GSICS Lunar Model Comparison Exercise

Tom Stone – USGS

Sébastien Wagner – EUMETSAT

with contributions from

Marc Bouvet – ESA

Hugh Kieffer – Celestial Reasonings

Toru Kouyama – AIST

Steve Miller – CIRA, Colorado State University

Introduction

A GSICS activity

Lunar calibration uses models to generate reference values for comparing to measurements made by sensors.

Several new lunar models have been developed recently, some with the intent to provide the lunar calibration reference for various agencies.

The accuracy of the models needs to be tested, but no standard "ground truth" currently exists that can be used to evaluate them.

Objective of the exercise: to examine the performance of different lunar models relative to each other

Methodology: compare model results generated for a common set of inputs

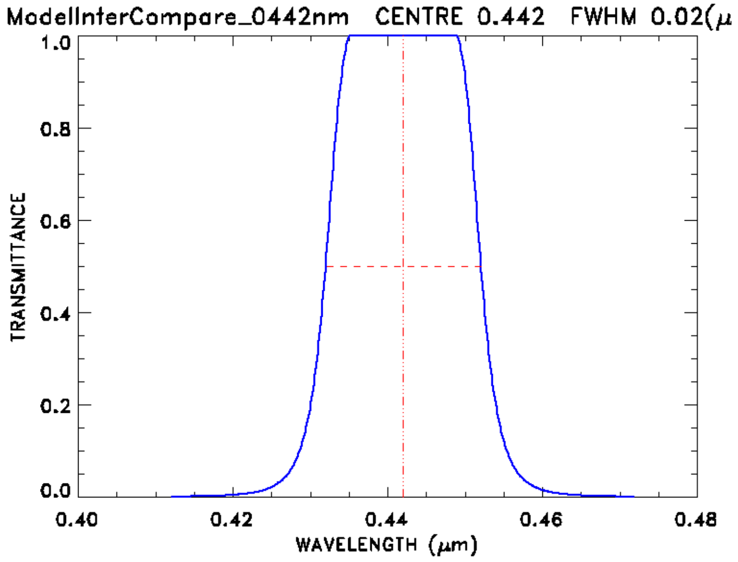
The common model inputs

The participating modelers agreed a set of test input parameters, to cover practical ranges of observation geometry (phase angles and librations) and spectral bands.

- <u>phase angle grid</u>: 3°–10° at 1° spacing, 10°–20° at 2° spacing, 20°–50° at 5° spacing, 50°–90° at 10° spacing, both before and after Full Moon
- <u>libration grid</u>: 0°, 4°, 8°, 12° in sub-observer longitude, 0°, 4°, 8° in latitude

All combinations gives 1610 total geometry points.

- <u>spectral bands</u>: 8 typical remote sensing channels 442, 550, 670, 765, 870, 1380, 1640, 2350 nm
- <u>spectral response functions</u>: 20 nm FWHM, flat-topped Gaussian



The models

Presented in roughly chronological order

Description slides contributed by the model PoCs as listed:

- ROLO (2003), Tom Stone
- CLIMES (Miller-Turner, 2009), Steve Miller
- Spectral Profiler (SP, 2016), Toru Kouyama
- GIRO (2018), Seb Wagner
- SLIM (2019), Hugh Kieffer
- LIME (2019), Marc Bouvet
- LESSSR (2020), Seb Wagner

ROLO model — the original lunar calibration reference

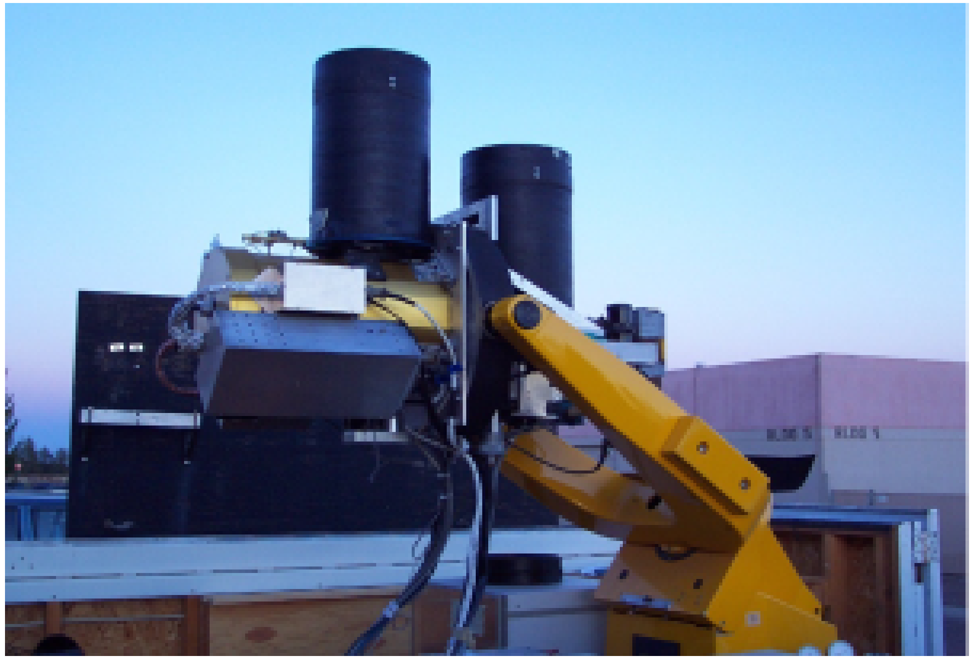
- Developed from ground-based Moon images acquired by the Robotic Lunar Observatory (ROLO)
  - telescopes operated from 1995 to 2003
  - collected >110,000 Moon images, >10^6 star images for atmosphere correction
  - 32 bands, 350–2450 nm, including common Earth remote sensing bands
  - spatially resolved radiance →

