ENICS 2008 Invited Speech

Hyperspectral imaging: sensors, algorithms and challenges

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- Problem definition
- Filtering methods
- Sensors
- Data processing issues
- Applications
- Future trends

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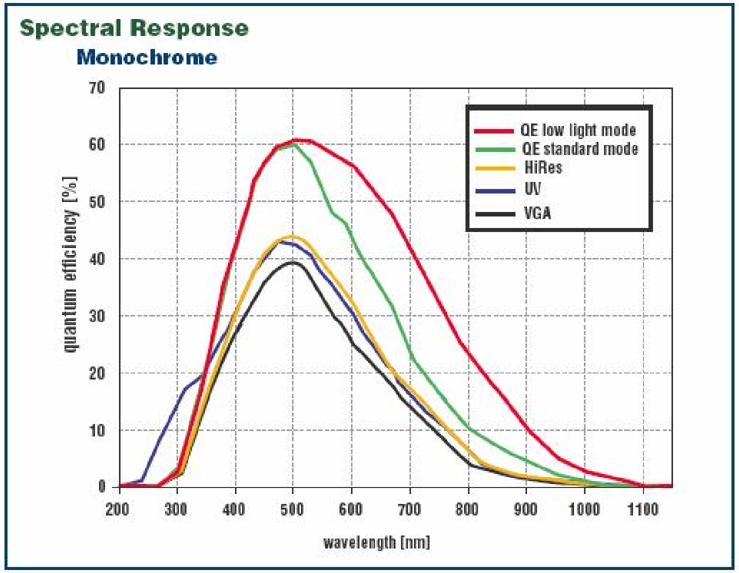
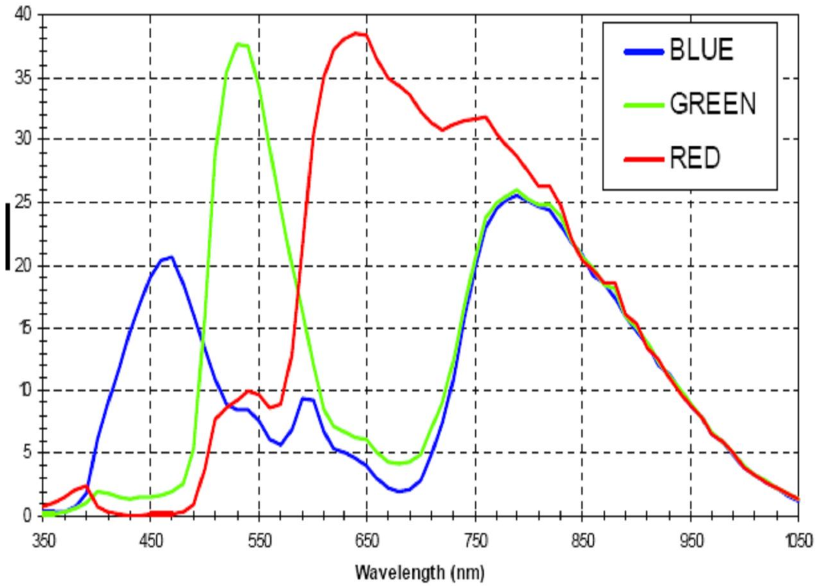
Problem definition

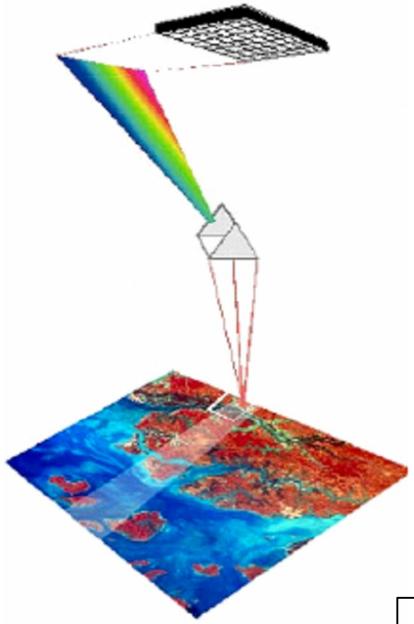


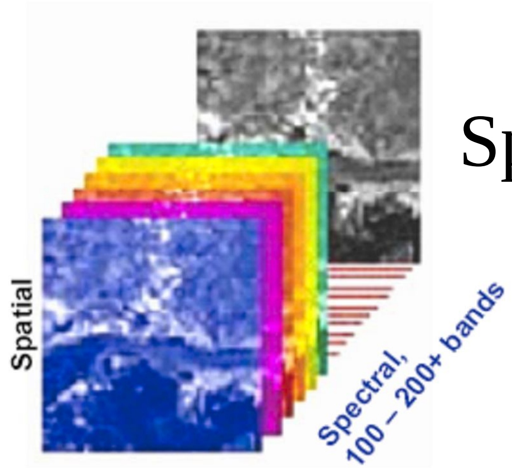


PixelFly monochrome CCD camera

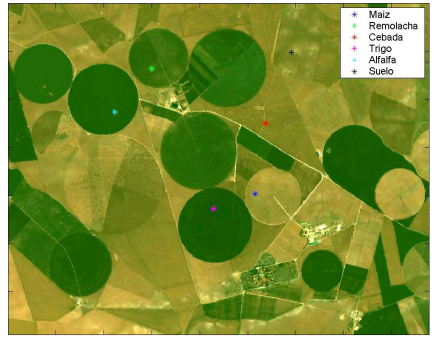
Spectral Response of a CMOS Sensor with RGB CFA

