Update on Lunar Calibration Development and Applications

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Background — Overview of Lunar Calibration

At reflected solar wavelengths, the Moon can be regarded as a solar diffuser, which has exceptionally stable reflectance.

To use the Moon as a calibration reference requires an analytic model

- to predict the lunar brightness for any Moon observations made an instrument (*i.e.* the Sun-Moon-Observer geometry)
- the model comprises the lunar calibration reference

To build a lunar photometric model requires a large set of characterization measurements of the Moon, spanning several years

- to capture the periodic brightness variations sufficiently for modeling
- the range of available Moon views is constrained by orbital mechanics

Development of the lunar calibration system at USGS found the most useful radiometric quantity is the spatially integrated lunar irradiance.

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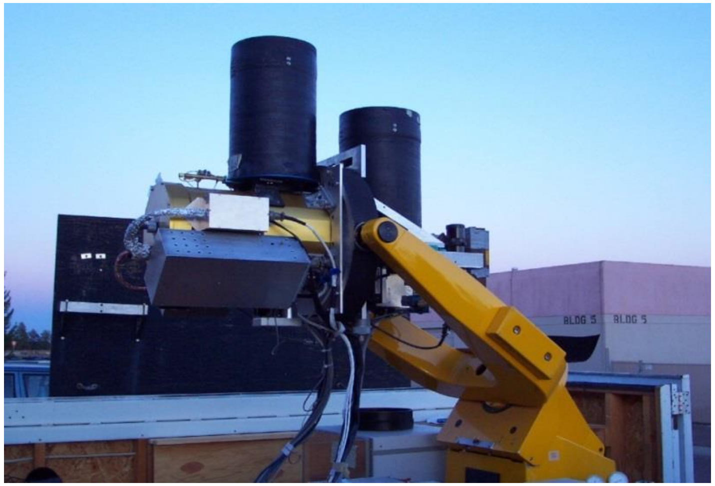
Lunar Model Development at USGS — ROLO

A dedicated ground-based telescope facility — the Robotic Lunar Observatory (ROLO):



- located at Flagstaff, AZ   2143 m altitude
- acquired >110 000 Moon images in 32 multispectral bands
- in operation more than 8 years

Lunar disk reflectance model

- empirically derived formulation
- a function of only the geometric variables of phase and the lunar librations:

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

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

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

Lunar Irradiance Model — Operation

The fundamental model outputs ($\boldsymbol{A_k}$) at 32 ROLO bands are fitted with a lunar reflectance spectrum, which is convolved with the instrument band spectral response functions and the solar spectrum to give the lunar irradiance ($\boldsymbol{E}_\mathrm{M}$):

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

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.

Current Capabilities of Lunar Calibration

Applications

- in-flight calibration stability — evaluating sensor response changes with time
  - SNPP-VIIRS:
    - NASA model for solar diffuser BRDF changes (*TGRS* **55**, 1537 (2017))
    - on-orbit calibration for ocean color (*Appl. Optics* **54**, 1984 (2015))
  - SeaWiFS:
    - achieved 0.13% stability for water-leaving radiances (*Appl. Optics* **51**, 8702 (2012))
- inter-calibration of instruments that have viewed the Moon
  - sensors' lunar irradiance measurements are normalized using the lunar model, enabling cross-comparison
  - the accuracy of lunar inter-calibration depends on the relative accuracy of the model, and on the similarity of the instruments' Moon view geometries and spectral response functions

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Current Capabilities of Lunar Calibration

<u>Access</u>

- GIRO: GSICS Implementation of the ROLO model
  - supported by EUMETSAT: software development and repository
  - software license agreement is prepared and being distributed to the lunar calibration community (participants in the workshop at Darmstadt, + ESA)
  - benchmarking system is under development
    - for tracing the GIRO to ROLO
    - for testing and validating local implementations (or other lunar models)
  - now the available international lunar calibration reference standard
  - online info:

  http://gsics.atmos.umd.edu/bin/view/Development/LunarWorkArea

Note: a second lunar calibration workshop is being planned – Fall 2017, China

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Limitations of the Current System

Although the ROLO/GIRO model is the most precise and reliable lunar radiometric reference available, it typically is not used for absolute calibration. ***Why not?***

- uncertainty in the model absolute scale is ~5-10%
  - originates with the ROLO telescope dataset
  - the main source of error is the atmospheric correction
    - derived nightly from star observations, but airmass range is limited to ≤2
    - applies also to Vega, which is the calibration reference for ROLO

The current absolute accuracy limitation is solely with the lunar model.

- the Moon potentially can provide an absolute calibration reference with total uncertainty under 1% (k=2)

To achieve a high-accuracy, SI-traceable absolute lunar calibration reference requires acquisition of a new measurement database.

