The new effort for Hyperspectral Standarization IEEE P4001

2019 IS&T International Symposium on Electronic Imaging (#EI2019)

Paper #IMSE-370 (Keynote)

Session: Color and Spectral Imaging

Chris Durell, Labsphere, Inc

Chair IEEE P4001

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Contents

- Overview of different types of hyperspectral imaging
- Deeper dive into "Pushbroom" Spatial Scanning systems
- Why a standard is needed.
- What is the focus of IEEE P4001 and what we are doing.

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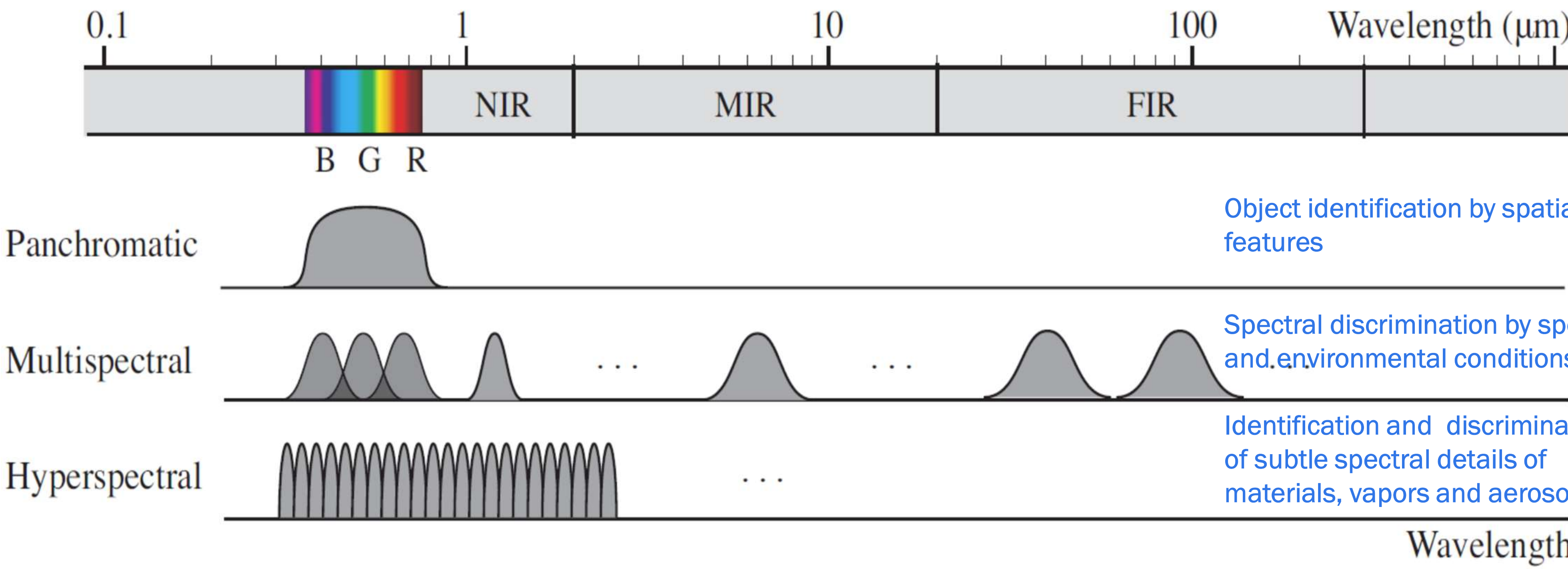
Spectral Sensing and Imaging



Object identification by spatial features

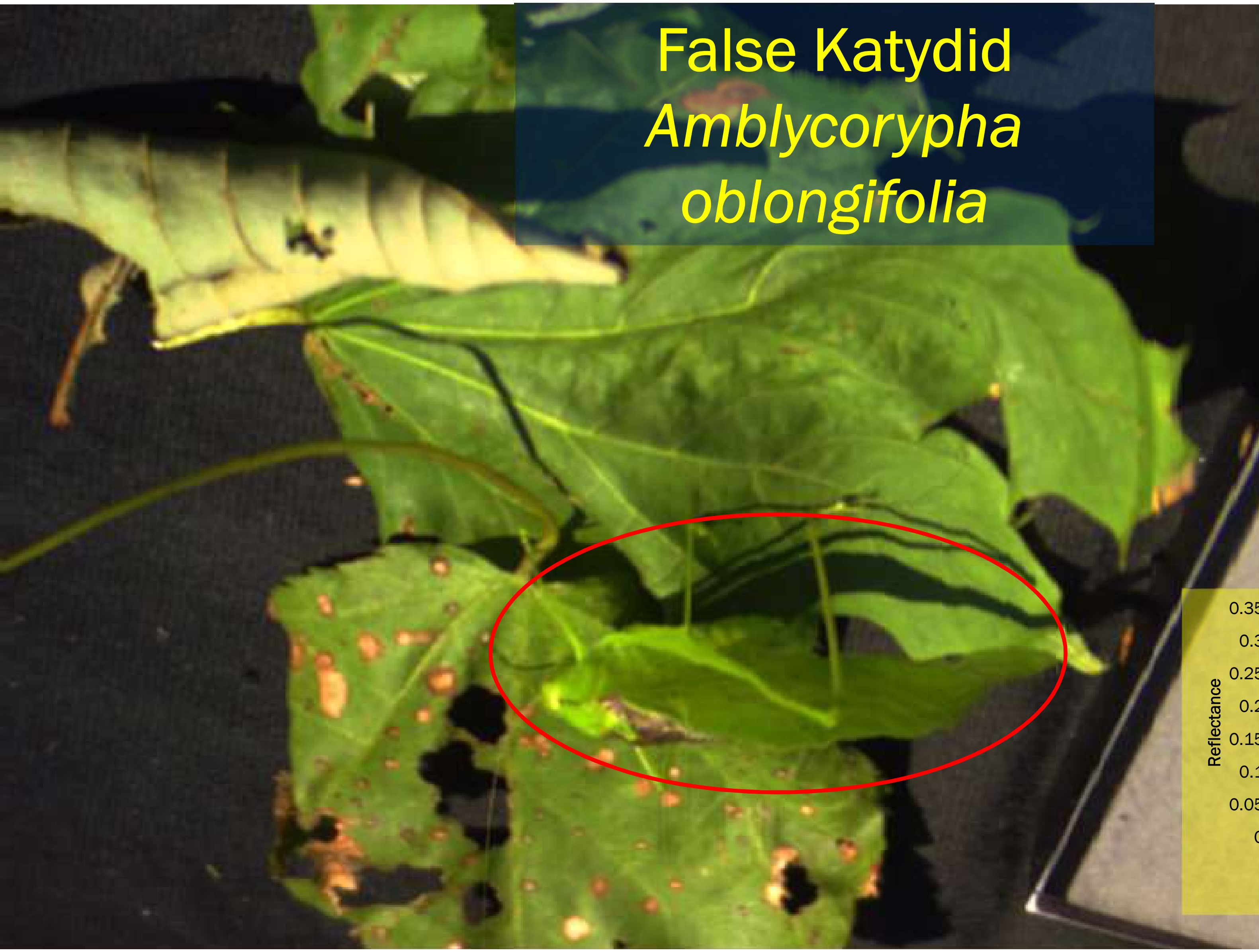
Spectral discrimination by species, and environmental conditions

Identification and discrimination of subtle spectral details of materials, vapors and aerosols

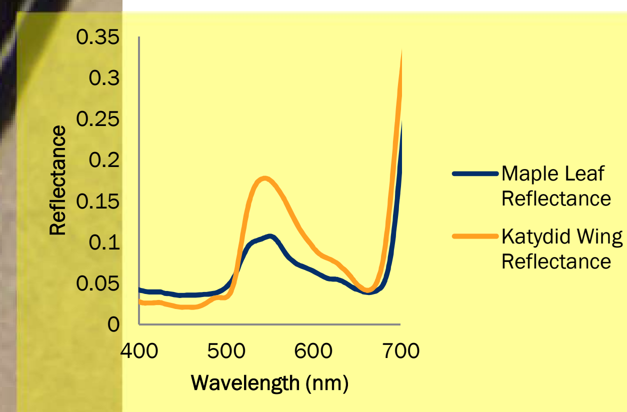
Source: M. Velez-Reyes, J. A. Goodman, and B.E. Saleh, "Chapter 6: Spectral Imaging." In B.E. Saleh, ed., *Introduction to Subsurface Imaging*, Cambridge University Press, 2011.

Adapted from
From 1993 MUG

False Katydid *Amblycorypha oblongifolia*



Courtesy of
Dr. Brandon Russell,
UCONN.



Katydid Hiding on a Leaf (380-1040nm)

Courtesy of
Dr. Brandon Russell,
UCONN.

Domains of Spectral Imaging

Category	Spectral Band Content	Spectral Resolution	Application	Example System
Multispectral	A few to dozens	20-100nm	• Multispectral classification of dissimilar materials • Military target detection & camouflauge ident. • Geological • Oceanography • Atmospheric	LANDSAT (NOAA) AVHRR (JPL) SPOT 3 (France)
Hyperspectral	Hundred to a few hundred	10-15nm	• Precise surface material identification • Environmental monitoring • Detection of selected gases • Atmospheric effects must be known to detect gases	HYDICE (NRL) AVIRIS (JPL) HIRIS FTS (LLNL)
Ultraspectral (Spectroscopy)	Several Hundred	1nm	• Gas Specied Detection • High resolution permits in-situ correction of atmospheric effects (water, ozone, etc)	Mostly ground based spectrographs Fourier-Transform spectrometers Coming to Space

Source: SPIE SC194

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Definition of Hyperspectral Imaging

- The term, "hyperspectral" seems to be grounded in the incorporation of higher sensitivity focal plane technology that enabled contiguous spectral band sampling through adjacent sensors (aka, two-dimension CCDs, InGaAs, MCT and other focal planes). These technologies allow single frame capture of a spatial image with all the corresponding spectral bands on one chip. This new single frame contiguous band capture was nicknamed hyperspectral to differentiate from multispectral sampling. Technically, hyper and multi are still forms of imaging spectroscopy. However, this form-factor innovation also allowed for much more compact optical and instrument geometries which shrunk the size, improved the speed and lowered the cost of these products. This instrument and name change allowed the instruments to really develop into commercially viable technology. Therefore, the name hyperspectral is now synonymous with small, fast, lightweight camera like spectral imagers and it is the way the market has adopted this concept and terminology.
- <u>"A hyperspectral imaging system is one which is capable of collecting distinct, yet contiguous bands across the instrument's spectral range (SR) with a spectral sampling interval (SSI) to spectral range ratio of less than 1:50 (SSI/SR <= 0.02)."</u>

