Advances in SI-traceable Detector Standards for the Reflected Solar Region

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cal con
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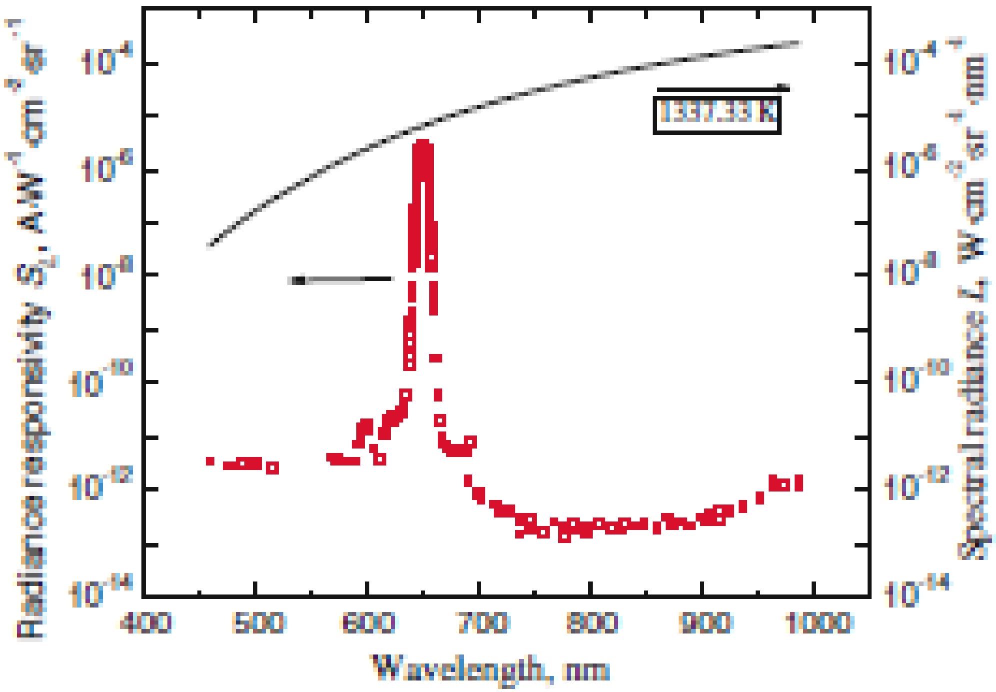
Development of Transfer and Working Standard Detectors Traceable to Cryogenic Radiometers

- Low-noise Pyroelectric Detectors
  - Calibrate in the Vis-NIR and use in the SWIR
- Replace broadly tunable SIRCUS lasers in transferring scale(s) against NIST cryogenic radiometers
  - Supercontinuum source-pumped Laser Line Tunable Filter
  - kHz repetition rate OPO
- Develop Irradiance-Mode ACR
- Working Standard Spectrographs (Si range)

Motivation

The SIRCUS facility has demonstrated that moving from source-based scales traceable to primary standard blackbodies to detector-based scales traceable to low temperature electric substitution cryogenic radiometers offer opportunities to reduce the uncertainties in disseminated standards.

Example: Radiance Temperature Measurements

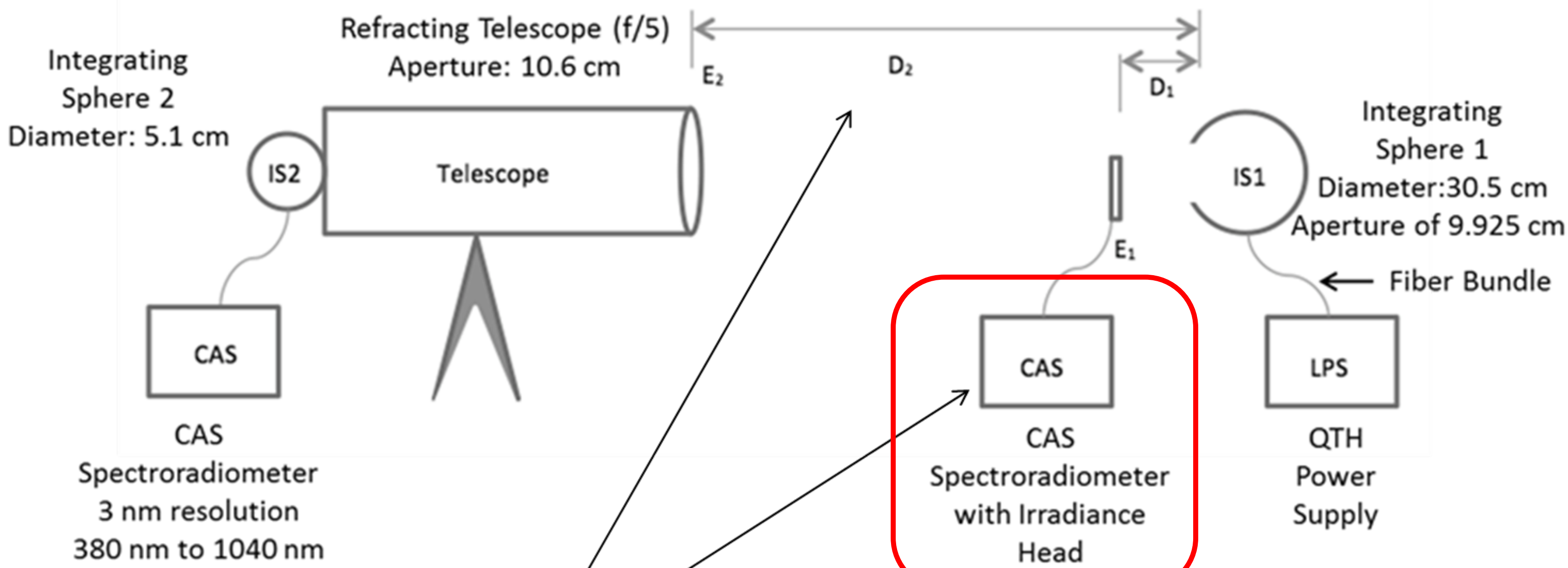


Expanded Uncertainties (k=2) ≈ 0.08 %

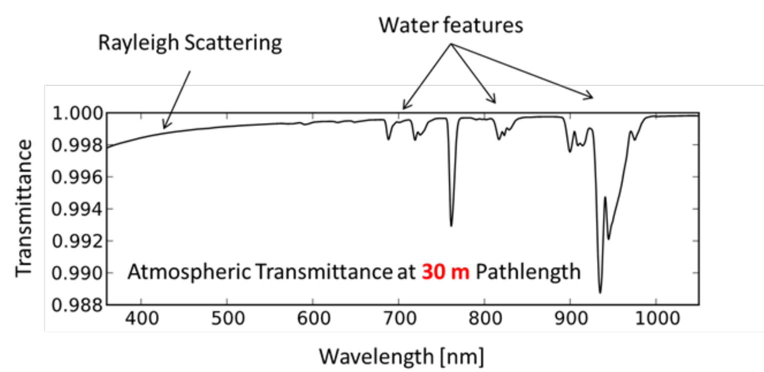
Yoon, H. W., et al., Appl. Opt. 46, 2870 (2007)

Background: **Spectrographs as Working Standards**

Came out of work at the Whipple Observatory, Mt. Hopkins, Amado AZ*



Atmospheric transmittance
Reference Instrument



Spectrographs as Candidate Working Standards

Came out of work at the Whipple Observatory, Mt. Hopkins, Amado AZ*

Spectrograph Characteristics

- CCD-based fiber-fed slit spectrograph
- 380 nm to 1040 nm, 4 nm resolution
- Temperature-stabilized CCD

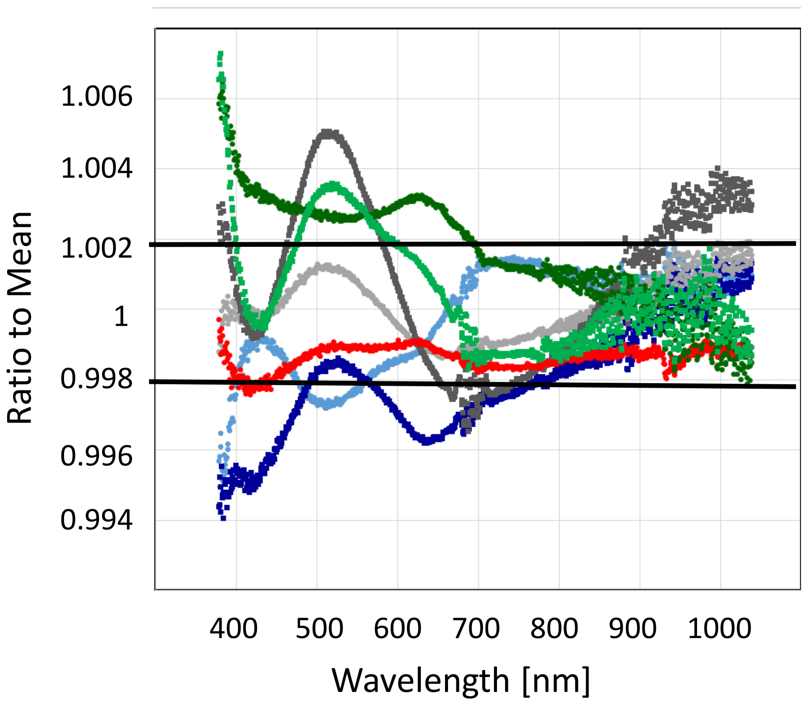
from 11/2012 – 6/2014

Deployed to Mt. Hopkins and returned to NIST several times

Event where water spilled onto the instrument – and it was left outside for a while to dry

