Techniques and applications for real-time spectral imaging: from gas sensing to in vivo imaging

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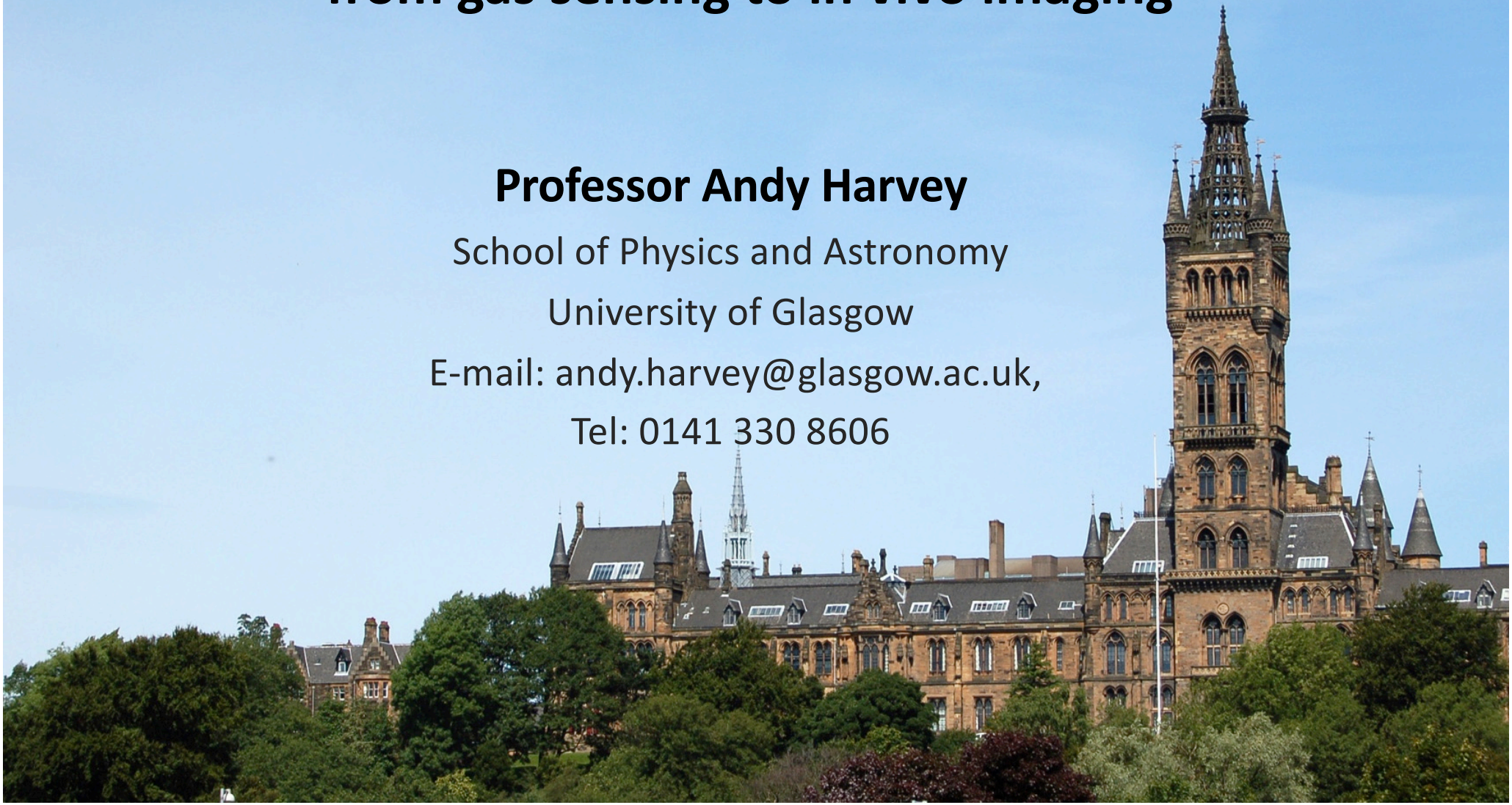
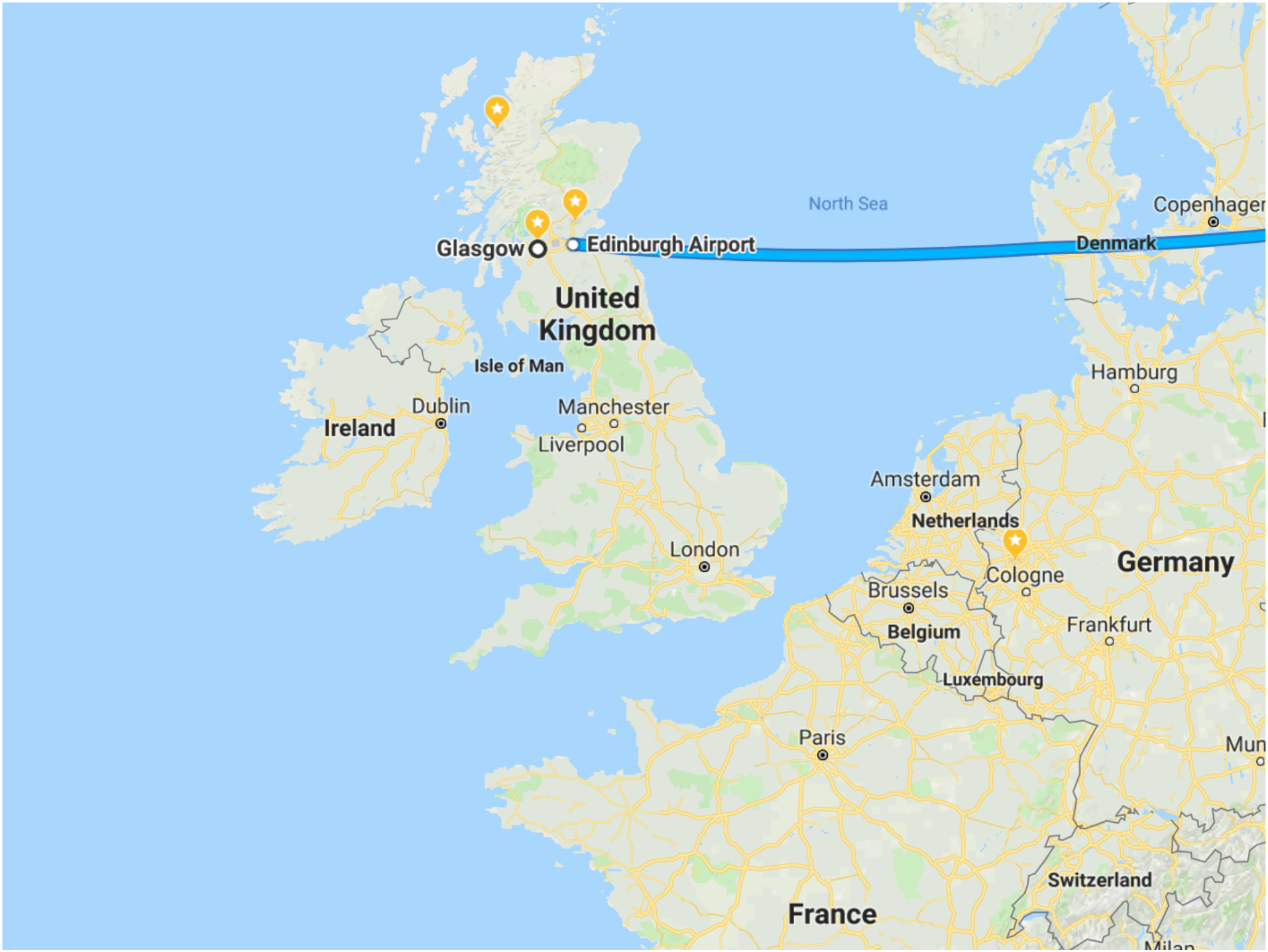
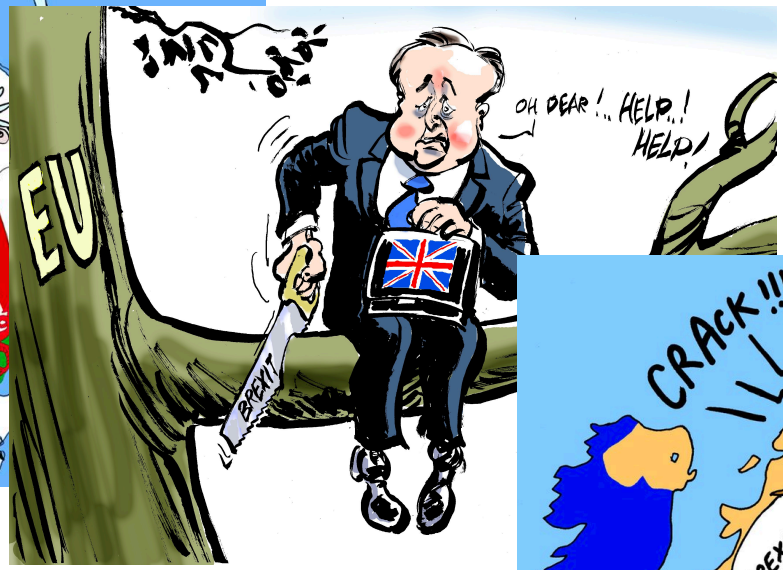
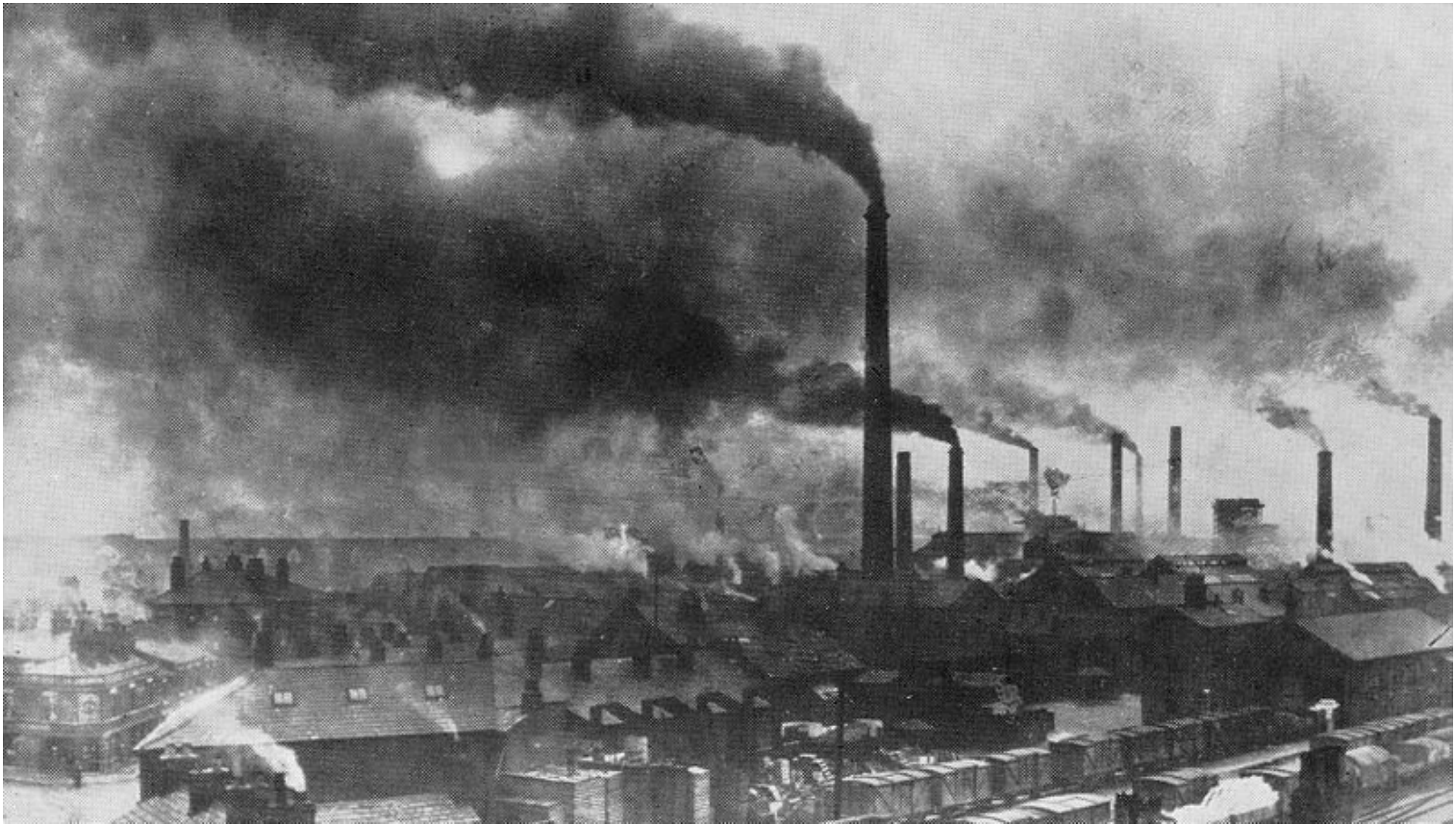



North Sea
Copenhagen
Glasgow
Edinburgh Airport
Denmark
United Kingdom
Isle of Man
Hamburg
Dublin
Ireland
Manchester
Liverpool
Amsterdam
Netherlands
London
Germany
Cologne
Brussels
Belgium
Frankfurt
Luxembourg
Paris
Switzerland
France


CHRIS MADDEN
NEWS
SCOTS INDEPENDENCE REFERENDUM


EU
BREXIT
OH DEAR!.. HELP..! HELP!

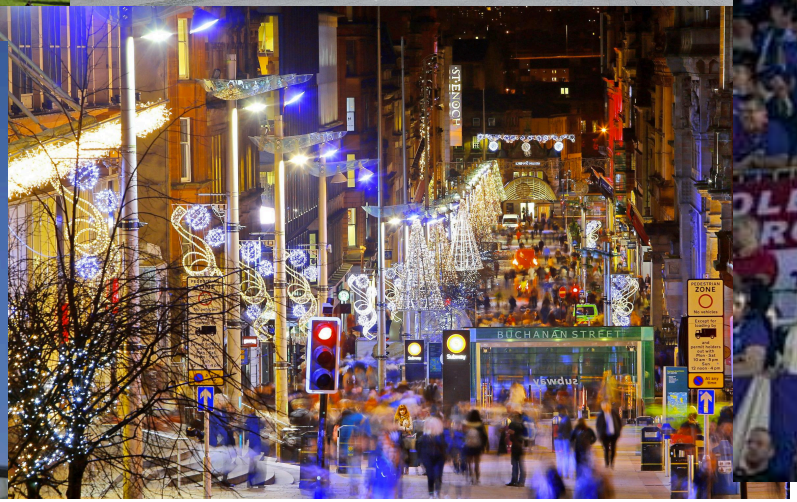

CRACK!!!
SCOTLAND
BREXIT
?
EU



Glasgow in 1848


PEOPLE MAKE GLASGOW
Let's Celebrate


OLERAINE
ROOPS
RANGERS


BUCHANAN STREET

University of Glasgow

1451
THE UNIVERSITY IS ESTABLISHED

1848
LORD KELVIN PROPOSES AN ABSOLUTE TEMPERATURE SCALE, NOW CALLED THE KELVIN SCALE

1896
JOHN MACINTYRE OPENS THE WORLD'S FIRST X-RAY DEPARTMENT

1926
JOHN LOGIE BAIRD INVENTS TELEVISION

1967
JOCELYN BELL BURNELL DISCOVERS RADIO PULSARS

2012
HIGGS BOSON DISCOVERED (EDINBURGH)

2015
SHEILA ROWAN LEADS THE GLASGOW TEAM THAT FIRST DETECTED GRAVITATIONAL WAVES

~1760s
JAMES WATT ENGINEER

1776
ADAM SMITH PUBLISHES *THE WEALTH OF NATIONS*

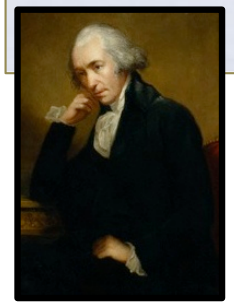
1867
JOSEPH LISTER INTRODUCES ANTISEPTIC IN SURGERY

1913
NOBEL PRIZEWINNER FREDERICK SODDY DISCOVERS ISOTOPES

1958
IAN DONALD SHOWS US THE FIRST ULTRASOUND IMAGE OF A FOETUS

1974
GRAHAM TEASDALE AND BRYAN JENNETT CREATE THE GLASGOW COMA SCALE

2017
NAMED SCOTTISH UNIVERSITY OF THE YEAR



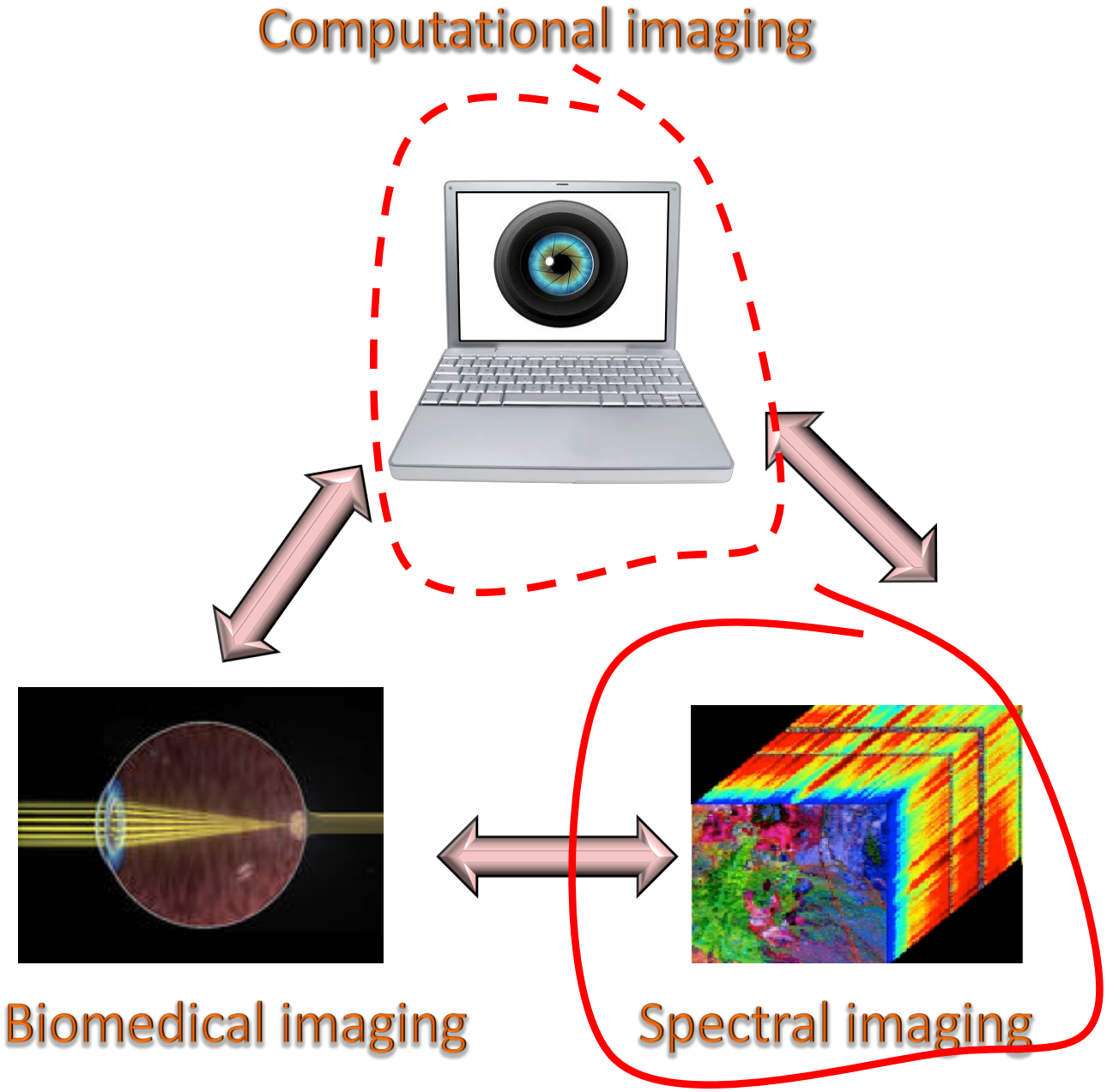
WORLD CHANGING CONTRIBUTIONS

Our current staff includes four **Fellows of the Royal Society**, twelve **Fellows of the Royal Society of Edinburgh** and a **Royal Society Research Professor**

World-leading achievements by our staff and students have been recognised by dozens of **national and international prizes**, **honours** and **awards** – far too many to list in full!

Here are a few recent examples of our **Physics & Astronomy World Changers** receiving their awards…

IMAGING CONCEPTS GROUP



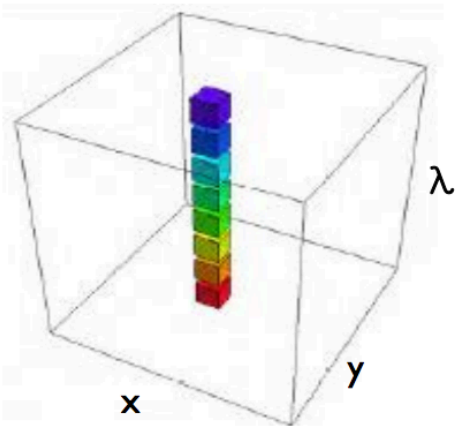
- R&T
  - Andy Harvey (Head)
  - Jonny Taylor
  - Caroline Müllenbroich
- Research Fellows
  - Guillem Carles
  - Chas Nelson
- PDRA
  - Miguel Preciado
  - Pavi Konda
- PhD
  - Yongzhuang Zhou
  - Stuart Wilson
  - Ross Dryesdale
  - Laura Cowan
  - Tomas Aidukas
  - Julia McFarlane
  - Jamie Foubister
  - Michael Handley
  - Uné Butaite
  - Chiara Garbelletto
  - Victor Gutierrez
  - Mohammad Pourmand
  - Daniel Olesker
  - Fernanda Alvim

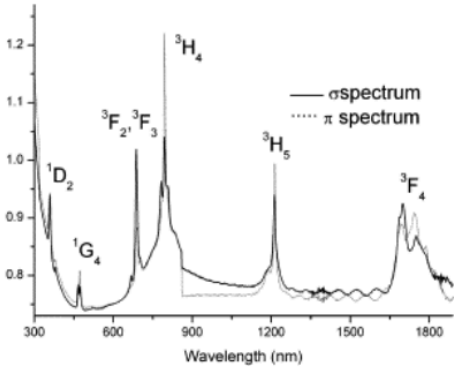
Techniques and applications for real-time spectral imaging: from gas sensing to in vivo imaging

- What is spectral imaging
  - and how is it done (well)?
- Real-time spectral imaging?
- Some applications
  - Biomedical
  - Thermal infrared

(Hyper)spectral imaging

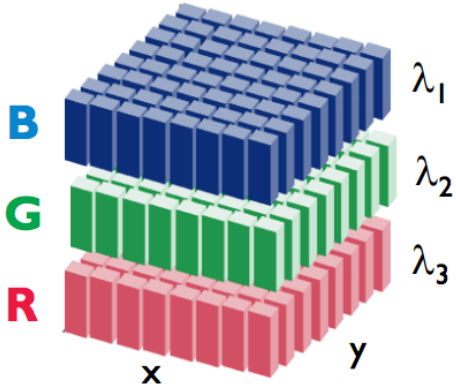
SPECTROSCOPY





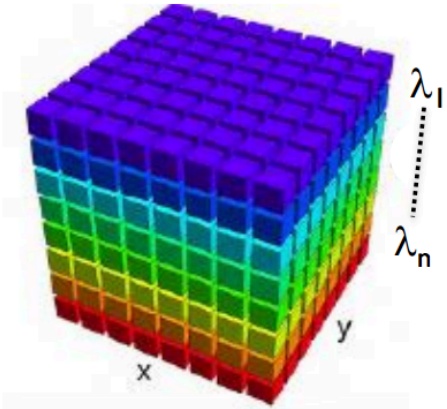
→ Accurate **spectral analysis** of **one spatial pixel** only

