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

Talk given by Joe Rice

Lead Author: Steven W. Brown/NIST

Keith Lykke (dec.), Claire Cramer (left NIST, now at DOE)
John Woodward/NIST
Gene Eplee/NASA Goddard
Tom Stone/USGS
Sophie Lacherade, CNES

FY2016 CLARREO Path Finder Meeting:

Can the Moon be used as an absolute exo-atmospheric calibration target for CLARREO and other Earth-observing instruments?

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

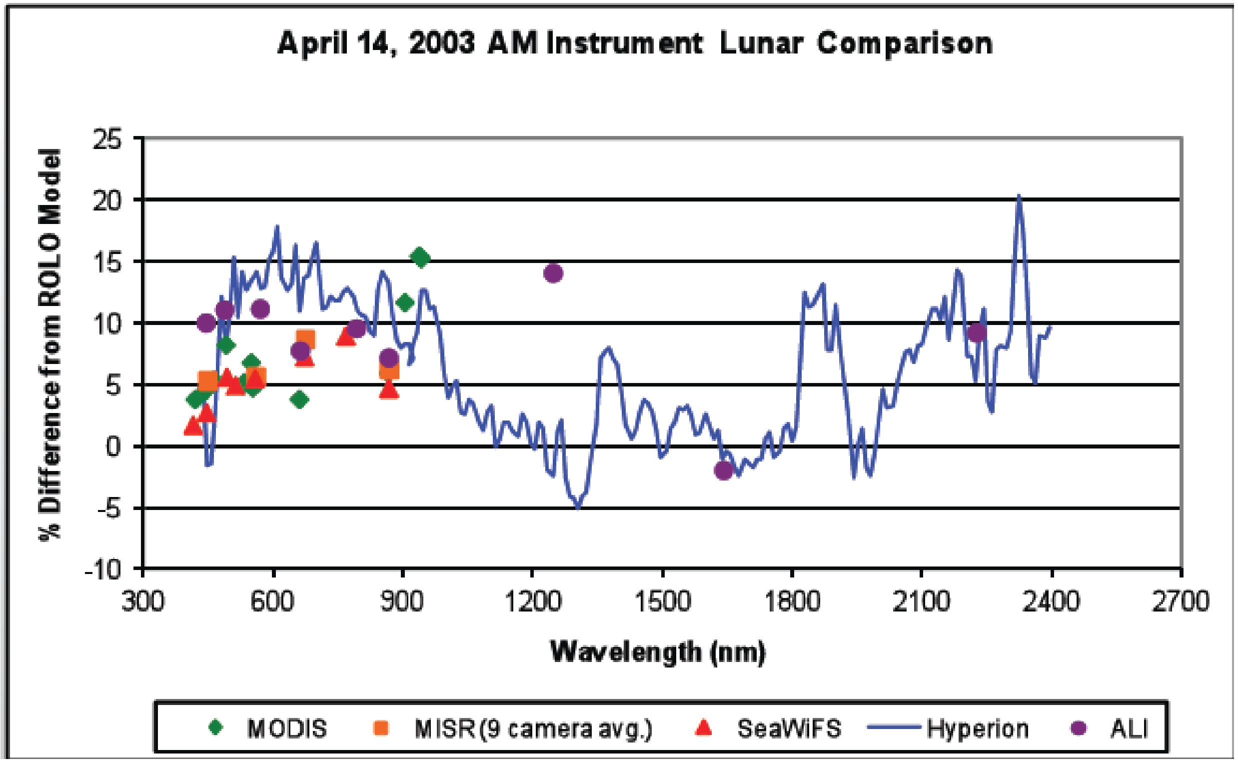
OUTLINE

- 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^{o} (VIIRS)

(Phase-dependence and libration items:) Gene Eplee NASA

How well does it do? & What are the uncertainties?

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

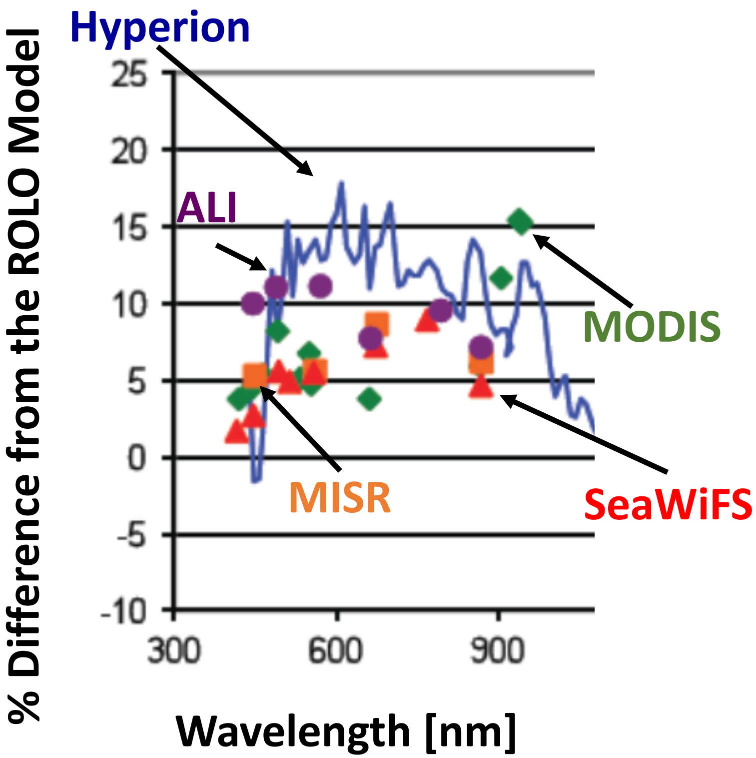


Relative differences between instruments include uncertainty components from:

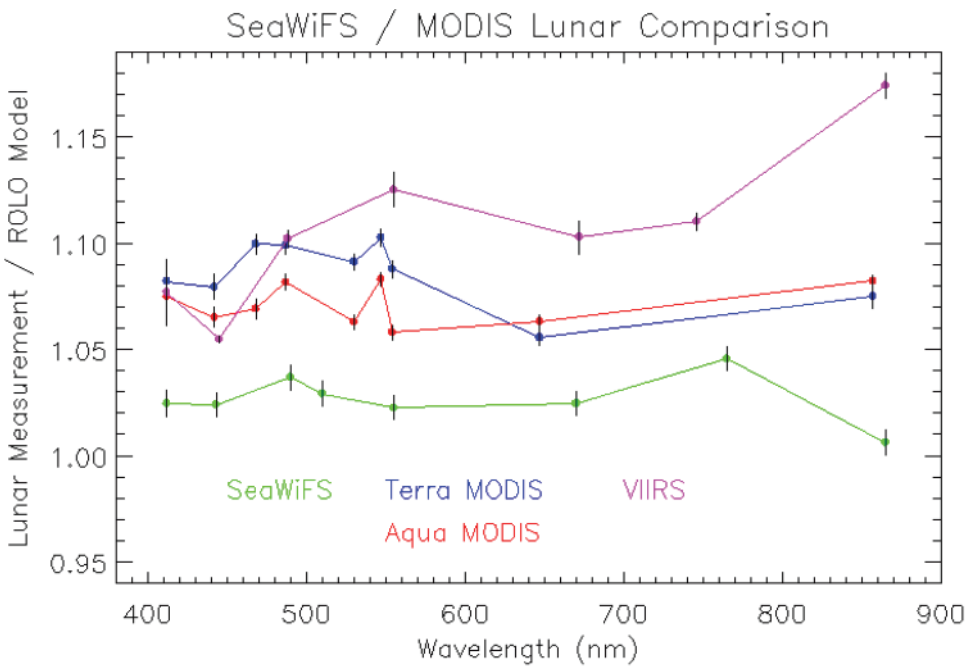
- Use of different solar irradiance spectra
- Different approaches in calculating integrated lunar irradiances
- Inherent differences/uncertainties in instrument calibrations

Uncertainties in the ROLO Model estimated to be 5 % to 10 %, not SI traceable.

ROLO Model v Satellite sensors (Absolute)



SeaWiFS
MODIS
VIIRS



Stone, USGS

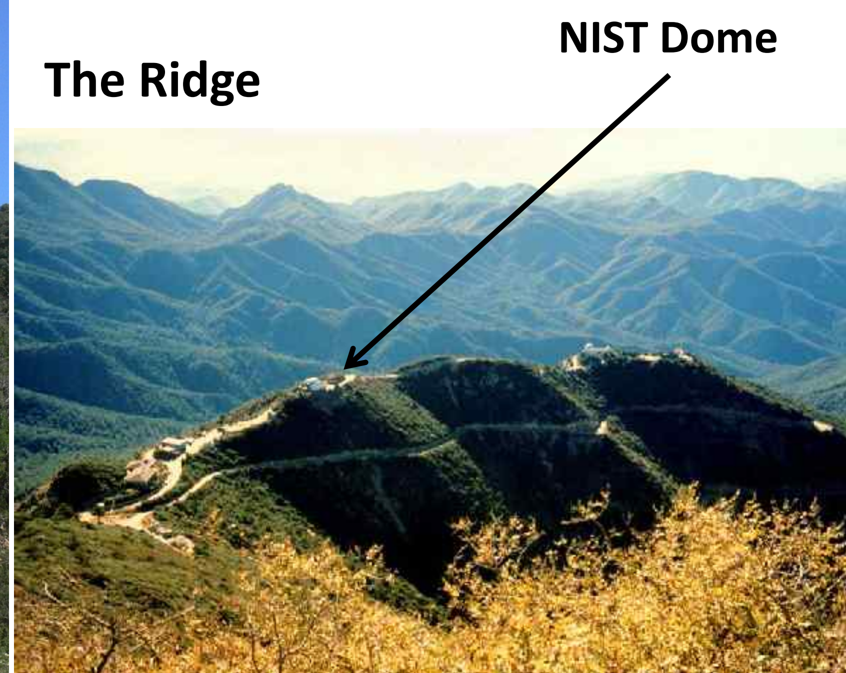
Eplee, Goddard

NIST measurements of TOA Lunar Irradiance
Whipple Observatory, Mt Hopkins, Amado AZ

