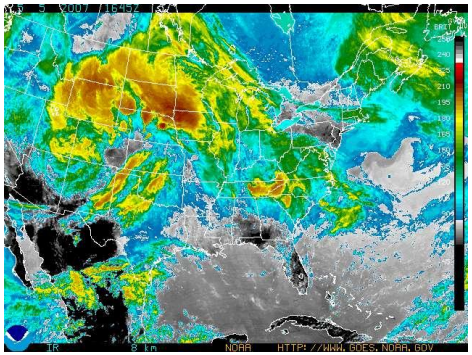
CORM 2007 Annual Conference, Gaithersburg, Maryland, May 8-11, 2007



# Spatial Stray Light Correction for Imaging Instruments Using Matrix Method

**Yuqin Zong**

# Outline

1) Introduction
2) Principle of spatial stray light correction
3) Validation of spatial stray light correction
4) Examples of applications
5) Summary

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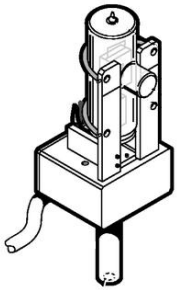
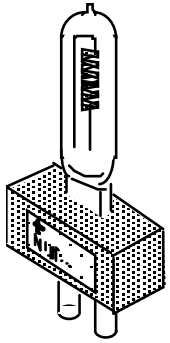
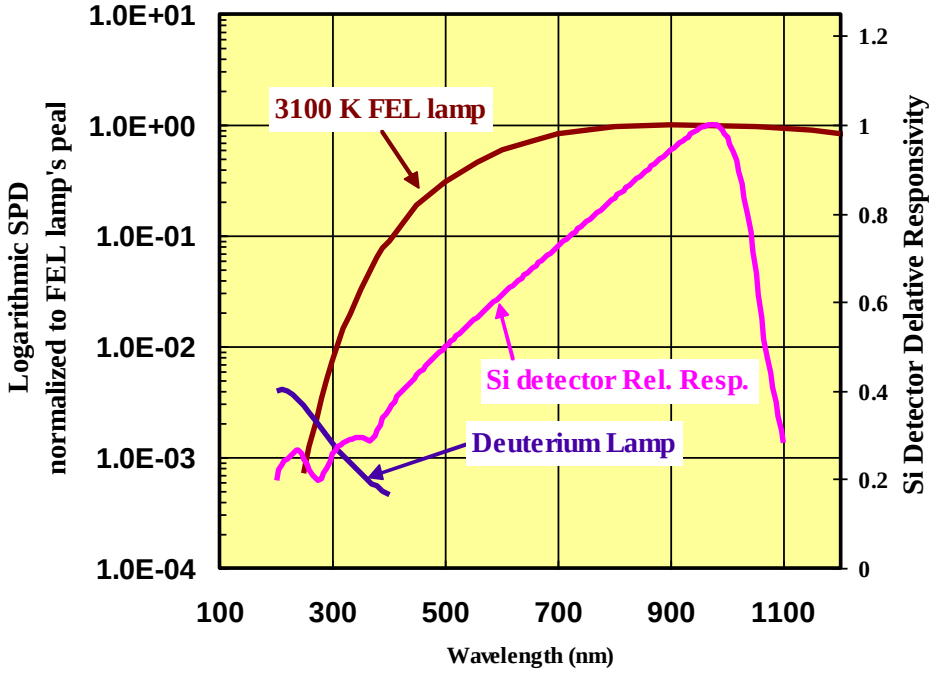
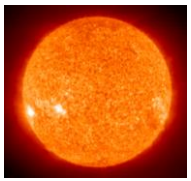
# SPECTRAL stray light (Spectrometer measures a 'point' source)

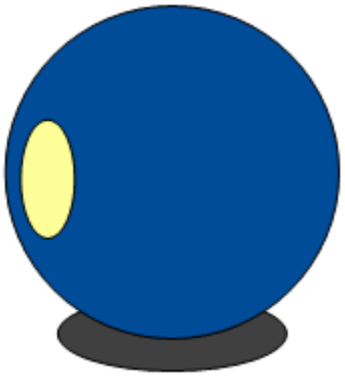






# SPATIAL stray light in imaging instruments for measurements of extended sources



**Size-of-source effect (radiometry)**
**Out-of-field sensitivity or veiling glare (photometry)**


Wire character contrast

Display contrast

# Methods for dealing with stray light

1) Improve instruments by hardware
   - limited, low signal, …

2) Avoid it, by matching the spectrum power distribution of the calibration source and that of the test source.
   - need to know the source to be measured
   - need many standard sources …, and a reference instrument