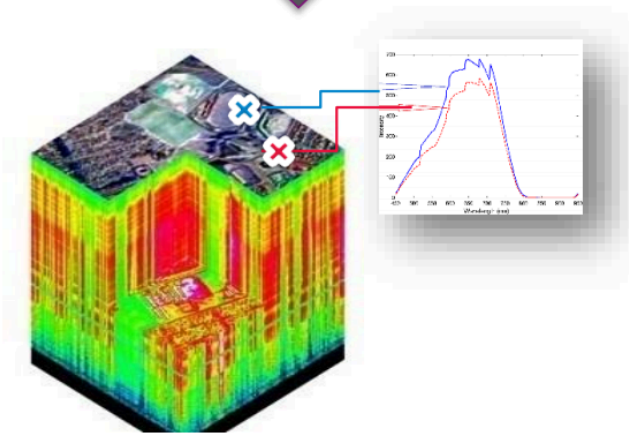
COLOR IMAGING



→ Seeing **RGB colors** of **one image** only

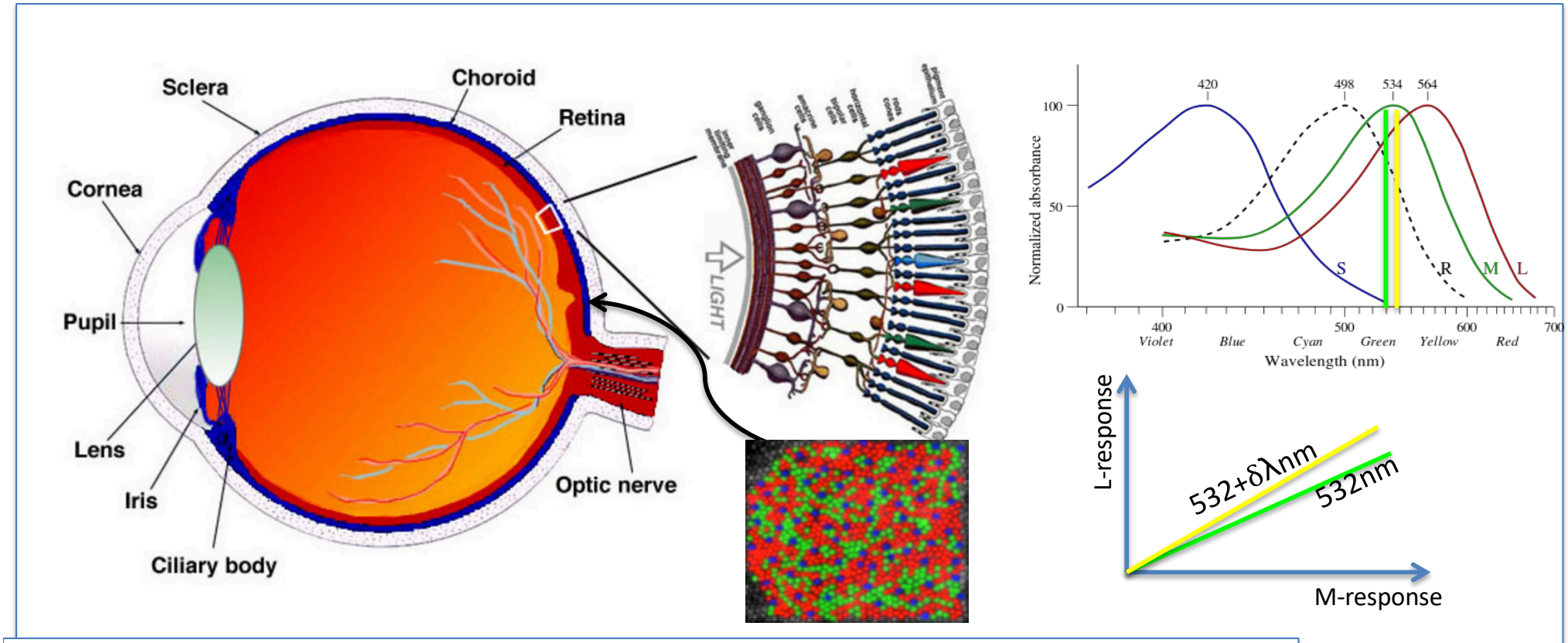
HYPERSPECTRAL IMAGING

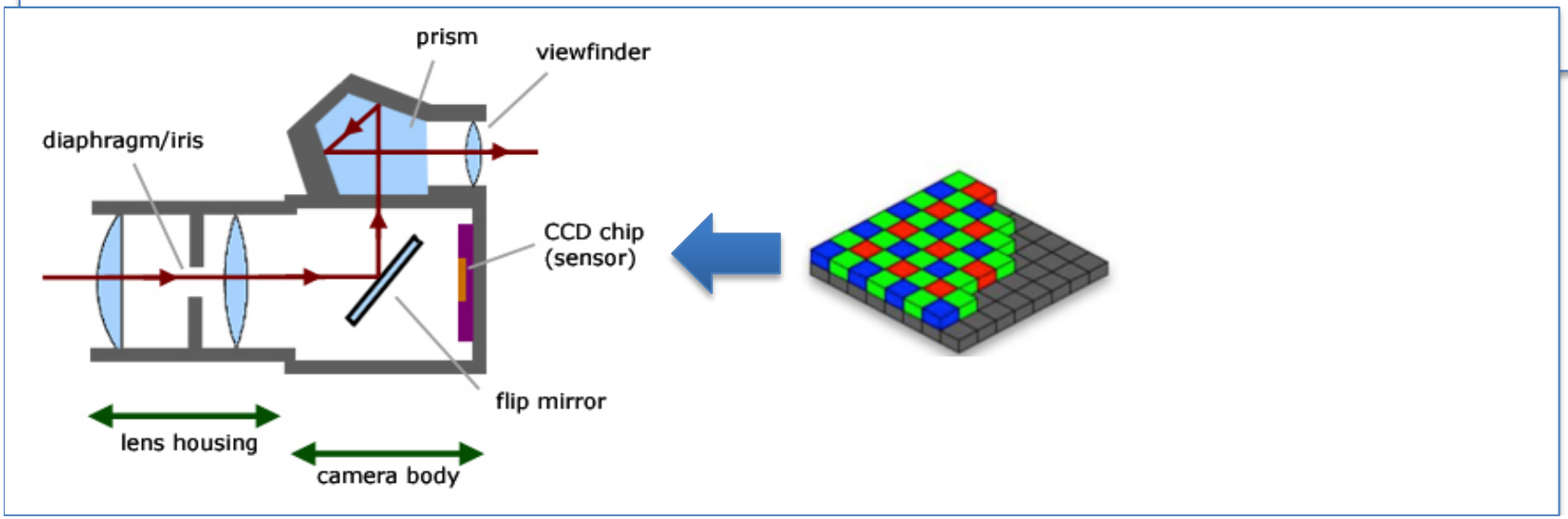




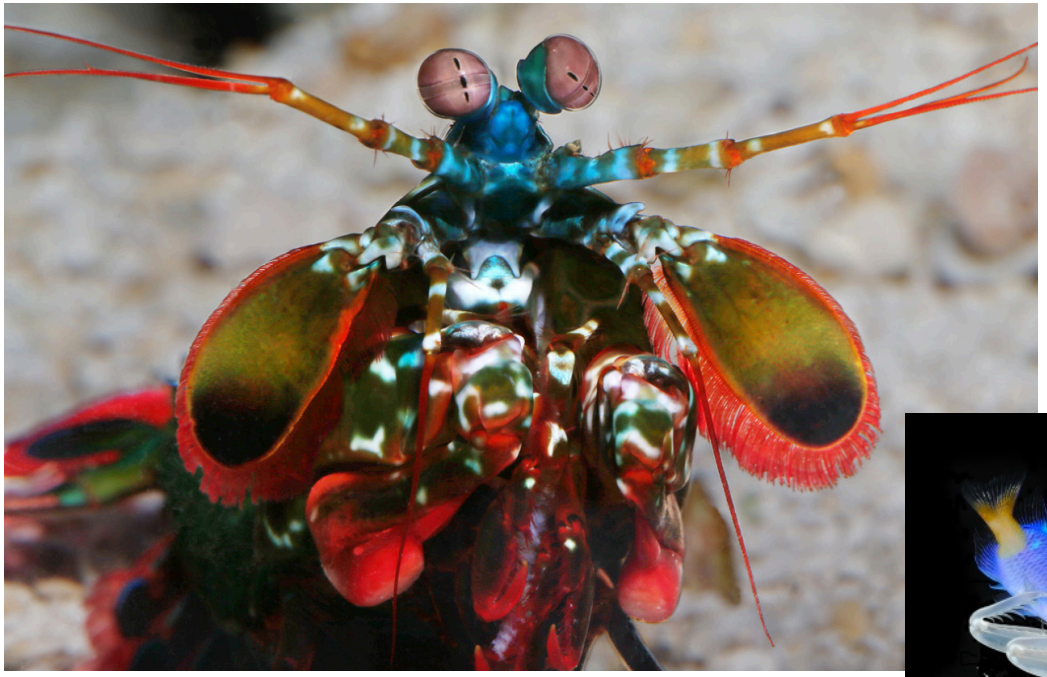
→ **spectral signature** images revealing **objects chemical composition**

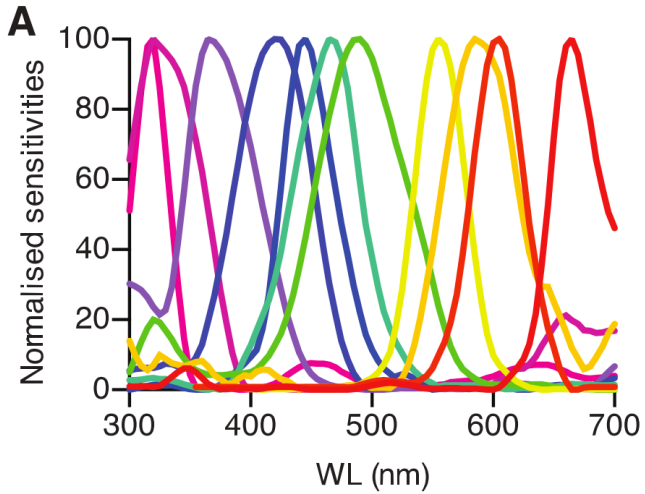
Colour imaging

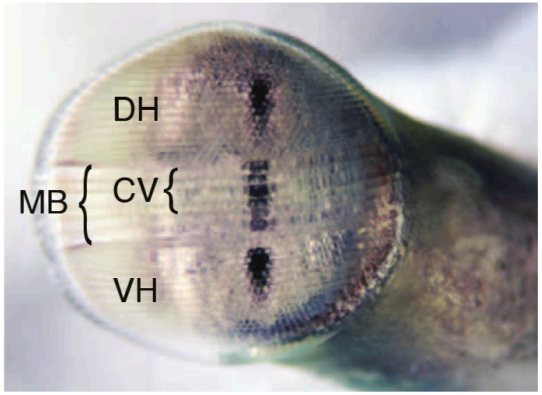




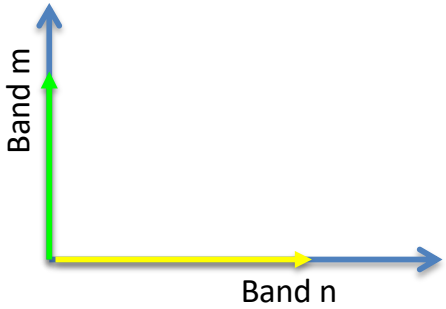
The Mantis shrimp: polarimetric, multi-spectral





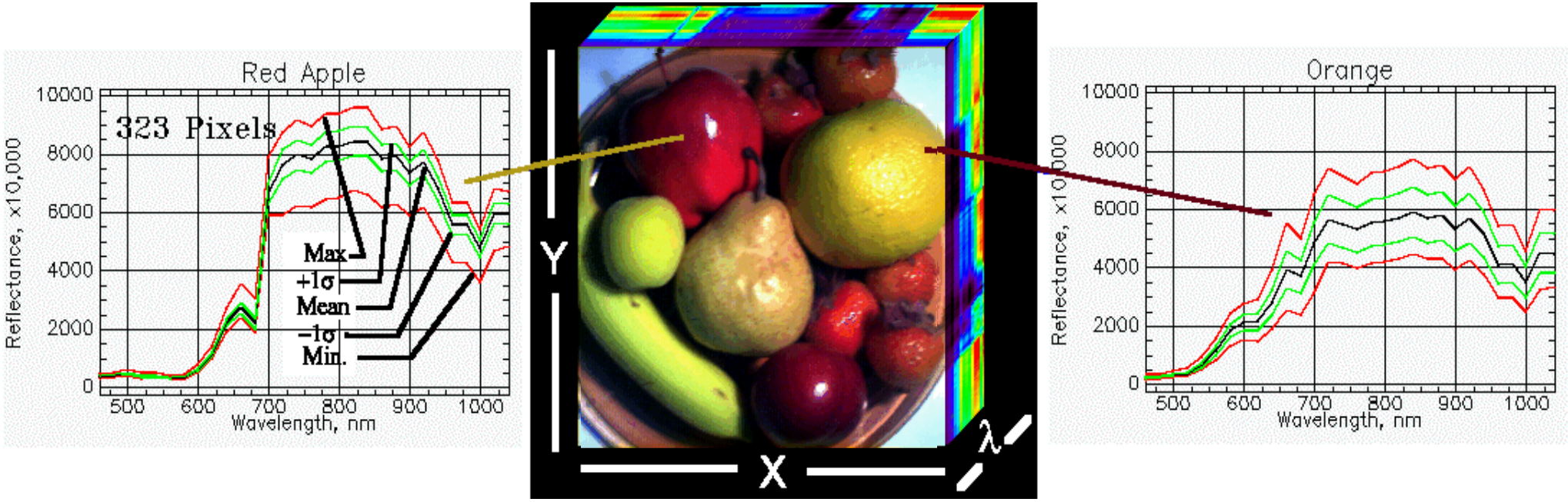


- 12 spectral bands plus polarisation
- Spectral recognition rather than ‘colour’
  - Lower acuity than trichromatic humans
- More like a pushbroom scan than a matrix filter
- Optimal spectral imaging architectures are application specific



Thoen, H. H., How, M. J., Chiou, T.-H. & Marshall, Science (80-.). 343, 411–413 (2014)
Osorio, D. & Vorobyev, M. *Proc. Biol. Sci.* **272,** 1745–1752 (2005)

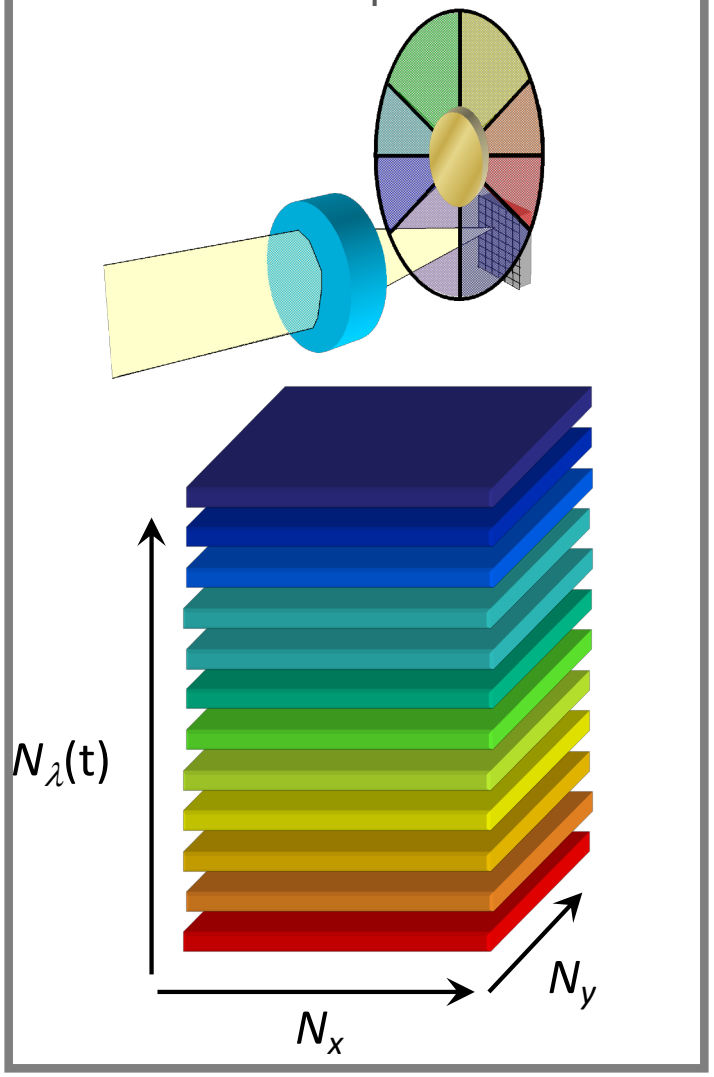
What is scientific *spectral imaging* ?



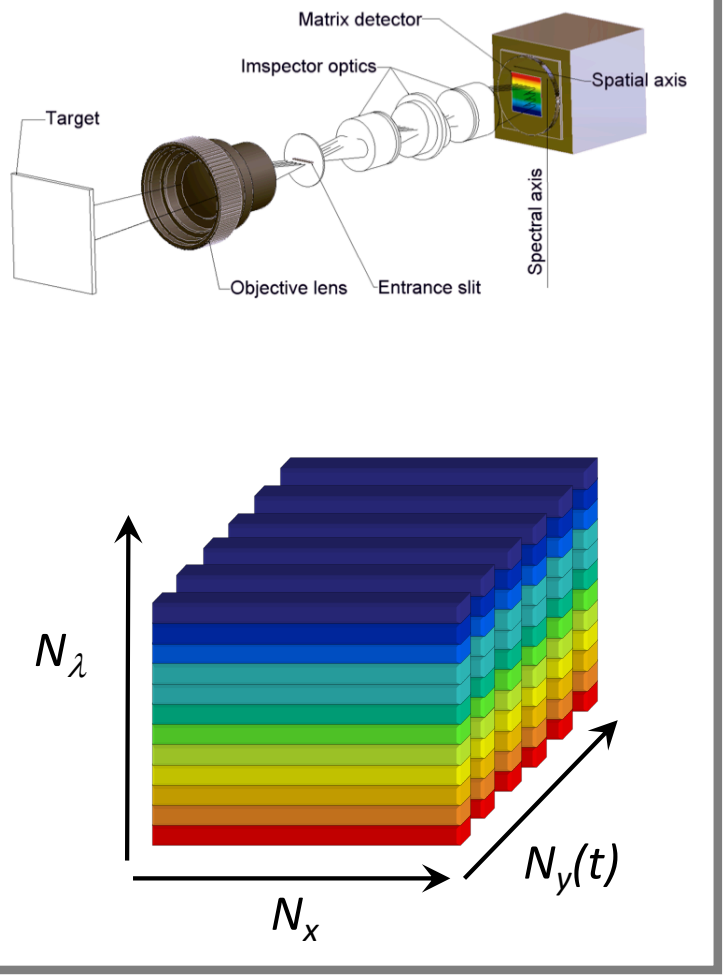
- Equivalent to scanning a spectrophotometer across the scene
- Synergistic combination of imaging and spectrometry
  - eg detection of targets improved by combining both shape and spectral information
  - ‘chemical imaging’

Spectral Imaging:
The Restriction of Traditional instrumentation

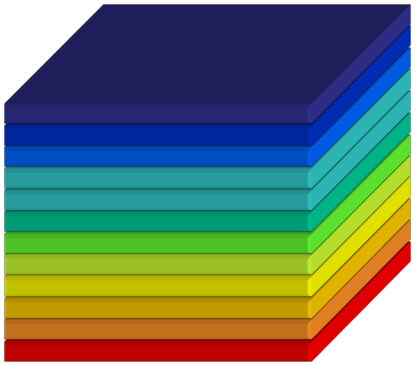
Time-sequential spectral multiplex



Time-sequential spatial multiplex



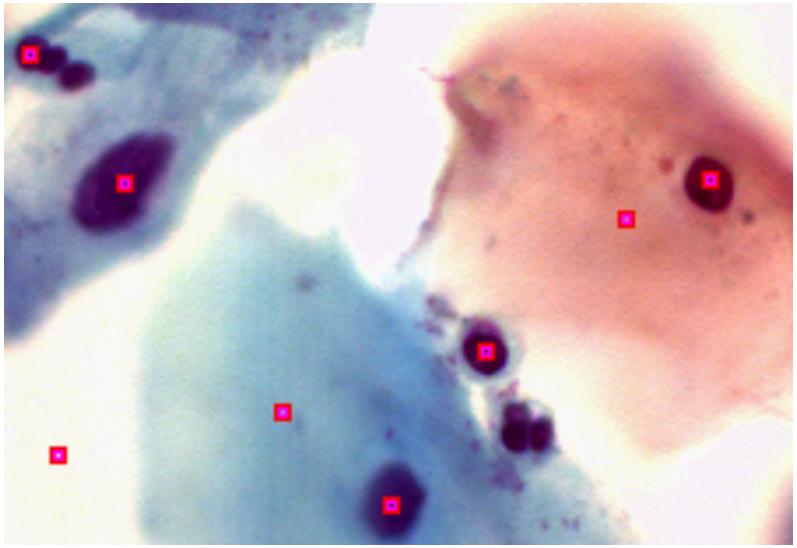
- Limitations
  - Optically inefficient
  - 2D time-varying scenes
- 2D snapshot

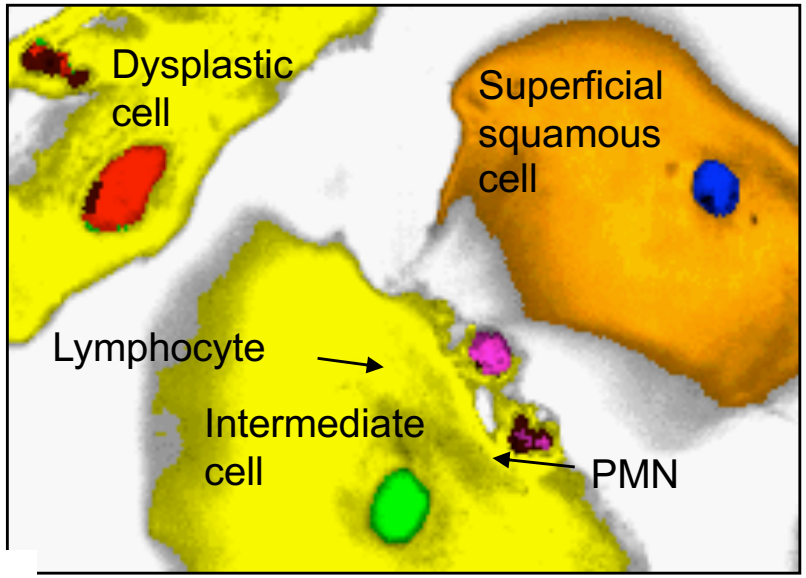


  - required for:
    - *in vitro, in vivo* imaging
    - Surveillance
    - Retinal

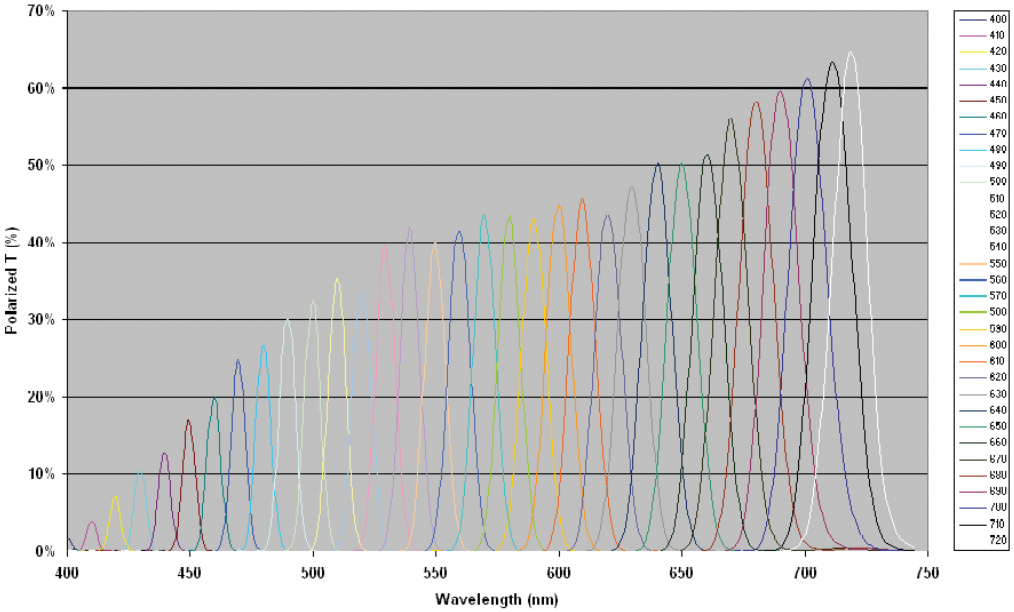
And Fourier-transform equivalents

LCTF Spectral Imaging for classification: Cervico-vaginal smear: moderate dysplasia





Typical VIS-10 VariSpec Filter

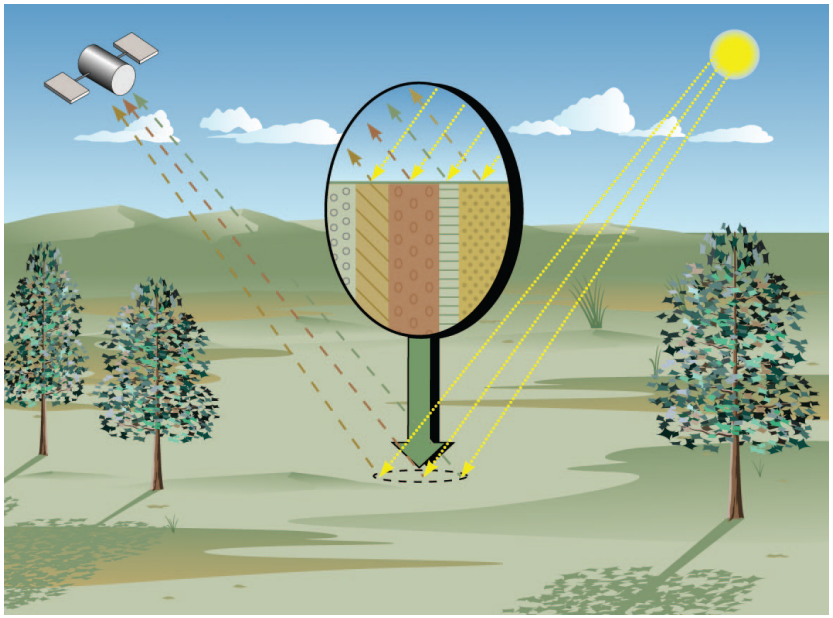


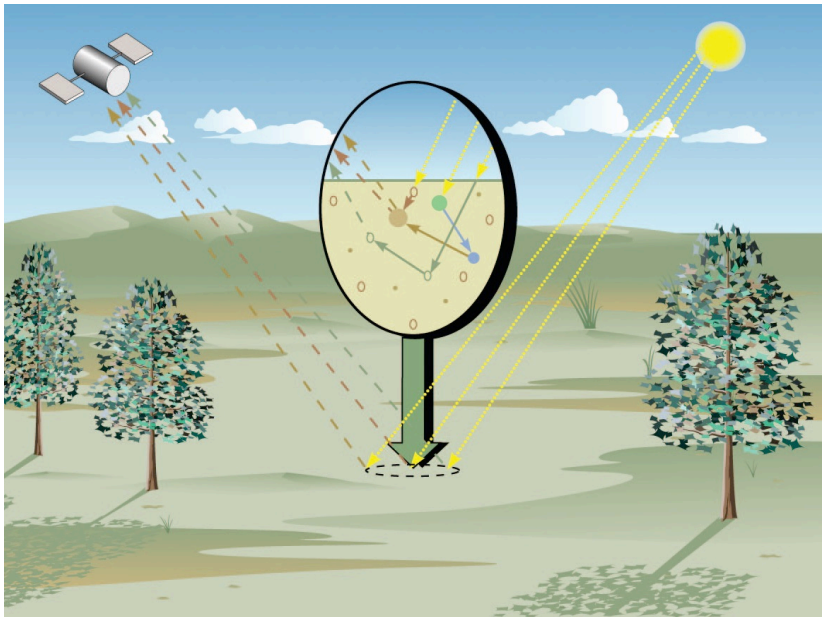
- Coregistration necessary
- Cannot record time-resolved images
- Low optical throughput

