Hyperspectral Imagery Radiometry Improvements for Visible and Near-Infrared Climate Studies

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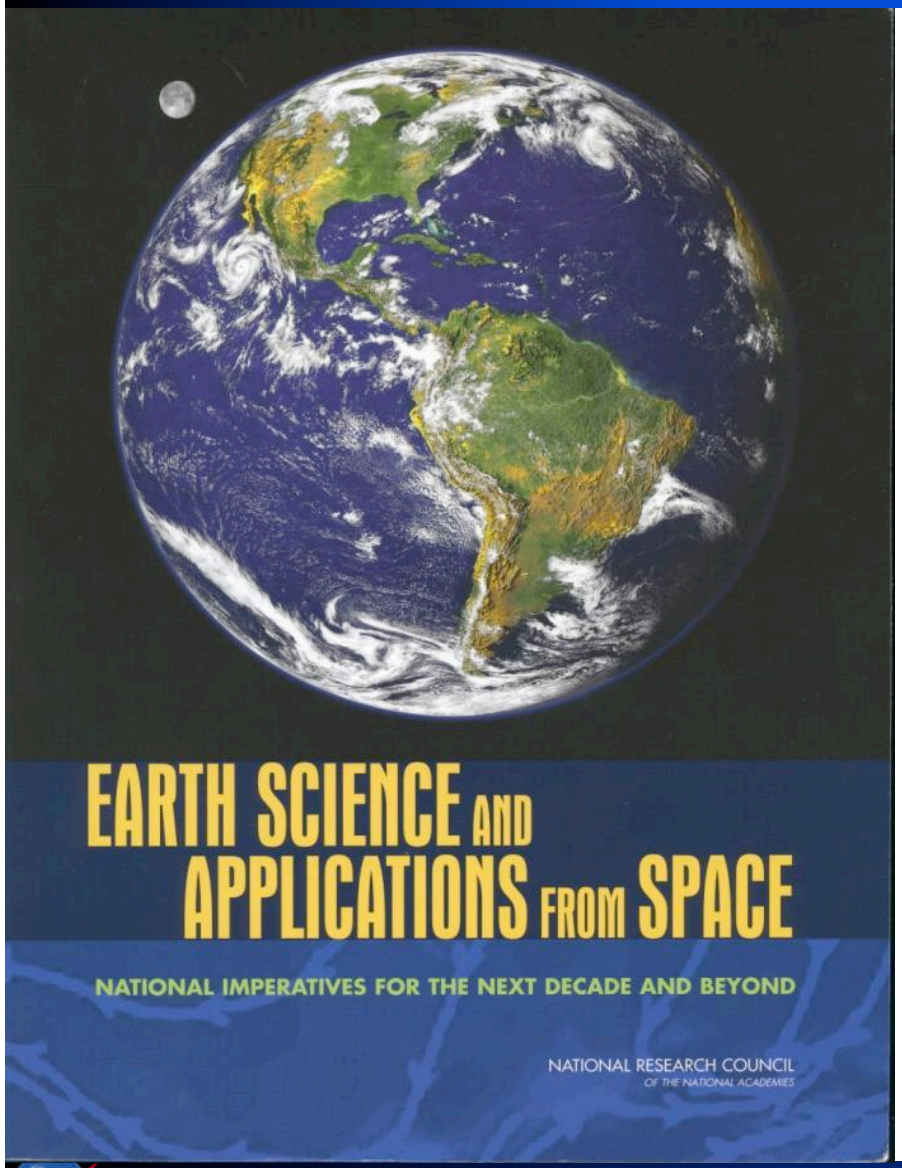
Decadal Survey defines CLARREO



NOAA CLARREO

- CERES (Clouds and Earth's Radiative Energy System)
- TSIS (Total Solar Irradiance Sensor)

NASA CLARREO

- Solar reflected spectra (SI traceable accuracy of 0.3% 2s)
- Infrared emitted spectra (SI traceable accuracy of 0.1K 3s)
- Global Navigational Satellite System Radio Occultation (SI traceable accuracy of 0.1K 3s)
- Three 90-degree polar orbits with IR/GPS on all 3, solar on 1.

CLARREO is a Cornerstone of the Climate Observing System

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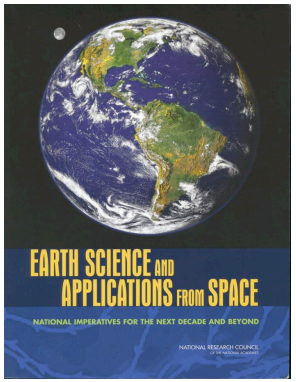
Decadal Survey defines NASA CLARREO



Societal Benefits

Enable knowledgeable policy decisions based on internationally acknowledged climate measurements and models through:

- Observation of high accuracy long-term climate change trends

- Use the long term climate change observations to test and improve climate forecasts.

Science Objectives

Make highly accurate and SI-traceable decadal change observations sensitive to the most critical but least understood climate radiative forcings, responses, and feedbacks

- Infrared spectra to infer temperature and water vapor feedbacks, cloud feedbacks, and decadal change of temperature profiles, water vapor profiles, clouds, and greenhouse gas radiative effects
- GNSS-RO to infer decadal change of temperature profiles
- Solar reflected spectra to infer cloud feedbacks, snow/ice albedo feedbacks, and decadal change of clouds, radiative fluxes, aerosols, snow cover, sea ice, land use
- Serve as an in-orbit standard to provide Reference Intercalibration for broadband CERES, and operational sounders (CrIS, IASI)

A Mission with Decadal Change Accuracy Traceable to SI Standards

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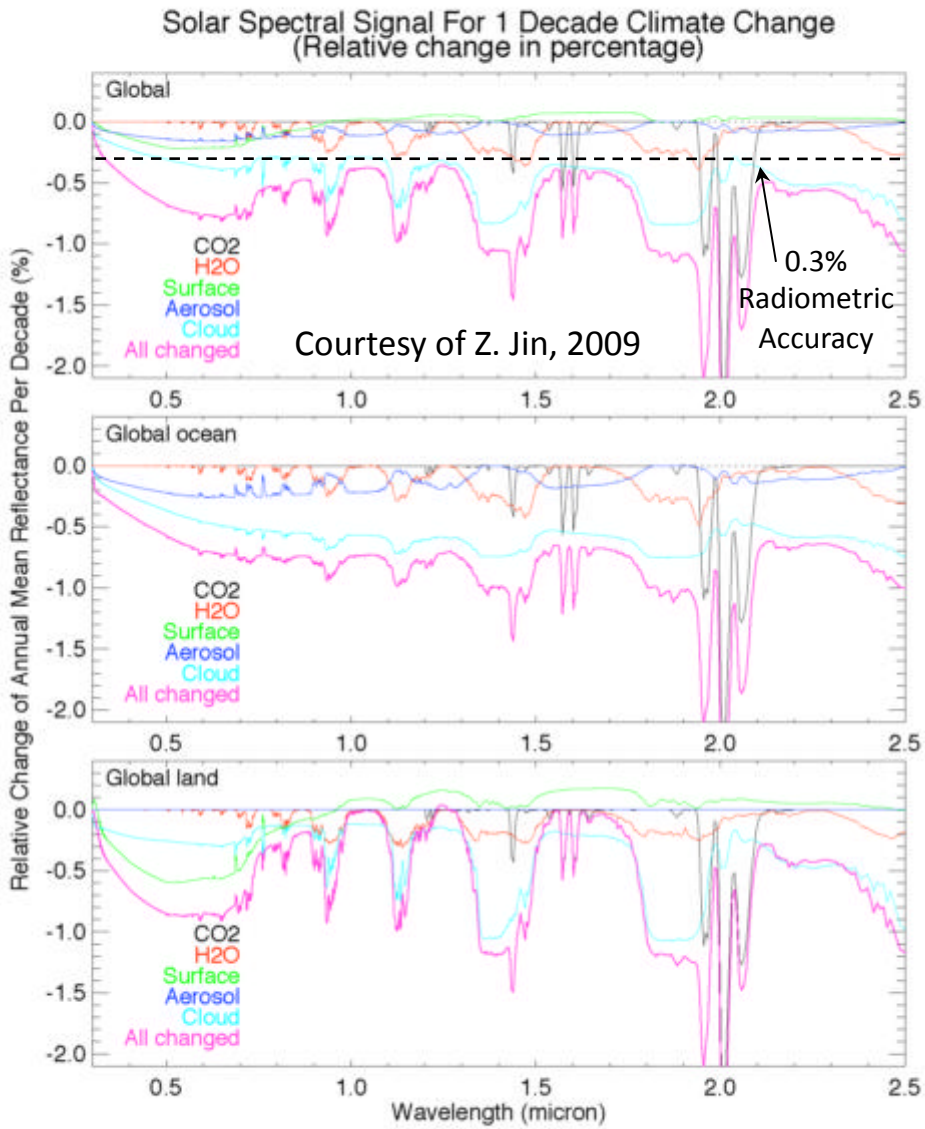
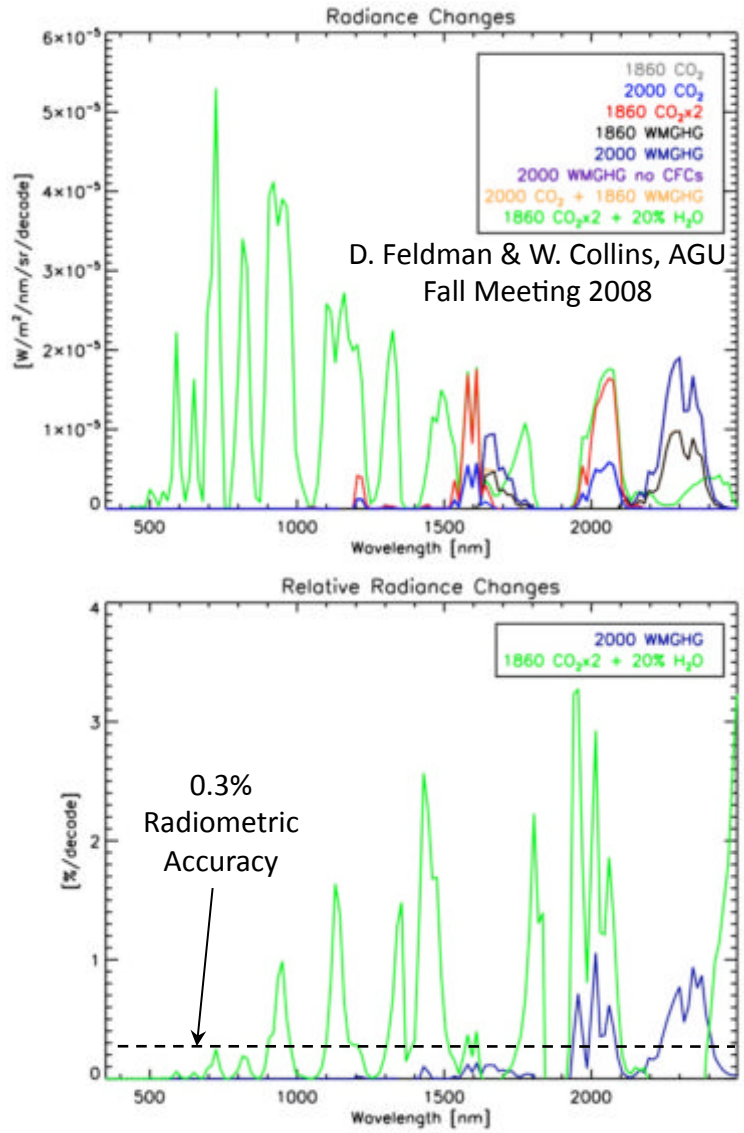
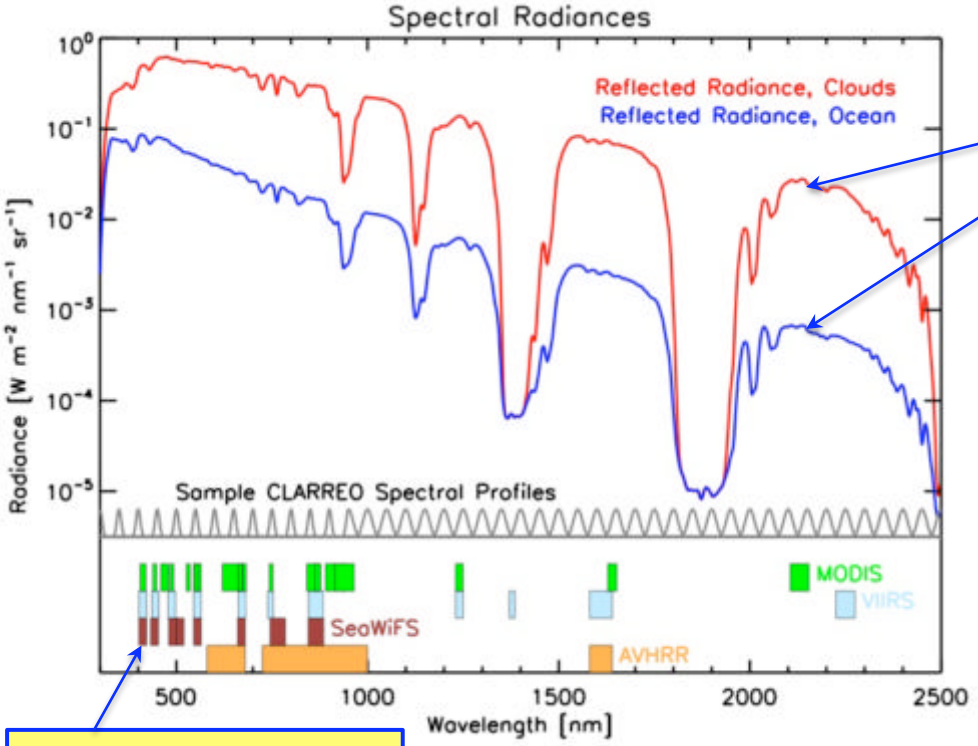
Climate Sensitivity of Shortwave Radiances





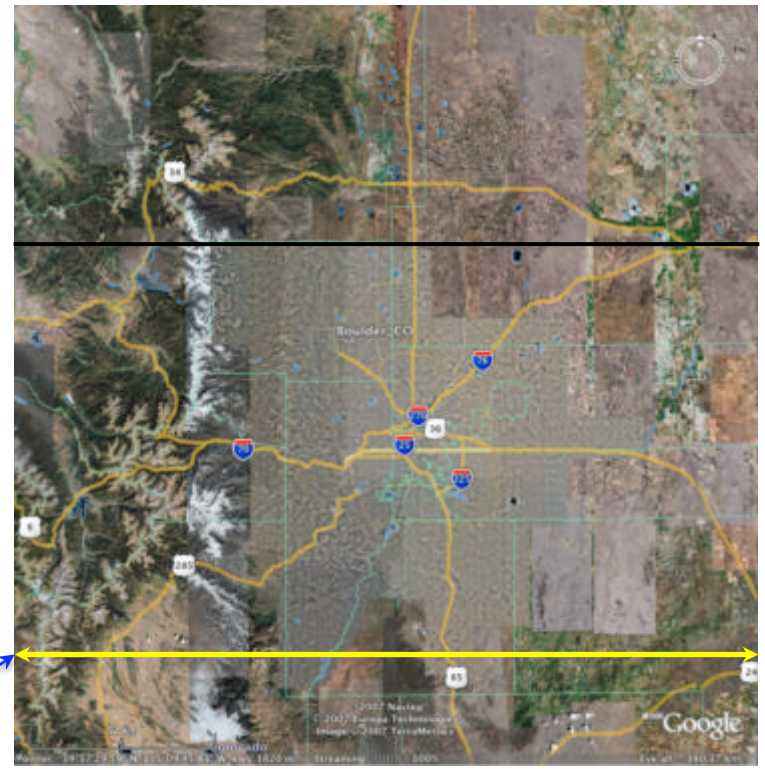
CLARREO Shortwave Requirements



Climate benchmarking requires 0.15% (1 s) absolute accuracy and 320-2300 nm spectral coverage

Reference inter-calibrations require continuous spectral coverage with 8 nm spectral resolution

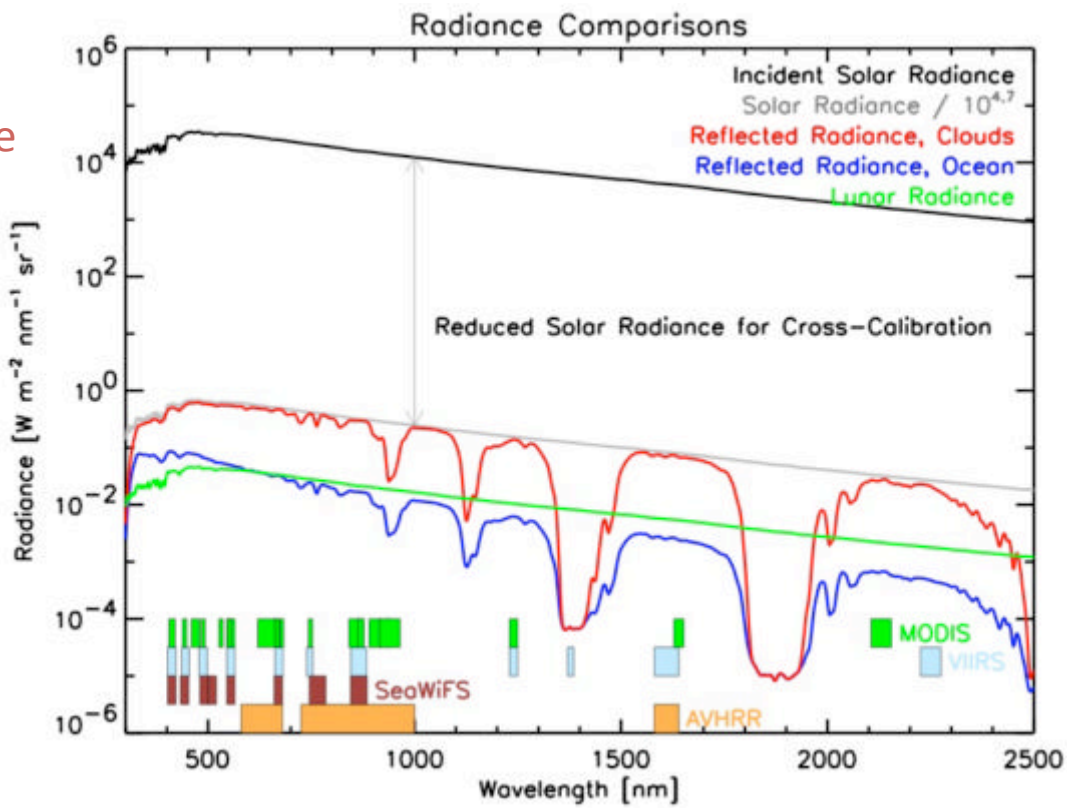
0.5 km (2.5 arcmin) IFOV

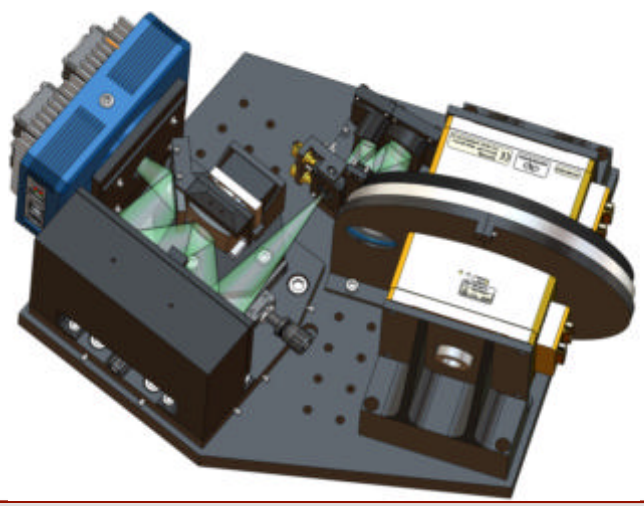


Ground sampling requires 0.5 km resolution and >100 km coverage

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
- Shortwave reflectance measurements benchmark climate
- CLARREO/TSIS spectral solar irradiances provide SI traceability



