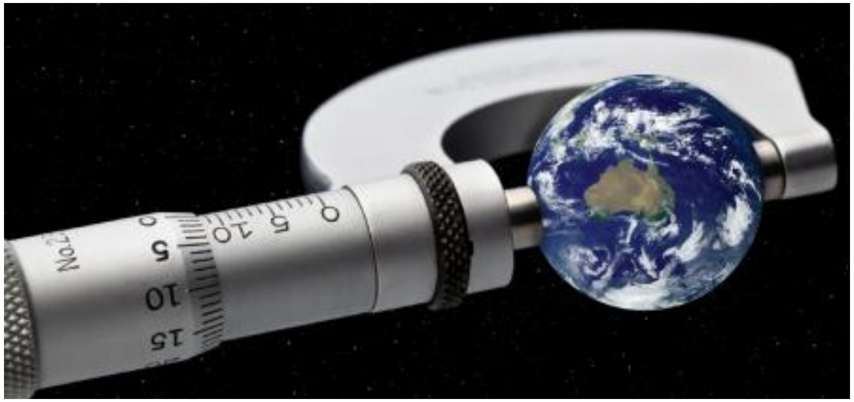
National Aeronautics and Space Administration
Goddard Space Flight Center

Lunar metrology for satellite instrument characterization

Joel McCorkel
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

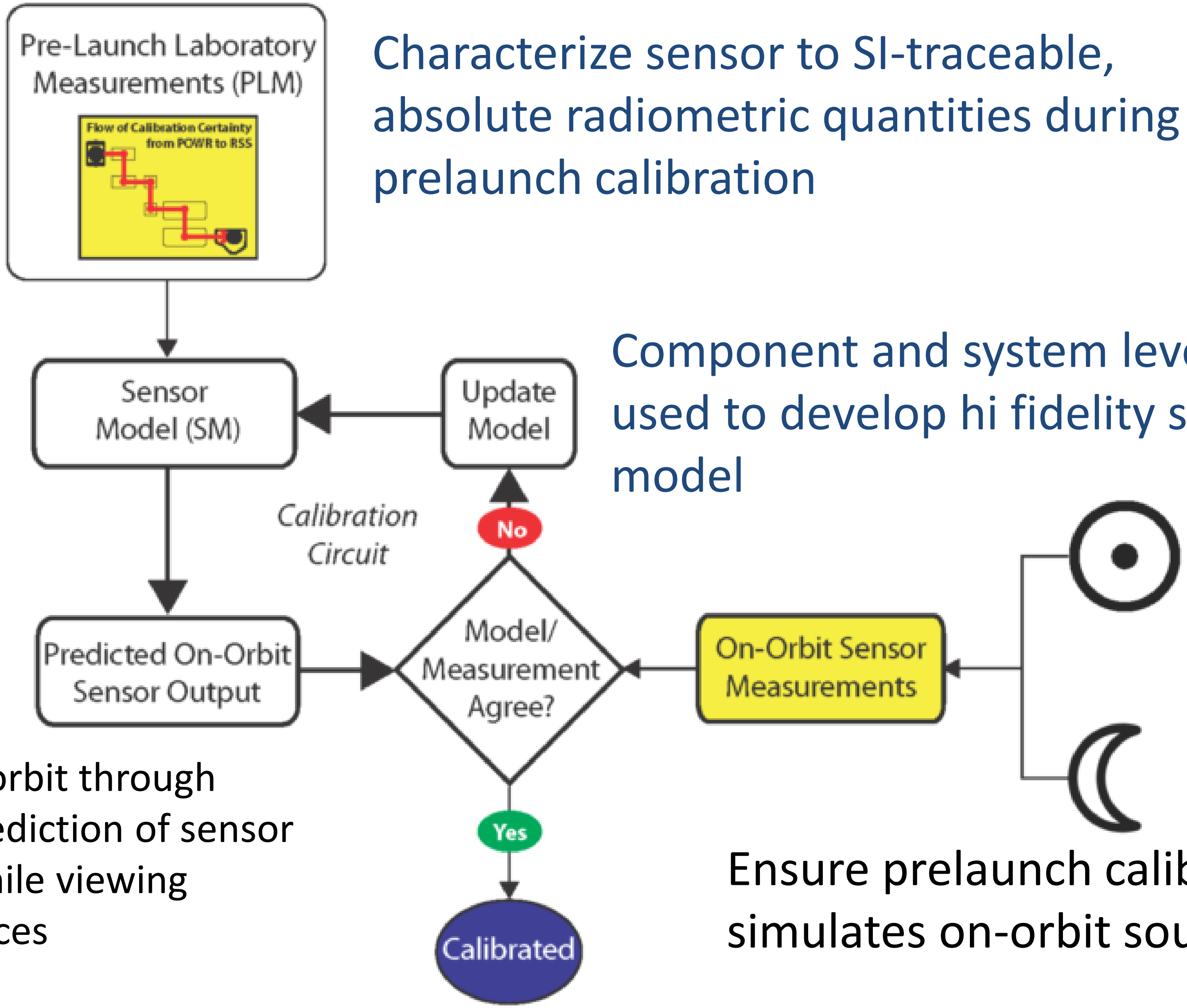


- CLARREO Mission
  - High accuracy calibration requirements
- SI traceability in the laboratory
  - NIST's SIRCUS (detector-based calibration with laser sources)
  - Calibration of G-LiHT, ORCA, SOLARIS (CLARREO), HyPlant, VIIRS
- Model-based sensor inter-calibration
  - Value of imaging spectrometer 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 hi fidelity sensor model

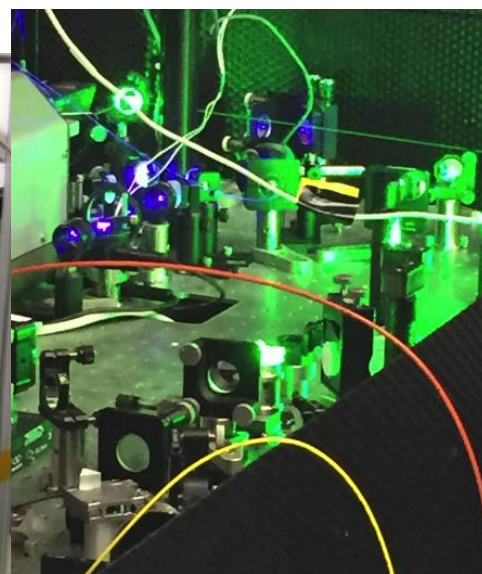