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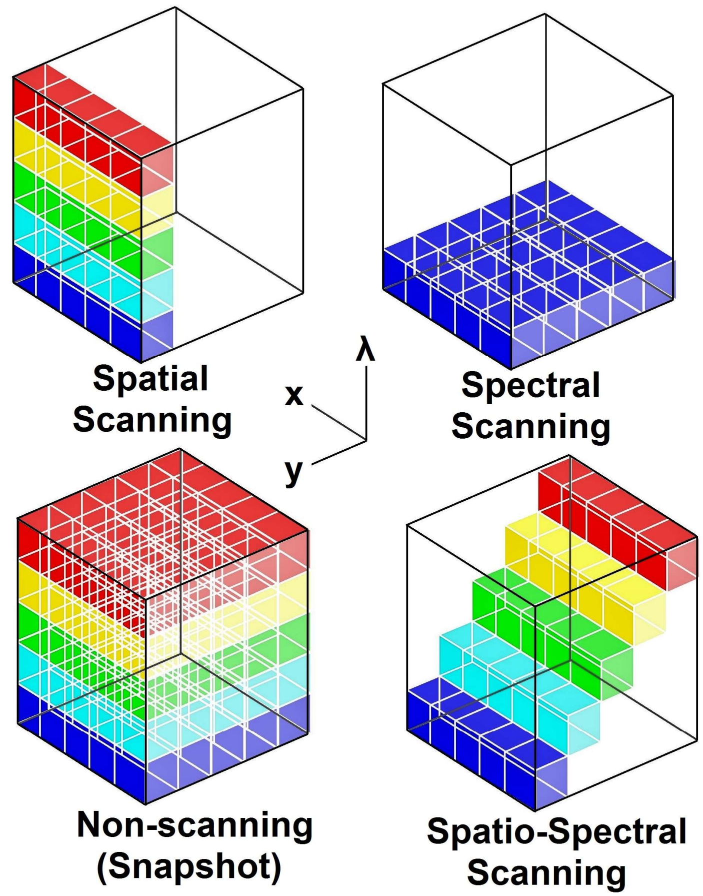
Types of Hyperspectral Instruments

- Spectral Scanning (Multispectral or Band Illuminated)
- Non-Scanning (Snapshot)
- Spatio-spectral scanning
- Spatial Scanning (Pushbroom/Scanning)



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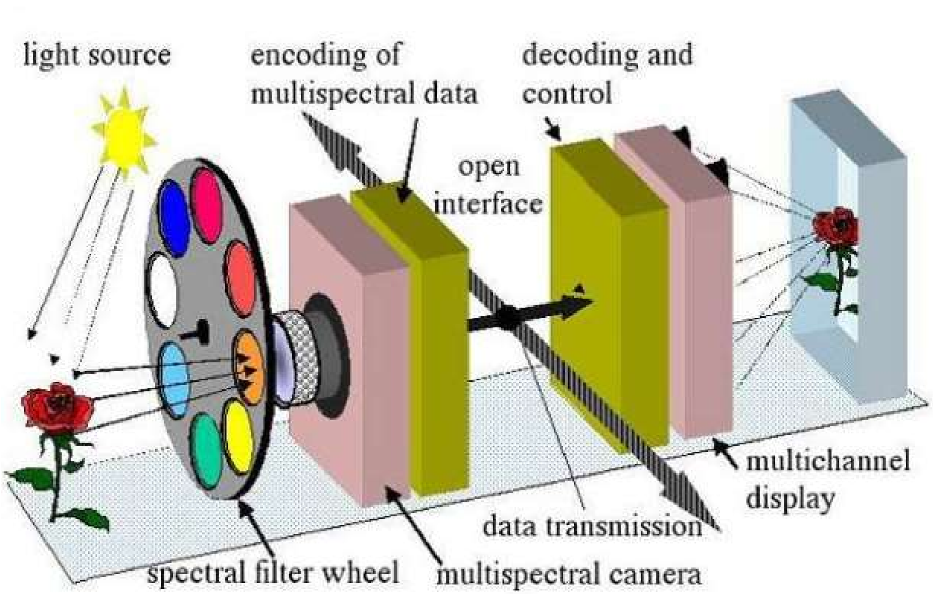
Spectral Scanning & Multispectral



- Scene illumination is via selected spectral bands
  - Broadband Source with Filters (pictured)
    - OR
  - Discrete LEDs (camera broadband)
  - Laser lines (camera broadband)
- Conventional camera used to capture scene in each band illumination
- Process mosaic of banded 2D images to create hyperspectral data

Spectral Scanning (Multispectral)

Advantages

- Uses conventional cameras
- Can be relatively fast
- No movement or sample or camera required.
- Radiometric accuracy well understood.
- Small footprint

Disadvantages

- Needs well defined bands
- Band resolution and spacing
- Sources can get complicated/expensive
- Target needs to be stationary or have to have a fast camera

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Non-Scanning – Snapshot

- Scene illumination with broadband source
- Image is broken into channels via techniques below
- Image compilation and post-processing required.

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Non-Scanning – Snapshot

Advantages

- Uses conventional cameras
- Uses low cost components
- Fast imaging
- Very small packages
- Best potential to head to commercial products

Disadvantages

- Data processing unclear
- Data accuracy unclear
- New Technology still under development
- Band, detector and resolution limited
- Requires camera or object movement
- Radiometric accuracy not well understood.
    - Straylight and crosstalk.

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Spatio-Spectral Scanning

- Scene illumination is broadband
- Dispersive element between camera and target
- Camera “tilted” or scanned through “rainbow” of image to reconstruct hyperspectral data.

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Spatio-Spectral Scanning

Advantages

- Uses conventional cameras
- Uses low cost components
- Compact

Disadvantages

- Data processing unclear
- Data accuracy unclear
- New Technology still under development
- Requires camera or object movement

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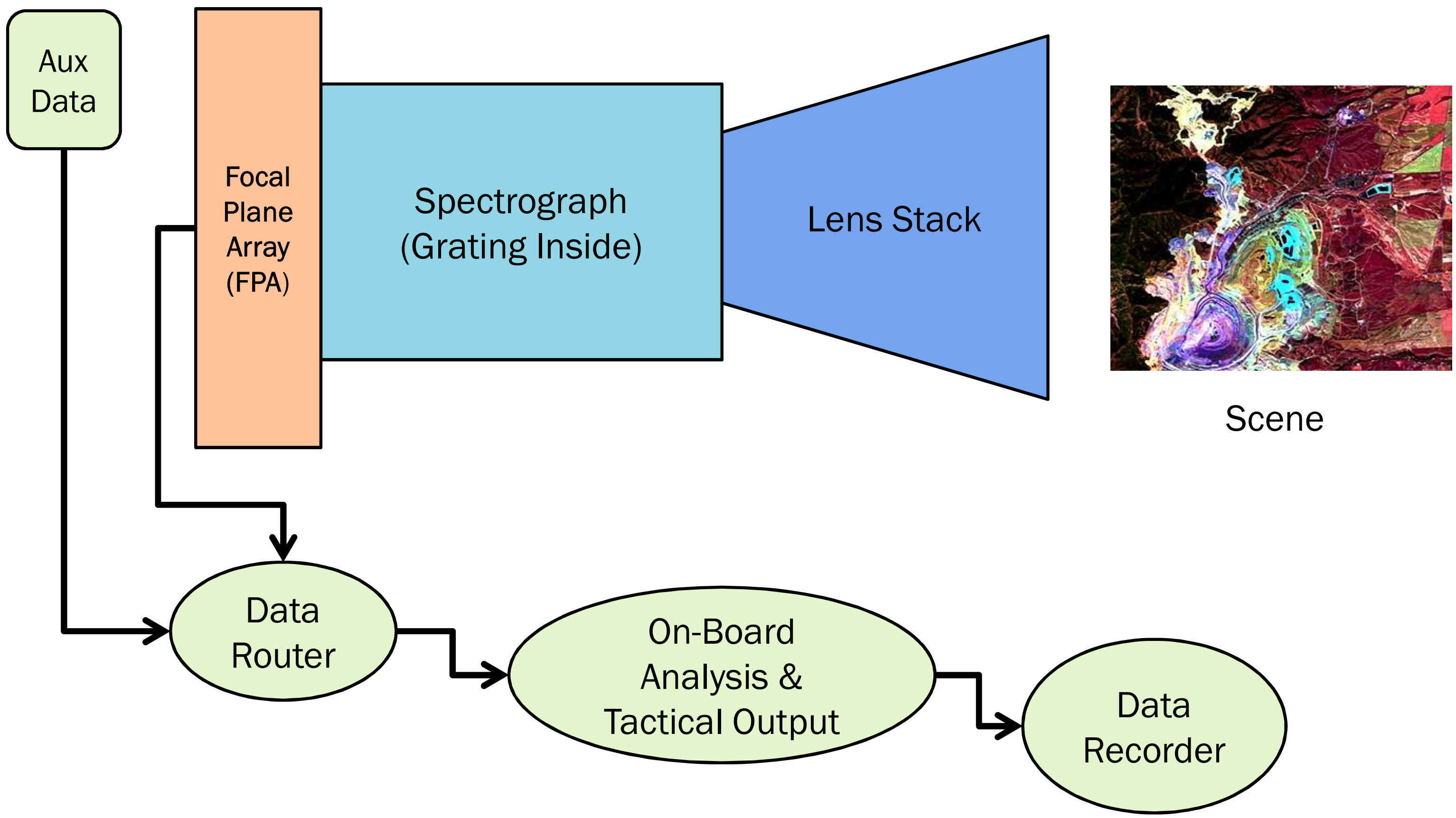
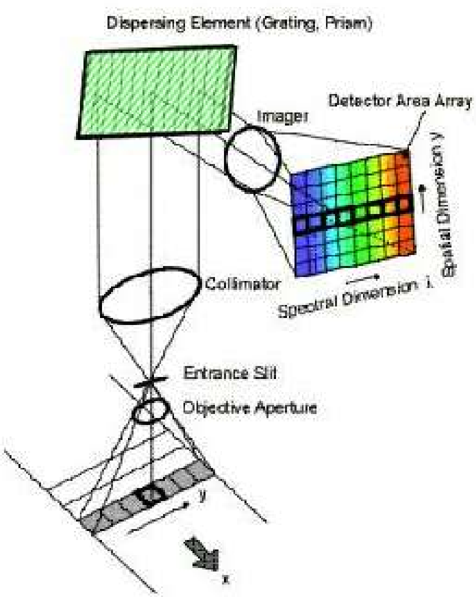
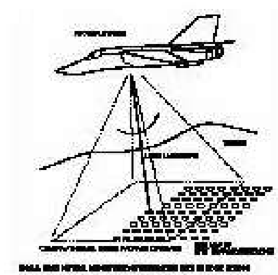
Essentials of the Pushbroom Spectral Imager System:

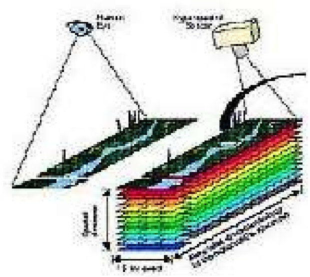


Spatial Scanning – Pushbroom

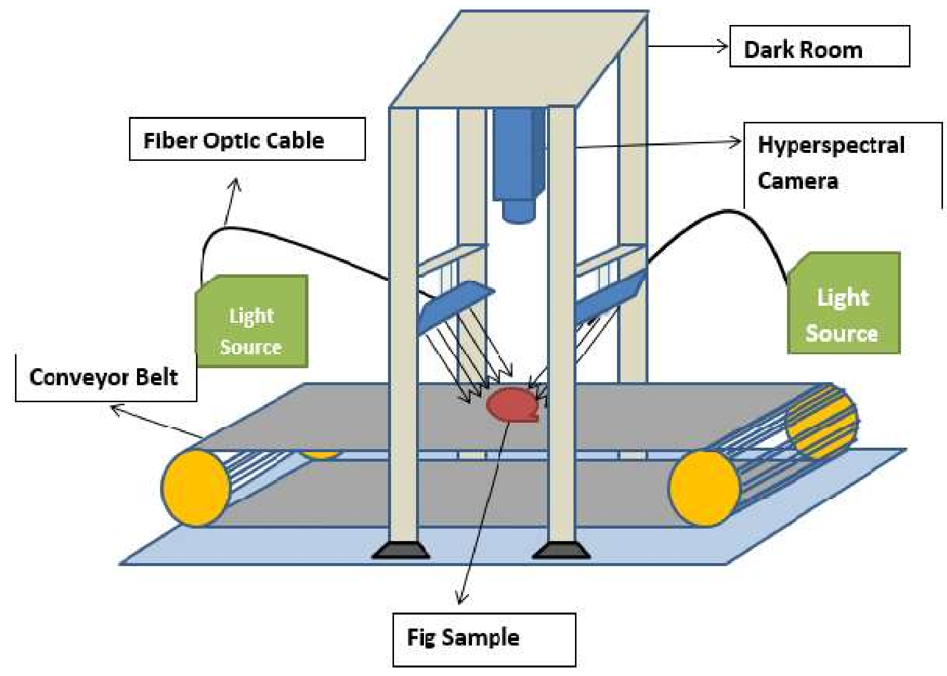
Imager Moves (Aircraft or Satellite)



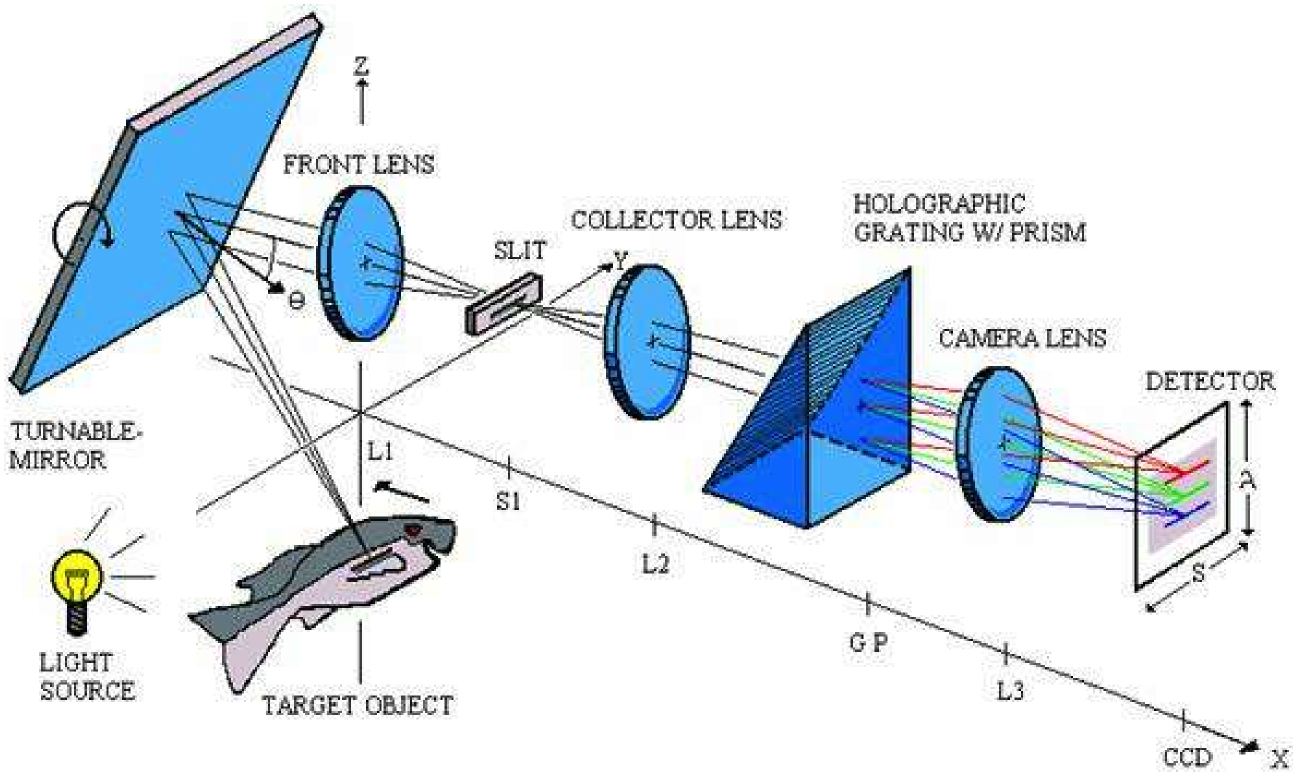




Sample Moves (Industrial)



Spatial Scanning – Stationary Object & Moving Mirror System



Spatial Scanning - Pushbroom Advantages & Disadvntages

Advantages

- Longest heritage and most mature technology
- Most prevalent design on the market
- Configurable technology for variety of applications
- Well understood radiometry
- Software relatively mature (ENVI, IDL, MATLAB, etc).
- Takes advantage of natural sources (Sun)

Disadvantages

- Requires scanning or movement
- Instrument architectures can be expensive
- Limit on how small we can go on instrument size.
- Large data outputs

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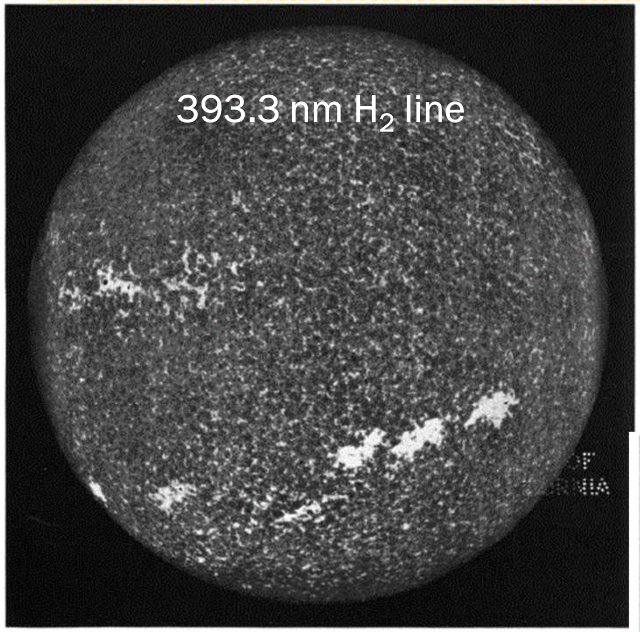
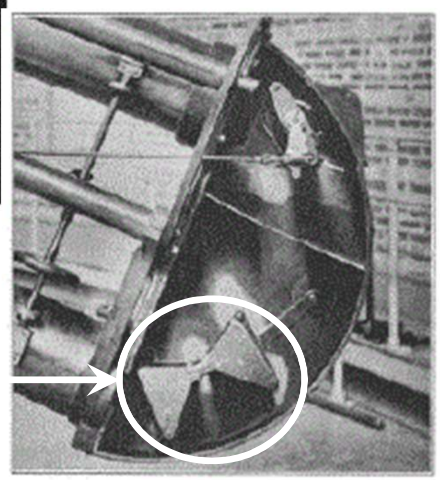
Pushbroom Hyperspectral History and Architectures

The First Imaging Spectrometers – 1920’s



Two prisms

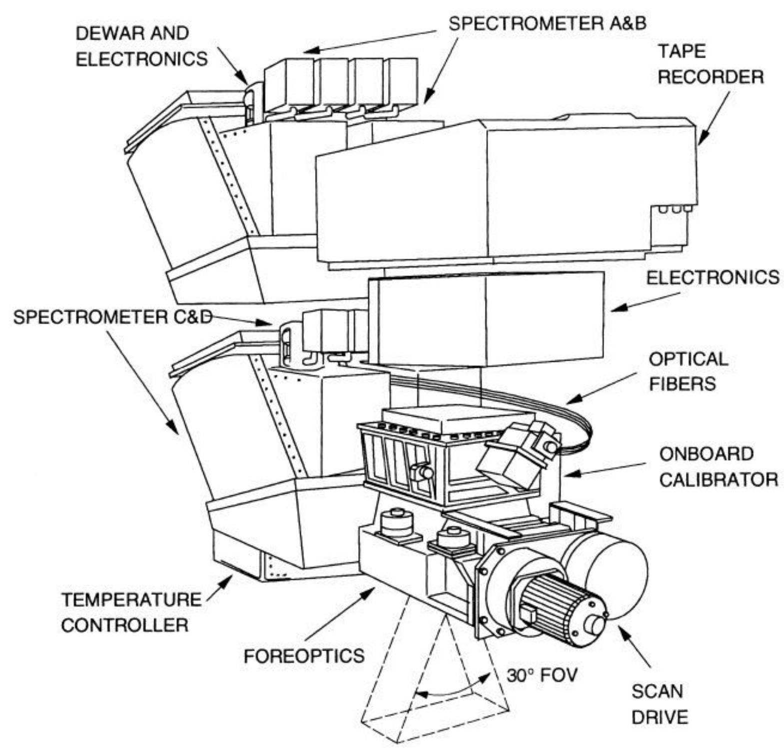


- Primitive imaging spectrometers were developed to record monochromatic images of the sun
  - First demonstrated independently at about the same time by George Hale (US) and Henri Deslandres (France)
- The entrance slit was moved across the image of the sun with a photographic plate moved behind the exit slit
- Monochromatic images were recorded at a range of wavelengths corresponding to various emission and absorption features

*Slide used with permission of R. Lockwood, MIT-LL, IGARSS18

Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)

- Based on AIS (Airborne Imaging Spectrometer) and other successful precursers in the 70's and early 80s
- The "gold standard" for imaging spectrometer performance
- Design was partially driven by the detector technology available
- Strengths
  - Well calibrated data
  - Stable
  - Inherent spatial-spectral uniformity
  - High etendue
  - High SNR (~1000 @ JPL reference radiance)
- Downside
  - Weight: 327 kg
  - Envelope volume: 84 x 160 x 117 cm^3