- Moon disk summed to obtain irradiance:

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

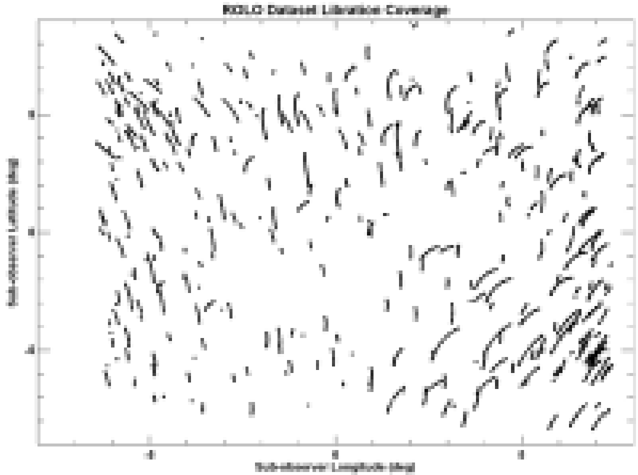
L_i = pixel radiance
Ω_{p} = pixel solid angle
N_{p} = # of pixels on Moon

  - atmospheric correction by multi-star Langley analysis
  - radiometric calibration to Vega
- Irradiance converted to disk reflectance for modeling



ROLO telescopes zenith-pointed at dusk

ROLO dataset lunar libration coverage



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ROLO model formulation

- Model for disk reflectance A_k →
  - fitted to ROLO measurements for 32 bands k independently
  - ~1200 data points for each band
  - mean absolute residual ~1% in $\ln A$

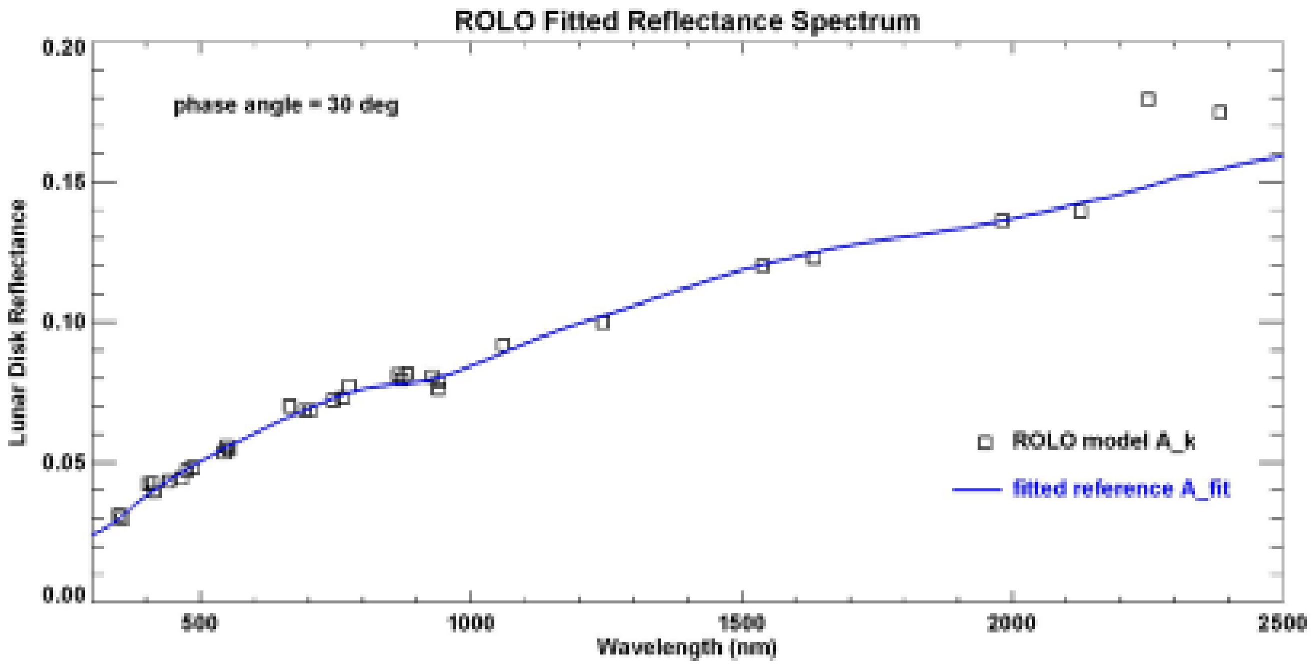
$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\phi + c_2\theta + c_3\Phi\phi + c_4\Phi\theta$$
$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

