Development of Transfer Standard Spectrographs: Implications for Earth Remote Sensing

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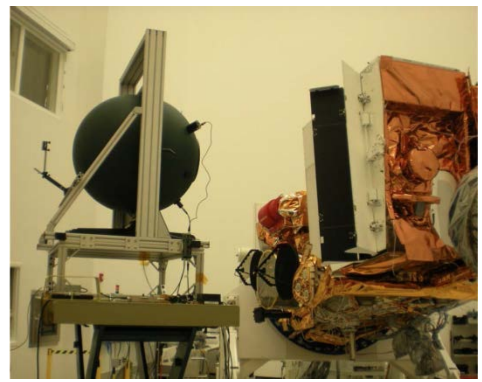
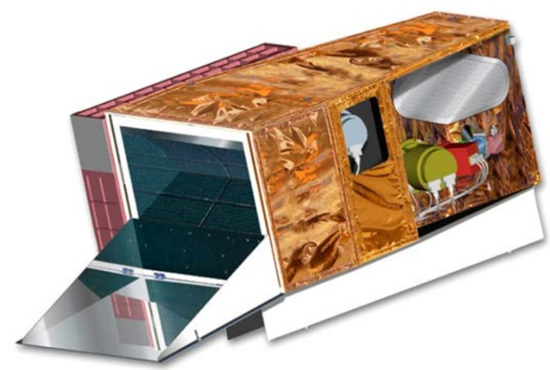




Detector-based Radiance Scale

Lamp-Illuminated Integrating Sphere

- During NASA's Earth Observing System-era, a series of source radiance validation campaigns were planned and executed by the EOS Project Office with the goal of validating the radiances assigned to laboratory calibration sources, principally lamp-illuminated integrating spheres, and establishing an uncertainty budget for the disseminated radiance scale.
- Based on an analysis of 7 years' worth of data, Butler *et al*.[1] assigned an **uncertainty in disseminated radiance scales of 2% to 3% in the Vis/NIR (silicon) region**, increasing to 5 % in the short-wave infrared region.

Using a Transfer Standard Spectrograph in radiance mode should reduce the uncertainties in the disseminated Radiance Scale an order of magnitude.

[1]Butler, J. J., et al., Validation of radiometric standards for the laboratory calibration of reflected-solar Earth observing satellite instruments, Proc. SPIE 6677, 667707 (2007).

Basic Concept:
Develop compact spectrographs as high-accuracy transfer standards that are traceable to SI units for radiance and irradiance measurements.

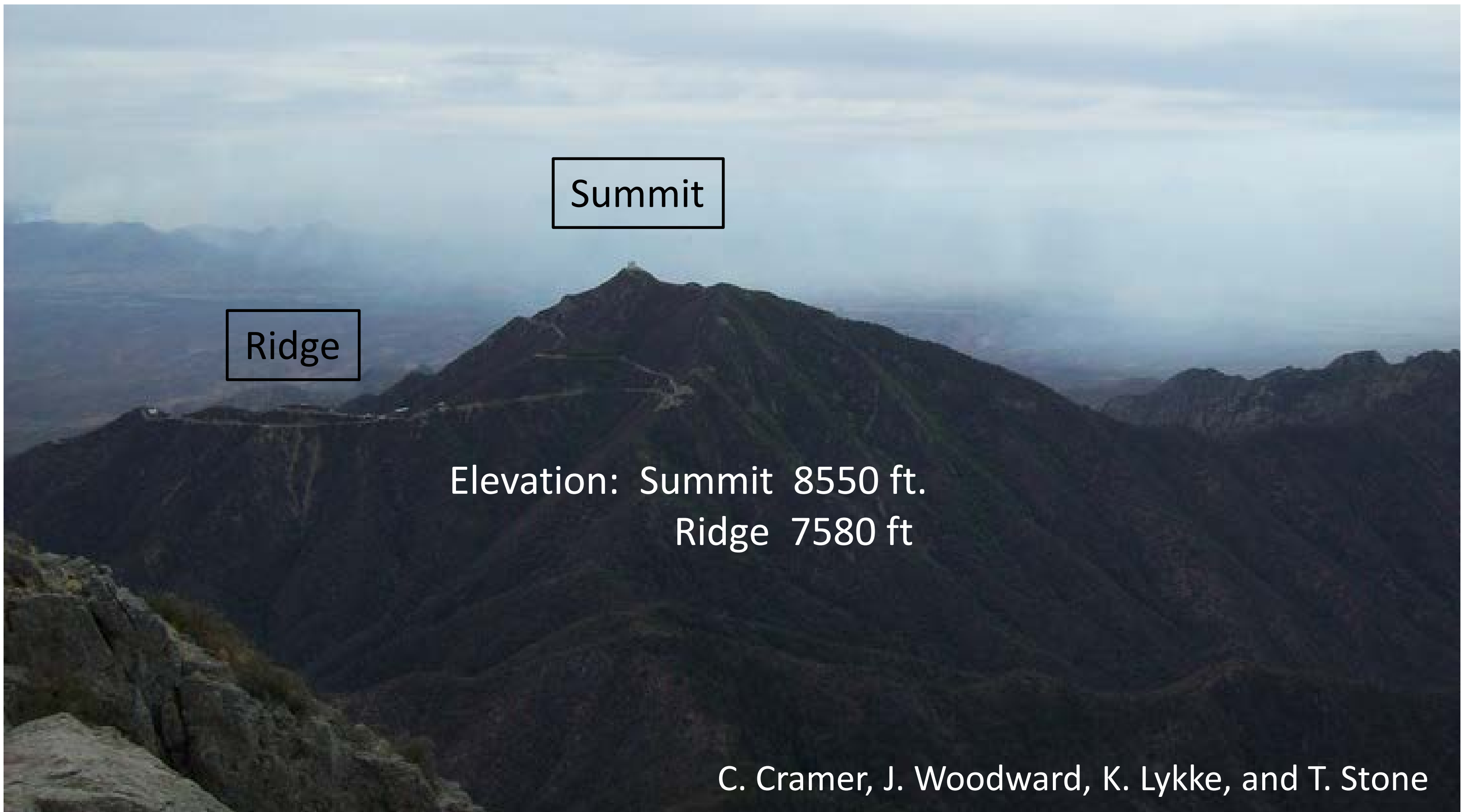
Uncertainty goals:
Less than 0.5% (k=2) in Radiance/irradiance to meet future uncertainty requirement of less than 1% (see NIST pub. HB157 "Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing" May 2015).

Application:
- Remote sensing electro-optical sensor calibration
- Radiometry
- Photometry
- Colorimetry

Why Spectrograph?

A Transfer Standard Spectrograph Was Used to establish Irradiance Scale for NIST's Absolute Measurements of TOA Lunar Irradiance at Whipple Observatory, Mt Hopkins, Amado AZ

Santa Rita Mountains, Coronado National Forest, ~30 miles from Nogales, Mexico



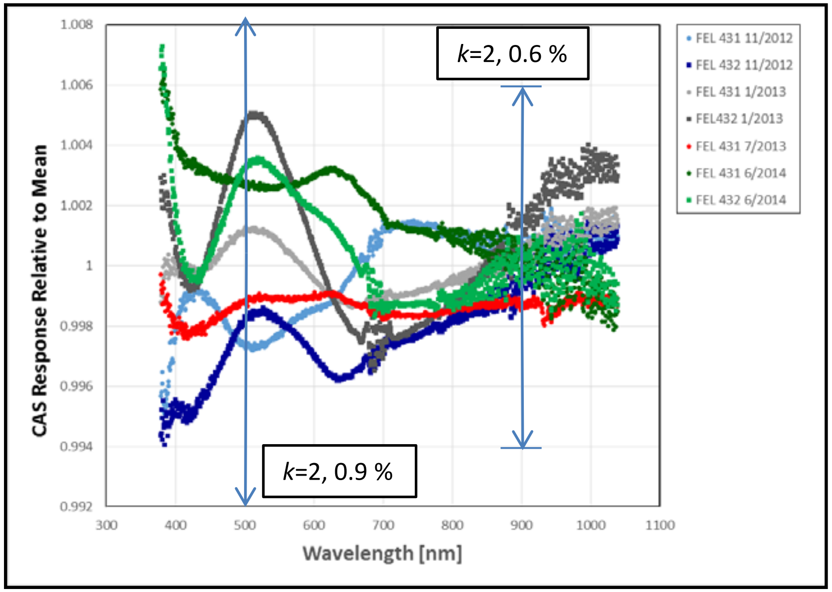
Performance of Transfer Standard Spectrograph Used for Lunar Irradiance Measurement

Compact Array Spectrometer

- CCD-based fiber-fed slit spectrograph
- 380 nm to 1040 nm, 4 nm resolution
-Temperature-stabilized CCD
- Appears to be radiometrically stable over reasonable long time frames

Radiometric Stability v an FEL-lamp

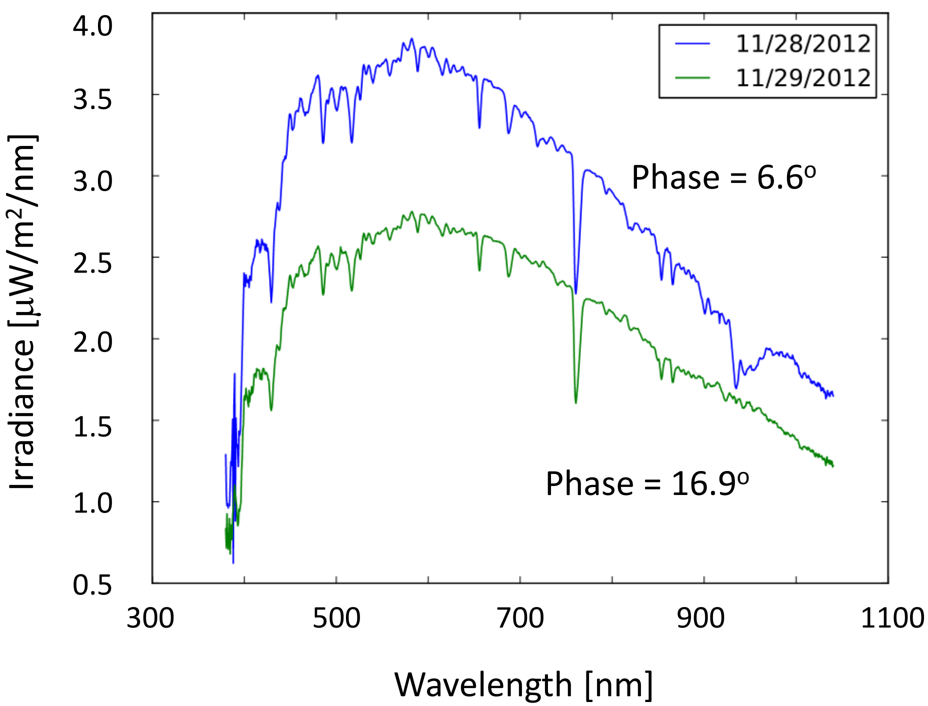
Calibration setup not maintained; reproduced for each measurement.