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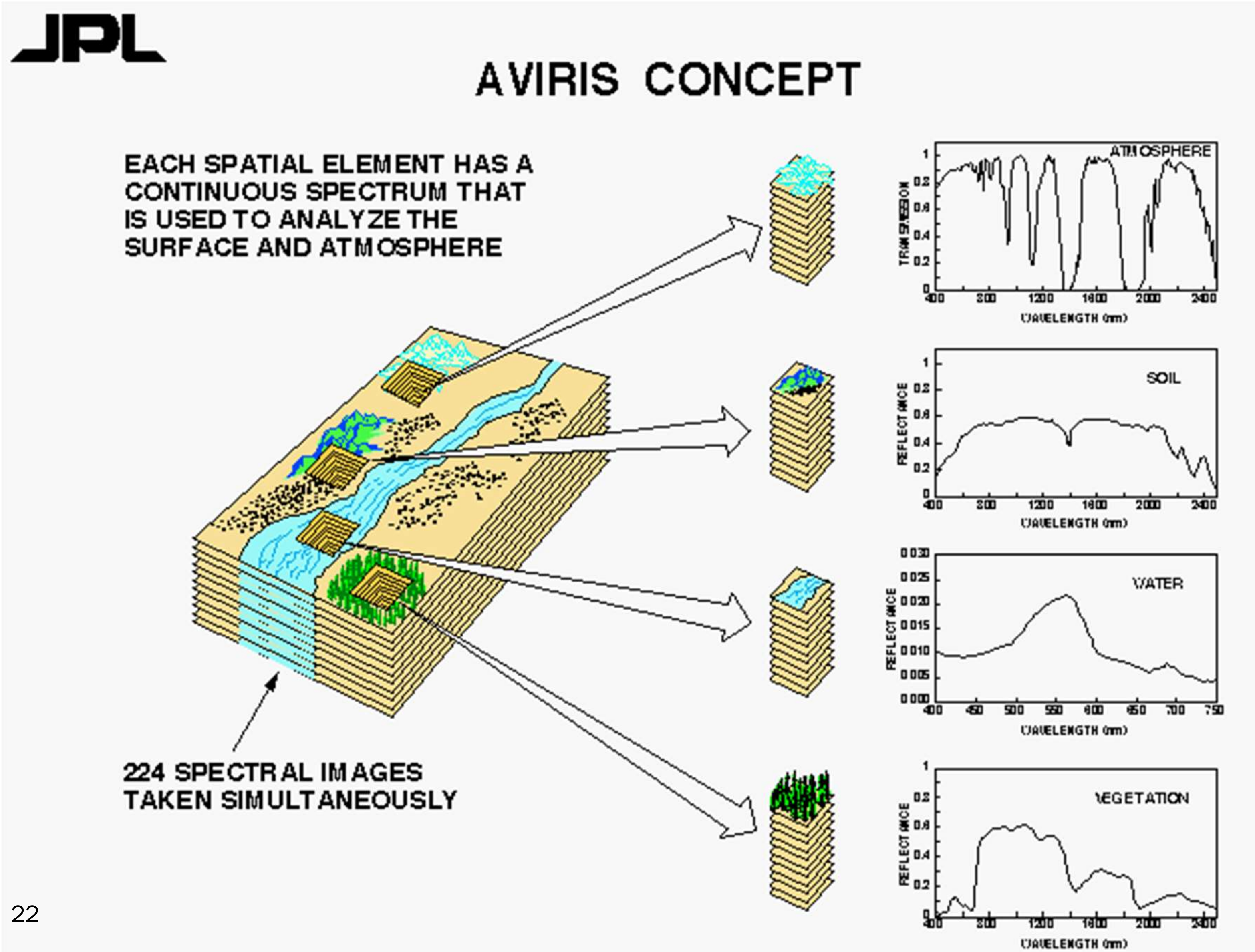
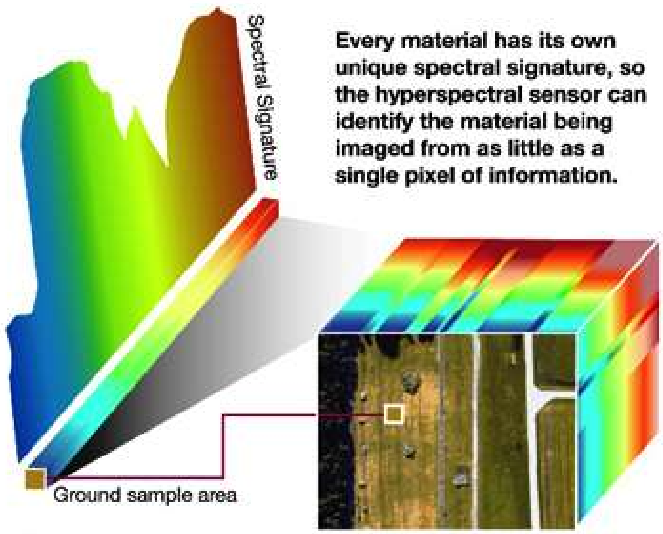
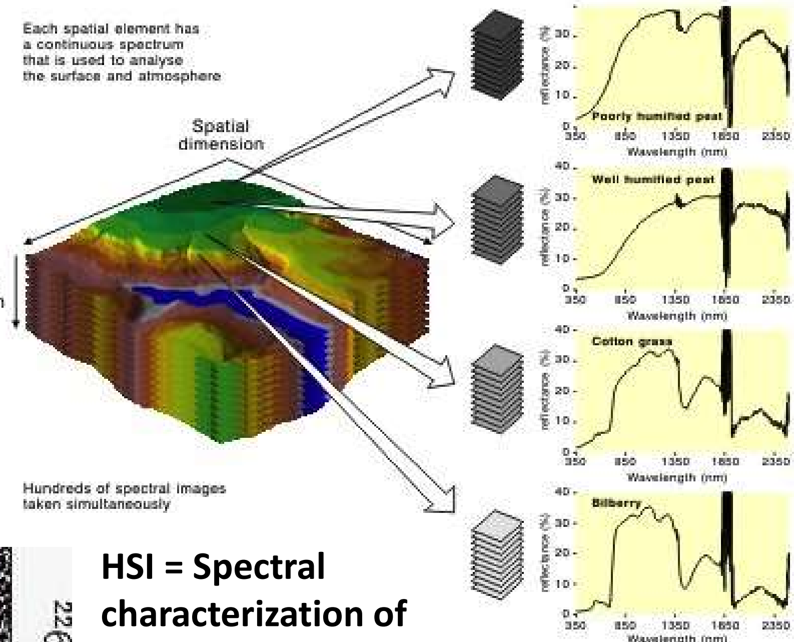
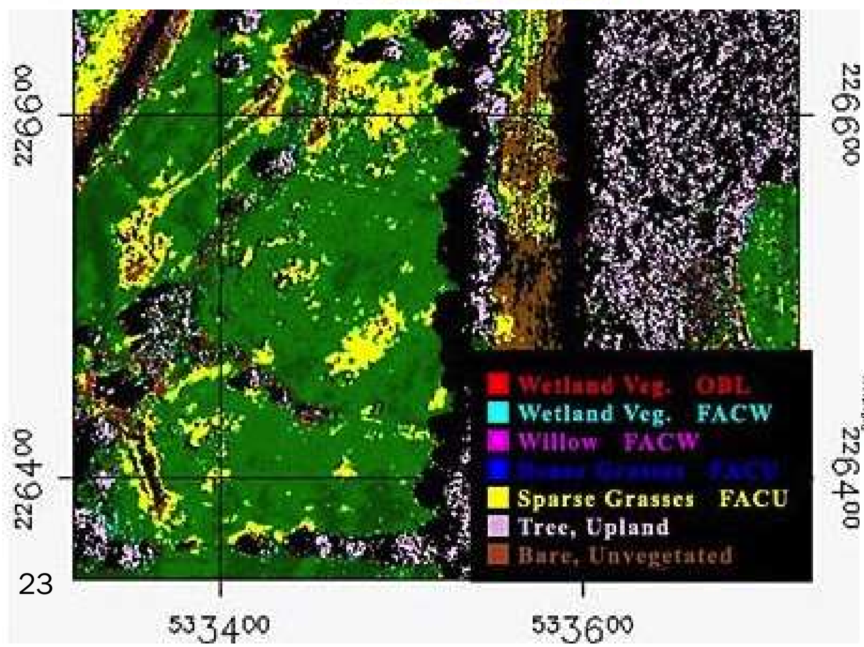


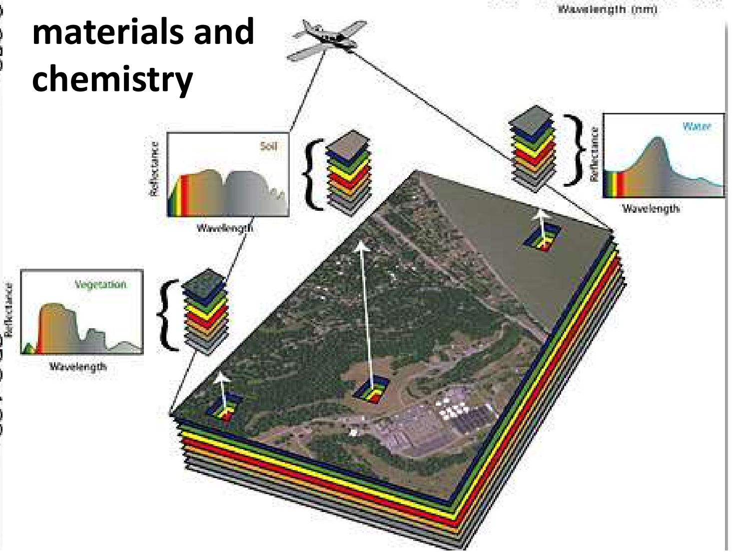
JPL
AVIRIS CONCEPT
EACH SPATIAL ELEMENT HAS A CONTINUOUS SPECTRUM THAT IS USED TO ANALYZE THE SURFACE AND ATMOSPHERE
224 SPECTRAL IMAGES TAKEN SIMULTANEOUSLY
ATMOSPHERE
TRANSMISSION
WAVELENGTH (nm)
SOIL
REFLECTANCE
WAVELENGTH (nm)
WATER
REFLECTANCE
WAVELENGTH (nm)
VEGETATION
REFLECTANCE
WAVELENGTH (nm)





HSI = Spectral characterization of materials and chemistry

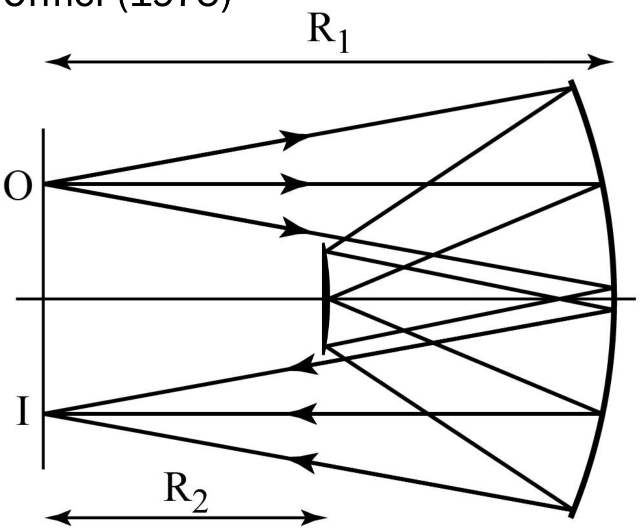




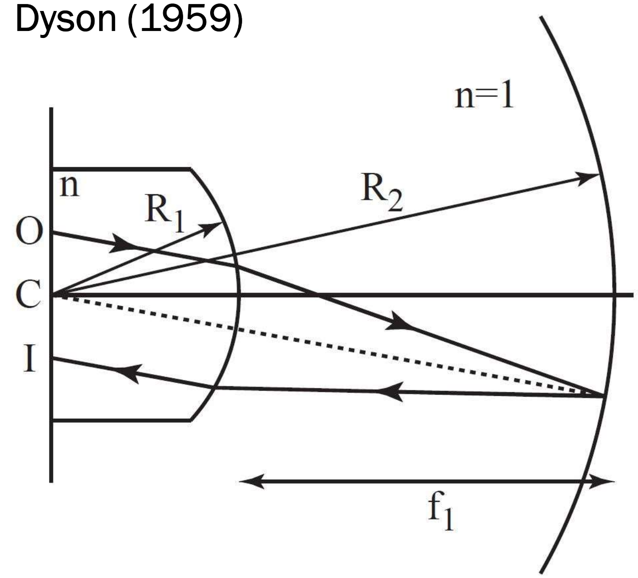
Imaging Spectrometer Evolution

- AVIRIS size, weight and power (SWaP) limits its application
- FPA development has advanced sufficiently to support more sophisticated designs
- Concentric imaging forms developed for microlithography are explored due to their high level of aberration control

