Achieving SI traceability in orbit

Presenter: Kurt Thome

A Hyperspectral Imager to Meet CLARREO Goals of High Absolute Accuracy and On-Orbit SI Traceability

LASP Shortwave IIP Studies

CLARREO Science Team Telecon

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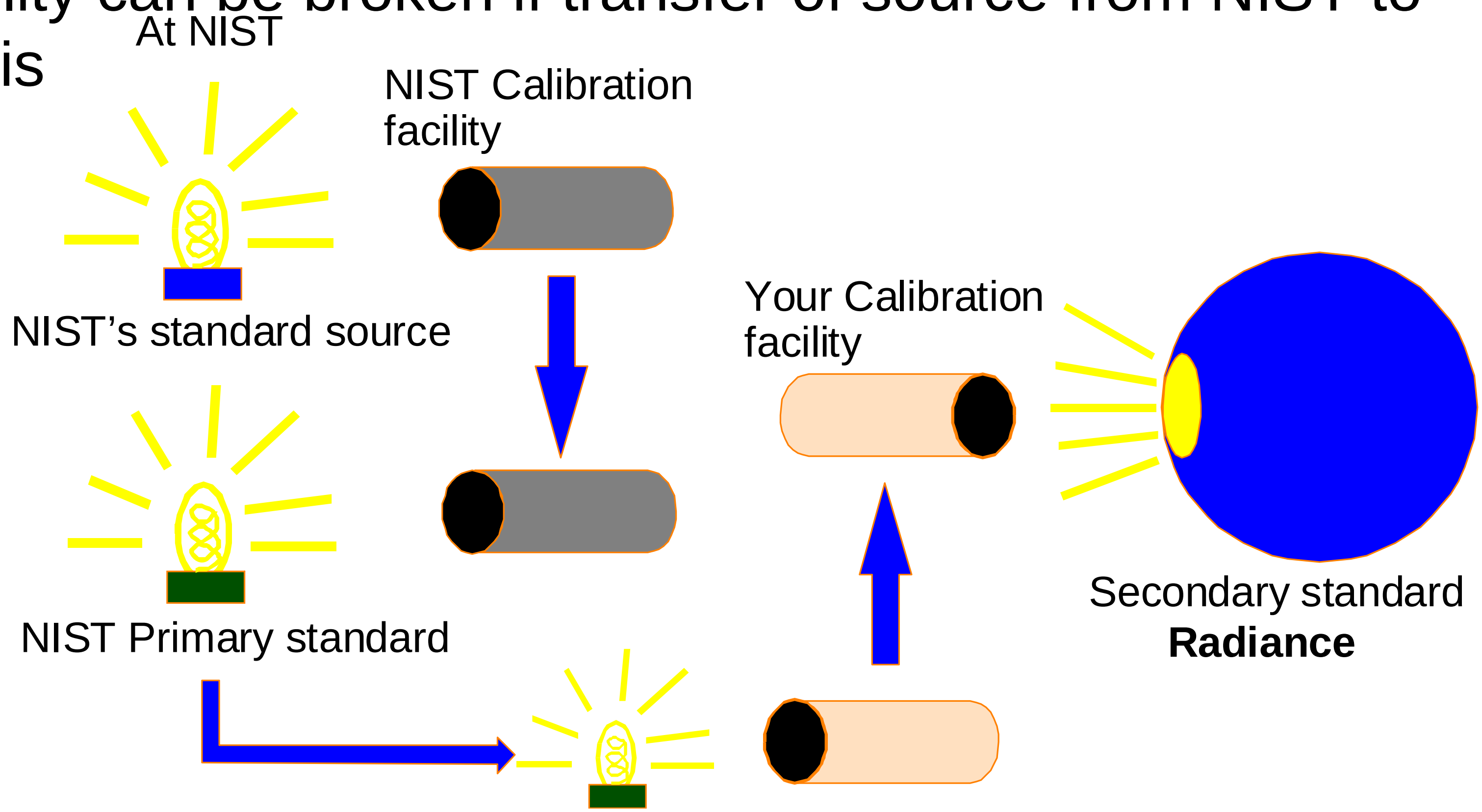
Talk overview

- Philosophy of SI traceability already discussed
  - Included definitions and basic concepts
  - E. Shirley's talk from Tuesday
  - S. Leroy's and A. Mannuci's talks from Tuesday
  - J. Dykema's and M. Mylnczak's talks from yesterday
- Concentrate on applying SI traceability to RS instrument
  - Past approaches for imaging systems
  - In orbit detector-based approach
  - In orbit solar-based approach
  - Sensor-model traceability

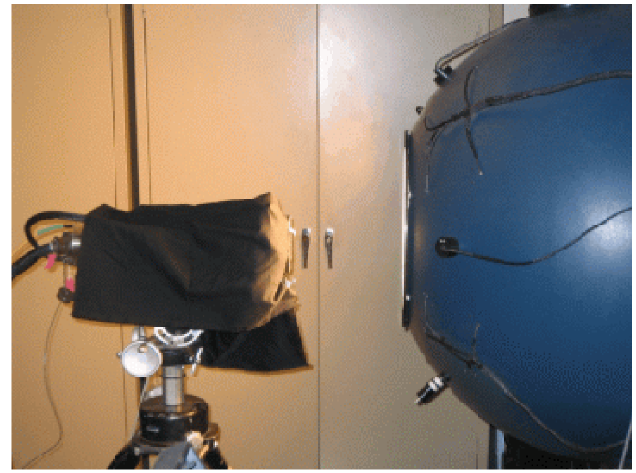
Sphere source example

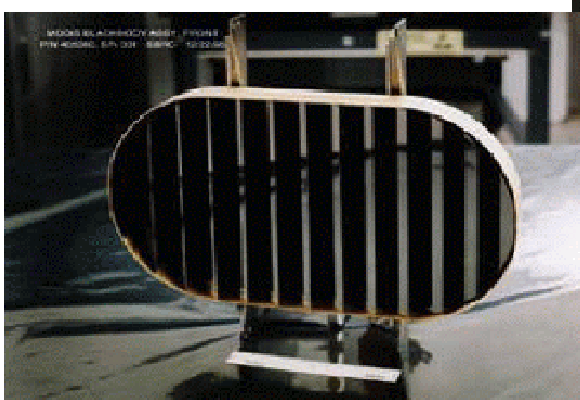
- NIST-traceable standards can be primary, secondary, etc.
- Uncertainties increase the "further" from primary
- SI traceability is through the primary standard
- SI traceability can be broken if transfer of source from NIST to laboratory is not done properly

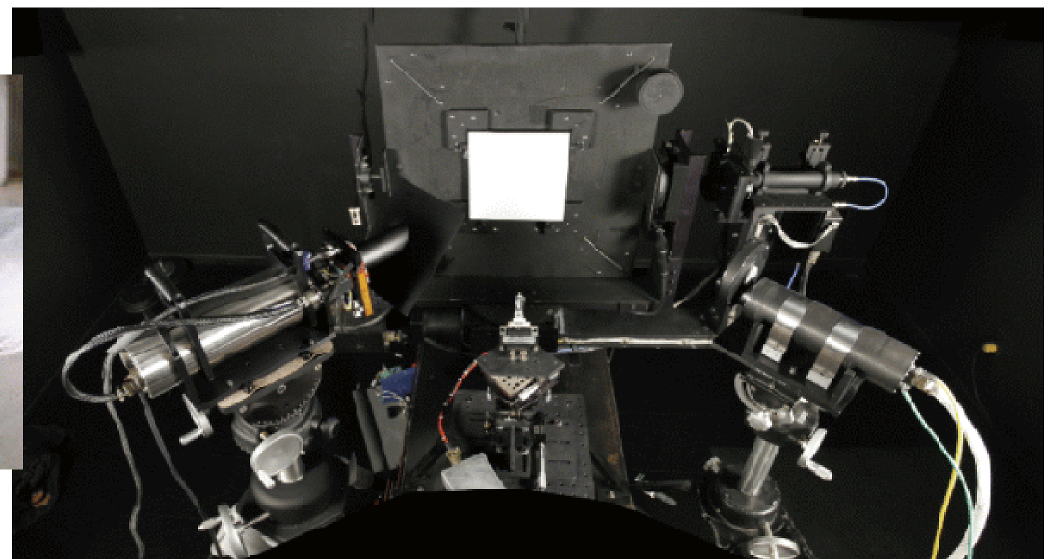


Source-based calibration

- Preflight and inflight calibration require sources of known output
- Lamps and sphere sources
- Calibrate source on ground and assumes it maintains itself going to orbit or a monitoring system

