Can the Moon be used as an Absolute Exo-Atmospheric Calibration Target for CLARREO?

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

Claire Cramer*, Keith Lykke, John Woodward, Ping Shaw, Steve Brown/NIST

Tom Stone/USGS

Gene Eplee/NASA Goddard

*ccramer@nist.gov

On-Orbit Sensor Accuracy Requirements

SI-traceable reflectance, *k*=2

- Commercial systems
  - 10 % absolute with better than 0.1 % relative detector-to-detector
    - Future systems will require much better accuracy
    - SNRs>100 for low reflectance, low solar elevation
- Operational systems
  - 3 % absolute with 1 % sensor-to-sensor
    - Future systems will require better sensor-to-sensor
    - SNRs>100 for low reflectance, low solar elevation
- Climate applications (CLARREO)
  - 0.3 % in integrated albedo; 0.3 % spectral as well (TBR)
    - Sensor-to-sensor at the same level
    - SNR on the order of 10 for single measurements

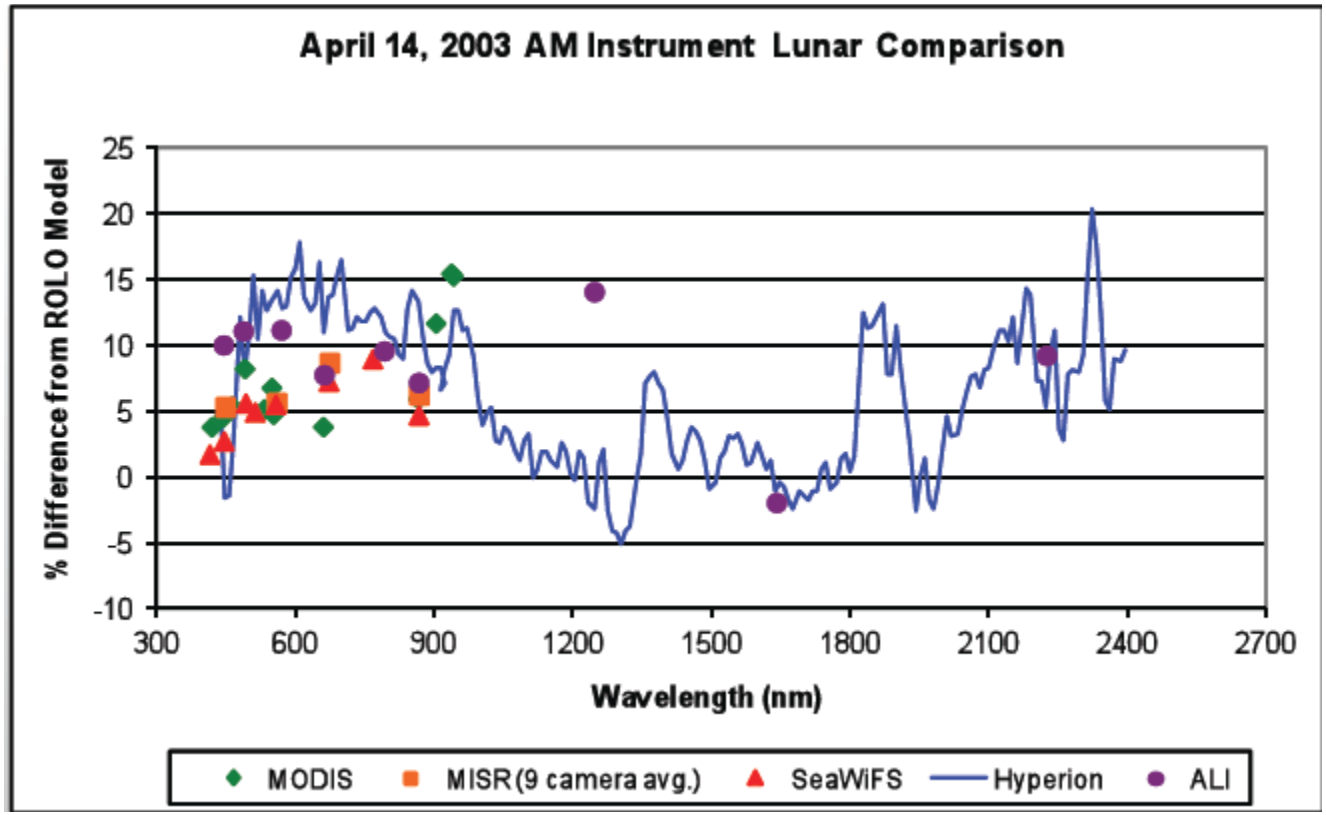
Kurt Thome, presented at the Lunar Calibration Workshop; Gaithersburg, MD, May 2012

Can we use the Moon as an on-orbit calibration target?

- Currently the uncertainty in the USGS lunar model (aka the ROLO Model) is 5 % to 10%
  - Does not support current or future Earth remote sensing uncertainty requirements as an on-orbit radiometric calibration standard
- However, the Moon is radiometrically stable
  - Uncertainties limited by instrumentation; that is, how well we can make lunar measurements.
  - Any reductions in the uncertainty in Lunar irradiance (or radiance) can be post-applied to sensor data

Tom Stone, USGS, Lunar Calibration
'Where we are today and how we got here'
Lunar Calibration Workshop, Gaithersburg, MD, May 2012

Where we were in 2003

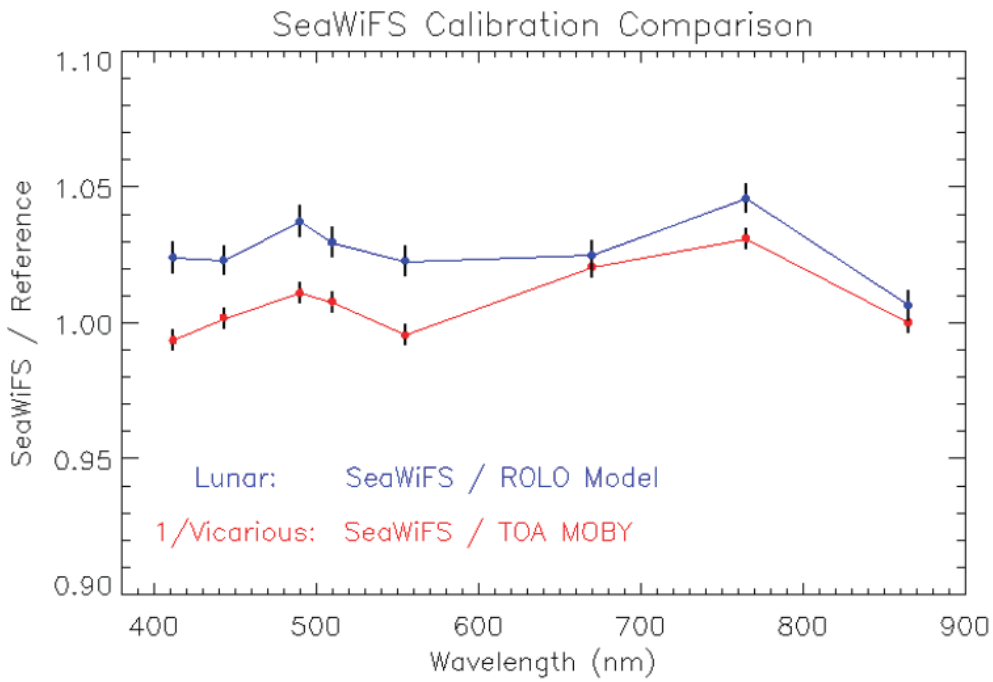


Relative differences between instruments include uncertainty components from:

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

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

Robert E. Eplee, Jr., et al., Cross calibration of SeaWiFS and MODIS using on-orbit observations of the MOON, Appl. Opt., 50, 120-133 (2011).



MOBY: Bryan Franz, et al., Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry, Appl. Opt., 46, 5068 (2007).

