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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 $I(\boldsymbol{x},\boldsymbol{y},\boldsymbol{\lambda})$ 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 $\varepsilon(\lambda)$.

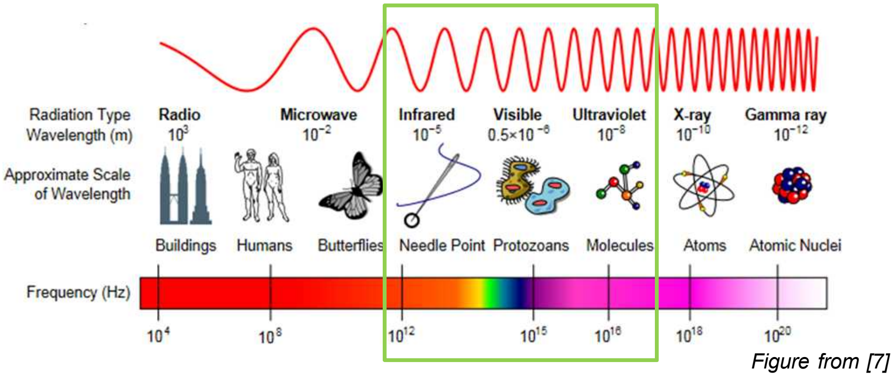
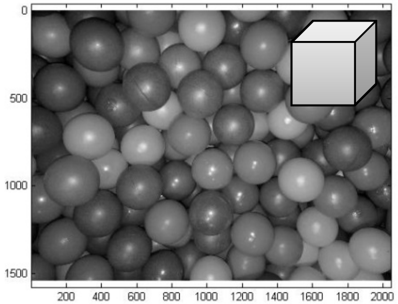


Figure from [7]



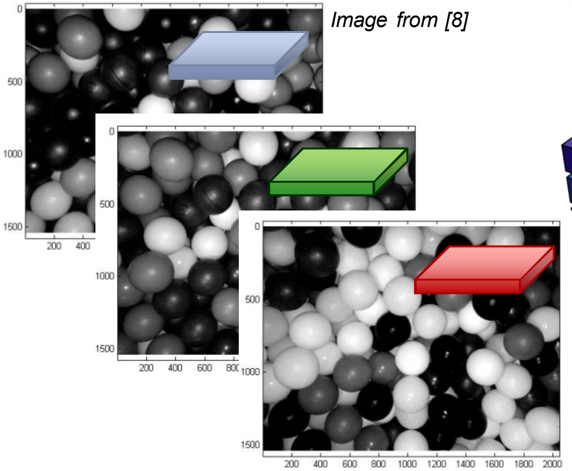


Image from [8]

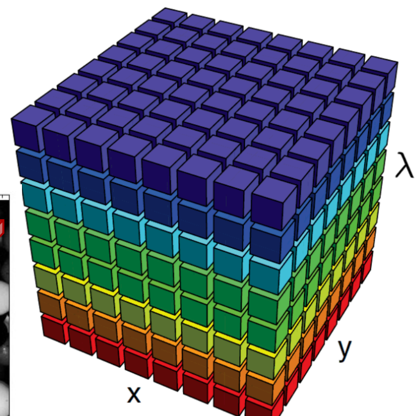
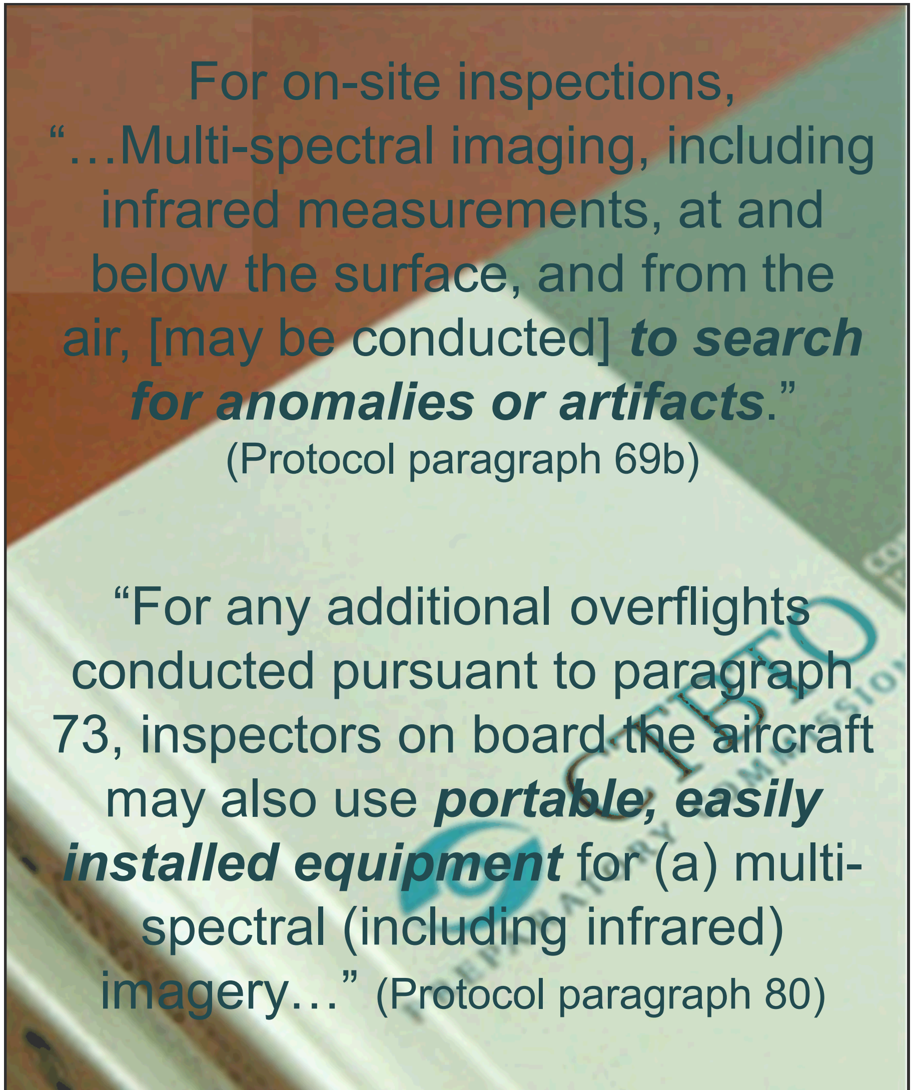


