An Overview of the Emerging P4001 Hyperspectral Standard

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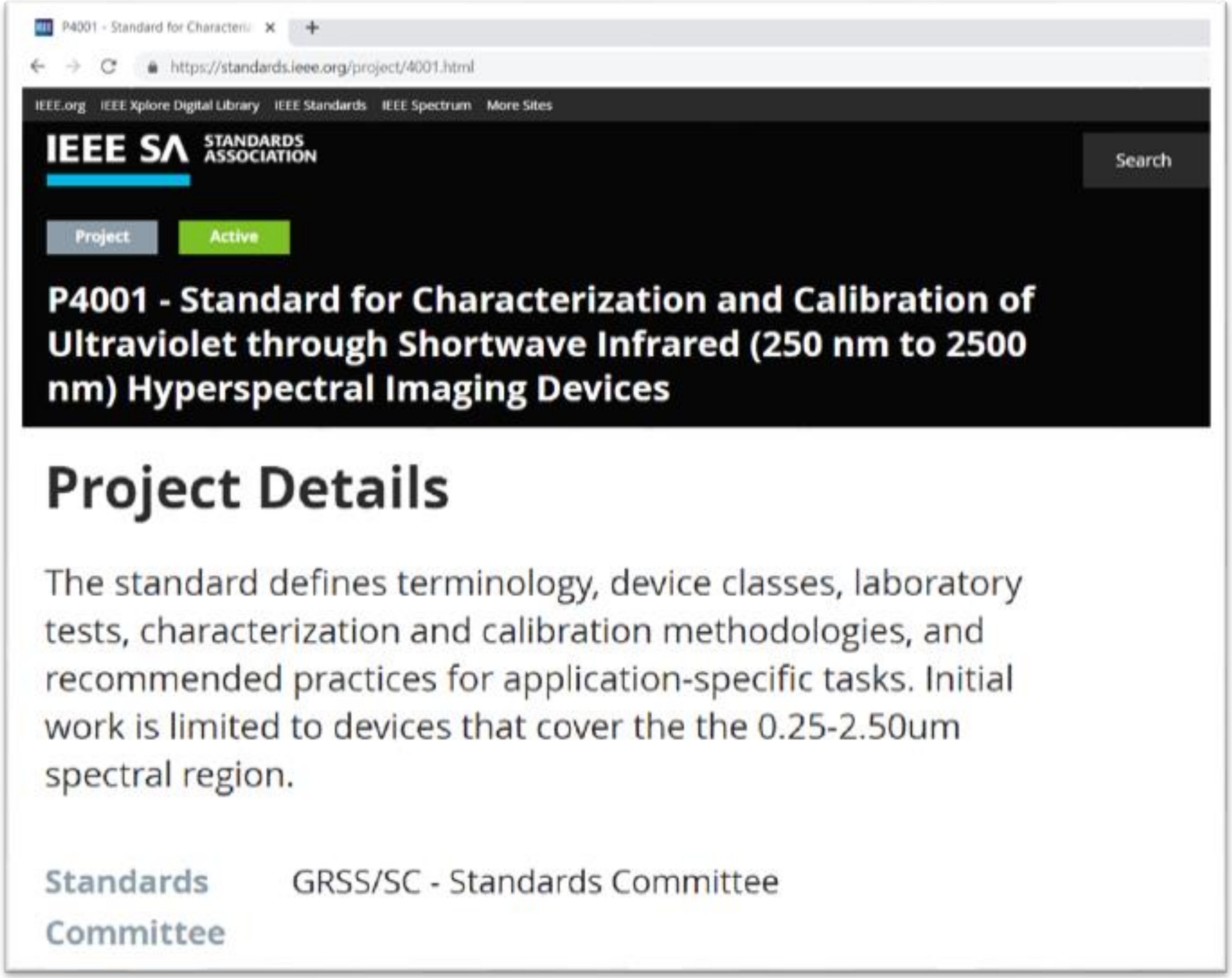
September 1, 2022 – USGS Reston, VA

IEEE P4001 WG status as of August 2022

- 254 members, 42 Voting Members, with usually >35+ meeting attendees
- Manufacturers, users, government labs, and academia represented
- Links to other standard groups: EMVA 1288, ISO 19124-1 TC211, SNIP and IEEE P4005
- 36 meetings held – Trying to meet every 4-6 weeks, plus weekly sub-group meetings
- Timeline completed as of Dec 31, 2021: 12 month extension requested
- Next meeting: August 30 @ 1000 EDT (Zoom)
  - https://labsphere.zoom.us/j/88159298627?pwd=TU5MLzNwVnc3SktVYzl0ZmVibnZ1UT09
- Officers:
  - Chair: John Gilchrist, Clyde HSI & Technology
  - Co-Chair: Torbjorn Skauli, Univ. of Oslo and FFI
  - Secretary: Chris Durell, Labsphere
  - Webmaster: Alex Fong, Hinalea Imaging
  - GRSS Chair: Dr. Siri Jodha Khalsa, National Snow and Ice Data Center

P4001 Website:
https://sagroups.ieee.org/sagroups-hyperspectral/

An ambitious charter


P4001 - Standard for Characteri

https://standards.ieee.org/project/4001.html

IEEE.org IEEE Xplore Digital Library IEEE Standards IEEE Spectrum More Sites

IEEE SA STANDARDS ASSOCIATION

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Project Active

P4001 - Standard for Characterization and Calibration of Ultraviolet through Shortwave Infrared (250 nm to 2500 nm) Hyperspectral Imaging Devices

Project Details

The standard defines terminology, device classes, laboratory tests, characterization and calibration methodologies, and recommended practices for application-specific tasks. Initial work is limited to devices that cover the the 0.25-2.50um spectral region.

Standards Committee	GRSS/SC - Standards Committee

1. Camera performance characteristics
2. Test methods
3. Data, metadata & use cases
4. Terminology

April - Papers at SPIE DCS 2022 & (2) Day Workshop

12094-1 Gilchrist, J, et al "The P4001 Standard for hyperspectral imaging: Overview and status update for draft standard" 12094-1 for SPIE DCS 2022

12094-2 Skauli, T., et al "Specification of hyperspectral camera performance - status of The IEEE P4001 Standard development" 12094-2 for SPIE DCS 2022

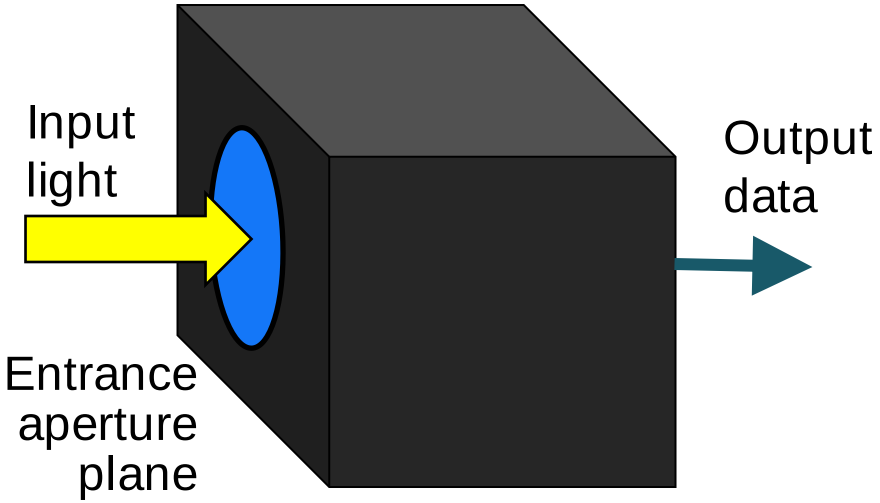
12094-3 Ientilucci, E., Conran, D. et al "Development of Test Methods for Hyperspectral in the P4001 Standards Development" 12094-3 for SPIE DCS 2022

12094-4 Makowski, J., et al "Metadata definitions for a set of notional use cases in the IEEE P4001 standard for hyperspectral imaging" 12094-4 for SPIE DCS 2022

12094-5 Arlen, R. et al "Choice of Terminology in the IEEE P4001 standard for hyperspectral imaging" 12094-5 for SPIE DCS 2022

Camera characteristics - principles

- Camera characterized as a "black box"
  - Enables comparison between camera types
  - Need to identify adequate and appropriate characteristics for a "black box" camera
- Characteristics defined as physical quantities
  (rather than results of a particular test method)



A black box camera

- Recognizing that hyperspectral imaging is imaging spectroscopy
  (leads to somewhat different characteristics than for imaging of spatial contrast)
- Spec should convey the actual performance
  - All aspects of performance to be covered
  - Worst-case values should be included

Extensive set of characteristics needed

- **Spatial:** resolution, field of view, geometric accuracy
- **Spectral:** resolution,spectral range, wavelength accuracy
- **Radiometric:** light collection, noise, dynamic range, radiometric accuracy
- **Coregistration:** spatial, spectral, temporal, and interdependencies
- **Stray light:** spatial and spectral
- **Imperfections:** dead pixels, polarization dependence, nonlinearity, ...
- **Other:** SWaP, environmental, interface, ...

Camera testing - principles

- P4001 will describe a set of methods to *verify* the defined characteristics
- Other test methods may be equally valid, since characteristics are defined as <u>physical quantities</u>
- Testing should not require excessive time or exotic equipment
- In production, manufacturers may use simplified methods for acceptance test
- Because we do <u>spectroscopy</u>: Detailed characterization of spectral and spatial response functions is needed

Recommended tests

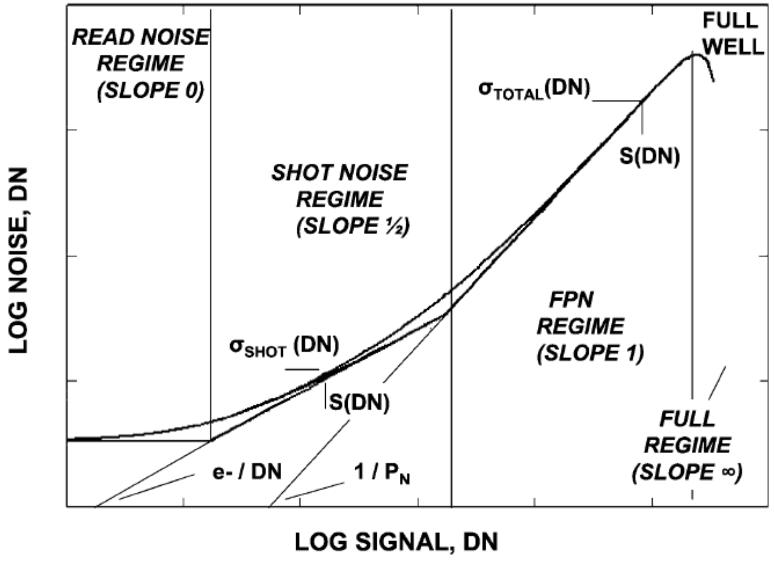
- Four working groups for testing and specification created:
  - **Radiometric:** Variable broadband source (Linearity), Dark test, Non-Uniformity, RSR
  - **Spatial resolution:** point or line source to measure point spread function
  - **Spectral resolution:** monochromator, laser, or atomic line spectra
  - **Stray light:** bright source having application-relevant spectrum, blocking filters
- Calibration as needed by the application: spectral, spatial and radiometric

