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

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Climate Data Records

<u>Climate Data Record</u>: 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

	Accuracy	Stability
Ocean color	0.5 %	0.1 %
Vegetation	2 %	1 %
Aerosols	3 %	0.6 %
Surface albedo	5 %	1 %

Datla, et al., J Res NIST **116** p. 621 (2011)

- 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

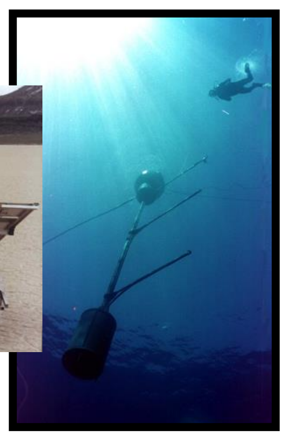
Current On-orbit Calibration Strategies

On-board solutions: solar diffusers, lamps

degrade over time

uncertainty ~ 2%

Calibrated scenes: Earth surface sites, Moon



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surface sites require

atmospheric correction

Moon’s irradiance depends on time, geometry

USGS Lunar Model

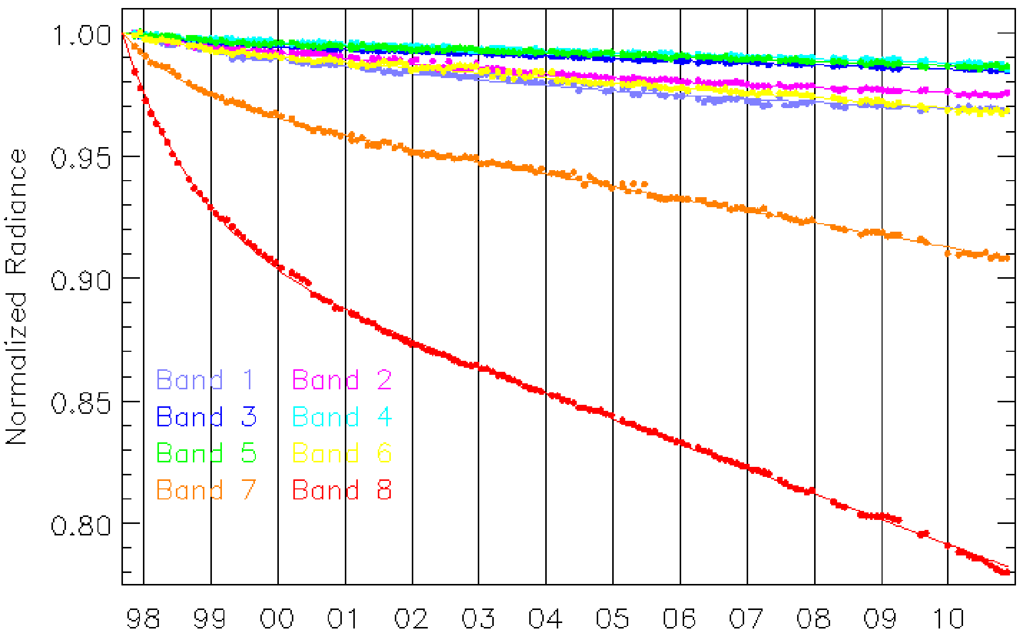
$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\phi + c_2\theta + c_3\Phi\phi + c_4\Phi\theta$$
$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

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

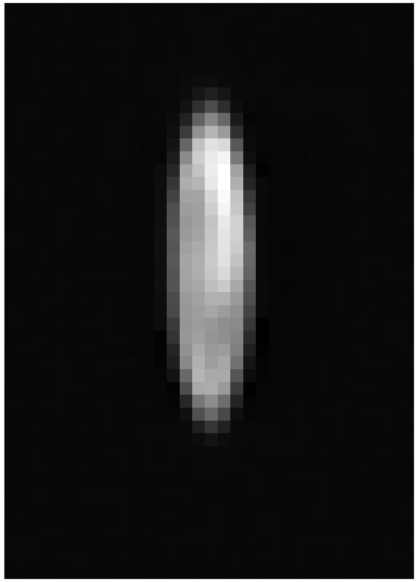
Empirically-determined analytic function of phase and libration angles based on 8 years of lunar images in 32 visible and infrared passbands

Kieffer & Stone, *AJ*, **129**, 2887-2901 (2005)

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)

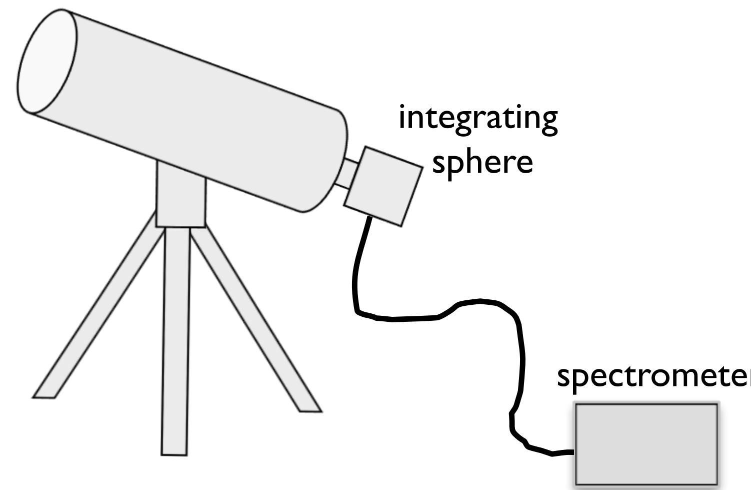
Thanks to: Tom Stone, United States Geological Survey
Emilio Falco, Smithsonian Astrophysical Observatory