Courtesy CRI

Spectral imaging in colour monitoring and matching

Spectral Unmixing





- Linear mixing model

$$x = a_1 S_1 + a_2 S_2 + a_3 S_3 + \ldots + a_M S_M + w$$

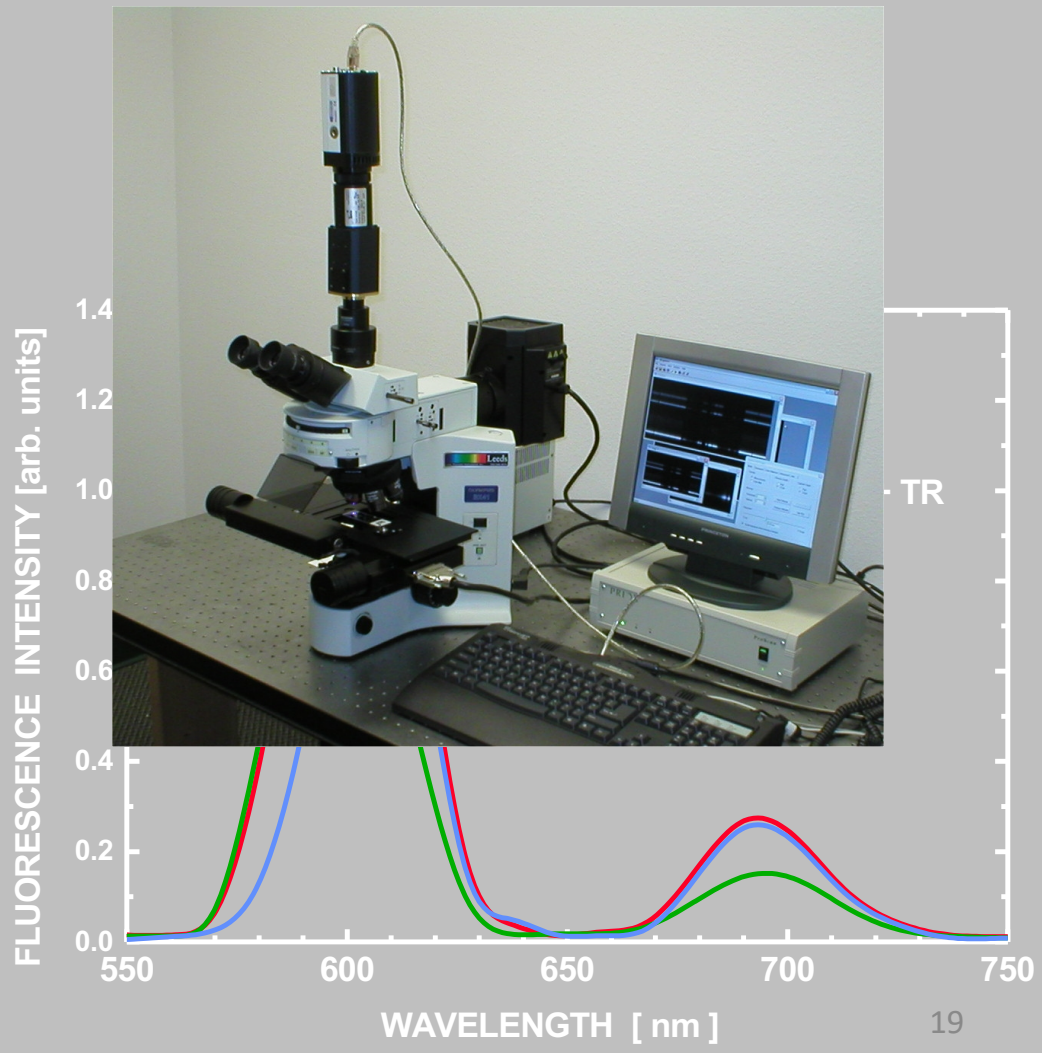
$$= \sum_{i=1}^{M} a_i S_i + w$$

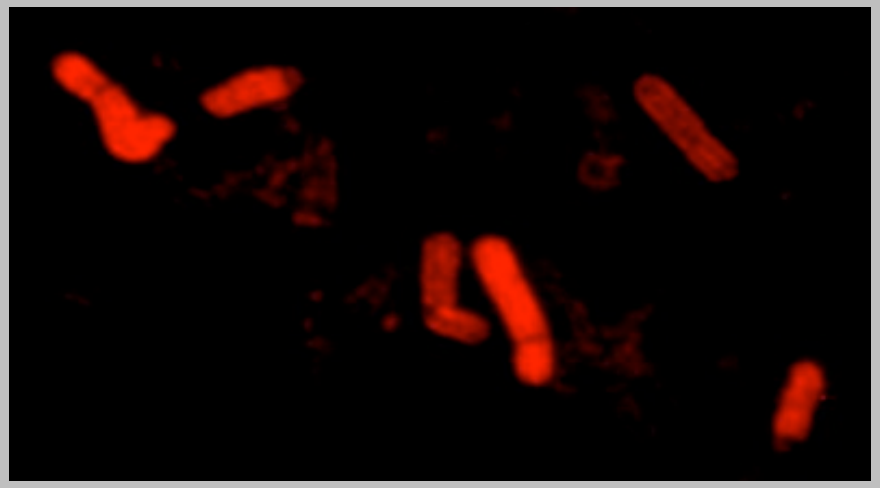
$$\mathbf{X} = \mathbf{AS} + \mathbf{W}$$

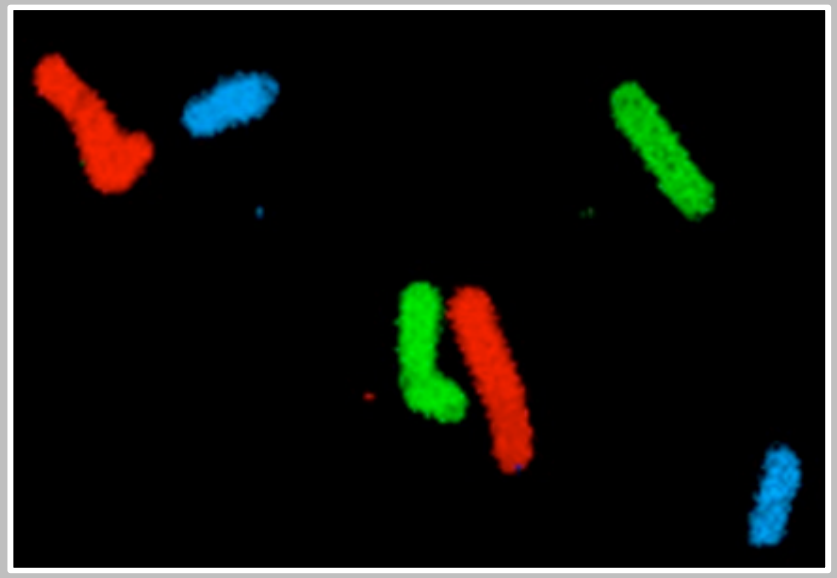
- Solve for A
  - need S!

- Non-linear mixing model
  - X =f(A,S) and depends on how S is mixed
  - Employ physical model to calculate abundances, A
    - Note S often not important

Identification overlapping dyes

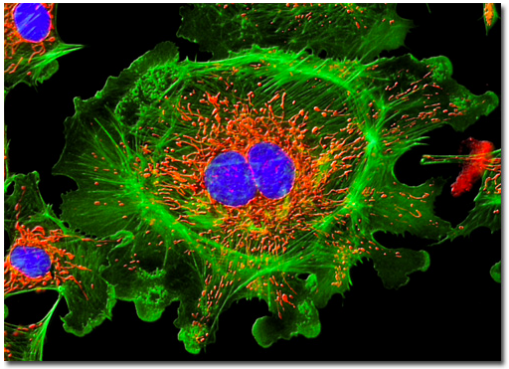


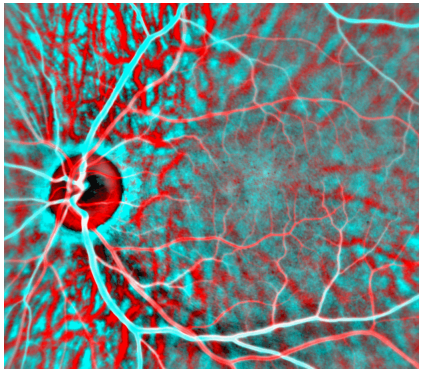




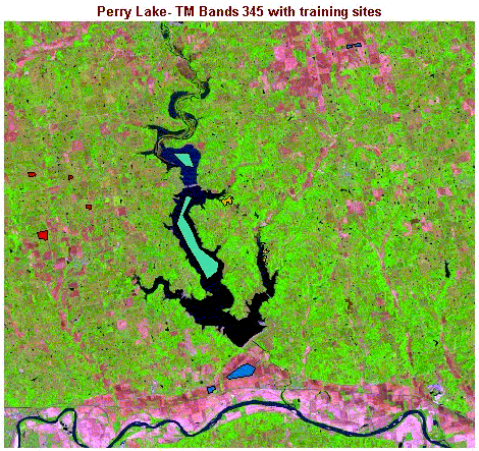
What can be done with spectrum?

- Quantification
  - Spectral unmixing
  - Fluorophore concentration
    - molecular imaging
    - Blood oxygenation

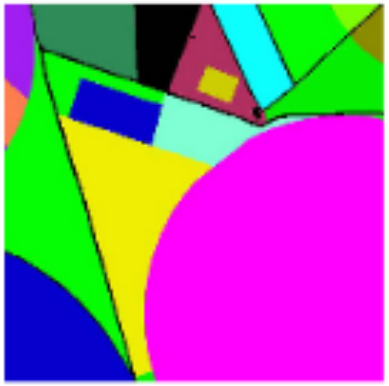




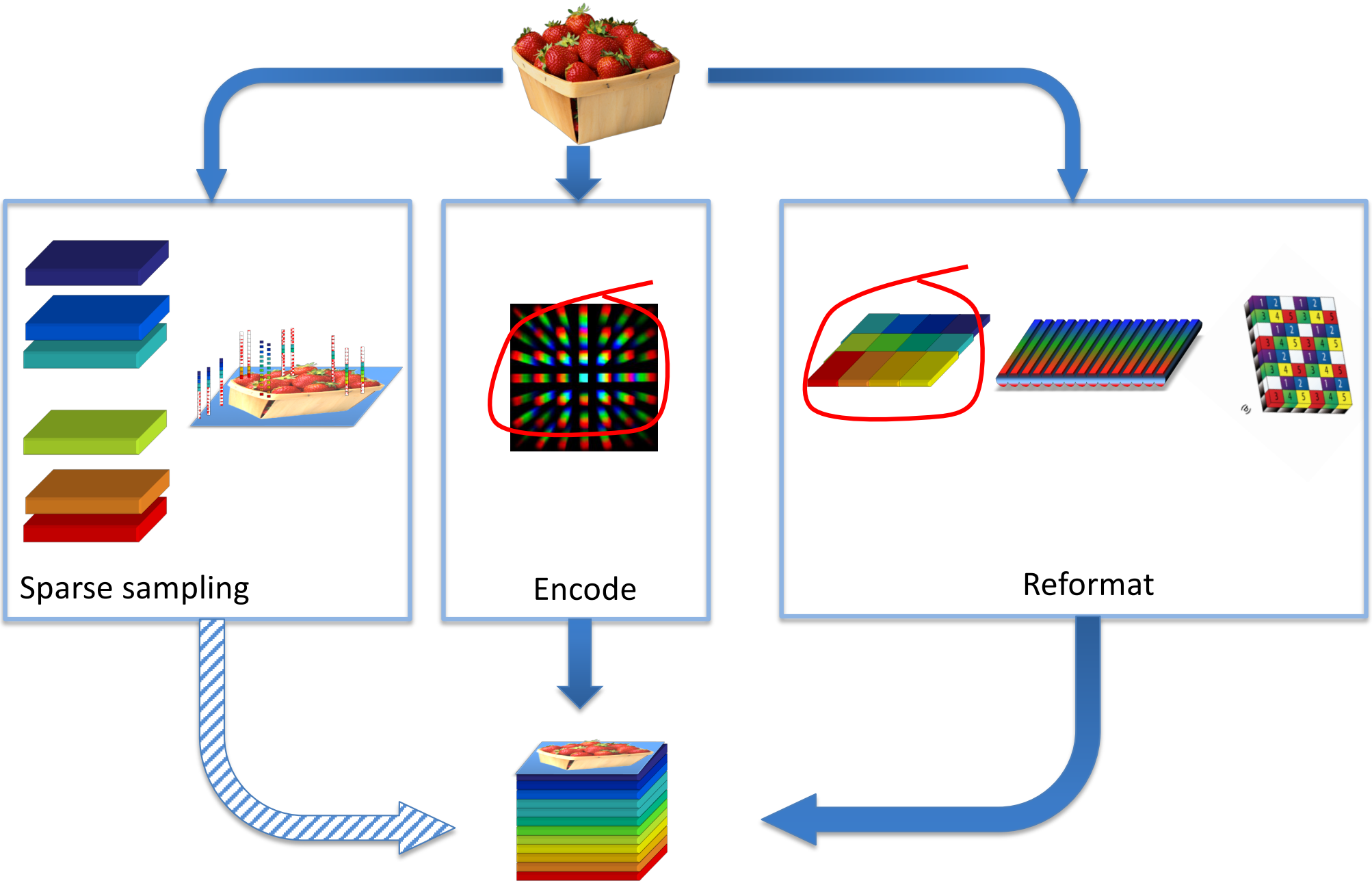
  - Agriculture



- Classification

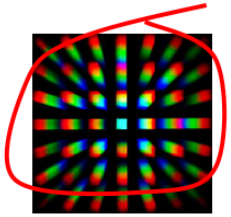


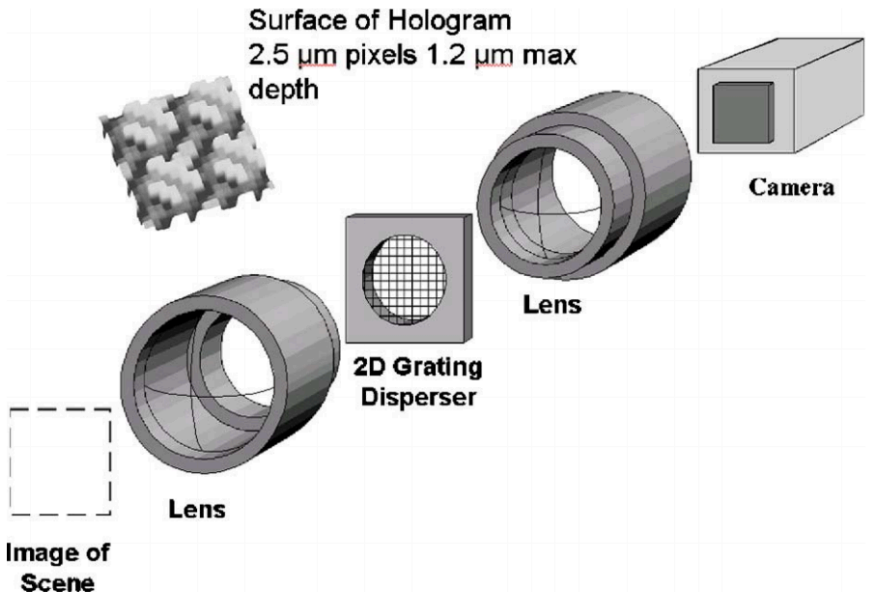
How to record multispectral ‘video’

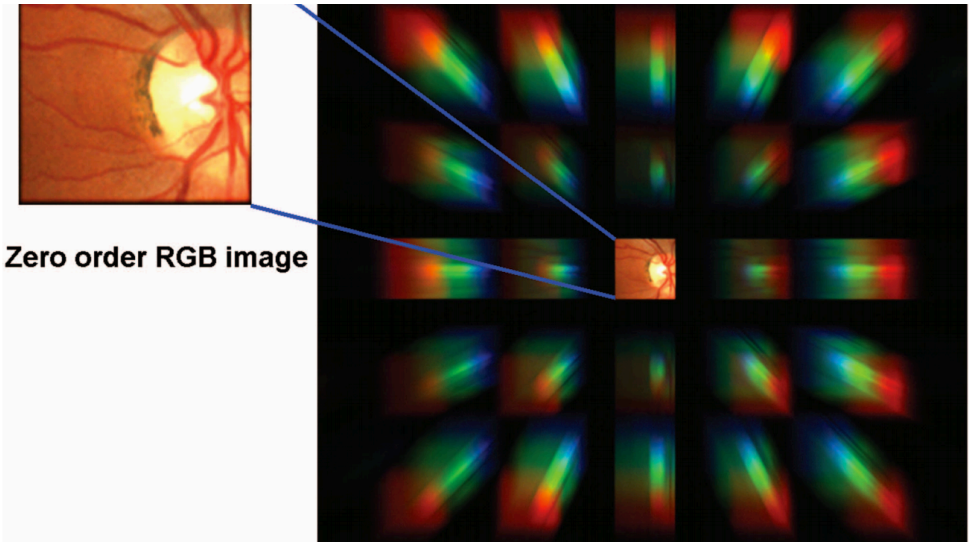


Hagen, N. & Kudenov, M. W. Opt. Eng. 52, 90901 (2013).

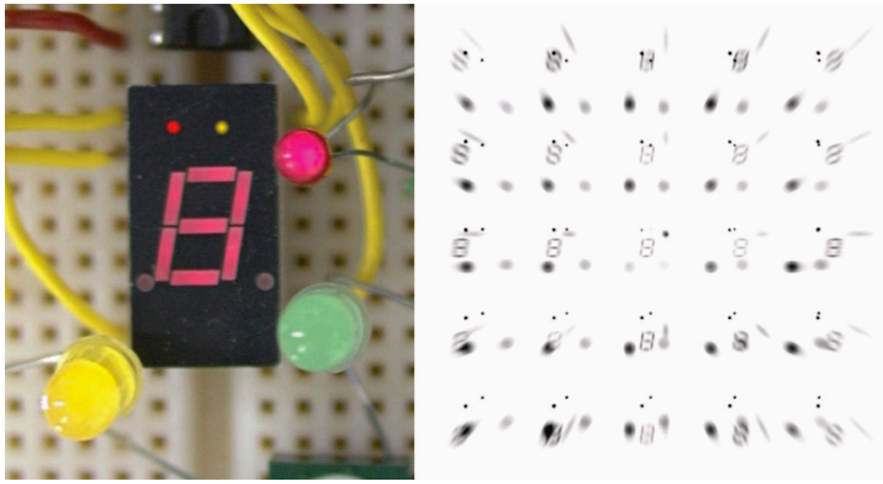
Computed tomographic spectral imaging:CTIS

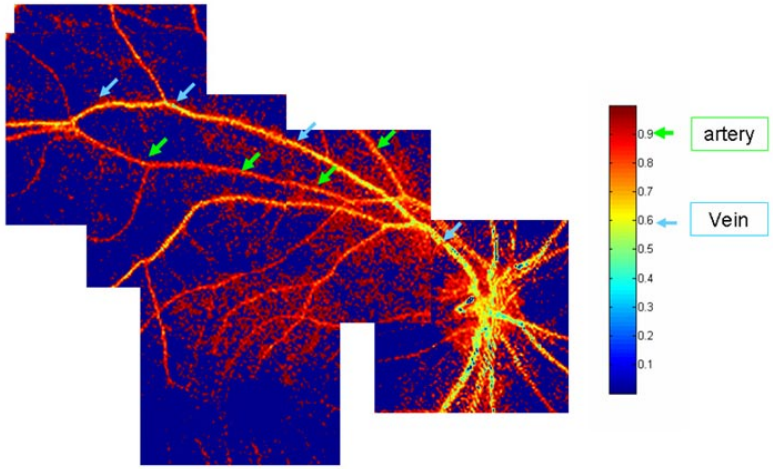






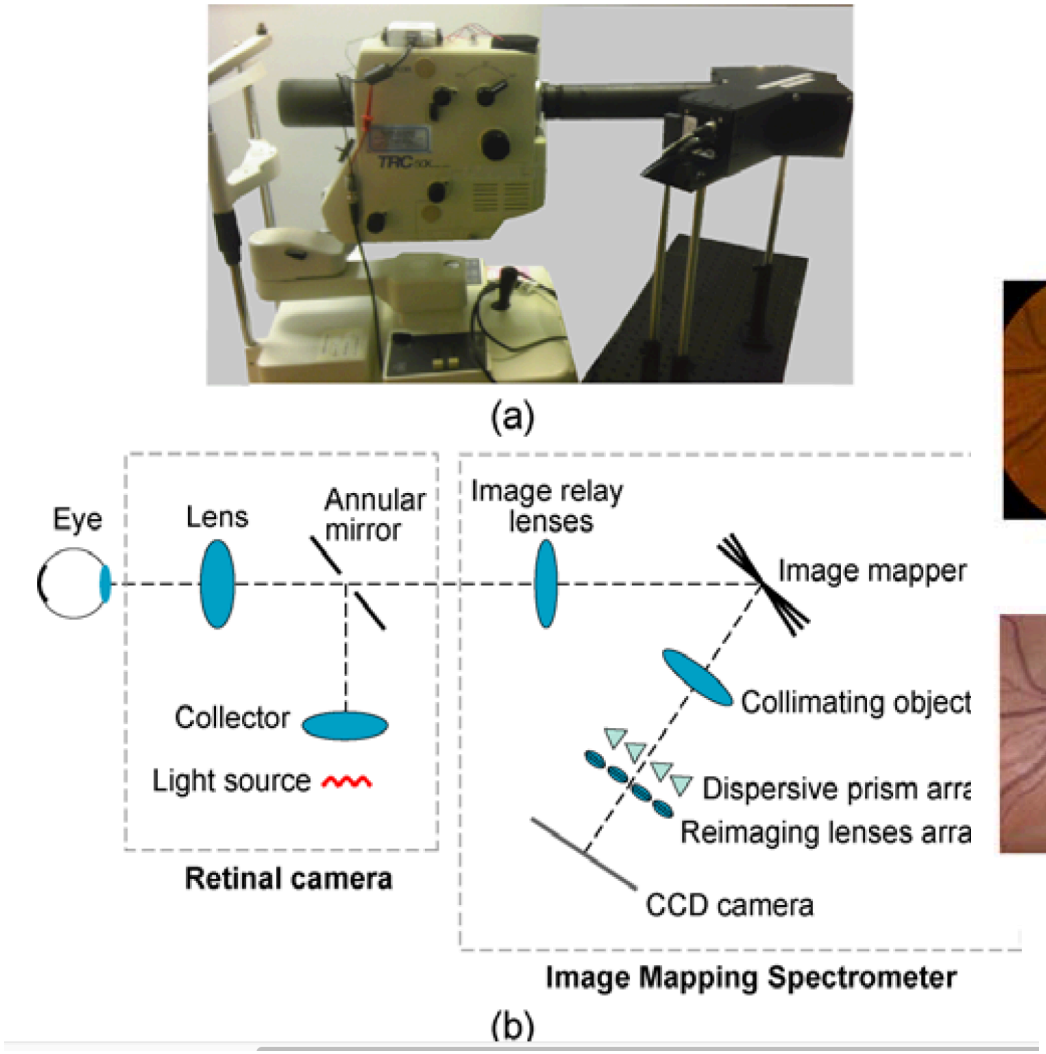
$$\hat{X}^{k+1} = \hat{X}^{k} \frac{H^T g}{H^T H \hat{X}^{k}}$$

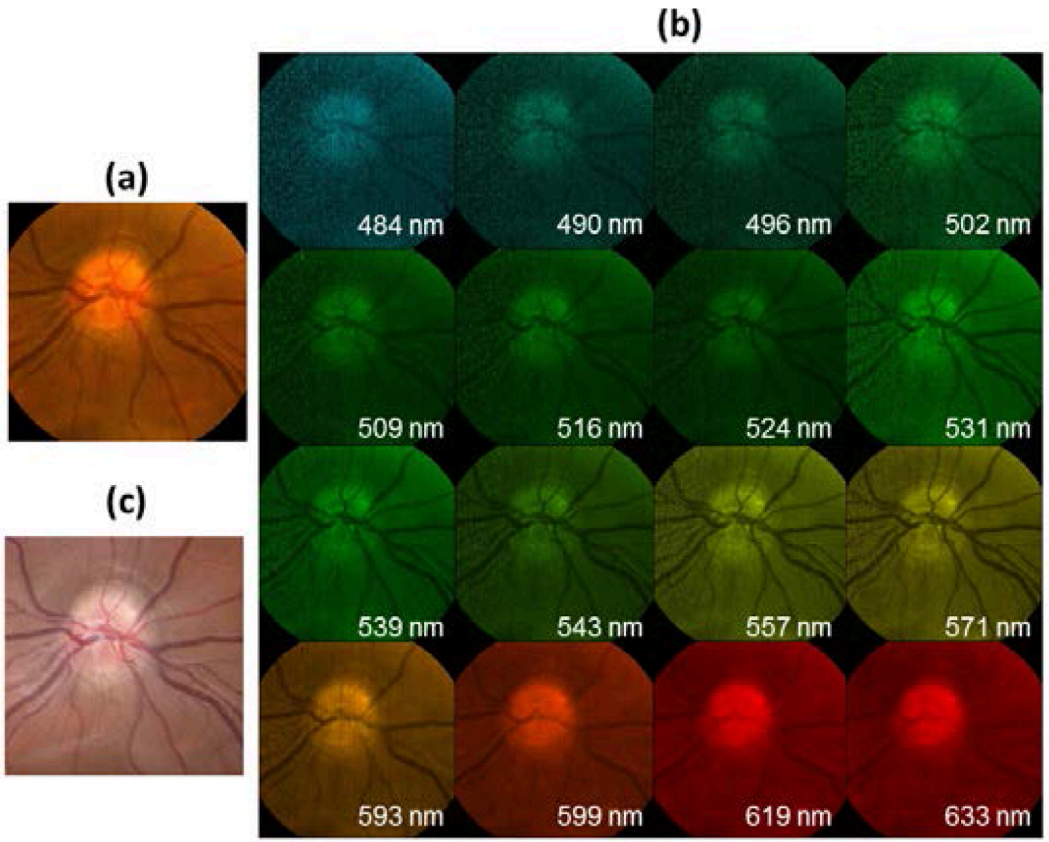




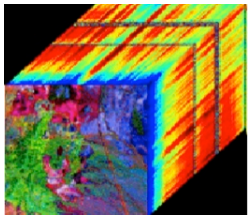
Johnson, W. R., Wilson, D. W., Fink, W., Humayun, M. & Bearman, G J. Biomed. Opt. 12, 014036 (2007).

Image Slicing: spectral retinal imaging

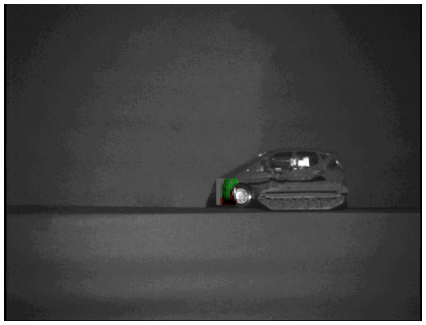




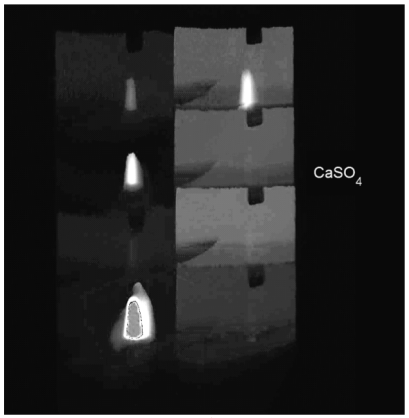
1. Gao, L., Smith, R. T. & Tkaczyk, T. S Biomed. Opt. Express 3, 48 (2012).

