A Solar Irradiance Cross-Calibration Method Enabling Climate Studies Requiring 0.2% Radiometric Accuracies

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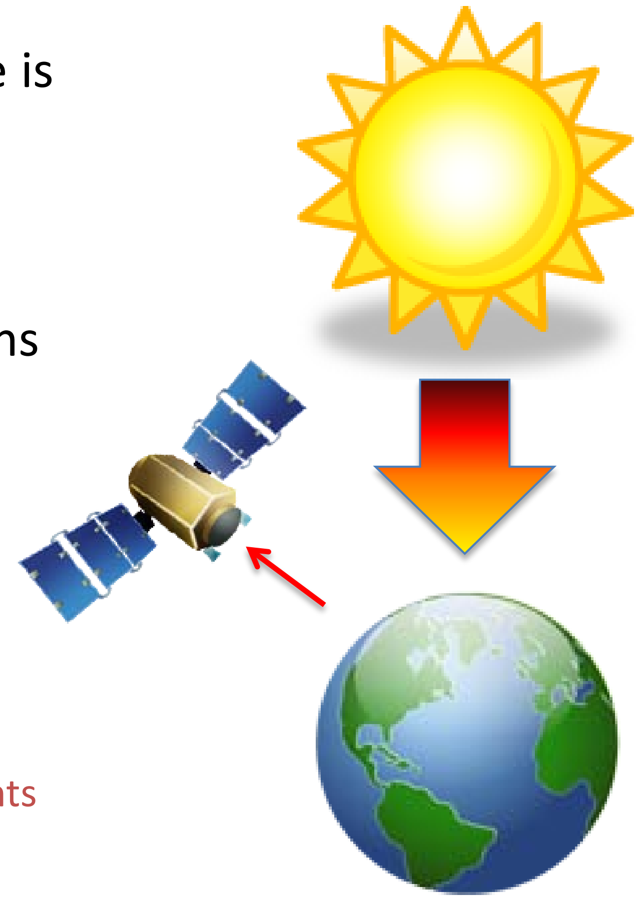
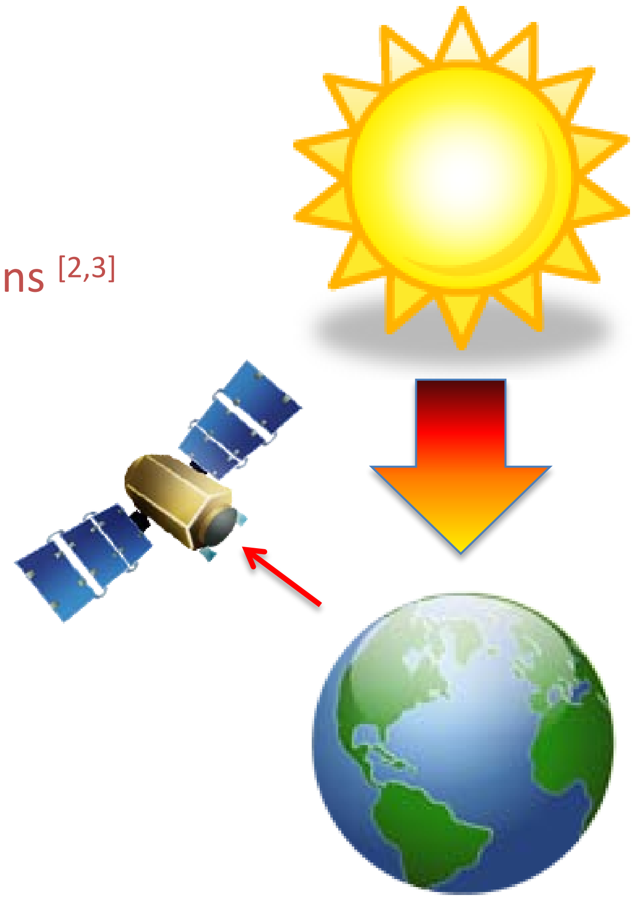
CLARREO Requirements

- A key point to understanding Earth's climate is the energy balance between the Earth and Sun
- 2007 NRC Decadal Survey[1] and the Committee on Earth Science and Applications from Space states:
  - The required accuracy of radiative measurements of the Earth is 0.2%.
  - The central objective is to create an accurate, long term measurement
  - SI traceable benchmark
    - Can cross-calibrate with other on-orbit instruments to increase accuracy of climate record
    - Data will be used to develop operational forecast models
    - Provide a framework for future policy decisions



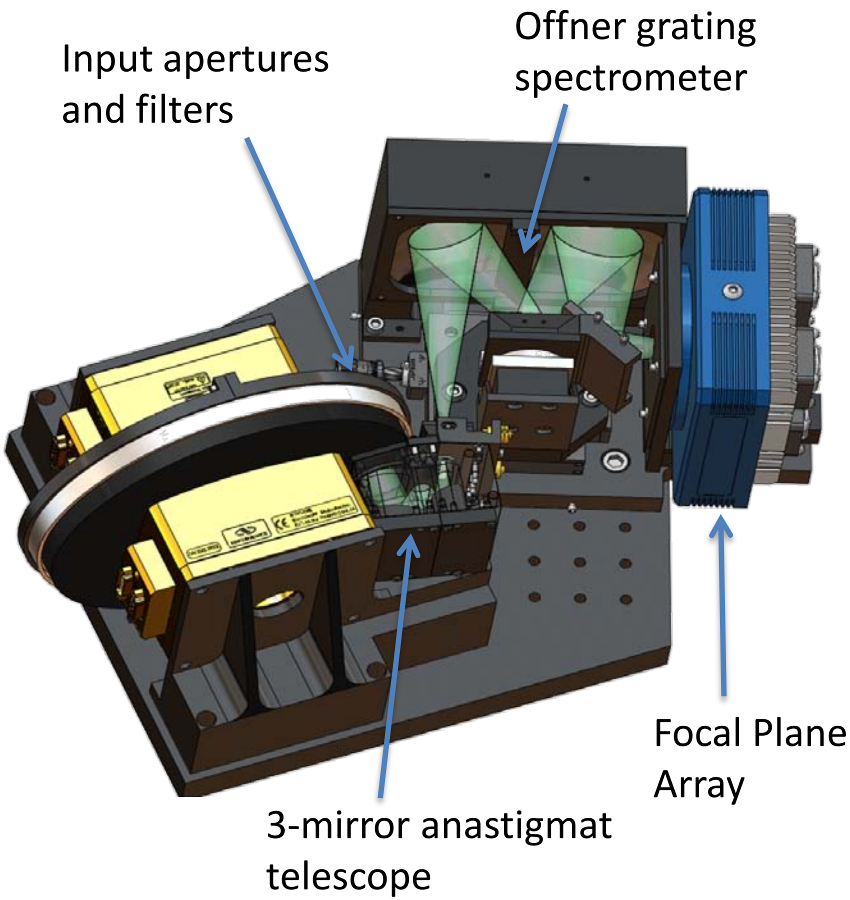
Current Satellite Limitations

- Today's measurement accuracy is approximately 2%
  - Satellite limitations consist of:
    - Traditional methods of pre-launch calibrations [2,3]
    - On-board calibration systems [4,5]
    - Vicarious calibrations [6-8]