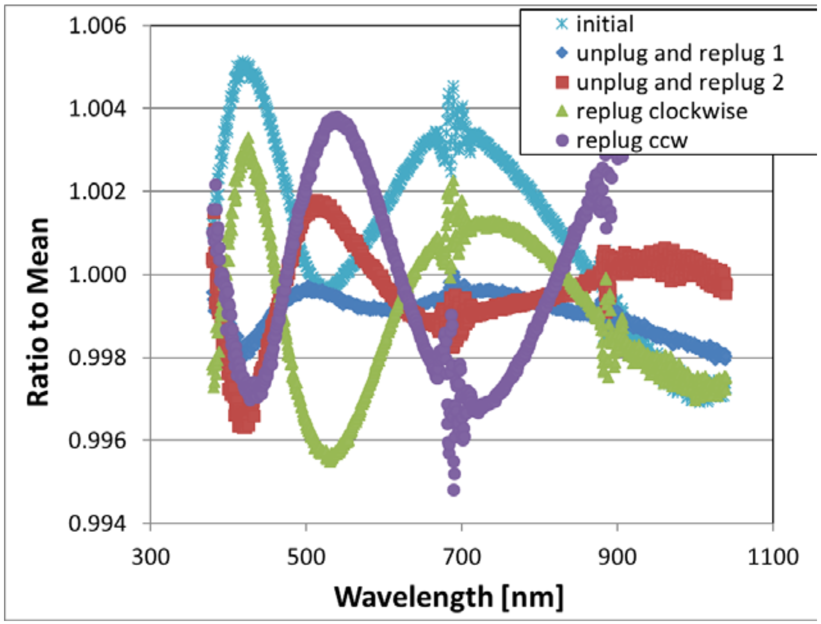
Radiometric Stability v an FEL-lamp

Calibration setup not maintained; reproduced for each measurement.

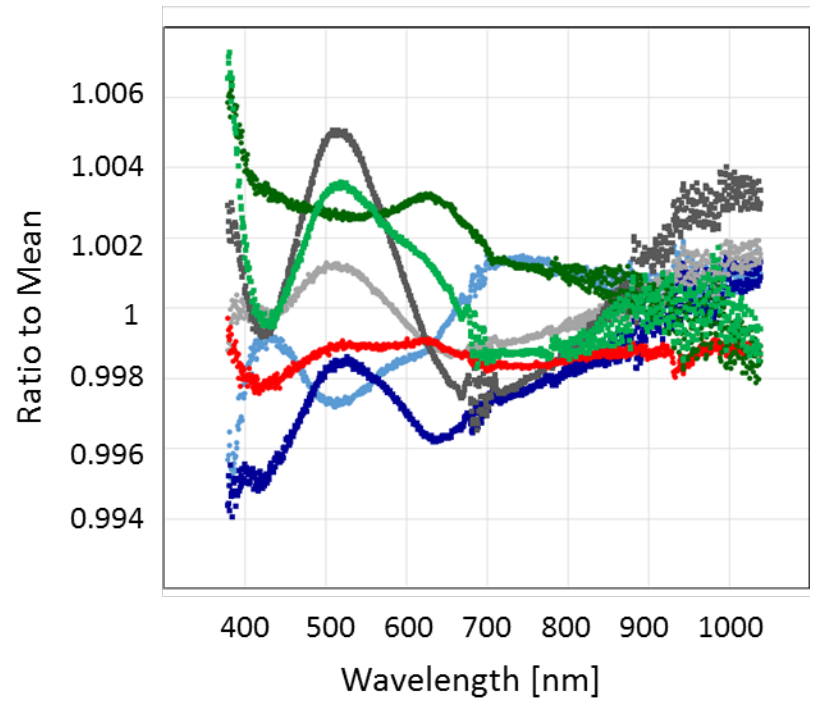


Repeatability of Fiber insertion into spectrograph

Fiber plug-in repeatability



Mt. Hopkins Stability Data



Most of the observed variability from fiber insertion into the spectrograph

Spectrograph Characterizations
to evaluate its potential for use as a Working standard

- Absolute spectral responsivity (SIRCUS)
- Wavelength scale (SIRCUS)
- Stability (FEL lamps)
- Stray light correction (SIRCUS)
- *Bandpass correction* (SIRCUS)

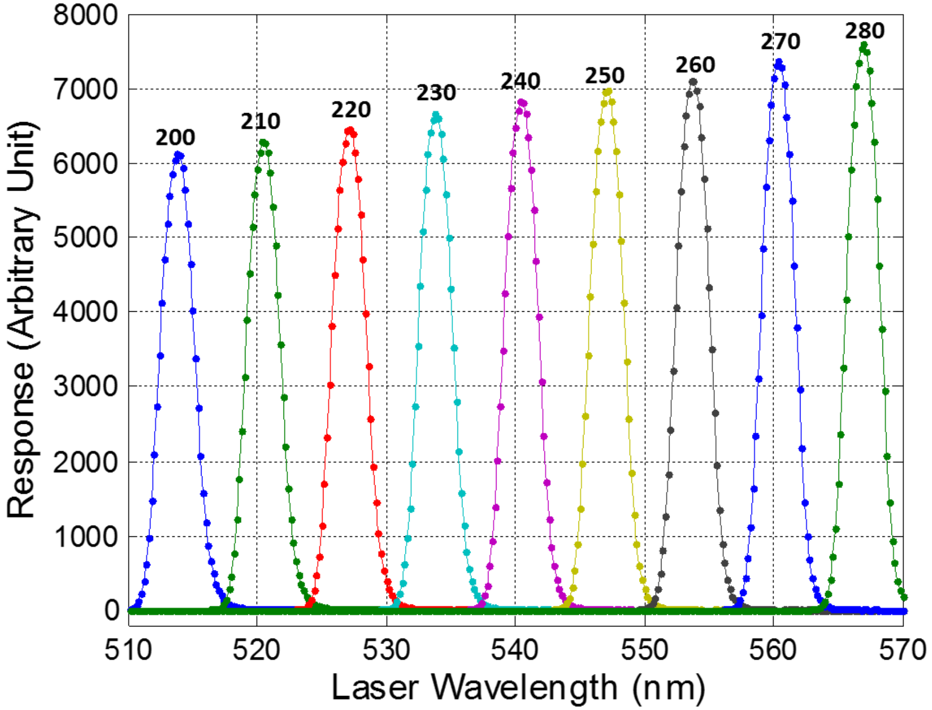
- Linearity
- Temperature dependence
- …

Absolute Calibration of a Reference Spectrograph

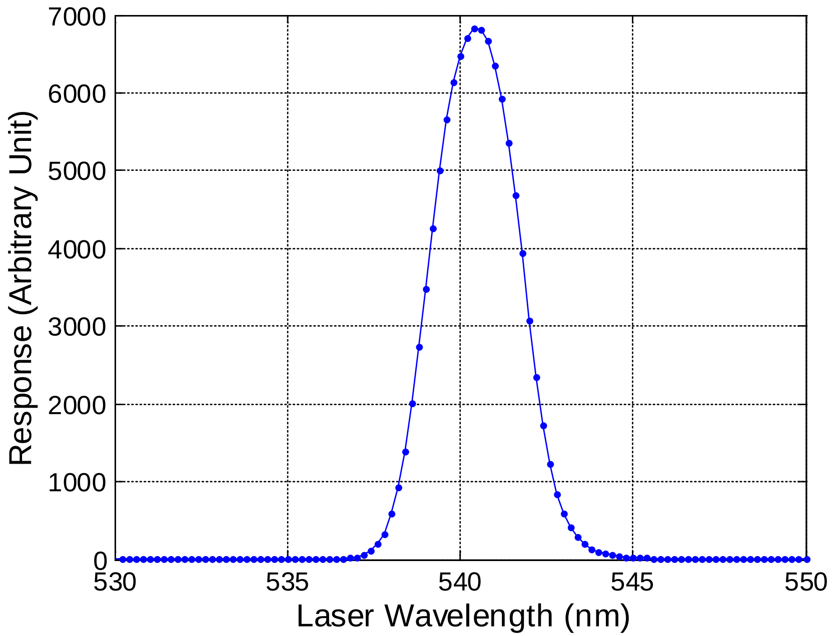
FEL-Lamp calibration often the single largest source of uncertainty
Solution: Map out the Single Pixel Responsivity of every pixel using SIRCUS

