Exo-atmospheric Standards for Satellite Sensor Calibration and Nighttime Aerosol Quantification

Claire Cramer  
Steve Brown  
Keith Lykke  
John Woodward  

Laser Applications Group  
Sensor Science Division
Climate Data Records

**Climate Data Record**: time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change

Satellite images provide our primary CDRs for critical climate variables, including: vegetation, snow and ice albedo, clouds, aerosols
Impending Gap: Polar Satellite System

- Polar-orbiting NOAA satellite used for mid-range weather forecasting
- Suomi-NPP end of life in 2016; JPSS-1 earliest possible launch in 2017, expected gap of 17-54 months

Instrumentation:

- Advanced Technology Microwave Sounder (ATMS)
- Cross-Track Infrared Sounder (CrIS)
- Visible Infrared Imaging Radiometer Suite (VIIRS)
- Ozone Mapping and Profiler Suite (OMPS)
- Cloud and Earth Radiant Energy System (CERES)

Climate variables:

- atmospheric temperature, pressure, moisture
- biosphere, snow and ice albedo
- surface temperature (land, ocean, snow/ice)
- clouds, aerosols, ozone
Radiometric Calibration Requirements

- Stability requirements are more stringent than accuracy requirements.
- Stability requirements can be met through relative measurements (sensor trending) as long as there aren’t gaps in the data record.
- Adequate calibration of satellite sensors is essential to maintaining CDRs.

<table>
<thead>
<tr>
<th></th>
<th>Accuracy</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean color</td>
<td>0.5 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Vegetation</td>
<td>2 %</td>
<td>1 %</td>
</tr>
<tr>
<td>Aerosols</td>
<td>3 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>Surface albedo</td>
<td>5 %</td>
<td>1 %</td>
</tr>
</tbody>
</table>

Current On-orbit Calibration Strategies

On-board solutions: solar diffusers, lamps
degrade over time
uncertainty ~ 2%

Calibrated scenes: Earth surface sites, Moon
surface sites require
atmospheric correction
Moon’s irradiance depends on
time, geometry
Empirically-determined analytic function of phase and libration angles based on 8 years of lunar images in 32 visible and infrared passbands

Sensor Trending with USGS Model

The Sea-viewing Wide Field-of-view Sensor (Sea WiFS) performed a monthly pitch-over to view the Moon in a narrow (±7°) range of phase angles starting in 1997.

Periodic lunar views together with the USGS Model have allowed sensor trending at the level of 0.1 % per year.
Utility of USGS Lunar Model

• very effective for sensor trending
• absolute scale known to 5-10%; not SI-traceable
• spectral coverage limited to 10 nm passbands, use requires interpolation with solar spectrum
• possible systematic effects when comparing different spectral regions or phase angles

Establishing an accurate, SI-traceable scale for the USGS Lunar Model could help bridge gaps in satellite coverage, preserving integrity of climate data records
Lunar Calibration Advantages

- Extremely stable reflecting surface
- Smooth reflectance spectrum, with only broad, shallow features
- Accessible to all spacecraft, regardless of orbit
- Can back-calibrate old data – the calibration will only get better with time
- Utilizes instrument’s normal Earth-viewing optical path
- Appropriate brightness for terrestrial environment sensors (vs. Sun, stars)
- Complementary to earth surface sites -- no atmosphere
- Common source for intersensor comparison, coincident views not required
Proof-of-principle Measurement

Goal: SI-traceable calibration of lunar spectral irradiance at visible wavelengths from the ground with < 2 % accuracy.

- Lunar observations on ~40 nights at Fred Lawrence Whipple Observatory on Mt. Hopkins, AZ yielded two “good” measurements
- Langley analysis to determine atmospheric extinction
- Successful result: J Res NIST 118, p. 396 (2013)

Thanks to:  
Tom Stone, United States Geological Survey
Emilio Falco, Smithsonian Astrophysical Observatory
Proof-of-principle Measurement

- 106 mm refracting telescope
- 4 mm lunar disk easily fits inside 12 mm sphere aperture
- integrating sphere scrambles incident light
- light guide ensures stable, uniform illumination of spectrometer

- large integrating sphere acts as artificial moon
- lab-calibrated spectrometer monitors large sphere via irradiance head as transfer standard
Lunar Spectra, 29 November 2012

measured lunar irradiance, 2012.1129

593 spectra
one-minute spacing

airmass range: 1.02-6
lunar phase: 17°-20°
Langley Analysis

If the atmosphere is temporally stable and isotropic:

\[ I_{meas}(\lambda, t) = I_0(\lambda, t)e^{-\sum m_i \tau_i} \]

- use USGS model to account for time/geometry-dependence of \( I_0 \)
- components of atmosphere include ozone, stratospheric aerosols, mixed gases (Rayleigh scattering), tropospheric aerosols

At each wavelength, fit a line to the log of our measurement vs. airmass. 

If assumptions are satisfied, then:

- \( y \)-intercept gives TOA irradiance
- slope gives atmospheric extinction
Calibrated Lunar Spectral Irradiance

Nov. 30, 2012

fractional uncertainty (k = 1)

fit statistics, ozone, aerosols

NIST Climate Workshop, 4 August 2014
Moving Forward Post-pilot

Next steps:
- Improve laboratory calibration of transfer standard spectrometer
- Develop suite of atmospheric monitoring tools to validate and/or substitute for Langley method
- Move to higher altitude site to reduce magnitude of atmospheric effects
- Obtain measurements spanning a range of phase and libration angles

Future goals:
- Expand wavelength range out to 2.5 μm
- Use high-altitude aircraft or balloons to reduce atmospheric extinction for 0.5 % accuracy at visible wavelengths and 2-3 % in SWIR
- Mobile laboratories for atmospheric characterization
Alternate Atmospheric Monitoring Schemes

**Facility Lidar for Astronomical Monitoring of Extinction (FLAME):**
- Multi-wavelength elastic backscatter (355, 532, 1064 nm)
- Short and long-range receivers
- Clouds, aerosols, Rayleigh scattering

**Astronomical Extinction Spectrophotometer (AESoP):**
- Calibrated spectroradiometry + set of standard stars well-distributed across the sky
- Molecular absorption: water, oxygen
- Both instruments are under development at the University of New Mexico (John McGraw, Pete Zimmer)
- Together, they will provide state-of-the-art atmospheric monitoring for astronomy and a detailed atmospheric data stream
Nighttime Aerosol Monitoring

- The Aerosol Robotic Network (AERONET) continuously monitors atmospheric aerosols around the globe with a network of sun photometers.
- There is no comparable tool for aerosol monitoring at night or during polar winters.
- Lunar and stellar spectroradiometry could provide a solution.

- Lunar spectroradiometry yields detailed information about the atmosphere.
- Lunar apparatus could be adapted for solar observations to provide improved spectral coverage.
Summary and Conclusions

Developing a lunar irradiance model with 1 % to 3 % uncertainty relative to the SI is possible using ground-based measurements at visible wavelengths and potentially from high-altitude platforms in the short-wave infrared, making the Moon a viable on-orbit source for:

- on-orbit sensor trending and absolute calibration
- absolute, on-orbit calibration of some (but not all) operational sensors
- ensuring consistency between data products derived from sensors with no temporal or spatial overlap

Possibilities for future work include:

- Lunar measurements spanning the phase/libration parameter space from a robotically-controlled observatory on Mauna Loa
- Collaboration with external agencies to develop instrumentation for and make observations from balloons or aircraft
- Adaptation of atmospheric monitoring techniques to nighttime aerosol monitoring