Santa Rita Mountains, Coronado National Forest, ~30 miles from Nogales, Mexico

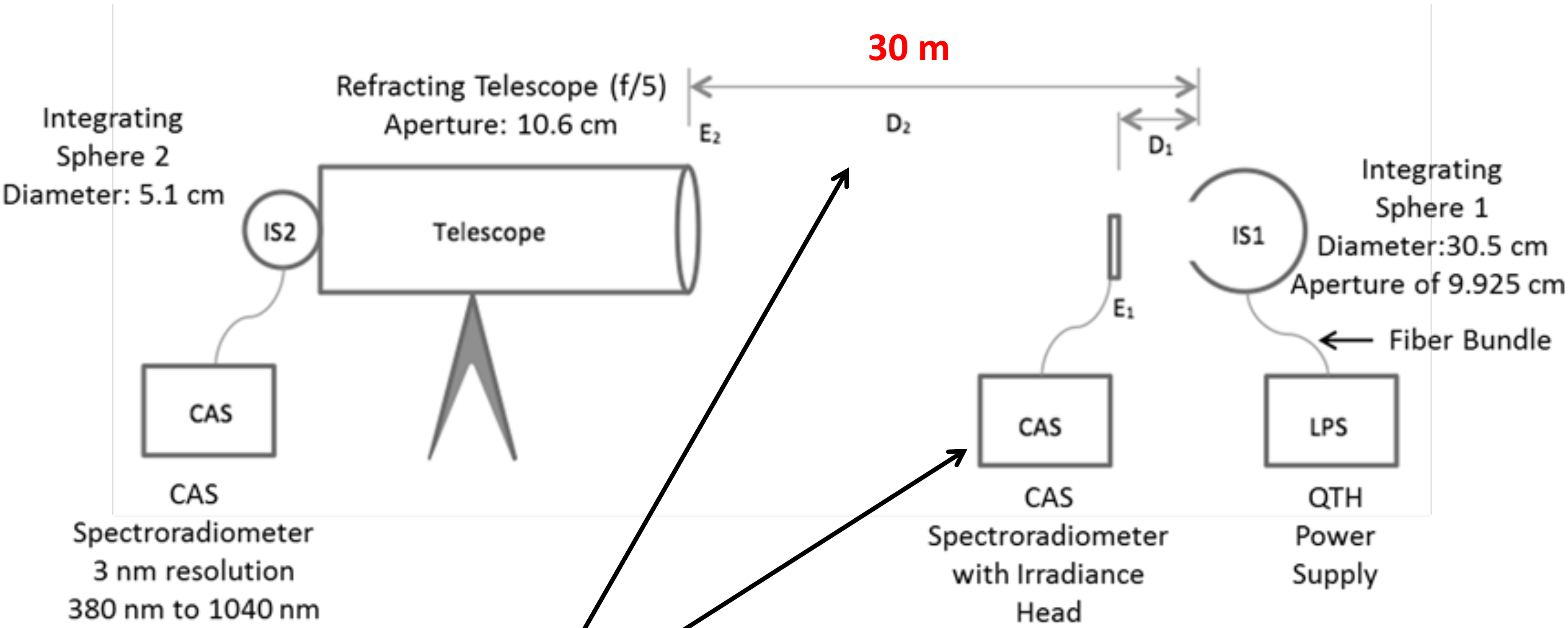
NIST Absolute Top-of-the-Atmosphere (TOA) Lunar Irradiance Measurements have been made at the Whipple Observatory, Mt. Hopkins, AZ for ~ 3 years (two two-week visits, Spring and Fall, per year)

Lunar measurements piggy-backing on a longer time series of stellar measurements designed to establish a suite of SI-traceable absolutely calibrated 'standard' stars



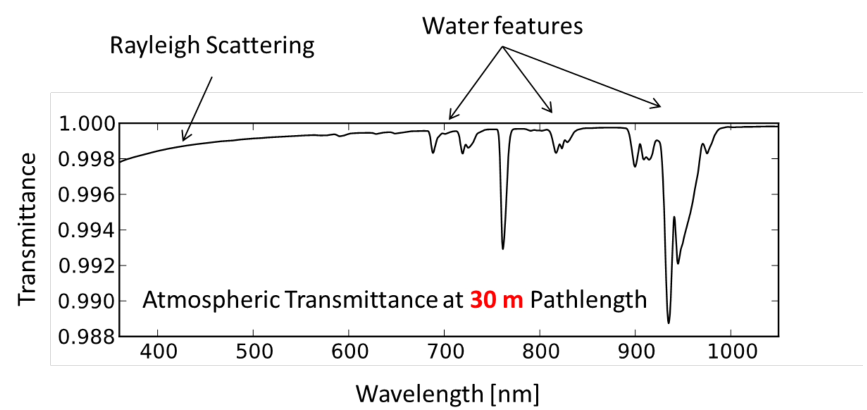
ROLO calibration based on measurements of Vega; NIST standard star measurements include Vega.