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

- Post-processing
  - reference lunar reflectance spectrum fitted to model-generated A_k values →
  - provides continuous spectral coverage for convolving with sensor bands:

$$E_M = \frac{\Omega_M}{\pi} \frac{\int A_{fit}(\lambda)\, E_{Sun}(\lambda)\, S(\lambda)\, d\lambda}{\int S(\lambda)\, d\lambda}$$

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



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CIRA Lunar Irradiance Model for Earth Science (CLIMES)

Steven Miller, Bob Turner, and Cindy Combs

Cooperative Institute for Research in the Atmosphere, Colorado State University, Ft. Collins

Inputs:

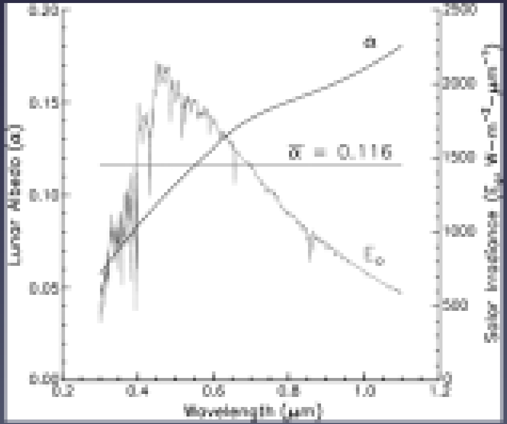
- Full model: date, time, and observer earth-relative location (lat/lon/altitude)
- Standard geometry geocentric model: date and time

Outputs:

- Downwelling top-of atmosphere lunar irradiance spectra, mW/m^2/micron
- Valid range: 0.2-2.8 μm at 1 nm resolution
- Results longward of 1.2 μm based on extrapolation, not observations

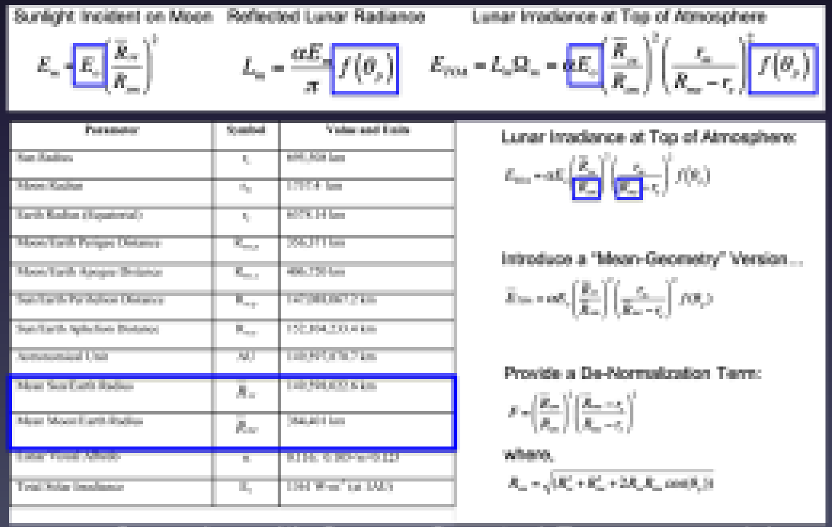
Model Basis:

- Lunar spectral albedo (α_λ) and phase function (f(θp) from composite Lane and Irvine (1973), Lawrence et al (2003).
- Adjustments to phase function to account for disk heterogeneity and opposition surge based on MSG satellite lunar views.



The Standard Geometry Model:

Miller & Turner, IEEE TGRS 47(7), 2009

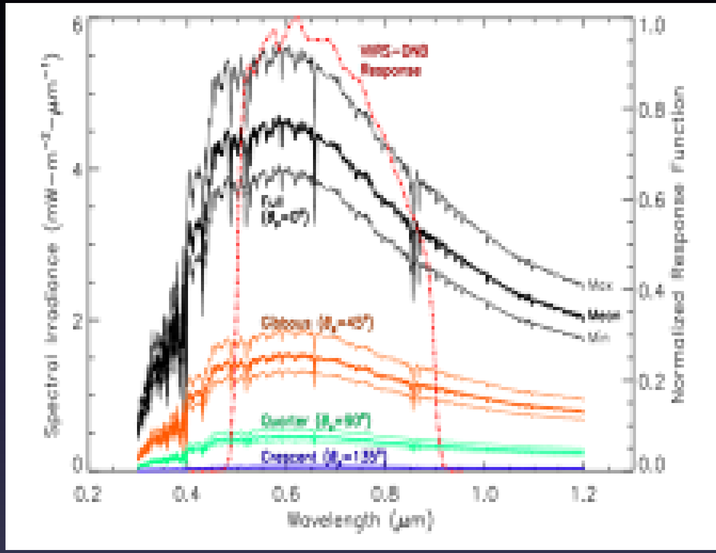


Convolve with Sensor Spectral Response, $\varphi(\lambda)$

$$E(\theta_p)_{DNB} = \int_\lambda E_{TOA}(\lambda,\theta_p)\varphi(\lambda)d\lambda \Big/ \int_\lambda \varphi(\lambda)d\lambda$$