Figure from [1]

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)

Image from [2]

- [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.

Data Acquisition Approaches

- How is spectral imagery typically acquired?

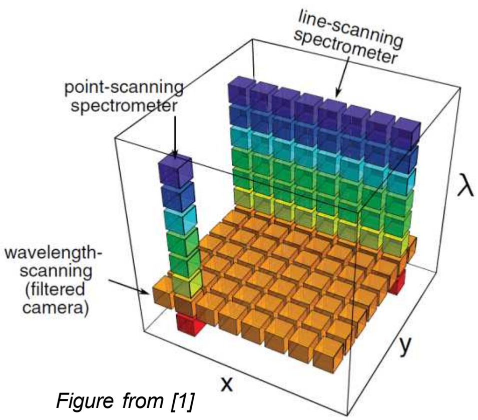


Figure from [1]

In Fourier transform approaches, optical path difference (OPD) is measured to recover ***λ***

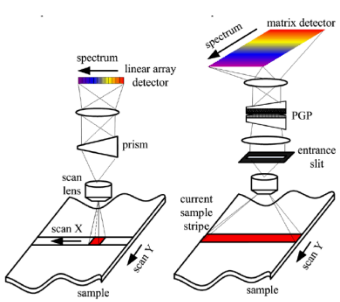


Figure from [9]

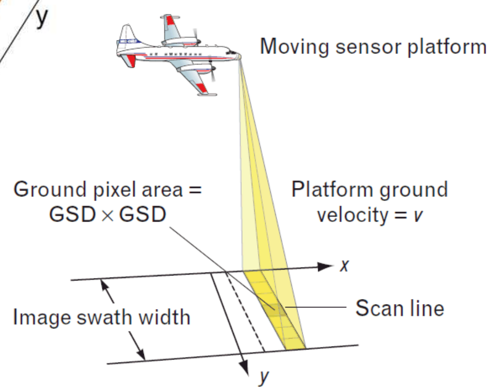


Figure from [10]

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

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

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

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

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

Snapshot Data Acquisition

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

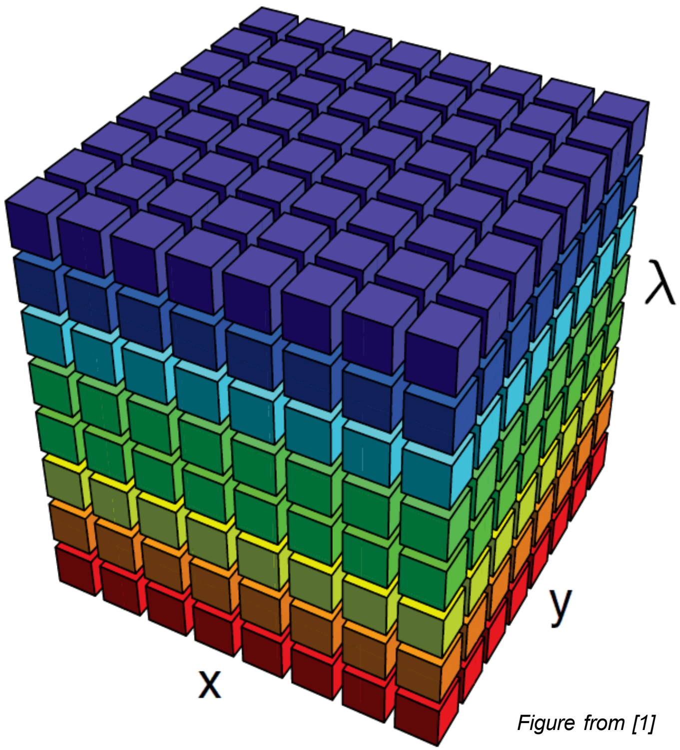


Figure from [1]

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

Image from [11]

