FFI Forsvarets forskningsinstitutt

Specification of spectral imager performance

- a rough outline

Torbjørn Skauli
Norwegian defence research establishment

Overview

- What do we need imager specifications for?
- Nominal performance characteristics
  - radiometric
  - spatial
  - spectral
  - temporal
- Nonideality characteristics
  - stray light
  - coregistration error
  - responsivity falloff
  - ...etc.
- Comments and conclusion

How good is your hyperspectral imager?

- How can we give an adequate answer?
- How can we specify the imager in a way that guarantees a certain performance?
- How can we compare one hyperspectral imager against another?
- Today, no commercial imagers are adequately specified

Requirements for a standardized specification

- Give a lower bound on performance
- Give an upper bound on imperfections that may affect the user
- As simple as possible to measure (but no simpler)
- As simple as possible to express and understand (but no simpler)
- Characterize the output image quality, after preprocessing
- Emphasize the needs of spectrometry rather than imaging

Some tacit assumptions in imaging spectrometry

- All bands see the same pixel area
- All pixels see in the same bands
- All bands in a pixel are measuring the same input spectrum
  - even when bands are measured at different times or viewing angles
- Spectral responses are constant within the pixel
- Point spread function is constant within a band

Deviations from such assumptions need to be specified.

Nominal radiometric characteristics

- Nominal performance is well described by conventional metrics, in principle

- But, beware:
  - Calibration using large uniform sources is insensitive to many types of imperfections (see later)
  - Hyperspectral imager designs always push for the widest possible spectral range...

Wavelength-dependent throughput: a useful graph

- Consider the overall throughput

  $$A_{eff}(\lambda) \equiv A\Omega_{pix}\eta_{eff}(\lambda)$$

  where

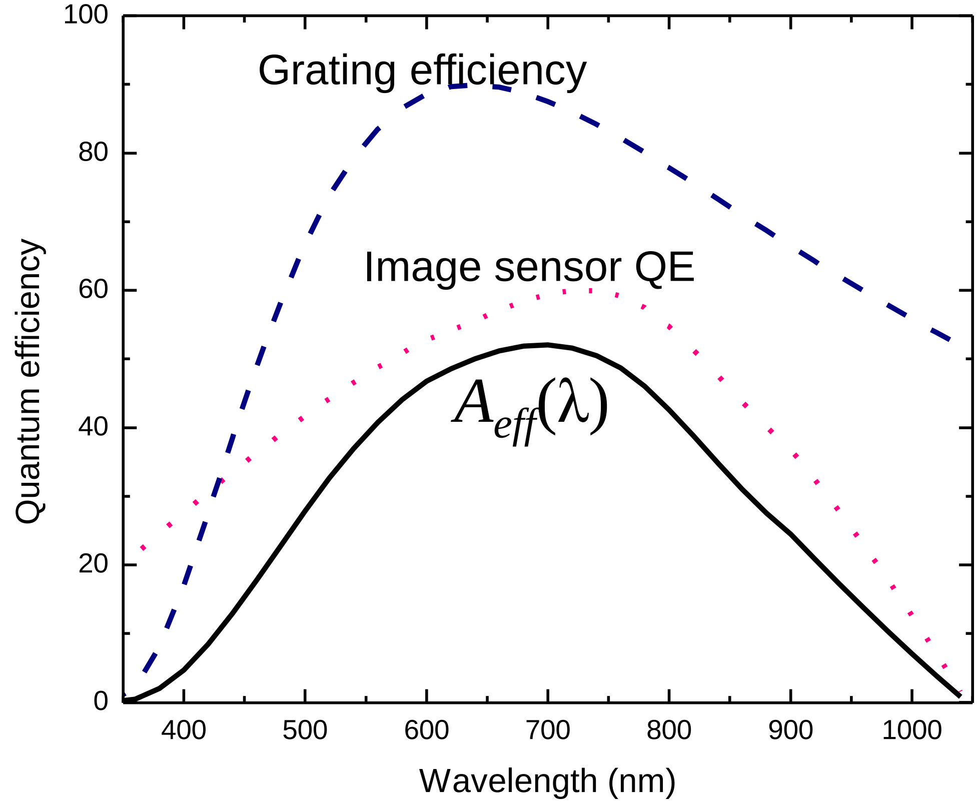
  A is entrance aperture area

  Ω_{pix} is pixel FOV

  η_{eff} is overall QE

- This light collection "effective area" may vary by a factor 10 or more across the spectral range

