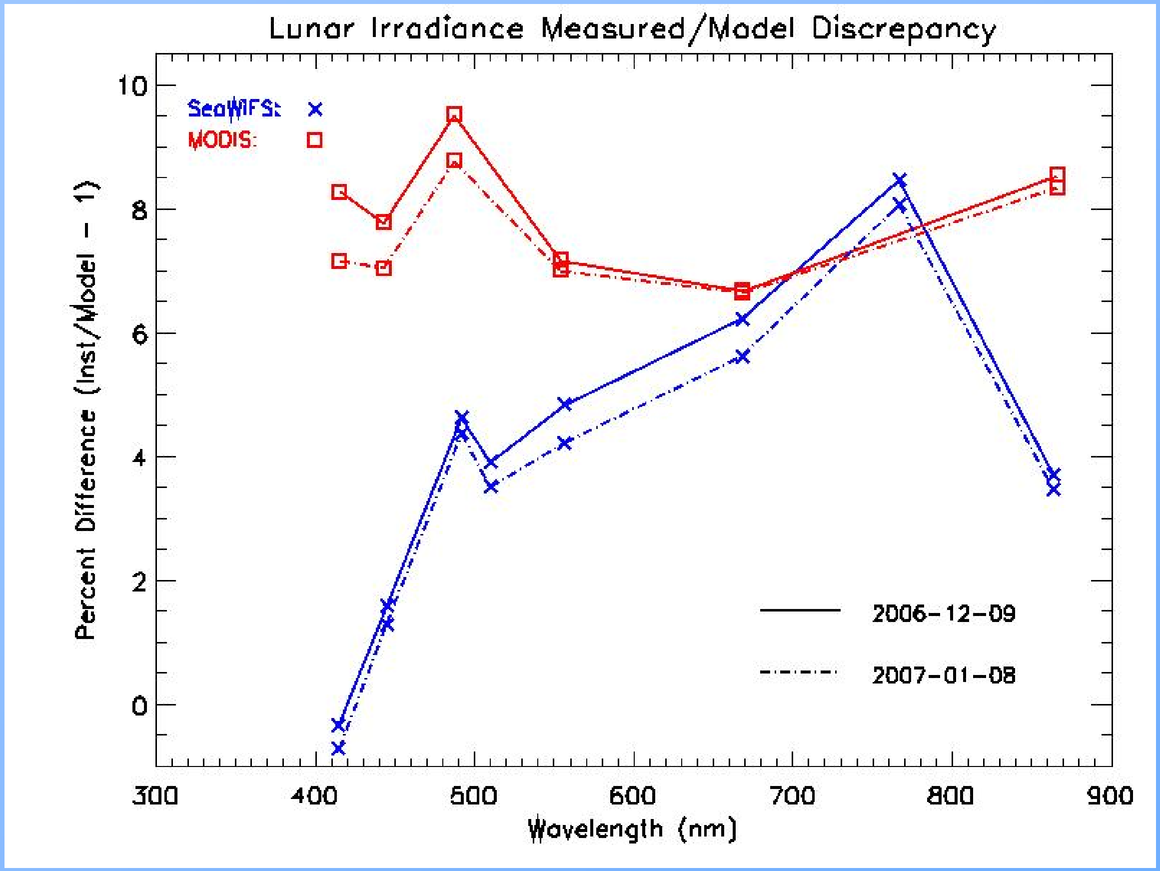


- offsets in model results are due to observation geometry differences
  - i.e. model corrections for lunar brightness variations due to illumination and view
- instrument-to-model offsets show calibration differences

Paired Moon Observations — Instrument / Model Comparisons

Standard lunar calibration results: percent difference in irradiance

- discrepancy = $\left(\frac{\text{INST}}{\text{MODEL}} - 1\right) \times 100\%$



The instrument/model discrepancies for the two observations track spectrally within 1% for both SeaWiFS and MODIS.

Double-differencing shows consistent sensor response biases between the two instruments.

