Update on VIIRS Lunar Calibration Using ROLO

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

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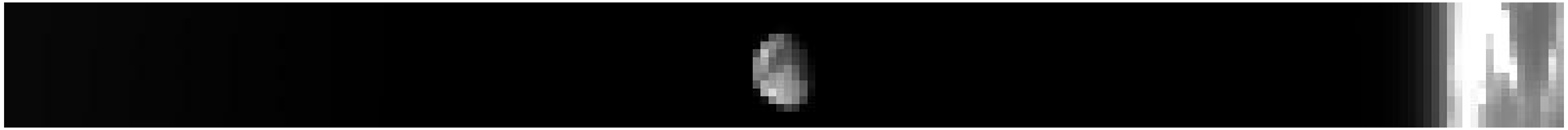
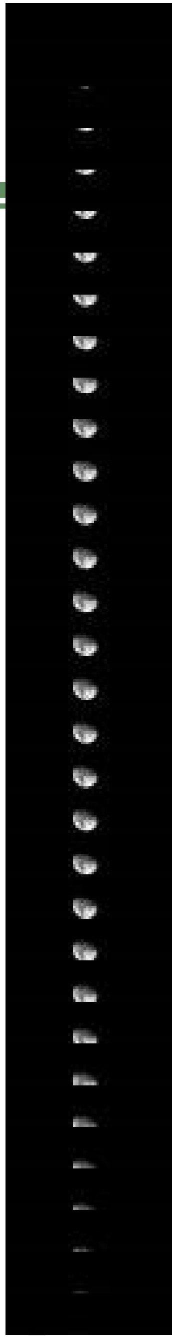
VIIRS Observations of the Moon

SNPP and NOAA-20 execute roll maneuvers each month to capture the Moon in the Earth-view sector at phase angle ~51° before Full Moon

- when the Moon is observable, typically October through June
- as the spacecraft traverses its orbit, the Moon passes through the field of view
- roll angle specified to center the Moon disk in Earth view:



SNPP VIIRS image d20170604_t1934579, band M7, scan 12



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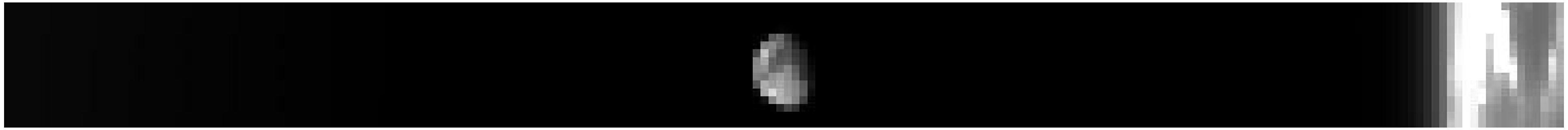

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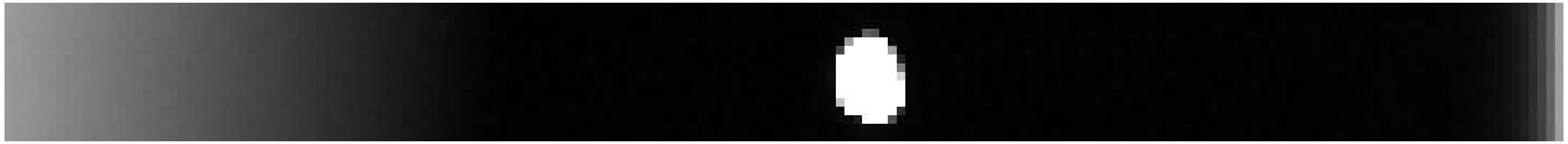
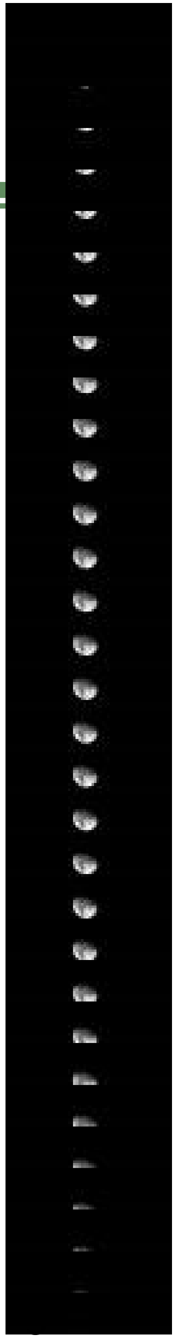
- centering avoids stray light, seen by stretching the display level:





Lunar Calibration

USGS lunar calibration works with lunar irradiances, comparing sensor measurements to corresponding reference values from the ROLO model.

- Irradiance measurements from Moon images involves spatial integration of pixels on the lunar disk:

$$E_{\mathrm{meas}} = \frac{\Omega_{\mathrm{p}}}{\eta} \sum_{i}^{N} L_i$$

Ω_{p} = pixel IFOV (solid angle)
η = oversampling factor
L_i = pixel radiance
N = # of pixels on Moon

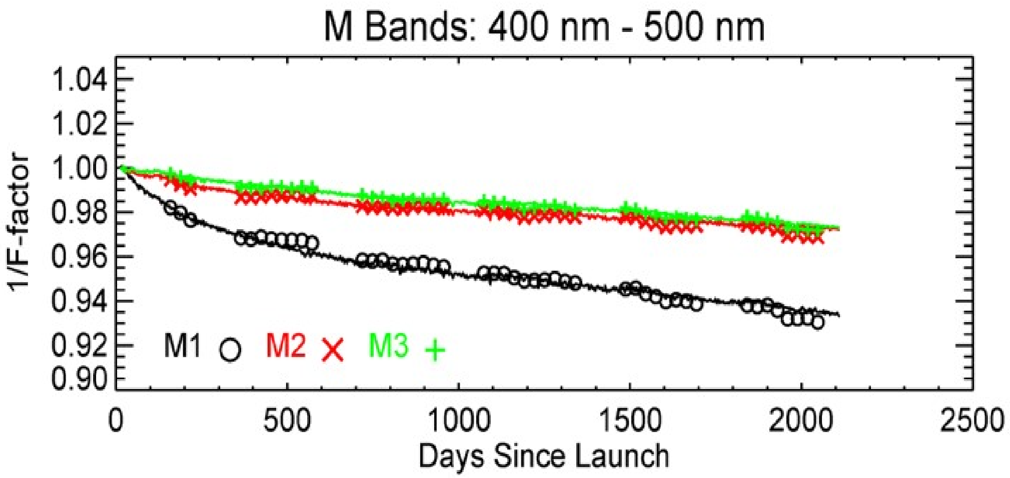
- Reference irradiances are generated for the photometric geometry of each Moon observation:

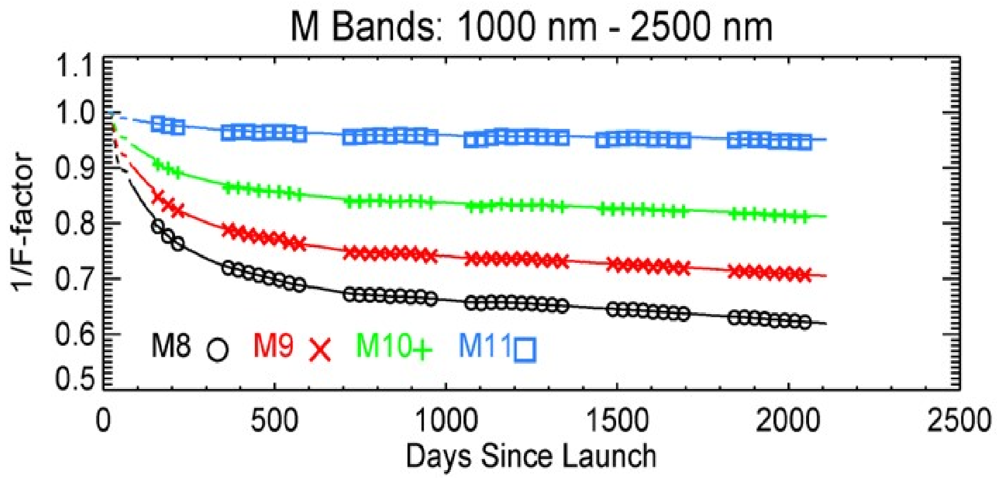
$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\phi + c_2\theta + c_3\Phi\phi + c_4\Phi\theta$$
$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