Offner (1975)



Dyson (1959)



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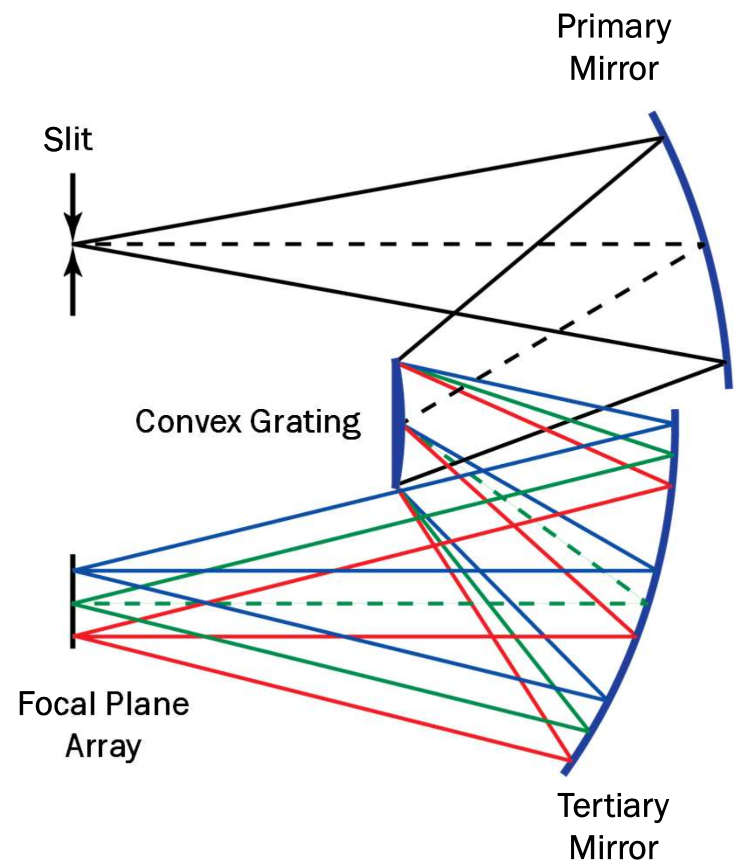
Offner-Chrisp Imaging Spectrometer

- Form invented by Michael Chrisp (US Patent 5,880,834, issued 1999)
  - Based on the Offner form with substantial modification
- Secondary mirror replaced with a convex grating
  - Significant impact to aberrations: primarily astigmatism and all gratings introduce spectral line curvature
- The grating forms the stop
  - System is symmetric about the stop minimizing coma and distortion
  - "Smile" and "Keystone" are the remaining aberrations



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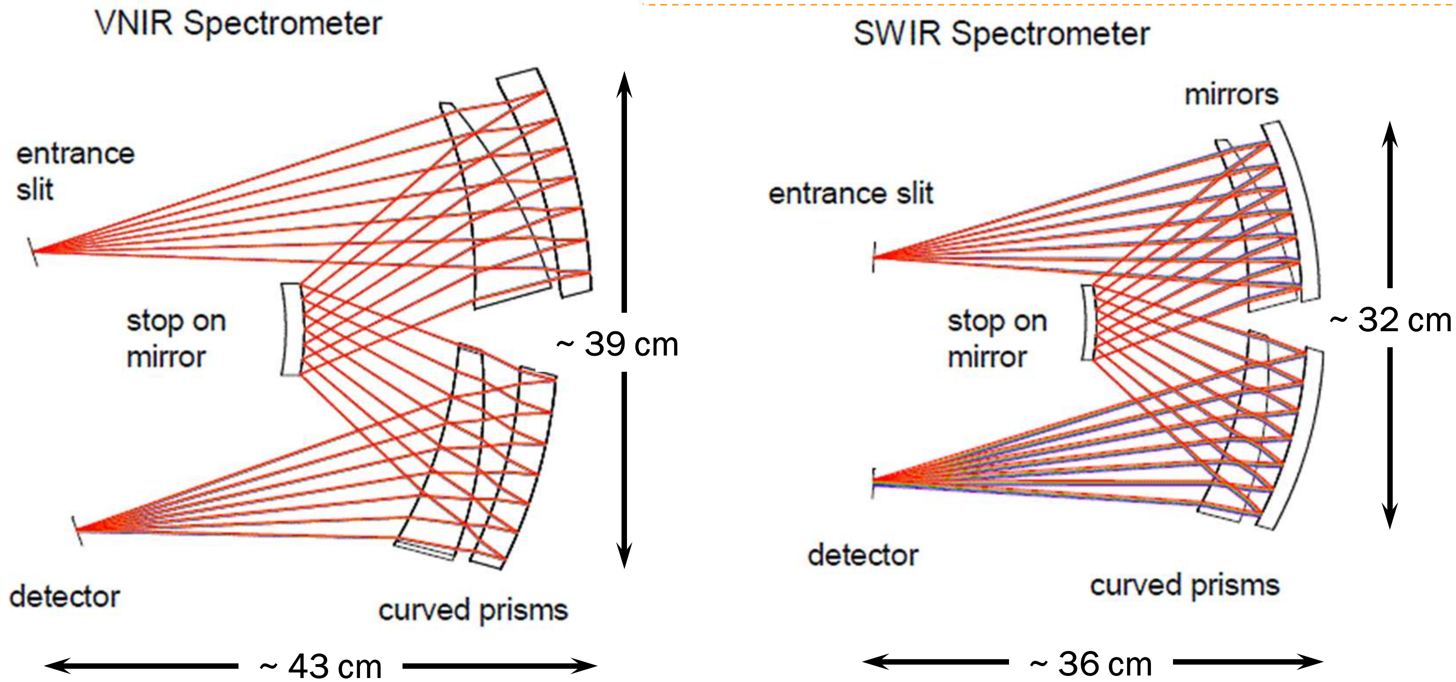
The Environmental Mapping and Analysis Program (EnMAP)



- F/3 dual-spectrometer optical design
- High spatial-spectral uniformity: > 90%
  - Relative to a detector element in reference to the local instrumental profile
- 1000 spatial samples
  - 30 m GSD

- Non-linear prism dispersion produces non-uniform instrumental profiles and spectral sampling distances (SSDs):
  - VNIR SSD: 4.8 nm to 8.2 nm (5.6 nm average) for 94 spectral bands
  - SWIR SSD: 7.5 nm to 12 nm (10.2 nm average) for 124 spectral bands

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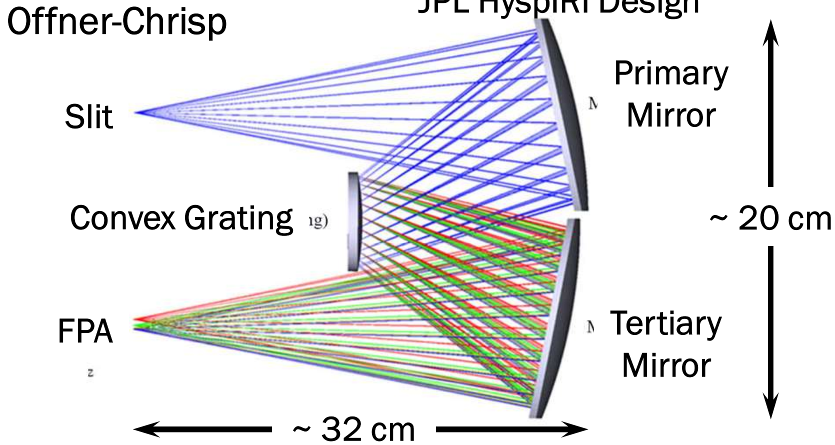
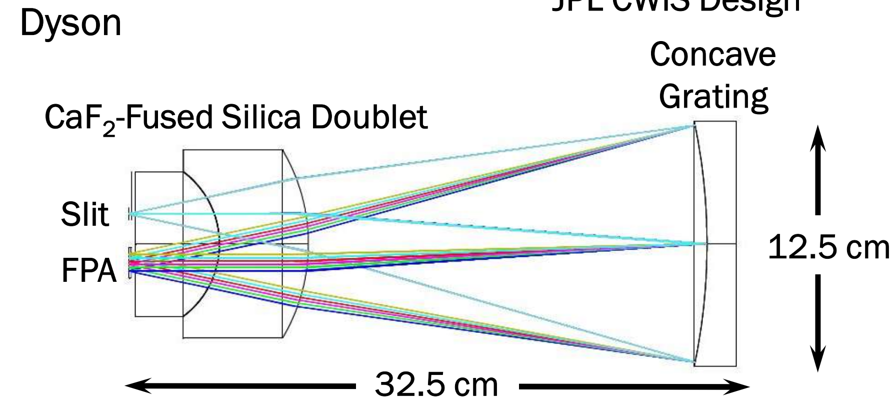
Existing VNIR/SWIR Imager Spectrometer Designs





	Offner-Chrisp	Dyson
Spatial Samples	1600	
Spectral range (nm)	380-2500	
Optics	All reflective	Reflective & refractive
F-number	2.8	1.8
Dual-blaze grating	Convex	Concave
Spatial-spectral uniformity	>95%	

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*Bender et al, *Wide-field imaging spectrometer for the Hyperspectral Infrared Imager (HyspIRI) mission*, Proc. SPIE 9222 92220E-1 – 92220E-8 (2014)

Why is a Hyperspectral Imaging Standard Needed Now?

Hyperspectral Imaging Standards…Why now?