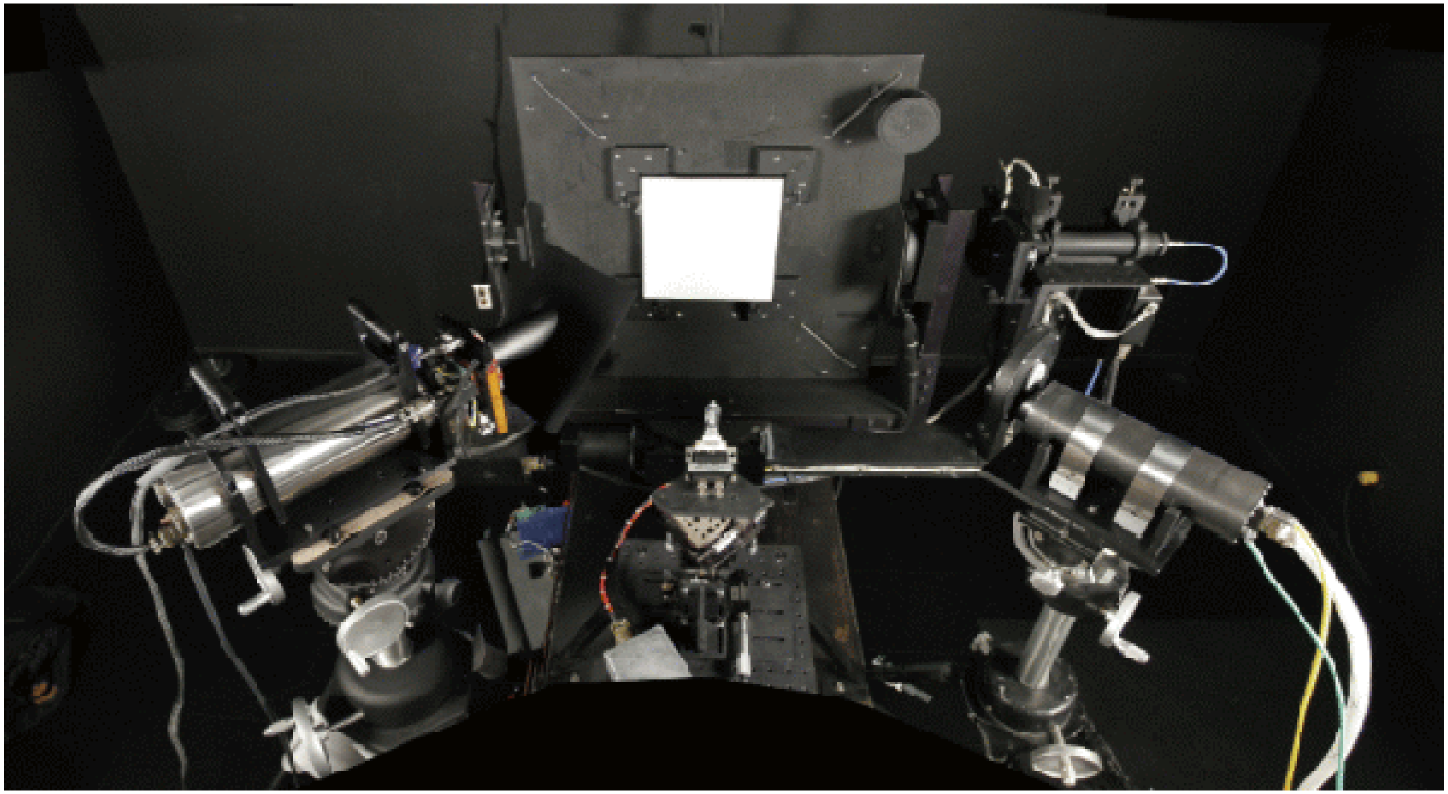






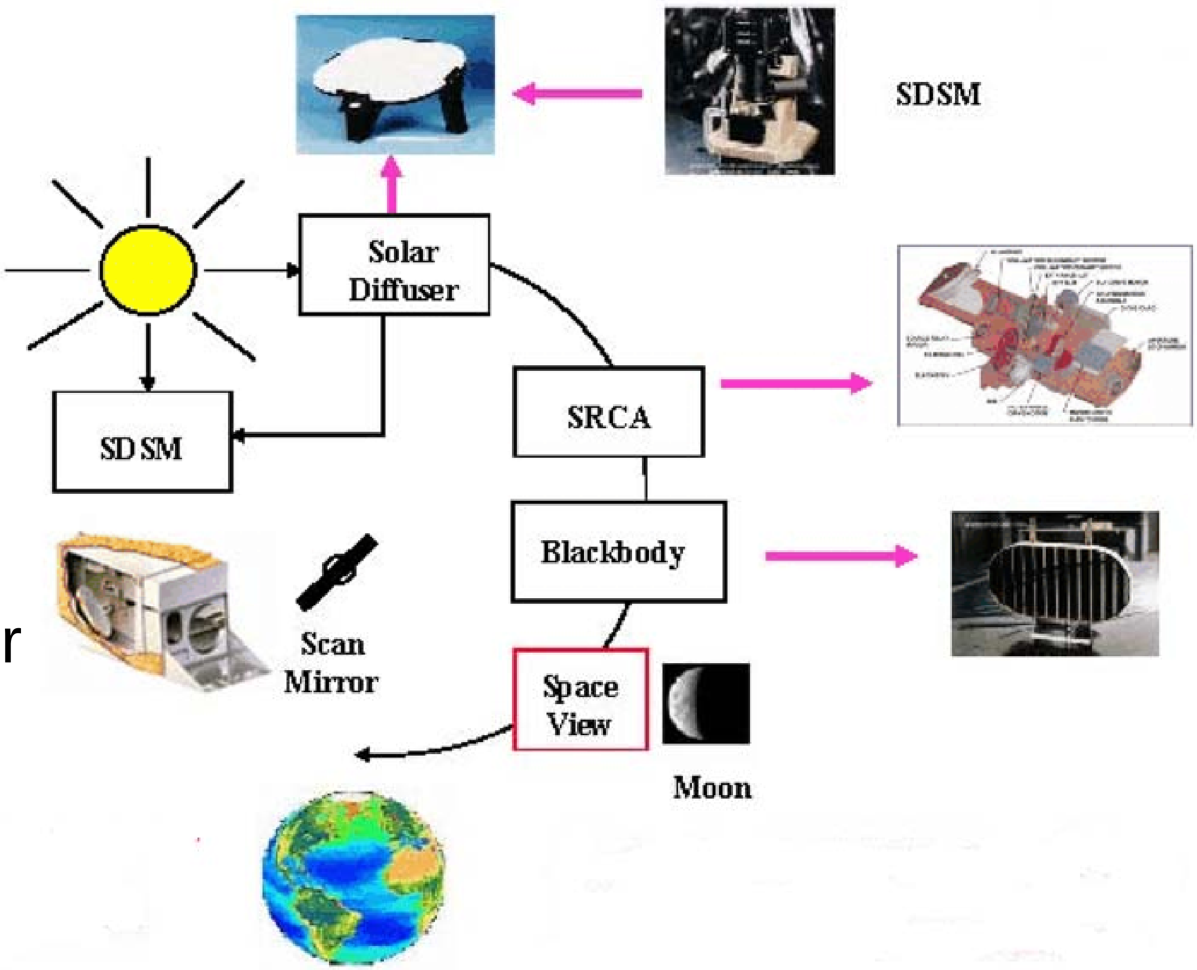
Detector-based approaches

- Detector-based approaches assume that radiometers can be used to assess a given source
- Detectors tend to degrade more slowly than lamp sources
- Radiometers more robust and portable than some sources



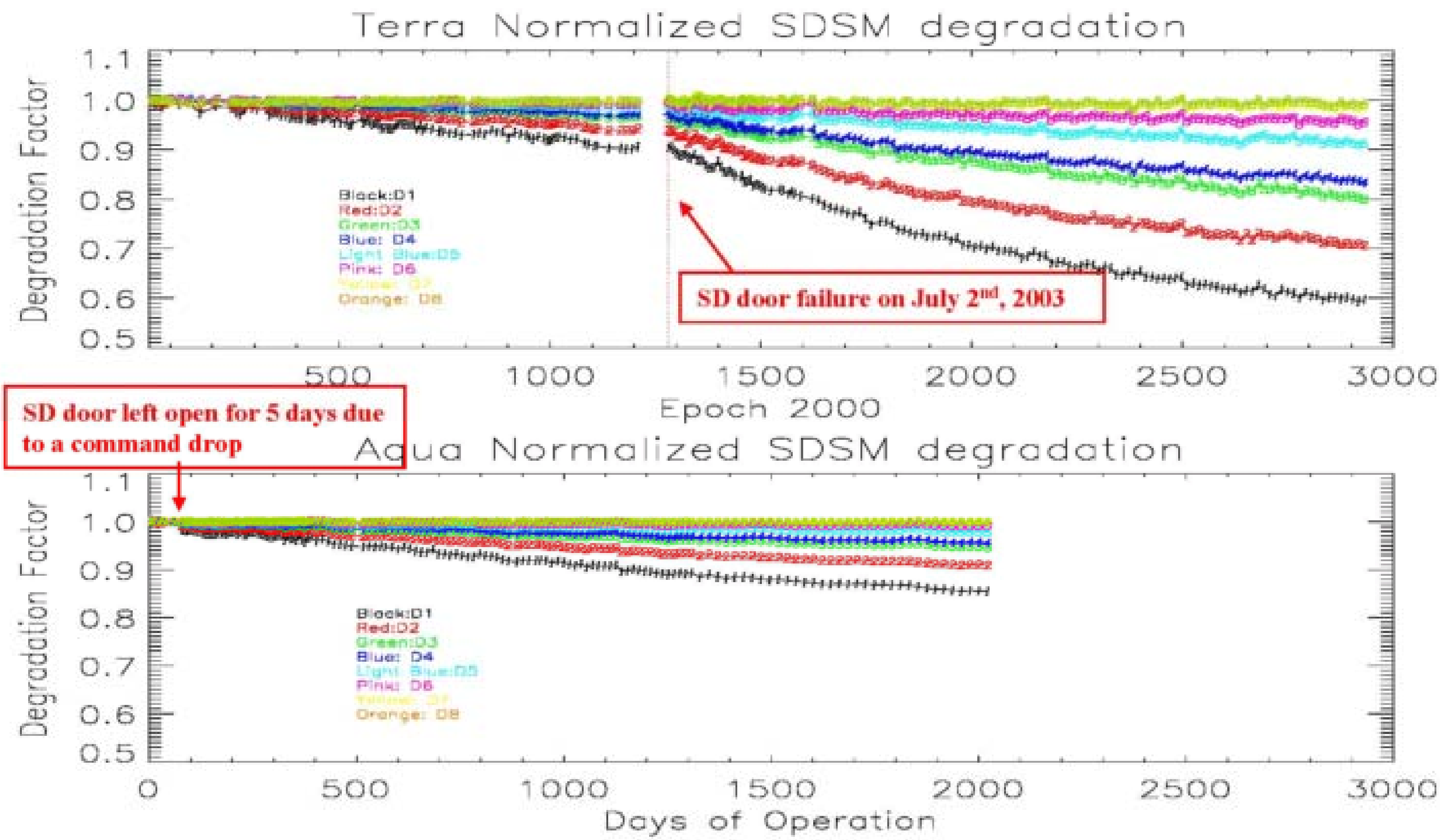
In orbit MODIS example

- Solar diffuser approach
- SRCA (spectroradiometric calibration assembly)
- Space view
- Lunar view
- SDSM (solar diffuser stability monitor)



Diffuser degradation

- MODIS monitors degradation of diffuser with time
- SI traceability would be broken without monitoring degradation