Single Pixel Responsivities

Uncertainty: 0.2 % or less (k=2) Si range

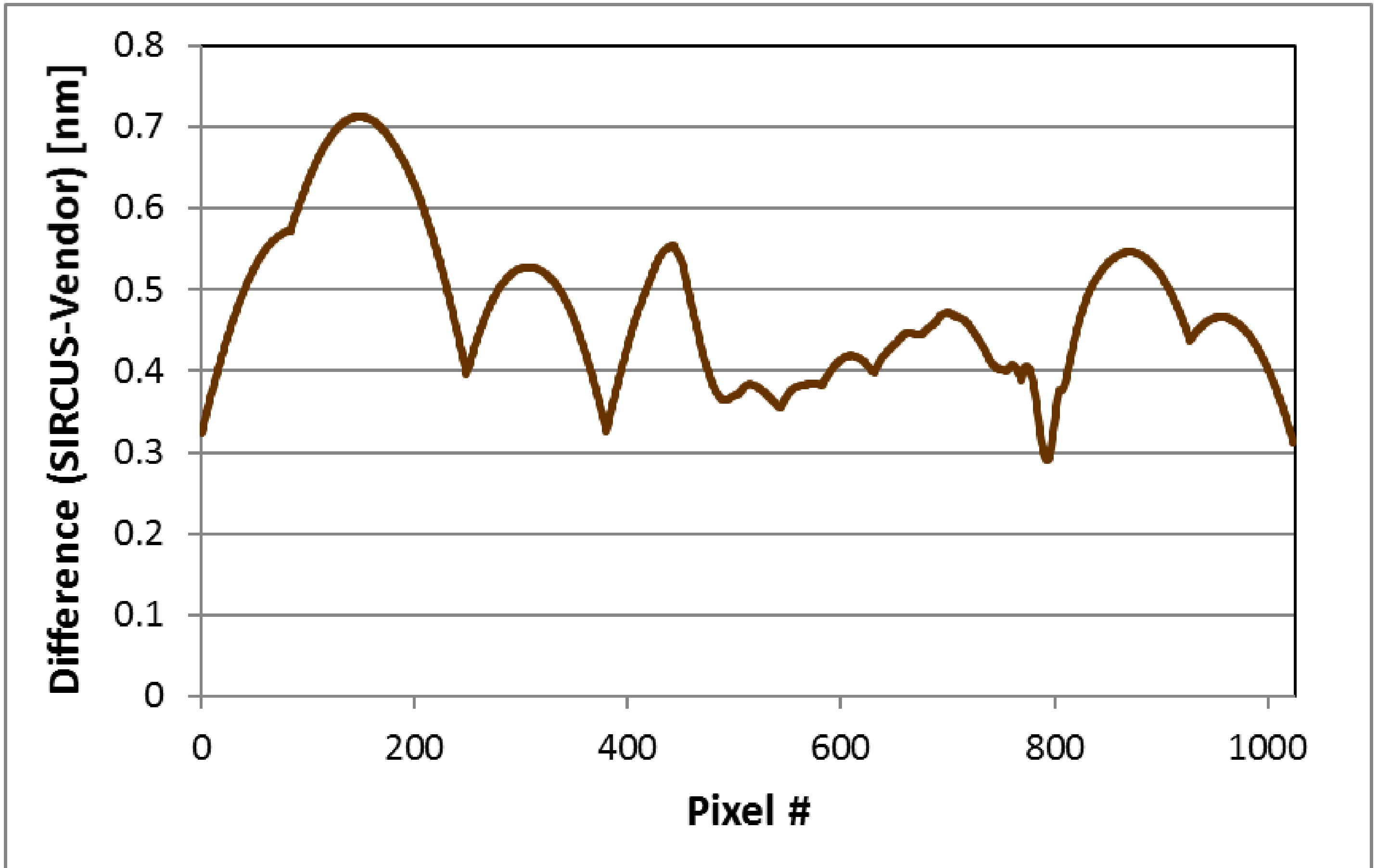


Single Pixel Spectral Response for Pixel 240



Wavelength scale Comparison between SIRCUS and the Instrument Vendor

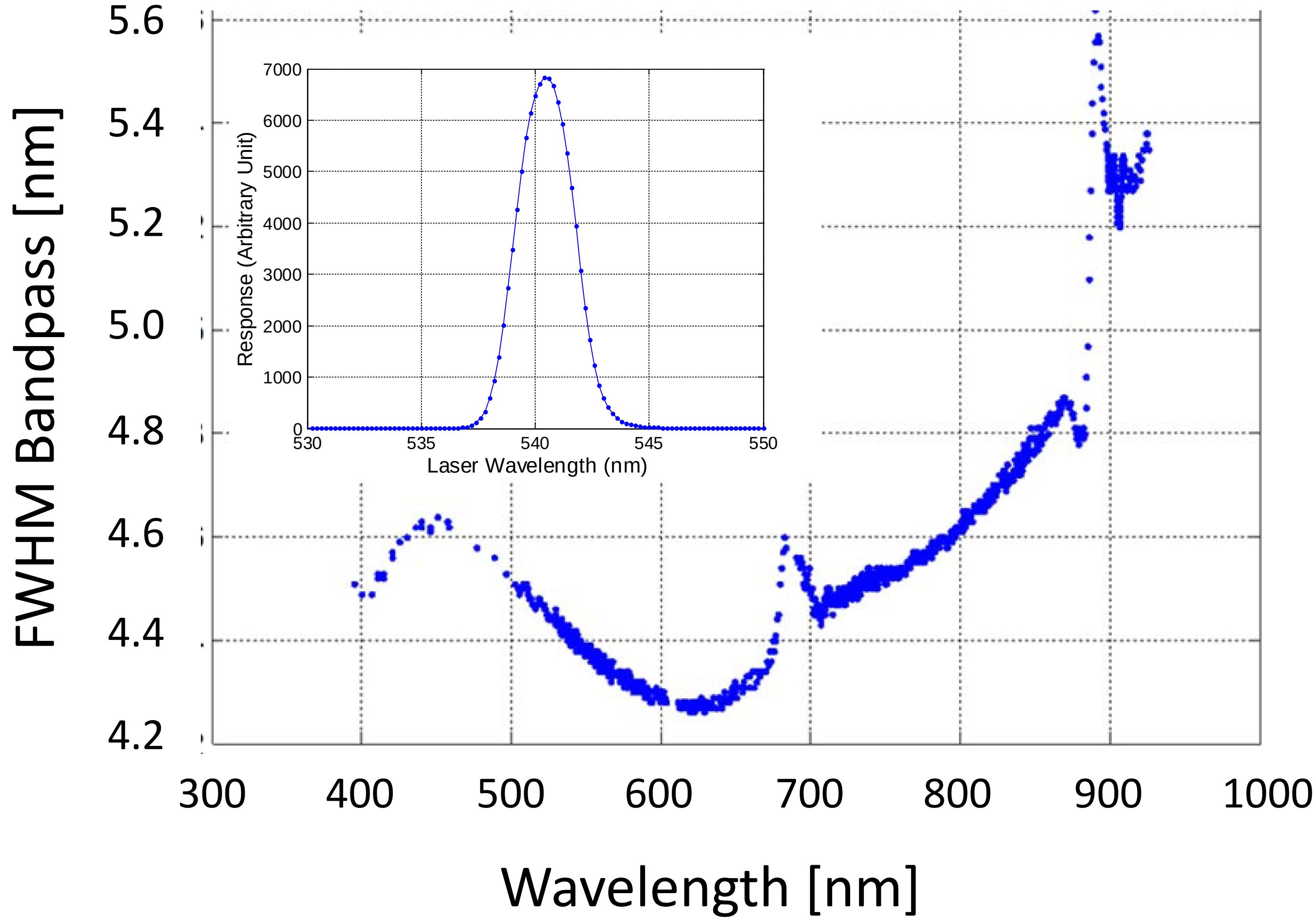
Vendor Wavelength uncertainty: ±0.5 nm



Bandwidth of a Spectrograph

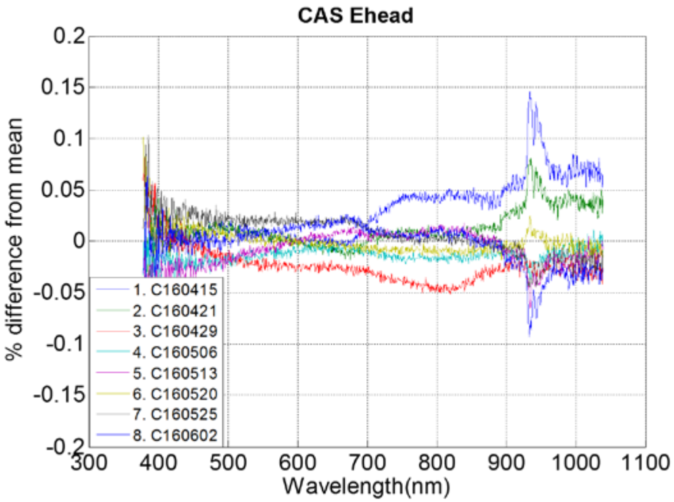
Vendor spec: 3 nm