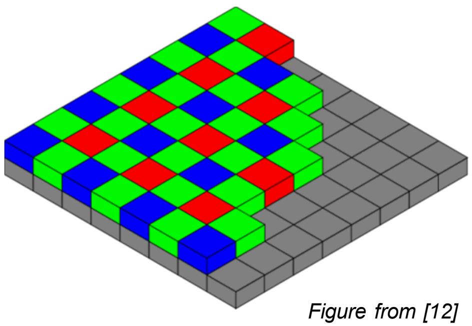


Figure from [12]

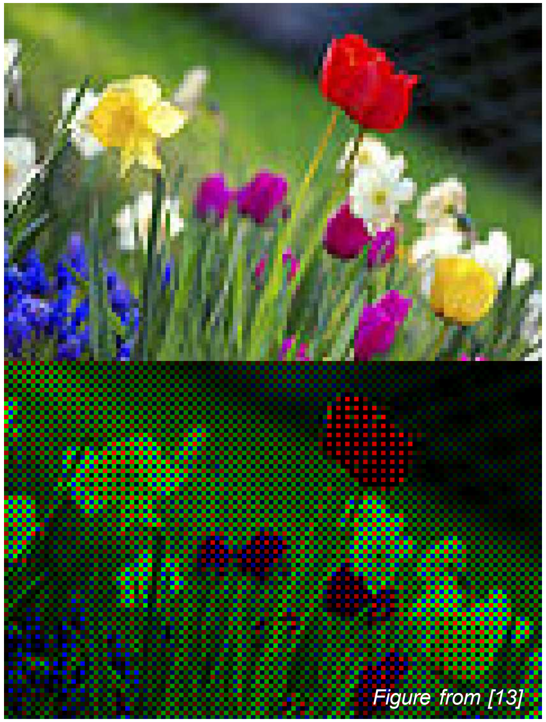
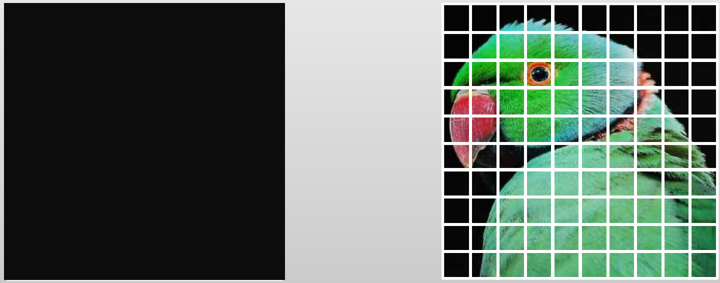


Figure from [13]

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



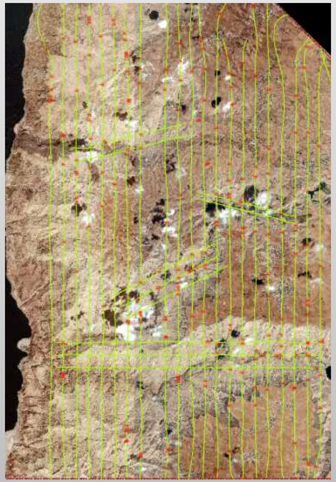
pushbroom
SNR = Ψ

t = 1

snapshot
SNR = [illegible]

Image from [14]

Optimize Data Acquisition & Reduce Acquisition Constraints



Landsat image used at IFE14

Image from [5]

Multi-configuration

Image from [16]

Simplify Data Analysis

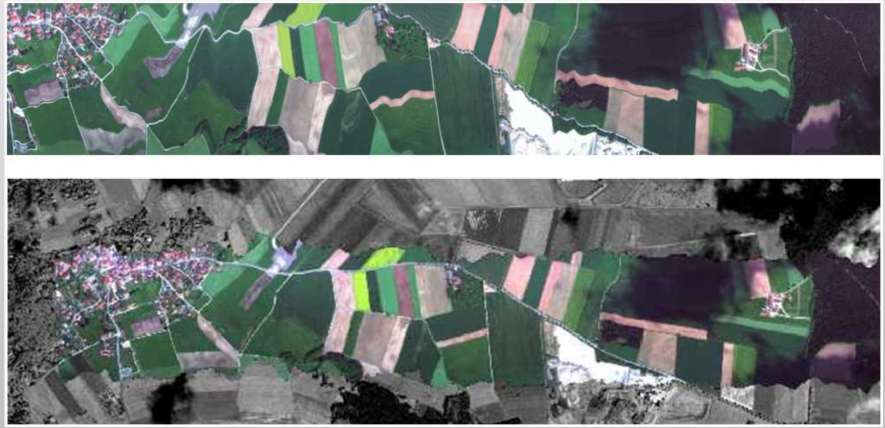


Image from [15]

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]