Transfer to orbit through accurate prediction of sensor behavior while viewing known sources

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

Uncertainty Estimates	Laboratory Calibration	Transfer to Orbit	Trending (MOON)	Combined Standard Uncertainty
SpMA-based	2 -3 %	2 % to 3 %	0.1% to 0.2%	3.5 %
SIRCUS-based	0.5 %	2 % % to 3 %	0.1% to 0.2%	3 %
Potential **w/1 % lunar cal-based Xfer to Orbit**	0.5 %	1 %	0.1% to 0.2%	1.25 %
Potential **w/0.25% lunar cal-based Xfer to Orbit**	0.1 %	0.25 %	0.1 %	0.3 %

*Butler, et al., Proc. SPIE 6677, 667707 (2007).

Studying the moon

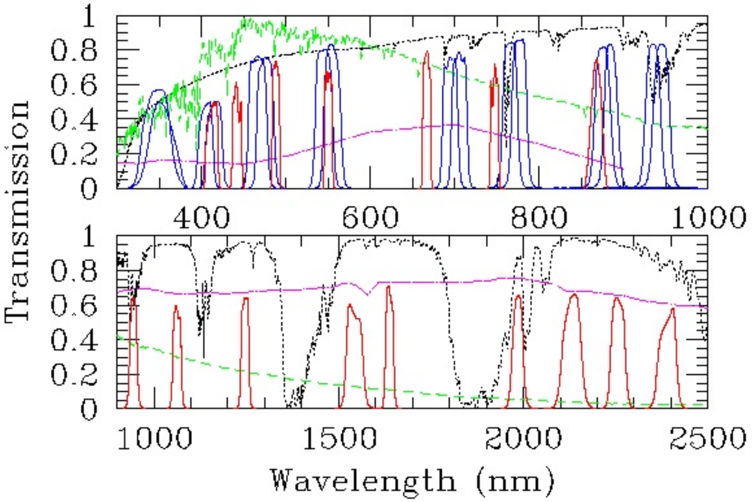
- USGS measurement/model
- NIST measurements
- CLARREO
  - Climate Absolute Radiance and Refractivity Observatory
- Satellite measurements
- EO-1 Hyperion measurements