The Proposed Hyperspectral Imager

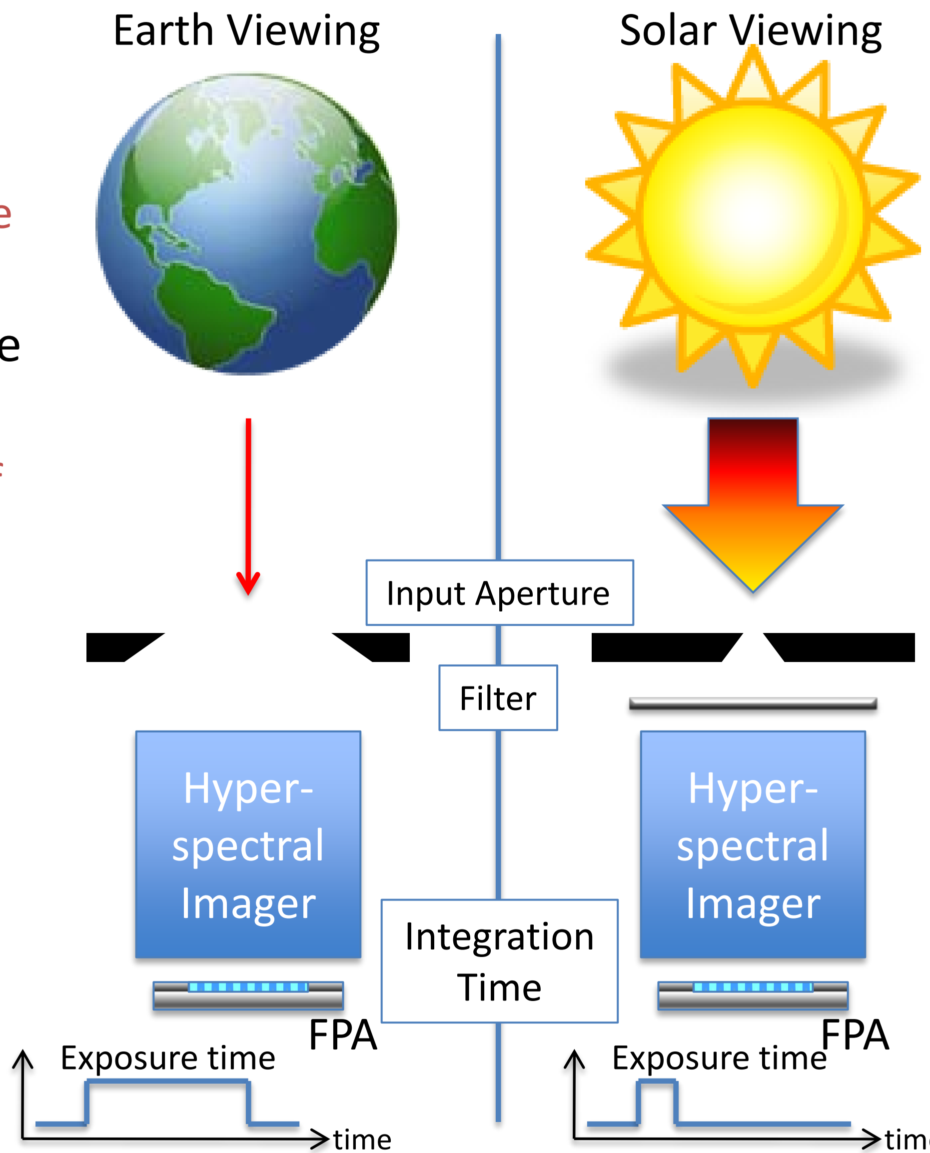
- We have the ability to observe the Sun to approximately 0.1% accuracy [9,10]
- The proposed CLARREO hyperspectral imager transfers the solar ~0.1% accuracy to an Earth-viewing instrument [11]
  - Instrument will operate in the 350-2300 nm region
  - Cross-calibration is accomplished through direct solar viewing
  - Requires nearly 5 orders of magnitude attenuation