Stray light correction:
  SIRCUS + Zong, *et al.* (2007)
Wavelength Correction:
  P.-S. Shaw and J. T. Woodward, unpub.

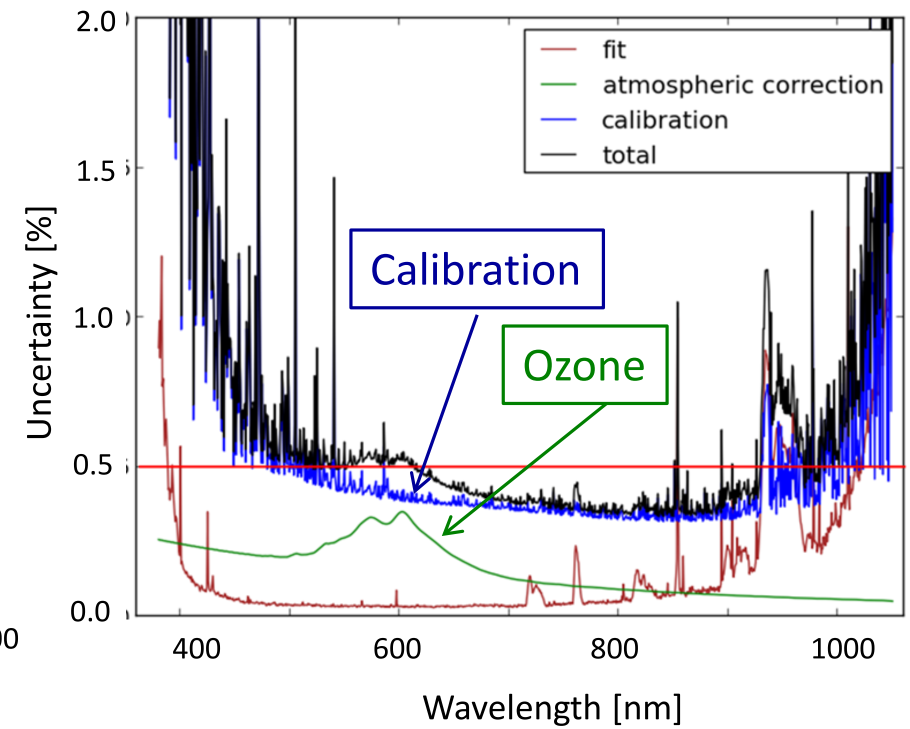
Absolute Top of the Atmosphere (TOA) Lunar Irradiance Measurements Based on a Transfer Standard Spectrograph

Measured Lunar Irradiance



~40 % difference in magnitude
Phase change between 7° and 17°

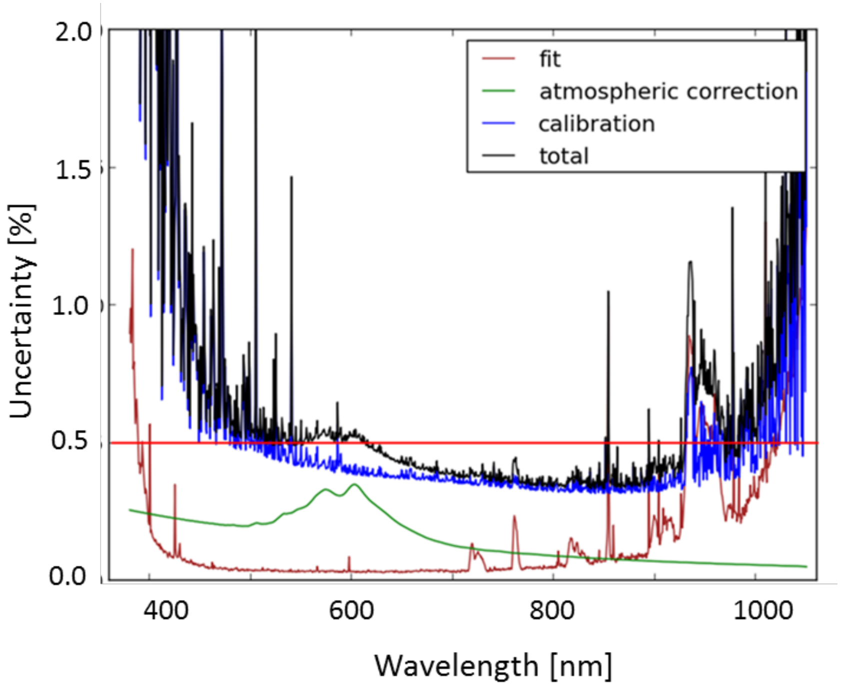
Uncertainty Budget (*k*=1)



Uncertainty dominated by the Telescope Calibration from 500 nm to 920 nm

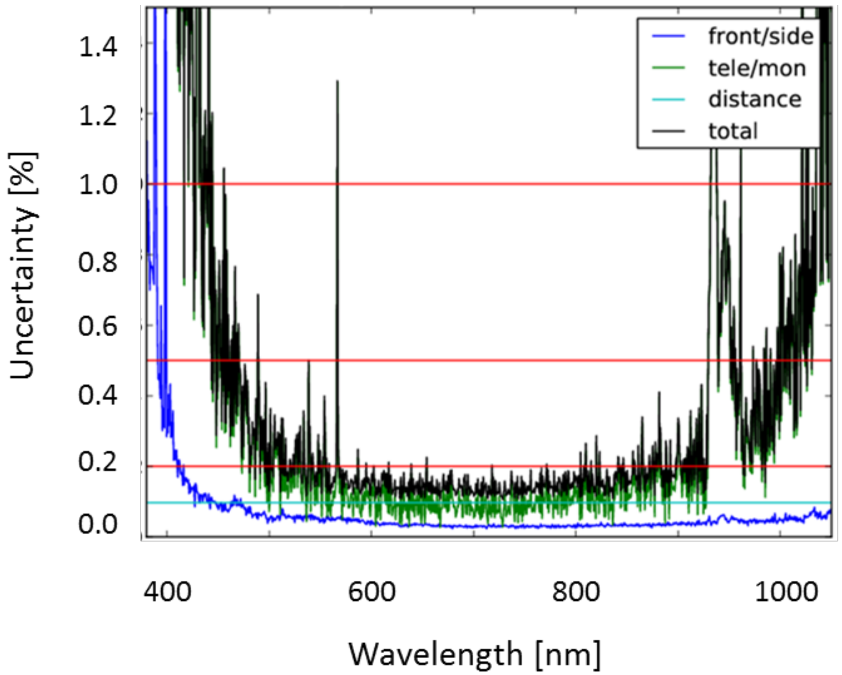
Uncertainties from FEL Lamp Calibration of Transfer Standard Spectrograph Dominate Uncertainty Budget

Total Measurement Uncertainty of Lunar Irradiance



With Telescope Uncertainty Only

(Assuming no uncertainty in the spectrograph calibration)



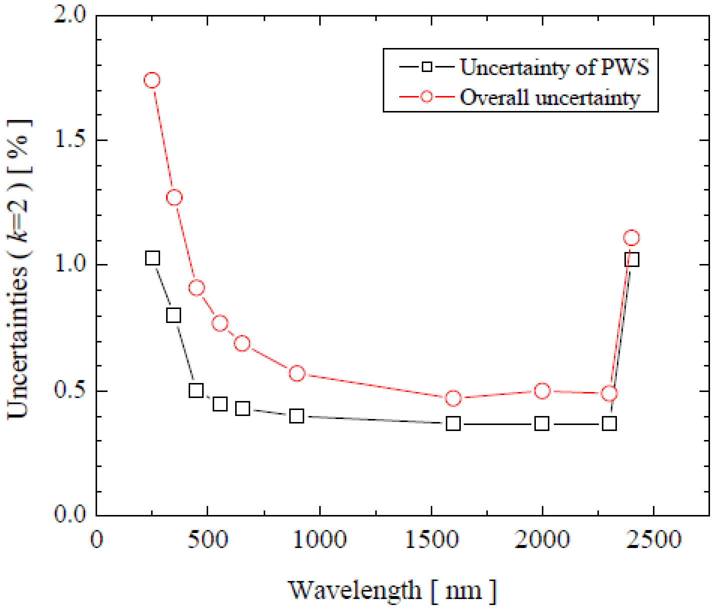
One way to reduce the uncertainty is to use detector-based calibration

Calibration and Characterization Techniques for the Establishment of Transfer Standard Spectrographs

1. Broad-band Sources
   - Absolute calibration using FEL lamps with source-based scale (**uncertainty >0.7%**).
   - Absolute calibration using blackbody sources (ongoing).
2. Narrow-band Tunable Lasers at SIRCUS
   - Absolute calibration using detector-based scale derived from cryogenic radiometer (**uncertainty <0.1%**).
   - Wavelength calibration (uncertainty <0.1nm)
   - Bandwidth characterization.
   - Stray-light characterization.
3. Algorithm to Compare Broad-band and Narrow-band Calibration

Absolute Calibration of the Transfer Standard Spectrograph Using Source-Based FEL Lamp and Detector-Based Laser System at SIRCUS