Calibrating the Telescope – on the Ground



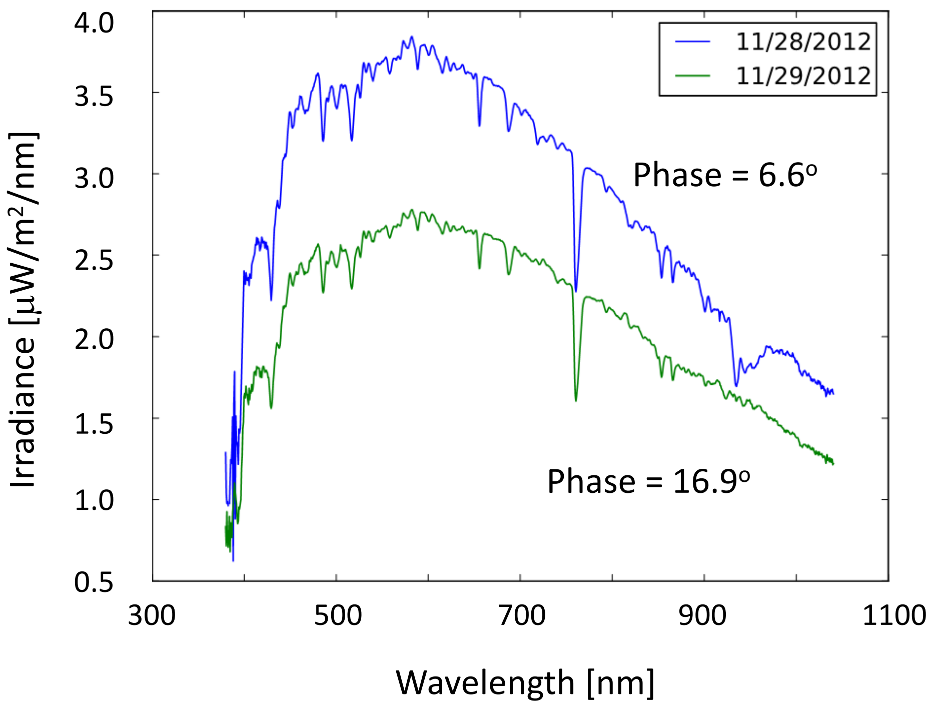
Uncertainties dominated by

- Atmospheric transmittance
- Reference Instrument



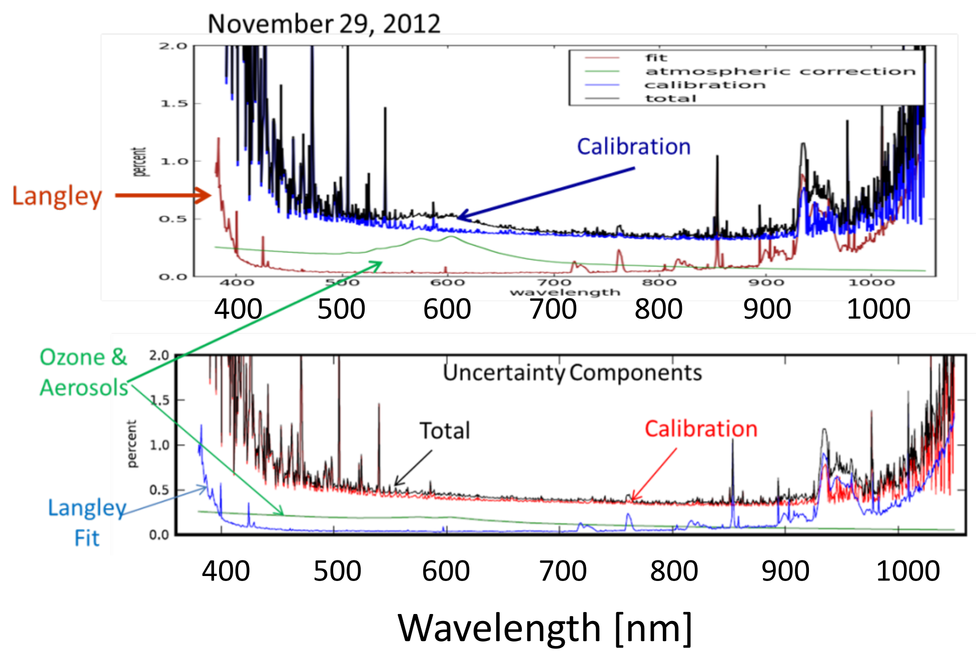
Absolute TOA Lunar Irradiance

Lunar Irradiance



~40 % difference in magnitude
10° difference in phase

Uncertainty Budget

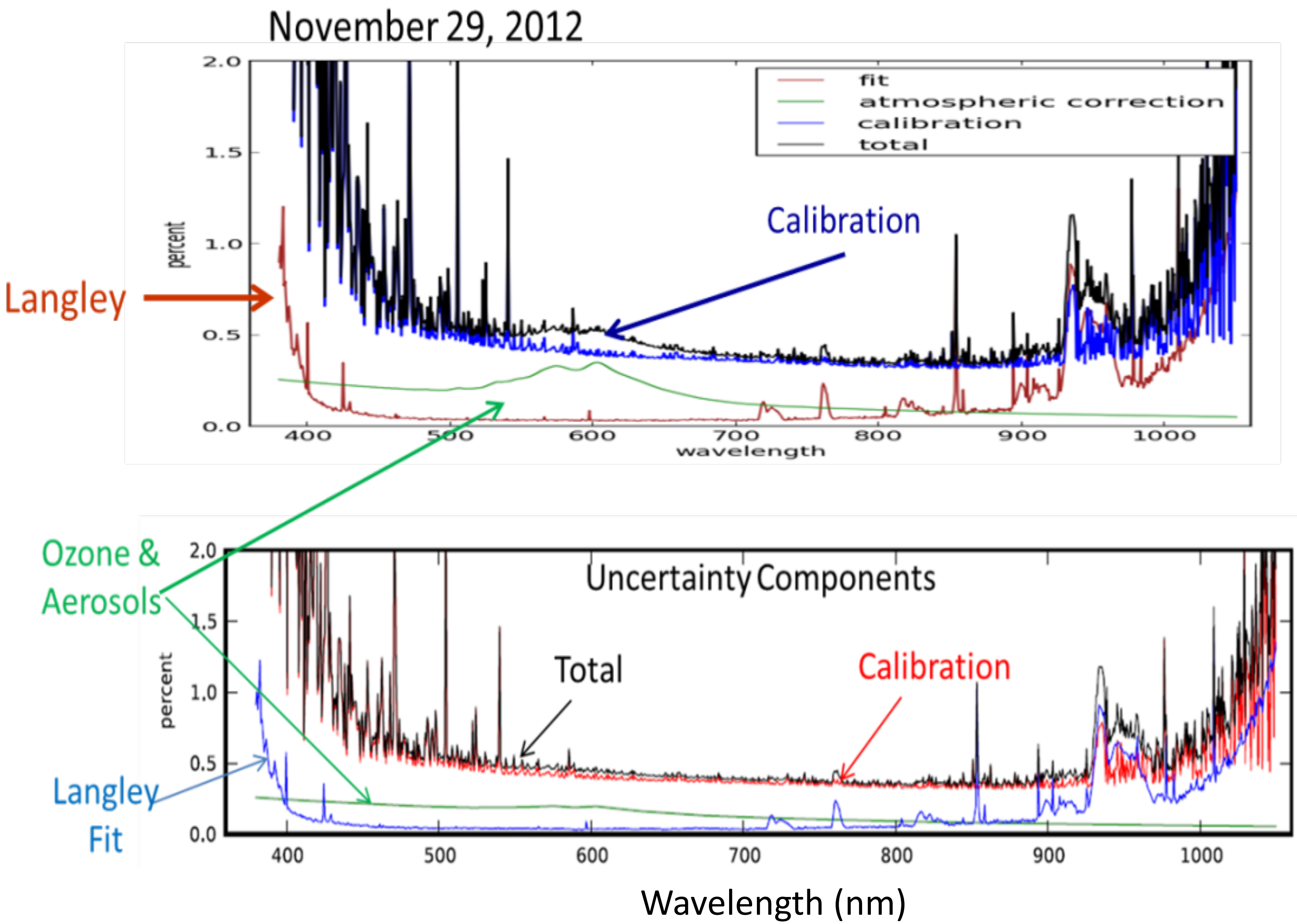


Uncertainty dominated by the Telescope Calibration from 500 nm to 920 nm

Cramer, C.E., et al., *Precise measurement of lunar spectral irradiance at visible wavelengths.* J. Res. Nat'l. Inst. Stds. Technol., 2013. **118**: p. 396-402.

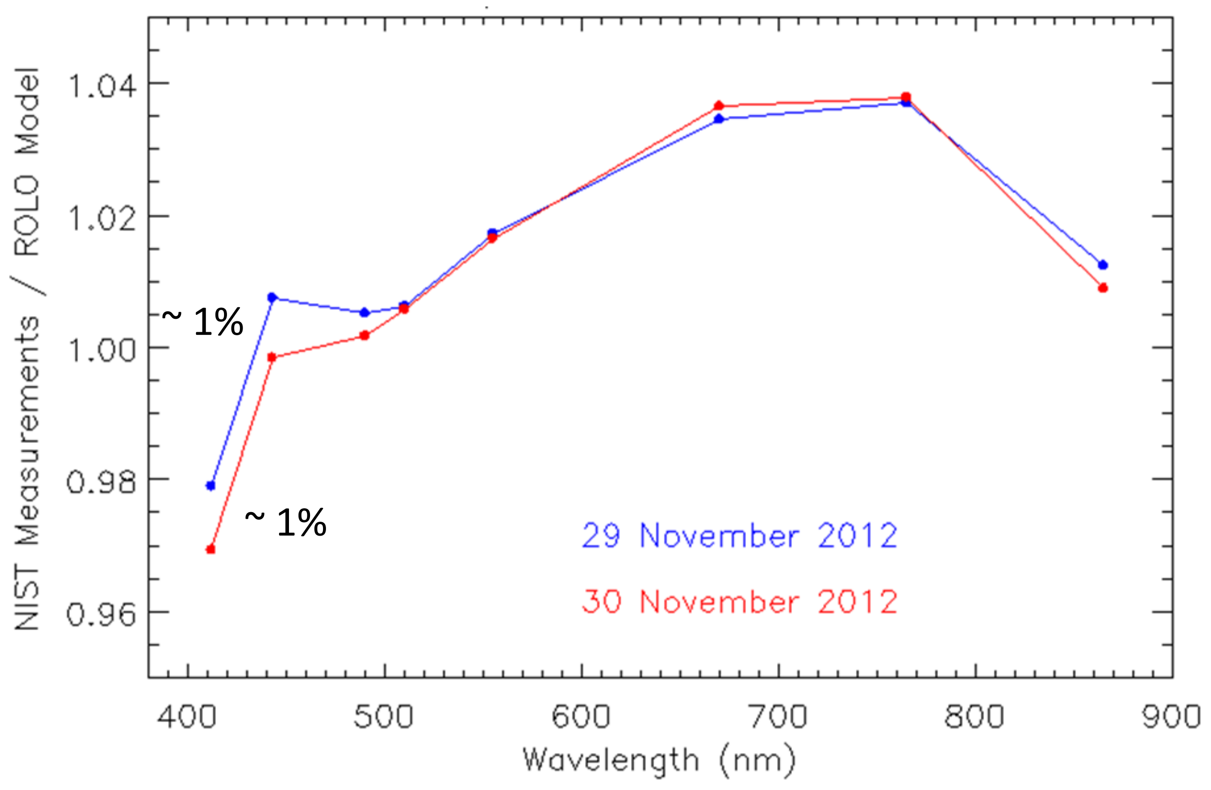
Absolute TOA Lunar Irradiance (*k*=1) Uncertainty Budget

Uncertainty dominated by the Telescope Calibration



Comparison between Measurements and the ROLO Model
Band-averaged to SeaWiFS Bands

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

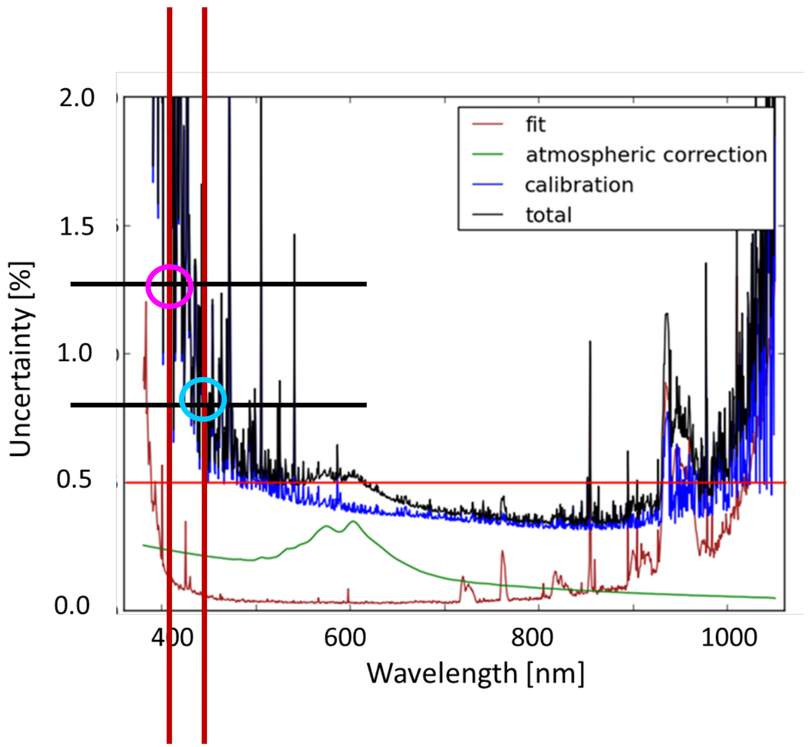


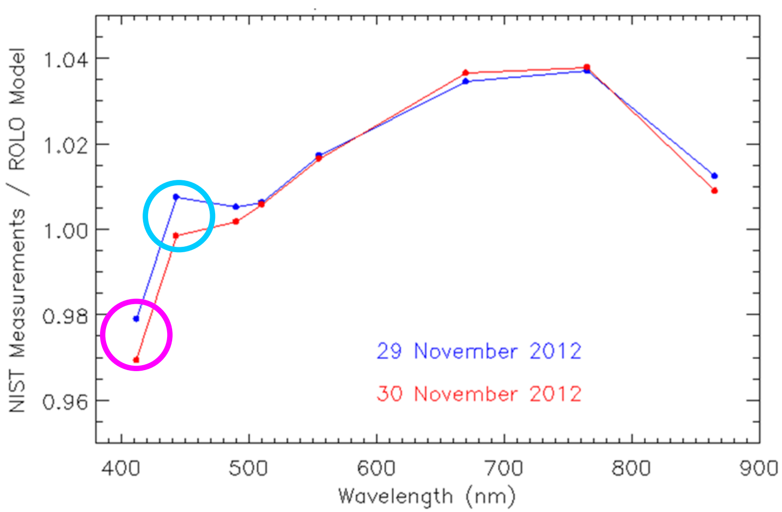
For the 2 nights, the irradiance differed by 40 % and the phase by 10 %.