Problem definition

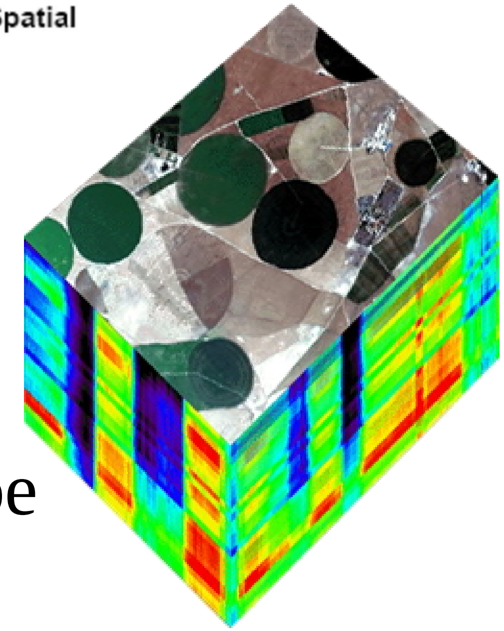


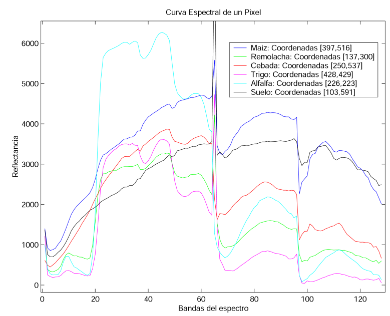


Spatial



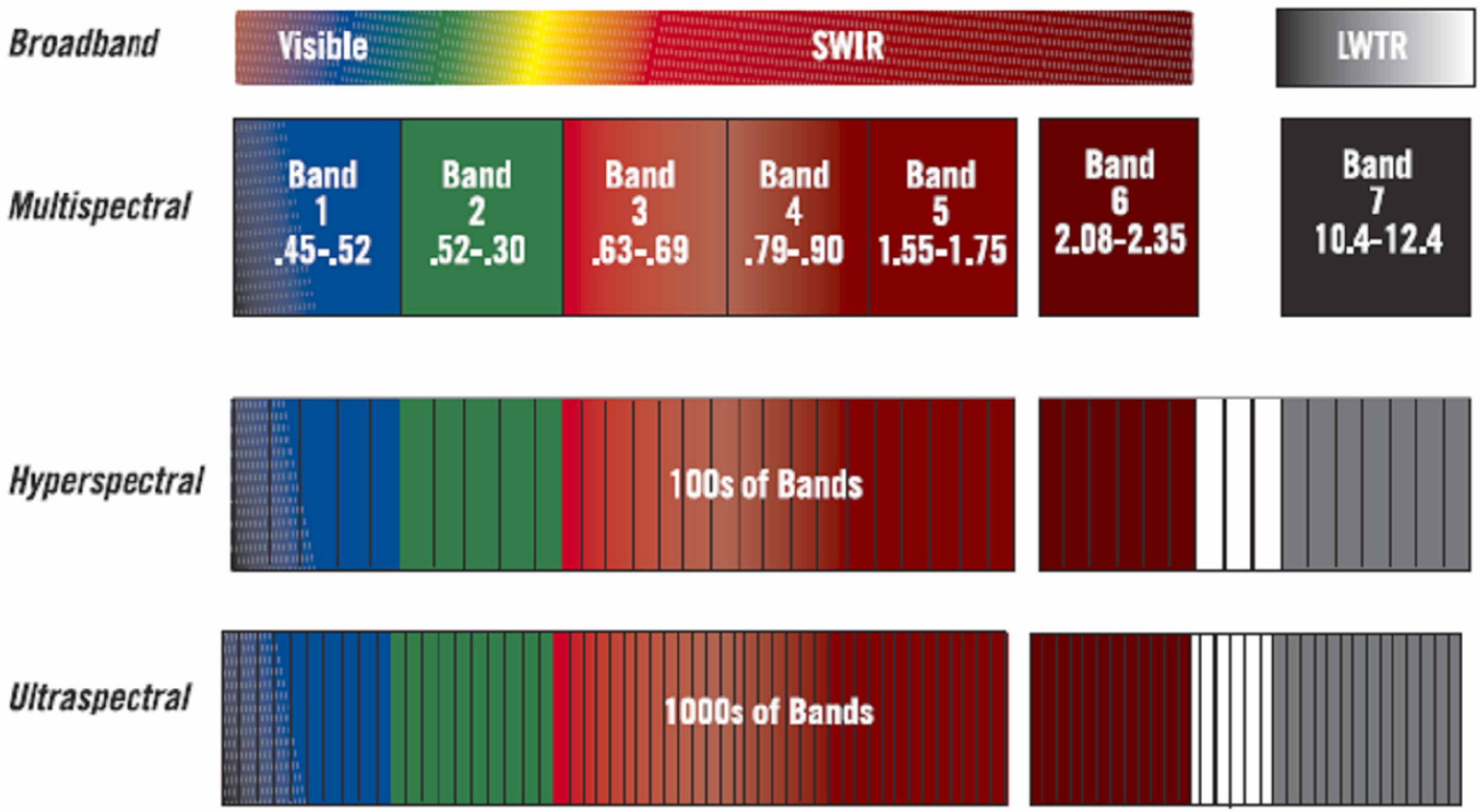
Spectral



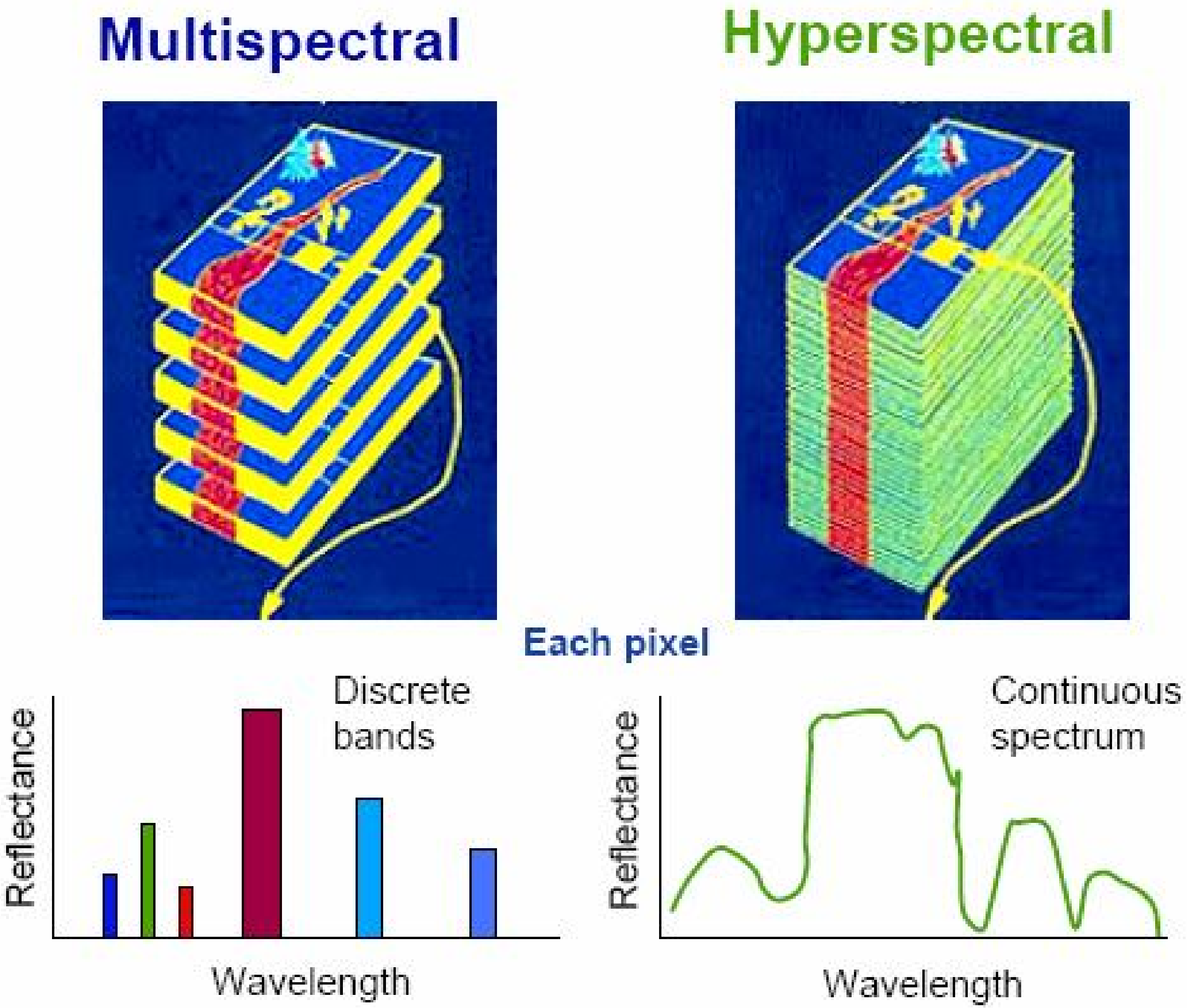


4D hypercube

Problem definition

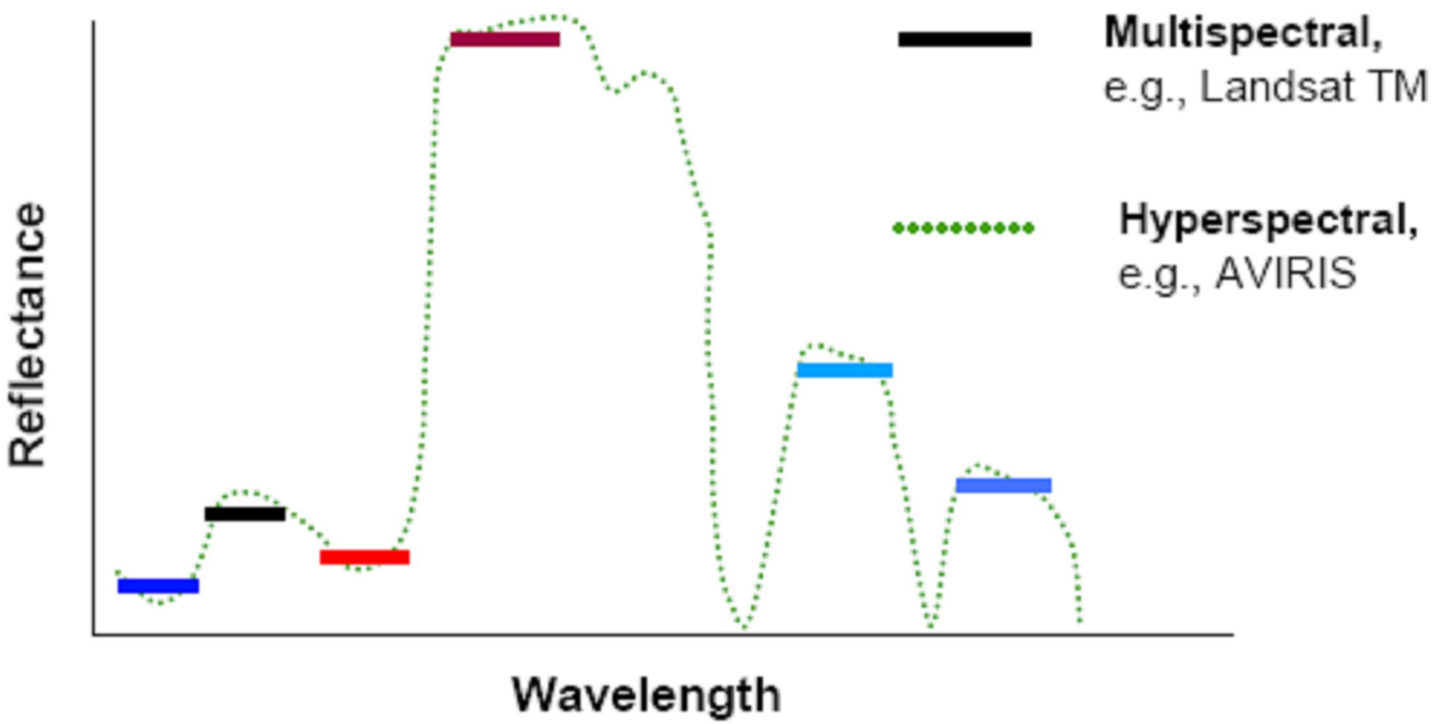


Problem definition



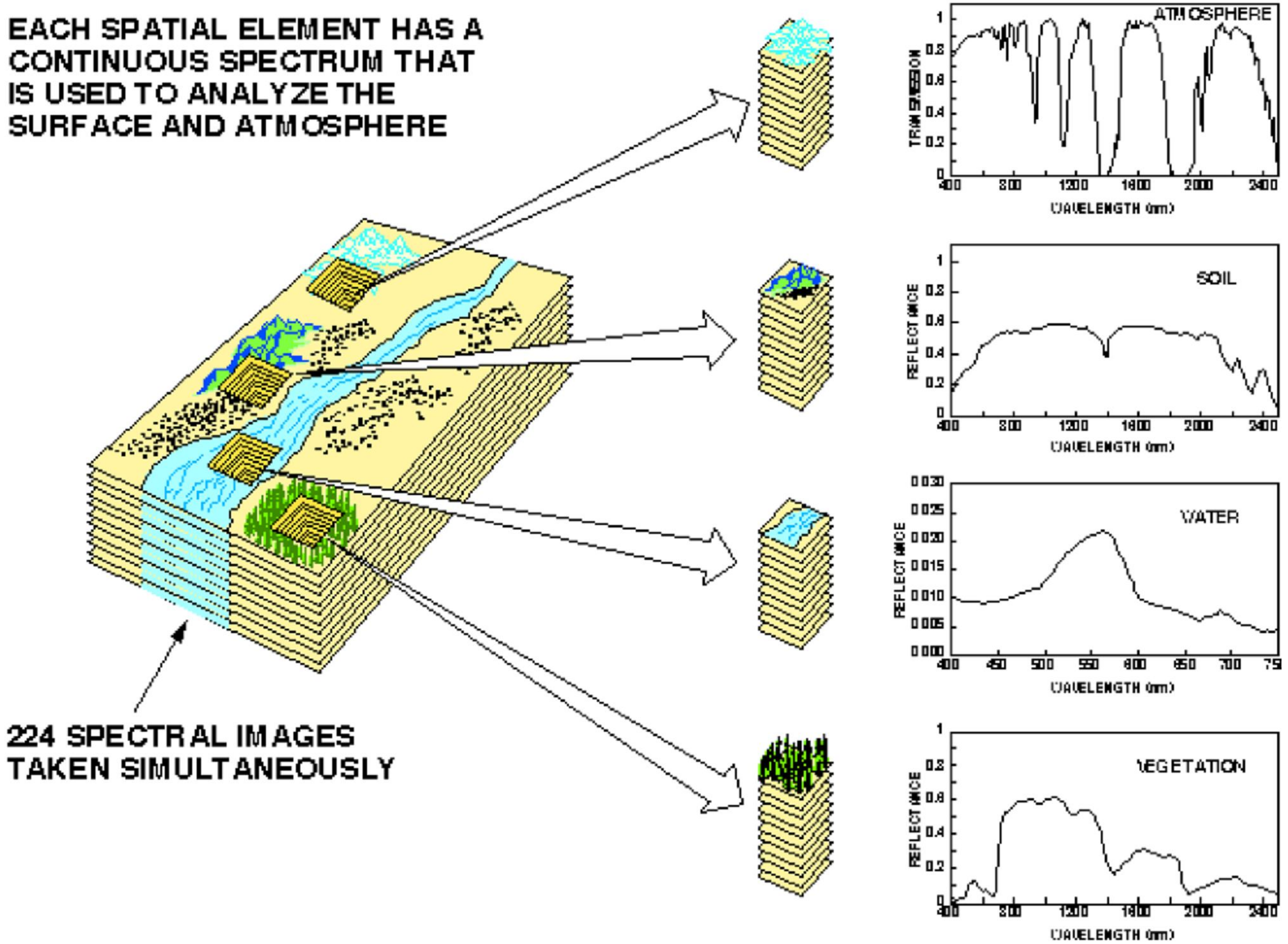
Problem definition

Multispectral vs. Hyperspectral Data



Problem definition

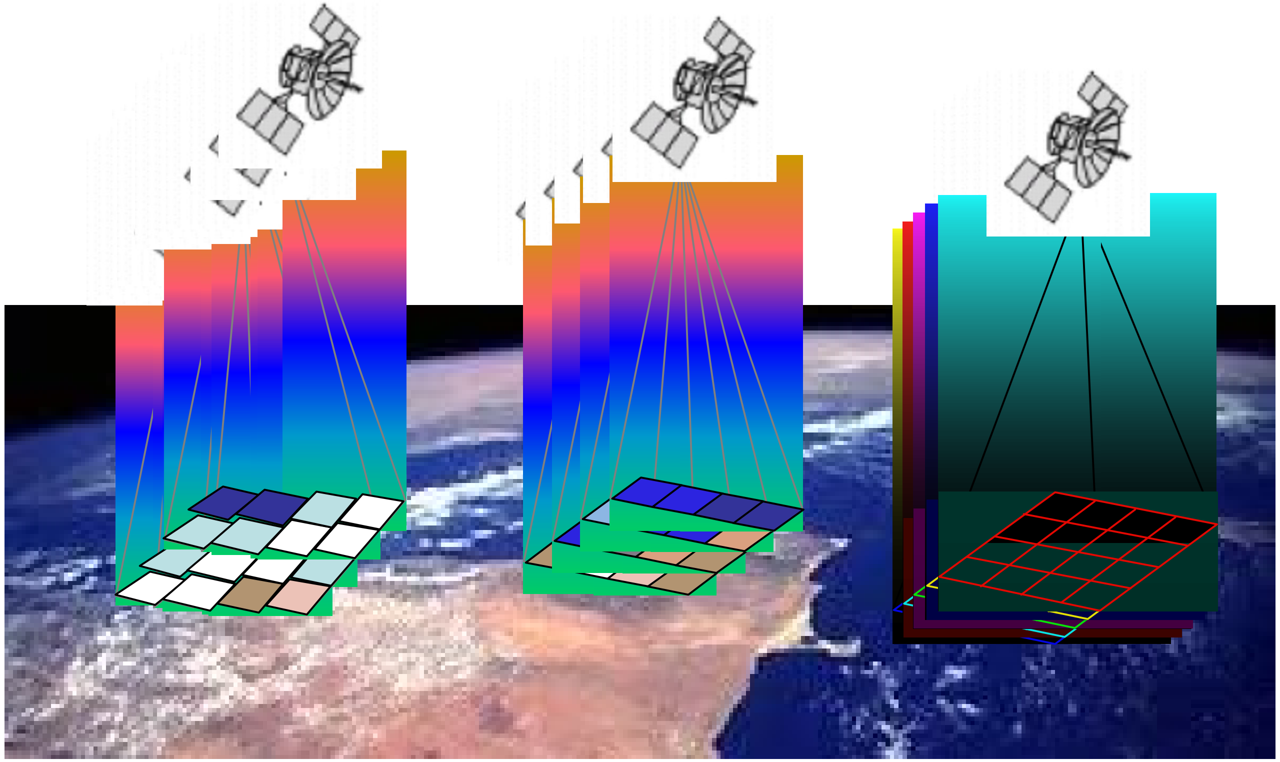
Imaging Spectrometry Concept



Courtesy Rob Green, JPL

Problem definition: Image formation

whiskbroom	**pushbroom**	**staring**
Band Interleved By Pixel (BIP)	Band Interleved By Line (BIL)	Band Sequential (BSQ)



Courtesy Luis Alonso, UV-EG

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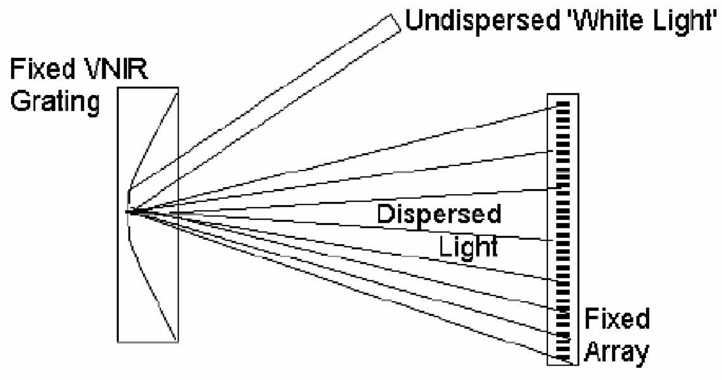
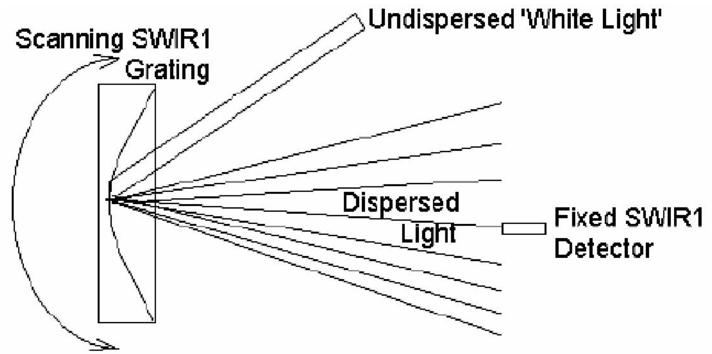
Filtering methods: Point spectrometer

Analytical Spectral Devices, Inc. FieldSpec Pro FR

Principle of measurement	**VIS-NIR**: A fixed concave holographic reflective grating disperses the light onto a fixed photodiode array **SWIR**: A rotating concave holographic reflective grating scans the light onto a fixed single InGaAs detector
Spectral range	350-2500 nm
Spectral resolution	3 nm @ 700 nm 10 nm @ 1400 nm & 2100 nm
Detectors	1 512 element Si photodiode array 350-1000nm 2 TE cooled, graded index InGaAs photodiodes 1-2,5um





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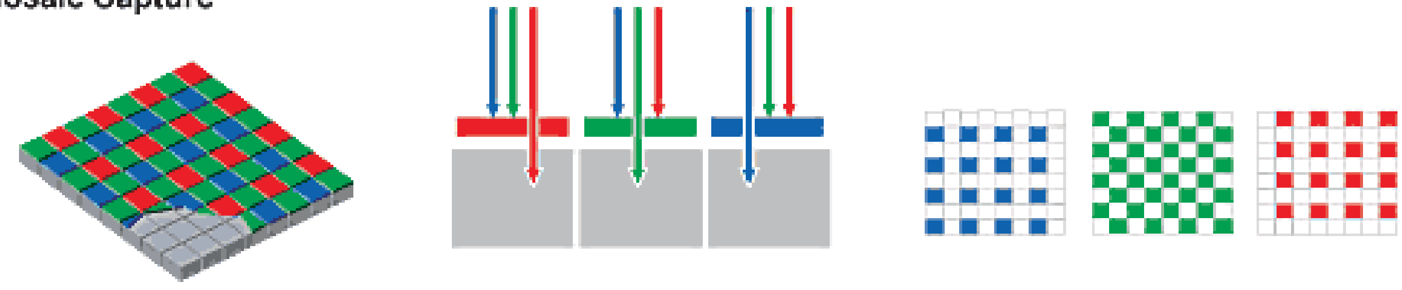
Filtering methods

Tri-CCD to Bayer pattern

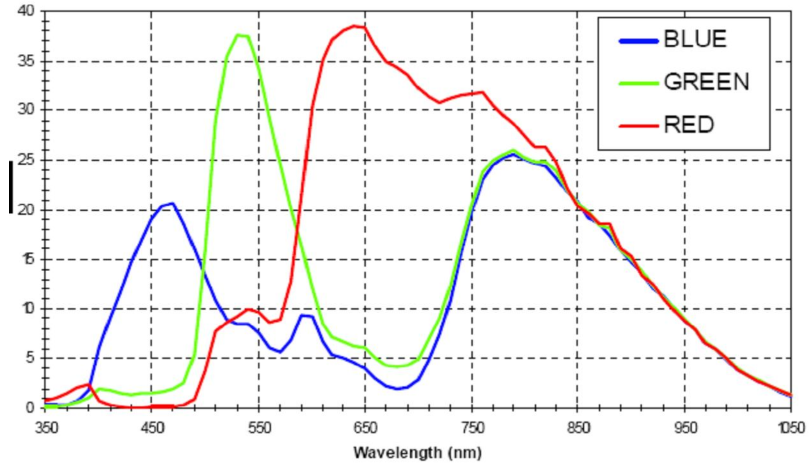
Mosaic Capture



In conventional systems, color filters are applied to a single layer of pixel sensors in a tiled mosaic pattern.

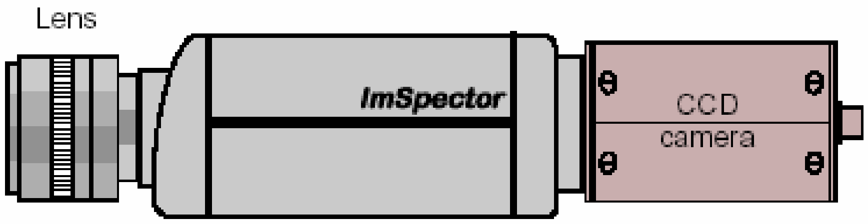
The filters let only one wavelength of light–red, green, or blue–pass through to any given pixel location, allowing it to record only one color.

As a result, mosaic sensors capture only 25% of the red and blue light, and just 50% of the green.

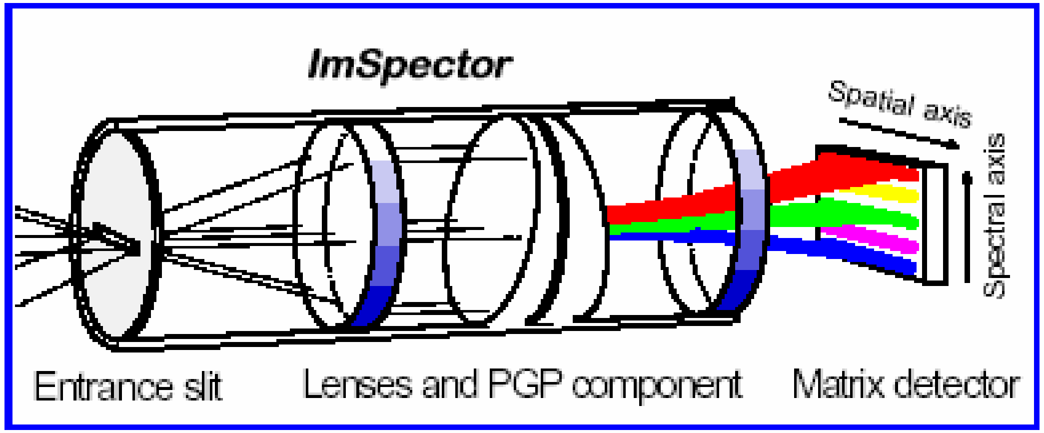


Filtering methods

ImSpector from Specim, Inc



Captures a line image and disperses it to a spectrum. Coupled to a B/W matrix camera converts it to a spectral line imaging system



Spectral range:
400-1000 nm

Spectral resolution:
5-7 nm

For Machine Vision

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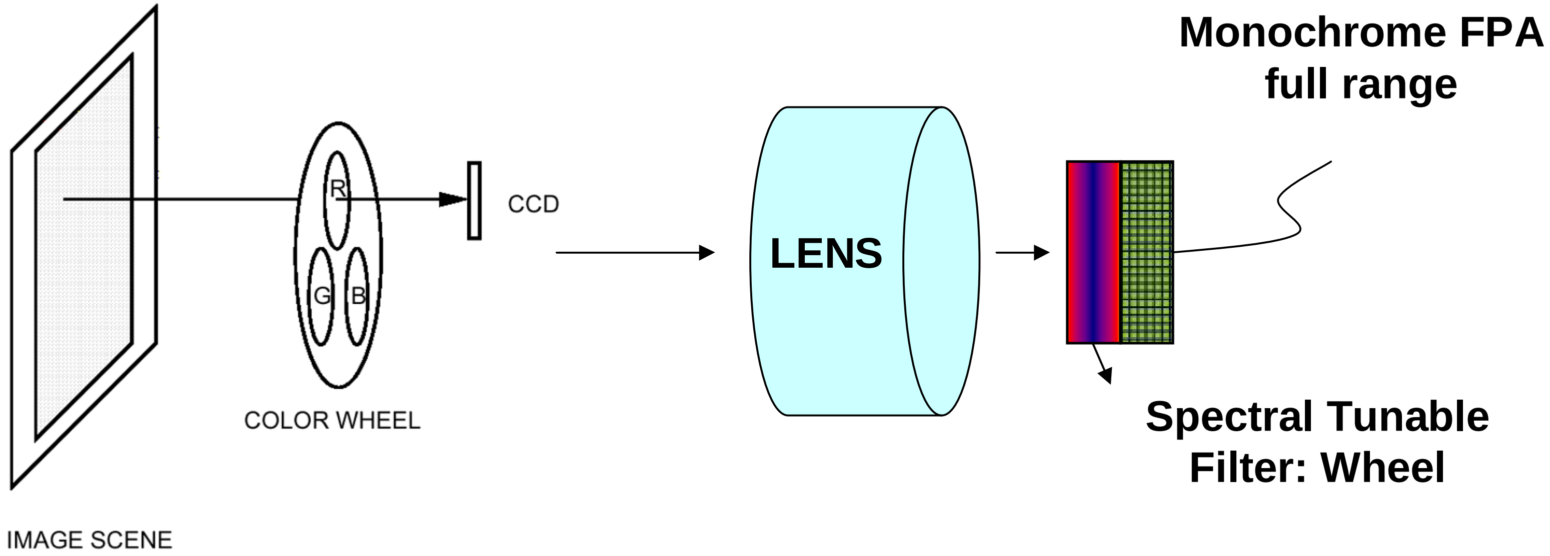
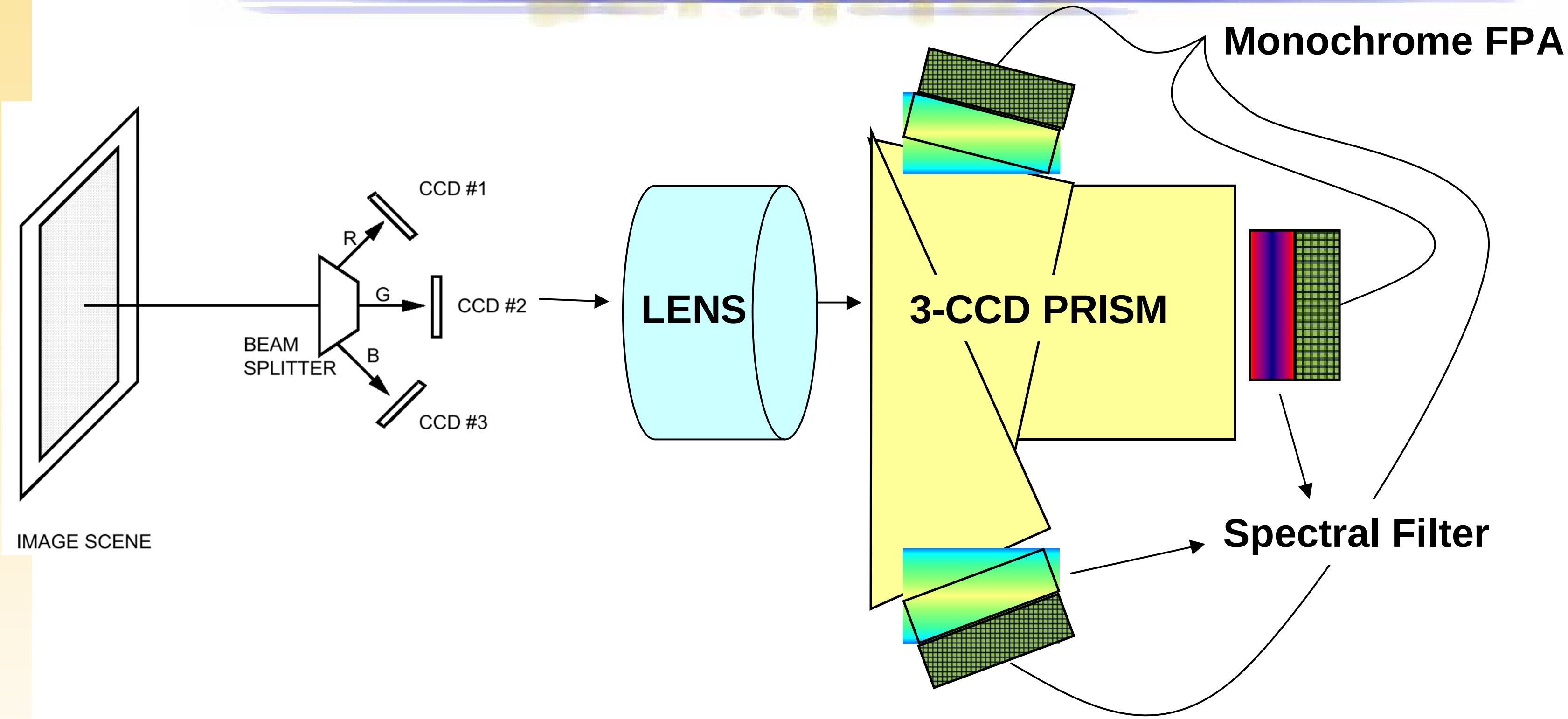
FPA with spectral filter wheel



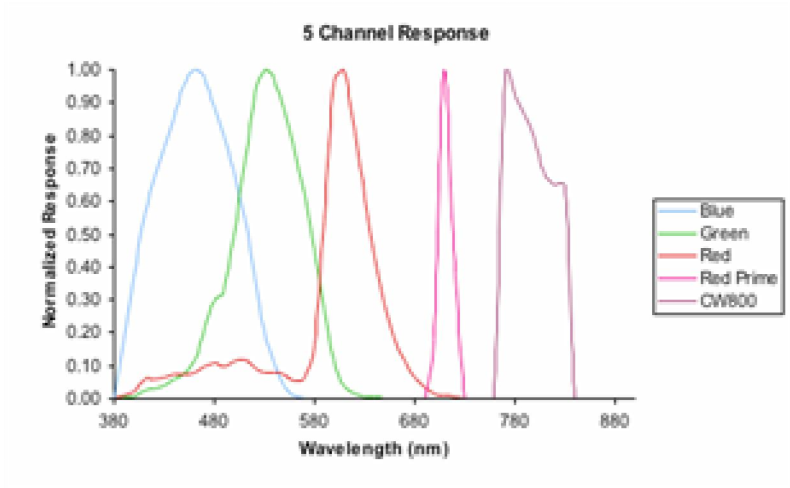
Key Features	User Advantages/Implications
Multiple spectral bands synthesized using different <u>spectral filters in a wheel</u>	Straightforward implementation <u>Spectral/spatial information not simultaneous</u> Useful for <u>several fix spectral bands</u> using a single filter wheel Dual color filter wheel implementation can result in large number of bands