USGS ROLO

RObotic Lunar Observatory

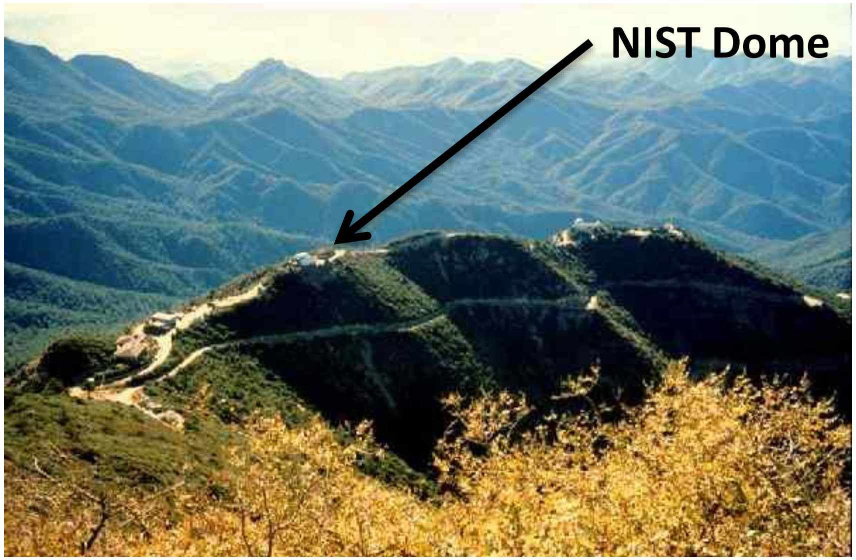
T. Stone and H. Keiffer

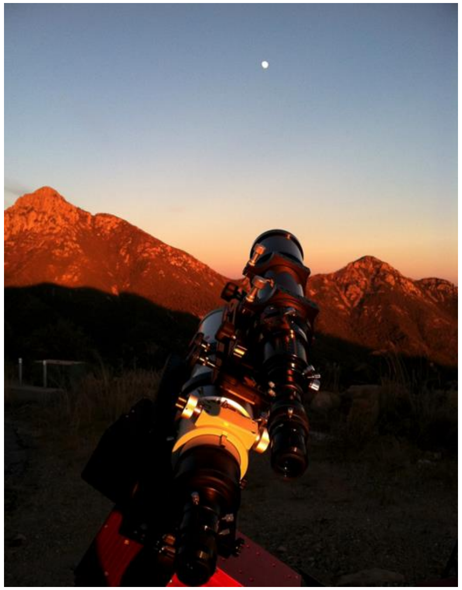
- Capture and model the moon's spectral and radiometric signal throughout its phase and librations.
- Measurements
  - 23 VNIR, 9 SWIR bands
  - 85k lunar images over 6 years
- Uncertainties
  - 5-10%