- This can be used to determine (combined with image sensor specs)
  - Peak SNR
  - Minimum light level
  - Saturation level
  - Volumetric efficiency ("compactness") of the imager



Example wavelength dependence of QE and $\mathbf{A_{eff}(\lambda)}$ *for a hyperspectral imager*

Nominal spatial characteristics

Ensquared energy of mean PSF within nominal pixel

- Nominal performance described mostly as for conventional imaging:
  - Field of view
  - Pixel count / sampling interval
  - Distortion / geometrical model

- Resolution specification:
  - MTF is inappropriate due to emphasis on spectroscopy
  - Better: Ensquared energy of mean PSF (over all bands) within the nominal pixel area
  - Alternatively: Ensquared energy of mean PSF within some specified resolution cell

Nominal spectral characteristics

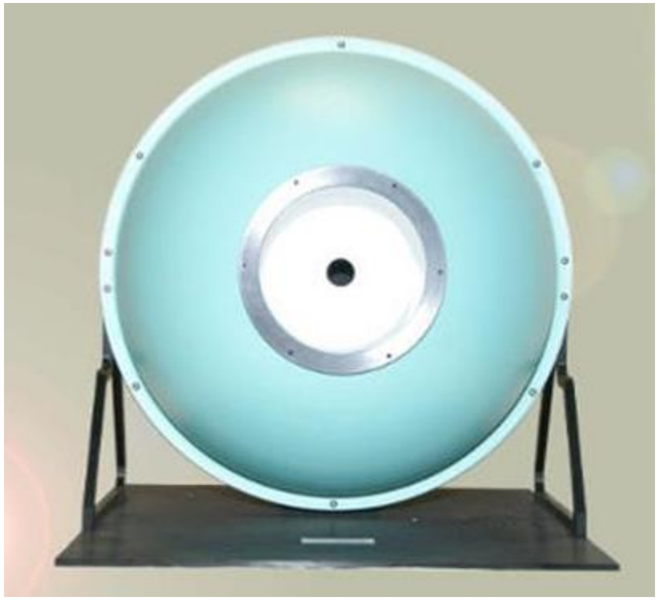
- Spectral range
- Spectral sampling interval
- Wavelength accuracy and stability
- Spectral resolution: "ensquared" energy of broadband light within nominal band

Nominal temporal characteristics

- Frame rate range
- Integration time range
- Dead time, if any
- Simultaneous recording of bands is essential for signal integrity if the scene is dynamic.
  - A possible metric for simultaneity:

    (*integration time per band*) / (*total recording time for a pixel*)

Stray light



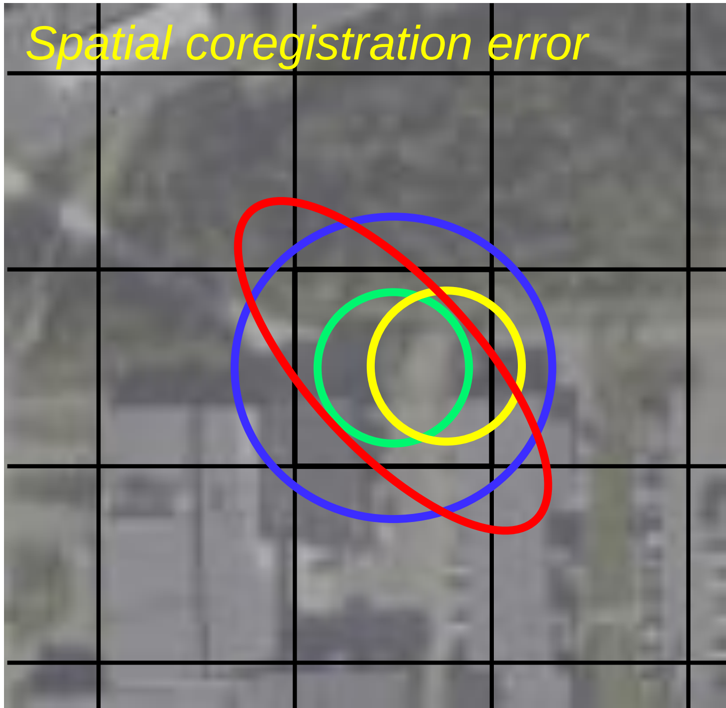
VGI measurement setup (www.hgh-infrared.com)

