Stray Light Correction Algorithm for Multi-channel Spectrographs

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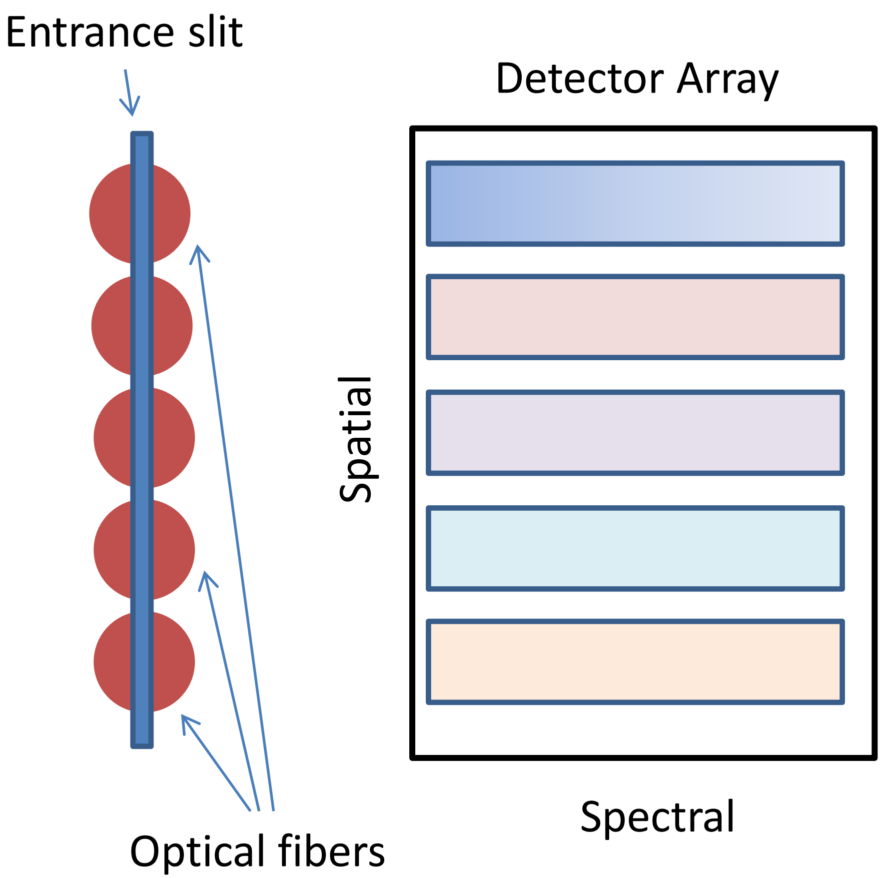
Multi-channel Spectrographs

Typical Layout

- In a conventional single-channel spectrograph, the entrance slit is imaged on the detector plane
- In a multi-channel spectrograph, the entrance slit is divided into channels for inputs from different targets
  - Simplest way to do this is to use optical fibers – often simply epoxied onto the entrance slit



Motivation for the work arises from survey of fields with applications using Multiple-input (or multi-channel) Spectrographs

- Medical imaging
  - High throughput screening
- Machine vision
  - Multi-channel process monitoring
- Remote sensing
- Astronomy

Intermediate step between 1-d SLC algorithm and full point spread response correction algorithm

Ocean Color Multi-channel Spectrograph built by Resonon for Moss Landing

14-channel spectrograph

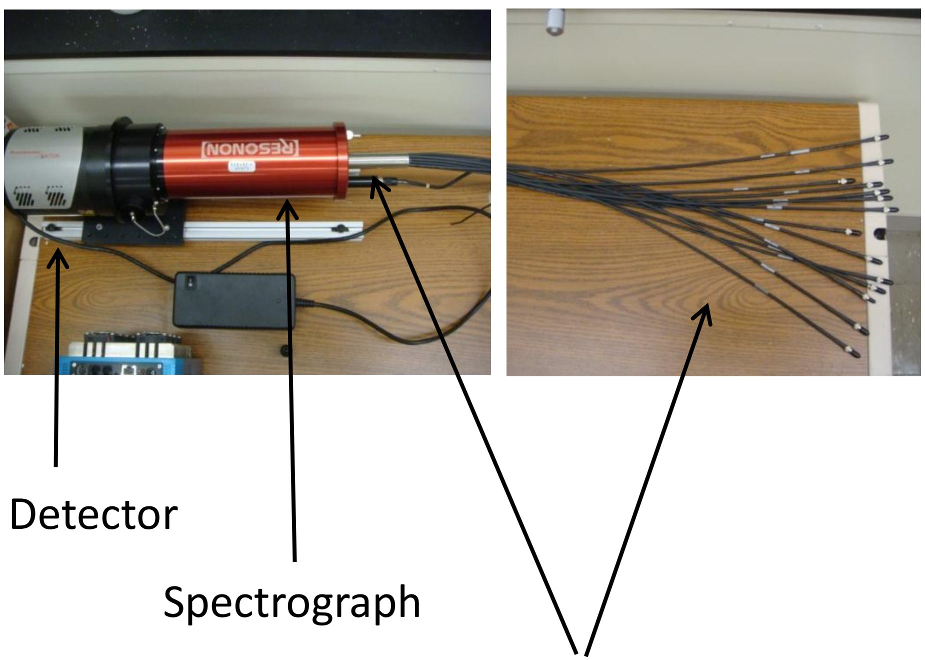
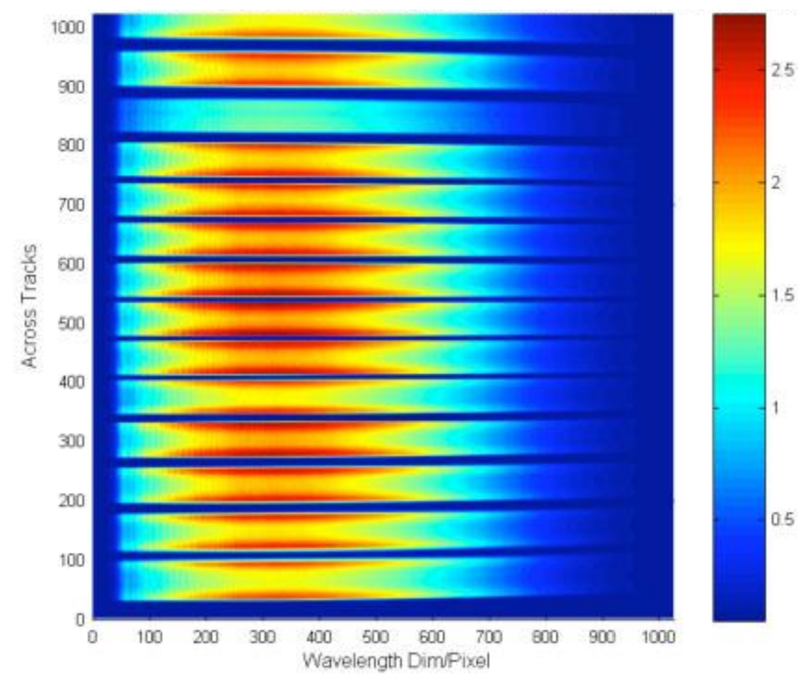
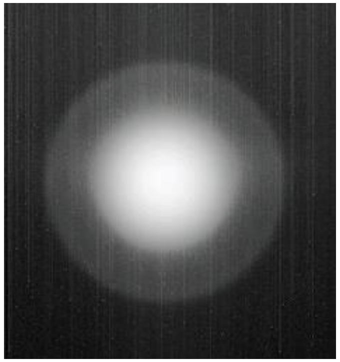


Image on the CCD from an 14-channel spectrograph



Characterization/Performance Issues

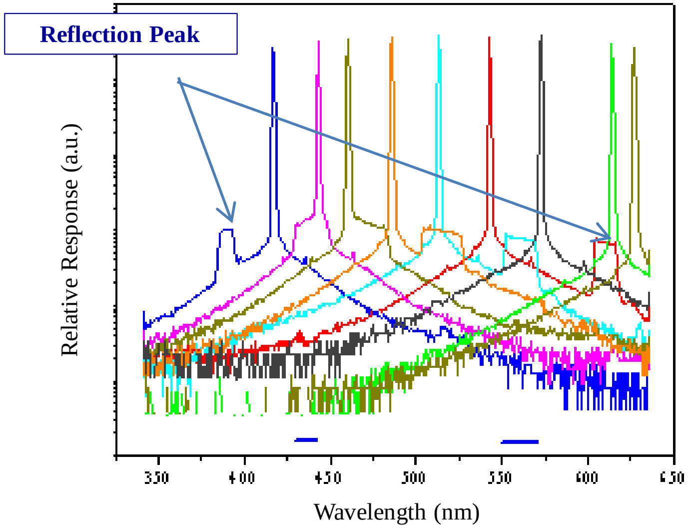
Output from a standard fiber shows an extended halo that may cause scattered light within the spectrograph



Grating scatter

Ghost image

Spurious reflection peaks



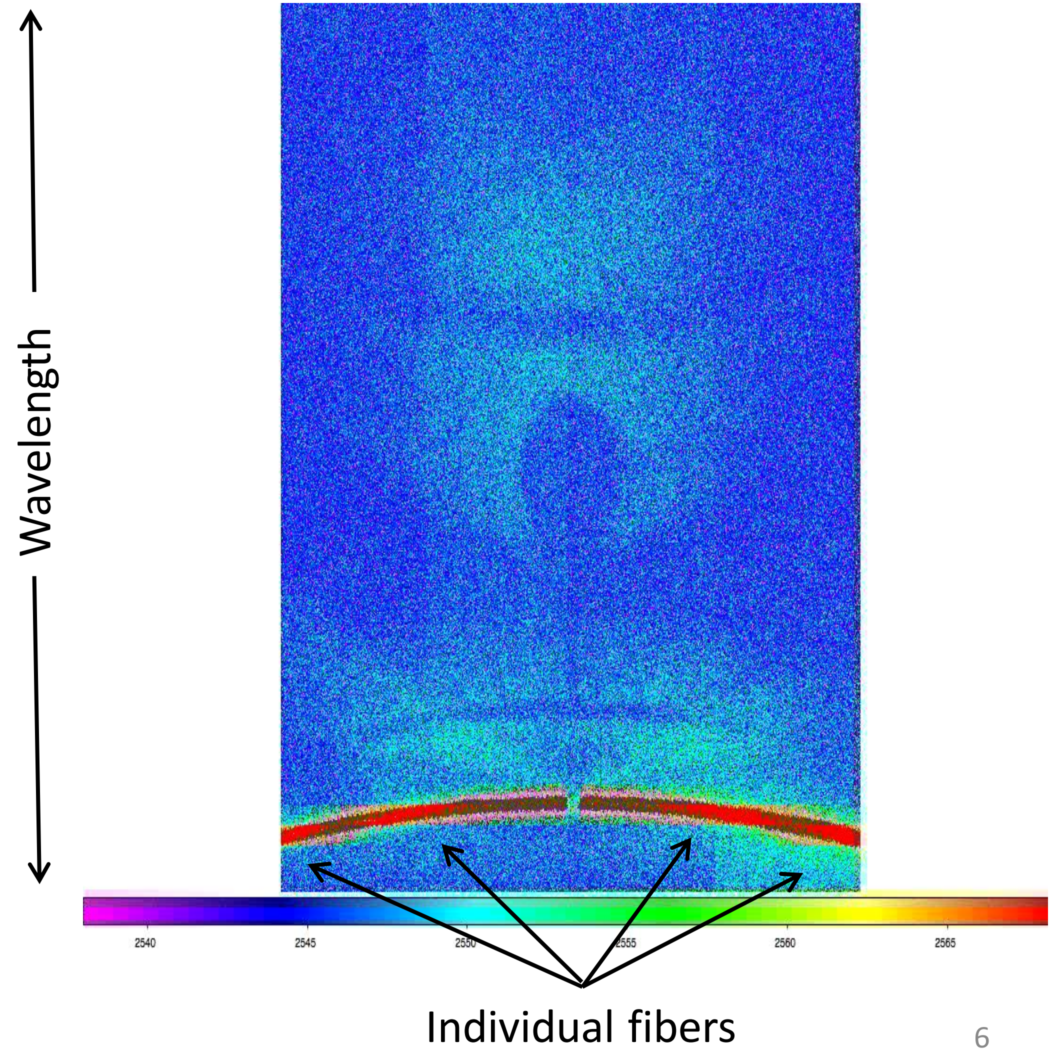
Impacts Along-track (spectral) and Cross-track (spatial) performance