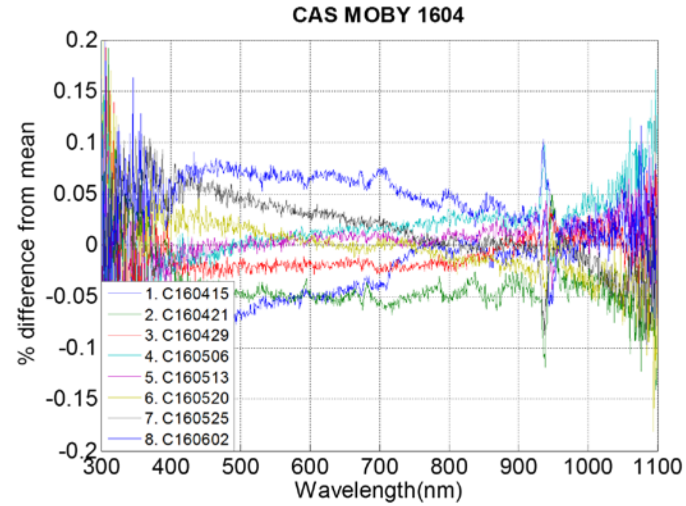
Pixel to pixel spacing ~ 0.6 nm

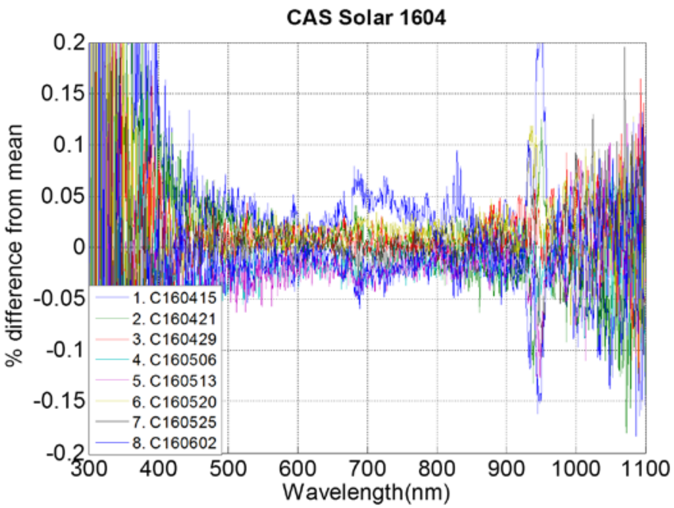


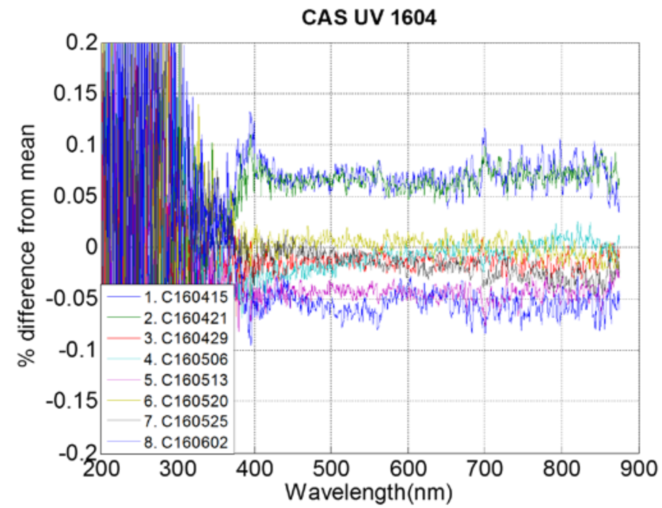
Stability measurements:

Weekly measurements with FEL lamp over 2 mos.

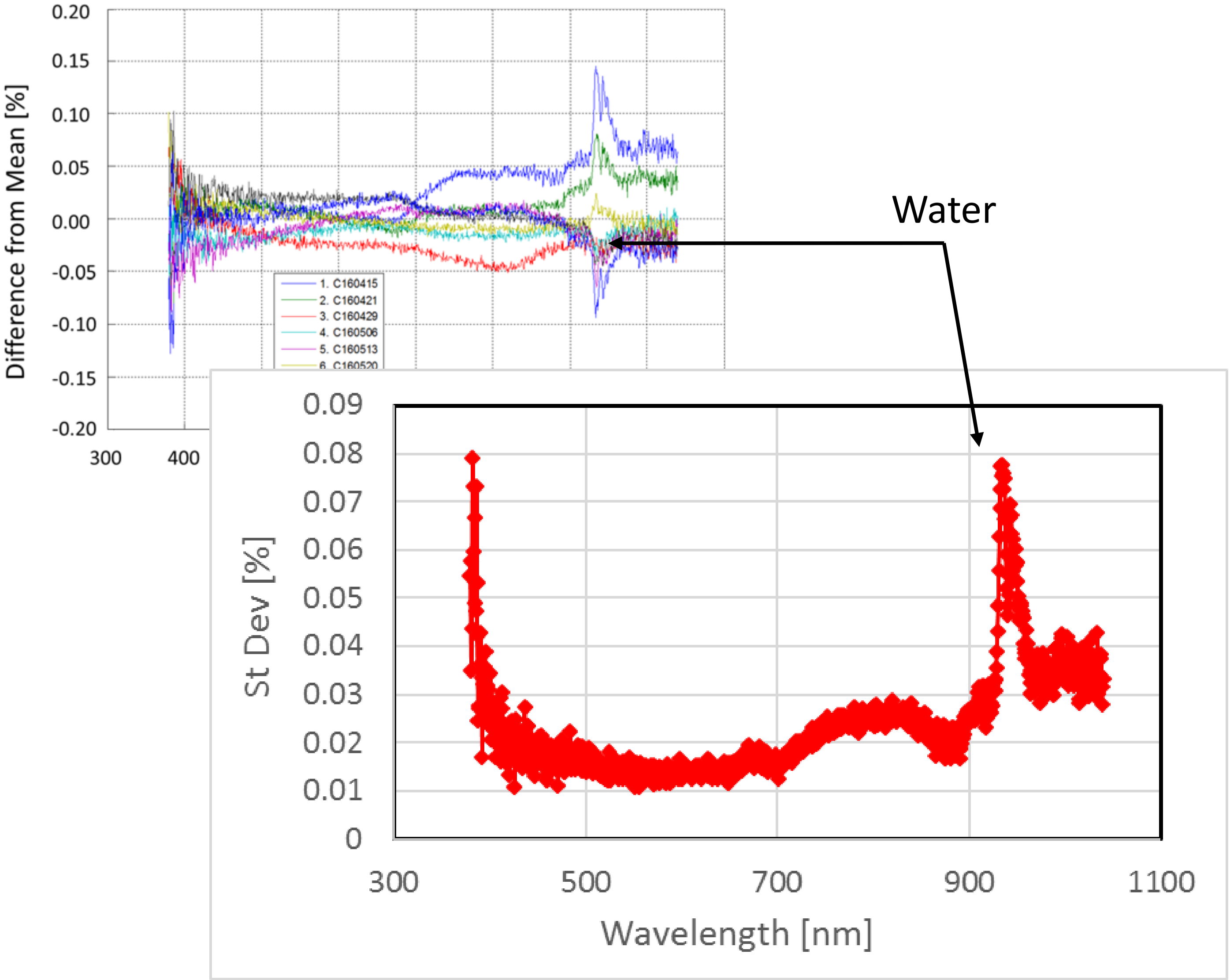








Stability measurements: E head

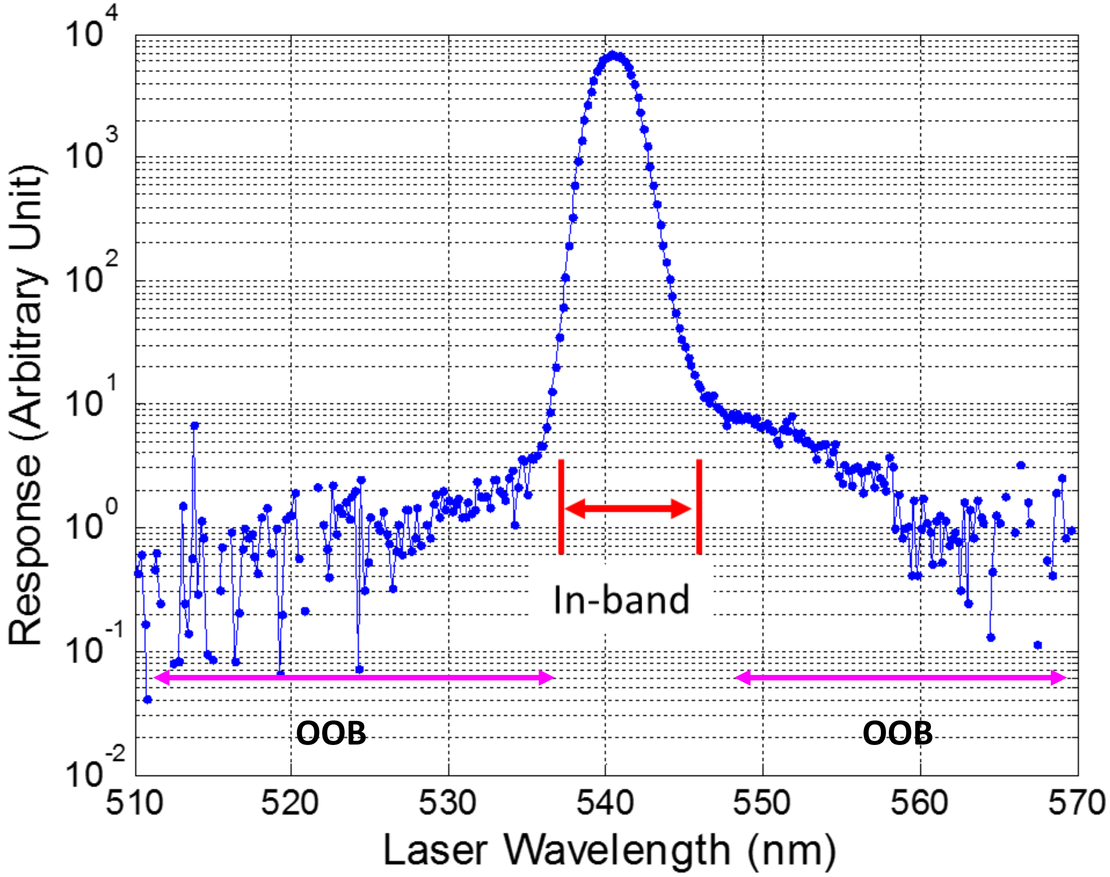


Measurements continue on a monthly basis for 6 mos. to a year.

