Re-scaling the Moon: A proposal for Refining the USGS Lunar Irradiance Model

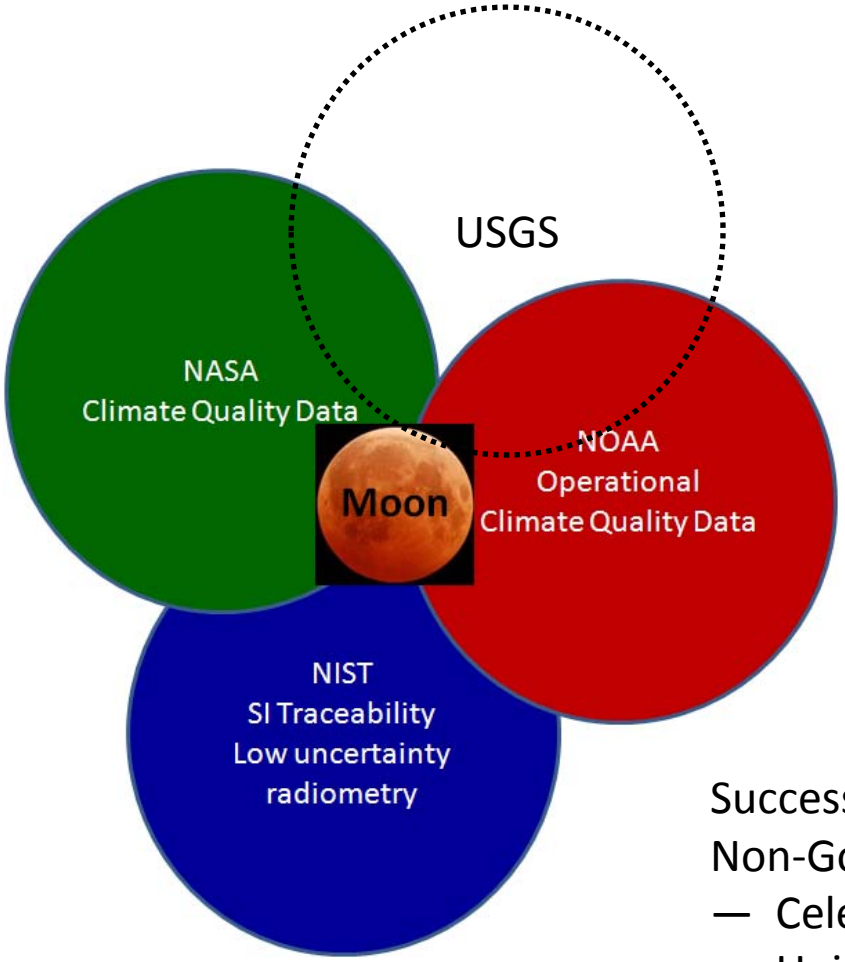
Steve Brown
NIST

Material from Tom Stone, USGS, Allan Smith, NIST, Steven Lorentz, L-1 Stds&Technol, Claire Cramer, NIST, John Woodward, NIST, Joe Rice, NIST

Rolo Observatory Lunar Image

2012 Feb 17

Generate discussion on the Moon between NASA, NOAA, (USGS), & NIST



Pooling Inst. Resources for common Projects

- Facilitates broader understanding of needs
- Creates synergy between institutions

Ideally, the result is a better product at less cost

Product in this case:
Absolute Lunar Spectral Irradiance
From 380 nm to 2500 nm with an
Uncertainty of 1% or less

Success will require contribution from
Non-Government Institutions

— Celestial Reasonings (Hugh Kieffer)
— University of New Mexico
— Harvard University
— Astronomers at mountain-top Observatories

Why do we need celestial calibration targets?

- Space is a harsh environment. The responses of all radiometric sensors change with time on-orbit in an unknown and unpredictable fashion.
- On-sensor calibration targets, diffusers with attenuator screens that view the sun, change with time as well and the current laboratory uncertainties (>1.44 %) are too large
- Earth targets exist – Libyan Desert; Tuz Golu, Turkey; Ivanpah Playa, US, and others – and are being promoted by CEOS for land reflectance.
  - They show promise; however, you always have to deal with the complexities of the atmosphere
  - Good for land reflectance, but not for ocean color

Why Use the Moon?

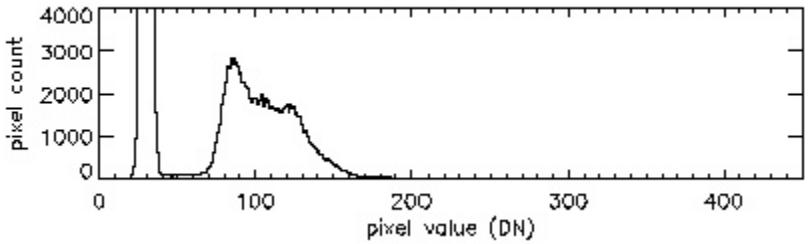
- Unmatched stability of the reflecting surface
  - better than 10^{-8} per year [Icarus 130, 323-327 (1997)]
- Smooth reflectance spectrum, with only broad, shallow features
- Accessible to all spacecraft, regardless of orbit
- Utilizes a spacecraft instrument's normal Earth-viewing optical path
  - overcomes a common limitation of on-board calibration systems
  - with the caveat that LEO sensors like MODIS&VIIRS will need to perform a maneuver to see the Moon, otherwise they view the Moon through the space port (at a different scan mirror angle than Earth measurements)
- Appropriate brightness for terrestrial environmental sensors
  - at visible to SWIR wavelengths

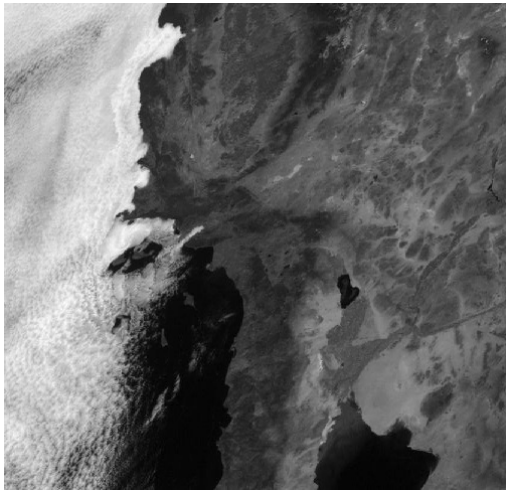
Because the radiometric properties of the Moon are stable, developing a lower uncertainty in the lunar irradiance means that previous sensors can be back-calibrated – as long as they have looked at the Moon

Extracts from GOES-12 vis-channel full-disk image, phase = 9.5°

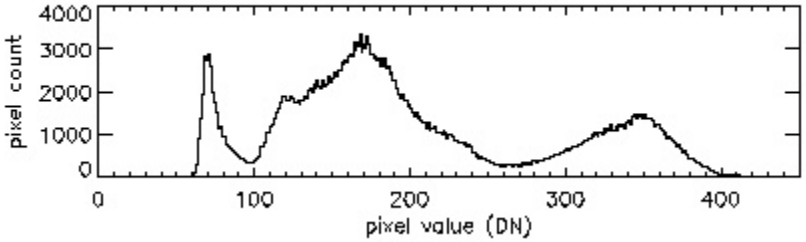
Dynamic range of the Moon at low phase angles is similar to clear land.
Sun is 4×10^5 brighter than the full moon.

space Moon





ocean land cloud



*Courtesy of Tom Stone, USGS, Flagstaff, AZ

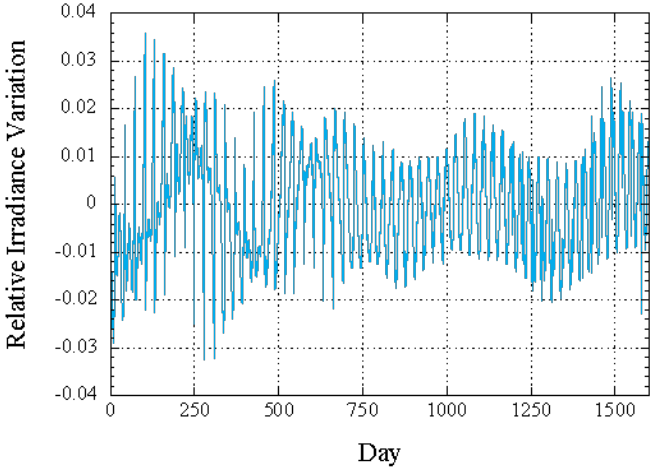
Celestial Targets

Why Not Use the Moon?

" it is non-uniform and changes brightness all the time "

Phase

Libration



From A. W. Smith, NIST.

Required that a model be developed, based on measurements

Led to the development of the Robotic Lunar Observatory (ROLO), USGS, Flagstaff AZ

ROLO Observatory

Flagstaff, AZ
Altitude 2143 m

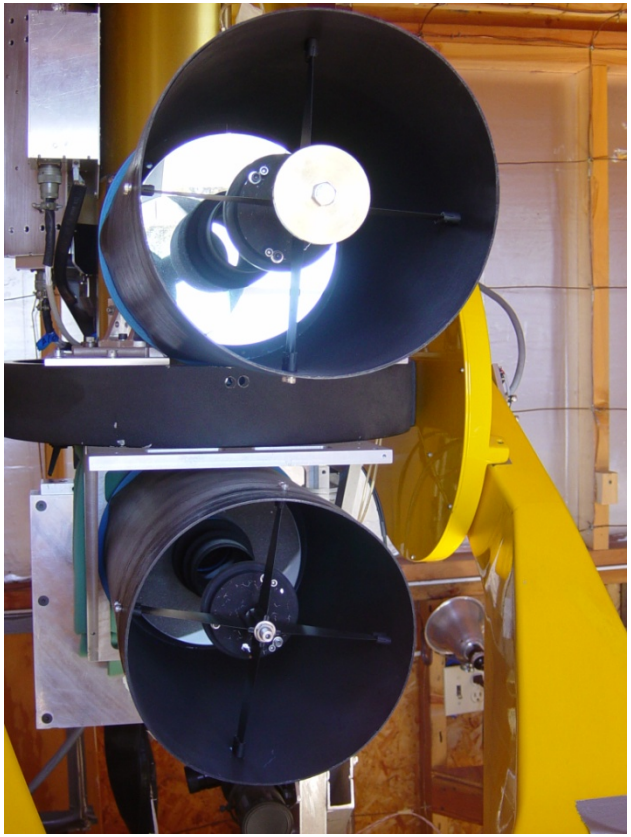
*Courtesy of Tom Stone, USGS, Flagstaff, AZ