Astronomy Example:
Baryon Oscillation Spectroscopic Survey (BOSS)

Movie Provided by
Claire Cramer, NIST

- BOSS has 1000 fiber inputs > "Big Boss" – 5000 inputs
- 2.5 m telescope at Apache Point Observatory, New Mexico
- Used to study large-scale structure of the universe

images, tunable laser excitation

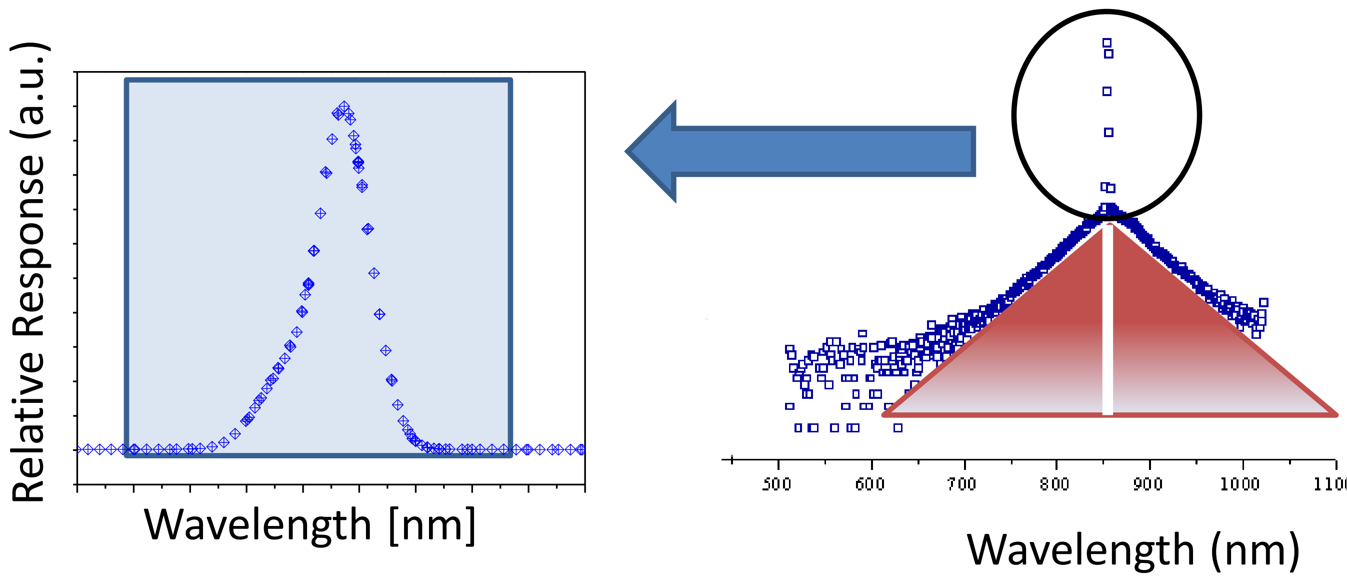


Algorithm for Single Input System: Review

$$S_{meas} = \int_{\lambda} r(\lambda) L(\lambda) d\lambda$$

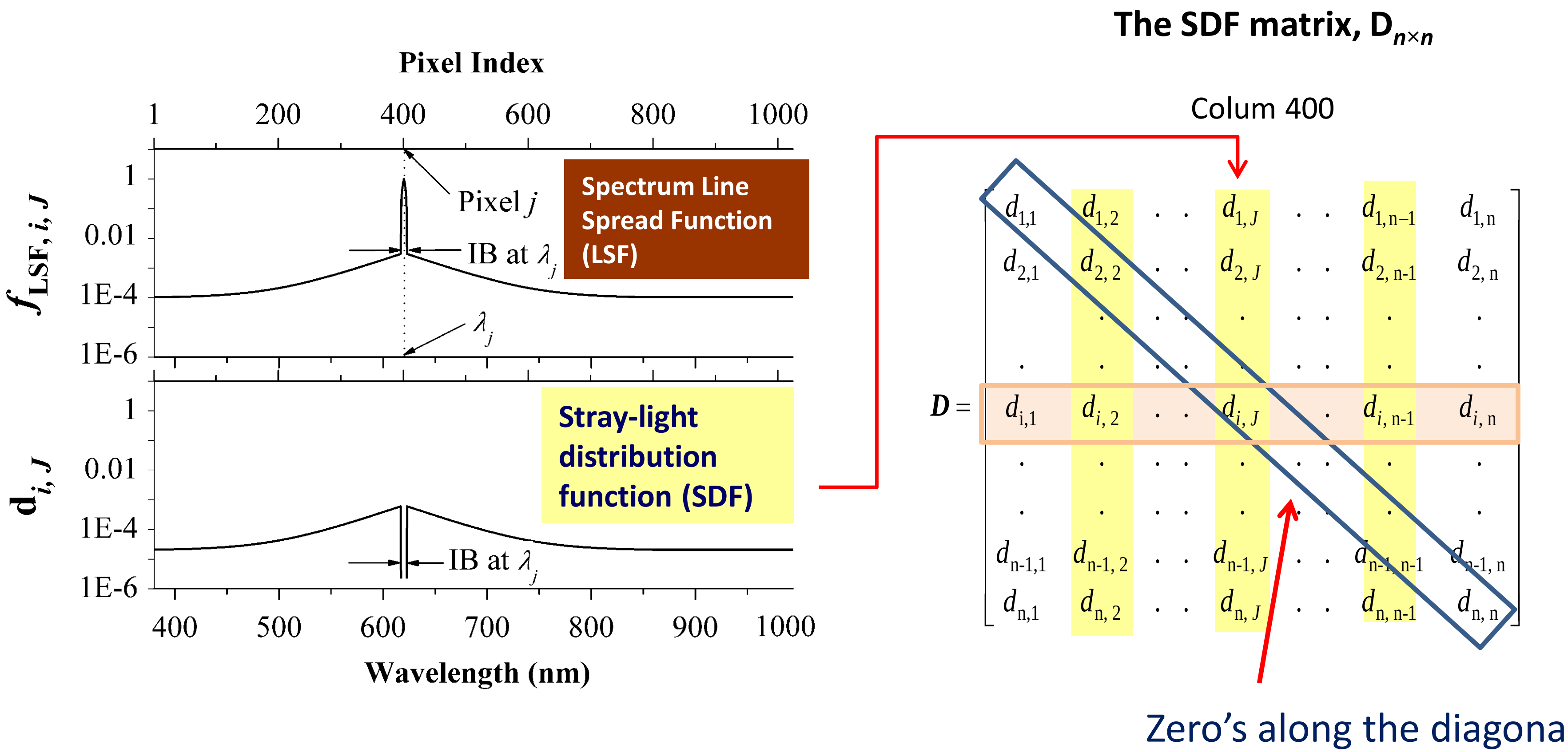
In-Band | Out-of-Band

$$S_{meas} = \boxed{\int_{ib} r(\lambda) L(\lambda) d\lambda} + \boxed{\int_{oob} r(\lambda) L(\lambda) d\lambda}$$



$$\boxed{S_{meas} = S_{\mathrm{IB}} + S_{\mathrm{SL}}}$$

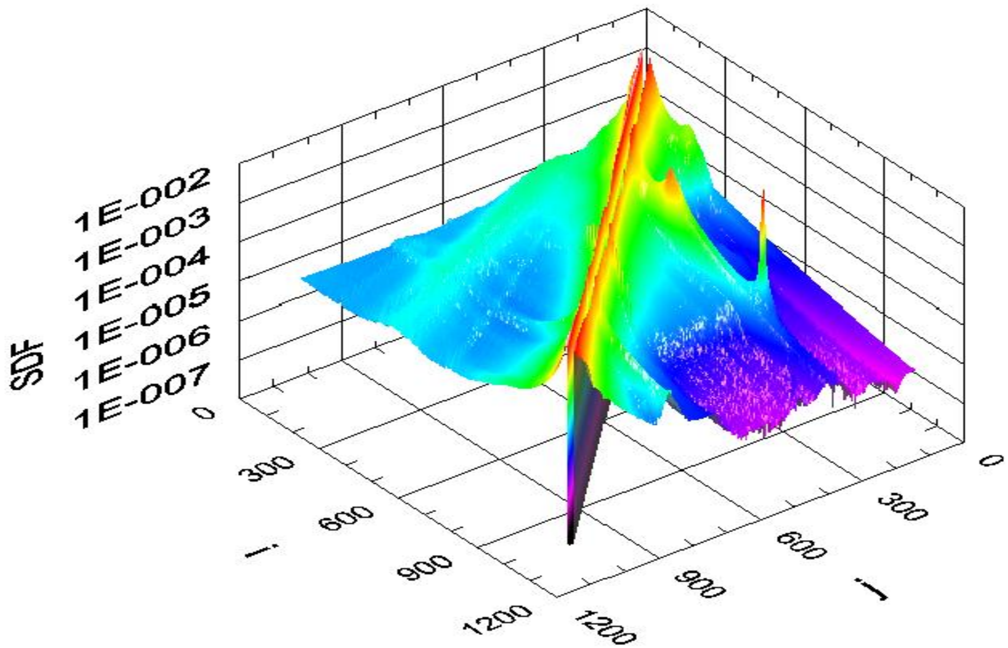
$S_{Stray\ Light}$: *Development of the SDF Matrix*



- Relative scattering from pixel *j* into all other pixels in the array
- Relative scattering from all other pixels in the array into pixel *i*

The Stray Light Distribution (SDF) matrix, **D**

$$\boldsymbol{D} = \begin{bmatrix} d_{1,1} & d_{1,2} & \cdot & \cdot & d_{1,J} & \cdot & \cdot & d_{1,\mathrm{n}-1} & d_{1,\mathrm{n}} \\ d_{2,1} & d_{2,2} & \cdot & \cdot & d_{2,J} & \cdot & \cdot & d_{2,\mathrm{n}-1} & d_{2,\mathrm{n}} \\ & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ d_{\mathrm{i},1} & d_{i,2} & \cdot & \cdot & d_{i,J} & \cdot & \cdot & d_{i,\mathrm{n}-1} & d_{i,\mathrm{n}} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ d_{\mathrm{n}-1,1} & d_{\mathrm{n}-1,2} & \cdot & \cdot & d_{\mathrm{n}-1,J} & \cdot & \cdot & d_{\mathrm{n}-1,\mathrm{n}-1} & d_{\mathrm{n}-1,\mathrm{n}} \\ d_{\mathrm{n},1} & d_{\mathrm{n},2} & \cdot & \cdot & d_{\mathrm{n},J} & \cdot & \cdot & d_{\mathrm{n},\mathrm{n}-1} & d_{\mathrm{n},\mathrm{n}} \end{bmatrix}$$



