Survey of Hyperspectral Imaging Techniques

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Compared Systems

- Baseline – Scanning Filter
- Baseline – Simple Pushbroom
- Gehm (Brady) – Multiplexed Pushbroom
  - “High-throughput, multiplexed pushbroom hyperspectral microscopy”
- Wagadarikar (Brady) – Single Disperser
  - “Single disperser design for coded aperture snapshot spectral imaging”
- Gehm (Brady) – Dual Disperser
  - “Single-shot compressive spectral imaging with a dual-disperser architecture”
- Descour – CTIS
  - “Computed-tomography imaging spectrometer: experimental calibration and reconstruction results”
- Mooney – Prism Tomographic
  - “High-throughput hyperspectral infrared camera”
- Gentry – ISIS
  - “Information-Efficient Spectral Imaging Sensor”
- Mohan (Raskar) – Agile Spectrum Imaging
  - “Agile Spectrum Imaging: Programmable Wavelength Modulation for Cameras and Projectors”

Points of Comparison

- Data volume
- Physical volume
- Architectural impact on acquisition time
- Computational reconstruction and scaling
- Photon efficiency (noise, sensitivity, etc.)
- Compression (Information efficiency)

Caveats

- Many quantities (like physical volume and reconstruction scaling) depend heavily on the specific implementation. Interpret these results as expected limits.
- Data quality metric – there is none. Different techniques can be expected to produce different amounts and types of artifacts. These are discussed qualitatively herein.

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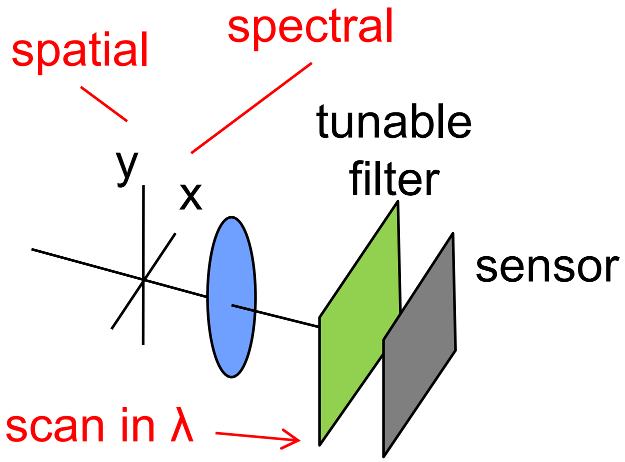
Baseline – Scanning Filter

Summary:

- Data Cube: N_x x N_y x L
- Volume: 1f * D^2
- Acquisition time: scanning.
- Reconstruction: None
- Photon Efficiency: 1/L
- Compression: 1

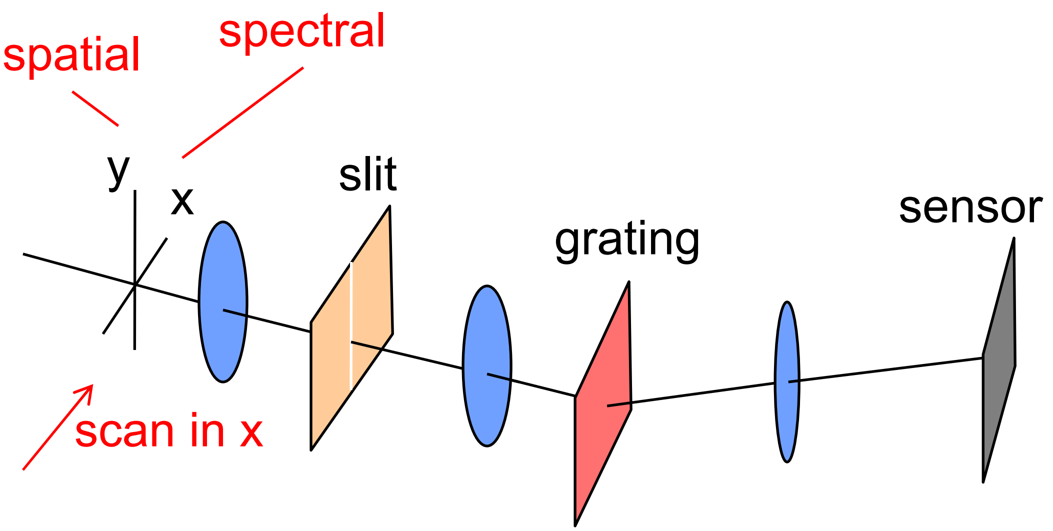


Scan in λ using an electronically-tunable filter. Typically, the filter is based on either liquid crystals or acousto-optic principles.