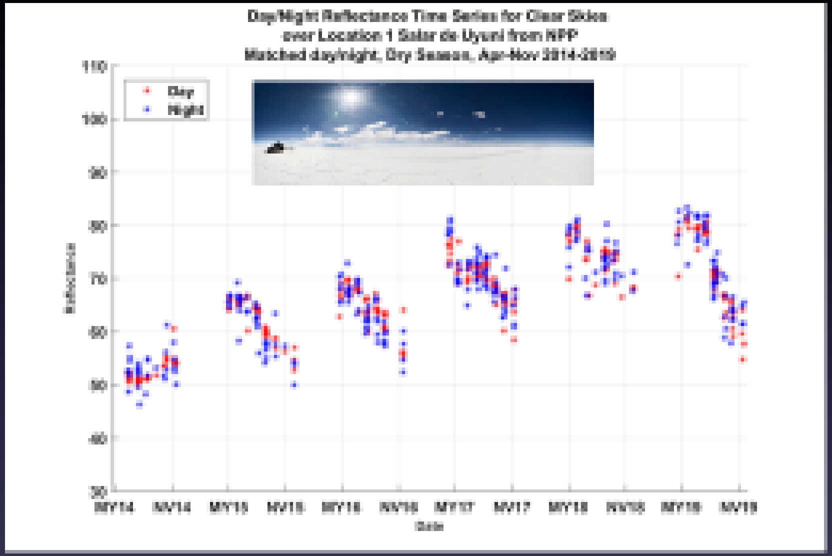
Enabling New Earth Science Applications

CLIMES Lunar Irradiance Spectra



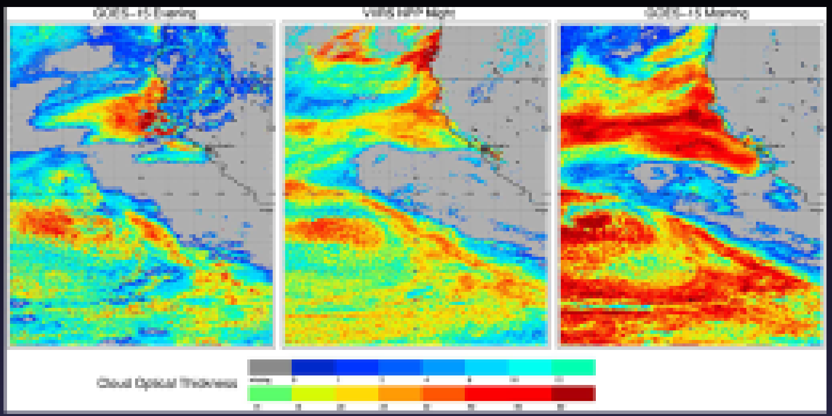
1 nm spectra of modeled moonlight for various lunar phases.

Applied to Day/Night Band Sensor, and Validated at Salar de Uyuni, Bolivia



First Visible-Based Retrievals of Cloud Optical Depth at Night

AFTERNOON NIGHT MORNING

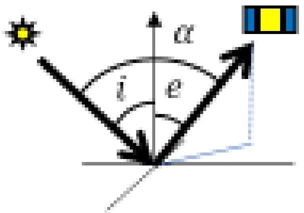


Day/Night Band fills nighttime gap in cloud optical depth of Marine Stratocumulus in the East Pacific

Walther et al., JGR 118, 2013

A version of CLIMES has been incorporated to the NOAA Enterprise operational cloud processing system and as pre-processing to NASA's Black Marble program

SP model: "Disk-resolved" hyperspectral lunar brightness model based on SELENE/Spectral Profiler (SP) reflectance map



Model Formulation

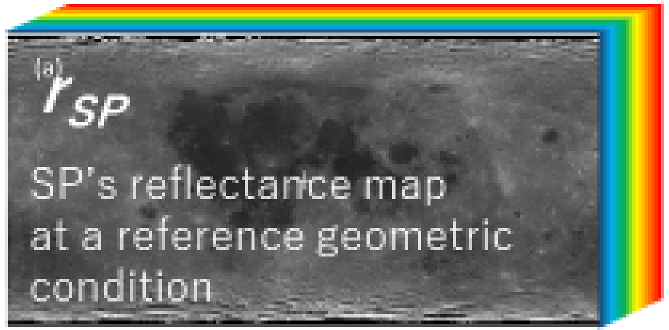
Converting reflectance to radiance for every map grid

