Snapshot Spectral Imaging Technologies for On-Site Inspection

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Introduction to Spectral Imaging

- **Spectrometers** characterize electromagnetic radiation as a function of wavelength.
  - Optical regime: 0.2 – 20.0 μm
- Spectral imagers provide spectral information as a function of spatial coordinates.
  - Acquire \( I(x,y,\lambda) \) datacubes
- Many scientific and commercial applications for multi-, hyper-, and ultra-spectral imagers.
- Parameters of interest in passive remote sensing are typically spectral reflectance \( \rho(\lambda) \) or emittance \( \varepsilon(\lambda) \).
Spectral Imaging for CTBTO OSI

For on-site inspections, “…Multi-spectral imaging, including infrared measurements, at and below the surface, and from the air, [may be conducted] to search for anomalies or artifacts.” (Protocol paragraph 69b)

“For any additional overflights conducted pursuant to paragraph 73, inspectors on board the aircraft may also use portable, easily installed equipment for (a) multi-spectral (including infrared) imagery…” (Protocol paragraph 80)

- [Multi-]Spectral imaging is allowed during an on-site inspection (OSI) to detect spectral features that could be used to prioritize regions within the inspection area (IA) and thereby accelerate and optimize the inspection process.
  - Infrared imaging also allowed; MSIR = multispectral + infrared imaging
  - The CTBT permits MSIR data acquisition from the air, or at or below the surface.
  - Operational constraints are imposed.
How is spectral imagery typically acquired?

**Point-scanning (whiskbroom) spectrometer:**
Recover spectrum for a point location: $I(x_i, y_j, \lambda)$

**Line-scanning (pushbroom) spectrometer:**
Recover spectra for one spatial dimension:
$I(x, y_j, \lambda)$

**Wavelength-scanning spectrometer:**
Recover two spatial dimensions for an integrated wavelength range: $I(x, y, \lambda_k)$

All scanning spectral imagers scan in time to assemble the 3D cube of information from multiple 2D projections or slices.

Whiskbroom and pushbroom spectral imagers are often implemented for airborne applications.
Snapshot Data Acquisition

- Snapshot spectral imagers (SSIs) capture the $I(x, y, \lambda)$ spectral datacube during a single detector integration period.

- Familiar example: A Bayer-filtered camera is snapshot for 3 wavelengths (red, green, blue).
SSI for OSI

- Previous OSI exercises have relied heavily on pushbroom imagers, which are well suited for an airborne scanning geometry – so what is the advantage of SSIs?

**Enable Longer Dwell Time**

- **pushbroom**
  - $SNR = \Psi$
- **snapshot**
  - $t = 1$

**Optimize Data Acquisition & Reduce Acquisition Constraints**

**Simplify Data Analysis**

- Image from [14]
- Image from [15]
- Image from [16]

Image from [5]

Landsat image used at IFE14
SSI for OSI

- CTBTO OSI applications impose particular requirements on spectral imagers. If an SSI architecture is to be well suited for CTBTO OSI, it must:
  - Enable fast data processing
  - Offer high spatial resolution
  - Offer moderate spectral resolution
  - Be rugged, portable, and suitable for field operation