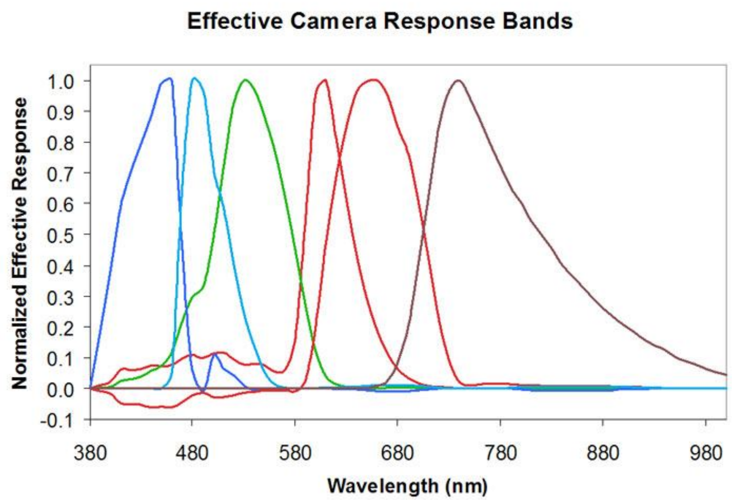
Multiple FPAs with spectral separation elements



Key Features	User Advantages/Implications
Diochroic <u>elements used to spectrally separate</u> and route light in specific spectral bandpasses to individual focal planes	Straightforward implementation for scanners or starers <u>Simultaneous spatial/spectral</u> information Straylight/radiometry implications <u>Small number discrete spectral bands</u>

Multiple FPAs with spectral separation elements





FluxData FD-1665 3CCD Multispectral Cameras

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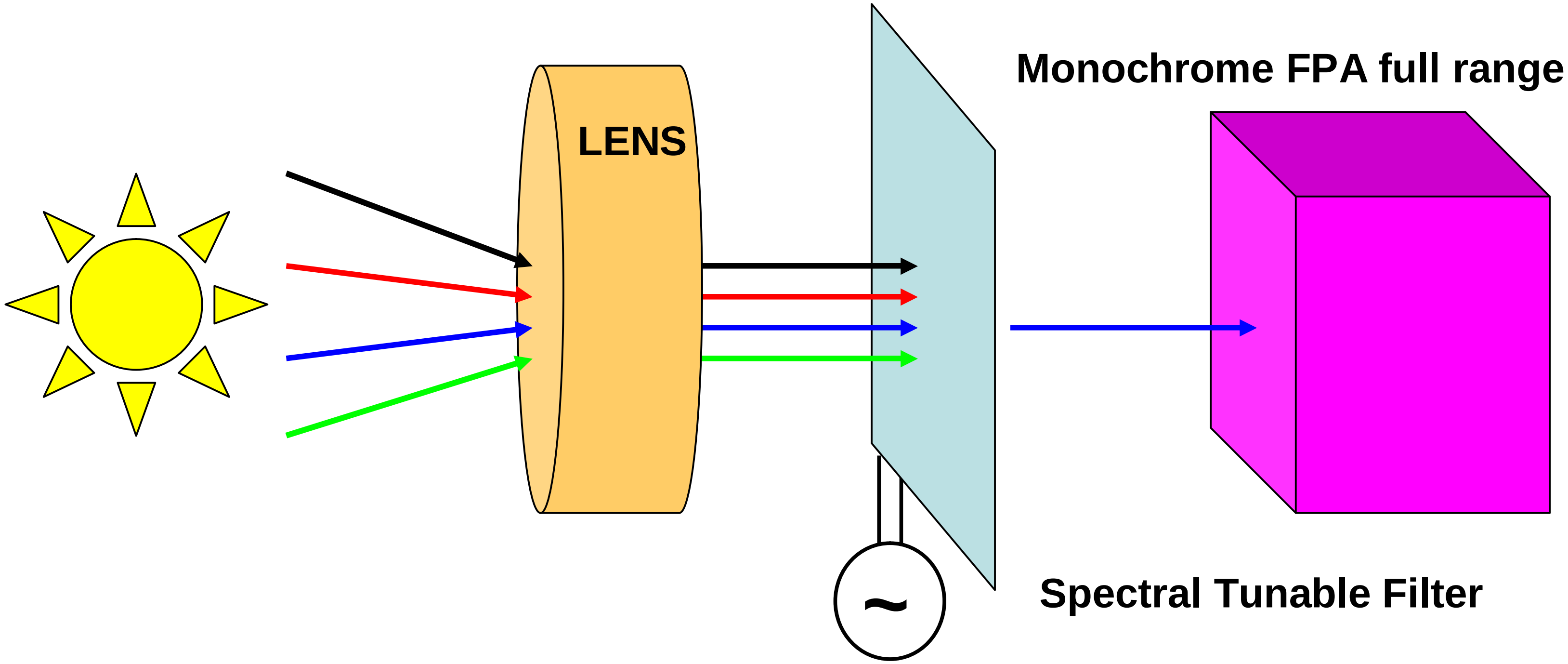
FPA with spectral tunable filter

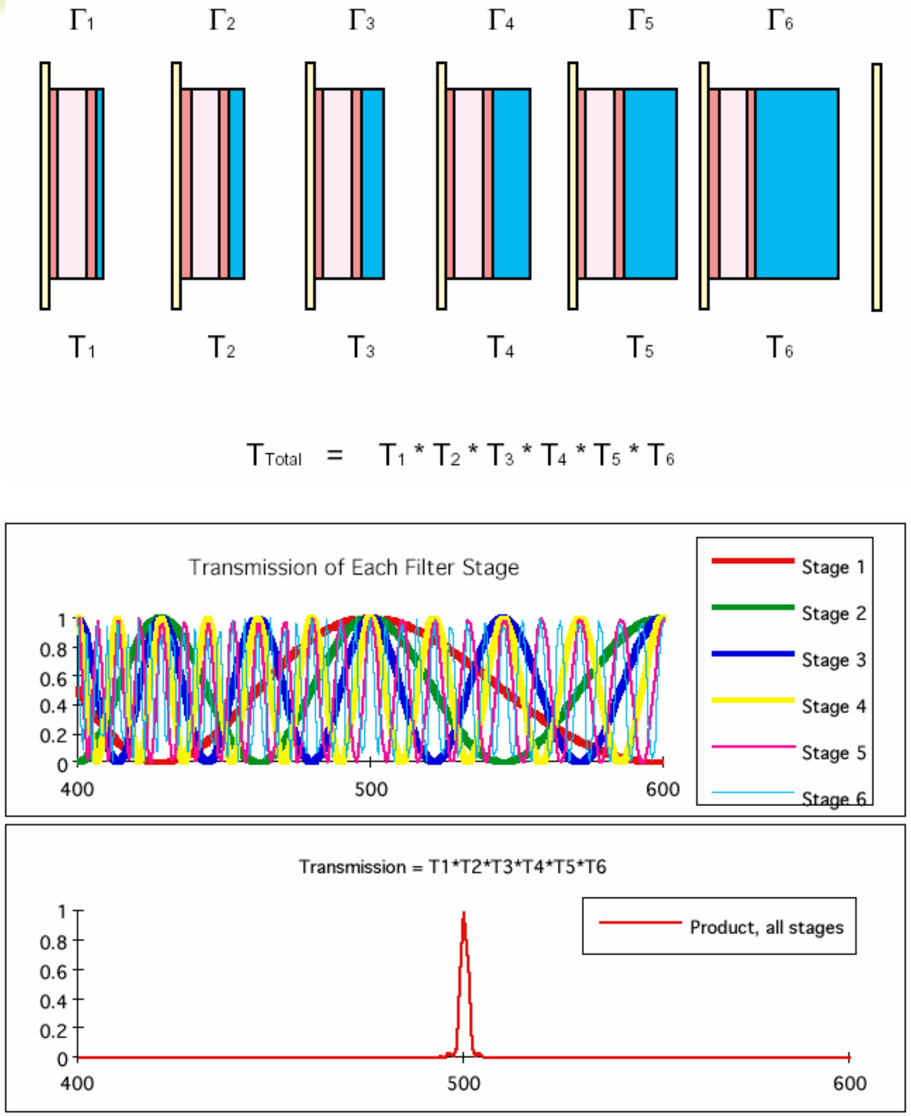


Key Features	User Advantages/Implications
Multiple spectral bands synthesized using the same <u>spectral tunable filter</u>	Straightforward implementation <u>Spectral/spatial information not simultaneous</u> Useful for <u>several tunable spectral bands</u> using a single filter

Filtering methods: LCTF

Liquid Crystal Tunable Filter

- Formed by a stack of polarizers and tunable retardation liquid crystal plates
- Combining the transmission of all the plate only a narrow band can be transmitted
- Changing the bandpass is very fast (~50 ms)



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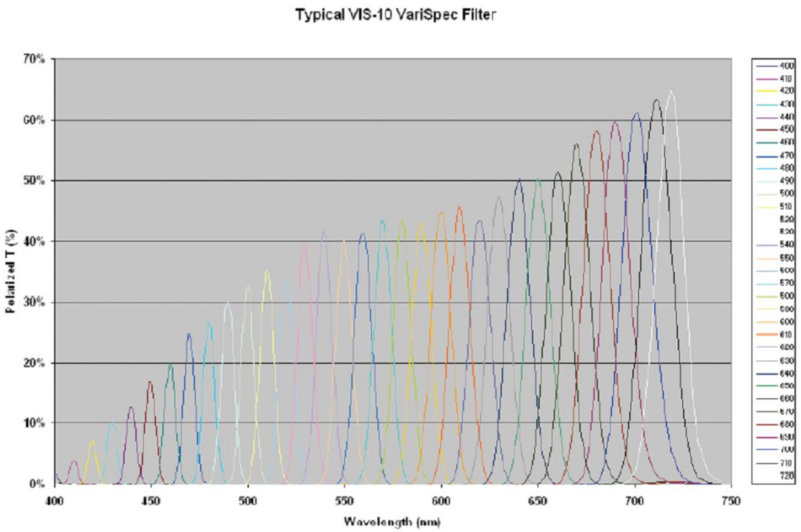
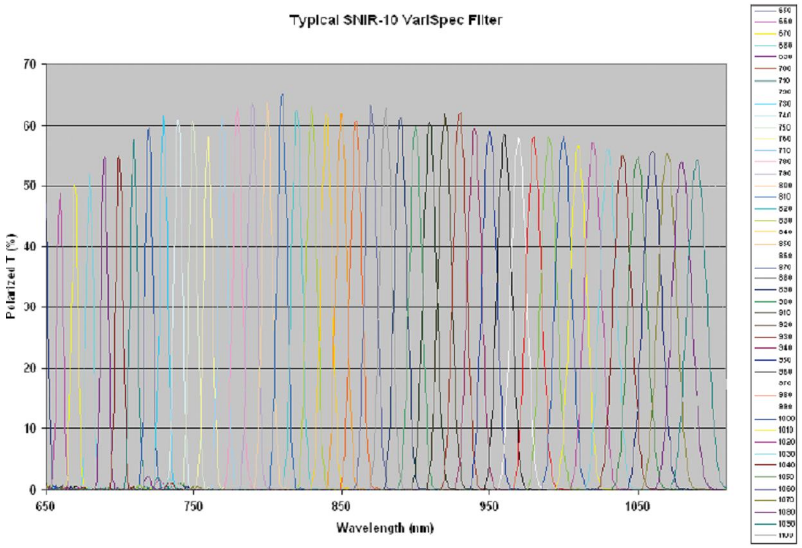
Filtering methods: LCTF

VarisPec Tunable Imaging Filter (*Cambridge Research, Inc*.)



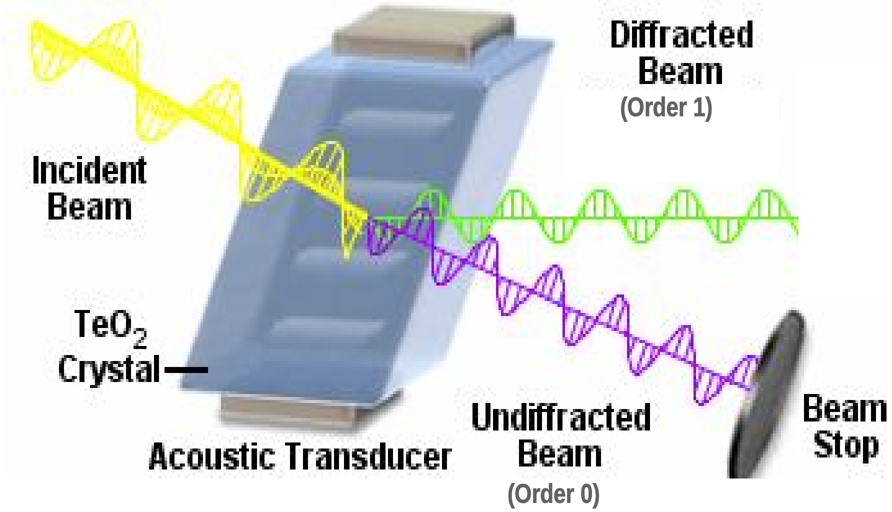


Filtering methods: AOTF

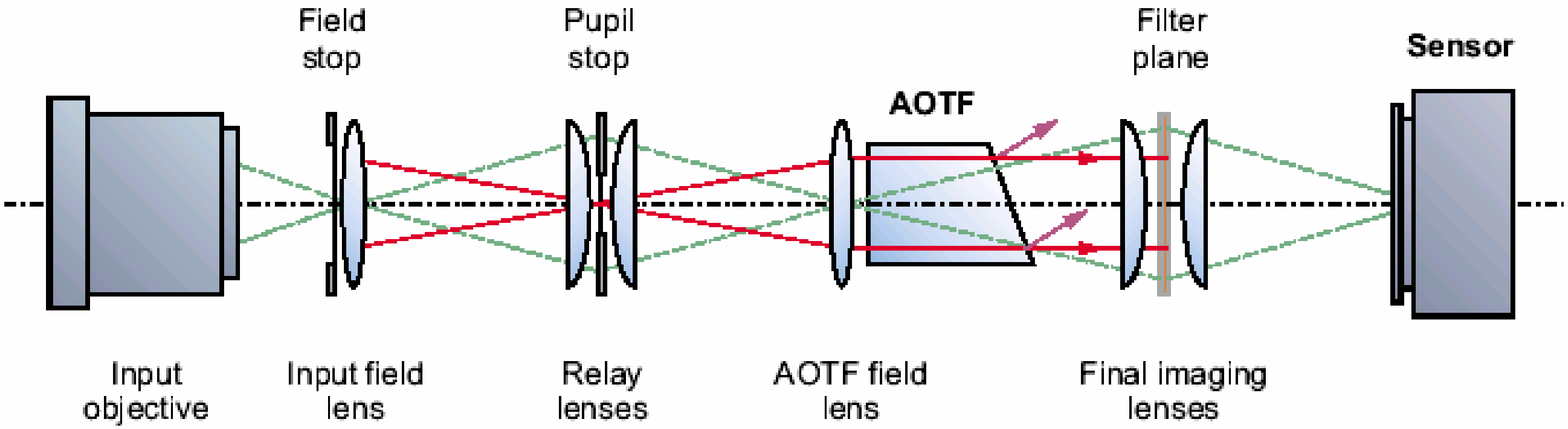
Acousto Optic Tunable Filter

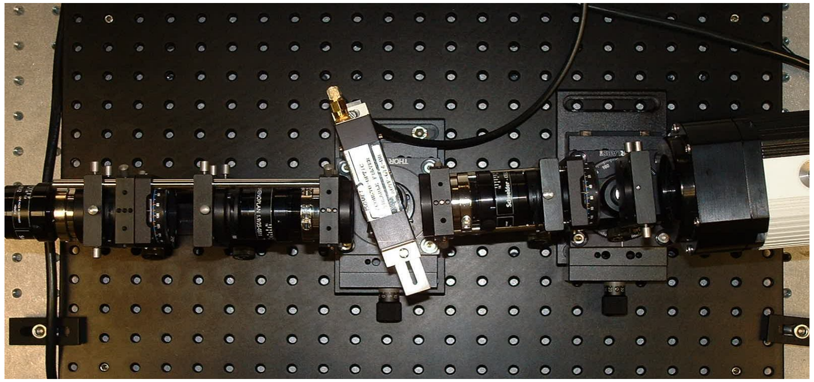
- An RF signal applied to a piezo-electric transducer, bonded to a suitable crystal will generate an acoustic wave.
- Any incident light ray will be diffracted. The wavelength of the 1st order diffracted ray depends on the acoustic frequency.

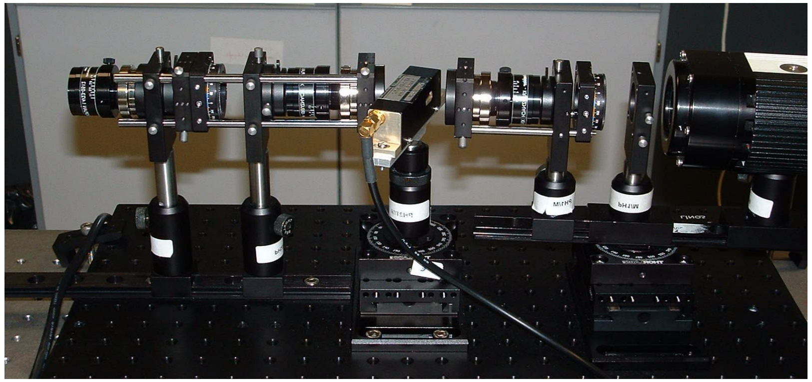
☺ Usable wavelengths: 0.4-5.1μm
☺ Spectral resolution: 0.7nm @400nm to 10nm @ 1000nm
☺ μs access time to a wavelength
☺ Random or sequential access to any wavelength
☹ Filter limited to about one octave
☹ AOTF are polarisation sensitive
☹ Small active aperture of crystal
☹ Cost



Filtering Methods: AOTF

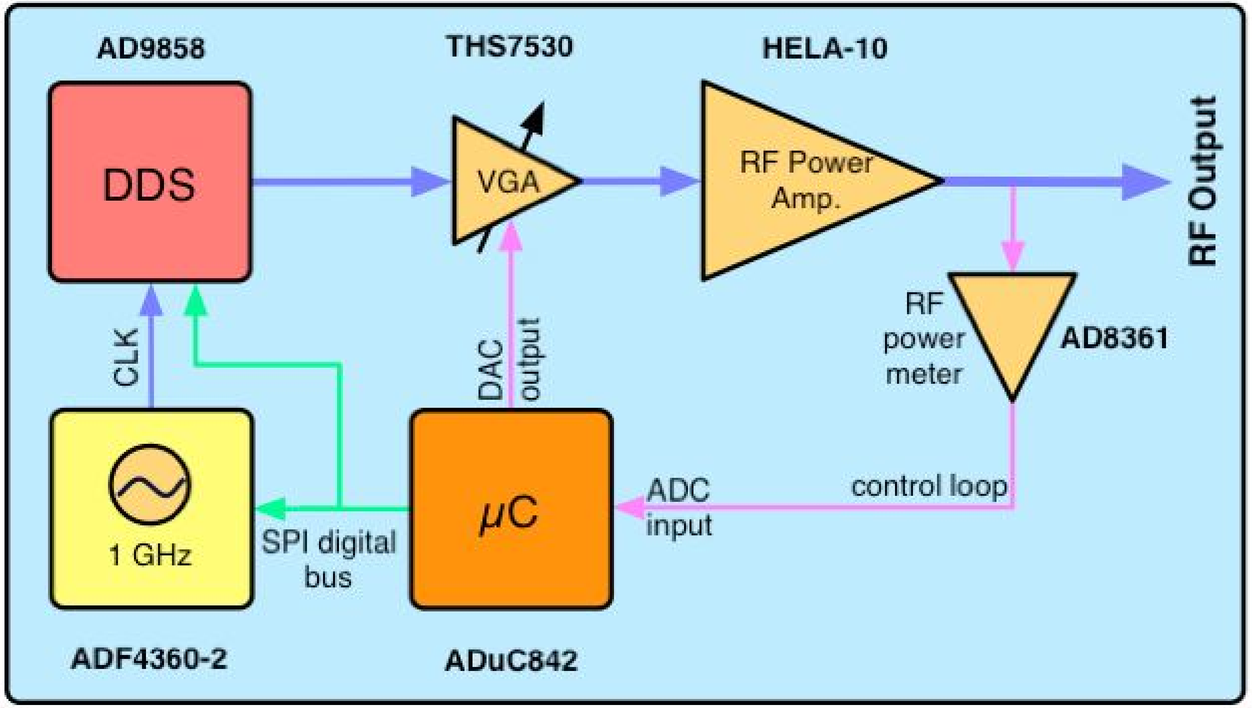




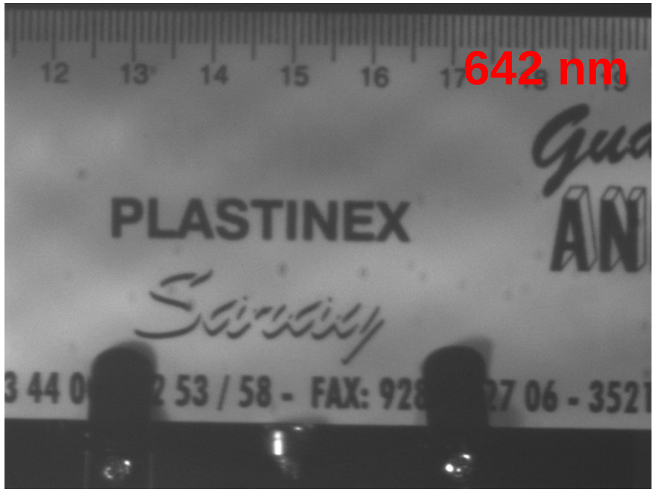


RF generator

- Generates an RF signal with the proper frequency and power to drive the AOTF crystal.
- Based on a Direct Digital Synthesizer circuit and two cascaded monolithic RF amplifiers.