Eq.1

$$R_{SP}(\lambda, lon, lat) = \underbrace{r_{SP}(\lambda, lon, lat, 30°, 0°, 30°)}_{\text{SP's lunar reflectance at a reference geometric condition}}\underbrace{A(\lambda, i, e, \alpha)}_{\text{Approximation of BRDF effect}}\frac{I_{Sun}(\lambda)}{\pi}\left(\frac{1AU}{D_{Sun-Moon}}\right)^2$$

Model Operation

SP's reflectance map (hyperspectral cube)



Observation geometry

Eq.1

Simulated radiance map (hyperspectral cube)

Camera projection

Band integration

Outputs

1. **Simulated Moon radiance image**

Disk integration (if needed)

2. **Simulated Moon irradiance**

Obs. image

Compare

Inputs

1. **SP's reflectance map**
2. **Observation geometry:**
   - Sun, Moon, and Satellite positions
3. **Camera specification:**
   - Resolution, SRF

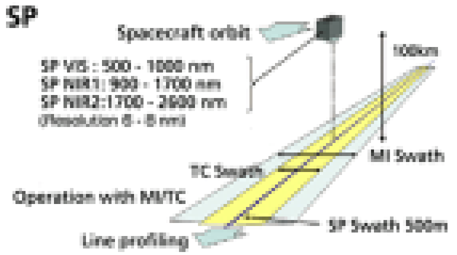
[Yokota et al., 2011, Kouyama et al., 2016]

SP model: “Disk-resolved” hyperspectral lunar brightness model based on SELENE/Spectral Profiler (SP) reflectance map

Dataset for the model

Spectral Profiler (SP) onboard SELENE

Japanese lunar orbiter (2007-2009)



Sensor specifications/observations

- **Measurement**
  Spectroscopy, 500 m swath (point observation)
- **Number of Observations**
  70 million spectroscopy observations
  Spectral coverage
  513 – 2600 nm (3 detectors: VIS, NIR1, NIR2)
- **Methods**
  Nadir observations from non-sun synchronous orbit
  => Various incident & phase angles are included,
  but limited emission angle range

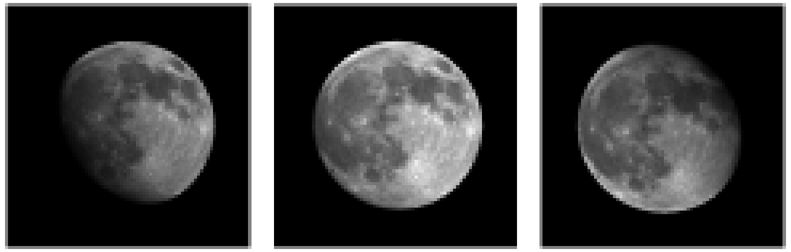
SP’s reflectance map

generated by integrating 70 million SP data

(see Yokota et al., 2011 for detail)

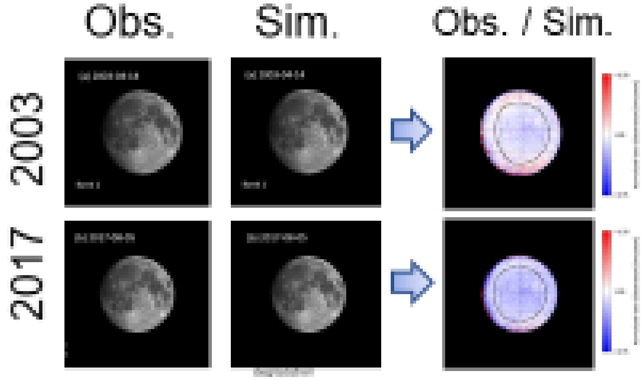
- **Map grid interval** (=spatial resolution of the model)
  0.5° x 0.5° in longitude and latitude
- **Map spectral coverage**
  516 – 1600 nm (160 channels) / $\Delta\lambda$ = 6 - 8 nm
- **BRDF effect**
  Simple approximation (will be updated in future)

Any observation can be simulated by SP model



Contributing ASTER’s RCC update

*Radiometric Correction Coefficients



- The amount of ASTER’s sensitivity degradation was successfully evaluated with < 1 % uncertainty.
- New RCC curves were defined by using the lunar calibration result as a constraint.

[Kouyama et al., 2019; Tsuchida et al., 2020]

GIRO model

- GIRO = GSICS Implementation of the ROLO model
- Same formulation as the ROLO
- Reflectance for a specific ROLO wavelength at 1AU + fixed distance Moon / Satellite (384400km):

$$A_j^{ROLO} = exp(P_A + P_B + P_C + P_D)$$

With

$$P_A(\lambda_j^{ROLO}) = a_0(\lambda_j^{ROLO}) + a_1(\lambda_j^{ROLO}) \cdot |g| + a_2(\lambda_j^{ROLO}) \cdot |g|^2 + a_3(\lambda_j^{ROLO}) \cdot |g|^3$$

$$P_B(\lambda_j^{ROLO}) = b_1(\lambda_j^{ROLO}) \cdot \Phi + b_2(\lambda_j^{ROLO}) \cdot \Phi^3 + b_3(\lambda_j^{ROLO}) \cdot \Phi^5$$

$$P_C = c_1 \cdot \phi + c_2 \cdot \theta + c_3 \cdot \Phi_{RAD} \cdot \phi + c_4 \cdot \Phi_{RAD} \cdot \theta$$

$$P_D(\lambda_j^{ROLO}) = d_1(\lambda_j^{ROLO}) \cdot e^{-\left(\frac{|g|}{p_1}\right)} + d_2(\lambda_j^{ROLO}) \cdot e^{-\left(\frac{|g|}{p_2}\right)} + d_3(\lambda_j^{ROLO}) \cdot cos[(|g| - p_3)/p_4]$$