Baseline – Pushbroom

Summary:

- Data Cube: N_x x N_y x L
- Volume: 5f * D^2
- Acquisition time: Mechanical motion is required between lines (resulting in photon dead-time) but object motion is treated stably.
- Reconstruction: None
- Photon Efficiency: $1/N_x$
- Compression: 1

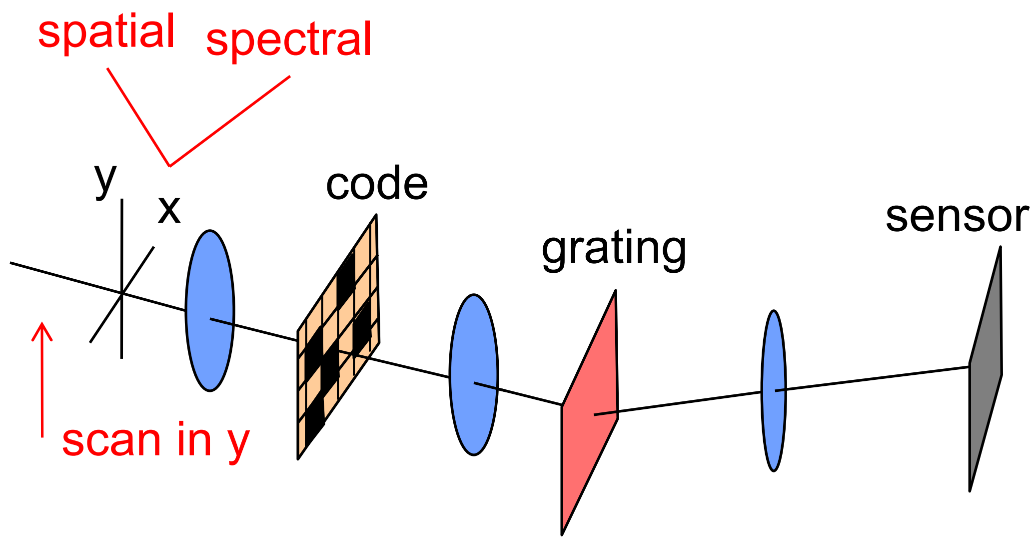


Each row on the sensor provides a spectrum at that y value. Scanning in x provides the other spatial dimension.

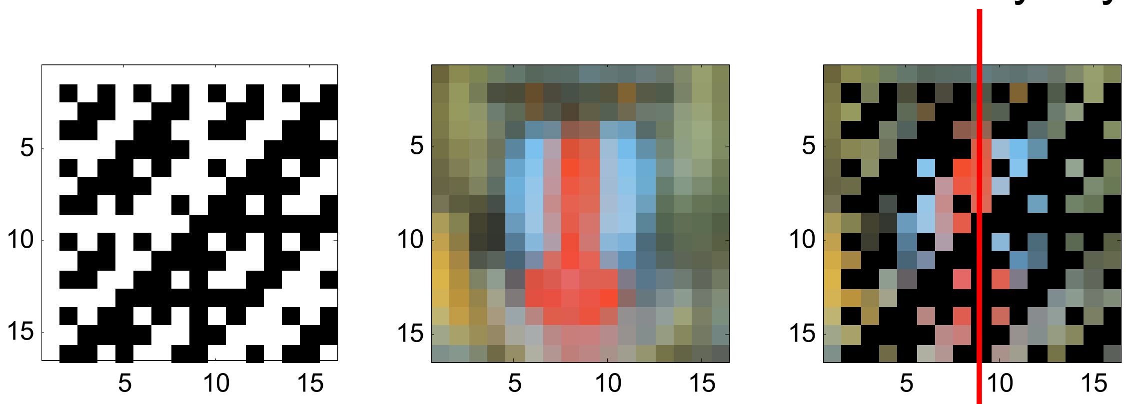
Gehm (Brady) – Multiplexed Pushbroom

Summary:

- Data Cube: N_x x N_y x L
- Volume: 5f * D^2
- Acquisition time: Mechanical motion is required between lines.
- Reconstruction: $O(N_xN_y^2L)$
- Photon Efficiency: ~1/2
- Compression: ~1



code/decode orthogonality requires scene uniformity in y.



by sliding code over scene vertically (or vice versa) one can mix rows to synthesize columns of uniform scene value.

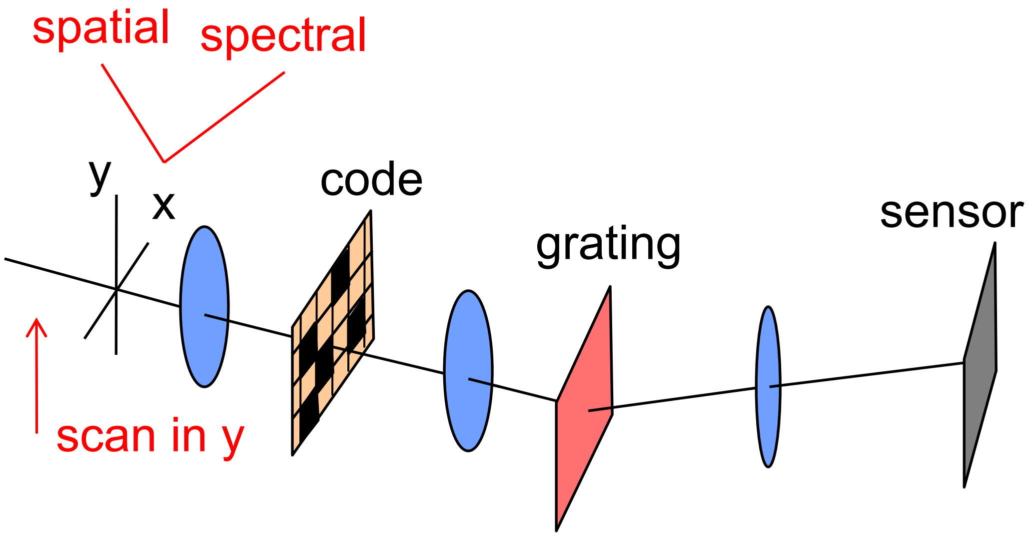
Gehm (Brady) – Multiplexed Pushbroom (2)