- Spatial stray light can be specified by the "Veiling glare index", ISO 9358

- Spectral stray light is being measured in an analog way, with band stop filters
  - Must measure at the wavelengths most susceptible to stray light. (Application dependent?)

Coregistration errors

- Nominally: All bands sample the scene in the same way
- In reality: Different bands do not see exactly the same scene parts
- Green, Mouroulis, et al. (NASA 1998):
  - Coregistration errors cause large errors in the signal.
  - The resulting spectra are unphysical.
- Coregistration error will tend to distort distribution of spectra so that it violates assumptions of image processing algorithms
- Specification should capture all forms of coregistration error: spatial, spectral, ...



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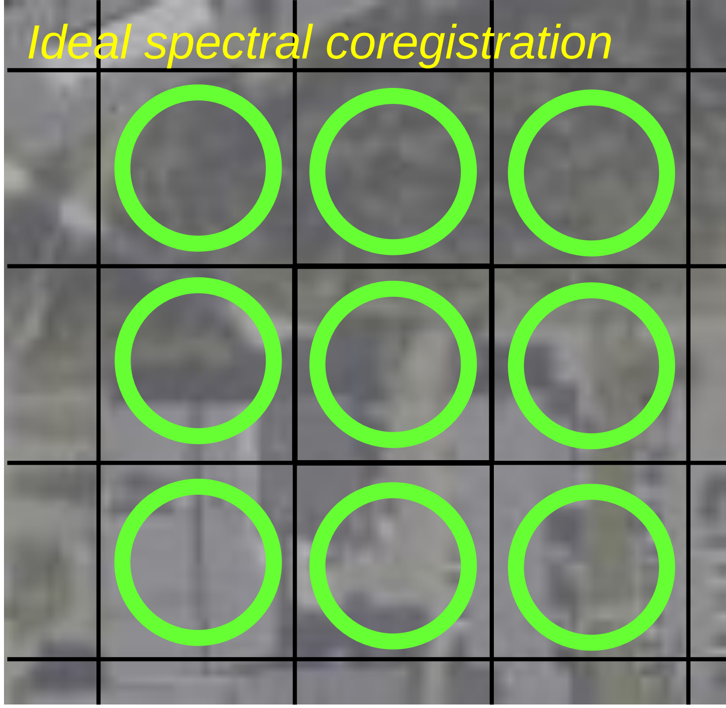
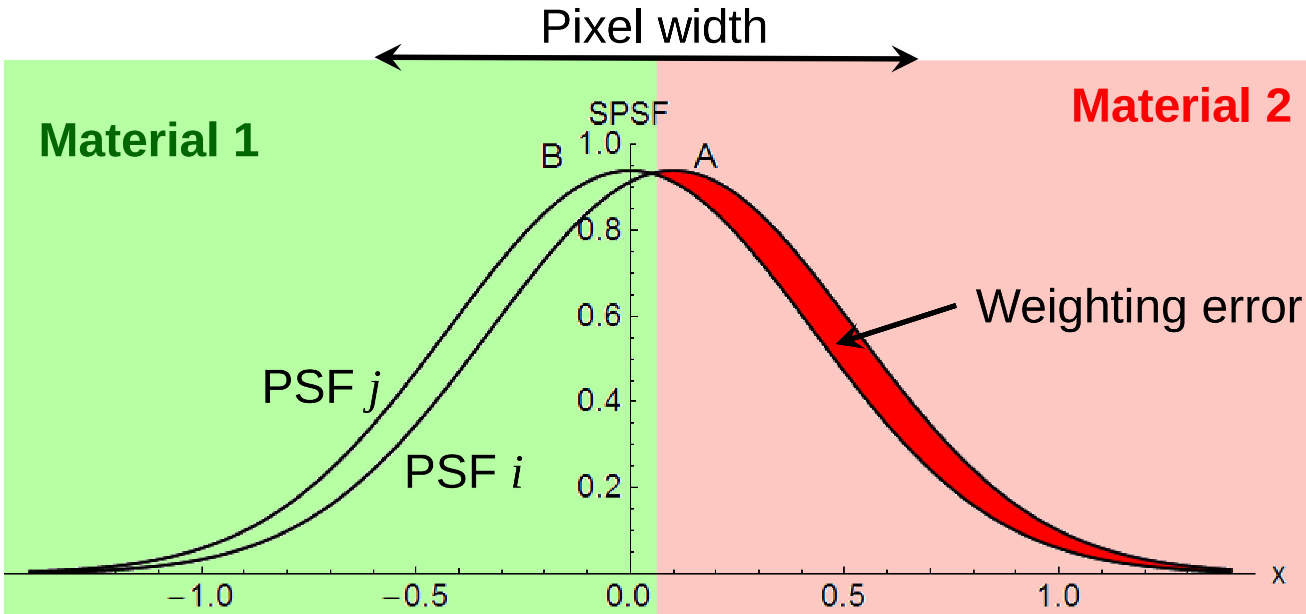