(Gene Eplee, NASA Goddard)

Comparison between Measurements and the ROLO Model

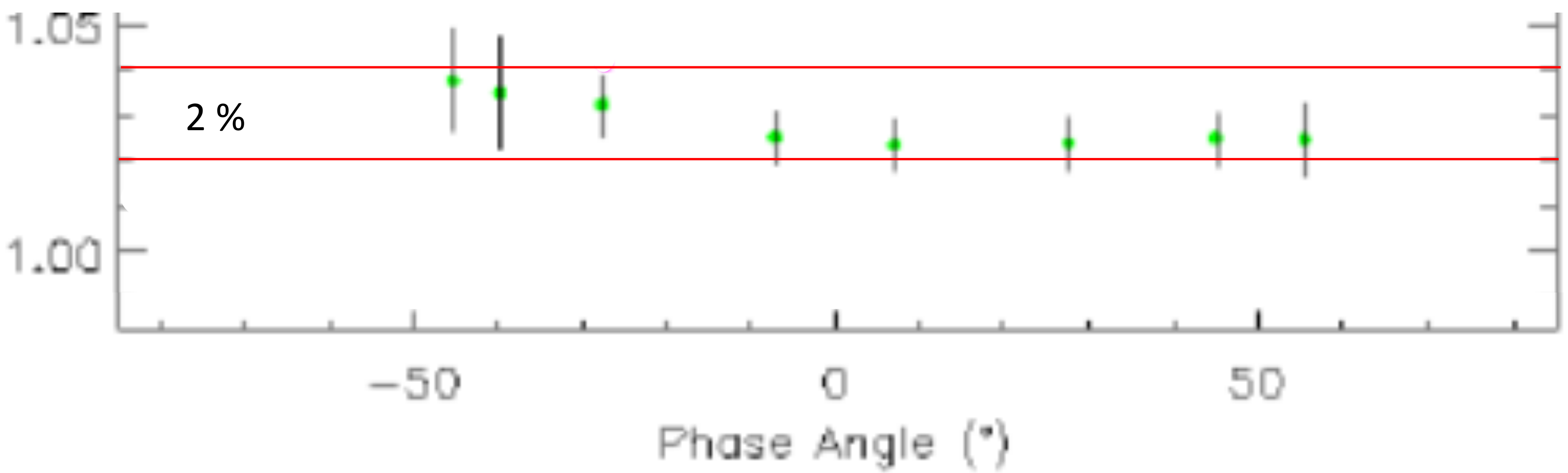
Consider Uncertainties





Empirical Phase Correction to the ROLO Model from SeaWiFS Measurements of the Moon

Uncertainty in lunar irradiance v phase : 1.7 % (-50° to -6° and 5° to 60°)



Magnitude of the uncertainty in the libration correction: 0.5 %

Gene Eplee, NASA Goddard

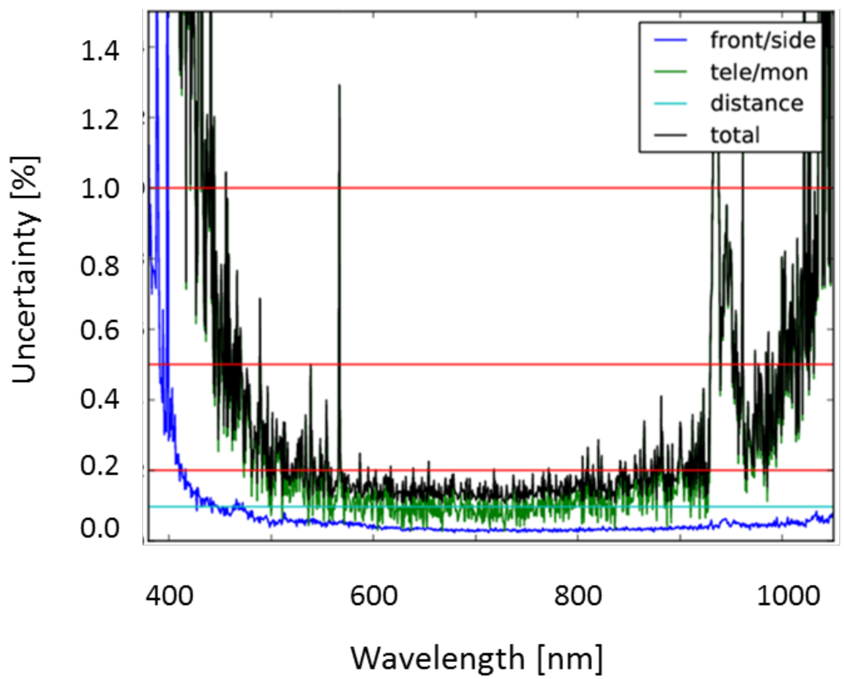
Absolute Lunar Irradiance Uncertainty Budget
(including uncertainties in phase and libration correction factors)

	Uncertainty component (k=1) [%]			
Wavelength [nm]	Absolute Irradiance	Phase Correction (7^{o} to 50^{o})	Libration correction	Combined Standard Uncertainty [%]
400	1.5	1.7	0.5	2.32
450	0.85	1.7	0.5	1.97
500	0.56	1.7	0.5	1.86
550	0.45	1.7	0.5	1.83
600	0.44	1.7	0.5	1.83
650	0.4	1.7	0.5	1.82
700	0.38	1.7	0.5	1.81
750	0.37	1.7	0.5	1.81
800	0.36	1.7	0.5	1.81
850	0.36	1.7	0.5	1.81
900	0.35	1.7	0.5	1.81

Multi-band filter radiometry → Hyperspectral measurements
Uncertainties reduced from 5 - 10 % to ~2 %; the tie-points are SI-traceable.

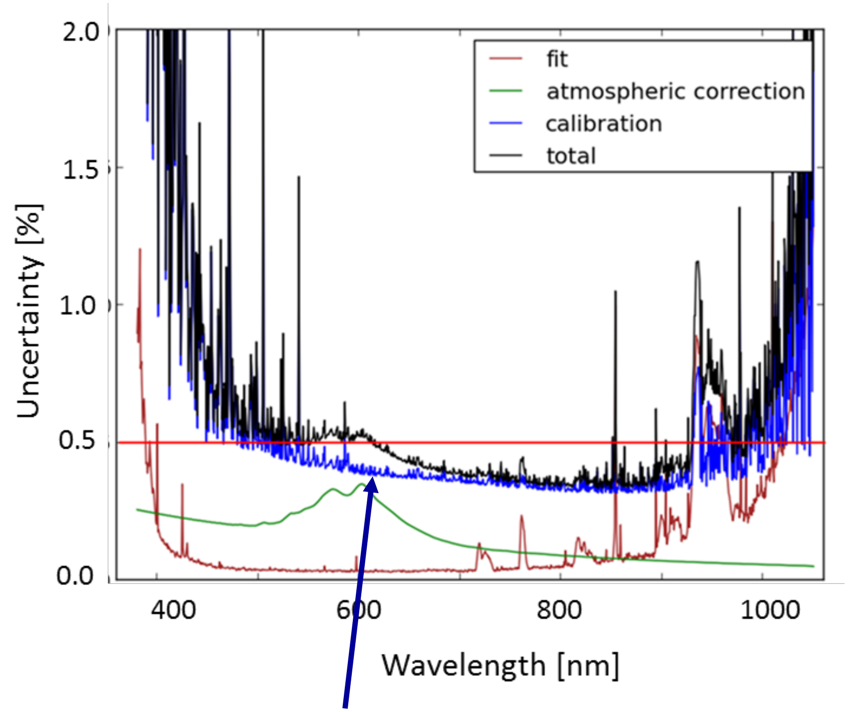
1. Absolute Irradiance

Calibration Uncertainty Telescope Only



Tele/Mon = telescope calibration
Assuming no uncertainty in the Reference CAS Calibration

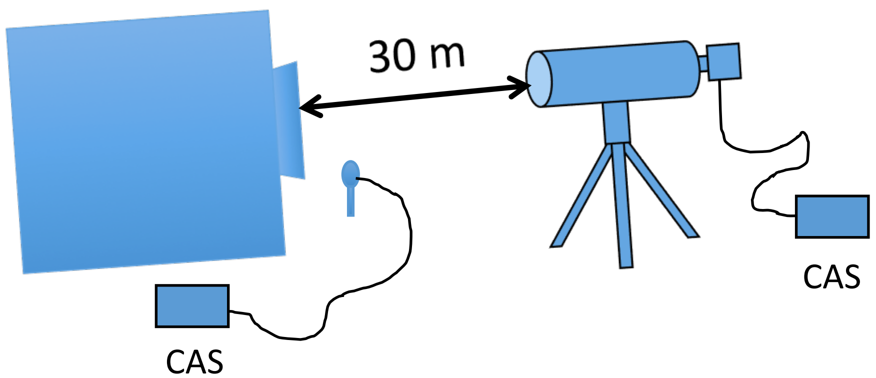
Measurement Uncertainty Lunar Irradiance