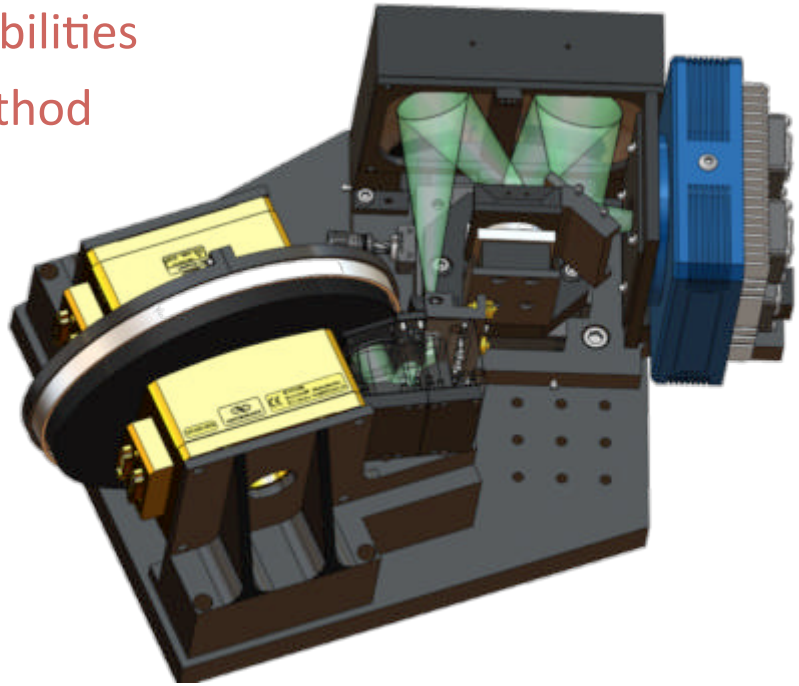


IIP to Demonstrate Cross-Calibration Approach

- **Intent** is to demonstrate cross-calibration capability from spectral solar irradiance to desired accuracies
- **Method** is to prototype a visible (Si-based) hyperspectral spectrometer with integrated attenuation methods and
  - Demonstrate accurate attenuation capabilities
  - Show a solar irradiance observation method

Hyperspectral Imager Requirements		
Parameter	Value	Units
Spatial Resolution	0.5	km
Spatial Range (cross-track)	200	km
Wavelength (min)	300	nm
Wavelength (max)	1050	nm
Spectral Resolution	10	nm
Relative Std Uncertainty	0.2	%

- Attenuation studies include broad spectral range
- IIP demonstrates attenuations over 300-1050 nm

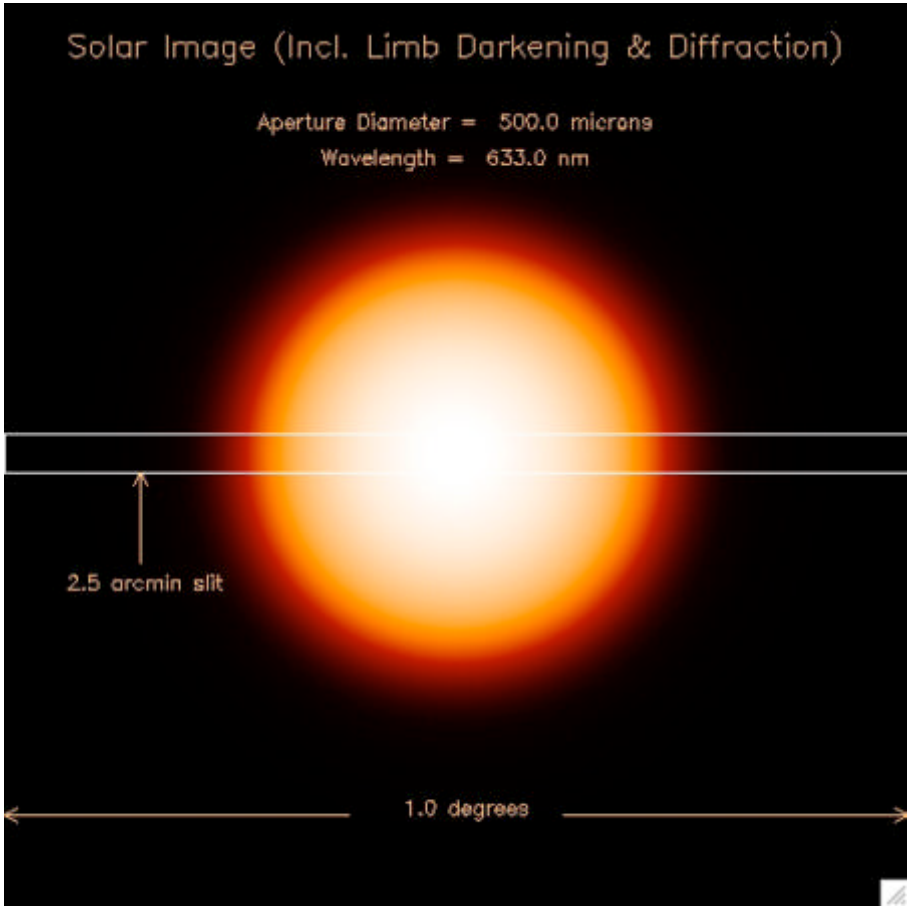


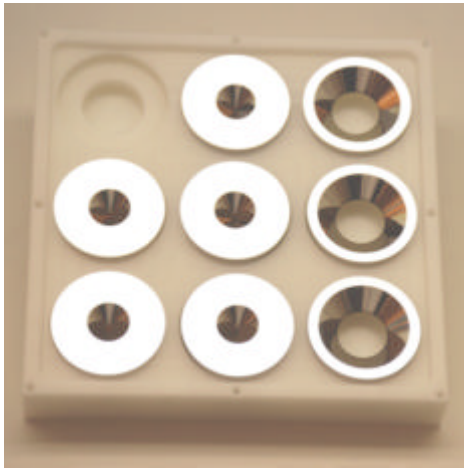
Cross-calibration concept applicable to many instruments; will be demonstrated in IIP using a hyperspectral imager.

Attenuation Methods Demonstrated With IIP

1. Aperture areas
2. Integration times
3. Filters

- *500-µm vs 2-cm diameter aperture attenuates light $10^{-3.2}$*
- *NIST aperture area calibration achieves desired accuracy*
- *Diffraction limits attenuations achievable*

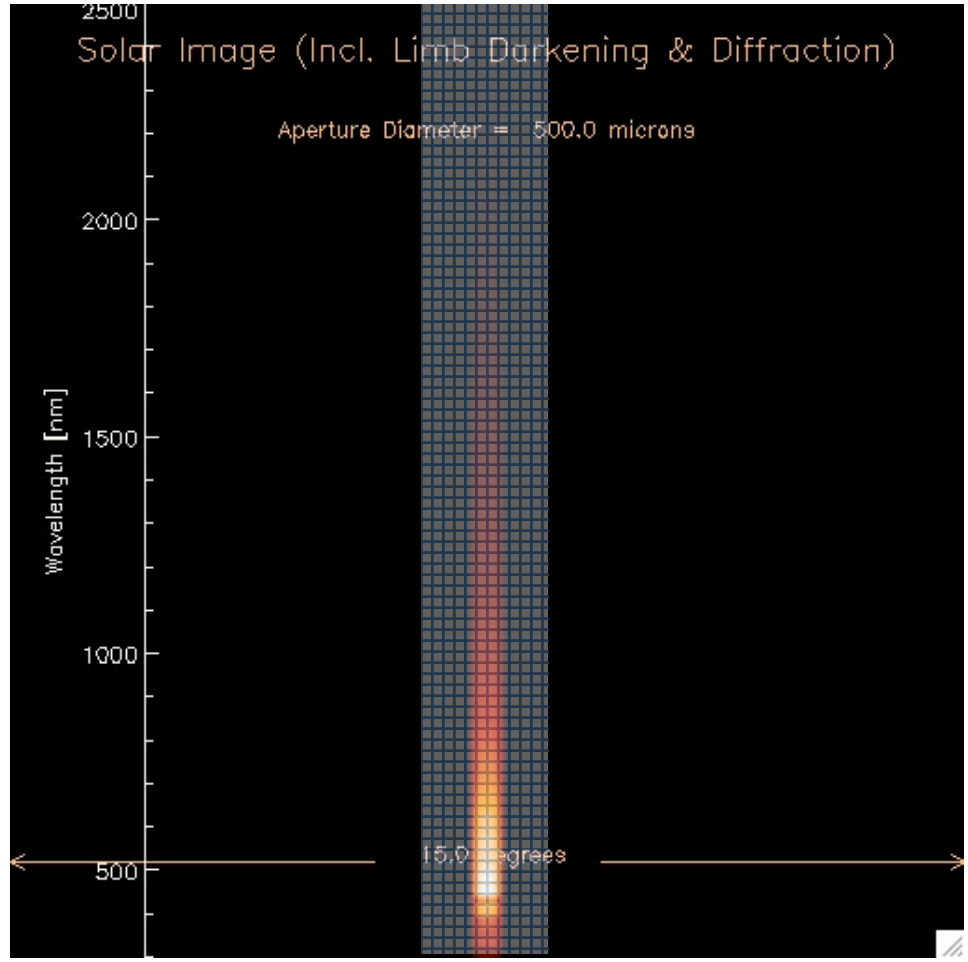




Attenuation Methods Demonstrated With IIP

1. Aperture areas
2. Integration times
3. Filters

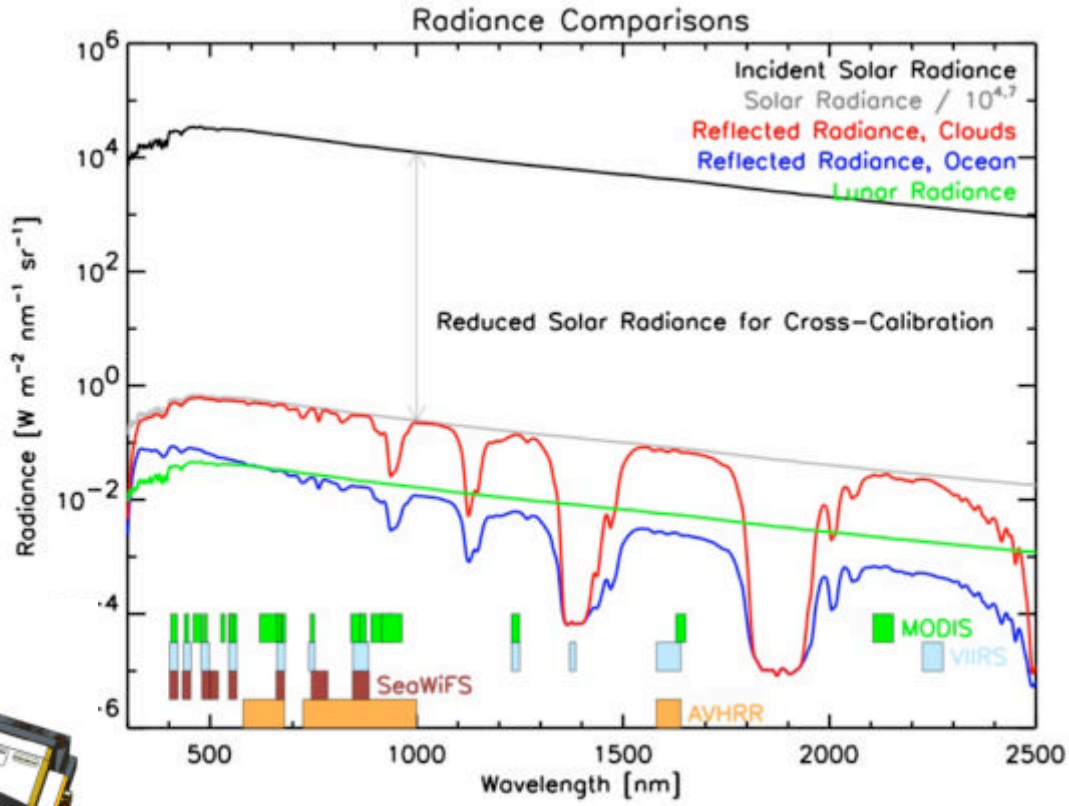
- *High-speed and ROI read-out nominally attenuate light 10^{-1}*
  - *CMOS detectors promise even greater attenuations*
  - *Electronics determine attenuations achievable*
- *Mechanical shutter an alternative*

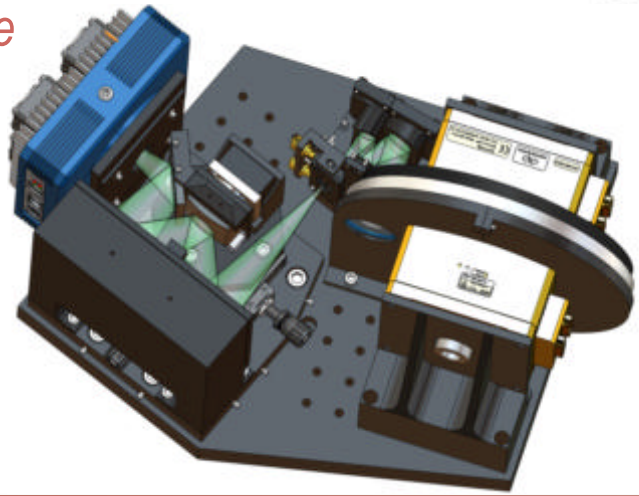


Attenuation Methods Demonstrated With IIP

1. Aperture areas
2. Integration times
3. Filters

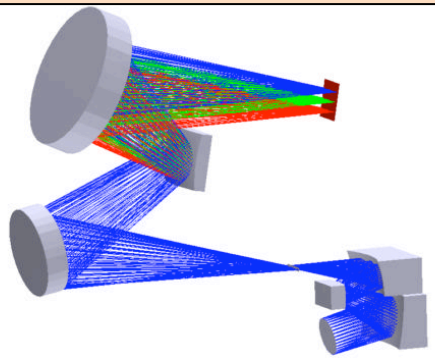
- *ND filters attenuate light 10^{-1} to 10^{-2}*
- *Filters are calibrated on-orbit via lunar observations*
  - *Same optical geometry as Sun*
- *Signal-to-noise limits attenuations achievable*

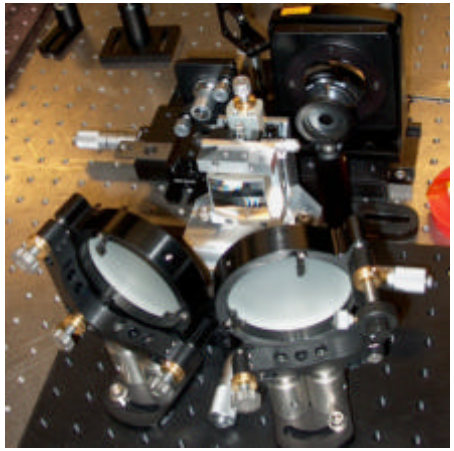


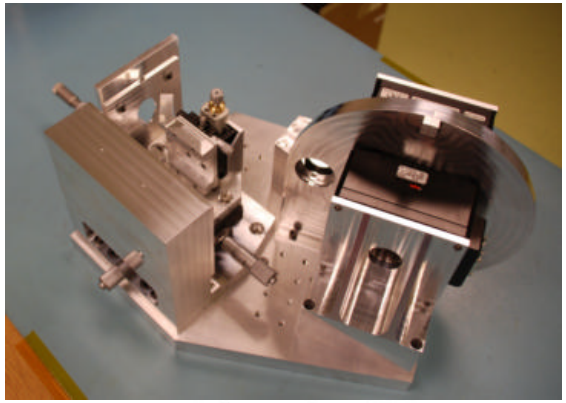


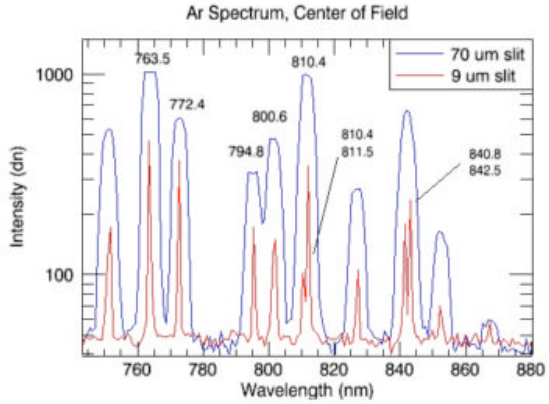
IIP Timeline Overview

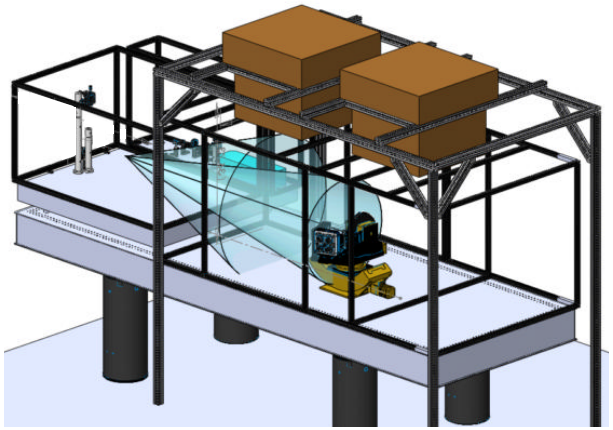
1st year	2nd year	3rd year
July 2008 – July 2009	July 2009 – July 2010	July 2010 – July 2011
Optical & Mechanical Design, Analysis & Trade Studies, Breadboarding, FPA Selection	Spectrometer Build & Test, Test Facility Construction, NIST Component Calibrations	Attenuation Method Validations in Test Facility

