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

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Tom Stone/USGS
Sophie Lacherade, CNES
FY2014 CLARREO SDT Meeting:

Can the Moon be used as an Absolute Exo-Atmospheric Calibration Target for CLARREO?

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

Today’s 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)
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

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**SWIR Telescope**

**VNIR Telescope**

*Courtesy of Tom Stone, USGS, Flagstaff, AZ*
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.

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

SeaWiFS Band-center Wavelengths and Bandwidths
Use of the ROLO Model to trend Satellite Sensors Band Response (Gene Eplee and the 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.
How well does it do? & What are the uncertainties?

Jim Butler, presented at the Lunar Calibration Workshop, May 2012

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)**

- **Hyperion**
- **ALI**
- **MODIS**
- **MISR**
- **SeaWiFS**

**SeaWiFS difference up to ~ 10 %**

**MODIS differences up to ~ 15 %**

**SeaWiFS**

**Terra MODIS**

**VIIRS**

**SeaWiFS, MODIS, & VIIRS**

Image of a graph showing wavelength [nm] on the x-axis and % difference from the ROLO Model on the y-axis. Different sensors are indicated with different markers and colors.

Tom Stone, USGS

Gene Eplee, Goddard
On-Orbit SI-traceable, $k=2$, Sensor Accuracy Requirements
Kurt Thome, NASA, NIST Lunar Calibration Workshop, May 2012

- Operational systems
  - 3 % absolute with 1 % sensor-to-sensor

- Climate applications (CLARREO)
  - 0.3 % 500 nm to 900 nm; 1 % other spectral regions

Jim Butler, NASA, NIST Lunar Calibration Workshop, May 2012

While CLARREO needs 0.3 % $k=2$, a lunar irradiance model with 1 % to 3 % absolute uncertainties $k=2$ relative to the SI makes the Moon a viable (affordable) on-orbit source for

1. Transfer to Orbit Effects
2. Ensuring consistency between the calibrations not only of overlapping but also non-overlapping sensors (to help minimize gap effects)
3. Possibly/potentially as an absolute SI traceable on-orbit calibration source
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

Set our uncertainty goals to be 1 % or less (k=2)
NIST Absolute Top-of-the-Atmosphere (TOA) Lunar Irradiance Measurements have been made at the Whipple Observatory, Mt. Hopkins, AZ for ~ 2 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.

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
Calibrating the Telescope

- Independent of the uncertainty in the Reference Instrument
  - Uncertainty is between 0.1 % and 0.2 % 500 nm to 900 nm
Absolute TOA Lunar Irradiance

Lunar Irradiance

- Phase = 6.6°
- Phase = 16.9°

~40% difference in magnitude
10° difference in phase

Uncertainty Budget

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

- **Uncertainty [\%]**: 400, 600, 800, 1000
- **Wavelength [nm]**: 0.5, 1.5, 2.0

**Graph Details**:
- Red: fit
- Green: atmospheric correction
- Blue: calibration
- Black: total

**Annotations**:
- **Telescope Calibration**
- **Ozone**
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>
</tr>
<tr>
<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

Two lunar irradiance data sets (potential absolute tie-points to the ROLO Model) have $k=2$ uncertainties 1% or less from ~500 nm to ~940 nm.
Empirical Phase Correction to the ROLO Model from SeaWiFS Measurements of the Moon

Magnitude of the phase correction: 1.7% (-50° to -6° and 5° to 60°)

Let the uncertainty in the phase dependence of the ROLO Model = 1.7%

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>
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<tr>
<td>600</td>
<td>0.44</td>
<td>1.7</td>
</tr>
<tr>
<td>650</td>
<td>0.4</td>
<td>1.7</td>
</tr>
<tr>
<td>700</td>
<td>0.38</td>
<td>1.7</td>
</tr>
<tr>
<td>750</td>
<td>0.37</td>
<td>1.7</td>
</tr>
<tr>
<td>800</td>
<td>0.36</td>
<td>1.7</td>
</tr>
<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

Calibration uncertainty component

Uncertainties in the Reference Instrument calibration dominating the TOA Lunar Irradiance Uncertainty budget
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.

![Graph showing radiometric stability](image)

Most of the observed variability from fiber insertion into CAS

± 0.2 %
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>

WL scale verified by high res SG
Digression: 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.

\begin{quote}
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.
\end{quote}

Digression 2: How do we Validate the Spectrograph Calibration
NIST primary standard Blackbody Sources

Gold-point blackbody: 1337 K
Variable temperature blackbody: 3000 K
Carbon-Metal Eutectics: up to 2800 K
II. Phase dependence

Consider PLEIADES data set

Gene Eplee et al., GSFC
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 ??
- [\sim 0.2 \% - about 10 \% of the total correction]

(Just a best guess. Need to more closely examine PLEIADES data set)

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

1. we can maintain the Spectrograph Uncertainties in the Field
2. 0.2 % uncertainty in the Phase Correction holds up

<table>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute Irradiance</td>
</tr>
<tr>
<td>400</td>
<td>0.2</td>
</tr>
<tr>
<td>450</td>
<td>0.2</td>
</tr>
<tr>
<td>500</td>
<td>0.2</td>
</tr>
<tr>
<td>550</td>
<td>0.2</td>
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<tr>
<td>600</td>
<td>0.2</td>
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<td>650</td>
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<td>0.2</td>
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<tr>
<td>850</td>
<td>0.2</td>
</tr>
<tr>
<td>900</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**CLARREO Uncertainties:** 0.3 % from 500 nm to 900 nm
1 % in other regions

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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 %
Additional Tie-points: LASP’s HySICS measurements
Hear more about the second balloon flight from Greg Kopp

• HySICS instrument
  • 350 nm to 2500 nm; 8 nm resolution or better
  • Uncertainties less than 0.2 %

• 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
Reducing the Measurement Uncertainty

1. Consider 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 validate the reflectance model of the Moon

1. Solar/Lunar measurements taken on different flights
   - instrument can be configured for the particular measurement.
2. Pre and post calibrations in addition to in-flight monitoring
Reducing the Measurement Uncertainty
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
  • a remotely operated permanent facility

Ideally, generate a new data set to refine the ROLO Model.