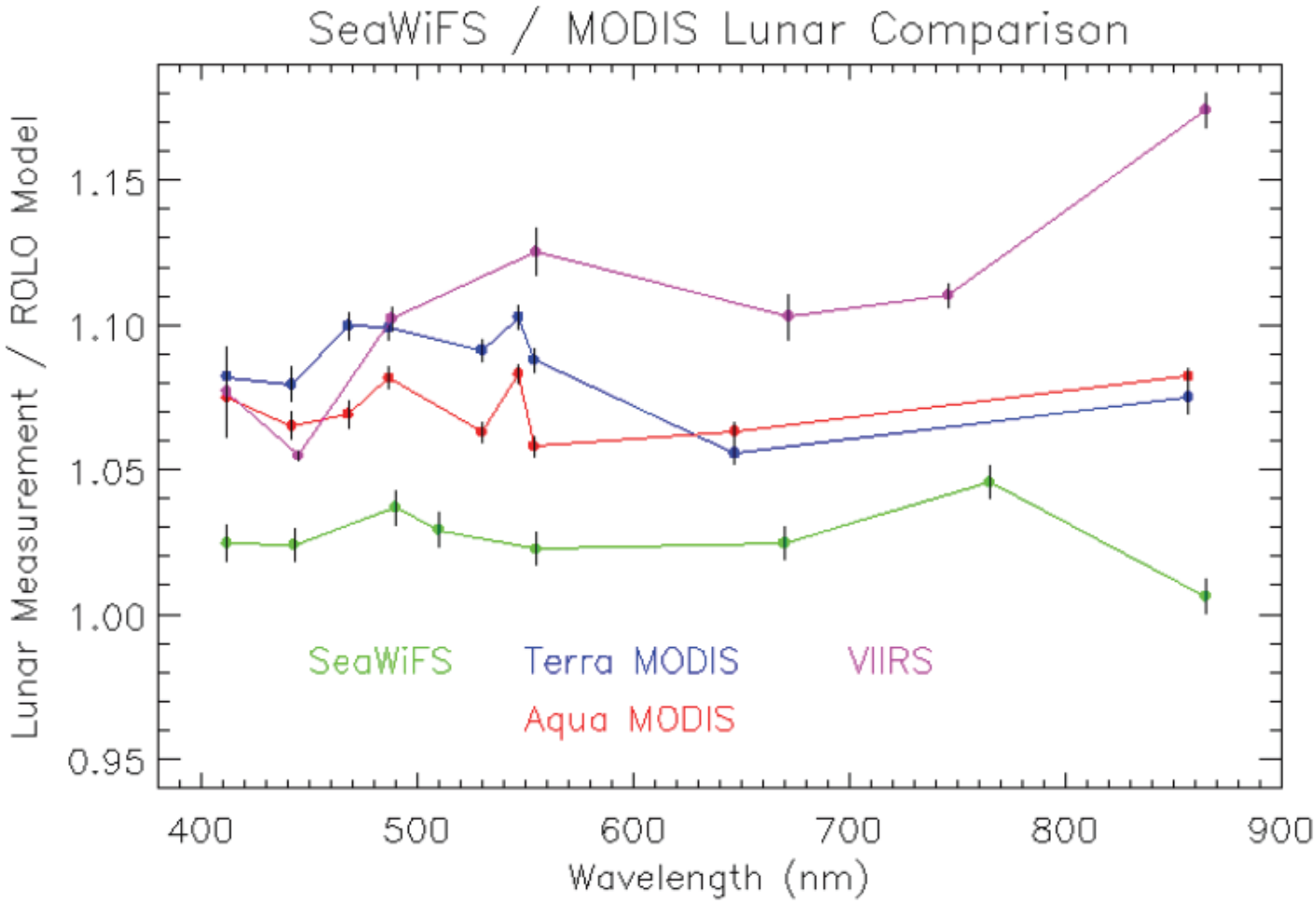
SeaWiFS TOA Uncertainties

Uncertainty		B1	B2	B3	B4	B5	B6	B7	B8	Overall
Accuracy (%)	ROLO	2.35	2.25	3.68	2.90	2.22	2.43	4.52	0.60	2-3
	MOBY	-0.656	0.170	1.09	0.766	-0.468	2.05	3.09		1-2
Stability (%)	TOA	0.124	0.0778	0.0334	0.0456	0.0578	0.0958	0.188*	0.129	0.13
	VC TOA	0.28	0.24	0.26	0.25	0.26	0.35	0.22*		0.30
Precision (%)	Solar	0.155	0.126	0.102	0.0987	0.105	0.120	0.117	0.130	0.16
	Lunar	0.124	0.0778	0.0334	0.0456	0.0578	0.0958	0.116	0.129	0.13
	Vicarious	0.07	0.07	0.07	0.07	0.07	0.06	0.11		0.10

*Error includes Gain 3 drift uncertainty.

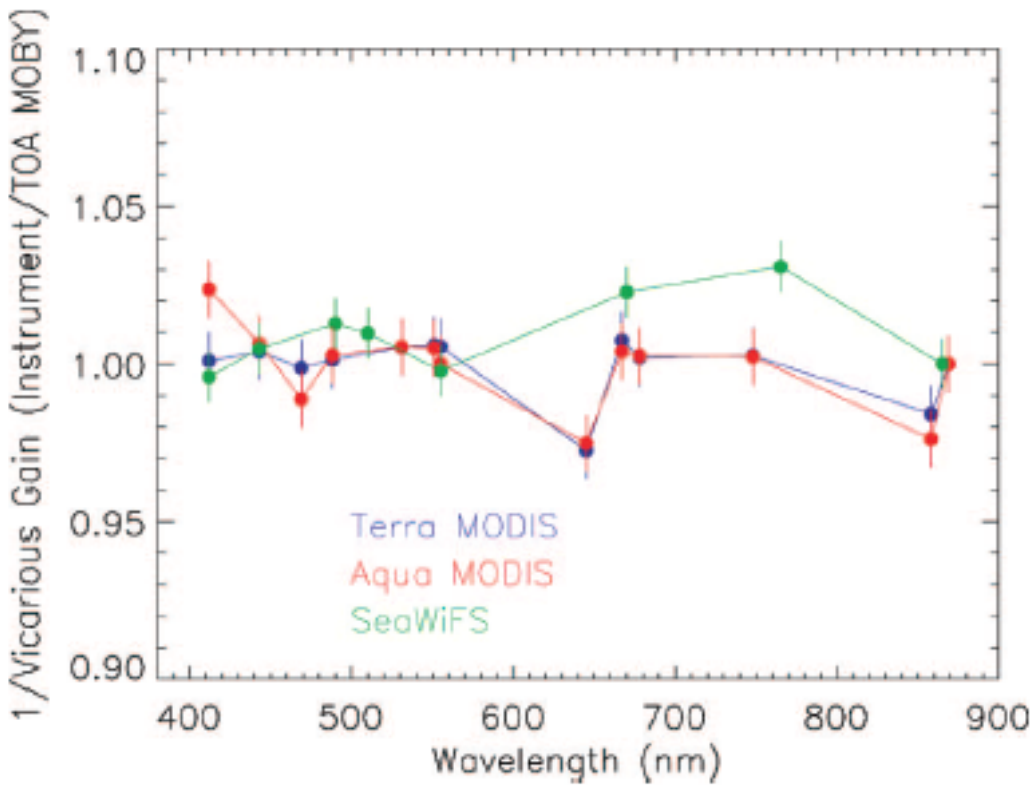
Eplee, et al.

SeaWiFS and MODIS Lunar Comparison



Eplee, et al.

SeaWiFS and MODIS v MOBY



Phase Dependence of MODIS Terra/Aqua and SeaWiFS Lunar Measurements

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

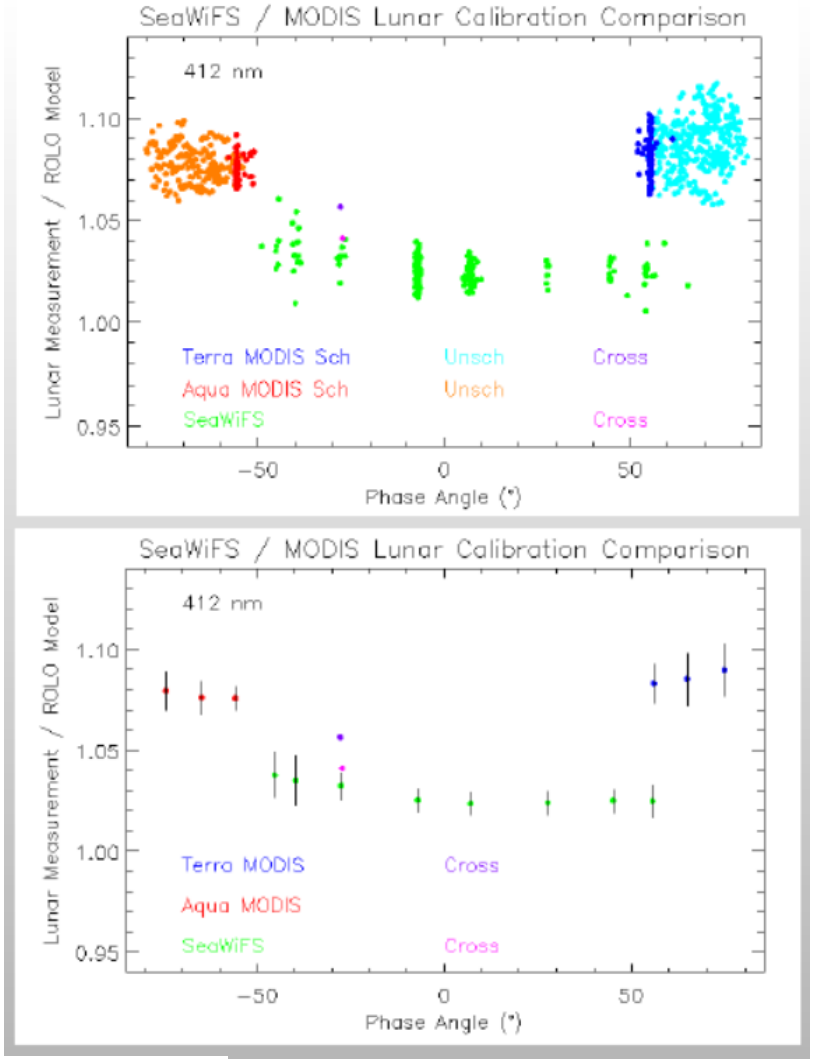
- SeaWiFS uncertainty primarily due ot oversampling correction
- MODIS uncertainty primarily due to lower lunar signal at higher lunar phase

