SI Traceable Calibration of the Moon

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The moon is nature's on-orbit, solar reflector

- Radiometrically stable reflectance.
- Radiance similar to Earth.
- No atmospheric effects (if you are in space).
- Free!
- Anyone (everyone) can use it.
- It does move in inconvenient, but predictable, ways.

Outline

1. Take-aways from NIST Lunar Calibration Workshop
2. NIST Lunar Calibration Project
3. Future Plans

Can we use the Moon as an on-orbit absolute 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

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

<u>Phase Dependence</u> of MODIS Terra/Aqua and SeaWiFS Lunar Measurements

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

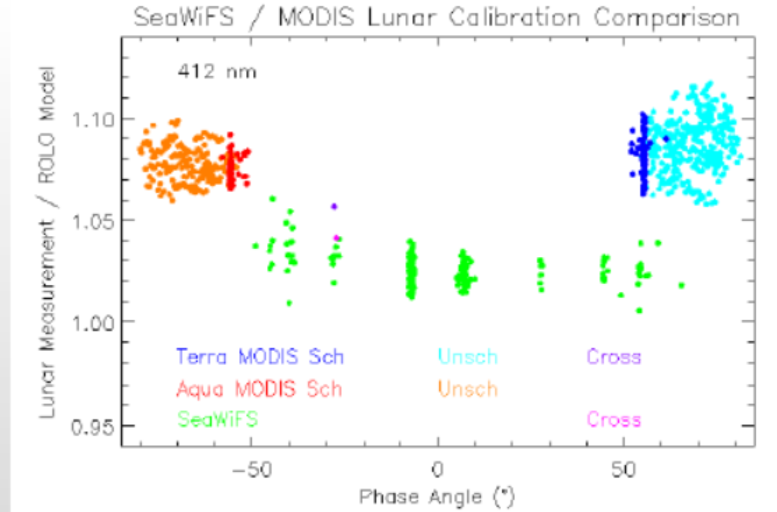
- SeaWiFS uncertainty primarily due to oversampling correction
- MODIS uncertainty primarily due to lower lunar signal at higher lunar phase

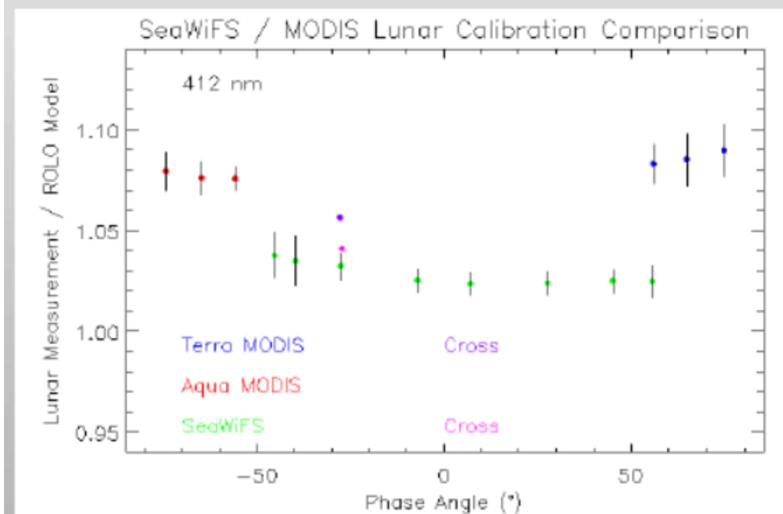
Bottom Plot: binned residuals plotted as means with STDs (412 nm)

- Phase dependence (Phase Angle):
  - MODIS Aqua: 1.1 % from -80^{o} to -51^{o}; Terra 1.5 % from 52^{o} to 82^{o}.
  - SeaWiFS: 1.7 % from -45^{o} to -6^{o} and 5^{o} to 56^{o}

Uncertainty in lunar phase : 1.7 % (-80^{o} to -6^{o} and 5^{o} to 82^{o})