Metric for coregistration: volume between PSFs



PSFs for two bands, in a pixel containing red and green materials

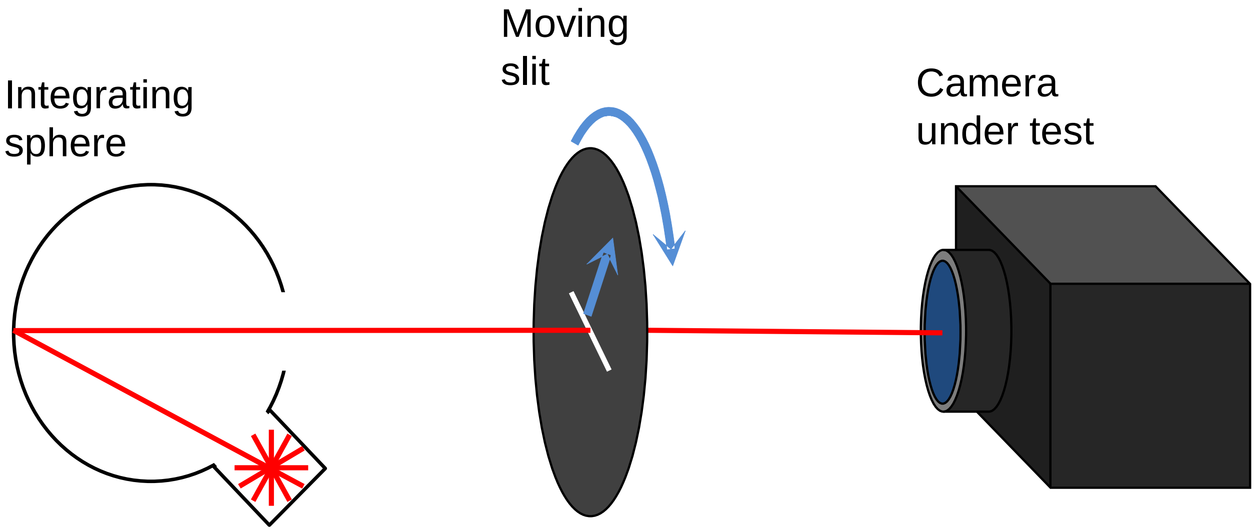
- At a material boundary in a pixel: Largest weighting error Δw_{max} occurs when the boundary coincides with the intersection between the PSFs.
- Metric for coregistration error between two bands i and j:

$$\varepsilon_{s,ij} \overset{def}{=} \frac{1}{2} \iint_{x,y} \left| \mathrm{PSF}_j(x,y) - \mathrm{PSF}_i(x,y) \right| dxdy = \Delta w_{\max}$$