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°

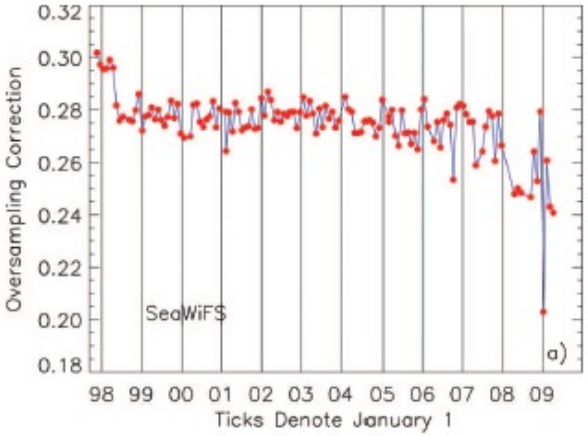
Uncertainty in lunar phase : 1.7 % (-80° to -6° and 5° to 82°)

- USGS Model uncertainty 1 % (from a much larger database of lunar measurements)

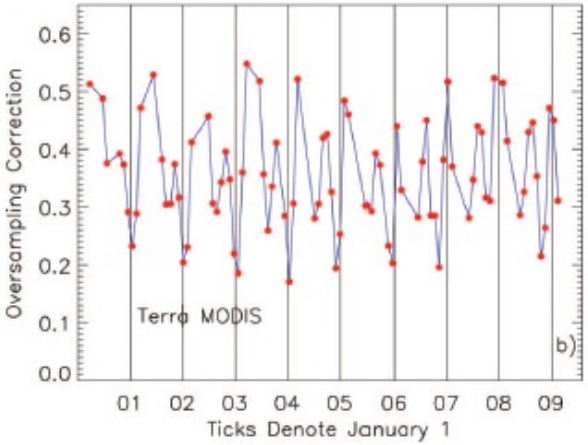


Phase Dependence from Eplee, et al.,
presented by Jim Butler at the 2012 Lunar Irradiance Workshop

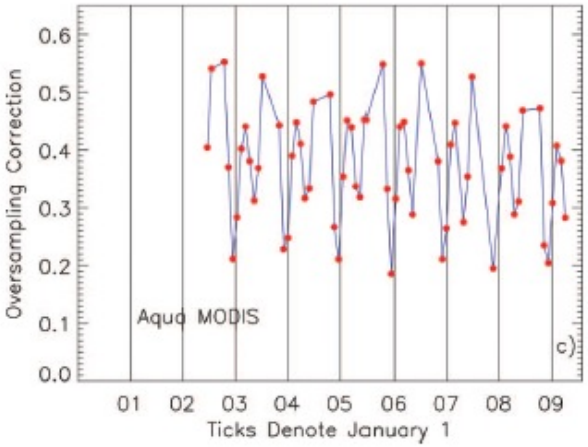
Oversampling correction



SeaWiFS



Terra MODIS



Aqua MODIS

Integrated Lunar Irradiance Calibrations: What is currently realized and what is possible.

Jim Butler, Lunar Irradiance Workshop May 2012

- Individual instrument degradation trending can be realized with uncertainties of 0.1 % per year
- Instrument comparisons on-orbit with uncertainties less than 1 % achievable
- While CLARREO needs 0.3 % *k*=2, a lunar irradiance model with 1 % to 3 % absolute uncertainties *k*=2 relative to the SI makes the Moon a viable (affordable) on-orbit source for
  1. Transfer to Orbit Effects
  2. Ensuring consistency between the calibrations not only of overlapping but also non-overlapping sensors (to help minimize gap effects)
  3. Possibly/potentially as an absolute SI traceable on-orbit calibration source

Lunar Irradiance Summary

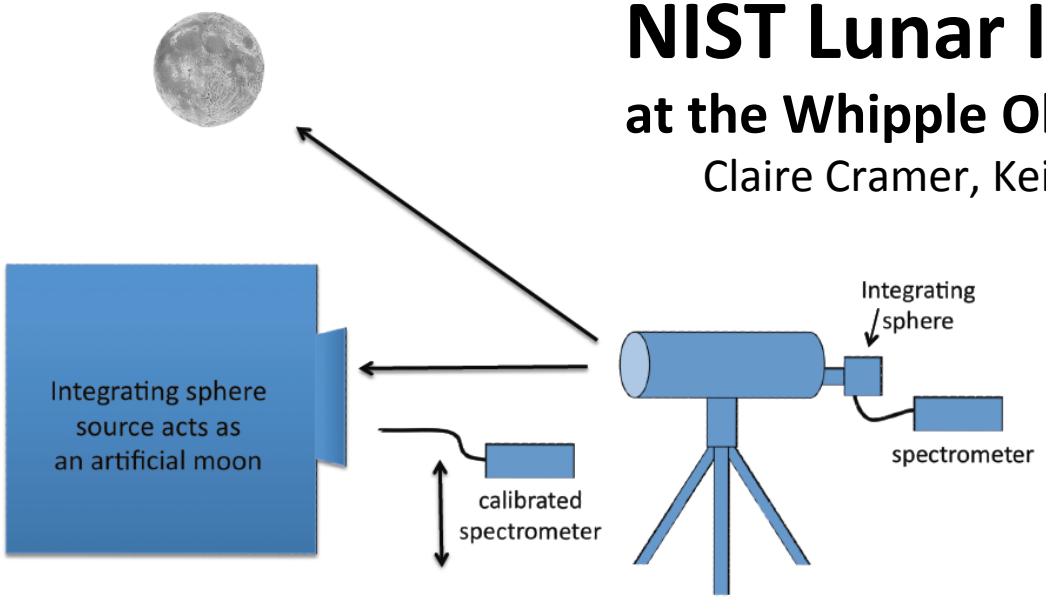
- Lunar Irradiance uncertainty requirements
  - 0.3 % (*k*=2) for CLARREO (golden target)
  - lots of benefit with *k*=2 uncertainties of 1% to 3 %
- Where the lunar irradiance model currently stands:
  - SeaWiFS only (412 nm)
    - 2 % to 3 % constant phase 7 deg plus
    - 1.7 % uncertainty in phase dependence
    - 0.5 % in libration uncertainty

      = total combined unc of 2.6 % to 3.5 %
    - MODIS/VIIRS/USGS (Tom Stone)
      - Uncertainty in USGS lunar irradiance model still 5 % to 10 %