- g : lunar phase
- Φ : sun selen. longitude
- θ : obs. selen. latitude
- ϕ : obs. selen. longitude

Modelled instrument irradiance:

$$Irr_{ROLO} = \frac{\sum_l \left(SRF_k(\lambda_l^k) \cdot S_k^{WEHRLI}(\lambda_l^k) \cdot A_k^{ROLO}(\lambda_l^k)\right)}{\sum_l SRF(\lambda_l^k)}$$

- SRF : instrument spectral response function
- S^{wehrli} : internal solar spectrum (based on Wehrli)

GIRO model

- Spectral range = [350,2500]nm
- Phase = [-92, -2] and [2,92] degrees

- Input = time + satellite position (J2000 or IRTF) + instrument SRF
- Output = simulated lunar irradiance for the target instrument
- Command line interface needed in order to isolate the core of the lunar calibration system (the model itself)

- Methodology + reference instrument dataset = ROLO

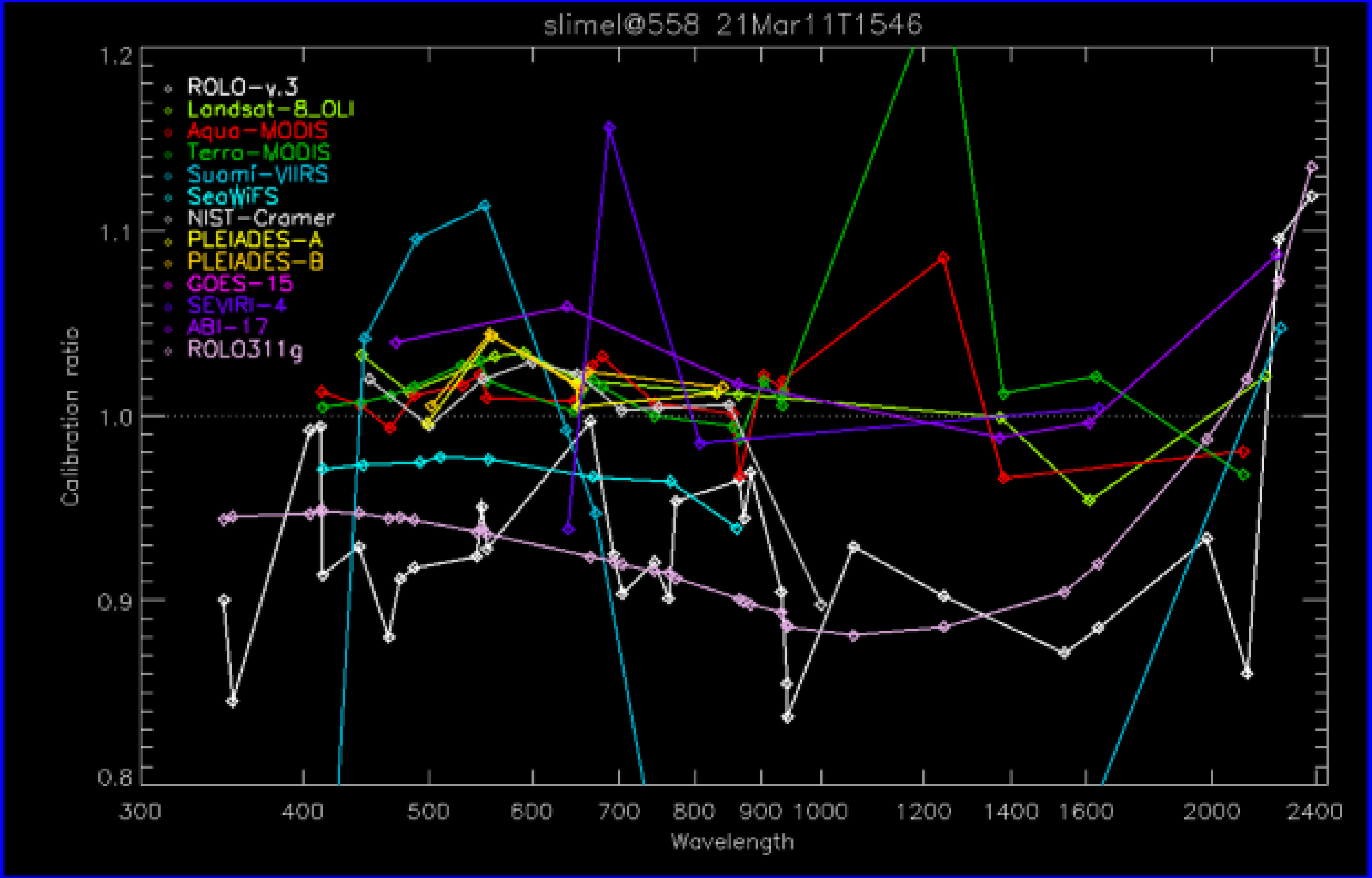
- GIRO = current Lunar Calibration Community Reference
- Available to GSICS members upon license agreement (+ action R.GVNIR.2020.16f.2)