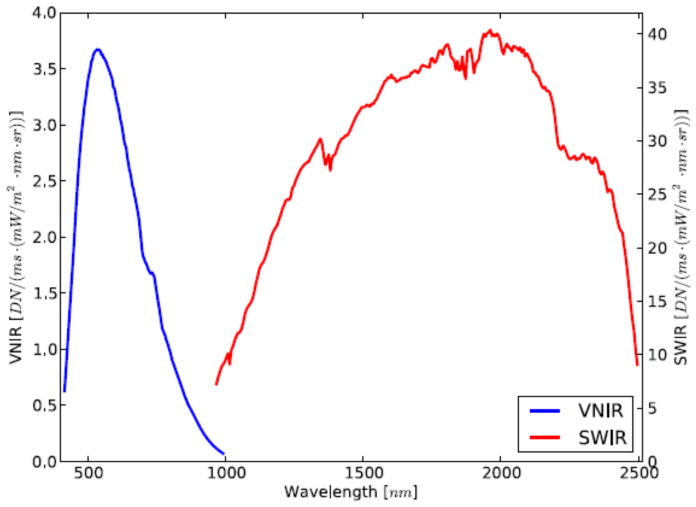
Test development in P4001

- Characteristics defined for testability at the outset
- Setting up task groups to work out draft test procedures
- Testing the procedures in labs of volunteering members
- Status May 2021:
  - Radiometric testing: RIT, NRC, Headwall, NEO-Hyspex, NIST, WPAFB and others
  - Spectral / Spatial: RIT, WPAFB, Univ. of Edinburgh (NERC), NEO-Hyspex and others
  - Stray light: Labsphere, Headwall, NIST, Spectral Solutions and others

Radiometric Testing: Methods

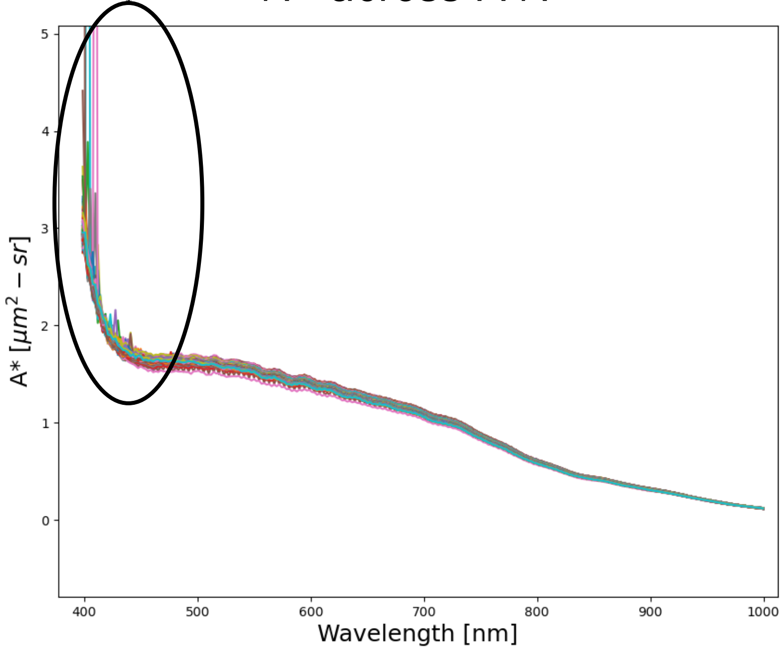
- Photon Transfer Curve (PTC)
  - Signal from dark noise to saturation
  - Extract gain coefficient (e^-/DN)
  - Nonlinearity assessment
- Radiometric calibration
  - Vary integrating sphere illumination
  - NIST tracible spectral radiance
  - Multi-point calibration
- Dark current assessment
  - Extract noise sources with zero illumination



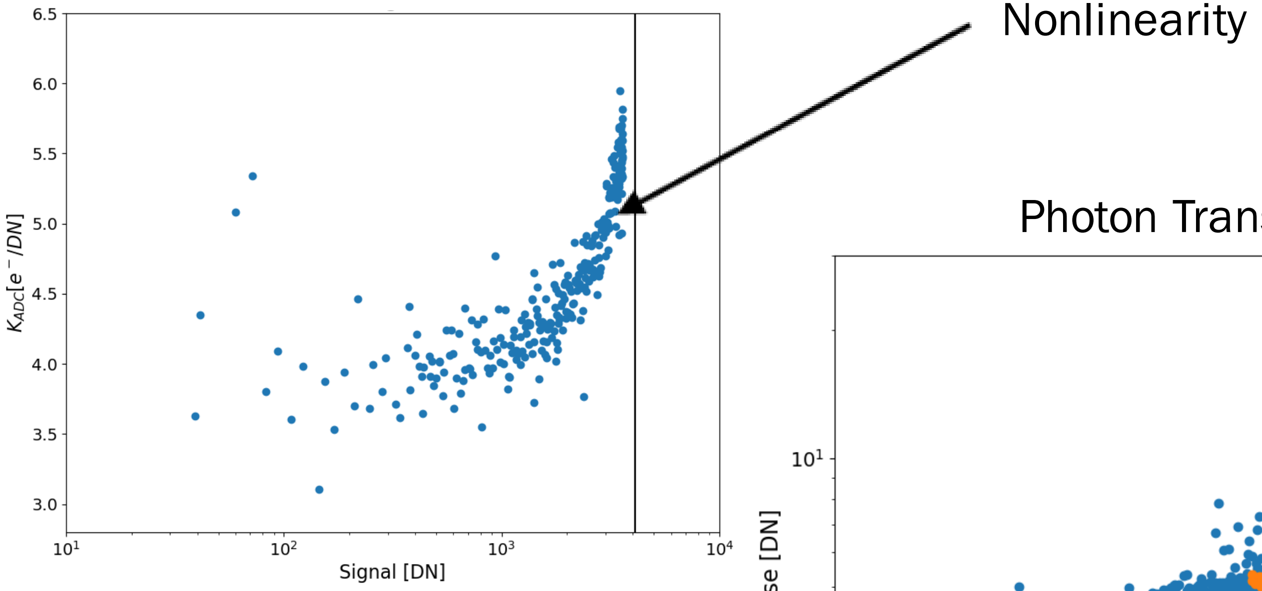


Radiometric Testing: Example Results

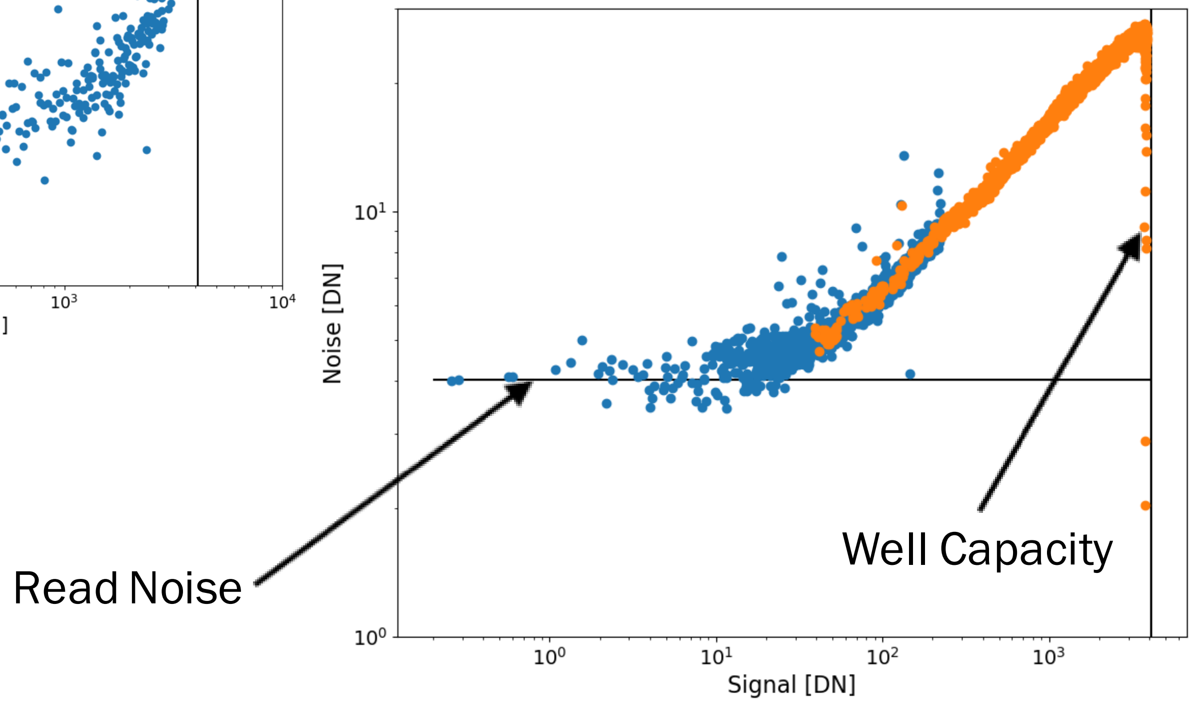
A* across FPA



Gain vs. Signal



Photon Transfer Curve



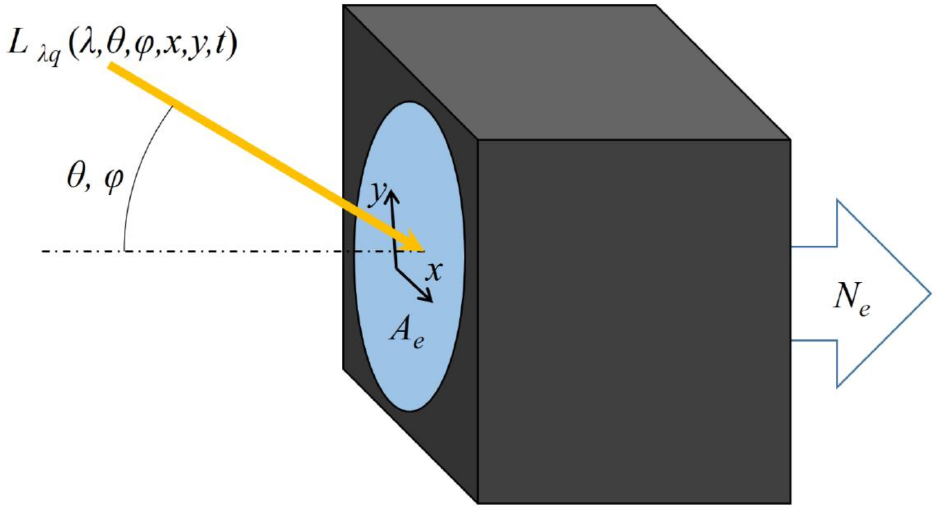
Example: Light collection characteristic –

- Conventional camera signal model:

$$\underbrace{N_e}_{\text{output signal}} = \underbrace{L_\lambda(\lambda)}_{\text{input signal}} \underbrace{t_i \Delta\lambda}_{\text{camera settings}} \underbrace{\frac{\lambda}{hc}}_{\text{photon energy}} \underbrace{\overset{A_{entrance}\Omega_{IFOV}\ /\!/}{A_{det}\Omega_{det}}}_{\text{collection}} \underbrace{T(\lambda)\eta(\lambda)}_{\text{loss}}$$