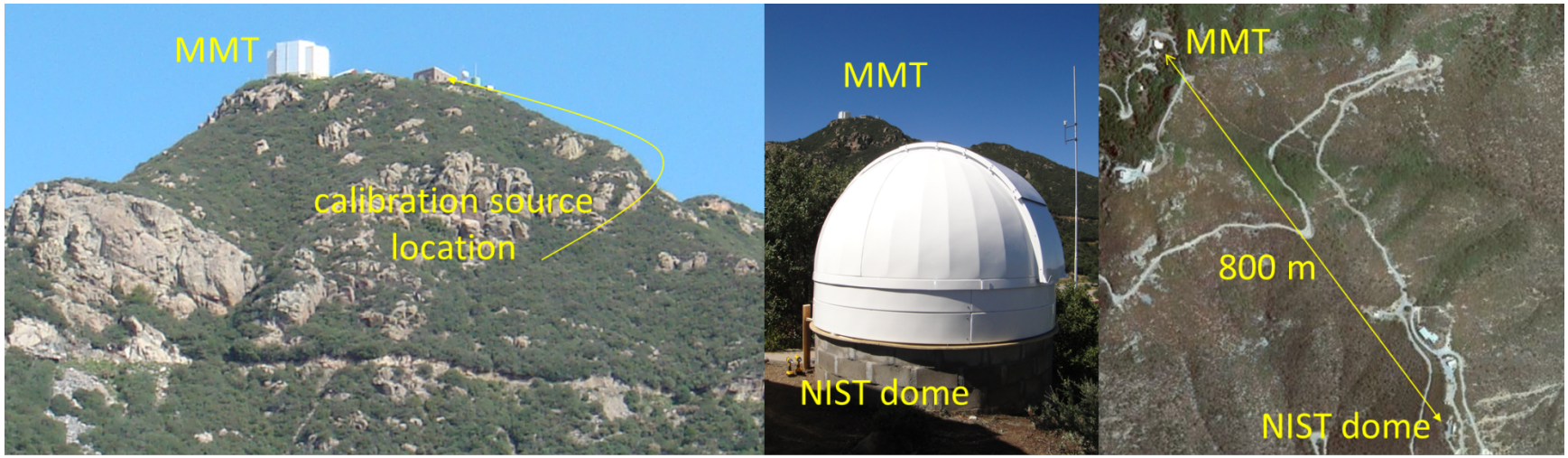
NIST Lunar Irradiance Program

at the Whipple Observatory, Mt. Hopkins AZ

Claire Cramer, Keith Lykke and John Woodward

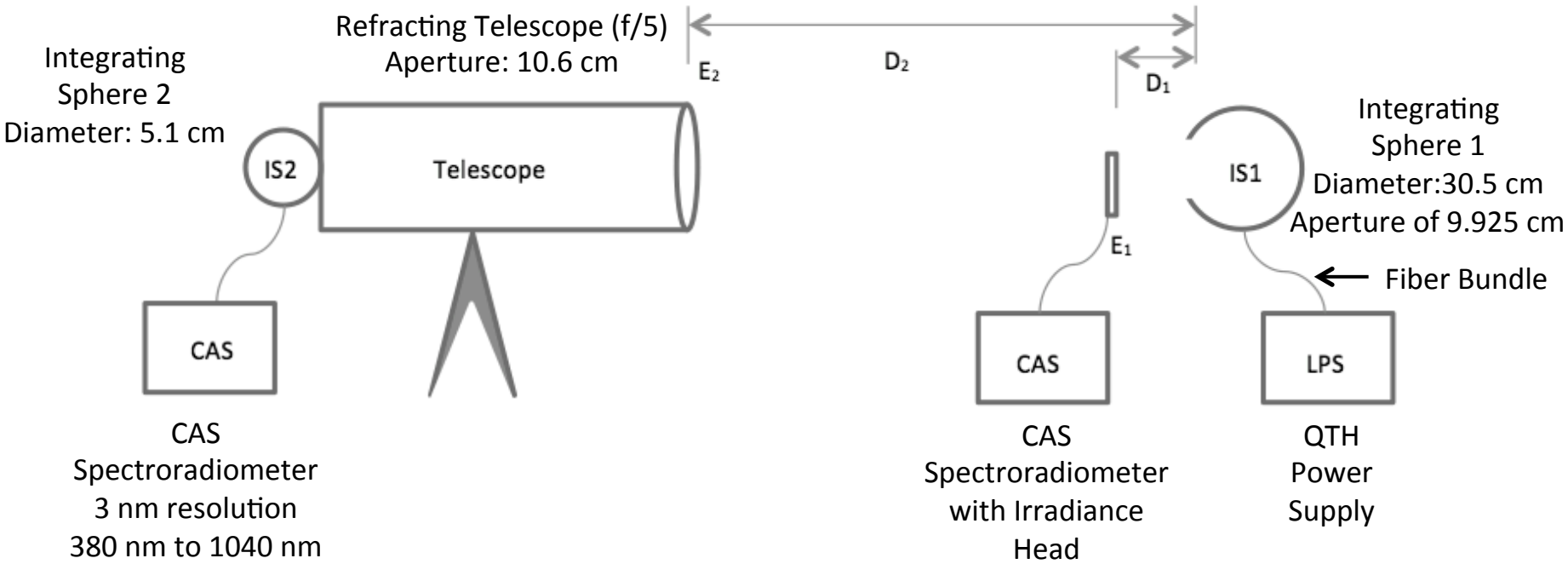


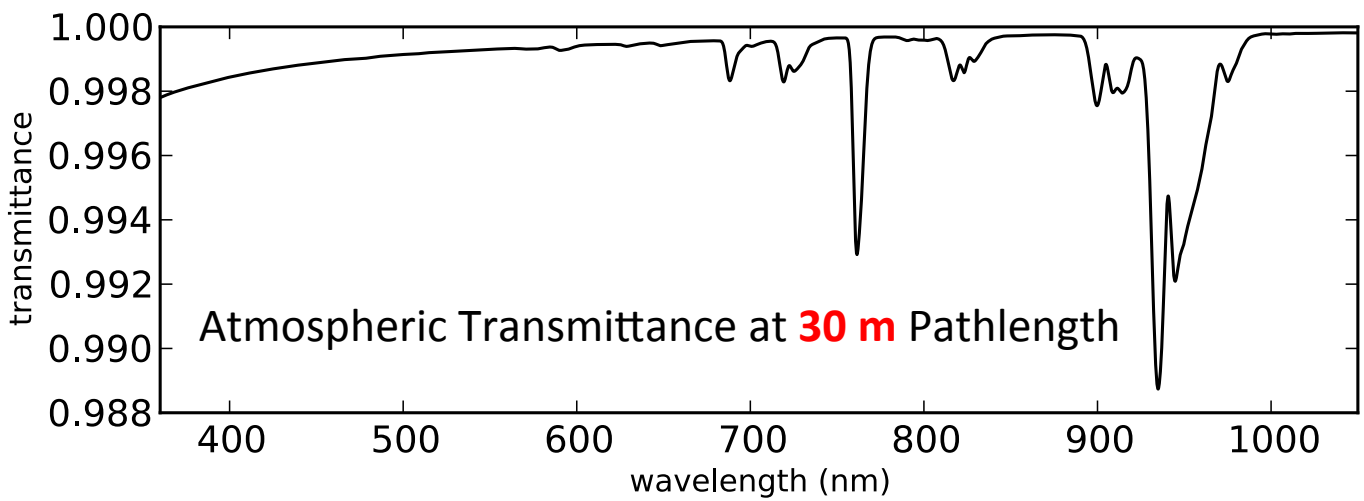
Goal: a lunar irradiance measurement with k=2 uncertainties of 1 % or less over the spectral range from 400 nm to 1000 nm



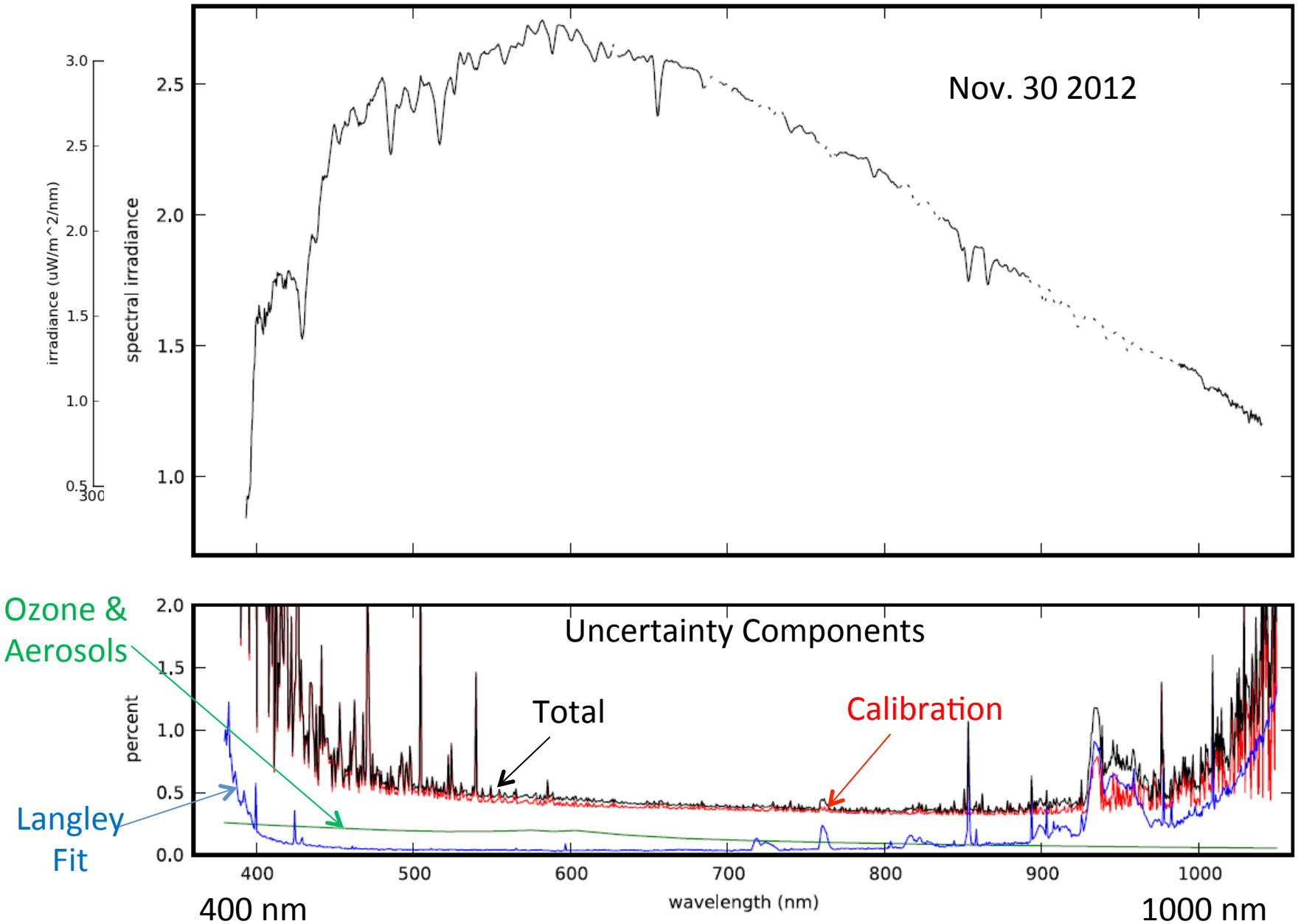
Dome location on the 'Ridge' (from the Summit)