3) Correct it mathematically
   - **Spectral**
   - **Spatial**

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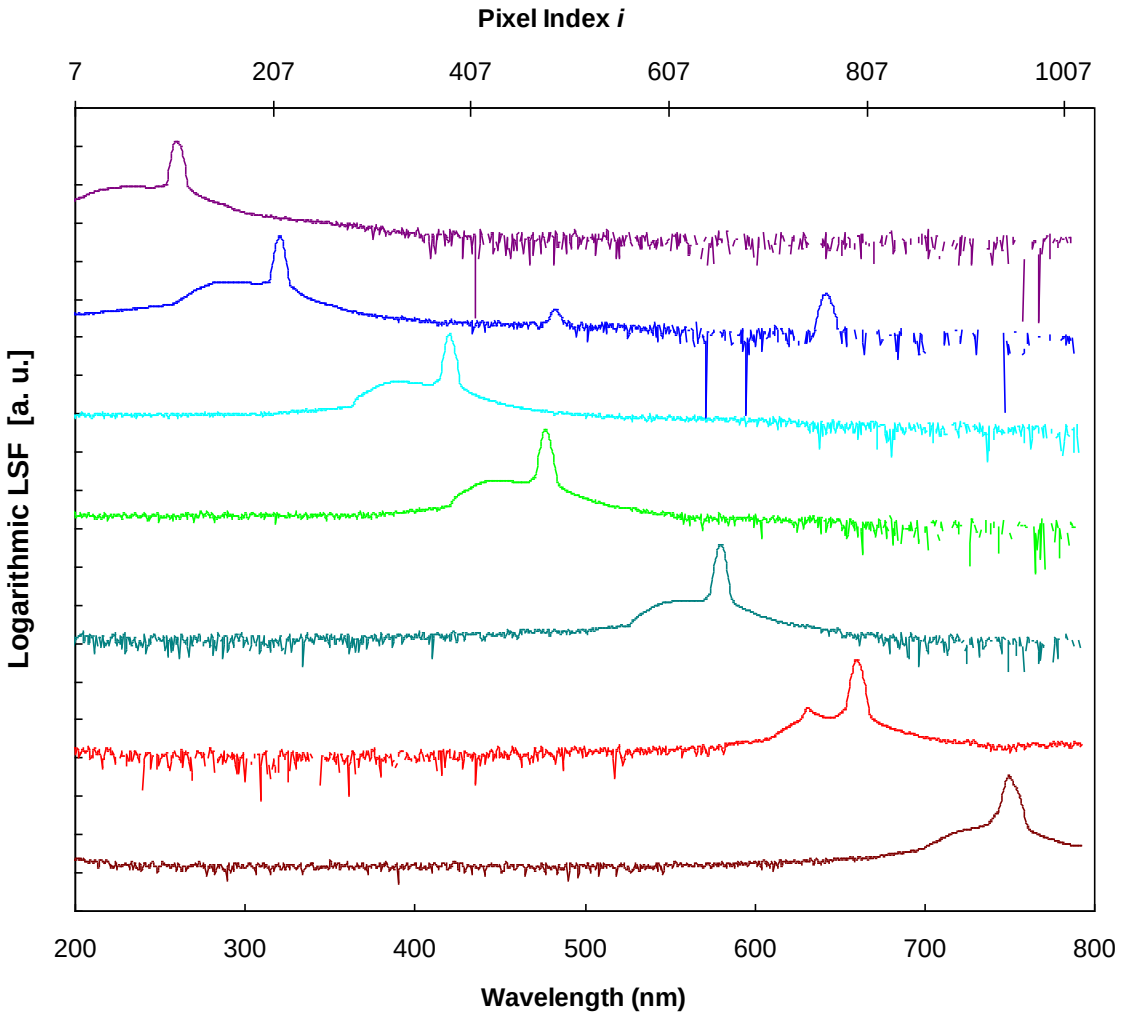
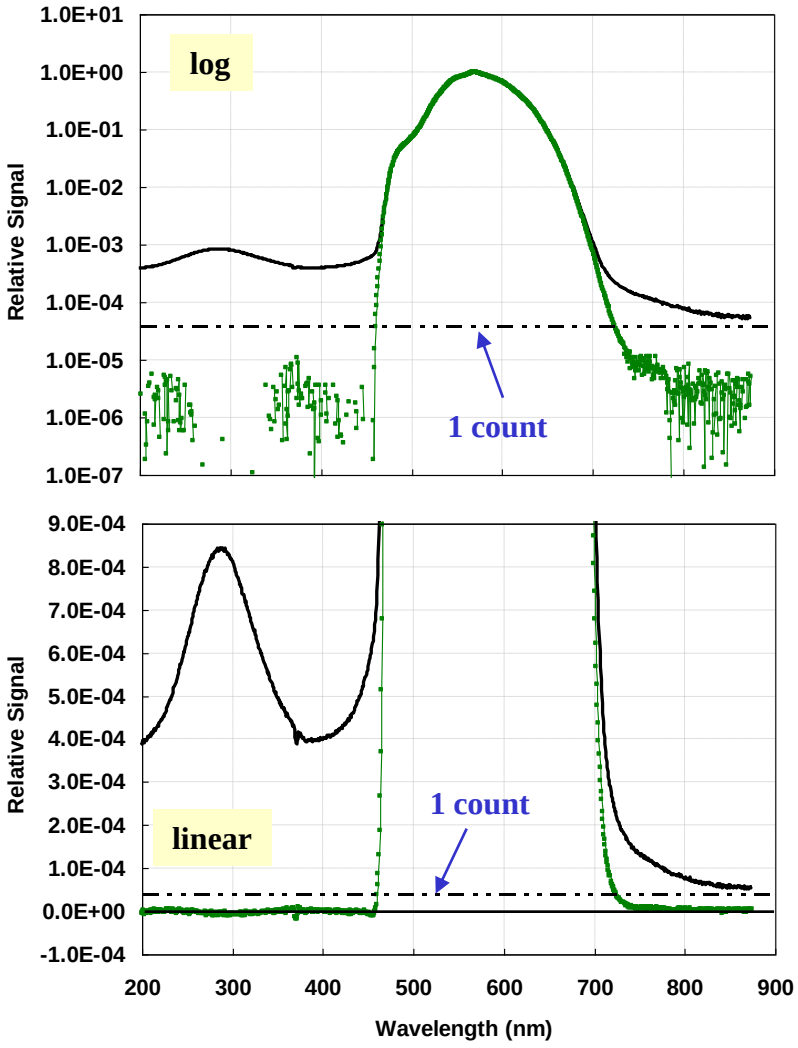
# Characterization of a spectrometer for Line Spread Functions (LSF) for Spectral Stray-light Correction