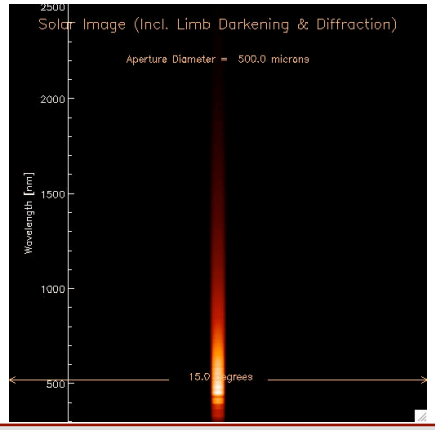






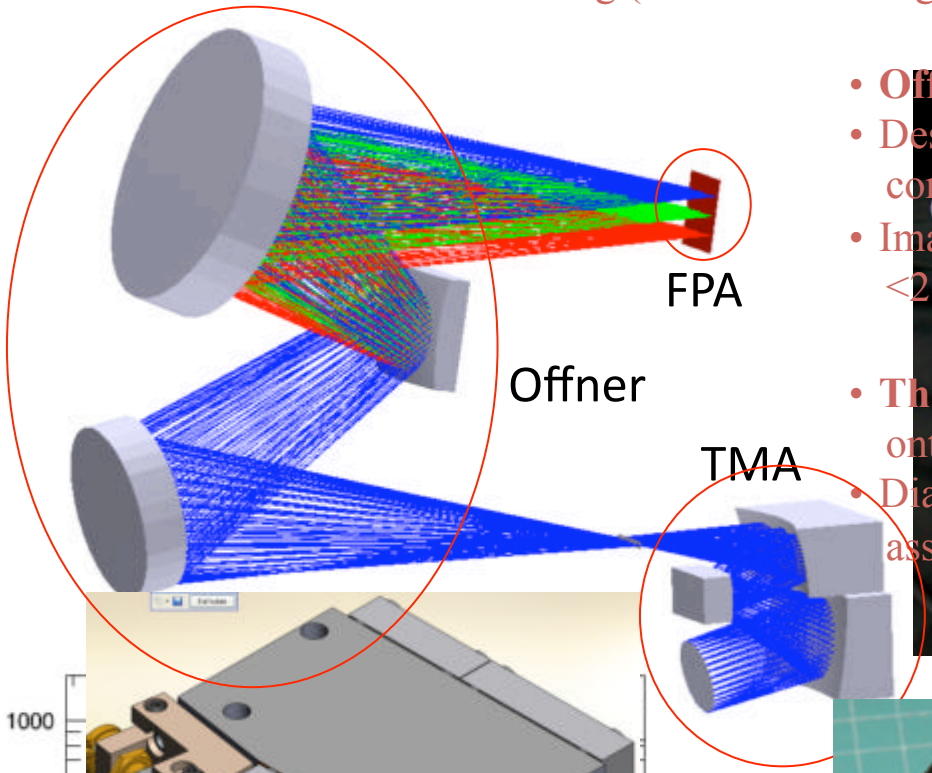




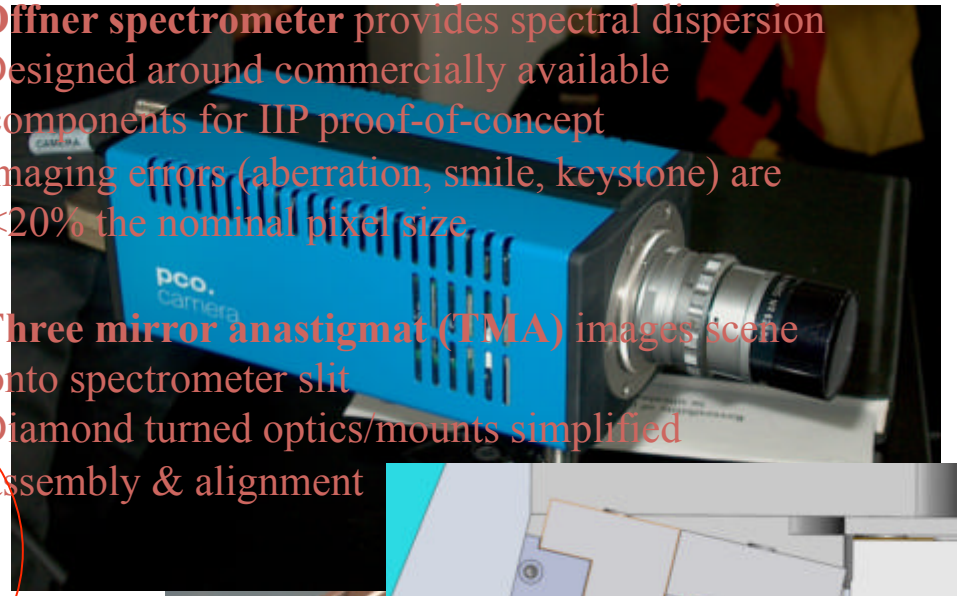


Overview of the Optical Design

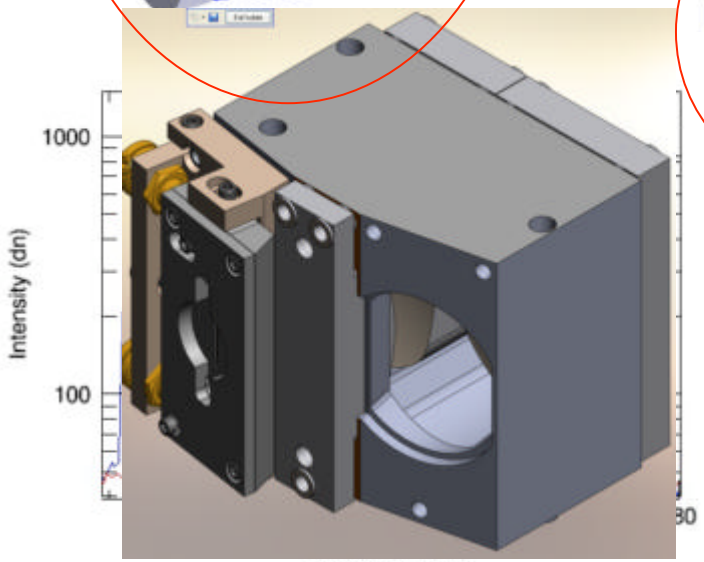
- **CMOS FPA** provides fast readout (to test integration time attenuations) and electronic shuttering (to eliminate image smear for accurate radiometry)

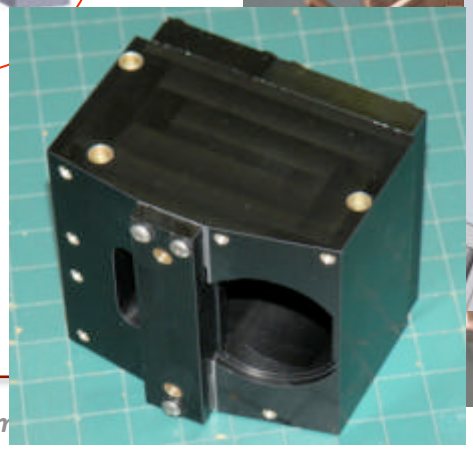


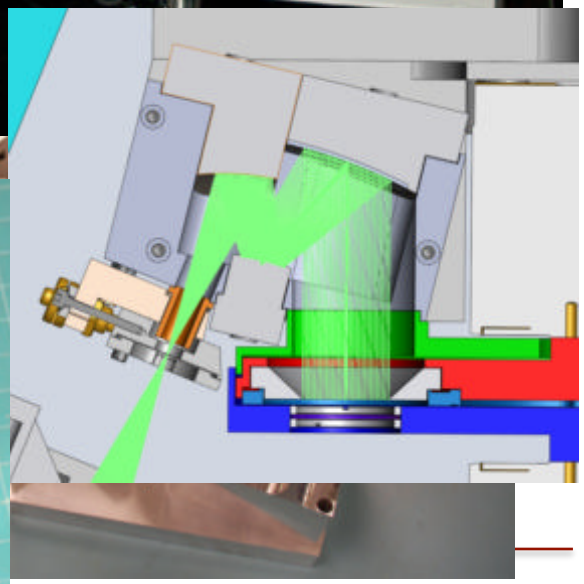
- **Offner spectrometer** provides spectral dispersion
- Designed around commercially available components for IIP proof-of-concept
- Imaging errors (aberration, smile, keystone) are <20% the nominal pixel size



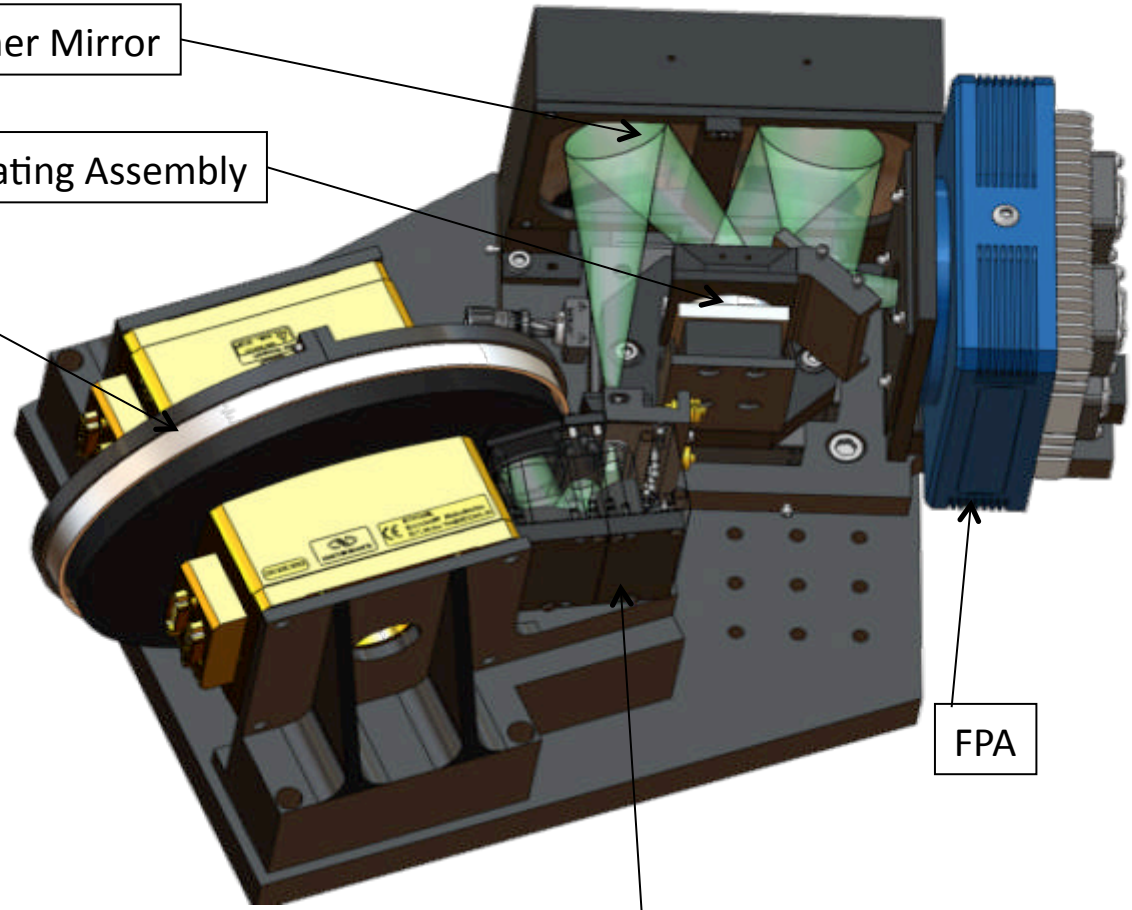
- **Three mirror anastigmat (TMA)** images scene onto spectrometer slit
- Diamond turned optics/mounts simplified assembly & alignment





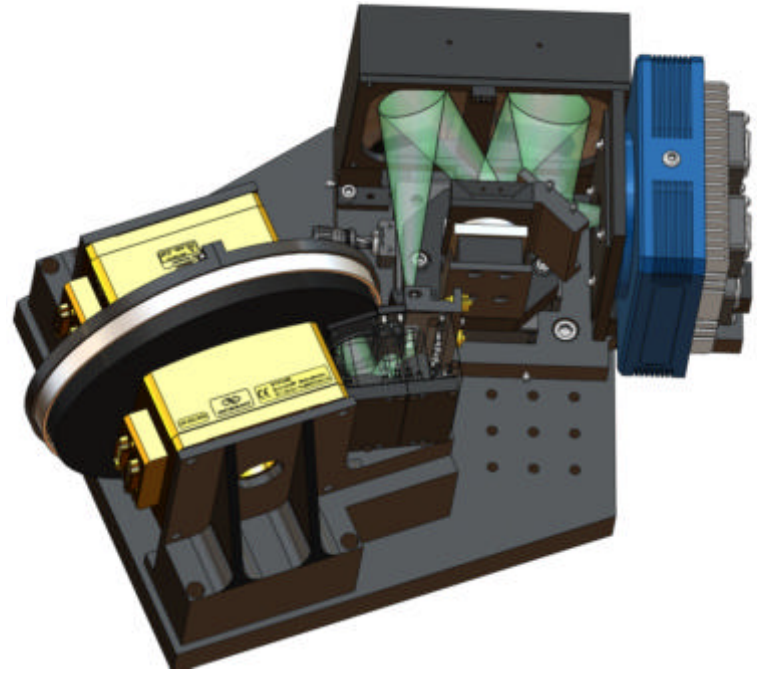


Overview of Mechanical Design



- The instrument is on an optical bench with locating pins for positioning and rigid mounting of optical elements
- Some components have allowances for minimal motion for one time alignment (shims and alignment fixtures)
- The loose tolerances in the optical design make this "snap-together" assembly possible

Current Status of Optics and Optical Testing



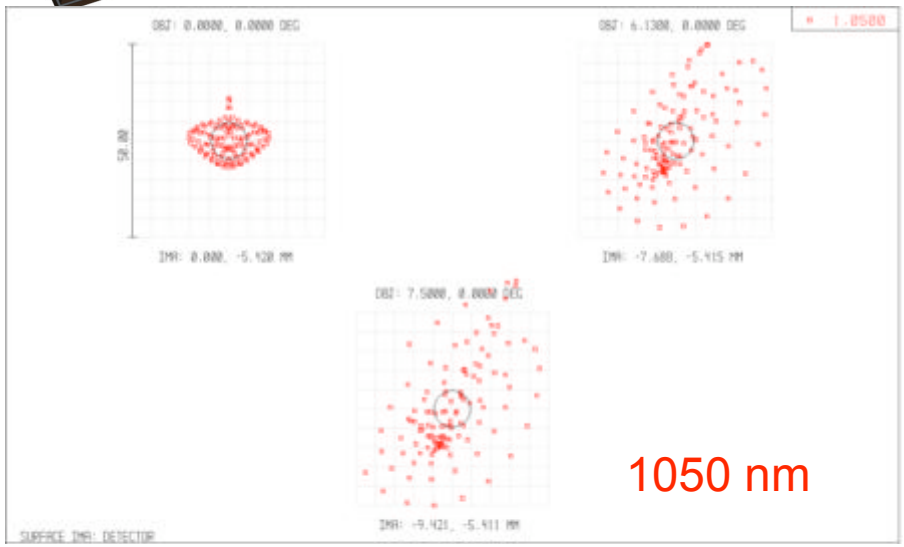
Tasks Completed:

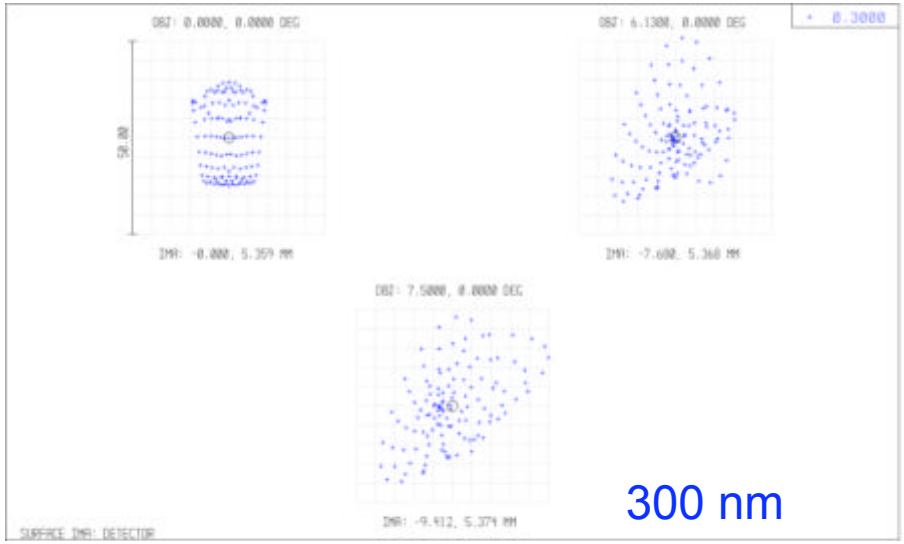
- Optical and mechanical components for spectrometer and TMA in house and assembled
- Modeling complete
  - Stray light/baffling analysis
  - Analysis of metal mirror surface roughness/scattering in the TMA
- Optical measurement/characterization of the integrated hyperspectral imager initiated
  - Point spread function
  - Spectral dispersion
  - Scattering/stray light from a collimated source

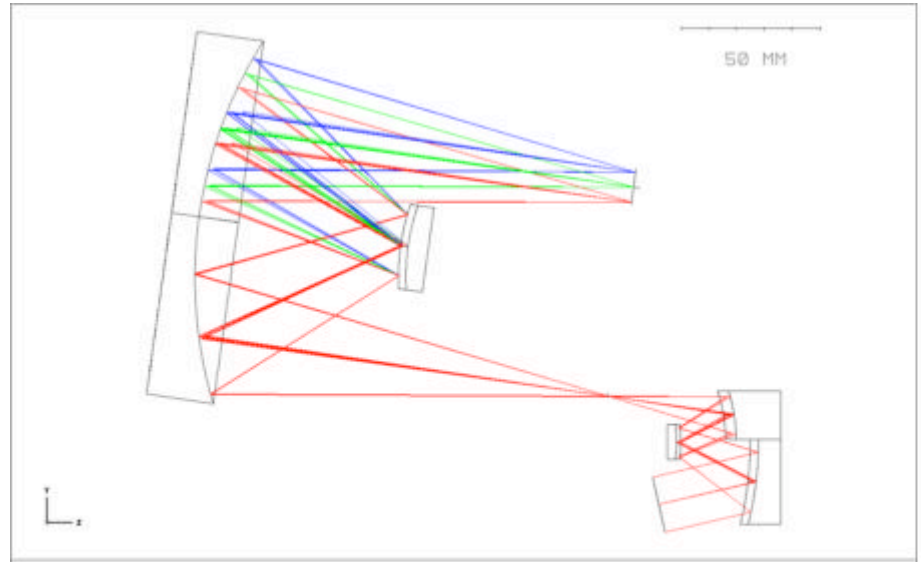
Future Tasks:

- Complete optical characterizations
  - Smile and keystone (completed for breadboard)
  - Repeat PSF with 500 µm and 20 mm apertures
  - Verify polarization sensitivity in both standard and orthogonal configurations
- **Perform attenuation studies**

ZEMAX Model of System Optical Performance



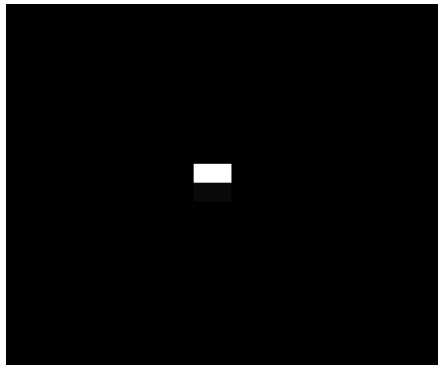




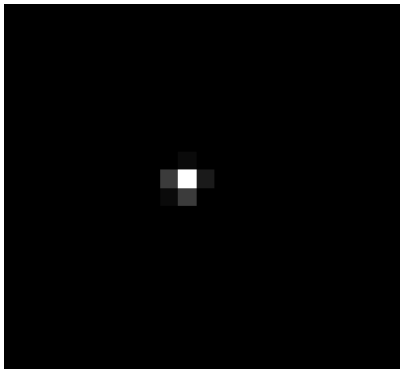
- Smile error < 11 μm (< 15% effective pixel size)
- Keystone error < 9 μm (< 16% pixel)
- RMS spot radius < 14 μm (< 25% pixel)
- PSF energy in pixel > 91 %

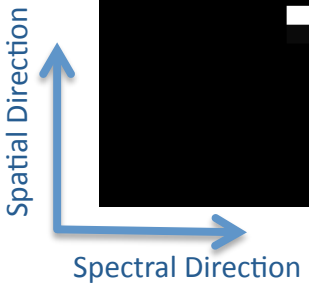
Point Spread Function (PSF) Measured on Integrated System Tests Both TMA and Spectrometer

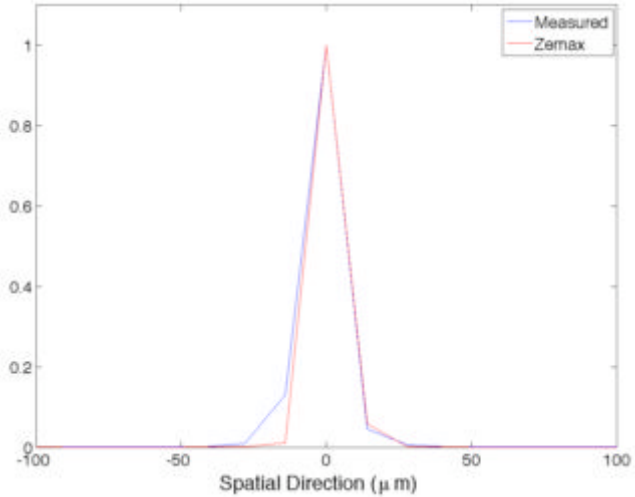
ZEMAX

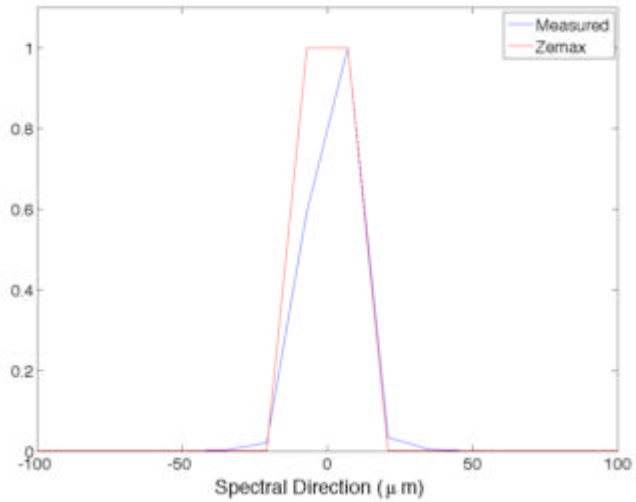


Measured









Approach

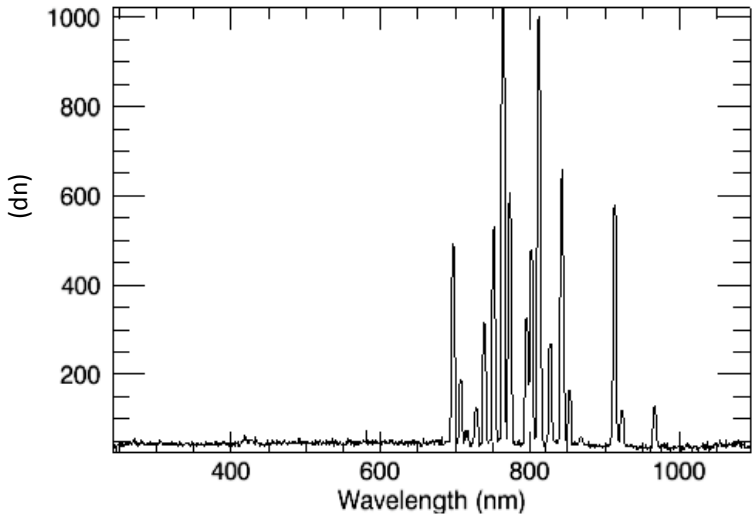
- Overfill 8-mm entrance aperture with a collimated HeNe laser
  - λ = 632.8 nm
  - $1/e^2$ = 10 mm

Results

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

Spectral Dispersion Validated Using Line Sources

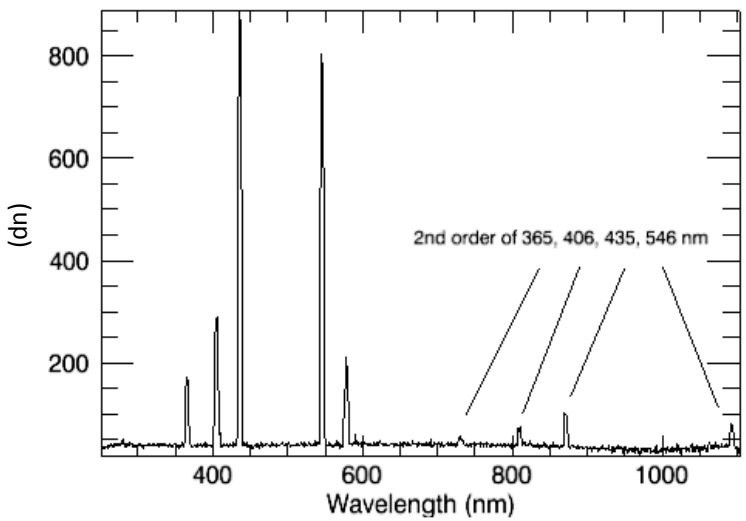
Ar spectrum, center of field



Argon Lamp

Published ** Wavelength (nm)	Measured Wavelength (nm)
415.9,419.1	418
696.54	696
706.72	707
714.7	715
727.29	727
738.4	738
750.39,751.46	751
763.51	763
772.38	773
794.82	795
800.62,801.48	801
810.37,811.53	811
826.45	827
840.82,842.46	842
852.14	853
866.79	867
912.3	912
922.46	922
965.78	966

Hg spectrum, center of field



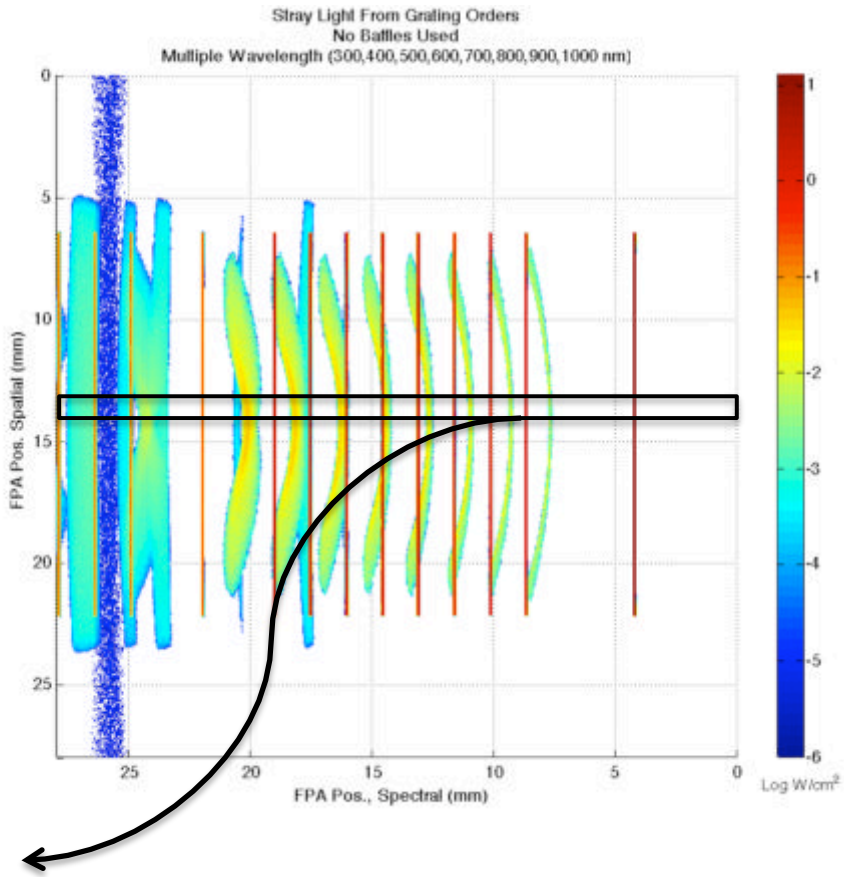
Mercury Lamp

Published ** Wavelength (nm)	Measured Wavelength (nm)
312.5,313.1	--
365.0,366.3	365
404.7,407.8	406
434.8,435.8	436
546.1	546
577.0,579.0	578

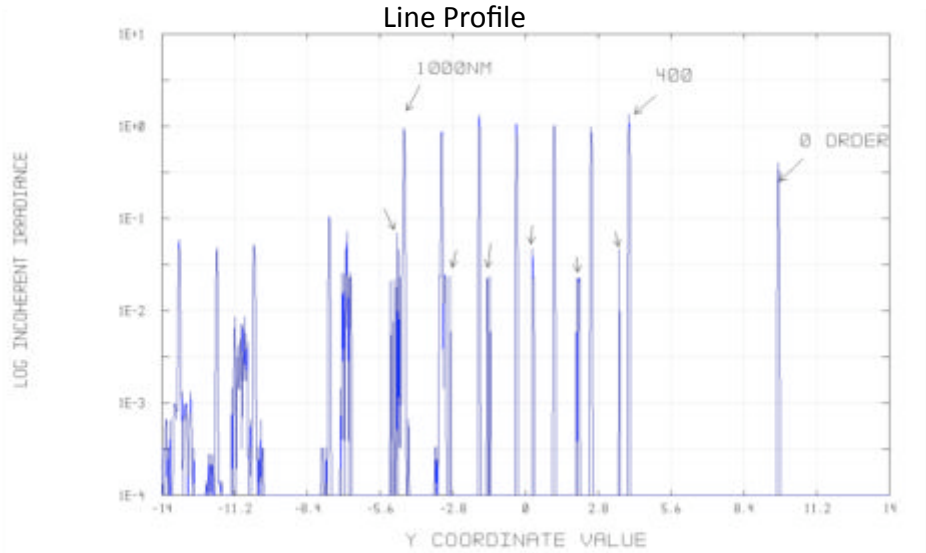
**Line data from the NIST Atomic Spectra Database

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

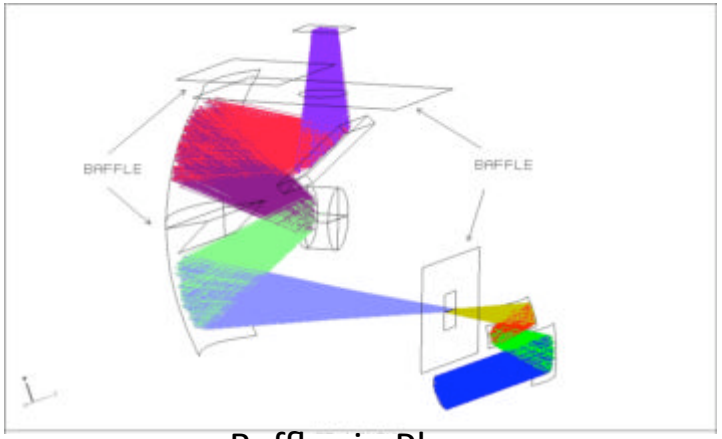


Line Profile

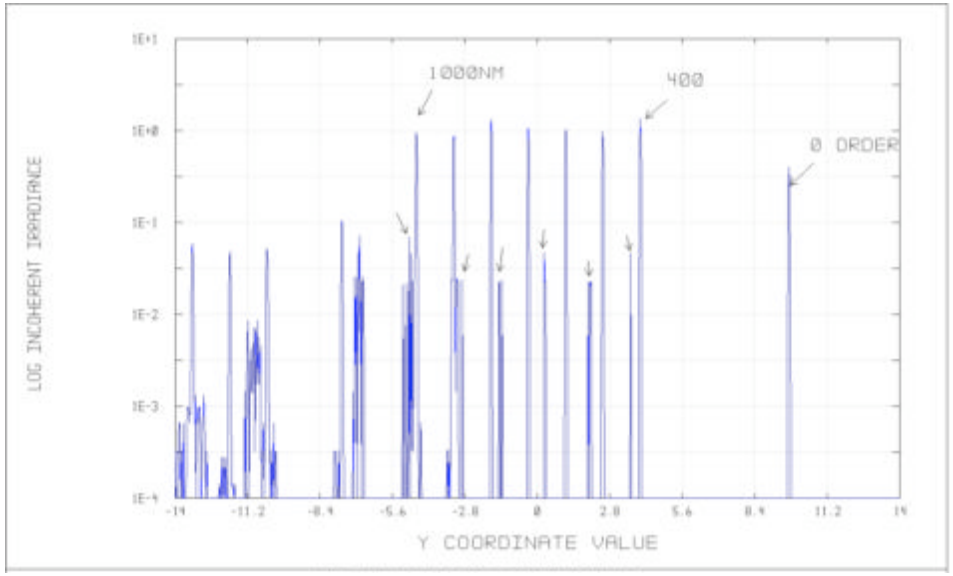


Stray/Scattered Light Analysis Performed: Baffling Blocks Unwanted Grating Orders

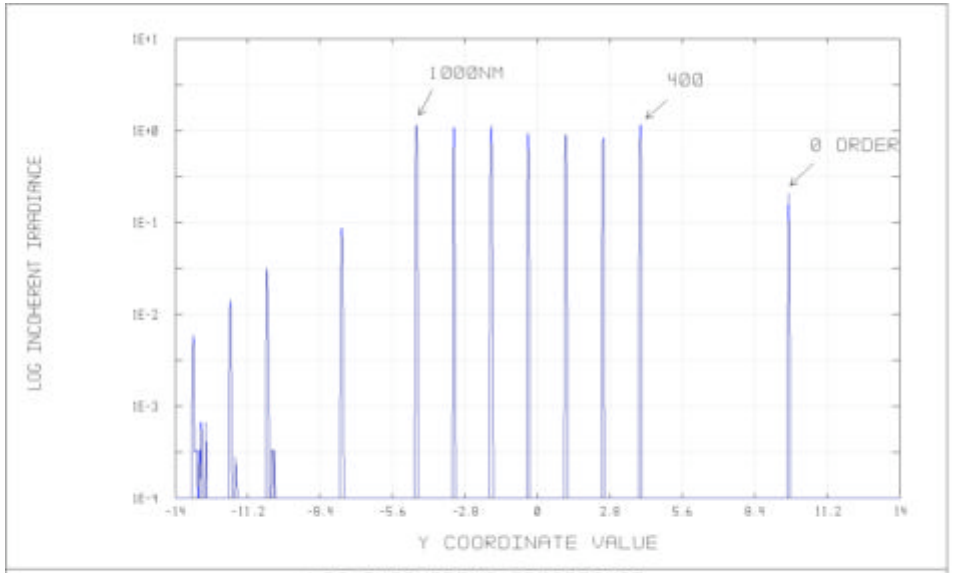
- Baffles added to the design block unwanted orders (below left) from reaching the FPA (below right)