NIST lunar measurements

Mt Hopkins, AZ





Steve Brown

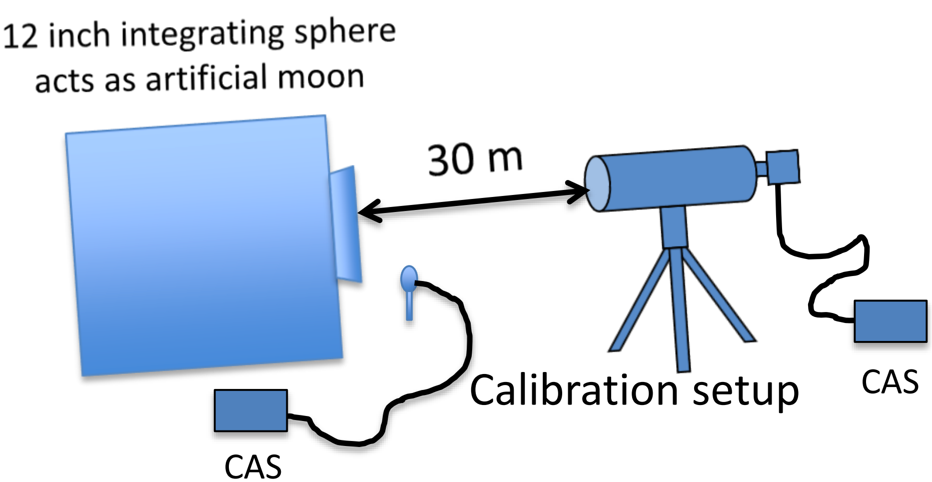
Keith Lykke

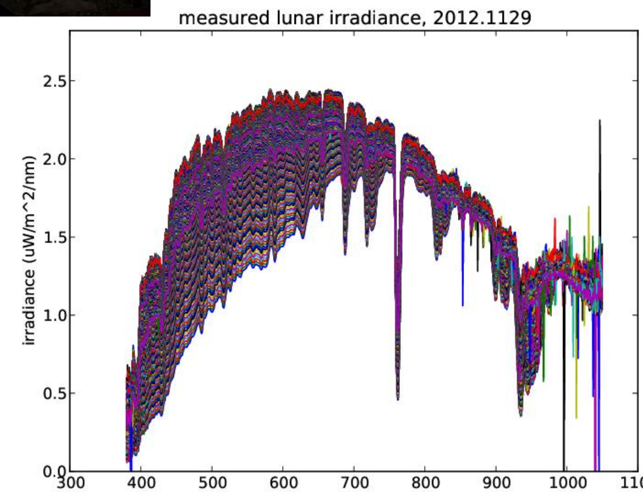
Claire Cramer

John Woodward

NIST

Gaithersburg, MD

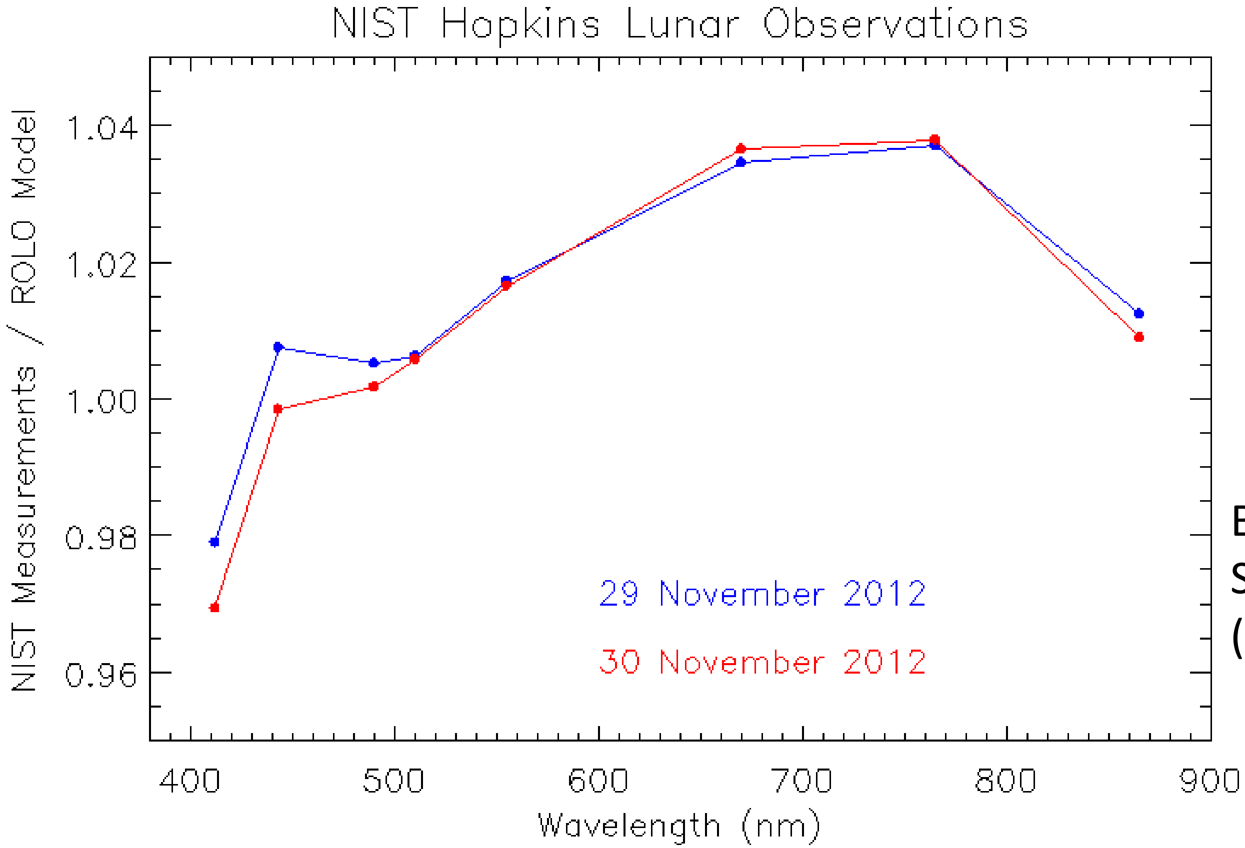




$$I_{meas}(\lambda, t) = I_0(\lambda, t)e^{-\sum m_i \tau_i}$$

Comparison with ROLO model

NIST-measured Irradiance/ROLO-predicted Irradiance



Band-averaged to SeaWiFS Bands (Lunar Model v311g)