Prototype Hyperspectral Imager

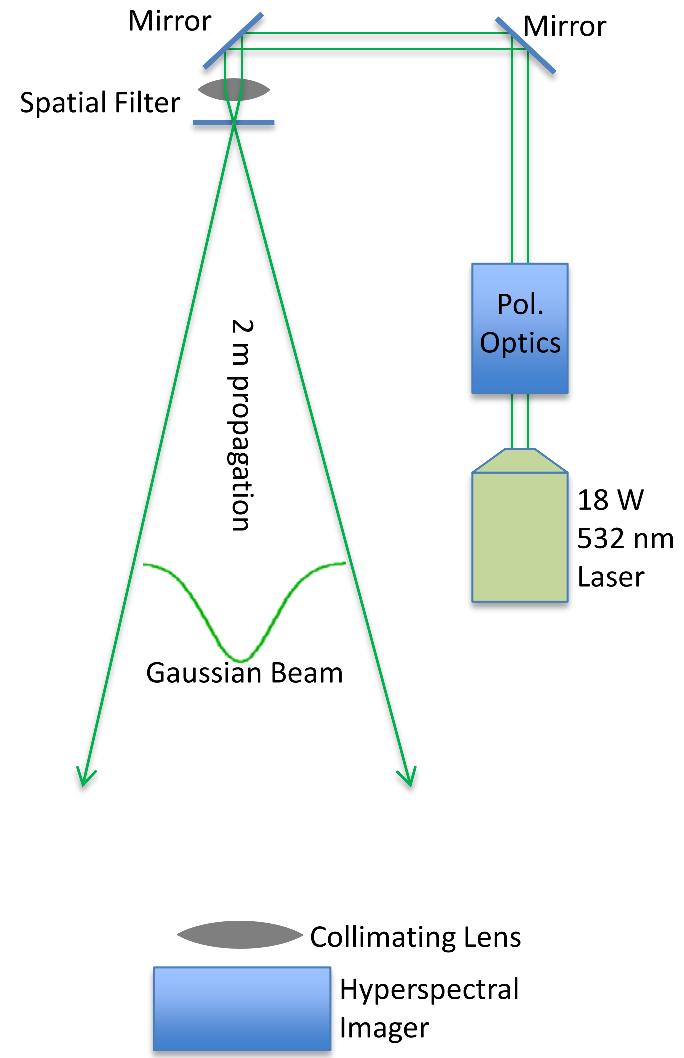
The Attenuation Methods

- Reduction of input aperture area (aperture attenuation)
  - Can achieve over 3 orders of magnitude of attenuation
- Reduction of detector integration time (integration time attenuation)
  - Can achieve 1.9 orders of magnitude of attenuation
- Inserting attenuation filters into light path
  - Can achieve 1 order of magnitude of attenuation
- All attenuation methods are relative measurements. No direct measurement of the Solar or Earth irradiance will be made.



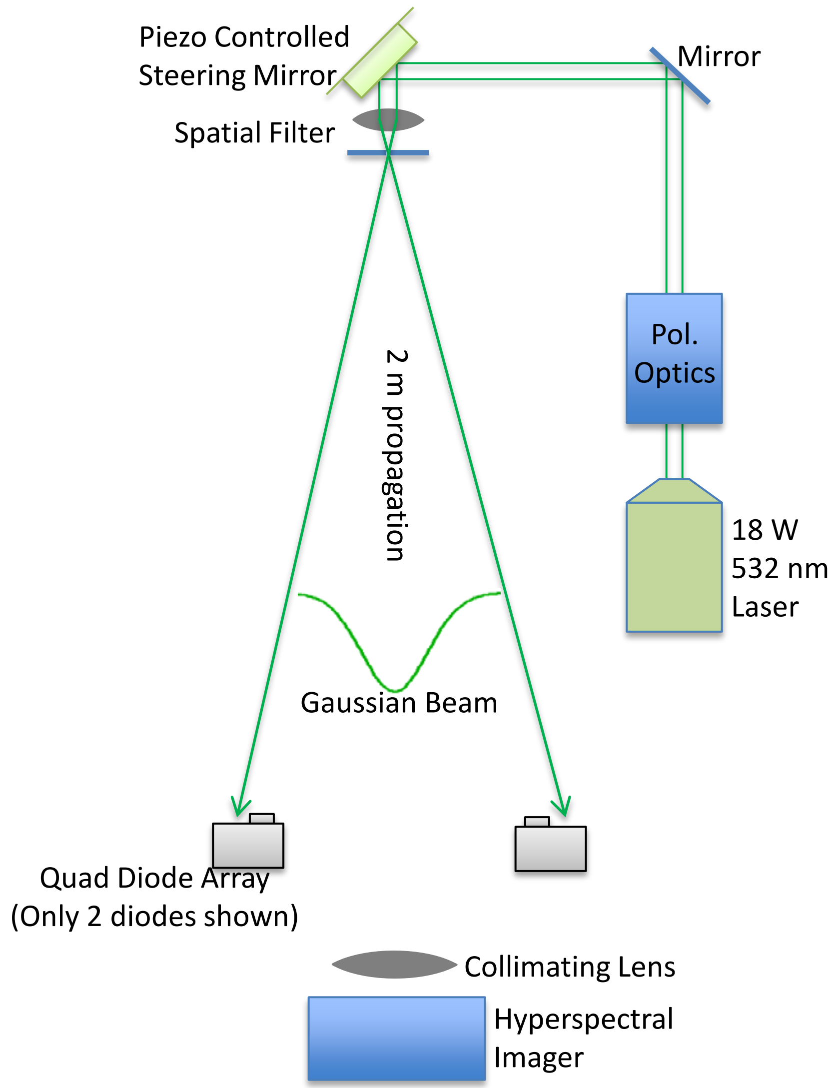
Experimental Setup

- 18 Watt, 532 nm laser is used to generate very uniform Gaussian field
  - Beam propagates 2 m after spatial filter
  - High power spatial filter expands beam by a factor of 130
  - $1/e^2$ diameter is 29 cm
- Collimating lens is placed in beam directly in front of hyperspectral imager
- Facility is capable of generating highly uniform beam with typical solar power levels (1.88 mW/cm²)



Active Stabilization

- With such a high magnification factor, small perturbations on input optics (thermal, air currents) cause large deviations in beam position at hyperspectral imager.
- Three types of active stabilization are employed:
  - Quad diode positioning feedback sensors control a piezo steering mirror placed upstream of the spatial filter (5 Hz bandwidth)



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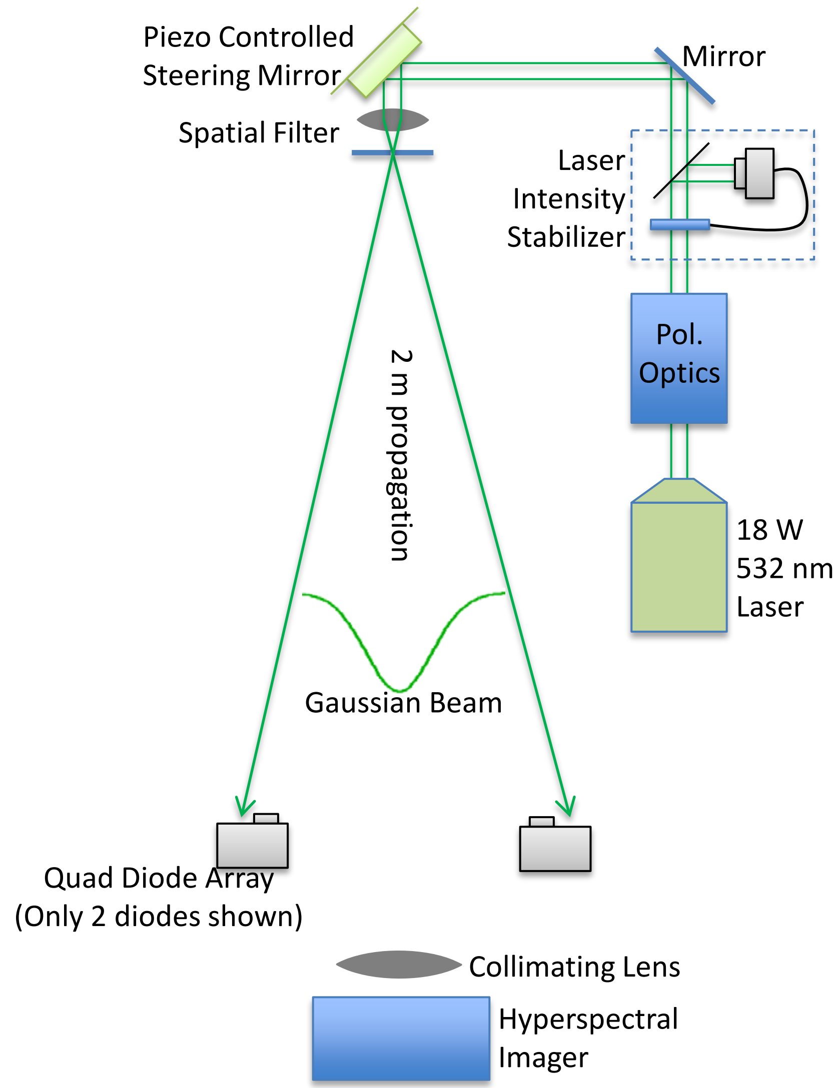