No Baffles



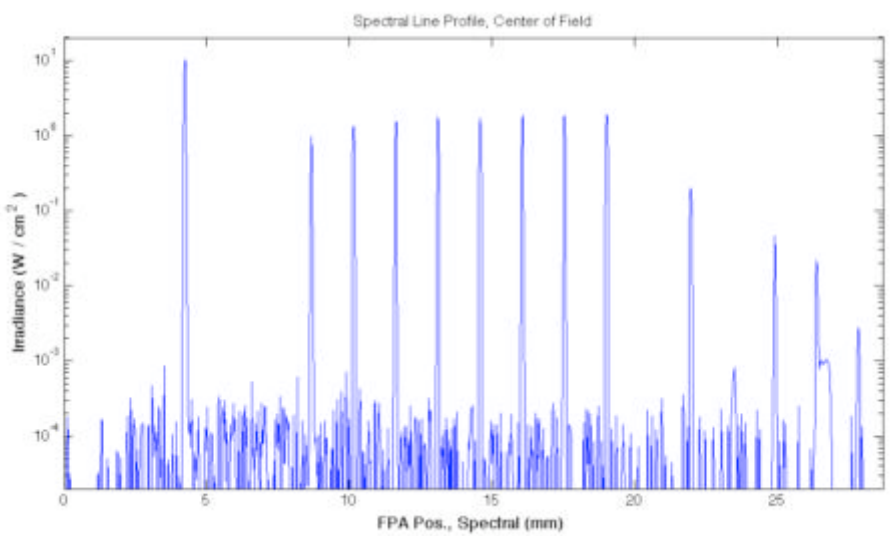
Baffles in Place

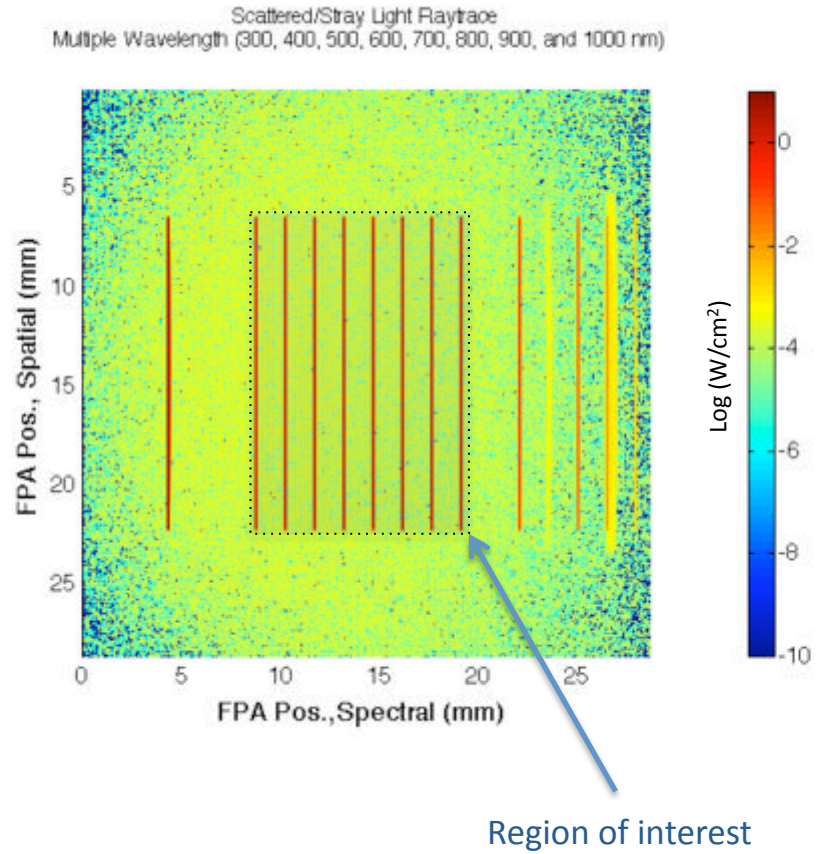


Stray/Scattered Light Analysis Performed: Stray Light Reduced Below FPA Sensitivity

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



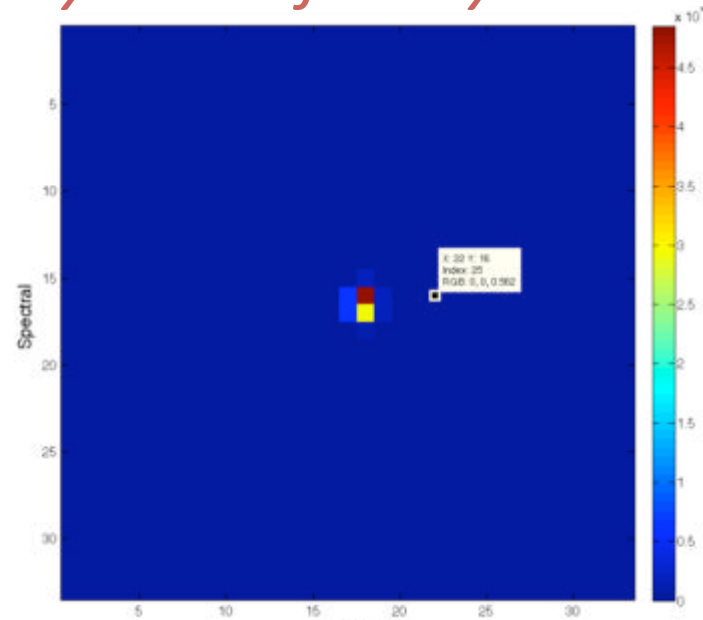


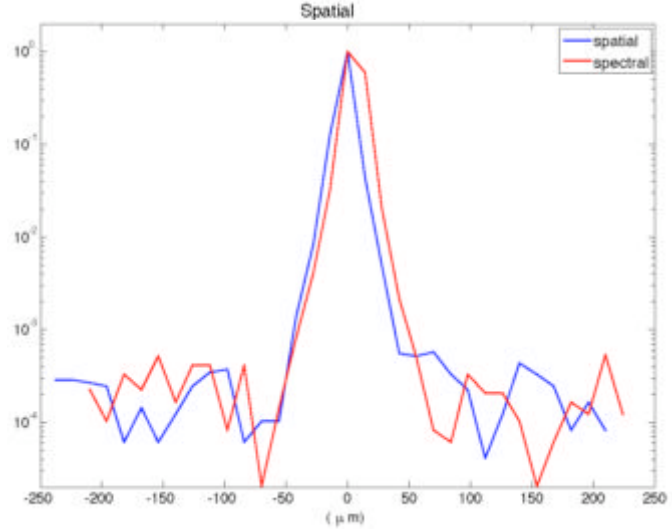
Region of interest

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

Stray/Scattered Light Analysis Verified by PSF

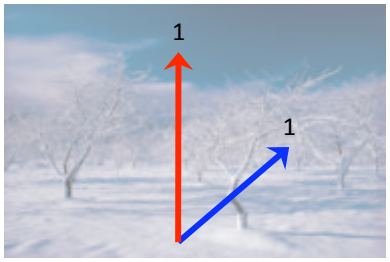
- PSF measured at 0° and ±4.5°
- Scattering and stray light, if present, will:
  - Cause the PSF to spread out
  - Cause spots/streaks in other areas of the image plane
- No scattering/stray light could be seen within the FPA noise limit
  - Signal to noise at the focal plane is approximately 10^4
-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



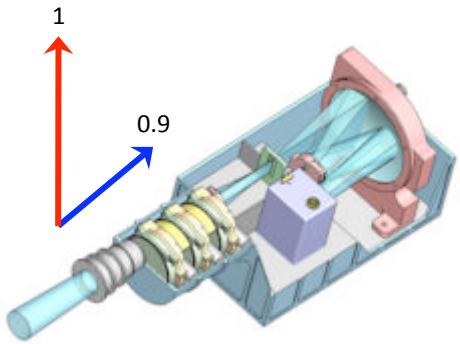


Polarization Can Affect Accurate Radiometry

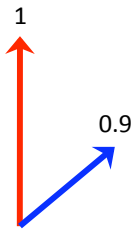
Scenes of unknown polarization cause errors in absolute radiometry



unpolarized scene light



10% instrument polarization sensitivity

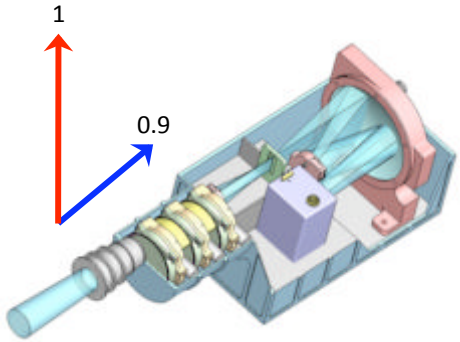


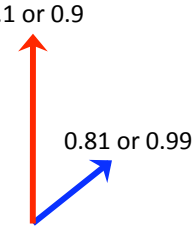
normalized intensity 1

×

=

10% polarized scene light

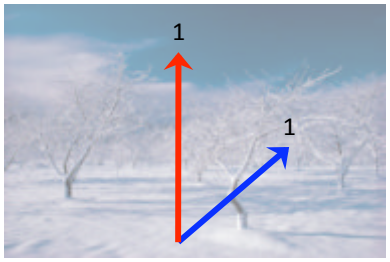




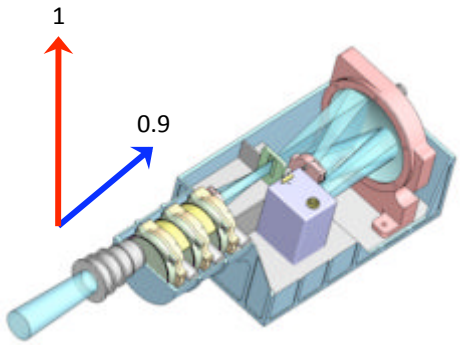
1% radiometric error

Eventual CLARREO Polarization Needs

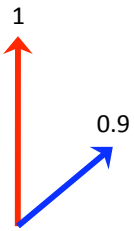
- Polarization effects must be <0.1% to meet radiometric accuracy
- Roughly, (scene polarization) × (instrument polarization) = (error), so want
  1. Low instrument polarization sensitivity, and/or
  2. Known scene polarization states



unpolarized scene light



10% instrument polarization sensitivity

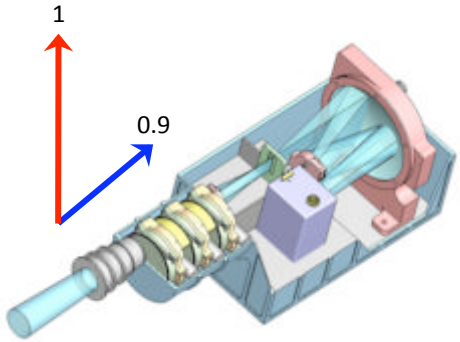


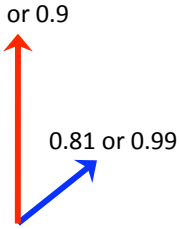
normalized intensity 1

×

=

10% polarized scene light





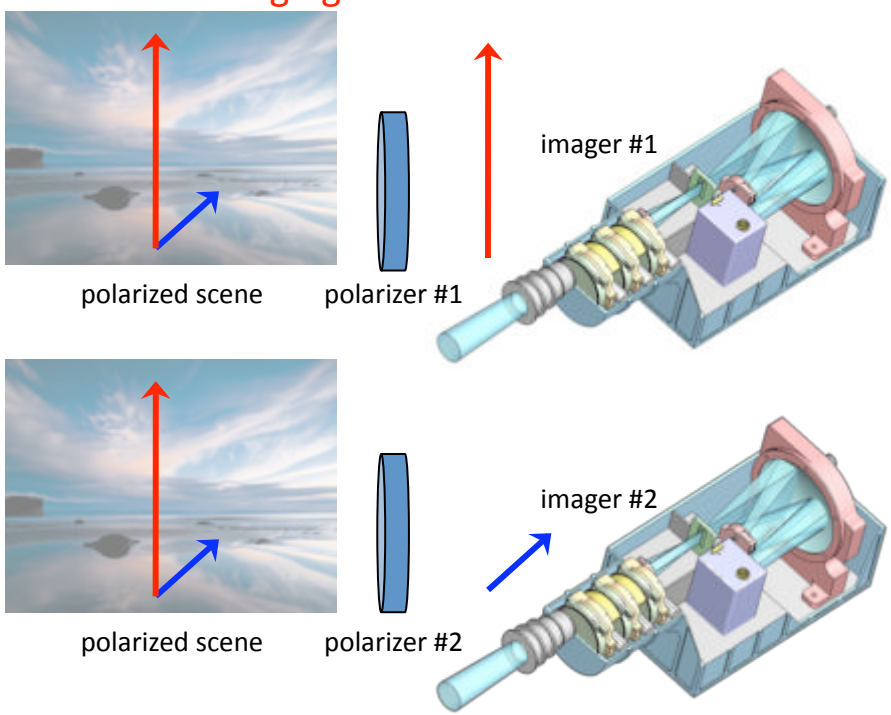
1% radiometric error

Polarization Must Be Accommodated By SW Radiometer

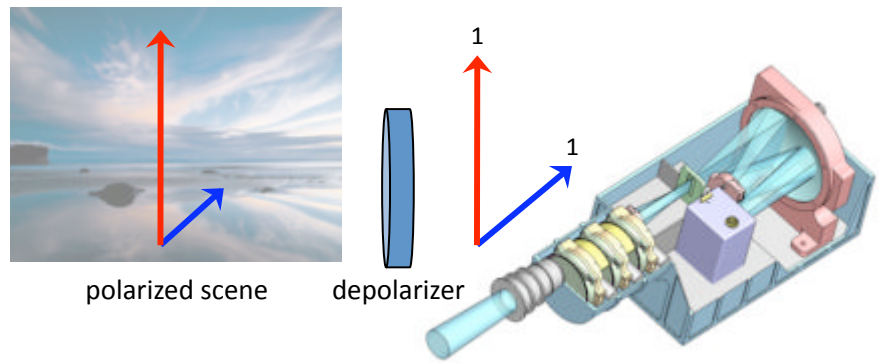
- Some polarization accommodation method will be needed on SW CLARREO flight instrument for accurate radiometry
  - Solar radiance is unpolarized to $<10^{-4}$
  - Earth scenes and reflected lunar radiances are partially polarized (~20%)
  - Instrument will have some small amount of polarization sensitivity (<1%)
  - Possible approaches:
    - Characterize scene polarization (i.e. instrument is a polarimeter)
    - Depolarize input light
    - Reduce instrument polarization sensitivity

Methods of Knowing Input Scene Polarization

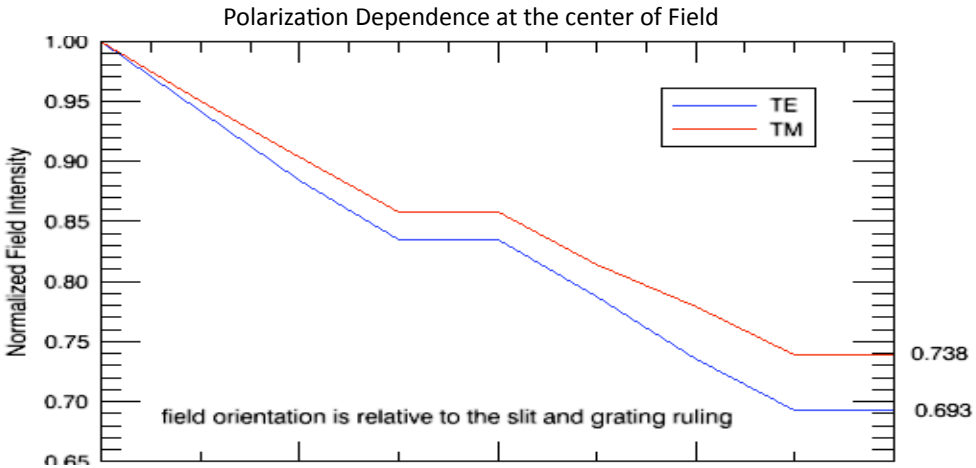
- Orthogonal polarizers
  - Define polarization state entering instrument
  - Offers additional science
  - Complex: Nearly requires two instruments for simultaneous scene imaging in both states

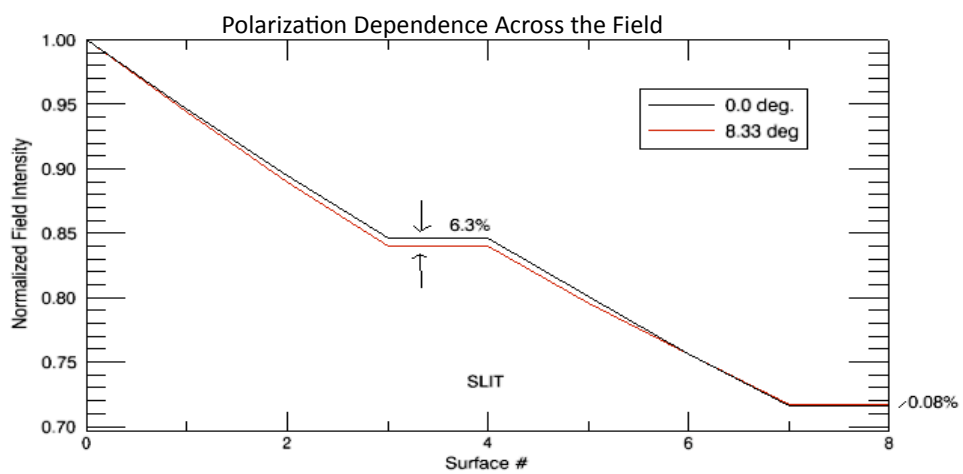


- Depolarizer
  - Greatly reduces sensitivity to scene polarization state
  - Simple: Single depolarizing optic



Instrument Polarization Sensitivity Is Modeled

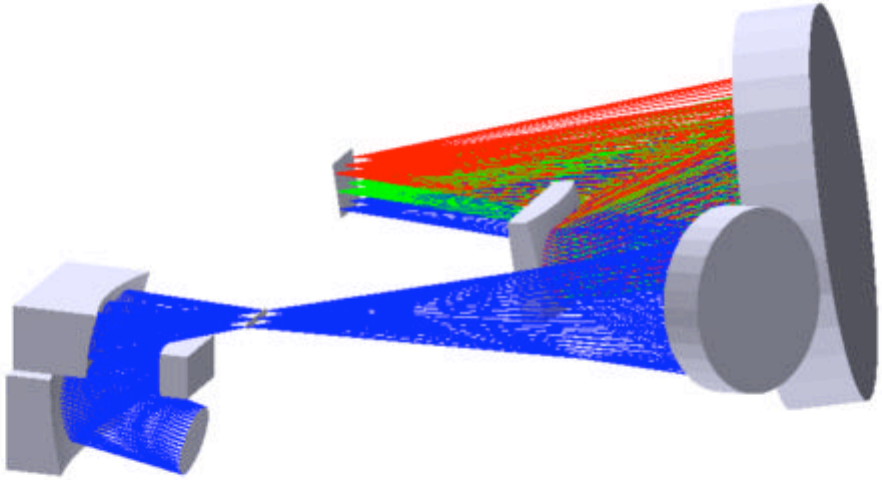




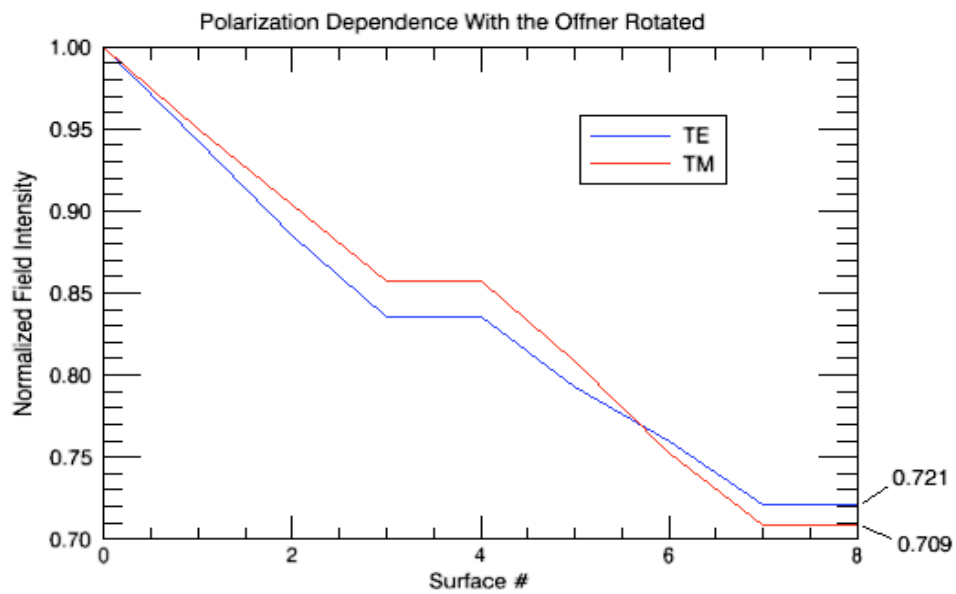
← TMA → ← Offner →

- 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 sources of polarization are 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**