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

NIST measurement uncertainty

Combined Standard Uncertainty in Lunar Irradiance

Spectral Irradiance of the Moon at 11:40:43 on 30 November, 2012 UT

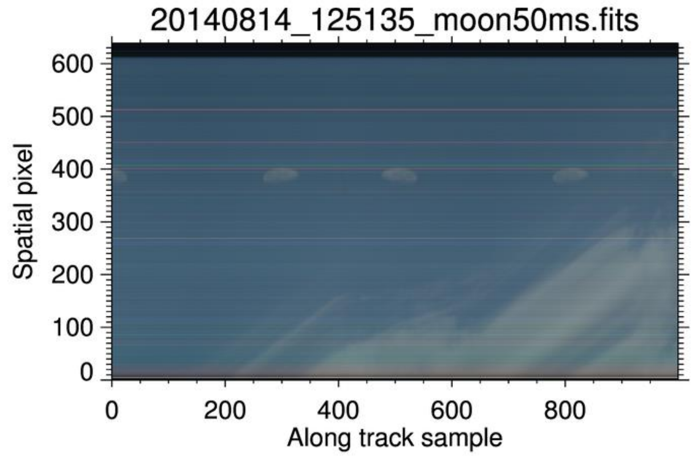
Wavelength (nm)	Spectral irradiance (μW m^{-2} nm^{-1})	Uncertainty (percent)
449.7	2.348	0.85
499.9	2.395	0.56
550.0	2.633	0.45
600.2	2.669	0.44
650.1	2.598	0.40
702.8	2.474	0.38
750.0	2.314	0.37
850.2	1.870	0.36
1000.2	1.387	0.54

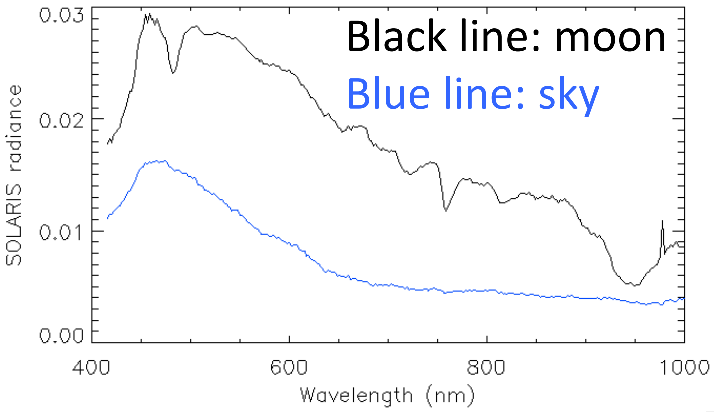
Over this spectral range:

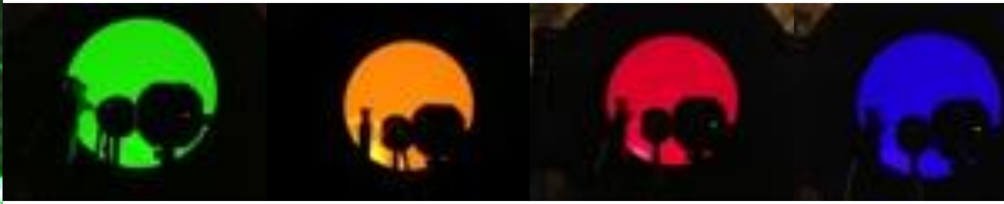
- Magnitude and an uncertainty (at the particular phase and libration angles) with the telescope calibration tied to the SI.
- Provides a means to re-scale the ROLO Model (by the TOA Lunar Irradiance)and to develop a constrained uncertainty budget including phase and libration uncertainties and establish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

CLARREO measurements at Goddard

CLARREO calibration demonstration system





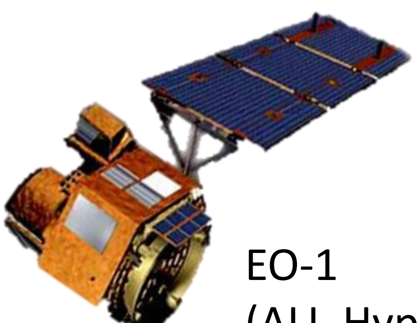


Space-based measurements

Orbview 2 (SeaWiFS)

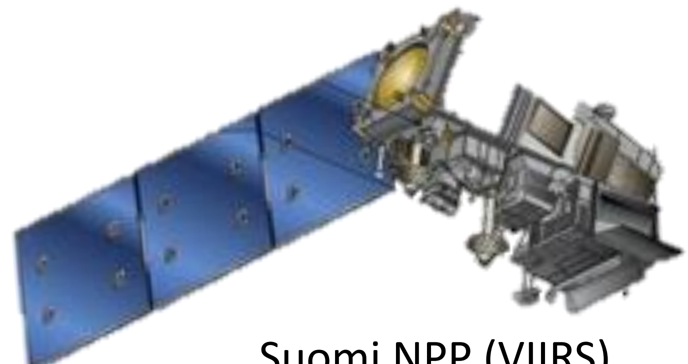
Landsat 8 (OLI, TIRS)

Terra (MODIS)



EO-1
(ALI, Hyperion)