Calibration Approach

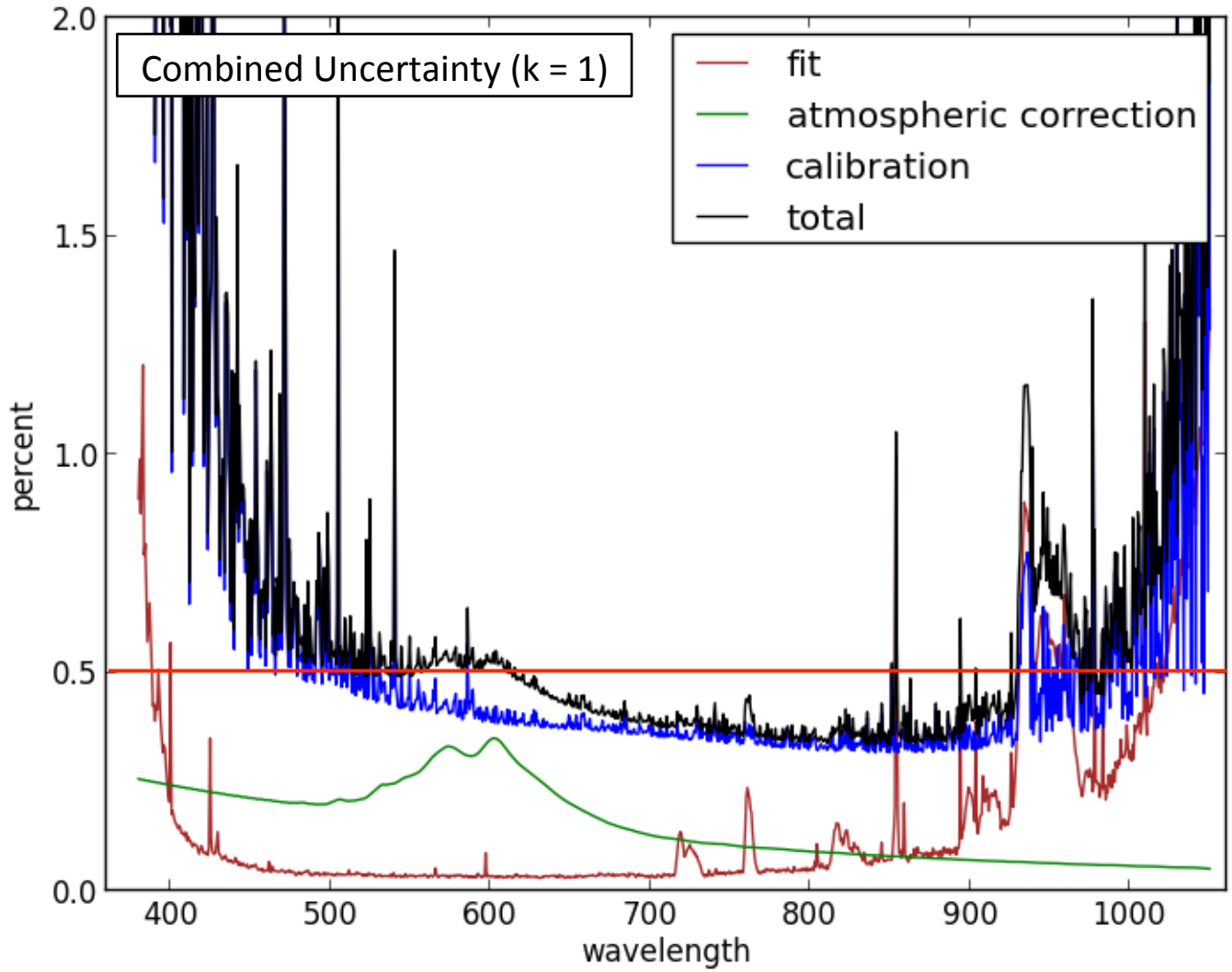




Results: Lunar Spectral Irradiance



C. E. Cramer, et al., Precise Measurement of Lunar Spectral Irradiance at Visible Wavelengths, J. Res. NIST 118, 396-402 (2013).



Dominated by the uncertainty in the telescope calibration, and ozone & aerosols around 600 nm.

Combined Standard Uncertainty in Lunar Irradiance at Select Wavelengths

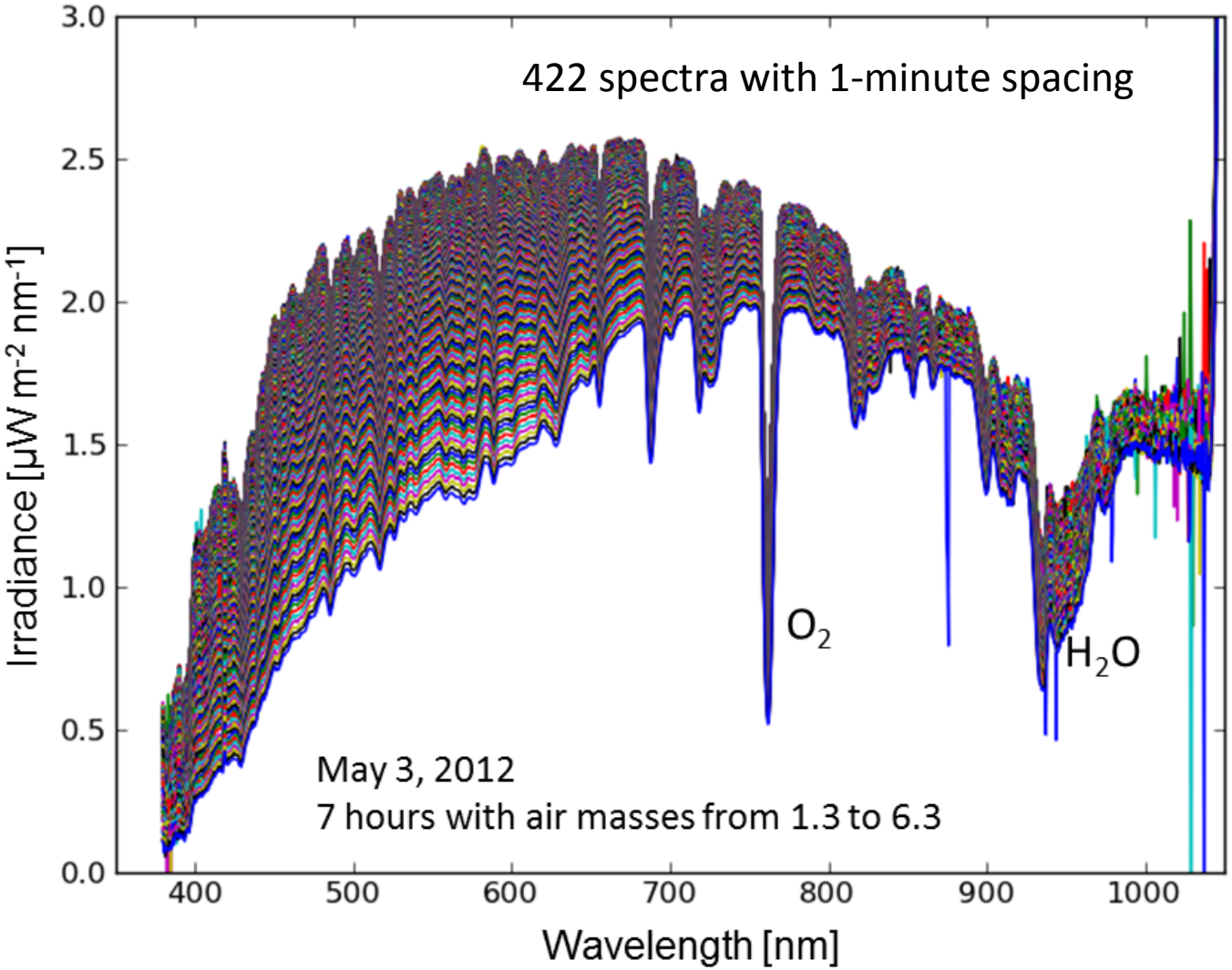
Table 1. Spectral irradiance of the Moon at 11:40:43 on 30 November, 2012 UT

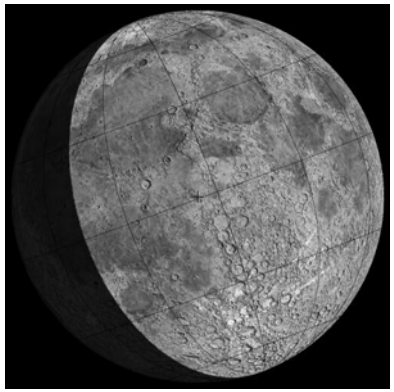
Wavelength (nm)	Spectral irradiance (μW m^{-2} nm^{-1})	Uncertainty (percent)
449.7	2.348	0.85
499.9	2.395	0.56
550.0	2.633	0.45
600.2	2.669	0.44
650.1	2.598	0.40
702.8	2.474	0.38
750.0	2.314	0.37
850.2	1.870	0.36
1000.2	1.387	0.54

Pretty close to achieving our target uncertainty of 1 % *k*=2 from 400 nm to 1000 nm

No LIDAR: Langley plots for atmospheric extinction

Example:





lunar phase: 29° to 25°

Analysis Approach

ROLO Model: Time dependence of TOA lunar irradiance

Ozone Monitoring Instrument: Data to correct for ozone absorption

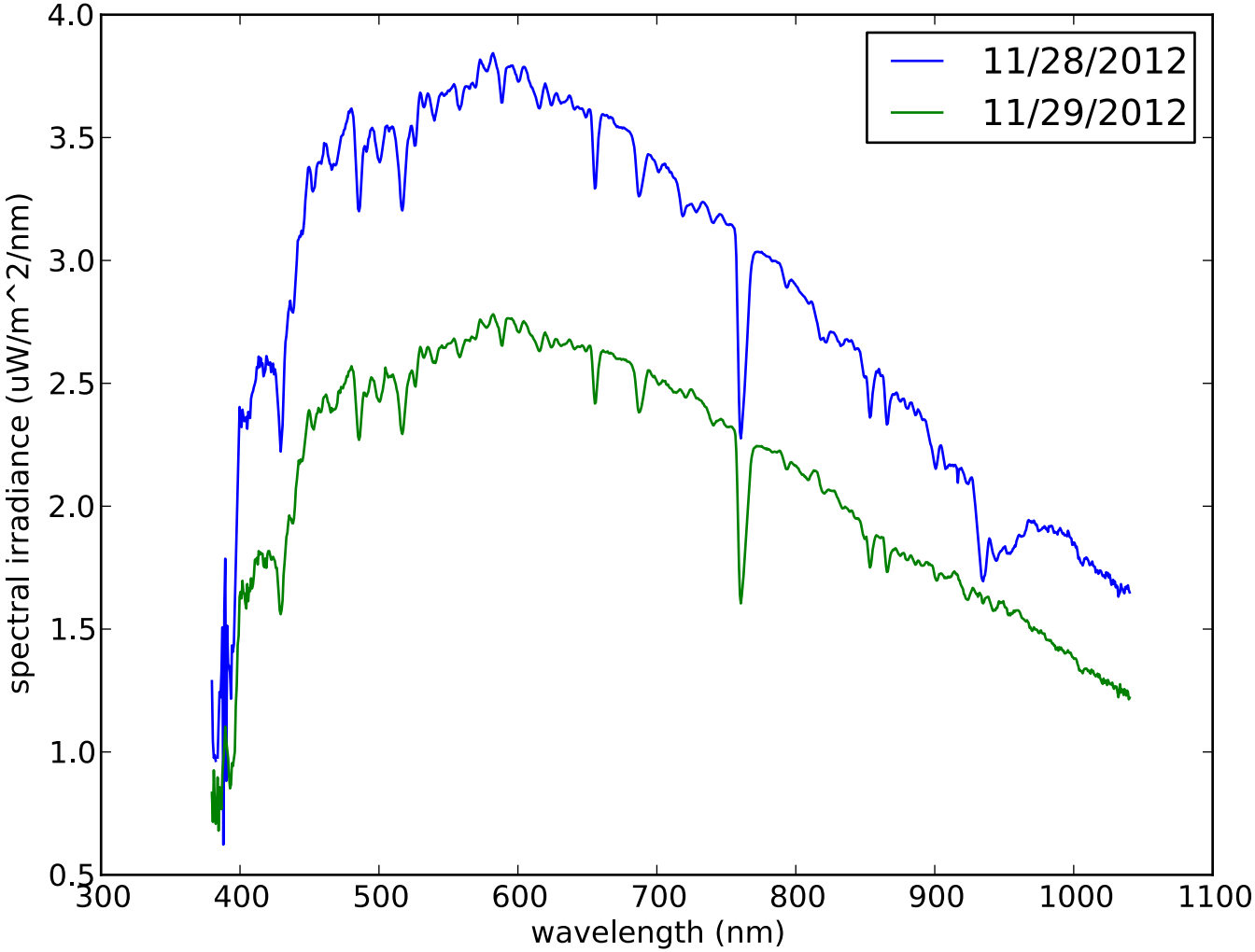
Stratospheric Aerosol and Gas Experiment (SAGE II): Stratospheric aerosol corrections

Integrated Global Radiosonde Archive/Tucson: Data needed for Rayleigh scattering corrections

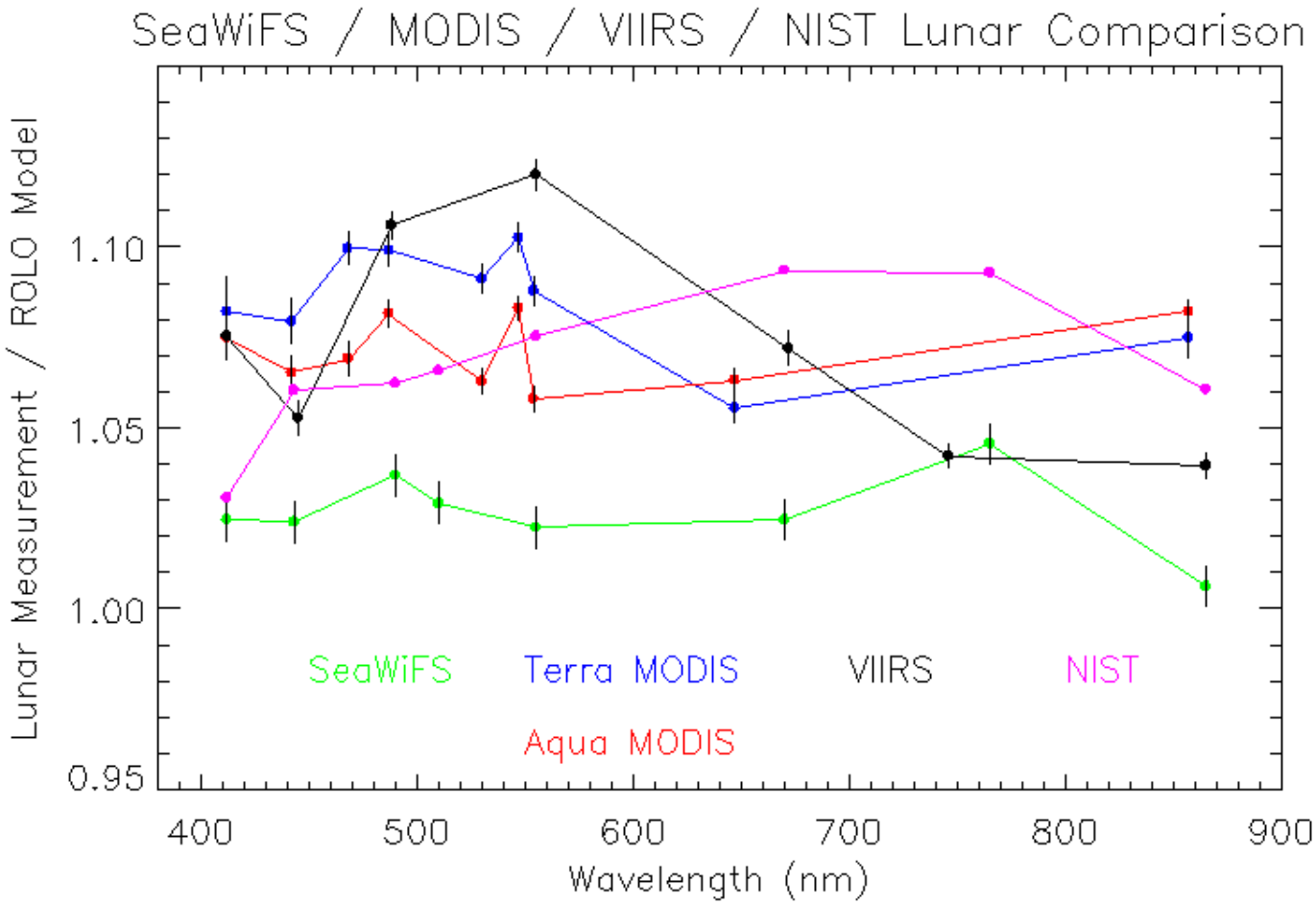
MODTRAN 5: Atmospheric modeling

Langley-Type Fits: Extract TOA Irradiance

Results: Calibrated Lunar Spectral Irradiance



Comparison with the current USGS Model for SeaWiFS*



*graph provided by Gene Eplee, NASA Goddard
new model currently underdevelopment by Tom Stone, USGS

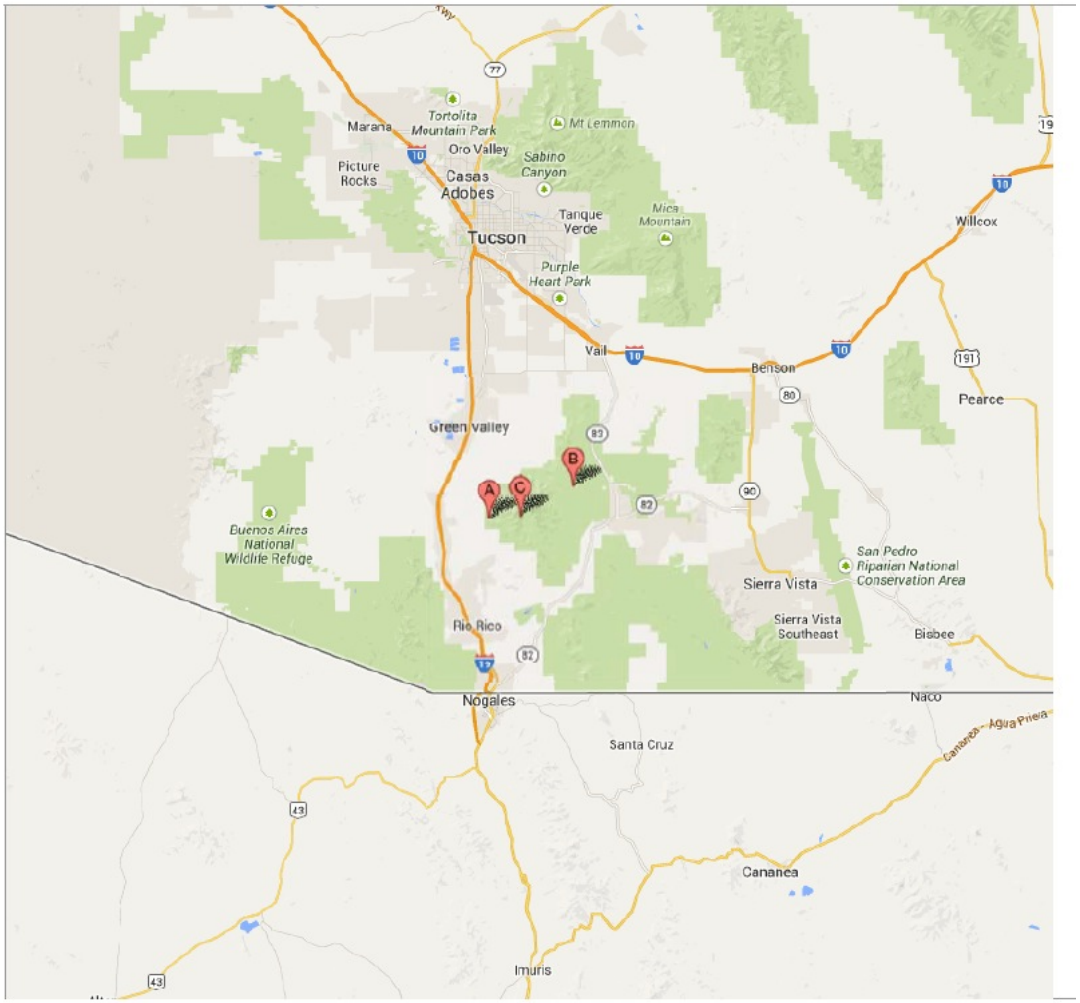
Issues to deal with at Mt. Hopkins

1. No Lidar. We were hoping to have a LIDAR system ready and operational at Mt. Hopkins for atmospheric characterization
   - System is slowly coming on-line
2. Not a continuous time-series of measurements
   - Rainy season, site closed down
   - Measurements taken ~ twice per year with durations of approx. 2 week during site visits.