Stray Light

Spectral Response of Pixel 240

$$S_{meas} = [I+D]S_{IB}$$

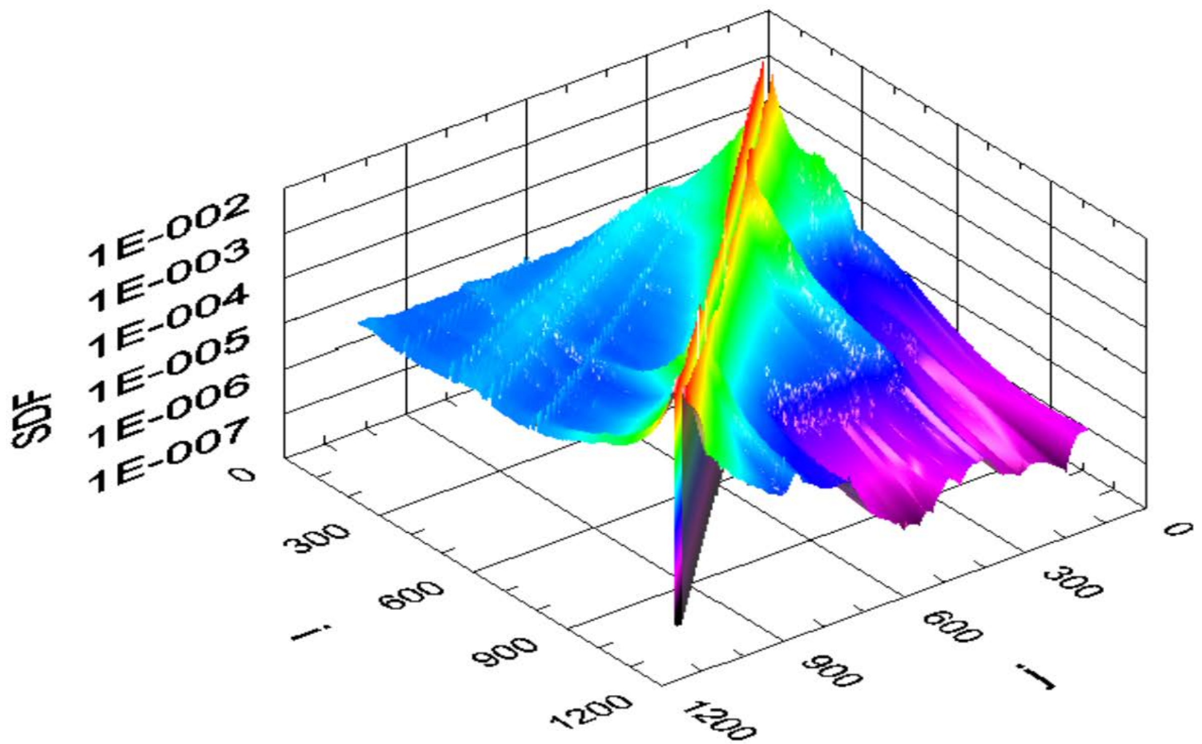


Stray light correction algorithm

$$S_{meas} = [I+D]S_{IB}$$

Stray Light Distribution Function, D

Describes the scattering properties of the spectrograph

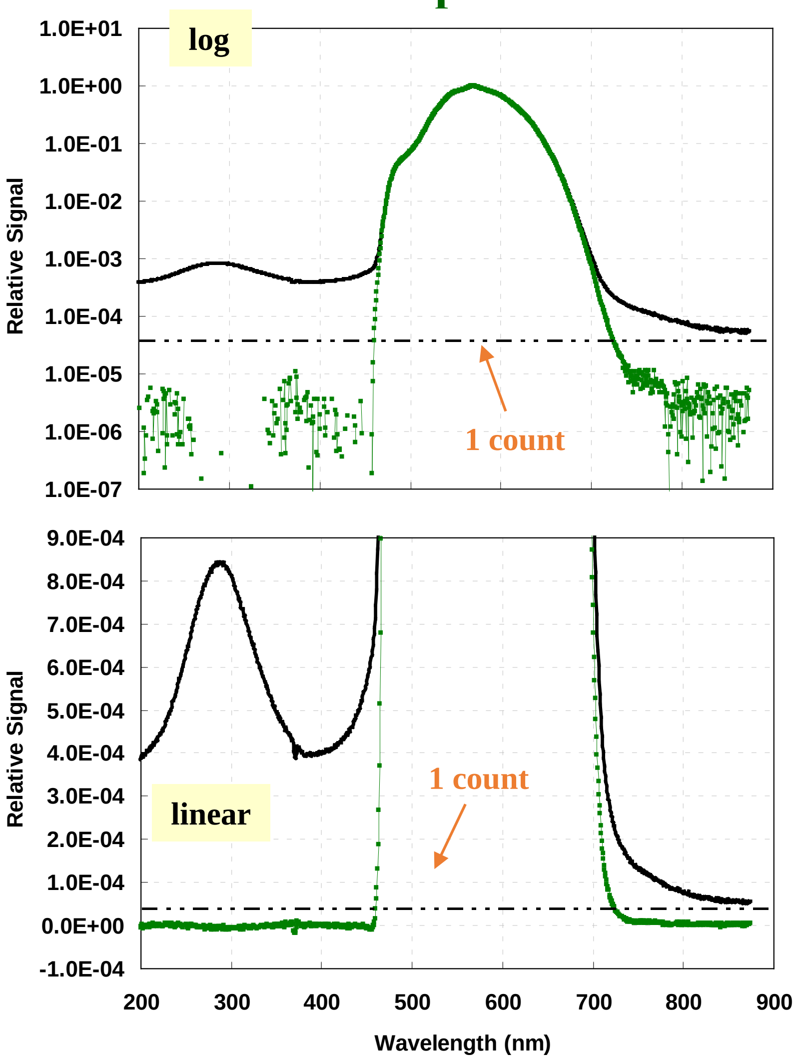


Y. Zong, et al., Simple spectral stray light correction method for array spectroradiometers, Appl. Opt. 45(6), 1111 – 1119 (2006).

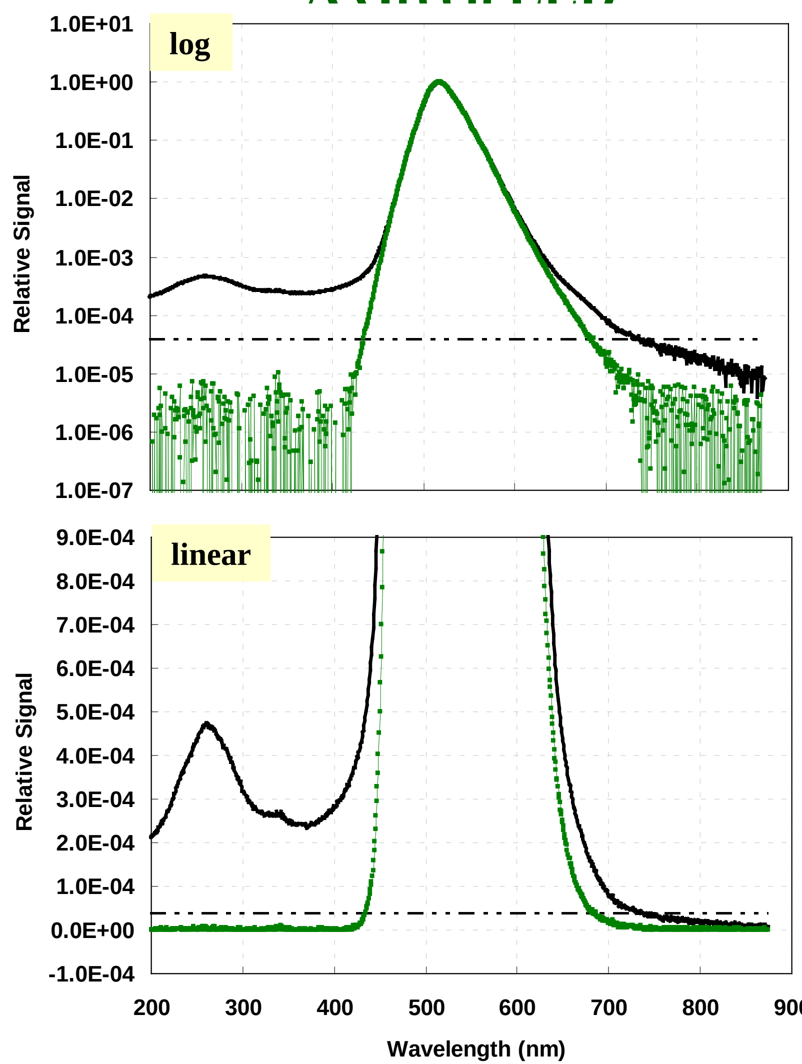
Example Results of Stray Light Correction

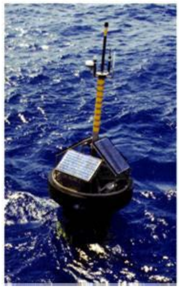
$$S_{IB} = [I+D]^{-1} S_{meas} = C \cdot S_{meas}$$

A Green Optical Filter



A Green LED





Stray Light Corrected Marine Optical Buoy (MOBY) Response

Impact on MODIS Imagery: Chlorophyll-a concentration

Courtesy of Dennis K. Clark, NOAA (ret.)