Lunar Calibration — Application

Typical usage: tracking sensor response changes on orbit

- the Moon is an exceptionally stable solar diffuser
- time series of measurement/ROLO ratios reveal sensor response trends
- found to be particularly useful for on-orbit calibration for ocean color





X. Xiong — NASA GSFC

USGS Results for VIIRS Lunar Calibration

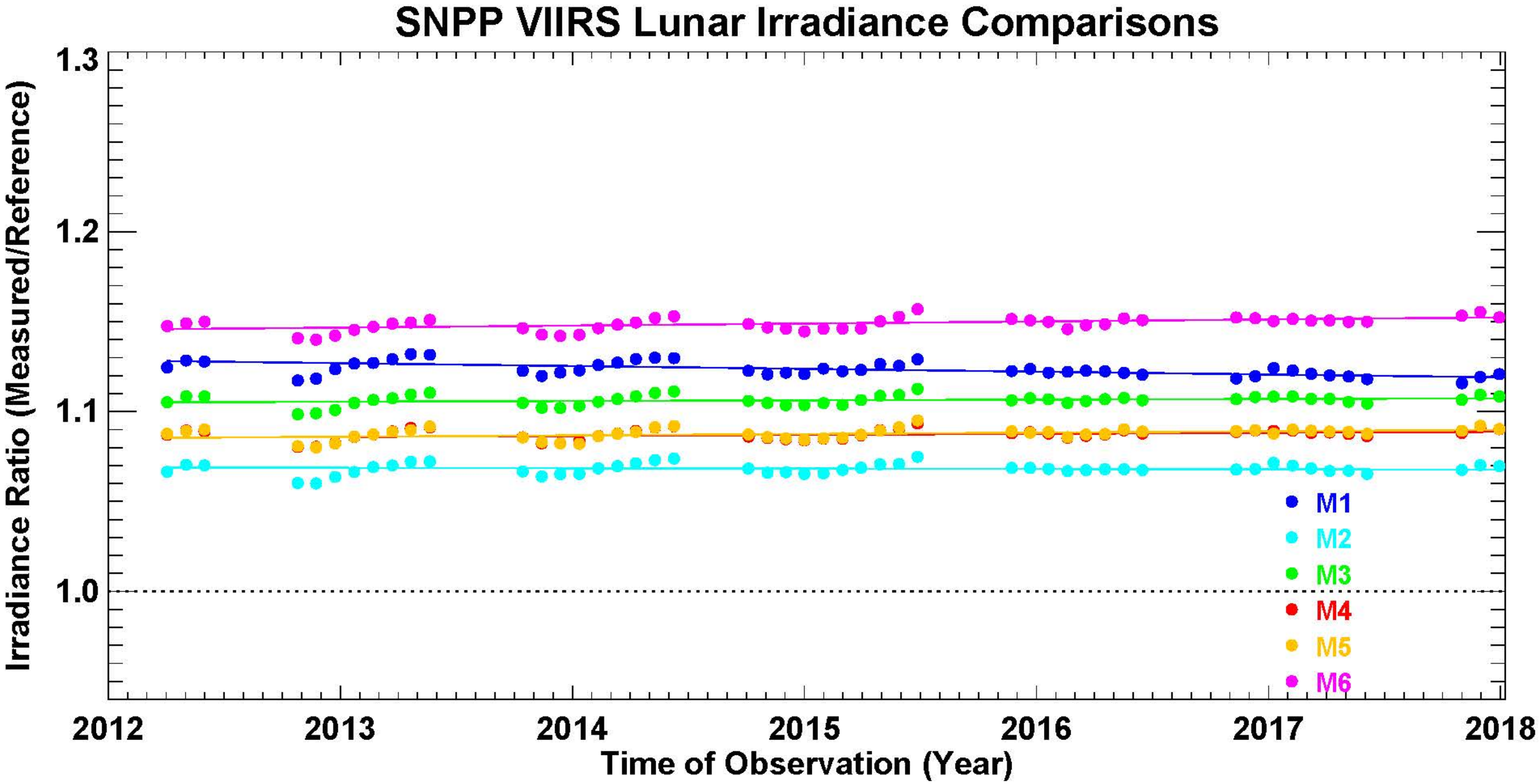
Lunar irradiance ratios (measured/ROLO) — **not normalized**