- Reconstruction: $O(N_x N_y^2 L) = O(N_x N_y L \times N_y)$
  Every point in the data cube is a dot-product of length-N_y vectors.
- Scanning options:
  - Scan scene over code for “continuous” pushbroom mode, requiring slightly more complex data re-mapping, or
  - Circularly scan code through the field stop for fixed-field capture
- In prototype systems, resolution was set by code size to order 6x6 CCD pixels for processing/sampling convenience. The re-binning and digital aberration (smile) correction was not included in the reconstruction scaling.

Wagadarikar (Brady) – Single Disperser

Summary:

- Data Cube: N_x x N_y x L
- Volume: 5f * D^2
- Acquisition time: Mechanical motion is required between lines (if any).
- Reconstruction: $O((N_x N_y L)^3)$, L_1 minimization
- Photon Efficiency: ~1/2
- Compression: 1/L to 1



- Identical hardware to Multiplexed Pushbroom
- Skip scan steps or don't scan at all
- Reconstruct via L_1 minimization
- Reduced spatial information in single-shot mode – object pixels imaged to closed code addresses are completely lost

Gehm (Brady) – Dual Disperser

Summary:

- Data Cube: N_x x N_y x L
- Volume: 9f * D^2
- Acquisition time: Snapshot
- Reconstruction: $O((N_x N_y L)^3)$, L_1 minimization
- Photon Efficiency: ~1/2
- Compression: 1/L

- Raw measured frames are spatially isomorphic with scene – each pixel is a spectral projection.

Images removed due to copyright restrictions.
Source: Gehm, M. E. et al. "Single-shot Compressive Spectral Imaging with a Dual-disperser Architecture." *Optics Express* 15, no. 21 (2007): 14013-14027.

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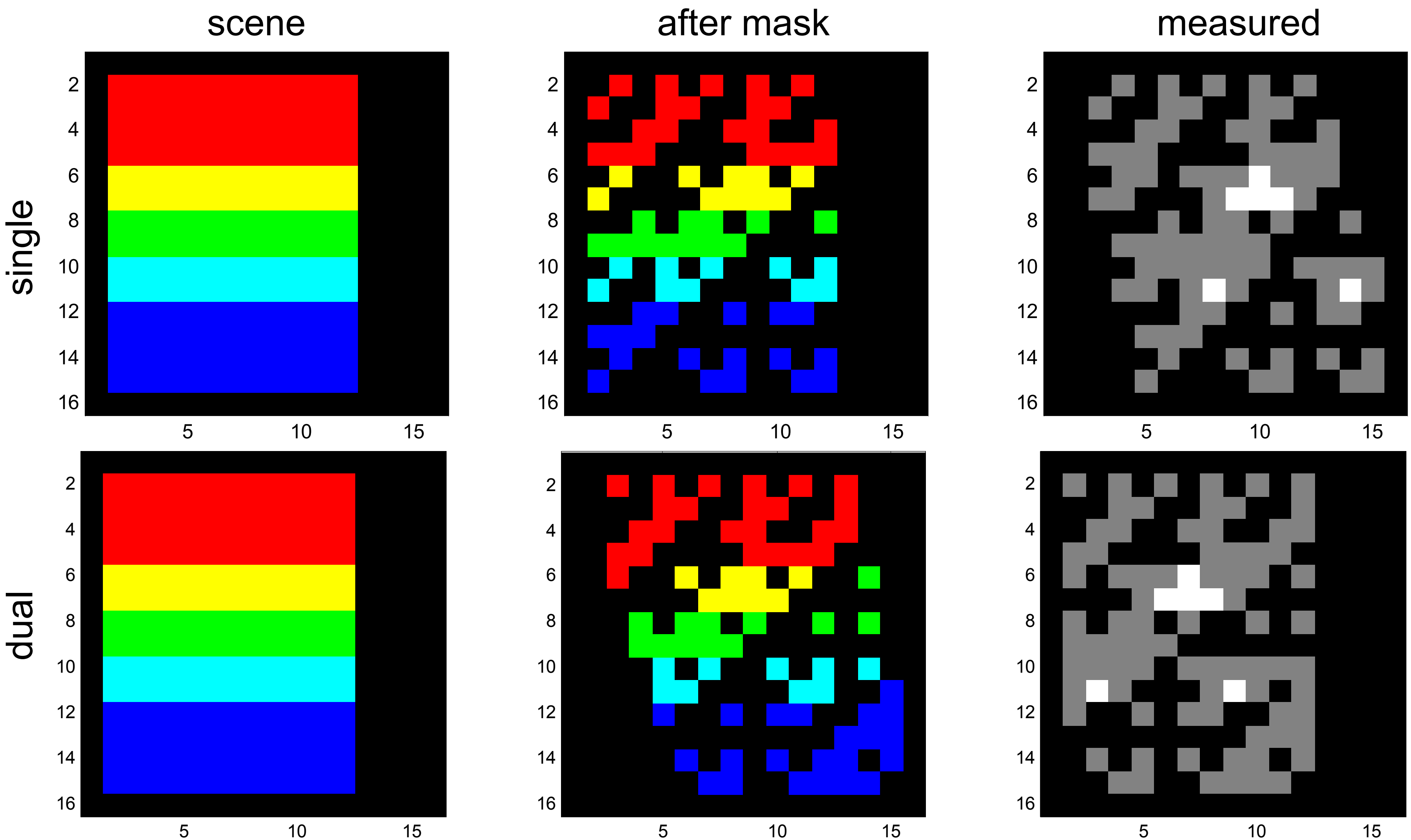
Single/Dual Disperser Comparison