Issues to deal with at Mt. Hopkins (cont.)

4. Site location

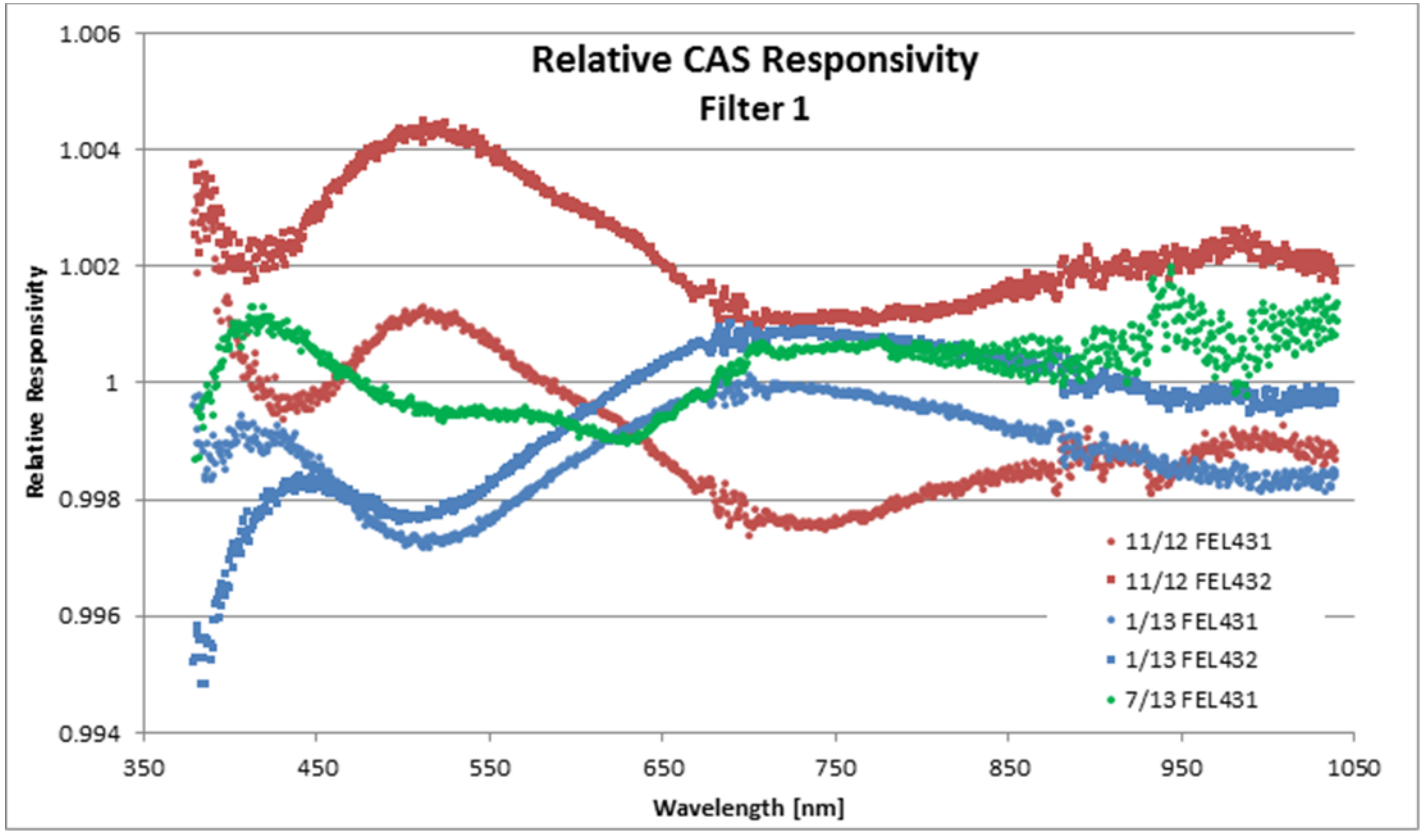
Occasions where burning fields and trash dumps in Mexico impacted the atmosphere at Mt. Hopkins and prevented accurate measurements.



Reducing the Measurement Uncertainty:

1. Reducing the telescope calibration uncertainties

CAS Spectrometer Radiometric Stability

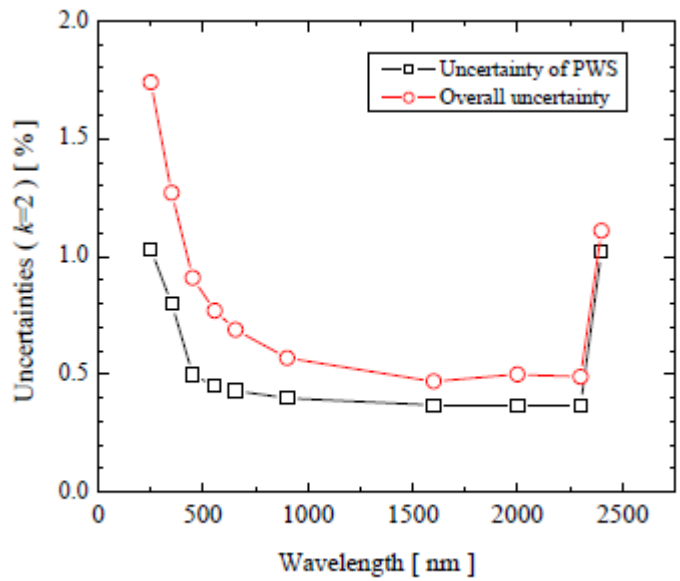


Calibration setup not maintained; reproduced for each measurement.

Potential sources of measurement error

First responsivity stability measurement uncertainty, ± 1 %

- FEL lamp calibration
  - Uncertainty in issued FEL irradiance standard lamps
  - Two different FEL lamps were used
- Setup not maintained between calibrations
  - Reproducibility errors, e.g. source to detector distance, lamp current
- Lamp calibration wavelengths sparse – every 50 nm
  - Potential for interpolation errors

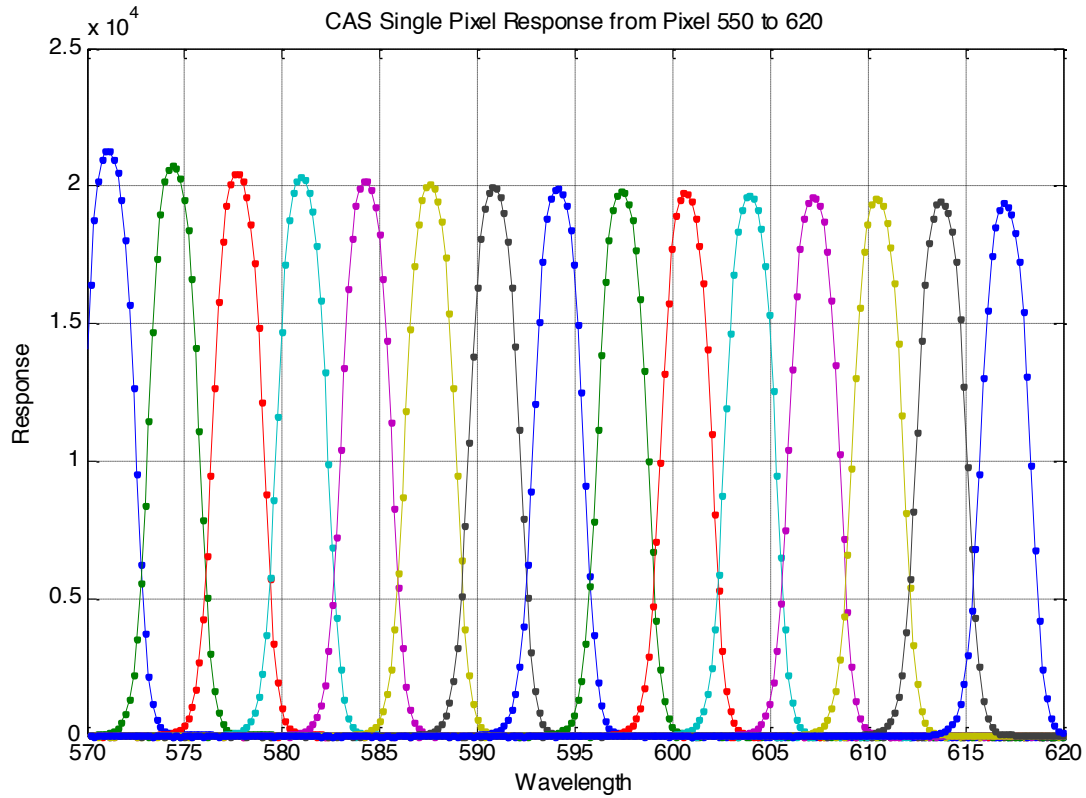


We can possibly reduce the magnitude of the differences in repeat calibrations, implying that the instrument itself is more stable than the difference in two calibrations.