Expanded (k = 2) uncertainties of the 2011 NIST Irradiance Scale



Issued Lamps,

k = 2 uncertainty approximately

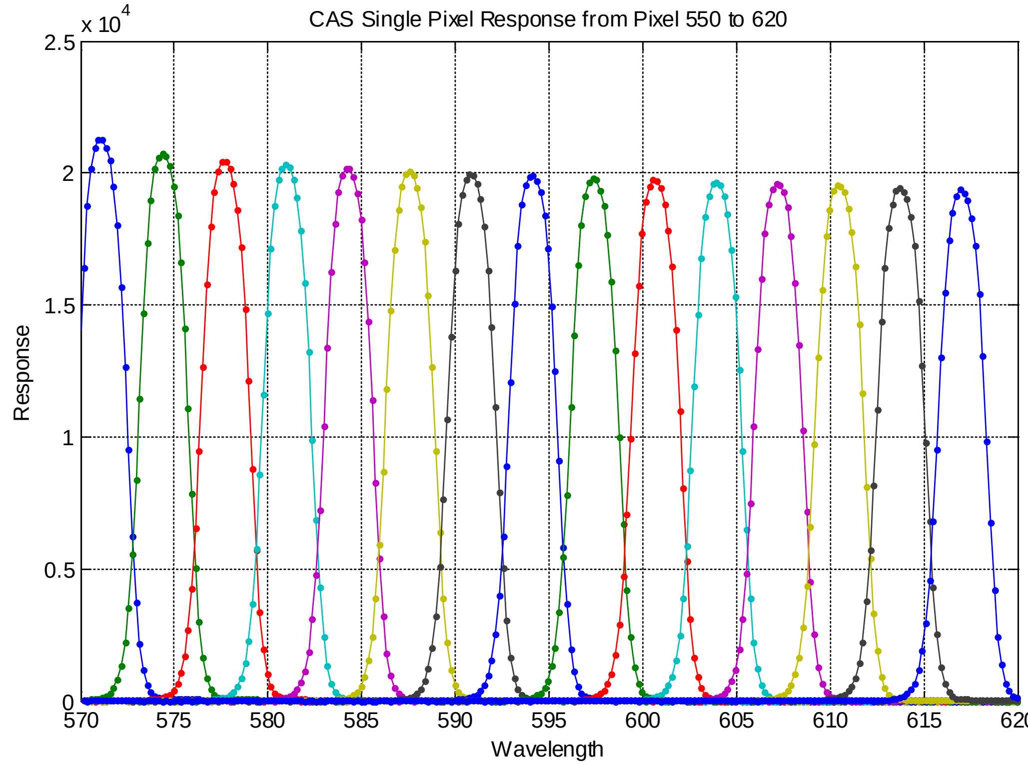
0.6 % @ 900 nm

0.9 % @ 500 nm

1.25 % @ 350 nm

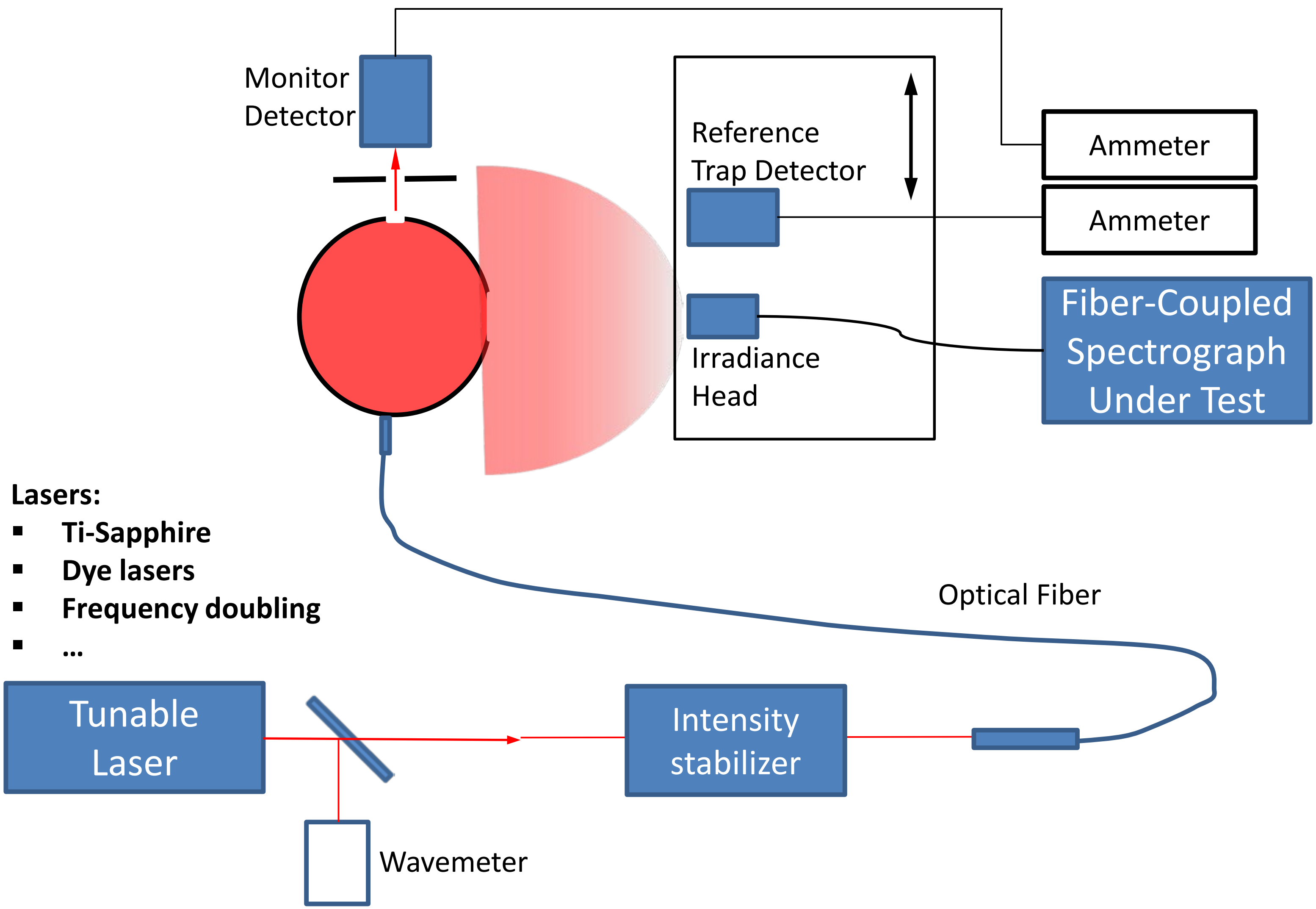
H. Yoon and Charles Gibson, Spectral Irradiance Calibrations, NIST Special Publ. 250-89 (July2011).

Single Pixel Responsivities



Uncertainty: 0.1 % or less (k=1) everywhere.

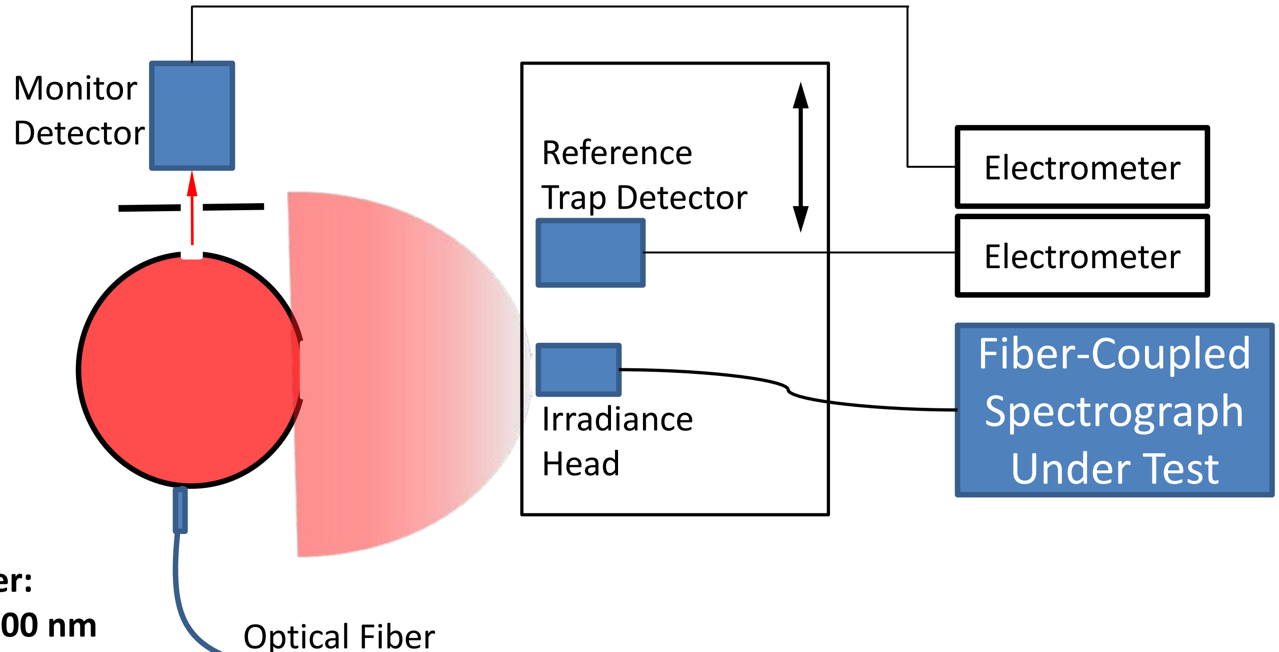
Two methods for detector-based spectrograph calibration:
1. Tunable CW or quasi-CW laser with intensity stabilization



Lasers:

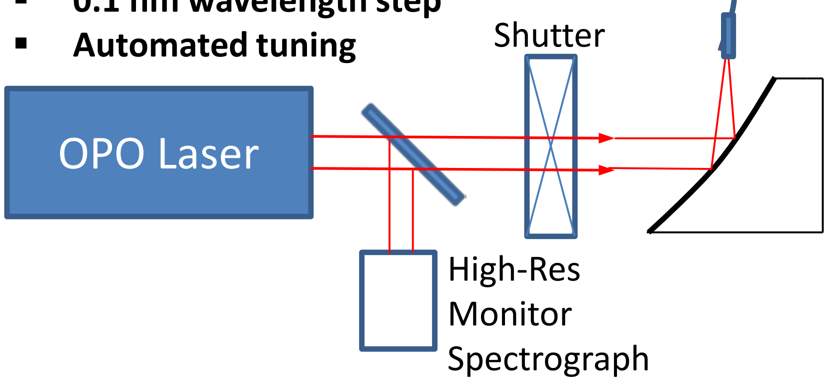
- **Ti-Sapphire**
- **Dye lasers**
- **Frequency doubling**
- **…**