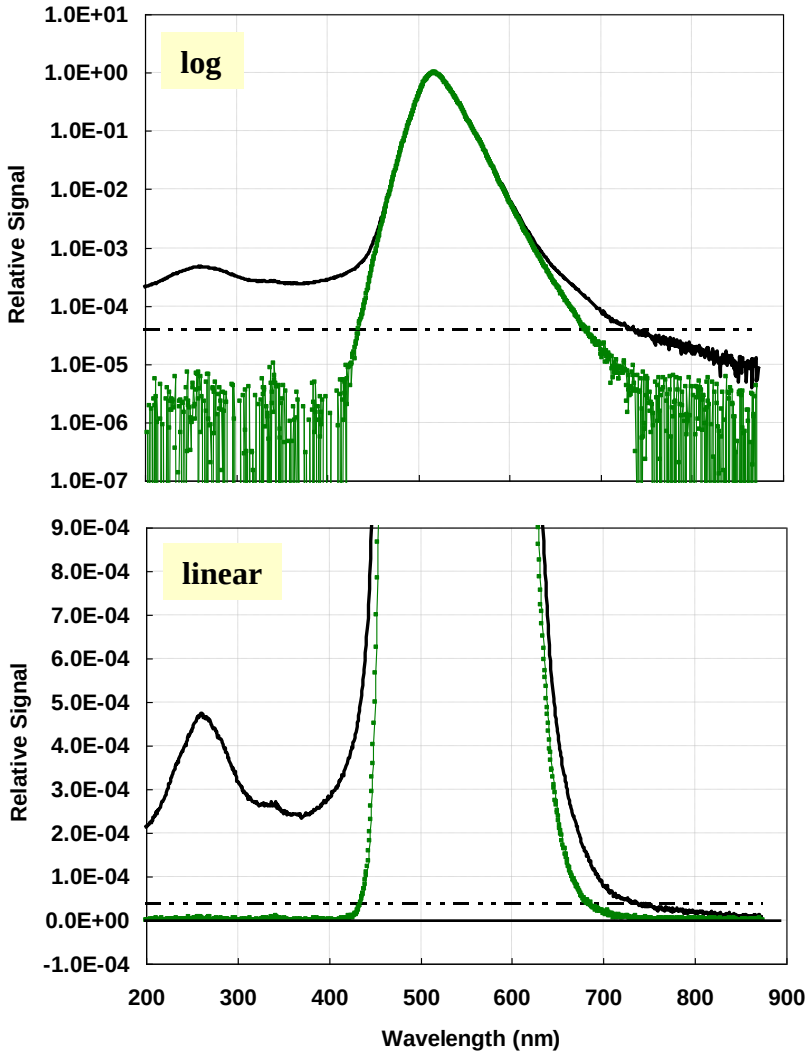


# Result of a Spectral Stray-light Correction using a 1024x1024 Correction Matrix

## A Broadband Source

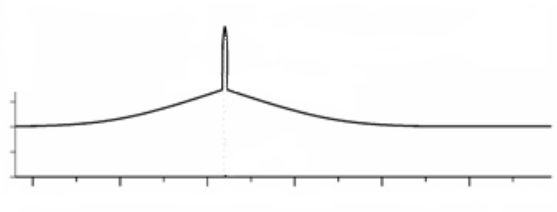



## A Green LED



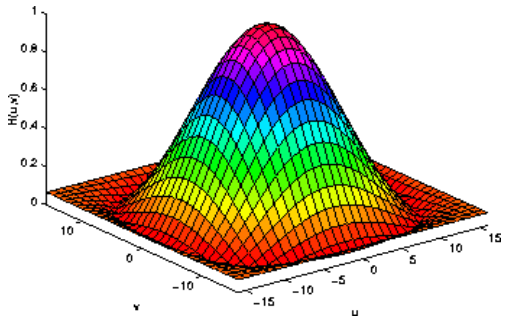
# Principle of Spatial Stray-light Correction

LSF



1-D Line Spread Function (LSF)
2-D Stray light Correction Matrix

PSF




2-D Point Spread Function (PSF)
3-D Stray light Correction Matrix

Problem!
3-D matrix inversion!

**Point Spread Function (PSF) at Pixel (3, 3)**

| | | | | |
|---|---|---|---|---|
| $y_{1,1}$ | $y_{1,2}$ | $y_{1,3}$ | $y_{1,4}$ | $y_{1,5}$ |
| $y_{2,1}$ | $y_{2,2}$ | $y_{2,3}$ | $y_{2,4}$ | $y_{2,5}$ |
| $y_{3,1}$ | $y_{3,2}$ | $\mathbf{y_{3,3}}$ | $y_{3,4}$ | $y_{3,5}$ |
| $y_{4,1}$ | $y_{4,2}$ | $y_{4,3}$ | $y_{4,4}$ | $y_{4,5}$ |
| $y_{5,1}$ | $y_{5,2}$ | $y_{5,3}$ | $y_{5,4}$ | $y_{5,5}$ |

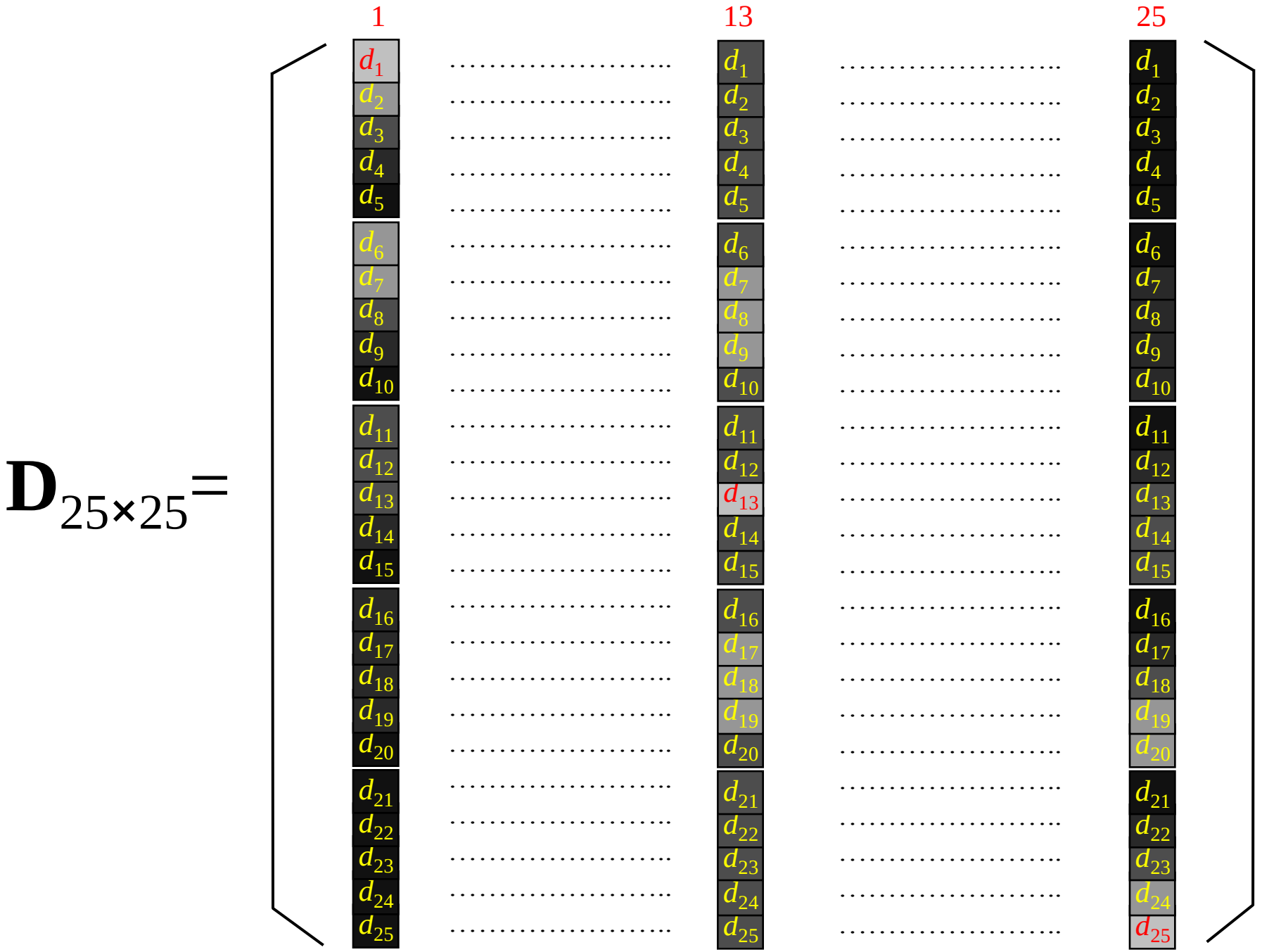
$$d_{i,j} = \frac{y_{\text{scatter},i,j}}{\sum_{i,j \in \text{IR}(3,3)} y_{\text{true},i,j}}$$