A little Matrix Algebra …

$$\boxed{S_{\mathrm{SL}} = \overleftrightarrow{D} \cdot S_{IB}}$$

$$S_{meas} = S_{\mathrm{IB}} + \overleftrightarrow{D} \cdot S_{IB}$$

$$S_{meas} = \left[I + \overleftrightarrow{D} \right] \cdot S_{IB}$$

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

$$C = \left[I + \overleftrightarrow{D} \right]^{-1}$$

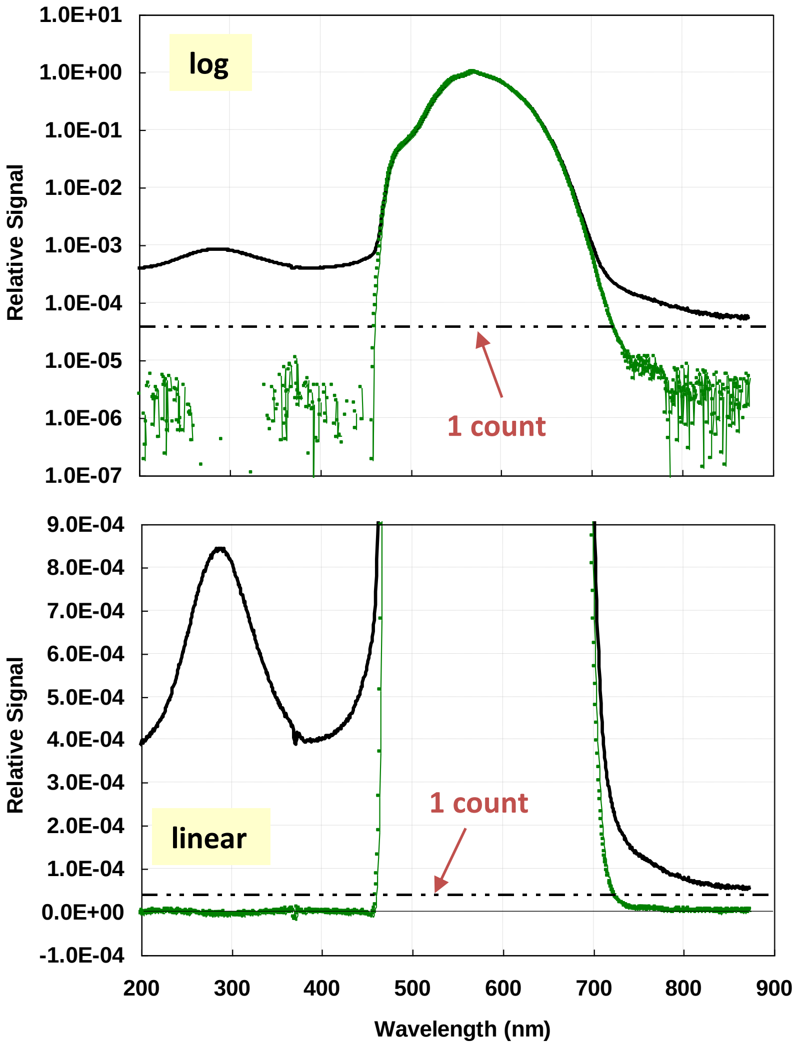
$$S_{IB} = C \cdot S_{meas}$$

"Truth"

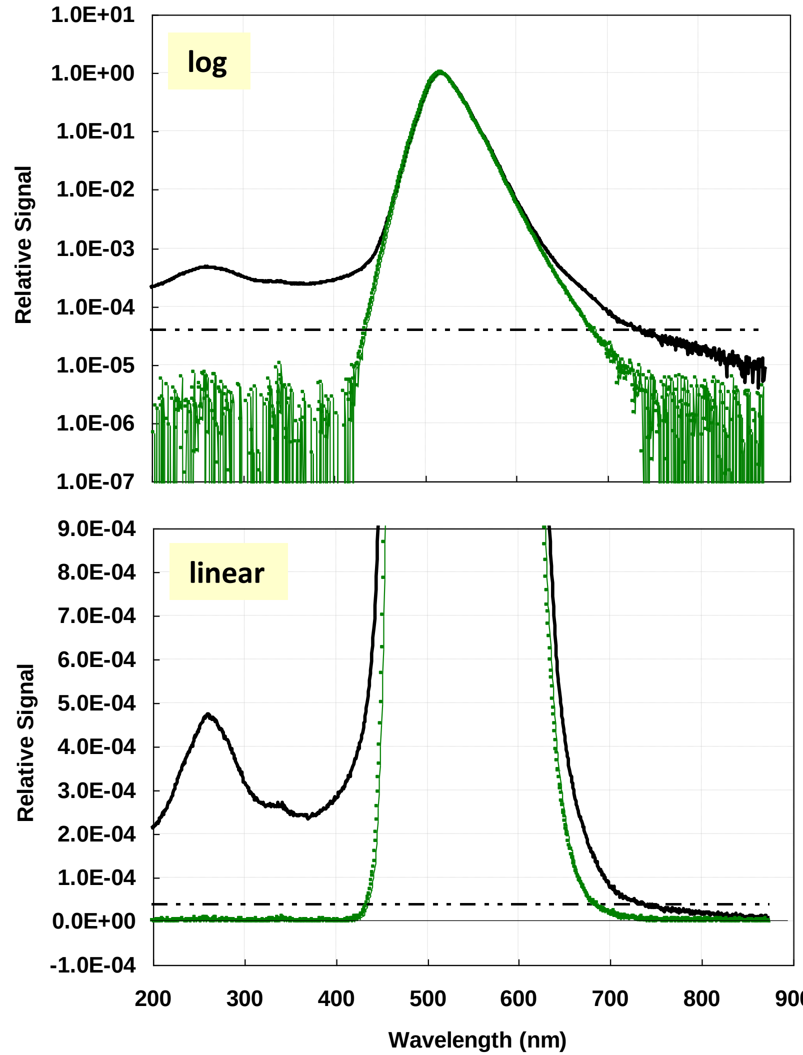
Stray-light correction matrix.

Two Example Results of Stray-light Correction

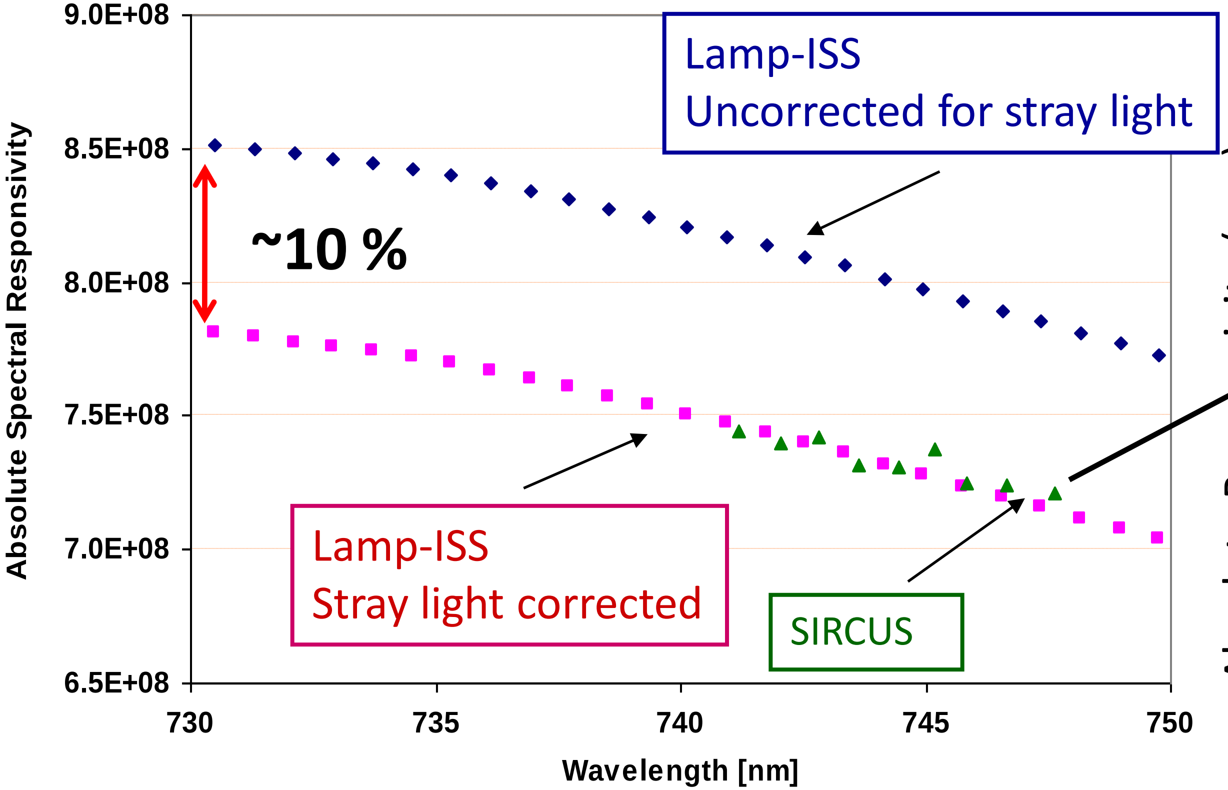
A Green Optical Filter



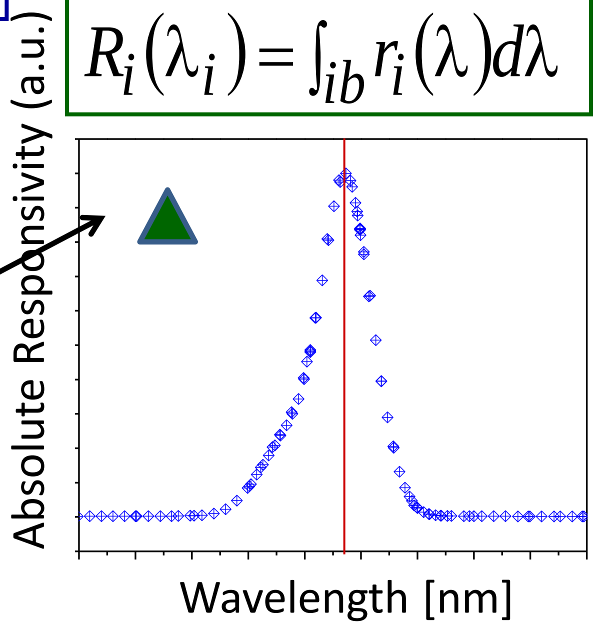
A Green LED



Magnitude of Stray Light: Broadband v. Narrowband calibrations



$$R_i(\lambda_i) = \int_{ib} r_i(\lambda) d\lambda$$



Extension of the Algorithm to a Multiple Channel Spectrograph

- Take each of the input channels and create one long nx1 matrix, where n=# of channels multiplied by the number of elements in the array (dispersion direction)
- Example:
  - For a system with 4 inputs, 1024 elements in the along track direction, the array is a 4096 x 1 array

As with the 1-d case,

$$S_{\mathrm{SL}} = \overleftrightarrow{D}\square S_{IB}$$

Only D and S now have different meanings.