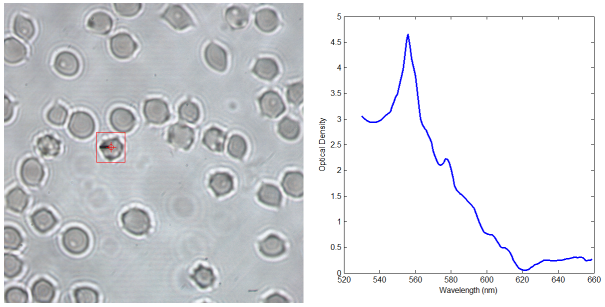


Real-time spectral imaging: Surveillance and Biomedicine

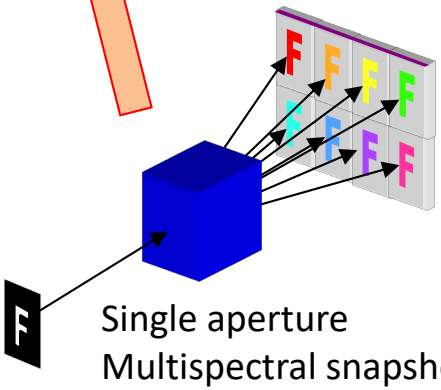


Foveal Hyperspectral

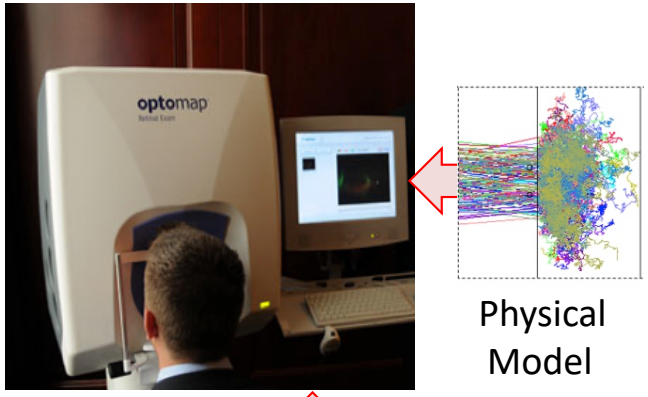




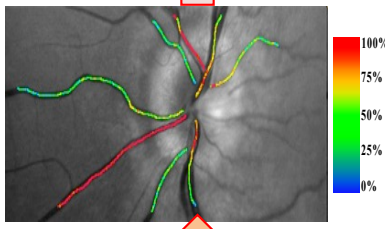
Tracking Random Access Hyperspectral

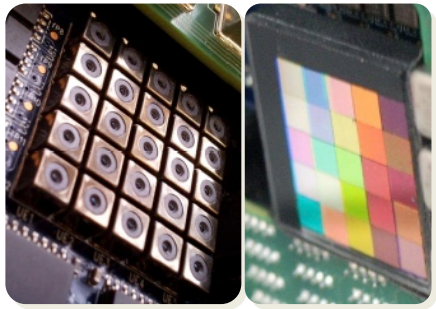


Single aperture
Multispectral snapshot/video

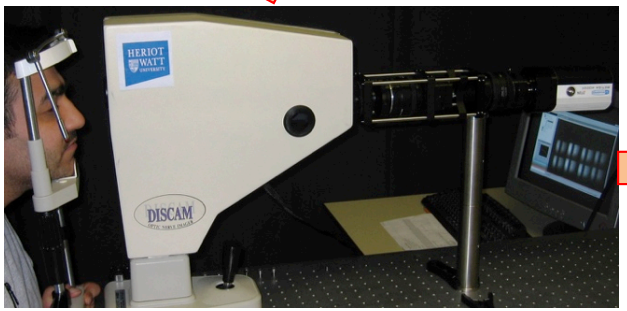


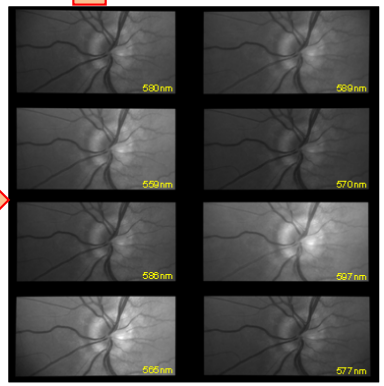
Physical Model





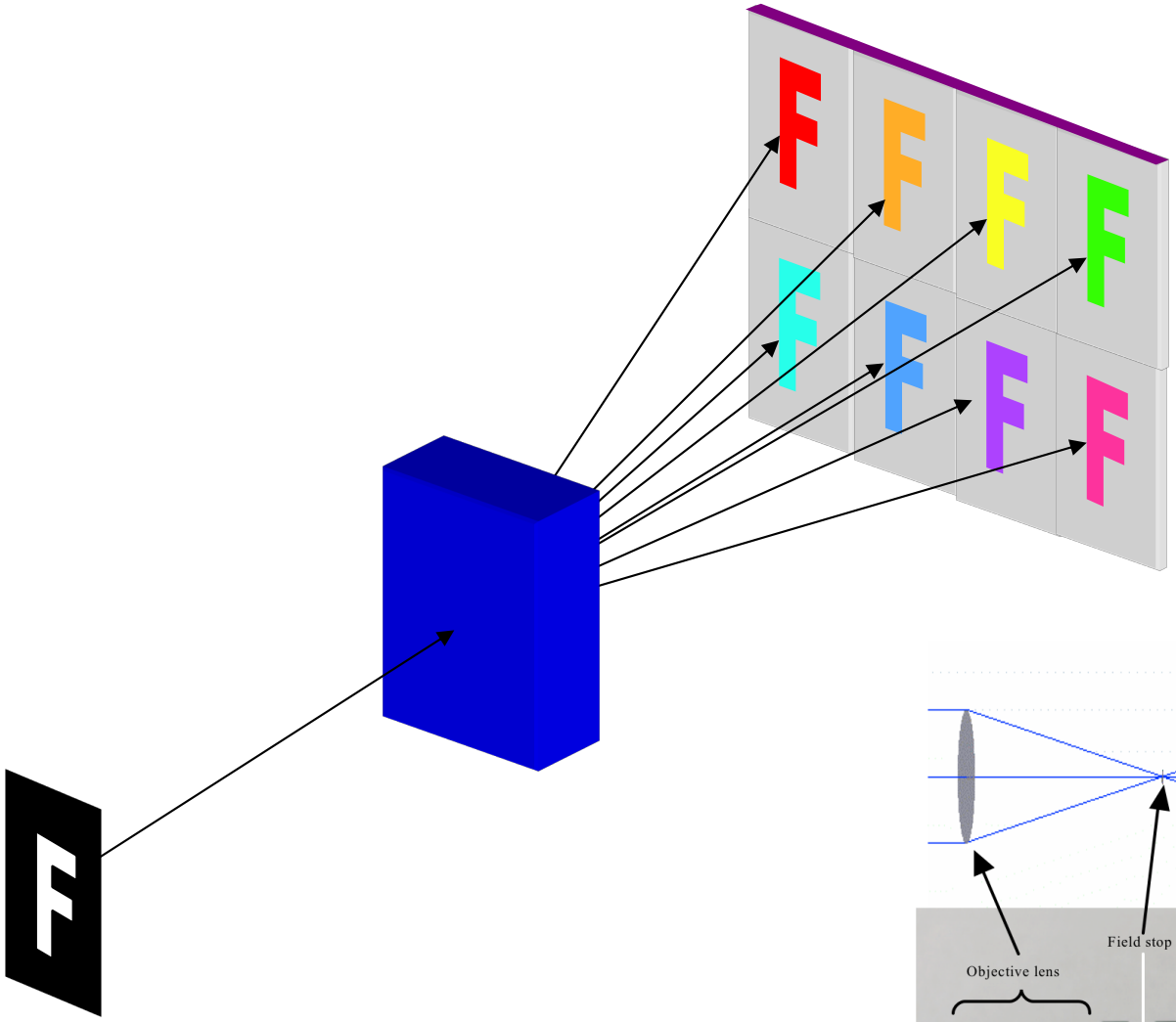
Multi aperture

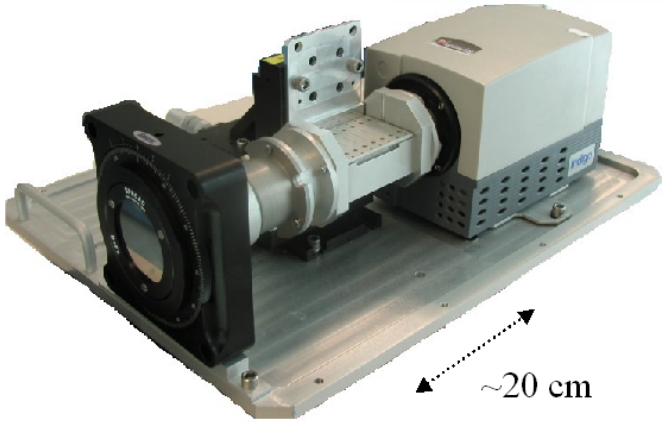


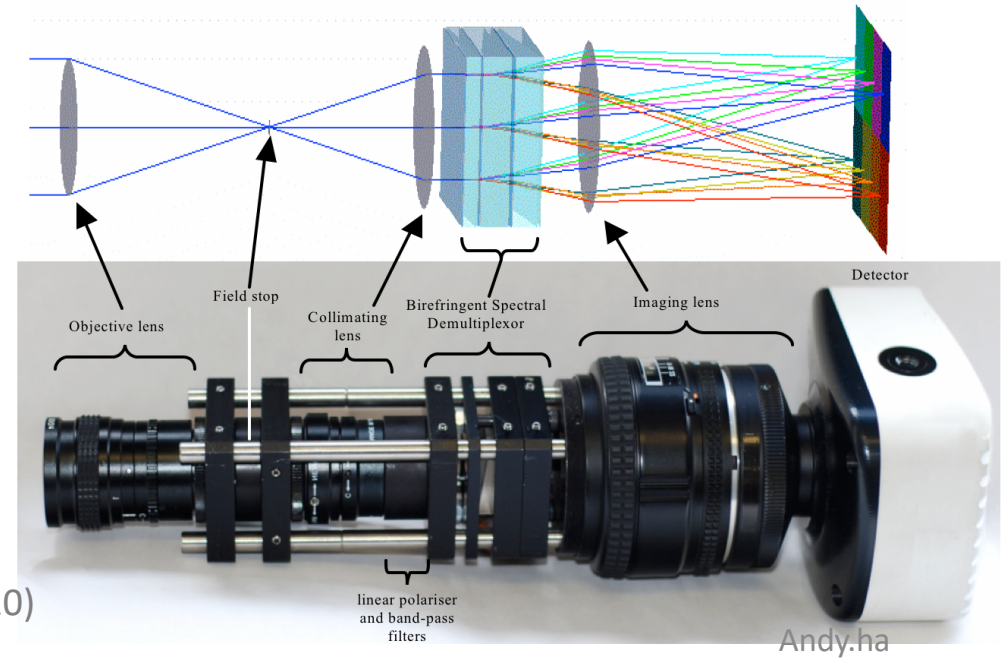


Biomedical chemical quantification

An example snapshot spectral imager:
*I*mage *R*eplication *I*maging *S*pectrometer:

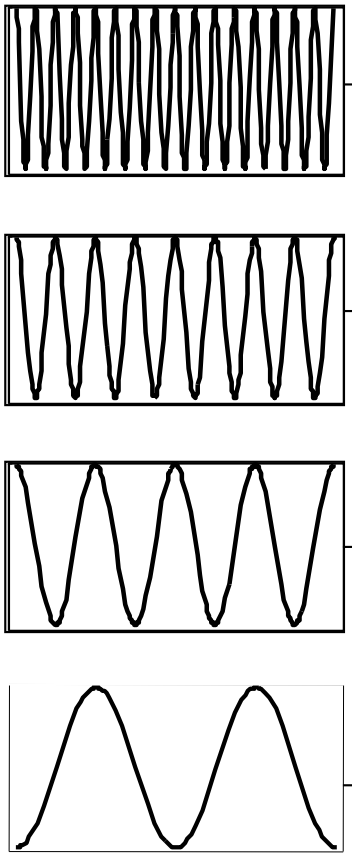




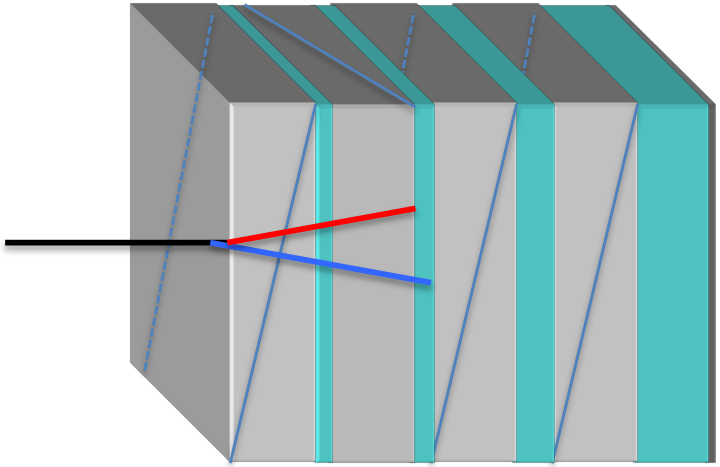


A Gorman & AR Harvey Optics Express 18, 6, pp 5602 (2010)
G Wong & A R Harvey, Opt Let. 36 8, pp 1332 (2011)

Andy.harvey@glasgow.a

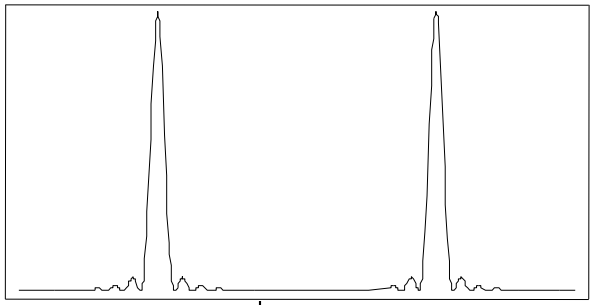


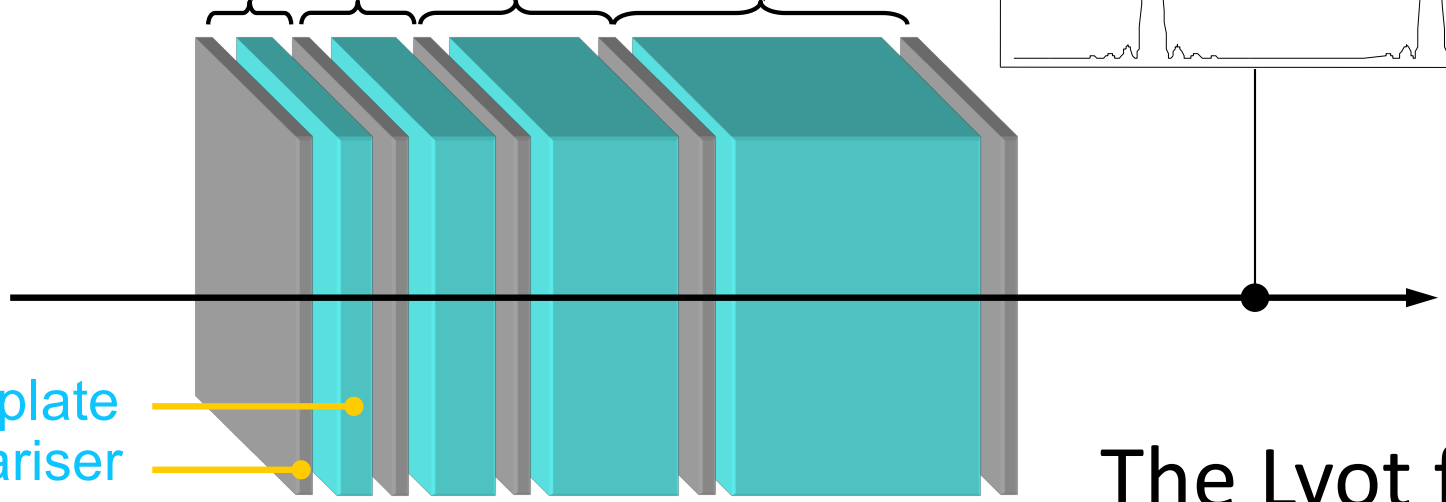
$$\nu = \frac{1}{\lambda}$$



The Generalised Lyot filter

$$T(\nu) = \cos^2(\pi\nu\Delta)\cos^2(2\pi\nu\Delta)\cos^2(4\pi\nu\Delta)\cos^2(8\pi\nu\Delta)$$

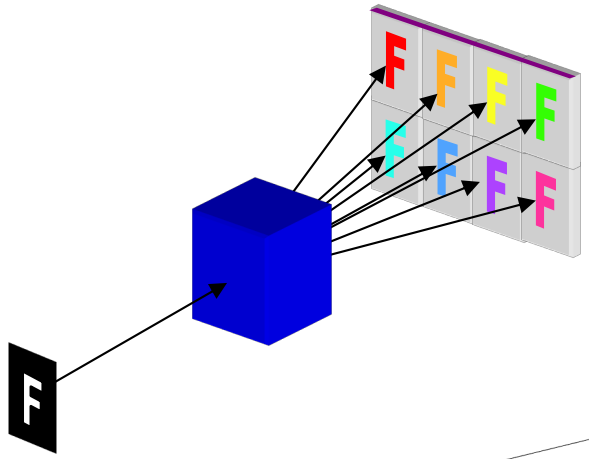


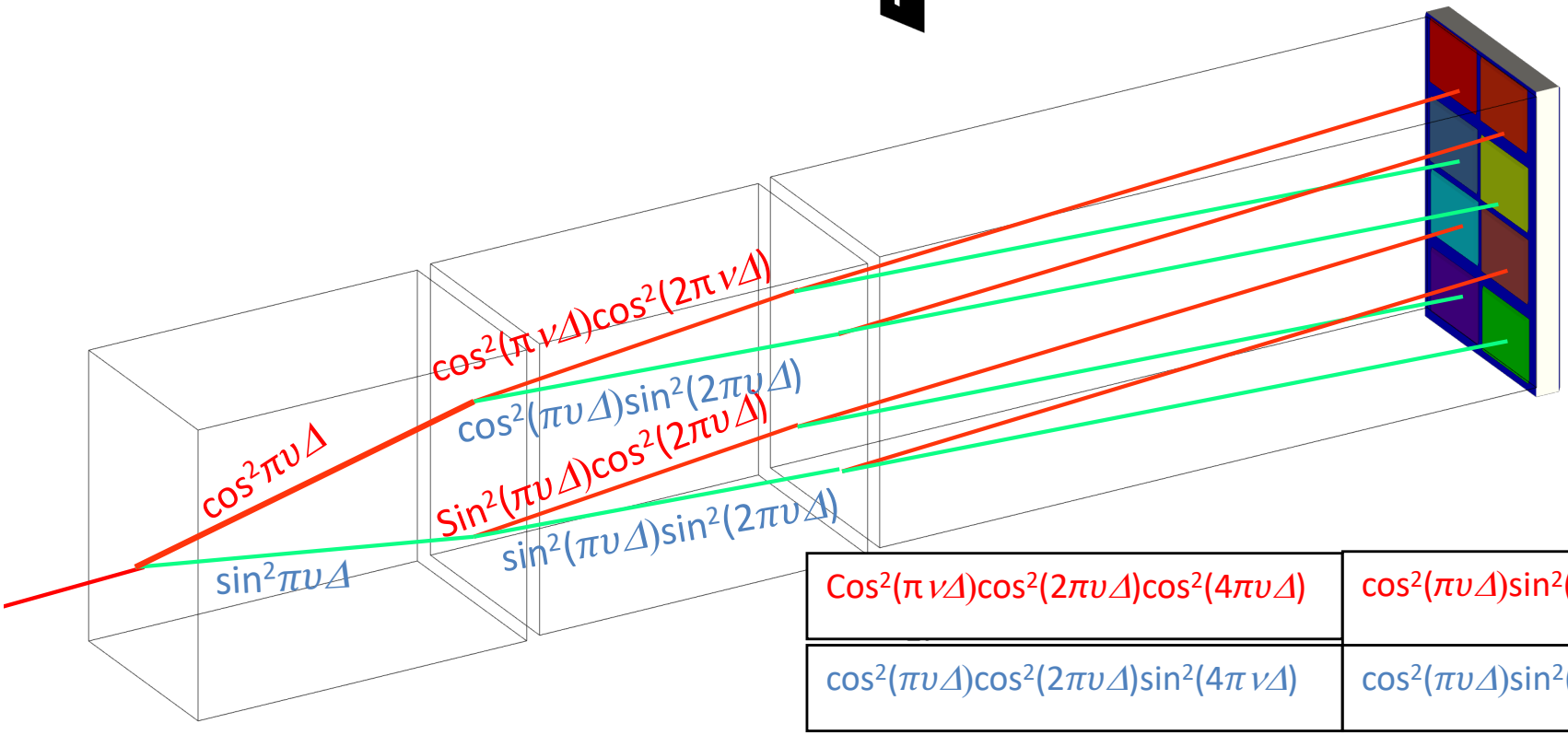


The Lyot filter

Transmission functions for the Generalised Lyot Filter

- Snapshot
- 100% throughput
- 100% pixel use
- No inversion

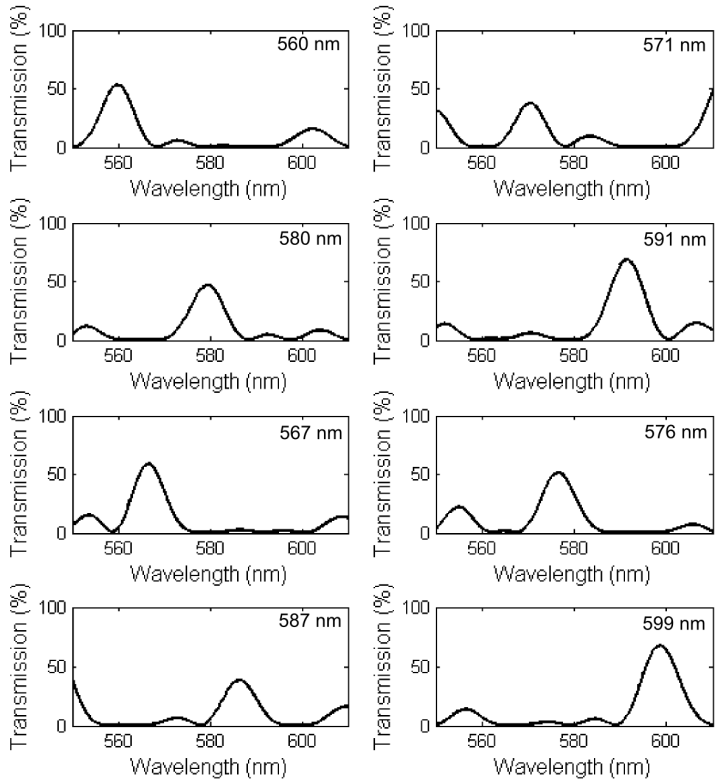


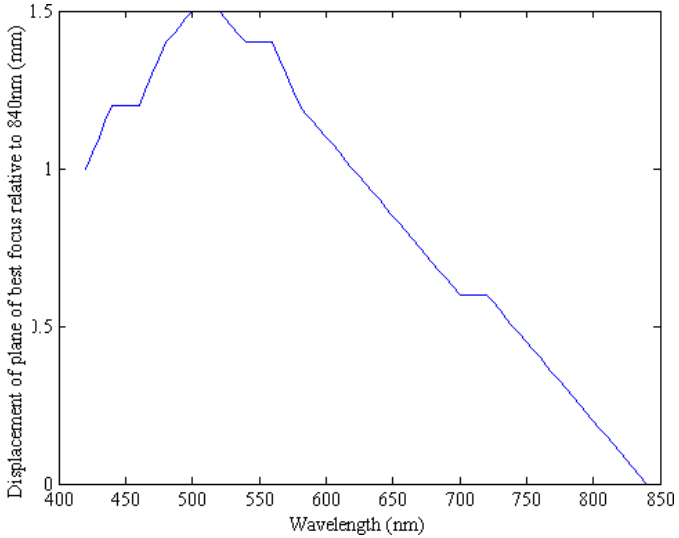


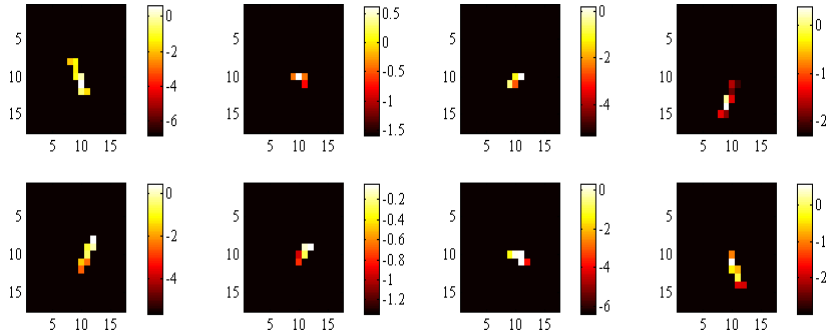
$\cos^2(\pi\nu\Delta)\cos^2(2\pi\upsilon\Delta)\cos^2(4\pi\upsilon\Delta)$	$\cos^2(\pi\upsilon\Delta)\sin^2(2\pi\upsilon\Delta)\cos^2(4\pi\upsilon\Delta)$
$\cos^2(\pi\upsilon\Delta)\cos^2(2\pi\upsilon\Delta)\sin^2(4\pi\nu\Delta)$	$\cos^2(\pi\upsilon\Delta)\sin^2(\pi\upsilon\Delta)\sin^2(4\pi\upsilon\Delta)$
$\sin^2(\pi\upsilon\Delta)\cos^2(2\pi\upsilon\Delta)\cos^2(4\pi\upsilon\Delta)$	$\sin^2(\pi\upsilon\Delta)\sin^2(2\pi\upsilon\Delta)\cos^2(4\pi\upsilon\Delta)$
$\sin^2(\pi\nu\Delta)\cos^2(2\pi\upsilon\Delta)\sin^2(4\pi\upsilon\Delta)$	$\sin^2(\pi\upsilon\Delta)\sin^2(2\pi\upsilon\Delta)\sin^2(4\pi\upsilon\Delta)$

IRIS improvements

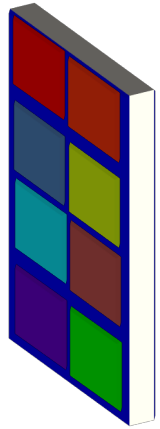
- Issues:
  - Sidelobes in the spectral transmission
  - Dispersion of the Wollaston prisms
  - Longitudinal chromatic aberration for lenses