G&H VIS laboratory setup imaging



Brimrose optical system

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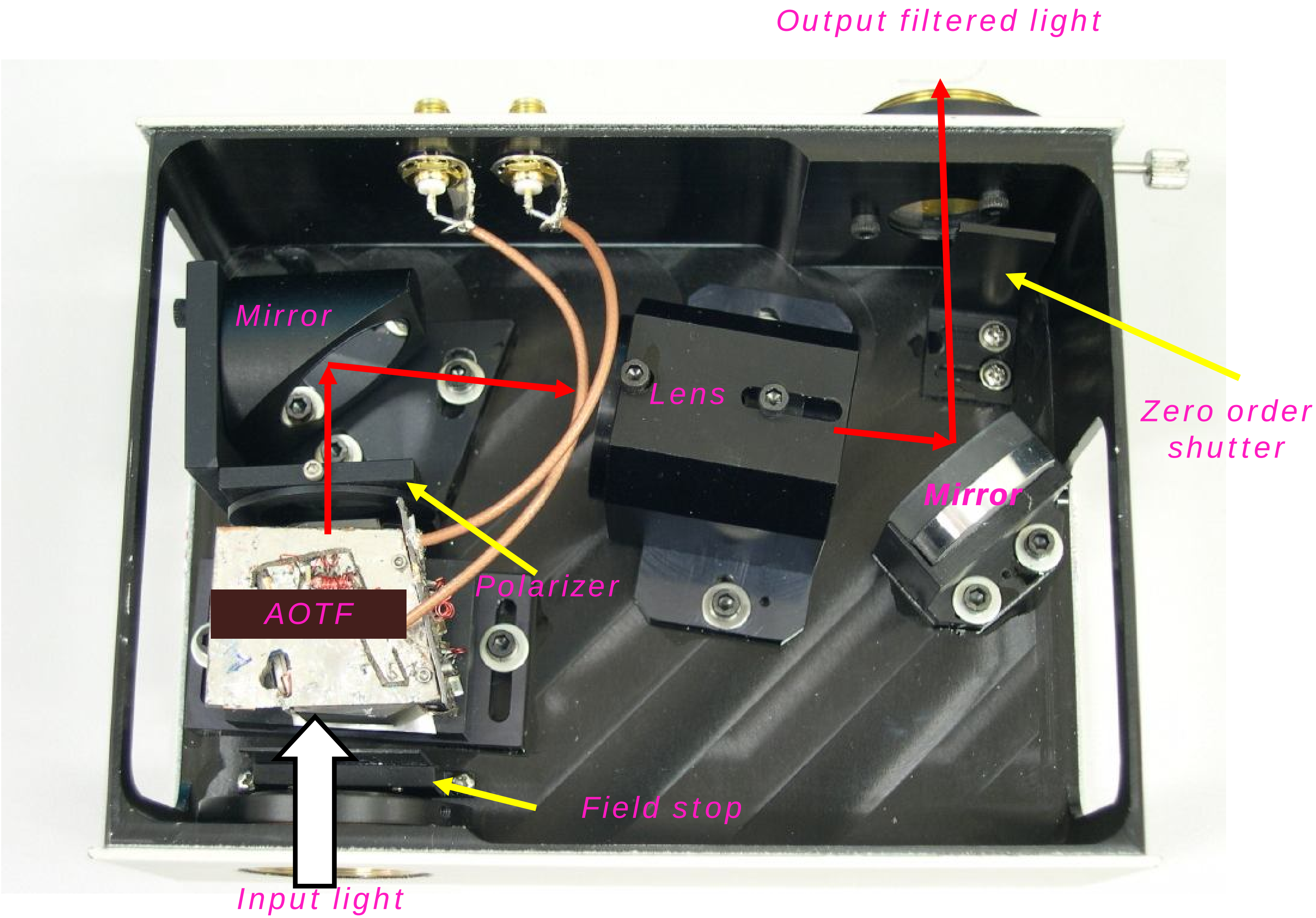
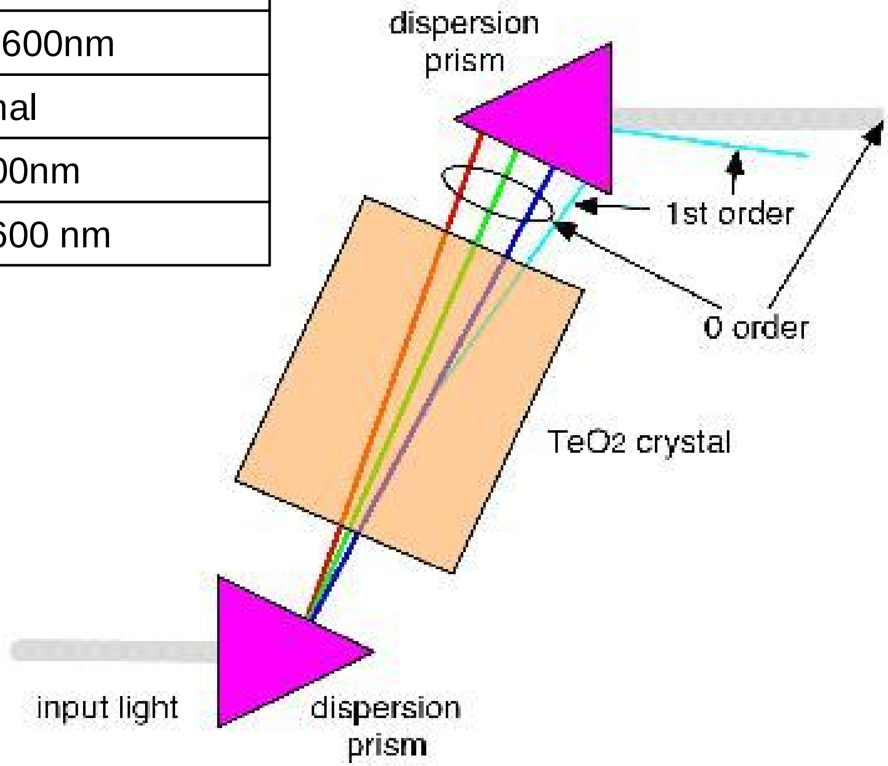
Brimrose optical system



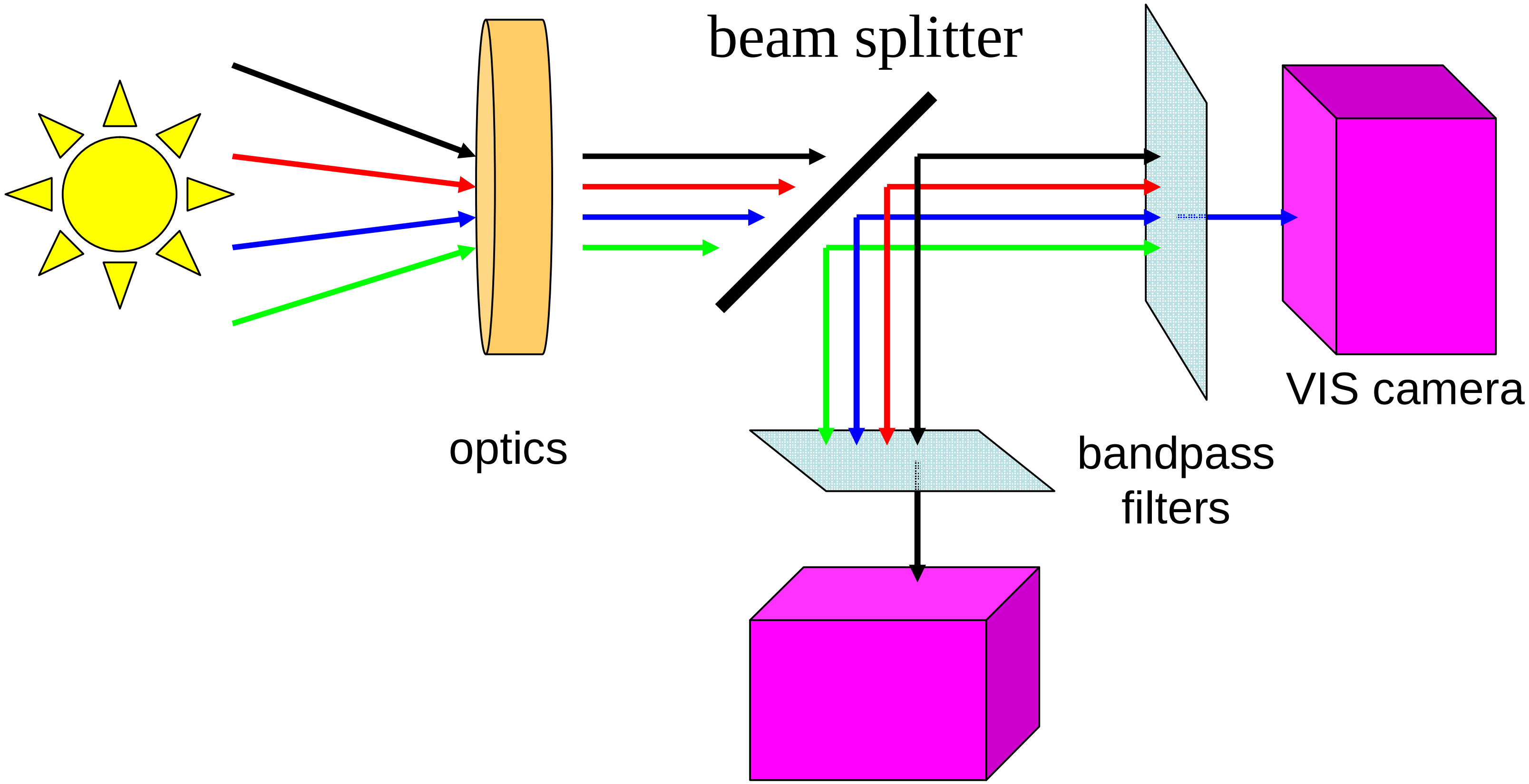
Brimrose AOTF

OSTF (Isomet)

Aperture	5mm x 5mm
Wavelength range	400nm – 1000nm (nominal)
Frequency range	445-110 MHz (nominal)
Diffraction efficiency	>85%
Bandwidth	3.5nm @ 600nm
Incidence Angle	Normal
Acceptance angle	4º @ 600nm
Separation angle	3.36º @ 600 nm



Multiple arrays sensor



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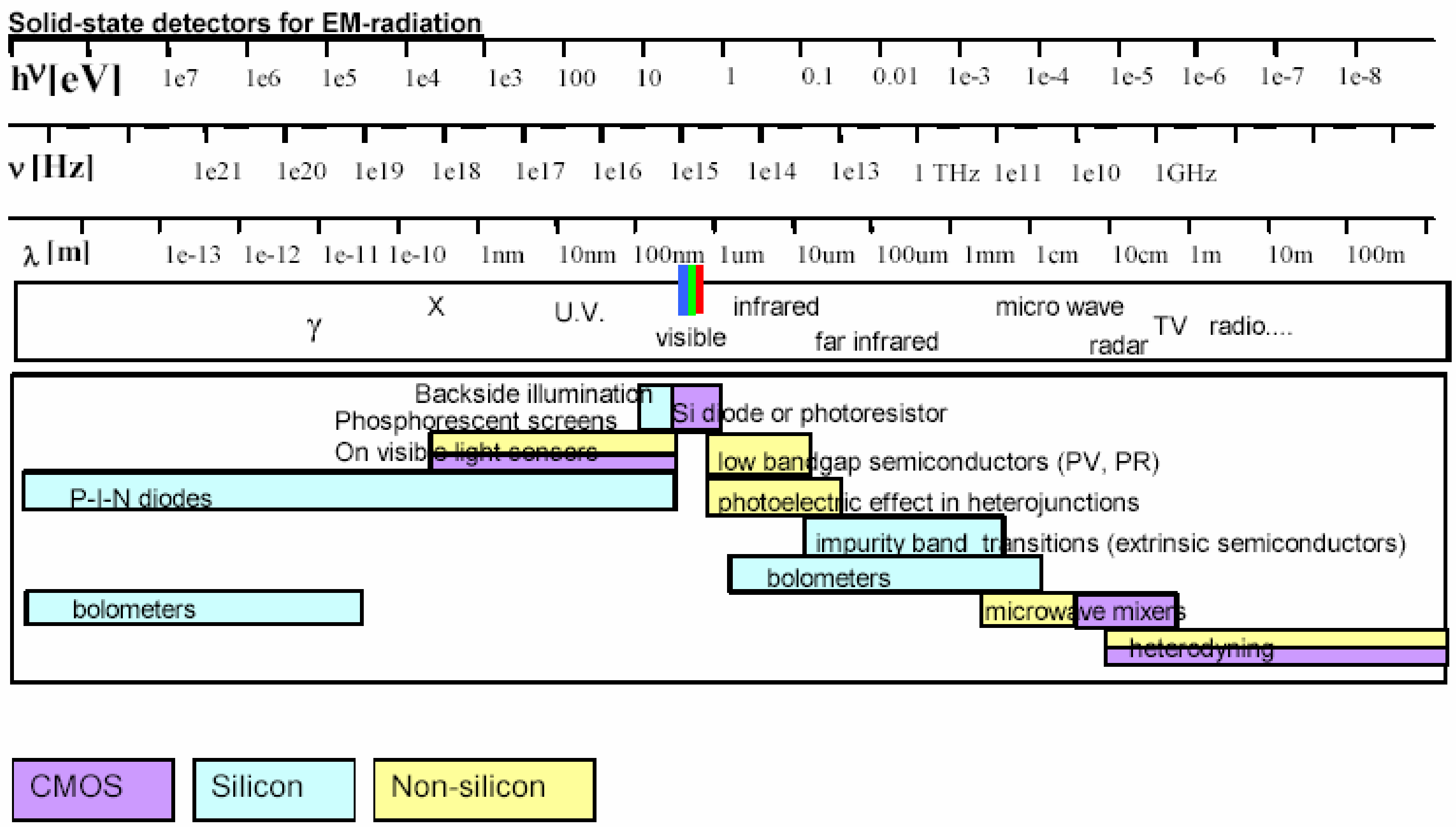
Sensors

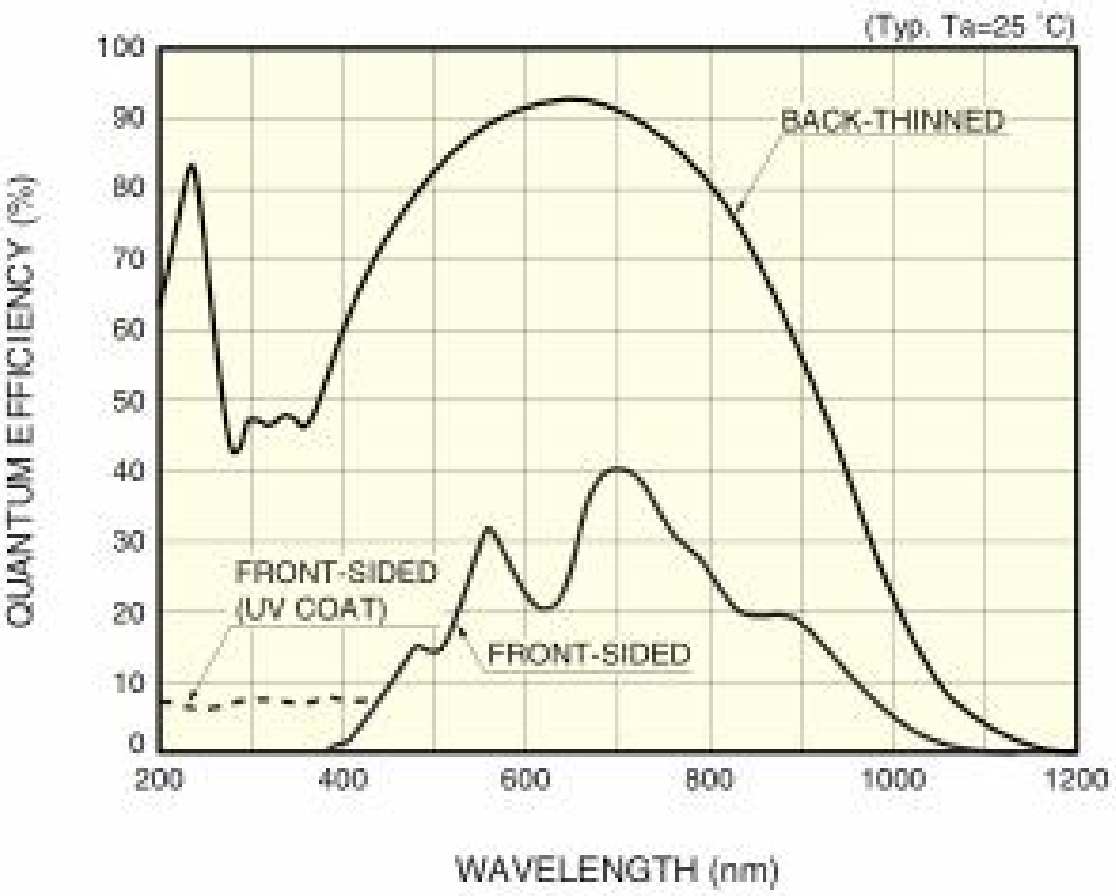


Solid-state detectors for EM-radiation
hν[eV] 1e7 1e6 1e5 1e4 1e3 100 10 1 0.1 0.01 1e-3 1e-4 1e-5 1e-6 1e-7 1e-8
ν [Hz] 1e21 1e20 1e19 1e18 1e17 1e16 1e15 1e14 1e13 1 THz 1e11 1e10 1GHz
λ [m] 1e-13 1e-12 1e-11 1e-10 1nm 10nm 100nm 1um 10um 100um 1mm 1cm 10cm 1m 10m 100m
γ
X
U.V.
visible
infrared
far infrared
micro wave
radar
TV
radio....
Backside illumination
Phosphorescent screens
On visible light sensors
Si diode or photoresistor
P-I-N diodes
low bandgap semiconductors (PV, PR)
photoelectric effect in heterojunctions
impurity band transitions (extrinsic semiconductors)
bolometers
bolometers
microwave mixers
heterodyning
CMOS
Silicon
Non-silicon