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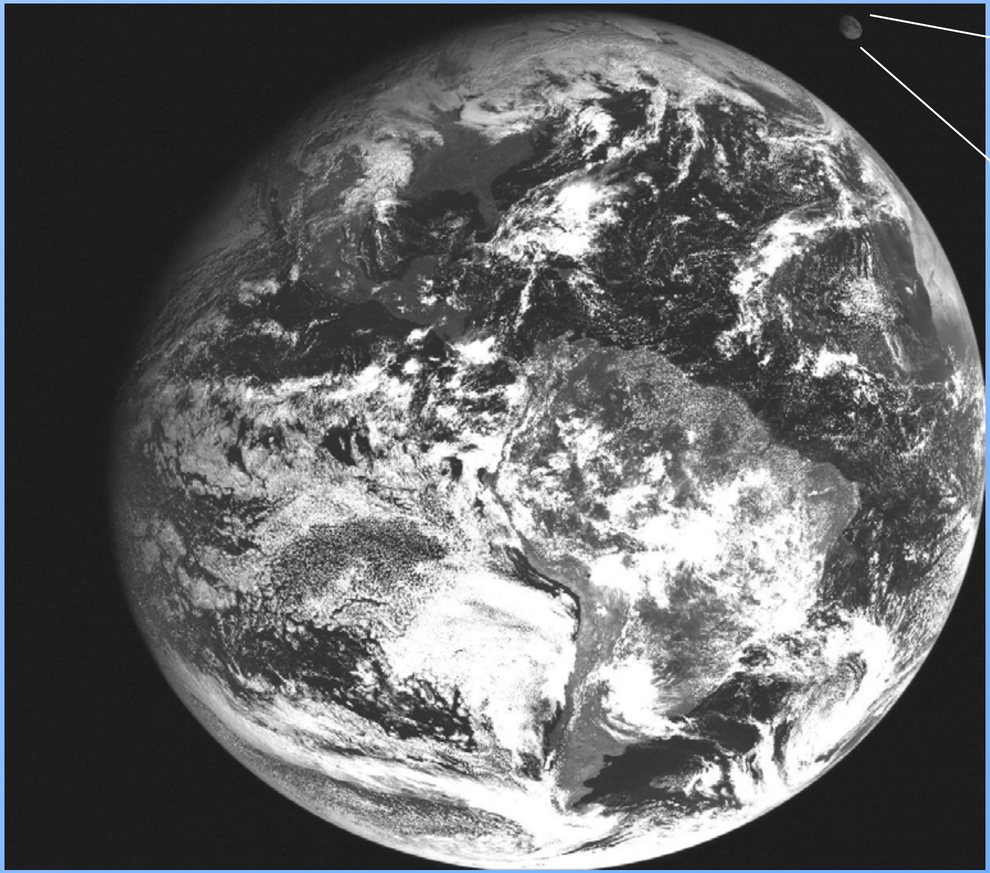
Application to extended time-series — GOES archive

Geostationary satellite imagers capture the Moon periodically in the corners and margins of a rectangular field of regard.

Vis-channel meteorological imagers typically do not have on-board calibration.