Signature	Spectral Region	Spectral Resolution	Spatial Resolution	Temporal Behavior
Primary Observables				
Surface disruption (spectral)	VIS, NIR, SWIR required; LWIR useful	Low to Medium	10-30 m goal < 1 km required	Weeks if dry Hours to days if weathering
Surface fluffing (thermal - reconnaissance mode)	Thermal IR	N/A	10-30 m goal < 1 km required	Data taken around maxiumum ΔT
Thermal hot spots/plumes	Thermal IR	N/A	0.3-1 m goal < 10 m required	Stable for years/ Days to weeks
Spectral anomalies	All	Low to Medium	0.3-1 m goal < 10 m required	Weeks to months
Secondary Observables				
Material plumes	VIS, NIR, SWIR required; LWIR useful	Low to Medium	0.3-1 m goal < 10 m required	Permanent until covered
Surface fluffing (thermal - hypothesis mode)	Thermal IR	N/A	10-30 m goal < 1 km required	Data taken around maxiumum ΔT
Geology		Low to High		N/A
Undefined				
Vegetation stress	VNIR, SWIR	Low	10-30 m goal < 1 km required	Low after 7 days, senescence after weeks

Snapshot Imager Technologies [1]

Technology	Class	η	*M* (pixels used)
IFS-F	F	1	$N_xN_y(N_w + s)(2s + 1)$
IFS-L	F	1	$N_xN_y(N_w + s)(2s + 1)$
IFS-M	F	1	$N_x(N_y + 2s)(N_w + 2s)$
IFS-μ	F	1	$N_x(N_y + 2s)(N_w + 2s)$
IMS	F	1	$N_x(N_y + 2s)(N_w + 2s)$
IRIS	A	1/2	$(N_x + 2s)(N_y + 2s)N_w$
MAFC	P	1	$(N_x + 2s)(N_y + 2s)N_w$
MSBS	A	1	$(N_x + 2s)(N_y + 2s)N_w$
MSI	F	1/4	$N_xN_y(2N_w + 1)$
SHIFT	P	1/4	$(N_x + 2s)(N_y + 2s)N_w$
SRDA	F	$1/N_w$	$N_xN_yN_w$
TEI	A + F	1	$(N_x + 2s)(N_y + 2s)N_w$
CTIS	A*	1/3	$\sim N$
CASSI	X*	1/2	$N_y(N_x + N_w - 1)$

SSI Architectures for OSI

Spatially Resolved Detector Arrays (SRDA)

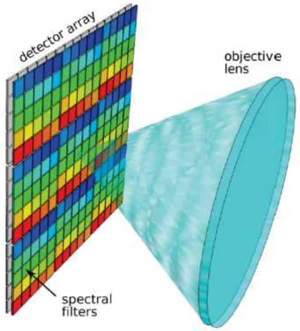


Figure from [1]

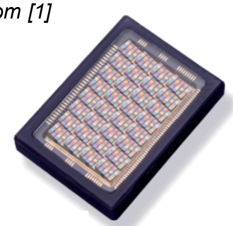


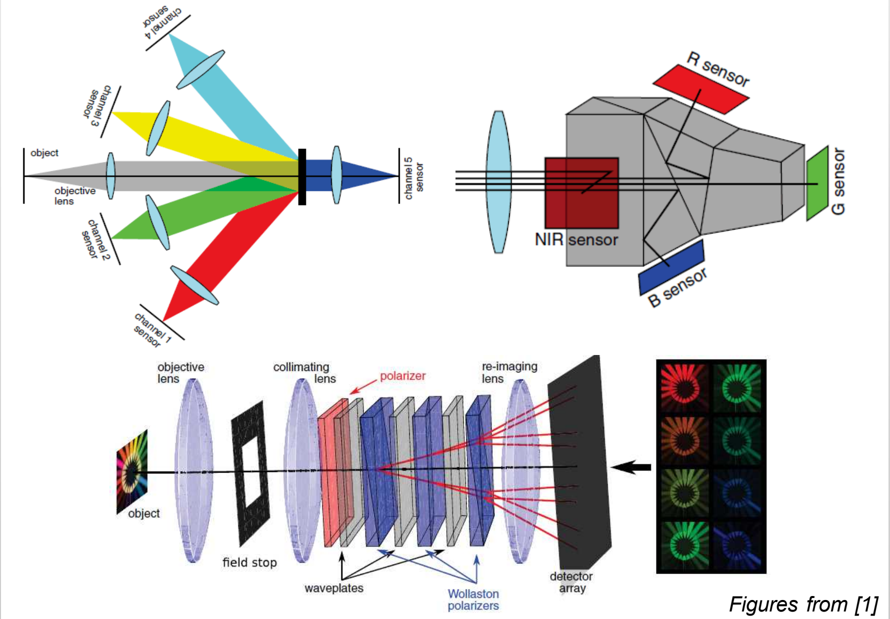
Image from [18]

Figure from [17]

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)



Figures from [1]

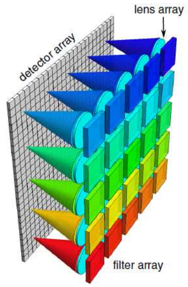
Produces 4-16 spectral images, but image registration must be implemented to accurately reconstruct.