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





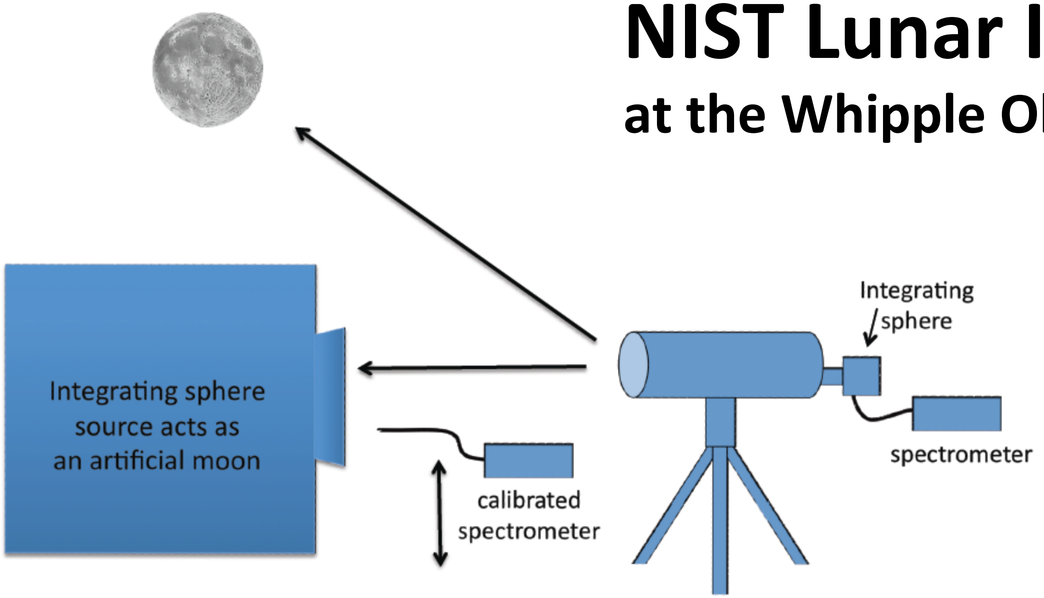
Phase Dependence from Eplee, et al., presented by Jim Butler at the 2012 Lunar Irradiance Workshop

Lunar Irradiance Summary

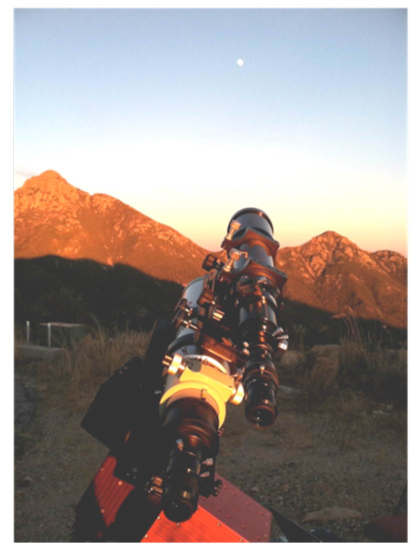
- Lunar Irradiance uncertainty requirements
  - 0.3 % (*k*=2) for CLARREO (golden target)
  - lots of benefit with *k*=2 uncertainties of 1% to 3 %
- Where the lunar irradiance model currently stands:
  - SeaWiFS only (412 nm)
    - <u>2 % to 3 %</u> constant phase 7 deg plus
    - 1.7 % uncertainty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