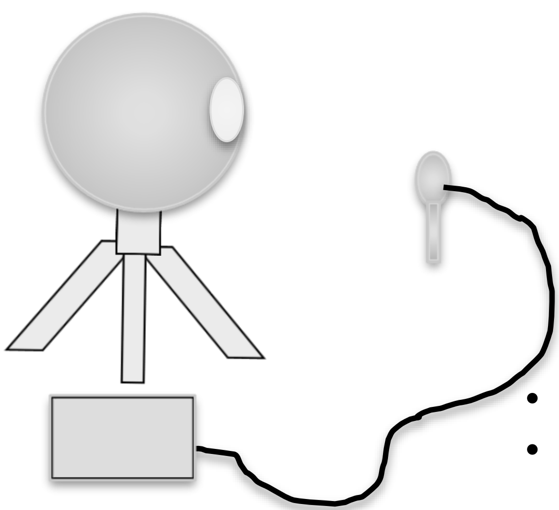
Proof-of-principle Measurement

- 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

measurement

calibration

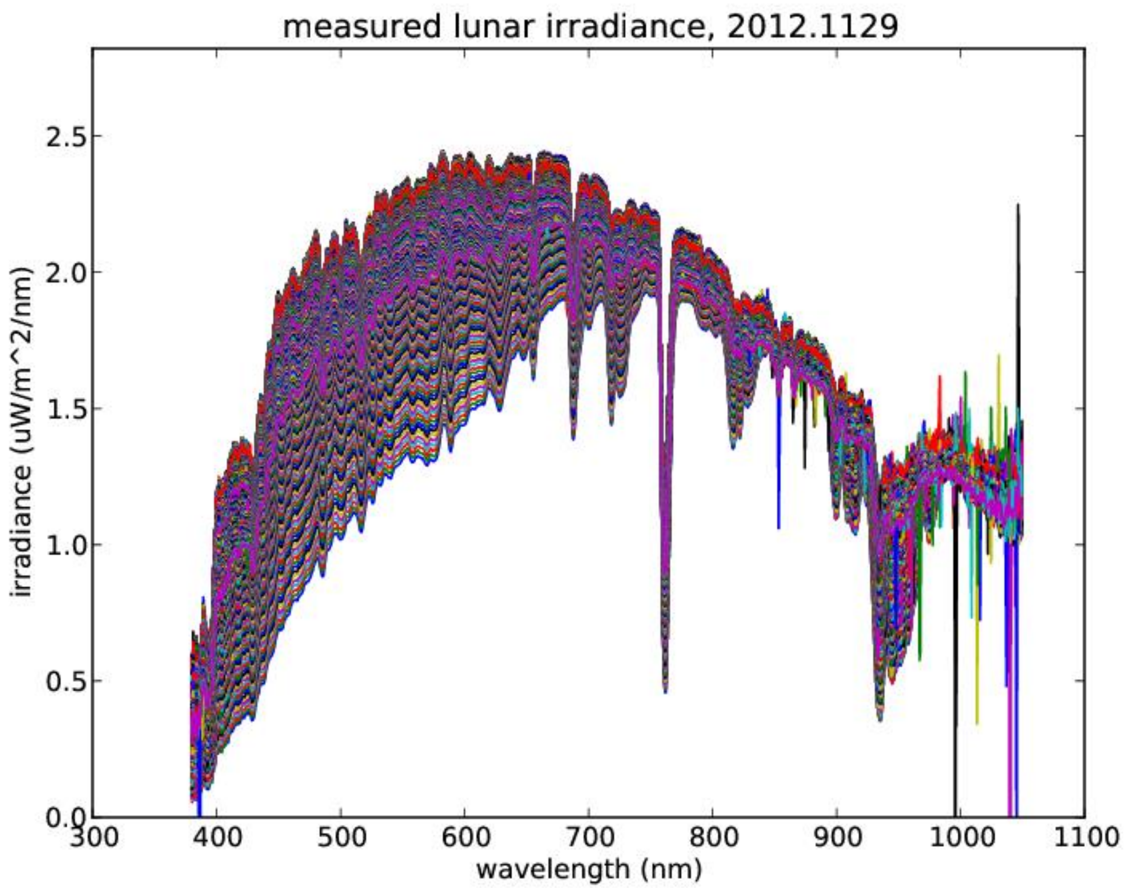




- large integrating sphere acts as artificial moon
- lab-calibrated spectrometer monitors large sphere via irradiance head as transfer standard