Optical Design to Reduce Polarization Sensitivity



- **Proposed Solution**: rotate the Offner 90° with respect to the TMA
- This causes an equal number of TE and TM plane reflections for any input polarization



- Offner rotation results in a predicted **1.2% difference in sensitivity**
- The current configuration is overcorrected, but intent is to demonstrate that this is a viable means of reducing polarization sensitivity
- A birefringent depolarizer is alternative method to scramble/randomize the polarization of incident light

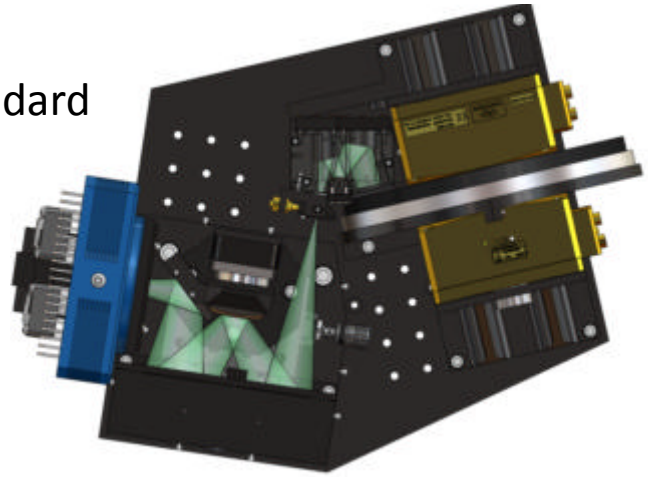
Polarization Studies

- ZEMAX model estimates instrument's polarization sensitivity
  - 90° orientation of telescope and spectrometer reduces sensitivity
  - Model indicates an optimized design could nearly eliminate sensitivity
- Validate model with incoming polarized beam at discrete wavelengths
  - Test in both planar and orthogonal configurations
  - Ball polarization generator or polarizing input sources at LASP are options
- Depolarizers remain an option

Validated model provides confidence in optimizing future flight design to nearly eliminate polarization sensitivity

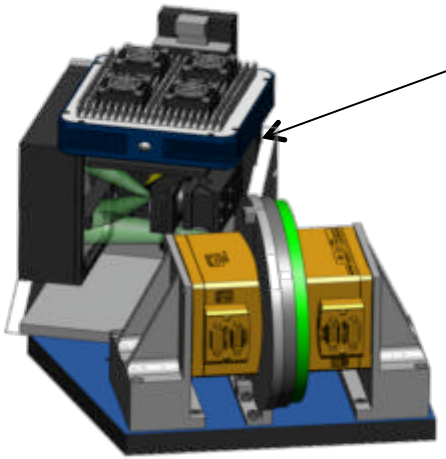
Mechanical Design: Polarization Sensitivity Reduction Configuration

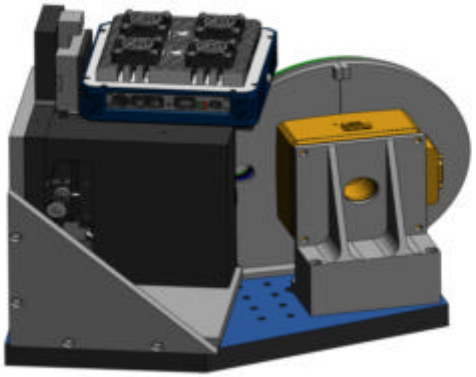
Standard



Standard assembly can be mechanically reconfigured with a 90° rotation of spectrometer to reduce polarization sensitivity

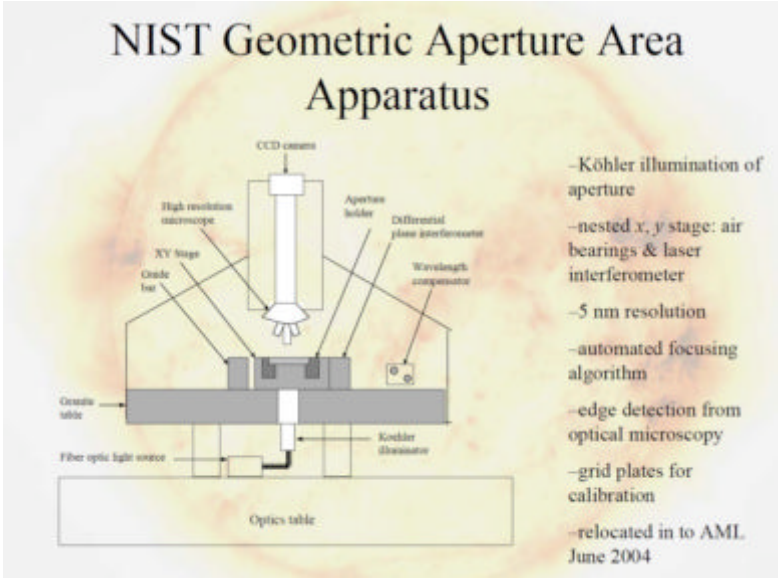
Rotated Spectrometer

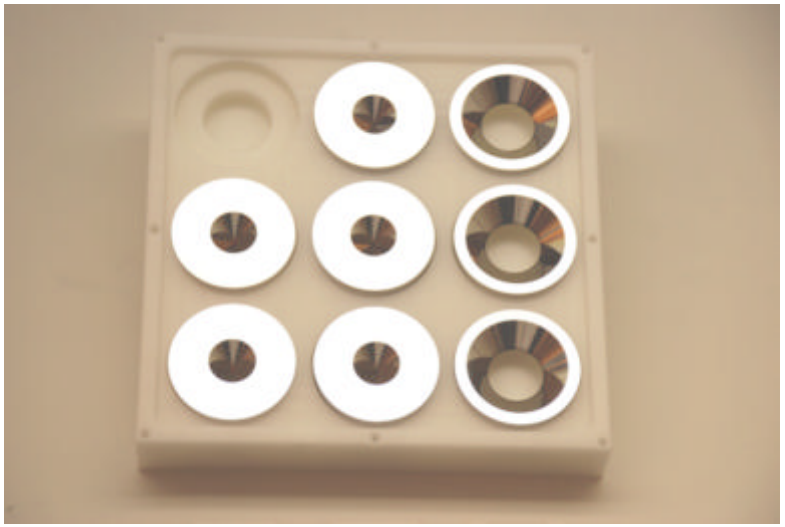




Apertures

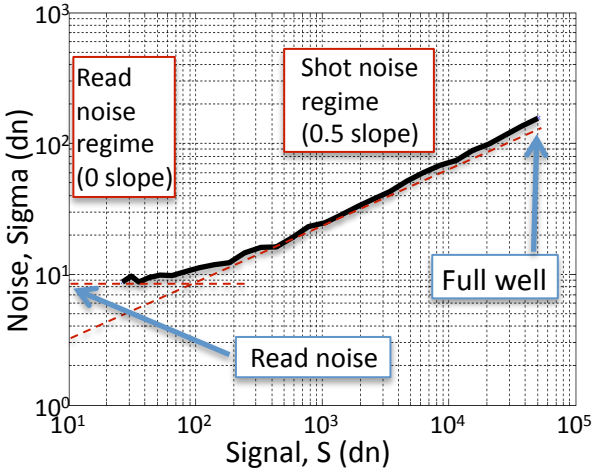
- Apertures measured at NIST May 2010
  - Apertures returned 26 May 2010
  - Awaiting official measurements
- 8 Apertures
  - (3) 20.0 mm dia Al/Ni
  - (3) 0.5 mm dia. Al/Ni
  - (2) 0.5 mm dia. Al/UBAC
- Area calibrated by NIST at the Optical Technology Division. *Anticipated measurement uncertainties (k=1)*:
  - 20 mm aperture = 0.0025%
  - 0.5 mm aperture = 0.04%





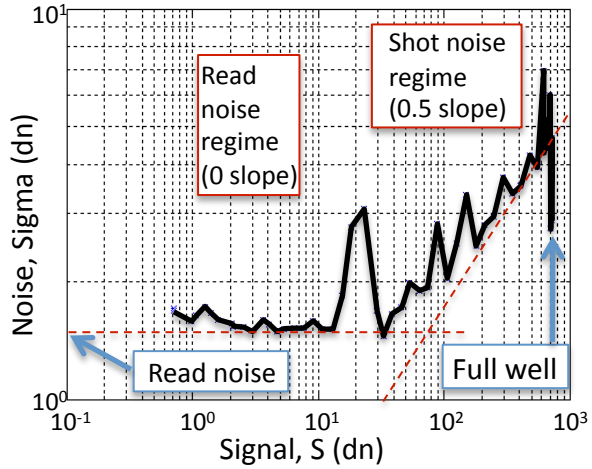
Photon Transfer Curves Characterize FPAs

Apogee CCD



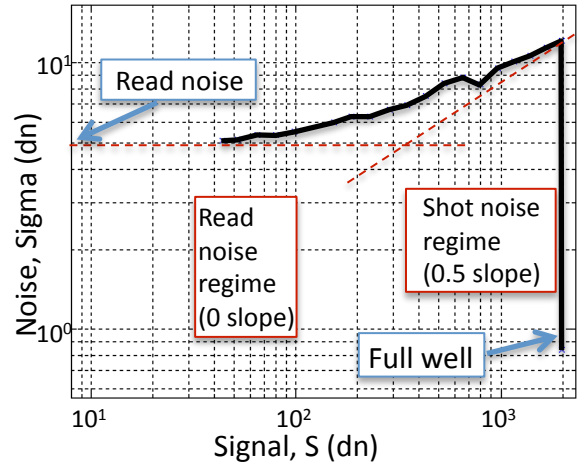
- Read noise: 8.95 dn (17 e-)
- Full well: 125 ke-
- Gain: 1.95 e-/dn
  - Measured from single image gain histogram
  - Also can be estimated from shot noise asymptote zero crossing
  - Since curve is well behaved, this estimation is probably within 5%

PCO CMOS



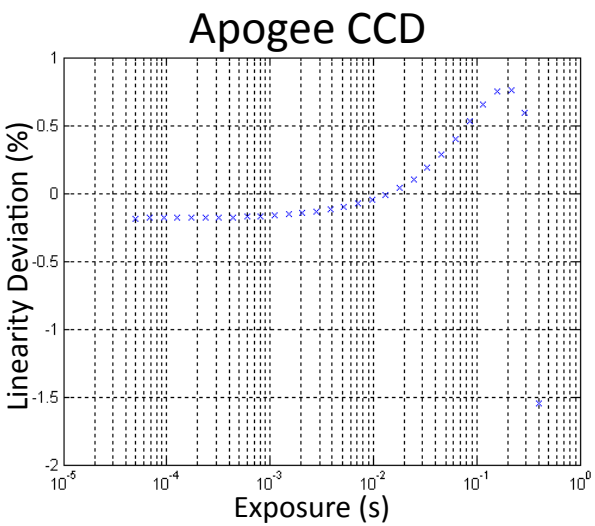
- Sensor exhibits unexpected noise, making photon transfer curve ill-behaved
- Read noise: 1.49 dn (83 e-)
  - Probably accurate in flat region of curve
  - Gain from Fe^{55} experiment used for electron conversion
- Full well: 40 ke-
  - Difficult to measure in noisy portion of curve
- Gain: 29 e-/dn
  - Likely to be estimated low due to increased sensor noise.
  - Measurement technique assumes that the sensor is shot noise limited, which is not the case

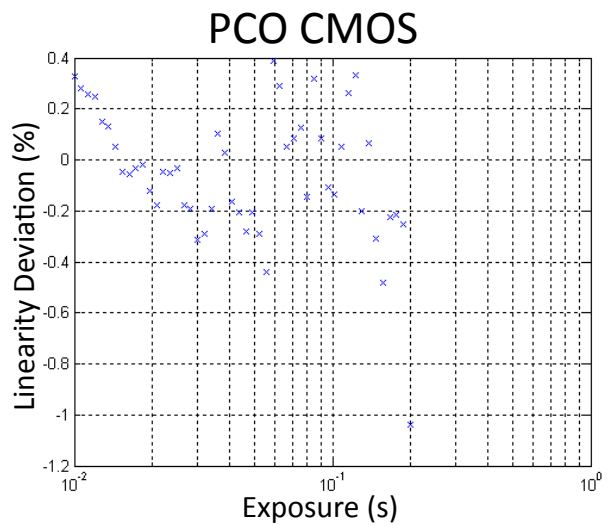
Photon Focus CMOS

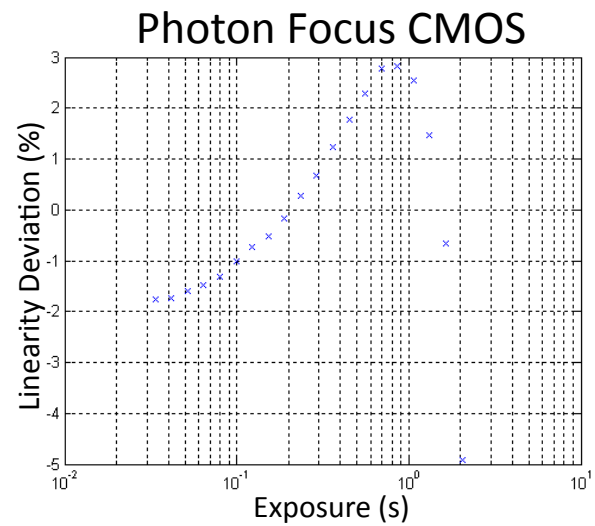


- Read noise: 5 dn (98 e-)
  - Gain from Fe^{55} experiment used for electron conversion
- Full well: 39 ke-
- Gain: 15 e-/dn
  - Measured from single image gain histogram
  - Likely to be estimated low since curve never reaches shot noise regime

FPA Linearity Is Characterized







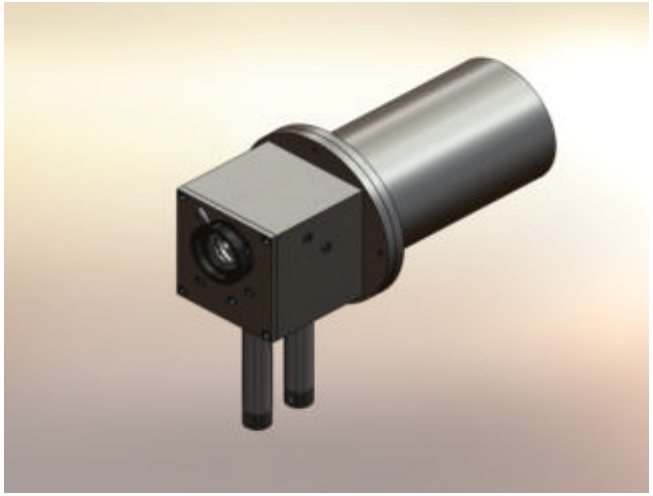
- Nonlinearity: ±1.5% (across 82% of full range, attenuation 3.9 Log scale)
  - Linearity deviation can be compensated down to 0.17% (standard deviation) due to smoothness of curve
- Nonlinearity: 0.26% (standard deviation) (across 55% of full range, attenuation 1.1 Log scale)
  - Leakage light is un-measureable using the current setup, but supposed to be < 0.1% of signal according to data sheet
  - Noise in data implies that electronic shutter attenuation measurement cannot be more accurate than 0.26%.
- Nonlinearity: ±2.5% (across 40% of full range, attenuation 1.8 Log scale)
  - **Linearity deviation can be compensated down to 0.04% (standard deviation) due to smoothness of curve**

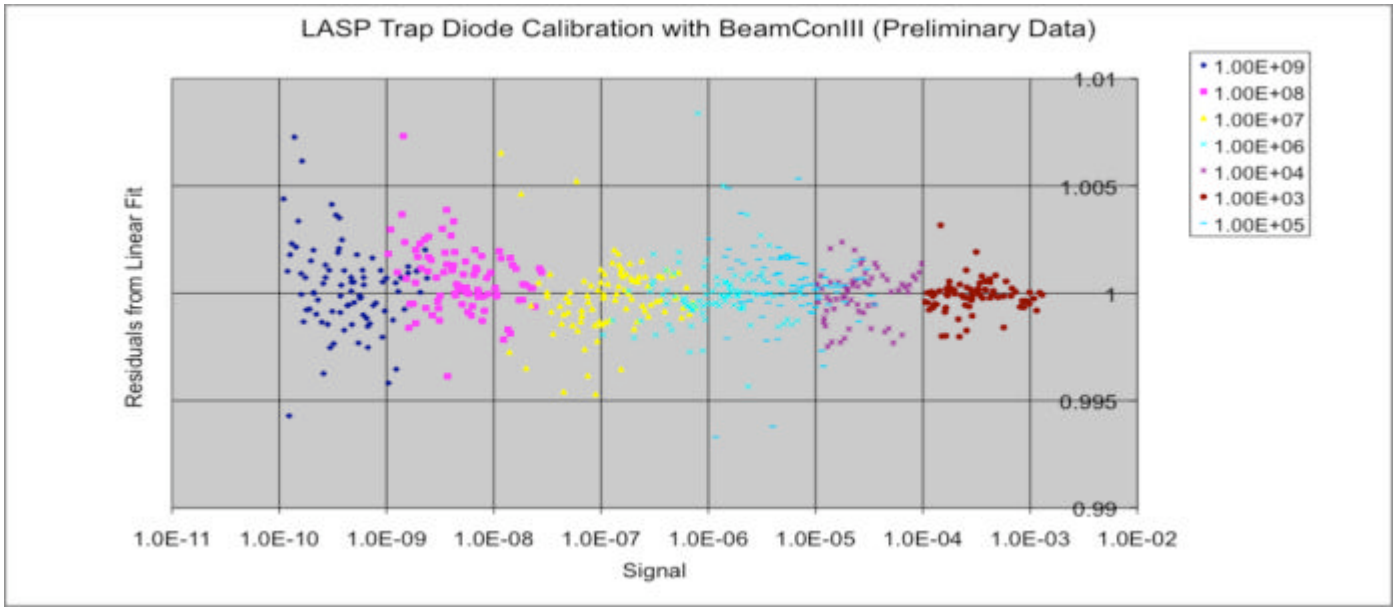
Attenuation Validation Method

1. Illuminate hyperspectral imager with uniform Earth-like (i.e. low power) radiance level in Test Facility
   - Monitor light intensity with NIST-calibrated trap detector
2. Apply attenuation method
3. Increase light intensity until hyperspectral imager reads original signal level
4. Change in signal from calibrated, large dynamic range trap detector indicates actual attenuation magnitude applied
   - Hamamatsu trap photodiode detector and paired transimpedance amplifier calibrated at NIST for linearity across 10^7 range
5. Repeat Steps 2 through 4 for each of the three attenuation methods, demonstrating $10^{-4.7}$ net attenuation