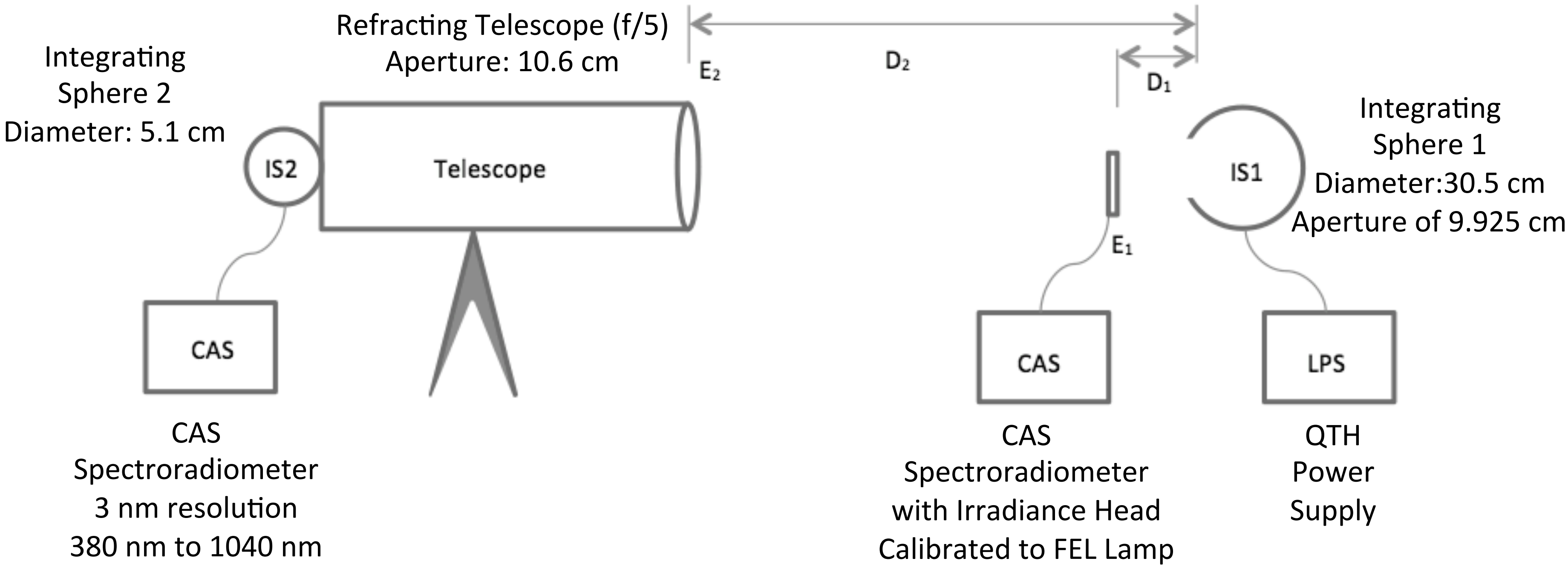


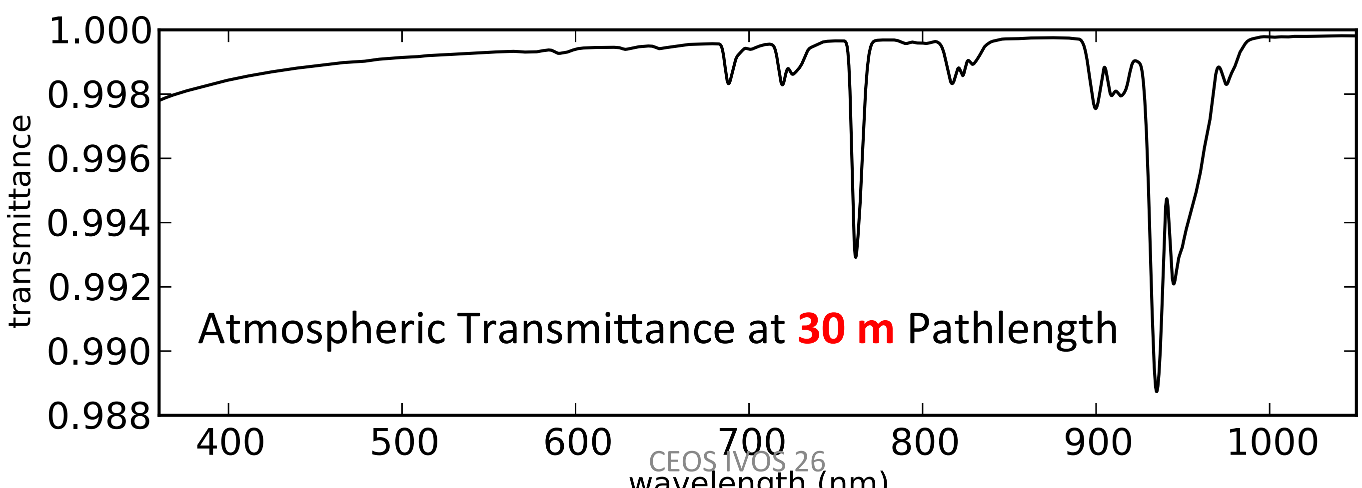
Goal: a lunar irradiance measurement with k=2 uncertainties of 1 % or less over the spectral range from 400 nm to 1000 nm