Camera internals

N_e	total electron count ∝ internal raw signal
$L_\lambda(\lambda)$	input spectral radiance to be measured
t_i	integration time
$\Delta\lambda$	spectral bandwidth
A_{det}	area of pixel detector element
Ω_{det}	solid angle subtended by lens exit pupil
$T(\lambda)$	optics transmission
$\eta(\lambda)$	detector quantum efficiency



Courtesty: T. Skauli

Example: Light collection characteristic – A*

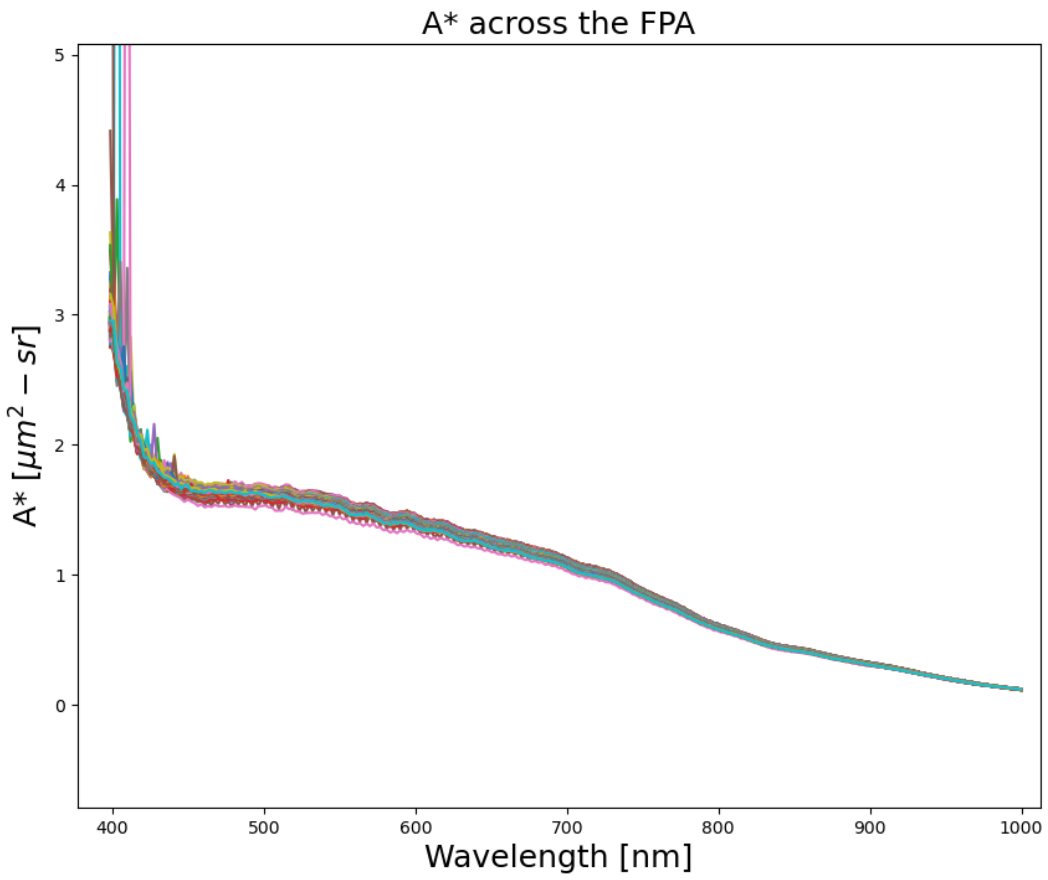
- Because we want "black box" characteristics":
  - Avoid reference to camera internals

- Net light collection characterized by a "normalized pixel area" denoted $A^*(\lambda)$

$$A^*(\lambda) = A_{entrance}\Omega_{IFOV}T(\lambda)\eta(\lambda)$$

- Combines light collection and loss factors that are not individually observable outside the black box

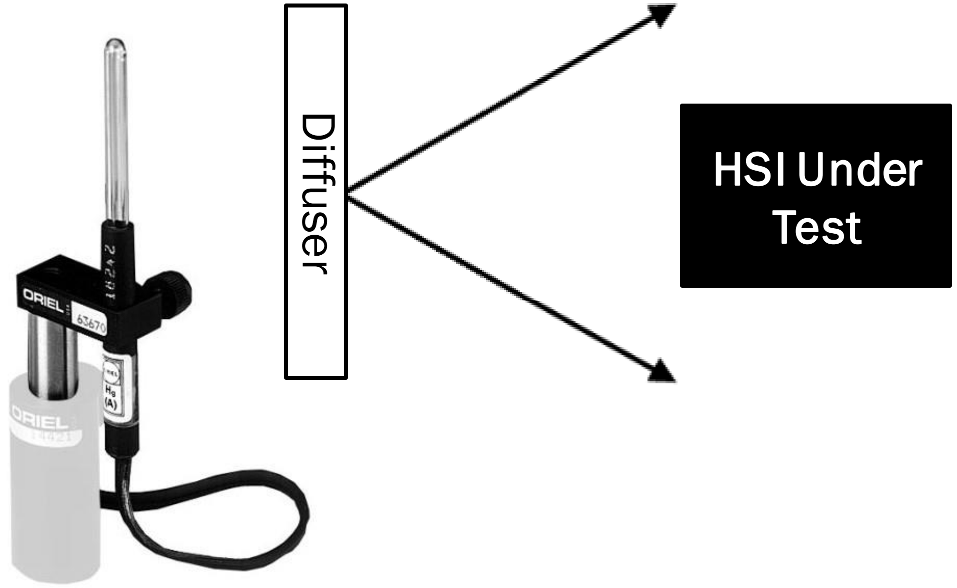
- Enables comparison of signal-dependent photon noise between cameras

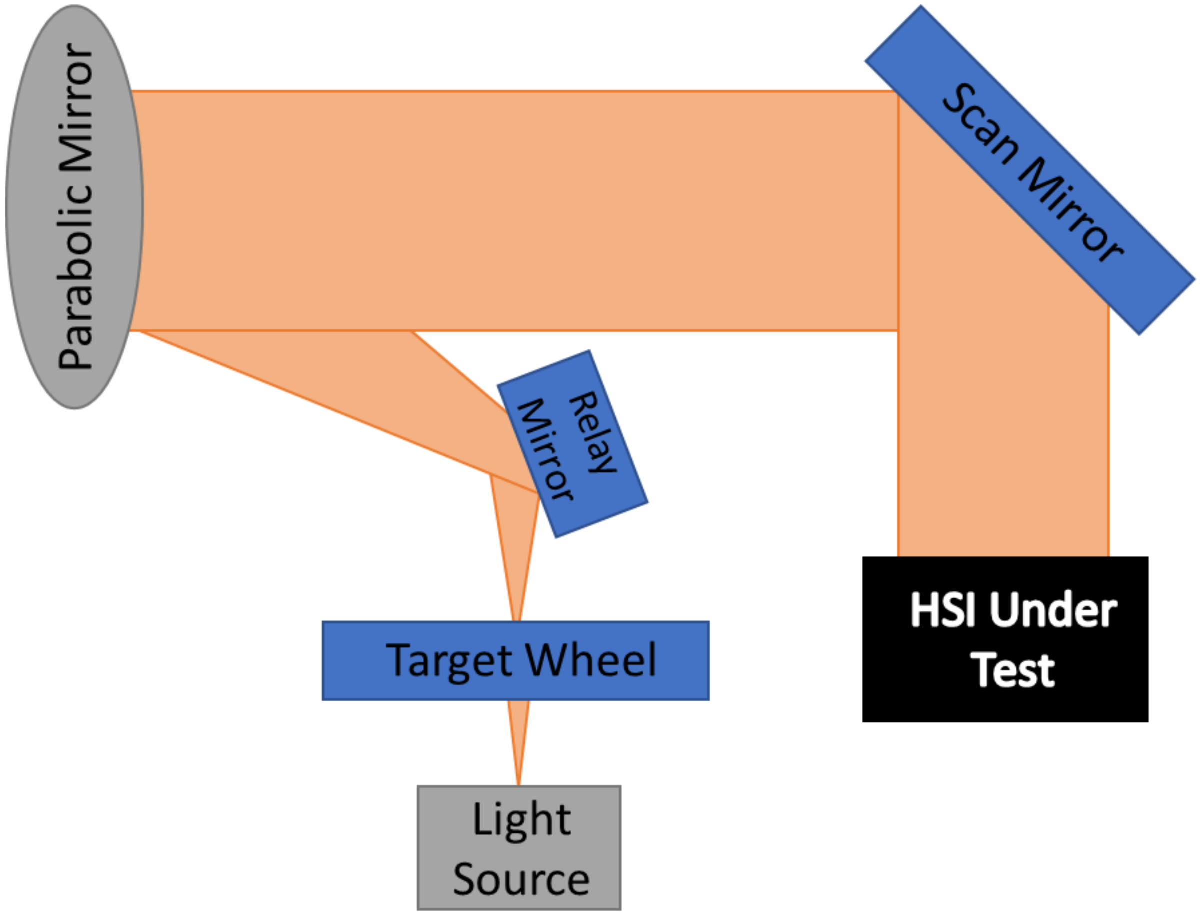


A* Preliminary Results courtesy of D. Conran, RIT

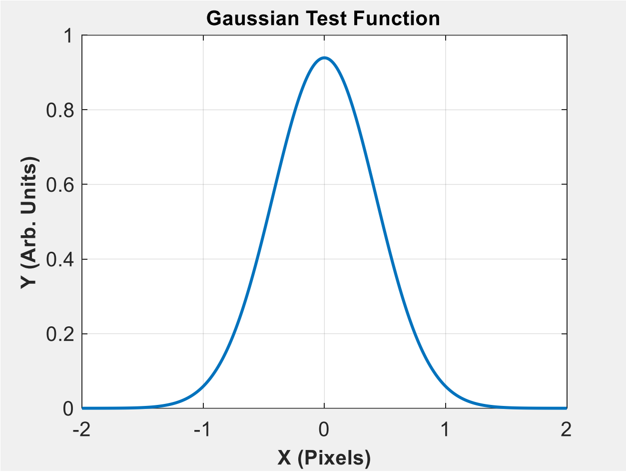
Spectral Testing: Equipment

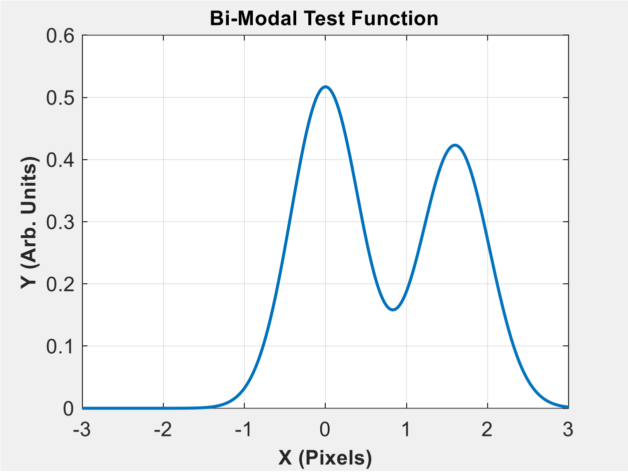
- Recommended equipment:
  - Monochromator with a broadband light source
  - Atomic spectra line lamps
  - Integrating sphere or diffuser