Sensors

Few photons get to the sensors

- Intensified technologies:
  - ICCD
  - EBCCD
  - L3CCD



Sensors: Intensified technologies. ICCD

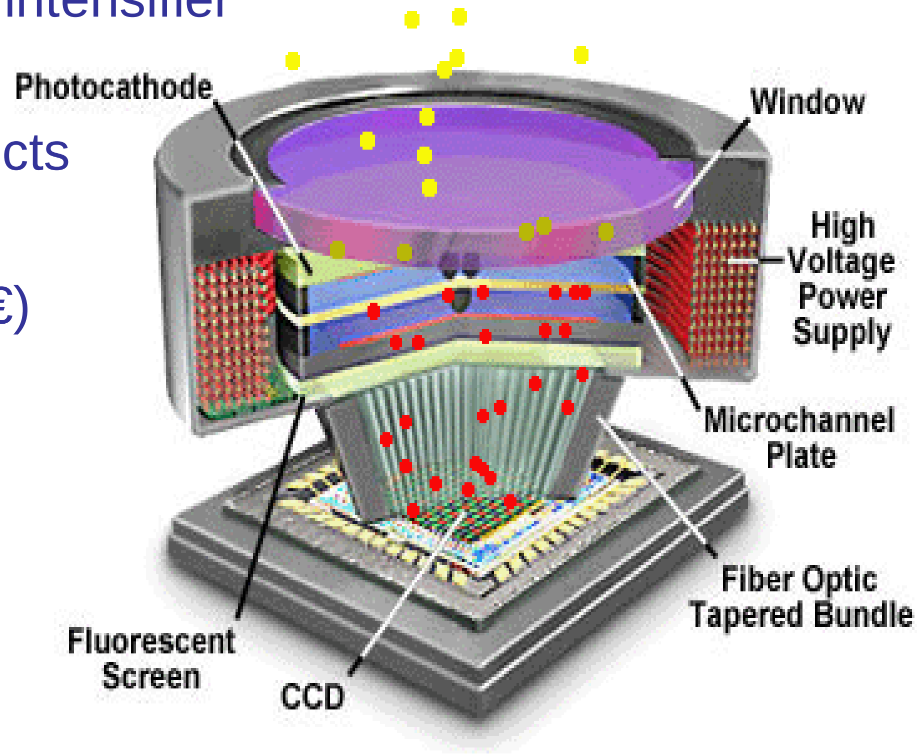
CCD plus image intensifier fibre-optically coupled

Spectral sensitivity depending of the photocatode

High voltage for accelerating electrons

Pulse amplifier for gated intensifier

- Delft Electronic Products
- Intevac
- Hamamatsu (10,000 €)
- Proxitronic

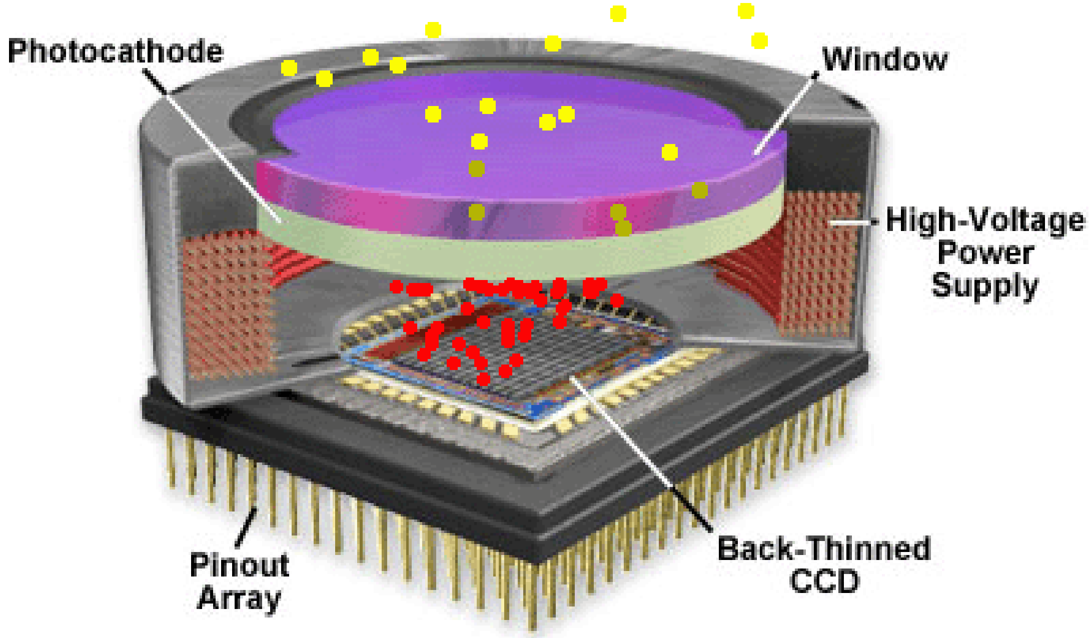


Sensors: Intensified technologies. EBCCD

Hybrid of an image intensifier and a CCD camera

Electrons impact on the back side of a back thinned CCD

- EB-CCD N7640 Hamamatsu (640x480)
    - Spectral range . . . . 370–920 nm
    - Frame rate 60 Hz interlaced
- EBAPS Intevac



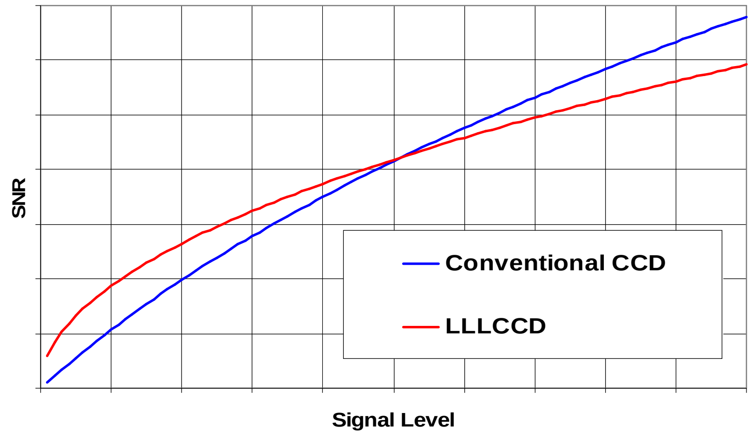
Sensors: Intensified technologies. L3CCD

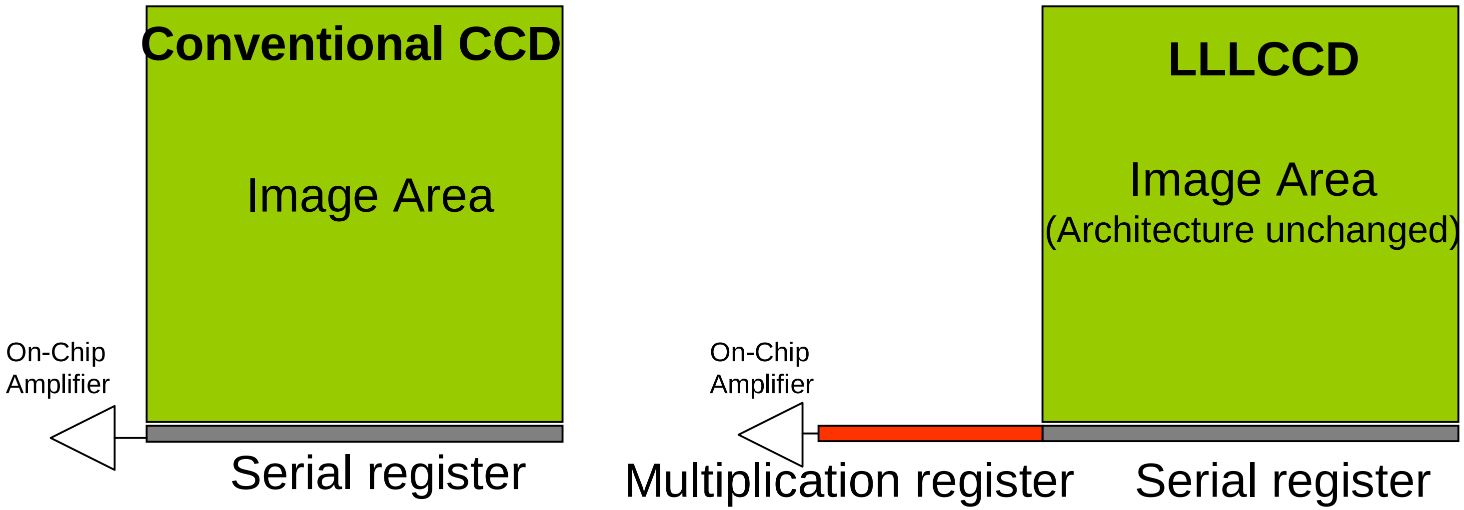
Applies gain to the signal charge prior to the output node.

This effectively reduces the magnitude of the read out noise

E2V Technologies CCD87 (512x512)
- **Spectral range . . . 400–1060nm**
- **Fill factor 100%**
- **Frame rate . . . . . . 30 Hz**

TI TC253SPD (680x500)
- **High Uniformity from DUV to NIR**
- **Frame rate . . . . 30 Hz**





Sensors: Intensified technologies

ICCD

- ✓ Much higher gain than EBCCD
- ✓ Spectral range depending on selected photocatode
- ✗ Reducing average contrast
- ✗ Gated intensifier needs pulse amplifier and high voltage power supply
- ✗ Noise factor due to MCP
- ✗ Image intensifier are “lifed” items (function of the faceplate illumination)
- ✗ Significant phosphor lag, improves SNR at the expense of DR
- ✗ Saturated even with modest light levels
- ✗ Image intensifier can be damaged by high light overloads

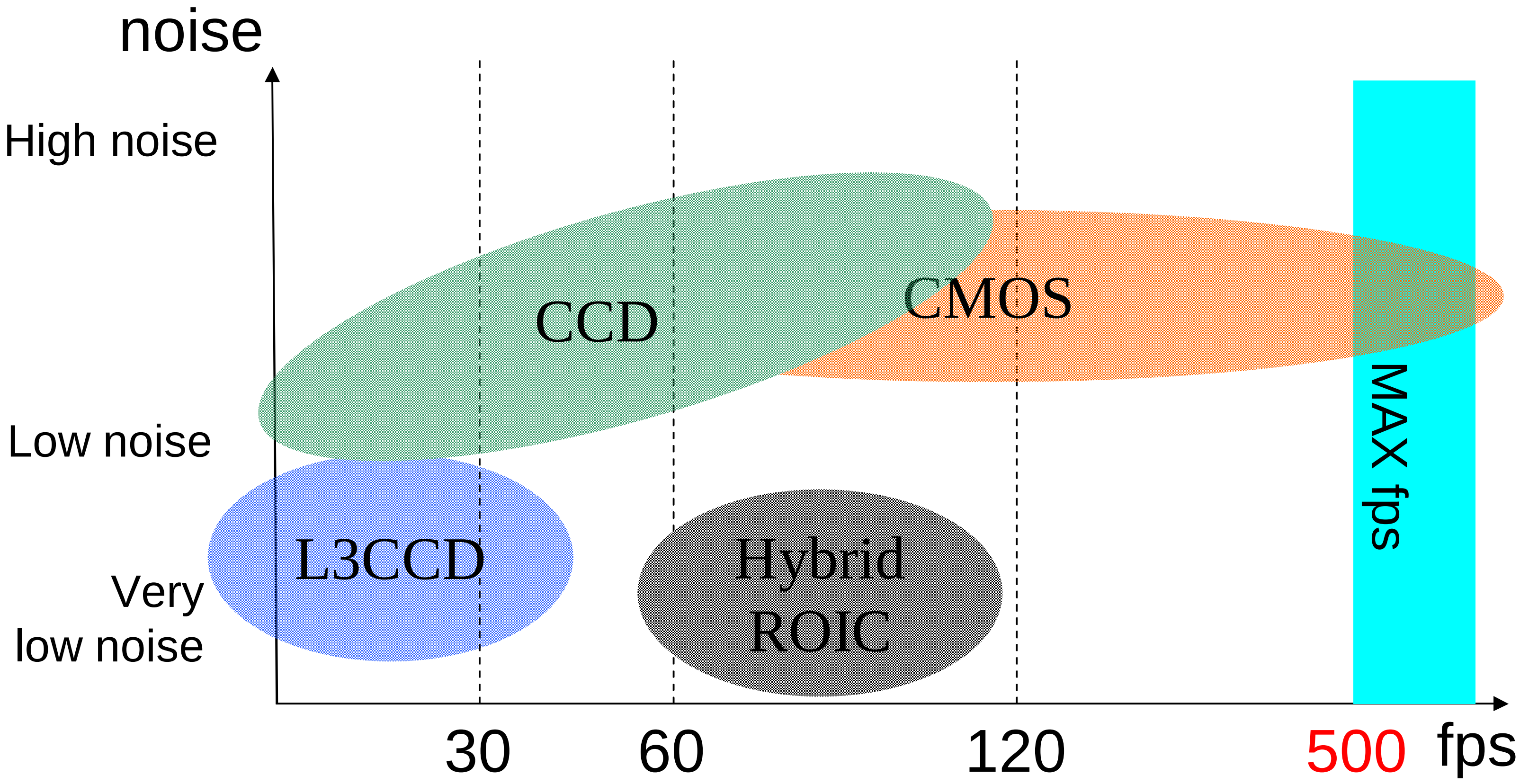
EBCCD

- ✓ Gain means speed
- ✓ Relatively low noise (40 e-/ pixel)
- ✓ No Lag, No distortion
- ✓ Better spatial resolution and SNR at moderate light levels than ICCD
- ✗ DR limited for increased gain
- ✗ Modest low light level detection capability (gain not as high as ICCD)
- ✗ Very expensive (around 16000 $)

LLLCCD

- ✓ CCD working at very different light conditions without image intensifier (three different modes)
- ✓ No risk of hardware damage due to overexposure
- ✓ Spatial resolution is the same as for an standard CCD and not reduced by a photocathode or MCP
- ✓ Price not so high (4,500 € for front illuminated)
- ✓ Higher SNR than ICCDs and CCDs (at low light levels)
- ✗ High voltage clock (more electronics involved)
- ✗ Degradation of QE in High Gain Mode
- ✗ Dark current electrons are amplified above the readout noise (cooling possibly needed)

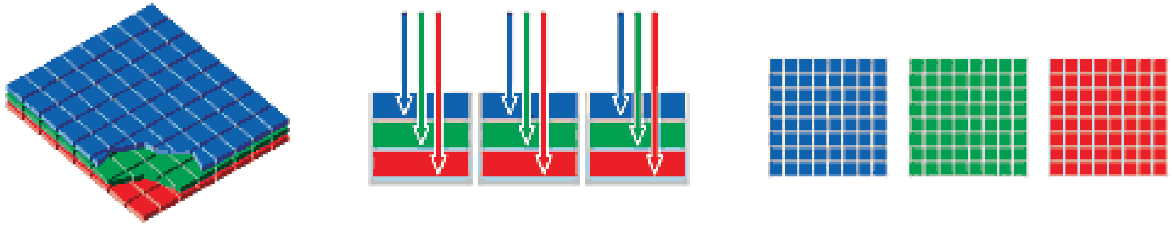
Sensors


noise
High noise
Low noise
Very
low noise
CCD
CMOS
L3CCD
Hybrid
ROIC
MAX fps
30
60
120
500
fps

Foveon Image Sensors

DIRECT IMAGE SENSOR
FOVEON

Foveon X3® Capture

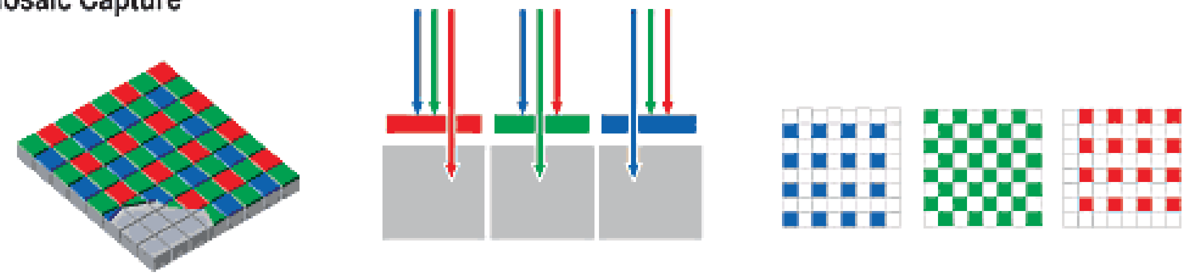


A Foveon X3 direct image sensor features three separate layers of pixel sensors embedded in silicon.

Since silicon absorbs different wavelengths of light at different depths, each layer records a different color. Because the layers are stacked together, all three colors are captured.

As a result, only Foveon X3 direct image sensors capture red, green, and blue light at every pixel location.

Mosaic Capture



In conventional systems, color filters are applied to a single layer of pixel sensors in a tiled mosaic pattern.

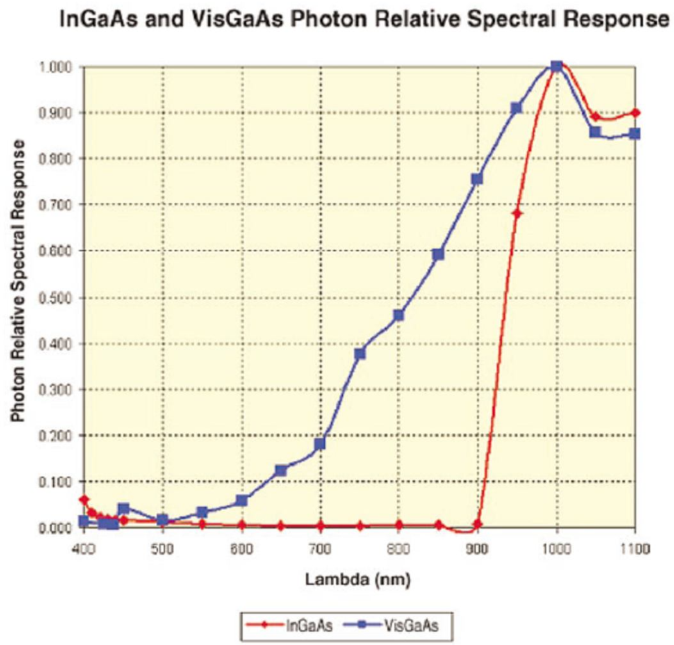
The filters let only one wavelength of light–red, green, or blue–pass through to any given pixel location, allowing it to record only one color.

As a result, mosaic sensors capture only 25% of the red and blue light, and just 50% of the green.