- VIIRS Moon image processing by USGS: RDRs from NOAA CLASS; ADL
- temporal trends removed using SD f-factors (thanks to VCST)

Notable plot features:

- discrepancies (offsets) 7-16% for M1 to M6
- band-correlated oscillation pattern

Uncertainty in the ROLO model is typically quoted as 5-10%



USGS

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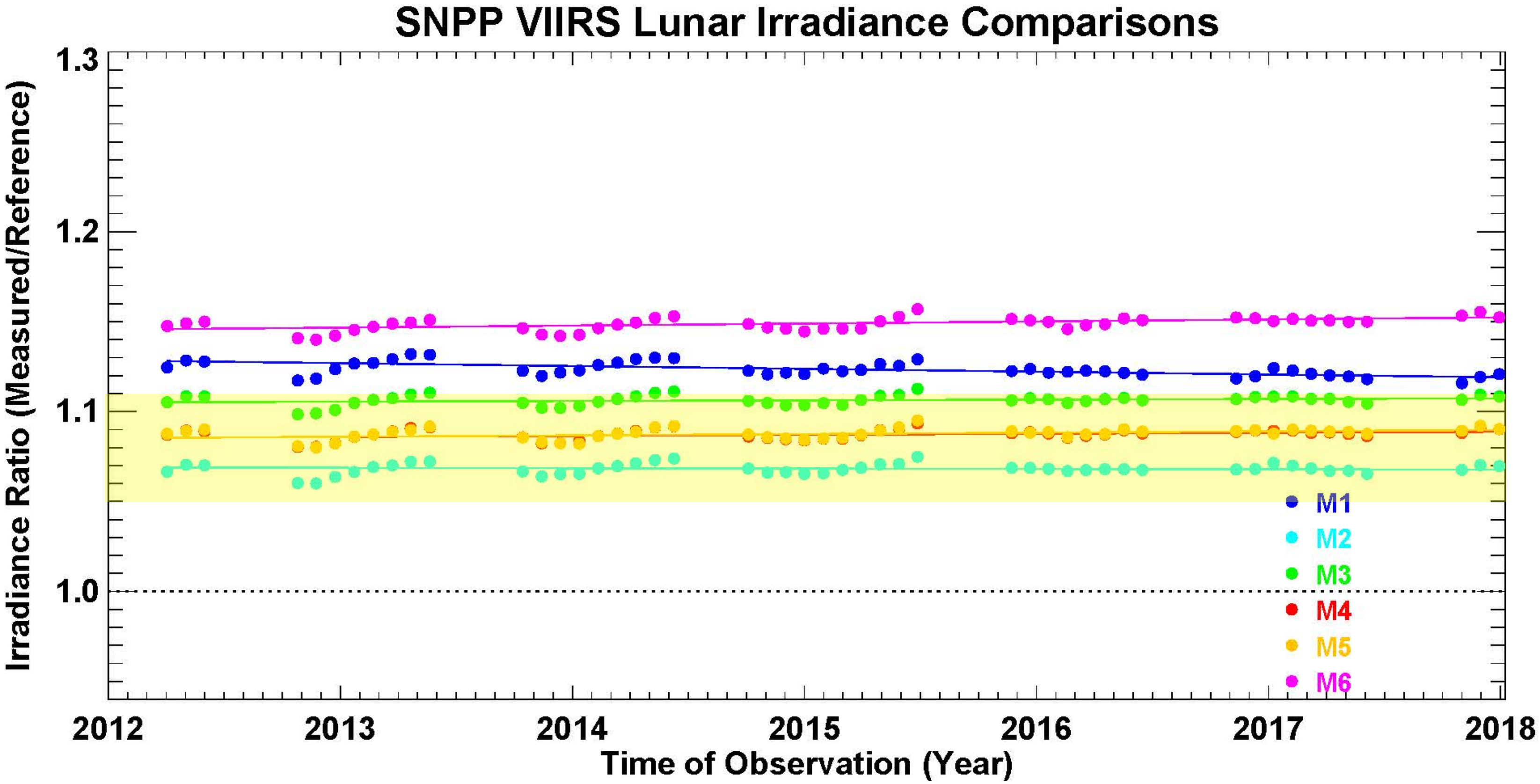
- highlighting shows the effect of 5-10% offset in ROLO values
- bands M1 and M6 fall outside this range