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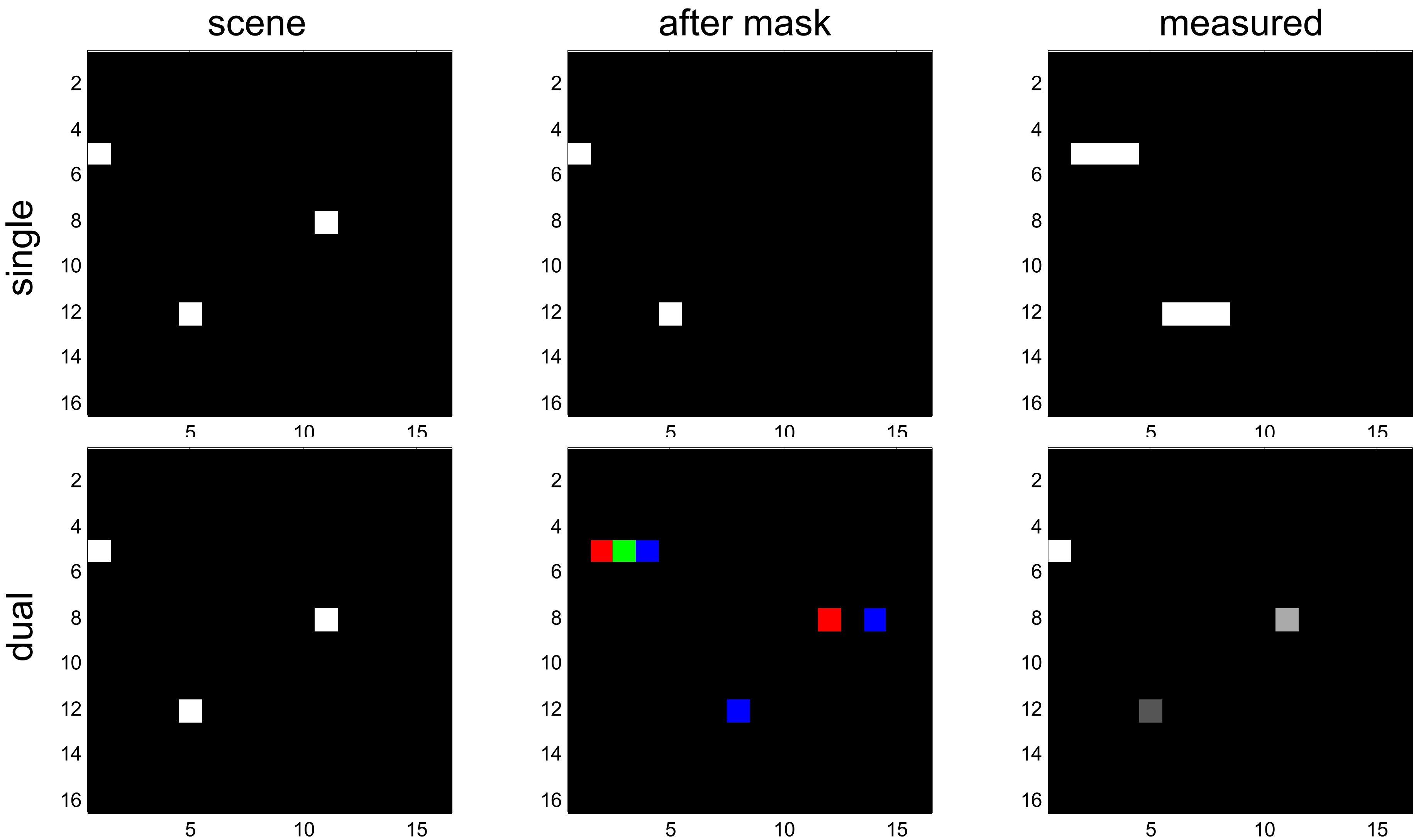
Single/Dual Disperser Comparison