Foveon Image Sensors: Samples

VISGaAs sensors: Indigo and FLIR

InGaAs: 0.9 – 1.7 µm
VisGaAs: 0.4 – 1.7 µm



SmartSpectra project

- Develop a Multispectral System that can be used on a wide range of commercial and industrial applications.
- Camera characteristics:
  - Cost-effective sensor for commercial applications
  - Provide up to 6 electronically configurable spectral bands
  - Spectral resolution: 5-50 nm
  - Spatial resolution: 640 x 480
  - Wide spectrum range: 400-1800nm

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SRI

ANALOG DEVICES

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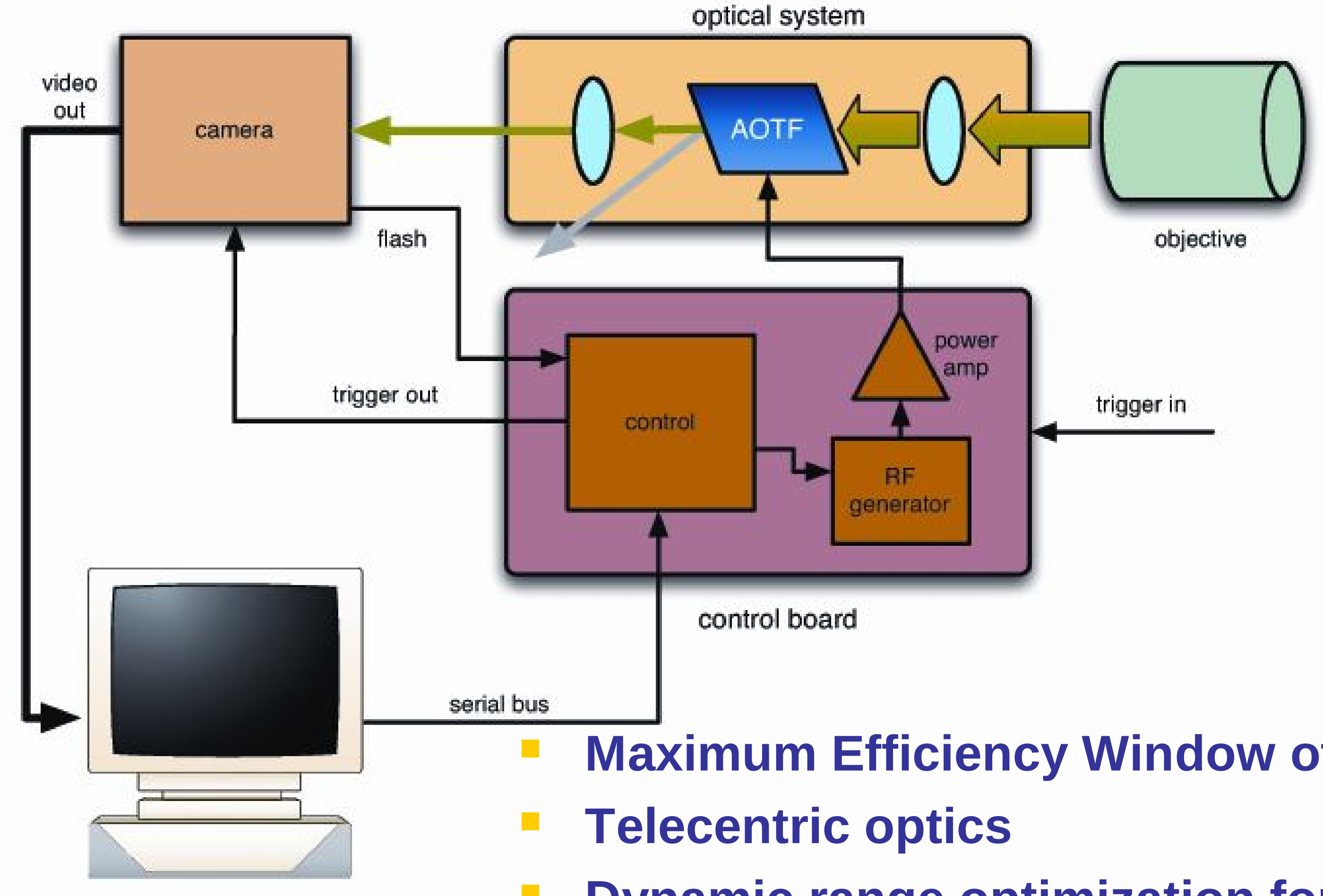
Autonomous Tunable Filter System ATFS



- Maximum Efficiency Window of AOTF
- Telecentric optics
- Dynamic range optimization for each spectral band: Gain, RF power & Texp
- 8 to 12-bit sensor

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Processing issues

- Hyperspectral sensors generate lots of data
- Is it manageable?
  - How to store them?
  - How to transmit them?
  - How to process them?
- Coregistration
- Comparison among sensors

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Processing issues: Preprocessing

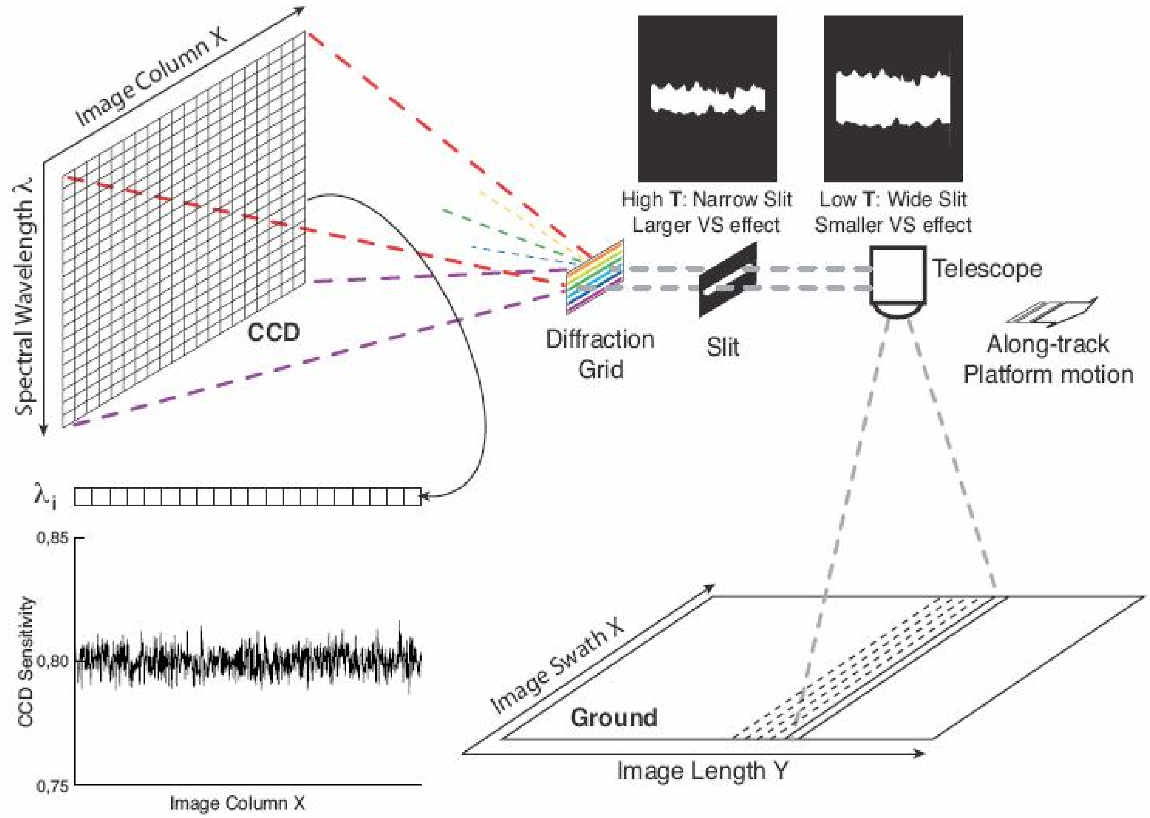


Figure 4.1: Design of a push-broom imaging spectrometer that shows its operation mode and the sources of the coherent spatial noise patterns.(Credit: figure based on an original of Barducci and Pippi (2001))

Courtesy Luis Gómez. UV-EEG

Processing issues: Preprocessing

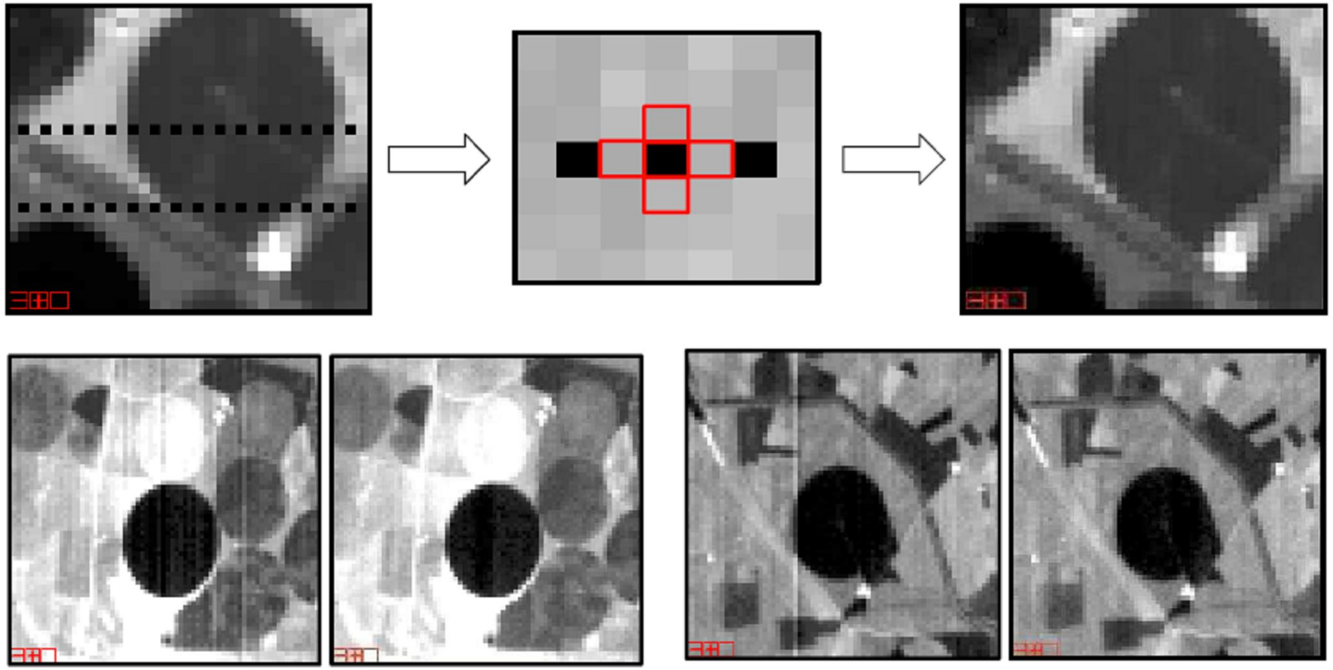
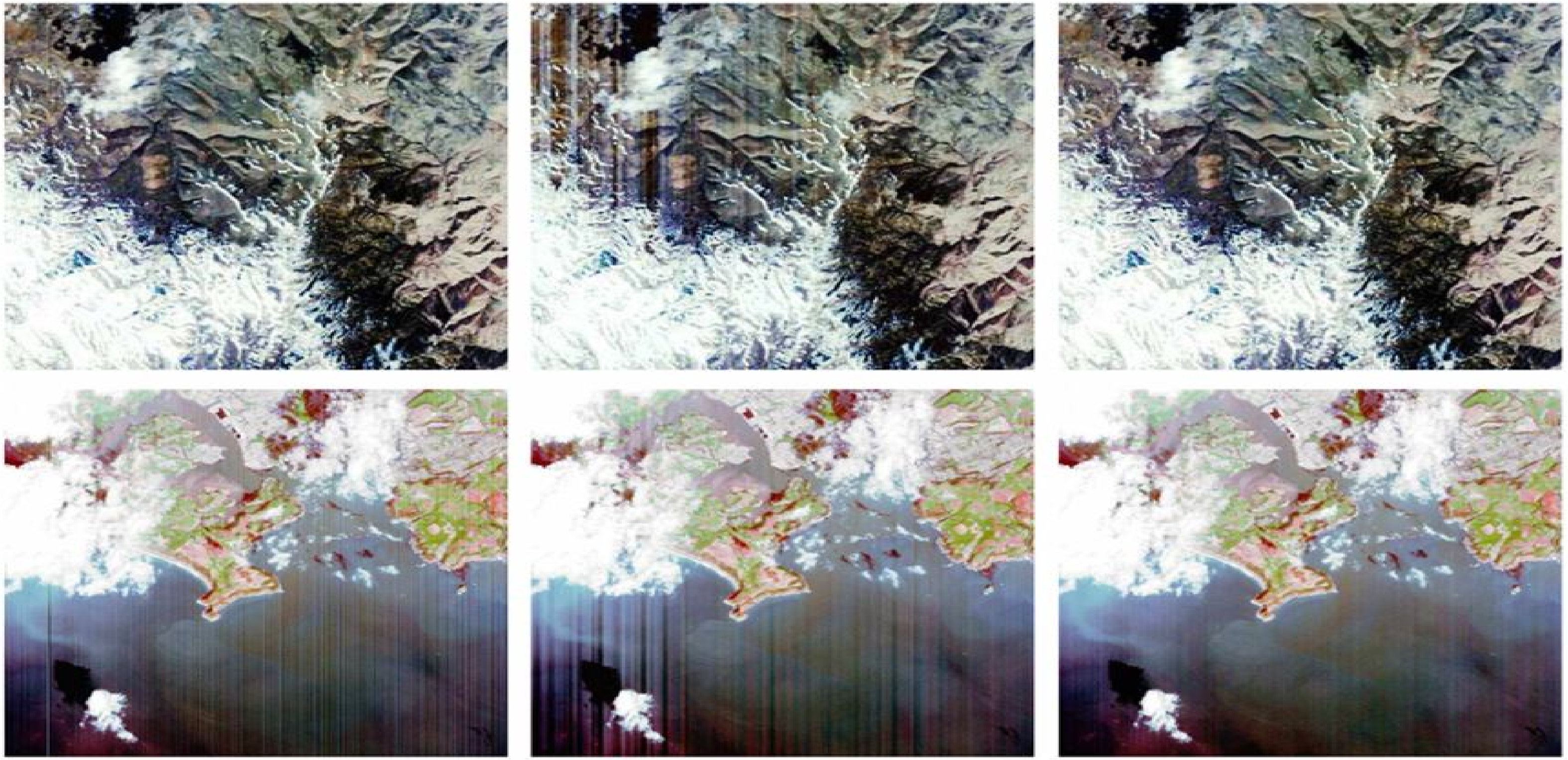


Figure 4.2: Illustration of the correction of the drop-out errors based on the four-connected neighbors (*top*) and the vertical striping (*bottom*). Credits: Garcia and Moreno (2004).