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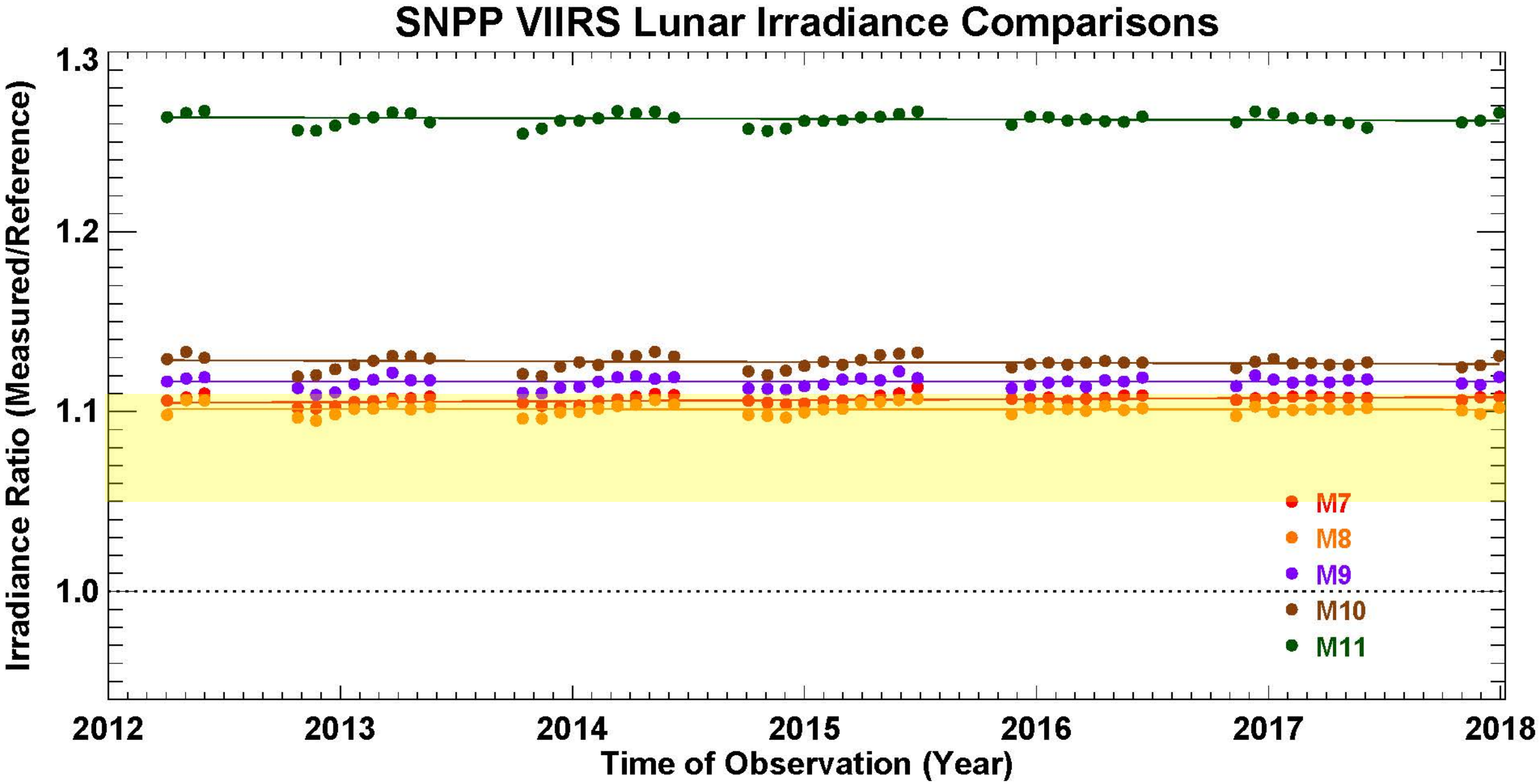
- bands M9, M10, M11 fall outside this range