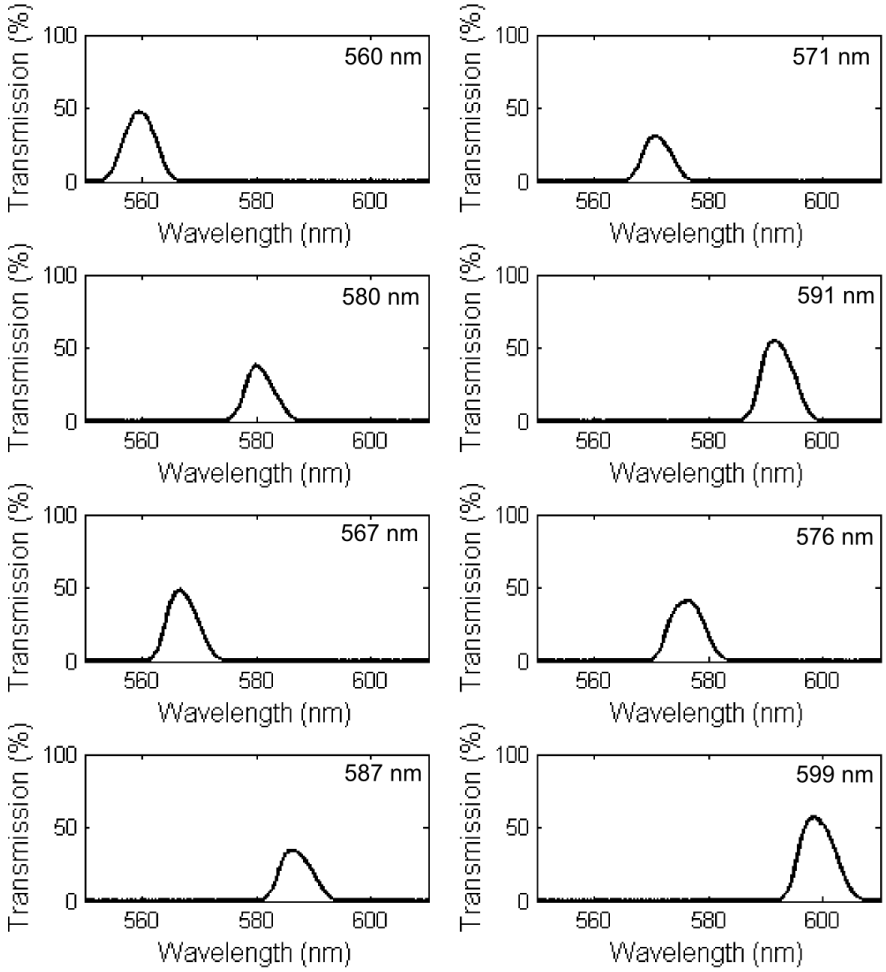


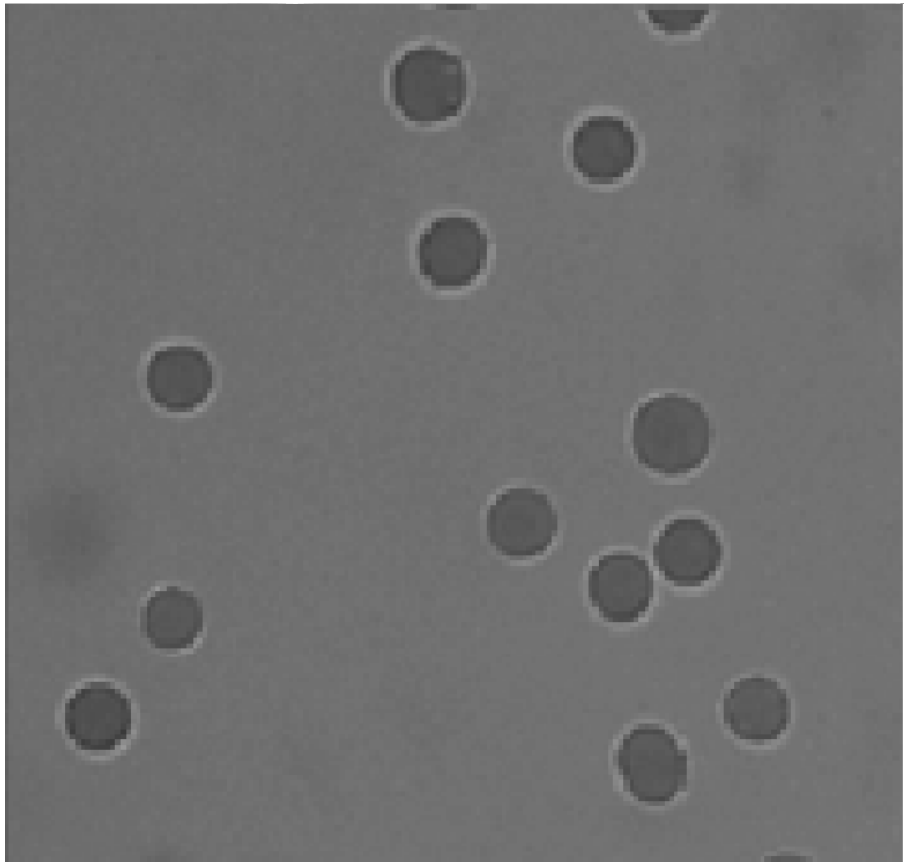


Sidelobe elimination



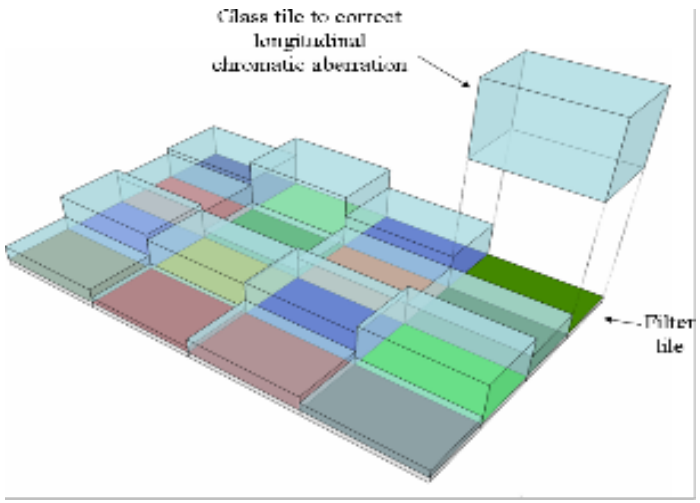
- Image-plane mosaic filter cleans sidelobes



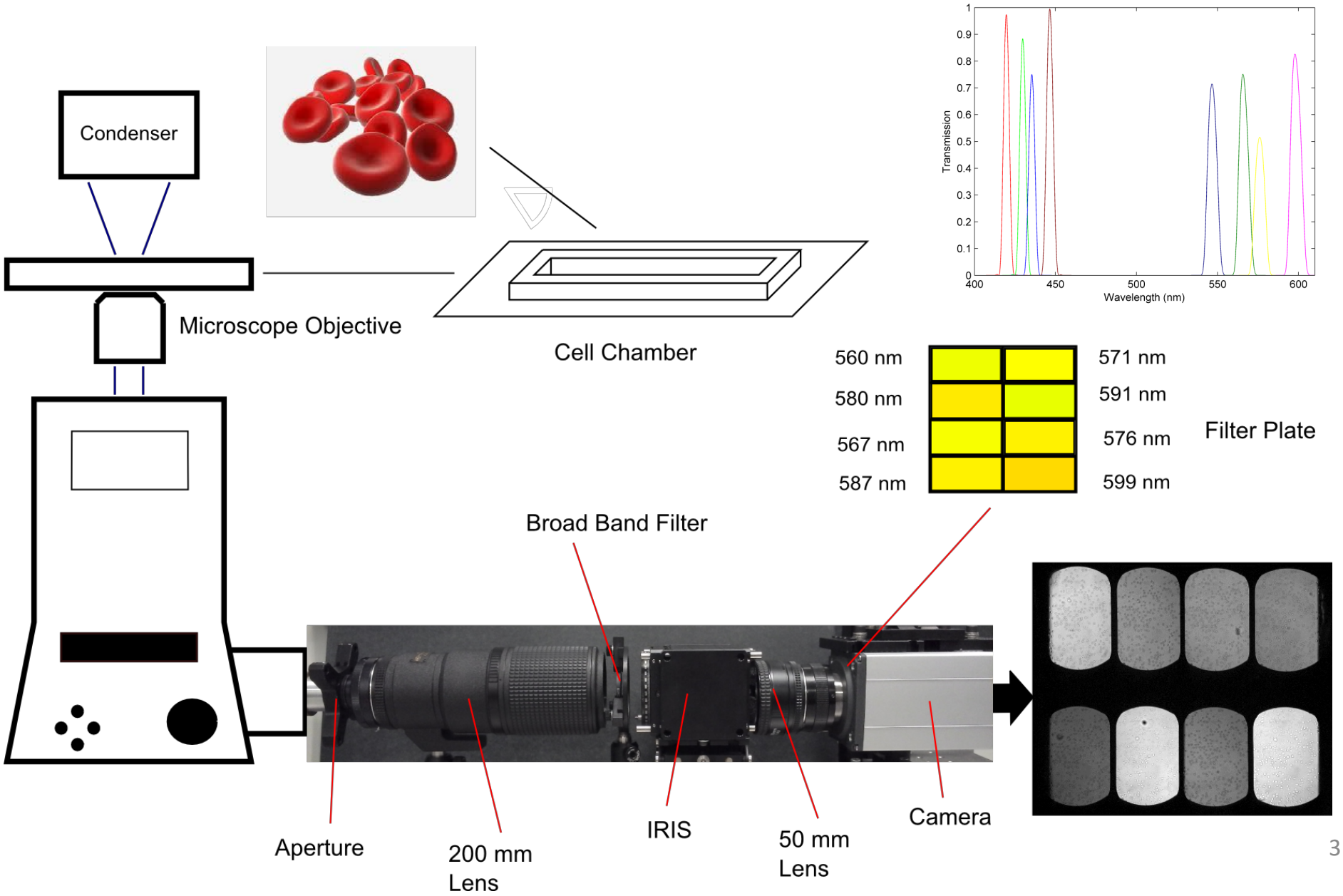


Chromatic aberration correction

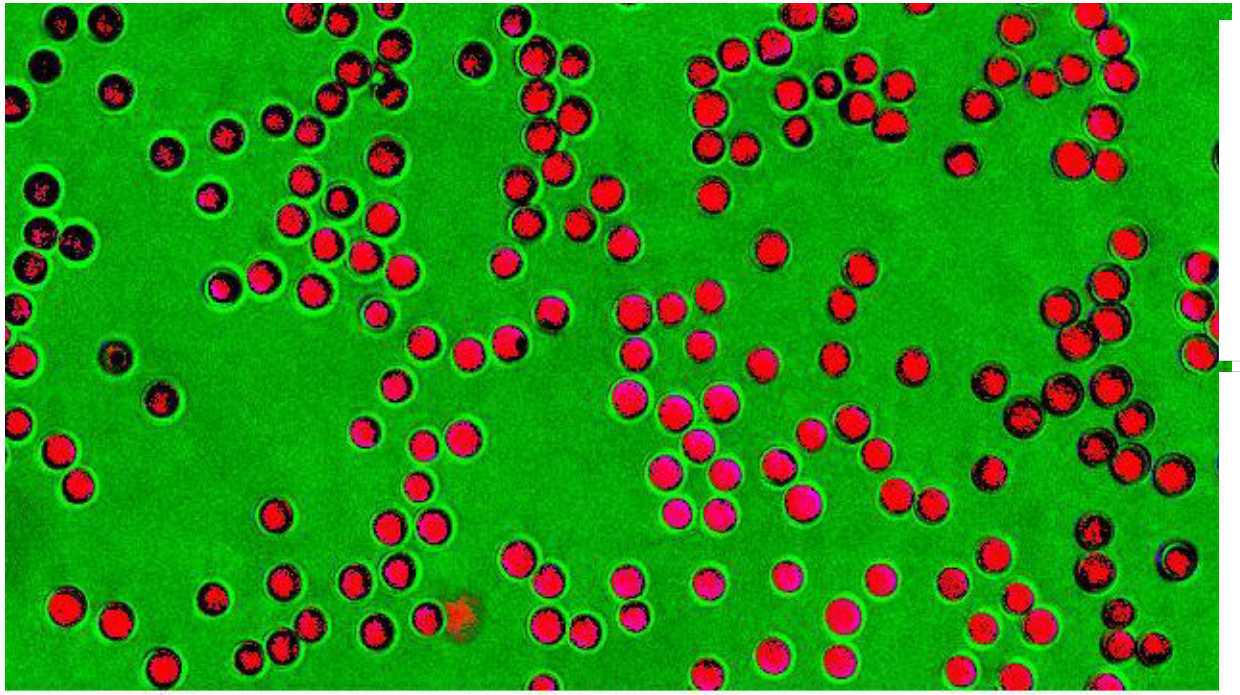
- Introduction of corrective glass tiles to the narrowband filters to modify the pathlength of the different wavebands

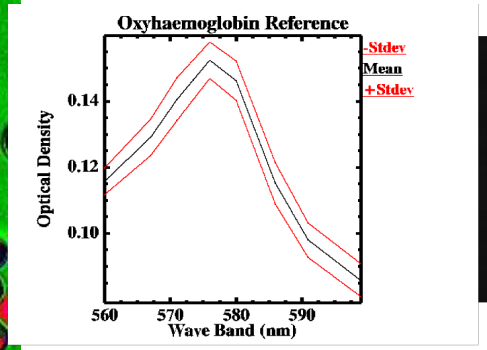


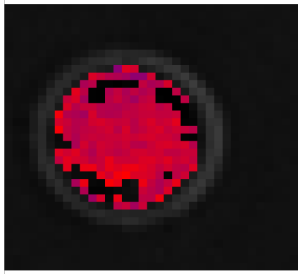
Video-rate single RBC oximetry

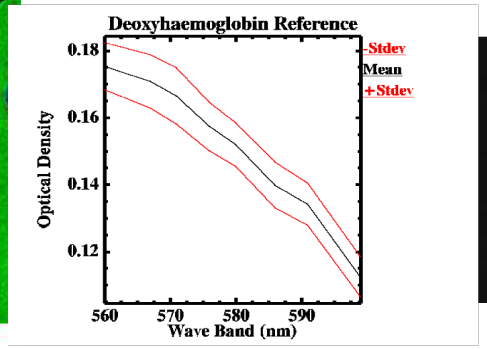


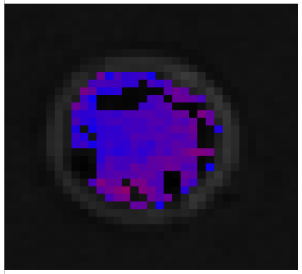
Video rate oximetry of red blood cells

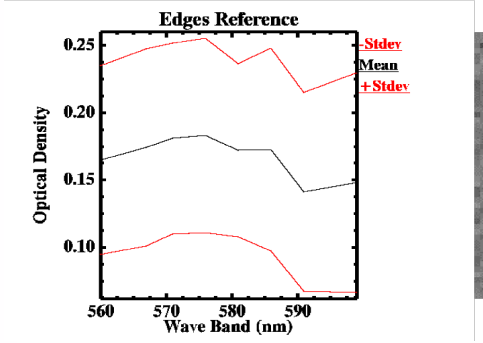


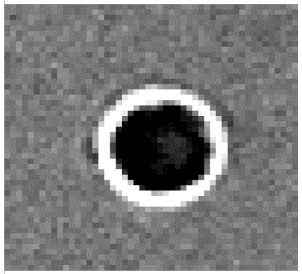


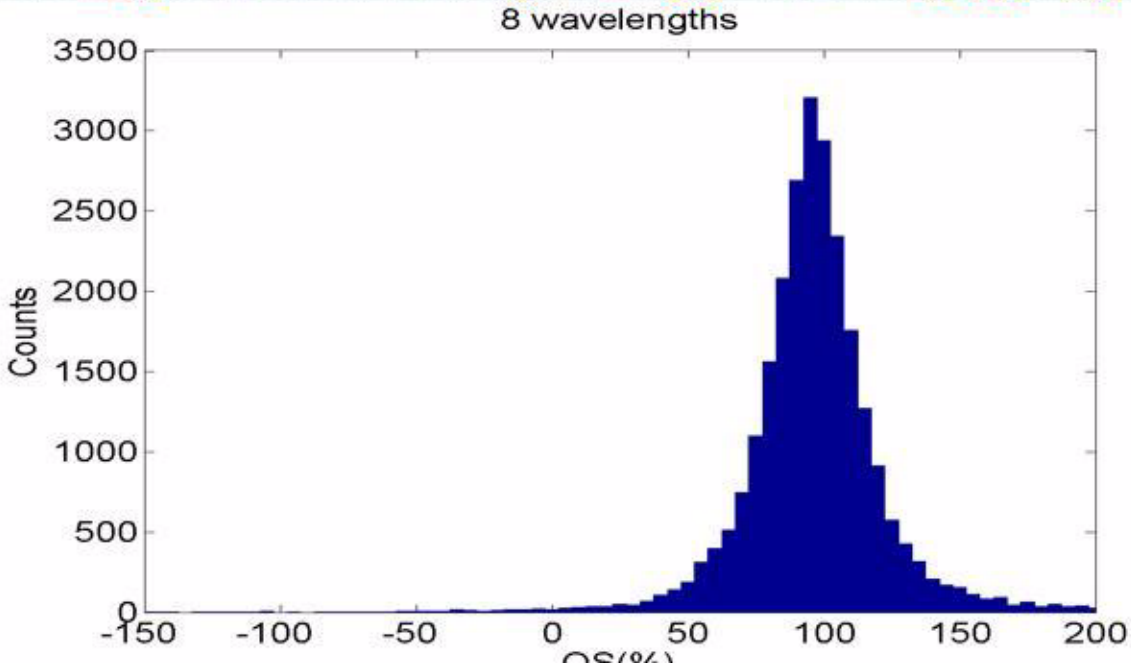




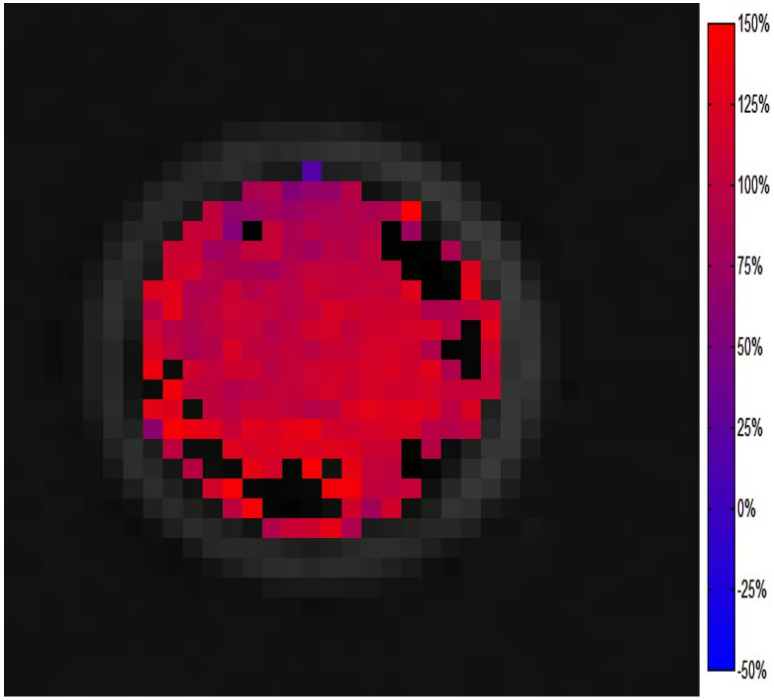


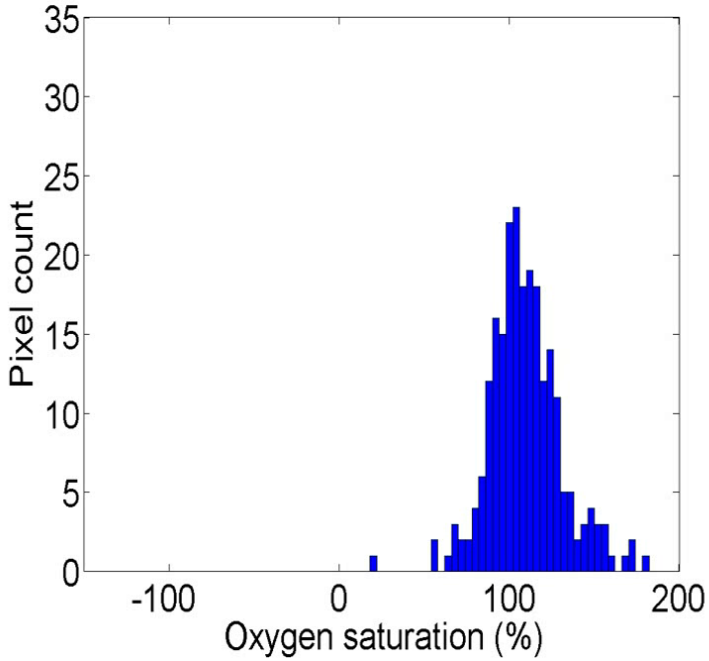




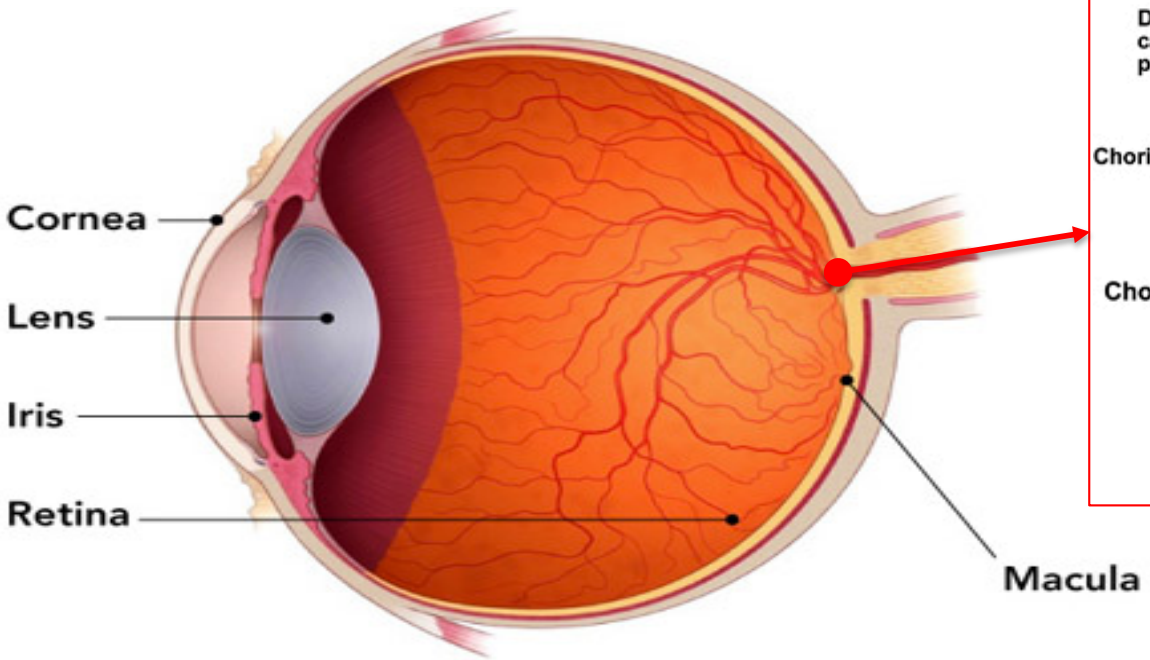


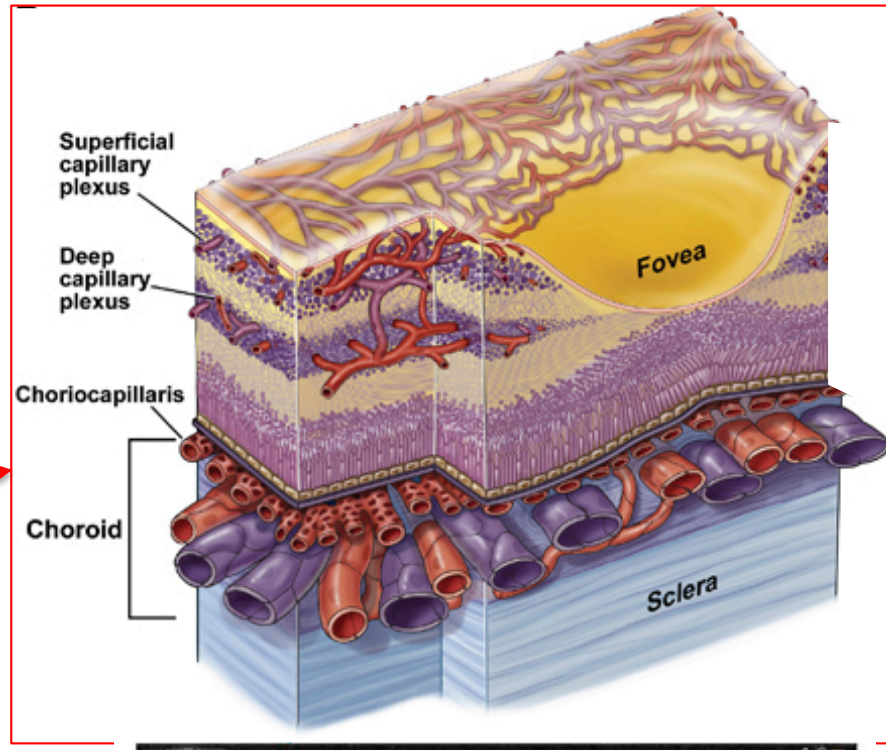
Single RBC

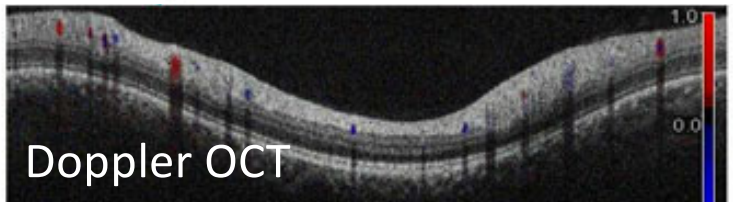

150%
125%
100%
75%
50%
25%
0%
-25%
-50%


Pixel count
35
30
25
20
15
10
5
0
-100
0
100
200
Oxygen saturation (%)

Multispectral Retinal oximetry: the challenges







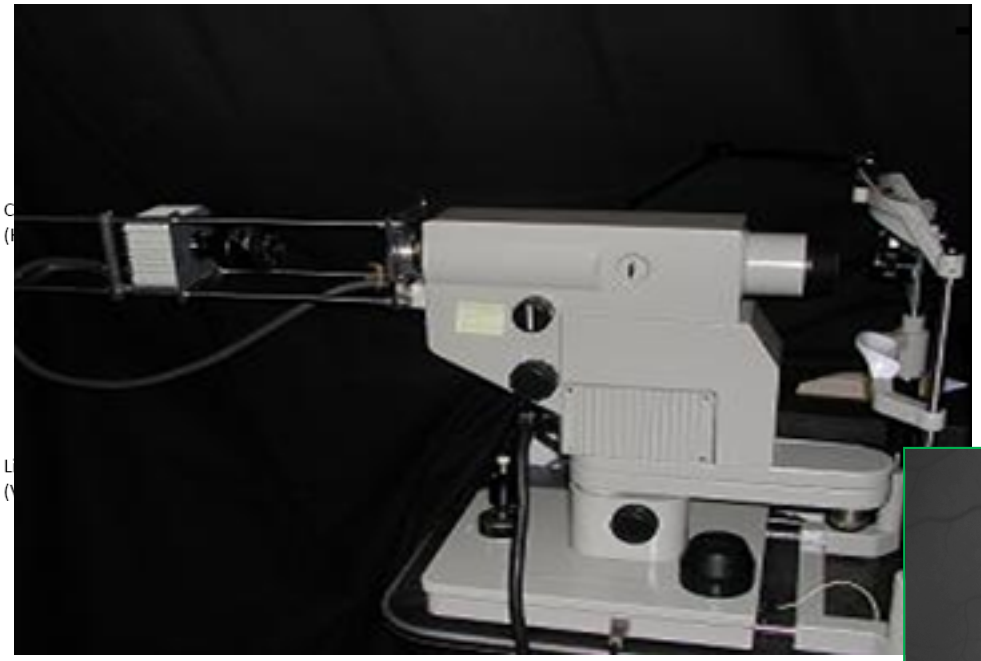
- Quantitative imaging in the eye: challenges
  - PSF
    - Optical: ~8µm
    - Tissue : 30µm-1mm
      - Heterogeneous; birefringent cornea, lens, nerves
  - Eye Contrast (Ocular media scatter): ~0.2-0.9
  - Optically fragile
  - Saccades

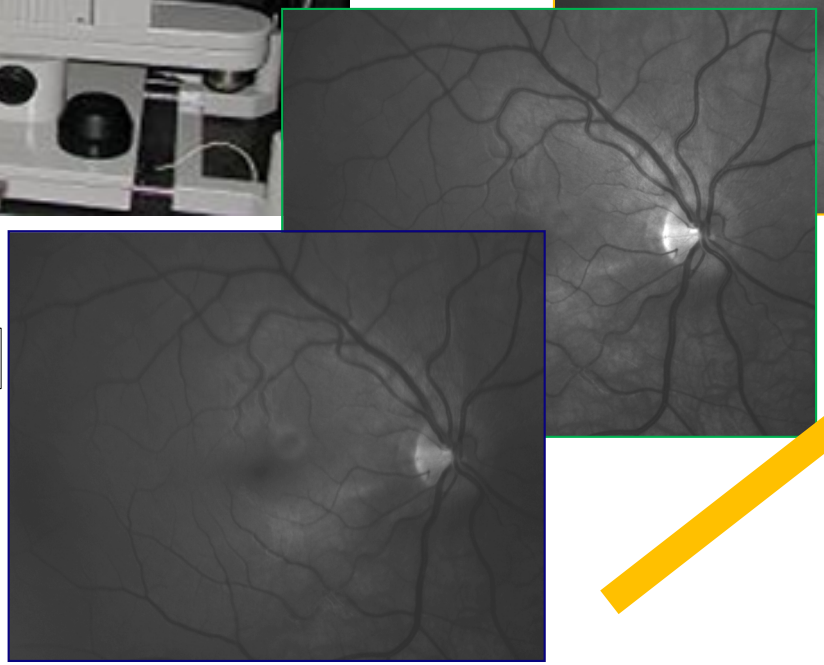
Complex light paths: PCA/ICA useless: quantification requires physical model

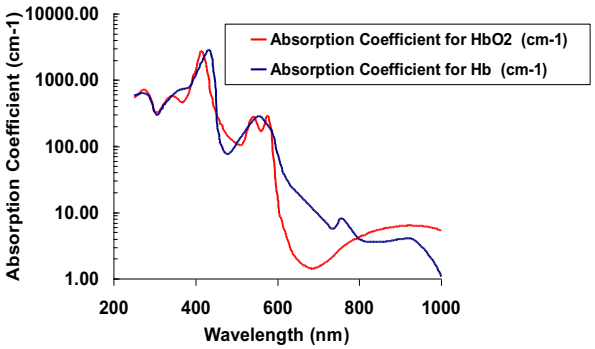
Requires optical efficiency

Requires (?) snapshot

Characterizing and understanding:
Time-sequential hyperspectral imaging of the retina



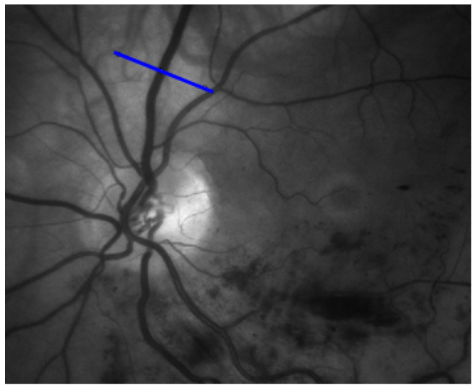




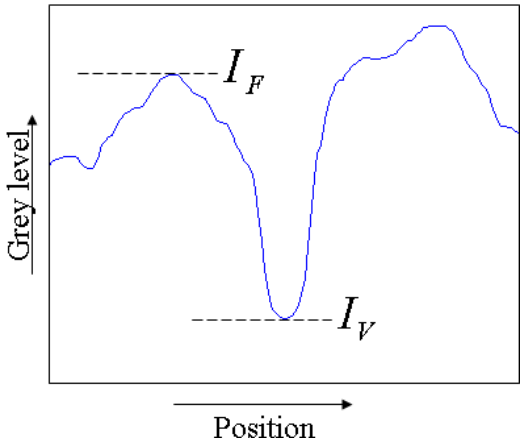
Mordant, D. et al., 2011. *Eye*, 25(3), pp.309–320.

