SI-traceable TOA Lunar Irradiance
Potential Tie-points for the ROLO Model

Talk given by Joe Rice

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Gene Eplee/NASA Goddard
Tom Stone/USGS
Sophie Lacherade, CNES
Can the Moon be used as an absolute exo-atmospheric calibration target for CLARREO and other Earth-observing instruments?

What are the current uncertainties in the Absolute Exo-Atmospheric Lunar Irradiance? and How low do we think they might go?

**OUTLINE**

- Summarize absolute TOA lunar irradiance measurements by NIST from the Whipple Observatory, Mt. Hopkins, AZ
  - Development of spectrograph-based transfer standards
- Phase-dependence to lunar irradiance
  - SeaWiFS/MODIS and PLEIADES
- Libration correction by NASA at 55° (VIIRS)
Relative differences between instruments include uncertainty components from:

- Use of different solar irradiance spectra
- Different approaches in calculating integrated lunar irradiances
- Inherent differences/uncertainties in instrument calibrations

Uncertainties in the ROLO Model estimated to be 5% to 10%, not SI traceable.
ROLO Model v Satellite sensors (Absolute)

% Difference from the ROLO Model

Wavelength [nm]

SeaWiFS
MODIS
VIIRS

SeaWiFS / MODIS Lunar Comparison

Lunar Measurement / ROLO Model

Stone, USGS

Eplee, Goddard
NIST measurements of TOA Lunar Irradiance
Whipple Observatory, Mt Hopkins, Amado AZ

Santa Rita Mountains, Coronado National Forest, ~30 miles from Nogales, Mexico

Elevation: Summit 8550 ft.
Ridge 7580 ft
NIST Absolute Top-of-the-Atmosphere (TOA) Lunar Irradiance Measurements have been made at the Whipple Observatory, Mt. Hopkins, AZ for ~ 3 years (two two-week visits, Spring and Fall, per year)

Lunar measurements piggy-backing on a longer time series of stellar measurements designed to establish a suite of SI-traceable absolutely calibrated ‘standard’ stars.

The Summit
6.5m MMT

The Ridge

NIST Dome

ROLO calibration based on measurements of Vega; NIST standard star measurements include Vega.
Calibrating the Telescope – on the Ground

Uncertainties dominated by Atmospheric transmittance Reference Instrument
Absolute TOA Lunar Irradiance

Lunar Irradiance

- Phase = 6.6°
- Phase = 16.9°

~40% difference in magnitude
10° difference in phase

Uncertainty dominated by the Telescope Calibration from 500 nm to 920 nm

Absolute TOA Lunar Irradiance ($k=1$) Uncertainty Budget

Uncertainty dominated by the Telescope Calibration

November 29, 2012

[Graph showing wavelength (nm) vs. percent uncertainty for various components: fit, atmospheric correction, calibration, total.]

- Ozone & Aerosols
- Langley
- Fit
- Calibration

Uncertainty Components

Wavelength (nm)
Comparison between Measurements and the ROLO Model
Band-averaged to SeaWiFS Bands

<table>
<thead>
<tr>
<th>SeaWiFS Band</th>
<th>Band Center Wavelength [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>412</td>
</tr>
<tr>
<td>2</td>
<td>443</td>
</tr>
<tr>
<td>3</td>
<td>490</td>
</tr>
<tr>
<td>4</td>
<td>510</td>
</tr>
<tr>
<td>5</td>
<td>555</td>
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<td>6</td>
<td>670</td>
</tr>
<tr>
<td>7</td>
<td>765</td>
</tr>
<tr>
<td>8</td>
<td>865</td>
</tr>
</tbody>
</table>

For the 2 nights, the irradiance differed by 40% and the phase by 10%.

(Gene Eplee, NASA Goddard)
Comparison between Measurements and the ROLO Model

Consider Uncertainties
Empirical Phase Correction to the ROLO Model from SeaWiFS Measurements of the Moon

Uncertainty in lunar irradiance v phase: 1.7 % (-50° to -6° and 5° to 60°)

Magnitude of the uncertainty in the libration correction: 0.5 %
## Absolute Lunar Irradiance Uncertainty Budget
(including uncertainties in phase and libration correction factors)