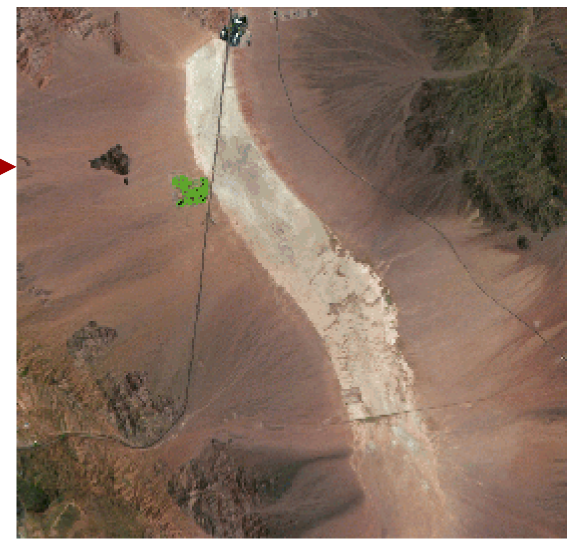
Inflight - vicarious

Measurements of surface reflectance of a homogeneous test site

Measurements of atmospheric conditions

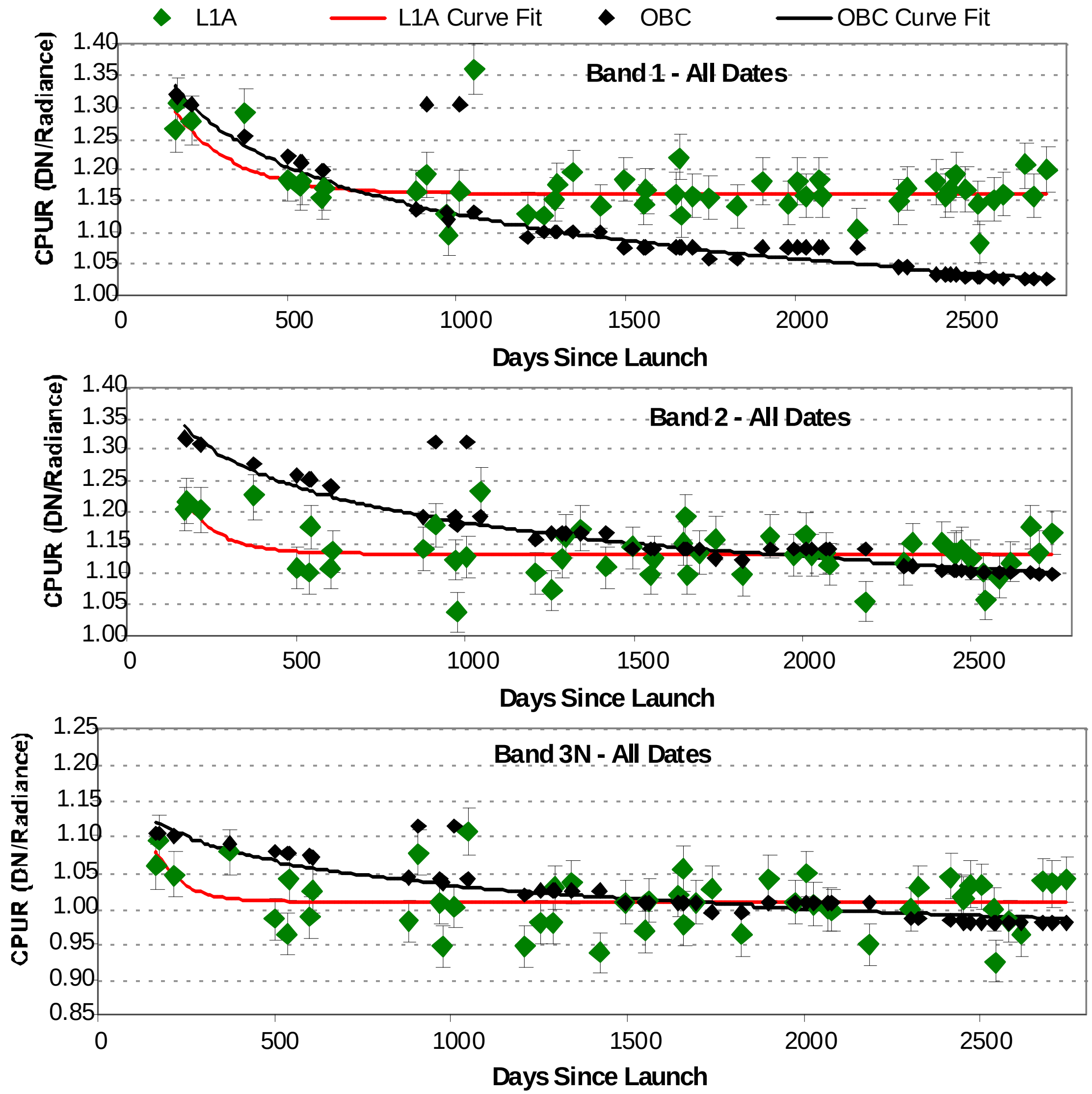
RTC Code

Predict at-sensor radiance for a selected area of the site and compare to imagery



Vicarious versus lamp example

- Example from ASTER which relies on a lamp-based calibrator
- Lamps monitored by photodiodes
- Lamp data have been corrected for degradation in these graphs
- Key result is that the lamp data are not consistent with the reflectance-based results

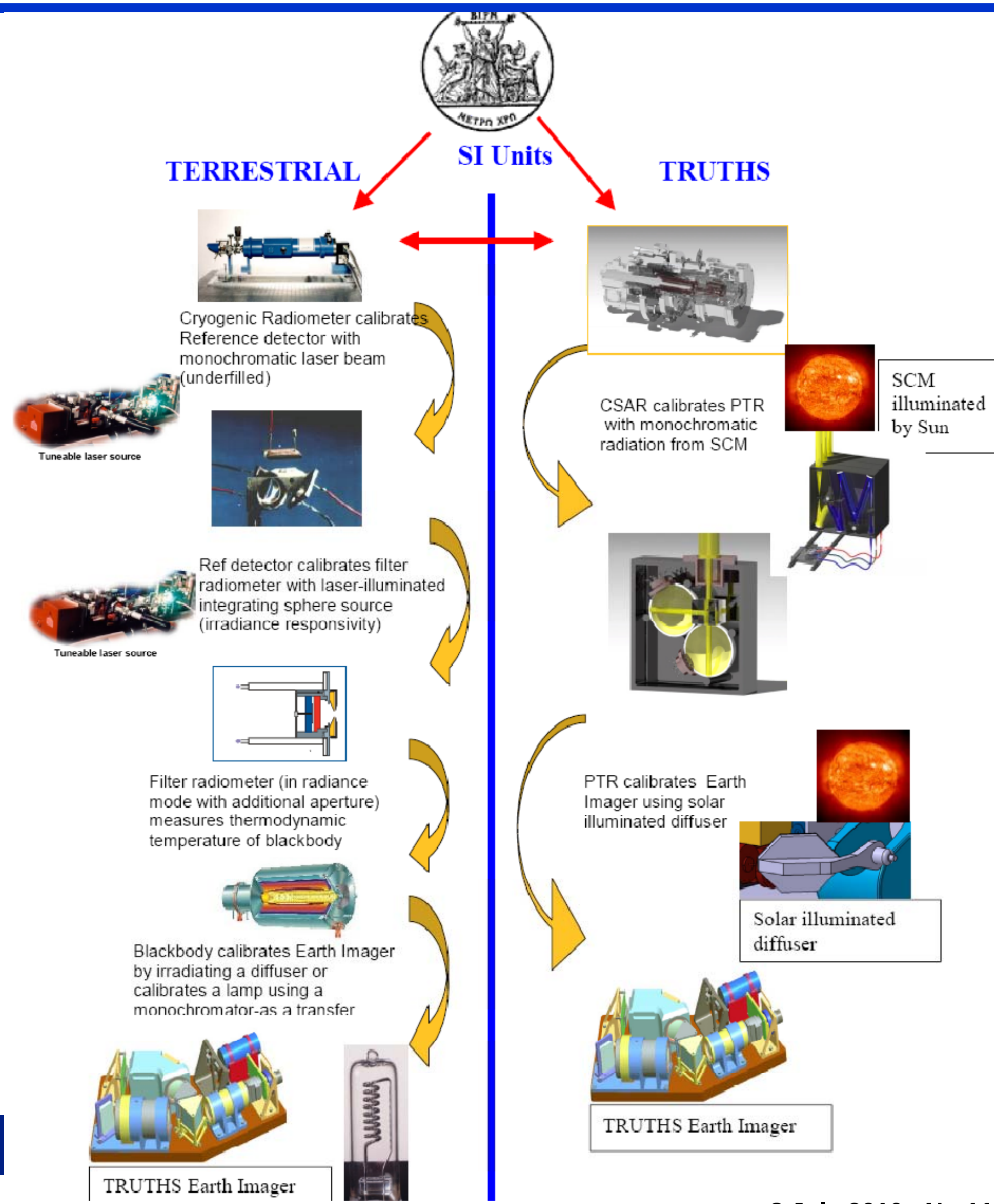


Approaches for CLARREO

- Require a new approach to achieve the high accuracy needed for the RS
  - Lamps lack full path and aperture
  - Diffuser approaches precision/accuracy limited by BRDF
  - Detector-based approaches require a method to monitor the monitors
- TRUTHS methodology is a “NIST” in space thinking
- Current CLARREO methodology is to rely on an absolute “relative” measurement

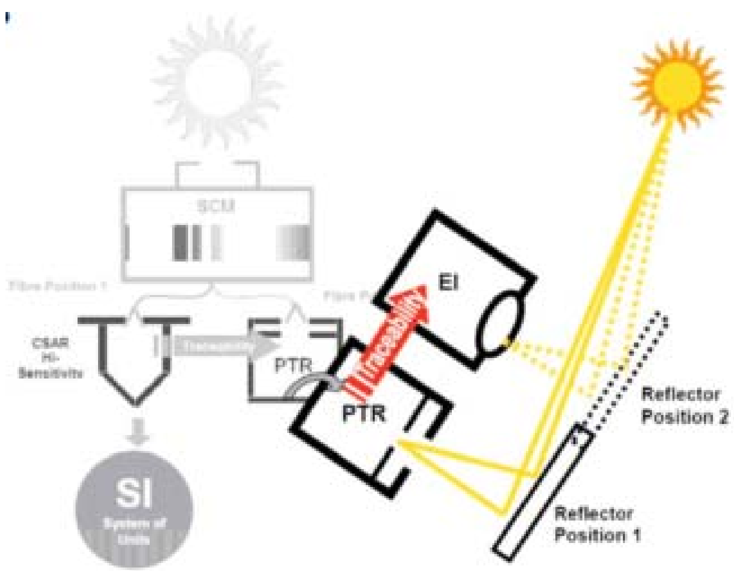
TRUTHS

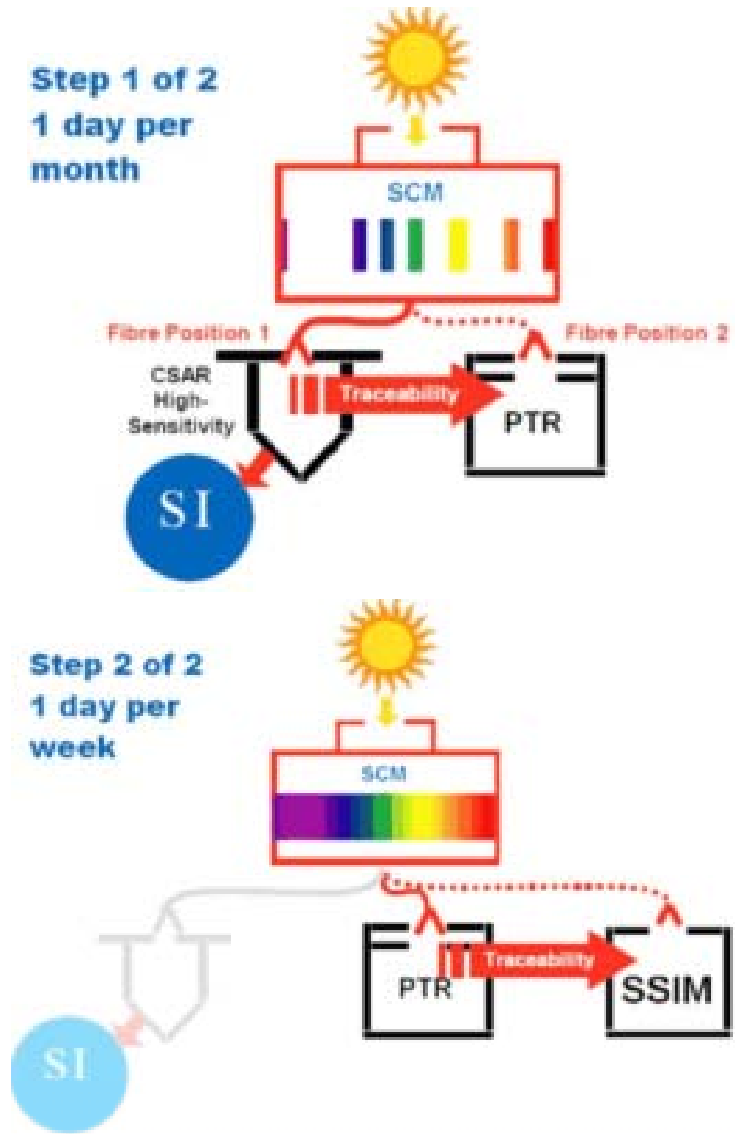
- Recall the basic traceability for TRUTHS
- Primary reference standard is cryogenic radiometer
- Tunable monochromatic Optical beam (monochromator dispersed solar) calibrates other TRUTHS instruments
- Earth imager aperture illuminated by diffuse solar from deployable diffuser (or Moon, or Earth)
- Radiance measured by multi-channel polarized filter radiometer calibrated traceable to CSAR as above.