**Stray-light Distribution Function (SDF) at Pixel (3, 3)**

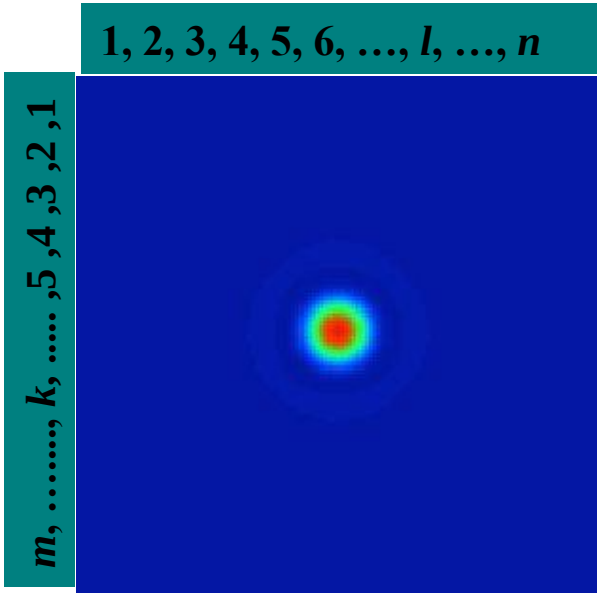
| | | | | |
|---|---|---|---|---|
| $d_{1,1}$ | $d_{1,2}$ | $d_{1,3}$ | $d_{1,4}$ | $d_{1,5}$ |
| $d_{2,1}$ | $d_{2,2}$ | $d_{2,3}$ | $d_{2,4}$ | $d_{2,5}$ |
| $d_{3,1}$ | $d_{3,2}$ | $\mathbf{d_{3,3}}$ | $d_{3,4}$ | $d_{3,5}$ |
| $d_{4,1}$ | $d_{4,2}$ | $d_{4,3}$ | $d_{4,4}$ | $d_{4,5}$ |
| $d_{5,1}$ | $d_{5,2}$ | $d_{5,3}$ | $d_{5,4}$ | $d_{5,5}$ |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $d_{1,1}$ | $d_{1,2}$ | $d_{1,3}$ | $d_{1,4}$ | $d_{1,5}$ | $d_{2,1}$ | $d_{2,2}$ | $d_{2,3}$ | $d_{2,4}$ | $d_{2,5}$ | $d_{3,1}$ | $d_{3,2}$ | $d_{3,3}$ | $d_{3,4}$ | $d_{3,5}$ | $d_{4,1}$ | $d_{4,2}$ | $d_{4,3}$ | $d_{4,4}$ | $d_{4,5}$ | $d_{5,1}$ | $d_{5,2}$ | $d_{5,3}$ | $d_{5,4}$ | $d_{5,5}$ |

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $d_1$ | $d_2$ | $d_3$ | $d_4$ | $d_5$ | $d_6$ | $d_7$ | $d_8$ | $d_9$ | $d_{10}$ | $d_{11}$ | $d_{12}$ | $d_{13}$ | $d_{14}$ | $d_{15}$ | $d_{16}$ | $d_{17}$ | $d_{18}$ | $d_{19}$ | $d_{20}$ | $d_{21}$ | $d_{22}$ | $d_{23}$ | $d_{24}$ | $d_{25}$ |

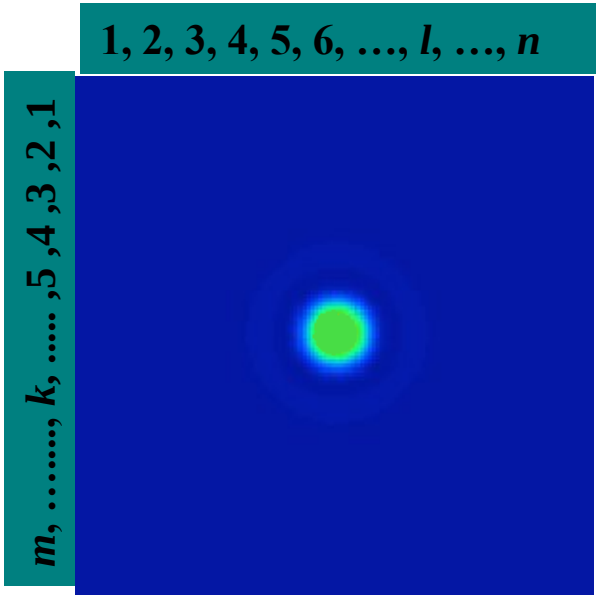

D25×25=
1
13
25
d1 d2 d3 d4 d5
d6 d7 d8 d9 d10
d11 d12 d13 d14 d15
d16 d17 d18 d19 d20
d21 d22 d23 d24 d25

## 2D Point Spread Function (PSF)



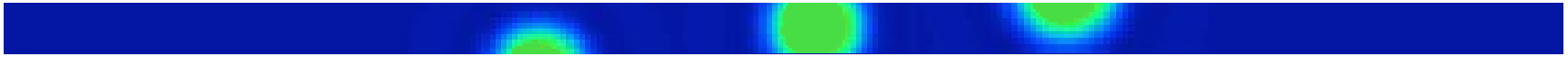

$$d_{k,l} = \frac{y_{\text{scatter},\,k,l}}{\sum_{i \in \text{IR}} y_{\text{true},\,k,l}}$$

## 2D Stray-light Distribution Function (SDF)




$$i = (k\text{-}1) \times n + l$$

2D SDF:($k$, $l$) → 1D SDF ($i$)



**The SDF matrix, $D_{(m\times n)\times(m\times n)}$**

$$\begin{bmatrix} d_{1,1} & d_{1,2} & \cdots & d_{1,J} & \cdots & d_{1,n-1} & d_{1,n} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,J} & \cdots & d_{2,n-1} & d_{2,n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ d_{i,1} & d_{i,2} & \cdots & d_{i,J} & \cdots & d_{i,n-1} & d_{i,n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots \\ d_{n-1,1} & d_{n-1,2} & \cdots & d_{n-1,J} & \cdots & d_{n-1,n-1} & d_{n-1,n} \\ d_{n,1} & d_{n,2} & \cdots & d_{n,J} & \cdots & d_{n,n-1} & d_{n,n} \end{bmatrix}$$

2-D $\mathbf{Y}_{meas}$ → $i = (k-1)\times n + l$ → 1-D $\mathbf{Y}_{meas}$

$$\mathbf{Y}_s = \mathbf{D}\,\mathbf{Y}_{IR}$$

$$\mathbf{Y}_{meas} = \mathbf{Y}_{IR} + \mathbf{Y}_s = \mathbf{Y}_{IR} + \mathbf{D}\,\mathbf{Y}_{IR}$$

$$= [\mathbf{I} + \mathbf{D}]\;\mathbf{Y}_{IR} = \mathbf{A}\;\mathbf{Y}_{IR}$$

$$\mathbf{Y}_{IR} = \mathbf{A}^{-1}\,\mathbf{Y}_{meas} = \mathbf{C}_{spat}\,\mathbf{Y}_{meas}$$

**Correction Matrix**

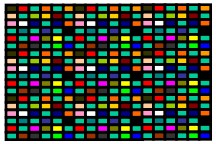
Any problem!

A 1024×1024 image → A trillion element matrix!