GOES-12 vis channel 2008-11-10 14:45

The Moon appears skewed as a result of satellite motion during image acquisition

phase angle = −36°

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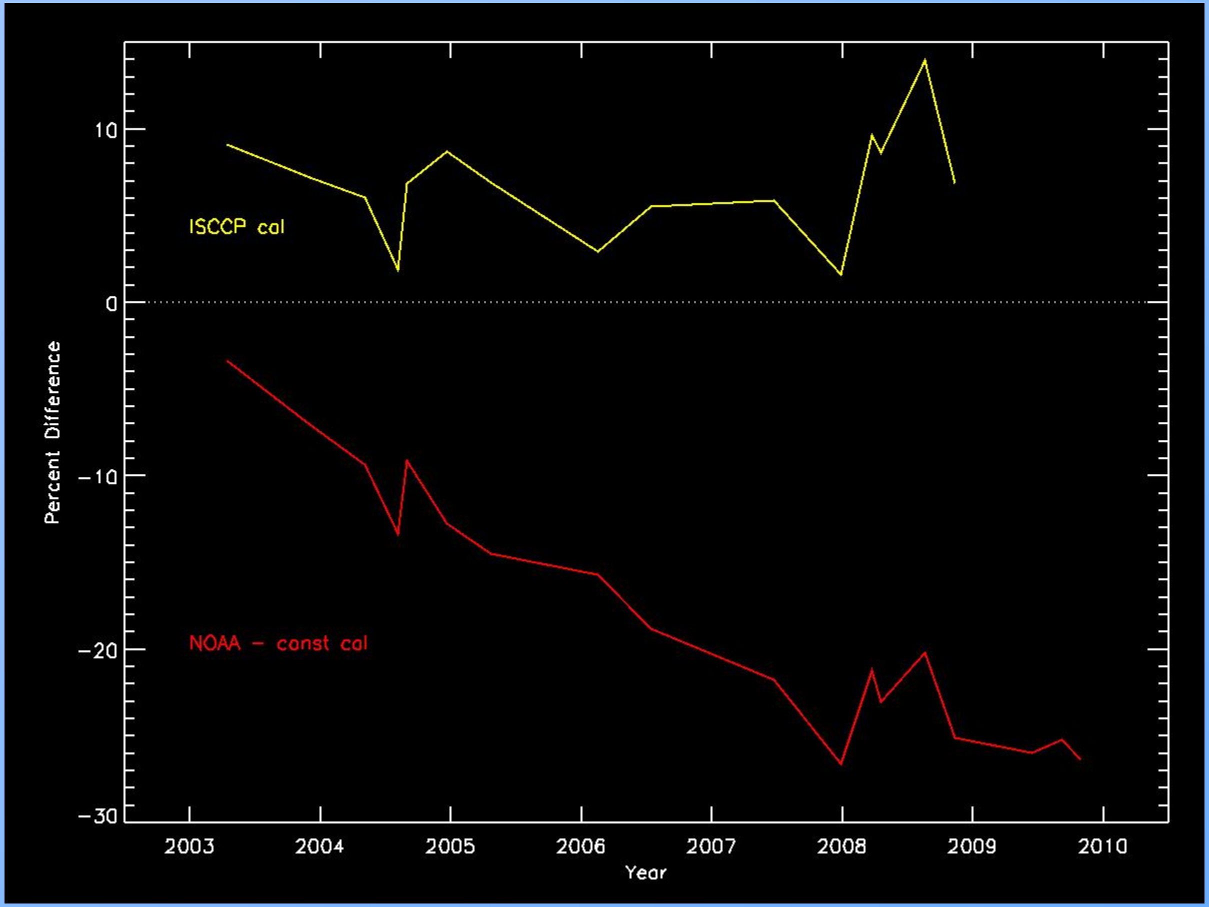
Lunar irradiance comparison results for GOES−12 series

GOES 3-hour operational imaging schedule limits Moon capture opportunities

- 18 useable Moon images over ~6.5 years (April 2003 − October 2009)
- ISCCP calibration corrects the temporal decrease in sensor response