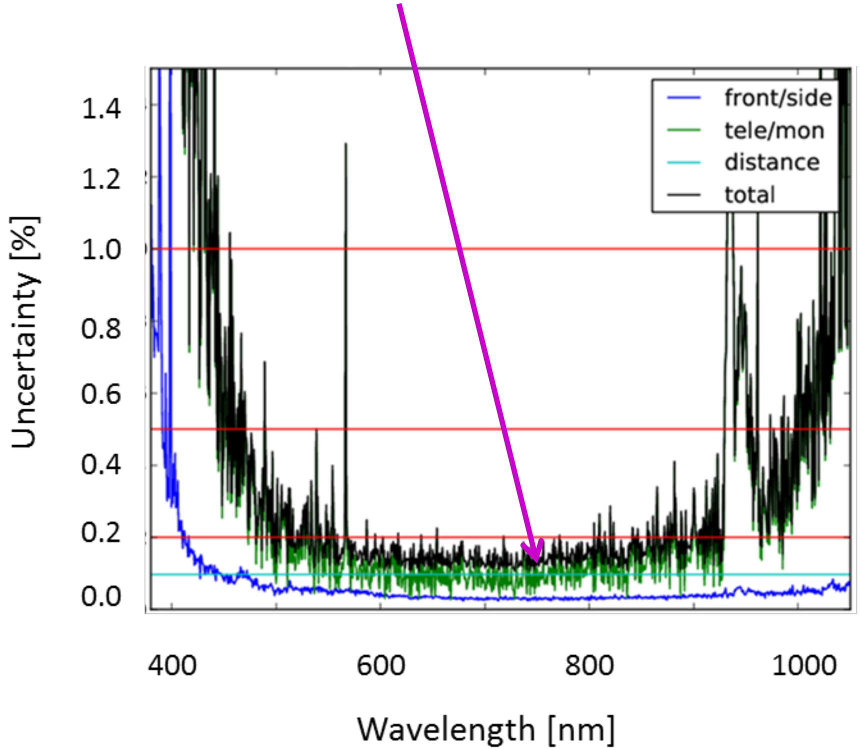
Calibration uncertainty component

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

Calibrating the Telescope in the field



Tele/Mon = telescope calibration



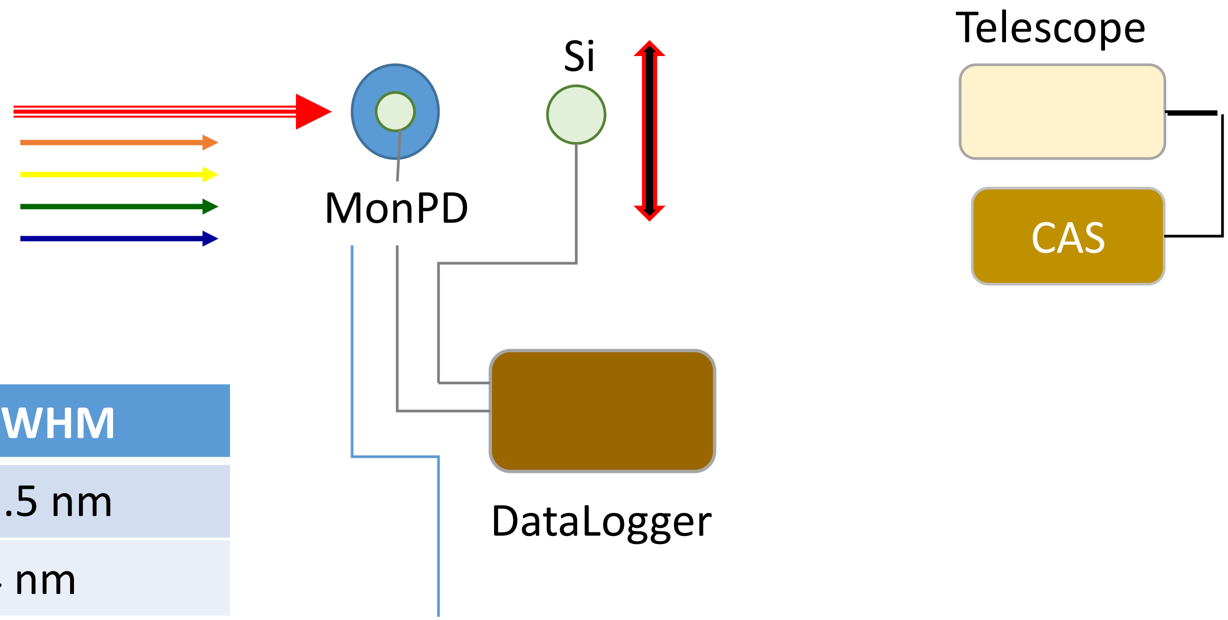
-Uncertainty component for this part is between 0.1 % and 0.2 %
500 nm to 900 nm

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



	Range (nm)	FWHM
Vis-NIR	400 - 1000	2.5 nm
SWIR	1000 - 2300	4 nm

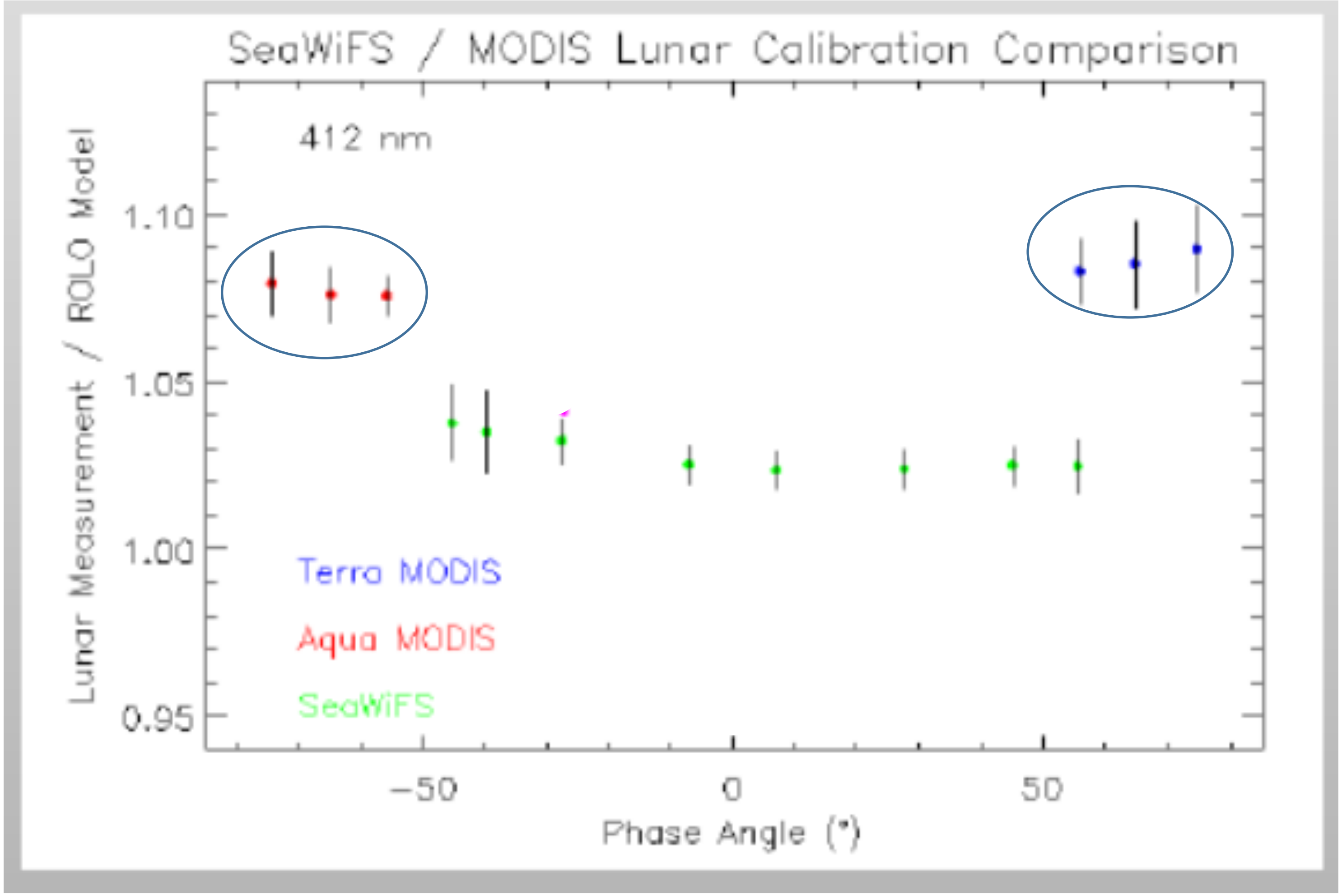
WL scale verified by high res SG

Scale held on Si PDs

2. Back to the ROLO Model: Phase dependence

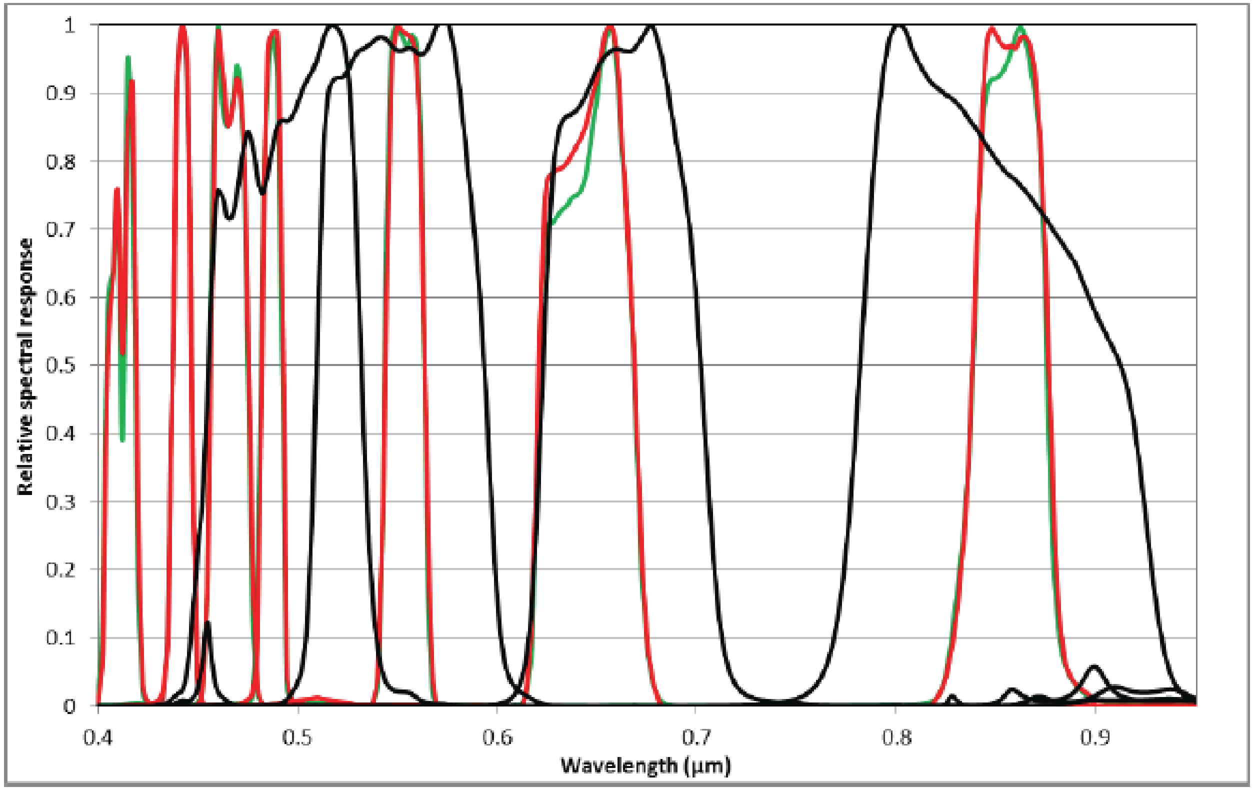
Look at other instruments for consistency.