ROLO Telescopes and cradle

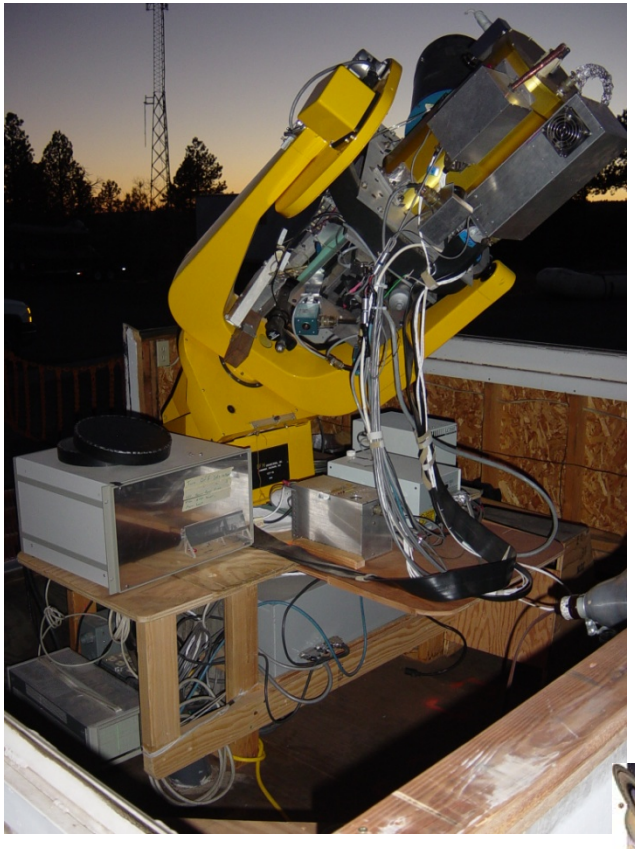
The twin ROLO telescopes are 20 cm (8 inch) diameter Ritchey-Chretien Cassegrains.

SWIR

VisNIR



ROLO telescope cradle



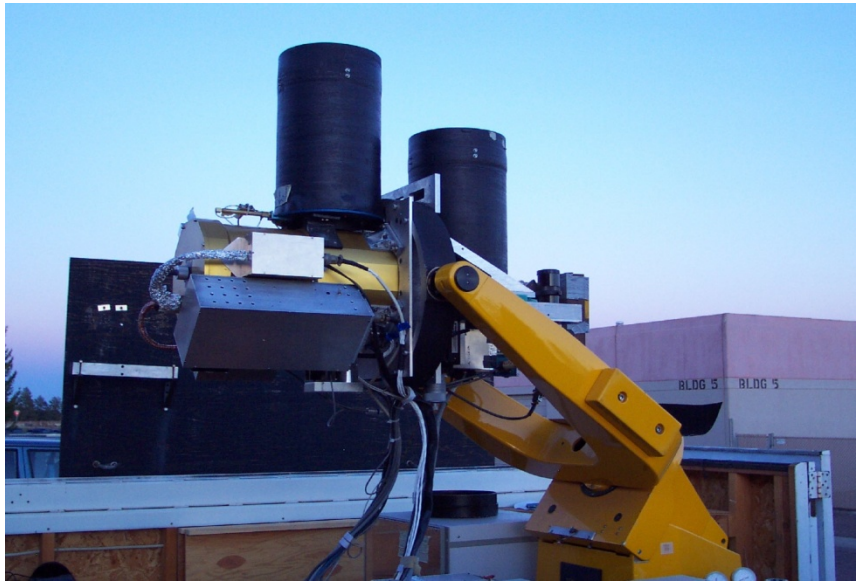
*Courtesy of Tom Stone, USGS, Flagstaff, AZ

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 emphasized extinction
  - >800,000 star images
- Dormant since Sept. 2003

*Courtesy of Tom Stone, USGS, Flagstaff, AZ

Lunar Irradiance Model – performance

- ~ 1200 observations fitted for each band
  - sufficient libration coverage gained by multiple years of observations
- Mean absolute residual over all bands is 0.0096 in ln A, ~1%

This is a measure of the model's geometric prediction capability over the full range of phase and libration angles covered. This is an upper limit; precision is better for small ranges of phase angles.

- Absolute scale tied to Vega, field calibration at ROLO involving NIST
- Smoothing of model reflectance spectrum using Apollo return samples
- Current absolute uncertainty: 5-10%
  - ultimate accuracy goal is 1-2% absolute

*Courtesy of Tom Stone, USGS, Flagstaff, AZ

USGS Lunar Irradiance Model

Model inputs for fitting developed from calibrated exoatmospheric radiance images, spatially integrated to irradiance and converted to disk-equivalent reflectance A_k:

$$I_k = A_k \cdot \Omega_M E_k / \pi$$

$$E_k = \text{Solar spectral irradiance}$$
$$\Omega_M = 6.4236 \times 10^{-5} \text{ sr}$$

Analytic form derived empirically, from correlation study of fit residuals. For band *k*:

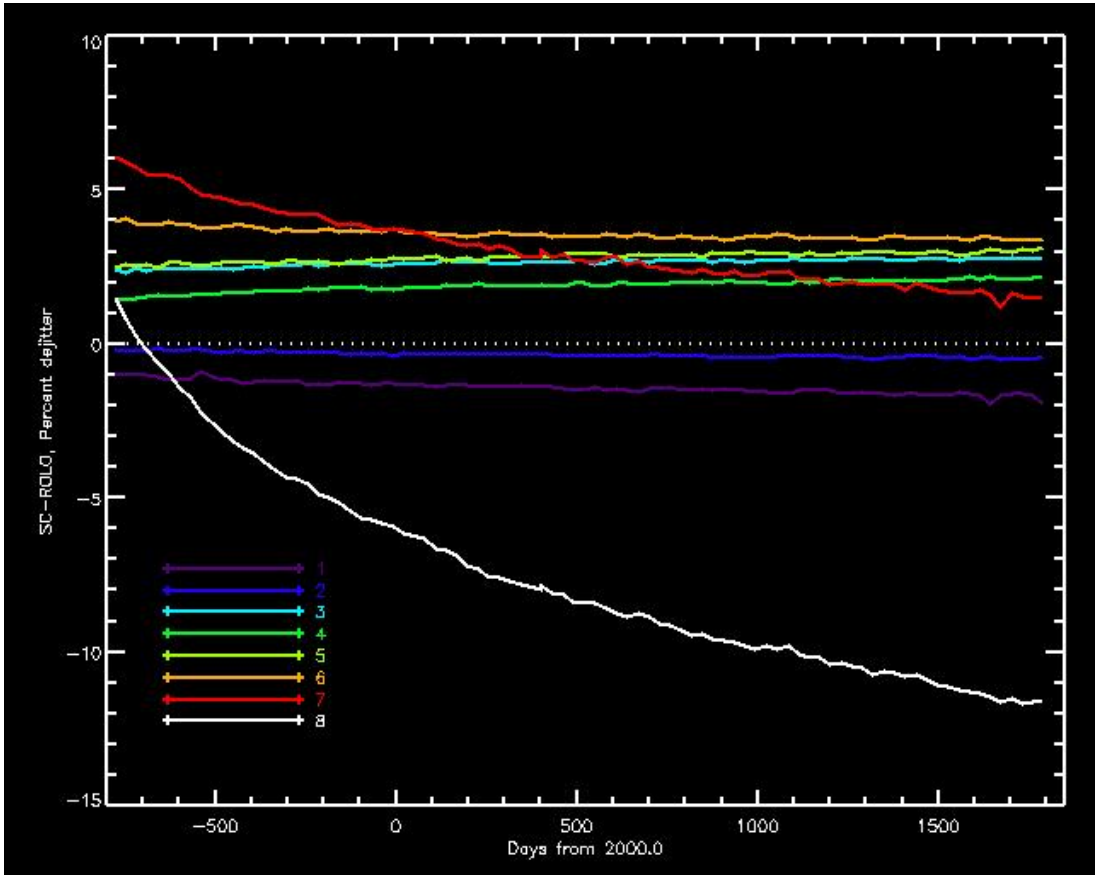
$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\theta + c_2\phi + c_3\Phi\theta + c_4\Phi\phi$$
$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

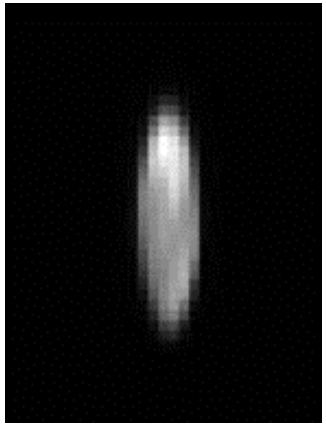
$$g = \text{phase angle}$$
$$\theta = \text{observer selenographic latitude}$$
$$\phi = \text{observer selenographic longitude}$$
$$\Phi = \text{selenographic longitude of the Sun}$$

Publication Ref.: Astronomical Journal 129, 2887-2901 (2005 June)

The stability of the lunar irradiance model means that given a time series of lunar views acquired by a spacecraft instrument, sensor relative response trending with sub-percent precision can be achieved.