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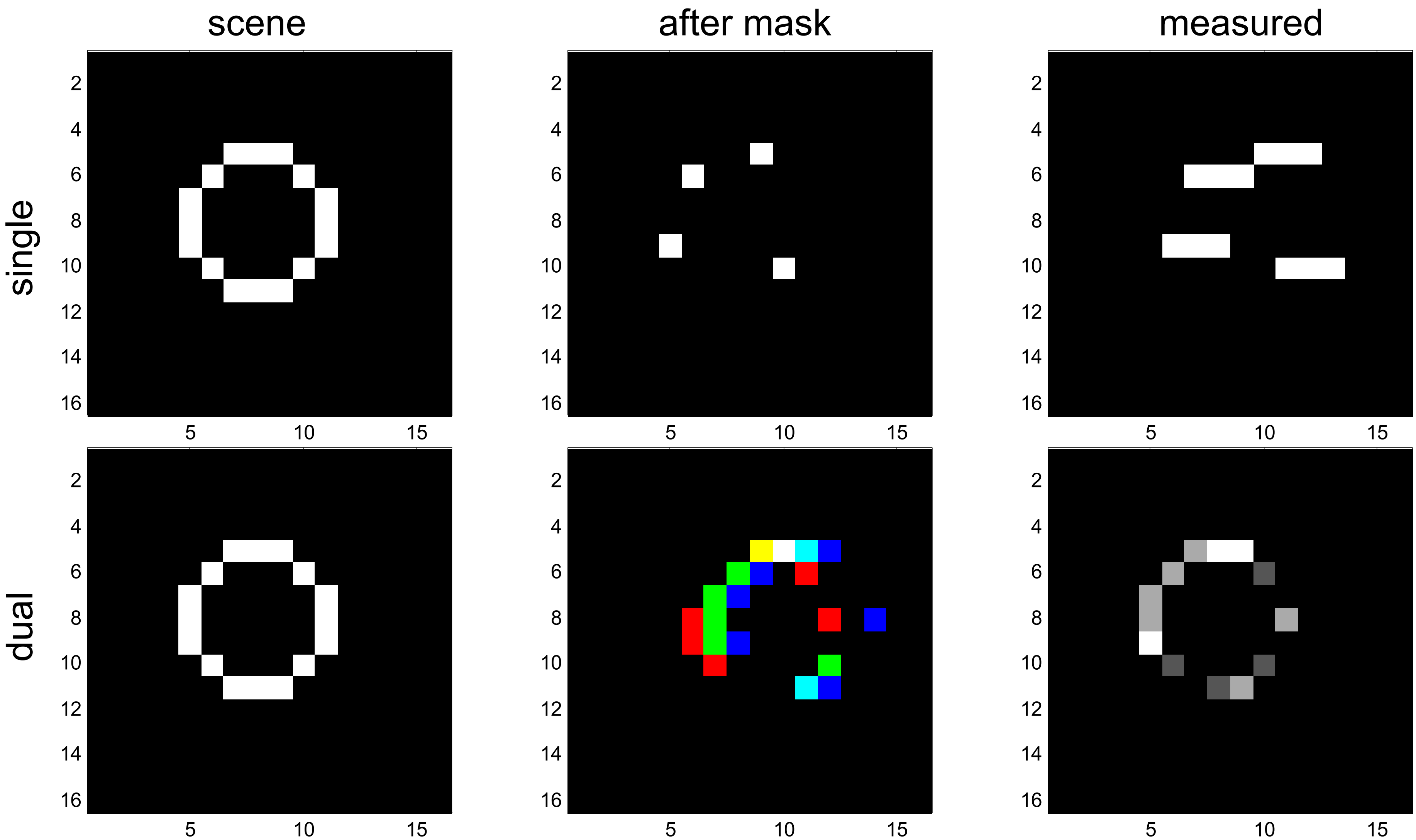
Single/Dual Disperser Comparison



Descour – CTIS

Summary:

- Data Cube: N_x x N_y x L
- Volume: 4f * D^2
- Acquisition time: Snapshot
- Reconstruction:
  - $O(n^3)$, FBP
  - $O(n^2 \log n)$, Fourier
- Photon Efficiency: 1
- Compression: ~1