- POC = EUMETSAT – S. Wagner
- Web page: https://www.eumetsat.int/lunar-calibration

SLIM model status. Hugh Kieffer

Goal: System that can incorporate all useful data, progressively approach the real Moon
SLIMED model of lunar spectral irradiance. Continuous in all 6 dimensions
Based on many[10] instruments, 90,000 measurements. Includes TSI and SSI variation.
Optional: libration model derived from 10 maps by Lunar orbiters. ⇖ ⇧ 0.1% effect
Basis functions (BF): abs. phase angle; Viewer Longitude, latitude; Solar lat., lon.
Selected polynomials and cross-products of each, and those times polynomials in λ
Judgement: 1) Teams rarely provide uncertainties, must be assigned.
2) Heft: Overall weighting factor for each instrument to address abundance of points.
3) Which of the thousands of possible BF combinations to use.
Nested fit iterations for outlier rejection and gain of each instrument band.
Typical model has about 30 coefficients | ROLO=GIRO has 328 |
Mean absolute residual ~0.6%
Calibrate all 24 instruments in inventory. Get mean gain bias of each band [figure]
Absolute scale still uncertain, but differences between instruments are solid.
LEO's mostly within a few %, outliers may be due to maneuver or team procedures.
Fit trends; look for periodic behavior. Sensitivity ~0.01% [in progress]

Gain bias for bands in 12 Instruments



Model based on top 10: 2 surface and 8 LEO. White is ROLO data, pink is ROLO model
Showing 1 of each GEO series; calibrations are [much] more noisy than LEO.

LIME: Lunar Irradiance Model ESA

Based upon the work done by Kieffer and Stone [Kieffer and Stone,2005] with minor modifications:

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

k = model spectral band

A = lunar reflectance

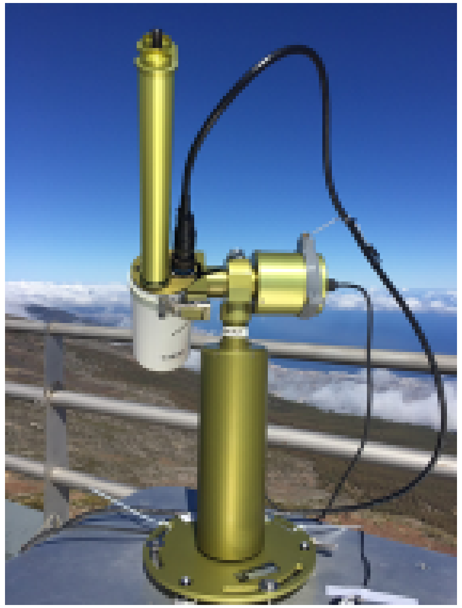
g = absolute phase angle [radians]

θ = selenographic latitude of observer [degrees]

ϕ = selenographic longitude of observer [degrees]

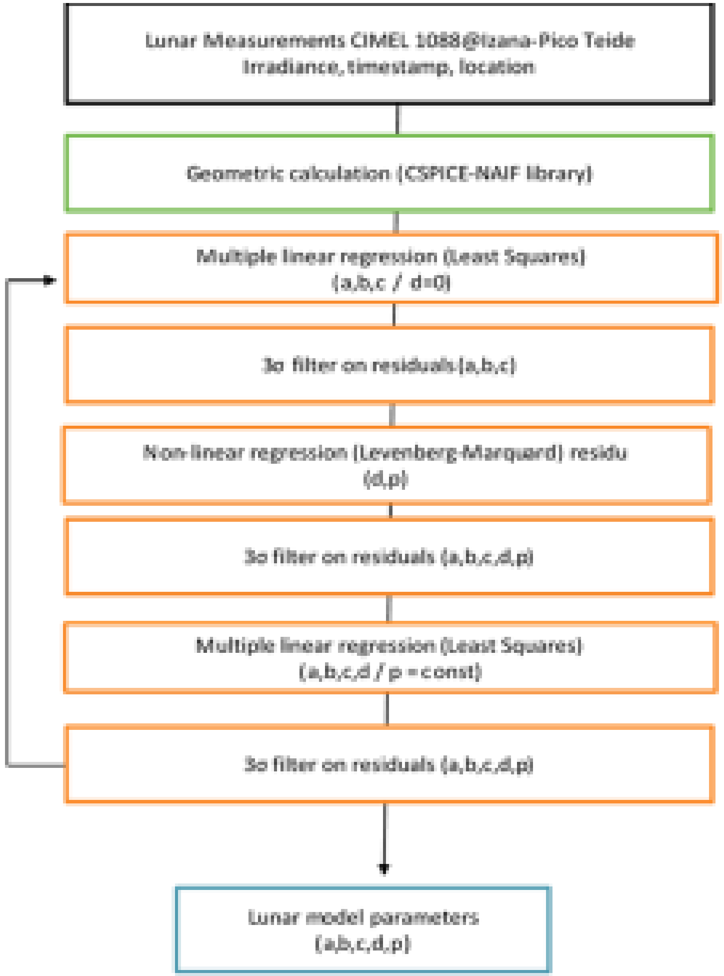
Φ = selenographic longitude of the Sun [radians]