Consider a 4-channel system

$$\overleftrightarrow{D}\square S_{IB} = \begin{bmatrix} \overleftrightarrow{D}_{11} & \overleftrightarrow{D}_{12} & \overleftrightarrow{D}_{13} & \overleftrightarrow{D}_{14} \\ \overleftrightarrow{D}_{21} & \overleftrightarrow{D}_{22} & \overleftrightarrow{D}_{23} & \overleftrightarrow{D}_{24} \\ \overleftrightarrow{D}_{31} & \overleftrightarrow{D}_{32} & \overleftrightarrow{D}_{33} & \overleftrightarrow{D}34 \\ \overleftrightarrow{D}_{41} & \overleftrightarrow{D}_{42} & \overleftrightarrow{D}_{43} & \overleftrightarrow{D}_{44} \end{bmatrix} \begin{bmatrix} S_{IB}^{1} \\ S_{IB}^{2} \\ S_{IB}^{3} \\ S_{IB}^{4} \end{bmatrix}$$

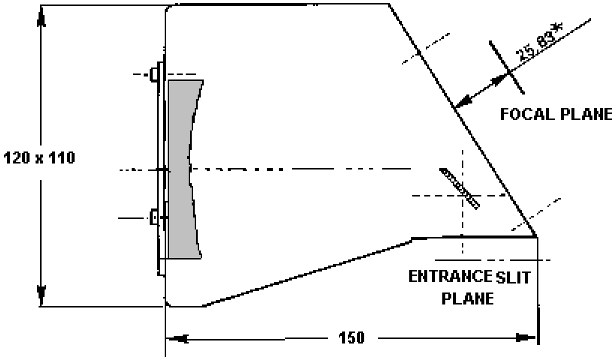
$\overleftrightarrow{D}$ matrix now comprised of sub-arrays

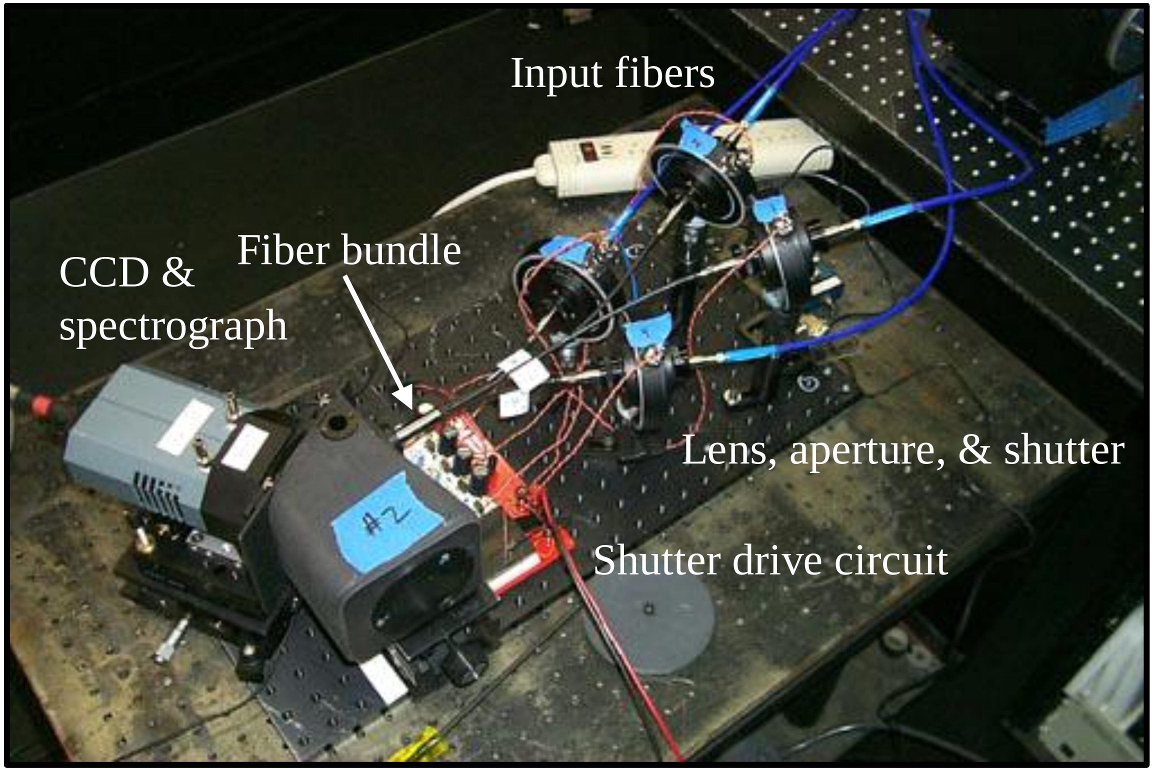
$\overleftrightarrow{D}i,i$ describes the along-track scattering

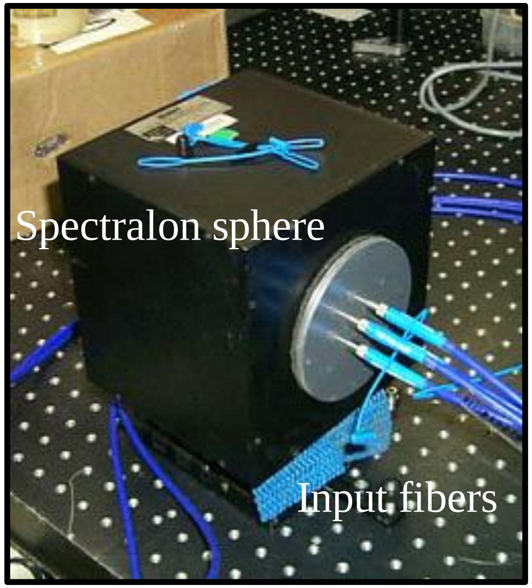
$\overleftrightarrow{D}i,j$ describes the cross-track scattering from track I into track j

Multiple Input Spectrograph System

- ISA (Jobin Yvon) f/2 spectrograph with reflective concave holographic grating; 25 mm slit
- Andor 1024x256 cooled CCD array, 25 mm pixels
- Breadboard system had 4 1 mm fibers separated by ~500 mm







4-Channel Input into Spectrograph

All 4 channels illuminated with LED

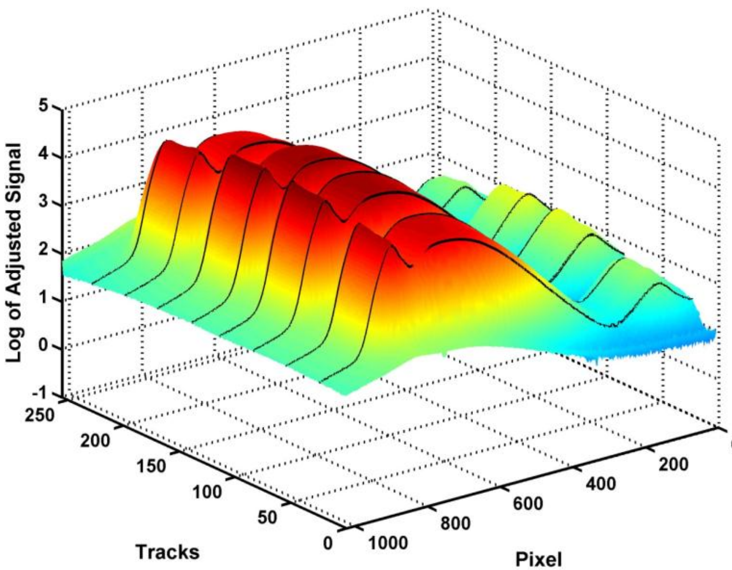
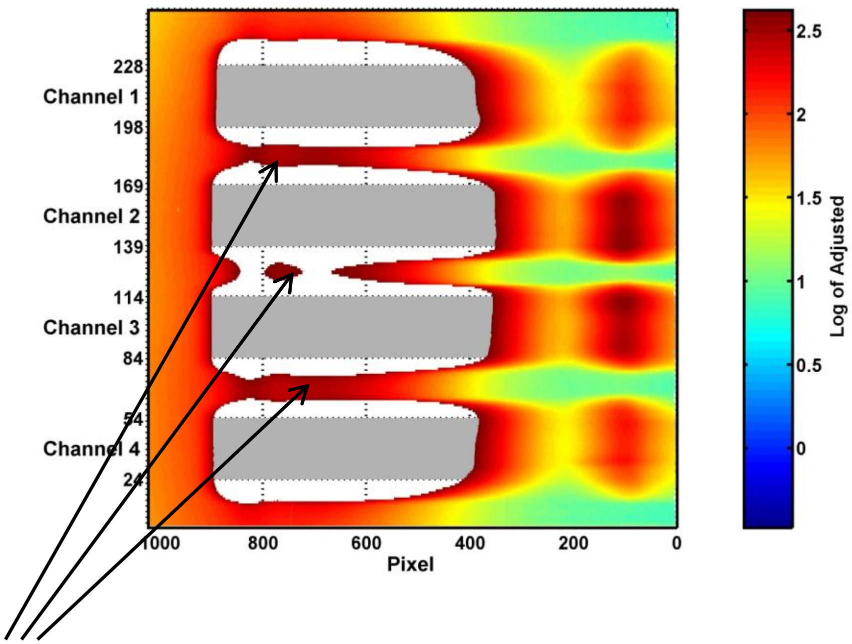
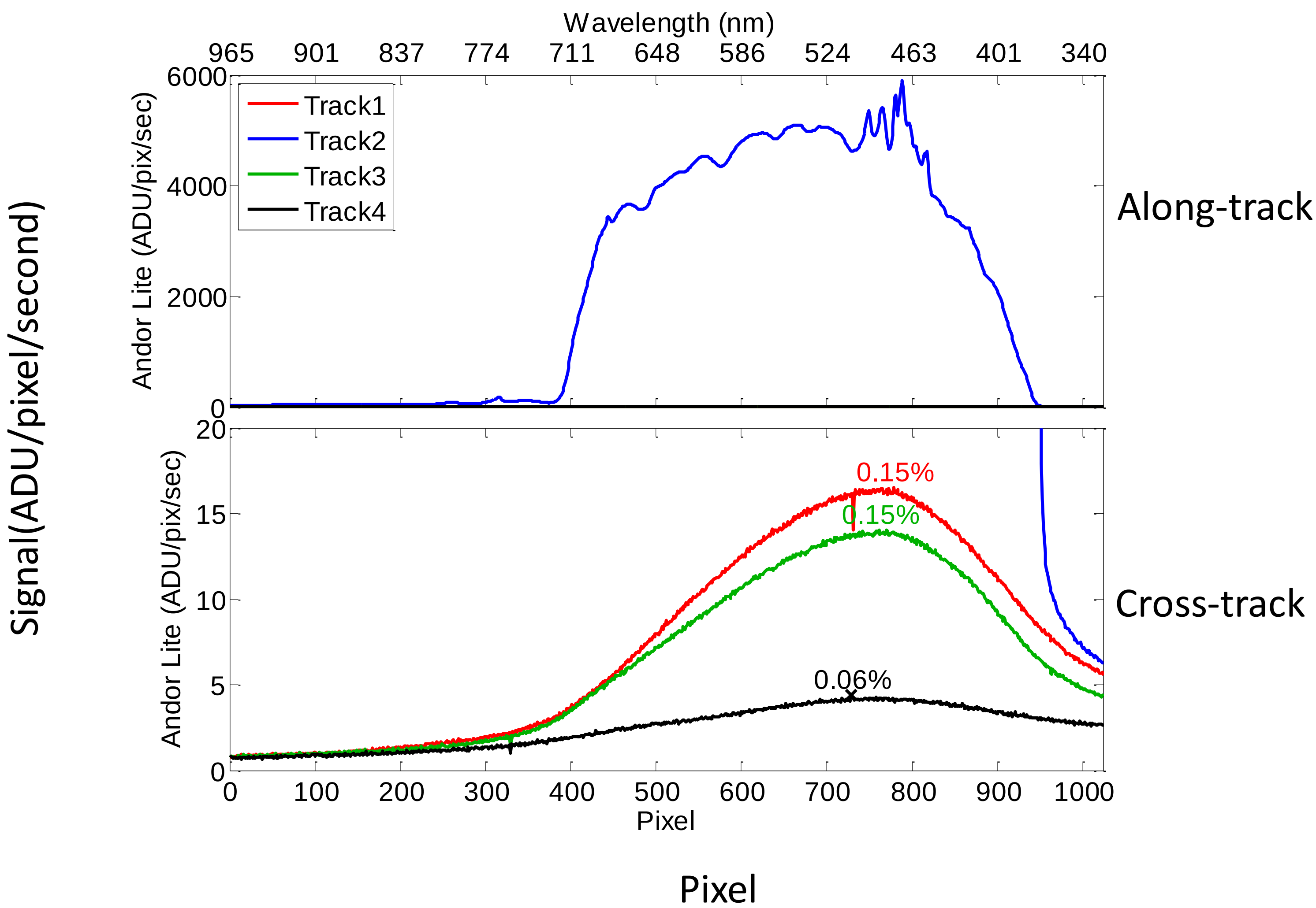