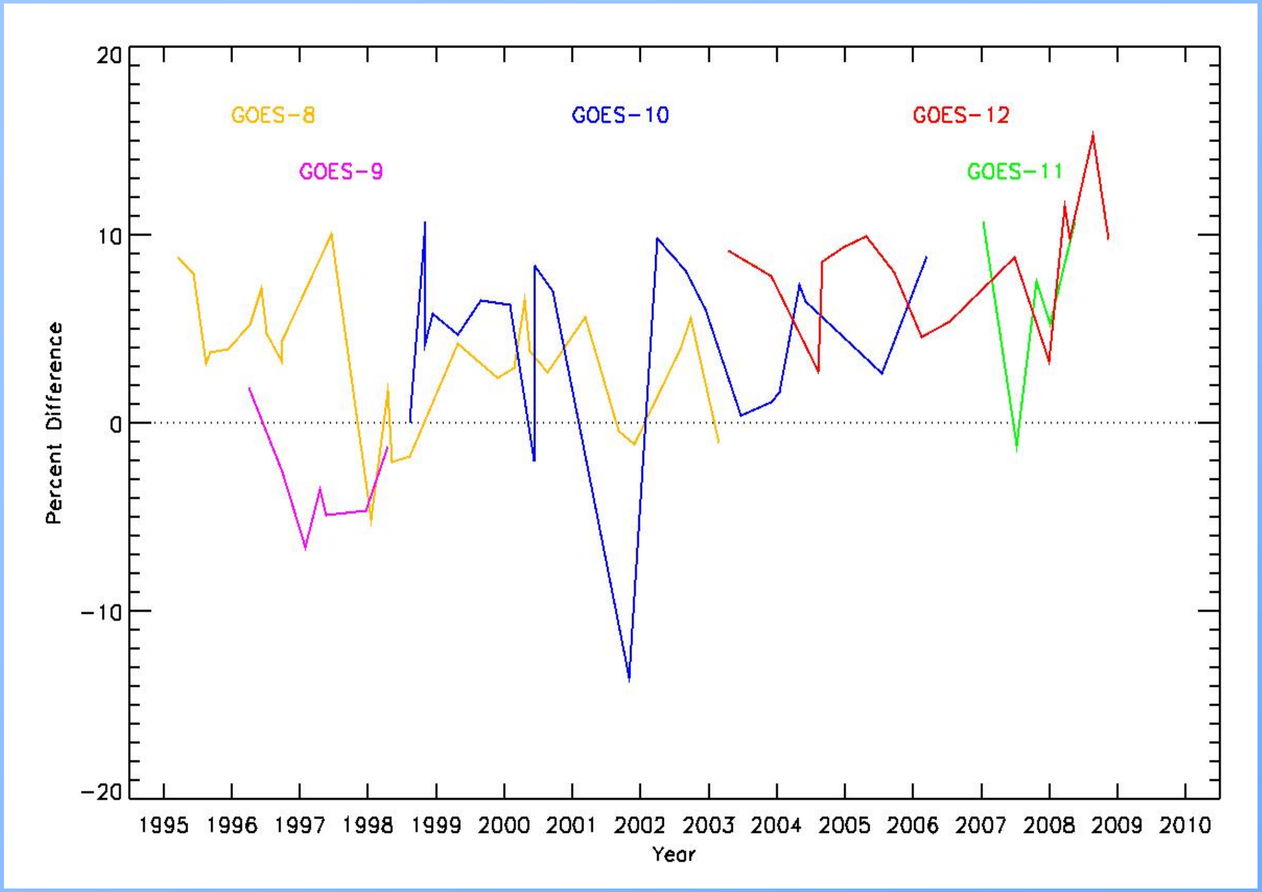


yellow: using ISCCP sensor gain for radiance calibration; space background level measured from off-Moon image areas

red: using NOAA pre-launch (constant) calibration – shows response decrease >20% over 6½ years

GOES−8 through −12 series lunar cross-comparison

- ISCCP sensor gain used for radiance calibration of all Moon images



major error sources:

- actual sensor gain fluctuations
- radiance calibration
- space level measure
- Moon image spatial extent / integration

minor error sources:

- spectral differences between sensors
- lunar model geometry dependencies

~14-year time-series record!