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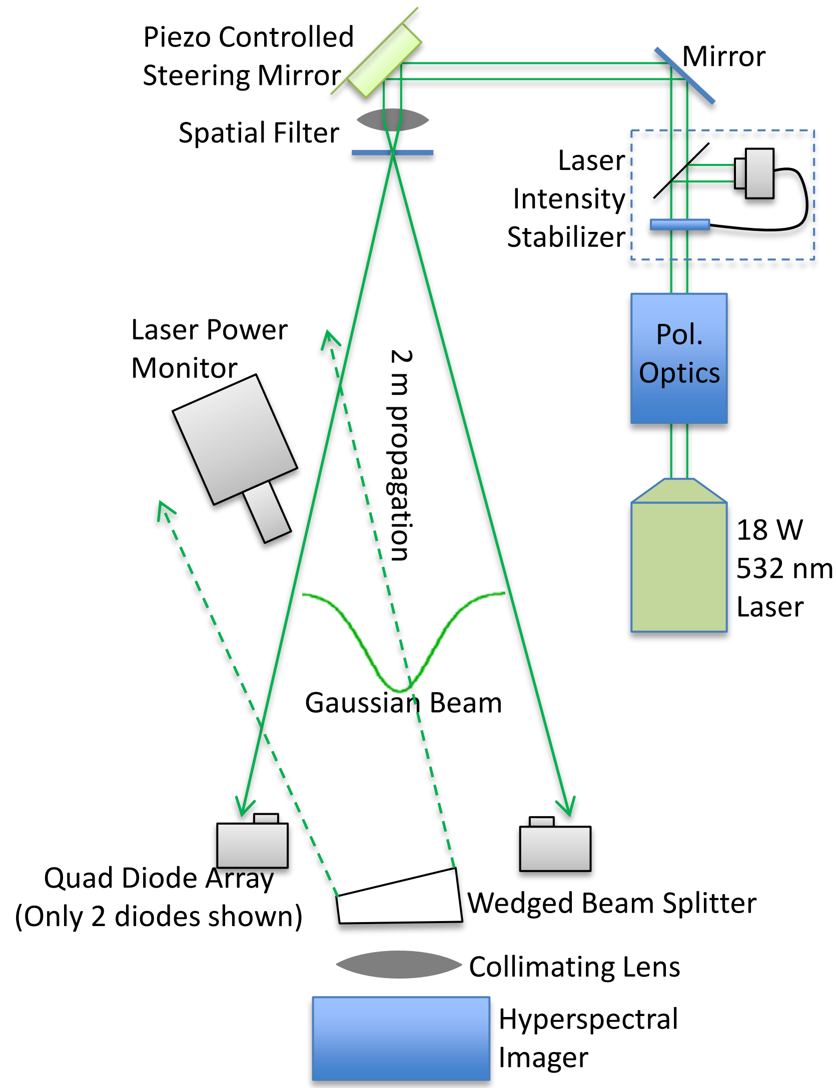
  - A wedged beam splitter placed directly in front of the hyperspectral imager input aperture is used to pick off the center 2 mm^2 portion of the beam, which is monitored by a NIST calibrated trap detector (with known gain and uncertainty over 7 orders of magnitude)



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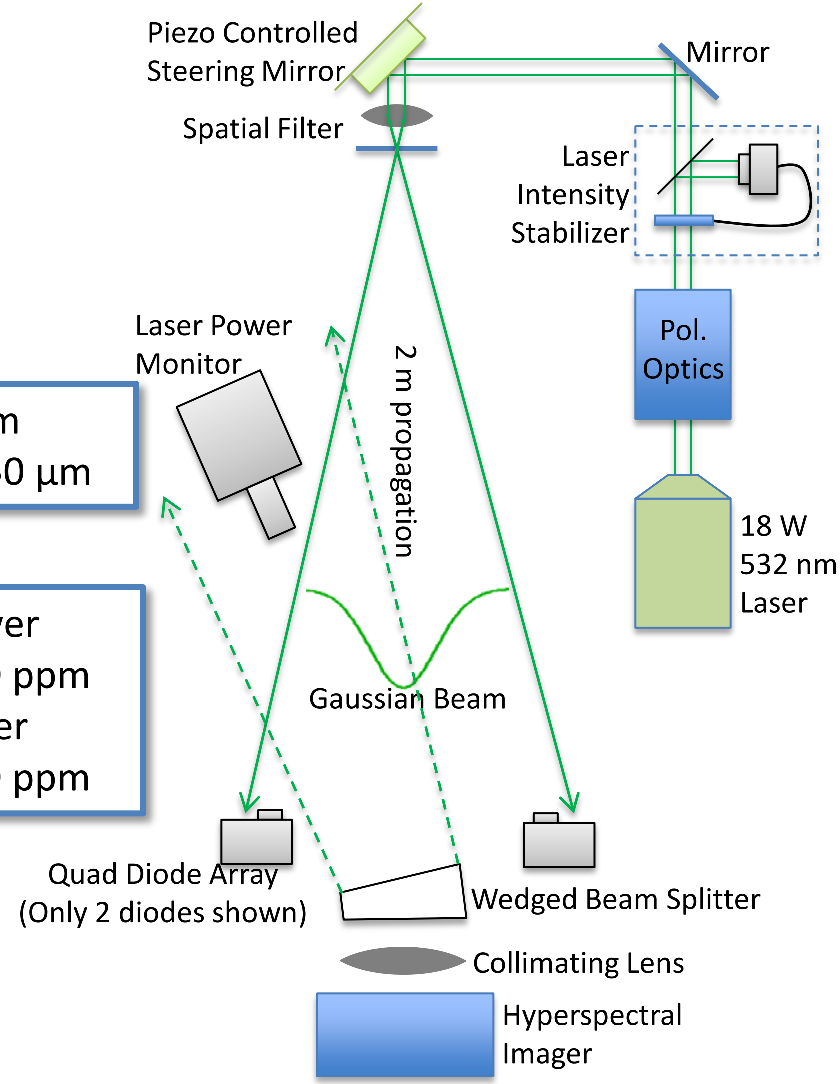
Long-term beam spatial jitter: 350 µm