Image expanded to 1 % full scale

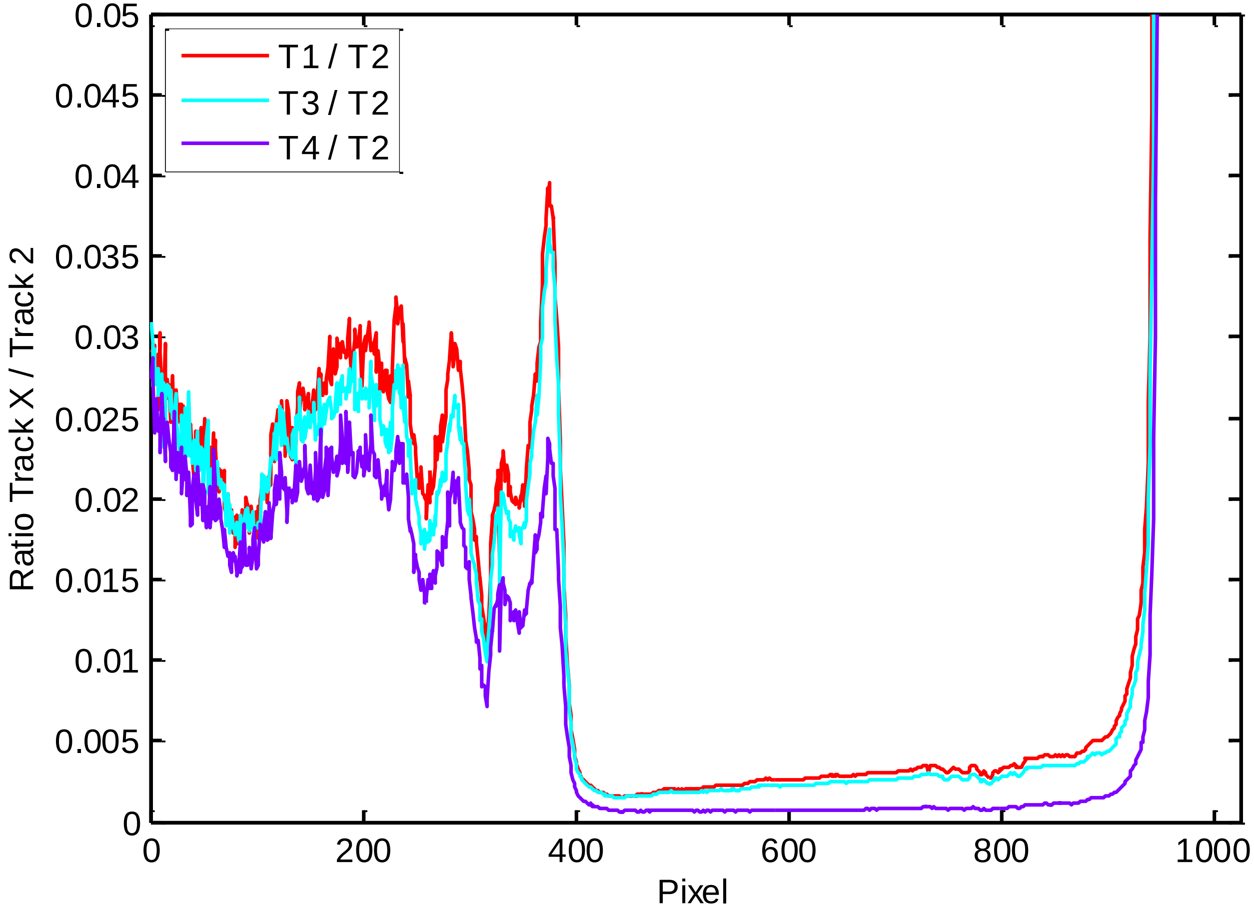


Cross-track coupling

Xenon source, Only Track 2 Illuminated

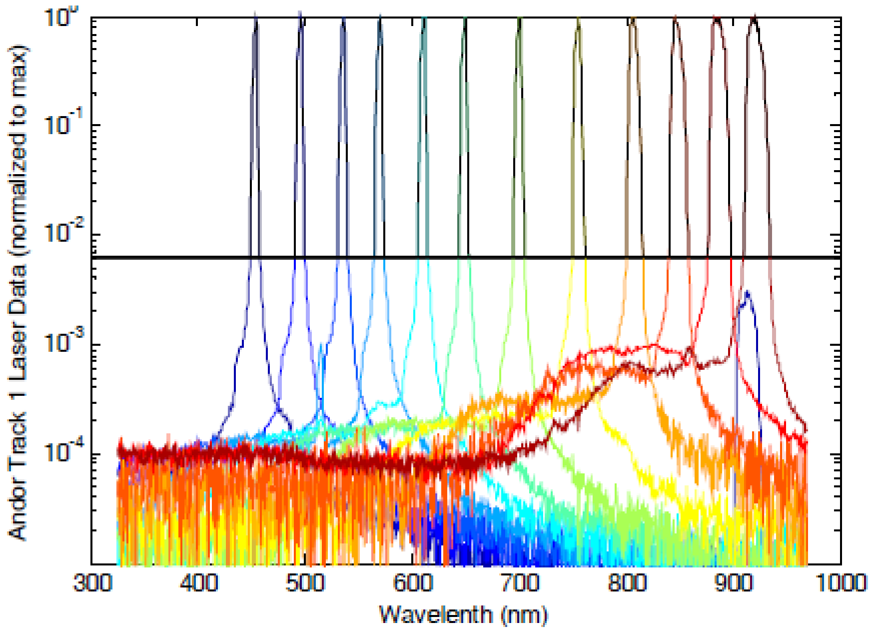


Ratio of Track x to Track 2

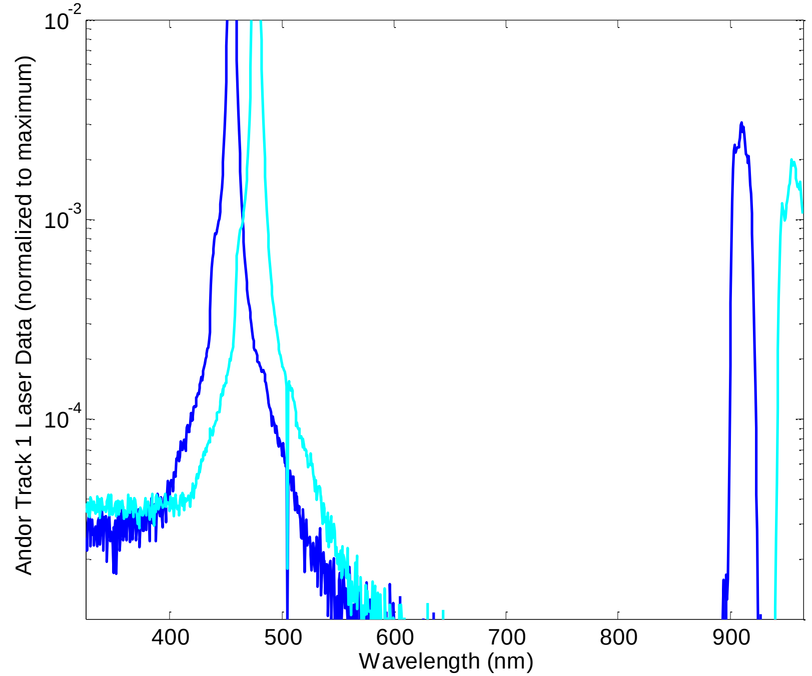


Stray light characterization using tunable lasers

Laser characterization data (subset of full data set)



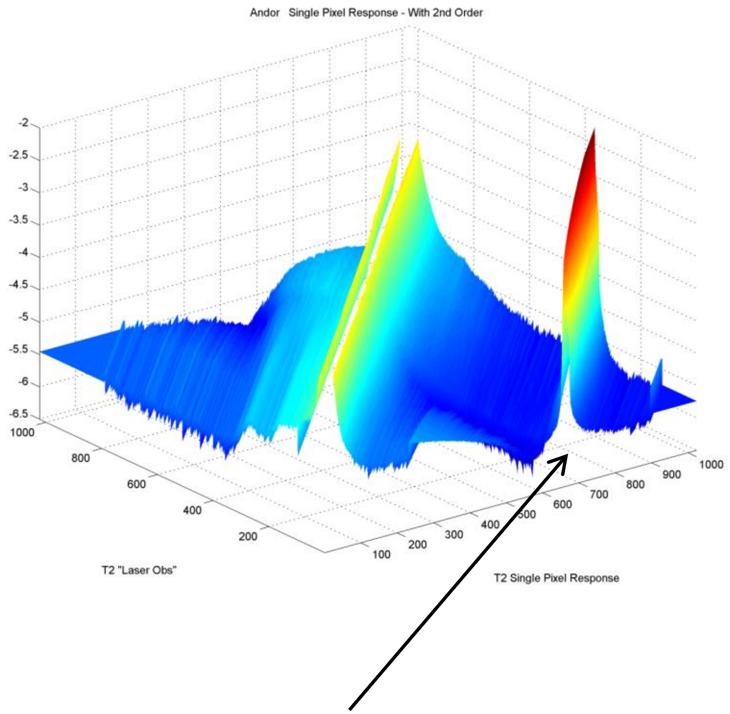
Second order diffraction



Stray Light Distribution Function Matrix

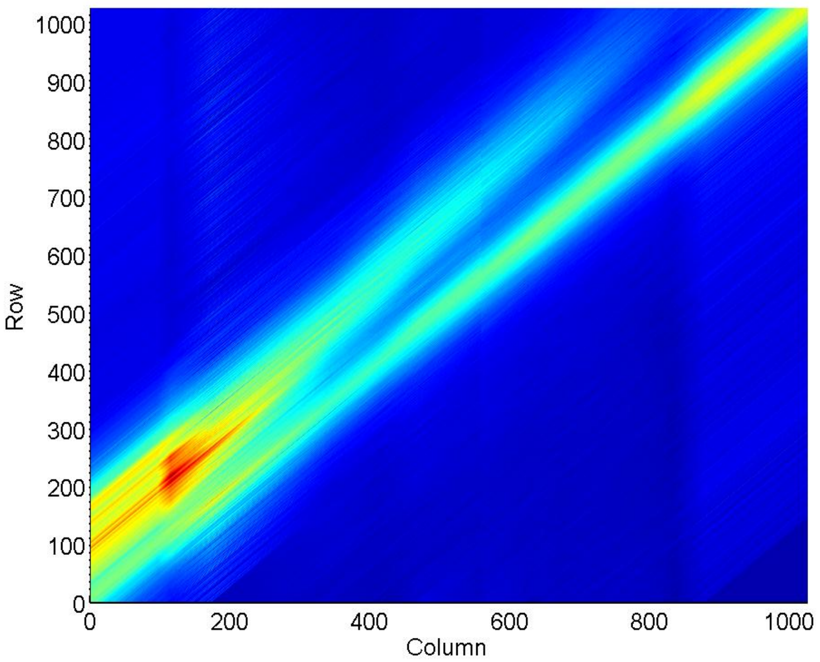
(normalized by the in-band area)