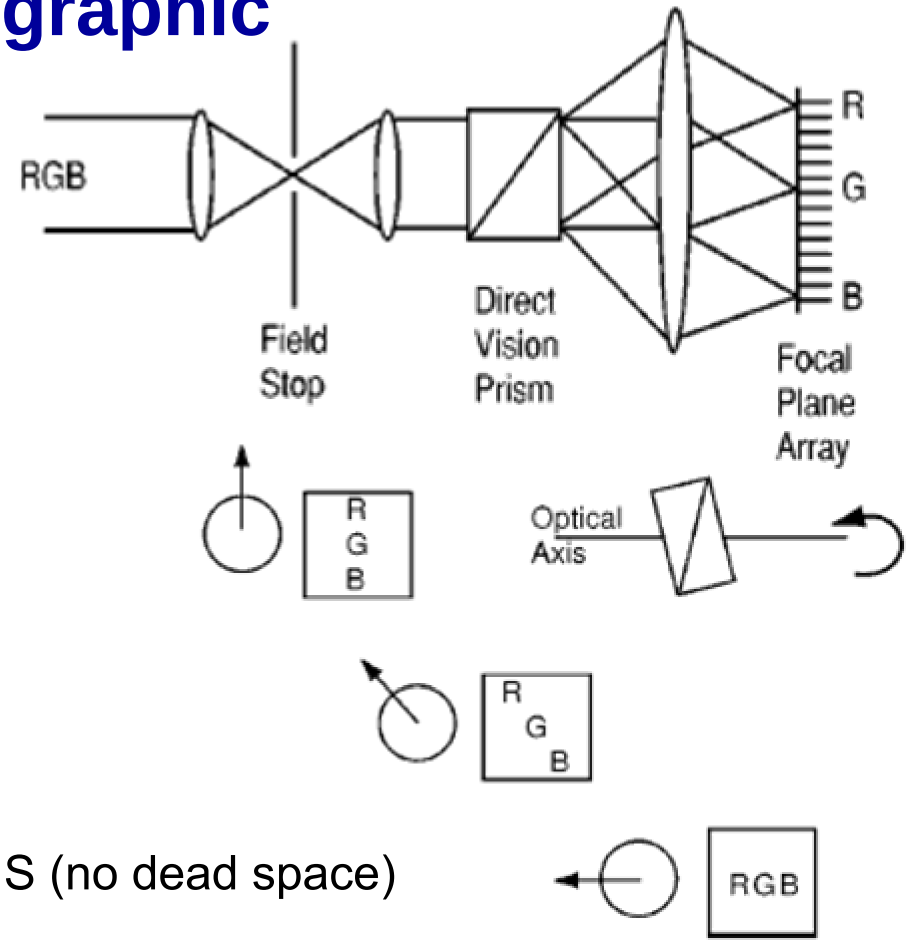
Images removed due to copyright restrictions.
Source: Descour, M., and E. Dereniak. "Computed-tomography Imaging Spectrometer: Experimental Calibration and Reconstruction Results." *Applied Optics* 34, no. 22 (August 1, 1995): 4817-4826.

- Inefficiently uses sensor; dead spaces required to avoid overlap.
- Requires P > N_x x N_y x L pixels
- Limited information efficiency; missing cone problem
- Reconstruction approaches have been proposed to improve missing cone (extrapolation and model-based approaches)

Mooney – Prism tomographic

Summary:

- Data Cube: N_x x N_y x L
- Volume: 4f * D^2
- Acquisition time: Scanning
- Reconstruction:
  - $O(n^3)$, FBP
  - $O(n^2 \log n)$, Fourier
- Photon Efficiency: 1
- Compression: ~1



- More efficiently uses pixels than CTIS (no dead space)
- Requires P = N_x x N_y pixels.
- Limited information efficiency; missing cone problem
- Reconstruction approaches have been proposed to improve missing cone (extrapolation and model-based approaches)

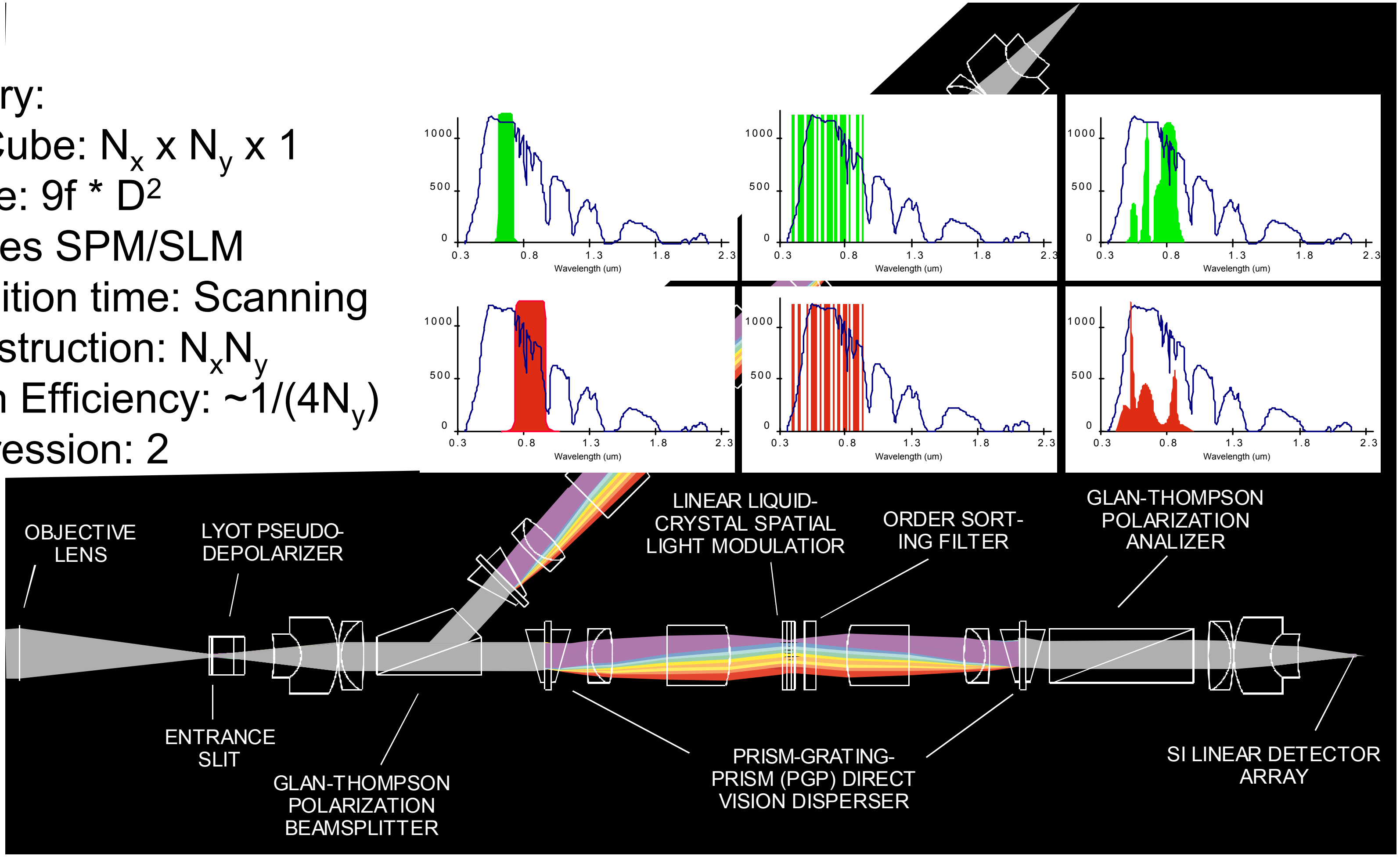
Image from Mooney, JM et al. "High-throughput hyperspectral infrared camera." *JOSA A* 14, no. 11 (1997): 2951-2961. (All authors with US Air Force.)