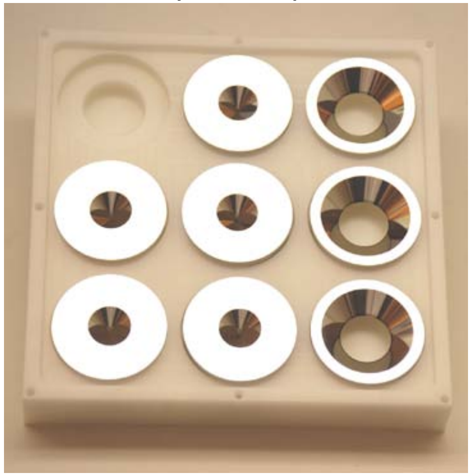
Short-term power fluctuation: 120 ppm
Long-term power fluctuation: 240 ppm

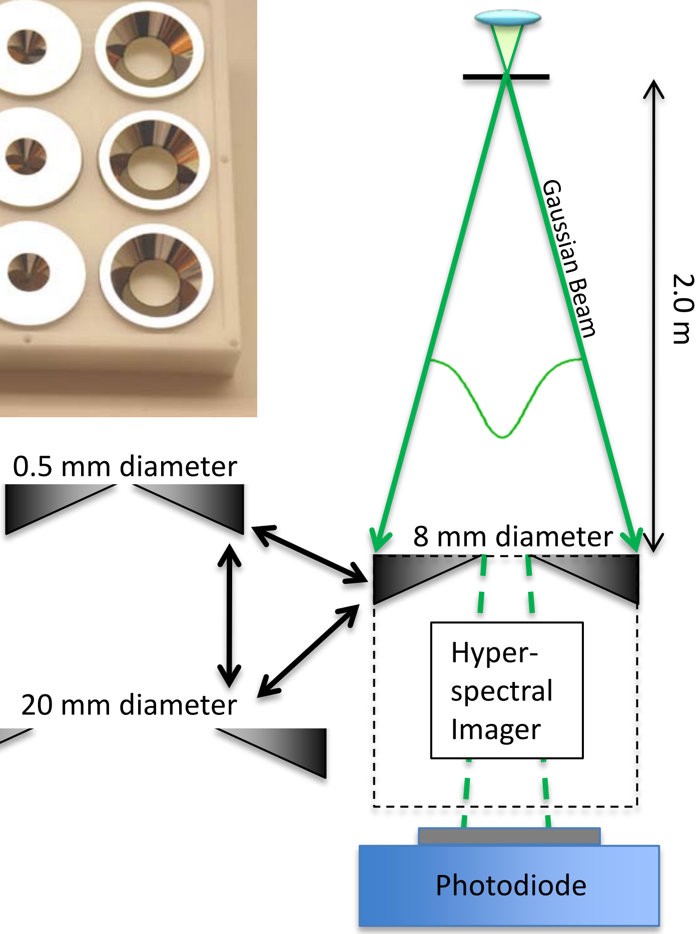


Aperture Area Attenuation Measurement

- Input apertures are aluminum
- Aperture edge is precision diamond turned
- The amount of optical power entering system is directly proportional to the input aperture area
  - This relationship, and the uncertainty in the associated measurement, are quantified by measuring the power passing through the aperture
  - Only a relative power measurement is used, and accuracy will be determined by a comparison with a NIST measurement of the aperture area
- Three aperture sizes are used: 20 mm, 8 mm, and 0.5. mm diameters

Actual system apertures

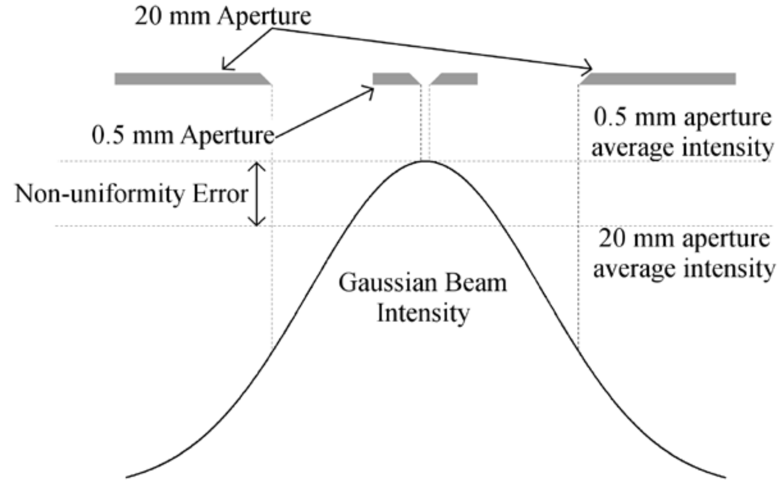




Aperture Diameter (mm)	Aperture Area (mm^2)	Area Uncertainty (ppm) (k=1)
19.9862	313.72454	35
7.9732	49.9290	50
0.51542	0.20865	633

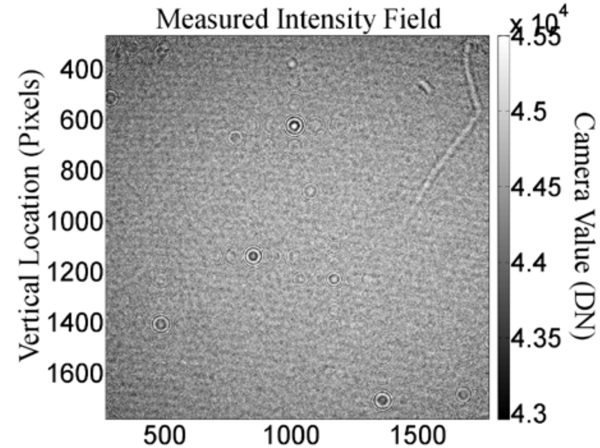
Power Ratio Uncertainties

- The power measurement standard deviation (after 100 averages) is 12 ppm
- An irradiance non-uniformity correction is applied to the power ratio measurements
  - In a Gaussian field, the 0.5 mm aperture has a higher irradiance than the 20 mm aperture