128 Gbytes memory Windows Vista 64

# Dealing with huge number of pixels (binning)

18×18 raw sig



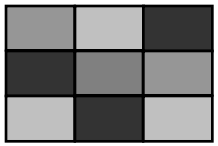
3×3 binned raw sig

$$\overline{\mathbf{Y}}_{IR} = \overline{\mathbf{C}}_{spat}\ \overline{\mathbf{Y}}_{meas}$$

3×3 binned corrected sig

$$\overline{\mathbf{Y}}_{spat} = \overline{\mathbf{Y}}_{meas} - \overline{\mathbf{Y}}_{IR}$$

3×3 binned stray light sig

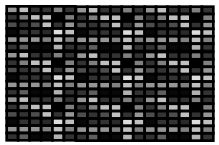


$\overline{\mathbf{Y}}_{spat}$

2-D Surface Interp

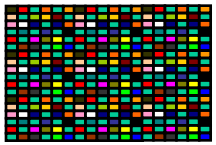
$\mathbf{Y}_{spat}$

18×18 stray light sig



$$\mathbf{Y}_{IR} = \mathbf{Y}_{meas} - \mathbf{Y}_{spat}$$

18×18 corrected sig



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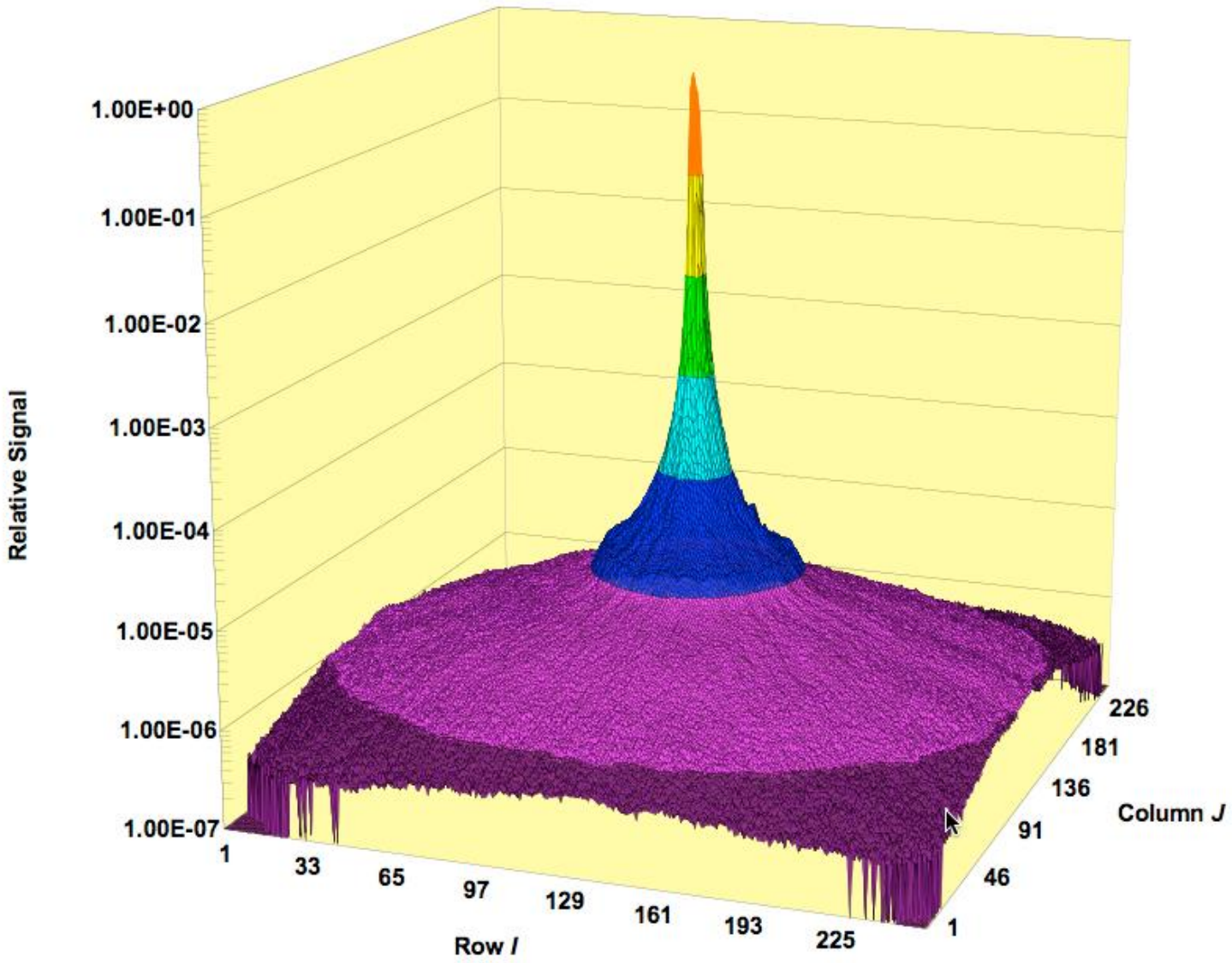
An imaging radiometer/photometer:

- 2-D CCD array: 1392x1040
- CCD size: 4.65 µm × 4.65 µm
- A/D: 12 bits
- Lens: 55 mm
- No TE-cooler

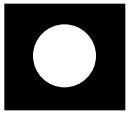
PSF test conditions:
Distance: 2 m
Pin hole size: 0.2 mm diameter
Iris: F2.8
Signal Dynamic range: > 6 orders

# A measured Point Spread Function (PSF)

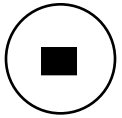


# Results of Spatial Stray-light Corrections

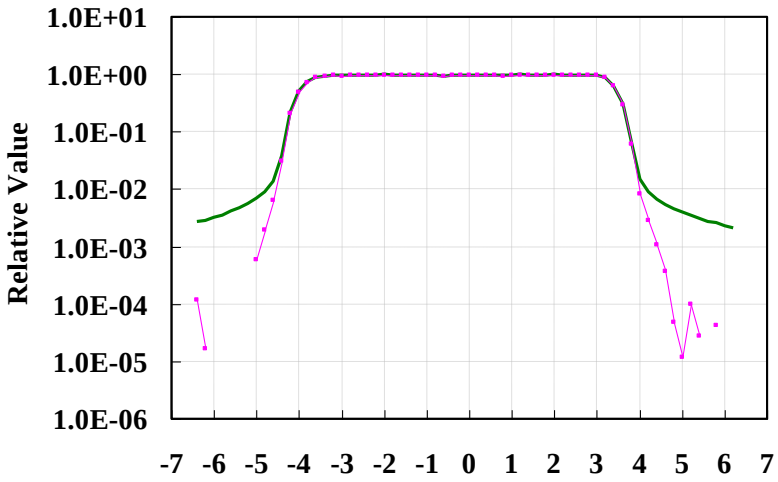
(4096x4096 Correction Matrix)