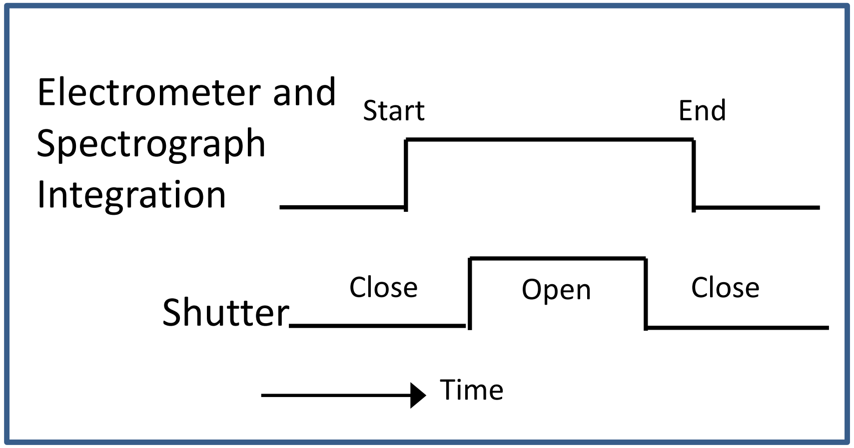
Two methods for detector-based spectrograph calibration:
2. Tunable pulsed laser using charge integration mode



Tunable OPO laser:

- **210 nm to 2400 nm**
- **5 ns pulses at 1kHz**
- **0.1 nm wavelength step**
- **Automated tuning**

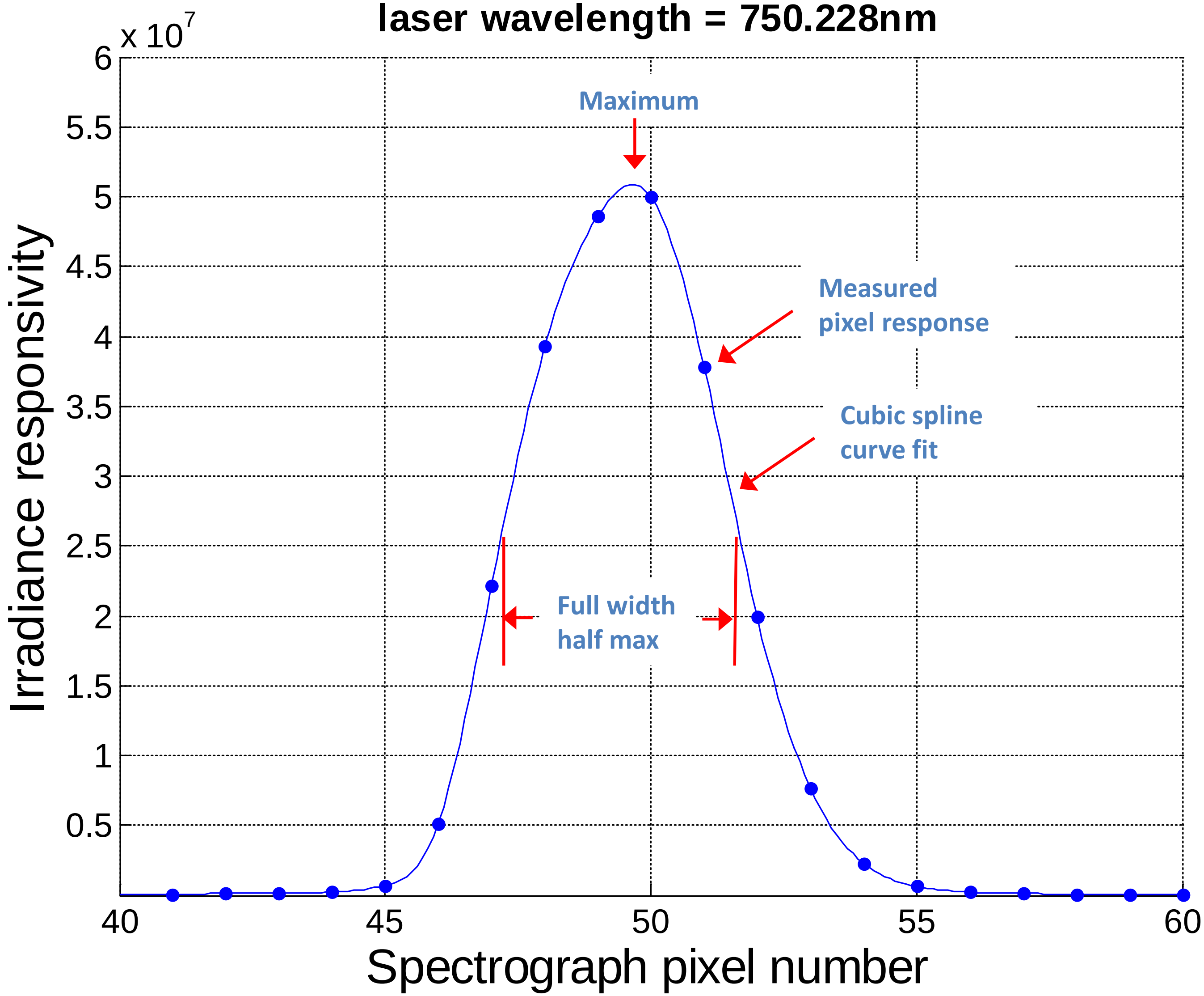




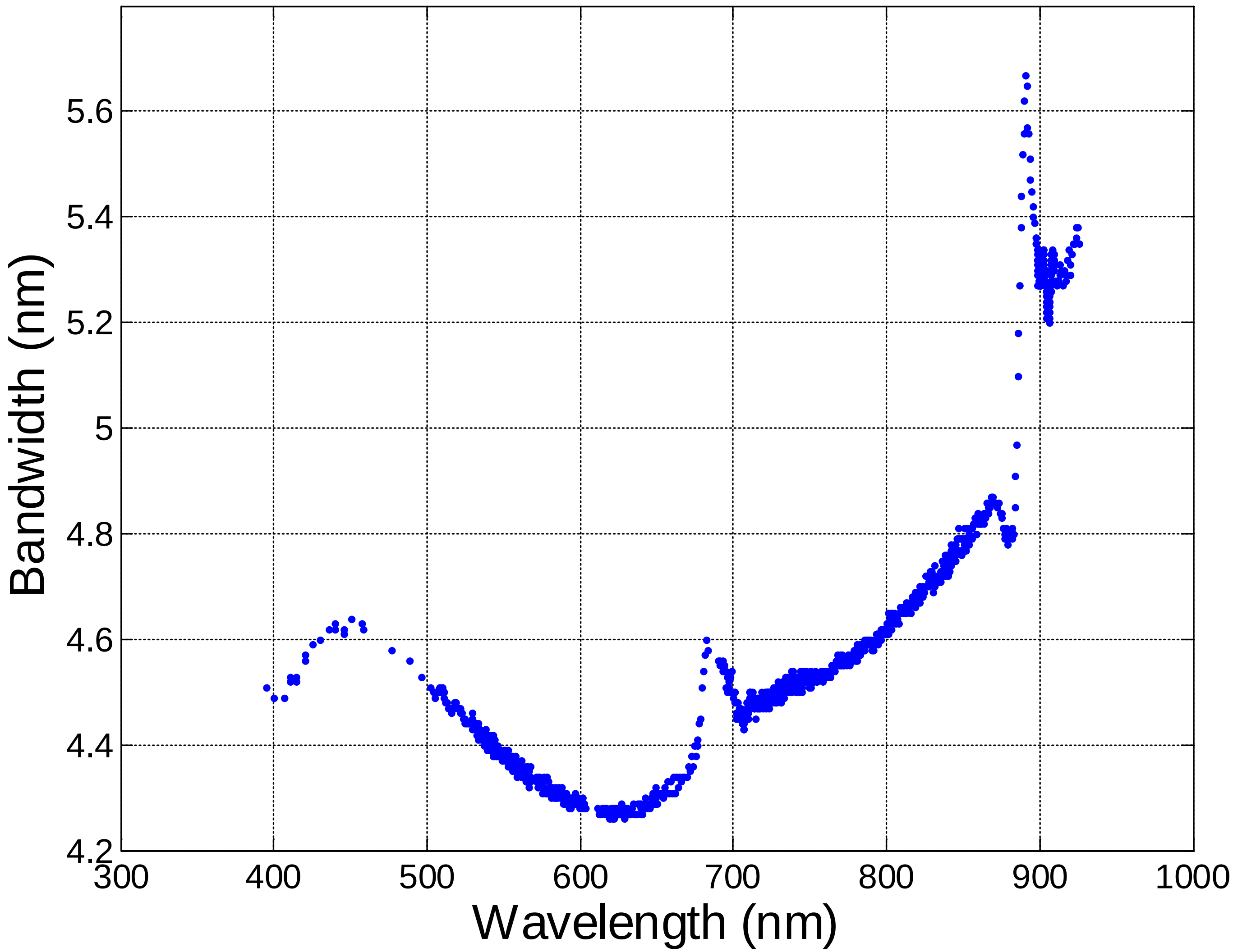
Transfer Standard Spectrograph Calibration and Characterization Using Lasers

1. **Wavelength calibration and bandwidth characterization.**
2. Stray light characterization and reduction.
3. Short-term stability test.
4. Detector-based spectrograph calibration.