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Uncertainty component (k=1) [%]</th>
<th>Combined Standard Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute Irradiance</td>
<td>Phase Correction (7° to 50°)</td>
</tr>
<tr>
<td>400</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>450</td>
<td>0.85</td>
<td>1.7</td>
</tr>
<tr>
<td>500</td>
<td>0.56</td>
<td>1.7</td>
</tr>
<tr>
<td>550</td>
<td>0.45</td>
<td>1.7</td>
</tr>
<tr>
<td>600</td>
<td>0.44</td>
<td>1.7</td>
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<td>0.4</td>
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<td>700</td>
<td>0.38</td>
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<td>750</td>
<td>0.37</td>
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<td>800</td>
<td>0.36</td>
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<tr>
<td>850</td>
<td>0.36</td>
<td>1.7</td>
</tr>
<tr>
<td>900</td>
<td>0.35</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Multi-band filter radiometry ➔ Hyperspectral measurements
Uncertainties reduced from 5 - 10 % to ~2 %; the tie-points are SI-traceable.
1. Absolute Irradiance

Calibration Uncertainty
Telescope Only

Measurement Uncertainty
Lunar Irradiance

Tele/Mon = telescope calibration
Assuming no uncertainty in the Reference CAS Calibration

Uncertainties in the Reference Instrument calibration dominating the TOA Lunar Irradiance Uncertainty budget
Calibrating the Telescope in the field

- Uncertainty component for this part is between 0.1 % and 0.2 %
  500 nm to 900 nm
Developing Protocols to characterize and calibrate Spectrographs
Validate Instrument Responsivity in the field based on Si detectors

**Monochromatic Light from Supercontinuum Source-pumped Laser Line Tunable Filter**

**Detector-based Scale held on Si photodiodes**

<table>
<thead>
<tr>
<th>Range (nm)</th>
<th>FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vis-NIR</td>
<td>400 - 1000</td>
</tr>
<tr>
<td>SWIR</td>
<td>1000 - 2300</td>
</tr>
</tbody>
</table>

Scale held on Si PDs

WL scale verified by high res SG
2. Back to the ROLO Model: Phase dependence

Look at other instruments for consistency.
MODIS and PLEIADES
MODIS (US) & PLEIADES I (Fr and Italy) v the ROLO Model
Relative Spectral Response of Pleiades and MODIS Bands

MODIS has many of the same bands as SeaWiFS

Pleiades: Black; Terra MODIS: Green; Aqua MODIS: Red

Pleiades and Modis v ROLO Model
Phase angles of +/- 55.5°

MODIS has an on-board diffuser – derives calibration from solar looks
PLEIADES calibration from ground-truth sites.
(SeaWiFS used a lamp-illuminated Integrating Sphere.)

Empirical correction to the Phase dependence of the ROLO Model using MODIS, Pleiades-1B and SeaWiFS measurements

Offsets for SeaWiFS, MODIS and PLEIADES set to 0 at 7° phase using absolute measurements. Fit residual empirical correction, ±60° with an uncertainty of ~0.2 % (about 10 % of the total correction)

3. Libration
Lunar Phase and Libration Corrections to the ROLO Model using SeaWiFS as a proxy

In 2015, Eplee et al. re-examined the SeaWiFS-based empirical libration correction and came up with an additional 0.2 % over the previous empirical correction. Estimate a 0.2 % uncertainty in the empirical libration correction.

Expectations if we can maintain the Transfer Spectrograph Uncertainties in the Field

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Absolute Irradiance</th>
<th>Phase Correction</th>
<th>Libration correction</th>
<th>Combined Standard Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.35</td>
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<tr>
<td>450</td>
<td>0.2</td>
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CLARREO Uncertainties: 0.3 % from 500 nm to 900 nm
1 % in other regions

Meet CLARREO uncertainty requirements outside of the 500 nm to 900 nm range
To meet CLARREO requirements 0.3 %, $k=2$: All components reduced to 0.1 %
4. High-altitude Tie-points For Validation

Laboratory for Atmospheric and Space Physics (LASP)
HyperSpectral Imager for Climate Science (HySICS)

HySICS instrument was discussed earlier in this meeting by Greg Kopp

• Balloon flights
  • 29 Sept 2013 and 18 Aug 2014
  • 8.5 H and 9 H duration
  • ~120,000 ft

18Aug2014 flight:

Measured Solar and Lunar Spectral Radiance
May provide an additional tie point to the ROLO model &
facilitate a comparison with Mt. Hopkins-based Lunar Irradiance
Establish a Lunar/Solar Observatory on Mauna Loa, HI

- Elevation
  - Mt Hopkins elevation 2367m
  - Mauna Loa elevation 4169 m

- Atmospheric Characterization

- Increase our yield through continuous daily measurements of Solar & Lunar Spectral Irradiance
  - Using a remotely operated/more permanent facility