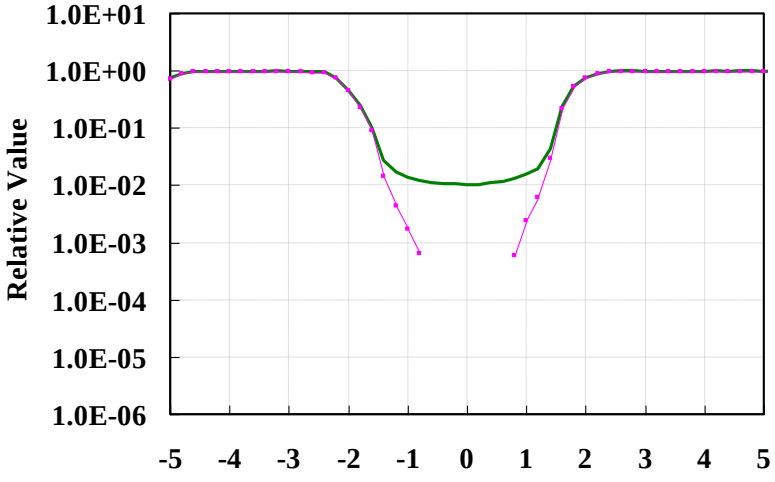
A White Spot

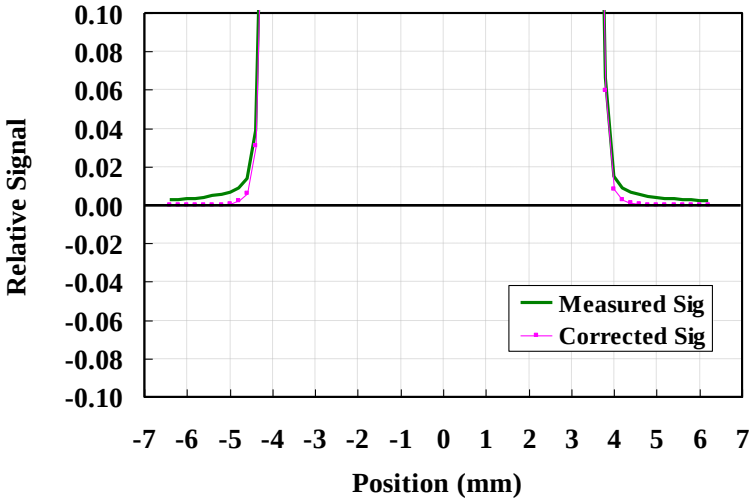


A Black Spot

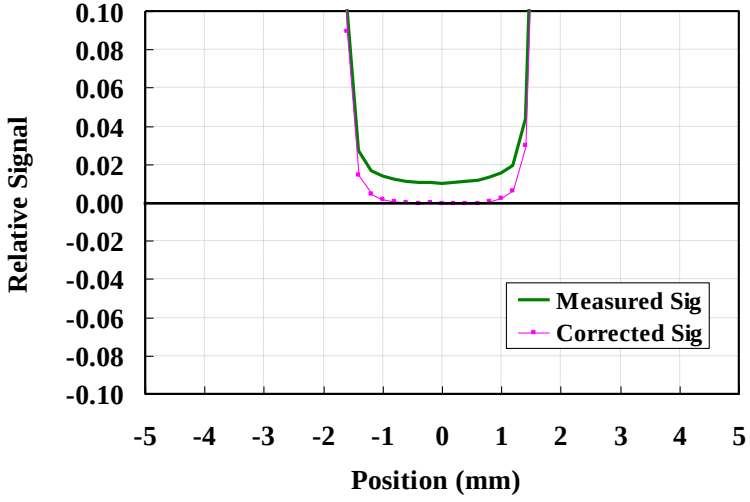



log




linear



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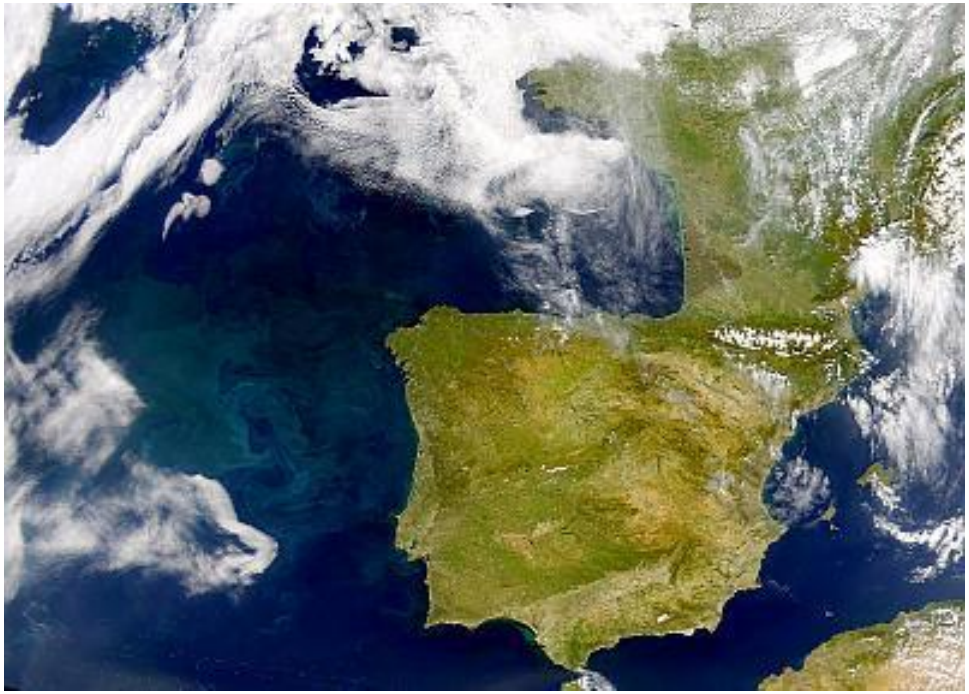
# **Remote Sensing** (S. W. Brown, J. Rice, B. C. Johnson)


Gerhard Meister, NASA,

The MODIS Aqua Point-Spread Function for Ocean Color Bands, ISPRS, Vol XXXVI (7/W20)



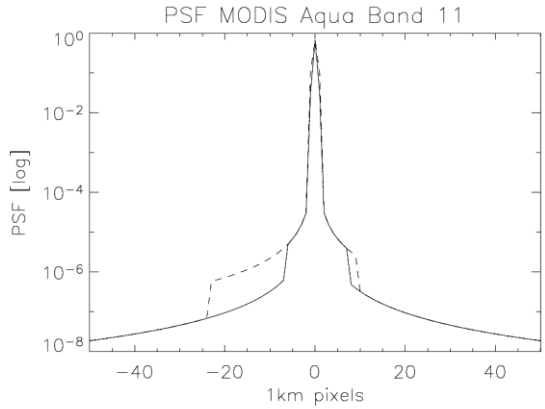



Figure 2. MODIS Aqua band 11 PSF in track direction (solid line) and scan direction (dashed line).