Retinal vessel oximetry with multi-spectral fundus camera measurements

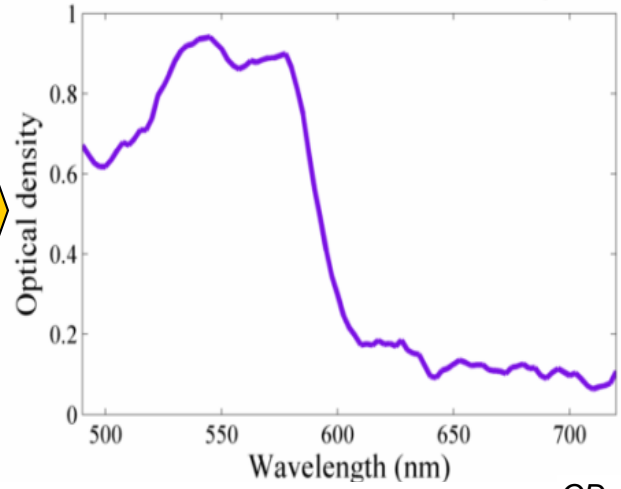
Image of human retina at 586nm



Plot of profile across retinal blood vessel

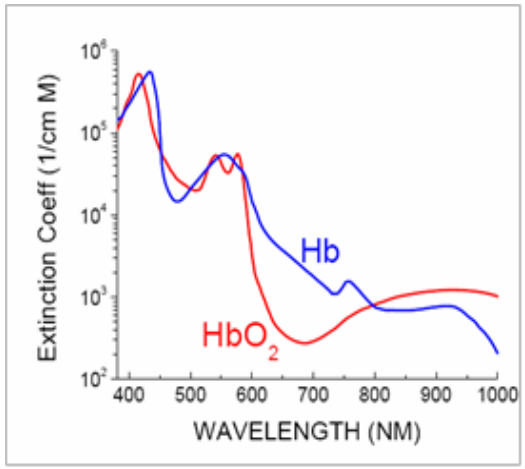


Vessel OD as a function of wavelength



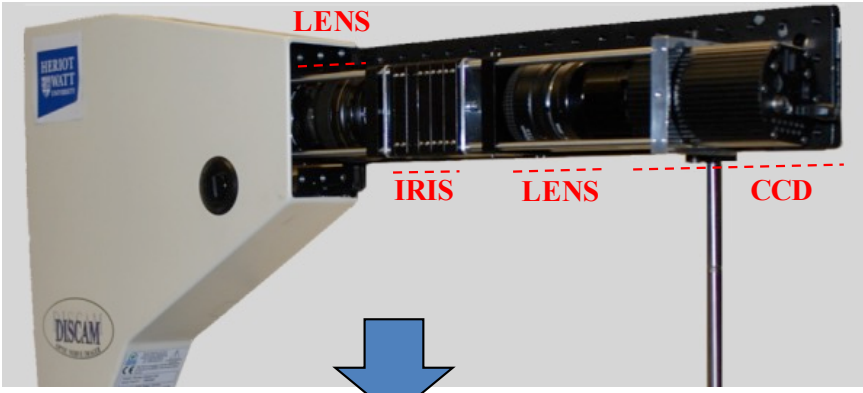
$$OD_{\lambda_A} / OD_{\lambda_B} \propto OS$$

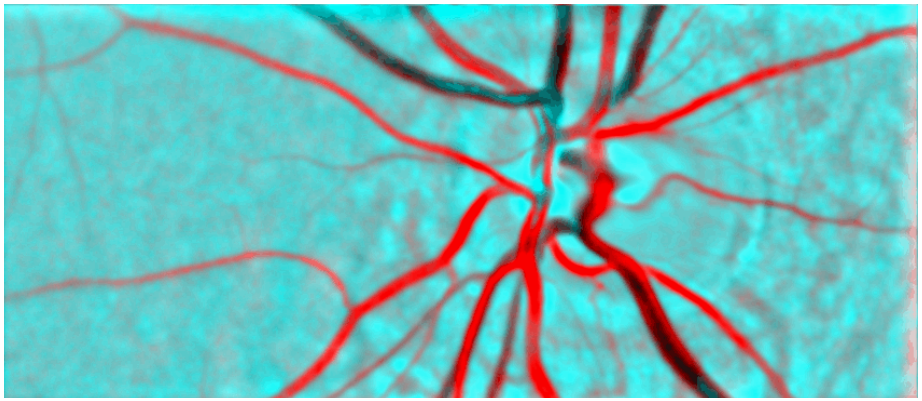
$$OD = -\log_{10} \frac{I_v}{I_F}$$

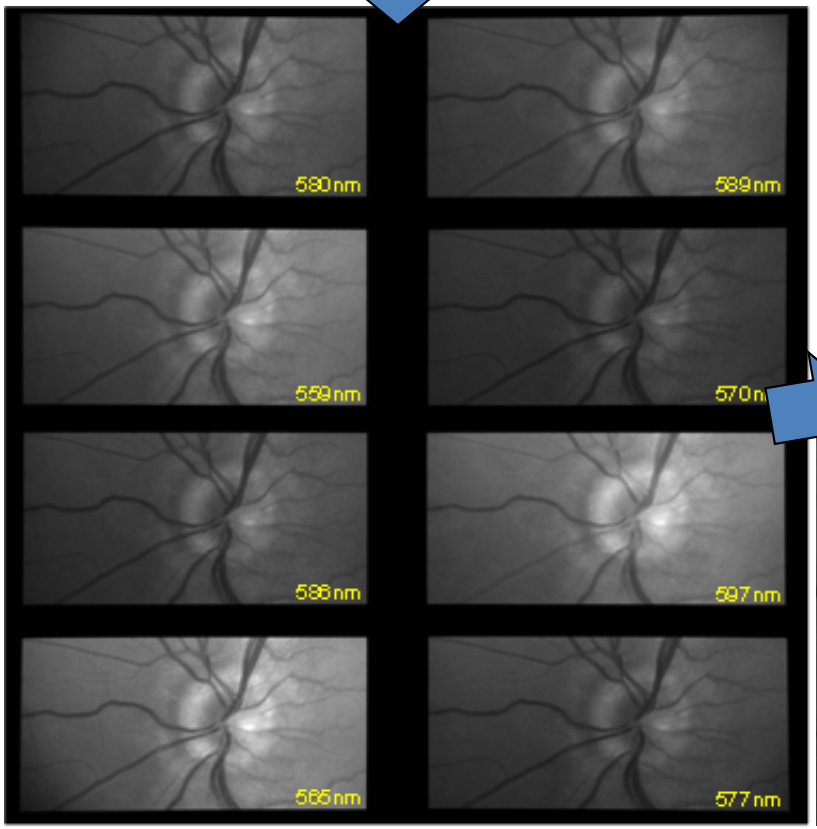


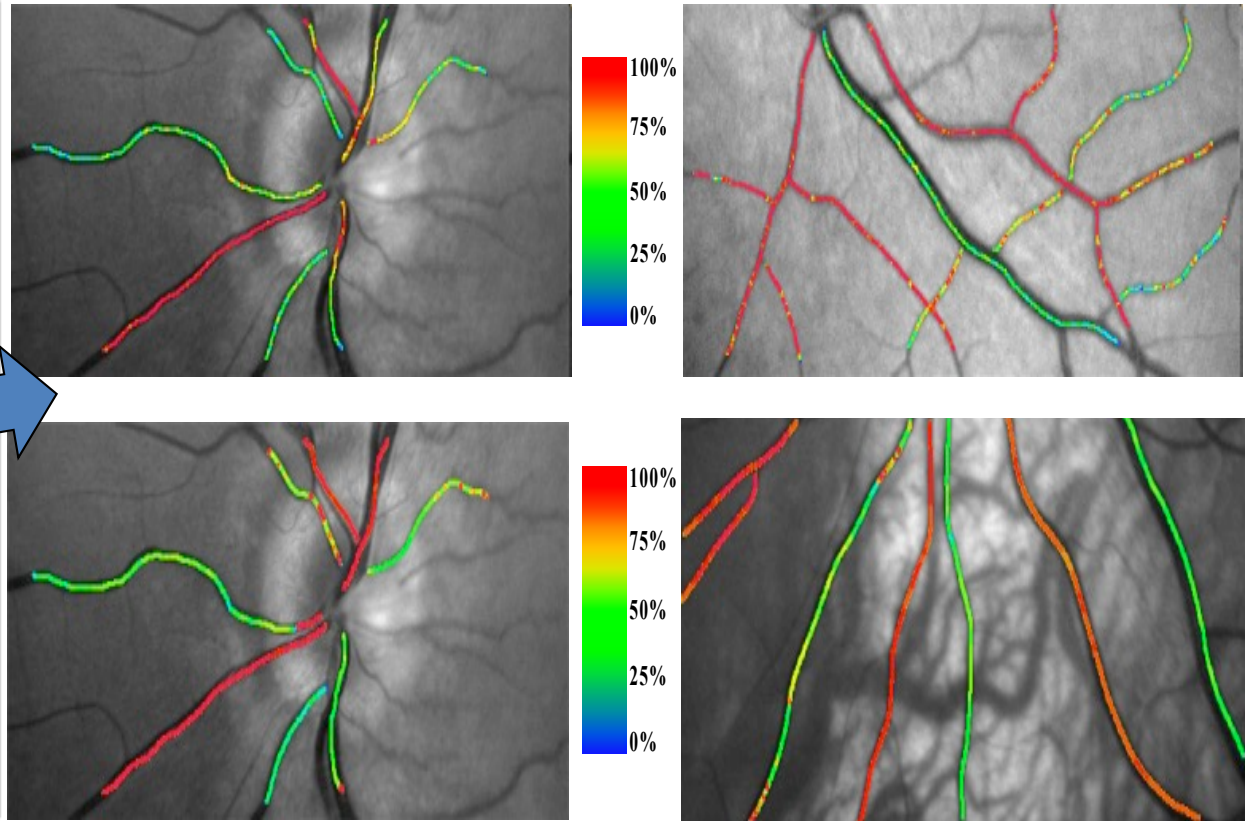
$$OD(\lambda) = S(\lambda) + \eta c_{Hb_{TOTAL}} d\left[\left(\varepsilon_{HbO_2}(\lambda) - \varepsilon_{Hb}(\lambda)\right)OS + \varepsilon_{Hb}(\lambda)\right]$$

Mordant, D. et al., 2011. *Eye*, 25(3), pp.309–320.









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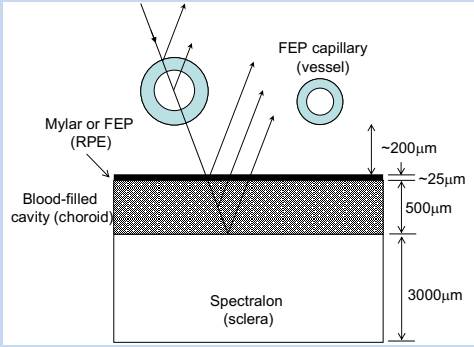
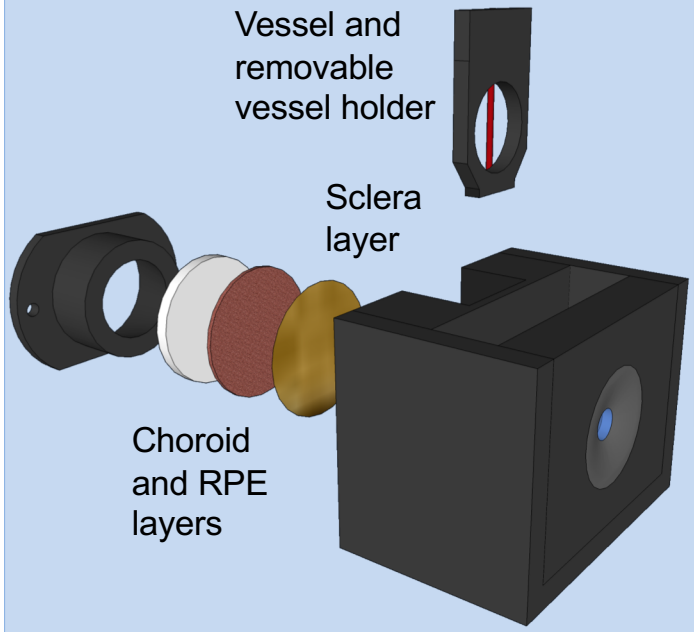
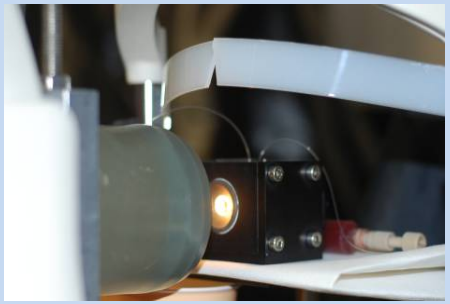
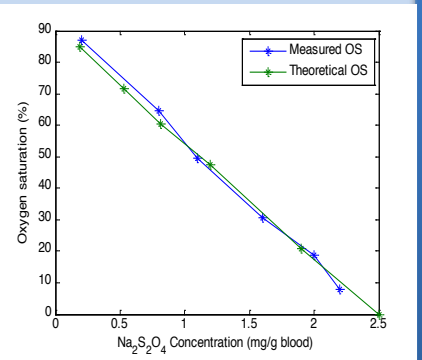
Validation



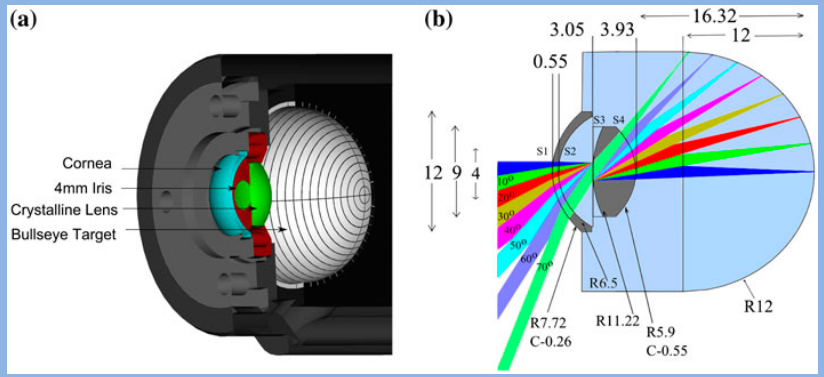




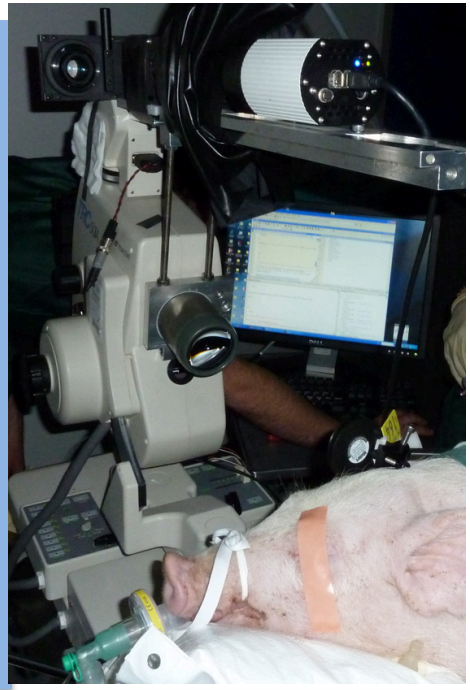


Mordant, D. J. et al, Investig. Opthalmology Vis. Sci. 52, 2851 (2011).

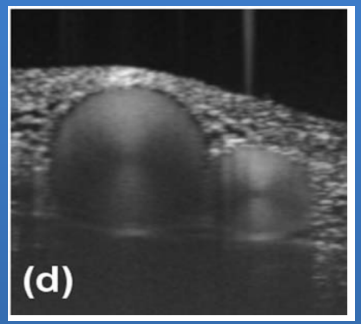
Rigorous ultra wide-field phantom

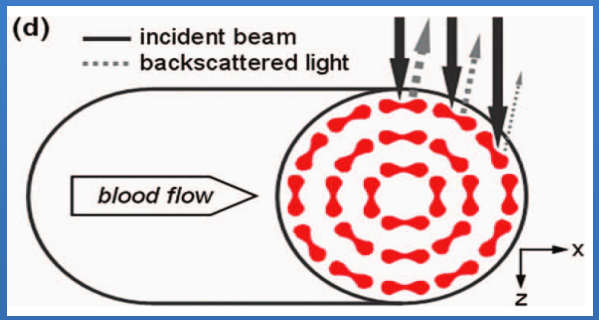


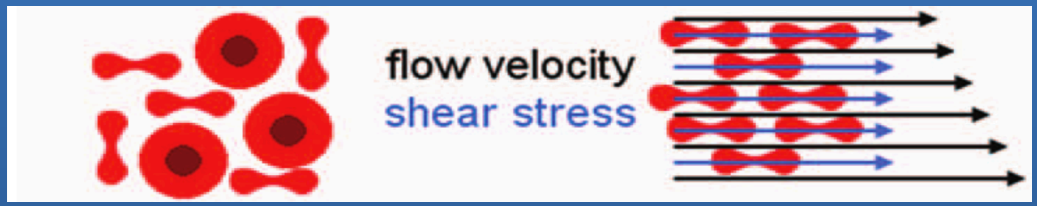
Corcoran, A. et al J. Mod. Opt. 1–11 (2015).



The effect of flow

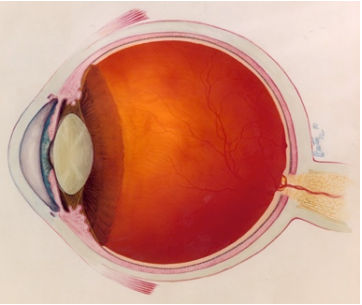




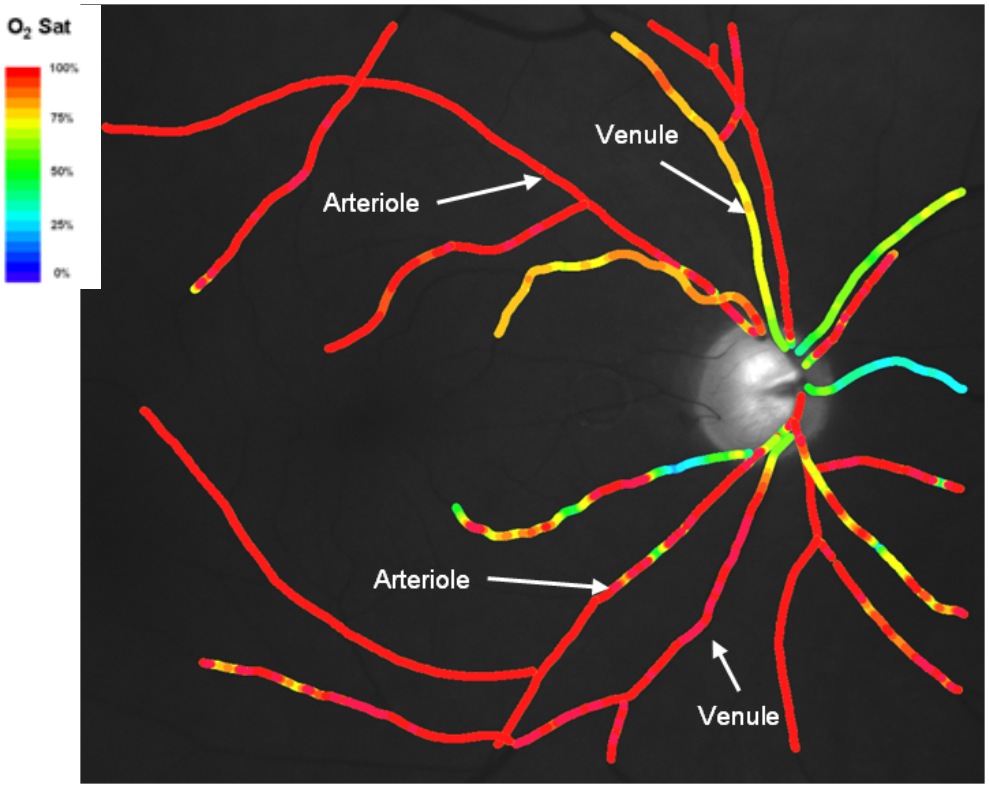


Cimalla, P., et al. J. Biomed. Opt. 16, 116020 (2011).