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Considerations for a High-Accuracy Lunar Reference

Requirements for new measurements of the Moon to use as a basis dataset for a revised lunar reference model:

1. Primary consideration: absolute accuracy ≤1% with SI traceability
   – the potential achievable accuracy is limited only by capabilities for making calibrated measurements in the field
   – some absolute measurements above the atmosphere are required

2. Radiometric and geometric specification of the lunar irradiance
   – requires a multi-year measurement campaign, to sufficiently sample the parameter space of phase angles and lunar librations
   – the availability of different Moon views is governed by celestial mechanics

3. Spectral specification
   – the lunar reflectance spectrum is dependent on phase and on terrain type
   – requires spectrally resolved measurements
      - SCIAMACHY lunar observation data may be immediately useful

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Considerations for a High-Accuracy Lunar Reference

4. Polarization specification
   - moonlight is polarized up to ~13%, varying widely with phase angle
     - also dependent on wavelength and lunar terrain type (thus librations)
   - accounting for polarization effects is essential for achieving high accuracy
     - an inherent property of the Moon, thus must be part of the reference
     - effects are instrument-dependent — tied to the sensor's sensitivity
   - a polarization model is needed, separate from the radiometric one
     - requires collecting disk polarization measurements (basis dataset)

CGMS Working Paper on requirements for absolute lunar calibration

- prepared on behalf of GSICS, in response to CGMS action A43.01

http://cgms.eumetsat.int/views/agendas.xhtml → CGMS-44 → WG II → WG II/8 → CGMS-44-GSICS-WP-01

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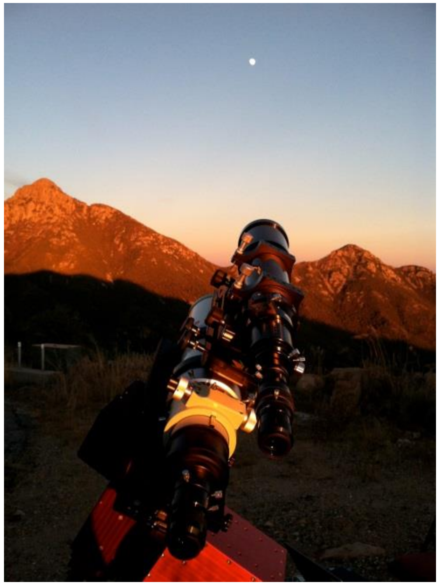
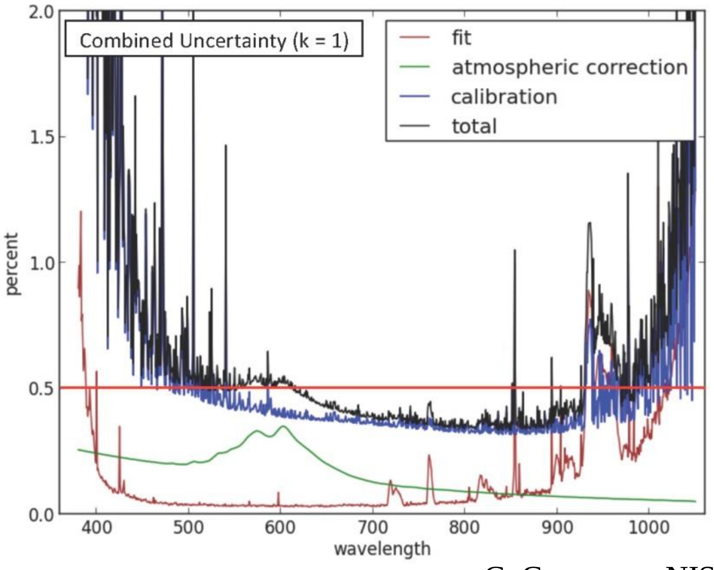
Recent Efforts — New Lunar Measurements

- NIST ground-based Lunar Spectral Irradiance (LUSI) project
  - non-imaging optical system, COTS spectrometer: 390−1040 nm
  - on-site calibration reference: 30 cm integrating sphere "artificial Moon"
  - Mt. Hopkins, AZ: two nights in Nov. 2012 with good viewing conditions
    - atmospheric correction by Langley analysis of the lunar data
    - combined total uncertainty under 1% (k=1) from 400 nm to 1000 nm
  - current status: NIST staff is budgeted for setup at Mauna Loa, Hawaii (3397 m alt); airborne project is funded by NASA (ER-2, 20 km alt)