Barriers to more extensive use of the Moon as a reference

- acquiring observations of the Moon
  - presents operational / flight-dynamics difficulties for LEO spacecraft — satellites need to be turned to view the Moon
  - full lunar disk must be captured, may require raster scanning
- access to Lunar Calibration service — currently only USGS has a viable system
  - US export controls can limit access for non-US instruments
- quality indicators — uncertainties in application of the lunar model to Moon observations made by EO instruments
  - spectral interpolation of 32-band model to instrument bands
  - model absolute scale
  - model specification of geometric dependencies

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Implications for Earth Observation Satellites

Flight operations

- scheduling dedicated observations of the Moon at regular intervals
  - recommended once per month (provides consistency in phase angle)
- post-launch check-out
  - recommended many observations, to establish baseline sensor response

Instrument and spacecraft design

- ability to view the Moon
  - preferably through nadir-view optics
    - for LEO spacecraft this usually requires a satellite attitude maneuver
  - space-view port, e.g. MODIS
    - possible scan mirror angle dependency
    - implementing limited spacecraft roll maneuvers adds view opportunities

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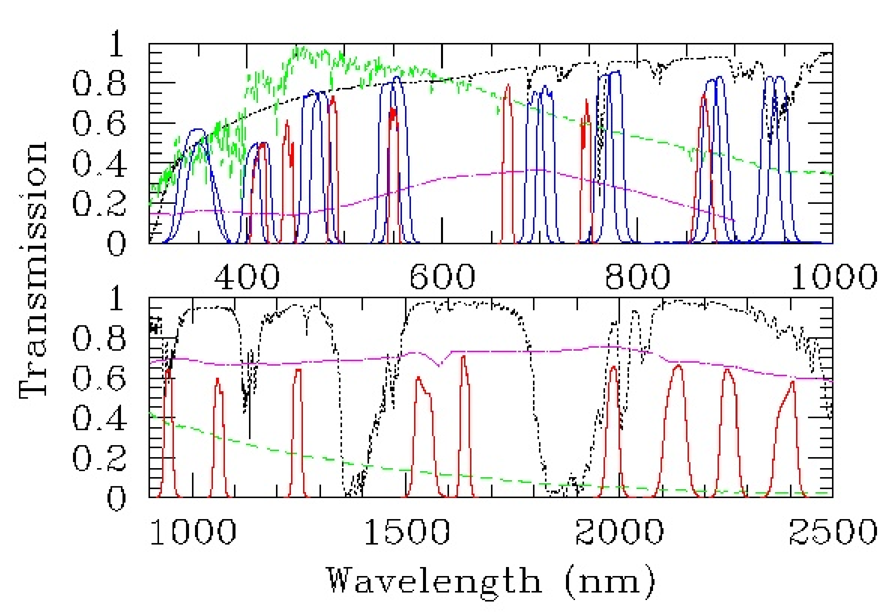
Supplemental Slides

The USGS Lunar Calibration System

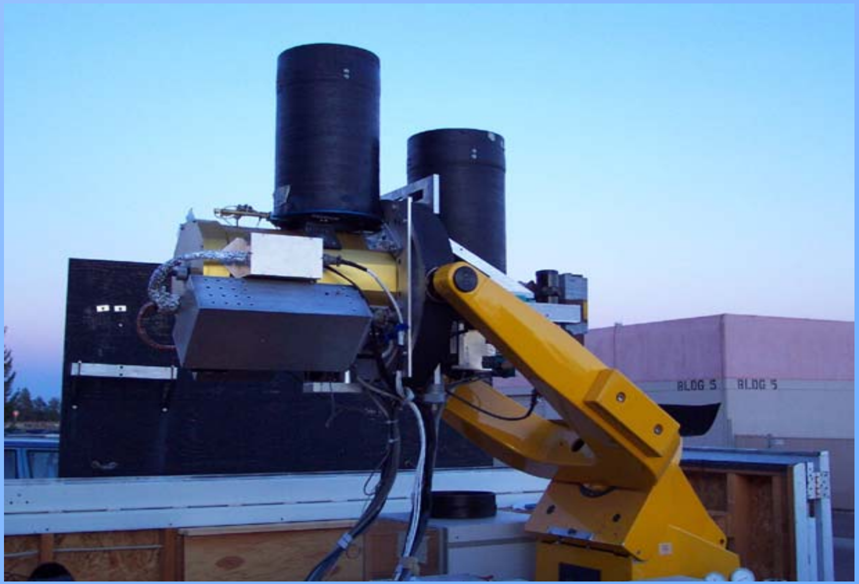
- Involves the quantity of irradiance
  - spatially integrated full lunar disk, regardless of illuminated fraction
- Model for the lunar spectral irradiance, a function of geometric variables:
  - phase angle, Sun lunar longitude, sub-observer lunar lon & lat (libration state)
  - analytic form — continuous geometry query ability
- Development from fitting 6+ year observational dataset acquired by the RObotic Lunar Observatory (ROLO)
  - 32 bands: 23 VNIR, 9 SWIR
  - spatially resolved Moon images calibrated to exoatmospheric radiance, summed to irradiance, converted to reflectance for fitting
  - mean fit residual ~1% — measure of model prediction precision over full range of geometric variables
  - reference: Astronom. J. 129, 2887–2901 (2005)