THORLABS

Lunar Spectra, 29 November 2012



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

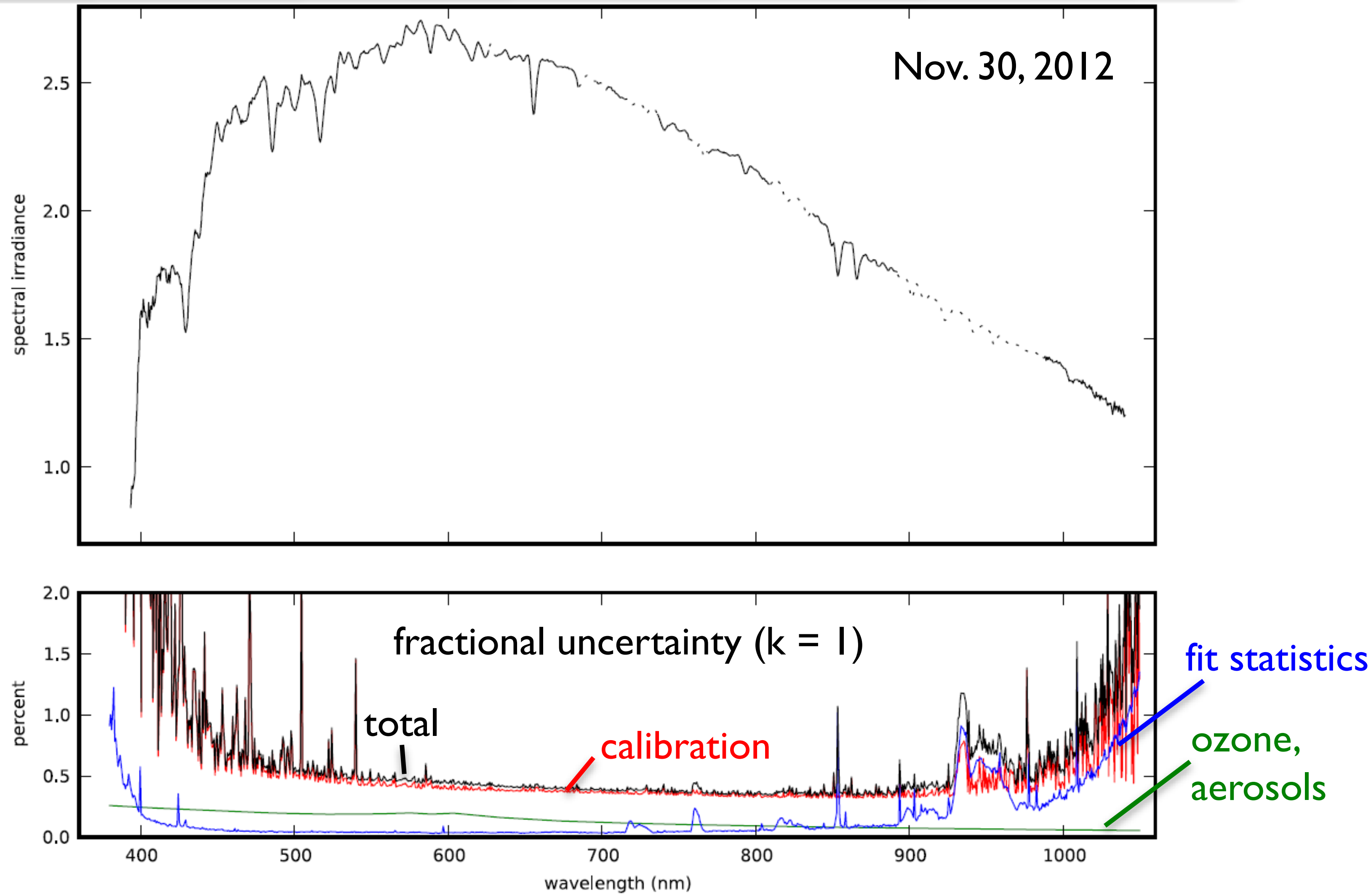
At each wavelength, fit a line to the log of our measurement vs. airmass.

If assumptions are satisfied, then:

y-intercept gives TOA irradiance

slope gives atmospheric extinction

Calibrated Lunar Spectral Irradiance



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):

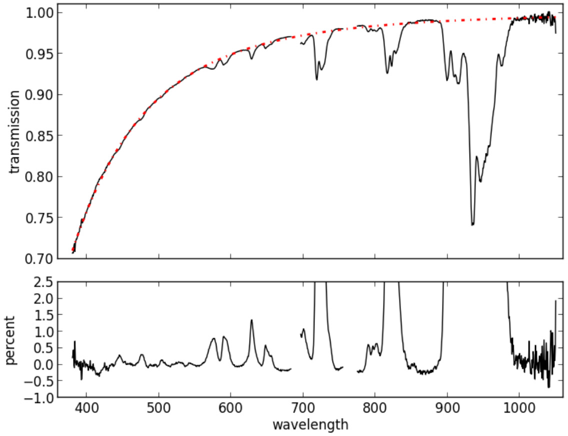
- Calibrated spectroradiometry + set of standard stars well-distributed across the sky
- Molecular absorption: water, oxygen

- 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