Key OSI Observables Relevant to MSIR Techniques [4]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Class</th>
<th>$\eta$</th>
<th>$M$ (pixels used)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFS-F</td>
<td>F</td>
<td>1</td>
<td>$N_xN_y(N_w+s)(2s+1)$</td>
</tr>
<tr>
<td>IFS-L</td>
<td>F</td>
<td>1</td>
<td>$N_xN_y(N_w+s)(2s+1)$</td>
</tr>
<tr>
<td>IFS-M</td>
<td>F</td>
<td>1</td>
<td>$N_x(N_y+2s)(N_w+2s)$</td>
</tr>
<tr>
<td>IFS-μ</td>
<td>F</td>
<td>1</td>
<td>$N_x(N_y+2s)(N_w+2s)$</td>
</tr>
<tr>
<td>IMS</td>
<td>F</td>
<td>1</td>
<td>$N_x(N_y+2s)(N_w+2s)$</td>
</tr>
<tr>
<td>IRIS</td>
<td>A</td>
<td>$1/2$</td>
<td>$(N_x+2s)(N_y+2s)N_w$</td>
</tr>
<tr>
<td>MAFC</td>
<td>P</td>
<td>1</td>
<td>$(N_x+2s)(N_y+2s)N_w$</td>
</tr>
<tr>
<td>MSBS</td>
<td>A</td>
<td>1</td>
<td>$(N_x+2s)(N_y+2s)N_w$</td>
</tr>
<tr>
<td>MSI</td>
<td>F</td>
<td>$1/4$</td>
<td>$N_xN_y(2N_w+1)$</td>
</tr>
<tr>
<td>SHIFT</td>
<td>P</td>
<td>$1/4$</td>
<td>$(N_x+2s)(N_y+2s)N_w$</td>
</tr>
<tr>
<td>SRDA</td>
<td>F</td>
<td>$1/N_w$</td>
<td>$N_xN_yN_w$</td>
</tr>
<tr>
<td>TEI</td>
<td>A + F</td>
<td>1</td>
<td>$(N_x+2s)(N_y+2s)N_w$</td>
</tr>
<tr>
<td>CTIS</td>
<td>A*</td>
<td>$1/3$</td>
<td>$\sim N$</td>
</tr>
<tr>
<td>CASSI</td>
<td>X*</td>
<td>$1/2$</td>
<td>$N_y(N_x+N_w-1)$</td>
</tr>
</tbody>
</table>
SSI Architectures for OSI

Spatially Resolved Detector Arrays (SRDA)

- Commercial SRDAs can be small - 77 x 142 x 36 mm³
- Compact and rugged, but require interpolation algorithms and spectral channels are fixed.

Multispectral Beamsplitters (MSBS)

- Produces 4-16 spectral images, but image registration must be implemented to accurately reconstruct.
SSI Architectures for OSI

**Multi-Aperture Cameras (MAC)**
- Filters bonded to FPA
- Filter array in front of lenslets
- SHIFT: Fourier transform approach
- Compact and light efficient, but subject to parallax induced artifacts and require image registration.

**Image Mapping Spectrometer (IMS)**
- Offers high spatial and moderate spectral resolution, but maintaining calibration may be challenging.

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*Figure from [1]*

*Image from [18]*

*Image from [1]*

*Image from [1]*
SSI Technology Comparison

- Comparison below is focused exclusively on the four sensor architectures reviewed.
- Signal to noise ratio (SNR) is proportional to optical efficiency and detector utilization.
  - Optical efficiency assumes lossless optics.
- Example shows achievable spatial samples given a 4096x4096 (~16M) pixel FPA and 12 spectral channels.
  - Pixel margin between spectra is assumed to be 5 pixels.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Ideal Optical Efficiency</th>
<th>FPA Pixels Used</th>
<th>Detector Utilization</th>
<th>Max Spatial Samples (given 12 spectral channels)</th>
<th>Calibration Robustness&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Airborne Robustness&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Commercially Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRDA</td>
<td>$1/N_w$</td>
<td>$N_x N_y N_w$</td>
<td>1.00</td>
<td>1182 x 1182</td>
<td>high</td>
<td>high</td>
<td>yes</td>
</tr>
<tr>
<td>MSBS</td>
<td>0.5-1</td>
<td>$(N_x + 2s)(N_y + 2s)N_w$</td>
<td>1.00</td>
<td>1182 x 1182</td>
<td>med-high</td>
<td>low-med</td>
<td>yes</td>
</tr>
<tr>
<td>MAC</td>
<td>0.25-1</td>
<td>$(N_x + 2s)(N_y + 2s)N_w$</td>
<td>0.98</td>
<td>1172 x 1172</td>
<td>med-high</td>
<td>medium</td>
<td>unknown</td>
</tr>
<tr>
<td>IMS</td>
<td>1</td>
<td>$N_x(N_y + 2s)(N_w + 2s)$</td>
<td>0.54</td>
<td>868 x 868</td>
<td>high</td>
<td>low</td>
<td>yes</td>
</tr>
<tr>
<td>Pushbroom</td>
<td>$1/N_y$</td>
<td>$N_x N_w$</td>
<td>1.00</td>
<td>4096</td>
<td>high</td>
<td>high</td>
<td>yes</td>
</tr>
</tbody>
</table>