- Stabilized pushbroom architectures are radiometrically reliable.
- Computational techniques and powerful computers are making the data easier to acquire and use.
- Hyperspectral Data has incredible amounts of information that can be extracted and used in a huge range of applications
  - Wide range of applications (too many to list). Some examples include agriculture, medical, environmental, manufacturing, and defense
- Rapidly growing market of next generation hyperspectral imagers (compact, lower cost, innovative designs)
- New platforms include benchtop, snapshot UAVs, and small satellites

2020 Global Market for Hyperspectral Imaging

- Military ($42.7M)
- Healthcare ($30.8M)
- Mineralogy ($22.3M)
- Research ($19.5M)
- Agriculture ($11.8M)
- Food processing ($16.0M)
- Others ($7.3M)

Total: $152.9 M by 2020

CAGR: 8.4%

Source: BCC Research, May 2016

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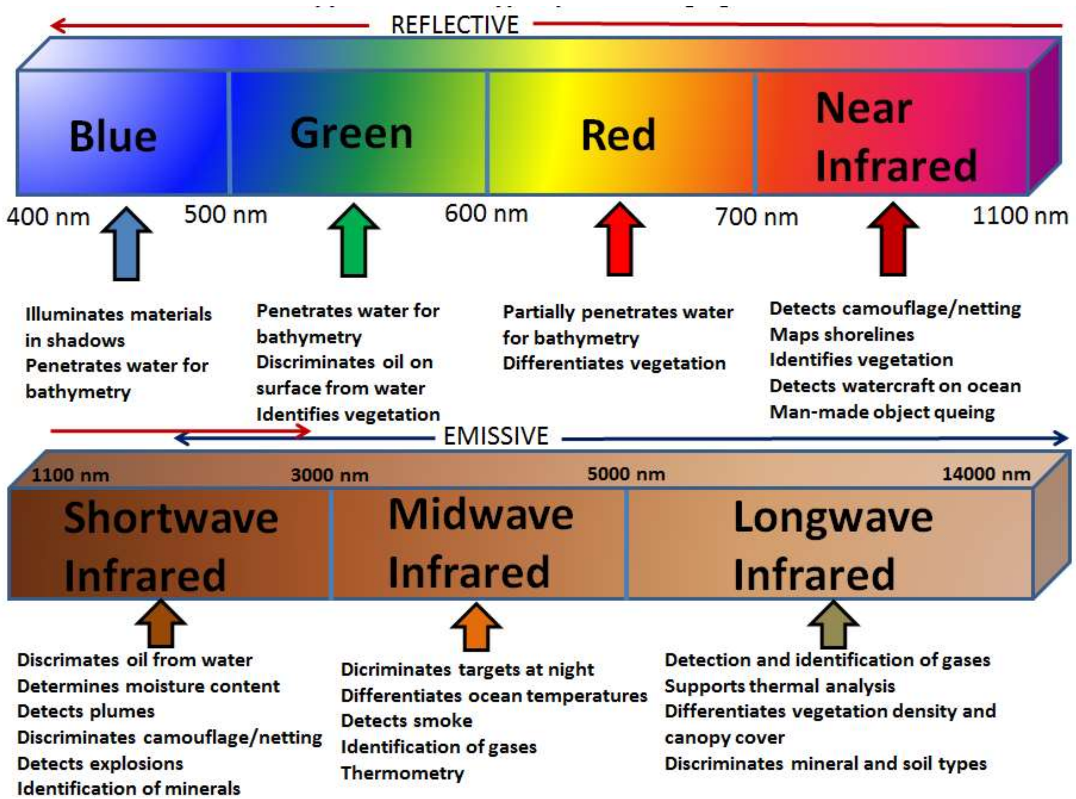
Applications of Spectral Imaging



Source: https://gis.stackexchange.com/questions/195015/hyperspectral-imaging-material-spectral-signature

Enablers

- **Instrument design,**
- **Signal processing,**
- **Data management,**
- **Computing**

Making HSI viable in applications ranging from food inspection to pathogen detection to airport security and more.

Hyperspectral Imaging Standards

- Few if any “Hyperspectral Imaging Standards”
- Pushbroom is a fundamental technology that the other, newer methods can be compared against
  - Further standards for other systems can be developed on a strong basis of a pushbroom standard
    - FTIR
    - Thermal
    - Fabry-Perot
    - Snapshot
    - Etc

IEEE Standards Development Process

- The GRSS Standards Committee
  - Operates under the IEEE Standards Association Policies and Procedures
  - Closely aligned with the GRSS Standards for Earth Observations (GSEO) TC
- Development is carried out in Projects initiated by Working Groups
  - WGs operate under a Policy and Procedures document
  - Openness and fairness is paramount
- Membership
  - Anyone can participate
  - Join the group to have your voice heard
  - Voting members need to register in IEEE myProjects (no cost)
  - Must join IEEE Standard Association (SA) to be an officer
- Cooperation with other Standards Agencies (ISO, EMVA, DIN, etc.)
  - Make sure copyright and use rights are in place with agreements.

- Takes years to bring a full standard – started in 2018.

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Technical Focus of the Standard Effort - http://sites.ieee.org/sagroups-hyperspectral/

- Providing basic tools, test recommendations and procedures for absolute characterization of HSI instruments to ensure proper performance for the selected applications and standardization of data output
- Visible, Near-IR and SWIR Sensors (300-2500nm)
  - Silicon, InGaAs or MCT-based Focal Plane Arrays (FPAs)
  - Grating-based systems
- Passive Remote Sensing – Airborne, Handheld and Benchtop
- Pushbroom and Scanning configurations
  - Apply foundation of pushbroom standard to other techniques
- Establish a Foundation for future efforts to other spectral regions and instrument architectures.
  - Snapshot imagers - working with EMVA-1288

P4001 Sub-Groups

- Three main areas are worked on by SUB-GROUPS - less formality, easier to focus
  - Terminology – SG-T1
  - Characterization – SG-C1
  - Data Structures – SG-D1
- Sub-Groups report to the P4001 on Progress
  - Items ready for evaluation can be submitted to the P4001 by any Sub-Group for official work.
- Each group has 20 members and many members work in all (3)
  - Correlation and Cooperation between the Subgroups is critical to success!

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Sub-Group T1 - Terminology

Dr. Oliver Weatherbee, SpecTIR (Chair)
Dr. David Allen, NIST (Vice-Chair)

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Why Terminology?

- English does not readily convey specific technical meanings
  - Example: Resolution, Stray Light, Bandpass, Data Cube

- Promote consistent use of terms across manufacturers and industries.

- There is some great work out there: but it needs an archive, an organizer and a lookup table.

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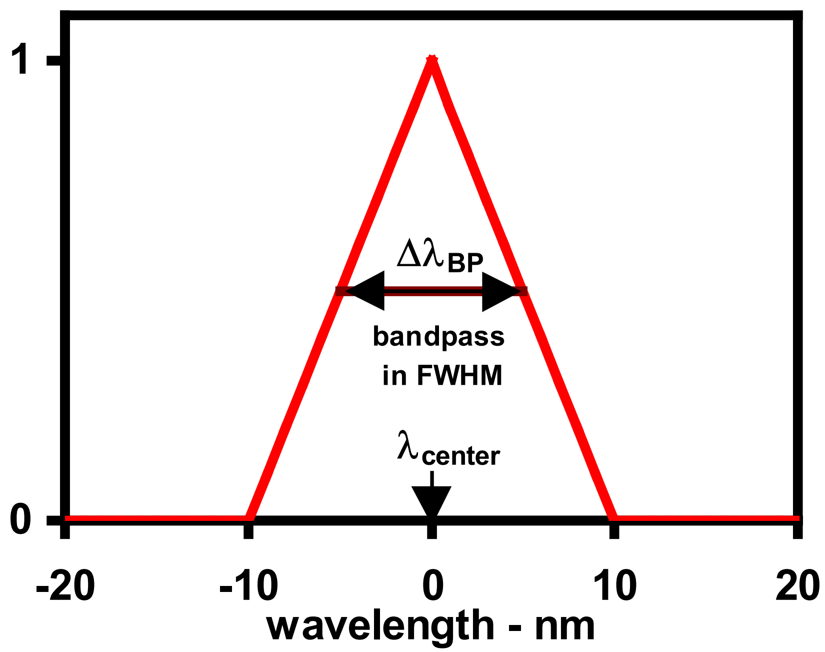
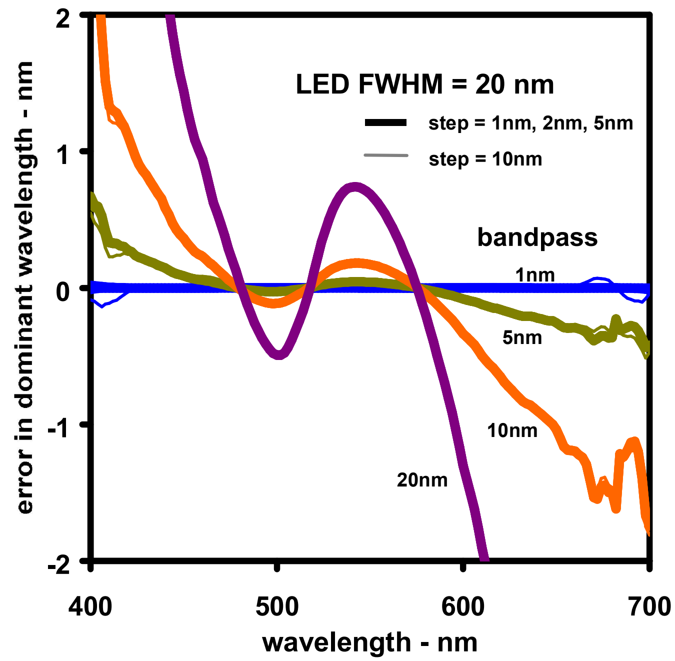
Example – Bandpass effects on LEDs (and other signatures...)

- Spectrograph bandpass model



- Effect of Spectrometer Bandpass on measured LED Dominant Wavelength



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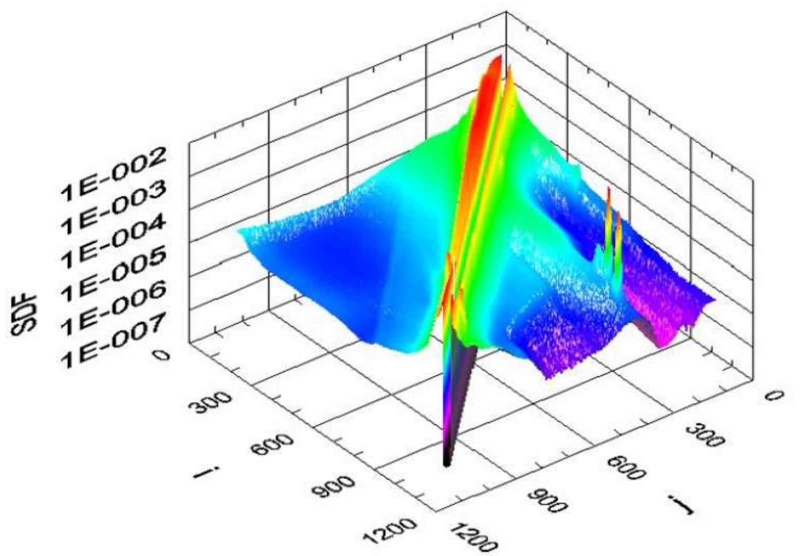
Example – Stray Light

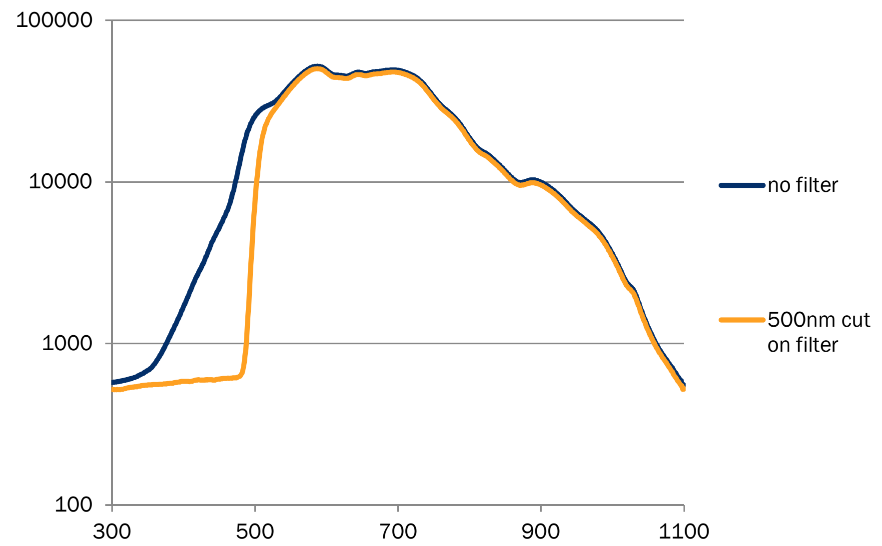
- Stray light is a function of the instrument and the observed target