TRUTHS

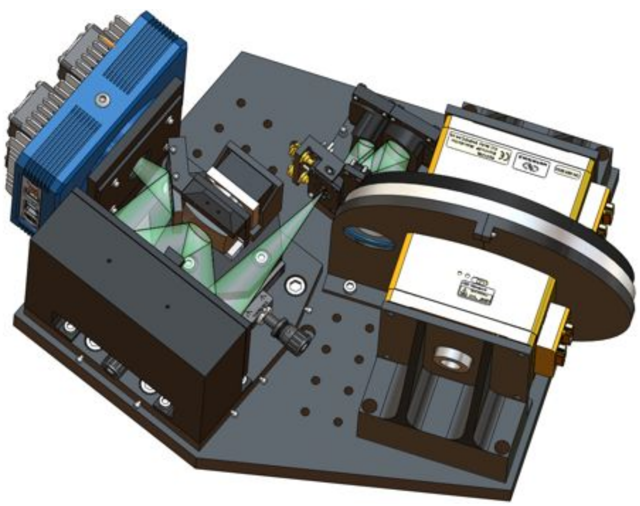
- TRUTHS calibration of the imager and solar sensor is effectively a detector-based approach
- Polarising Transfer Radiometer

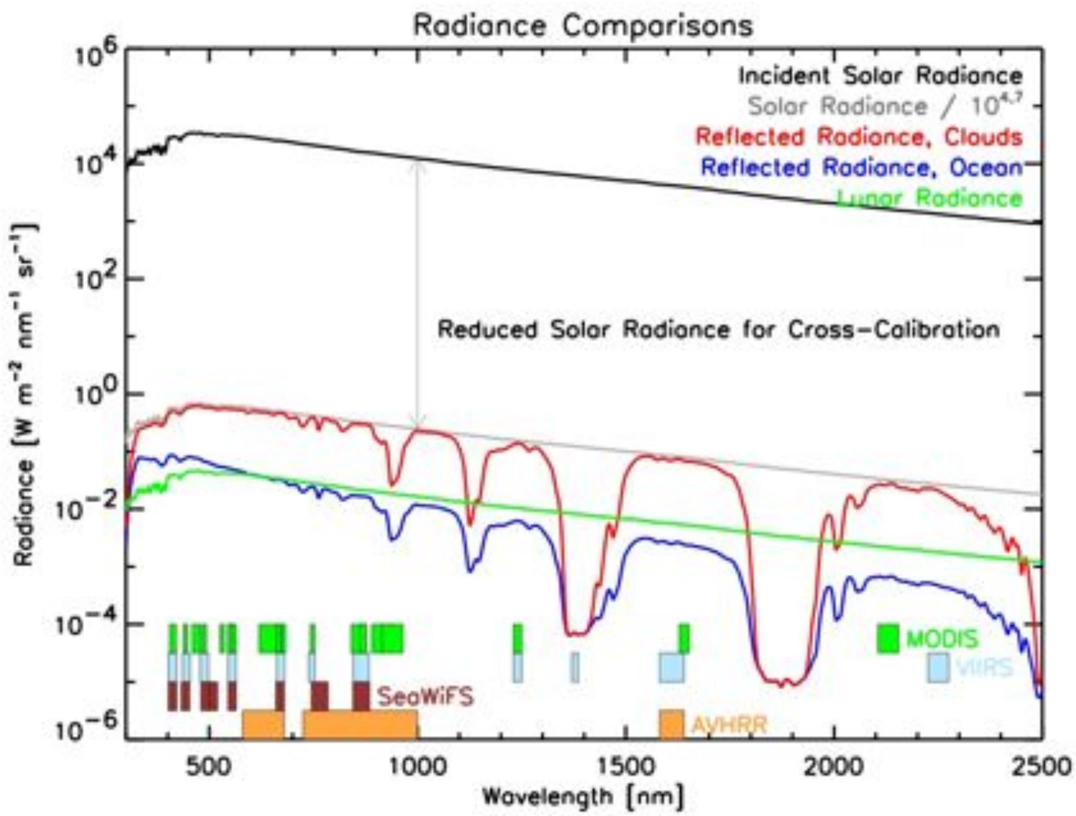




IIP Concept: Sun Provides On-Orbit Reference

- The Sun is the most stable on-orbit source across this spectral range
  - Direct solar cross-calibrations require precisely known attenuation methods
- Solar reflectances provide benchmark of climate





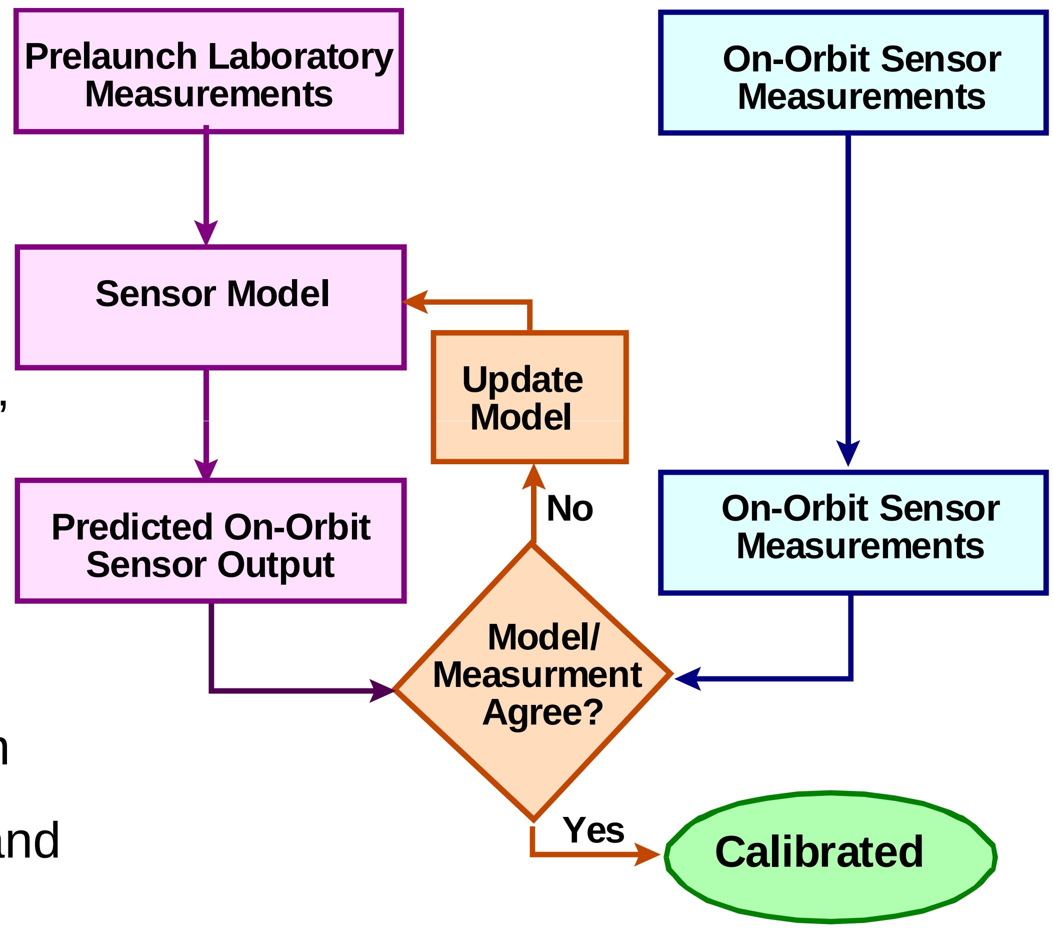
Calibration overview

- CLARREO reflectance retrieval relies on the ratio of the benchmark data to the solar data
  - Account for temporal variability in sensor
  - Can be converted to absolute radiance using a known solar irradiance
- Need to include uncertainties in sensor characterization
  - Straylight changing
    - Sensor solid angle (footprint)
    - Sensor aperture
    - Attenuator area
  - Detector response uncertainties
    - Nonlinearity
    - Polarization
    - Flat field correction

$$BRDF^{earth}_{i,\lambda} = \frac{S^{earth}_{i,\lambda}}{R^{sensor}_{i,\lambda} A_{sensor} \Omega_{sensor}} \frac{(T_{attenuator} A_{attenuator}) \langle R^{sensor}_{\lambda} \rangle}{\cos\theta_{solar} \sum_{k} \sum_{l} S^{solar}_{k,l} r^{flat\ field}_{k,\lambda}} \frac{a^{straylight}_{sensor} \omega^{straylight}_{sensor} a^{straylight}_{attenuator}}{r^{flat\ field}_{i,\lambda} r^{nonlinearity}_{i,\lambda} r^{polarization}_{i,\lambda}}$$

Calibration Approach

- Characterize the sensor to SI-traceable, absolute radiometric quantities during prelaunch calibration
  - Watt
  - Irradiance mode
  - Radiance mode
- Determine geometric factors for conversion to reflectance
  - On-orbit calibration “validates” the prelaunch calibration
  - Solar and lunar views used to determine temporal changes
- Key is to ensure prelaunch calibration simulates on-orbit sources
  - Absolute irradiance calibration for solar view
  - Simulated geometry of solar and lunar views for stray light
- Successful transfer to orbit achieved when sensor behavior can be accurately predicted



Simulating and predicting on-orbit sources is basis of calibration

Calibration Overview

Prelaunch

Attenuator characterization
$A_{attenuator}, T_{attenuator}$

Absolute response
$R_{i,j}^{sensor}$

Relative response
$r_{i,j}^{flat\ field}, \langle R^{sensor} \rangle$

Sensor Artifacts
$\frac{a_{sensor}^{straylight}\ \omega_{sensor}^{straylight}\ a_{attenuator}^{straylight}}{r_{i,j}^{nonlinearity}\ r_{i,j}^{polarization}}$

Post-launch

Attenuator verification
$A_{attenuator}, T_{attenuator}$

Absolute response eval *
$R_{i,j}^{sensor}$

Relative response
$r_{i,j}^{flat\ field}, \langle R^{sensor} \rangle$

Sensor Artifacts *
$\frac{a_{sensor}^{straylight}\ \omega_{sensor}^{straylight}\ a_{attenuator}^{straylight}}{r_{i,j}^{nonlinearity}\ r_{i,j}^{polarization}}$