View of Mt. Hopkins Ridge (from the Summit)

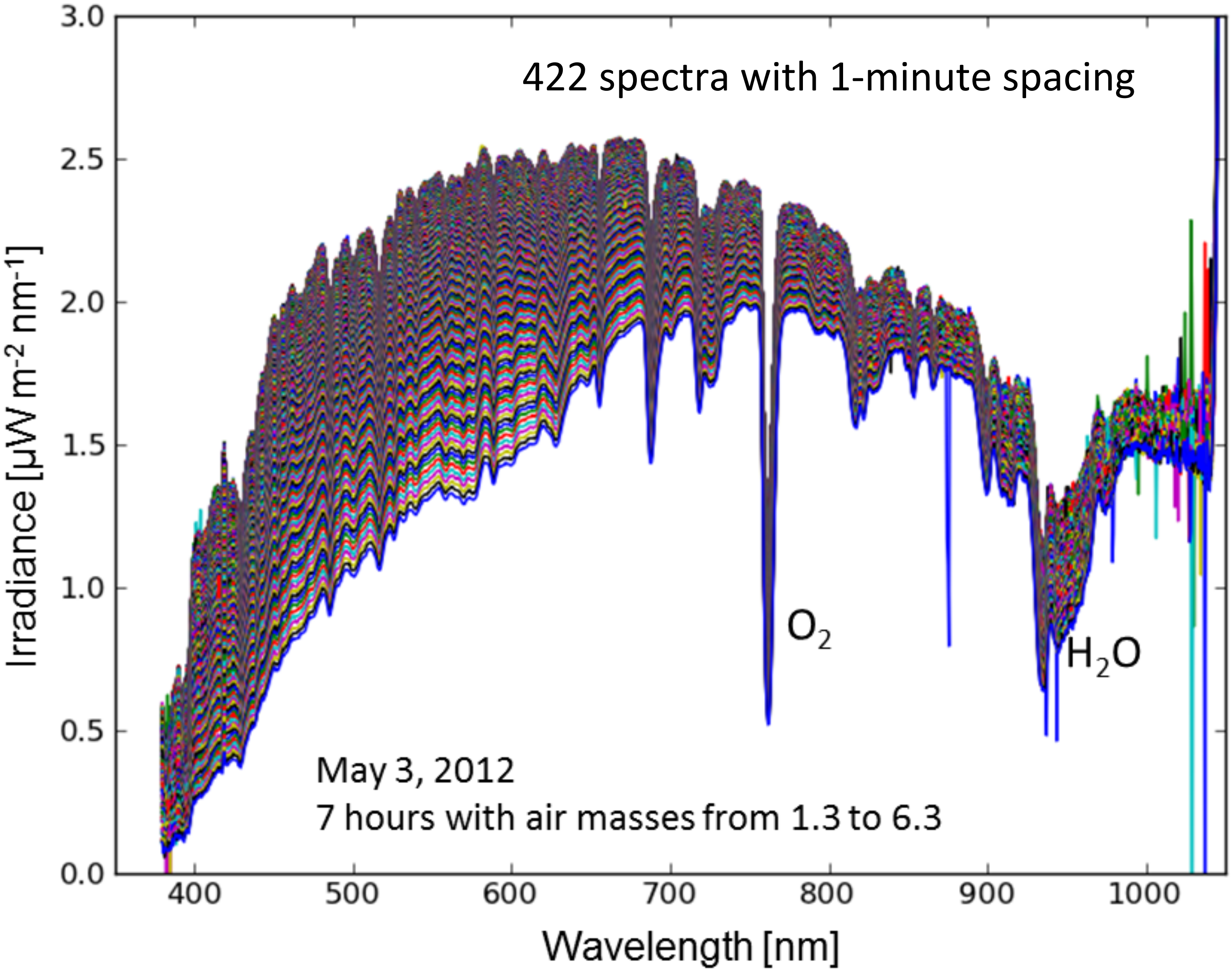
Calibration Approach

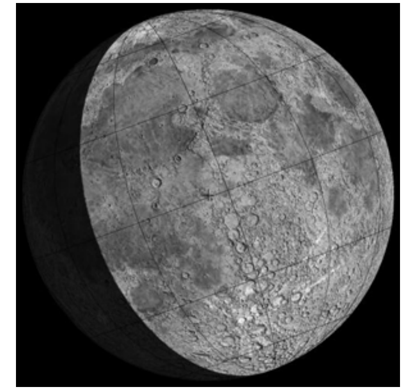




No LIDAR: Langley plots for atmospheric extinction

Example:





lunar phase: 29° to 25°

Analysis Approach