MODIS and PLEIADES



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

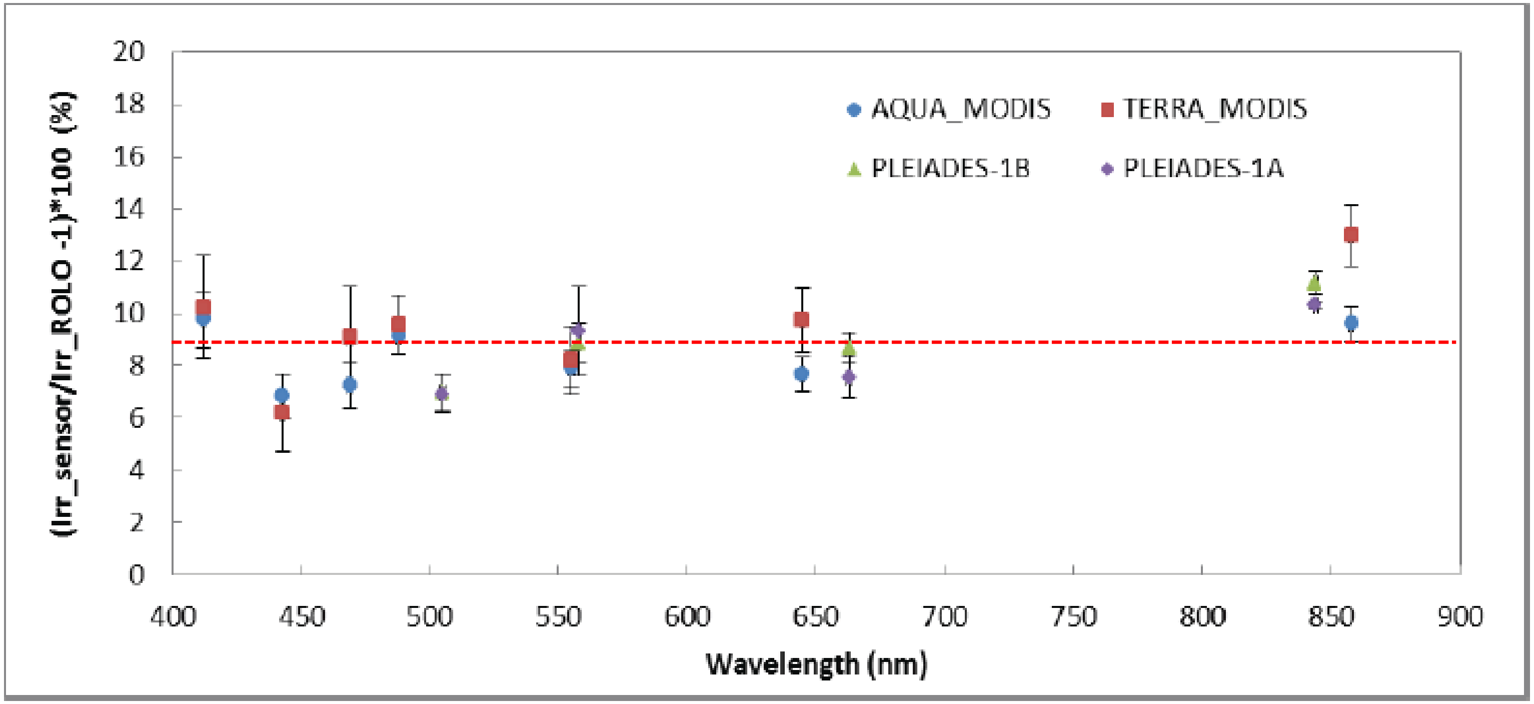


Pleiades: Black; Terra MODIS: Green; Aqua MODIS: Red

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

Pleiades and Modis v ROLO Model

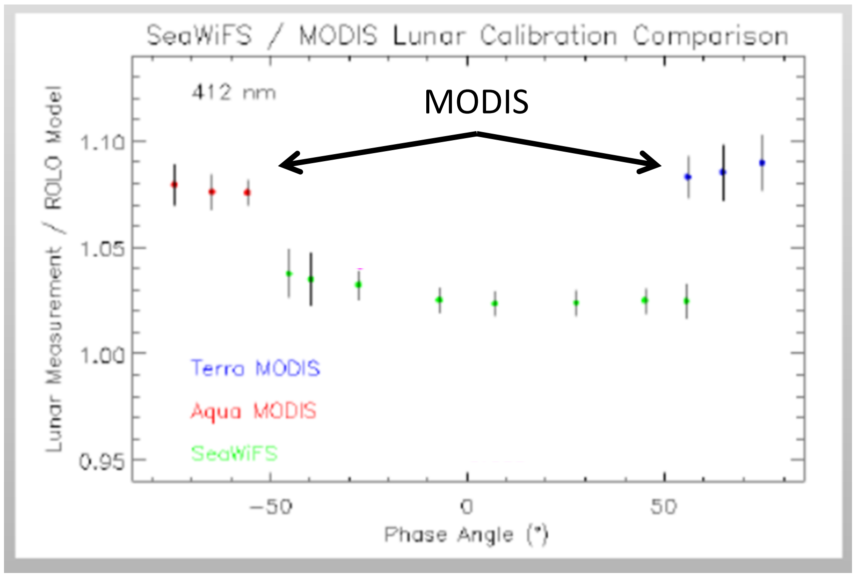
Phase angles of +/- 55.5°

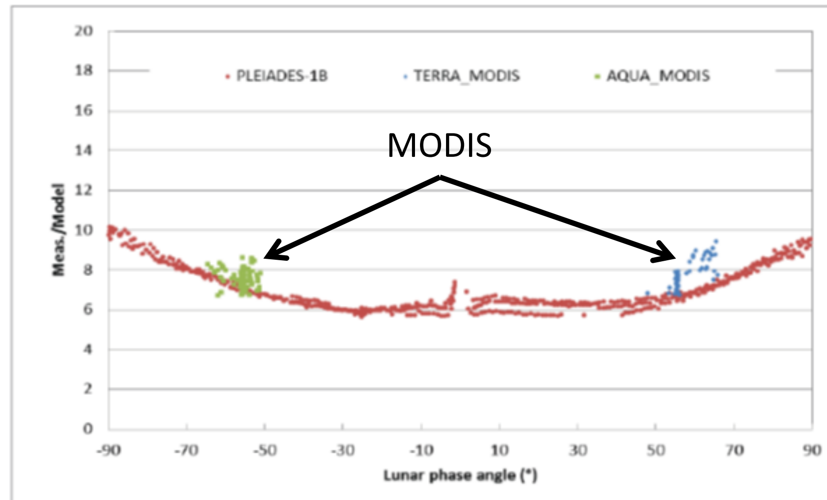


MODIS has an on-board diffuser – derives calibration from solar looks
PLEIADES calibration from ground-truth sites.
(SeaWiFS used a lamp-illuminated Integrating Sphere.)

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

Empirical correction to the Phase dependence of the ROLO Model using MODIS, Pleiades-1B and SeaWiFS measurements

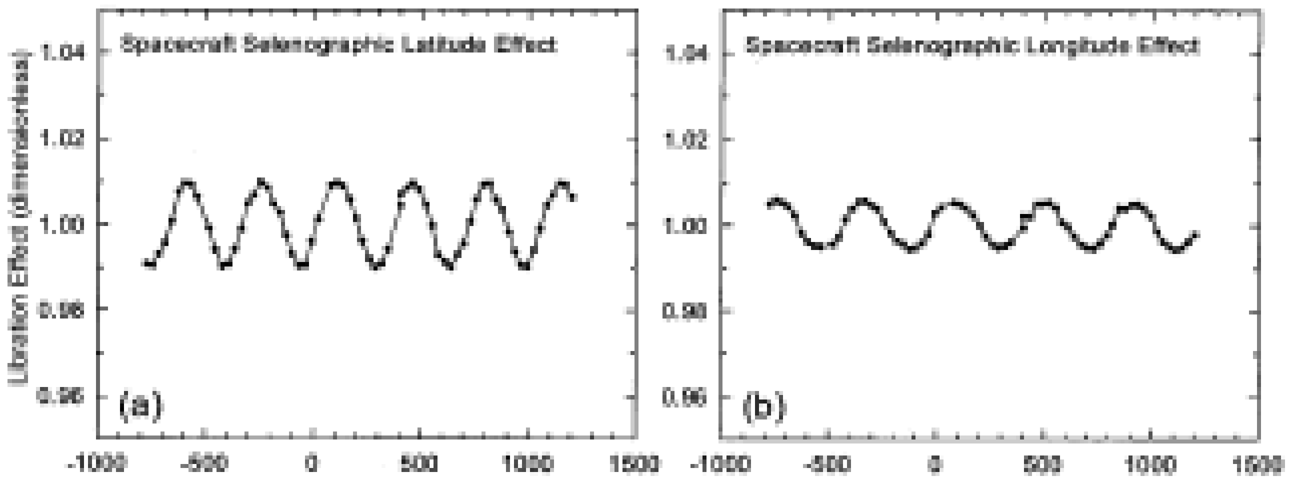




Offsets for SeaWiFS, MODIS and PLEIADES set to 0 at 7° phase using absolute measurements.
Fit residual empirical correction, ±60° with an uncertainty of ~0.2 %
(about 10 % of the total correction)

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

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.

Eplee, J., R. E., F.S. Patt, and G. Meister, *Geometric effects in SeaWiFS lunar observations.* Proc. SPIE, 2015. **9607**: p. 960704-1.