Time

Operations

Attenuator verification
$A_{attenuator}, T_{attenuator}$

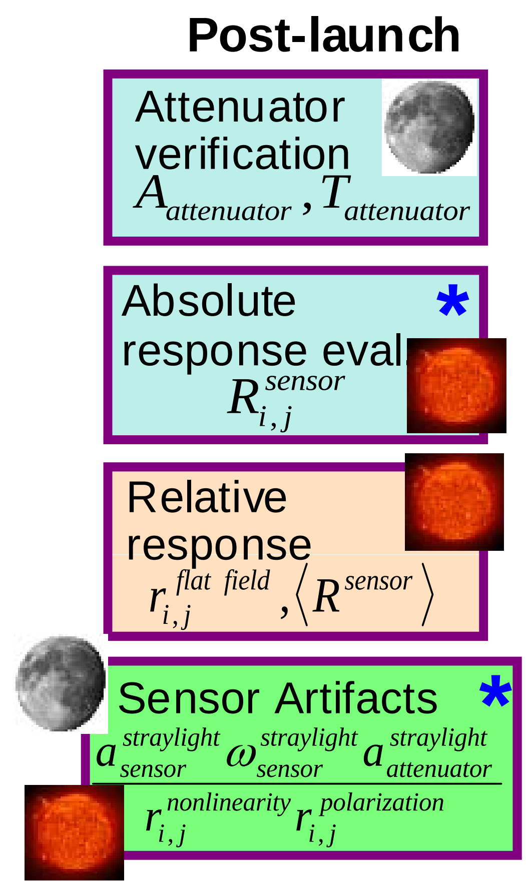
Relative response
$r_{i,j}^{flat\ field}, \langle R^{sensor} \rangle$

Green box shows dominant parameters determined for transfer to orbit

*** Measurements to achieve SI traceability for transfer to orbit**

Calibration overview

- Attenuator verification relies on trending of lunar views without attenuator
  - Compare to trend of sensor output while viewing sun with attenuator in place
  - Different trend behavior indicates attenuator issue
- Comparison of solar irradiance reported by CLARREO to other on-orbit sensors indicates whether absolute calibration is maintained in going to orbit
  - Indicates whether geometric factors are well understood (attenuator area)
  - Stability of absolute detector response
- Relative response measured in laboratory compared to that derived on orbit for consistency
- Artifact determination
  - Sun and moon provide sharp boundaries for stray light, ghosting
  - Stellar and planetary sources provide point sources for evaluation of spatial response
  - Polarization sensitivity assessed using earth-view scenes (e.g., ocean views at large angles)
  - Non-linearity evaluated by varying attenuators
  - Size of source effect is most difficult to issue to understand



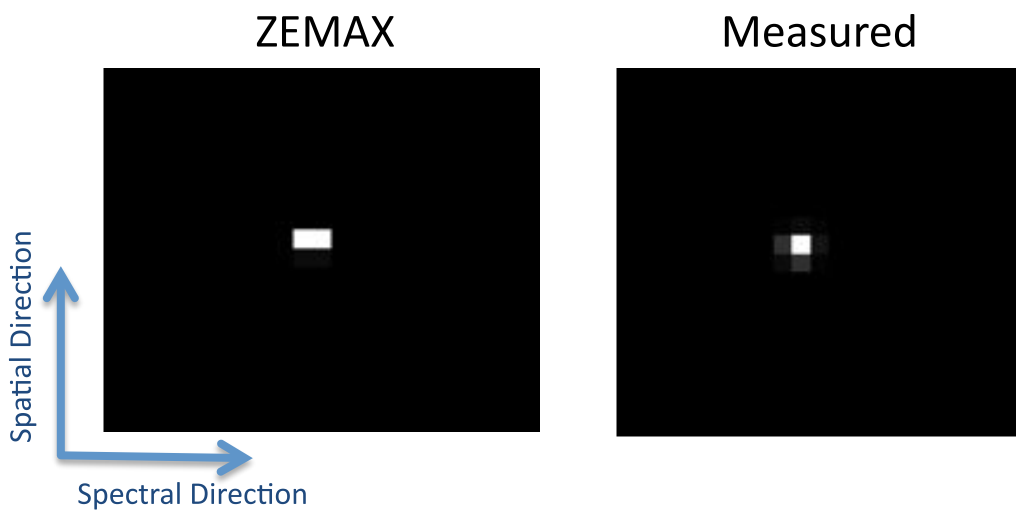
Uncertainties Guide Attenuation Selections

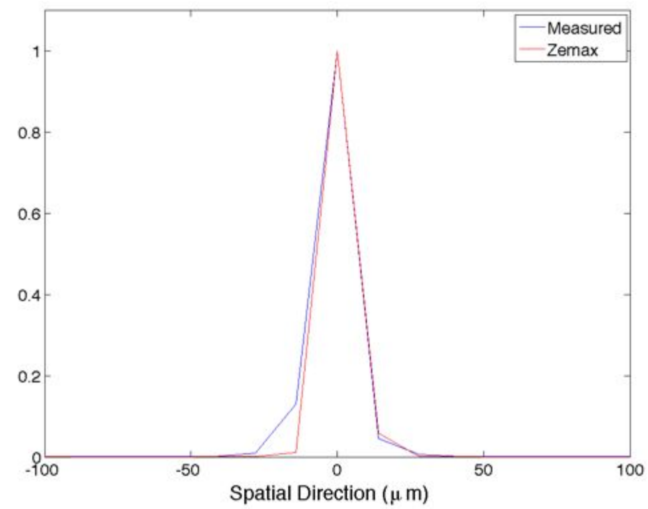
- Uncertainties estimated and to be measured will guide levels of attenuation from each method
  - Values below are for example only

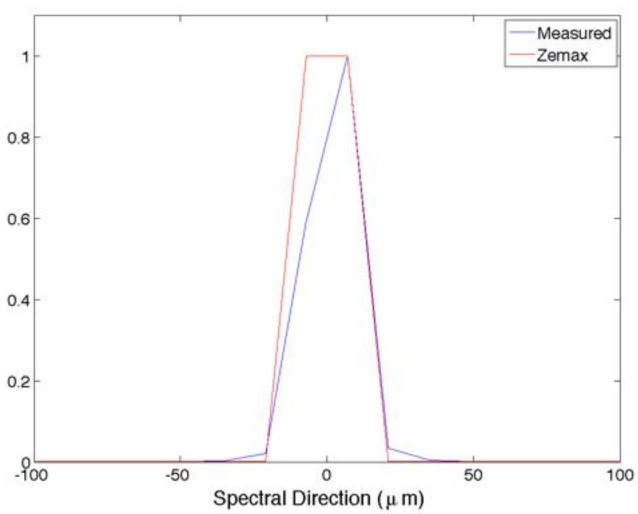
Calibration Transfer Uncertainties

Parameter	Value	Attenuation Amt. (Log)	Uncertainty
Aperture	2 cm/500 μm	3.2	0.14%
Aperture Ratio	*1600.0*	*3.2*	*0.08%*
Diffraction		-	*0.10%*
Underfilled Optics		-	*0.05%*
Integration Time	0.07/0.002 s	0.6	0.09%
Elect. Integration Time	17 ms min	*0.6*	*0.09%*
Mech. Shutter Time	360 μs min	*0.0*	*0.00%*
Filter	ND 1	0.9	0.05%
Lunar Meas. Accuracy	meas. noise		*0.02%*
Underfilled Optics			*0.03%*
Surface Reflections	1° tilt		*0.03%*
Linearity	0.05%/10^2		*0.02%*
Linearity of Signal Levels	-	-	0.05%
Noise	-	-	0.10%
Polarization	0.25%	-	0.05%
Total		**4.7**	**0.21%**

Point Spread Function (PSF) Measured on Integrated System Tests Both TMA and Spectrometer







<u>Approach</u>

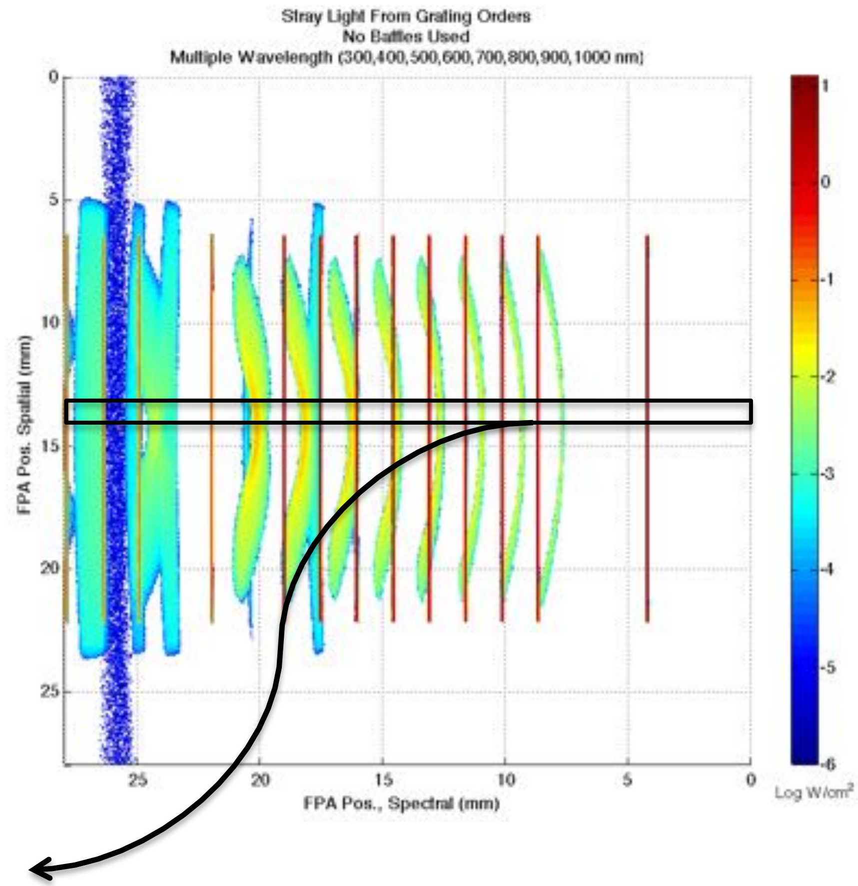
- Overfill 8-mm entrance aperture with a collimated HeNe laser
  - λ = 632.8 nm
  - $1/e^2$ = 10 mm

<u>Results</u>

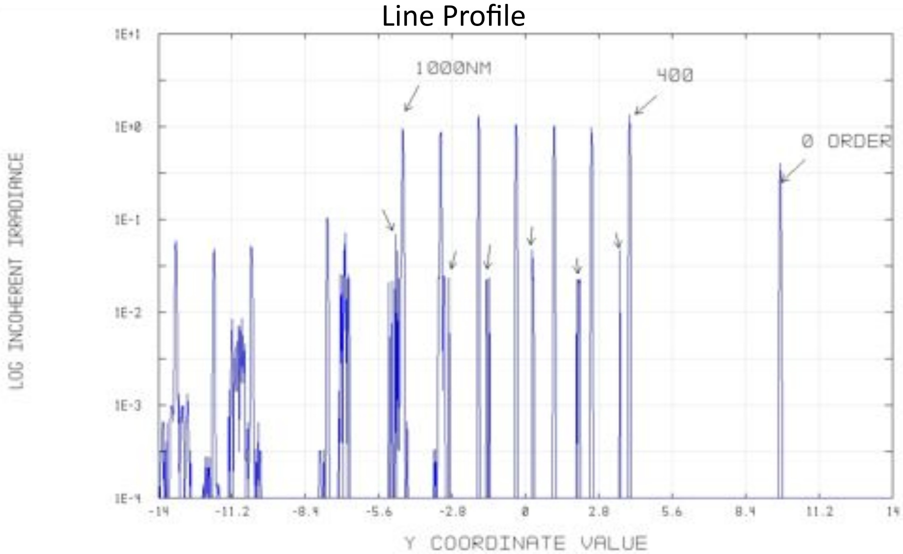
- Performance is comparable to ZEMAX model
  - Aberrations are smaller than the resolution of the FPA (12 μm pitch)