- plot is 85 lunar observations (SeaWiFS took over 200)
- ordinate is discrepancy: [inst – model] / model × 100%
- band-correlated temporal jitter removed, attributed to size measurement error in small lunar images (~6×20 pixels)



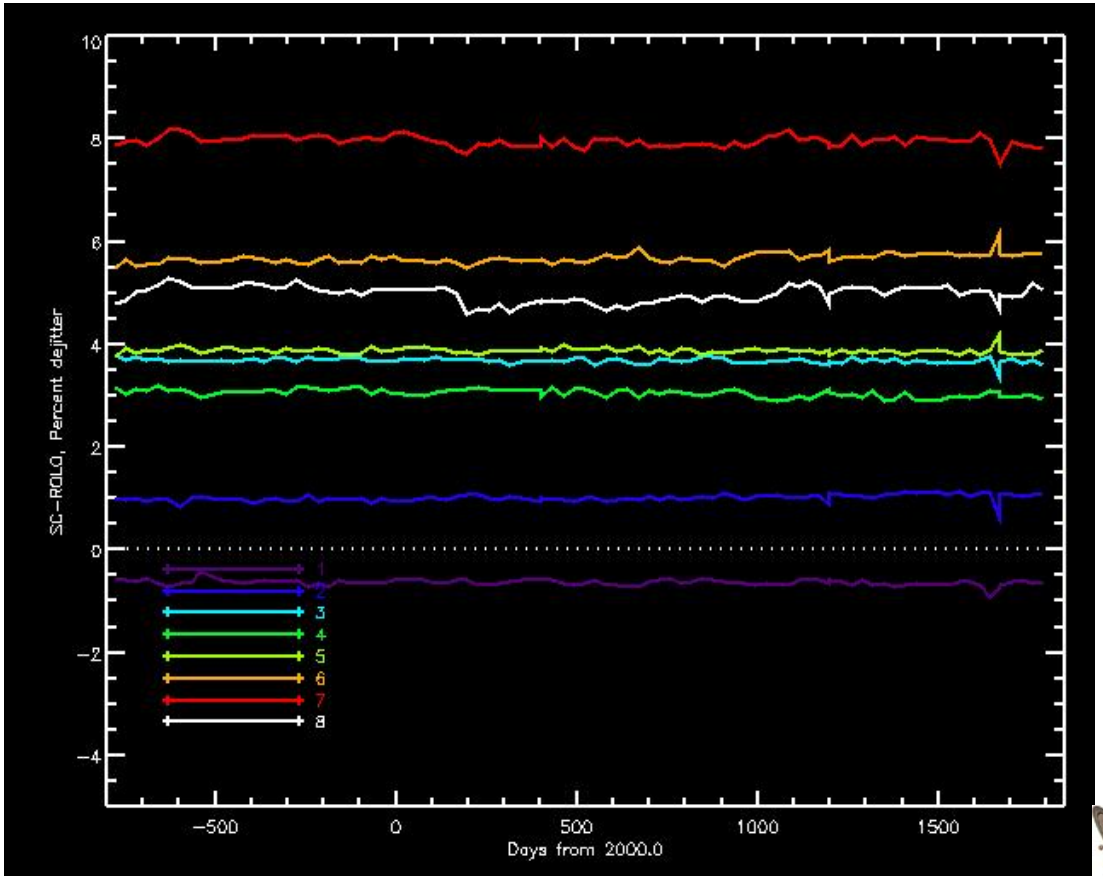


USGS Lunar Model enabled tracking changes in SeaWiFS at the 0.1 % level

After correction for sensor degradation based on lunar views, residual SeaWiFS band response trends are < 0.1% per year[1]

This meets the stability requirement for visible-wavelength radiometer measurements of environment variables for climate change

- 85 SeaWiFS lunar observations
- asymptotic temporal correction applied for each band



*Courtesy of Tom Stone, USGS, Flagstaff, AZ

[1]Applied Optics 43 (31), 5838-5854 (2004)

Lunar calibration for space-based climate monitoring

- Instrument stability benchmark is achieved now
- Potential for absolute accuracy to exceed that achievable with on-board radiance/reflectance calibration hardware
- Capability for instrument inter-calibration and consistency of radiometric scale
  - instruments view the same, ultra-stable source
- Bridge for possible gap in observations prior to NPP/NPOESS
  - requires series of lunar views by current instruments prior to failure

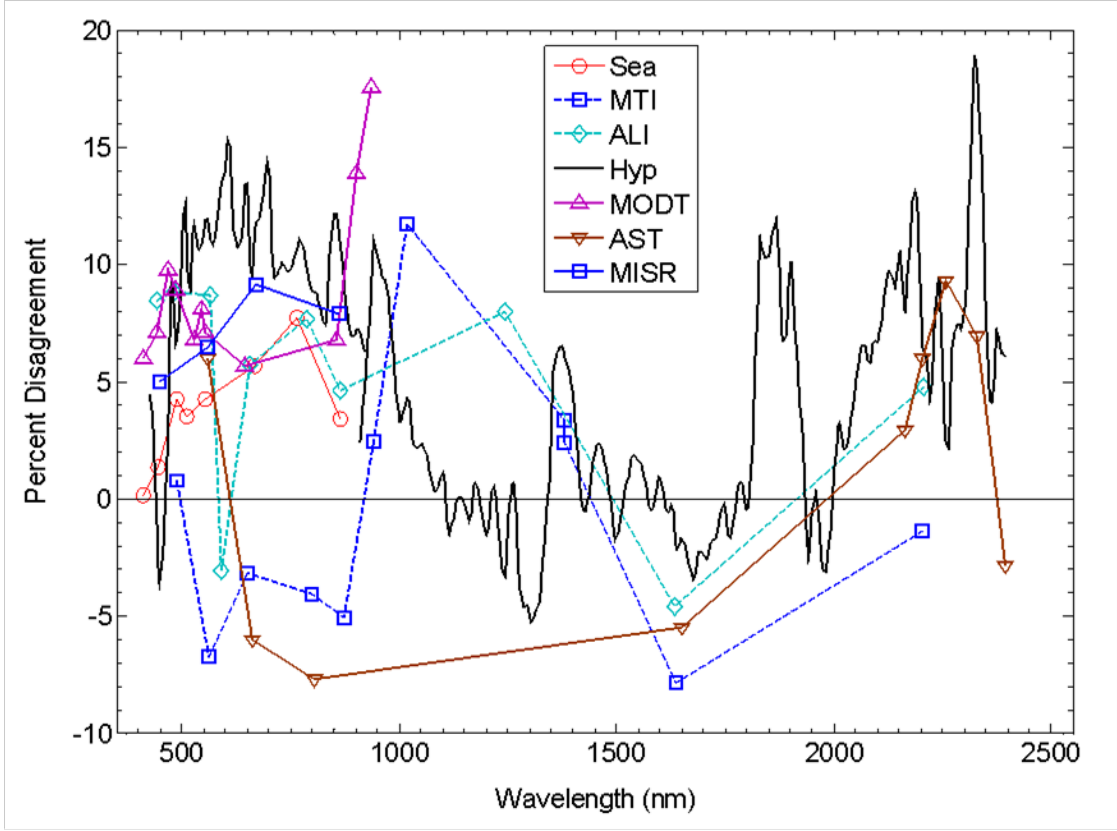
Regular lunar observations need to be part of spacecraft operational plans for calibration

- called for in GEOSS 10-year Implementation Plan Reference Document
- no mention in: US CCSP Strategic Plan, GCOS Climate Monitoring Principles

*Courtesy of Tom Stone, USGS, Flagstaff, AZ

Lunar calibration comparison of EOS instruments

- average of all observations for each instrument
- Includes instrument artifacts
- differences between instruments represent current best practices

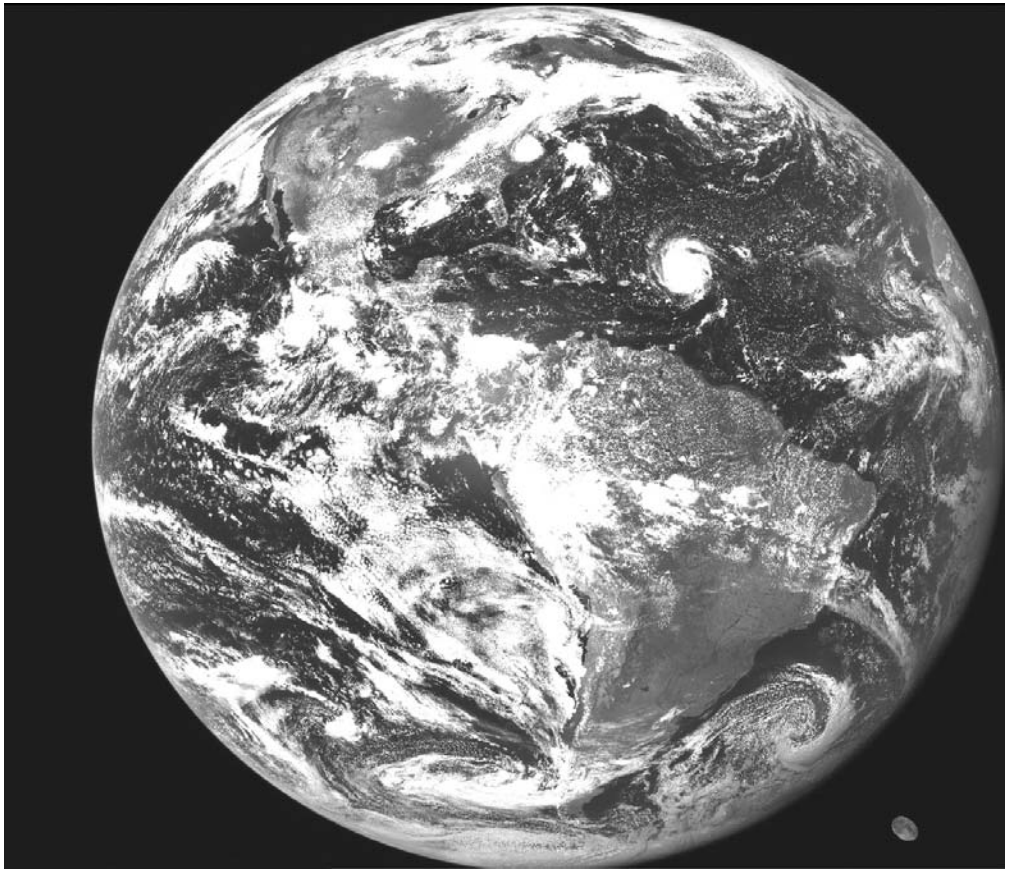


*Courtesy of Tom Stone, USGS, Flagstaff, AZ

Application for geostationary instruments

The Moon appears regularly in the margins of GEO full-disk images

- GEO visible-channel imagers typically lack on-board calibration
- Archived Moon images can provide calibration history, including for instruments not currently operational
- USGS has tools for predicting GEO Moon appearances from orbit TLE
- Lunar calibration for GOES – work in progress



GOES-12 vis channel 2004 August 30 17:45:14

NOAA has recently instituted regular lunar views for GOES-10 and -12

- monthly observations since November 2005
- subsample format: 1000 lines × 5000 elements