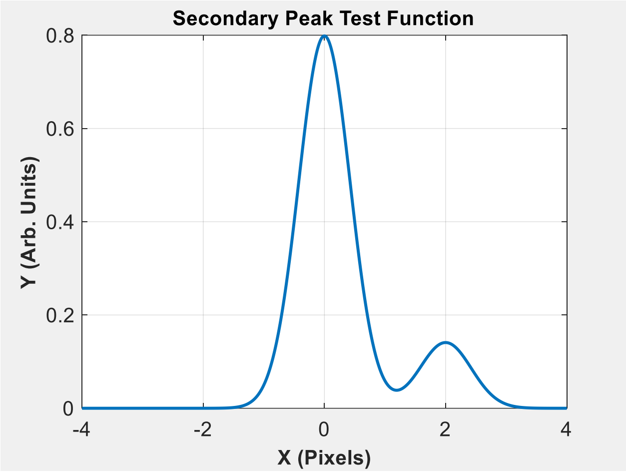


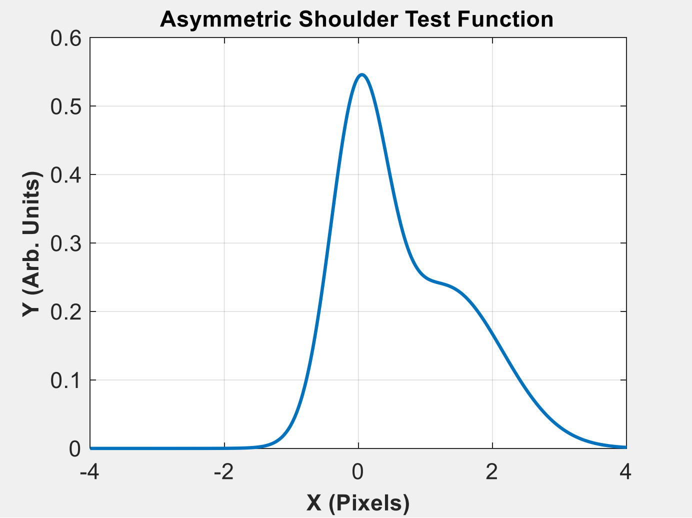


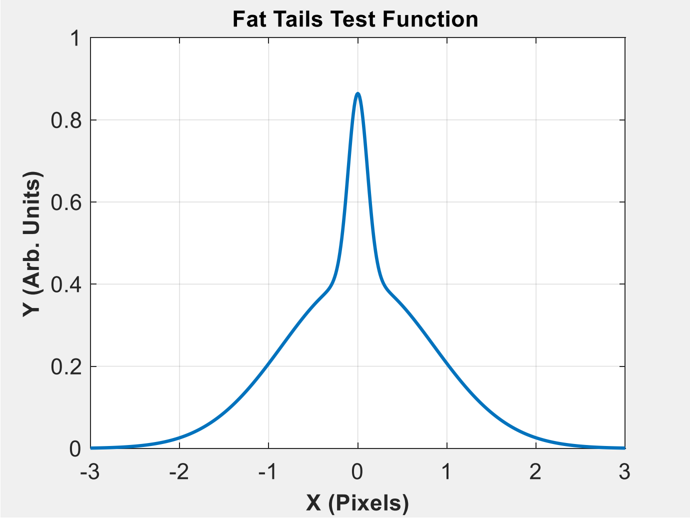
Tested Response Shapes





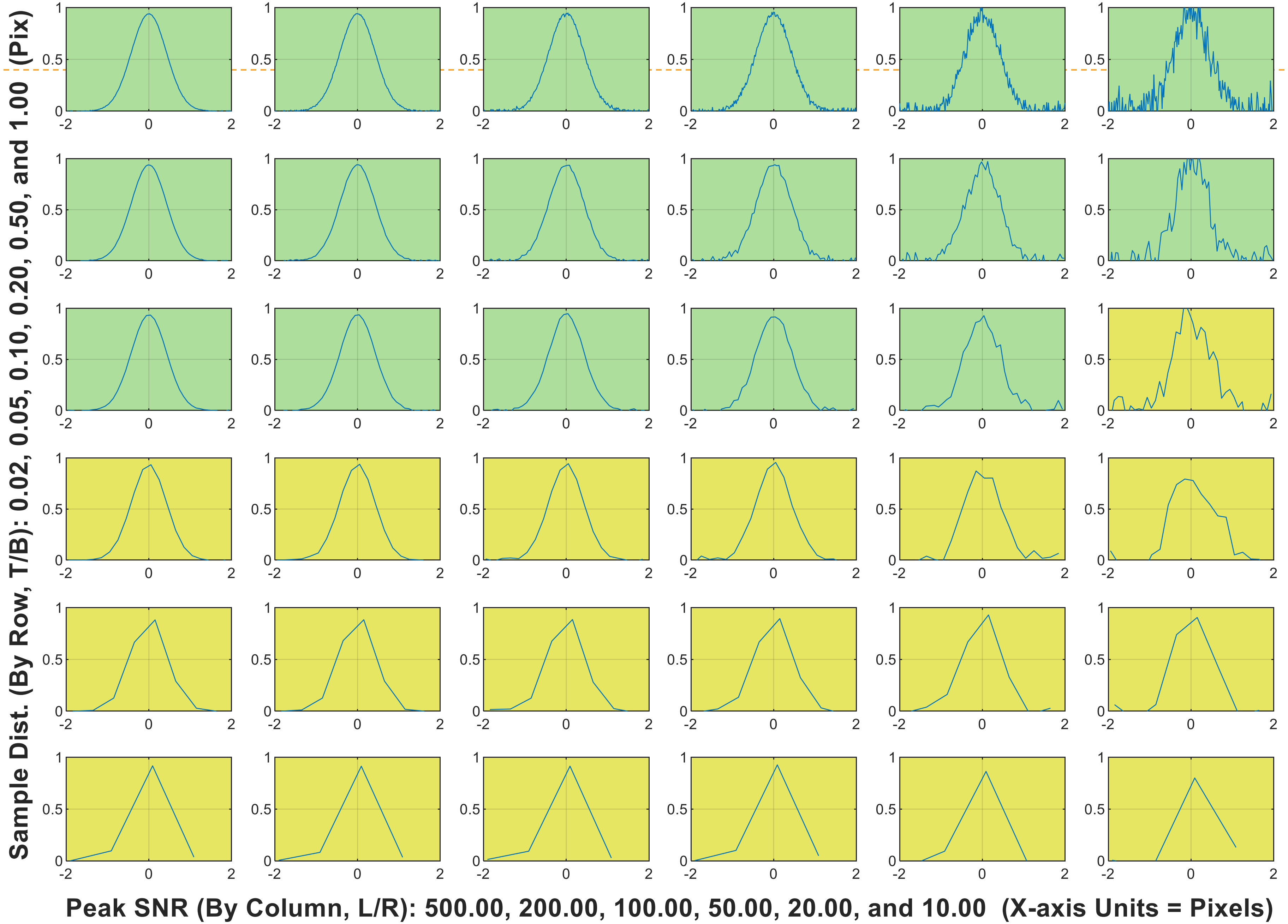






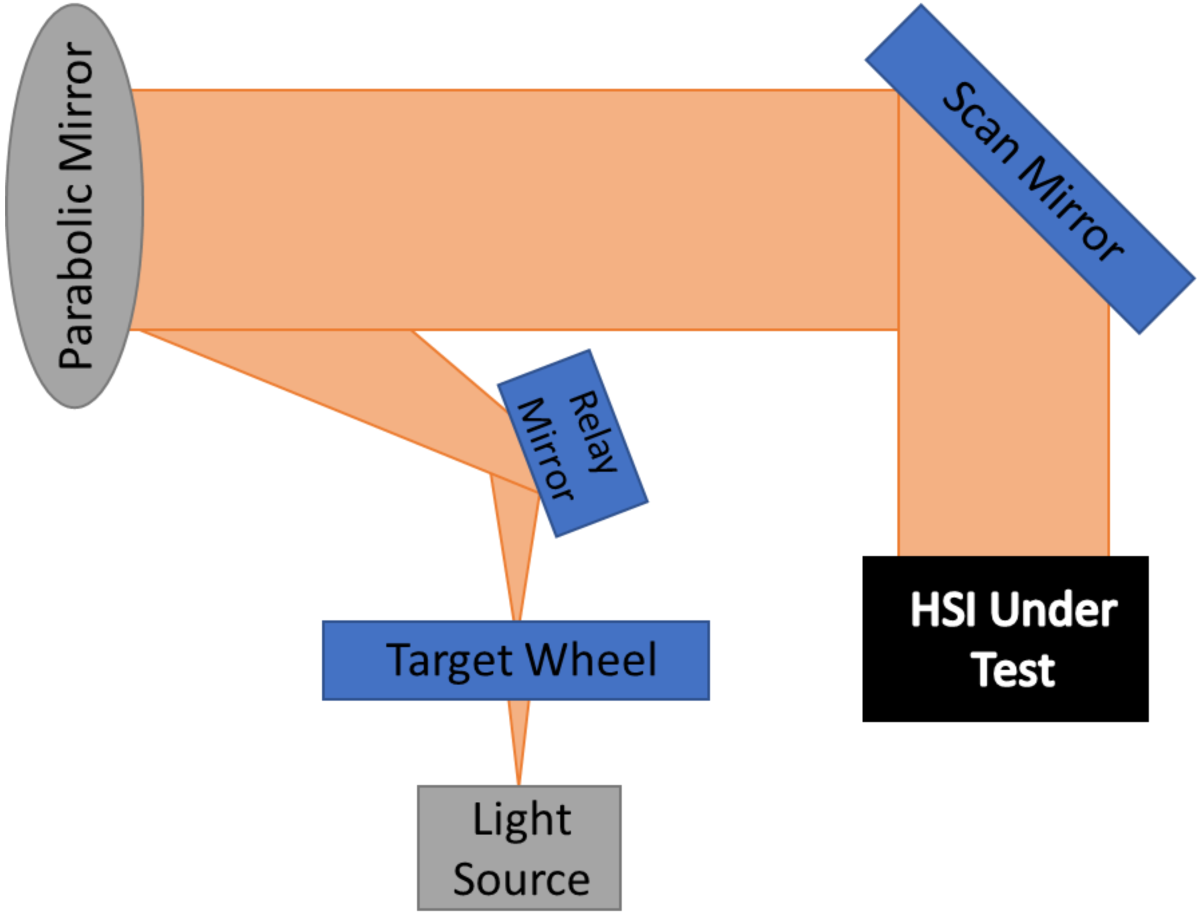
Lab Test of Gaussian Function With Conv. Peak Center Method

Function Width = 1.0 Pix.   (Green Results: Acc. < 0.05 Pix,)