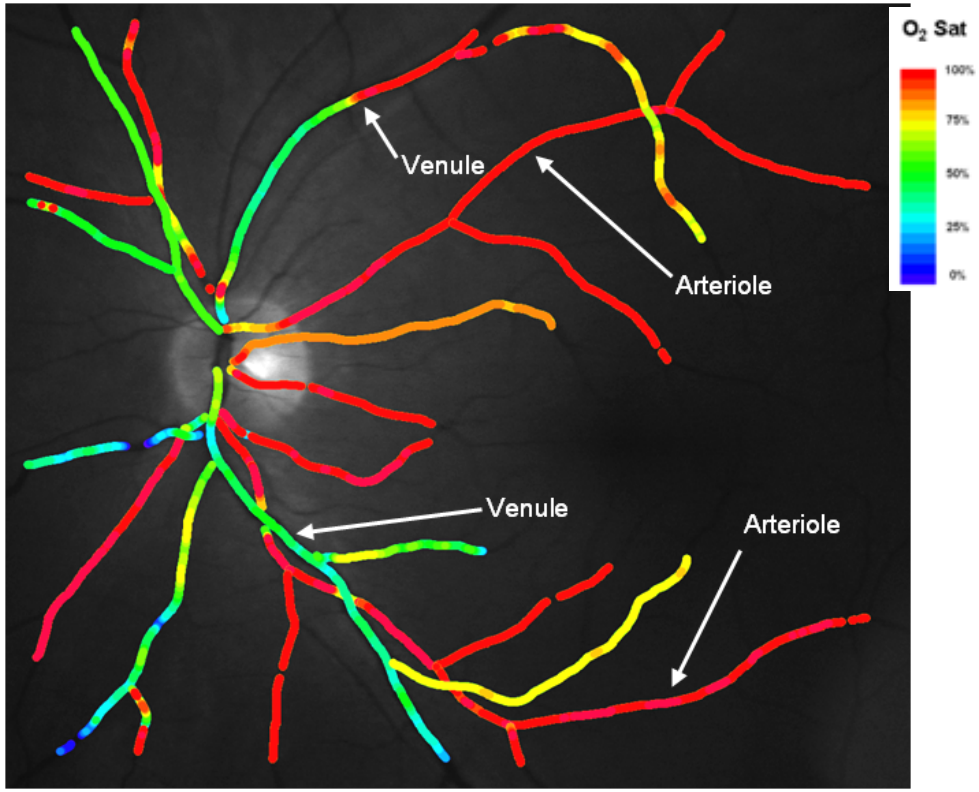
Gloucestershire Hospitals NHS
NHS Foundation Trust

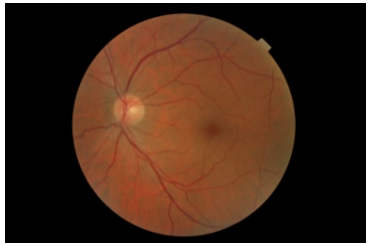


OS



OS



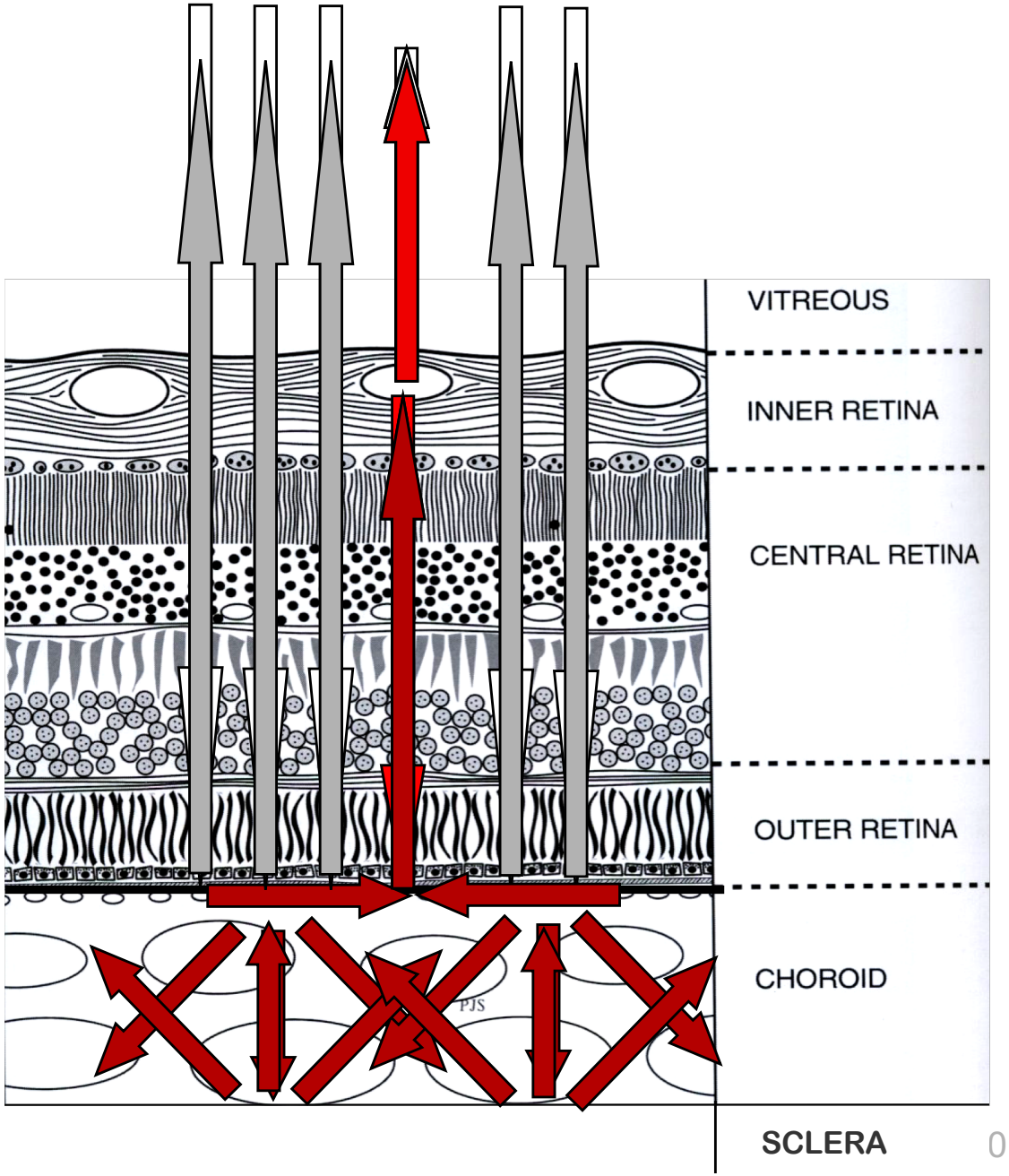


Note: *higher* venular OS in more glaucoma damaged eye

Light paths in retina

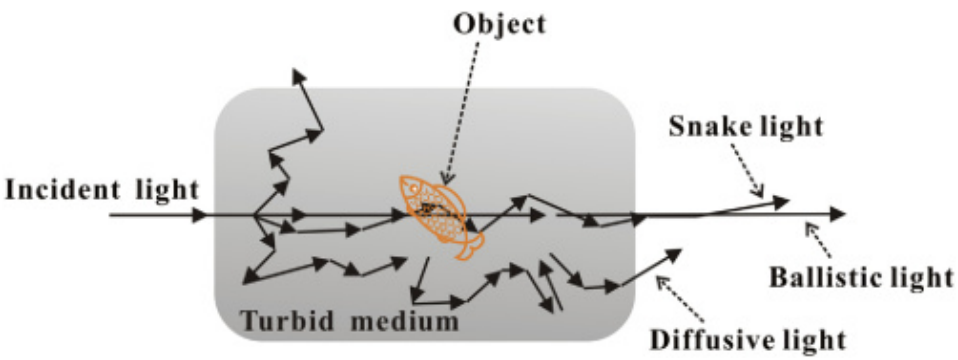
- Recorded light intensity is due to the sum of many light paths. Dominant paths:
  - **Double pass**
  - **Specular**
  - **Backscatter**
  - **Single pass**

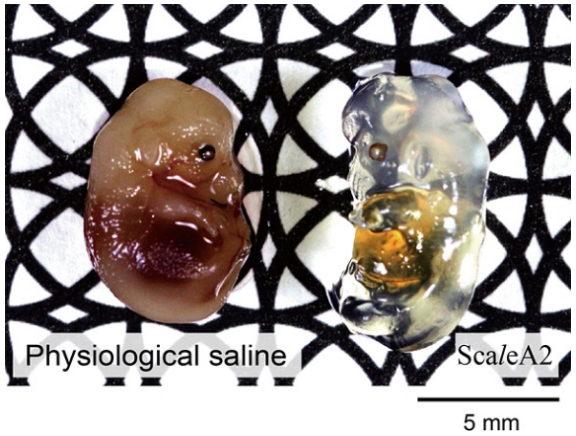
- Physical model required to derive accurate oximetry algorithms

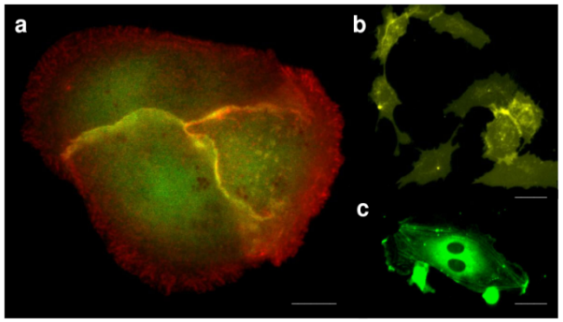


Imaging in turbid media

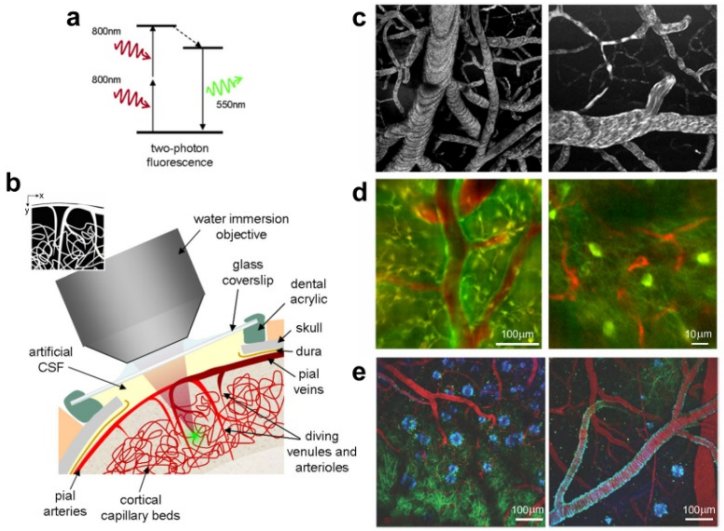
– Scattering: dominant limitation in biological imaging



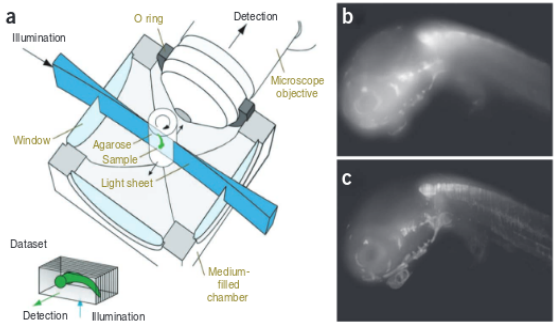




Fluorescence [Kerlopian 2008]



Multi-photon microscopy [Kerlopian 2008]

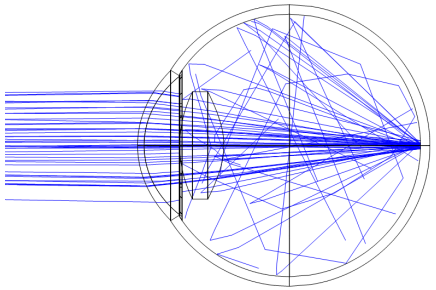


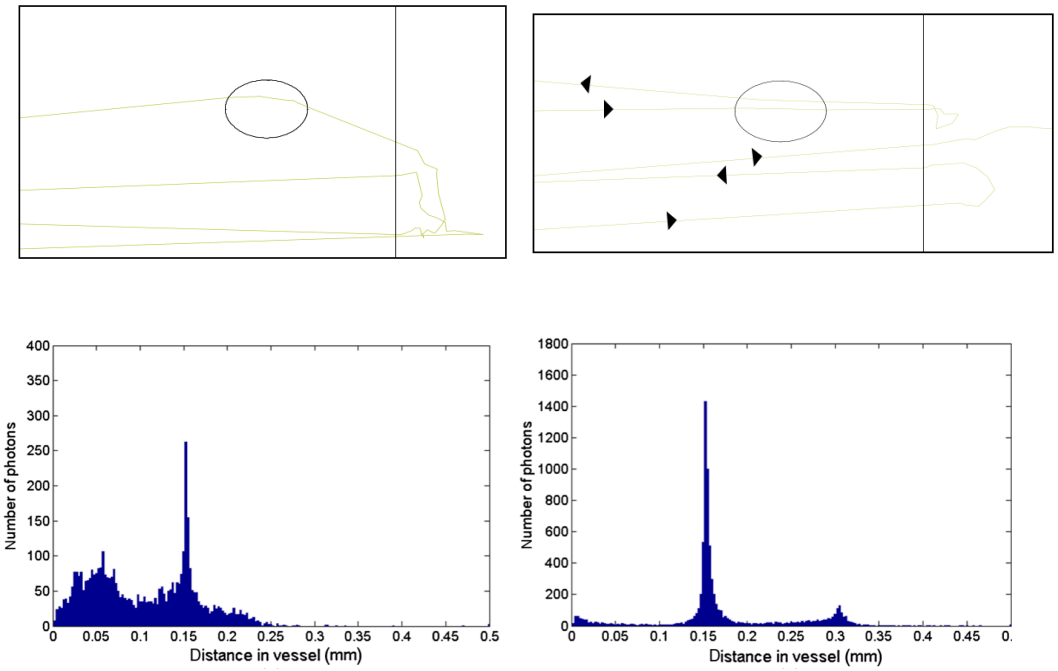
SPIM Microscopy [Ntziachristos 2010]

– Also for

- imaging underwater, atmospheric obscurants, remote sensing of clouds, aerosols etc.

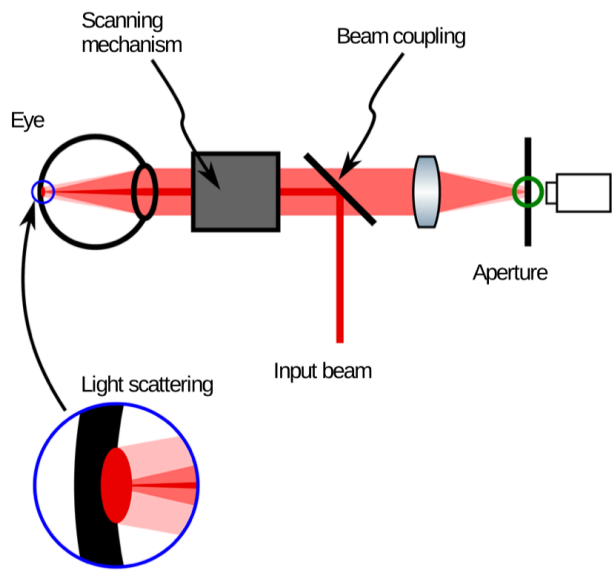
Monte-Carlo modelling of light propagation in tissue and optical instruments: the slow way





Fundus camera

Scanning Laser Ophthalmoscope

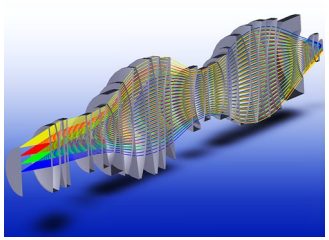


Rodmell, P. I. et al.. J. Biomed. Opt. 19, 36008 (2014)

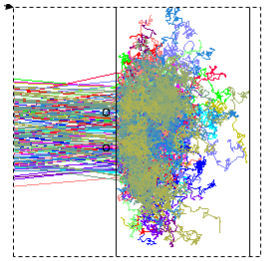
G. Carles, et al , J. Biomed Opt. **22**, 1–11 (2017).

Ray tracing & Monte Carlo:What's the difference?

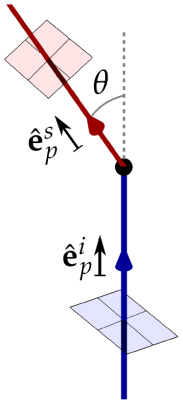
- Ray-tracing
  - Deterministic
  - Reflection, Refraction, Absorption

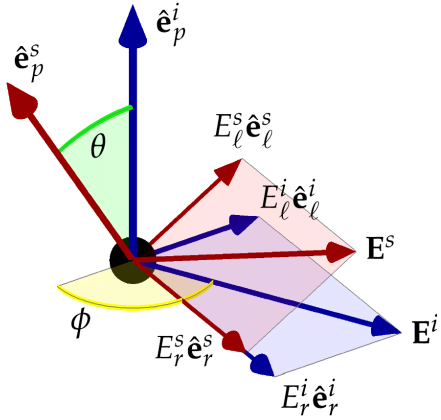


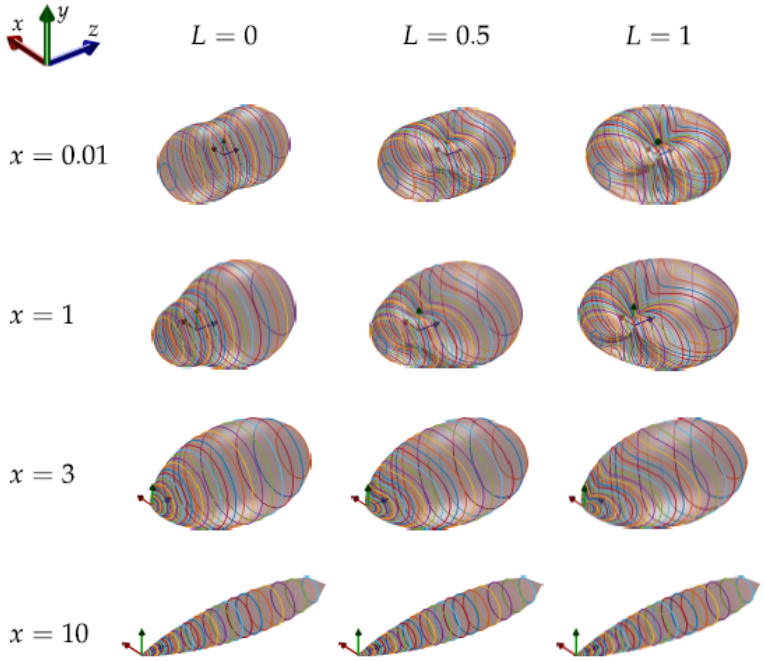
- Monte-Carlo propagation
  - Stochastic
  - Reflection, Refraction, Absorption,
    Bulk (multiple) Scattering



- We extend *Zemax* to simulate complete systems; integrating:
  - Ray-tracing, *Monte-Carlo* light propagation
  - Using The *Zemax* user-friendly interface
  - Polarisation-sensitive Mie scattering



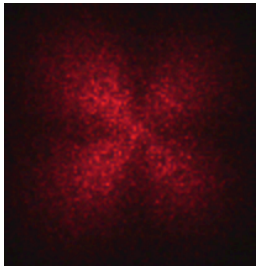


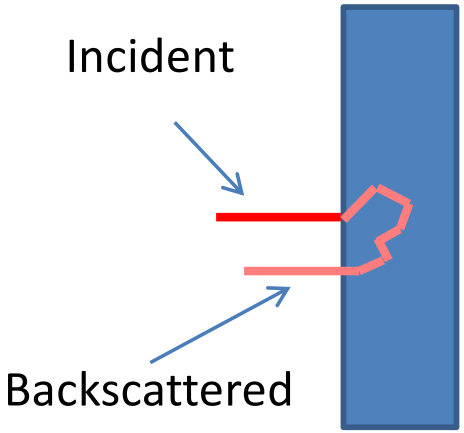


Carles et al, submitted for publication

Monte Carlo modelling of scattering

- Mueller matrices from backscattering (validation)



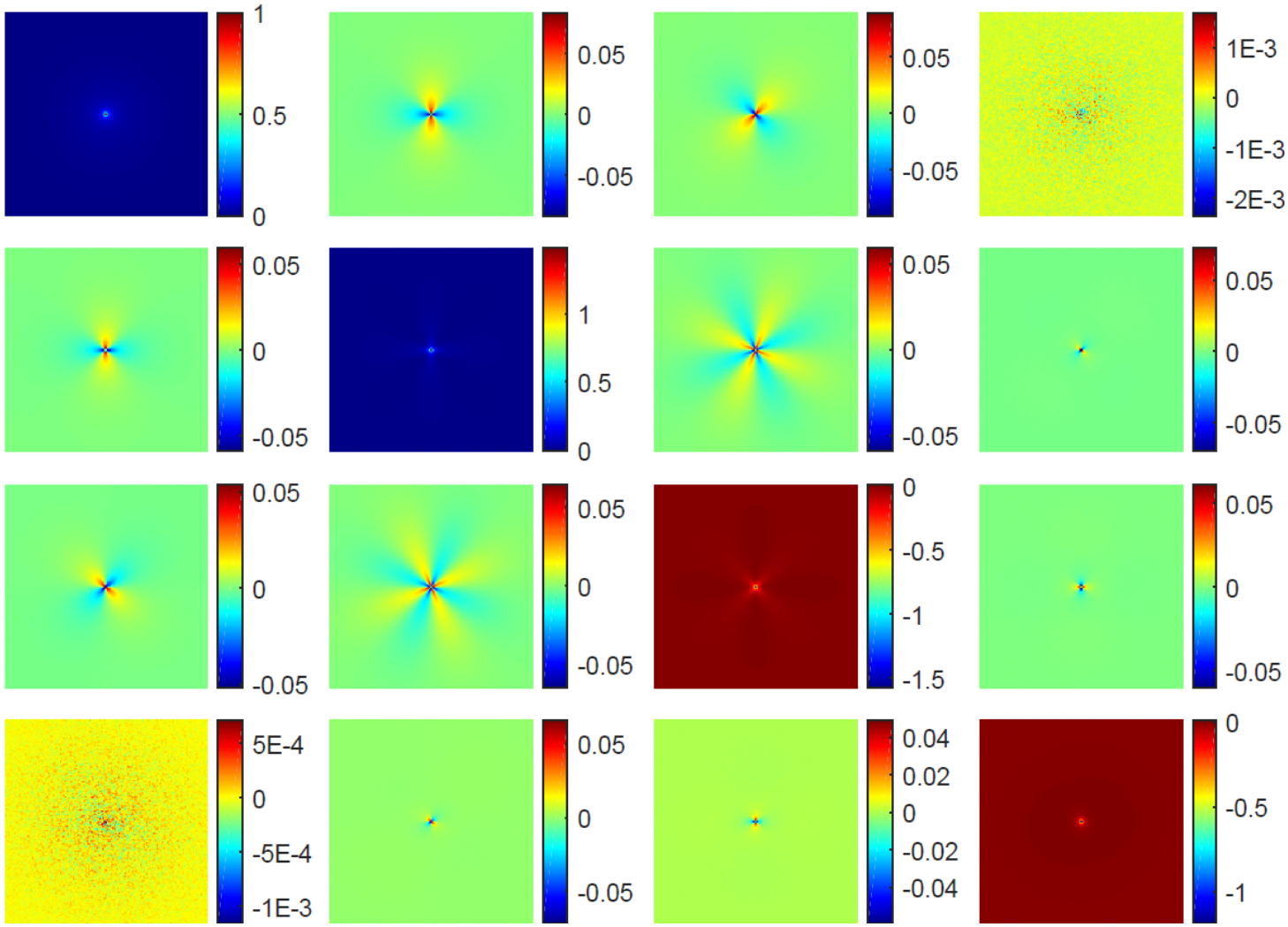


Polarisation:

$$\vec{S}_b = \mathbf{M}\,\vec{S}_i$$

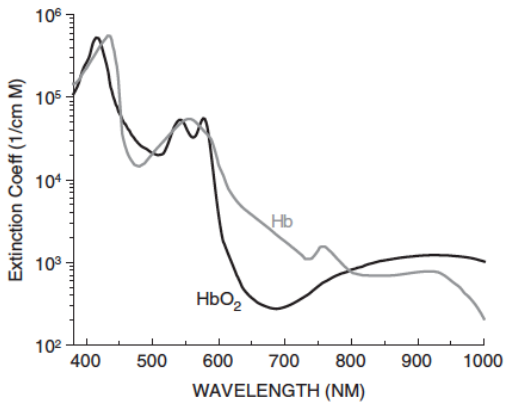
Mueller matrix (4x4)

Stokes vector (1x4)



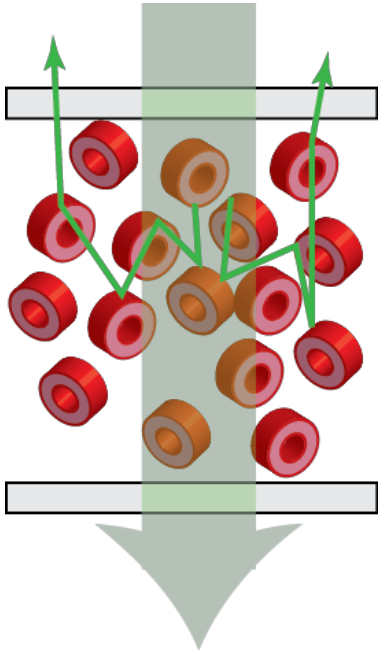
https://github.com/gcarles/RayPolMieScattering

Experimental polarisation & speckle scattering: Laser illumination of a slab of blood

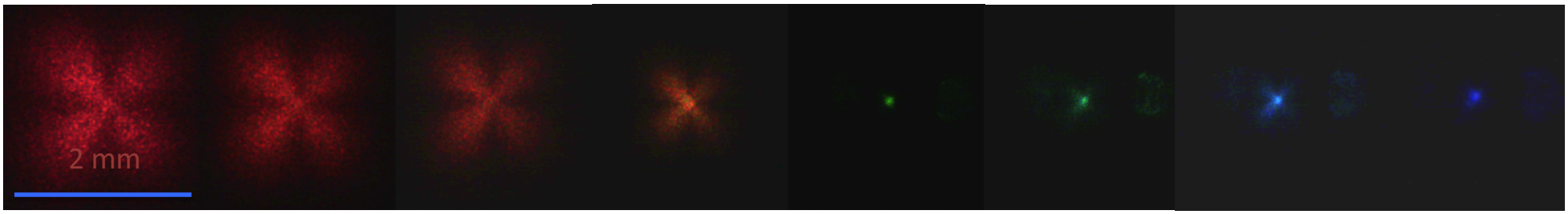


Molar extinction coefficients of oxy- and deoxyhaemoglobin

PSF scale, pupil-plane speckle vary with absorption (oxygenation)

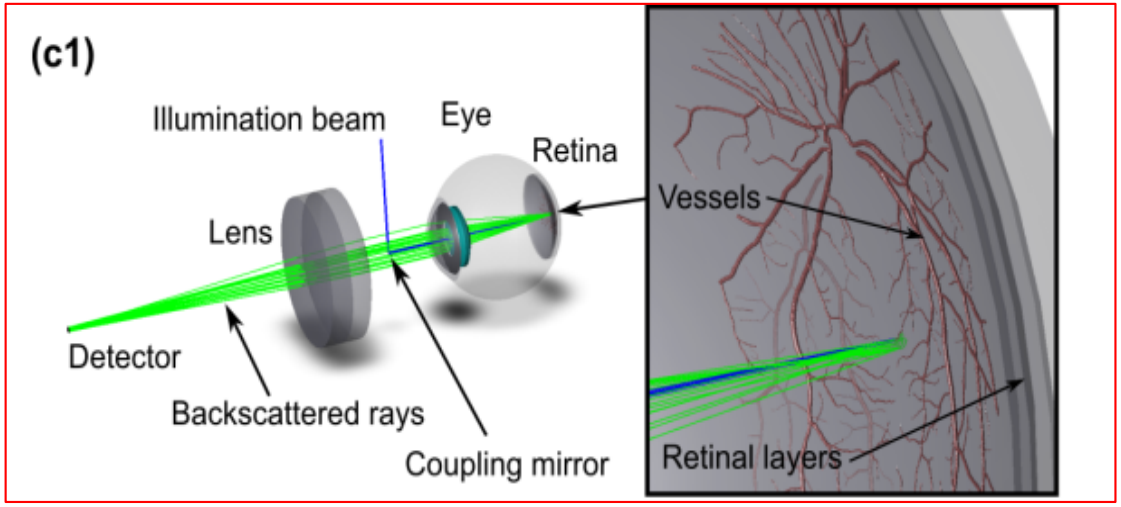


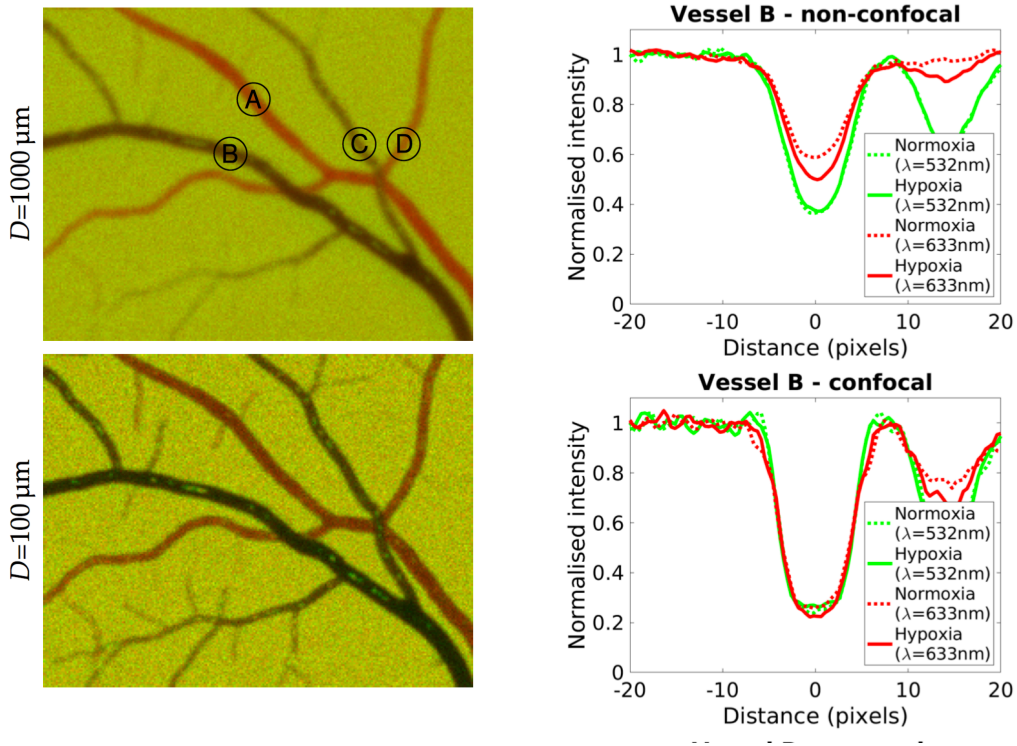
Slab Blood PSF for 83% sO2 horse blood (cross-polarization)