Gentry – ISIS

Sandia National Laboratories, US Department of Energy

Summary:

- Data Cube: N_x x N_y x 1
- Volume: 9f * D^2
- Requires SPM/SLM
- Acquisition time: Scanning
- Reconstruction: N_xN_y
- Photon Efficiency: ~1/(4N_y)
- Compression: 2

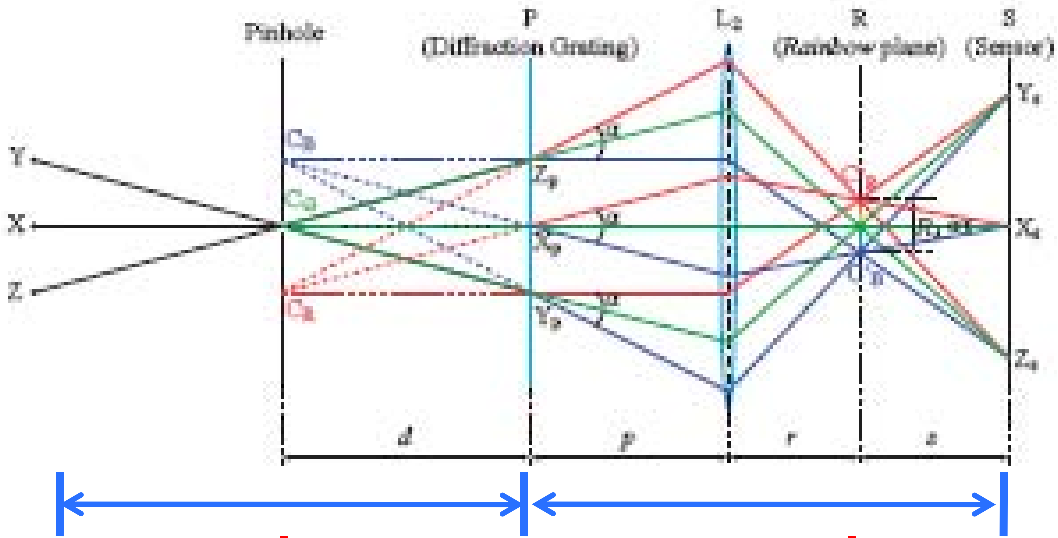


- Reconstruction: subtraction required for every N_xN_y point
- Photon efficiency: for any given pixel-channel band, one arm is always zero (losing half the light) and the other will in in general be between 0 and 1.

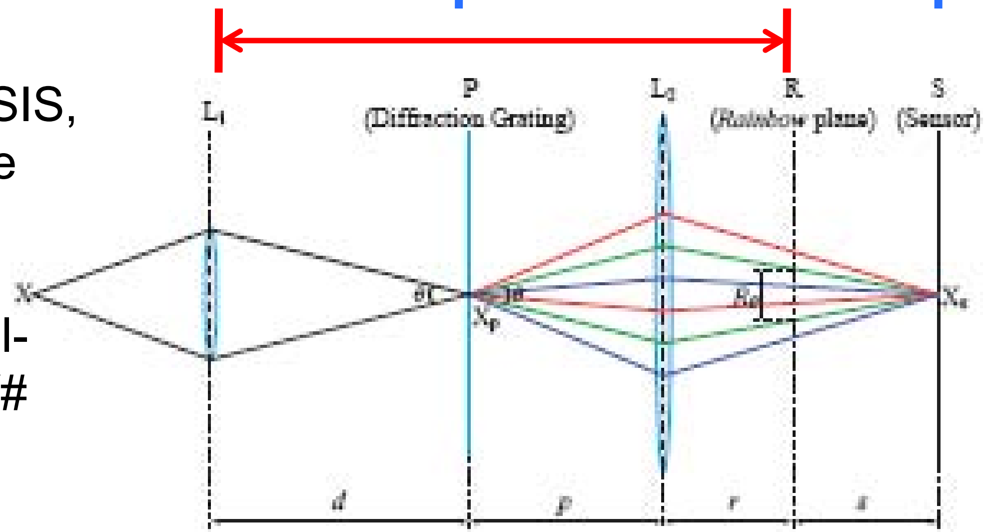
Mohan (Raskar) – Agile Spectrum Imaging

Summary:

- Data Cube: N_x x N_y x 1
- Volume: 5f * D^2
- Requires SLM
- Acquisition time: Snapshot
- Reconstruction: None
- Photon Efficiency: ~1/2
- Compression: 1



Not designed to be a HSI, but like ISIS, allows for spectrally-weighted image acquisition. Differences from ISIS:



- Limited spectral filtering and spatial-spectral coupling as a function of F/#
- Positive-only filter functions

Images courtesy of Ramesh Raskar. Used with permission.
Source: Mohan, A., R. Raskar, and J. Tumblin. "Agile Spectrum Imaging: Programmable Wavelength Modulation for Cameras and Projectors" *Eurographics* 2008, Vol 27 no. 2 (2008).

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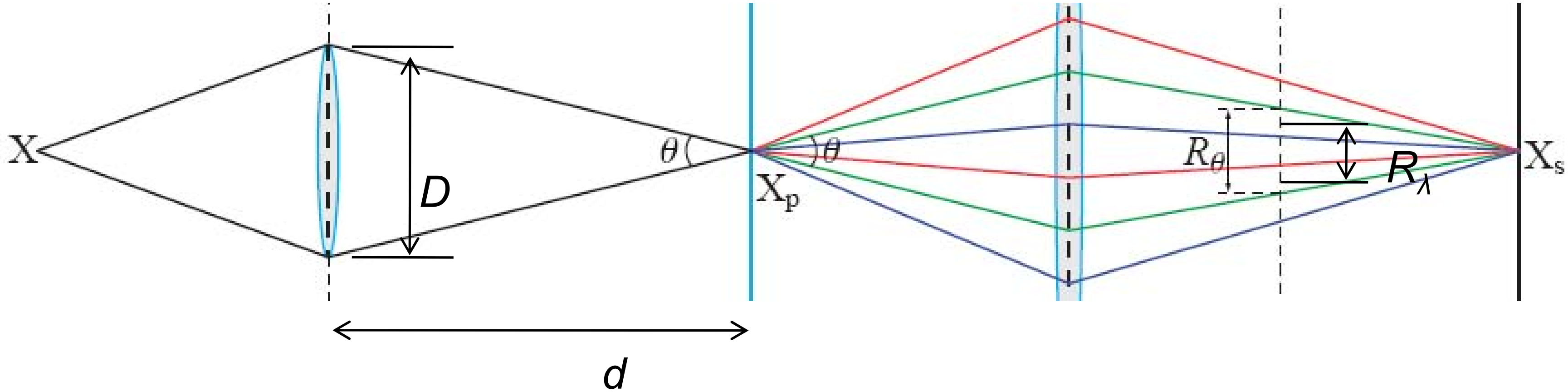
Mohan (Raskar) – Agile Spectrum Imaging spectral selectivity



R_θ = width of one wavelength in rainbow plane
R_λ = distance between centers of extreme wavelengths

Maximum number of distinct wavelengths = $\frac{R_\lambda}{R_\theta} + 1 = \frac{d}{D} + 1 = F + 1$

Where *F* is the F-number of the objective lens. Therefore, high spectral selectivity requires a very slow system.

Image courtesy of Ramesh Raskar. Used with permission.
Source: Mohan, A., R. Raskar, and J. Tumblin. "Agile Spectrum Imaging: Programmable Wavelength Modulation for Cameras and Projectors" *Eurographics* 2008, Vol 27 no. 2 (2008).

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Summary

	Data Cube	Physical Volume	Acquisition	Reconstruction	Photon Efficiency	Compres-sion
Scan. Filter	N_x x N_y x L	1f * D^2	Scanning	None	1/L	1
Pushbroom	N_x x N_y x L	5f * D^2	Scanning	None	$1/N_x$	1
Multiplexed Pushbroom	N_x x N_y x L	5f * D^2	Scanning	$O(N_x N_y^2 L)$	~1/2	1
Single Disperser	N_x x N_y x L	5f * D^2	Scanning/ Snapshot	$O((N_x N_y L)^3)$, L_1 minimization	~1/2	1/L to 1
Dual Disperser	N_x x N_y x L	9f * D^2	Snapshot	$O((N_x N_y L)^3)$, L_1 minimization	~1/2	1/L
CTIS	N_x x N_y x L	4f * D^2	Snapshot	$O(n^3)$, FBP $O(n^2 \log n)$, Fourier	1	~1
Prism Tomographic	N_x x N_y x L	4f * D^2	Scanning	$O(n^3)$, FBP $O(n^2 \log n)$, Fourier	1	~1
ISIS	N_x x N_y x 1	9f * D^2	Scanning	$N_x N_y$	$\sim 1/(4N_y)$	2
Agile Spectrum	N_x x N_y x 1	5f * D^2	Snapshot	None	~1/2	1

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