ROLO Model (Tom Stone, USGS): Time dependence of TOA lunar irradiance

Ozone Monitoring Instrument: Data to correct for ozone absorption

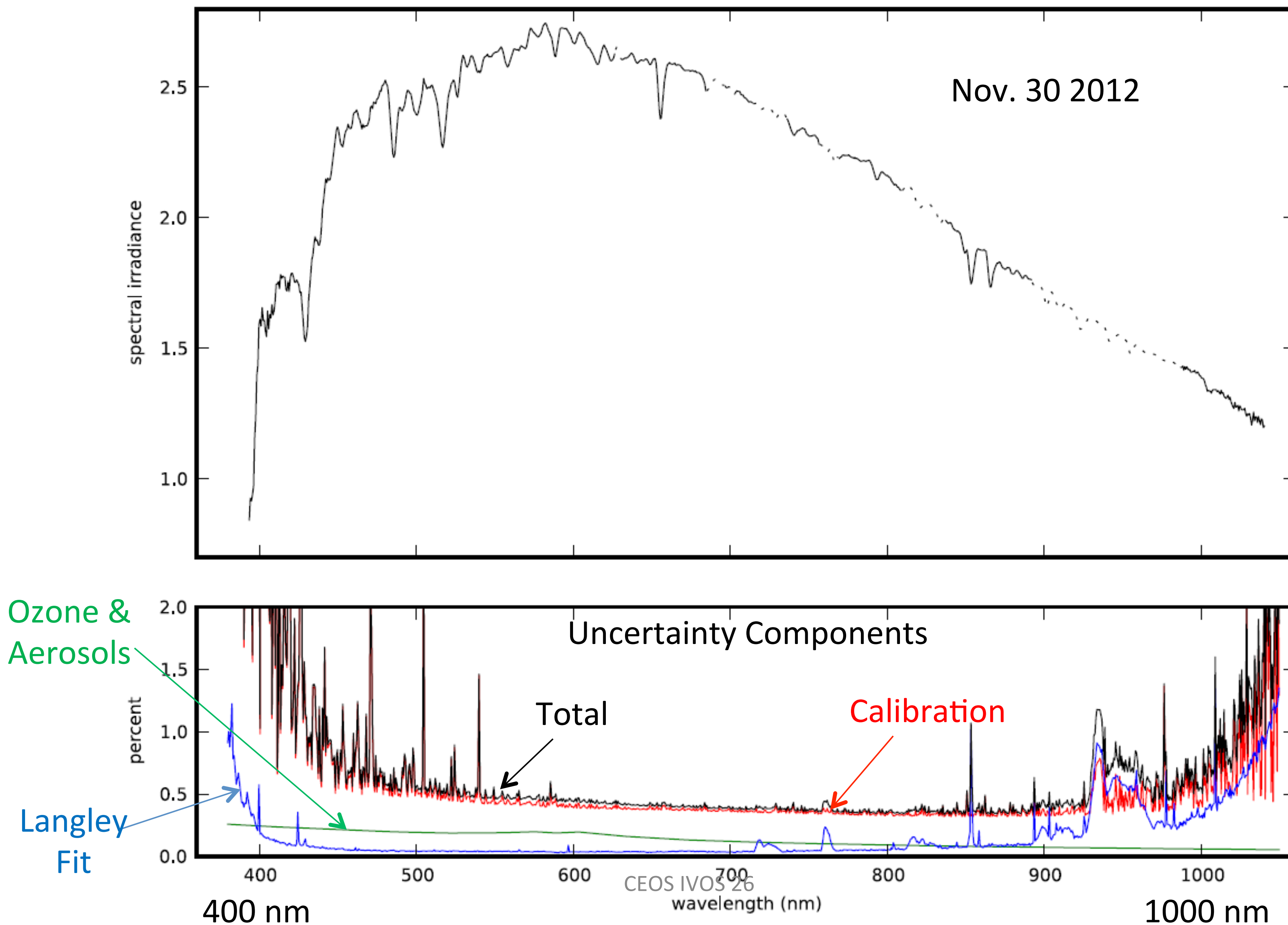
Stratospheric Aerosol and Gas Experiment (SAGE II): Stratospheric aerosol corrections