Stray/Scattered Light Analysis Performed: No Baffling Gives Unwanted Grating Orders

- The sinusoidal profile of the COTS grating splits a significant amount of light into diffractive orders that we are not using
- To investigate any potential problems that this might cause, a raytrace of the full system accounting for the actual (measured) grating order splitting was performed
  - Overfilled 20 mm aperture
  - 20° cone angle
  - Multiple wavelength
  - 10^9 rays traced
  - Scattering not considered
- The unwanted orders, particularly the +1 and +/-2 orders, cause ghosting of the main lines



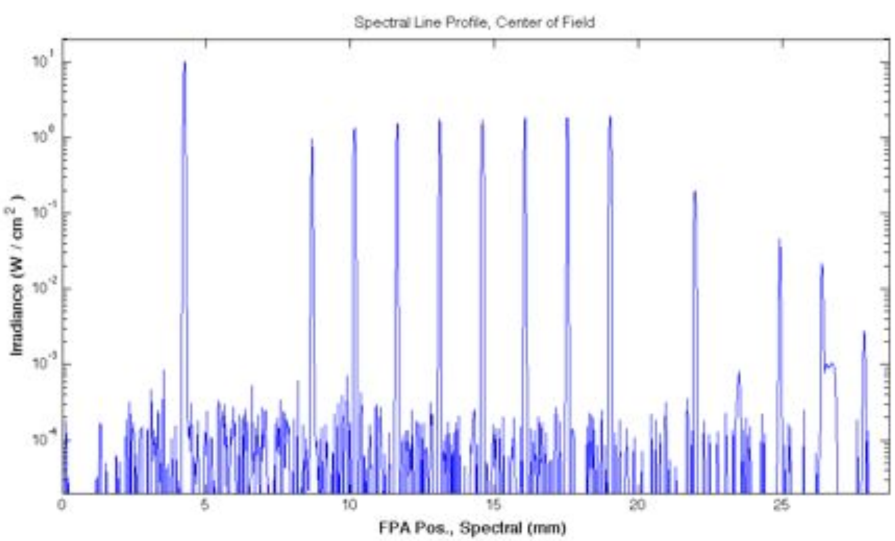
Line Profile

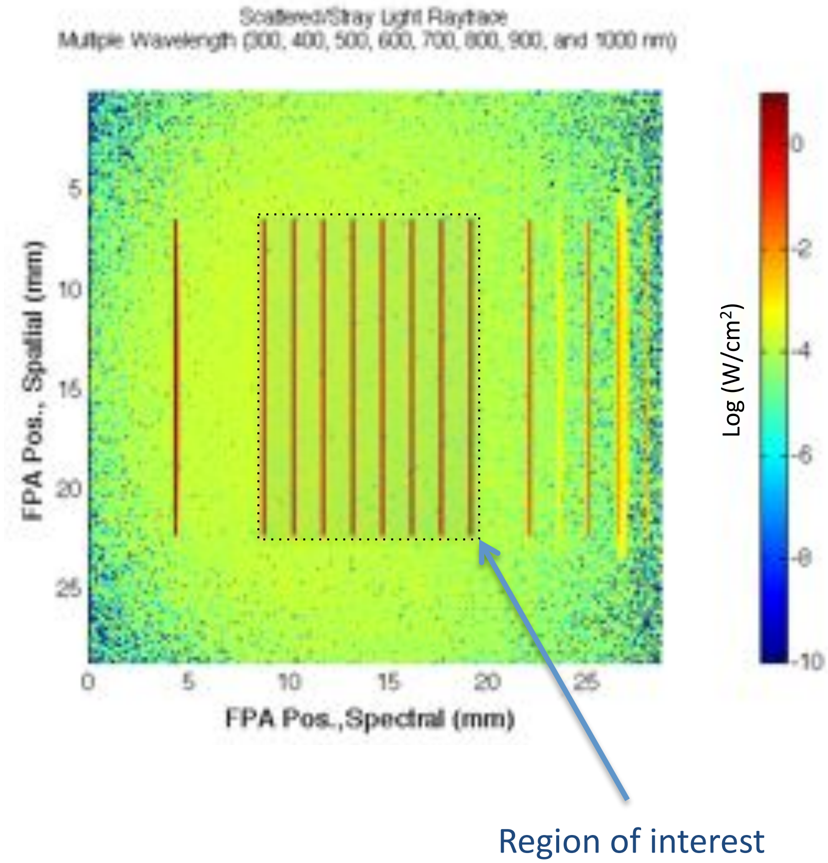


Stray/Scattered Light Analysis Performed: Stray Light Reduced Below FPA Sensitivity

Full system scattered light raytrace

- Overfilled 20 mm aperture
  - 20° cone angle
  - Multiple wavelengths
- "Real" optical surfaces
  - 10 nm RMS surface finish on TMA
  - 5 nm RMS surface finish on grating and Offner mirror
- Black coating on baffles and TMA housing treated as 0.3% Lambertian reflector

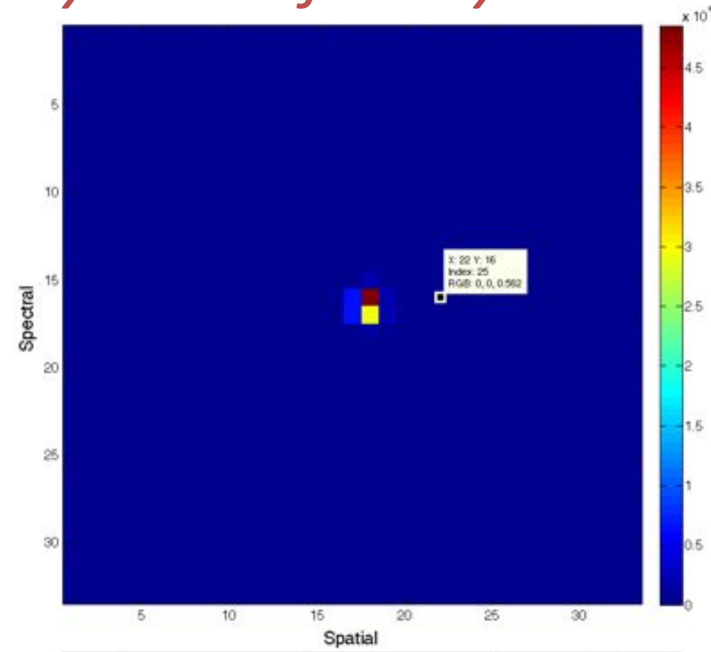


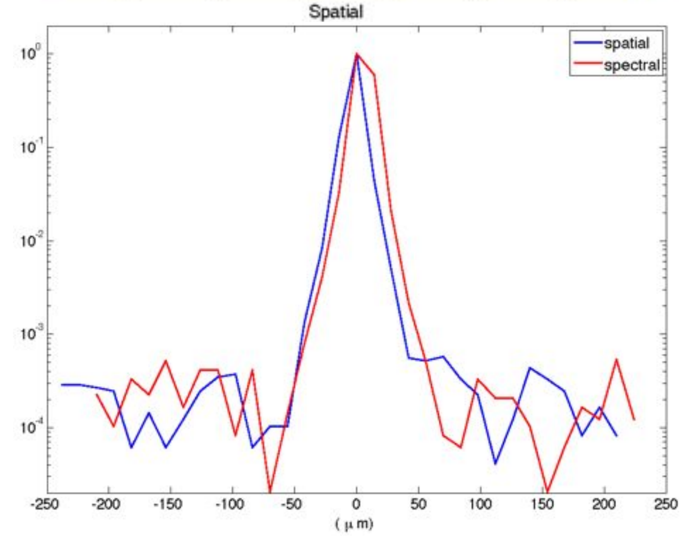


Signal to noise at the focal plane is approximately 10^4

Stray/Scattered Light Analysis Verified by PSF

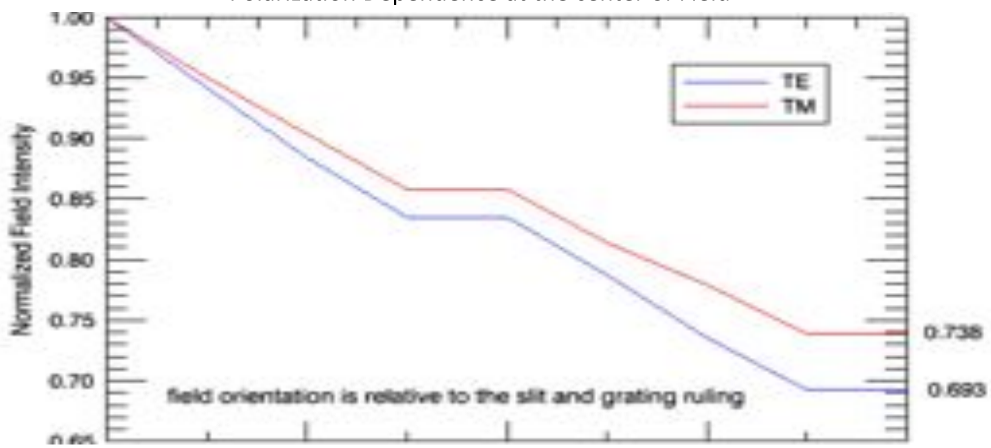
- PSF measured at 0° and ±4.5°
- Scattering and stray light, if present, will:
  - Cause the PSF to spread out
  - Cause spots/streaks in other areas of the image plane
- No scattering/stray light could be seen within the FPA noise limit
  - Signal to noise at the focal plane is approximately 10^4
- Need to repeat for all acceptance angles through the aperture