Pléiades

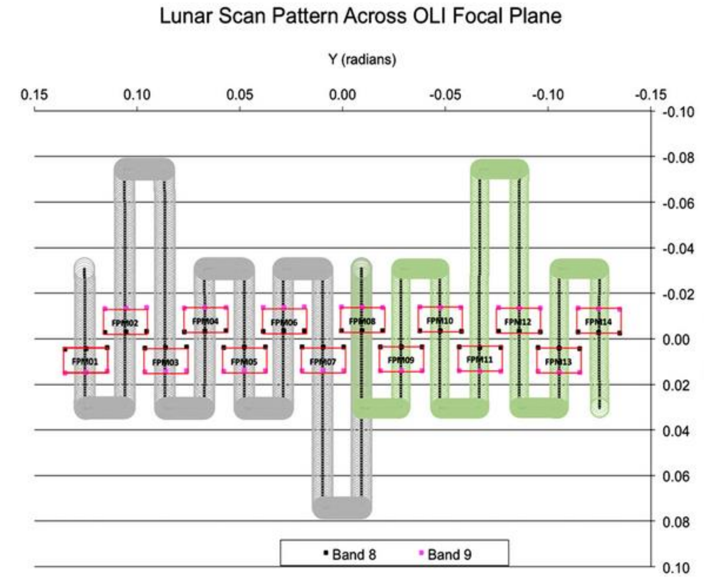


Suomi NPP (VIIRS)

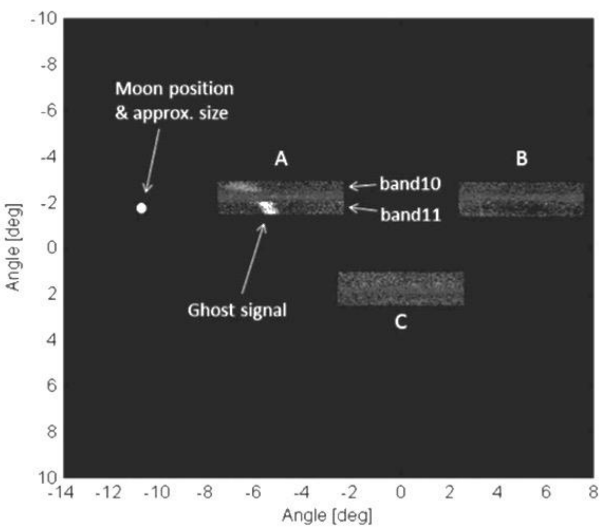
Landsat 8 measurements

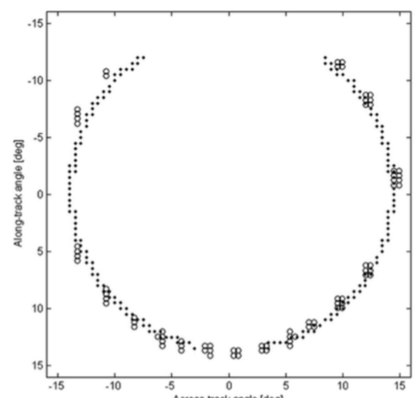
- Operational Land Imager (OLI)

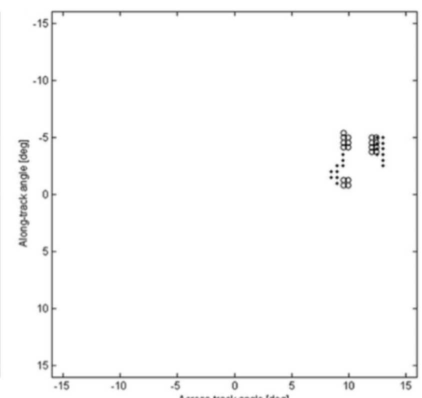
Monthly measurements
at ~7 degree phase angle



- Thermal Infrared Sensor (TIRS)

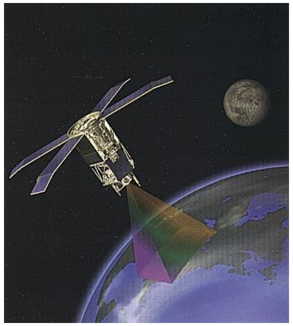






Montanaro, Matthew, Aaron Gerace, and Scott Rohrbach. "Toward an operational stray light correction for the Landsat 8 Thermal Infrared Sensor." Applied Optics 54.13 (2015)

