Lunar metrology for satellite instrument characterization

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Biospheric Sciences, Code 618
Calibration approaches for climate measurements

Last year’s talk was a discussion of complementary laboratory and on-orbit calibration methods for climate measurements

- **CLARREO Mission**
  - High accuracy calibration requirements

- **SI traceability in the laboratory**
  - NIST’s SIRCUS (detector-based calibration with laser sources)
  - Calibration of G-LiHT, ORCA, SOLARIS (CLARREO), HyPlant, VIIRS

- **Model-based sensor inter-calibration**
  - Value of imaging spectrometer for site characterization
CLARREO calibration approach

Characterize sensor to SI-traceable, absolute radiometric quantities during prelaunch calibration

Component and system level data used to develop high-fidelity sensor model

Transfer to orbit through accurate prediction of sensor behavior while viewing known sources

Ensure prelaunch calibration simulates on-orbit sources
Sensor characterization

- Spectral/Radiometric
- Linearity
- Spectral out-of-band response
- Stray light
- Polarization response
- Optic degradation
Coarse sensor on-orbit uncertainty budget

- Laboratory calibration using incandescent sources SpMA for RSR and lamp-illuminated integrating sphere for absolute gain setting is 2 % to 3 %*
- On-orbit calibration using the solar diffuser with a solar attenuator screen is at its limit at ~ 1.6 % at best due to uncertainty in solar spectral irradiance (2 % to 3 % in Vis/NIR and 5 % or larger in SWIR)
- SIRCUS-based calibration at 0.2 %, can achieve 0.1 %
- Ignoring Vicarious Calibration option in the Transfer-to-Orbit column

<table>
<thead>
<tr>
<th>Uncertainty Estimates</th>
<th>Laboratory Calibration</th>
<th>Transfer to Orbit</th>
<th>Trending (MOON)</th>
<th>Combined Standard Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>SpMA-based</td>
<td>2 -3 %</td>
<td>2 % to 3 %</td>
<td>0.1% to 0.2%</td>
<td>3.5 %</td>
</tr>
<tr>
<td>SIRCUS-based</td>
<td>0.5 %</td>
<td>2 % % to 3 %</td>
<td>0.1% to 0.2%</td>
<td>3 %</td>
</tr>
<tr>
<td>Potential w/1 % lunar cal-based Xfer to Orbit</td>
<td>0.5 %</td>
<td>1 %</td>
<td>0.1% to 0.2%</td>
<td>1.25 %</td>
</tr>
<tr>
<td>Potential w/0.25% lunar cal-based Xfer to Orbit</td>
<td>0.1 %</td>
<td>0.25 %</td>
<td>0.1 %</td>
<td>0.3 %</td>
</tr>
</tbody>
</table>

Studying the moon

• USGS measurement/model
• NIST measurements
• CLARREO
  – Climate Absolute Radiance and Refractivity Observatory
• Satellite measurements
• EO-1 Hyperion measurements
USGS ROLO

RObotic Lunar Observatory

_T. Stone and H. Keifffer_

- Capture and model the moon’s spectral and radiometric signal throughout its phase and librations.

- Measurements
  - 23 VNIR, 9 SWIR bands
  - 85k lunar images over 6 years

- Uncertainties
  - 5-10%
NIST lunar measurements
Mt Hopkins, AZ

12 inch integrating sphere acts as artificial moon

30 m

Calibration setup

Steve Brown
Keith Lykke
Claire Cramer
John Woodward
NIST
Gaithersburg, MD

4 June 2015
HyspIRI Symposium
Comparison with ROLO model

NIST-measured Irradiance/ROLO-predicted Irradiance

For the 2 nights, the irradiance differed by 40 % and the phase by 10 %.
Combined Standard Uncertainty in Lunar Irradiance
Spectral Irradiance of the Moon at 11:40:43 on 30 November, 2012 UT