3-D plot of the Stray Light Distribution (SDF) matrix, ***D***



[1] Zong, Y., Brown, S. W., Johnson, B. C., Lykke, K. R., Ohno, Y., "Simple spectral stray light correction method for array spectroradiometers", Applied Optics, Vol. 45, No. 6, 1111-1119 (2006)

Raw counts from spectrograph with QTH input



[24] Jablonski, J., Practical Implications of Standard Spectrograph Stray Light Specifications, International Symposium on Lighting 2011

T1 – Terms and Grouping

Spectral Terminology	Spatial Terminology	Signal/Radiometric Terminology	System and Operational Terminology
Bandpass	Angular resolution	Bit Depth	Absolute Calibration
Diffraction Grating	Angular Response Function (ARF)	Dark Current	Achromatic Lens
Full Width Half Maximum	Distortion	Dynamic Range	Bad Pixels
Higher-Order Diffraction	Field of View (FOV)	Flat Field	Binning (Spectral and Spatial)
Order Blocking Filter	Ground Sampling Distance (GSD)	Gain	Charge-Coupled Device (CCD)
Spectral Band	Input slit	Ghosts	Complementary Metal-Oxide Semiconductor (CMOS)
Spectral Bandwidth	Intantaneous Field of View (IFOV)	Linearity	Dead Time
Spectral Radiance	Keystone	Noise	F-Number
Spectral Range	Nonuniformity Correction (NUC)	Offset	Focal Plane Array
Spectral Resolution	Point Spread Function (PSF)	Polarization Sensitivty	Frame
Spectral Response	RMS Spot Size	Quantum Efficiency (QE)	Framerate
Spectral Response Curve	Slit width	Radiometric Correction	Global Shutter (FPA)
Spectral Sampling Interval	Smile	Radiometric Resolution	Integration Time
Spectral Sampling Ratio	Spatial Fill Factor	Read Noise	Interlaced Scan Readout (CCD)
Transmission Grating	Spatial Nonuniformity	Responsivity	Pixel Pitch
Wavelength Calibration	Swath	Saturation	Progressive Scan Readout (CCD)
		Stray Light	Readout Smear
		Signal-to-Noise Ratio (SNR)	Relative Calibration
		Well Depth	Rolling Shutter (FPA)
		Vignetting	Scan Line
		Temporal Fill Factor	Slit Width
			Telecentric Lens
			Vicarious Calibration

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A word document with this listing is available for download from the IEEE iMeet site: https://ieee-sa.imeetcentral.com/sg-t1/

Subgroup C1: Calibration and Testing of HSI Instruments

Dr. Andreas Baumgartner, DLR (Chair) – Stray Light
Dr. Kwok Wong, Headwall (Vice-Chair) - Radiometric
Dr. Andrei Fridman, NEO HySPEX (Vice-Chair) – Spatial/Spectral
Dr. Torbjorn Skauli, FFI (Vice-Chair) – Physical Instrument

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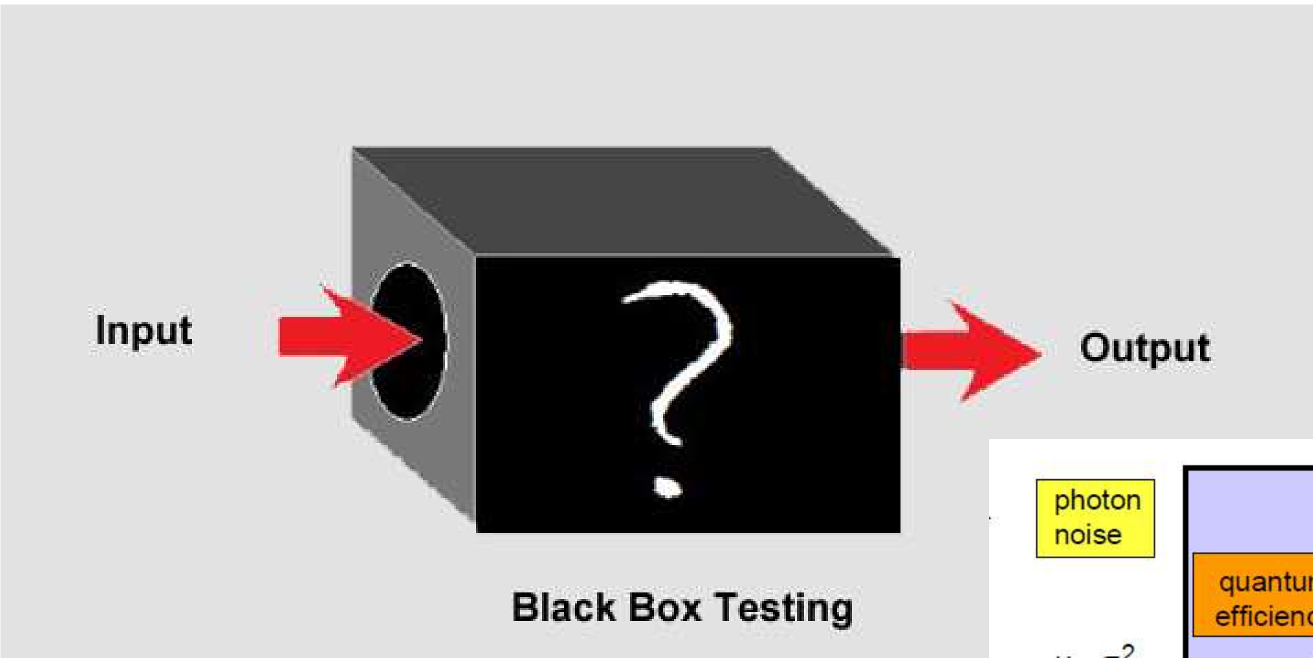
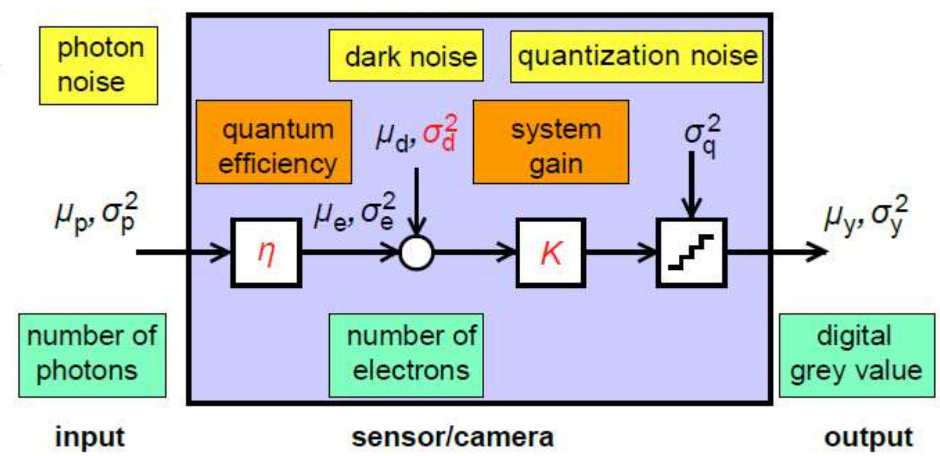
Physics-Based "Black Box" testing will be first approach to Characterization Efforts





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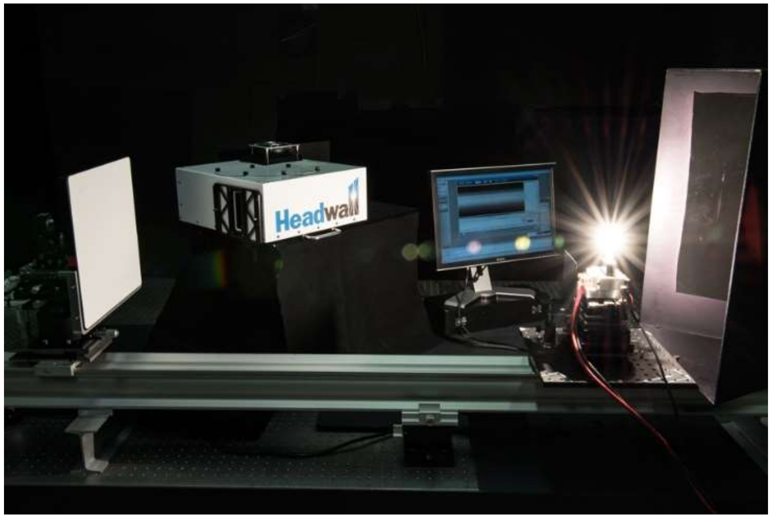
Calibration and Characterization of HSI Instruments

- Calibration standards provide a means of comparison to recognized scales and units (SI). Traceability provides an unbroken chain of comparisons with stated uncertainties
  - https://www.nist.gov/nist-policy-traceability
- The use of standards facilitates the ability to compare results from different instruments, at different physical locations and times.
- National Metrology Institutes (NMIs), such as NIST play a key role in establishing and or disseminating these scales



Disclaimer
Certain commercial products are identified to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose

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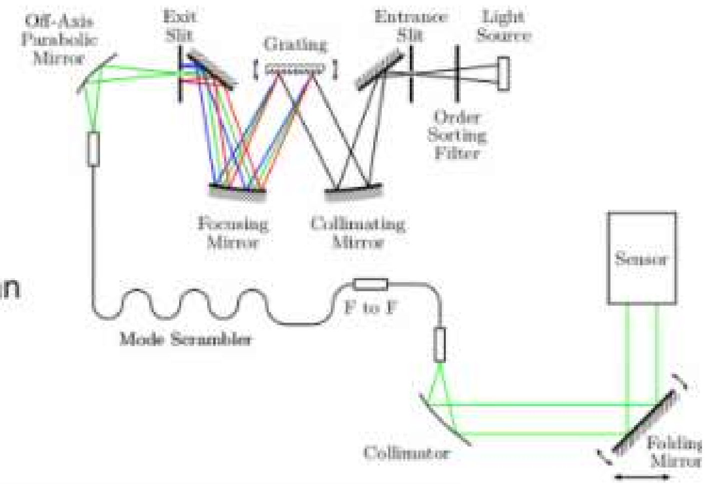
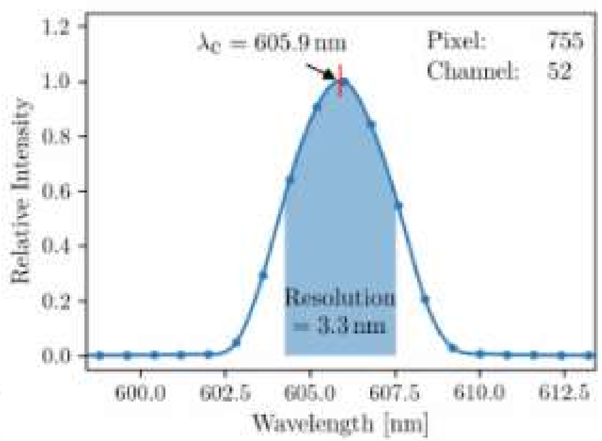
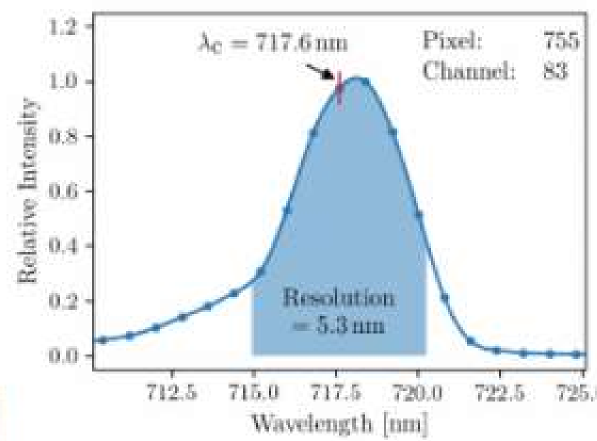
Example – Center Wavelength and Resolution