SeaWiFS

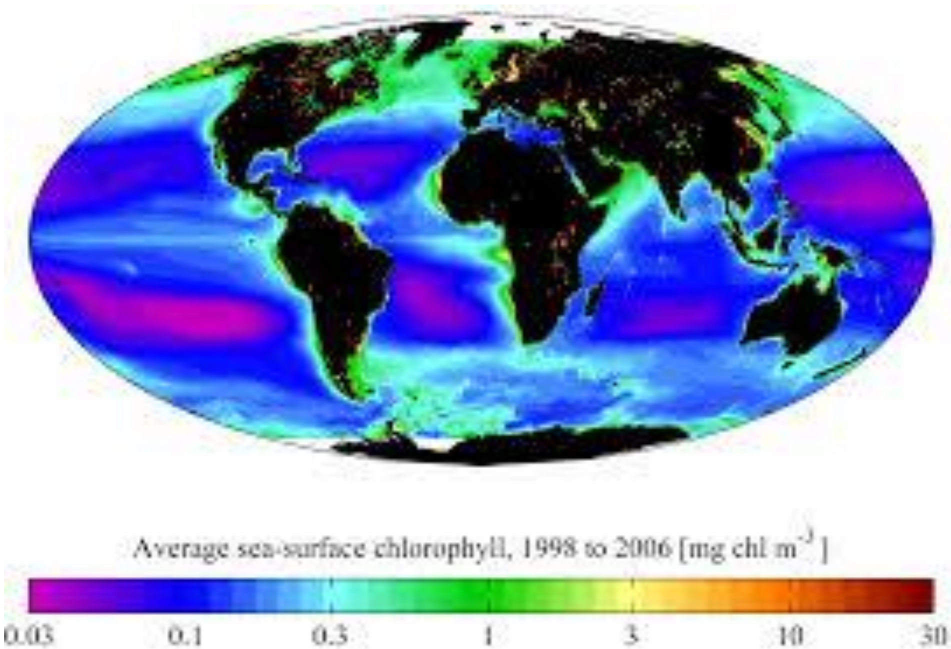


Gene Eplee, NASA Goddard

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

Aug. 1, 1997 – Dec. 10, 2010

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



Chl concentration [mg chl m^{-3}]

SeaWiFS Bands

SeaWiFS Band	Band Center Wavelength [nm]	Bandwidth [nm]
1	412	20
2	443	20
3	490	20
4	510	20
5	555	20
6	670	20
7	765	40
8	865	40

Phase Dependence of MODIS Terra/Aqua and SeaWiFS Lunar Measurements

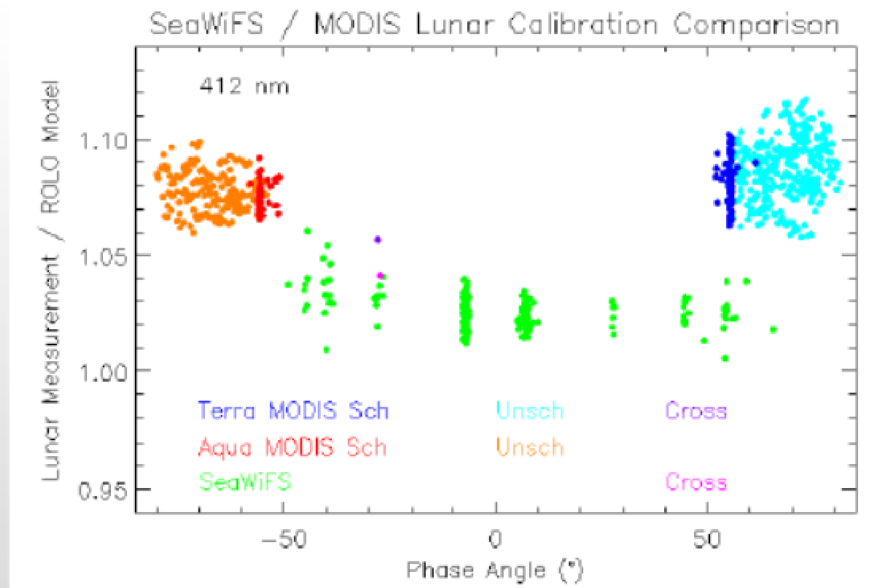
Top Plot: Inherent scatter in a series of lunar measurements at 412 nm

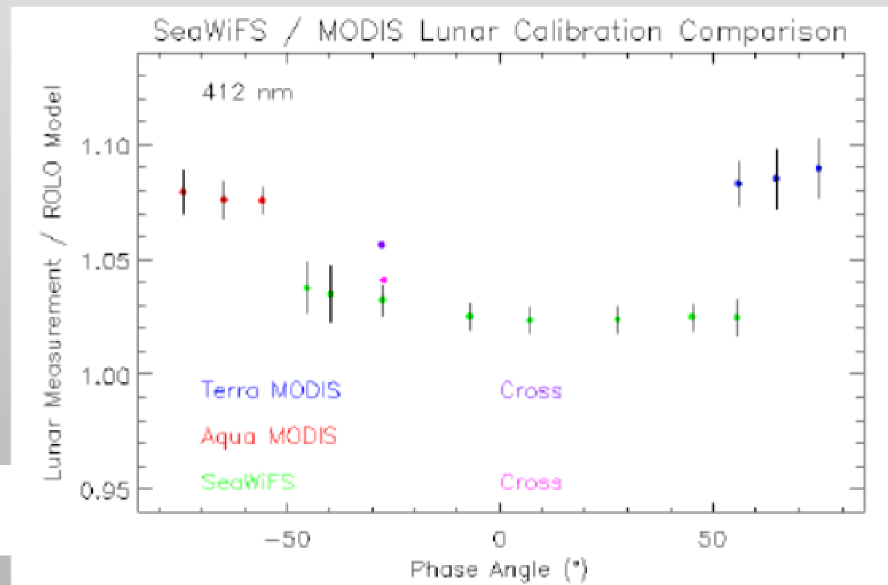
Bottom Plot: binned residuals plotted as means with STDs (412 nm)