ROLO observational program

Dedicated observatory, located at USGS in Flagstaff, AZ
Altitude 2143 m

- Dual telescopes
  - –23 VNIR bands, 350-950 nm
  - –9 SWIR bands, 950-2500 nm



- Spatially resolved radiance images
  - 6+ years in operation, >85000 lunar images
  - Coverage in phase from eclipse to 90°, all librations viewable from Flagstaff
  - >800,000 star images, for nightly atmospheric extinction corrections

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USGS lunar irradiance model – development of basis data

Model inputs for fitting are derived from ROLO lunar images, calibrated to exoatmospheric radiance, and spatially integrated to irradiance I. For each band k:

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

$L_{i,k}$ = pixel radiance
Ω_p = pixel solid angle
N_p = # of pixels on Moon

Model operates in disk-equivalent reflectance A_k, converted from irradiance:

$$I_k = A_k \cdot \Omega_M E_k / \pi$$

E_k = Solar spectral irradiance
$\Omega_M = 6.4236 \times 10^{-5}$ sr

Involves a model for solar spectral irradiance; have used Wehrli (1986)

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Lunar disk reflectance model

Empirically-derived model form, a function of the geometric variables of phase and libration. For band *k*:

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

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

Ref.: Astronomical Journal 129, 2887-2901 (2005 June)

- ~ 1200 observations fitted for each band
- Mean absolute fit residual over all bands is 0.0096 in ln *A*, ~1%

This is a measure of the model's capability to predict the lunar irradiance over the full range of phase and libration angles covered