Laser Characterization of Wavelength and Bandwidth of the Transfer Standard Spectrograph

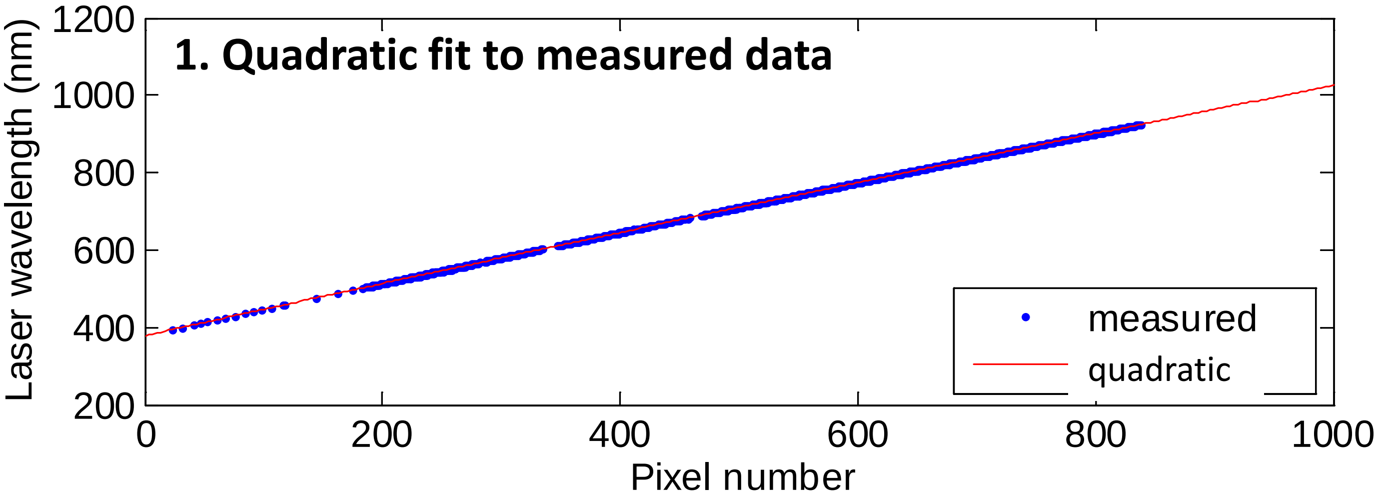


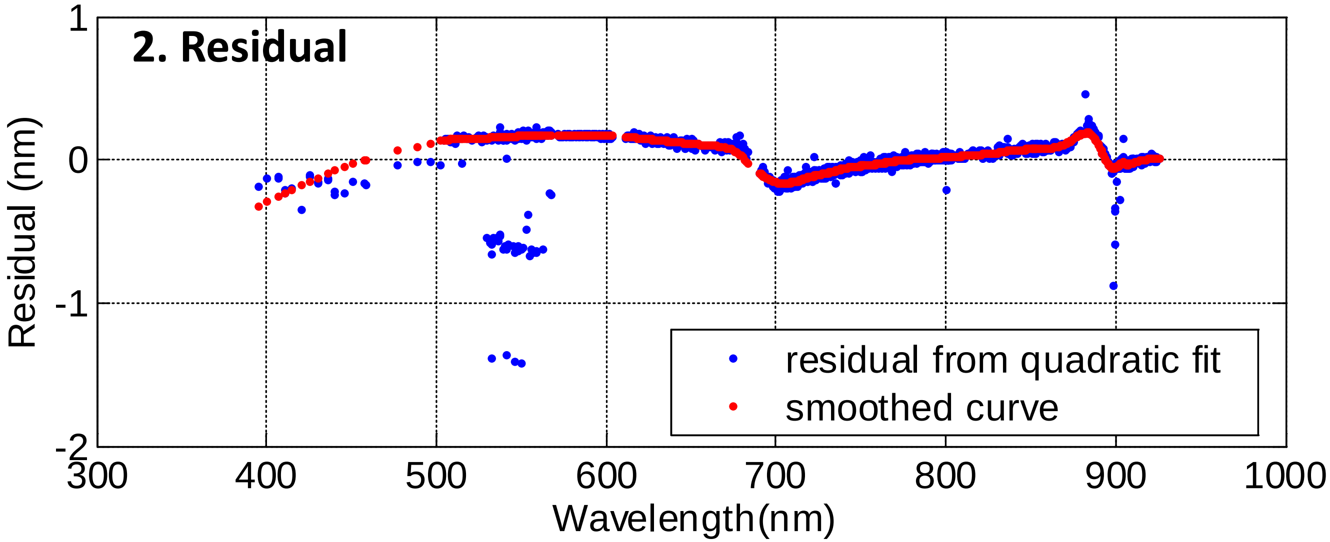
The Full-width-half-max Bandwidth of the Transfer Standard Spectrograph



Wavelength Calibration of the Transfer Standard Spectrograph using CW Lasers

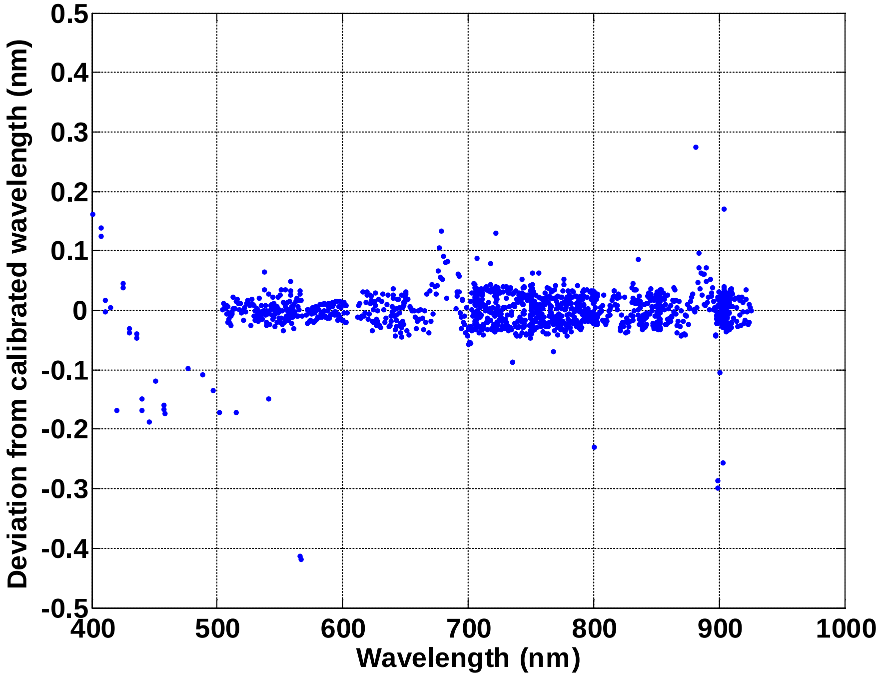
Wavelengths are derived based on quadratic fit and the fit residuals



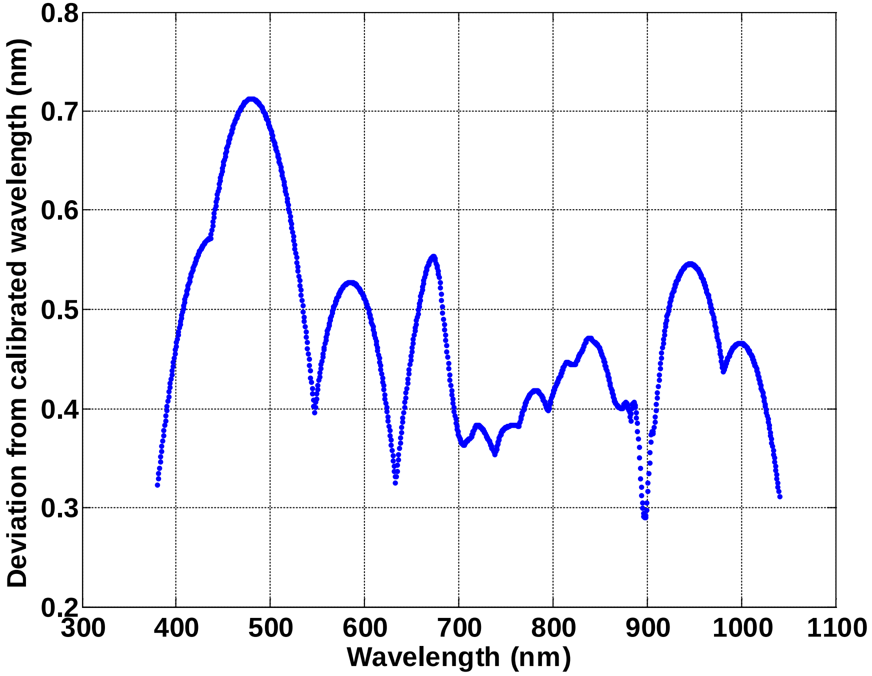


Wavelength Scale of the Transfer Standard Spectrograph

Deviation from CW laser measurements



Deviation from manufacturer supplied wavelengths



Transfer Standard Spectrograph Calibration and Characterization Using Lasers

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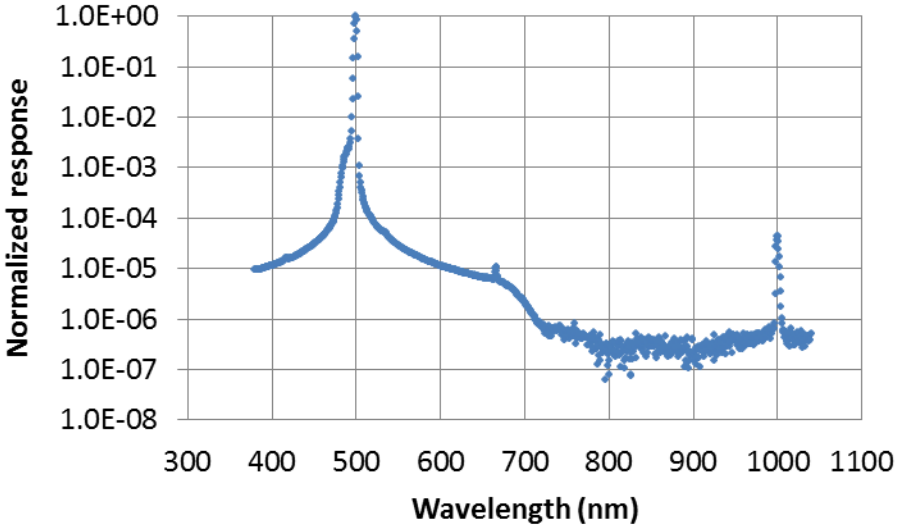
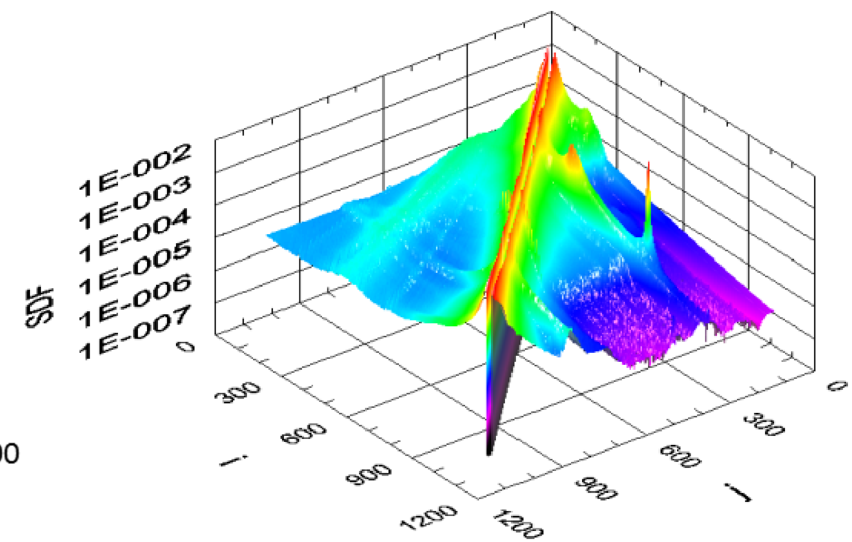
Stray-light Measurement of the Transfer Standard Spectrograph using Lasers to achieve more than 6 decades of dynamic range