Power Ratio Uncertainties

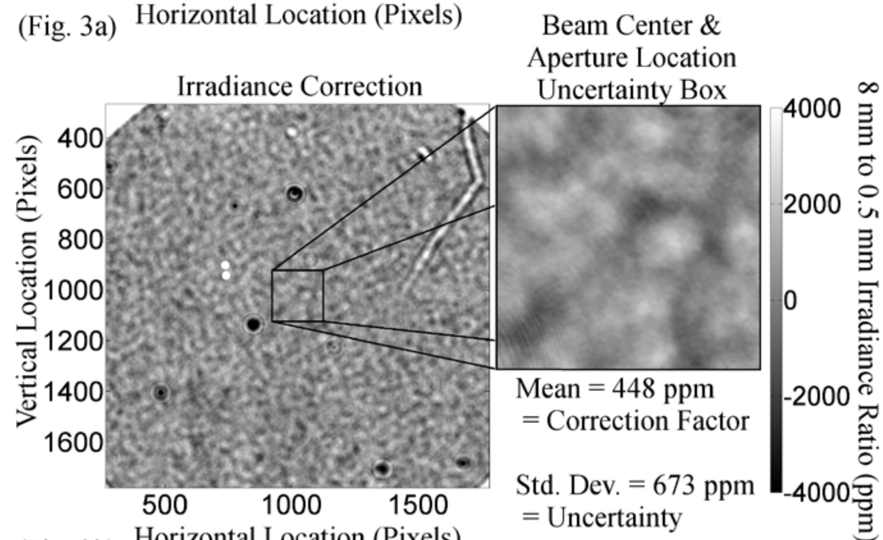
- A camera is placed at the input aperture location to measure the input irradiance
  - An irradiance correction is calculated at every pixel on camera
- Uncertainty in the location of the center of the beam (estimated as a 3 x 3 mm box in the center of the aperture) can be used to calculate an uncertainty in the irradiance correction



(Fig. 3a)

Power Ratio Measurements and Uncertainties

Aperture Ratio	NIST Area Ratio ± Uncertainty (k=1)	Power Ratio ± Uncertainty (k=1)
20/8	6.2834 ± 31 ppm	6.2834 ± 200 ppm
8/0.5	239.2954 ± 317 ppm	239.1930 ± 673 ppm

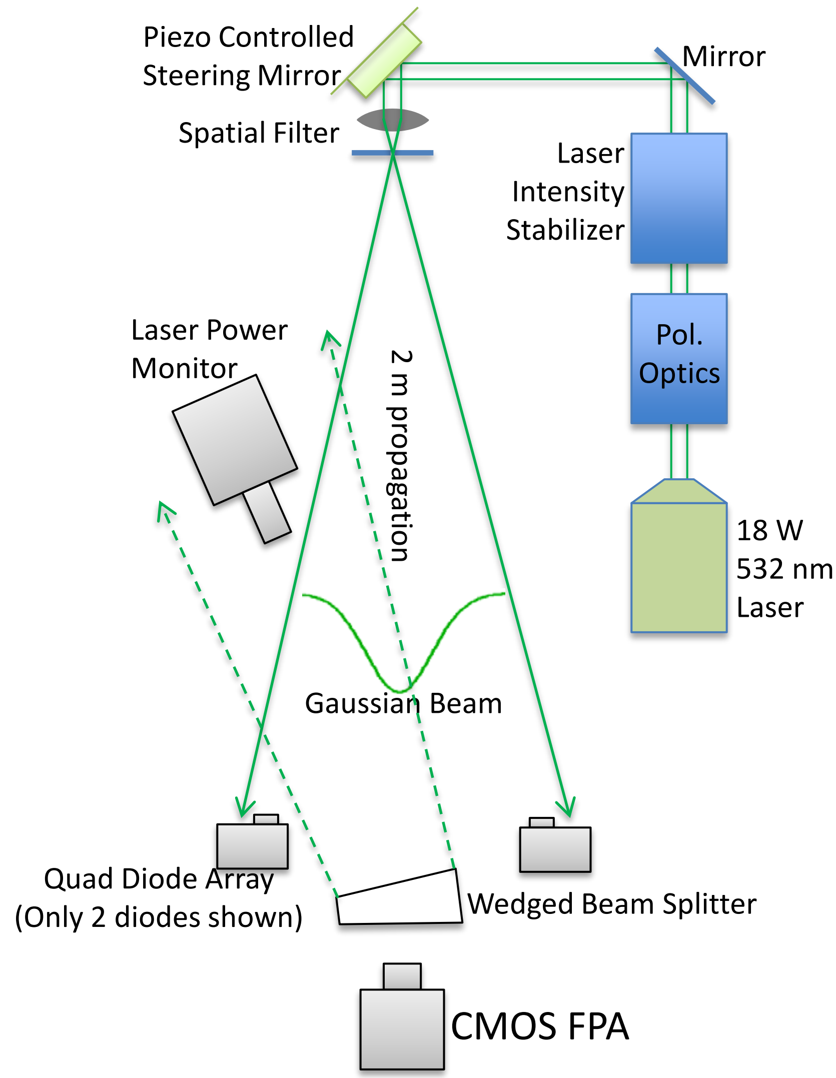


(Fig. 3b)

- Combined 20 mm to 0.5 mm attenuation uncertainty is 0.07%

Integration Time Attenuation

- The amount of detected power is inversely proportional to sensor integration time
  - Sensor is a CMOS FPA (12-bit Photon Focus MV1-1312-160) with global shuttering capabilities
  - Sensor exposure range extends from 0.01 to 420 ms (4.6 orders of magnitude if shown to have linear response)
- Measurement is made by increasing laser power (monitored on trap detector) while decreasing sensor integration time in order to maintain the same power level on the sensor
  - Measurement is relative