633nm 612nm 604nm 594nm 543nm 515nm 488nm 458nm

Monte-Carlo modelling of light propagation in tissue and optical instruments using Zemax®

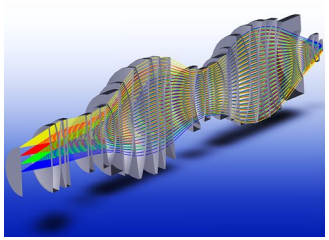




Brewer et al. in preparation
Carles et al. submitted

Optical modelling of complete optical systems

- Ray-tracing
  - Deterministic
  - Reflection, Refraction, Absorption



- Monte-Carlo propagation
  - Stochastic
  - Reflection, Refraction, Absorption,
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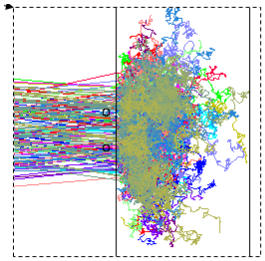
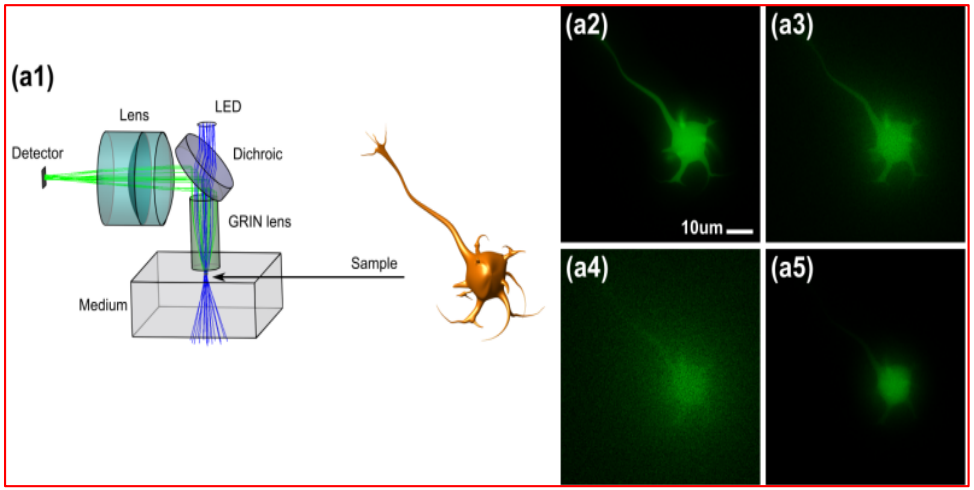
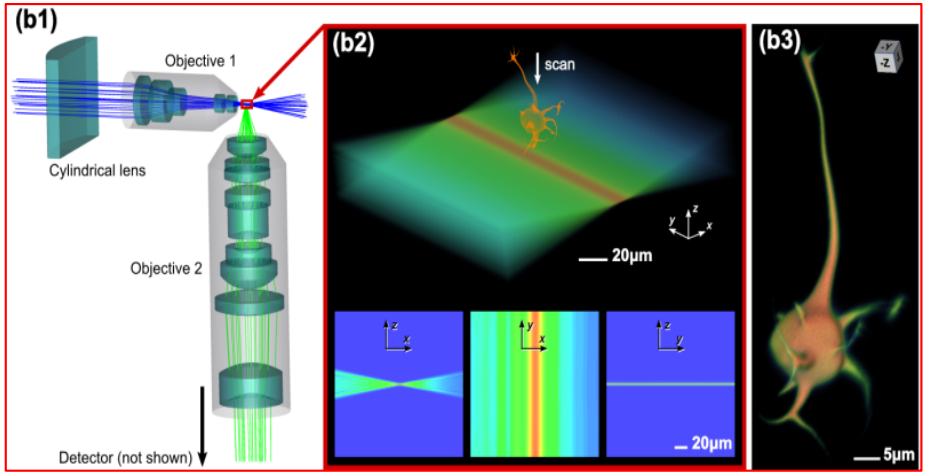
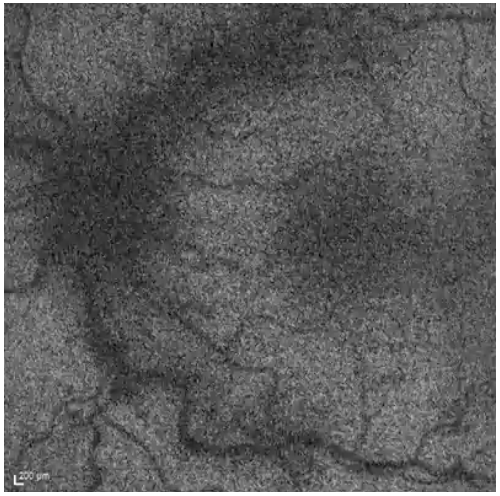






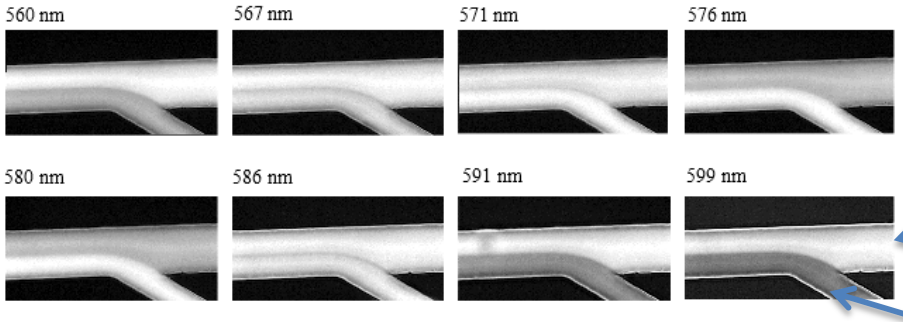
Carles et al, submitted for publication

Differential oximetry: dye-free angiography



Fluorescein angiogram

Oximetric angiogram



Oxygenated blood

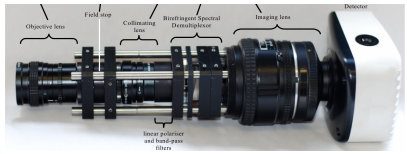
Deoxygenated blood

Microfluidic vascular phantom: venular branch

McKenzie et al submitted (2018)

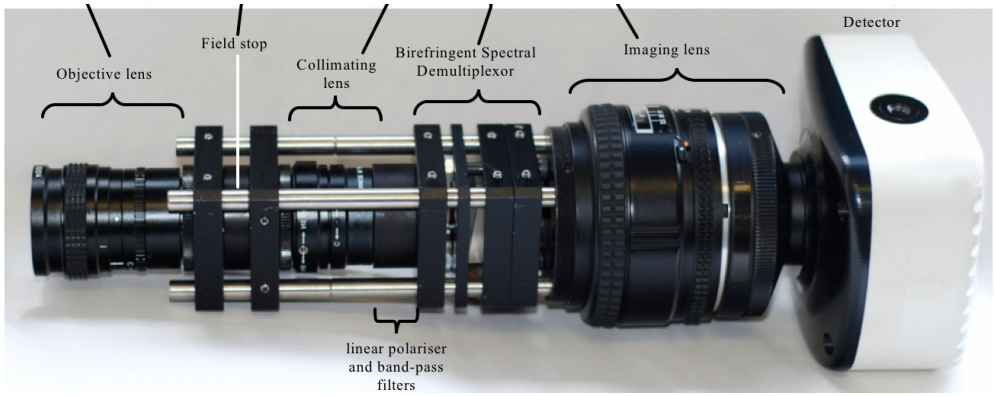
Back to Hyperspectral instrumentation:

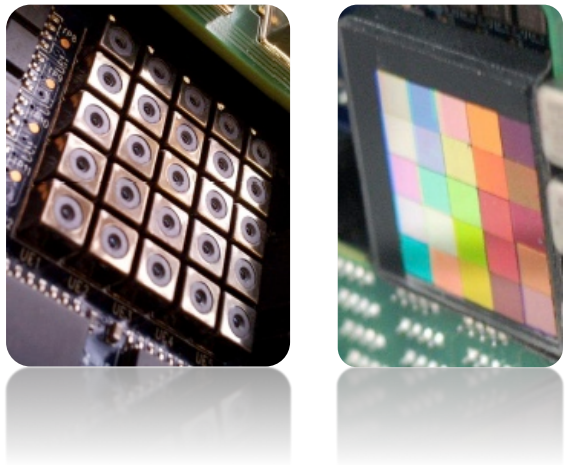
~~Hyperspectral imaging technologies are big and slow and expensive~~



IRIS

Camera Array





Why?

Sensor array

Space.spectrum ~4 Mvoxel	**50 Mvoxel ➔600Mvoxel**
Single integration time	**Per-band integration time (HDR)**

Objective Lens(es)

Full-band achromatisation!	**No achromatisation necessary**
Long optical track	**~10mm**
Single perspective/channel	Multi-perspective
Microscopy etc	

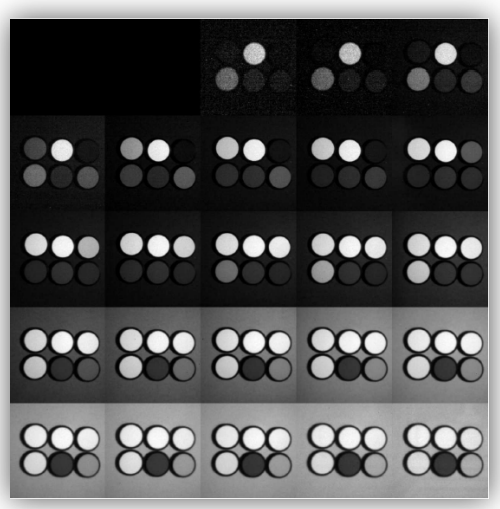
Spectral Coverage

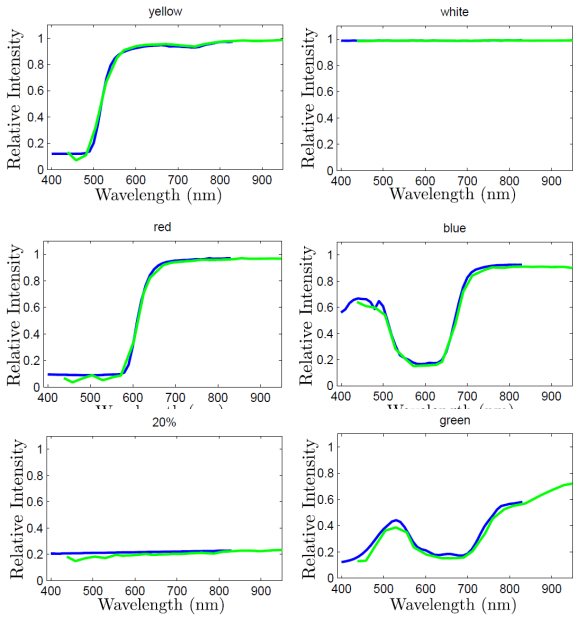
Contiguous/restricted	**Arbitrary (optimal, sparse) bands**

Cost

10,000s $	**100s $**

Spectral mage reconstruction





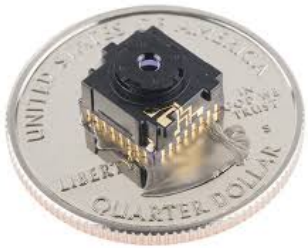
Perspective-corrected coregistration

Multispectral LWIR system

- 6x multiaperture multispectral system.

Based on low-cost FLIR LEPTON LWIR uncool detector

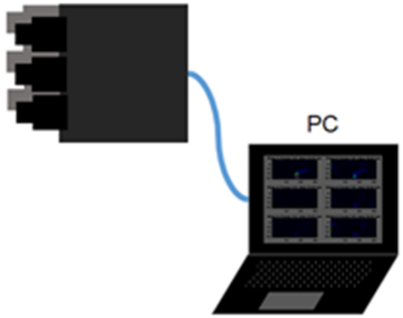
2 k£ system vs 100k£ systems!!

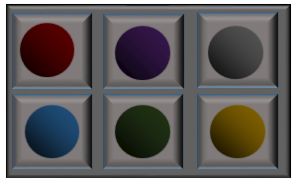


FLIR LEPTON LWIR uncool detector
Dimension: 10.6 x 11.7 x 5.9 mm
HFOV: 25 deg (50 deg also available)
LWIR: 8 to 14 µm
80 x 60 pixels
Thermal sensitivity <50 mK
Frame Rate 9 Hz (actual Frame rate 27Hz limited by firmware due to US export reg.)
~150 pounds

(1) FLIR LEPTON® based 6x LWIR detectors and filters
(2) 6x Raspberry-pi ® based CPU rack.
(3) Ethernet switch-hub for networking
4) USB hub for power supply.

Multispectral Imaging detector

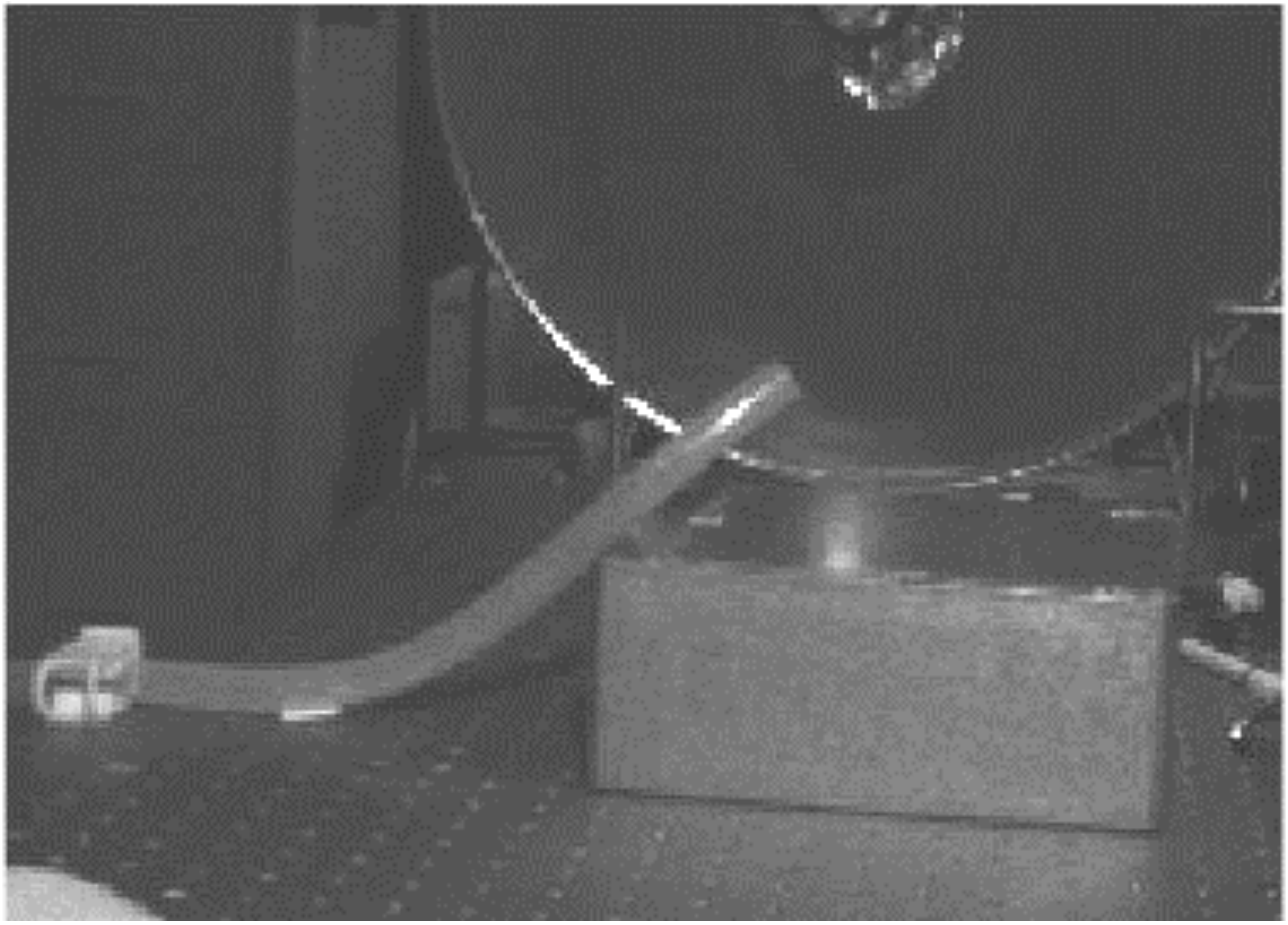




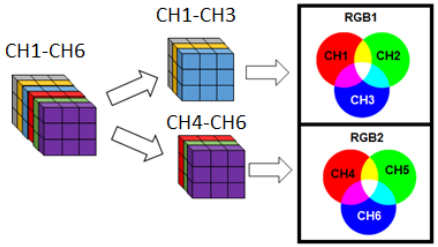
6 cameras
6 infrared interference filters
6 channels of LWIR

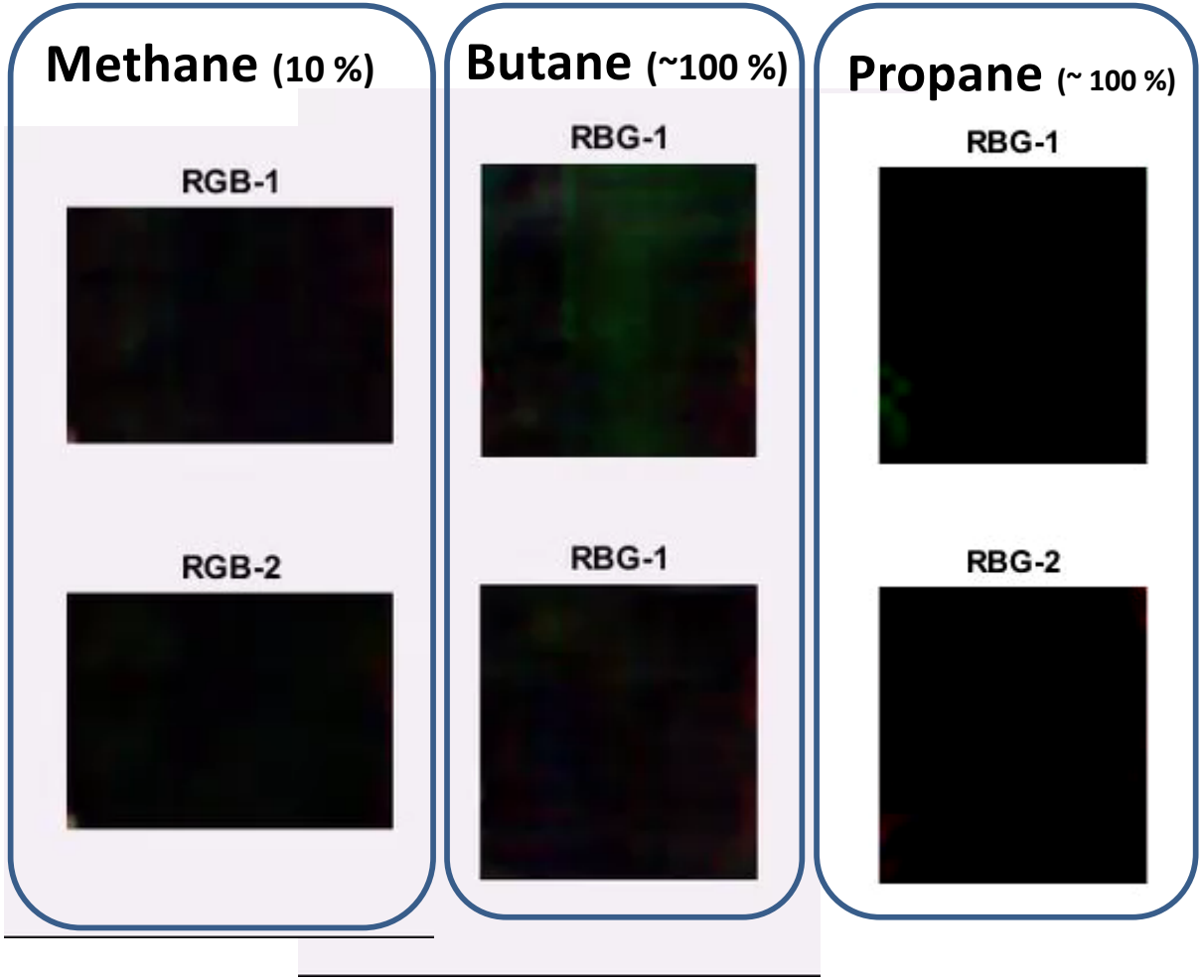
Gas imaging results

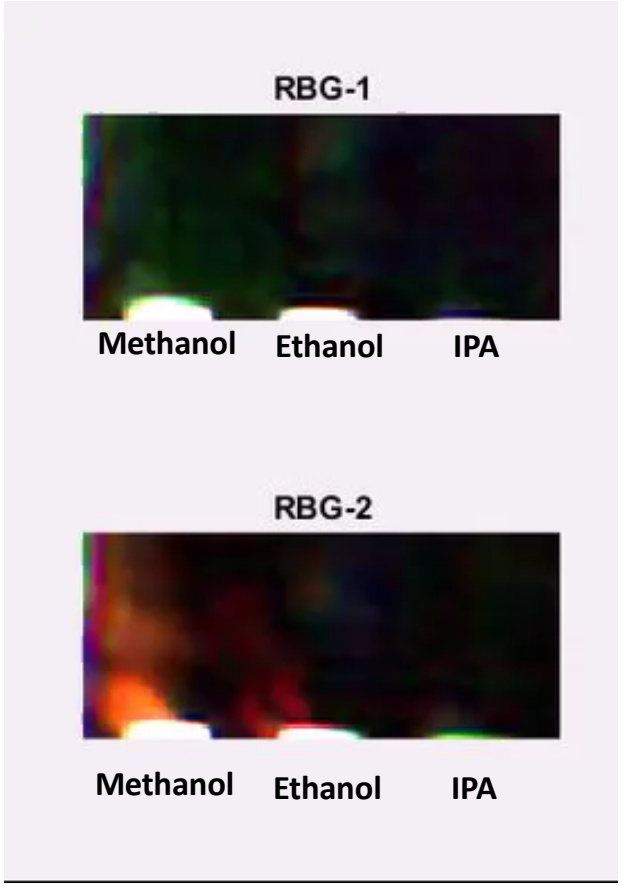
Detection of propane in 7.2 µm, overlapped with visible channel.



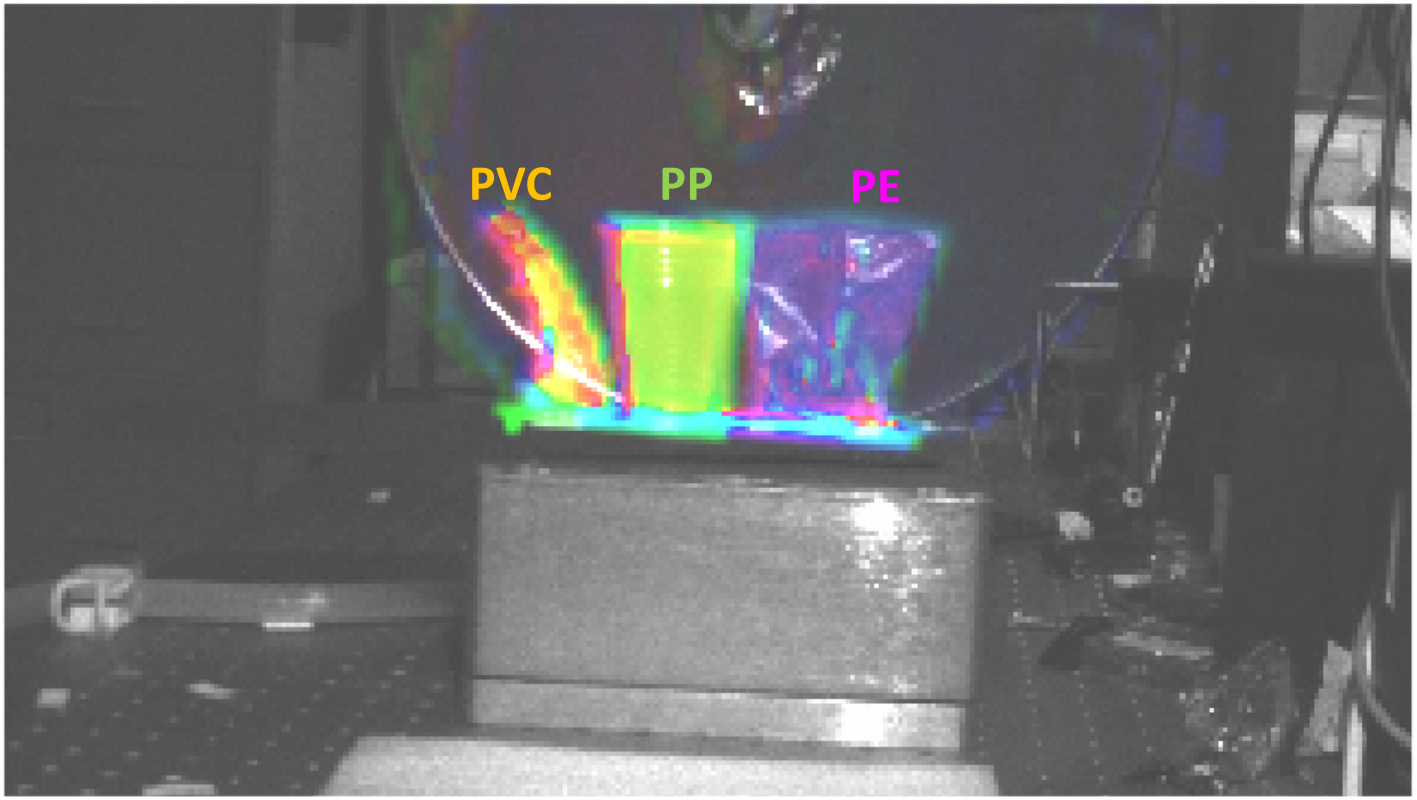
Gas imaging of hydrocarbons







Thin plastics classification



PVC: Polyvinyl chloride

PP: Polypropylene

PE: Polyethylene

Clear potential in recycling processes!

Conclusions

- Video-rate spectral imaging
  - Image Replication Imaging Spectrometer
    - Highest SNR
    - Single aperture
  - Multiple apertures
    - It’s really cheap and high performance
    - And now in the infrared
- What’s your application?

Thank you for listening

Professor Andy Harvey

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University of Glasgow

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Tel: 0141 330 8606

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