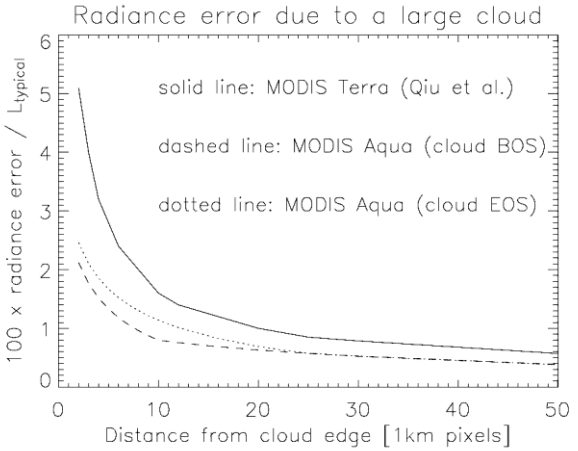
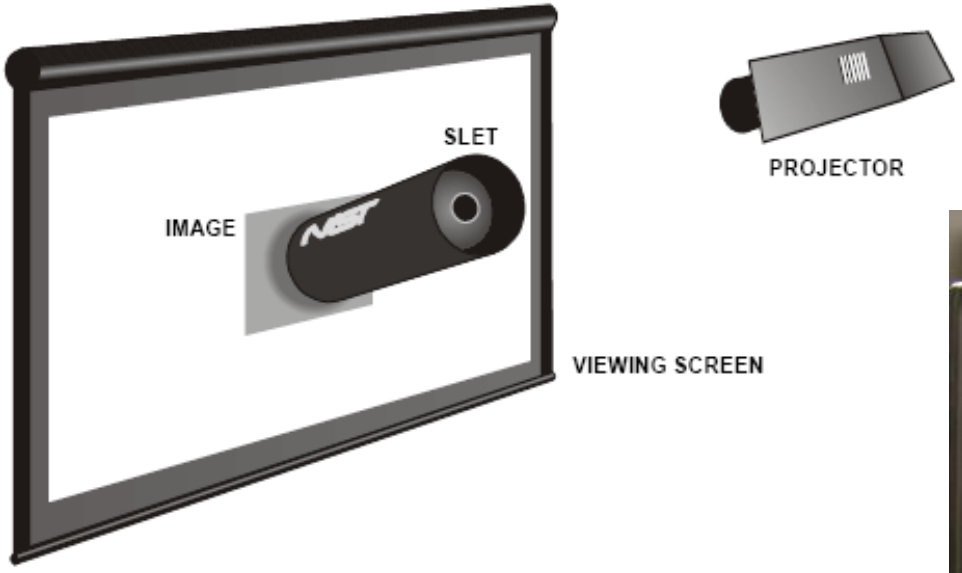



Figure 3. Contamination of top-of-atmosphere radiances over ocean due to a large cloud (semi-infinite) for band 11.

# Display measurements

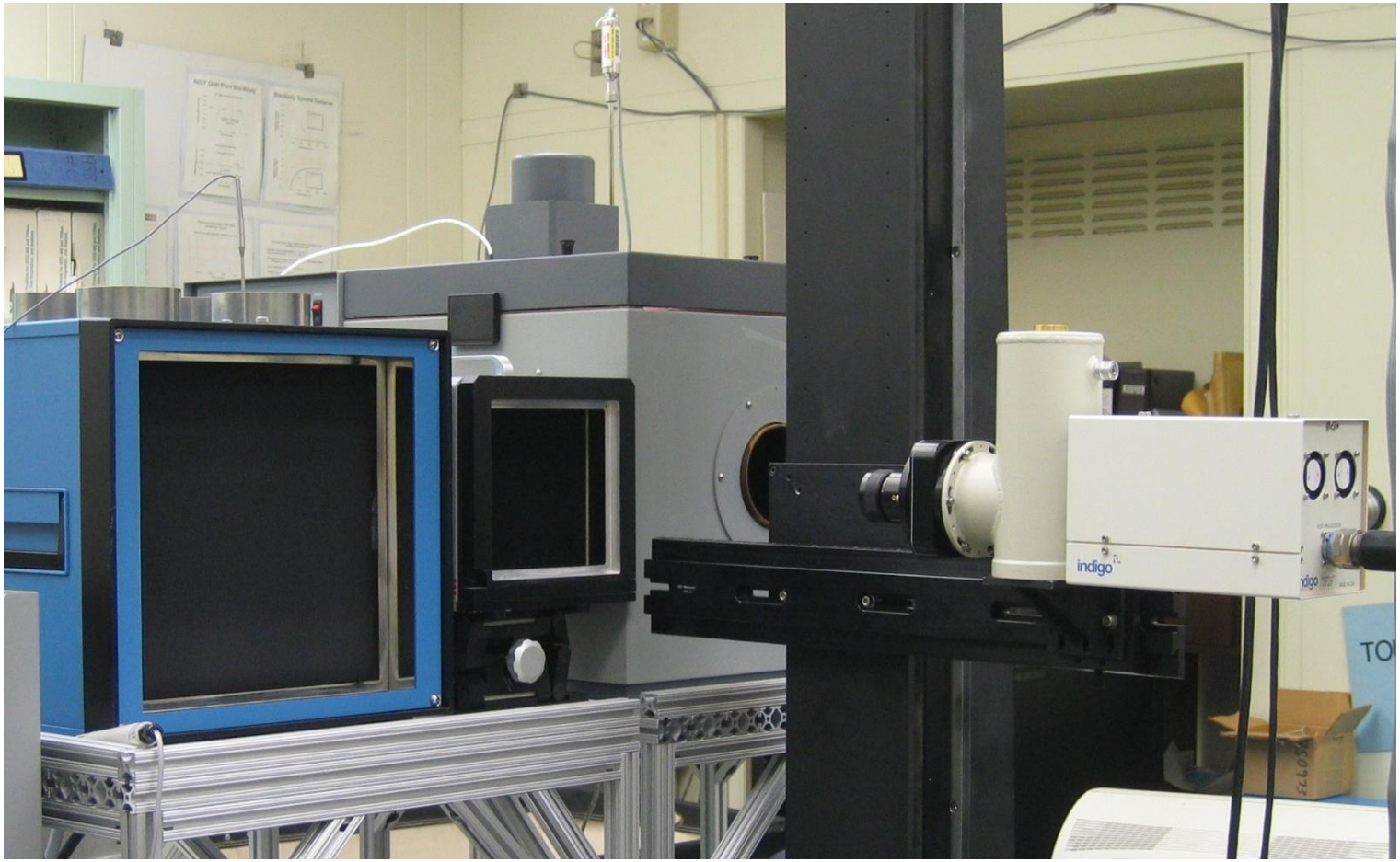
(E. F. Kelley, P.A. Boynton, EEEL, NIST)