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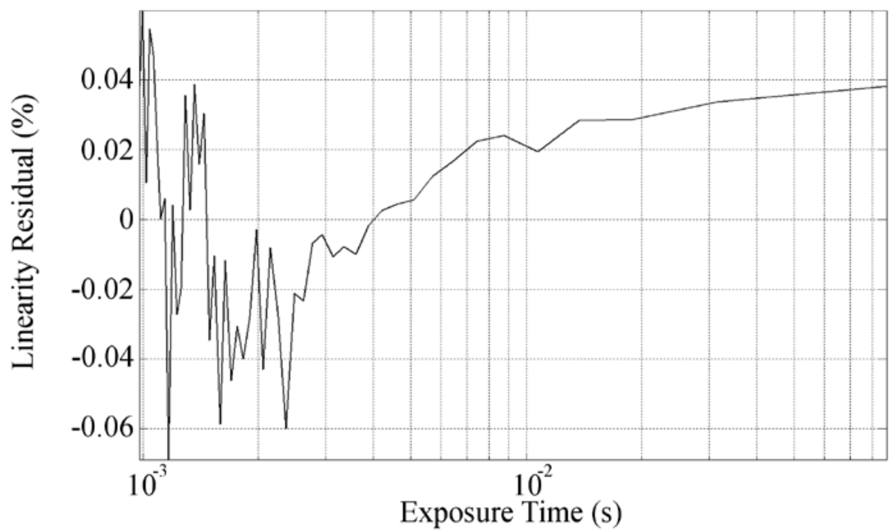
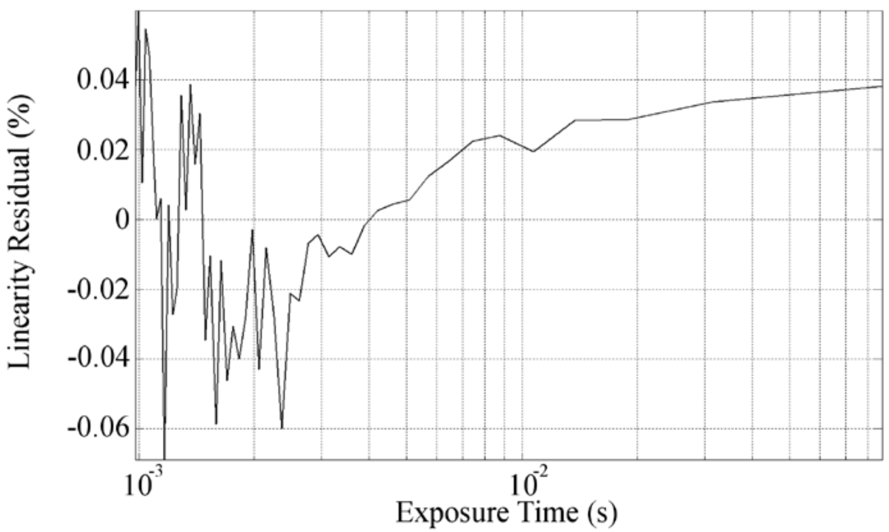
  - Measurement is relative
- Integration time deviation from linear is 302 ppm over 2 orders of magnitude attenuation (standard deviation across all exposure time linearity residuals)



Integration Time Attenuation Uncertainty

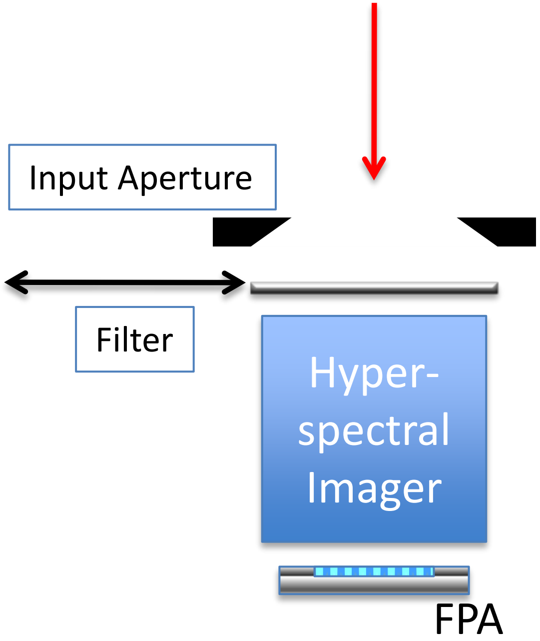
- Integration time measurement uncertainty is determined by standard deviation in repeated measurements
  - Uncertainty in integration time is 360 ppm
- Measurement linearity error and uncertainty increase at lower signal levels
  - Indicates a gain nonlinearity which can be compensated during post processing
  - If signal levels are kept above 1000 DN (digital number), uncertainty is < 0.1%



Filter Attenuation

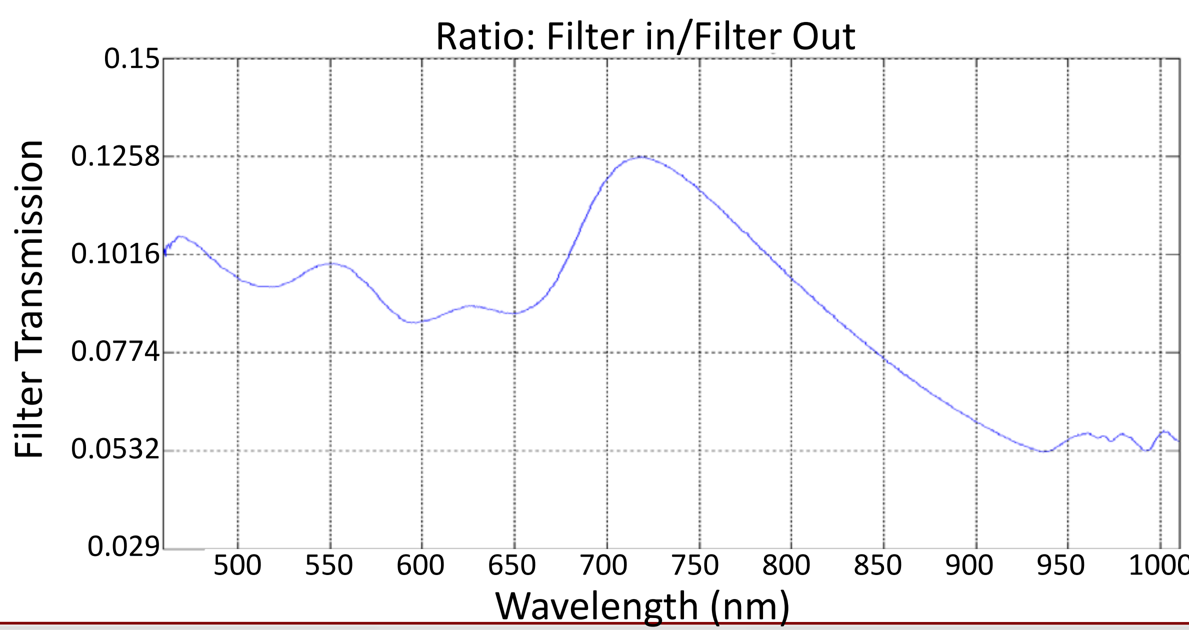
- Absorptive glass filter is used
  - Bulk effect is more stable than thin film
  - Lower reflected light
  - Simpler dependence on angle of incidence
- Lunar on-orbit relative calibration
  - Succession of filter in/filter out measurements radiance measurements
  - Track possible degradation
  - Low light level (compared to solar irradiance) limits attenuation factor to one order of magnitude