Impact of the Measurement-to-ROLO Discrepancies

The cause(s) of these discrepancies need to be understood to realize the important potential benefits of lunar calibration:

- Absolute calibration against a potentially SI-traceable reference
  - reduced time to converge and stabilize on-orbit calibration
- Inter-consistent calibration to the same reference standard
  - supports inter-operability of sensors, for aggregation into climate records
  - supports a constellation approach for future Earth remote sensing programs
- Ability to bridge a gap in an otherwise continuous measurement series
  - the accuracy of the bridge calibration depends on the accuracy of the lunar reference
- Transfer of pre-launch calibration to on-orbit operations

Addressing this discrepancy issue requires a 2-pronged approach:

1. An improved lunar irradiance model – the calibration reference
2. Revised techniques for extracting irradiance measurements from sensor Moon images

Lunar Irradiance Measurements from Images

Irradiance is measured by summing radiance pixels: $$E_{\text{meas}} = \frac{\Omega_{\text{p}}}{\eta} \sum_{i}^{N} L_i$$

Each factor has an associated uncertainty $\longrightarrow$

All contribute to the total uncertainty in irradiance measurements

Ω_{p} = pixel IFOV (solid angle)
η = oversampling factor
L_i = pixel radiance
N = # of pixels on Moon

- pixel radiance L_i $\longleftarrow$ *this is the only term where sensor calibration is accounted*
  - net radiance, above background level
  - inadequate background evaluation leads to phase angle dependence in measurements
- pixel IFOV Ω_{p}
  - effective detector spatial response (different from GSD)
- oversampling factor η
  - oversampling of the Moon disk (different from slew/sampling ratio)

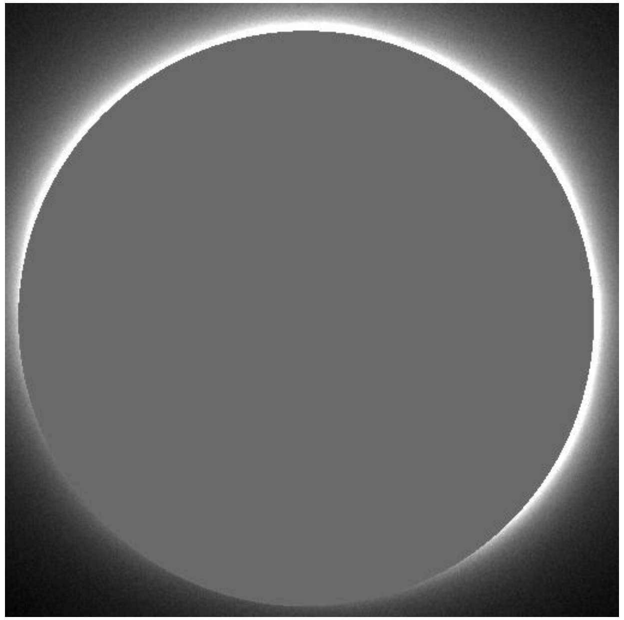
Improving the Lunar Reference: ROLO

The ROLO observational dataset is still an indispensable characterization of the Moon's brightness variations with phase angle and librations (i.e. time and observer location), but its absolute accuracy can be improved.