Expectations if we can maintain the Transfer Spectrograph Uncertainties in the Field

	Uncertainty component (k=1) [%]			
Wavelength [nm]	Absolute Irradiance	Phase Correction	Libration correction	Combined Standard Uncertainty [%]
400	0.2	0.2	0.2	0.35
450	0.2	0.2	0.2	0.35
500	0.2	0.2	0.2	0.35
550	0.2	0.2	0.2	0.35
600	0.2	0.2	0.2	0.35
650	0.2	0.2	0.2	0.35
700	0.2	0.2	0.2	0.35
750	0.2	0.2	0.2	0.35
800	0.2	0.2	0.2	0.35
850	0.2	0.2	0.2	0.35
900	0.2	0.2	0.2	0.35

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

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 %

4. High-altitude Tie-points For Validation

Laboratory for Atmospheric and Space Physics (LASP)
HyperSpectral Imager for Climate Science (HySICS)

HySICS instrument was discussed earlier in this meeting by Greg Kopp

- Balloon flights
  - 29 Sept 2013 and 18 Aug 2014
  - 8.5 H and 9 H duration
  - ~120,000 ft

Courtesy LASP/Joey Espejo

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

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
  - Using a remotely operated/more permanent facility

Apply some of our spectrograph calibration protocols, see if we can't lower the uncertainty in the telescope responsivity (in the field) below 0.35 % (*k*=1)

Extend spectral range to cover out to 2.5 μm

Reducing the Measurement Uncertainty

Considering high altitude aircraft flights for both Solar and Lunar Irradiance Measurements

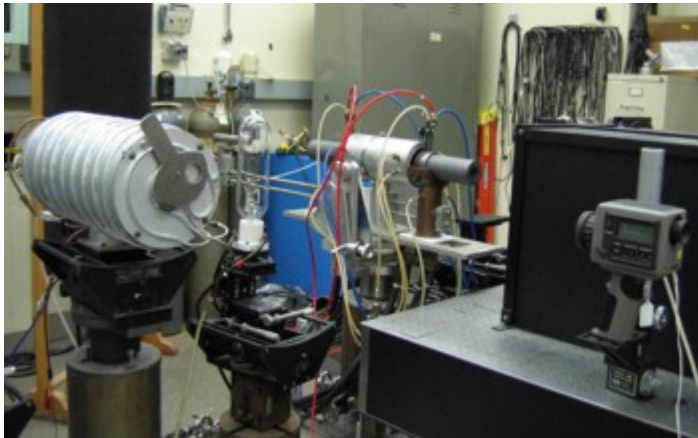
- ER2 Flights (2 campaigns/year, 1 to 2 weeks duration
  - Above 95 % of the atmosphere; lower uncertainties achievable quickly
  - Lunar measurements would provide tie-points for the ground-based measurements
    - ± 7^{o} phase (Tie to SeaWiFS/PLEIADES)
    - ± 55^{o} phase (Tie to MODIS/PLEIADES)
    - Phase changes ~10 % per night
  - Solar measurements at the same view angles to validate the reflectance model of the Moon

Summary

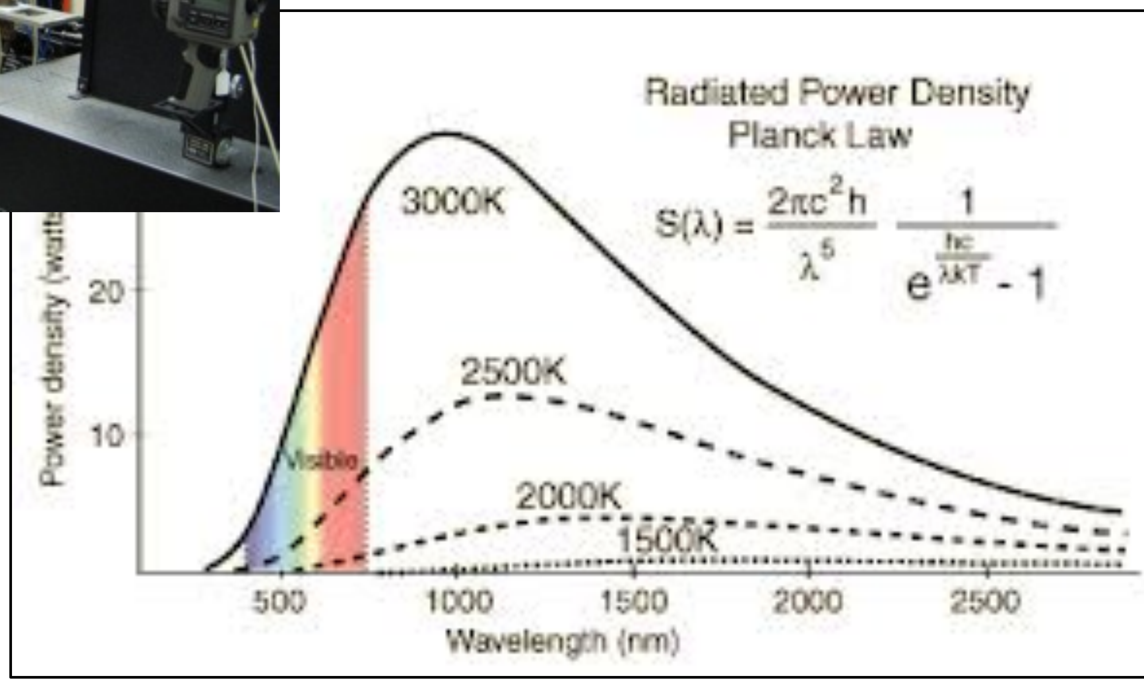
Can the Moon be used as an
absolute exo-atmospheric calibration target for CLARREO
and other Earth-observing instruments?

It looks like it is very promising to get to
0.35 % (k=1) uncertainty, but we need some help.

To Validate the Spectrograph Calibration
NIST primary standard Blackbody Sources



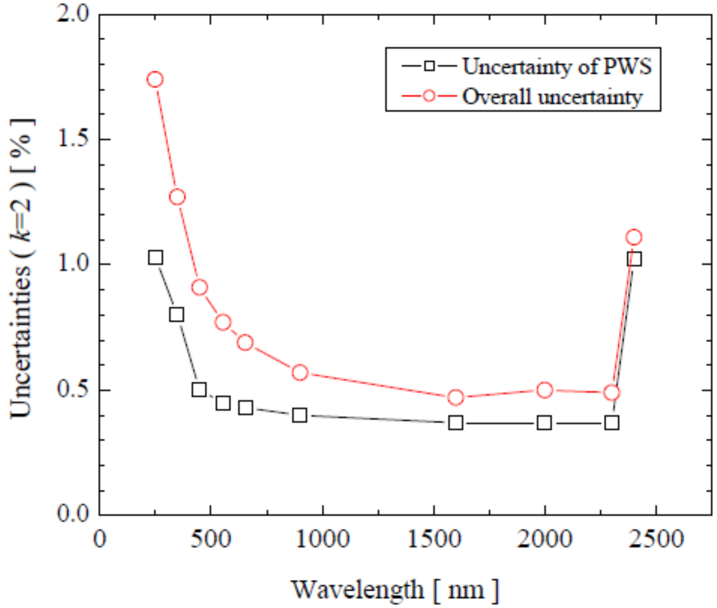
Gold-point blackbody: 1337 K
Carbon-Metal Eutectics: up to 2800 K