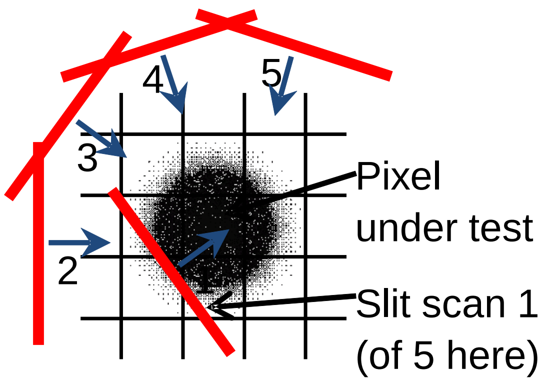
- Generalizes the "keystone" coregistration metric
- Generalizes to spectral and spectral-spatial coregistration

T. Skauli, Optics Express 2012

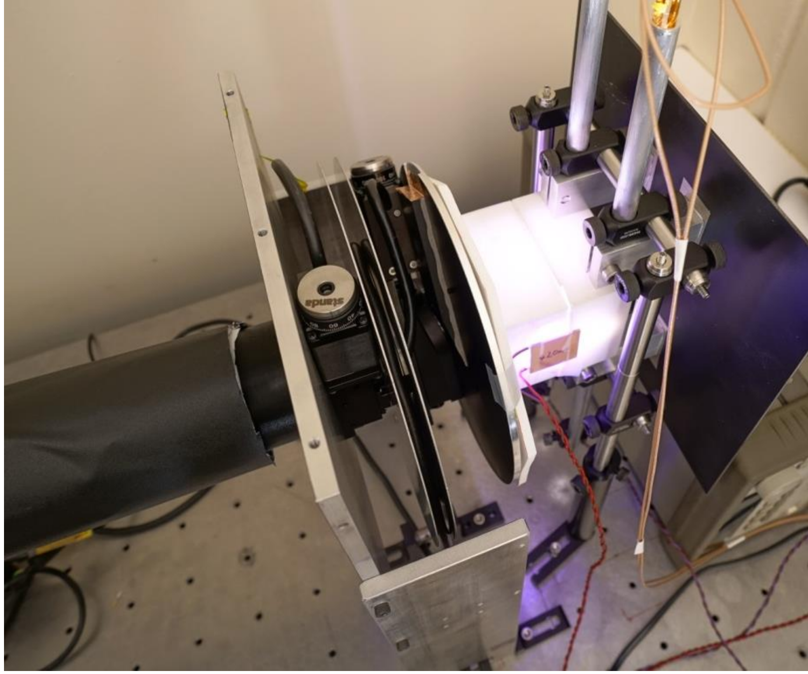
Setup for imaging the point spread function



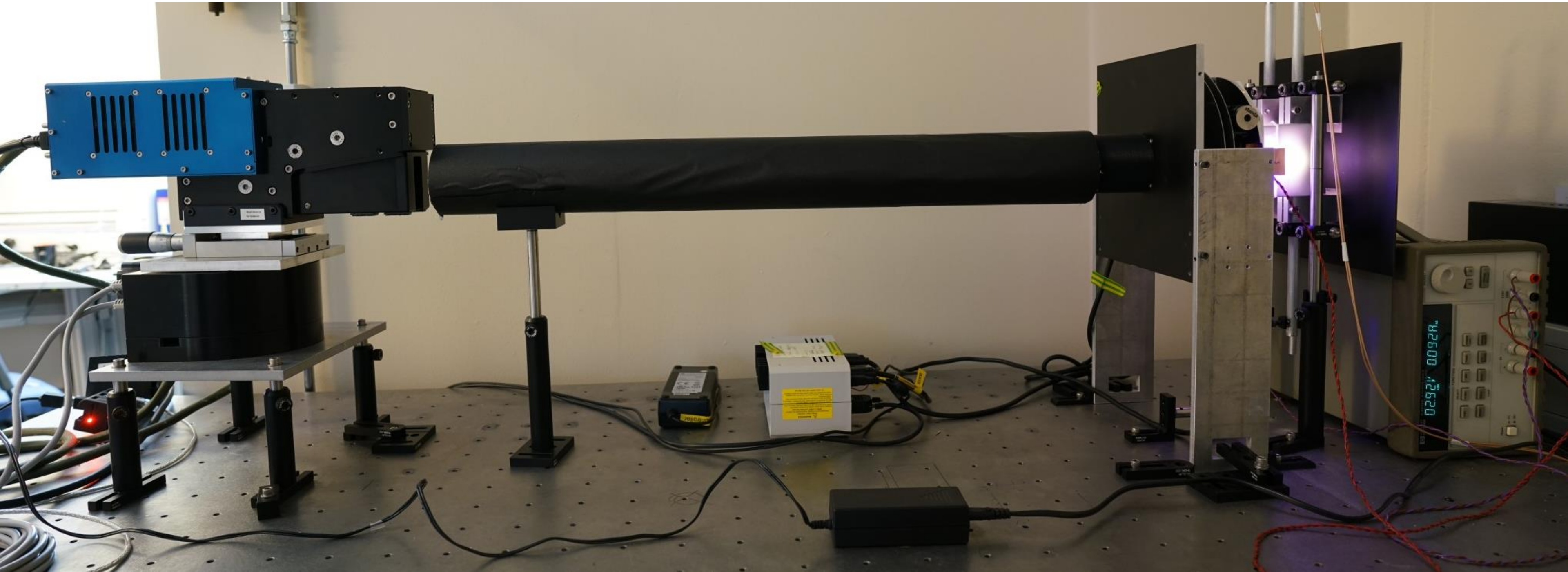
- Broadband subpixel line source
- Scan across a pixel → Line spread function
- Repeat in many different directions
- Tomographic reconstruction