SSI Architectures for OSI

Multi-Aperture Cameras (MAC)

Filters bonded to FPA

Image from [18]



Filter array in front of lenslets

Figure from [1]

SHIFT: Fourier transform approach

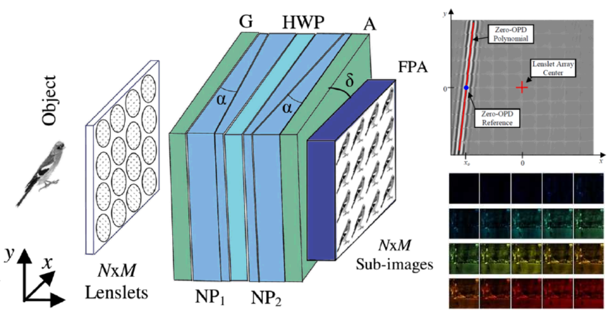


Figure from [1]

Compact and light efficient, but subject to parallax induced artifacts and require image registration.

Image Mapping Spectrometer (IMS)

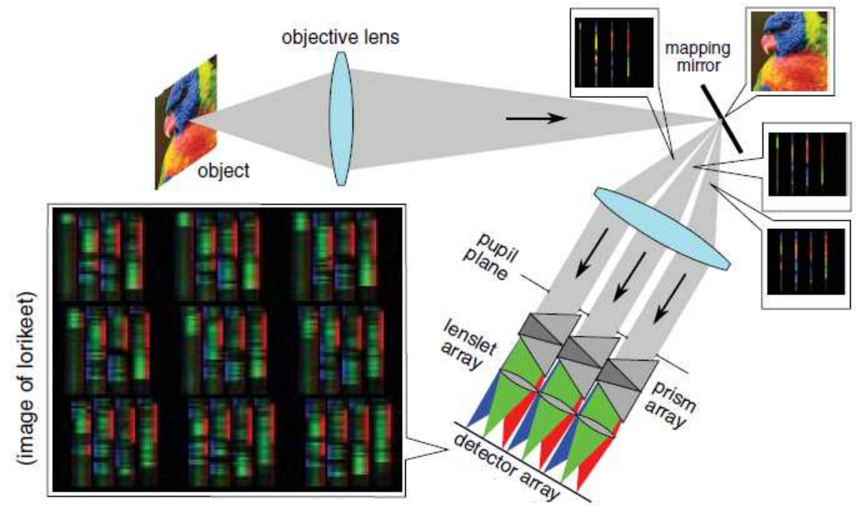


Figure from [1]

Offers high spatial and moderate spectral resolution, but maintaining calibration may be challenging.

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.

Technology	Ideal Optical Efficiency	FPA Pixels Used	Detector Utilization	Max Spatial Samples (given 12 spectral channels)	Calibration Robustness[a]	Airborne Robustness[b]	Commercially Available
SRDA	$1/N_w$	$N_x N_y N_w$	1.00	1182 x 1182	high	high	yes
MSBS	0.5-1	$(N_x + 2s)(N_y + 2s)N_w$	1.00	1182 x 1182	med-high	low-med	yes
MAC	0.25-1	$(N_x + 2s)(N_y + 2s)N_w$	0.98	1172 x 1172	med-high	medium	unknown
IMS	1	$N_x(N_y + 2s)(N_w + 2s)$	0.54	868 x 868	high	low	yes
Pushbroom	$1/N_y$	$N_x N_w$	1.00	4096	high	high	yes

[a]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*.
[b] 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*.

Portions of table from [3]

Commercially Available Sensors

- VNIR Spectral Imagers: Snapshot and limited pushbroom.

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

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

1. N. Hagen and M.W. Kudenov, "Review of snapshot spectral imaging technologies," Opt. Eng. 52 (9), 2013; doi: 10.1117/1.OE.52.9.090901.
2. Comprehensive Nuclear Test Ban Treaty: http://www.ctbto.org/the-treaty/
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6. D. Alleysson and S. Süsstrunk, Aliasing in Digital Cameras, *SPIE EI Newsletter, Special Issue on Smart Image Acquisition and Processing*, Vol. 14, Nr. 12, pp. 1,8, 2004.

Image and Figure Credits

7. http://commons.wikimedia.org/wiki/File:EM_Spectrum_Properties_edit.svg
8. http://commons.wikimedia.org/wiki/File:Toy_balls_with_different_colors.jpg
9. Figure from: Q. Li, X. He, Y. Wang, H. Liu, D. Xu, and F. Guo, "Review of spectral imaging technology in biomedical engineering: achievements and challenges." J. Biomed. Opt., 18(10), 2013; doi:10.1117/1.JBO.18.10.100901.
10. Figure from: G. Shaw and H.K. Burke, "Spectral Imaging for Remote Sensing," Lincoln Laboratory Journal 14(1), 2003
11. http://commons.wikimedia.org/wiki/File:Sony_DSC-H2_01.jpg
12. http://commons.wikimedia.org/wiki/File:BayerPatternFiltration.png
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14. http://commons.wikimedia.org/wiki/File:Rose-Ringed_Parakeet.jpg
15. Figure from: N. Oppelt and W.Mauser, "Airborne Visible / Infrared Imaging Spectrometer AVIS: Design, Characterization and Calibration", *Sensors7*(9), 1934-1953, 2007: http://www.mdpi.com/1424-8220/7/9/1934/htm
16. http://commons.wikimedia.org/wiki/File:DJI-Phantom2.png
17. Image from Bayspec datasheet, available upon request at: http://www.bayspec.com/spectroscopy/snapshot-hyperspectral-imager/
18. Image from IMEC datasheets, available at: http://www2.imec.be/be_en/research/image-sensors-and-vision-systems/hyperspectral-imaging.html

Thank you!