Current USGS efforts to refine irradiance measurements from ROLO images

- ground-based measurements require correction for observing through the atmosphere
- e.g. Moon image edge spread patterns are azimuthally asymmetric:

ROLO Moon image
acquired 06 May 2001
phase = 17.1°



Same image stretched
and with Moon disk
blanked

Improving the Lunar Reference: Modeling Efforts

Several projects worldwide to develop lunar irradiance models, including:

- Lunar Irradiance Model ESA (LIME)
  - calibrated aerosol photometer at Pico Teide, Izaña, Tenerife
- Spacecraft and Earth-based Aggregate Lunar Irradiance Model (SLIM)
  - effort by Hugh Kieffer, using ROLO and multiple spacecraft measurement sets
- Lunar Extended Satellite Simulation Solar Reflectance (LESSSR)
  - development done under contract to EUMETSAT
  - based on spectrally resolved Moon observations taken by SCIAMACHY

Presentations on the above given at the GSICS virtual Lunar Calibration Workshop, 16-19 November 2020

http://gsics.atmos.umd.edu/bin/view/Development/LunarCalibrationWS2020

This community of modelers have agreed on the need for a "ground truth" lunar irradiance scale, requiring new high-accuracy measurements

Improving the Lunar Reference: New Measurements

airborne Lunar Spectral Irradiance (air-LUSI)

Lunar irradiance measurements taken from the NASA ER-2 aircraft

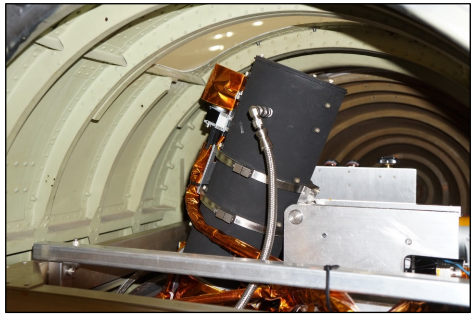
- flight altitude: 70,000 feet (21.6 km), above >90% of the atmosphere

A collaborative project with NASA, NIST, USGS, Univ. of Guelph (Canada)

- details to be presented in the next talk, by Kevin Turpie (air-LUSI PI)

Status:

- Successful 5-night campaign: 13-17 November 2019
- operational — ready for future flights



photos: K. Turpie

Improving the Lunar Reference: New Measurements

Lunar Spectral Irradiance at Mauna Loa Observatory (MLO-LUSI)

NIST-led effort to acquire ground-based measurements at a premier atmospheric research facility

- 3397 m altitude
- on-site atmospheric monitoring station (NOAA)

Anticipated 3 to 5-year continuous observing campaign

- dense coverage of phase angles and librations
- remote/autonomous operation
- spectral resolution: 3.7 nm, 0.8 nm sampling, 300-1100 nm range
  - expected to add SWIR spectrograph and polarization
- in-situ calibration with integrating sphere “artificial Moon”

Status:

- installation work paused due to covid travel restrictions
- expected 6-month effort to operational, starting mid-late 2021