Laser wavelength at 500 nm



Stray-light distribution function



Measurement method:

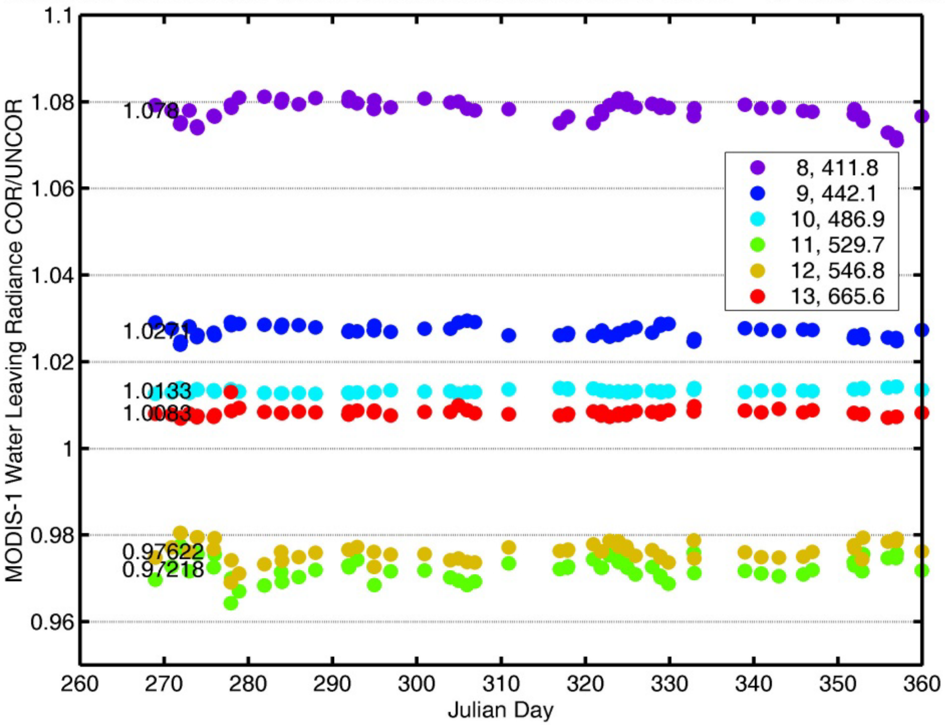
1. Measurement with low laser intensity for center in-band region.

2. Measurement with high laser power for out-of-band region while saturating in-band region.

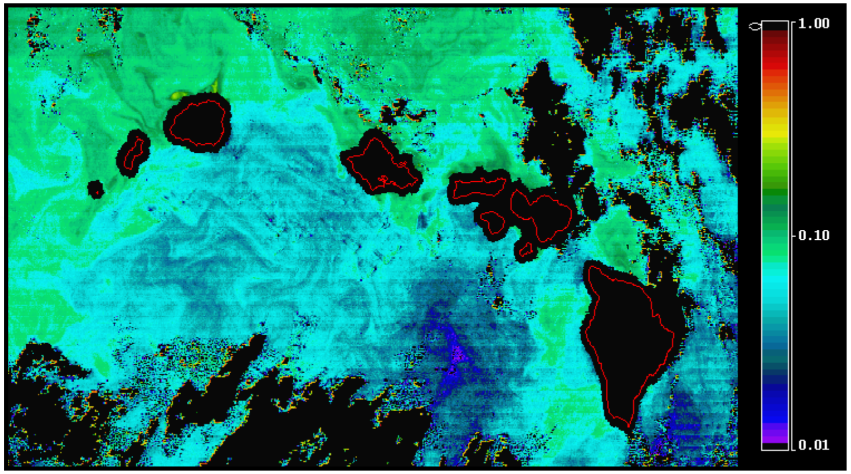
3. Two results are combined by matching overlapping regions.

Example of Stray light correction of spectrographs: Impact on MODIS Imagery

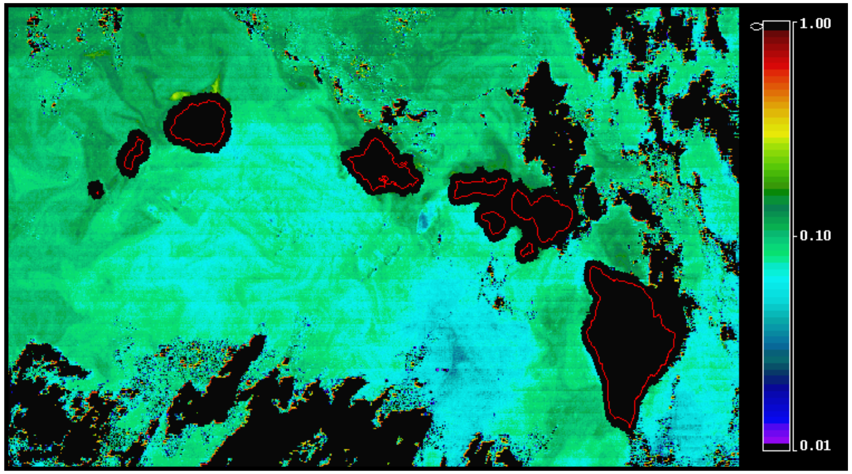
Impact on MOBY measurements (MODIS Bands)