Using the SLET for front-projection display measurements.

http://www.fpdl.nist.gov/straylight.html

# **IR Radiometry and Imaging** (Sergey Mekhontsev)



# **Traffic Signs (signals) Measurements** (Cameron Miller)







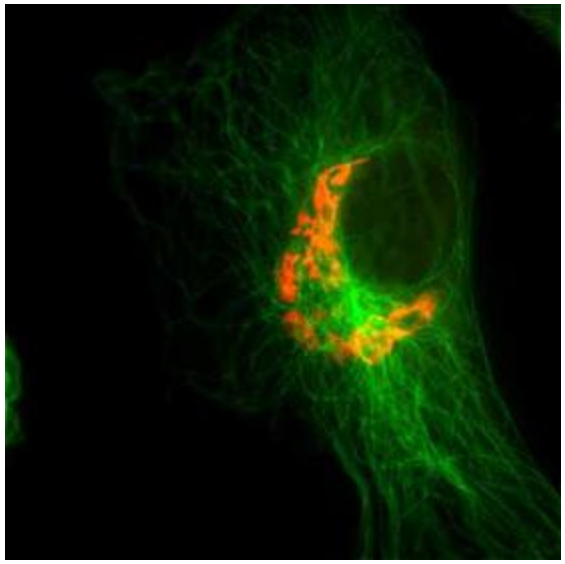


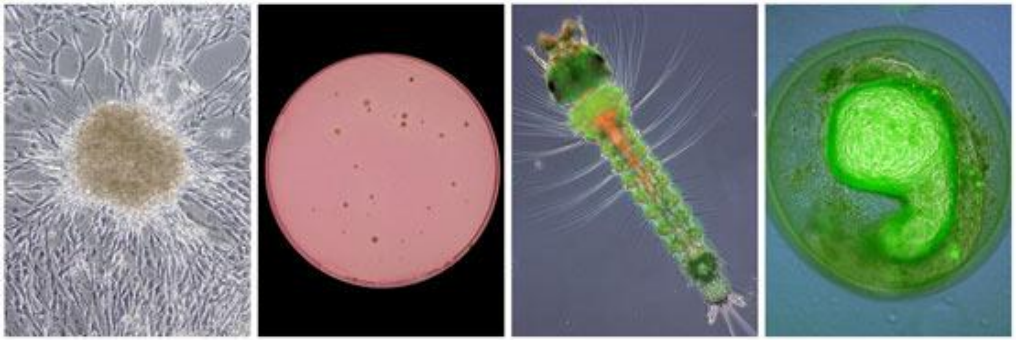






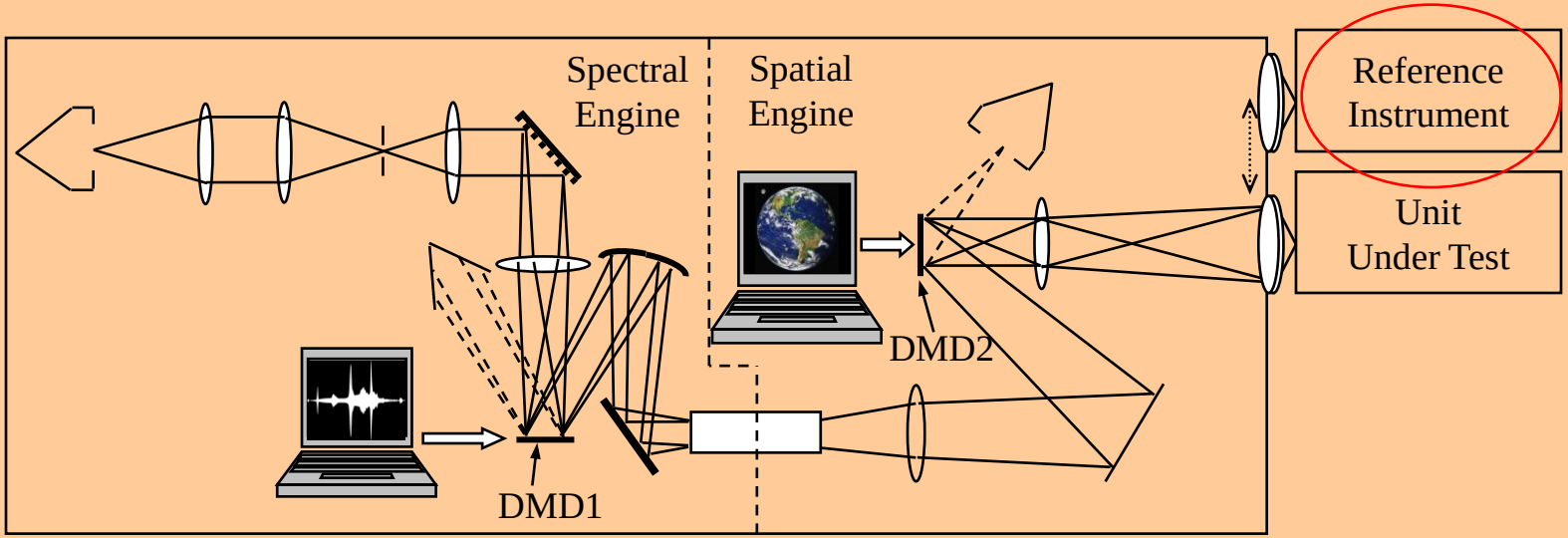
# **Quantitative medical imaging** (Maritoni Litorja)





# Hyperspectral Image Projector (HIP)

(Joe Rice, Steve Brown)



# Summary

- A simple, practical method has been developed for correcting spatial stray-light errors in imaging instruments (array detector or scanning) using stray light correction matrixes.
- This method can be used to correct stray light errors in imaging instruments with large number of pixels.
- The spatial stray light correction also eliminates other types of errors such as detector read-out smearing, and detector window reflection, etc.
- The errors are reduced by 1 to 2 orders of magnitude.
- This technique can be used in many fields and measurement uncertainty can be reduced significantly.

# References

[1] ZONG Y., BROWN S. W., JOHNSON B. C., LYKKE K. R., and OHNO Y., Simple spectral stray light correction method for array spectroradiometers, Appl. Opt., 2006, 45, 1111-1119.

[2] ZONG Y., BROWN S. W., JOHNSON B. C., LYKKE K. R., and OHNO Y., Correction of stray light in spectrographs: implications for remote sensing, Proc. SPIE, 2005, 5882, 588201-1 to 588201-8.

[3] Yuqin Zong, Steven W. Brown, Keith R. Lykke, and Yoshi Ohno, CORRECTION OF STRAY LIGHT IN SPECTRORADIOMETERS AND IMAGING INSTRUMENTS, Proc. 26th of the CIE, Beijing, 2007.

# Acknowledgements

Yoshi Ohno, Steve Brown, Keith Lykke,
and Many ….