Tent

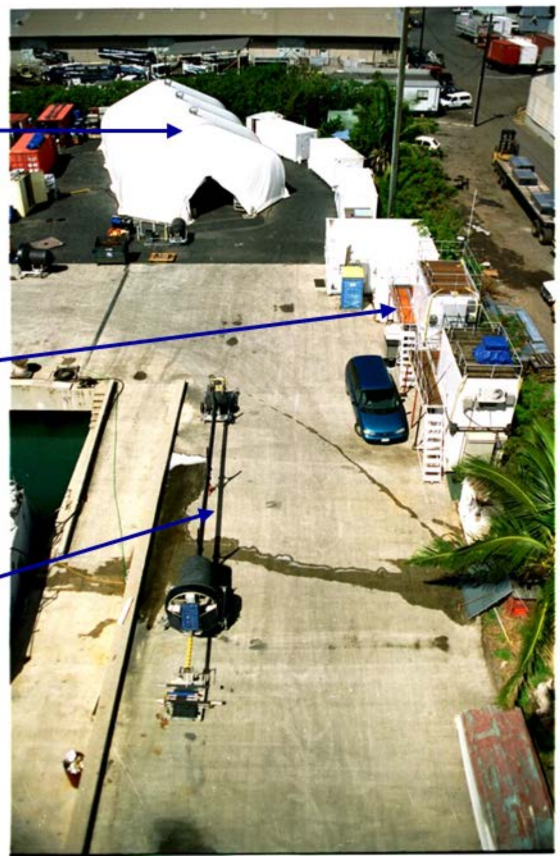
Assembly & System Calibration of MOBY

Sea Van

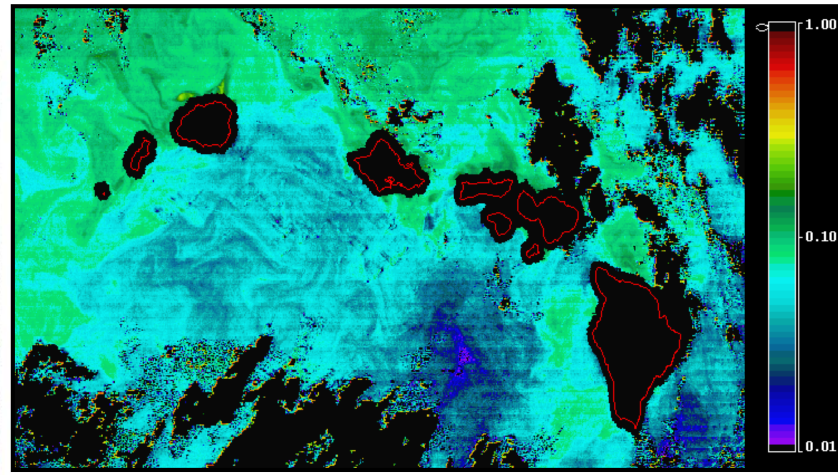
Lasers installed
Cal of MOS

MOBY

Arms fiber-optic coupled to MOS

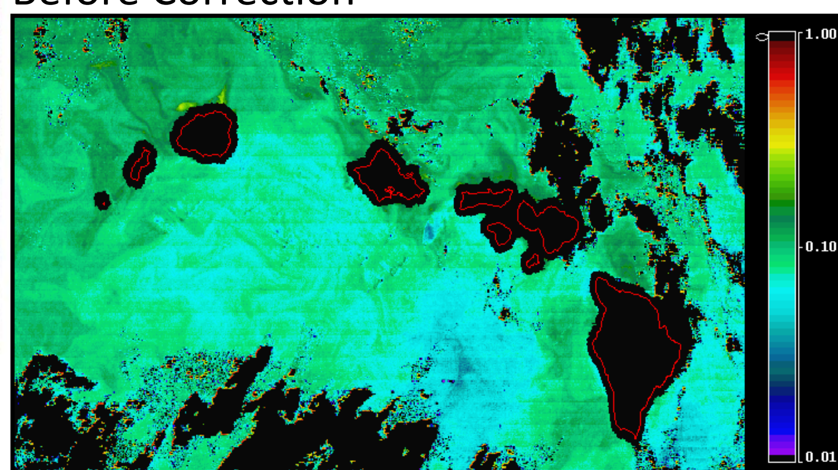


After Correction



Log of Total Chlorophyll-a

Before Correction



Log of Total Chlorophyll-a

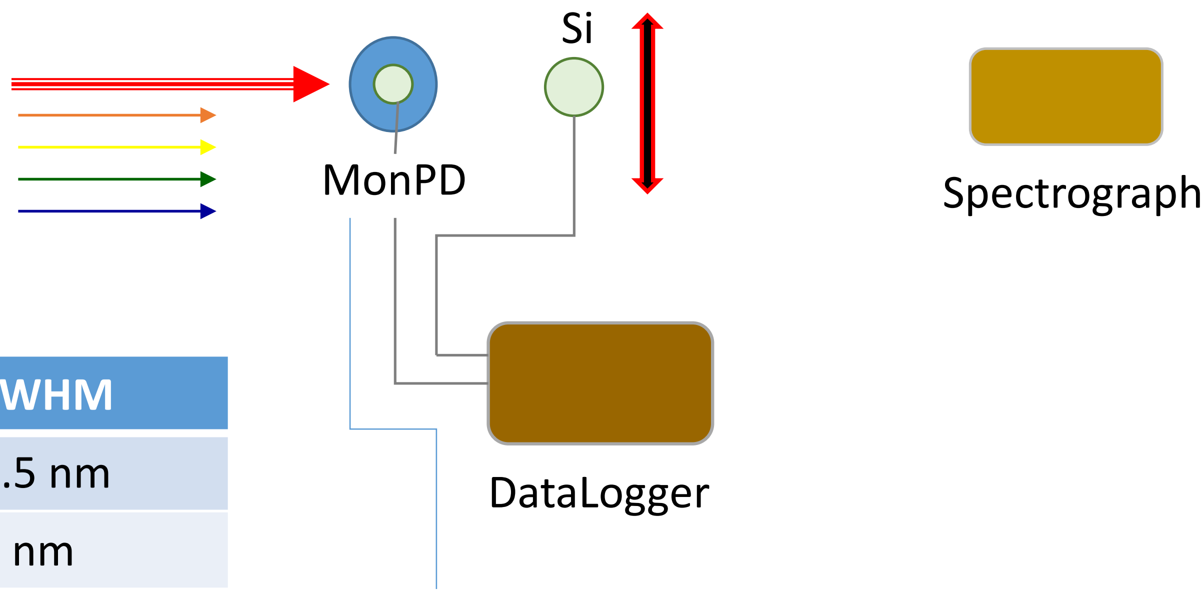
Developing Protocols to characterize and calibrate Spectrographs

Validate Instrument Responsivity in the field based on working standard detectors

Monochromatic Light from Supercontinuum Source-pumped Laser Line Tunable Filter

Vis-NIR Detector-based Scale held on Si photodiodes

Scale held on Si Working Standard Detector(s)



	Range (nm)	FWHM
Vis-NIR	400 - 1000	2.5 nm
SWIR	1000 - 2300	4 nm

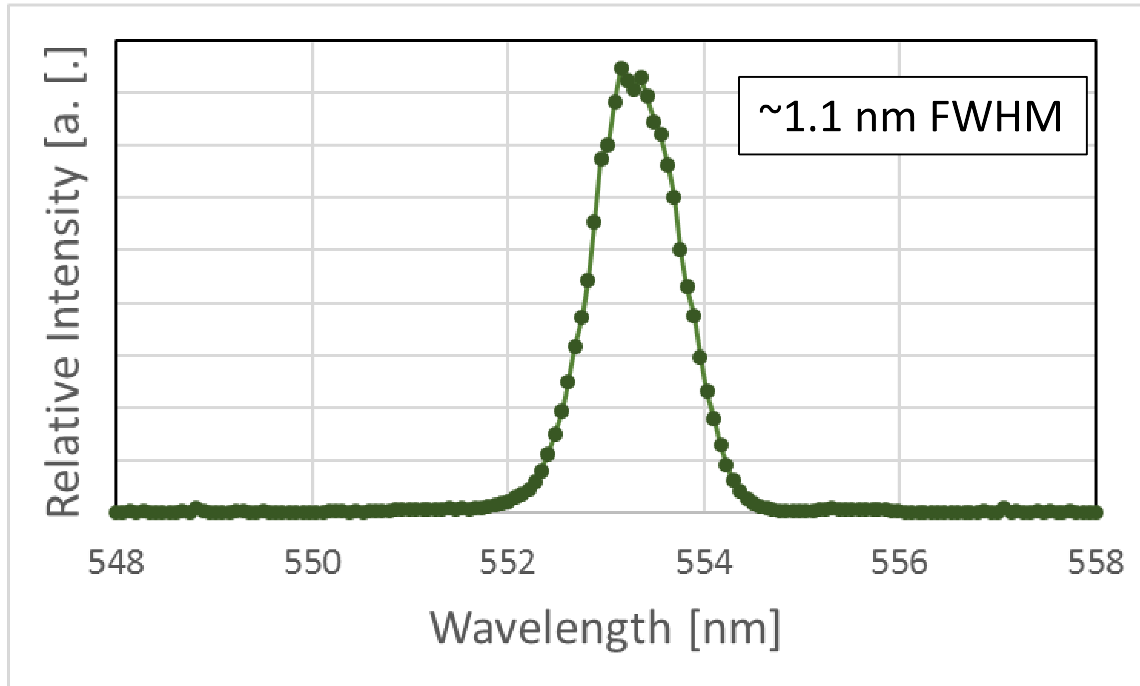
UV: replace SC source with Laser-driven Xe arc source