Along-track Sub-Matrix D_{22}



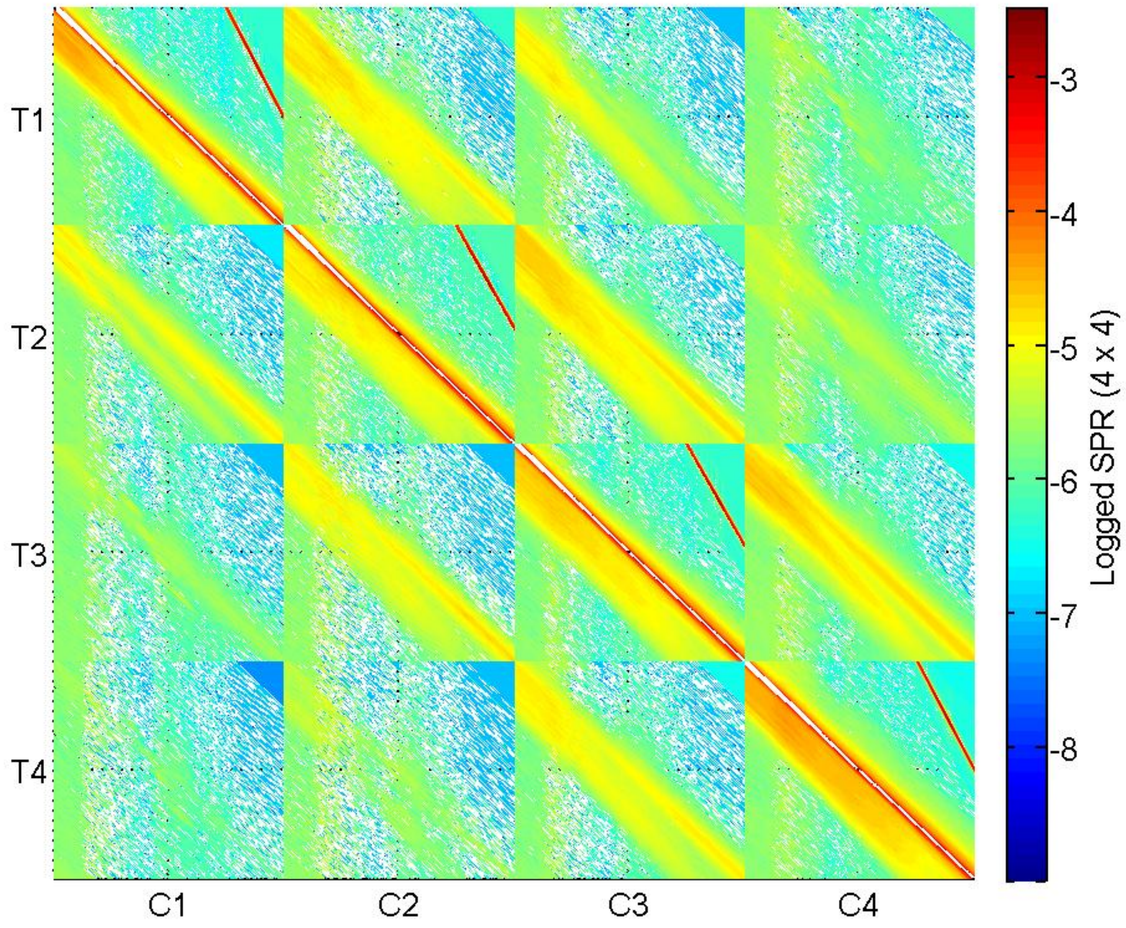
Second order diffraction peak

Cross-track Sub-Matrix D_{43}

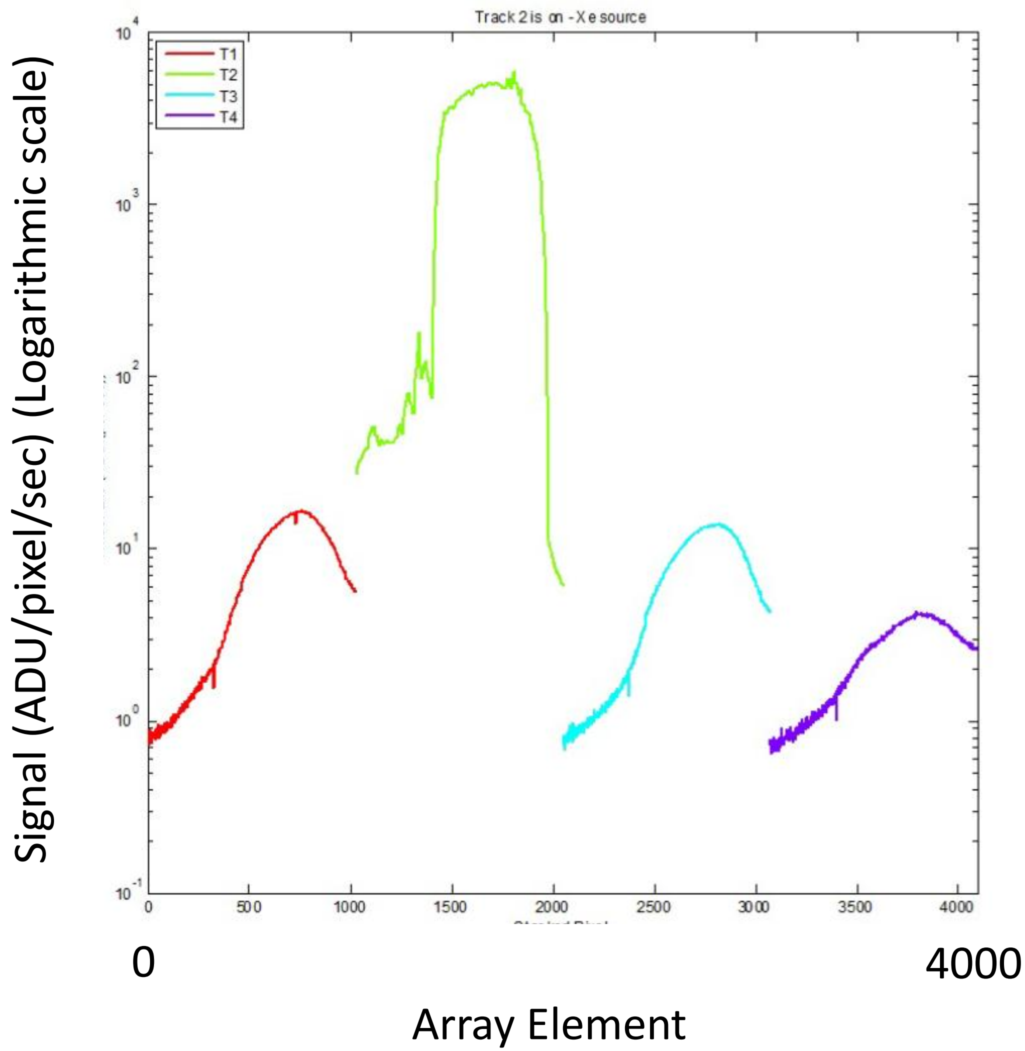


<u>Not</u> zero along the diagonal

4-channel D-matrix

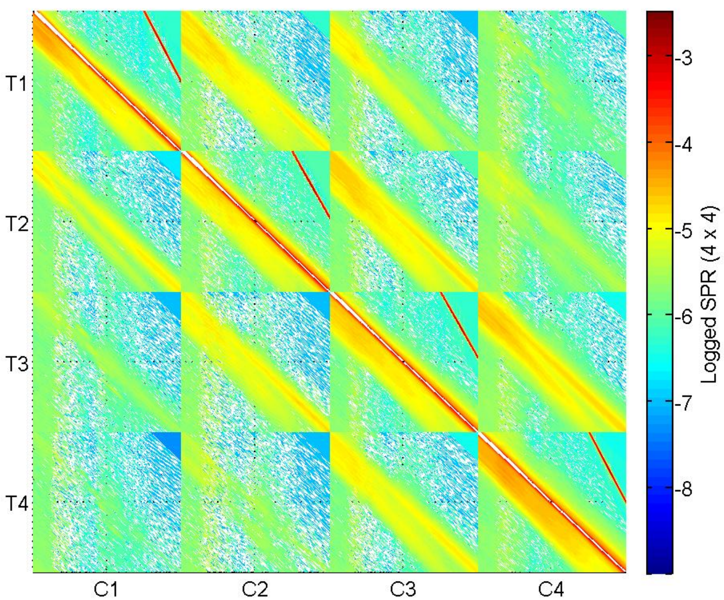


S_{meas}: Track 2 only Illuminated



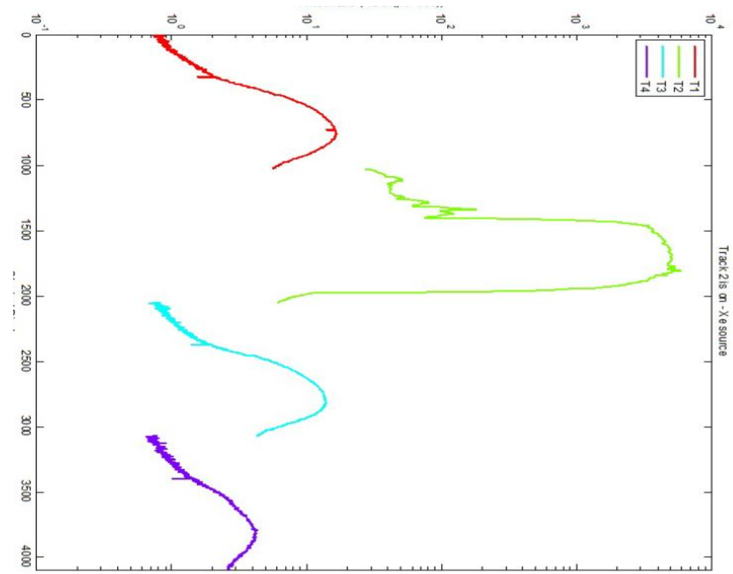
$$\overleftrightarrow{D} \cdot S_{IB} = \begin{bmatrix} \overleftrightarrow{D}_{11} & \overleftrightarrow{D}_{12} & \overleftrightarrow{D}_{13} & \overleftrightarrow{D}_{14} \\ \overleftrightarrow{D}_{21} & \overleftrightarrow{D}_{22} & \overleftrightarrow{D}_{23} & \overleftrightarrow{D}_{24} \\ \overleftrightarrow{D}_{31} & \overleftrightarrow{D}_{32} & \overleftrightarrow{D}_{33} & \overleftrightarrow{D}34 \\ \overleftrightarrow{D}_{41} & \overleftrightarrow{D}_{42} & \overleftrightarrow{D}_{43} & \overleftrightarrow{D}_{44} \end{bmatrix} \begin{bmatrix} S_{IB}^{1} \\ S_{IB}^{2} \\ S_{IB}^{3} \\ S_{IB}^{4} \end{bmatrix}$$