– 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)

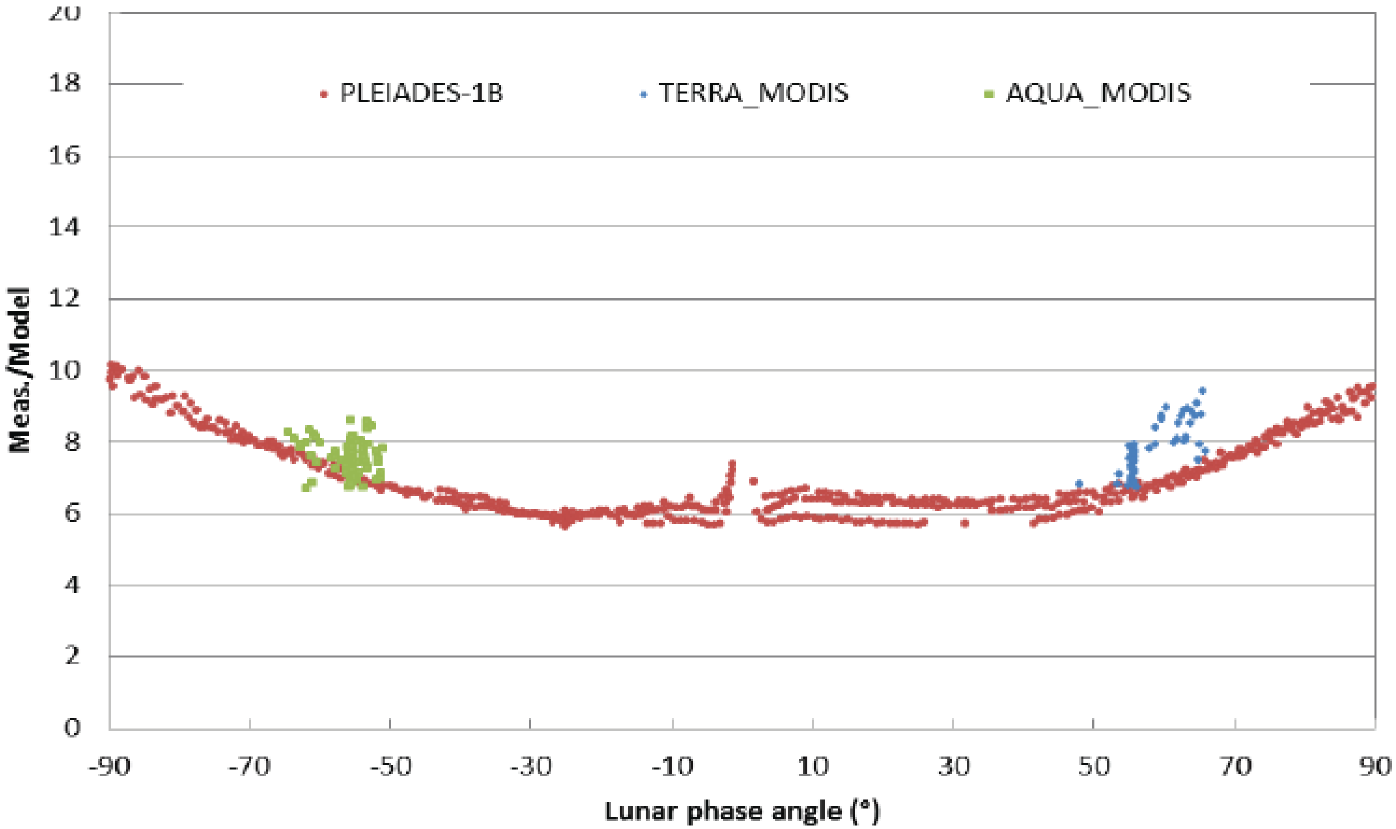




Phase Dependence from Eplee, et al., Appl. Opt. 50, 120 (2011). presented by Jim Butler at the 2012 Lunar Irradiance Workshop

Pléiades

Phase dependence of ROLO Model in comparison with MODIS and Pleiades-1B 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.

Xiong, et al., Comparison of MODIS ands PLEIADES Lunar Observations, Proc. SPIE 9241, 924111 (2014).

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