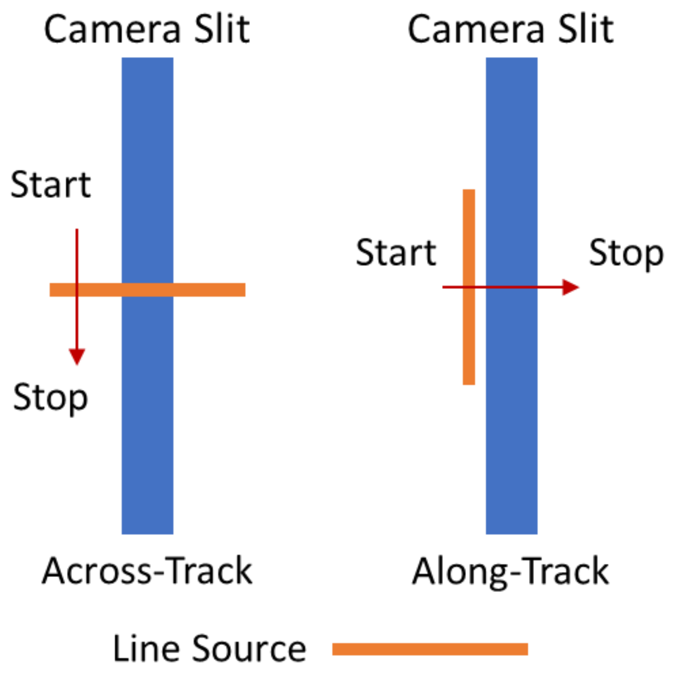
Spectral/Spatial Testing: Equipment

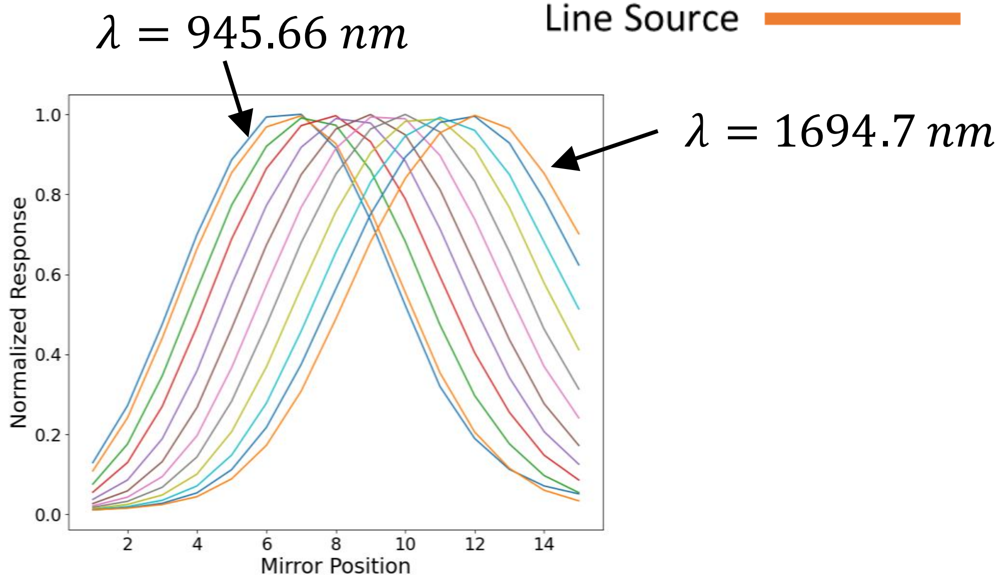
- Recommended equipment:
  - Broadband light source (QTH)
  - Collimator system (negligible WFE)
  - Spatial target - slit
    - $(w_{targ} \leq 0.25\, pix * IFOV_{sensor} * EFL_{coll})$
  - Scan mirror (sliding spatial target)



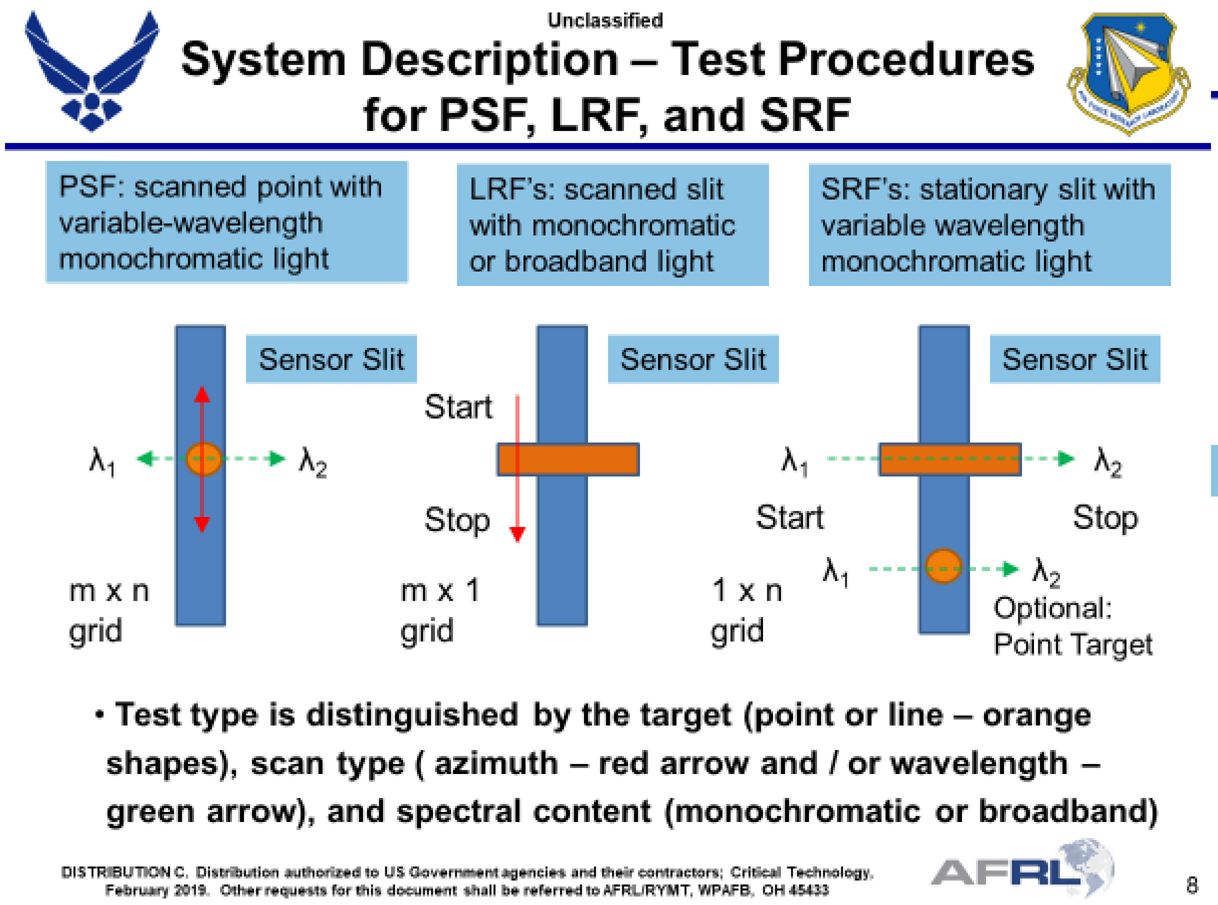
Spatial/Spectral Testing: Methods

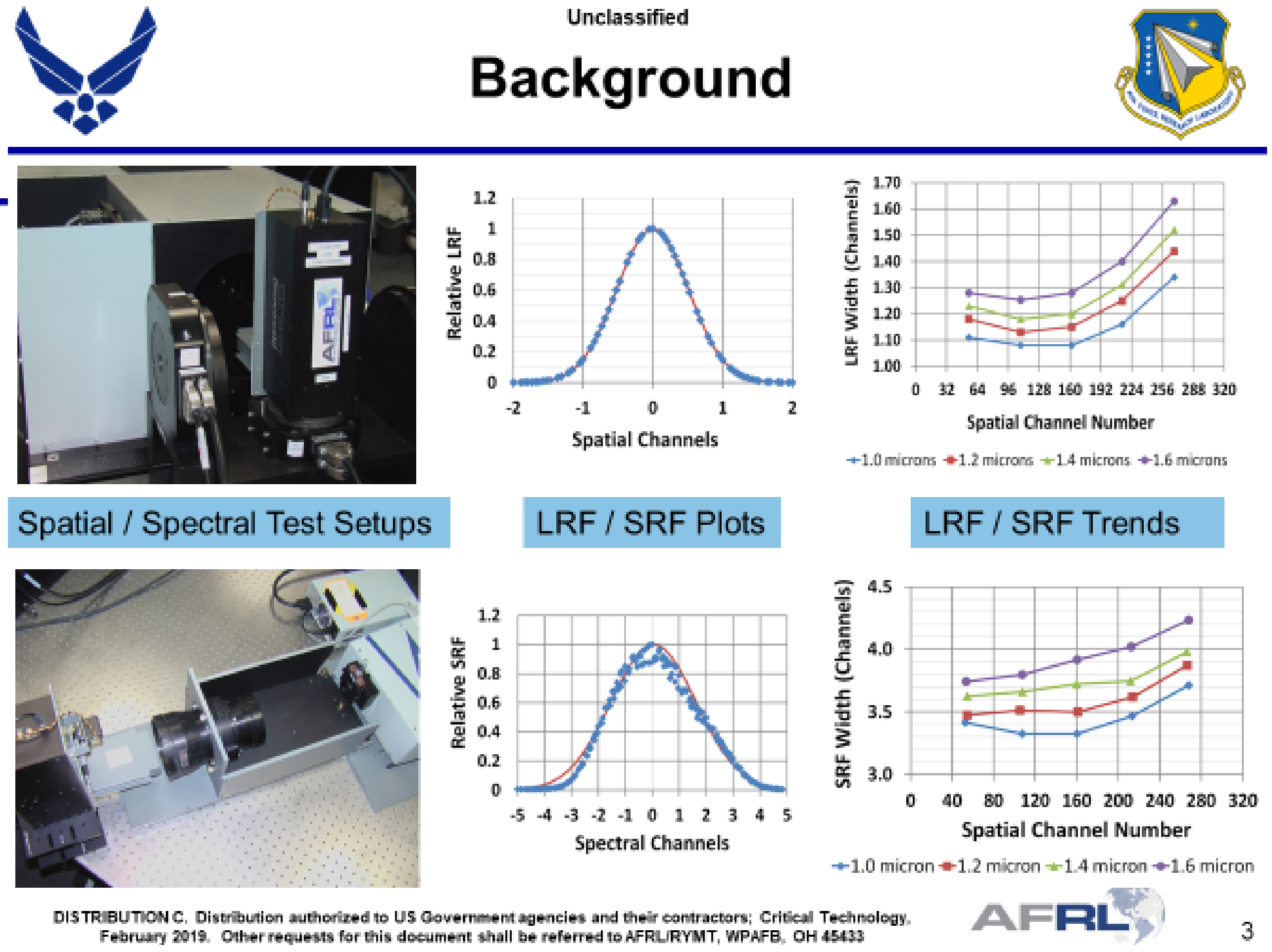
- Step scan mirror across the pixel-under-test
  - Record pixel intensity vs. scan mirror position
- Step size and total angular displacement
  - 10 points under the FWHM of the sLSF
  - 3x FWHM of the sLSF
  - Capture as much enclosed energy
- Across (x) and along-track (y) sLSF
  - Tomographic reconstruction of sPSF
- 7 points across spatial FOV