<sup>a</sup>The Calibration Robustness metric is assessing the relative maintainability of spatial and spectral calibration once a sensor is transitioned from the laboratory to the field. For example, a technology assessed as high means the technology will likely maintain its calibration better than a technology assessed as a medium.

<sup>b</sup>The Airborne Robustness metric is assessing the relative ability to withstand and successfully collect data under airborne deployment conditions. For example, a technology assessed as low will likely be less successful during an airborne deployment than a technology assessed as medium.
## Commercially Available Sensors

- **VNIR Spectral Imagers:** Snapshot and limited pushbroom.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Instrument</th>
<th>Architecture</th>
<th>Spectral Range</th>
<th>Spectral Samples</th>
<th>Spatial Samples</th>
<th>Frame Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayspec</td>
<td>OCI-2000</td>
<td>SRDA</td>
<td>600-1000 nm</td>
<td>25</td>
<td>256x256</td>
<td>8 Hz</td>
</tr>
<tr>
<td>Bodkin</td>
<td>Hyperpixel Array Camera</td>
<td>IFS-L</td>
<td>500-910 nm; or 450-675 nm</td>
<td>90; or 20</td>
<td>55 x 44; or 90 x 75</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Cubert</td>
<td>Hedgehog &amp; Firefly</td>
<td>SRDA (?)</td>
<td>450-950 nm</td>
<td>125</td>
<td>50 x 50</td>
<td>5-20 Hz</td>
</tr>
<tr>
<td>IMEC</td>
<td>Snapshot Tiled Imager</td>
<td>MAFC</td>
<td>600-1000 nm</td>
<td>32</td>
<td>256 x 256</td>
<td>340 Hz</td>
</tr>
<tr>
<td>IMEC</td>
<td>SM4x4 or SM 5x5</td>
<td>SRDA</td>
<td>470-630 nm; or 600-1000 nm</td>
<td>16; or 25</td>
<td>512 x 256; or 409 x 216</td>
<td>340 Hz</td>
</tr>
<tr>
<td>Opto Knowledge</td>
<td>HyperVideo 4DIS</td>
<td>IFS-F</td>
<td>400-1100 nm</td>
<td>300</td>
<td>44 x 40</td>
<td>30 Hz</td>
</tr>
<tr>
<td>P&amp;P Optica</td>
<td>Hyperchannel</td>
<td>IFS-F</td>
<td>450-900 nm</td>
<td>100</td>
<td>14 x 14</td>
<td>40-100 Hz</td>
</tr>
<tr>
<td>RL Associates</td>
<td>Multispectral Imager</td>
<td>MSBS - holographic</td>
<td>450 – 800 nm</td>
<td>4 - 12</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Rebellion Photonics</td>
<td>Arrow</td>
<td>IMS</td>
<td>413 - 766 nm; or 462 - 645 nm; or 417-497 nm</td>
<td>32</td>
<td>320x480</td>
<td>7-15 Hz</td>
</tr>
<tr>
<td>Headwall Photonics</td>
<td>Hyperspec E Series</td>
<td>pushbroom</td>
<td>400-1000 nm</td>
<td>923</td>
<td>1600</td>
<td>100-400 Hz</td>
</tr>
<tr>
<td>Gilden Photonics</td>
<td>HS Spectral Cameras</td>
<td>pushbroom</td>
<td>380-800 nm; or 400-1000 nm</td>
<td>840</td>
<td>1600</td>
<td>33 Hz</td>
</tr>
<tr>
<td>Specim</td>
<td>AisaEAGLE</td>
<td>pushbroom</td>
<td>400-970 nm</td>
<td>488</td>
<td>1024</td>
<td>30 Hz</td>
</tr>
</tbody>
</table>
Summary