*Courtesy of Tom Stone, USGS, Flagstaff, AZ

LUnar Spectral Irradiance (LUSI)

Allan Smith (NIST), Steven Lorentz (L-1), Tom Stone (USGS)

A New Program to Reduce the Uncertainty in
the Absolute Lunar Spectral Irradiance
(2005)

- The ability to more accurately predict the lunar irradiance in the future.
- Lower uncertainties in the absolute scale of the lunar irradiance
  - Advantages are lower uncertainties for cross-calibration and filling possible gaps between satellite missions
  - If a low absolute uncertainty is achieved then a low relative uncertainty is assured.
- Higher spectral resolution from 320 nm to 2500 nm
  - Reduces uncertainties in the application of the model to filter bands instruments—reduces interpolation
  - Aids in the atmospheric correction of lunar irradiance as measured from the Earth

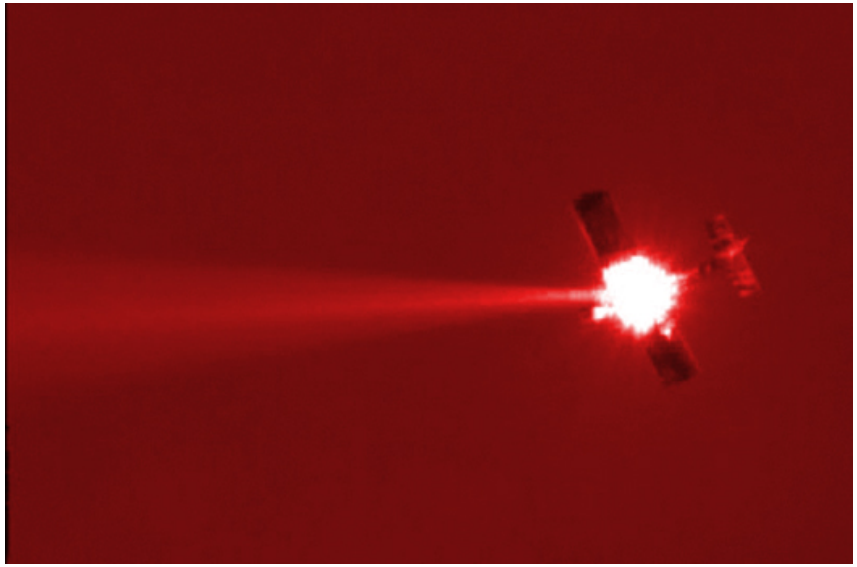
LUSI (LUnar Spectral Irradiance)

A New New Program to Reduce the Uncertainty in
the Absolute Lunar Spectral Irradiance
(2012 - What's changed?)

- From Bryan Franz, MODIS Aqua data users:
  - The quality of the MODIS Aqua ocean color products produced by the OBPG has degraded significantly over the past year, especially in the blue. … This is due to unpredictable changes in the instrument radiometric calibration and limitations of the on-board (solar and lunar) calibration capabilities to adequately track those changes.
  - NPP VIIRS showed a dramatic change in responsivity with initial door opening – much larger than the required on-orbit stability. Demonstrated the fragility of the current on-orbit calibration paradigm
- MOBY lost JPSS funding for a re-furbishing
  - may not be available (that is, lost or irreparably damaged)
  - or my not be able to hold the required uncertainty budget for JPSS VIIRS
- Successful full aperture illumination T-SIRCUS calibration of NPP VIIRS
  - *For the first time*, we were able to meet on-orbit ocean color requirements in the laboratory

You want to shoot lasers at VIIRS? You have to be kidding me!

Boeing's Matrix Laser
destroying an Air Drone



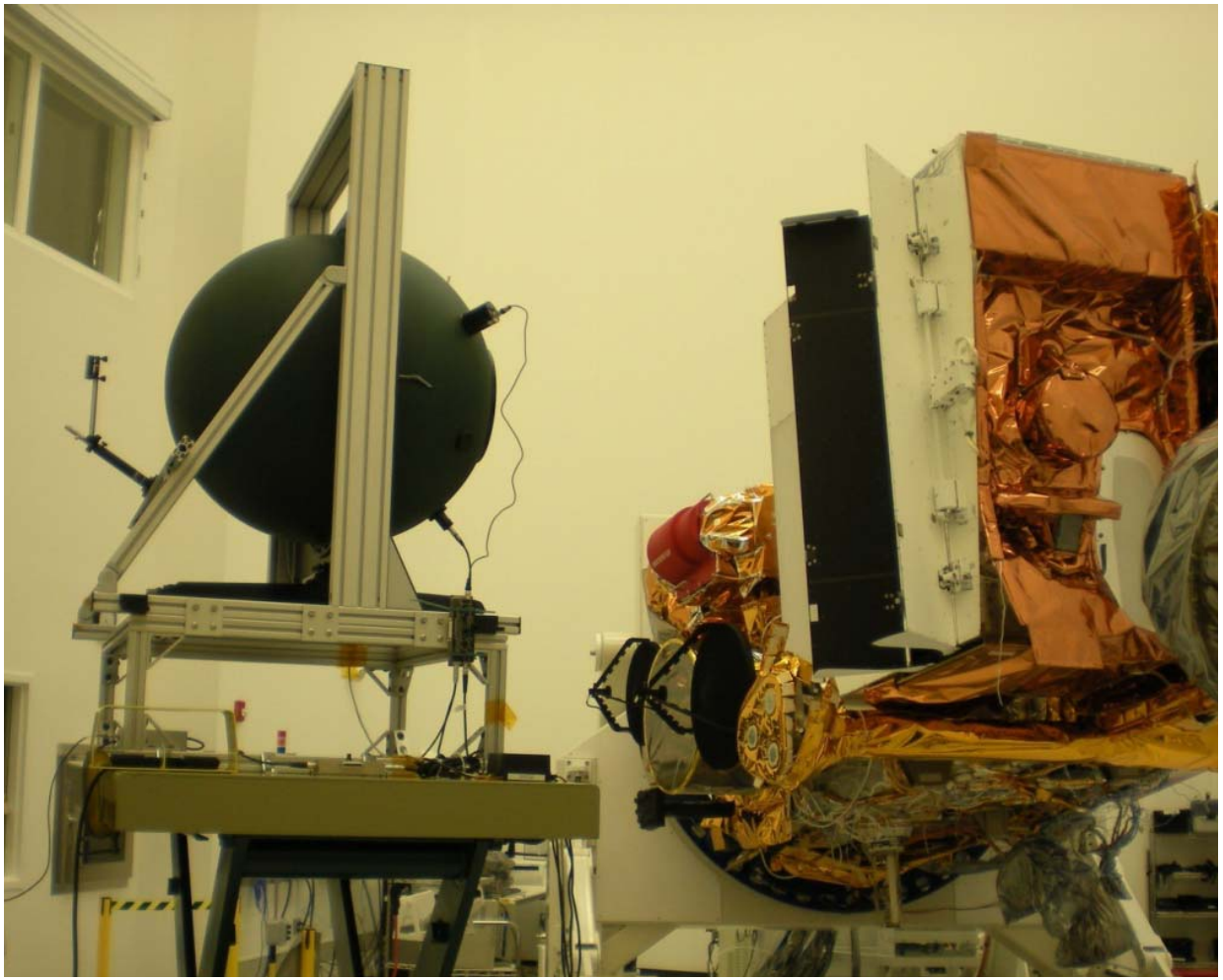
Marvin the Martian with his
Illudium PU-36 Explosive Space Modulator

Destroying the Earth because
It obscures his view of Venus

T-SIRCUS at Ball Aerospace, Boulder CO in 2010

NPP VIIRS Sensor on the Spacecraft

Credit for the test: Bruce Guenther, NOAA



Can achieve ~0.1 % uncertainties in the sphere radiance

Why does this test lead to the need for an absolute lunar irradiance scale?

Uncertainties

Coarse sensor on-orbit uncertainty budget.

	Uncertainty Estimates	Laboratory Calibration	Transfer to Orbit	On-orbit Calibration	Trending	Combined Standard Uncertainty
	SpMA-based	2 -3 %	2 % to 3 %	2 % to 3 %	1 to 2 %?	4.6 %
	SIRCUS-based	5 %	2 % % to 3 %	0 %	1 to 2 %?	3 %
1	Potential w/1 % lunar cal	0.5 %	1 %	1 %	1 %	1.8 %
2	Potential w/0.1 % lunar cal	0.1 %	0.25 %	0.25 %	0.1 %	0.38 %

1. A lunar calibration at 1 % gives an on-orbit uncertainty that fulfills land reflectance requirements
2. A lunar calibration at 0.25 % combined with a laboratory calibration of 0.1 % gives and on-orbit uncertainty that fulfills ocean color requirements

LUSI (LUnar Spectral Irradiance)

A New New Program to Reduce the Uncertainty in
the Absolute Lunar Spectral Irradiance
(2012 - What's changed?)