SNAPSHOT SPECTRAL IMAGING TECHNOLOGIES FOR ON-SITE INSPECTION

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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

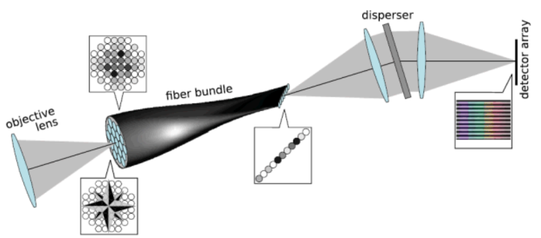


Image Mapping Spectrometer

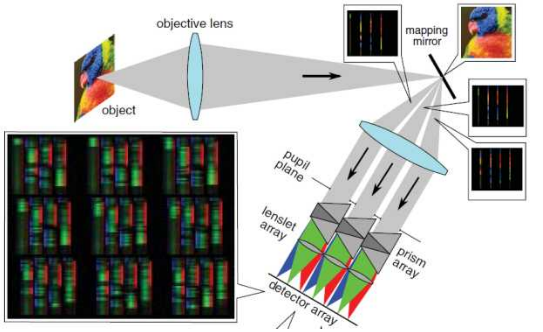


Image Replicating

Multiaperture Filtered Cameras

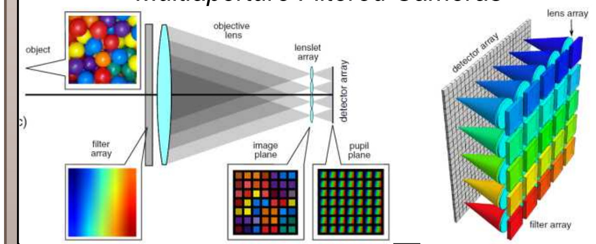
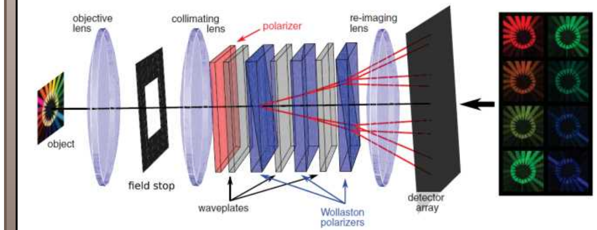
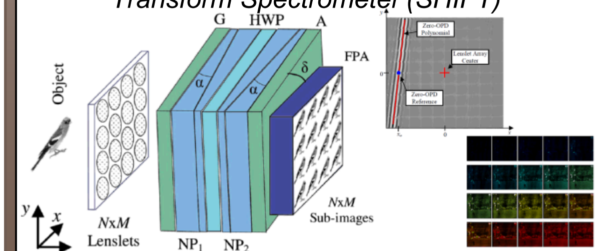


Image Replicating Imaging Spectrometer (IRIS)

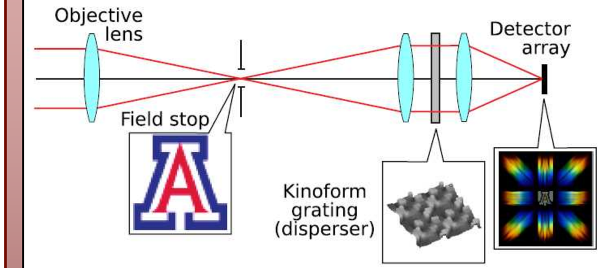


Snapshot Hyperspectral Imaging Fourier Transform Spectrometer (SHIFT)

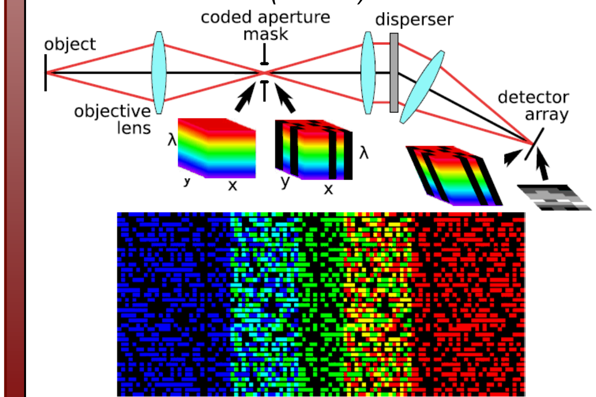


Computational

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

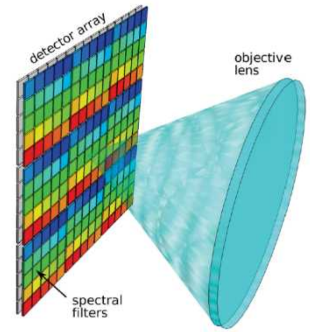


Figure from [1]

Image from [18]

Figure from [17]