- Snapshot spectral imagers (SSIs) offer unique advantages over scanning spectral imagers for remote sensing.
  - SSIs afford data acquisition under conventional airborne scanning configurations but also enable flexible and targeted collections.
  - Signal to noise ratio for SSIs can be higher versus scanning spectrometers.
  - Data collected can be processed faster allowing more time to be spent on analysis – and sooner.
- Further technology development may enable even more elegant snapshot approaches.
- The market for commercial SSIs is growing, many more solutions available today than even 2 years ago.
  - The future of SSIs may benefit from a number of emerging technologies, such as three dimensional focal plane arrays
- For more information on SSI designs and development, see ref. 3.
Bibliography

References

4. Report on OSI Expert Meeting on Multispectral and Infrared Imaging, see CTBT/PTS/INF.1133

Image and Figure Credits

Thank you!

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Additional Information

- More detailed information on select SSI architectures follows.
SSI Architectures

- Many different SSI architectures have been developed and demonstrated.

- **Image Reformatting**
  - Fiber Bundle Integrated Field Spectrometer

- **Image Replicating**
  - Multiaperture Filtered Cameras
  - Image Replicating Imaging Spectrometer (IRIS)
  - Snapshot Hyperspectral Imaging Fourier Transform Spectrometer (SHIFT)

- **Computational**
  - Computed Tomography Imaging Spectrometer (CTIS)
  - Coded Aperture Snapshot Spectral Imager (CASSI)

All figures from [1]
Spectrally Resolved Detector Arrays

- Division of focal plane based approach; a ‘super pixel’ of spectral filters is aligned and bonded to the focal plane array (FPA)
- Extremely compact and monolithic
- Robust to temperature fluctuations and vibration
- Can be subject to aliasing if image is not properly bandlimited
- Filter array manufacturing can be challenging

Data processing analogous to Bayer filtered cameras

Commercial SRDAs can be small - 77 x 142 x 36 mm³

Figure from [1]

Image from [18]
Multispectral Beamsplitters

- Division of amplitude based approach.
- Spectral images are produced through implementation of sequential spectral filters.
  - Multiple FPA and single FPA designs have been demonstrated.
- Most implementations are limited to 4-16 spectral images.
- Image registration must be implemented to accurately reconstruct.

Approaches use volume holograms, spectral filters, spectral beamsplitters, or Wollaston prisms

IRIS: Image-Replicating Imaging Spectrometer

All figures from [1]
Multi-Aperture Cameras

- Division of pupil approach: a lenslet array is used to produce multiple images of the scene on a single FPA.
- Filtered and filterless MACs have been developed.
  - Multiple filtered designs have been proposed using filter arrays in pupil space or bonded to the detector.
  - Fourier transform designs are filterless and reconstruct uses discrete Fourier transform processing techniques (ex: SHIFT)
- MACs require image registration and are subject to parallax effects, which can produce spectral artifacts and complicate datacube reconstruction.
Image Mapping Spectrometer

- Other image reformatting approaches exist, but the IMS architecture is the best choice for OSI applications
  - IMS offers high spatial resolution and moderate spectral resolution
- Intermediate image is ‘sliced’ by a microfaceted mirror to produce multiple picket fence images, which are then dispersed.
- Image slicing mirror can be difficult to manufacture.
- Maintaining alignment and calibration through airborne operations may be difficult.