- In the new paradigm of operational sensors embodied by the NPP VIIRS program, no data reprocessing is currently planned
  - For ocean color vicarious calibration using MOBY, it takes on the order of 2 years to set the gain coefficients
- Program in place at NIST to measure the spectral irradiance of stars, including Vega (ROLO standard calibration star)
  - Access to (high altitude) astronomical sites
  - Experience calibrating telescopes in the field
- LIDAR systems to characterize the atmosphere
- Include UAS/balloon flights to get above the atmosphere
  - Overflights looking at the ground to verify our atmospheric model(s)
  - Look directly at the moon

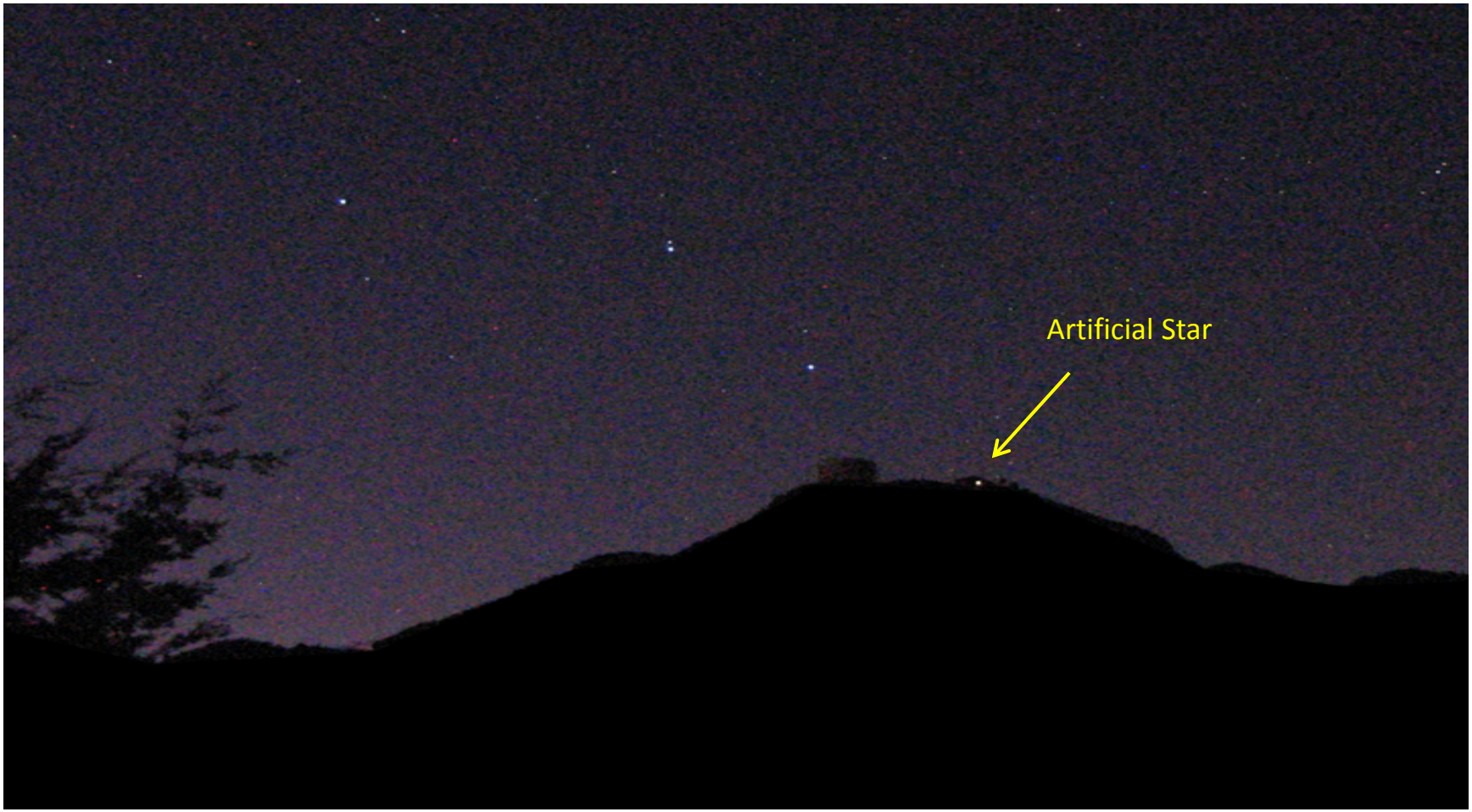
Stellar Irradiance program

Fred Lawrence Whipple Observatory, Mt. Hopkins, AZ

Mt. Hopkins summit showing the 6.5 m MMT

Stellar Irradiance program

Fred Lawrence Whipple Observatory, Mt. Hopkins, AZ

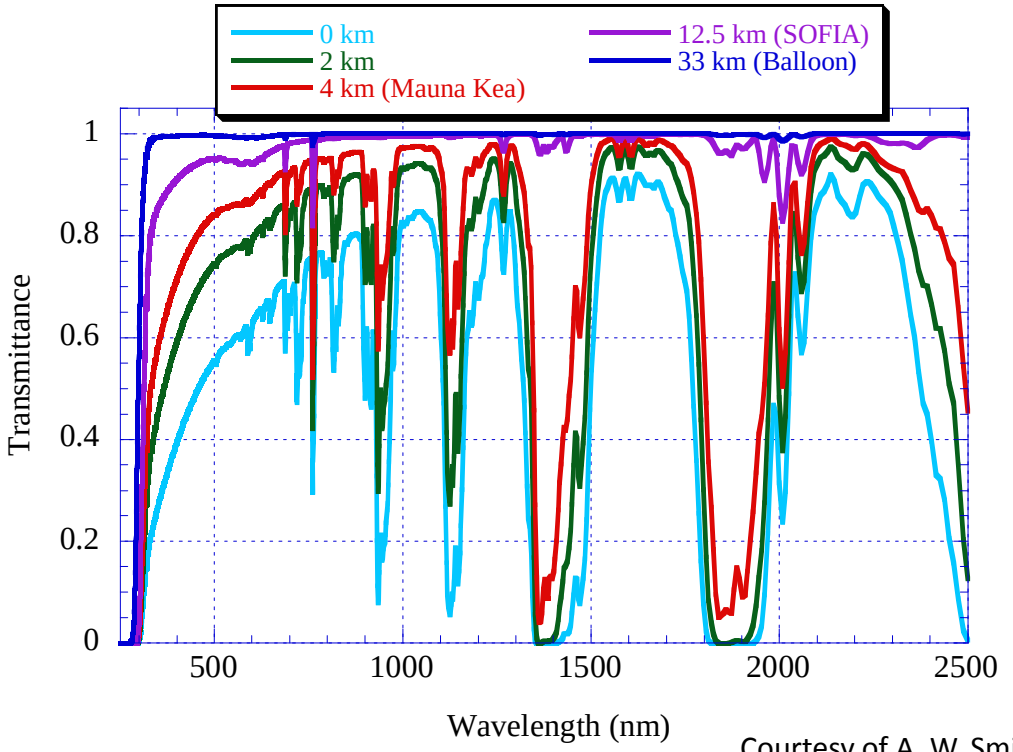


Cerro Tololo Inter-American Observatory
a division of the National Optical Astronomy Observatory
NOAO

CHILE
CTIO
ARGENTINA
PERU
BOLIVIA
PARAGUAY
BRAZIL
URUGUAY
Iquique
Antofagasta
Atacama Desert
San Pedro de Atacama
Salta
Pacific Ocean
Llullillaco
Bermejo
Puerto Iguazú
CHACO
Corrientes
S. Miguel de Tucuman
Ojos del Salado
Andes
Paraná
Coquimbo
San Juan
Córdoba
Santa Fe
Rosario
Aconcagua
Mendoza
Río de la Plata
Valparaíso
Santiago
Buenos Aires
La Plata
La Pampa
S. Rafael
Sta. Rosa
Bahía Blanca
Mar de Plata
Concepción
Bío-Bío
Colorado
Neuquén
Temuco
Nahuel Huapi Nat. Park
Negro
Valdivia
Osorno
Lake District
Bariloche
Viedma
Pto. Montt
Ancud
Península Valdés
Trelew
Isla de Chiloé
Los Alerces Nat. Park
Chico
Rawson
Arch. de Los Chonos
Atlantic Ocean
Comodoro Rivadavia
Patagonia
Golfo de Peñas
Fitz Roy
Pto. Santa Cruz
Calafate
Río Gallegos
Stanley
Paine Nat. Park
Strait of Magellan
Falkland islands
Pto. Natales
Tierra Del Fuego
Pta. Arenas
Ushuaia
300 Miles
Andes
Pampas & Patagonia
Central Valley & Forest
NE Lowlands
Northern Deserts
City or Town
Mountains

Atmospheric Transmittance

Transmittance of a U.S. standard atmosphere at a zenith angle of 30° generated using MODTRAN 4.0. The aerosol model parameters were rural with 23 km meteorological range at sea level, spring-summer profile and no volcanic activity.



Courtesy of A. W. Smith, NIST

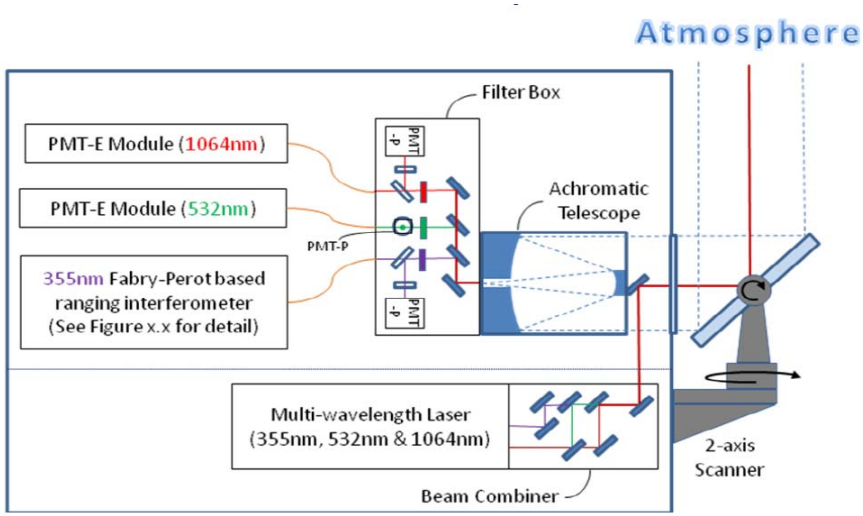
Aerosols – most problematic to model – typically at heights of 2 km or less.