Measurement setup



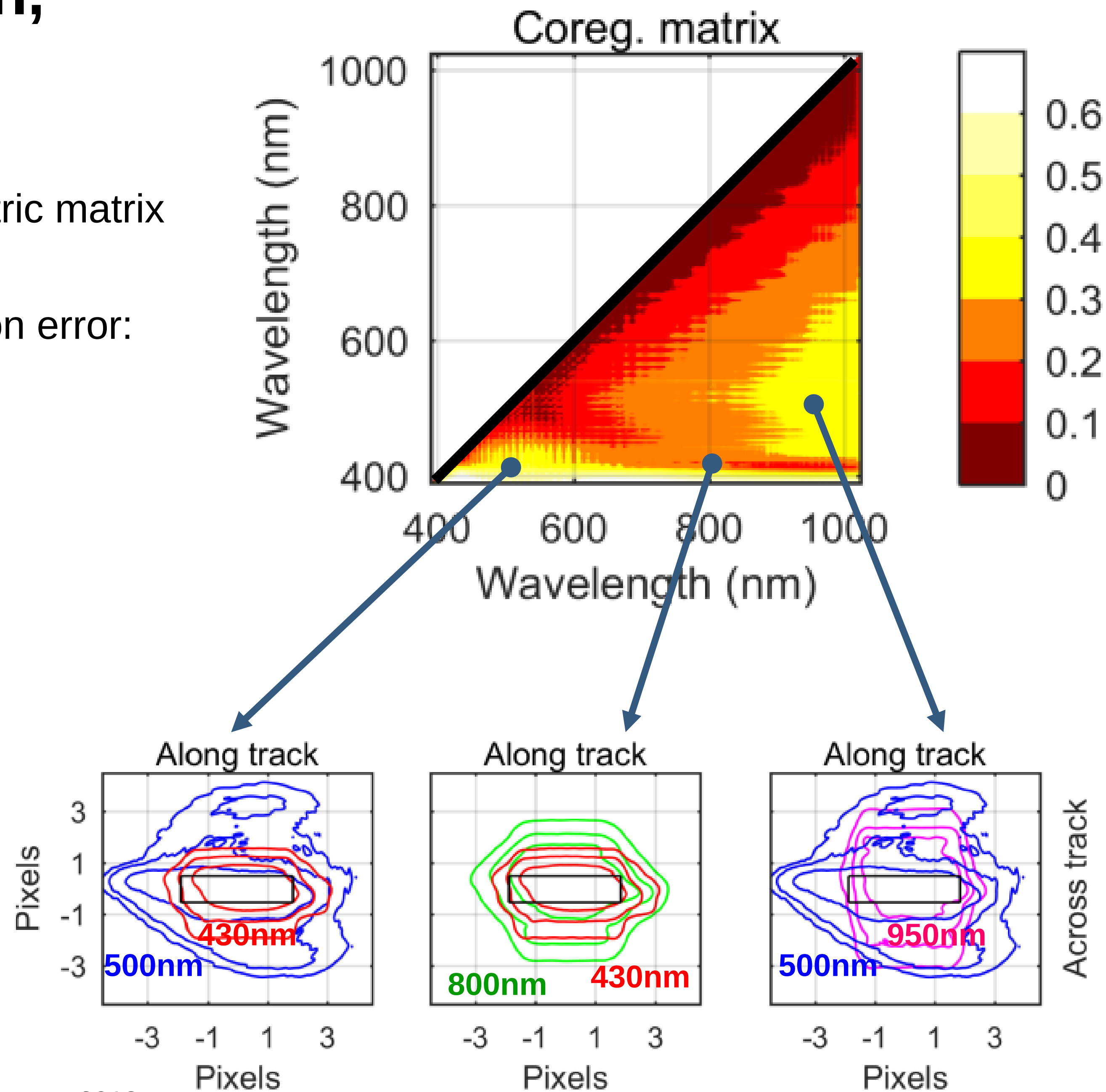
- Integrating sphere source
- Motorized translation and rotation stages
- Slit in metal film on glass
- Beam tube to eliminate turbulence blur