Courtesy Luis Gómez. UV-EG

Processing issues: Preprocessing



Courtesy Luis Gómez. UV-EG

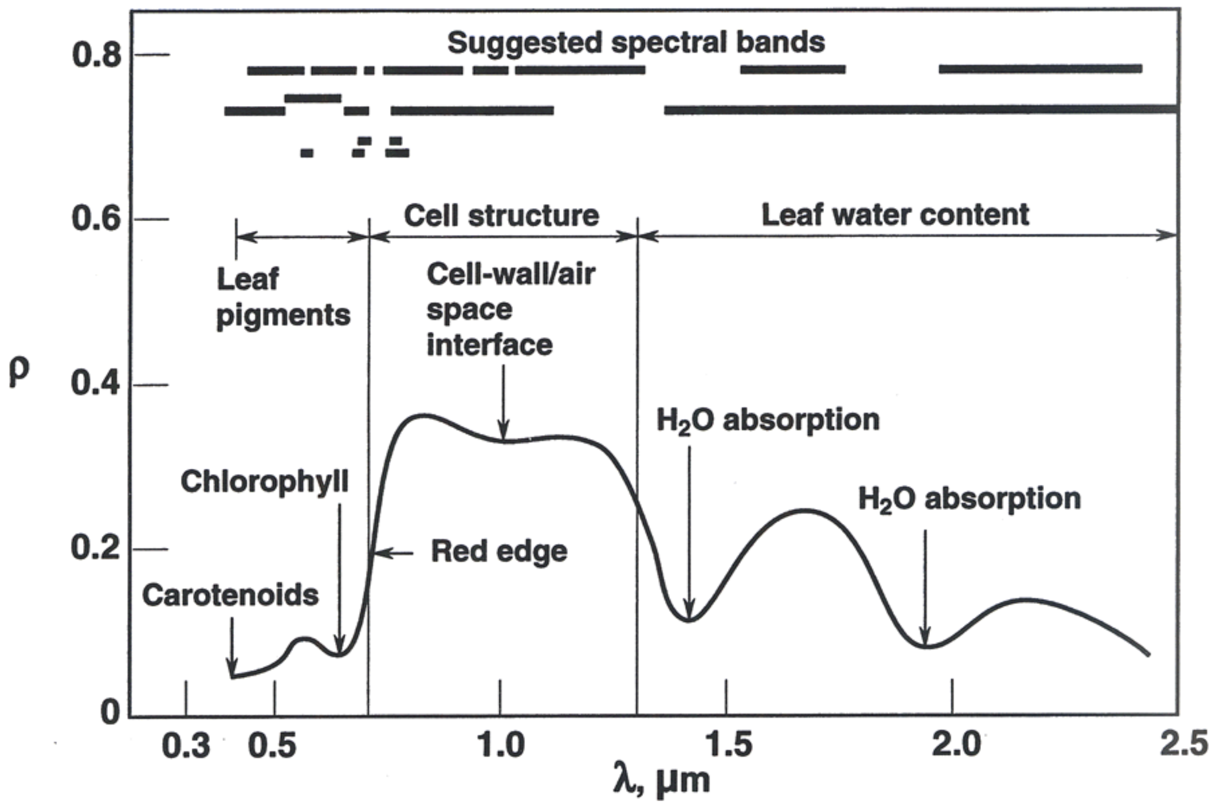
Processing issues: Band selection

- A priori knowledge
- Information theory

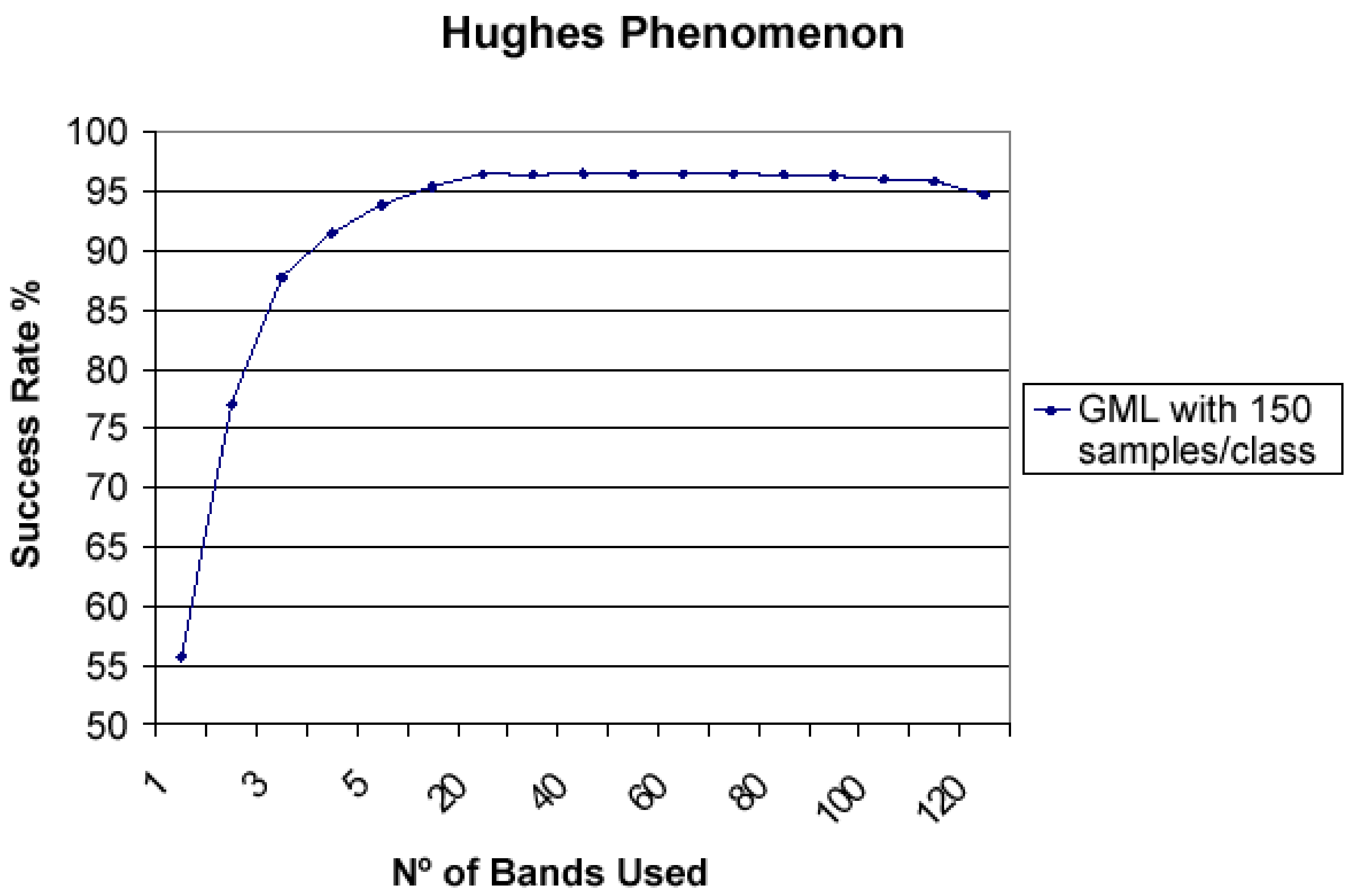
Processing issues: Band selection

Land surface classification with hyperspectral data

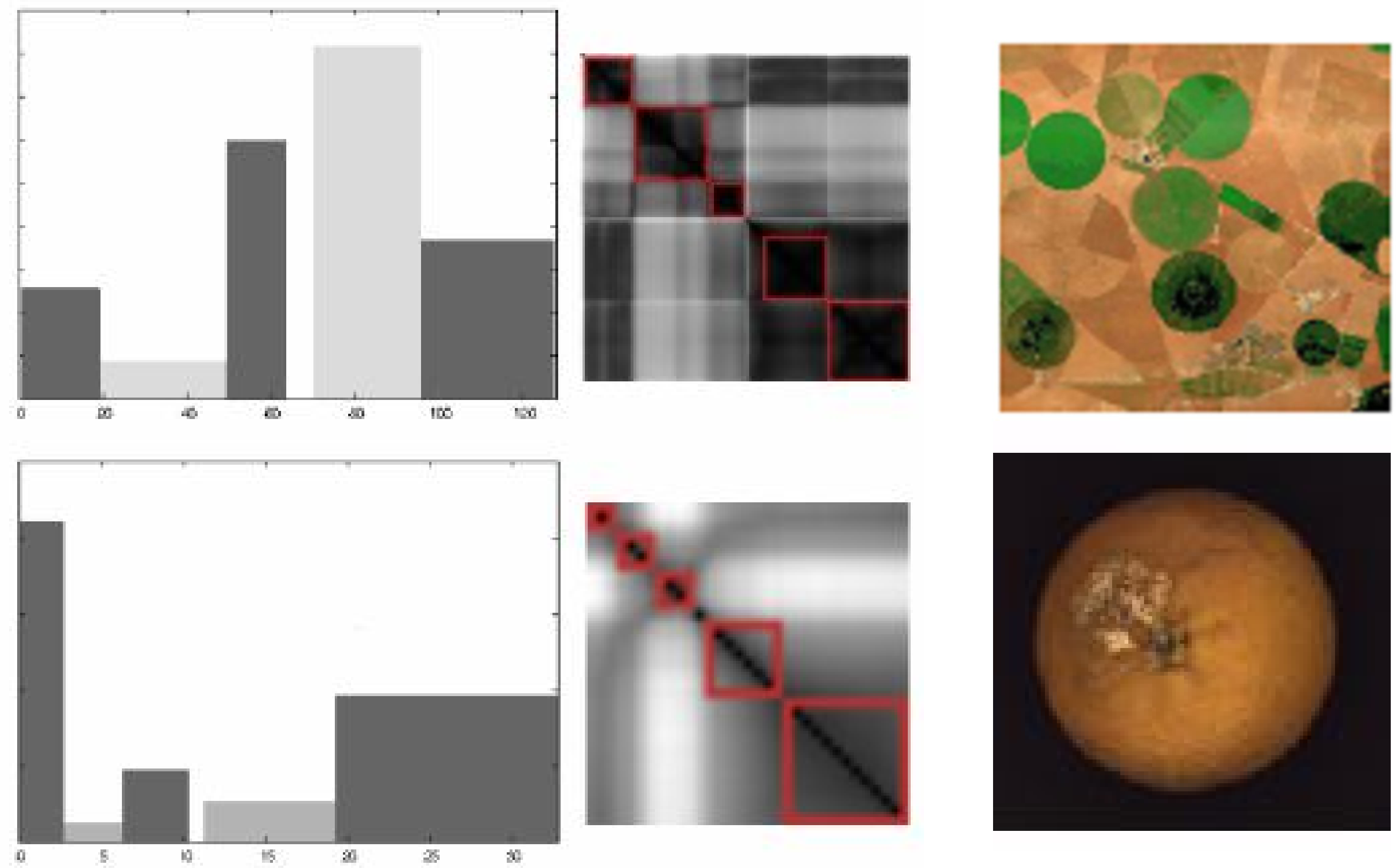
- **System: Analysis of HyMap data for band selection**
- **Spectral Bands: 6 significant wavelengths (6 class problem) 500, <u>670</u>, <u>740</u>, 770, 1980, 2320nm**



Processing issues: Band selection

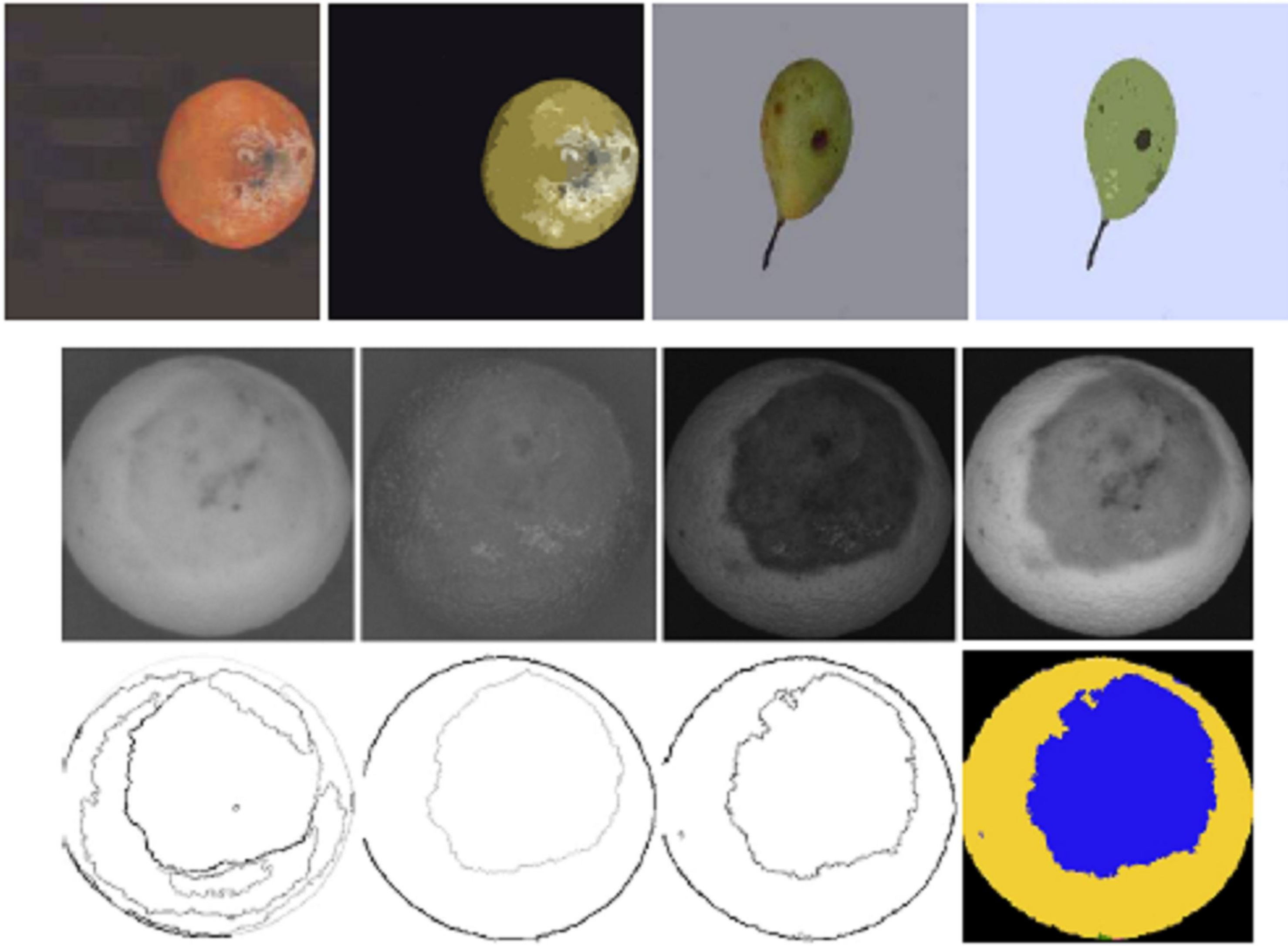


Processing issues: Band aggregation



From Martinez-Uso at altii ICIAR 2008

Processing issues: Segmentation

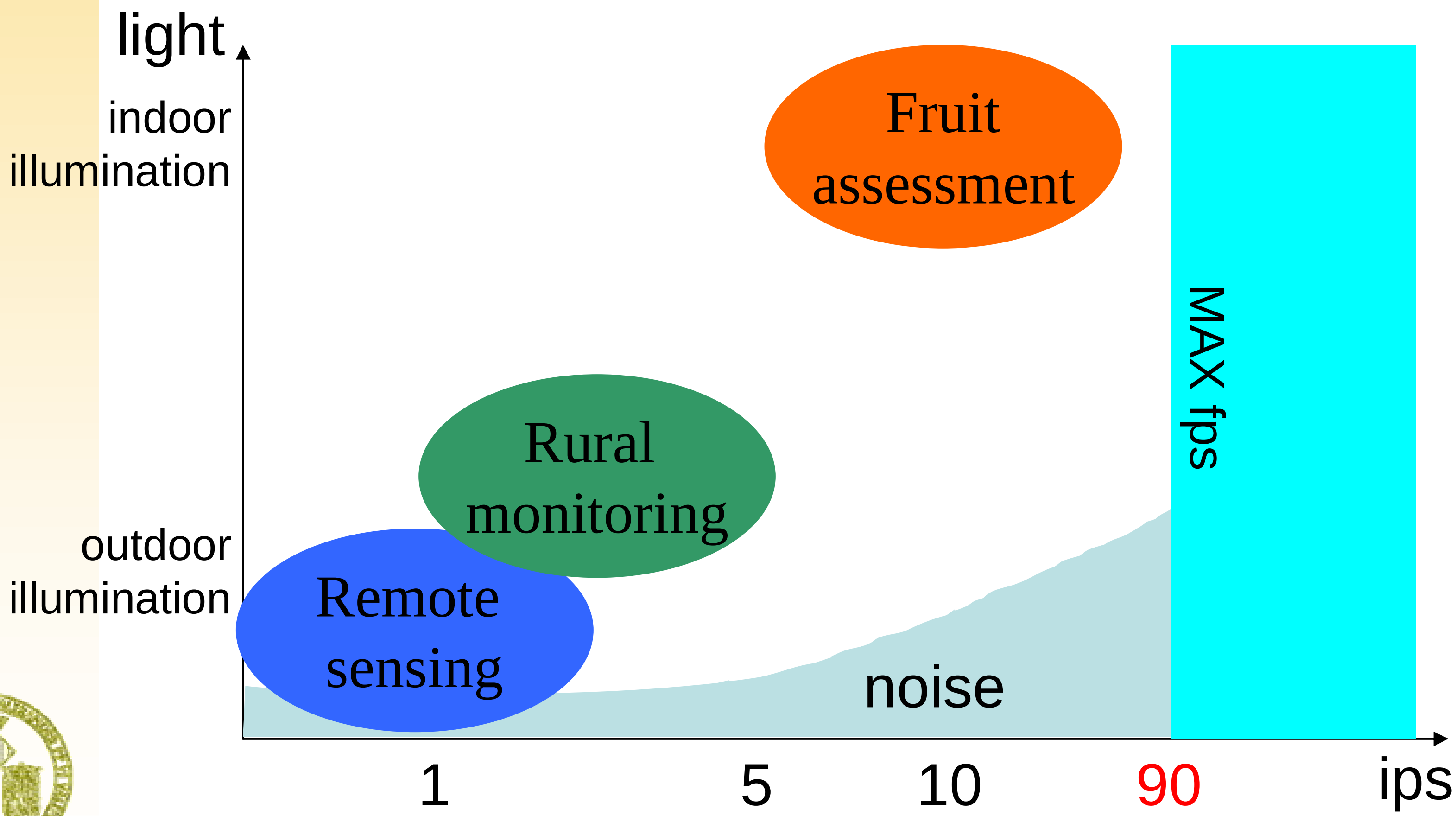


Courtesy Filiberto Pla, UJI

CONTENTS

- Problem definition
- Filtering methods
- Sensors
- Data processing issues
- **Applications**
- Future trends

Applications



worst case analysis ips = 6 fps

Applications: Remote Sensing

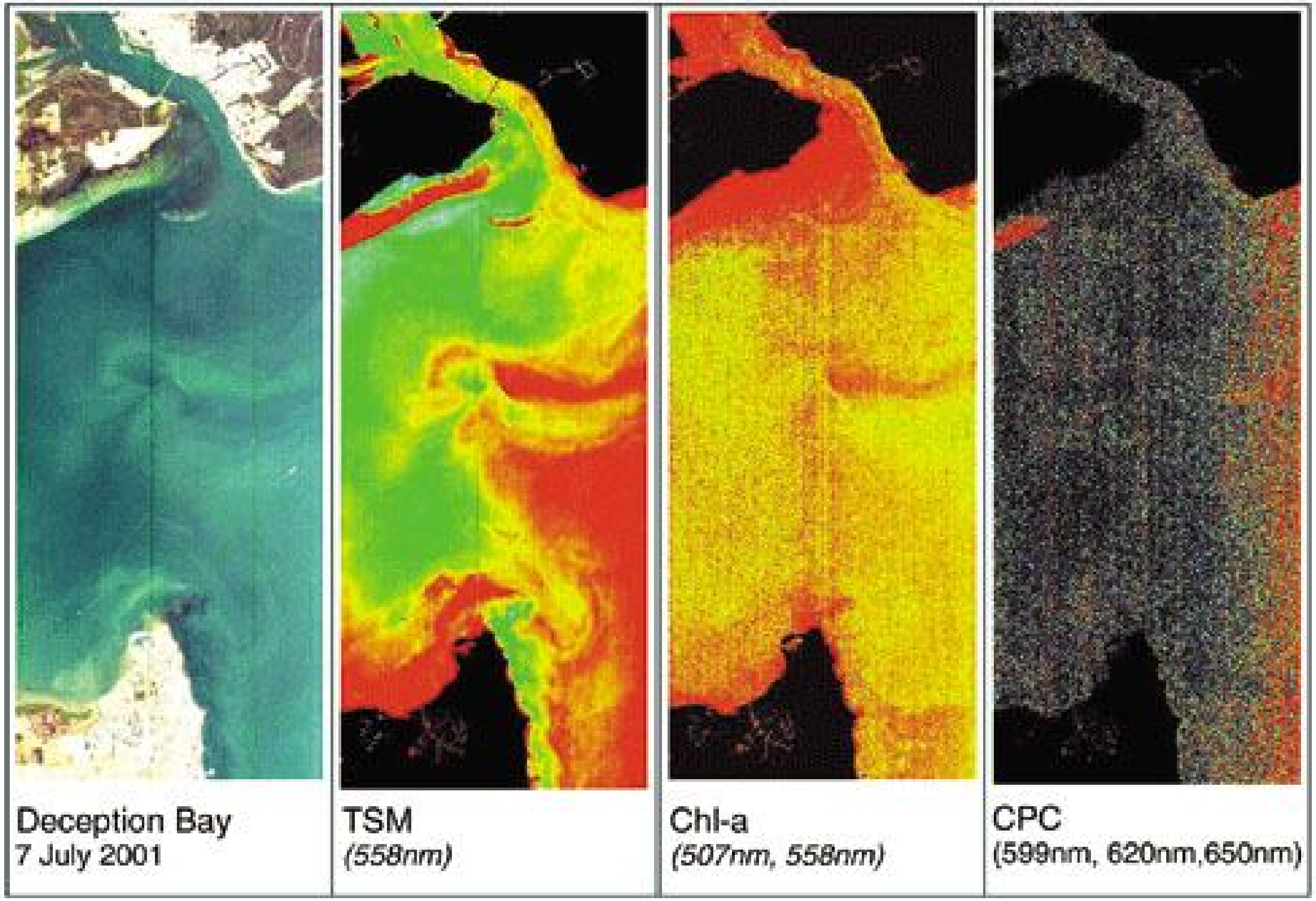
MERIS on Envisat

- MERIS 15 spectral bands

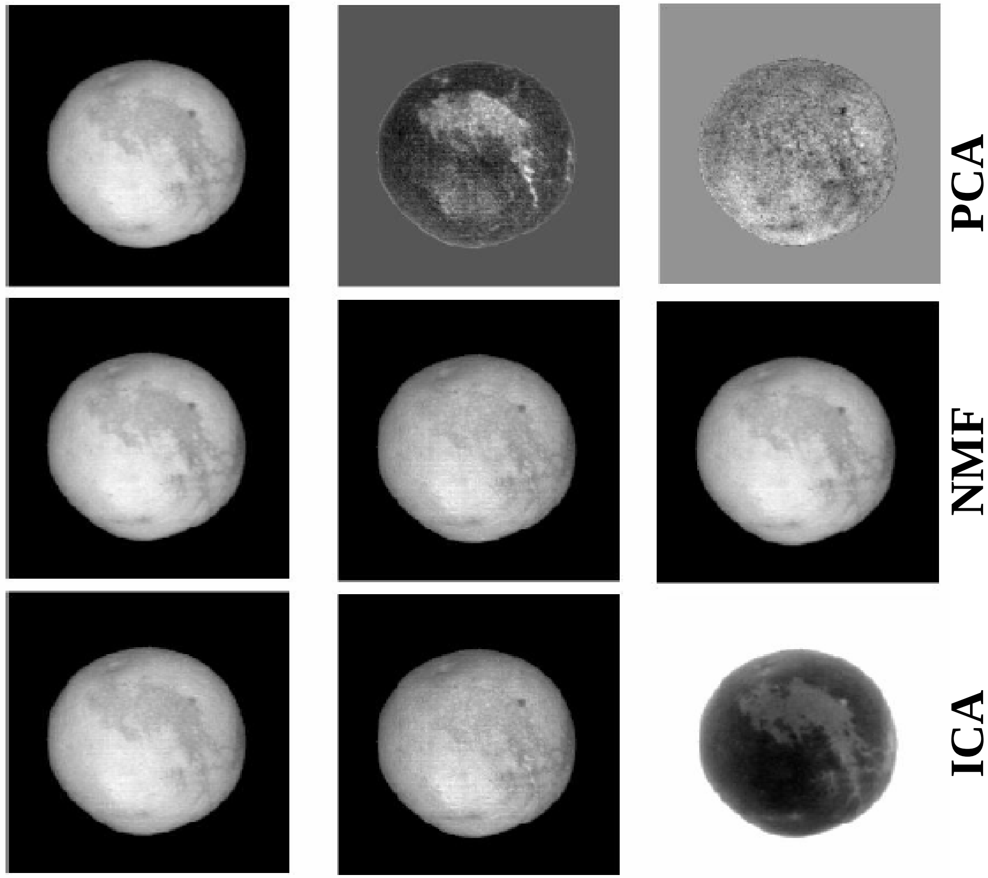
	Band	Band centre (nm)	Bandwidth (nm)	Primary Use
VISIBLE	1	412.5	10	Yellow substance and detrital pigments
	2	442.5	10	Chlorophyll absorption maximum
	3	490	10	Chlorophyll and other pigments
	4	510	10	Suspended sediment, red tides
	5	560	10	Chlorophyll absorption minimum
	6	620	10	Suspended sediment
	7	665	10	Chlorophyll absorption and fluo. reference
	8	681.25	7.5	Chlorophyll fluorescence peak
	9	708.75	10	Fluo. Reference, atmospheric corrections
INFRARED	10	753.75	7.5	Vegetation, cloud
	11	760.625	3.75	Oxygen absorption R-branch
	12	778.75	15	Atmosphere corrections
	13	865	20	Vegetation, water vapour reference
	14	885	10	Atmosphere corrections
	15	900	10	Water vapour, land