Commercial SRDAs can be small - 77 x 142 x 36 mm^3

Data processing analogous to Bayer filtered cameras

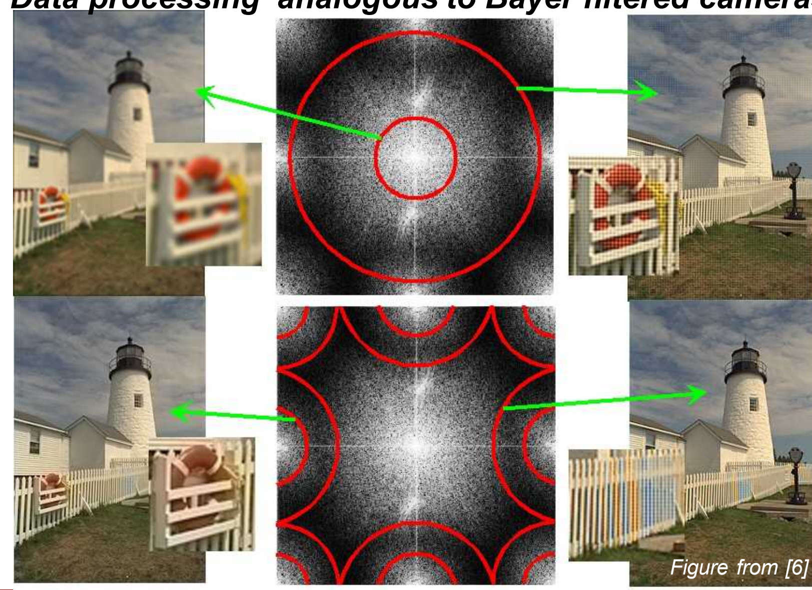
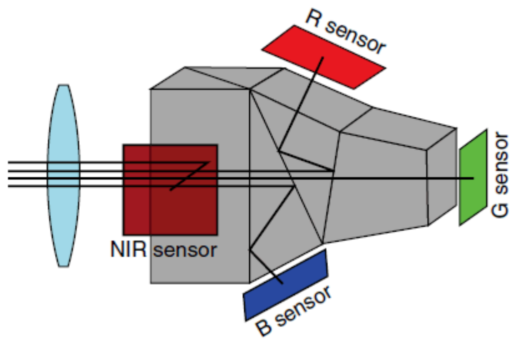
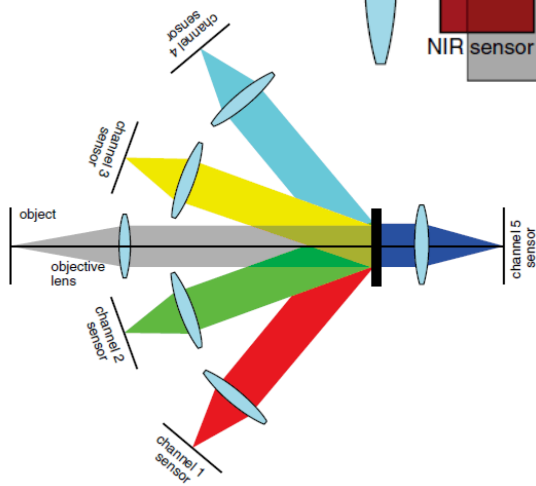


Figure from [6]

Multispectral Beamsplitters

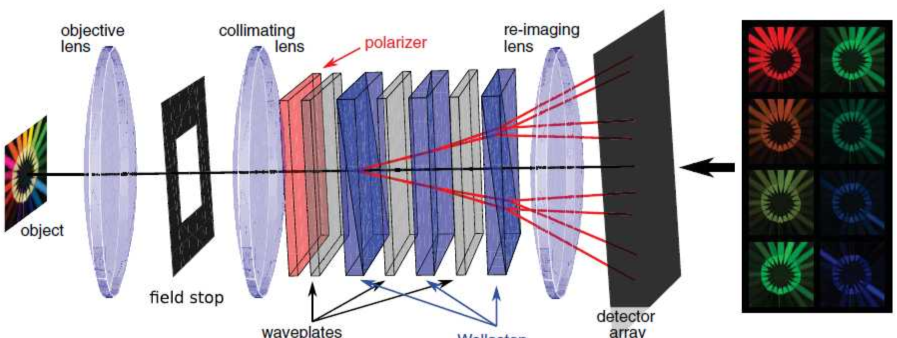
- Division of amplitude based approach.
- Spectral images are produced through implementation of sequential spectral filters.
  - Multiple FPA and single FPA designs have been demonstrated.
- Most implementations are limited to 4-16 spectral images.
- Image registration must be implemented to accurately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

Filters bonded to FPA

Image from [18]

Filter array in front of lenslets

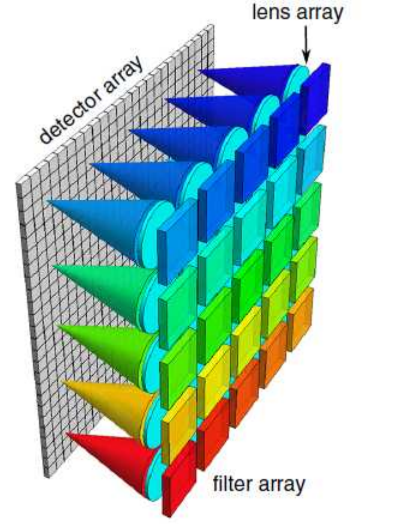


Figure from [1]