Coregistration, camera A

- Coregistration metric matrix
- Mean coregistration error:

$$\bar{\varepsilon}_s = 0.22$$



H. E. Torkildsen and T. Skauli, Optics Letters 2018

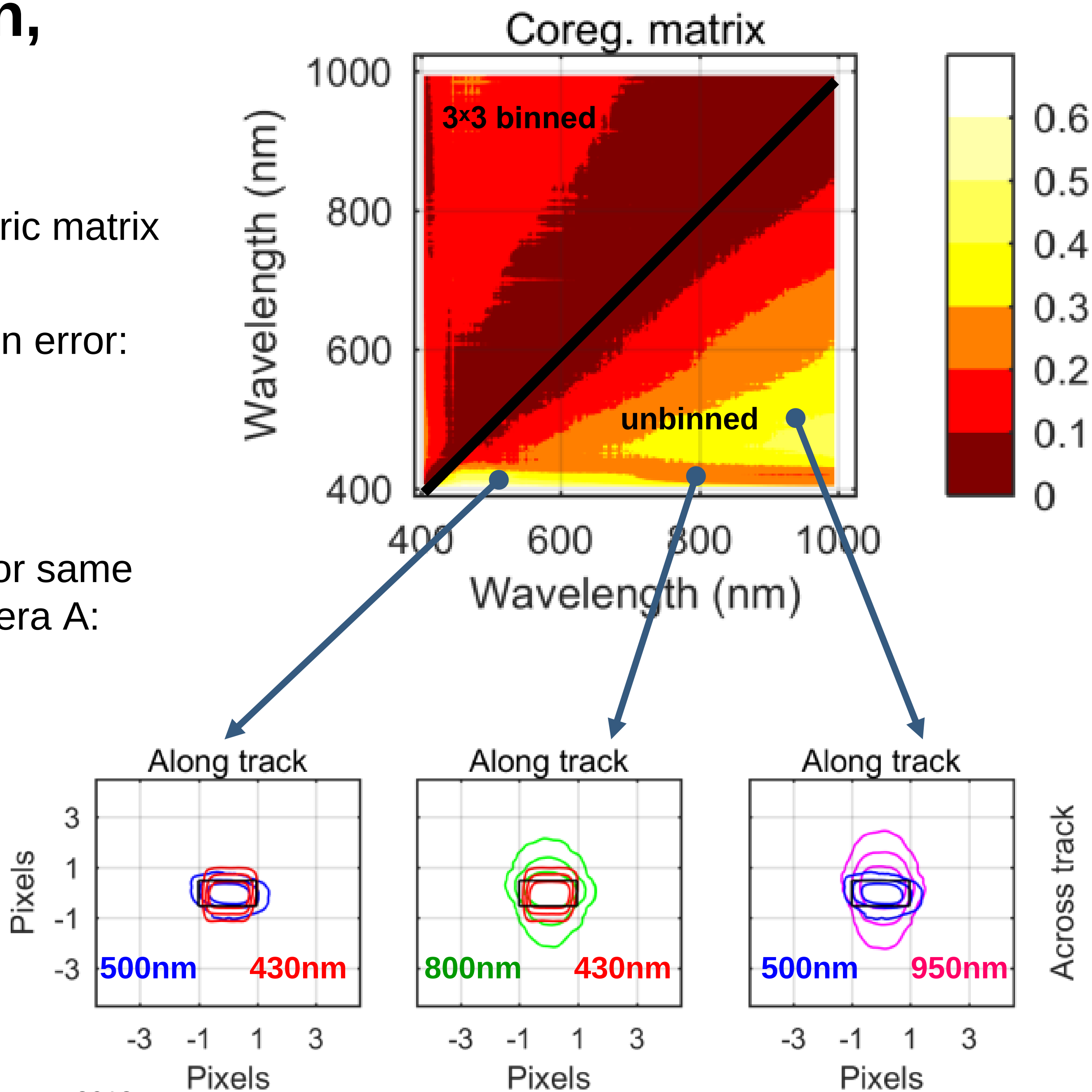
Coregistration, camera B

- Coregistration metric matrix
- Mean coregistration error:

$$\bar{\varepsilon}_s = 0.20$$

- With 3x3 binning for same PSF width as camera A:

$$\bar{\varepsilon}_s = 0.09$$



H. E. Torkildsen and T. Skauli, Optics Letters 2018

A possible standard for a full specification

Nominal performance characteristics	Unit	Comment
Wavelength range	µm	
Spectral sampling / band format		No. of bands, or band limits, as appropriate
Spectral resolution relative to spectral sampling interval	%	Average "band ensquared energy", a mean value over all pixels* and minimum over all bands
Pixel count		No. of spatial pixels in each dimension
Field of view	deg.	(Or lateral dimension, for finite range imaging)
Spatial resolution relative to pixel sampling interval	%	Ensquared energy of mean PSF over all bands
Frame rate	Hz	(Or line rate, for pushbroom imagers)

A possible standard for a full specification

Nominal performance characteristics (continued)	**Unit**	**Comment**
Throughput graph $A_{eff}(\lambda)$	μm^2	Can alternatively give min.value
Saturation level	e^-	Full well electron count
Dimensions	cm	
Mass	kg	
Power consumption	W	

A possible standard for a full specification

Imperfections	Unit	Comment
Wavelength accuracy and stability	µm	
Radiometric calibration accuracy	%	
Spatial coregistration $\bar{\varepsilon}_s$ and $\varepsilon_{s,max}$	%	May need another metric for point source imaging