Wavelength scale verified by high resolution spectrograph

Validation Source
SC source-pumped LLTF

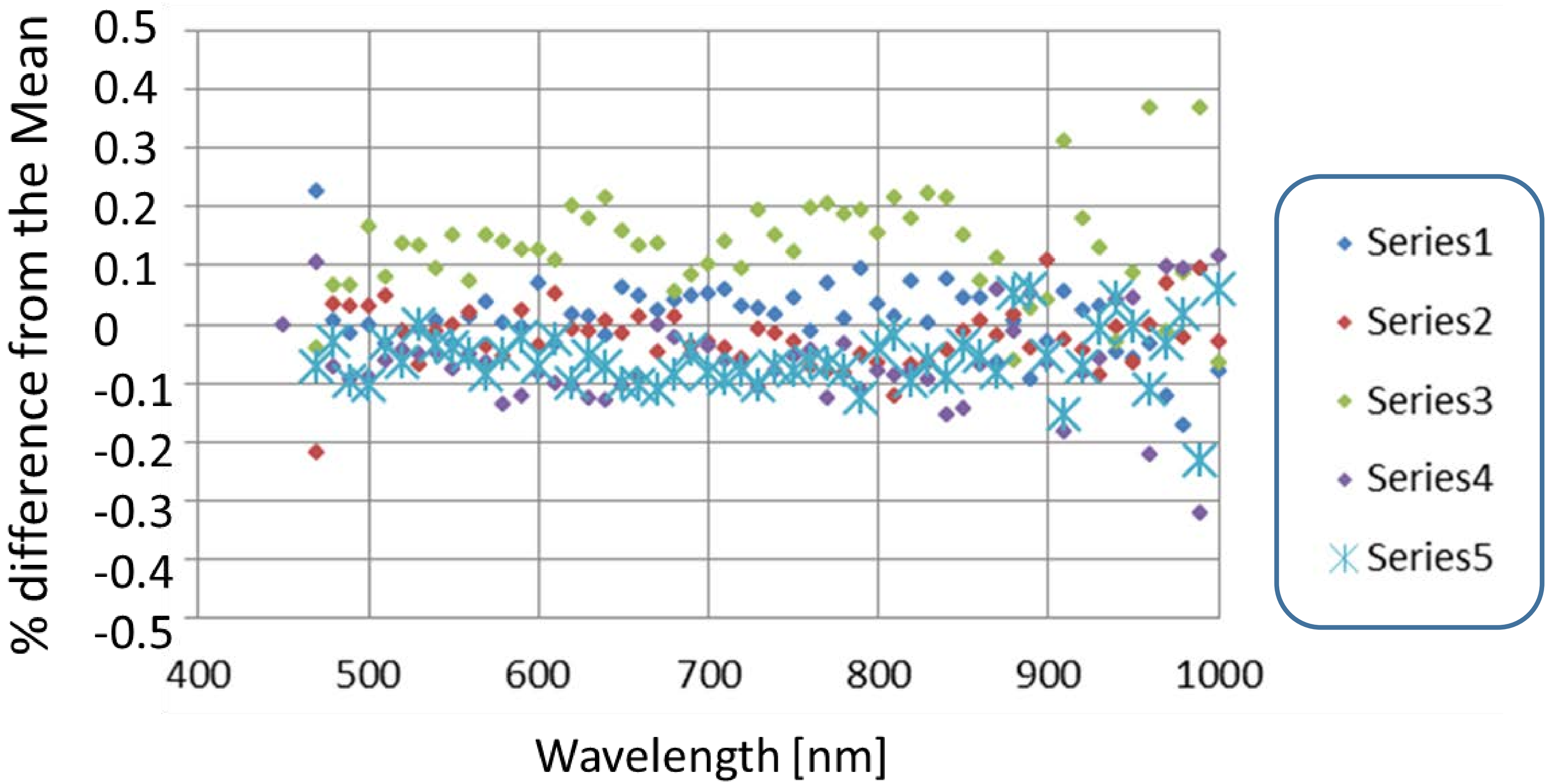
- LLTF output fiber-coupled to a 2“ integrating sphere equipped with a monitor photodiode
- Test spectrographs about 30 cm away
- Spectrograph integrates for 10 s
- Measurements from 450 nm to 1000 nm every 10 nm for 5 consecutive days.

Output of SC-LLTF source



LLTF-Based Stability

Measurements made on 5 consecutive days



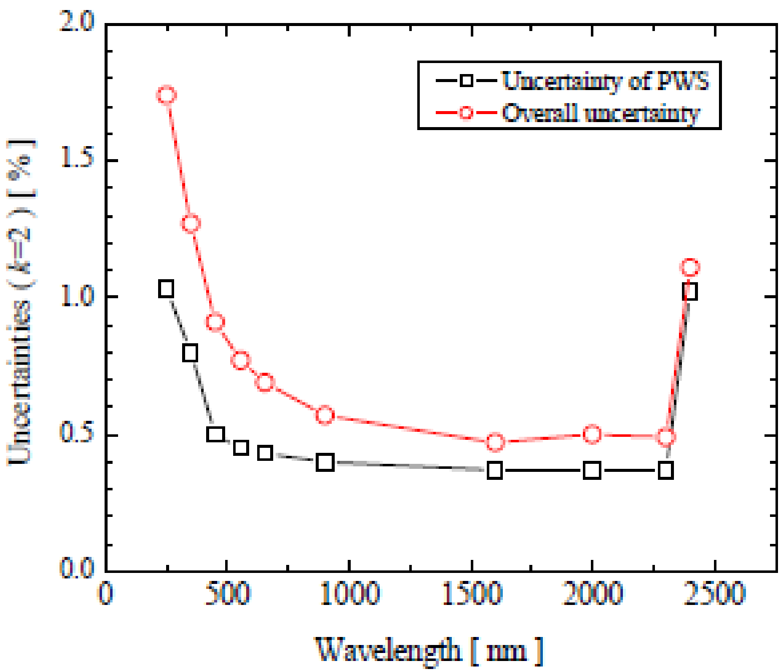
Uncertainty Estimate

Component	Uncertainty (k=1) %	Uncertainty (k=1) %
Absolute responsivity	0.1	0.2
Wavelength	<0.1	
Stability	0.02	0.02
Stray light	<0.01	
Field Validation	0.05	0.1
Other	0.1	0.1
Total	**0.15**	**0.245**

May be possible to achieve 0.5 % (k=2) uncertainties for A Working Standard Spectrograph

Implications: Irradiance scale

Uncertainty in NIST Irradiance Scale
Disseminated Standards (FEL lamps)



Wavelength [nm]	Unc (k=2) [%]
250	1.74
350	1.27
450	0.91
555	0.77
654.6	0.69
900	0.57

Spectrograph uncertainty target: 0.5 % k=2 or less over full spectral region

H. Yoon and Charles Gibson, Spectral Irradiance Calibrations, NIST Special Publ. 250-89 (July 2011).

Implications: Radiance Scale
Potential impact on lamp-Illuminated Integrating Sphere uncertainties

- From Butler *et al.*[1] the uncertainty in disseminated radiance scales are **2% to 3%** in the Vis/NIR (silicon) region.
  - Includes uncertainties in the reference radiance meters (not negligible)
- Uncertainties in a Working Standard Spectrograph on the order of **0.2 % to 0.3 %** (k=1) or less

Using a Working Standard Spectrograph *in situ* (at the time of measurement) may reduce the uncertainties in the disseminated Radiance Scale an order of magnitude, to a level that meets or exceeds most satellite sensor laboratory calibration uncertainty requirements.

Summary

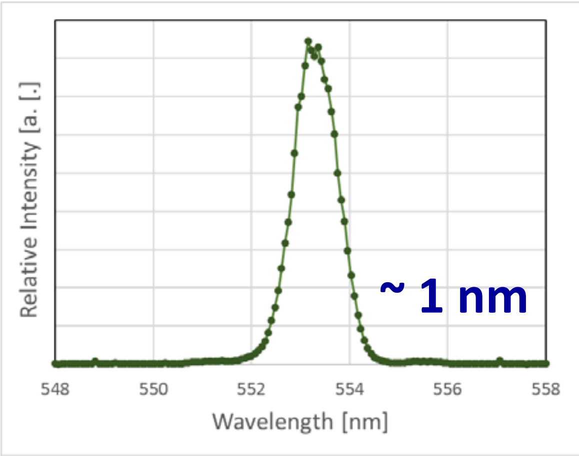
- Demonstrated the possibility of developing Working Standard Spectrographs in the silicon range
  - Expanded (k=2) uncertainty 0.5 %
- Demonstrated the field calibration/validation source based in single element working standard detectors, in this case Si
  - With a very limited set of measurements, validated the spectrograph stability with an uncertainty less than 0.1 %
- Explored the possibility of improving the resolution of a spectrograph beyond the single pixel responsivity limit
  - To the pixel-to-pixel spacing

Future Direction

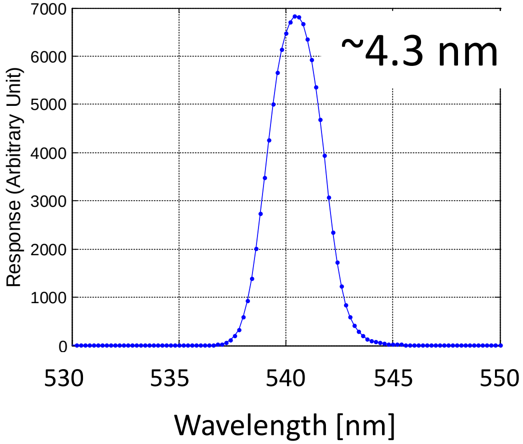
Bandpass Correction

Is it possible to have a spectral resolution below the SPR limit?