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Spectral irradiance ($\mu$W m$^{-2}$ nm$^{-1}$)</th>
<th>Uncertainty (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>449.7</td>
<td>2.348</td>
<td>0.85</td>
</tr>
<tr>
<td>499.9</td>
<td>2.395</td>
<td>0.56</td>
</tr>
<tr>
<td>550.0</td>
<td>2.633</td>
<td>0.45</td>
</tr>
<tr>
<td>600.2</td>
<td>2.669</td>
<td>0.44</td>
</tr>
<tr>
<td>650.1</td>
<td>2.598</td>
<td>0.40</td>
</tr>
<tr>
<td>702.8</td>
<td>2.474</td>
<td>0.38</td>
</tr>
<tr>
<td>750.0</td>
<td>2.314</td>
<td>0.37</td>
</tr>
<tr>
<td>850.2</td>
<td>1.870</td>
<td>0.36</td>
</tr>
<tr>
<td>1000.2</td>
<td>1.387</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Over this spectral range:

- Magnitude and an uncertainty (at the particular phase and libration angles) with the telescope calibration tied to the SI.
- Provides a means to re-scale the ROLO Model (by the TOA Lunar Irradiance) and to develop a constrained uncertainty budget including phase and libration uncertainties and establish traceability to the SI for the ROLO Model-predicted lunar irradiances.
CLARREO measurements at Goddard

CLARREO calibration demonstration system

20140814_125135_moon50ms.fits

Black line: moon
Blue line: sky

4 June 2015
HyspIRI Symposium
Space-based measurements

Orbview 2 (SeaWiFS)

Landsat 8 (OLI, TIRS)

Terra (MODIS)

EO-1 (ALI, Hyperion)

Pléiades

Suomi NPP (VIIRS)
Landsat 8 measurements

• Operational Land Imager (OLI)
  Monthly measurements at ~7 degree phase angle

• Thermal Infrared Sensor (TIRS)

SeaWiFS

Gene Eplee, NASA Goddard

SeaWiFS used the Moon to trend Responsivity with an Uncertainty of 0.13 %.


Avg. Sea-surface Chl-a, 1998-2006

SeaWiFS Bands

<table>
<thead>
<tr>
<th>SeaWiFS Band</th>
<th>Band Center Wavelength [nm]</th>
<th>Bandwidth [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>412</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>443</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>490</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>510</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>555</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>670</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>765</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>865</td>
<td>40</td>
</tr>
</tbody>
</table>

Chl concentration [mg chl m\(^{-3}\)]
Phase Dependence of MODIS Terra/Aqua and SeaWiFS Lunar Measurements

Top Plot: Inherent scatter in a series of lunar measurements at 412 nm
Bottom Plot: binned residuals plotted as means with STDs (412 nm)

- Phase dependence (Phase Angle):
  - MODIS Aqua: 1.1 % from -80° to -51°; Terra 1.5 % from 52° to 82°.
  - SeaWiFS: 1.7 % from -45° to -6° and 5° to 56°

Uncertainty in lunar irradiance v phase:
1.7 % (-80° to -6° and 5° to 82°)
- USGS Model uncertainty 1 % (from a much larger database of lunar measurements)

Ignoring the 6% Bias for PLEIADES and the 2% Bias for SeaWiFS, Phase Meas/Model Ratio v Phase Angle Is very similar to the SeaWiFS Phase Dependence.

What’s missing?

– full spectrum lunar signal (solar reflective)

– dense lunar phase and temporal sampling

– absolute accuracy, current is 5-10%

– 1–2.5 μm spectral region

– As Hyperion begins to take more measurements of the moon:

  • Substantially increase science value of mission
    – The data set would become the on-orbit standard for linking earth observing sensors – throughout time
    – Better link historical EO-1 data sets.
    – Link with CLARREO Pathfinder

  • Create New baseline for moon
    – Full solar reflective spectrum, including 1–2.5 μm spectral region
    – 2-3% absolute accuracy
    – Would be best with dense sampling for phase coverage and statistics