The LIME measurement dataset

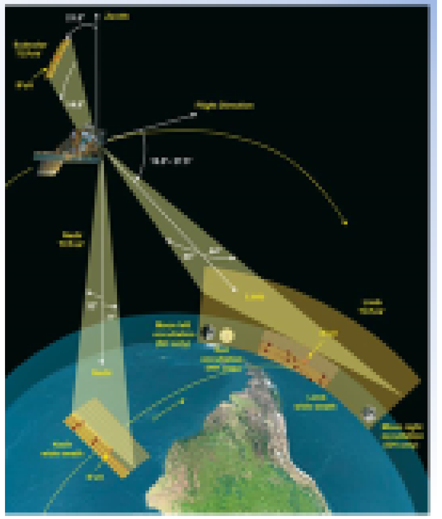


CIMEL 318-TP9

- Derived using SI-traceable ground-based measurements acquired with CIMEL 318-TP9 photometer from high altitude location at Teide Peak and Izaña Atmospheric Observatory in Tenerife
- About 300 lunar irradiance measurements between 03/2018 until 10/2020
- Multispectral measurements at 440 nm, 500 nm, 675 nm, 870nm, 1020 nm and 1640 nm
- Polarimetric measurement capabilities. DOP model of the lunar disk available.



LESSSR model



- **L**unar **E**xtended **S**atellite **S**imulation **S**olar **R**eflectance *
  - By Earth Space Solutions for EUMETSAT
- Based on
  - SCIAMACHY (ENVISAT, 250-2400nm, mirror pointing, #11K over 10yr)
  - RELAB LSCC (on-ground, 300-2600nm, i=30 degrees, #40)
  - SCIAMACHY measurements reconstructed with RELAB (fill gaps and remove remaining instrumental features) and fitted to:
- $\mathrm{Log}(R\_lunar) = P0 + P1\, g^{0.5} + P2\, g + P3\, g^{1.5} +$

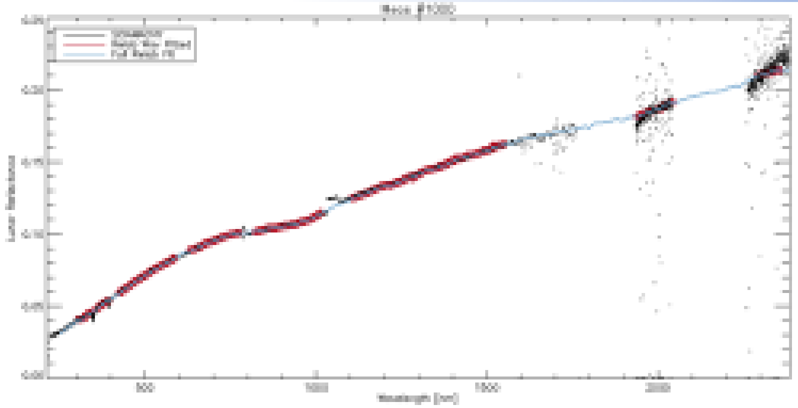
  $P4\, \Phi + P5\, \phi + P6\, \theta +$

  $P7 \cdot \exp(-g \cdot P8) + P9 \cdot \exp(-g \cdot P10) + P11 \cdot \cos((g - P12) \cdot P13)$

g: absolute phase angle, Φ,ϕ,θ : solar_longitude,libration_longitude,_latitude

*Because the Lesssr the better

LESSSR Conclusion



- Lunar reflectance model
  - 250nm – 2600nm with 5nm resolution
  - -80 to 20 phase angle validated
  - Accuracy: <1.5% 500nm-1600nm (~5% beyond)
  - Complete without need of post-model fits
    - Strongly reduced implementation error risk
    - Direct comparisons possible

- POC: EUMETSAT – S. Wagner
- Web page: https://www.eumetsat.int/lunar-reddening

Summary and Conclusion

Status:

- The test geometry grid and spectral response functions have been defined
  - specified as photometric parameters to eliminate potential errors due to conversion from geodetic or inertial coordinates
- Model outputs are being generated by the participants
- TBD: the format for comparing the results

Conclusion:

- Reliable, high-accuracy absolute lunar radiometric measurements are needed to constrain the predictions of lunar models