Silicon Trap Detector Has Been Calibrated at NIST

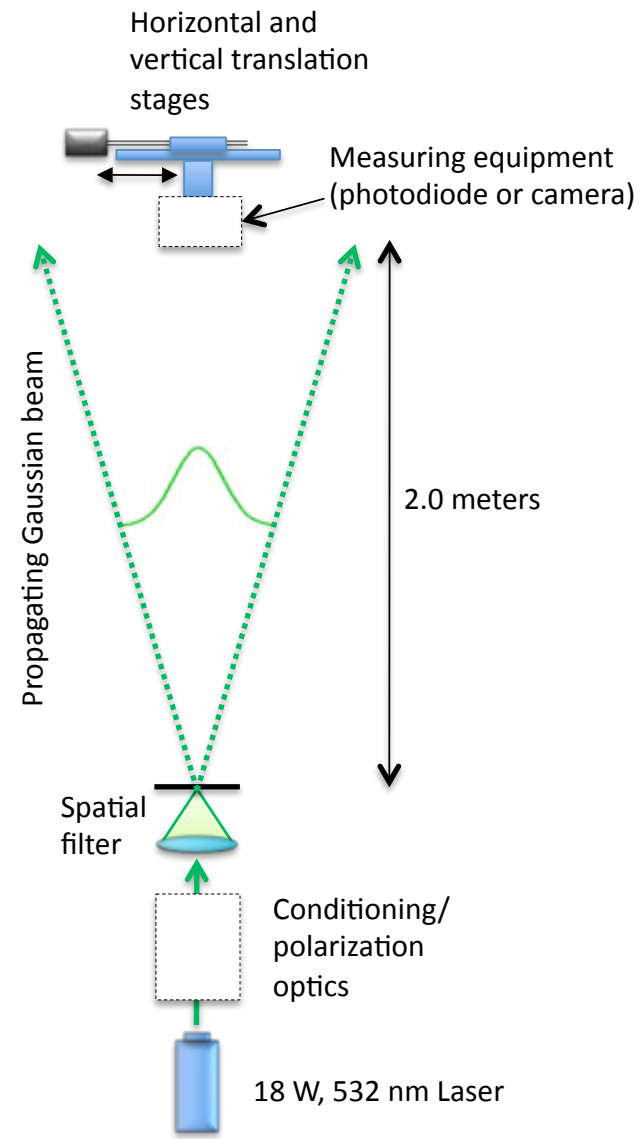
- Calibrated at NIST with Beamcon III beam conjoiner March 2010
- Preliminary data shows **linearity to 0.044% across 7 orders of magnitude of optical power**
- Awaiting final report from NIST



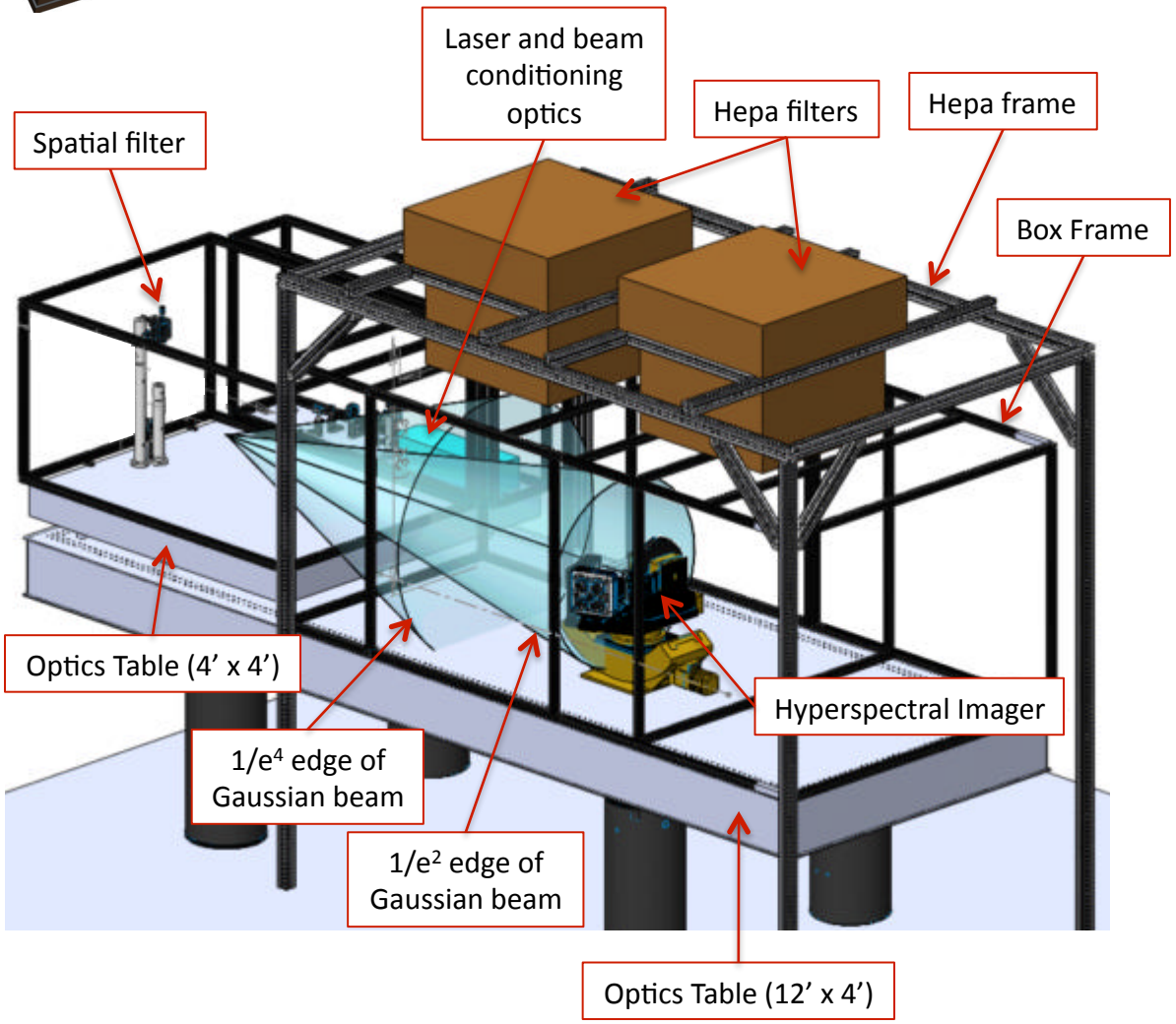


Test Facility Overview

- 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
- Field should have an irradiance difference of less than 1000 ppm between the 2 cm and 500 µm apertures
  - If the field is well characterized, non-uniformities can be compensated
- A propagating Gaussian beam generated by a spatial filter is the chosen method to generate a uniform field
- Facility contains an 18-W 532-nm laser along with an isolator, intensity stabilizer, power monitor, conditioning optics, and polarization optics (to control beam size, position and intensity)



Simplified Test Facility Setup



- Gaussian beam propagation provides uniform beam
- Entire setup inside light-sealed box
- Laser and conditioning optics in separate box from hyperspectral imager and Gaussian beam
- Two Hepa filters reduce dust
  - Placed on stand-alone frame to isolate vibration
- Secondary optics table placed on top of primary table to increase beam stability

Uncertainties Guide Attenuation Selections

Hyperspectral Imager Requirements

Parameter	Value	Units
Spatial Resolution	0.5	km
Spatial Range (cross-track)	200	km
Wavelength (min)	300	nm
Wavelength (max)	2400	nm
Spectral Resolution	10	nm
Relative Std Uncertainty	0.2	%

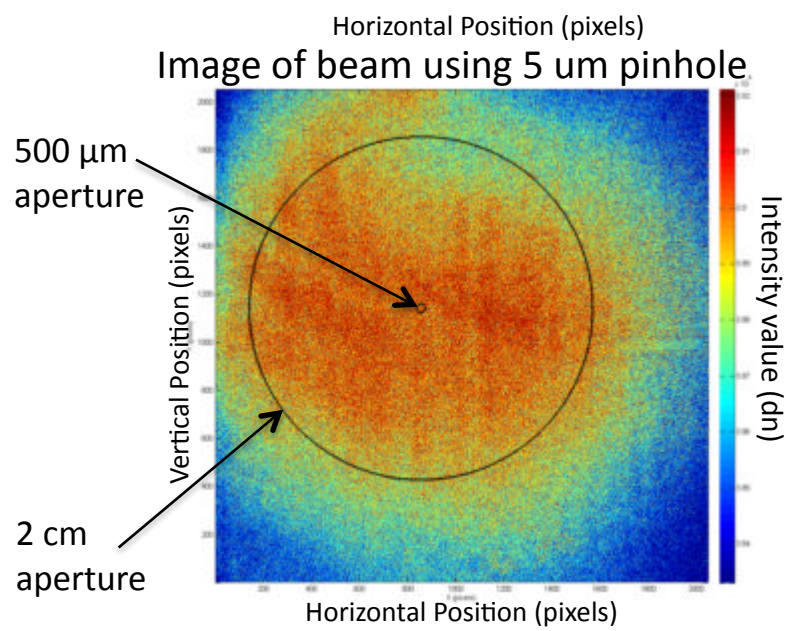
- IIP attenuation analyses include broad spectral range
- IIP imager limited to 300-1050 nm

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%**

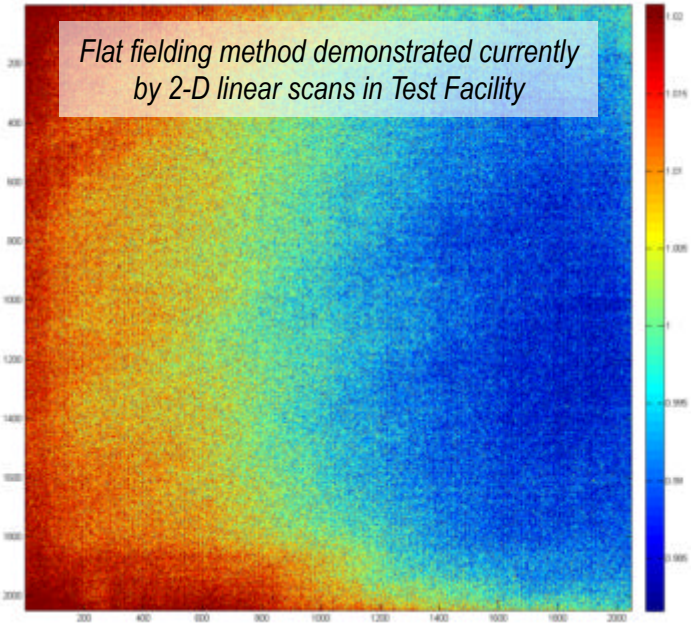
Beam Uniformity Measured to Needed Levels

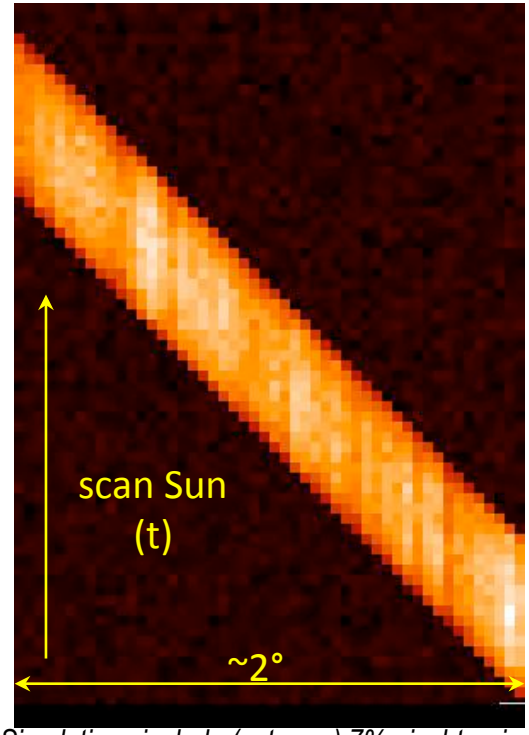
- Current non-uniformity is 1500-1800 ppm
  - Measured as an irradiance difference between a 500 µm aperture and a 2 cm aperture placed in the center of the beam
  - ±1 mm positioning tolerance causes ~300 ppm change in non-uniformity figure
- Uniformity of the beam is sufficient for required measurements
  - 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



Demonstrate Methods of On-Orbit Flat Fielding

- **On-orbit:** Scans of Sun along slit provide spatial/spectral flat field and scatter measurements
- **Ground Demonstration:** Simulate with goniometers
  - Test Facility provides stable light source with low spatial background similar to the on-orbit Sun
  - Real sunlight provides realistic spatial/spectral input but is limited by atmospheric stability and scatter
- **Current Status:** Method has been demonstrated by 2-D linear scans of FPAs in Test Facility beam





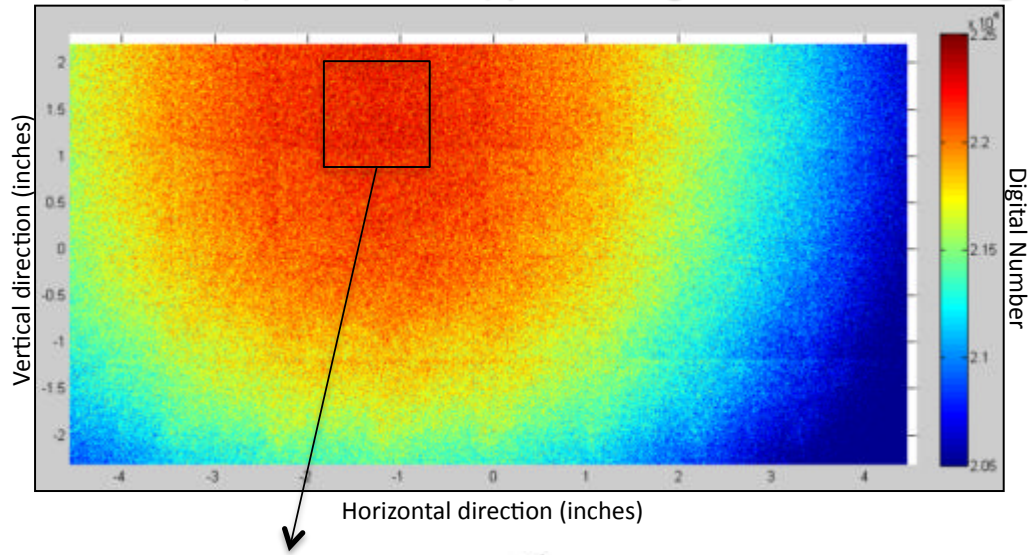
Simulations include (extreme) 7% pixel-to-pixel variations, 3% read noise, 1% solar variations

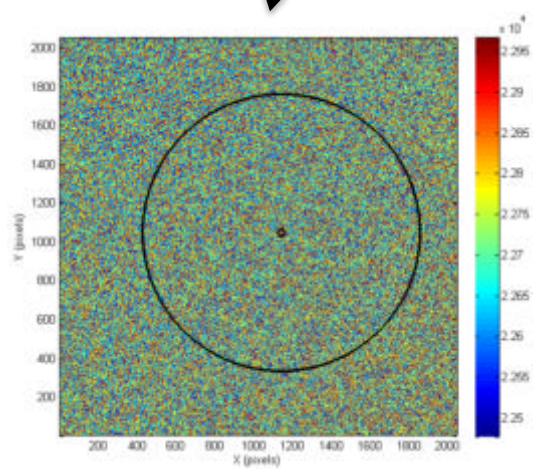
Goniometers provide 2-axis pointing of imager to simulate on-orbit solar scan method

Apogee CCD Flat Field

- **Full field variation** (standard deviation / mean) is 1.8%
- **Instability** (measured over 87 hours) is 0.019% (standard deviation)
- Average variation across 20x20 pixel area is 0.44% (standard deviation/mean)
- Flat field corrected image taken from uniform beam has less than 300 ppm irradiance difference between apertures across sensor
  - 5-95% non-uniformity is 1.6%
  - Standard Deviation/Mean is 0.48%
- With this flat field correction, the sensor has the ability to measure down to **300 ppm difference in the irradiance of a 2 cm aperture versus a 500 µm aperture**

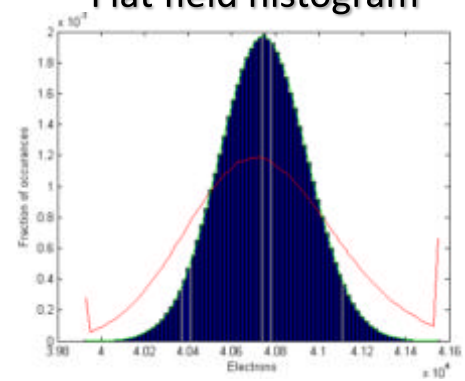
Full LED field (9 inches wide) pieced together from 32 images





Center circle – 500 µm aperture
Large circle – 2 cm aperture

Flat field histogram



Red outline – Un-corrected histogram
Blue – Flat field corrected histogram
Green outline – Theoretical shot-noise limited histogram.