Spectral coregistration $\bar{\varepsilon}_\lambda$ and $\varepsilon_{\lambda,max}$	%	
Spectral-spatial response interdependence $\bar{\varepsilon}_{\lambda s}$	%	
Dark signal	e^-/s	
Dead pixels	%	
Throughput falloff at edges of FOV	%	
Spatial stray light	%	VGI according to [9]
Spectral stray light	%	Analogous to VGI
Time difference between spectral components	%	Integration time relative to total pixel recording time

A possible standard for a full specification

Imperfections (continued)	Unit	Comment
Polarization sensitivity	%	
Nonlinearity	%	Max. integrated linearity error
Spatial distortion	%	
Effective spatial fill factor	%	Variation of total response across a pixel
Effective spectral fill factor	%	Variation of total response across a band
Dead time	% or ms	

Comments

- Some items more important than others
- Not all straightforward to measure - but spec only needs to give bounding values
- Specs for a general-purpose imager are less relevant for application-specific spectral sensing based on scene knowledge
- Some characteristics are unconventional due to the emphasis on spectrosopy

Conclusions

- A full specification is somewhat complex, with about 30 items (but spectral imaging is complex by its nature)

- The characteristics of spectral imaging lead to unconventional specs for
  - coregistration
  - spatial resolution
  - net throughput $A_{eff}(\lambda)$

- Many of the proposed specs need specific definitions: <u>work ahead for the standardization group</u>

References:

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