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

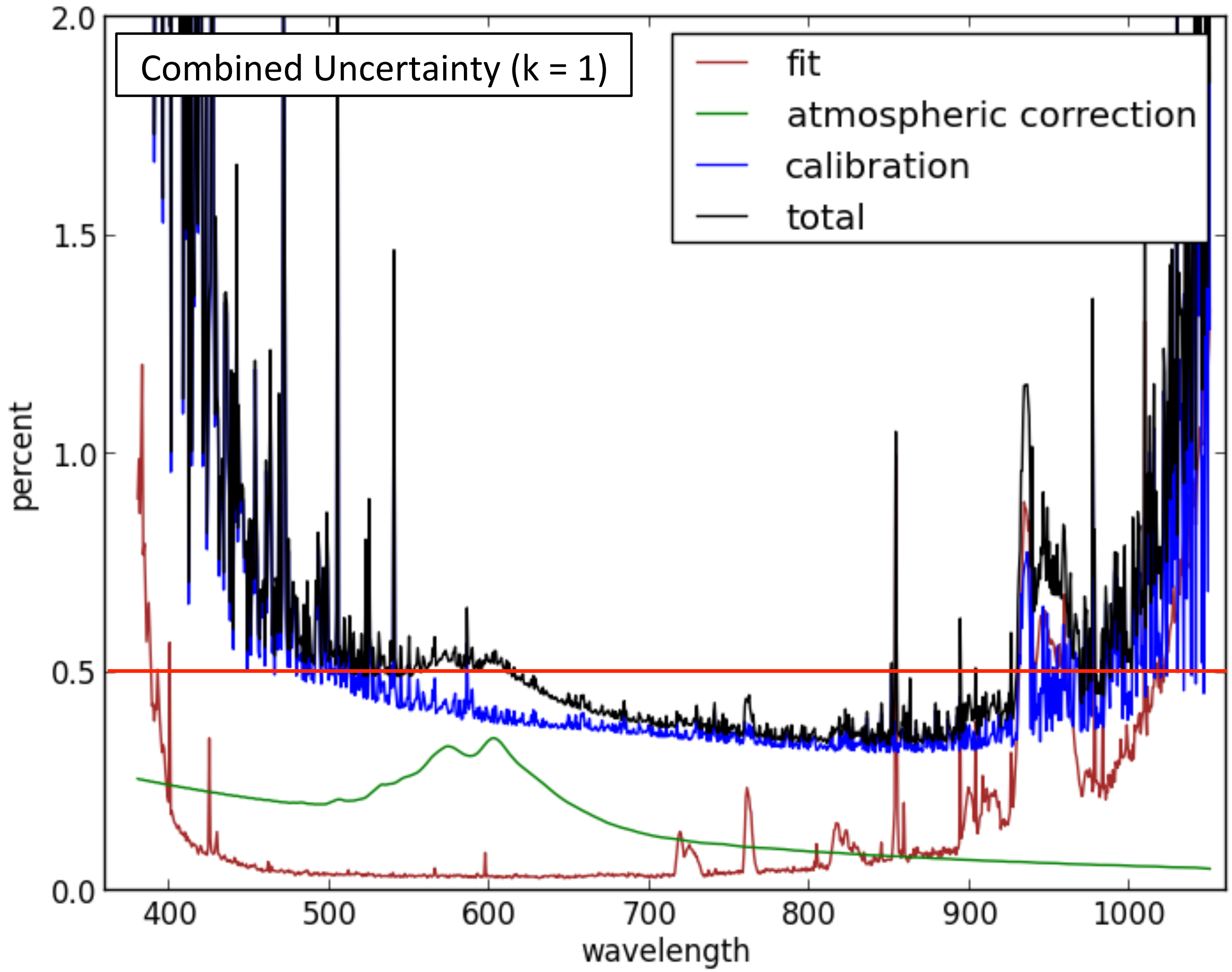
MODTRAN 5: Atmospheric modeling

Langley-Type Fits: Extract TOA Irradiance