Spectral/Spatial Testing – Work in Progress





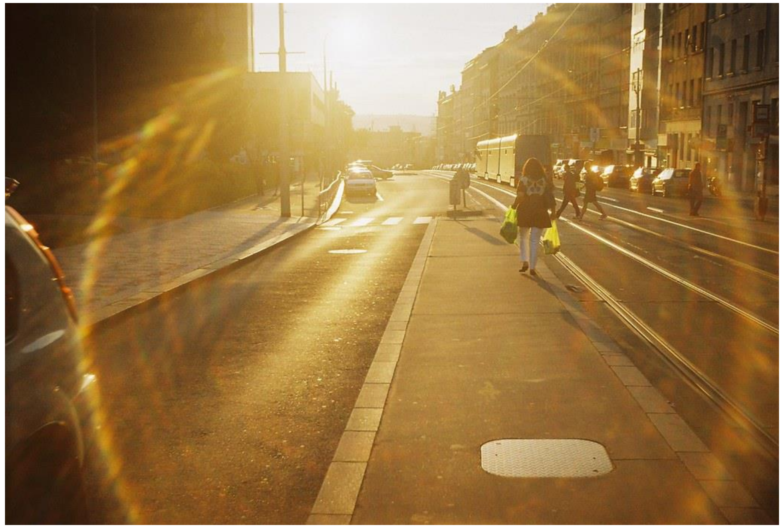
Example results courtesy of AFRL & Leidos:

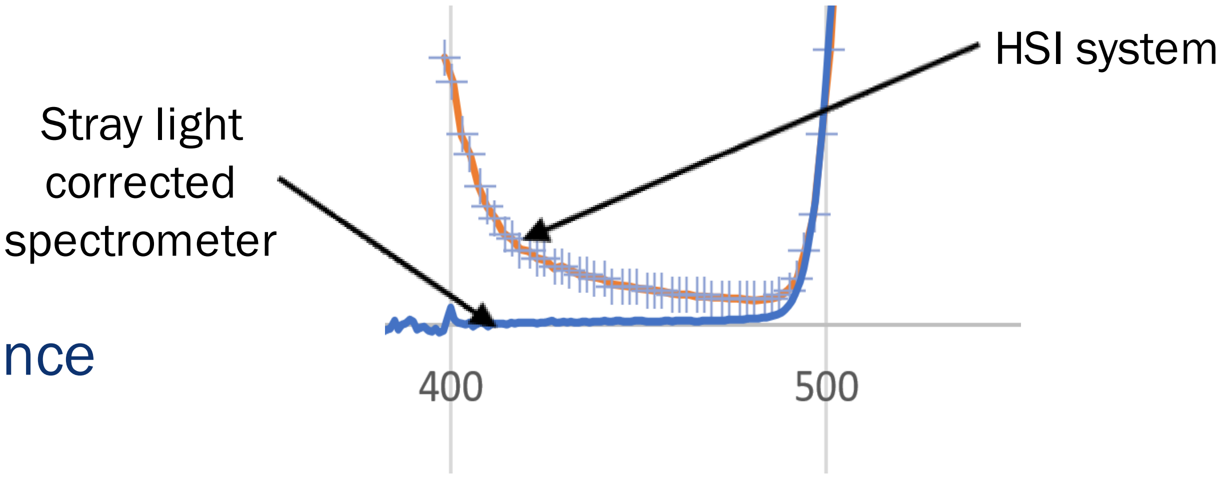
"An Automated Spatial-Spectral Test Fixture for Laboratory Evaluation of Passive Hyperspectral Sensors"

MSS February 2019 – D. Perry, N. Wurst, J. Meola et al

Stray Light Testing: Overview

- Stray light knowledge
  - Unwanted light
  - Relative comparison
  - Nonlinearity and noise source
  - CIE233:2019 Spectral Stray Light
  - ISO 18844 & ISO 9358 for Spatial Stray light
- Key descriptors of stray light
  - Spatial: unwanted scattering = *flare*
  - Spectral: unwanted colored light
- Stray light specification
  - Stray light apparent spectral reflectance



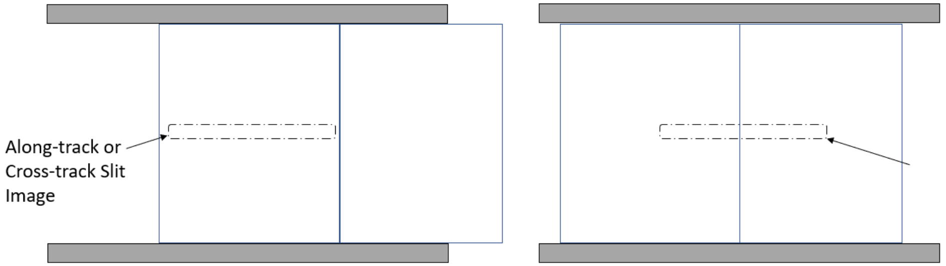


Spatial Stray Light Testing: Methods

- "Barndoor" Test Method for Along Track and Cross Track

1

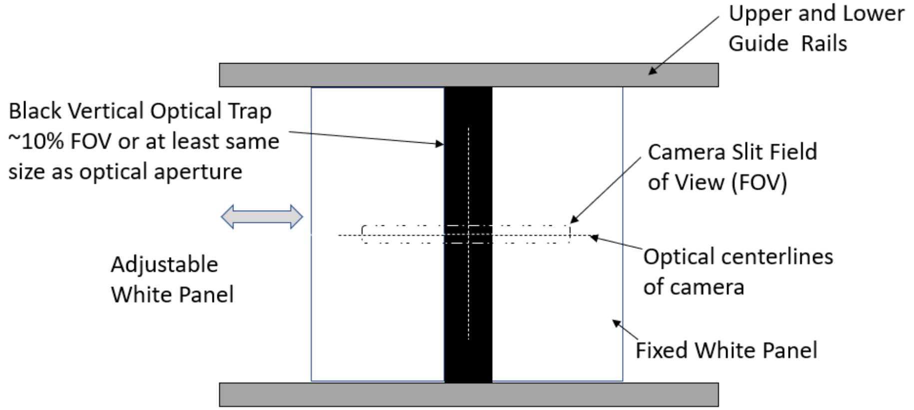
Black Reference is Lens Cap
White Reference is panels "closed"

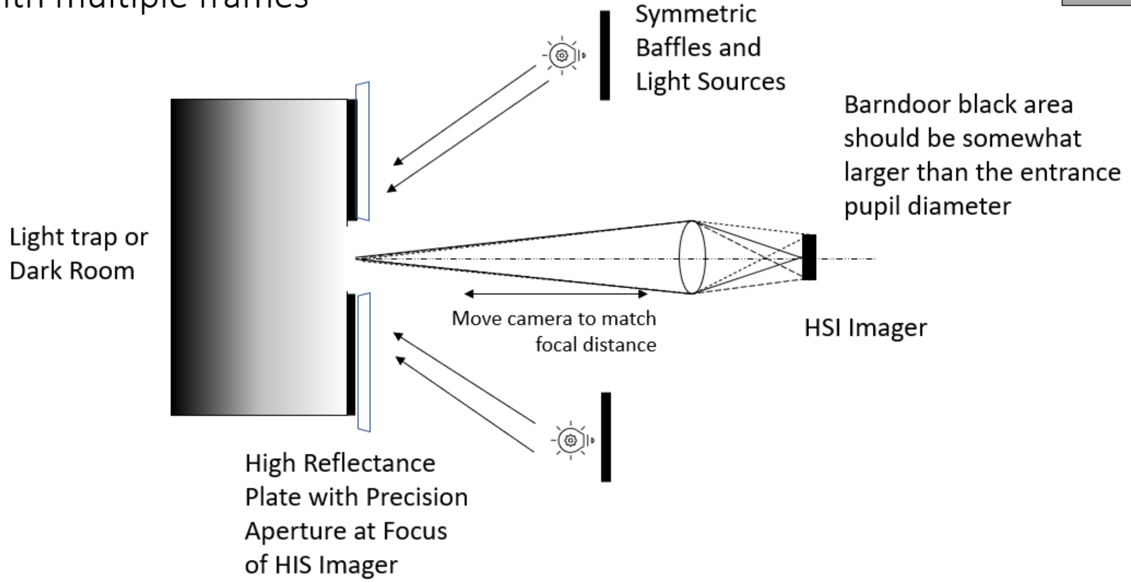


Use one panel or both (depending on FOV) – seam effects can be averaged with multiple frames

2

Barndoor Concept for Across-Track

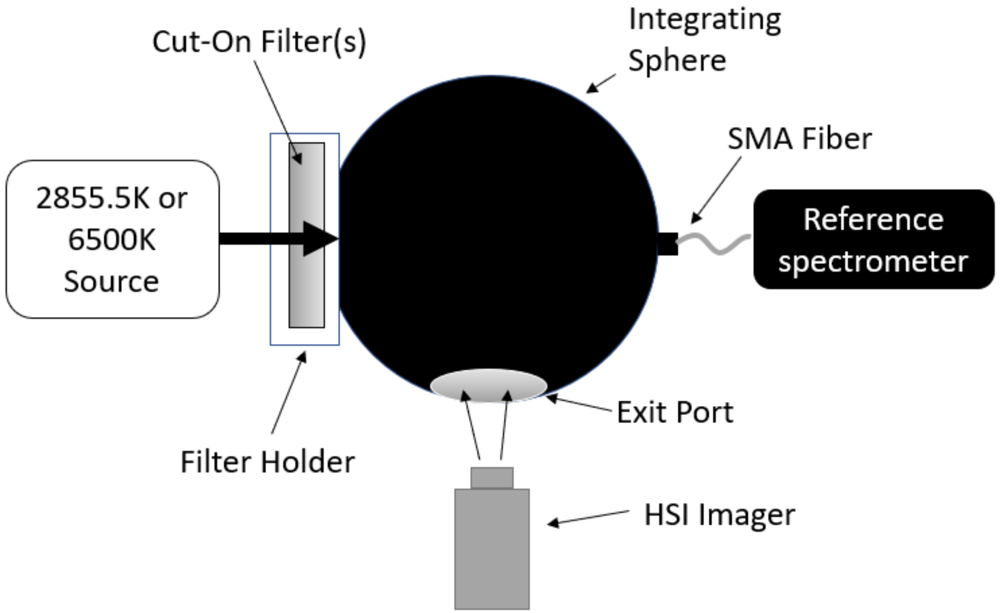


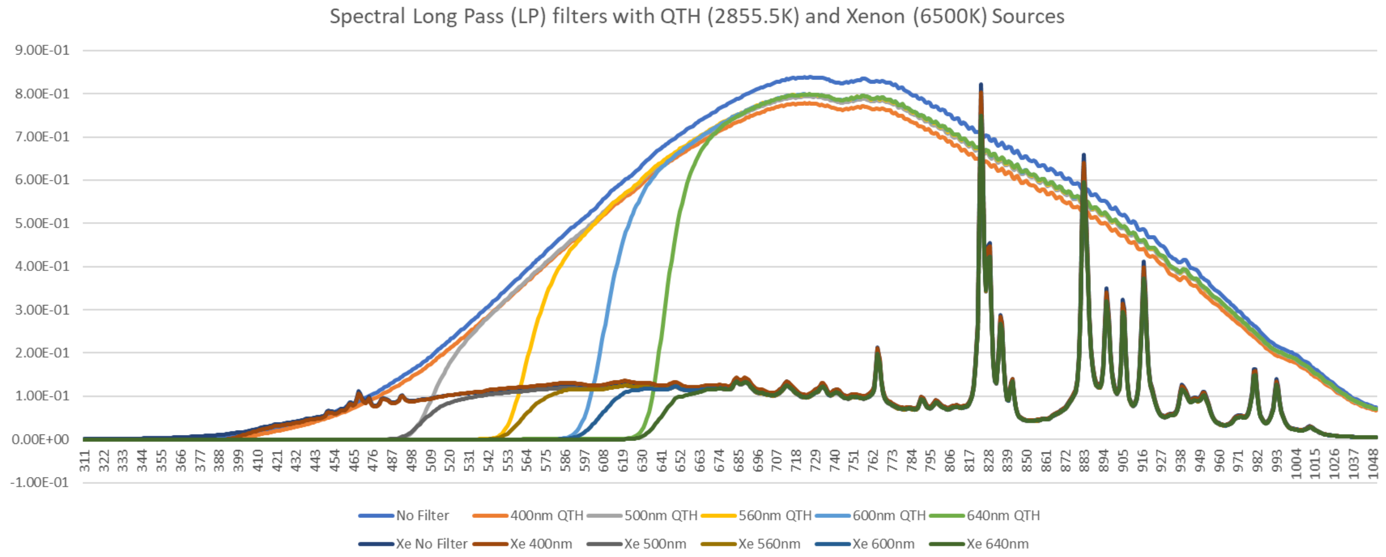


Spectral Stray Light Testing: Methods

- Cut-On Filter Test (300-1050nm Range)