LLTF Source spectral distribution

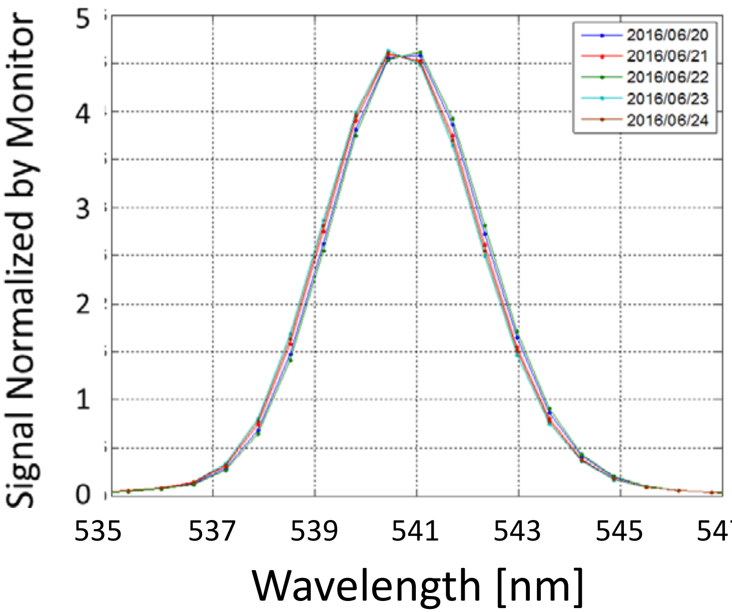


Single Pixel Responsivity



LLTF source spectral distribution measured by spectrograph

~ 4.5 nm



Bandpass Correction Algorithm

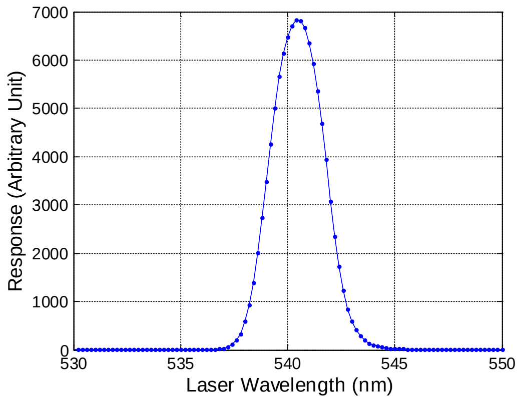
Measurement Equation after Stray Light Correction:

In-Band Responsivity collapsed along the diagonal.

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_n \end{bmatrix} = \begin{bmatrix} r_{11} & 0 & 0 & 0 \\ 0 & r_{22} & 0 & 0 \\ 0 & 0 & r_{33} & 0 \\ 0 & 0 & 0 & r_{nn} \end{bmatrix} \cdot \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_{nn} \end{bmatrix}$$

We have thrown away information about the in-band responsivity.

What if we put that information back into the Measurement Equation?



In Band-Expanded Measurement Equation after Stray Light Correction

$$S = R \cdot e$$

$$
\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \\ s_7 \\ s_8 \\ s_9 \\ s_{10} \\ s_{11} \end{bmatrix}
=
\begin{bmatrix}
z(1,0) & z(1,1) & z(1,2) & & & & & & & & \\
z(2,-1) & z(2,0) & z(2,1) & z(2,1) & & & & & \mathbf{0} & & \\
z(3,-2) & z(3,-1) & z(3,0) & z(3,1) & z(3,2) & & & & & & \\
 & z(4,-2) & z(4,-1) & z(4,0) & z(4,1) & z(4,2) & & & & & \\
 & & z(5,-2) & z(5,-1) & z(5,0) & z(5,1) & z(5,2) & & & & \\
 & & & z(6,-2) & z(6,-1) & z(6,0) & z(6,1) & z(6,2) & & & \\
 & & & & z(7,-2) & z(7,-1) & z(7,0) & z(7,1) & z(7,2) & & \\
 & \mathbf{0} & & & & z(8,-2) & z(8,-1) & z(8,0) & z(8,1) & z(8,2) & \\
 & & & & & & z(9,-2) & z(9,-1) & z(9,0) & z(9,1) & z(9,2) \\
 & & & & & & & z(10,-2) & z(10,-1) & z(10,0) & z(10,1) \\
 & & & & & & & & z(11,-2) & z(11,-1) & z(11,0)
\end{bmatrix}
\begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ e_7 \\ e_8 \\ e_9 \\ e_{10} \\ e_{11} \end{bmatrix}
$$

Knowing ***S*** and ***R***, can we solve the system of linear equations for ***e***?
What does **e** look like?

Proof-of-Principle Simulations

<u>Source Distribution</u>

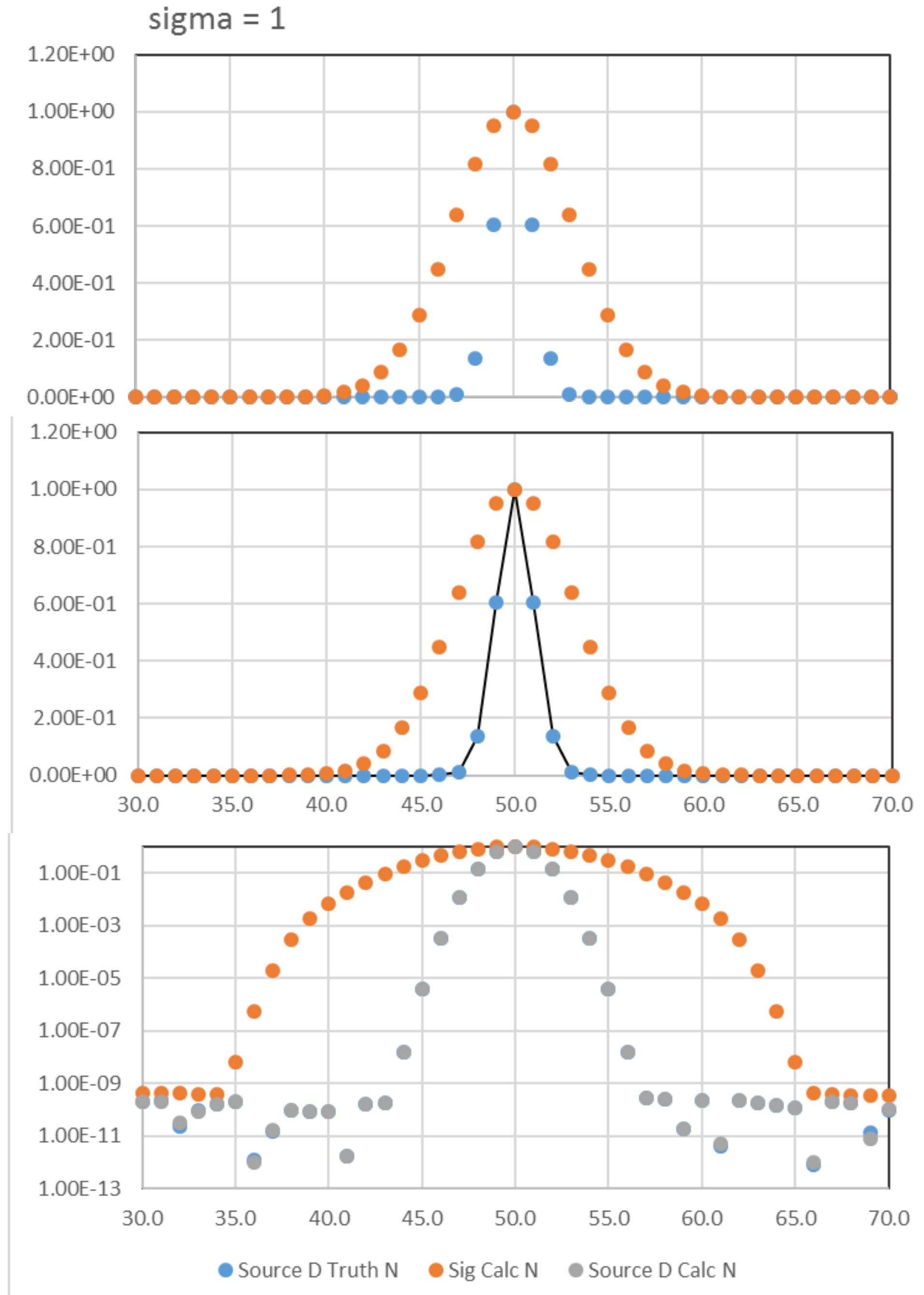
Assume a Gaussian source distribution σ=1

FWHM = 2.35*σ

<u>Single Pixel Responsivity</u>

Assume a Gaussian source distribution σ=3

FWHM = 7.05*σ



Simulation:

Look at the achievable resolution

Resolution achievable may be ~equal to the pixel-to-pixel spacing