Results: 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

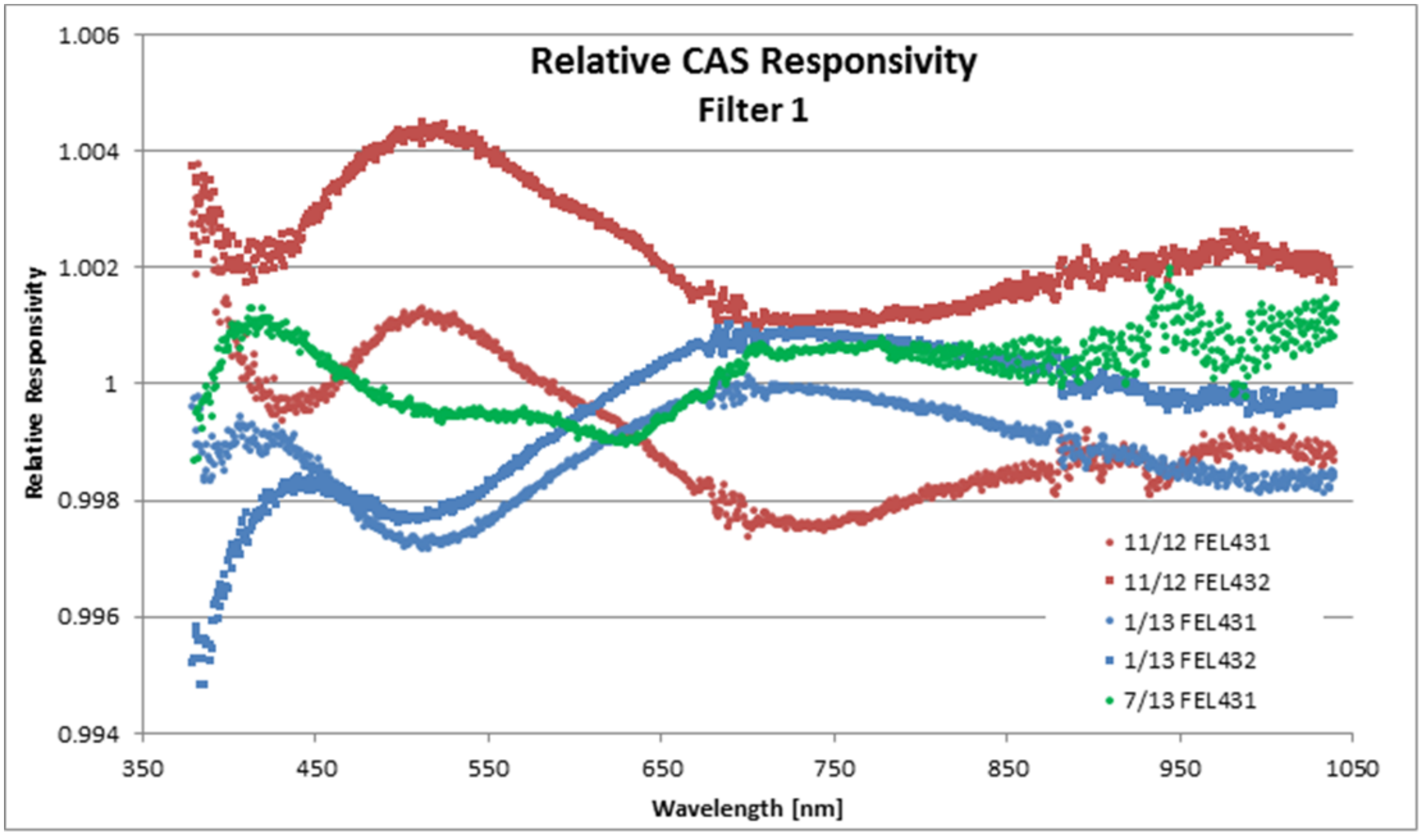
Table 1. Spectral irradiance of the Moon at 11:40:43 on 30 November, 2012 UT