C. Cramer — NIST

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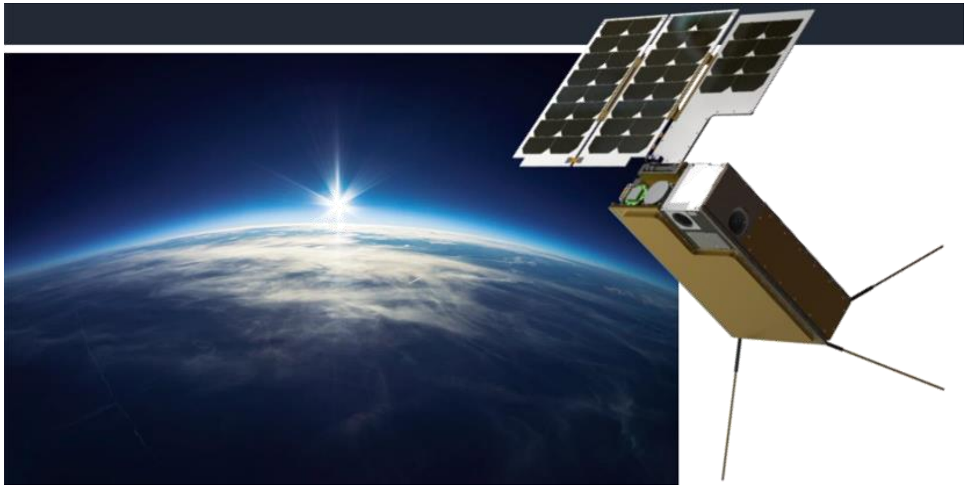
Recent Efforts — New Lunar Measurements

- China Meteorological Administration (CMA) ground-based campaign
  - multiple lunar imaging and spectral instruments, 350−2500 nm
  - ancillary atmospheric measurements: lidar, aerosol photometer, sounder
  - 3 months of dedicated acquisitions from Lijiang, Yunnan (3193 m alt)
    - December 2015 to March 2016
  - initial analysis shows some instrument issues still to be worked out
  - current status: instrument improvements and additional observations are planned, unspecified timeframe

China Meteorological Administration

Recent Efforts — New Lunar Measurements

- ARCSTONE: lunar reflectance measurements from a 6U cubesat
  - project led by NASA Langley Research Center
  - 2 non-imaging spectrometers: VNIR 350−950 nm, SWIR 900−2300 nm
  - lunar disk reflectance measurements by alternating observations of the Sun and the Moon
    - using the same optics for both measurements, accommodating the ~10^5 intensity difference with spatial dispersion and integration times
  - current status : breadboard spectrometers built, tested at NIST; funding approved by NASA Earth Science Technology Office – March 2017



Blue Canyon Technologies

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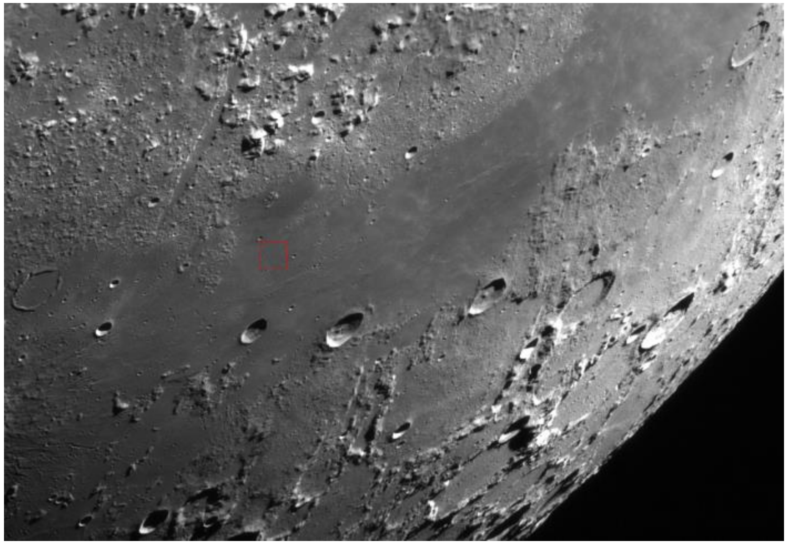
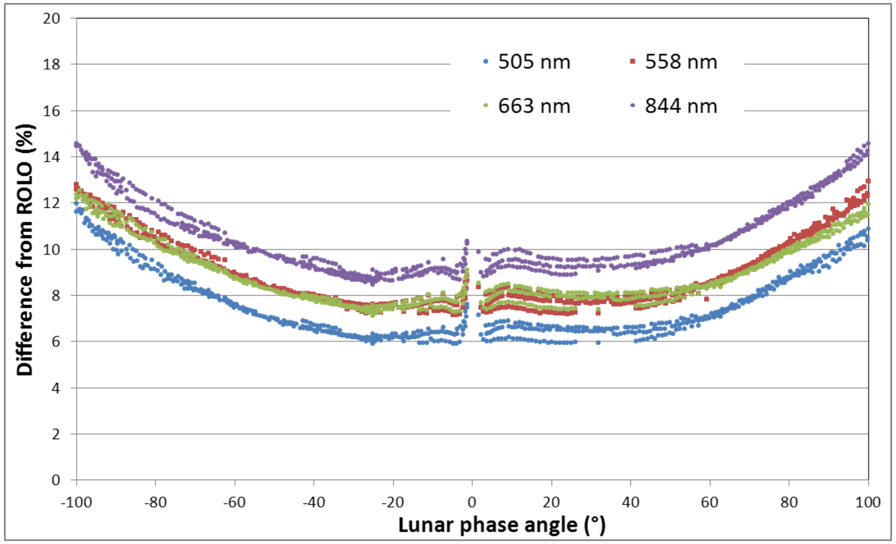
Recent Efforts — Measurements from Spacecraft

