Lunar Calibration:
Using the Moon as a Calibration Source for Earth-Observing Instruments in Orbit

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Outline

• The Moon as a radiometric source
  – USGS lunar calibration program
• Current capabilities of lunar calibration
• Ongoing development, needs
• Future improvements: LUSI proposal
The Moon as a radiometric source

- Available – accessible to all spacecraft in Earth orbit
- Surface reflectance is stable to $<10^{-8}$ per year\(^1\)
- Dynamic range similar to that of clear land

Extracts from GOES full-disk image:

\(^1\) Icarus 130, 323-327 (1997)
The Moon as a radiometric source

- Brightness is highly variable with geometry
  - phase, spatial non-uniformity, lunar librations, complex reflectance function

This variability mandates using a photometric model for calibration uses.

- Need to accommodate the geometry of illumination and viewing for a spacecraft lunar observation without restriction
- The stability of the lunar surface reflectance means that a model, once established, can be applied to observations made at any time
- In order to capture the lunar radiometric behavior sufficiently for modeling, a multiple-year database of measurements is required

The NASA-funded lunar calibration program at USGS has focused primarily on modeling the quantity of spatially-integrated lunar irradiance.

- Model basis is a dataset of lunar radiance measurements (images) acquired by the ground-based RObotic Lunar Observatory (ROLO)
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
USGS lunar irradiance model

Model inputs for fitting are developed from images calibrated to exoatmospheric radiance, spatially integrated to irradiance $I$, and converted to reflectance $A_k$:

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

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

Empirical model form, 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
$\theta = $ observer selenographic latitude
$\phi = $ observer selenographic longitude
$\Phi = $ selenographic longitude of the Sun

USGS lunar irradiance model

- 18 coefficients for each ROLO band, 8 are constant across all bands
- ~1200 observations fitted for each band
- Mean absolute fit residual over all 32 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

Comparison of lunar irradiance measurements made by an instrument involves a maximum uncertainty due to the model geometric precision ~1%
  - for any geometry of illumination and viewing (phase and libration)
  - restriction to narrow range of phase angles is not a requirement for lunar calibration
Current capabilities — sensor stability monitoring

Given a time series of lunar views acquired by a spacecraft instrument, relative response trending with sub-percent precision can be achieved.

Example: SeaWiFS

- plot is 85 lunar observations (SeaWiFS now has over 160)
- ordinate is discrepancy: \[ \frac{\text{inst}}{\text{model}} - 1 \times 100\% \]
- the lunar comparisons show sensor response degradations of ~5% in band 7 and ~13% in band 8

SeaWiFS lunar image, ~6×20 pixels
After correction for sensor degradation based on lunar views, residual SeaWiFS band response trends are < 0.1% per year\(^1\)

This meets the stability requirement for visible-wavelength radiometer measurements of environment variables for climate change

- 85 SeaWiFS lunar observations
- asymptotic temporal correction applied for each band
- distribution of the individual band plots is the difference in absolute scale between SeaWiFS and the lunar model

\(^1\)Applied Optics 43 (31), 5838-5854 (2004)
Lunar model development — absolute radiometric scale

• Current absolute scale is based on observations of the star Vega
  – Uncertainty in Vega absolute photon flux (astronomical measurements)

• Uncertainty in the lunar model absolute irradiance is 5–10%
  – Significantly exceeds model relative precision
  – Based on comparison with calibrated sources, e.g. field calibration at ROLO in collaboration with NIST, NASA, Univ. Arizona

On-axis collimated source at ROLO
• calibrated at NIST
Lunar calibration — applications for the climate mission

• On-orbit sensor stability monitoring
  – Current model capability (precision) can achieve climate requirement

• Instrument cross-calibration and continuity of observational datasets
  – Current cross-calibration capability is 1–3%, dependent on wavelength*
  – For non-overlapping datasets, SI-traceable absolute scale is needed
  – **Instruments must view the Moon**

*The lunar irradiance model operates in reflectance, which is smooth.
Lunar calibration — challenges in the IR

Possibility has been studied, significant challenges identified

• Temperature range of the sunlit lunar surface ~320–390K
  – 1–2 orders of magnitude larger than typical Earth upwelling radiance
  – 70–80K variations across the surface, requires precise targeting
  – Small-scale, ~5K surface features, requires detailed modeling

• Thermal behavior over the day–night transition must be understood

• Difficulty in acquiring measurements, sufficient number for modeling

The Infrared Moon
Future improvements — LUnar Spectral Irradiance (LUSI) proposal

• Based with NIST, collaboration with SDL, USGS, Univ. Hawai‘i
• Goal to establish the lunar spectral irradiance to <1% absolute (k=1) with direct tie to NIST radiometric standards
• Hyperspectral coverage, 320–2500 nm, spectral resolution 1–4 nm
• Ground-based component — mountaintop observatory site
  – Focus on atmospheric window spectral regions
  – Continuous on-site instrument calibration and characterization
  – Ideal site: Mauna Kea, 4 km altitude
• Flight component — high-altitude balloon (or SOFIA, or ??)
  – Extend spectral coverage to full range
  – Minimize atmospheric effects
  – Instrument calibration at NIST before and after flight
LUSI instrumentation

Twin telescopes, 25.4 cm (10”) f/4 Cassegrain design

Lunar telescope
• non-imaging system — feeds integrating sphere
• 3 fiber-optic coupled spectrographs
• on-board calibration source

Stellar telescope
• direct feed to fiber-optic coupled spectrographs (2)

Emphasis on stability
• sealed optics with dry N₂ purge
• minimal moving parts
• temperature-controlled environment
LUSI instrumentation — lunar system optical layout

Lunar Spectrographs
- f/3 concave flat-field gratings
- 300 – 900 nm, 1024 Si photodiode array, 1 nm bandpass
- 850 – 1700 nm, 1024 InGaAs photodiode array, 2 nm bandpass
- 1500 – 2400 nm, 1024 InGaAs photodiode array, 4 nm bandpass
LUSI instrumentation — calibration and characterization

• Complete instrument characterization at NIST
  – SIRCUS facility, direct tie to primary standards
  – Transfer scale to lunar instrument using detector-based methods
  – System-level testing to validate uncertainty goals

• On-site performance monitoring
  – Multi-wavelength LEDs and lamp, with reference detectors, fiber coupled to collection sphere
  – Deployable autocollimating source to measure system throughput
  – Periodic site visits with NIST field calibration facilities

Atmospheric correction expected to dominate uncertainty budget
Summary

- On-orbit sensor response trending with the precision needed for climate-quality measurements is achievable now.
- The Moon can provide a common target for cross-calibration of solar-band instruments and consistency of datasets to develop climate records; the instruments must view the Moon.
- Improvement is needed in the absolute accuracy of lunar irradiance and traceability to SI radiometric standards.
- Lunar calibration supports the CLARREO strategy of testing and verification against independent calibration methods.

USGS lunar calibration project website:

[www.moon-cal.org](http://www.moon-cal.org)
Lunar calibration comparison of EOS instruments

- average of all observations for each instrument
- differences between instruments represent current best practices
ROLO database phase/libration coverage
Lunar irradiance phase function – model and data