Definition of Center and Resolution

- Center wavelength: Median
- Resolution: Width of 75 % of total energy symmetric from median
  - FWHM of Gaussian normal distribution: 76.10 %
- Independent of PRNU

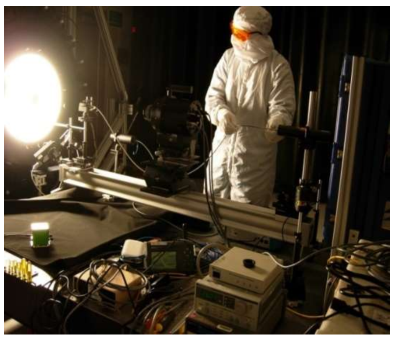




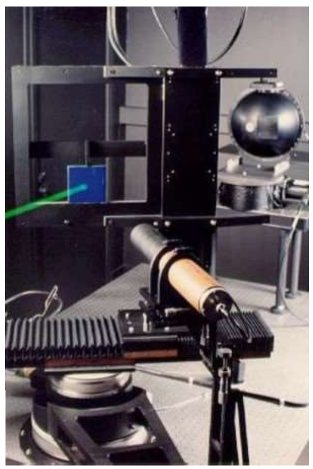


Basic Radiometric Standards & Procedures

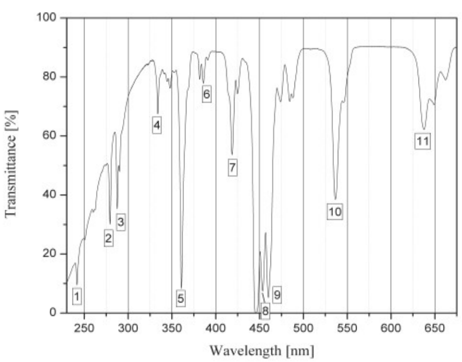
- The well established scales of radiance, reflectance and wavelength serve as our foundation



Radiance

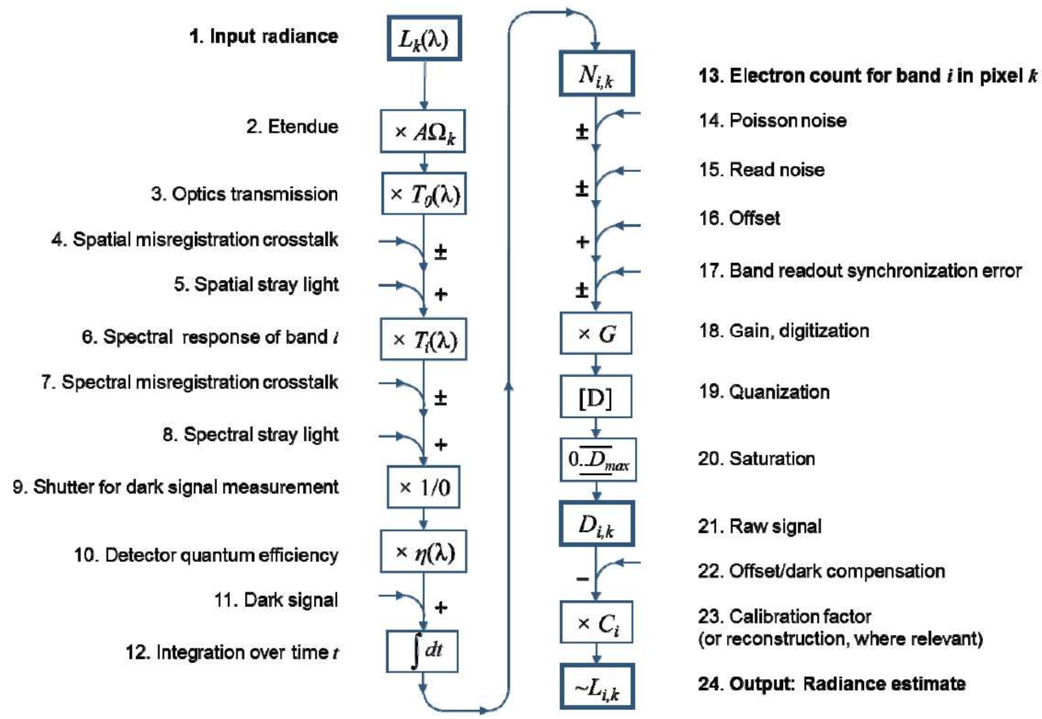


Reflectance



Wavelength

- Best practices for HSI still need to be refined in the application of these parameters



Spectral/Geometric, Radiometric

Spectral Performance

- spectral range (usable)
- spectral resolution (acceptance angle of a pixel; not FOV divided by number of pixels)
- spectral sampling interval (SSI) (distance of center wavelengths)
- spectral sampling ratio (resolution divided by SSI)
- spectral misregistration (Smile, in pixel and spectral units)
- SRF uniformity (How stable is a SRF within a band)
- spectral calibration accuracy and stability

Geometric Performance

- field of view (along- and cross-track)
- angular resolution (along- and cross-track; acceptance angle of a pixel; Not FOV divided by number of pixels)
- angular sampling interval (ASI) (distance of center angles)
- angular sampling ratio (resolution divided by ASI; measure for sharpness)
- geometric misregistration (Keystone, in pixel and angle units)
- angular response function (ARF) uniformity (How stable is a SRF within a geometric pixel)
- focus range / working distance
- geometric calibration accuracy and stability
- location of each pixel on the scene (precision, stability)

Radiometric Performance

- noise / SNR / NESR (signal dependent)
- read noise
- SNR vs. spectral radiance at specified operating conditions, unbinned (not binned peak SNR!)
- Well depth
- dynamic range / resolution
- ADC characteristics (bit depth, gain (DN/e-))
- sensitivity
  - wavelength and angle dependent (vignetting)
  - F/#
- polarization sensitivity
- non-linearity
- Detector QE/spectral response
- pixel pitch
- dark current
- operability?
- uniformity (DSNU?, PRNU)
- radiometric calibration accuracy and stability
- dynamic range and noise performance on a standard light source

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Stray Light, Physical Specs & Other Parameters

Stray light

From our experience, stray light is usually not separable in spectral and geometric components.

However, we distinguish between two kinds of stray light:

- diffuse stray light

  In general, the far tail, low frequency component of pixel response functions or PSFs which can distinguished in

  - in-band diffuse stray light (correctable to a certain extent)
  - out-of-band diffuse stray light (not correctable)
- ghosts

  In general, high frequency component in the tails of a pixel response functions or PSFs.

  - in-band ghosts (correctable)
  - out-of-band ghosts (not correctable)

Other

- min / max frame rate / readout rate / data rate
- min / max integrating time
- dead time?
- instrument stability
- focal length
- number of pixels (spectral and spatial) (usable)
- detector stabilized (yes / no, temperature, stability)
- number of bad pixels
- Fill-factor (spatial and temporal)

Physical Specs

- instrument dimensions, instrument mass, power consumption (V, A or W, peak, nominal) of system (including computer and cables if separate)
- valid range of temperature, humidity, (pressure?) (storage and operation)
- instrument stability (maybe hardest to measure and specify)
- computer interface (USB, CameraLink, GigE, standalone; remote control?)
- MTBF
- lens mount (if appropriate)
- mechanical interface (mounting)

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Sub-Group D1: Data Structures

Dr. Naresh Mallenahalli, IEEE GRSS (Chair)
Dr. Siri-Jodha Singh Khalsa, NSIDC (Vice-Chair)

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Relevant ISO/TC211 Standards

- ISO 19115 – Metadata
  - 19115:2003 Widely used in the science and applications community
  - 19115-1:2014 Major revision and update (not fully backwards compatible)
  - 19115-2:2009 remote sensing specific, revised (2018) to "Extensions for acquisition and processing"

- ISO 19130 - Imagery sensor models for geo-positioning
  - 19130:2010 for EOIR (undergoing revision, will be 19130-1)
  - 19130-2:2014 for SAR, InSAR, lidar and sonar

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Relevant ISO/TC211 Standards – Continued

- ISO 19159-1:2014 - Calibration and validation of remote sensing imagery sensors and data -- Part 1: Optical sensors
  - Applies to airborne and space-borne imagery sensors
  - Refers to geometric, radiometric, and spectral calibration
  - In laboratory as well as in situ calibration methods

- ISO 19159-2:2016 - Calibration and validation of remote sensing imagery sensors and data -- Part 2: Lidar
  - Also addresses data capture methods and relationships between the coordinate reference systems

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Encoding of ISO/TC211 Standards

- ISO 19139:2007 defines an XML implementation of 19115
- ISO 19139-2:2012 defines an XML implementation of ISO 19115-2
- ISO 19115-3 (under development) XML implementation of 19115-1
- ISO 19130-3 XML implementation of 19130-1 and -2
- ISO 19139-1 (under development) XML implementation -- Encoding rules

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P4001 – How to participate?

Send me an email:

cdurell@labsphere.com

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IEEE P4001 Working Group – Where & When

- Website: http://sites.ieee.org/sagroups-hyperspectral/

- Officers & Organization:
  - Chair - Chris Durell, Labsphere (USA)
  - Co-Chair - Dr. David Allen, NIST (USA)
  - Secretary – Dr. John Gilchrist, Camlin Group (UK)
  - Webmaster – Alex Fong, Hinalea Imaging (USA)
  - Part of GRSS – Geoscience & Remote Sensing Society: http://www.grss-ieee.org/
    - GRSS Chair – Dr. Siri Jodha Khalsa, NCSID (USA/Czech)
- 50+ Voting Members
- >200 Participants from 15+ countries

- (5) meetings held – Trying to meet every 4-6 weeks.
  - Next meeting on Jan 23 @ 10:00 EDT
  - March Meeting TBD

  - SPIE DCS (Baltimore – April)
    - Workshop & Virtual

  - IGARSS 2019 (Yokohama – July)
    - Workshop & Virtual Meeting
    - Technical Industry Education (TIE)
    - GRSS Standards Track Presentations

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Support of other standards groups are welcome

- EMVA-1288 has reached out and would like to offer their processes and tests as reference material to the new P4001 efforts.
- TC211 for ISO has also lent their support to the P4001 group on data structures and standards (see next slide)
- EUFARS, JACIE, ASPRS (ISPRS) and NGA interested to lend support
- DIN Standard in Germany – cooperative participation

Thank You!