- GSICS Lunar Observation Database (GLOD)
  - established as part of the GIRO, with users' agreement to contribute data
  - potential to set the lunar irradiance scale with well-calibrated instruments in orbit, *e.g.* Aqua-MODIS, NPP-VIIRS, Landsat-8 OLI, PLEIADES
  - instruments' lunar measurements must first be validated
  - example: PLEIADES (CNES)
    - several intensive data collects, some with Moon views every orbit





S. Lachérade — CNES

Recent Efforts — Nighttime Aerosol Photometry

- aerosol Sunphotometers adapted to measure moonlight
  - various instruments deployed around the world, several active research groups: AEMET (Spain), AERONET (USA), DWD (Germany), ISAC (Italy), NILU (Norway), PMOD (Switzerland), and recently ESA
  - with reliable calibration of the photometers, this represents a potential extensive set of lunar irradiance measurements
    - ground-based measurement, thus requires atmospheric correction

Cimel Sun/Moon photometer at ROLO site in Flagstaff (AERONET)

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Recent Efforts — Nighttime Aerosol Photometry

atmospheric transmission (optical depth) follows extinction law :

$$V_\lambda = \kappa\, I_{0,\lambda}\, \exp[-\tau_\lambda\, m_a(\theta)]$$

V = photometer output (voltage)
I_0 = exoatmospheric lunar irradiance
κ = calibration coefficient
τ = optical depth (extinction coeff)
m_a = airmass
θ = Moon zenith angle

- linear form for Langley analysis, to get cal coefficient κ and optical depth τ

$$\ln\left(\frac{V}{I_0}\right) = \ln\,\kappa\, -\, \tau\, m_a(\theta)$$

  – requires the exoatmospheric lunar irradiance, *i.e.* the ROLO reference
    - varies with time – phase angle and distance change with Earth rotation
  – errors in V and I_0 are indistinguishable in the ratio
    - nighttime aerosol analysis reveals uncertainties in both quantities

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Capabilities Enabled by a High-Accuracy Lunar Reference

- calibration to the same reference standard for all sensors that have viewed the Moon
  - removes cross-sensor biases; facilitates inter-operability of datasets
- back-calibration of data archives that contain lunar images
  - Moon observations acquired in the past are valid forever. An updated lunar model can be applied to irradiance measurements for any time.
  - example: geostationary meteorological imagers
    - the Moon is captured in the off-Earth regions of a rectangular FOR
    - potential consistent EO records extending back decades in time
- ability to bridge a gap in continuous Earth observation records
  - with views of the invariant Moon by instruments operating before and after the gap, the sensors can be inter-calibrated
  - the accuracy of the bridge calibration depends on the accuracy of the lunar reference
- transfer of pre-launch calibration to on-orbit operations

Way Forward

The goal is a reformulated lunar reference (model) with high accuracy and SI traceability (≤1.0% (k=2) is feasible).

- near term — reprocessing the ROLO dataset
  - to address observed residual geometry dependencies in the lunar model
  - work in progress; subject to funding and staffing constraints
- assimilating existing and current/ongoing Moon observations
  - requires validating the instruments' lunar irradiance measurements
  - utilize the GLOD holdings, operational views of the Moon
- collecting a new lunar measurement database
  - requirements outlined in CGMS Working Paper: CGMS-44 GSICS-WP-02
    - includes an above-atmosphere component
  - to achieve the full potential for accuracy, must consider polarization aspects
- increasing the cognizance of stakeholders to the value of a high-accuracy reference for reflective solar bands
  - *e.g.* motivate a change in traditional thinking for algorithm development

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Thank You!