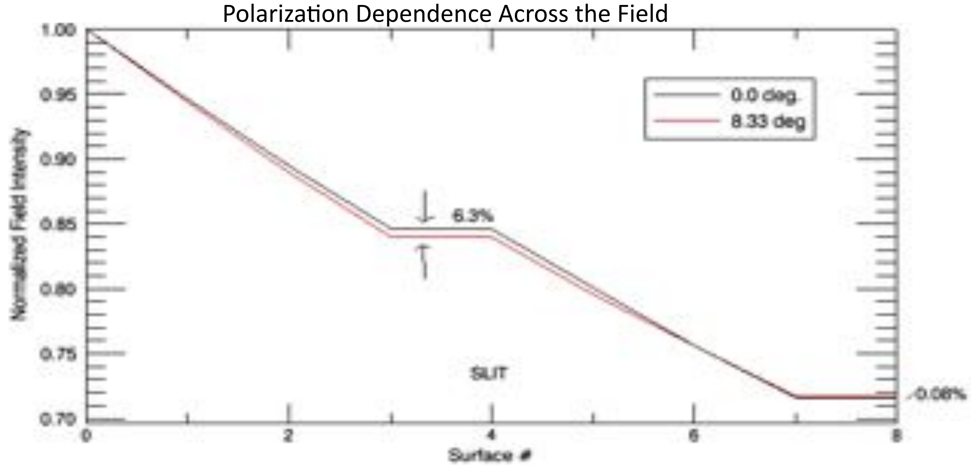


Instrument Polarization Sensitivity Is Modeled

Polarization Dependence at the center of Field



Polarization Dependence Across the Field

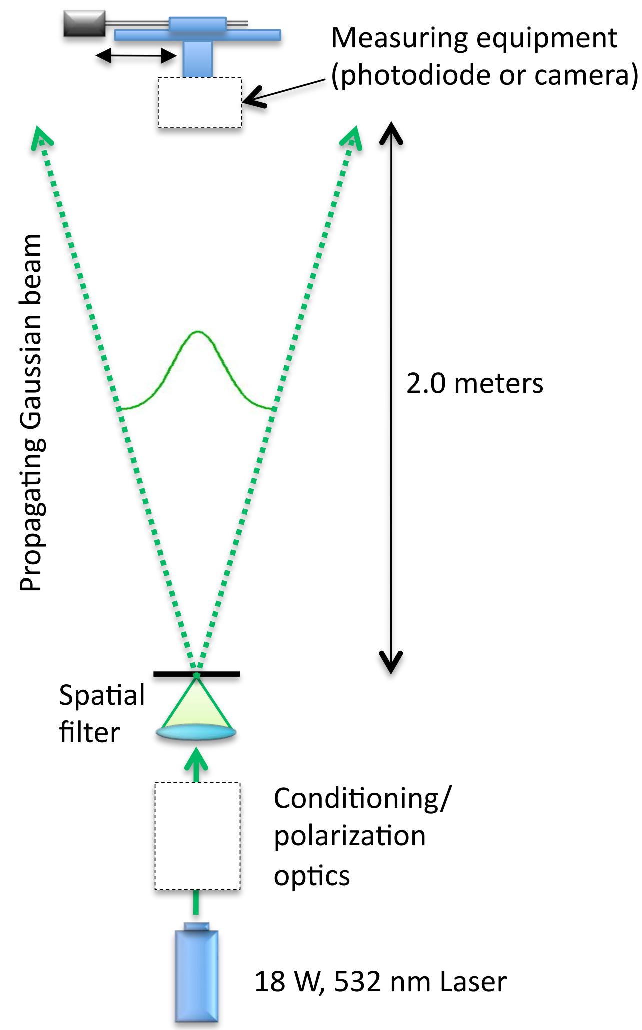


← TMA → ← Offner →

- According to the manufacturer, the polarization dependence of the grating is much less than 1% difference between the TE and TM efficiencies
  - This has been verified to be <0.5%
- The primary source of polarization is reflections off the aluminum surfaces
  - Since reflections occur mostly in the same plane, there is a net difference between TE and TM (upper plot)
  - **Expect a 4.5% sensitivity difference**

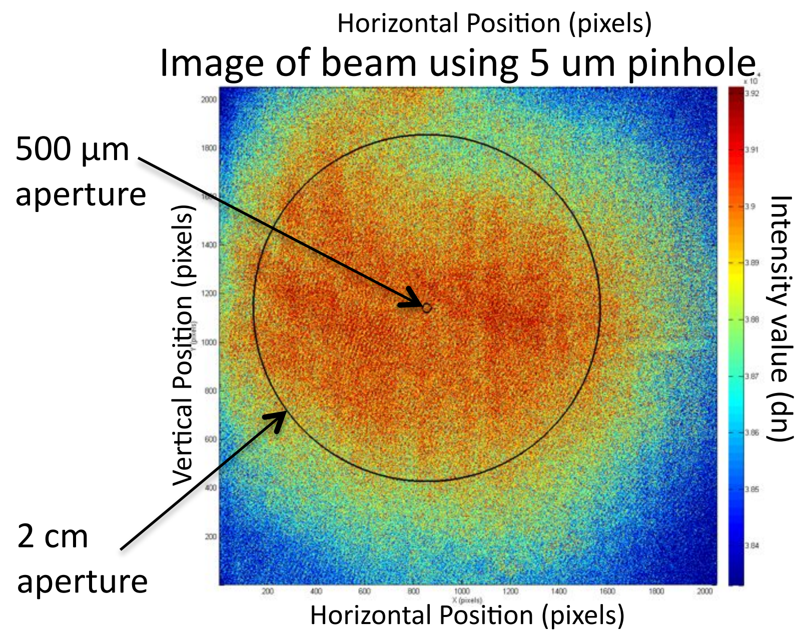
Test Facility Overview

- The goal of the test facility is to generate a known, stable light field with typical spectral irradiance of the Sun (~2 mW/cm^2) and the ability to vary it precisely by known amounts
  - Facility will be used to test the attenuation techniques required by the hyperspectral imager
- Ideally, field will have an irradiance difference of less than 1000 ppm between the 2 cm and 500 micron apertures, but if the field is well characterized, non-uniformities can be compensated during post-analysis
- A propagating Gaussian beam generated by a spatial filter is the chosen method to generate a uniform field
- Entire experimental setup is surrounded by a light-blocking box
- Facility contains an 18 W, 532 nm laser along with an isolator, power monitor, conditioning optics, and polarization optics (to control beam size, position and intensity)
- Facility also contains a laser power controller, which consists of a variable attenuator and feedback sensor
- Either a pinhole photodiode or a sensor array can measure the field
  – Accurate positioning of either detector is accomplished through horizontal and vertical translation stages



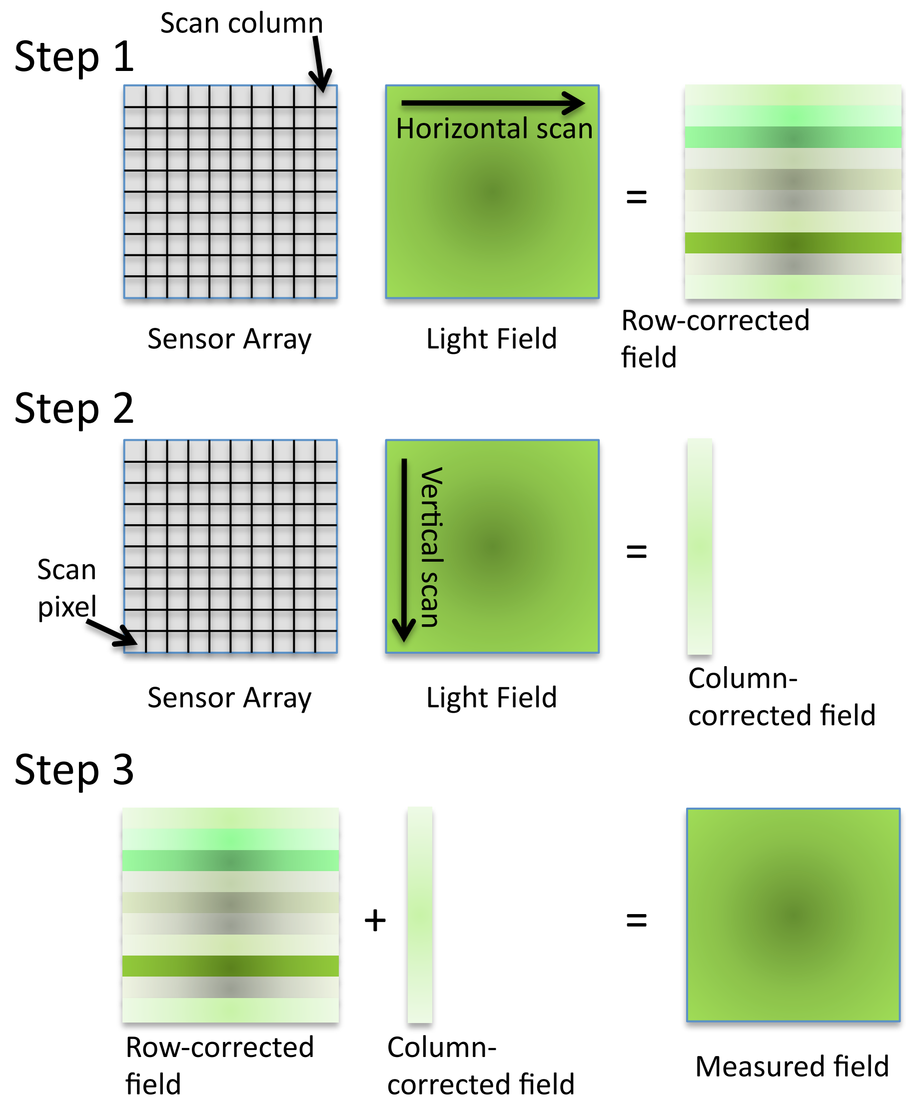
Beam Uniformity Measured to Needed Levels

- Current non-uniformity is 1500-1800 ppm
  - Measured as an irradiance difference between a 500 µm aperture and a 2 cm aperture placed in the center of the beam
  - ±1 mm positioning tolerance causes ~300 ppm change in non-uniformity figure
- Uniformity of the beam is sufficient for required measurements
  - The important parameter in this measurement is not the uniformity, since it can be corrected for if it is known, but the 300 ppm high spatial frequency variations in the measurement



Flat Field Estimation Simulates On-Orbit Method

- Demonstrated technique of flat field estimation by shifting camera in light field
  - In orbit, this method will be used by making a 1-D scan across the Sun
  - In prototype instrument, this method will be accomplished by scanning slit across sensor with goniometer during calibration procedure
- Method:
  - Scan one column of pixels across the full field (each row of scan will be performed by a single pixel, and therefore not subject to pixel non-uniformity)
  - Scan one pixel down the full field (again, the column will be unaffected by pixel non-uniformity)
  - Actual incident field is recovered by piecing together scans
  - Actual field is divided out of measured image, resulting in the flat field estimation
- Measured results show high correlation with actual flat field correction
  - Error in correlation comes from instabilities in measured field
  - Wavelength difference between LED measured correction and laser measured correction
  - Work continues in this area
- During low thermal variation periods (<1 ˚C), estimated variability is <0.4% (standard deviation of each pixel difference)



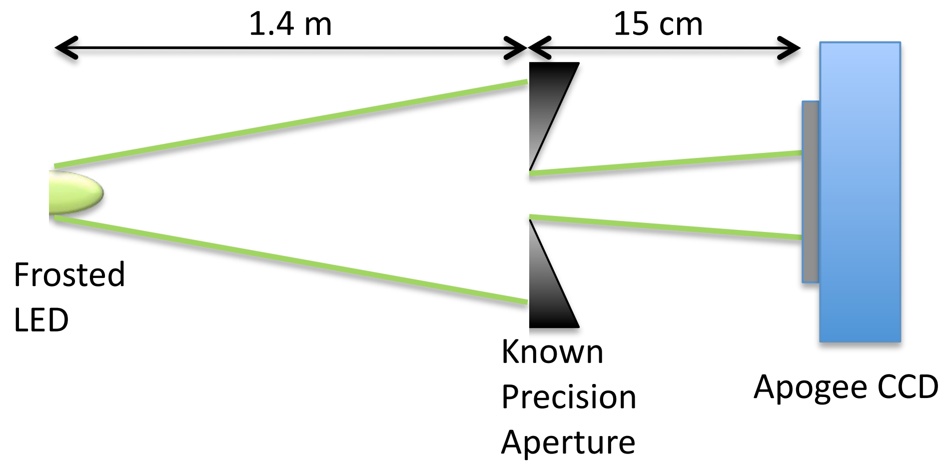
Preliminary Aperture Attenuation Measurements