SHIFT: Snapshot Hyperspectral Imaging Fourier Transform Spectrometer

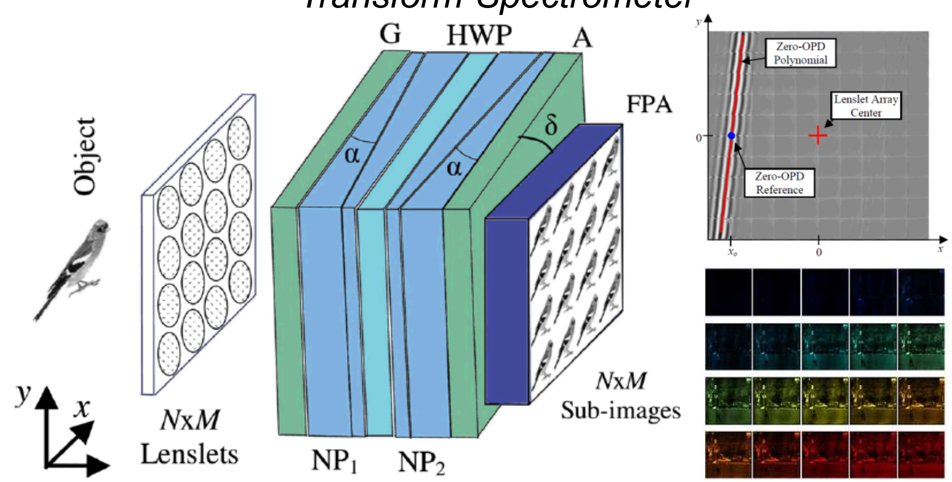


Figure from [1]

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.

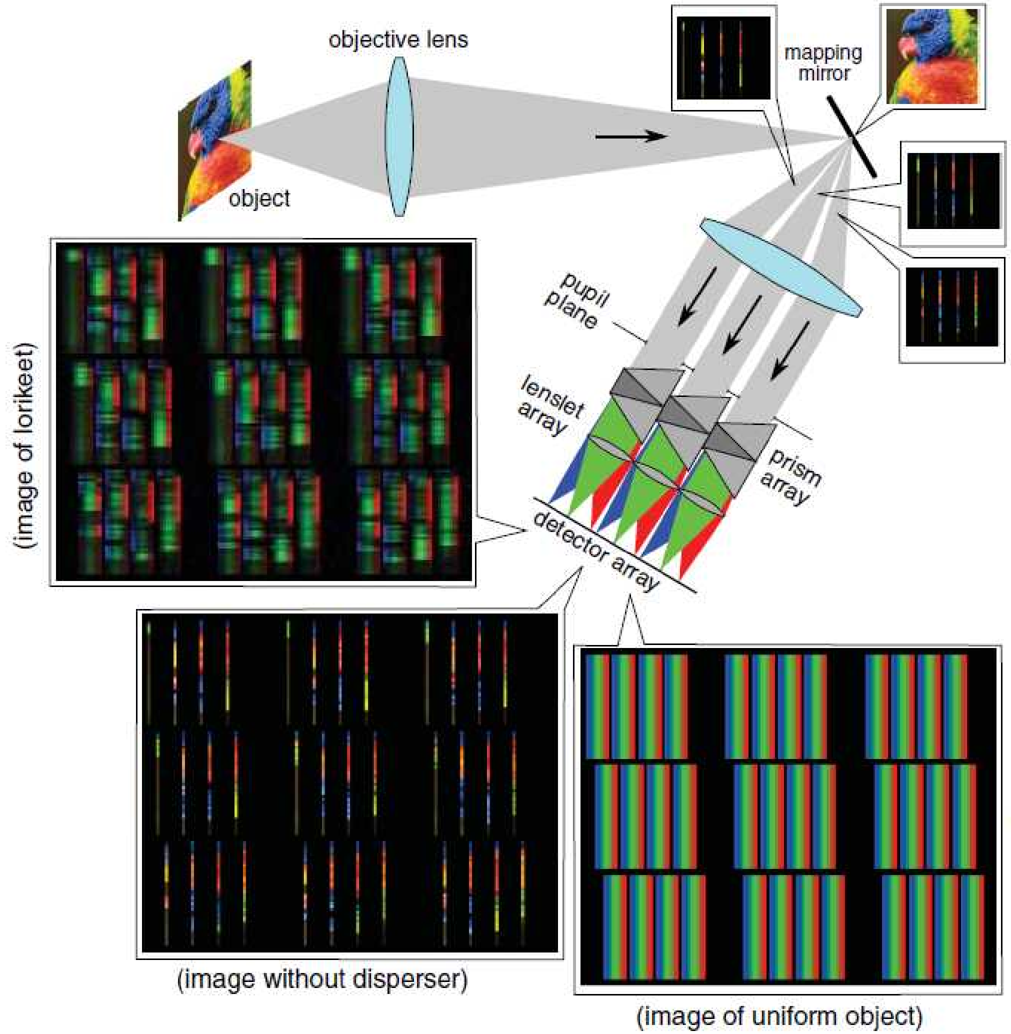


Figure from [1]