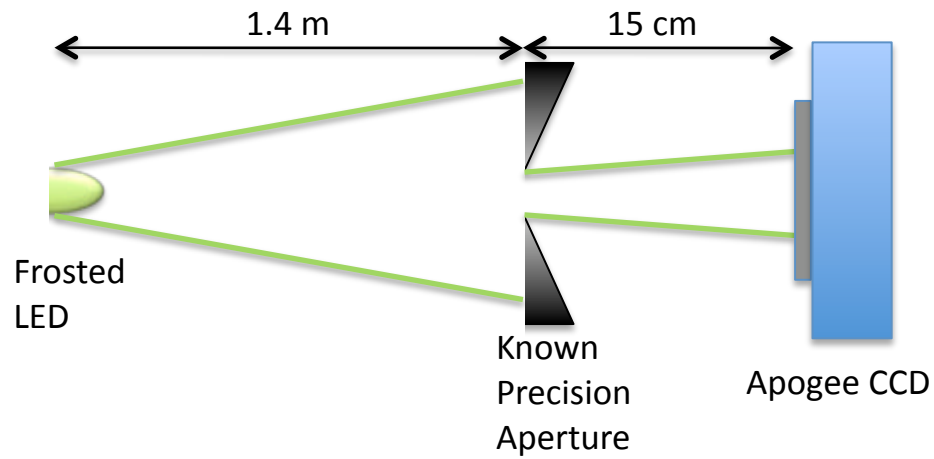
Preliminary Aperture Attenuation Measurements

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

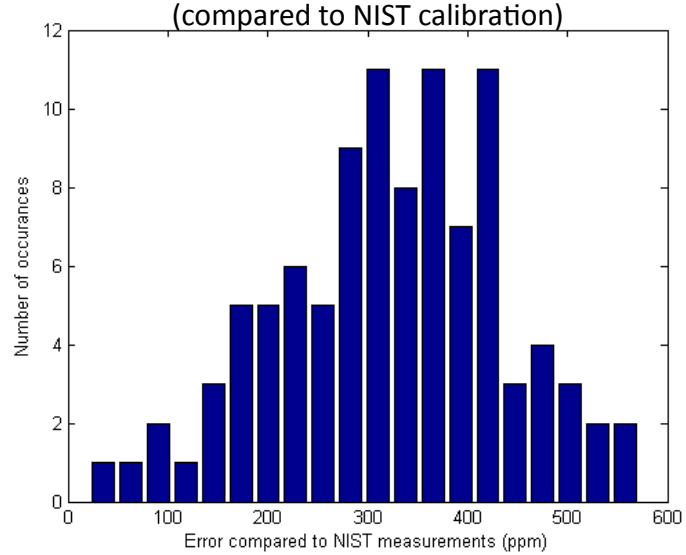
$$\frac{Power_1}{Power_2} = \frac{Area_1}{Area_2}$$

- 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)



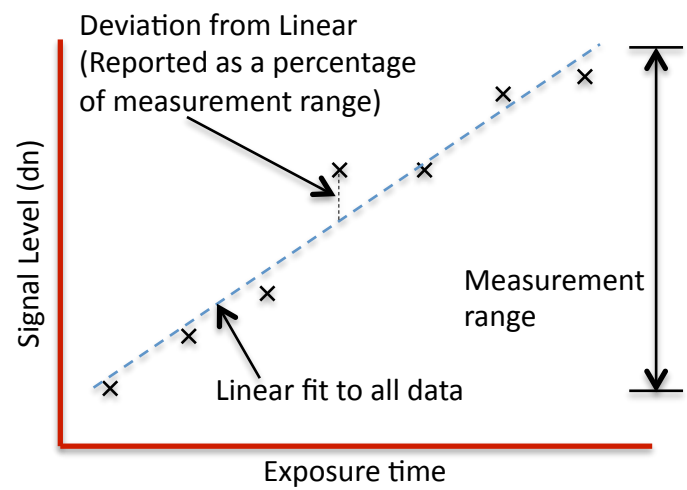
Integration Time Attenuation Measurements

- Goal: Prove that the attenuation ratio between two CMOS camera images is linearly proportional to their exposure ratio

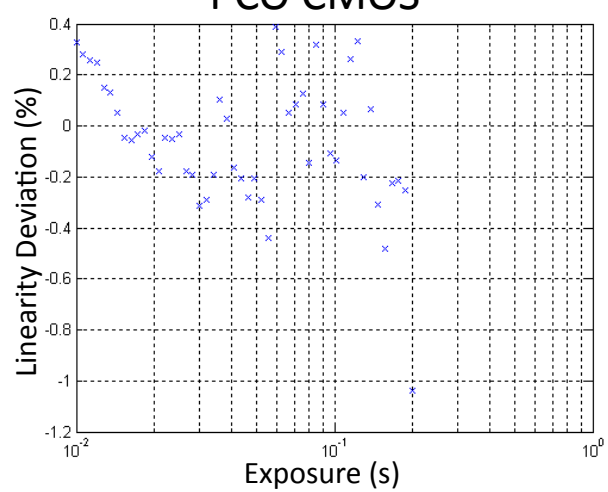
$$\frac{Power_1}{Power_2} = \frac{ExposureTime_1}{ExposureTime_2}$$

- PCO Linearity: 0.26% (standard deviation)
  - Measurement over 55% of sensor full range (represents 1.3 orders of magnitude attenuation)
- Photon Focus Linearity: ±2.5%
  - Measurement over 40% of sensor full range (represents 1.6 orders of magnitude attenuation)
  - **Can be compensated to 0.04% (standard deviation)**
  - **With compensation, this sensor is accurate enough for integration time attenuation studies**

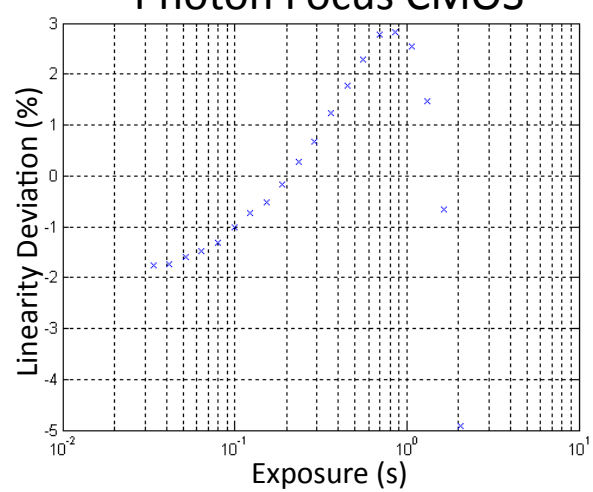
Example Plot



PCO CMOS



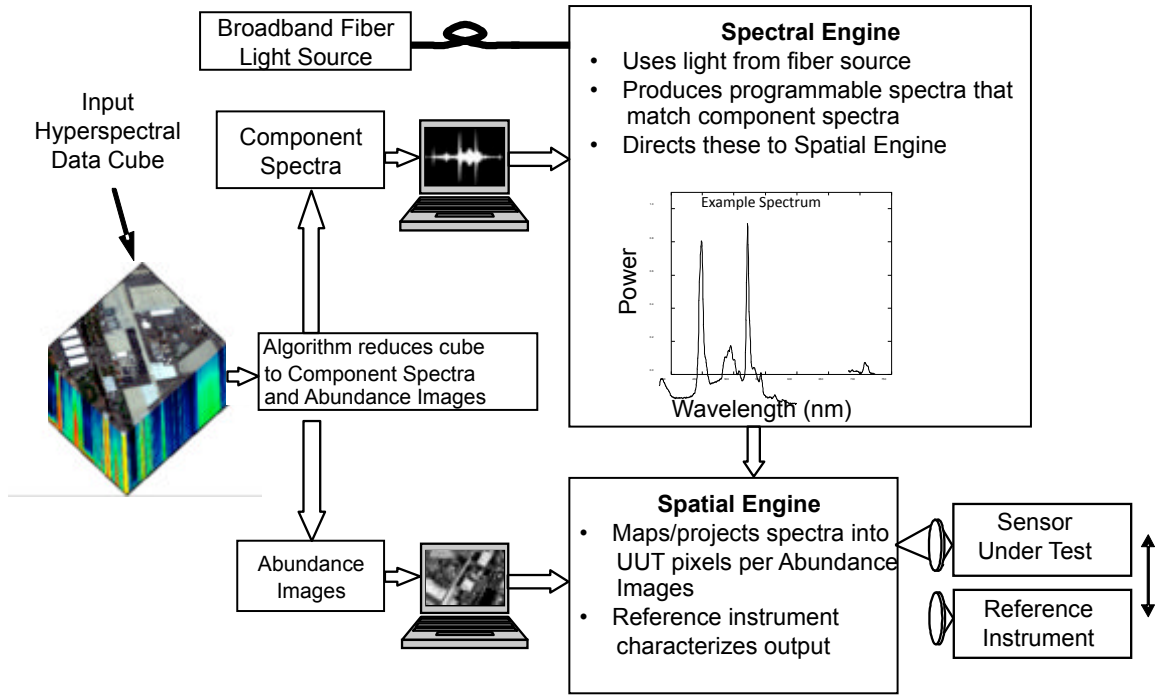
Photon Focus CMOS



Testing Planned at NIST's HIP

The HIP (Hyperspectral Image Projector) is a scene projector

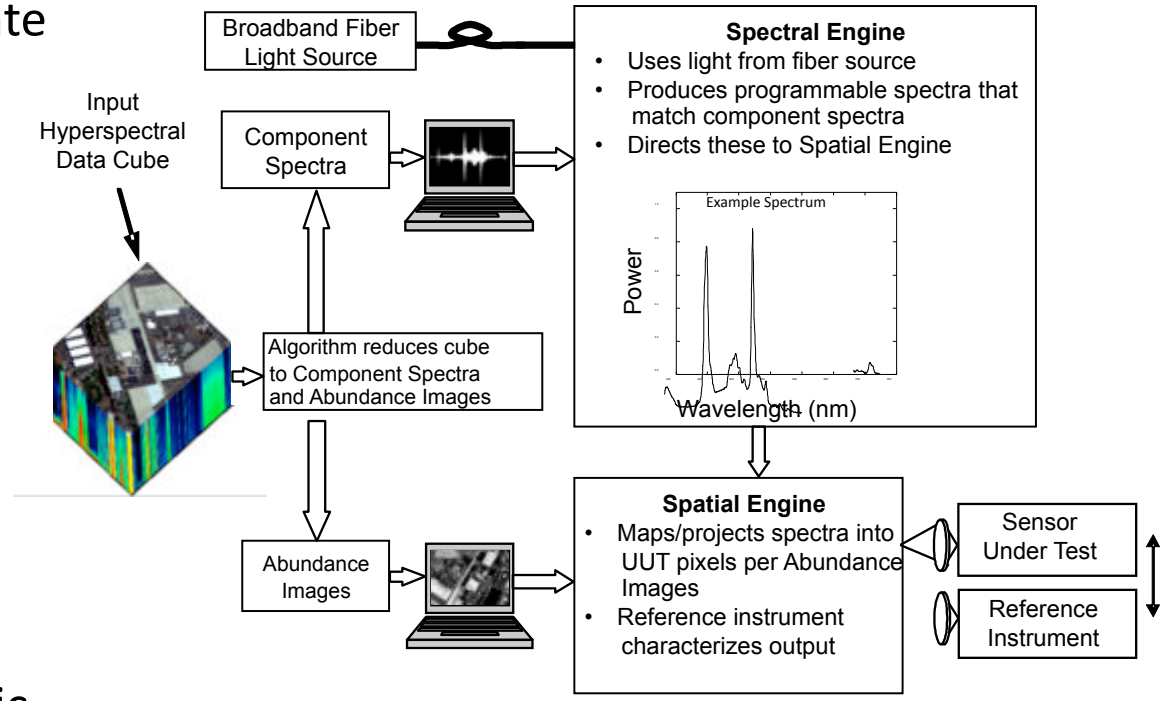
- Provides 2-dimensional image into a sensor under test
- Each pixel has an arbitrarily programmable spectrum
- Spectral radiance be measured with a calibrated spectroradiometer
- Can project dynamic real-time hyperspectral scenes



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

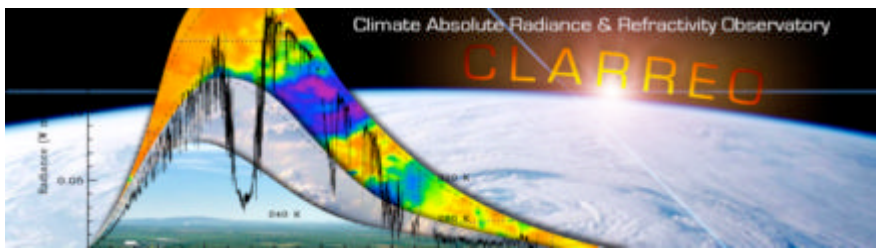
Test Concepts to Be Explored Using NIST's HIP

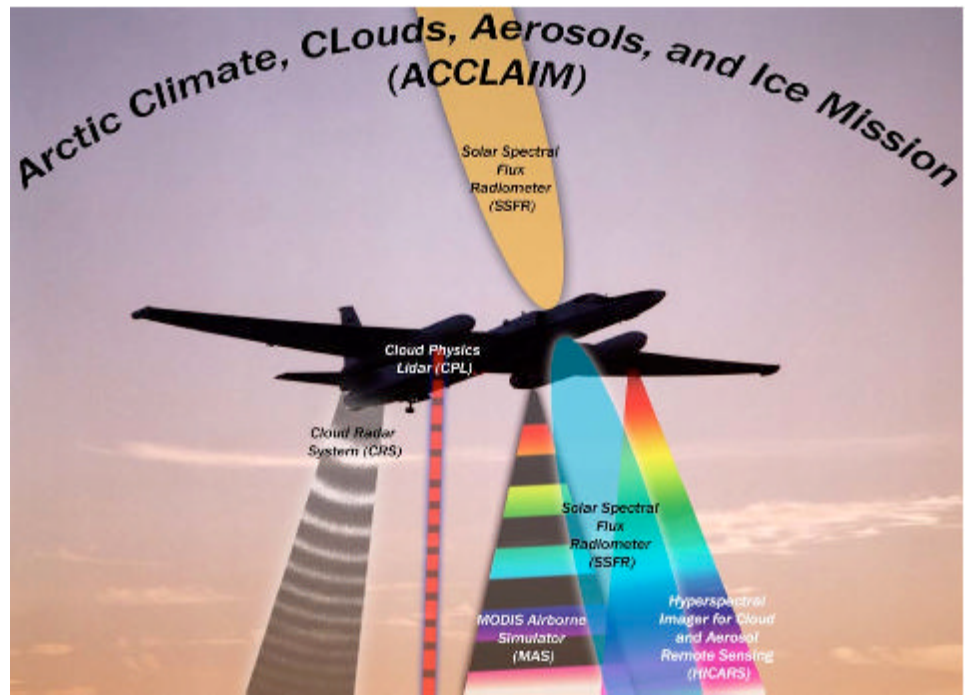
- Scanned line image to simulate track motion
- 2D flood images with various spectra
  - Earth-view scenes
  - Lunar scenes
  - Solar scene?
- Bright cloud next to darker ocean to test stray light
- Digital attenuation validates linearity over limited dynamic range
- Radiometric calibration (at ~2% level)



Potential Instrument Opportunities

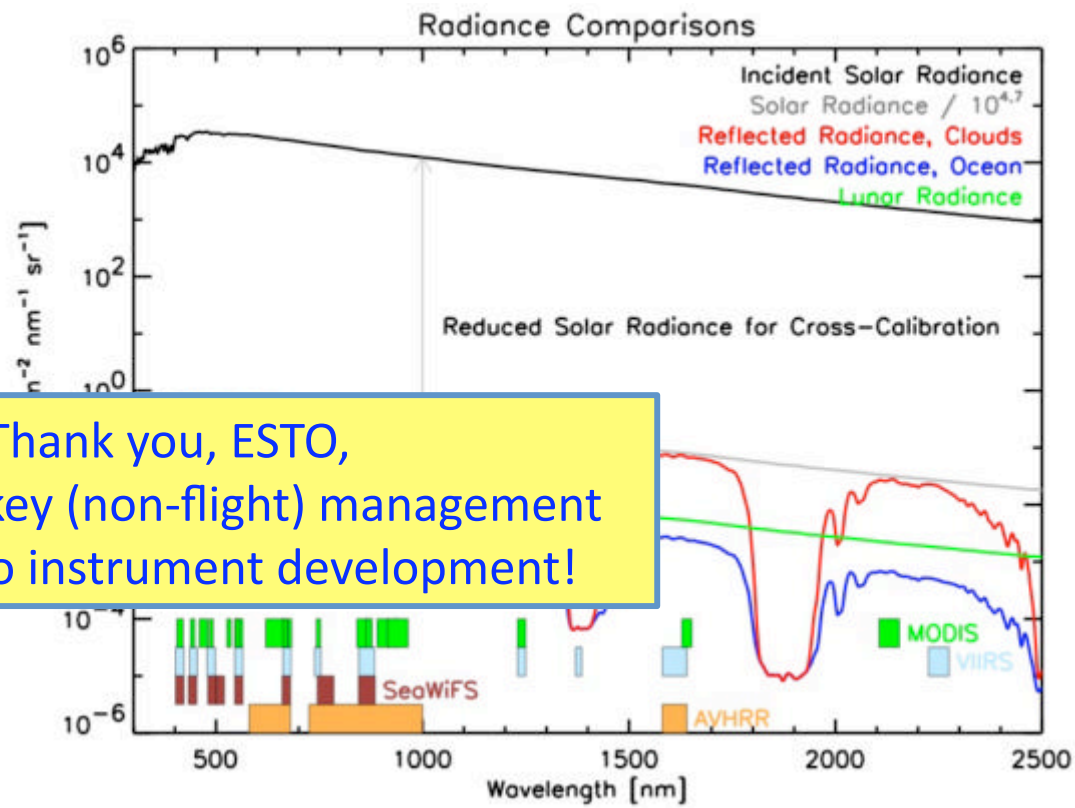
- CLARREO Reflected Shortwave Spectrometer
  - Enables improved radiometric accuracy on-orbit
- Suborbital programs for atmospheric studies, remote sensing of land use, local urbanization, ice sheet studies
  - EO-1 Venture Class (ACCLAIM)



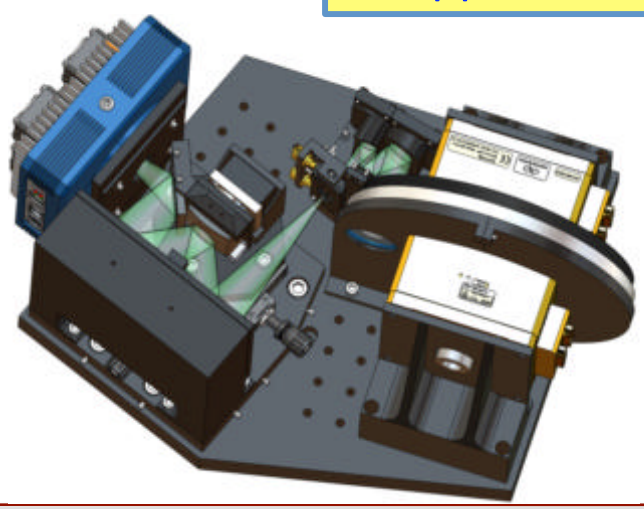


Summary

- Sun provides stable on-orbit source across SW spectral range
  - Solar reflectances benchmark climate
  - CLARREO/TSIS provides SI traceability
- Attenuate solar irradiances via
  - Apertures
  - Integration times
  - Filters



Thank you, ESTO,
for the low-key (non-flight) management approach to instrument development!



Test Facility and hyperspectral imager are ready to begin attenuation testing to validate solar cross-calibration concept