The Atmosphere

University of New Mexico
John McGraw and Pete Zimmer
Astronomical Lidar for Extinction (ALE)

measures the time-resolved absolute transmission of the atmosphere at 527nm by reference to stratospheric Rayleigh backscattering and sonde measurements

Michigan Aerospace Corporation
Multi-Wavelength Atmospheric Characterization System
(MWACS)

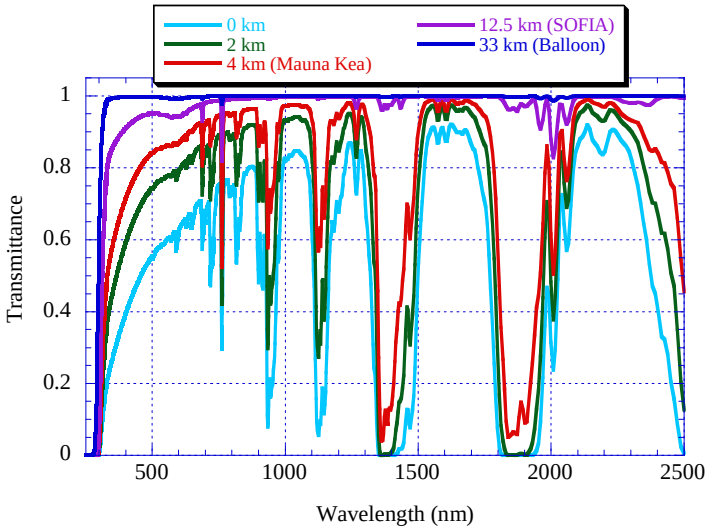


- Aerosol/molecular scattering ratio
- Extinction coefficients
- Molecular temperature/density
- Depolarization

Unmanned Aircraft Systems (UAS)
NOAA and NASA Global Hawk

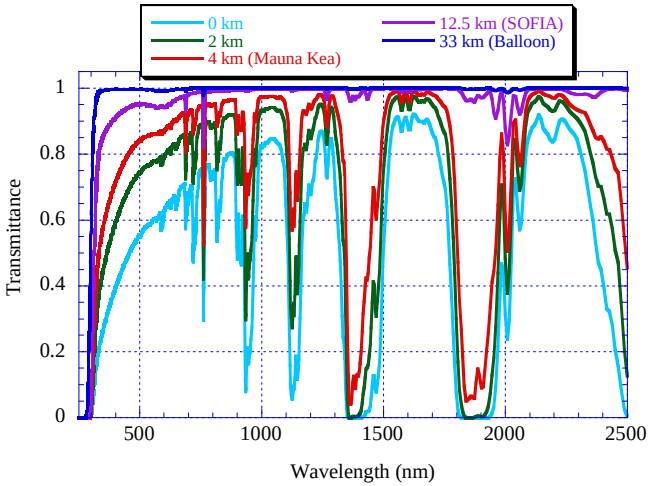
Ceiling: > 60, 000 feet (18.23 km)
Payload: 3000 lbs

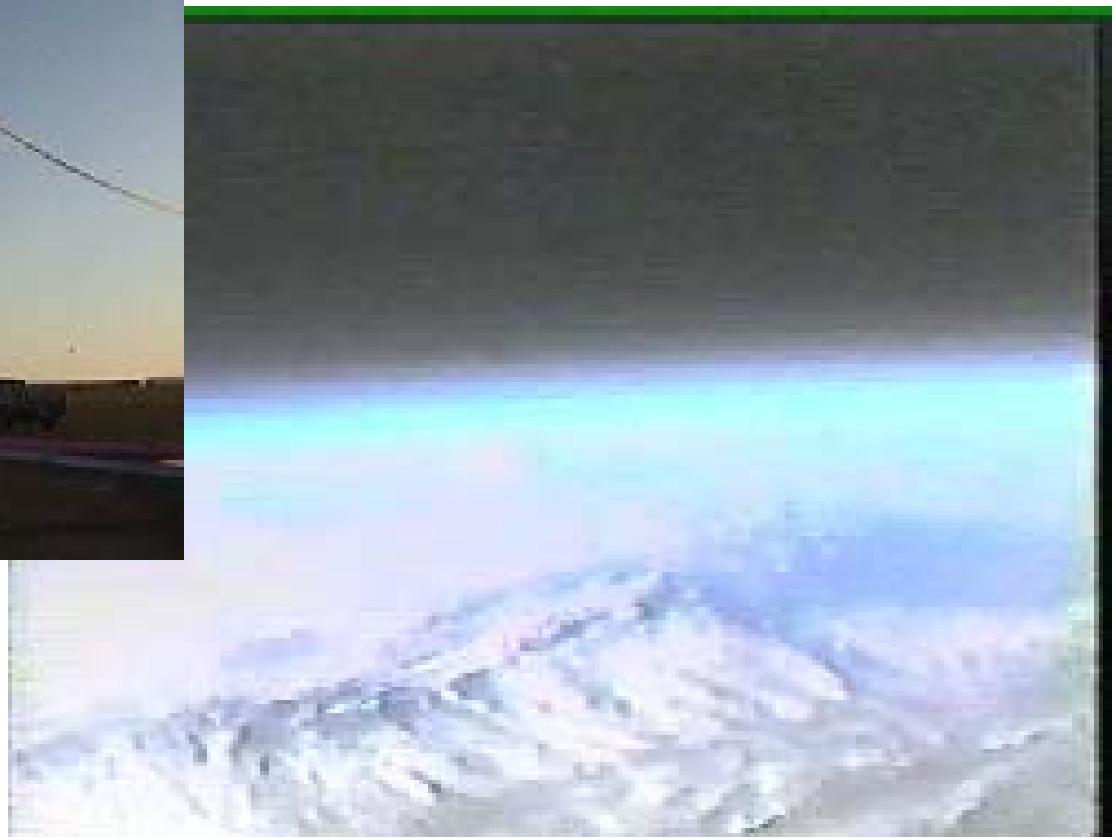
Can we look up?



Balloon Program

Christopher Stubbs, Harvard; Justin Albert,University of Victoria, BC Canada



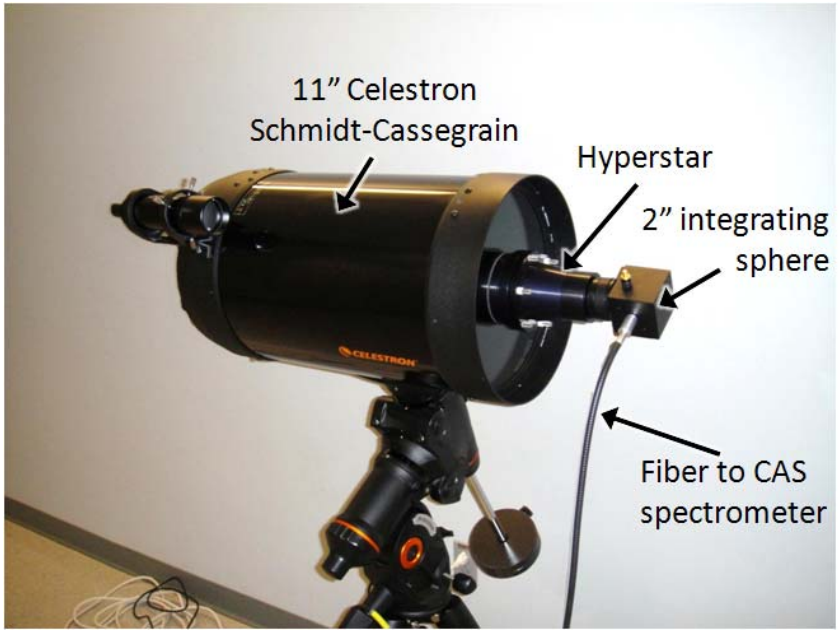


The Earth from 33 km (120,000 feet)

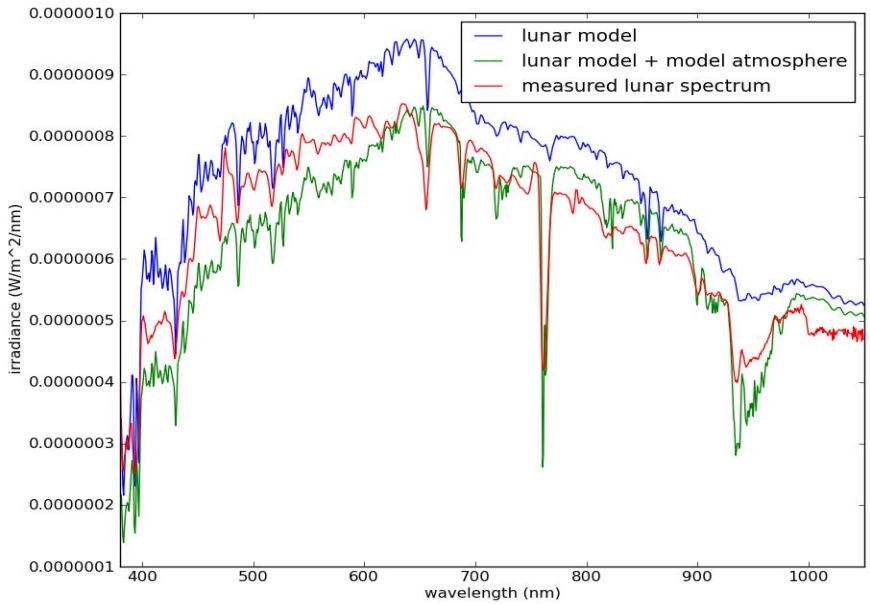
Lunar Measurements

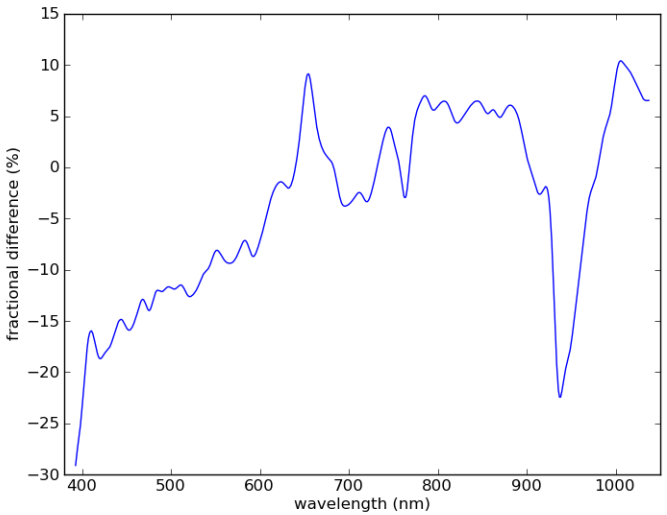
Keith Lykke, John Woodward, Claire Cramer

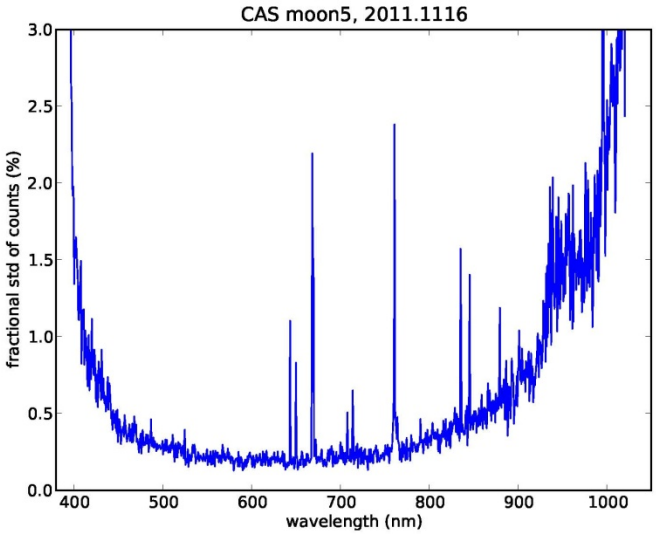
Mt. Hopkins, AZ November 2011



Proof-of-Principle Results:







Quick Uncertainty Budget

- Telescope calibration 0.25 %
- Scale maintenance 0.25 %
- Atmospheric Transmittance 0.5 %
- Lunar measurement precision 0.25 %

Combined Standard Uncertainty 0.66 %

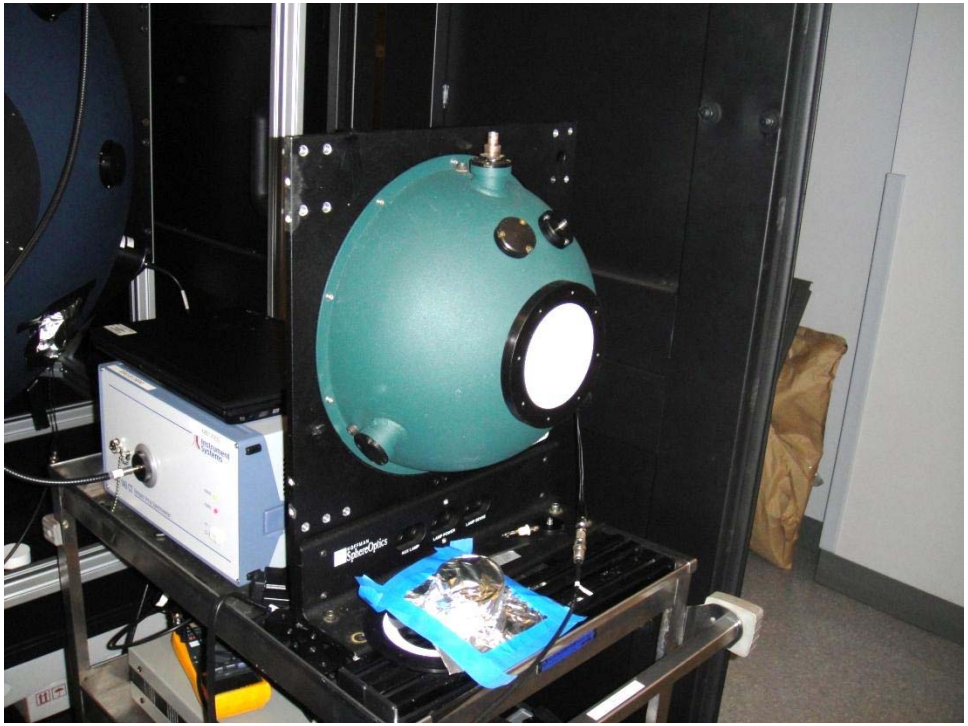
Laboratory size-of-source measurements at NIST

Proof-of-concept for field calibration concept

30” LabSphere

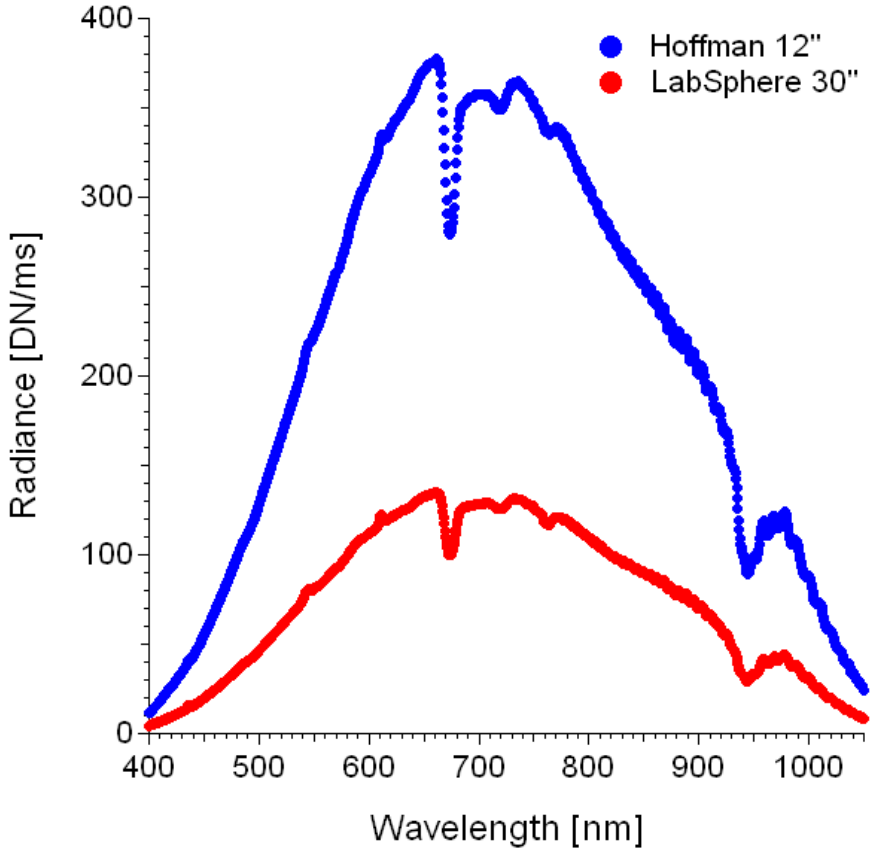
12” Hoffman sphere

Hoffman sphere with CAS spectrometer used as monitor

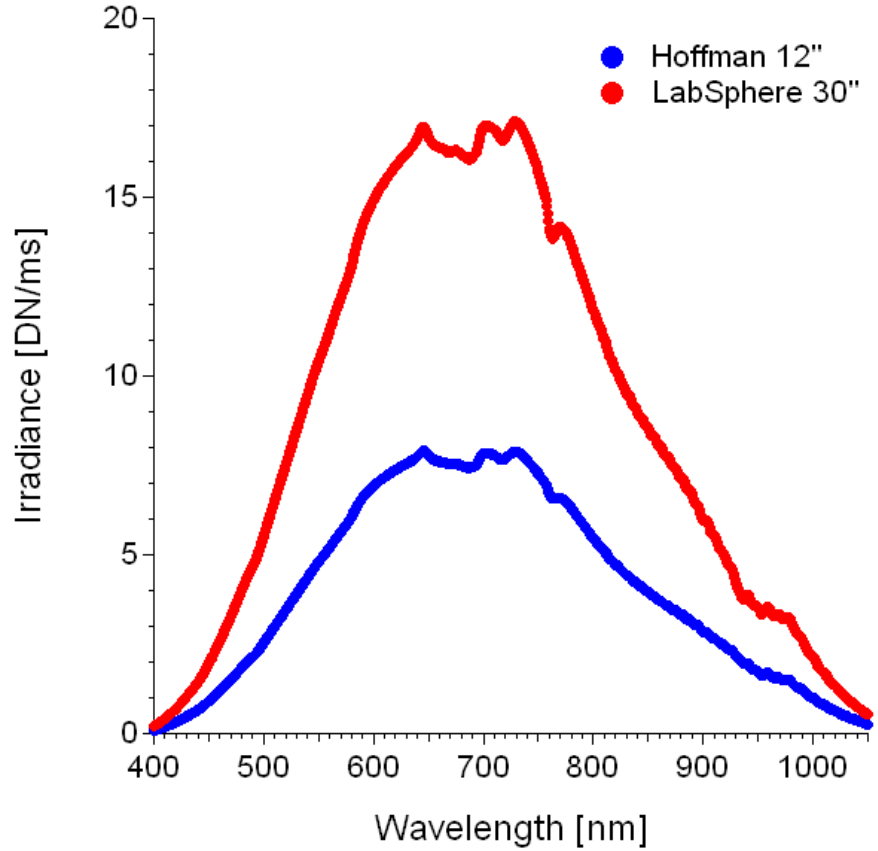


Courtesy of John Woodward, NIST

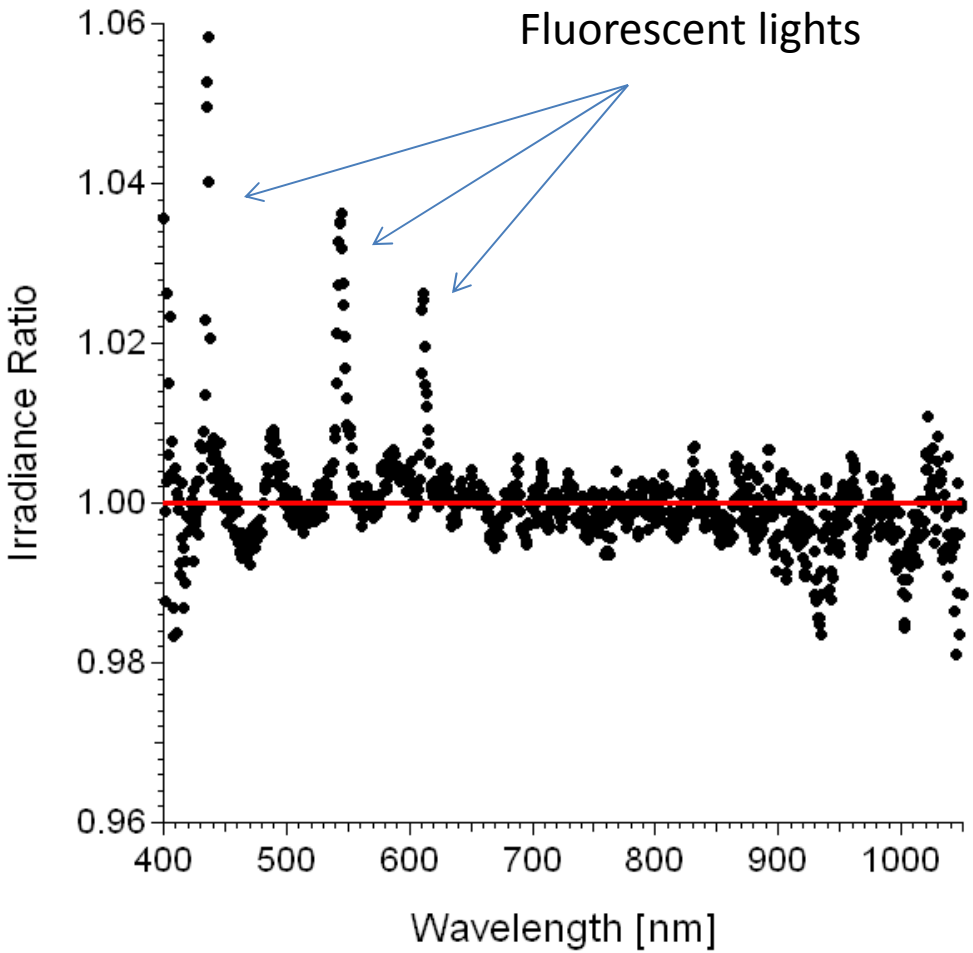
Spectral radiance of spheres measured with CAS radiance head.