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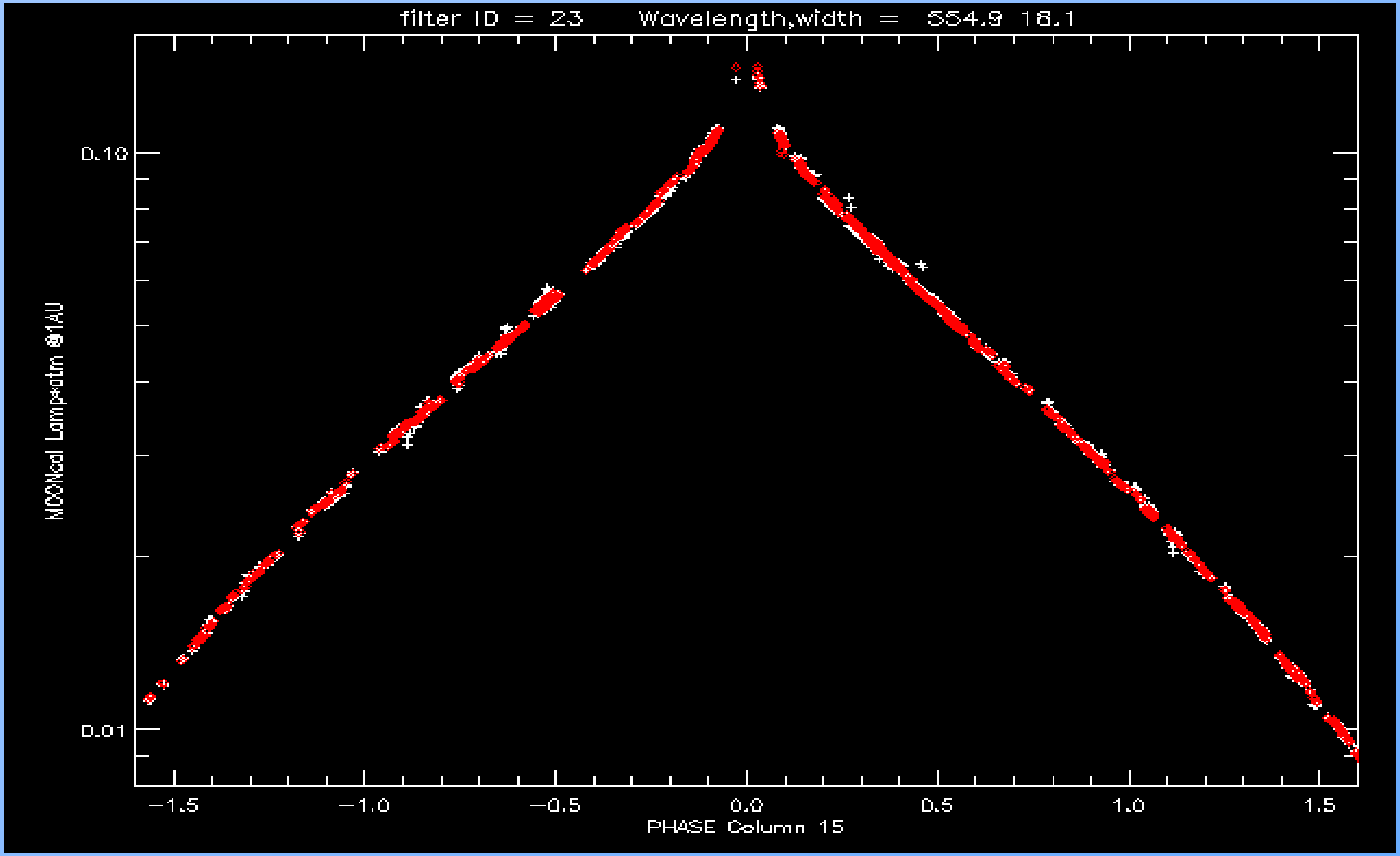
ROLO Lunar Phase Function

- disk-equivalent reflectance (albedo) for ROLO 555 nm band

white = data   red = model



phase angle in radians

scatter shows the effect of libration

Lunar irradiance model geometric precision ≈ 1%

- Precision exceeds uncertainty in absolute scale, currently ~ 5−10%
- Extends over the full range of geometric variables — restriction to narrow range of phase angles is not a requirement for lunar calibration
- Short-term fluctuations in atmospheric extinction may be a limiting factor for model precision

Given a time series of lunar observations acquired by an instrument, temporal response characterization with sub-percent precision is achievable * meets the stability requirement for visible-wavelength radiometer measurements of environment variables for climate change

For different instruments that view the Moon, capability for inter-comparison of similar bands is ~1%

- Regardless of separation in time

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Lunar Model Predictions for Spacecraft Moon Observations

The lunar irradiance model operates in reflectance.

- disk-equivalent reflectance generated for precise geometry of observations
  - double-precision ephemeris to compute Sun and Moon positions, libration state
  - spacecraft position provided by instrument team
- model reflectance at ROLO wavelengths interpolated to instrument spectral bands along reference lunar reflectance spectrum (smooth)
- reflectance converted to irradiance (@ instrument bands), and corrected to actual Sun-Moon and Moon-spacecraft distances
- results provided as comparison of instrument-measured irradiance to model predictions, given as percent discrepancy:

$$P = \left(\frac{\text{INST}}{\text{MODEL}} - 1\right) \times 100\%$$

  - may show bias equivalent to differences in calibration of the lunar model (ROLO data) and the instrument. Such biases will be consistent for all instrument Moon observations, at the level of the relative precision of the model, ~1%

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