Stray light Verification set up

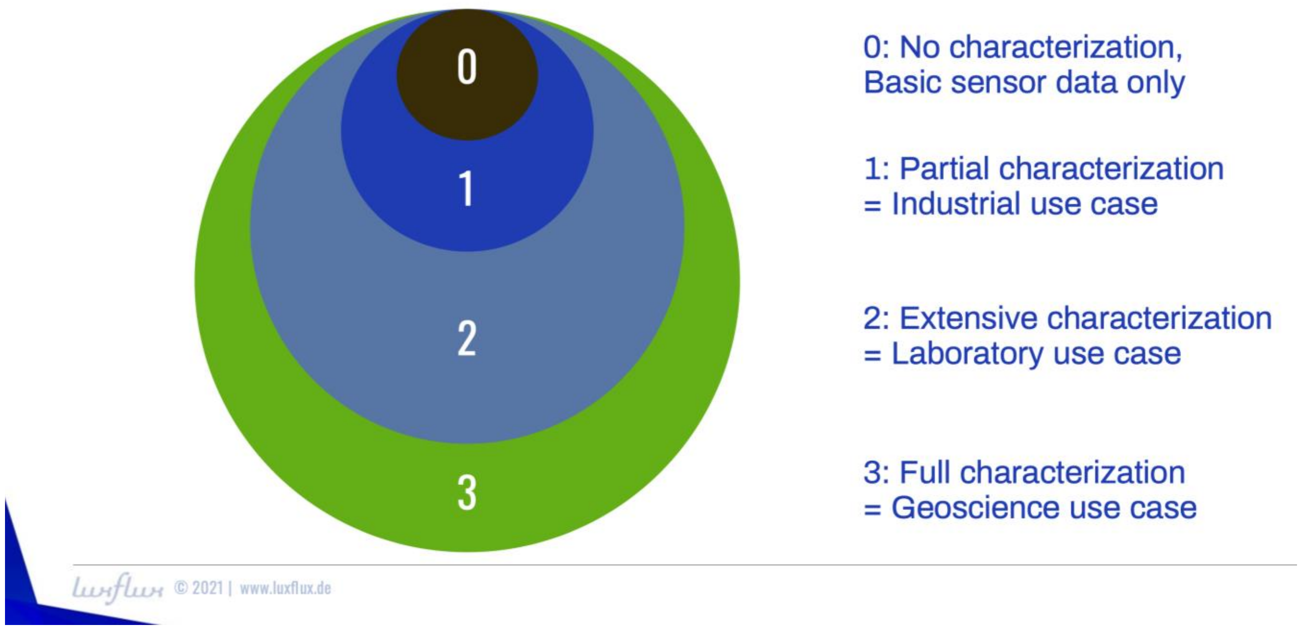




Similar tests can be run for extended wavelength ranges

Metadata & Use cases

- Mandatory metadata: use cases contained within each other



1. **Machine Vision/Industrial (MVI):** This use case covers cost-sensitive hyperspectral cameras used in industrial process control. The camera is part of a larger system which may take care of data correction.
2. **Laboratory (LAB):** This use case covers applications that record spatially varying spectral reflectance of material samples. It is assumed that a white reference and a dark reference are available, and that illumination is well characterized and controlled. Image quality depends on good correction for the effects of optics and image sensor.
3. **Geospatial Imaging (GEO):** This use case is characterized by a need for high data quality in order to infer scene properties from spectra sensed through atmosphere. two use cases. Illumination and other environmental properties are not controlled.

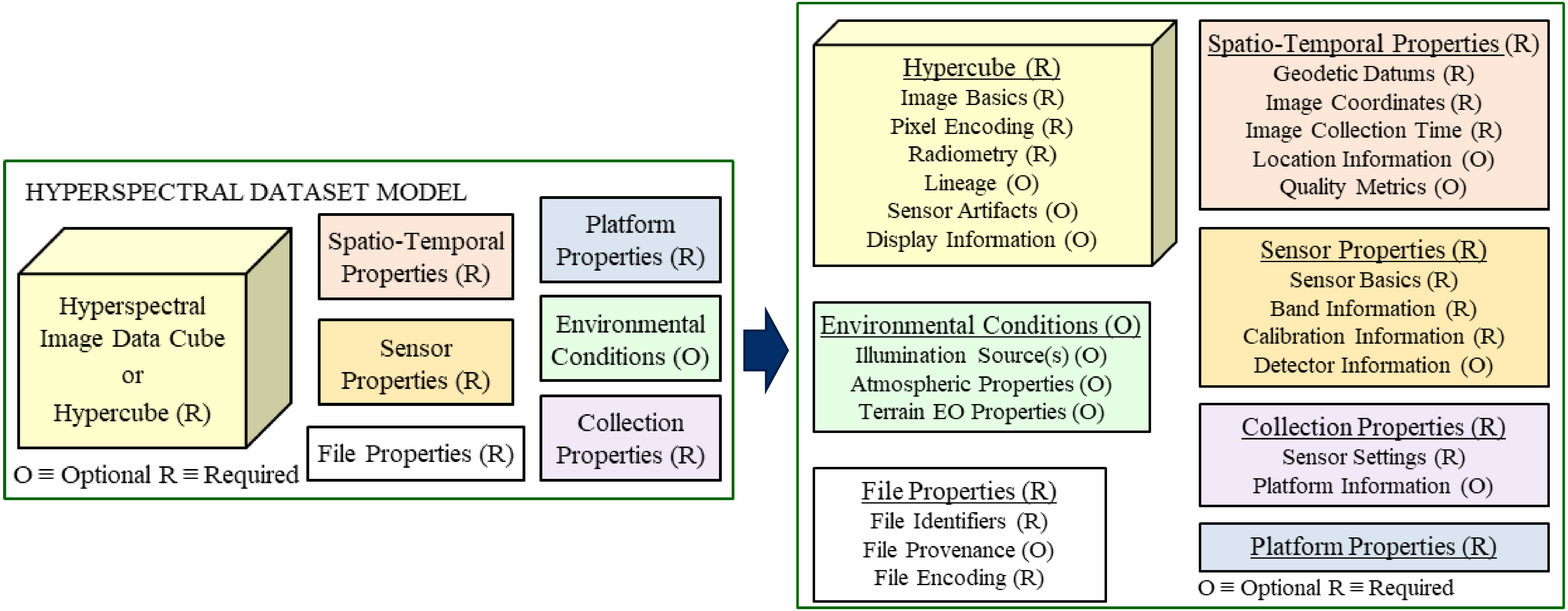
Current use cases - work in progress

- Remote sensing / Geoscience
  - Emphasis on high data quality
  - Radiometrically and spatially calibrated
  - Rich metadata

- Laboratory
  - Emphasis on reflectance spectroscopy
  - High data quality

- Industrial
  - Custom systems, emphasis on speed and cost
  - Data quality adequate for the application

Generating the details of metadata for a GEO use case hyperspectral dataset



Metadata Terms, Formats, Uses and Descriptions

Category	Term	Format	Units	Content	MachVis	Lab	Geo	Description	Example
Spatial	Number of Cross Track Pixels	Number	Pixel		1	1	1	For imagers, this corresponds to the x-direction	
	Number of Along Track Pixels	Number	Pixel		1	1	1	For imagers, this corresponds to the y-direction	
	Spatial Co-registration Error	Number	Pixel		0	0	1	Required only if a camera gives Spatial Response Function Width. Once SPSF and SRF are known, this figure can be calculated	
								This single number is the maximum error.	
Spectral	Number of Bands	Integer			1	1	1		
	Band Centre Wavelengths		Wavelength Unit		0	0	1	Vector of center wavelengths for each band in the spectral dimension	
	Spectral Co-registration Error	Number	Wavelength Unit		0	0	1	Required only if camera gives Spectral Response Function Width. Once SPSF and SRF are known, this figure can be calculated	
								This single number is the maximum error.	
Temporal	List of timestamps for each recording fr	Vector of Numl	Date/Time		0	0	0	Time stamp that records the beginning of each recording frame. Offsets within a recording frame are recorded with the datum "Band / Position	
	Start & End Collection Time	Number	Date/Time		0	1	1	Time step for beginning and end of data collection	
Radiometric	Unit of Measurement	Enumeration		DN, Reflectance, W/(m^2*nm*sr), W/(m^2*µm*sr), micro				Indicates the unit of the data in the datacube, unit is after rescaling (cf. Pixel Encoding -> Rescaling factor), radiometric Unit from list of radiom	
	Zero Point Handling	Enumeration		Negative values tr	0	0	1		
	Zero Point Value	Number			0	0	1	Offset (if any) for the zero value, only required to be non-zero if zero is offset	
	Saturation Handling	Enumeration		None, reserved va	0	1	1		
	Upper Bound reserved value	Number			0	1	1	Value to indicate that pixel is in saturation; if a pixel in the data cube has this value, the processing software knows that the pixel was in saturat	
	Satruration Map	Martrix of number			0	0	0	Same purpose as upper bound reserved value, but a map of the same x/y dimensions as the data cube that has an entry for each pixel in satu	
Pixel Encoding	Encoding Type	Enumeration	RAW		1	1	1	Indicates how data is saved, extensible for future formats, e.g.Only metadata for RAW specified here	
	Encoding Type Meta Data	Blob			0	0	0	Contains metadata required to read the data in the format set forth by encoding type	
	Pixel Order	Enumeration		BIL, BSQ, BIP	1	1	1		
	Pixel Value Type	Enumeration		uInt8, uInt16 , uInt	1	1	1	How is the data written to disk, e.g. uInt16, float32; data may not use the full range of available numbers	
	Pixel Big or Little Endian	Boolean		false (little endian)	1	1	1	Default Little Endian	
	Pixel Justification	Boolean		false (LSB justifiec	1	1	1	if the actual data uses less bits than the size of the data type, justification is left or right. Default is LSB justified	
	Number of Bits per pixel	Number	Bits		1	1	1	Indicates the number of bits in a stored value, can be equal or lesser than the pixel value type, e.g. data is only 12 bits but stored in 16 bits	