After Correction



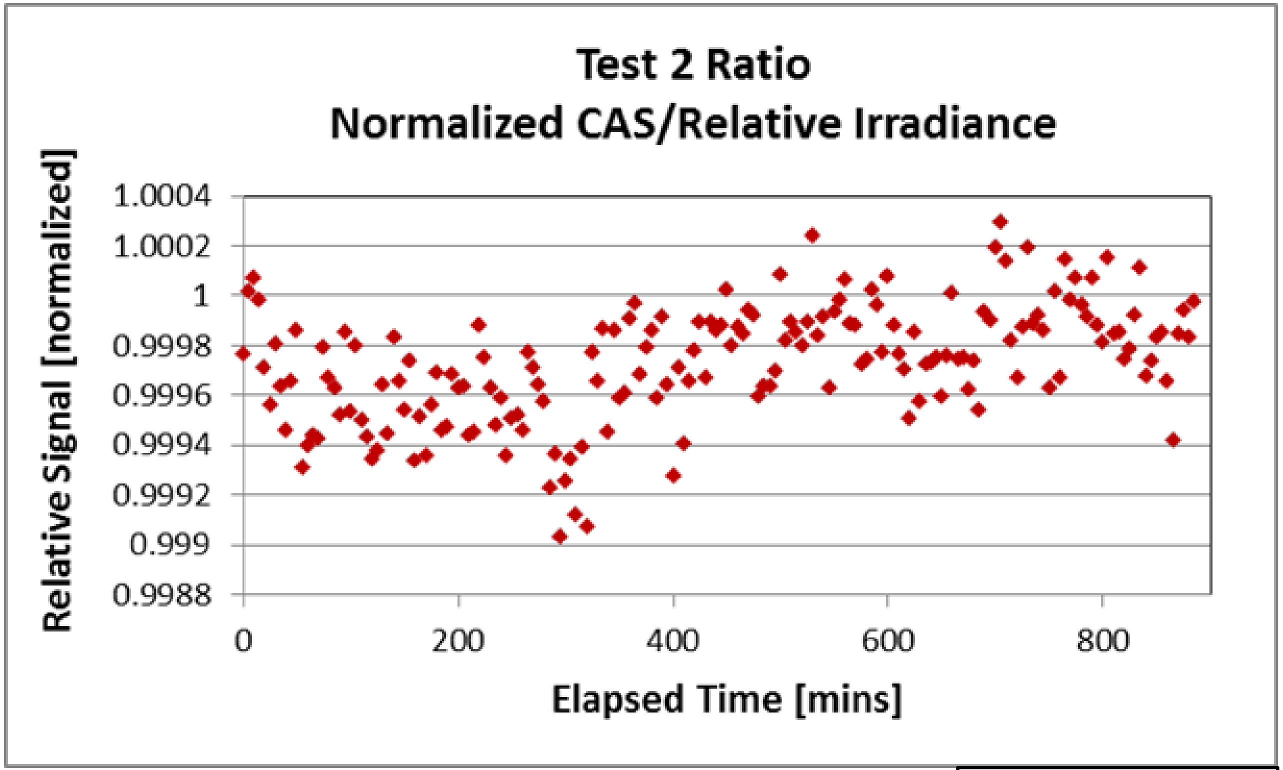
Before Correction



Transfer Standard Spectrograph Calibration and Characterization Using Lasers

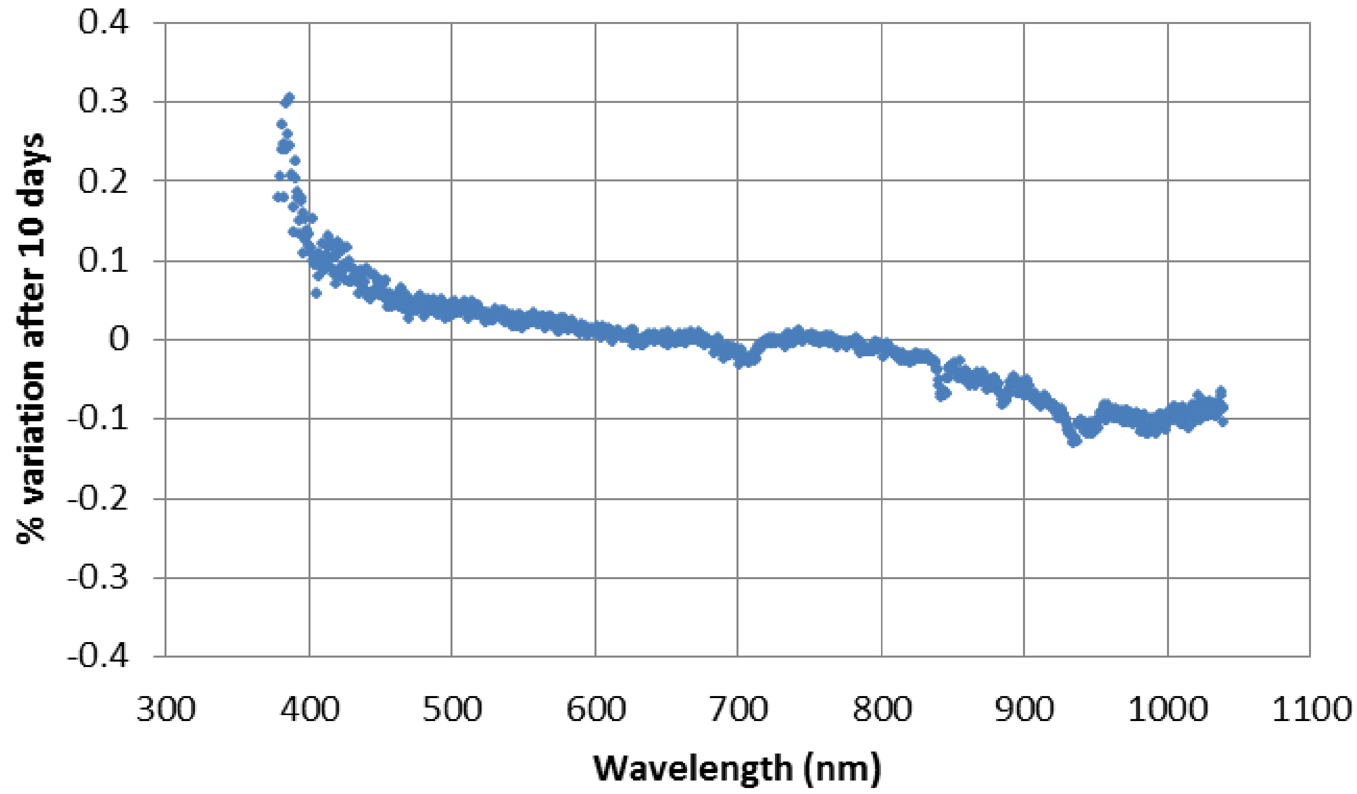
1. Wavelength calibration and bandwidth characterization.
2. Stray light characterization and reduction.
3. **Short-term stability test.**
4. Detector-based spectrograph calibration.

Transfer Standard Spectrograph 14-hour Short-term Stability Test Using a Laser



StDev: 0.02 %

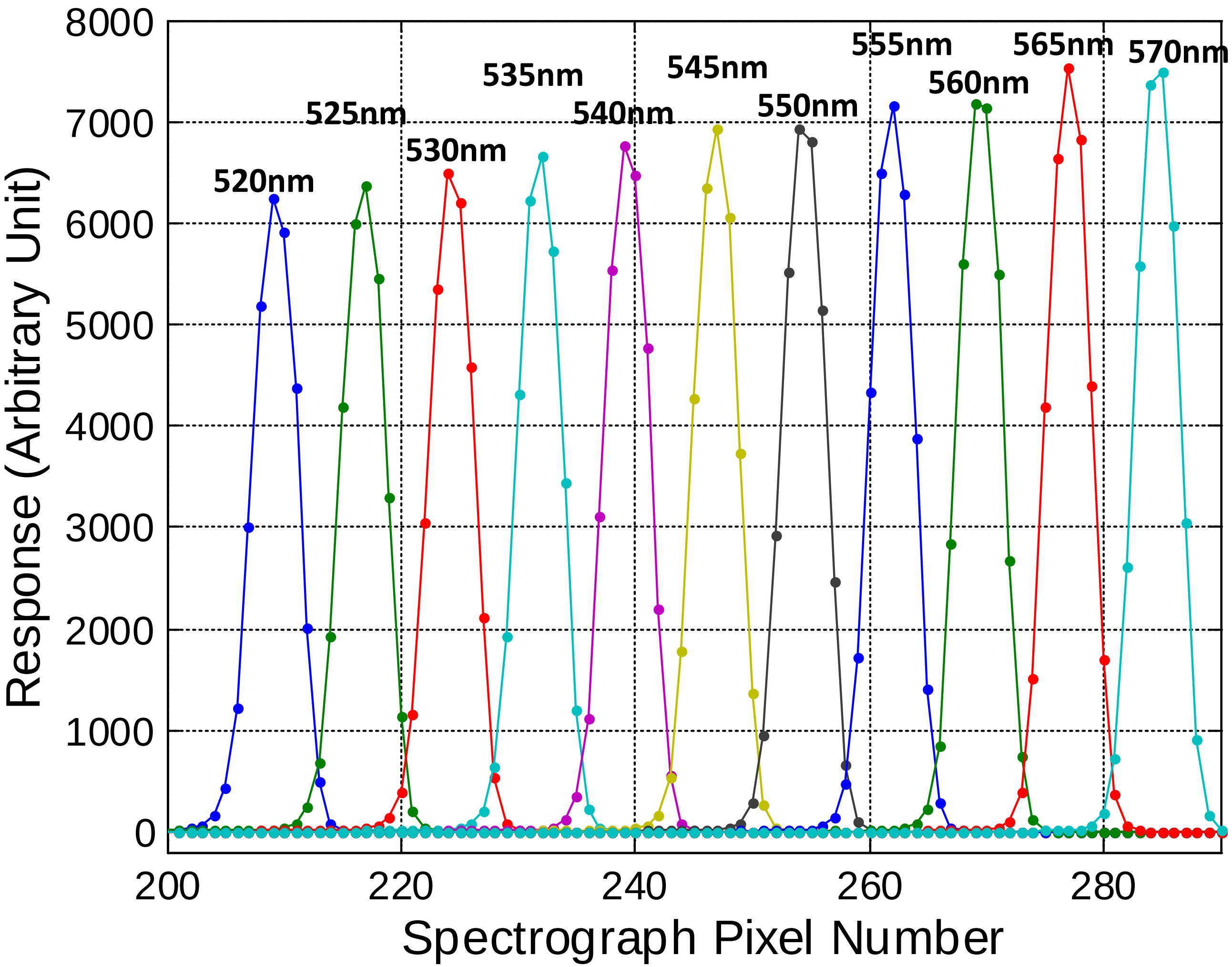
Transfer Standard Spectrograph's 10-day Stability Test with an FEL lamp



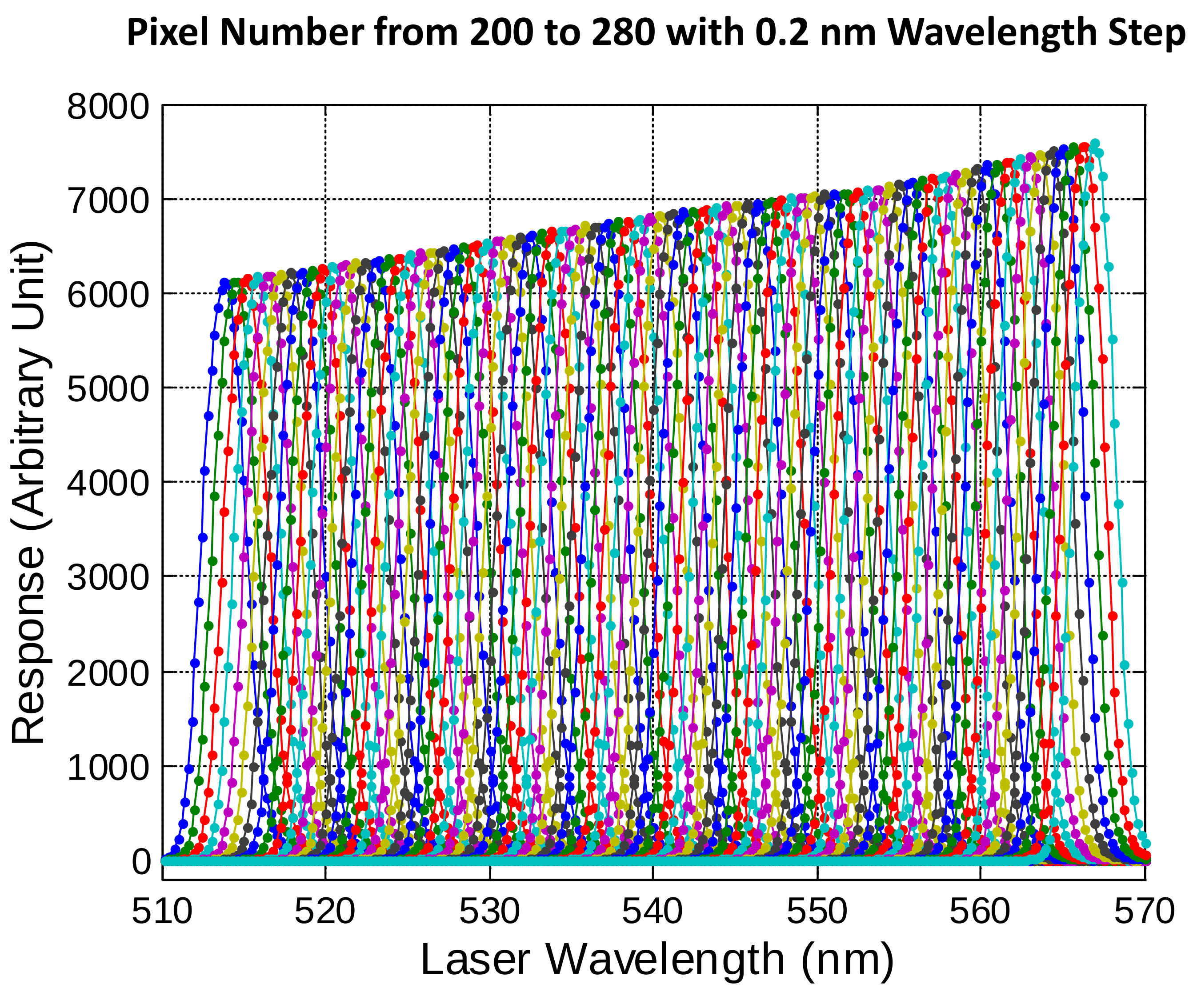
Transfer Standard Spectrograph Calibration and Characterization Using Lasers

