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.
Baseline – Scanning Filter

Summary:
• Data Cube: $N_x \times N_y \times L$
• Volume: $1f \times D^2$
• Acquisition time: scanning.
• Reconstruction: None
• Photon Efficiency: $1/L$
• Compression: 1

Scan in $\lambda$ using an electronically-tunable filter. Typically, the filter is based on either liquid crystals or acousto-optic principles.
Baseline – Pushbroom

Summary:
• Data Cube: $N_x \times N_y \times L$
• Volume: $5f \times D^2$
• 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: $N_x \times N_y \times L$
• Volume: $5f \times D^2$
• Acquisition time:
  Mechanical motion is required between lines.
• Reconstruction: $O(N_x N_y^2 L)$
• Photon Efficiency: $\sim 1/2$
• Compression: $\sim 1$

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.
• 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: $N_x \times N_y \times L$
• Volume: $5f \times D^2$
• Acquisition time: Mechanical motion is required between lines (if any).
• Reconstruction: $O((N_xN_yL)^3)$, $L_1$ minimization
• Photon Efficiency: $\sim 1/2$
• 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: $N_x \times N_y \times L$
• Volume: $9f \times D^2$
• Acquisition time: Snapshot
• Reconstruction: $O((N_xN_yL)^3)$, $L_1$ minimization
• Photon Efficiency: ~$1/2$
• Compression: $1/L$

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

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Single/Dual Disperser Comparison

scene

after mask

measured

single
dual
Single/Dual Disperser Comparison

scene

after mask

measured
Single/Dual Disperser Comparison

scene

after mask

measured

dual

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Descour – CTIS

Summary:
• Data Cube: \( N_x \times N_y \times L \)
• Volume: \( 4f \times D^2 \)
• Acquisition time: Snapshot
• Reconstruction:
  \( O(n^3) \), FBP
  \( O(n^2 \log n) \), Fourier
• Photon Efficiency: 1
• Compression: \( \sim 1 \)

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

Images removed due to copyright restrictions.
Mooney – Prism tomographic

Summary:
• Data Cube: \(N_x \times N_y \times L\)
• Volume: \(4f \times D^2\)
• Acquisition time: Scanning
• Reconstruction:
  O\((n^3)\), FBP
  O\((n^2 \log n)\), Fourier
• Photon Efficiency: 1
• Compression: \(\sim 1\)

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

Gentry – ISIS

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 general be between 0 and 1.
Mohan (Raskar) – Agile Spectrum Imaging

Summary:
• Data Cube: \( N_x \times N_y \times 1 \)
• Volume: \( 5f \times D^2 \)
• Requires SLM
• Acquisition time: Snapshot
• Reconstruction: None
• Photon Efficiency: \( \sim 1/2 \)
• 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.
Mohan (Raskar) – Agile Spectrum Imaging spectral selectivity

\[ R_\theta = \text{width of one wavelength in rainbow plane} \]
\[ R_\lambda = \text{distance between centers of extreme wavelengths} \]

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.
## Summary

<table>
<thead>
<tr>
<th>Data Cube</th>
<th>Physical Volume</th>
<th>Acquisition</th>
<th>Reconstruction</th>
<th>Photon Efficiency</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan. Filter</td>
<td>$N_x \times N_y \times L$</td>
<td>$1f \times D^2$</td>
<td>Scanning</td>
<td>None</td>
<td>$1/L$</td>
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<td>Pushbroom</td>
<td>$N_x \times N_y \times L$</td>
<td>$5f \times D^2$</td>
<td>Scanning</td>
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<td>$1/N_x$</td>
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<td>Multiplexed Pushbroom</td>
<td>$N_x \times N_y \times L$</td>
<td>$5f \times D^2$</td>
<td>Scanning</td>
<td>$O(N_x N_y^2 L)$</td>
<td>~1/2</td>
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<td>Single Disperser</td>
<td>$N_x \times N_y \times L$</td>
<td>$5f \times D^2$</td>
<td>Scanning/Snapshot</td>
<td>$O((N_x N_y L)^3)$, L$_1$ minimization</td>
<td>~1/2</td>
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<td>Snapshot</td>
<td>$O((N_x N_y L)^3)$, L$_1$ minimization</td>
<td>~1/2</td>
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<td>CTIS</td>
<td>$N_x \times N_y \times L$</td>
<td>$4f \times D^2$</td>
<td>Snapshot</td>
<td>$O(n^3)$, FBP</td>
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<td></td>
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<td>$O(n^2 \log n)$, Fourier</td>
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<td>Prism Tomographic</td>
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<td>$O(n^2 \log n)$, Fourier</td>
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<td>ISIS</td>
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<td>Scanning</td>
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<td>~1/(4N_y)</td>
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<td>$5f \times D^2$</td>
<td>Snapshot</td>
<td>None</td>
<td>~1/2</td>
</tr>
</tbody>
</table>
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