54 Categories Defined

>70 Metadata Attributes Assigned

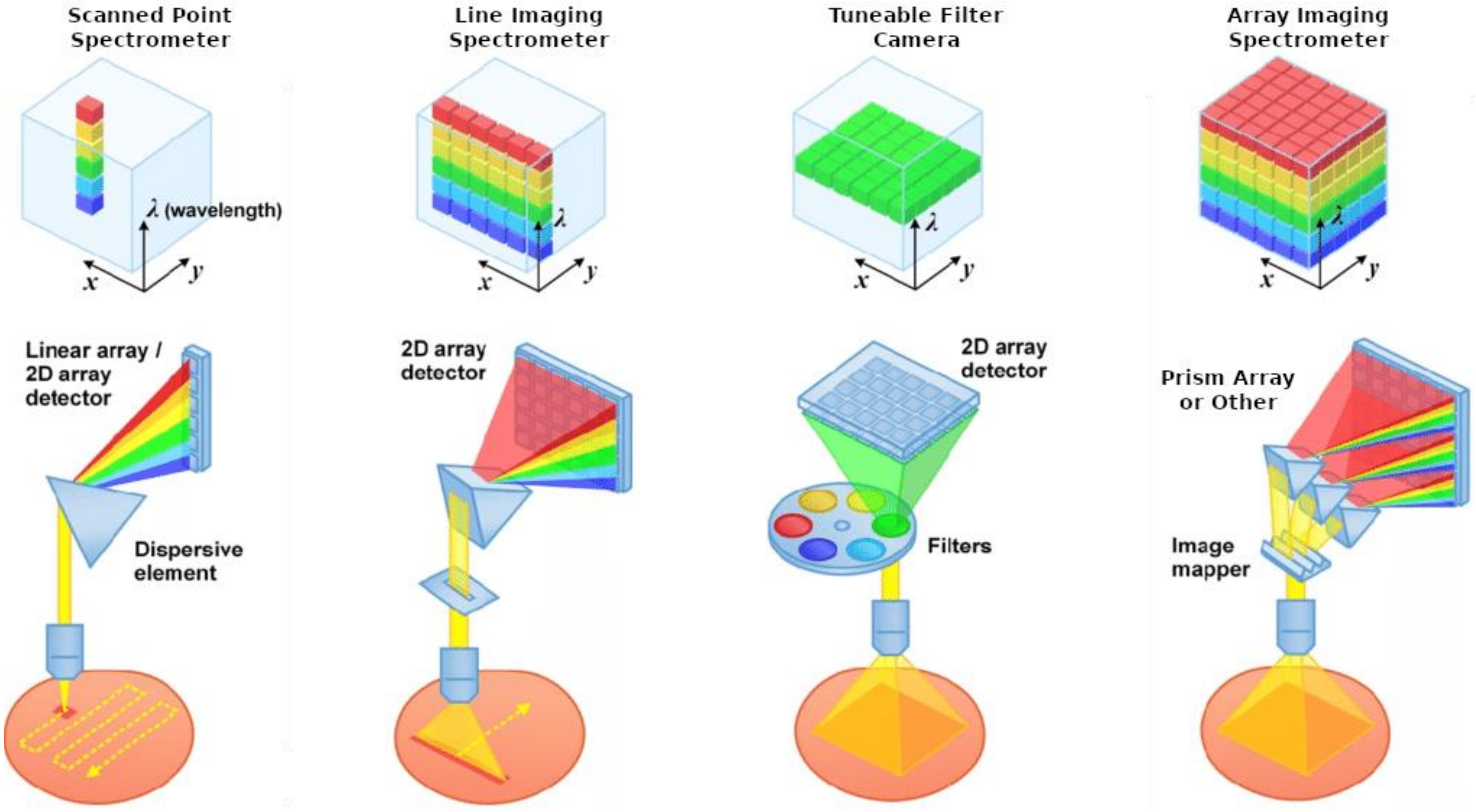
50+ Camera Characteristics

Spatial	Coregistration	Stray light	Calibration
Pixel format	Spatial coregistration error	Spatial stray light	Radiometric calibration accuracy
Object distance	Spectral coregistration error	Spectral stray light	Spectral calibration accuracy
Field of view	Temporal coregistration	**Temporal**	Geometrical model accuracy
Geometrical IFOV	Motion equivalent to coregistration error	Maximum frame rate	Calibration interval
Spatial distortion	**Radiometric**	Integration time	**Data output**
SPSF peak width	Effective throughput A*	Dead time	Output processing level
SPSF energy fraction within IFOV	Read noise	**Imperfections**	Assumed data processing
(Resolution index/ENOP)	NESR at noise floor	Bad pixels	Real time output
Spectral	Specific sensitivity S*	PRNU	Synchronization interface
Spectral range	Signal to noise ratio	Spectral response nonuniformity	SRF accuracy
Number of bands	Saturation level	Effective spatial fill factor	Invalid data flag
Spectral sampling interval	Dark current	Linearity error	**Other**
SRF peak width	Throughput variation over FOV	Polarization dependence	Environmental - operation
Band enclosed energy fraction	Dynamic range		Environmental - storage
(Resolution index/ENOB)	Dark correction		Detector type/temperature

Terminology

- What do you mean by "hyperspectral"?
  - ***"For the purposes of the P4001 effort, addressing systems operating within 250nm - 2500nm, a hyperspectral imaging system or data set is defined as one in which pixel spectra are measured over a specified spectral range without gaps and with a maximum spectral sampling interval not exceeding 1/30 of the spectral range."***
- For a standard, many terms need precise definitions
- A separate P4001 subgroup works on terminology

Camera Architectures



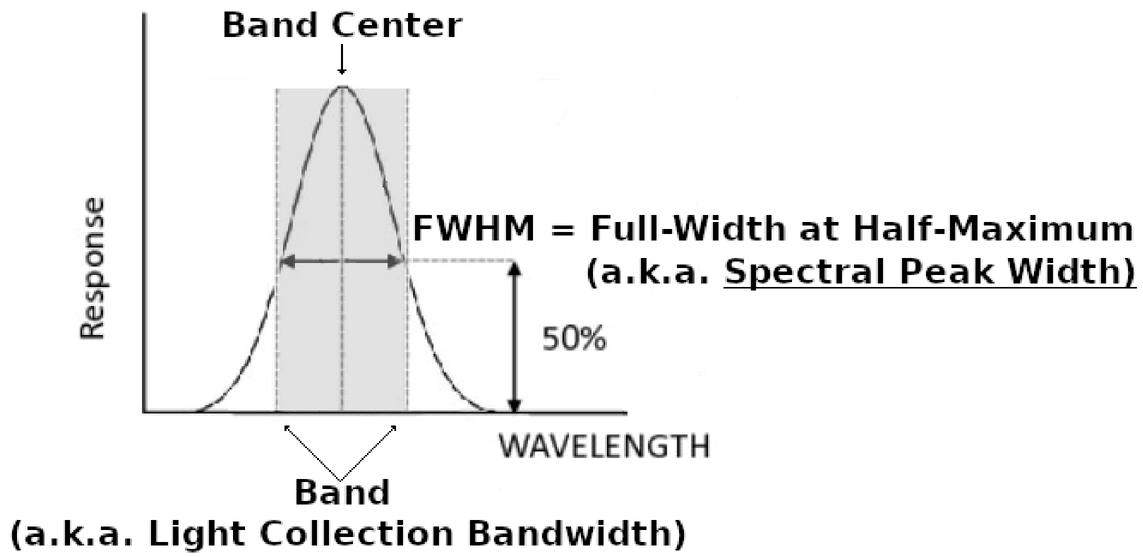
[Modified] Wang, Yu et al. (2017). Multiplexed Optical Imaging of Tumor-Directed Nanoparticles: A Review of Imaging Systems and Approaches. Nanotheranostics. 1. 369-388. 10.7150/ntno.21136.

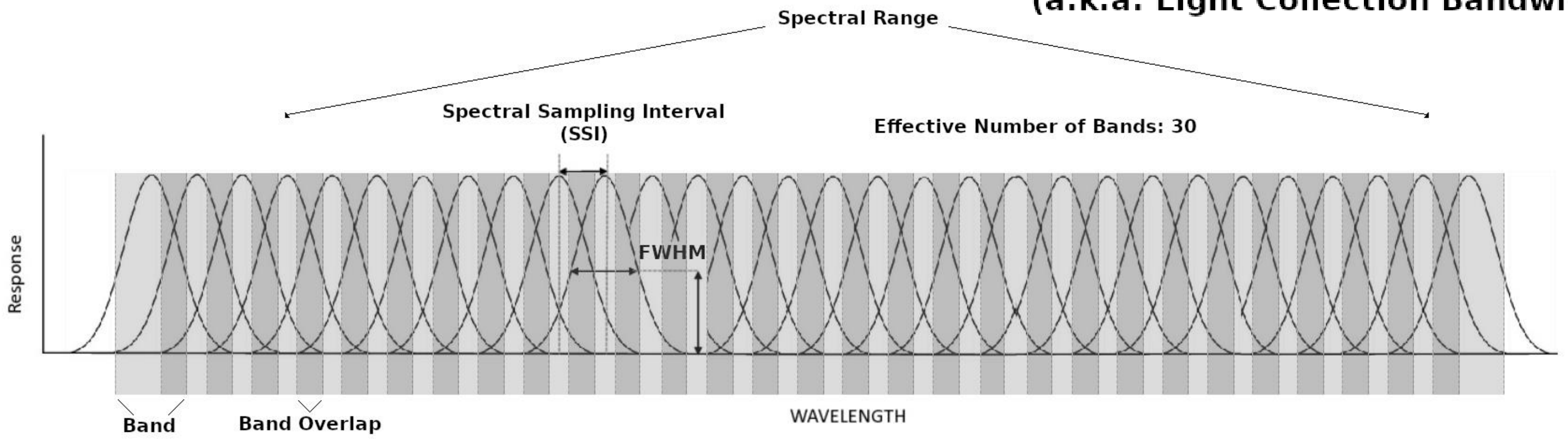
Terms & Definitions Under Consideration [continued…]

- Light Sample
- Output Image / Output Pixel
- Electron and Photo-electron are needed as signal units
- “Push-broom Scanning” and “Line Imaging”
- “Sampling Point Spread Function”
- “Effective Number of Pixels” or “Effective Number of Independent Pixels”
- “Effective Throughput” A*

Terms Related to Spectral Resolution

- Spectral sampling interval
- Spectral peak width
- Light collection bandwidth
- Effective Number of Bands





Conclusions

- A clear and urgent need for standardization in hyperspectral imaging
- P4001 defines characteristics for hyperspectral cameras
  - covering all aspects of performance
  - emphasizing the needs of imaging spectroscopy
- P4001 defines a possible set of verification tests
- Specification of metadata in accordance with different use cases
- P4001 will include definition of required terminology
- Standard Finalization will continue into Fall of 2022…
  - **Documenting, Linking and Harmonizing….**
- Working on a GET Sponsorship to make this an <u>Open</u> IEEE Standard
- Next meeting: August 30 @ 1000 EDT (Zoom)
  - https://labsphere.zoom.us/j/88159298627?pwd=TU5MLzNwVnc3SktVYzl0ZmVibnZ1UT09