Apply some of our spectrograph calibration protocols, see if we can’t lower the uncertainty in the telescope responsivity (in the field) below 0.35 % \( (k=1) \)

Extend spectral range to cover out to 2.5 \( \mu \)m
Reducing the Measurement Uncertainty
Considering high altitude aircraft flights for both Solar and Lunar Irradiance Measurements

• ER2 Flights (2 campaigns/year, 1 to 2 weeks duration
  • Above 95 % of the atmosphere; lower uncertainties achievable quickly
  • Lunar measurements would provide tie-points for the ground-based measurements
    • ± 7° phase (Tie to SeaWiFS/PLEIADES)
    • ± 55° phase (Tie to MODIS/PLEIADES)
    • Phase changes ~10 % per night
• Solar measurements at the same view angles to validate the reflectance model of the Moon
Can the Moon be used as an absolute exo-atmospheric calibration target for CLARREO and other Earth-observing instruments?

It looks like it is very promising to get to 0.35 % (k=1) uncertainty, but we need some help.
To Validate the Spectrograph Calibration
NIST primary standard Blackbody Sources

Gold-point blackbody: 1337 K
Carbon-Metal Eutectics: up to 2800 K
Absolute Calibration of the Reference CAS Instrument

FEL-Lamp calibration the single largest source of uncertainty
Solution: Map out the Single Pixel Responsivity of every pixel using SIRCUS

Expanded \((k = 2)\) uncertainties of the 2011 NIST Irradiance Scale

Issued Lamps,
\(k = 2\) uncertainty approximately
0.6 % @ 900 nm
0.9 % @ 500 nm
1.25 % @ 350 nm

What’s new?

Development of Transfer Standard Spectrographs to establish detector-based radiance and irradiance scales

**Spectrograph Characteristics**
- CCD-based fiber-fed slit spectrograph
- 380 nm to 1040 nm, 4 nm resolution
- Temperature-stabilized CCD

_from 11/2012 – 6/2014_

Deployed to Mt. Hopkins and returned to NIST several times

Event where water spilled onto the instrument – and it was left outside for a while to dry

**Radiometric Stability v an FEL-lamp**
Calibration setup not maintained; reproduced for each measurement.

Most of the observed variability from fiber insertion into CAS
Transfer Standard Spectrograph-based Radiance Scale
Potential impact on lamp-Illuminated Integrating Sphere uncertainties

• During NASA’s Earth Observing System-era, a series of source radiance validation campaigns were planned and executed by the EOS Project Office with the goal of validating the radiances assigned to laboratory calibration sources, principally lamp-illuminated integrating spheres, and establishing an uncertainty budget for the disseminated radiance scale.

• Based on an analysis of 7 years’ worth of data, Butler et al.\textsuperscript{1} assigned an uncertainty in disseminated radiance scales of 2\% to 3\% in the Vis/NIR (silicon) region, increasing to 5 \% in the short-wave infrared region.

From source-based to detector-based radiance scale (using a Transfer Standard Spectrograph to hold the radiance scale) may reduce the uncertainties in the disseminated Radiance Scale an order of magnitude.

ROLO Observatory
Flagstaff, AZ
Altitude 2143 m

*Courtesy of Tom Stone, USGS, Flagstaff, AZ
ROLO Observational Program

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

• Spatially resolved radiance images
  • 6+ years in operation, >85000 lunar images
  • phase angle coverage from eclipse to 90°
• Operations ended in 2003

*Courtesy of Tom Stone, USGS, Flagstaff, AZ
ROLO Model:
Equivalent Lunar Disk Reflectance

\[ \ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1 \theta + c_2 \phi + c_3 \Phi \theta + c_4 \Phi \phi \\
+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos\left[\left(g - p_3\right)/p_4\right], \quad (10) \]

1. There is a point-spread correction to the lunar data (for radiance).
   - Not needed for Irradiance, not clear to me how this is currently handled.

2. To get to Irradiance, a reference Solar spectrum is used; the ROLO Model v311g uses Wehrli, NASA Goddard was using Thuillier.
Use of the ROLO Model to trend Satellite Sensors Band Response
NASA Goddard OBPG

SeaWiFS bands temporal responsivity degradation

Corrected using the ROLO Model
Relative only
Phase angles kept to ± 7°

StDevMean = ~ 0.1 %

Lunar measurements can be used
To trend satellite sensor responsivity
With very low uncertainties.