D

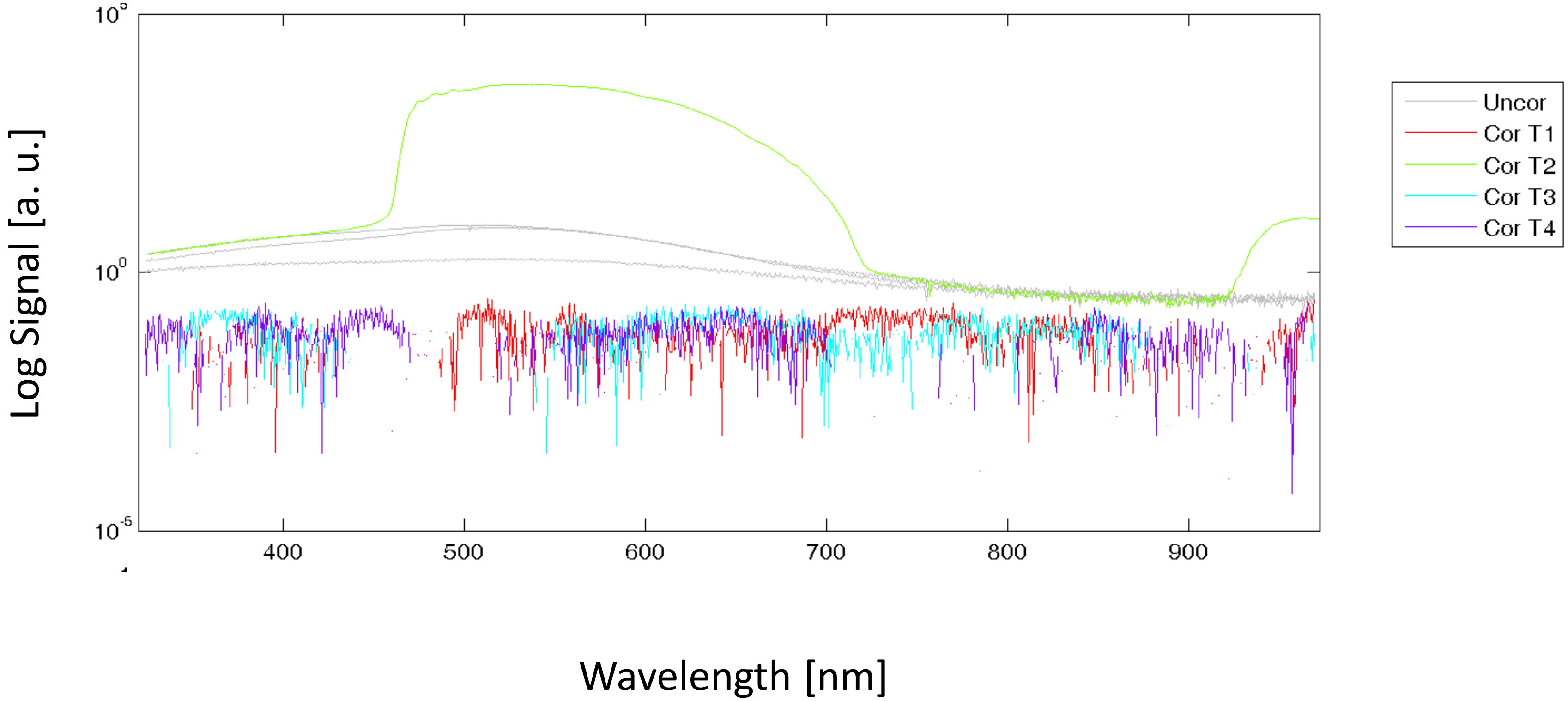


●

S



Validation: Single track Illuminated

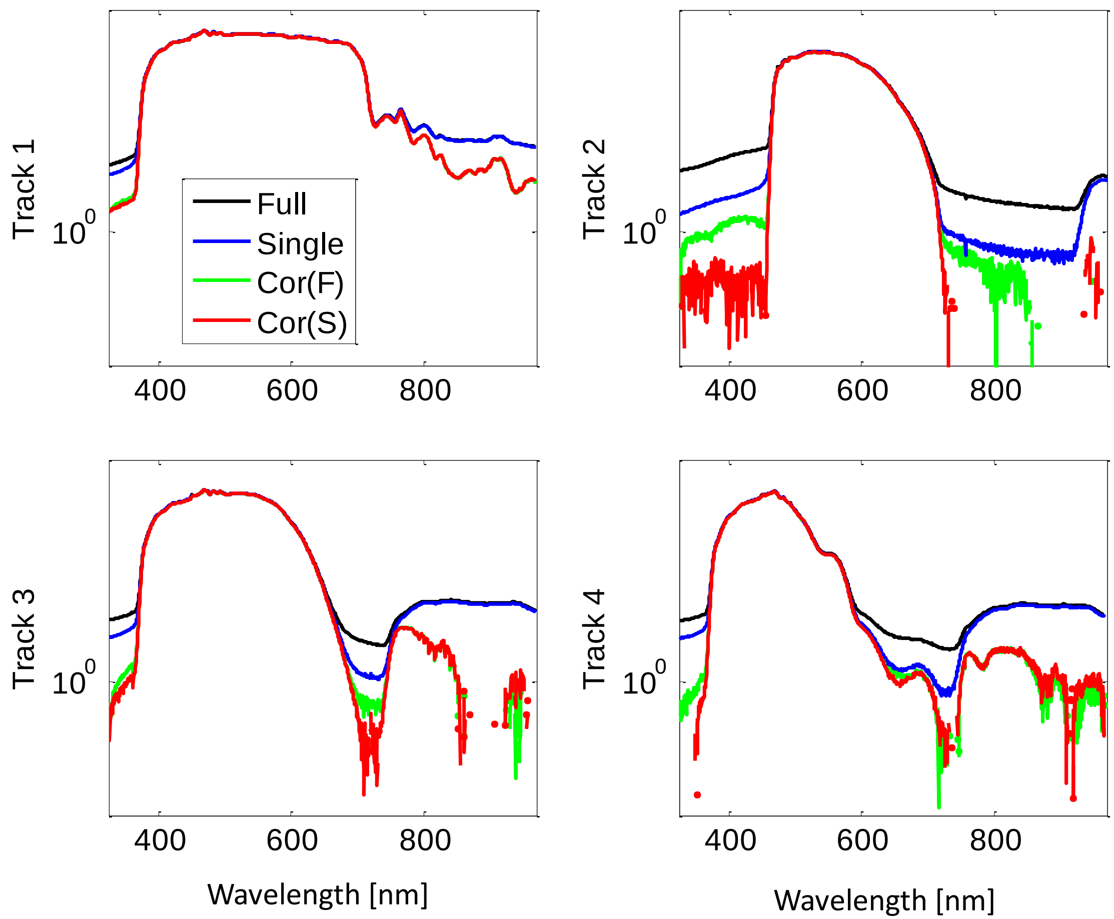


Validation (Logarithmic Scale)

Full = all tracks illuminated; Single = single track illuminated

Xe source

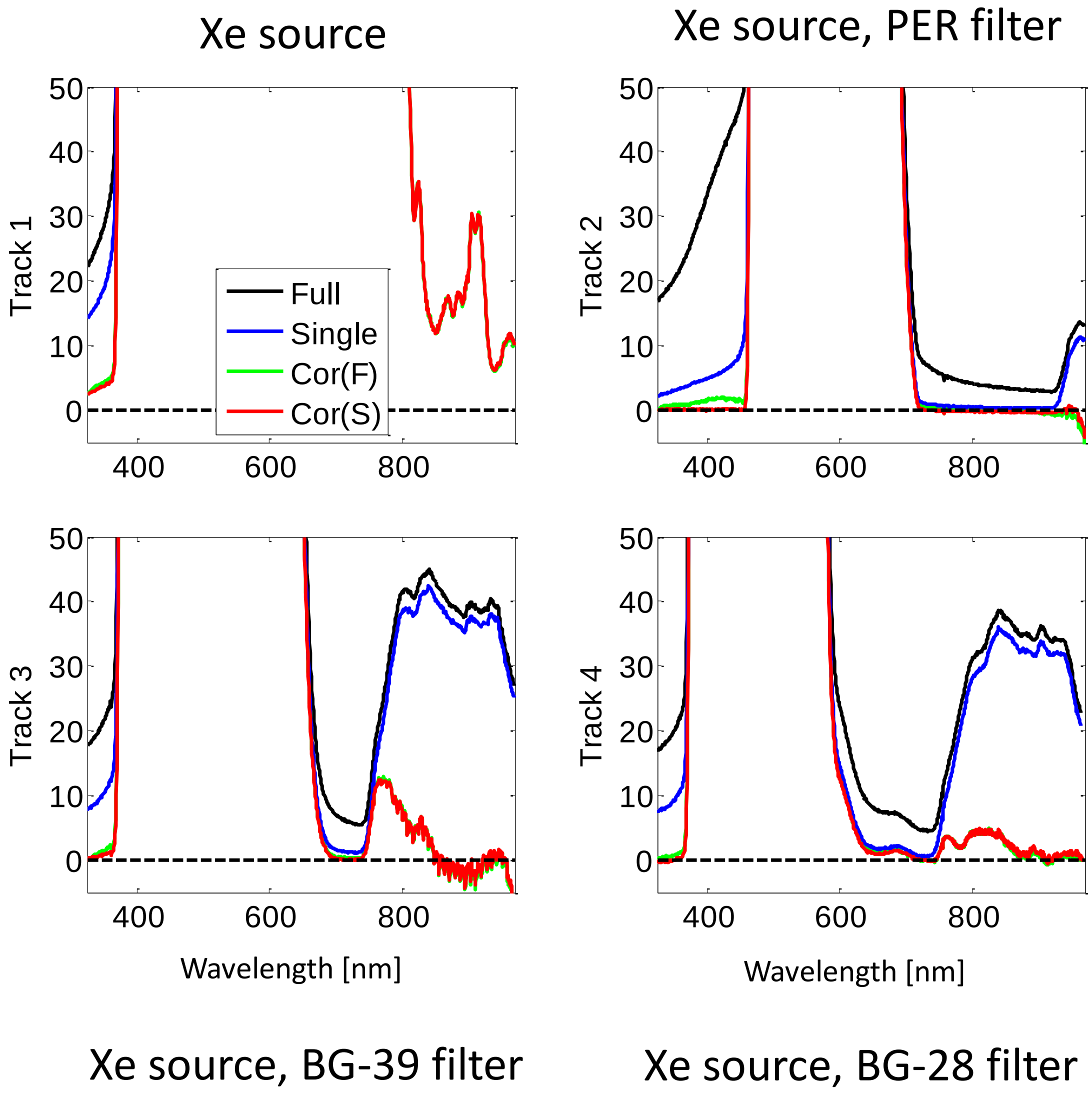
Xe source, PER filter



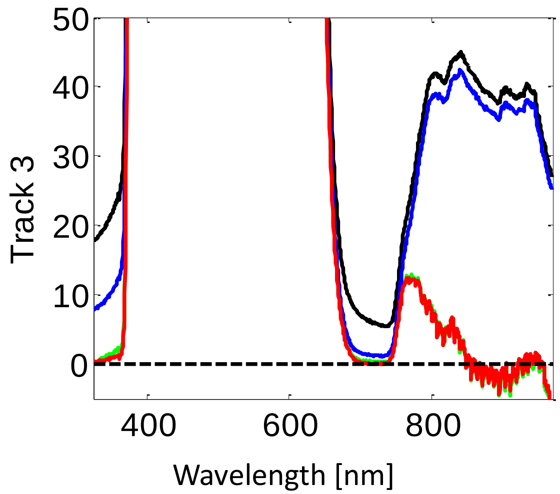
Xe source, BG-39 filter

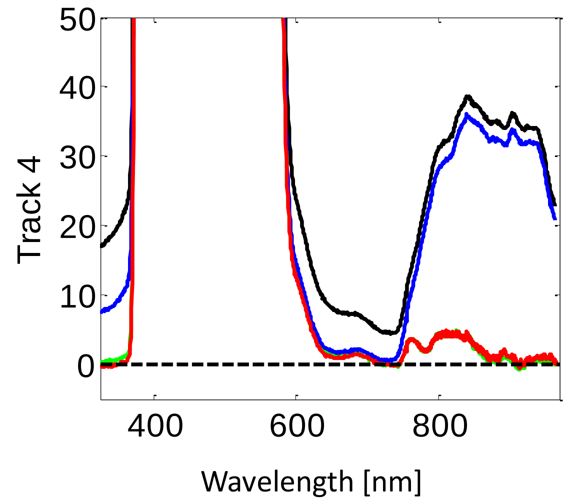
Xe source, BG-28 filter

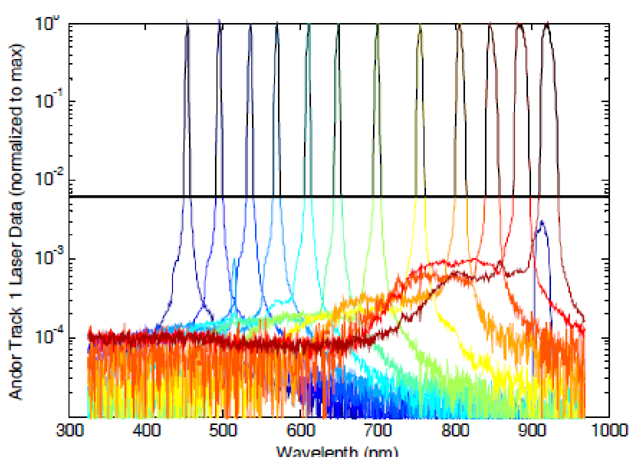
Validation (Linear Scale)