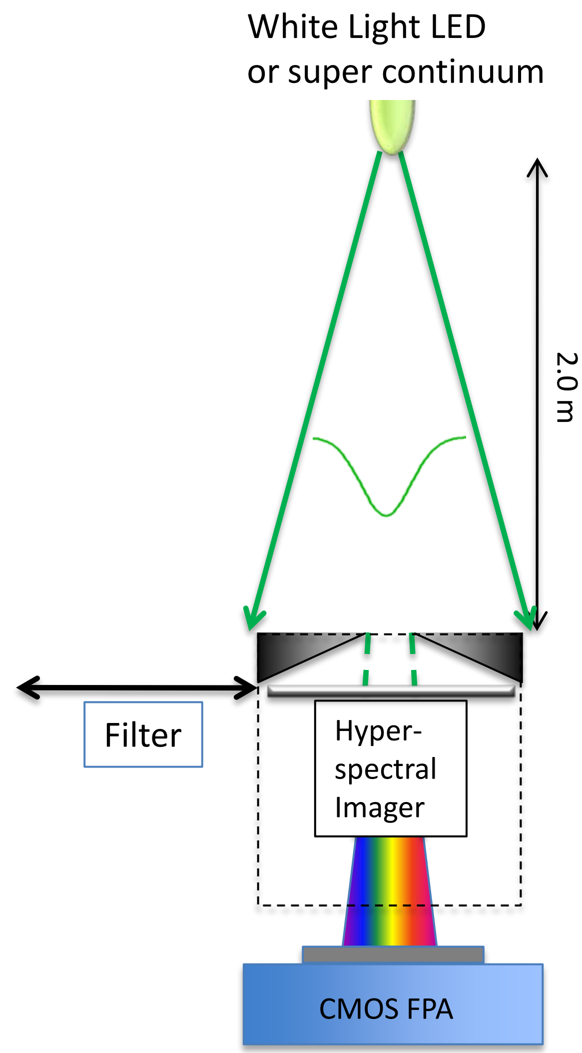
Lunar Filter Calibration



Filter Attenuation Measurements

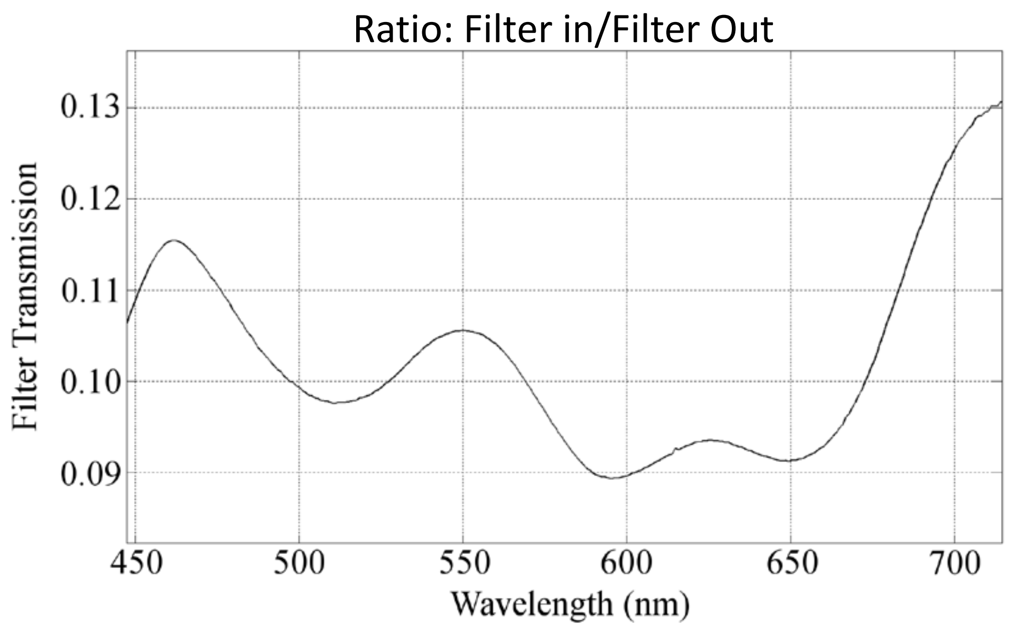
- Filter attenuation is wavelength dependent – requiring the use of a broadband source
  - Gaussian laser beam is replaced by white light LED
    - Measured long-term power stability is 190 ppm
  - Relative attenuation measurements have been made from 450 nm to 725 nm with LED
  - Relative attenuation measurements have been made from 475 to 1025 nm with super continuum source at NIST's Hyperspectral Image Projection Facility [13]





Filter Attenuation Uncertainties

- Uncertainty in the measurement is determined by deviation of each point from a smooth curve
  - Uncertainty is measured at 0.06%
  - Angular and thermal uncertainties will be estimated at a later date



Summary and Conclusions

- The amount of attenuation required for both solar and Earth viewing (5 orders of magnitude) has been achieved through 3 techniques:
  - Reduction of input aperture size
    - 3 orders of magnitude attenuation
    - Measurement uncertainty of 0.07%
  - Reduction of sensor integration time
    - 2 orders of magnitude attenuation
    - Measurement uncertainty of 0.04%
  - Addition of absorptive filter
    - 1 order of magnitude attenuation
    - Measurement uncertainty of 0.06%
  - Total root-sum-square uncertainty is 0.14%
- Combined attenuation from all 3 techniques is 10 times more attenuation than necessary
  - Still need to verify 6 orders of magnitude attenuation in full system
- Full system tests to verify root-sum-square uncertainty are in progress

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