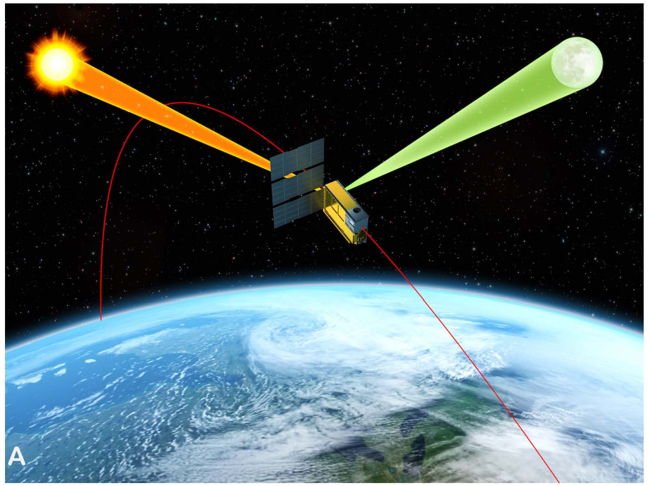
USGS

Improving the Lunar Reference: New Measurements

ARCSTONE

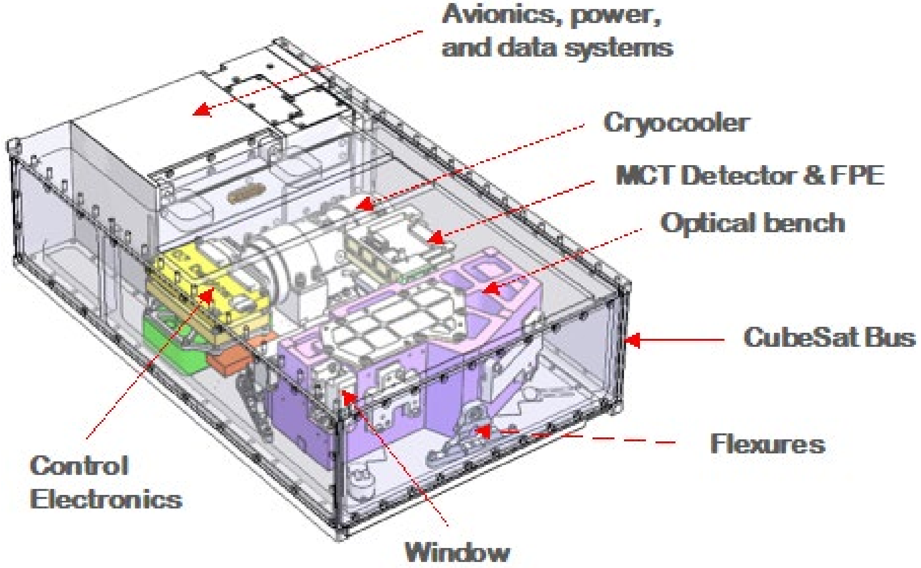
NASA Langley-led effort to measure lunar spectral reflectance from a 6U CubeSat in LEO

- full-disk Moon and Sun acquisitions with no change of optics
  - single-pixel FOV ~0.7°, no scanning
  - >7 orders of magnitude intensity difference accommodated by spatial and temporal integrations
- absolute scale and SI traceability tied to TSIS-SIM



Form-fit grating spectrograph with cooled HgCdTe array detector

- spectral range: 350-2300 nm, 4 nm sampling
- target absolute accuracy for reflectance: <0.5% (k=1) uncertainty



Status:

- development on track for TRL 5 by June 2021
- potential in-flight validation measurements in 2024 timeframe

Summary and Conclusions

- Comparisons of VIIRS lunar irradiance measurements to ROLO reference values show discrepancies larger than the absolute uncertainties in ROLO
  - these discrepancies need to be addressed to derive full benefits of lunar calibration
- New high-accuracy lunar irradiance measurements will allow to constrain the absolute scale of the ROLO model
  - near-term: air-LUSI, MLO-LUSI; future: ARCSTONE
  - other, non-U.S. projects are acquiring measurements to redevelop the lunar reference
- Future work:
  - examine spatial aspects of VIIRS Moon imaging pertinent to deriving lunar irradiance measurements:
    - the presumed 1.0 oversampling factor
    - motion of the Moon relative to the line of sight during scans
    - potential effects of pixel aggregation