1. Wavelength calibration and bandwidth characterization.
2. Stray light characterization and reduction.
3. Short-term stability test.
4. **Detector-based spectrograph calibration.**

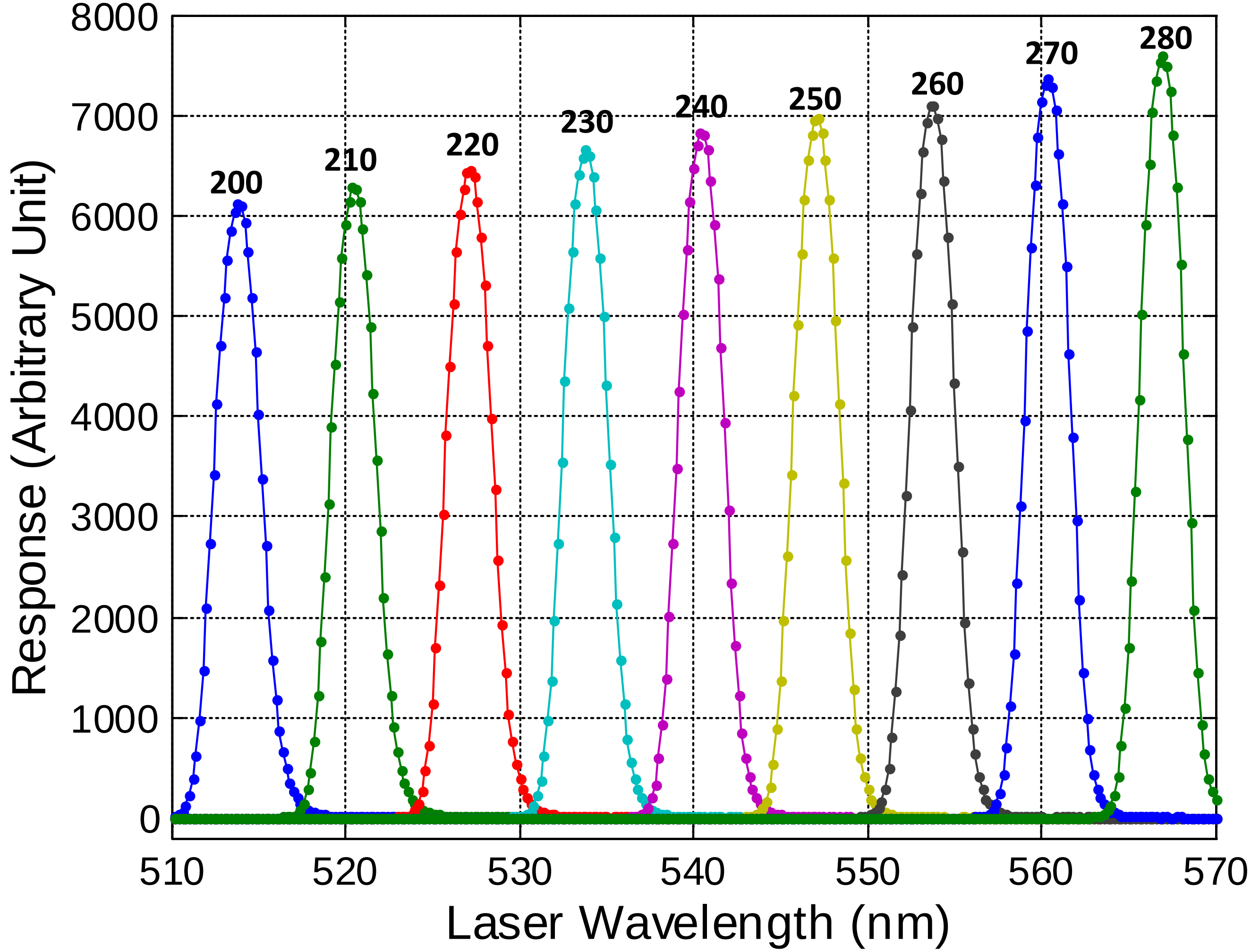
Spectrograph Response to Laser wavelength λ_0 as a function of pixel number (Line Spread Function)



Spectrograph Response to Laser wavelength *λ₀* as a function of pixel number (Line Spread Function)

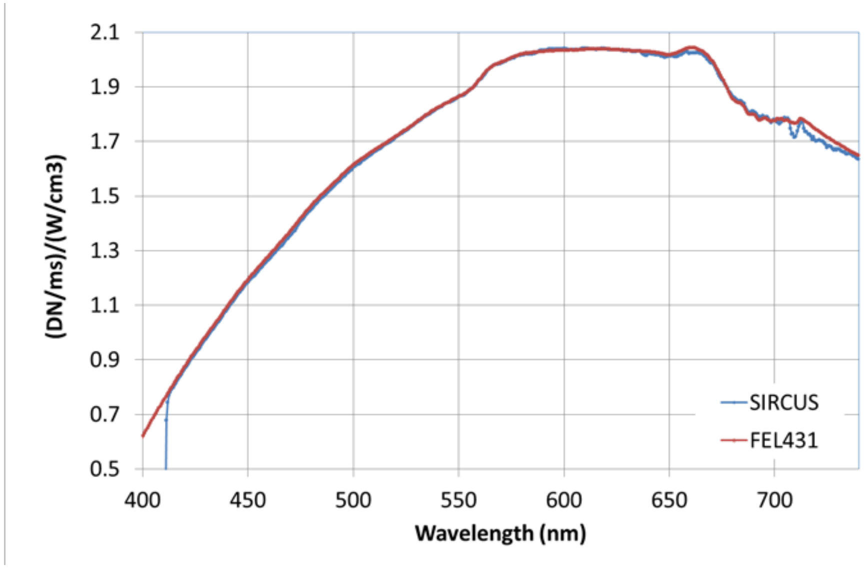


Single Pixel Spectral Response as a Function of Laser wavelength λ

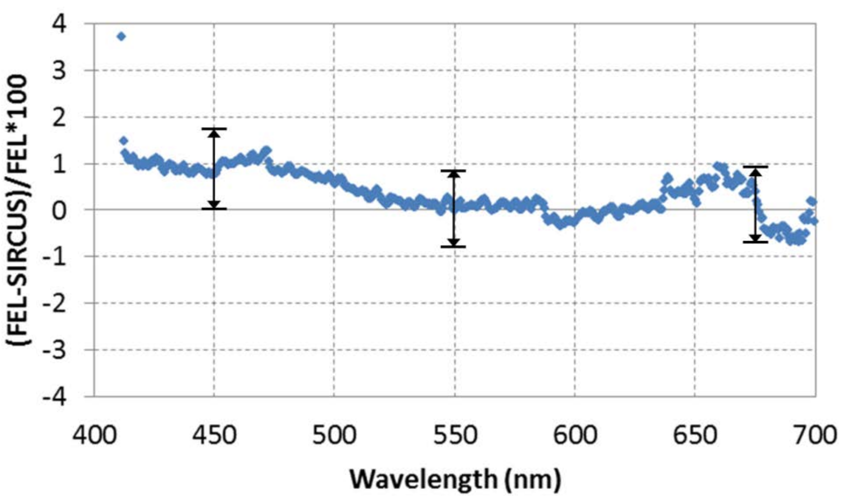


Comparison of Absolute Spectrograph Responsivity Based on Laser Calibration and FEL Lamp Calibration

Absolute Spectral Irradiance Responsivity



% Difference with FEL uncertainty bar



Summary

- A transfer standard spectrograph was characterized for wavelength, bandwidth, and stray-light using SIRCUS lasers .
- Short-term and long-term stability of the spectrograph was within the uncertainty of the Irradiance scale.
- The pixel responsivities of the spectrograph derived from laser and FEL were within the uncertainty of the irradiance scale.
- **Calibration with blackbodies which have much lower radiance/irradiance uncertainty is on going.**
- If 0.2 % uncertainty goals are reached, transfer standard spectrographs could lower the uncertainties of vendor calibration sources (both lamp-illuminated integrating spheres and FEL-type irradiance standard lamps) to ~0.5 % (k=2), achieving radiometric requirements for the laboratory calibration of next-generation Earth remote sensing satellite sensors/aircraft sensors/ground measurements of calibration targets e.g. the Moon and the Sun.

  - Current plan is to assess a group of spectrographs for their stability and uncertainties for radiance and irradiance transfer-standard both for in-house and field works.

Satellite sensor uncertainty requirements

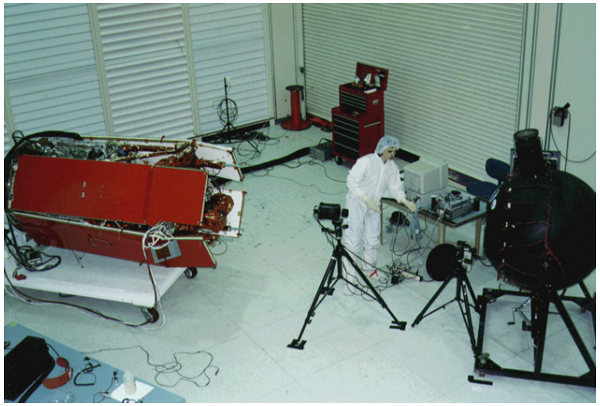
Typical at-sensor uncertainty requirements for radiometric measurements contributing to Climate Data Records (CDRs)*

- 0.5 % for Ocean Color
- 2 % for Vegetation
- 3 % for Aerosols

[*Datla, et al., J Res NIST **116** p. 621 (2011).]

Laboratory Calibration

U = 2 % to 3 %



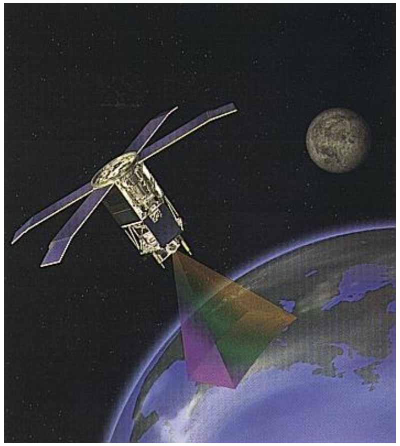
Time T=0 gain

Transfer to Orbit

U = 2 % to 3 %

Vicarious Calibration
U = 0.25 %

On-orbit Performance



Trending using the Moon
U = 0.13 %

Only way to meet
Ocean color requirements

Takes 2+ years to set the gains
Requires data reprocessing