Spectral irradiance measured with telescope at ~21m.



Courtesy of John Woodward, NIST

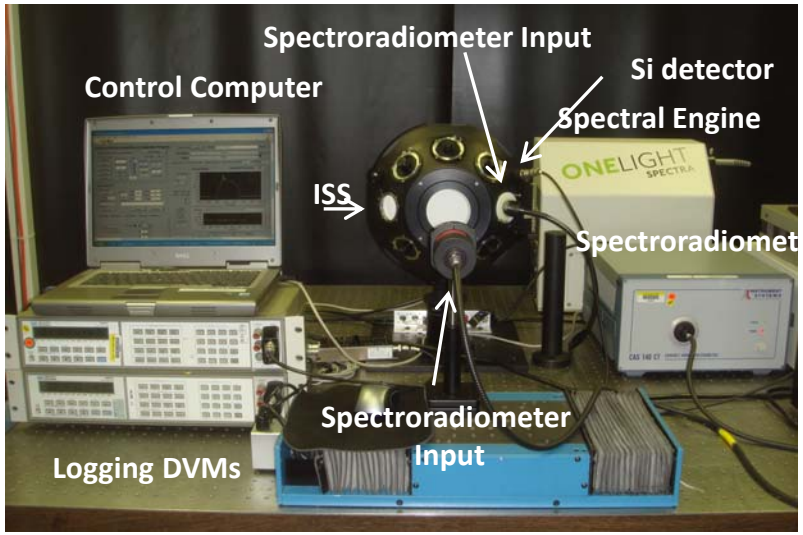


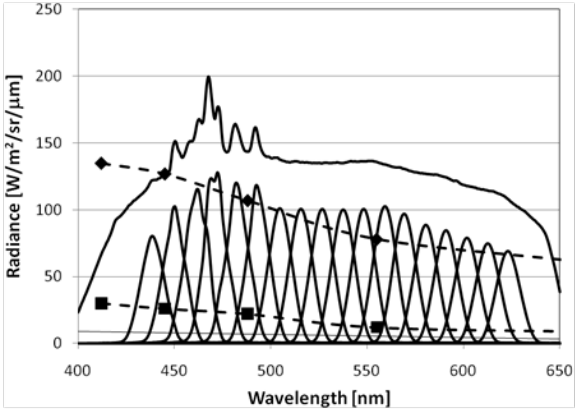
The measured irradiance of the two spheres scaled by the sphere radiances, the area of the apertures and the inverse square of the distances. The peaks between 400 nm and 600 nm are from the fluorescent lights in the hall. The ratio is consistent with unity indicating there is no size-of-source effect on the measurement.

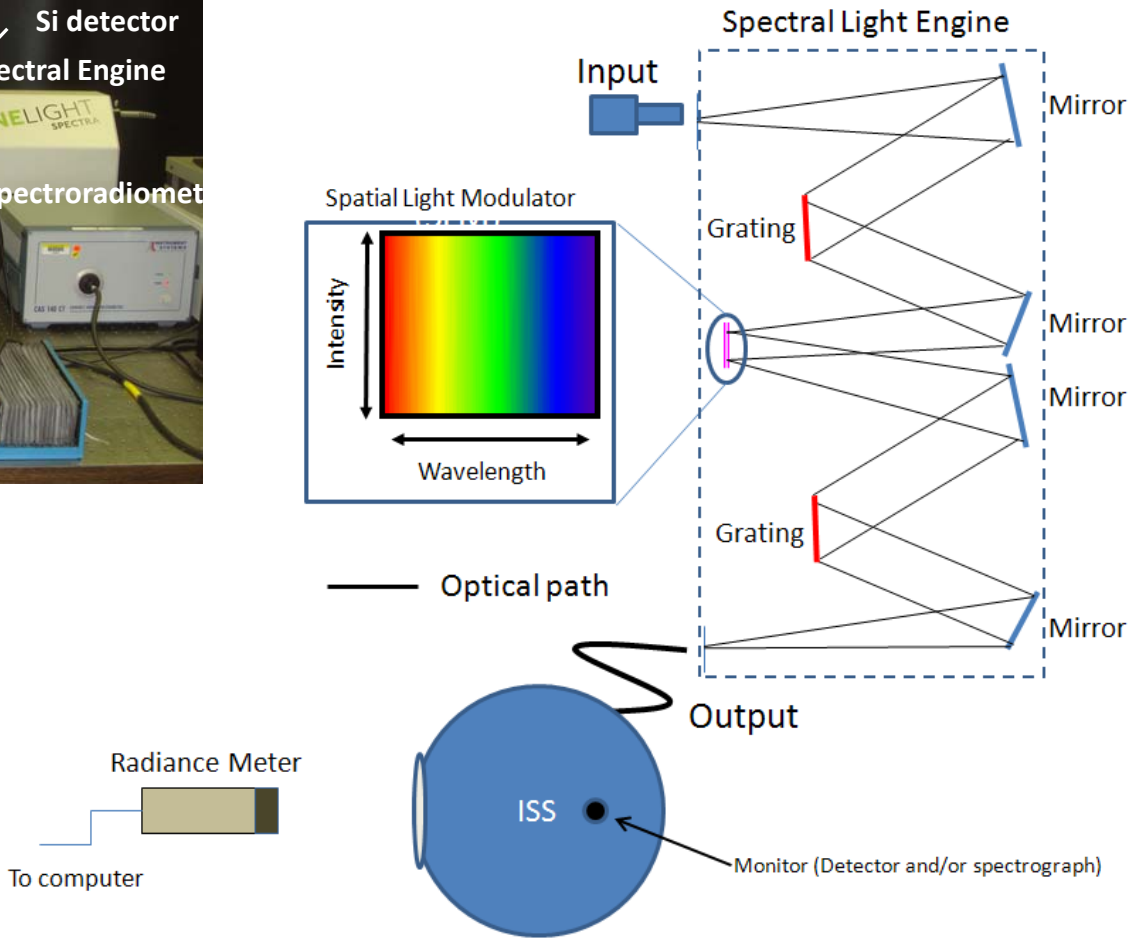
Courtesy of John Woodward, NIST

Scale Maintenance in the Field

Absolute Detector-based Source (ADbS)

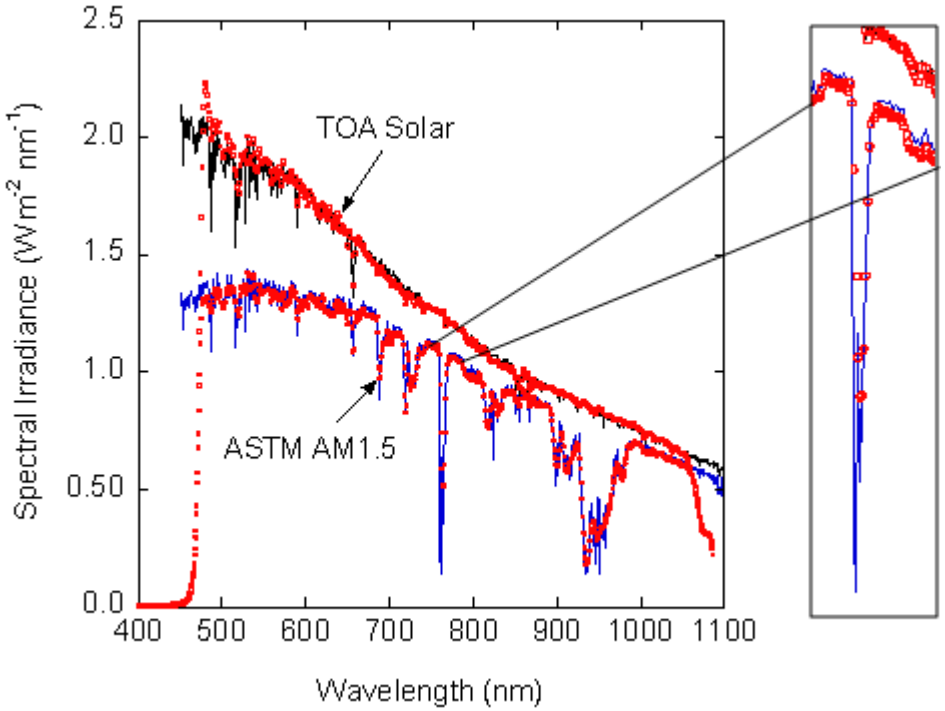






Radiance meter holds the scale

Spectral Engine:
High Resolution Spectral Matching Example



Hyperspectral Image Projector: Courtesy of Joe Rice/NIST

Summary
Now is a good time to re-examine the Moon

- NIST technologies have matured to the level where a lower lunar irradiance uncertainty makes sense
  - T-SIRCUS, stellar photometry efforts, LIDAR systems, ADbS
  - Collaborations with astronomical observatories established
  - Proof-of-principle experiment has been done

- To develop a new irradiance scale in time to support JPSS VIIRS (current launch date in 2016)
  - Approx. 3 years of measurements are needed to constrain a lunar irradiance model
  - However, we can still accomplish a lot in less time since the phase and libration dependence has already been established with high precision by the USGS ROLO team

- Lunar Workshop at NIST, May 2012 (Claire Cramer Organizer)
  - Tentative dates: May 14-15, following MODIS&VIIRS meetings
  - Better define and scope the lunar calibration project according to community & government needs
  - 'White' paper as a platform to stand on?

Thanks for your attention
Questions?