- Goal: Prove that the attenuation ratio between two apertures is equal to the area ratio of the two apertures

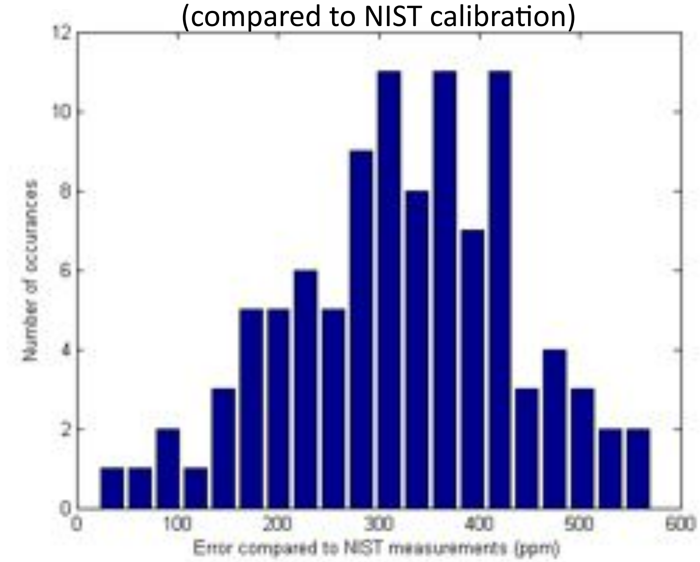
$$\frac{Power_1}{Power_2} = \frac{Area_1}{Area_2}$$

- Two in-house apertures previously measured by NIST are used
  - Aperture 1 area: 50.296828 mm^2
  - Aperture 2 area: 49.929441 mm^2
- Relative intensity measurement of aperture 2 area is within 300 ppm of NIST's measurement
  - Demonstrates attenuation technique is valid to at least 300 ppm at a single intensity level

Experimental setup

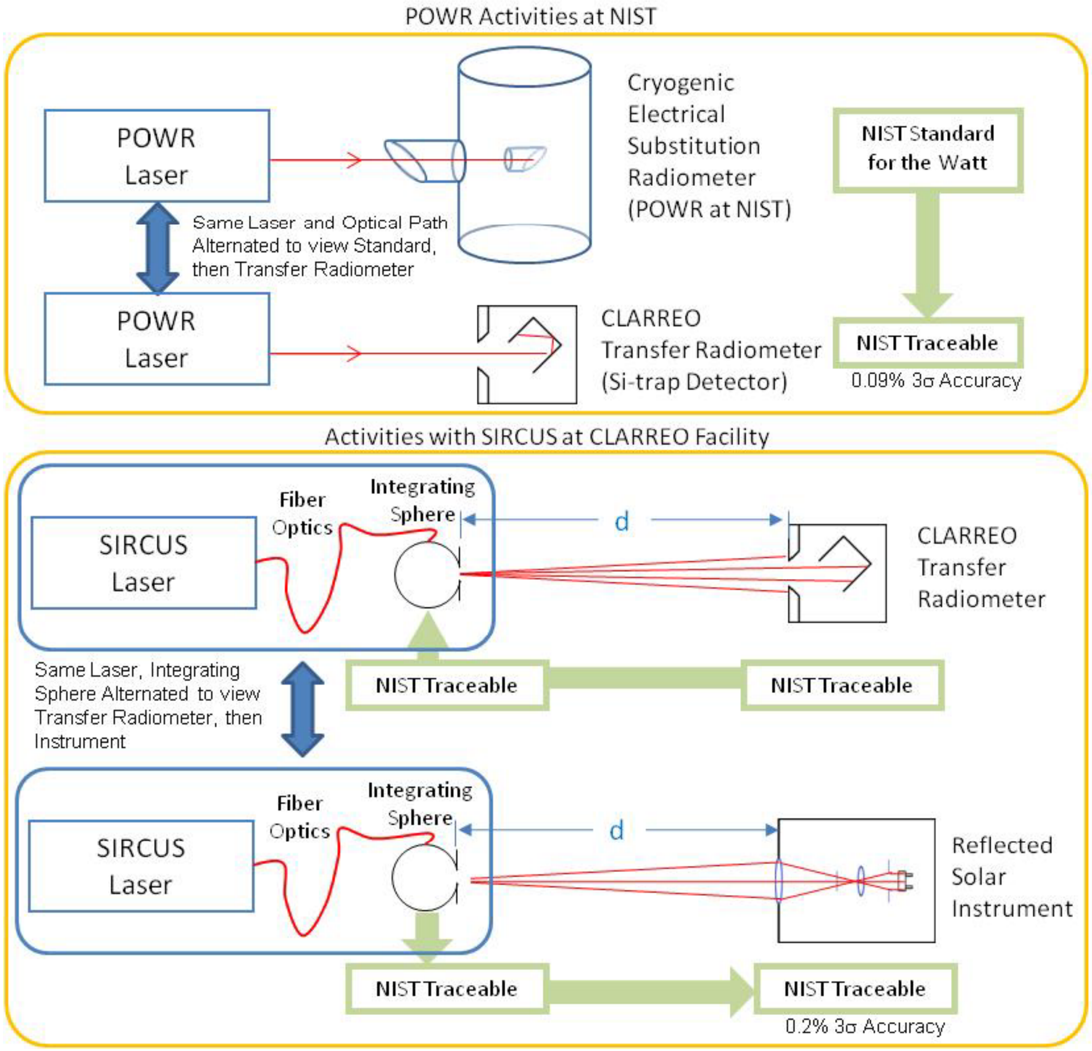


Repeated measurement difference (compared to NIST calibration)



SIRCUS Traceability

- SIRCUS provides a feasible option for simulating on-orbit sources
  - Absolute response
  - Stray light
- SIRCUS relies on a set of well-understood tunable lasers
  - Variety of techniques used to condition laser output
  - Output characterized by CLARREO Transfer Radiometer and monitors on sphere
- Provides a monochromatic source that can achieve 0.1% absolute uncertainty



* POWR – Primary Optical Watt Radiometer

Meeting L1 Measurement Requirements

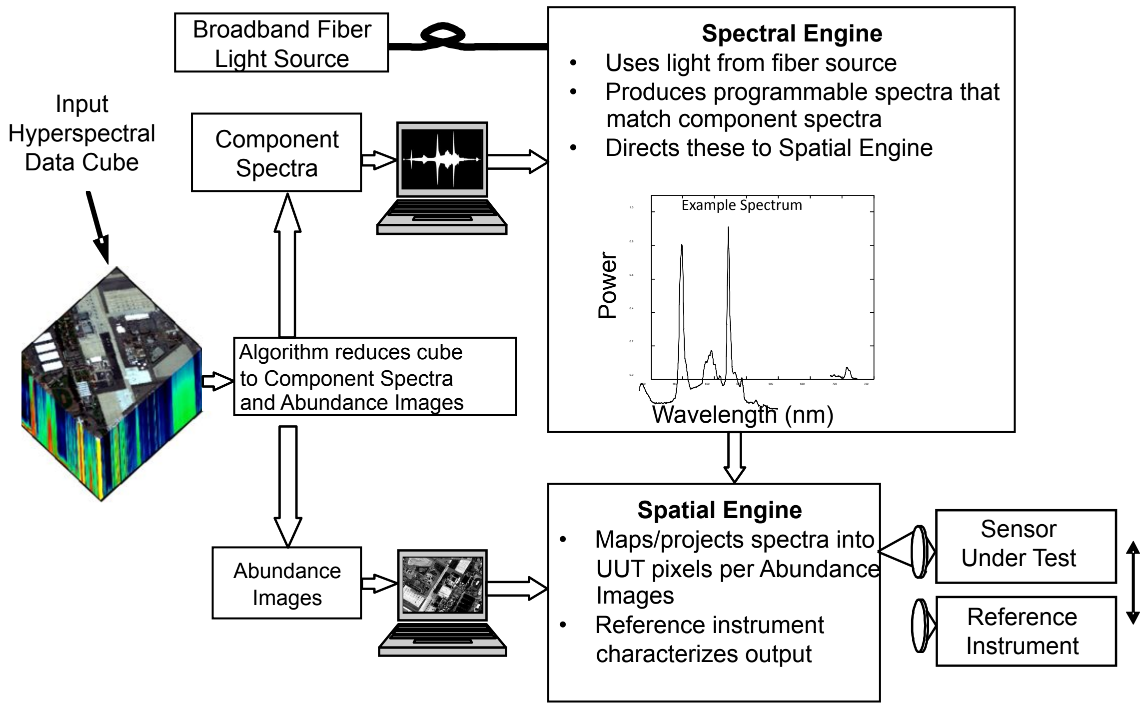
SIRCUS and CLARREO

- Ultimate goal is to have a portable SIRCUS-like facility for calibration of RS instrument
  - Portability needed to ensure its use at a vendor facility
  - Necessary to achieve needed accuracy
- SIRCUS-like facility includes
  - Monochromatic source
    - Irradiance
    - Radiance
    - Cover full spectral range of CLARREO
  - Broadband transfer radiometers
    - Monitor output of source
      - Transfer radiometer #1 – VNIR
      - Transfer radiometer #1 - SWIR
    - Maintain traceability to NIST laboratories
      - Transfer radiometer #2 – VNIR
      - Transfer radiometer #2 - SWIR

Testing Planned at NIST's HIP

The HIP (Hyperspectral Image Projector) is a scene projector

- Provides 2-dimensional image into a sensor under test
- Each pixel has an arbitrarily programmable spectrum
- Spectral radiance be measured with a calibrated spectroradiometer
- Can project dynamic real-time hyperspectral scenes



Enables pre-flight, system-level, characterizations & calibrations with controllable spectral, spatial, and temporal scenes

Test Concepts to Be Explored Using NIST's HIP

- Scanned line image to simulate track motion
- 2D flood images with various spectra
  - Earth-view scenes
  - Lunar scenes
  - Solar scene?
- Bright cloud next to darker ocean to test stray light
- Attenuation and linearity validation over limited dynamic range
- Radiometric calibration (at ~2% level)

Summary

- SI traceability of RS instrument at 0.3% absolute uncertainty is a challenge
- Traceability of using sun as calibration source is not at issue
- Key issues for traceability are
  - Proof of transfer to orbit
  - Methods to evaluate attenuator behavior with time
  - Stray light
- Issues are tractable
  - Absolute solar irradiance measurement and instrument modeling provide transfer to orbit
  - Lunar verification
  - Solar, stellar/planetary, and lunar sources
- Error budget demonstration is a must