Applications: Remote sensing

Qualitative products in Moreton Bay. TSM = total suspended matter. CPC refers to cyanophycocyanin

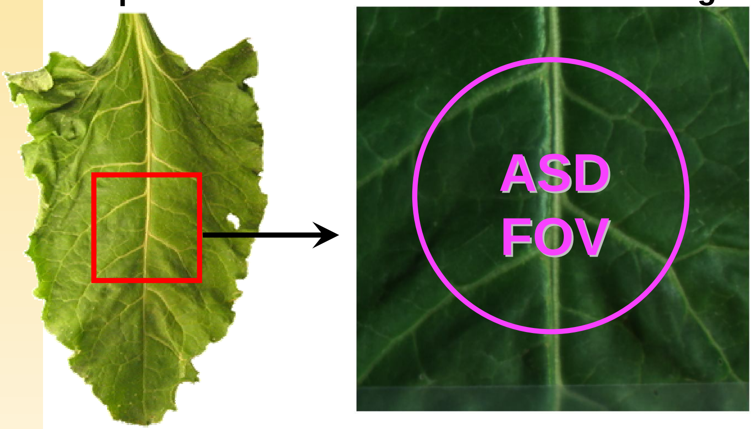


Applications: Classification

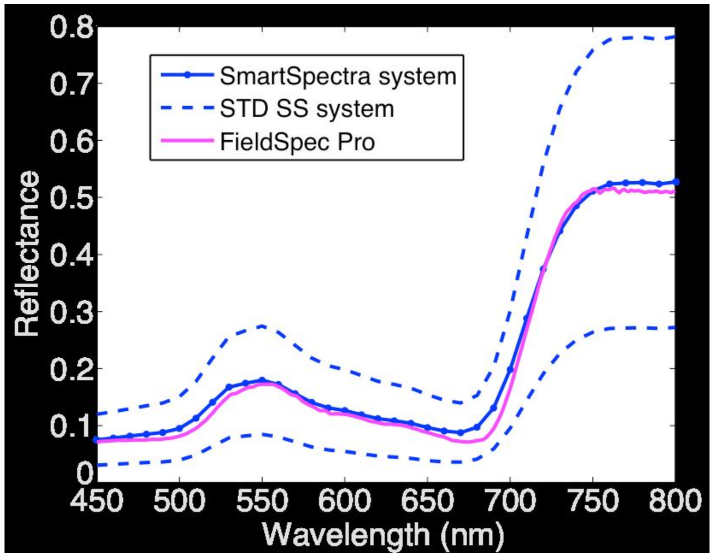


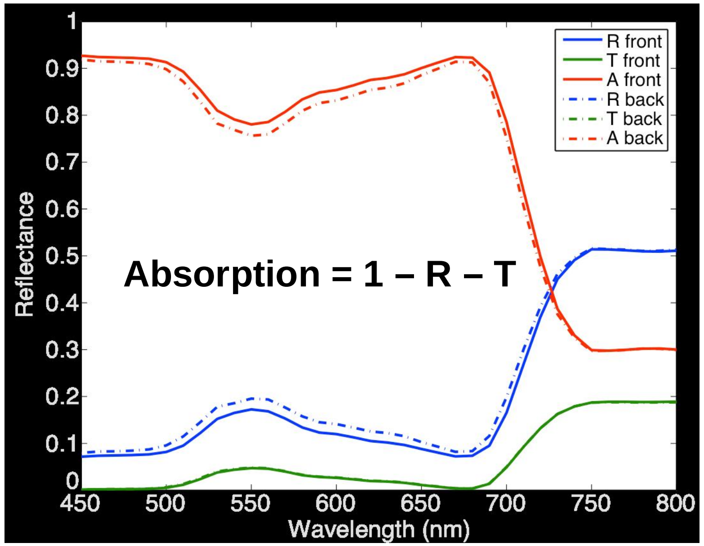
Orange with trip
Courtesy F. Pla

Applications: Light Absorption in Leaves



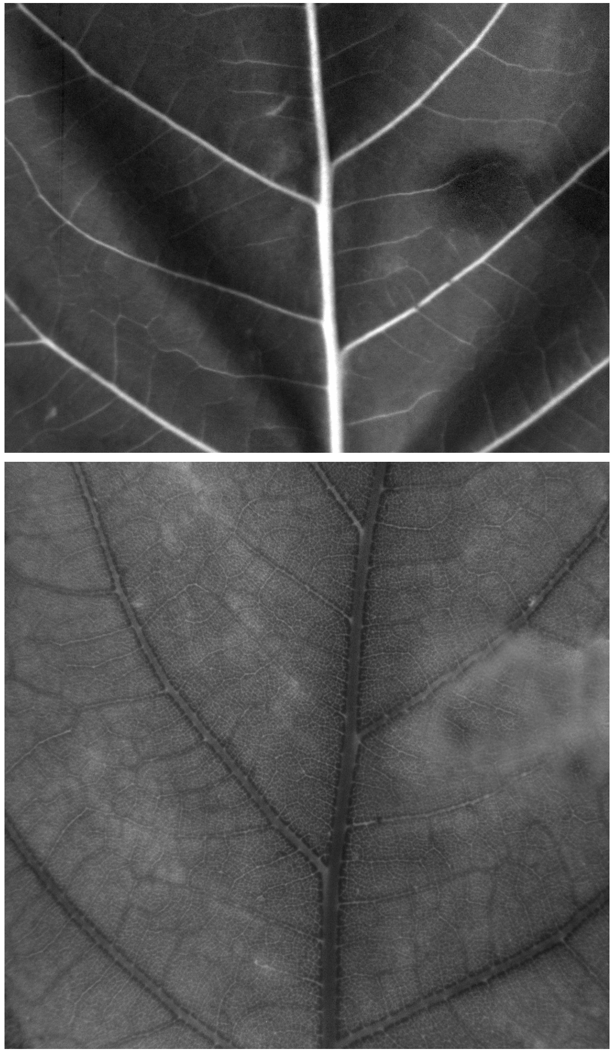
- Two sugar beet leaves were acquired with the FR at the same time that the ATFS
- FR Spectrum compared to the integrated area in the AOTF image
- Absorption estimated from abaxial and adaxial leaf measurements



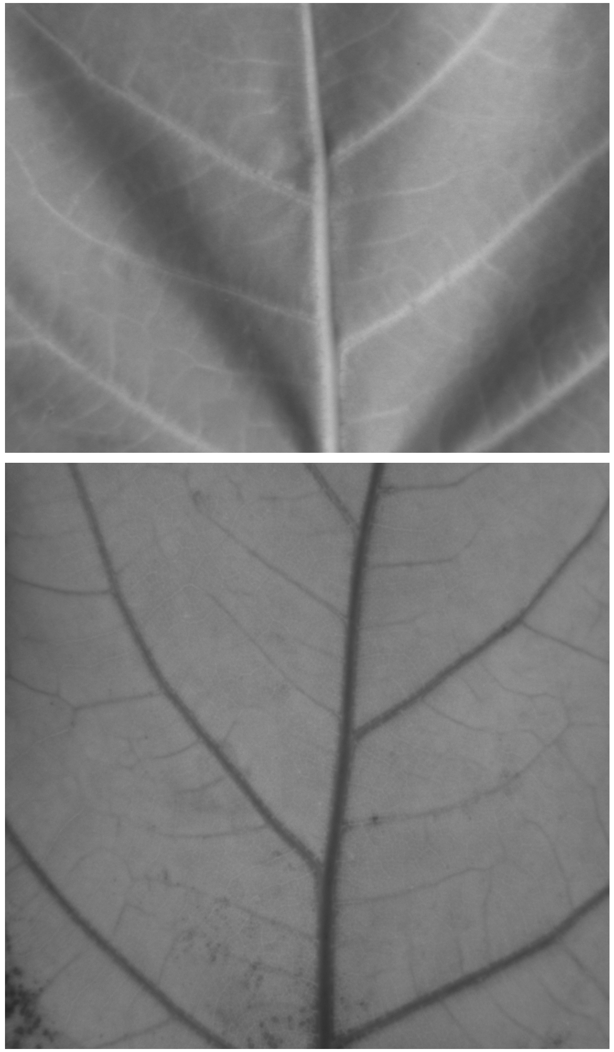


Applications: Light Absorption in Leaves

550 nm (equallized for visualization)



850 nm



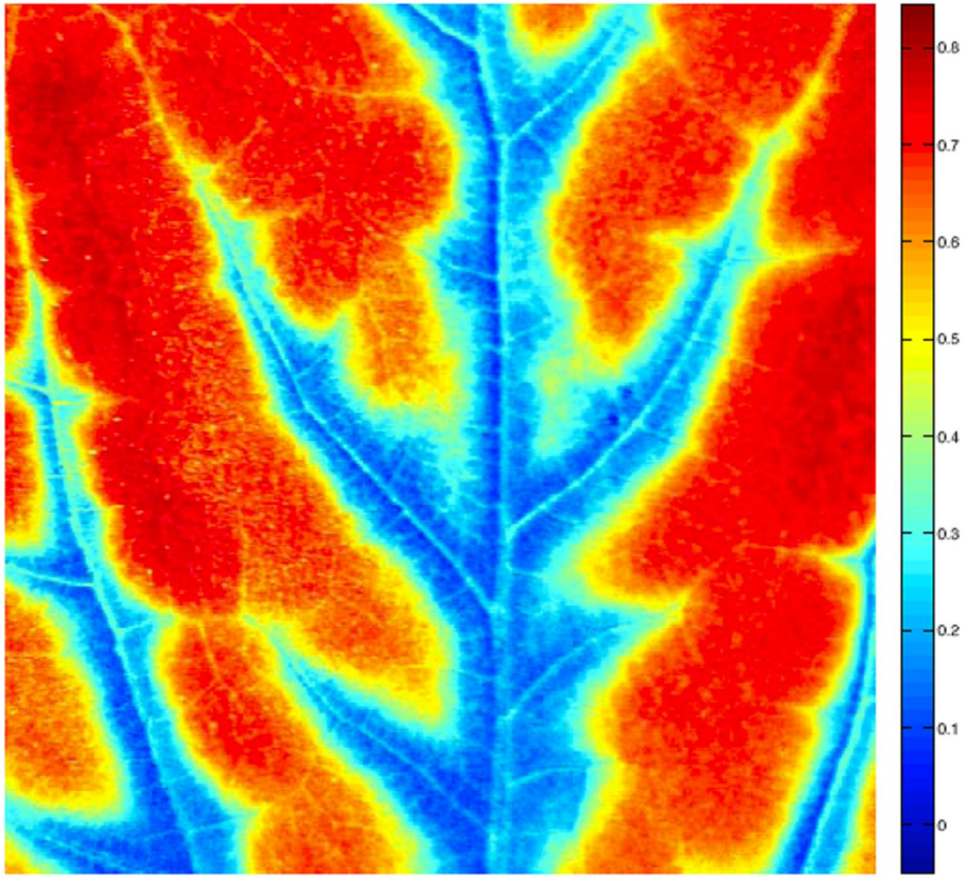
Sample A

Sample B

Applications: Light Absorption in Leaves

Potato

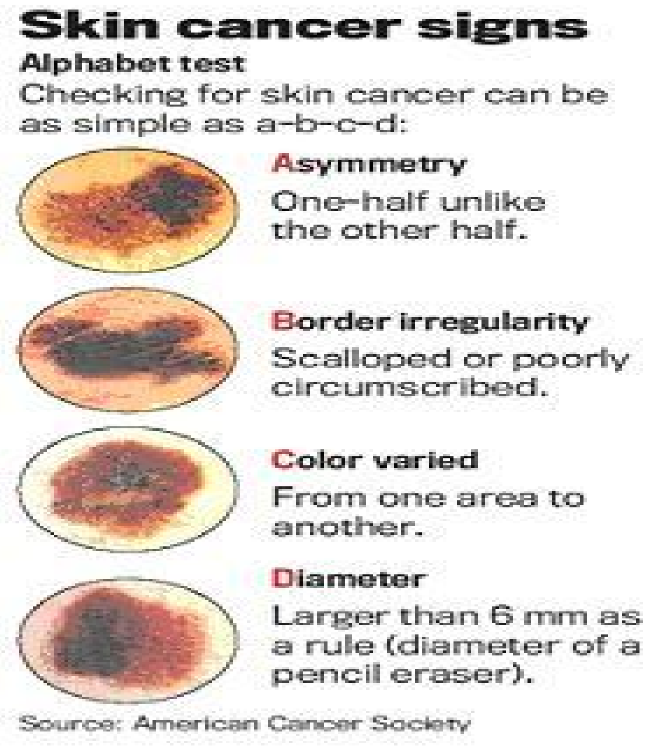
Applications: Light Absorption in Leaves

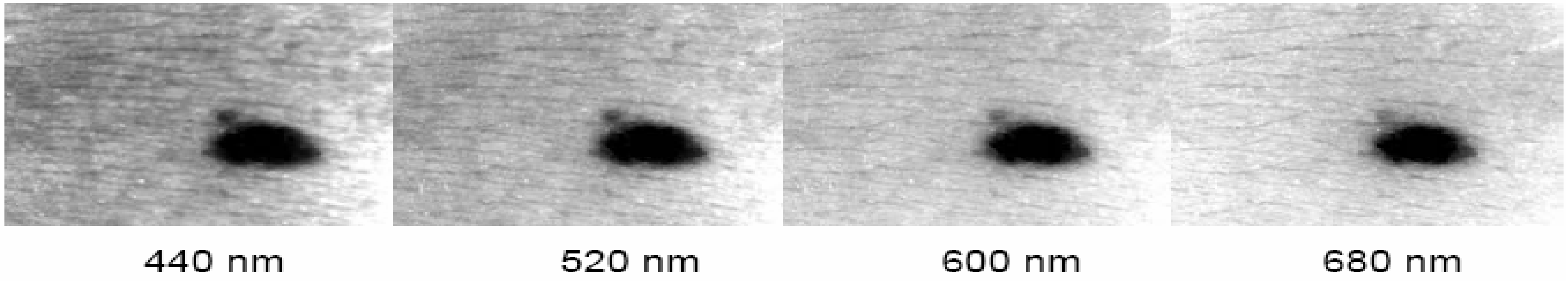


Chlorophyll content estimate for a sunflower (Helianthus annuus) leaf, using the NDVI index (R800-R680)/(R800+R680), Courtesy: Joan Vila

Applications: Dermatology

- Requirements:
  - Spectral range: 440 - 750nm
  - Bandwidth around 10nm
  - Resolution > 500x500 pixels.
  - SNR: > 50dB.



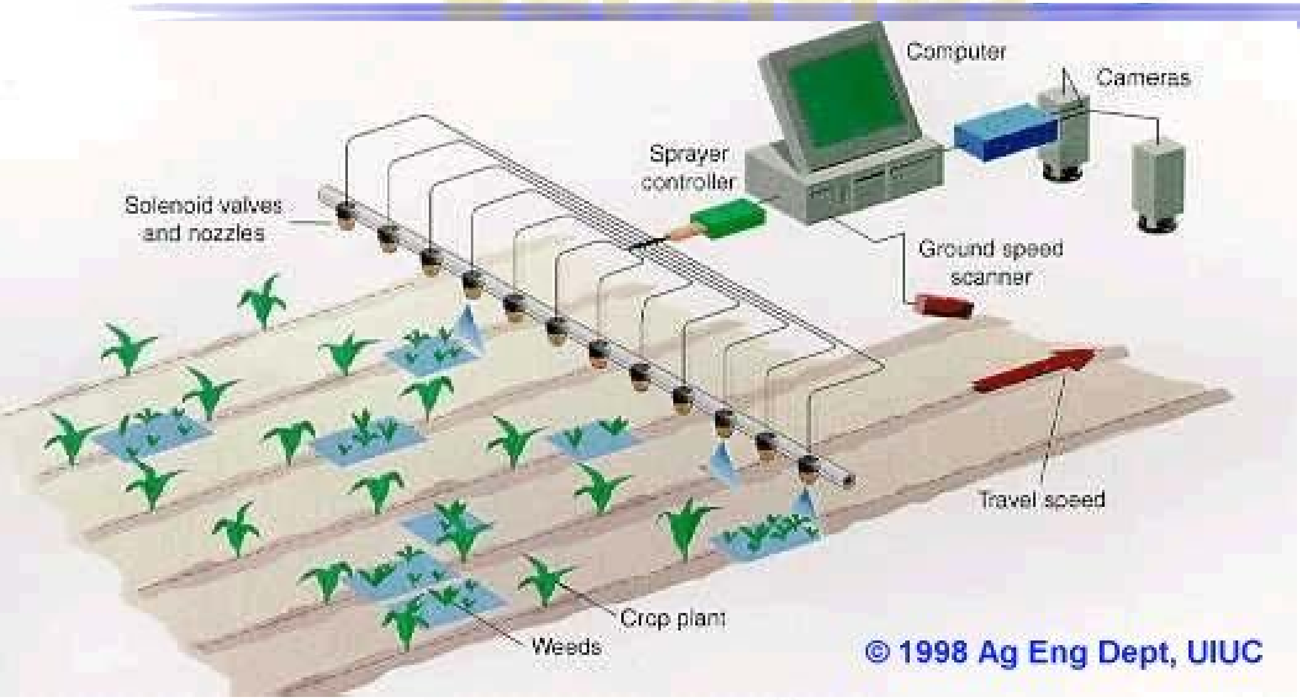


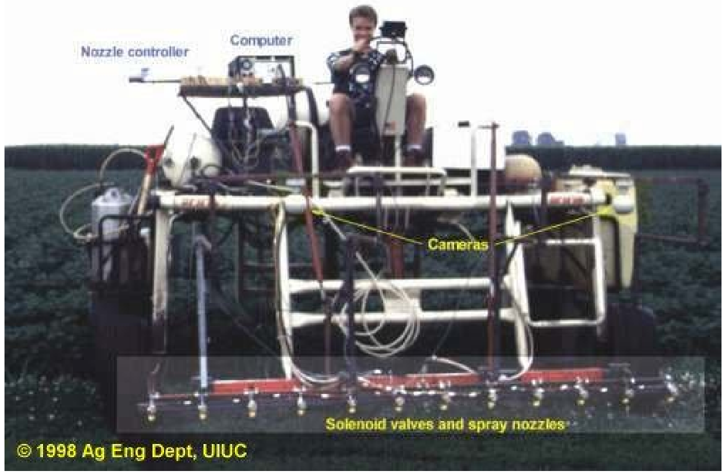
Applications: Food processing automation

Fecal and ingesta detection on poultry carcases (U.S. Dept. of Agriculture)

- **System: Three CCD (Monochrome) sensors with filters**
- **Spectral Bands: 3 spectral bands (470-960 nm)**
  445nm ⇒ deoxymyoglobin (DeoxyMb)
  485nm ⇒ metmyoglobin (MetMb)
  560nm ⇒ oxymyoglobin (OxyMb)
  635nm ⇒ sulfmyoglobin (SulfMb)
  465, 575, 705 nm ⇒ skin tumors
- **Speed: Real time (90 birds/min. ~ 2im./sec)**
- **Implications: Significant wavelengths required (Imspector)**

Applications: Precision agriculture





Future

- Imaging is evolving from few bands to many bands
- Remote sensing pioneered the field, shy industrial penetration
- More sensitive sensors pave the way to extension
- Synergy with different sensors
- New processing algorithms will be required

Monochrome

RGB

Multispectral

Hyperspectral

Ultraspectral