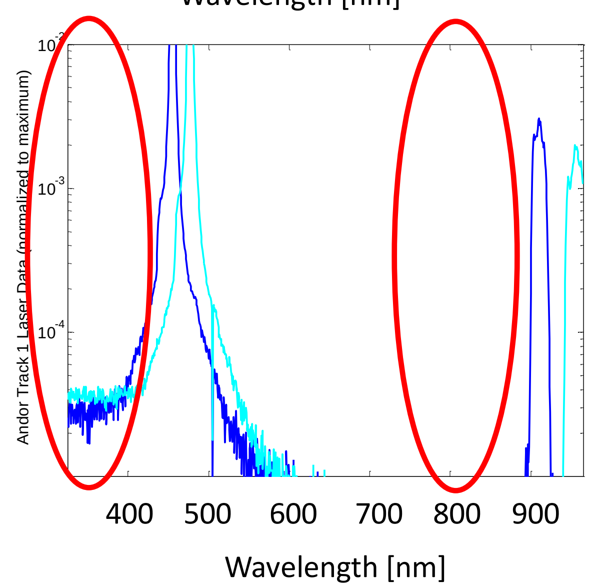


Residual signal near 800 nm originates from incomplete characterization

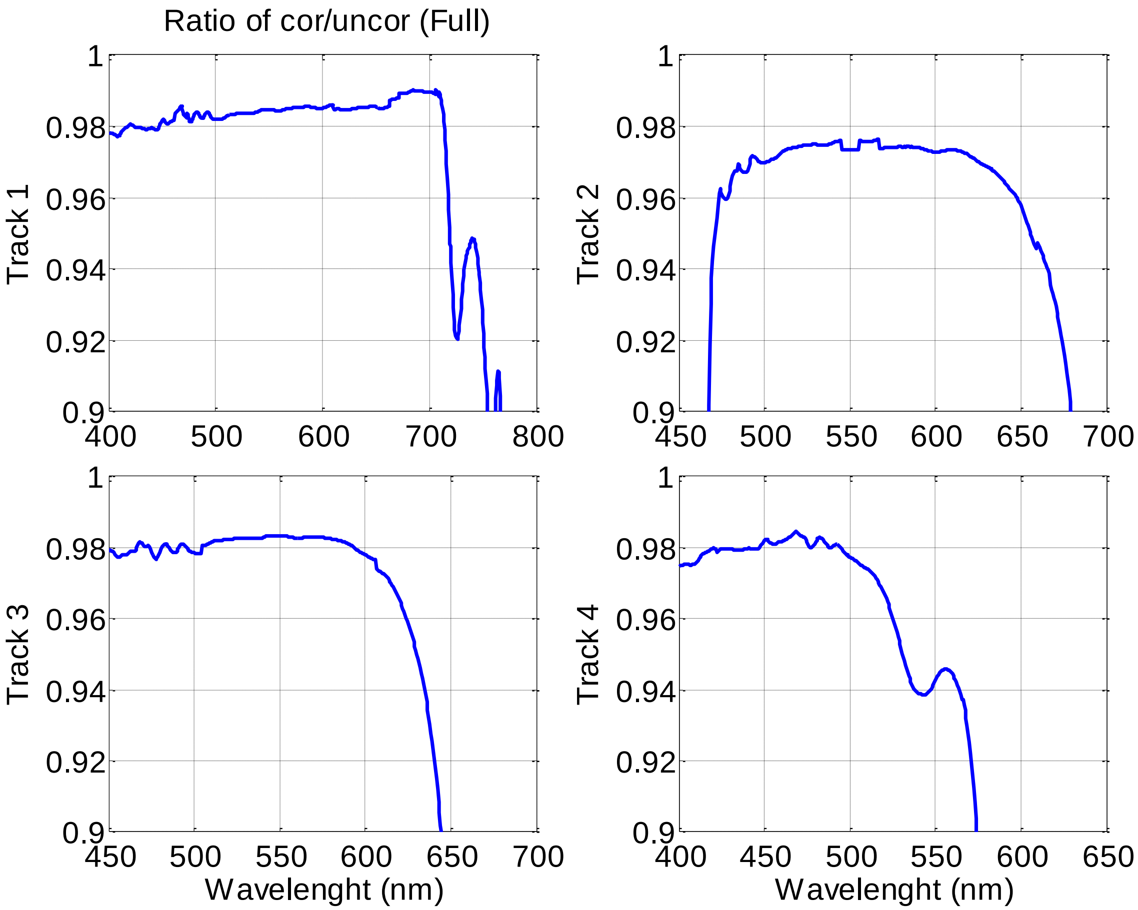






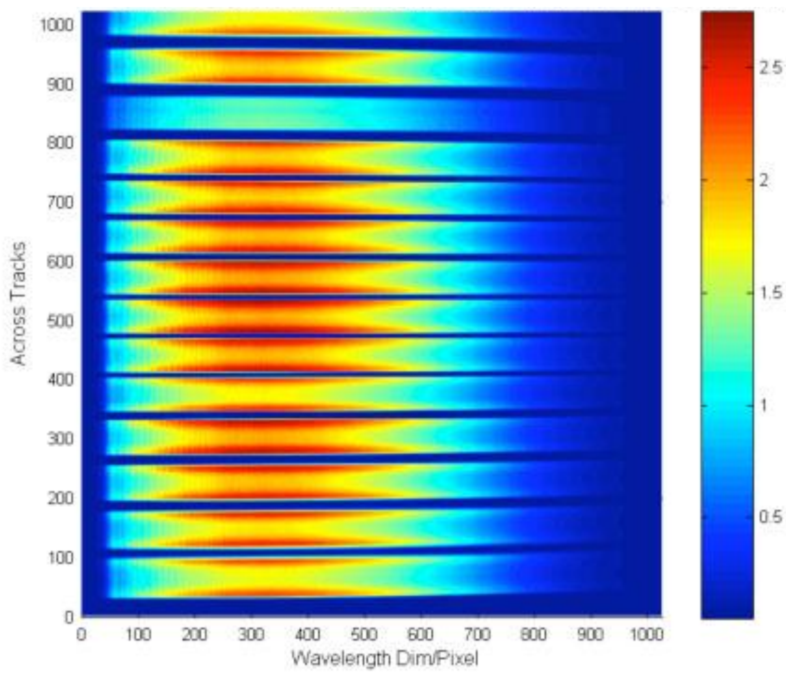


Magnitude of the correction



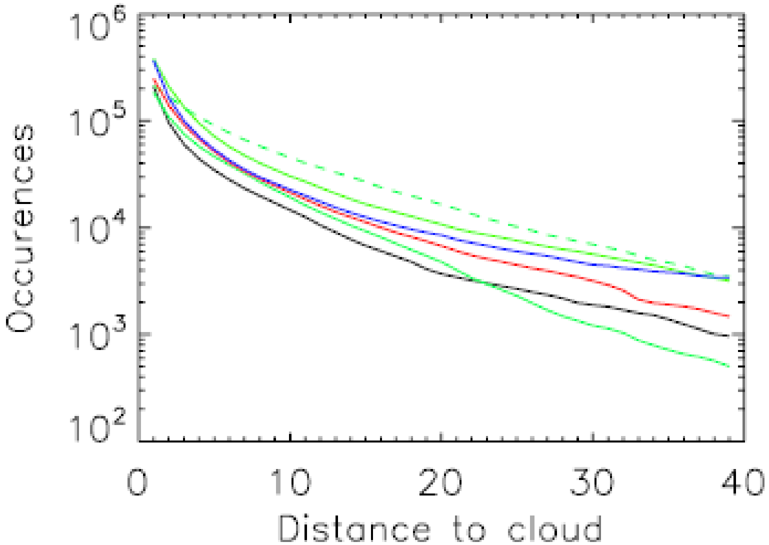
Future Direction: Finite Point Spread Response correction

- Limit as the width of a channel decreases to one pixel and the # of channels increases to # of elements



Proposed point spread response correction for MODIS

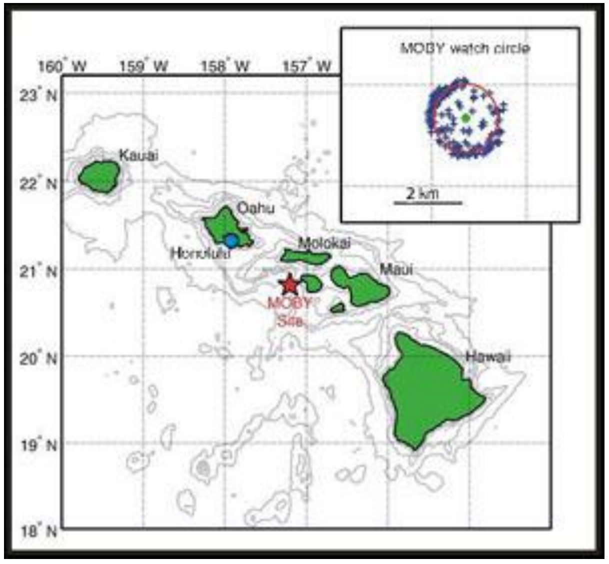
Random granules analyzed



Y-axis Logarithmic scale
For these granules, most measured elements are close to clouds!

Analysis of a time series of imagery (same site, different cloud cover)

1. Ground truth site (MOBY Site)

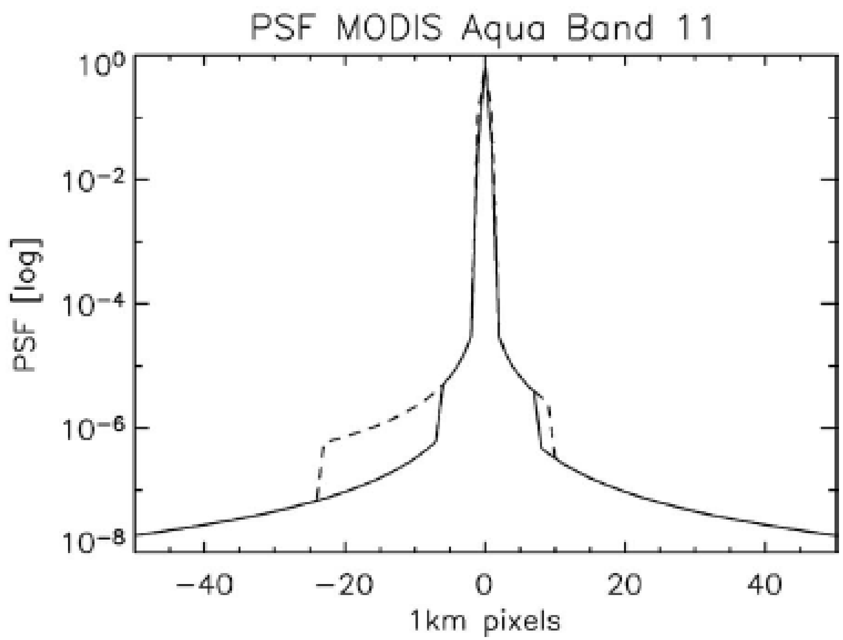


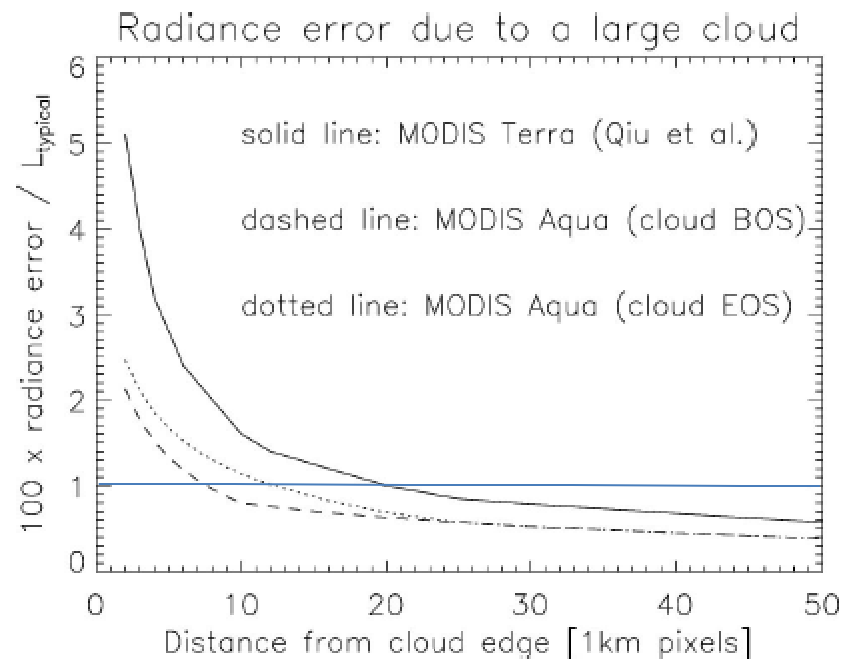
2. A site where the radiometric properties of the ocean are known and constant

Southern Ocean?

Future Direction

- MODIS





(Band 11 centered at 531 nm)

Gerhard Meister and Charles R. McClain, Appl. Opt. 49, 6276-6285 (2010)

Thank you for your attention.