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,

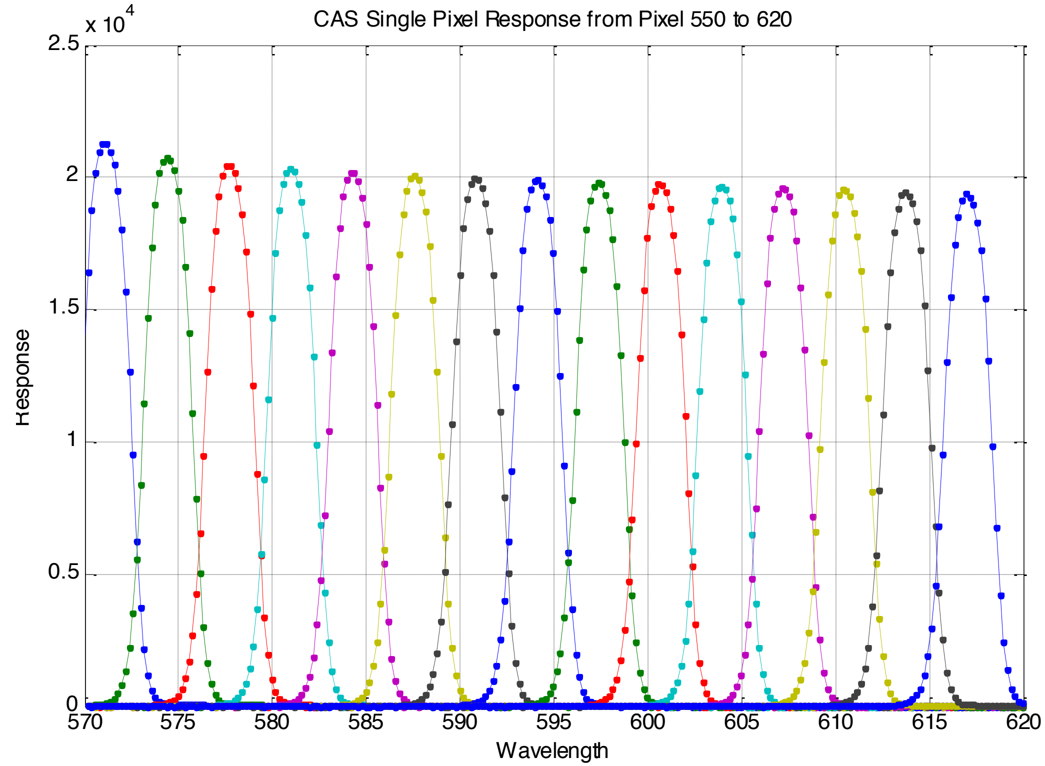
k = 2 uncertainty approximately

0.6 % @ 900 nm

0.9 % @ 500 nm

1.25 % @ 350 nm

Single Pixel Responsivities



Uncertainty: 0.2 % or less (k=2) Si range

H. Yoon and Charles Gibson, Spectral Irradiance Calibrations, NIST Special Publ. 250-89 (July 2011).

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

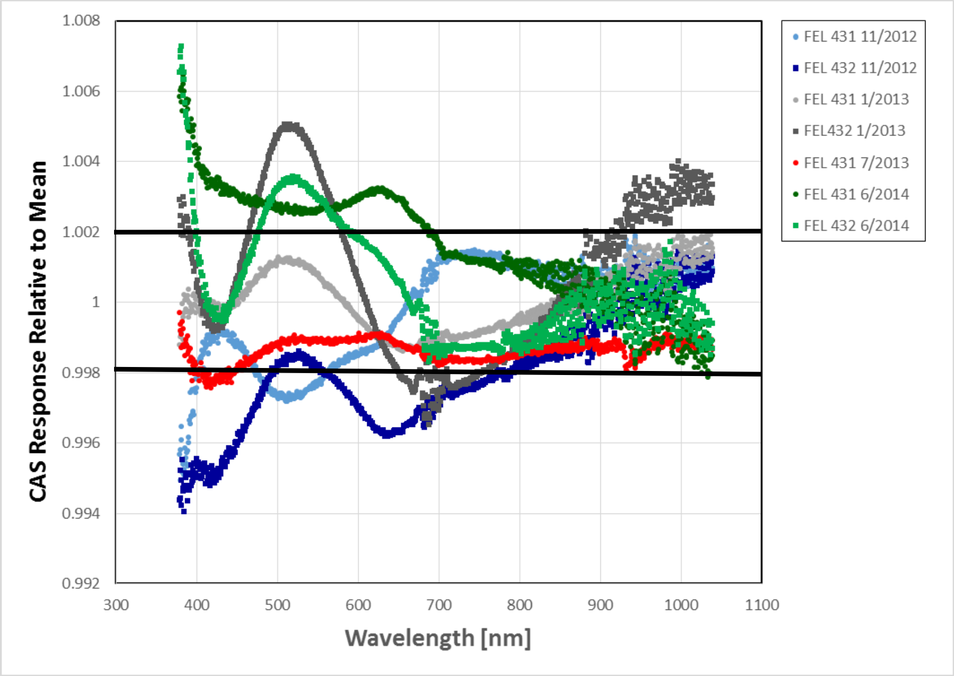
from 11/2012 – 6/2014

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.



Most of the observed variability from fiber insertion into CAS

Transfer Standard 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.*[1] assigned an **uncertainty in disseminated <u>radiance scales</u> of 2% to 3% in the Vis/NIR (silicon) region**, increasing to 5 % in the short-wave infrared region.

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.

[1]Butler, J. J., et al., Validation of radiometric standards for the laboratory calibration of reflected-solar Earth observing satellite instruments, Proc. SPIE 6677, 667707 (2007).

ROLO Observatory

Flagstaff, AZ

Altitude 2143 m

*Courtesy of Tom Stone, USGS, Flagstaff, AZ

ROLO Observational Program

Filter bands

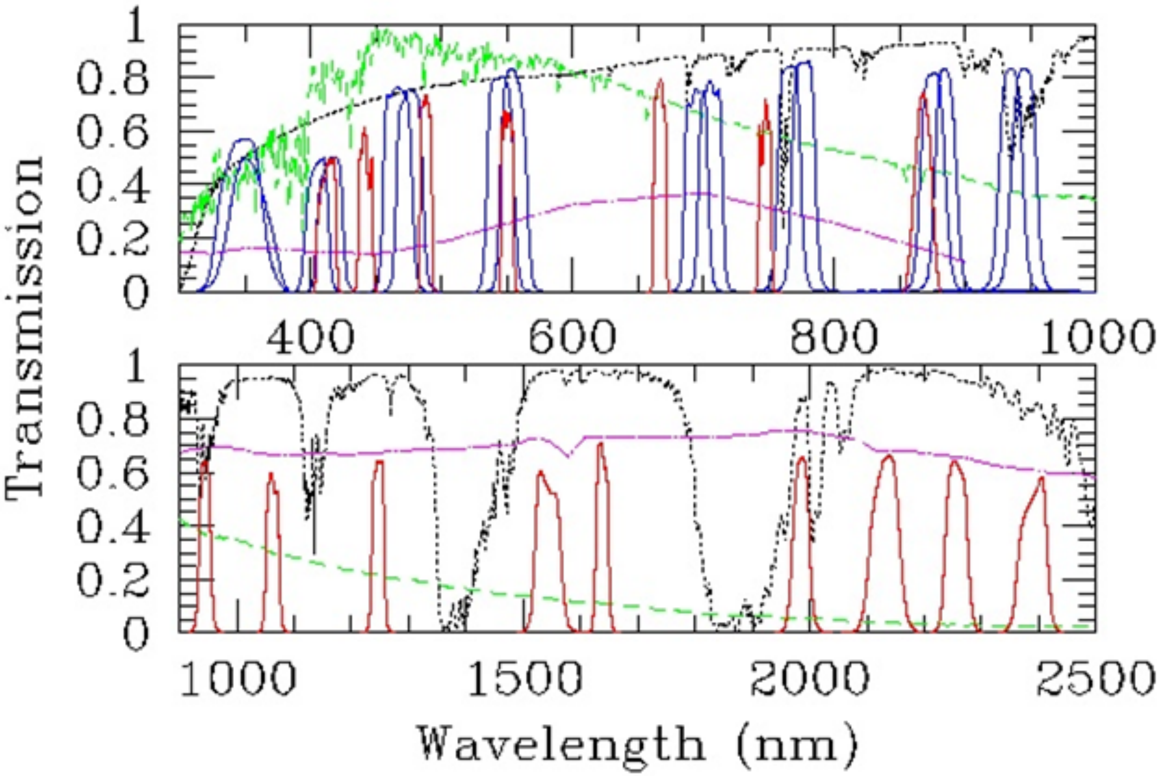
– VNIR 23 bands, 350-950 nm

– 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

SWIR Telescope

VNIR Telescope



*Courtesy of Tom Stone, USGS, Flagstaff, AZ

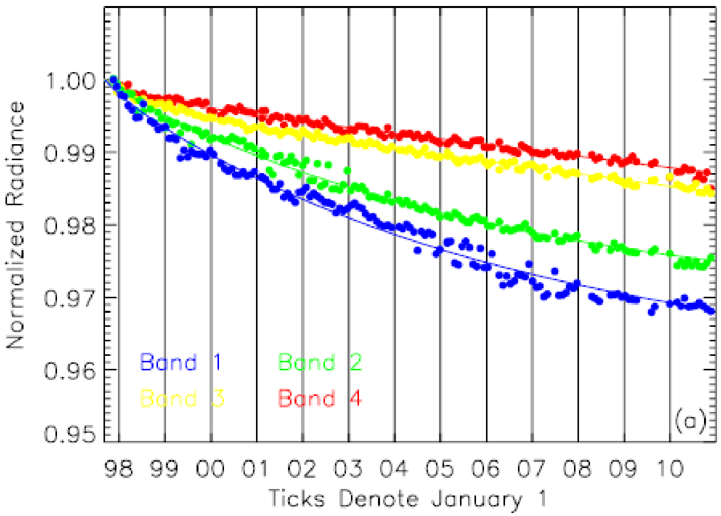
ROLO Model:
Equivalent Lunar Disk Reflectance

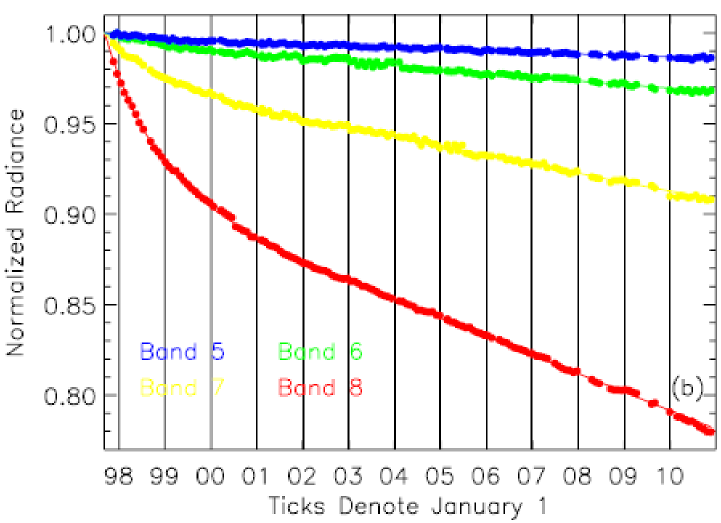
$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\theta + c_2\phi + c_3\Phi\theta + c_4\Phi\phi$$
$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos[(g - p_3)/p_4], \quad (10)$$

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.

Use of the ROLO Model to trend Satellite Sensors Band Response
NASA Goddard OBPG

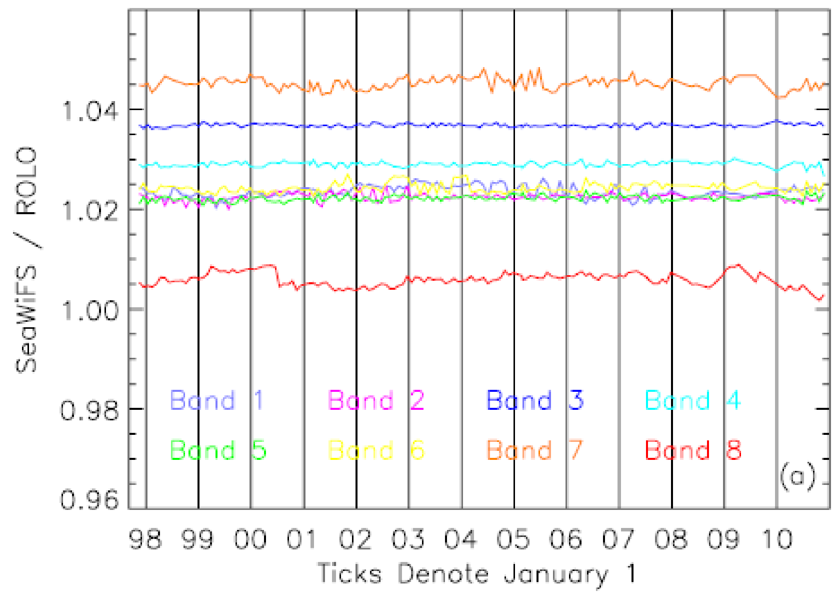
SeaWiFS bands temporal responsivity degradation





Corrected using the ROLO Model
Relative only
Phase angles kept to ± 7º

StDevMean = ~ 0.1 %



Lunar measurements can be used
To trend satellite sensor responsivity
With very low uncertainties.