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

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

CAS Spectrometer Radiometric Stability

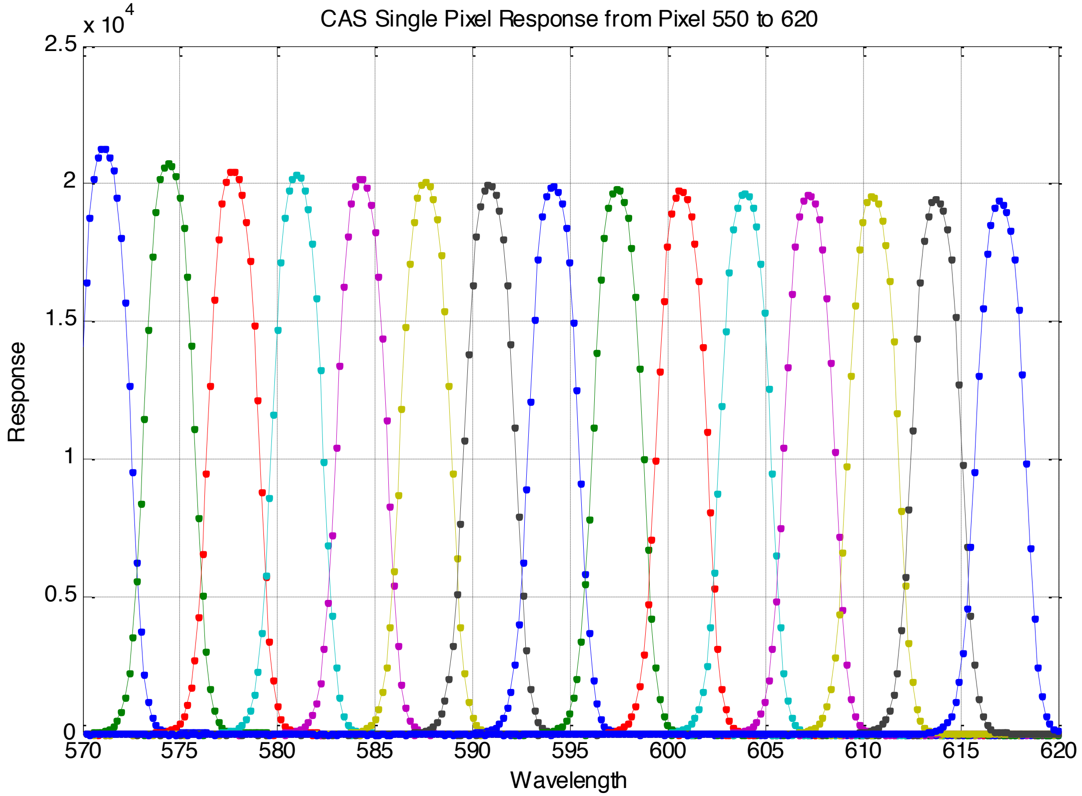


Calibration setup not maintained; reproduced for each measurement.

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



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.