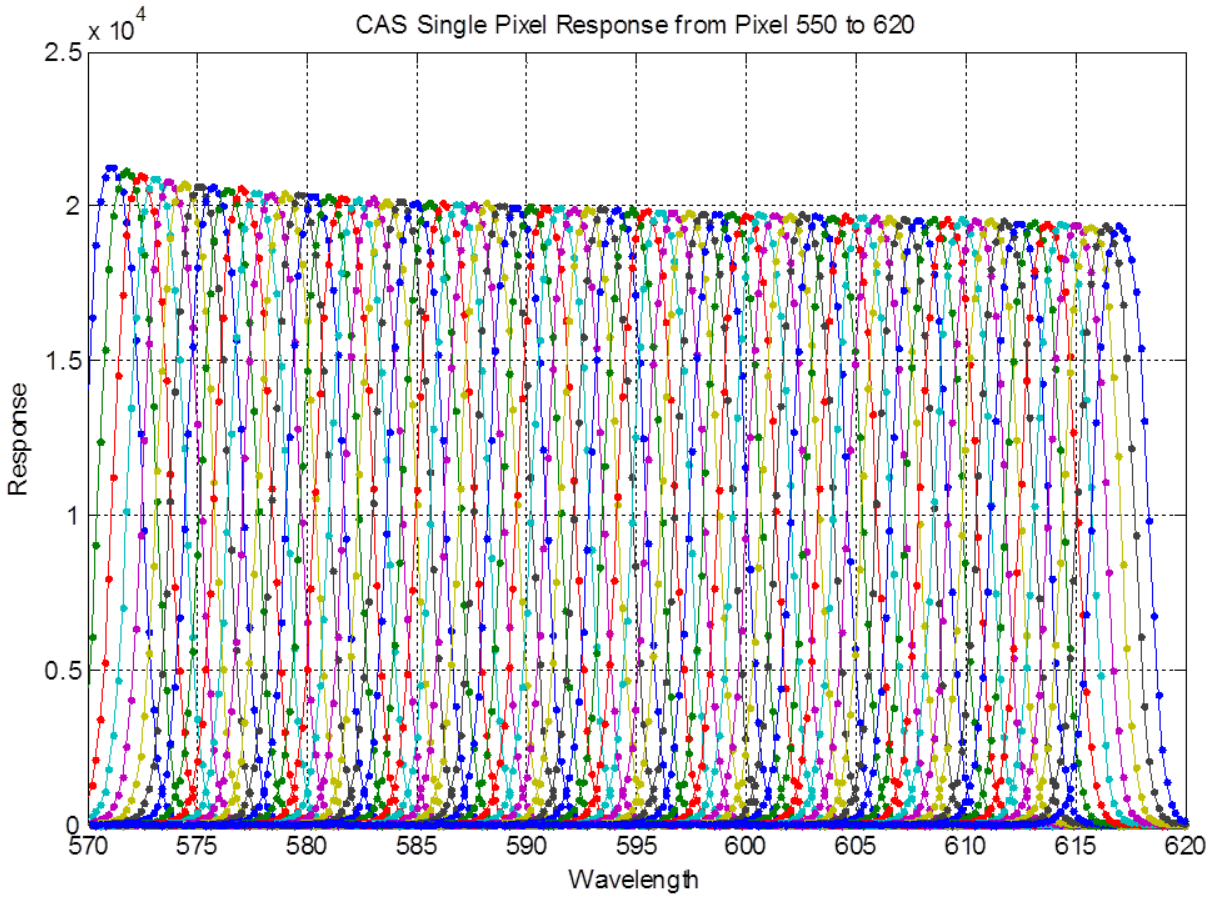
Reducing the Measurement Uncertainty:
1. Reducing the telescope calibration uncertainties

SIRCUS measurement uncertainties 0.1 % (*k*=2)

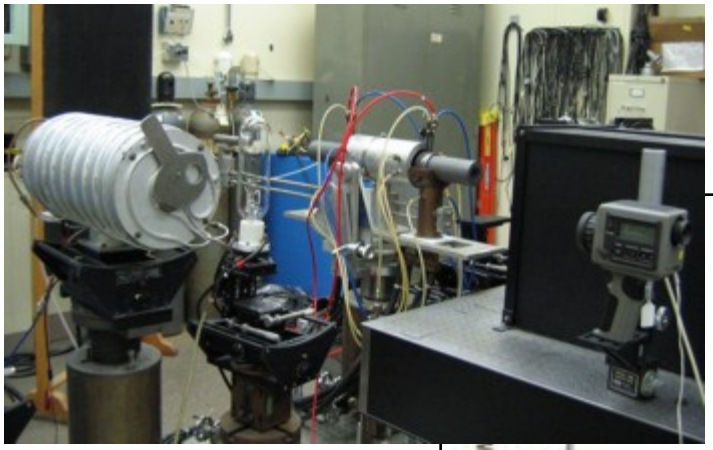
Map out the Single Pixel Responsivity of every pixel using SIRCUS

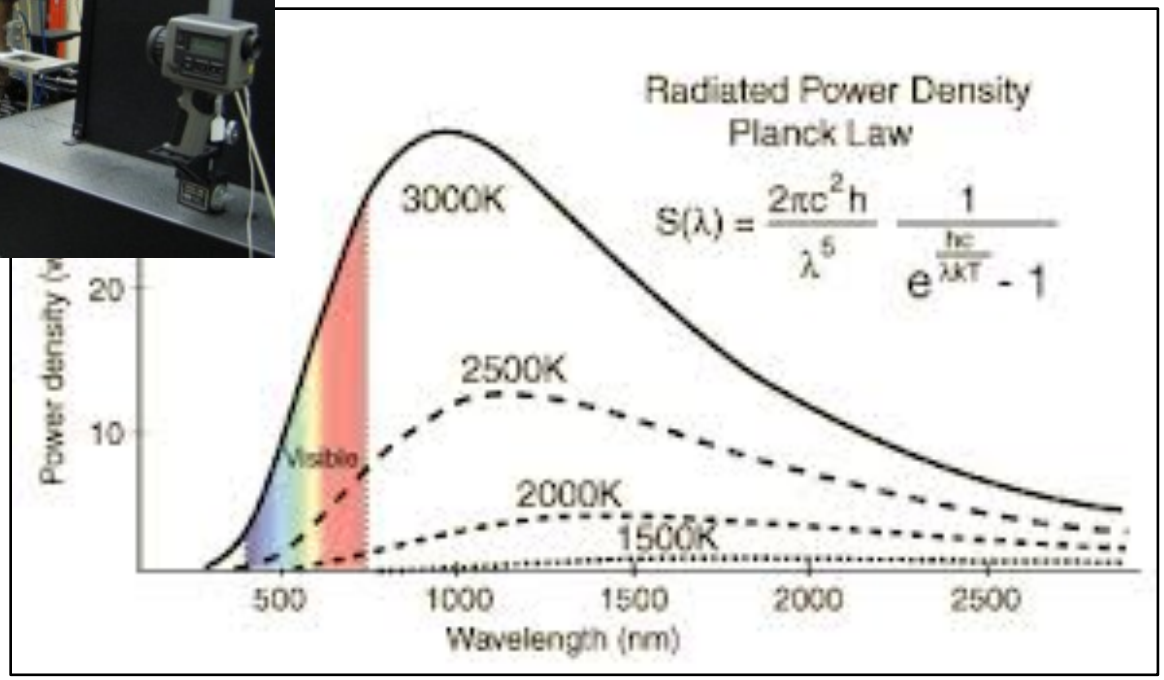


Truly a Hyperspectral Instrument



Calibration Validation of Spectrographs use NIST Blackbody sources





Coupled with *in situ* calibration validation sources

Reducing the Measurement Uncertainty

2. Considerations for moving Ground-based Measurement Program to Mauna Loa, HI

- Elevation
  - Mt Hopkins elevation 2367m
  - Mauna Loa elevation 4169 m
- Atmospheric Characterization
  - Mauna Loa Observatory (MLO) is a premier atmospheric research facility that has been continuously monitoring and collecting data related to atmospheric change since the 1950's. The undisturbed air, remote location, and minimal influences of vegetation and human activity at MLO are ideal for monitoring constituents in the atmosphere.
- Continuous daily measurements
  - Using a remotely operated/more permanent facility

In conjunction with trying to get a program going at Mauna Loa, we are working on funding for high altitude aircraft flights

- ER2 (and other aircraft, but not balloons)
  - Above 95 % of the atmosphere; lower uncertainties achievable quickly
  - These would be tie-points for the ground-based measurements

Summary of NIST Lunar Irradiance Program

- 2 lunar irradiance data sets with expanded (*k*=2)uncertainties of 1 % from 500 nm to 920 nm
- Setting up a facility at the Mauna Loa Observatory to provide low uncertainty phase and libration data*
  - Provide continuous measurements with expanded (*k*=2) uncertainties of 0.5 % from 380 nm to 980 nm
- Working on development of a high-altitude flight campaign to provide model tie points*
  - working to achieve expanded (*k*=2) uncertainties of 0.5 % from 380 nm to 980 nm
- Extend spectral coverage to cover reflected solar region, 360 nm to 2400 nm

*Desired resolution? Current spectrograph 3 nm.