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High resolution Fourier domain optical coherence tomography in the 2 micron wavelength regime for painted objects

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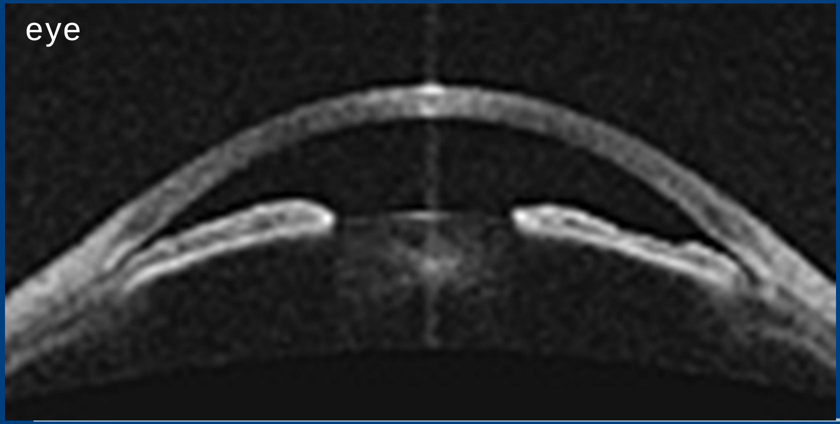
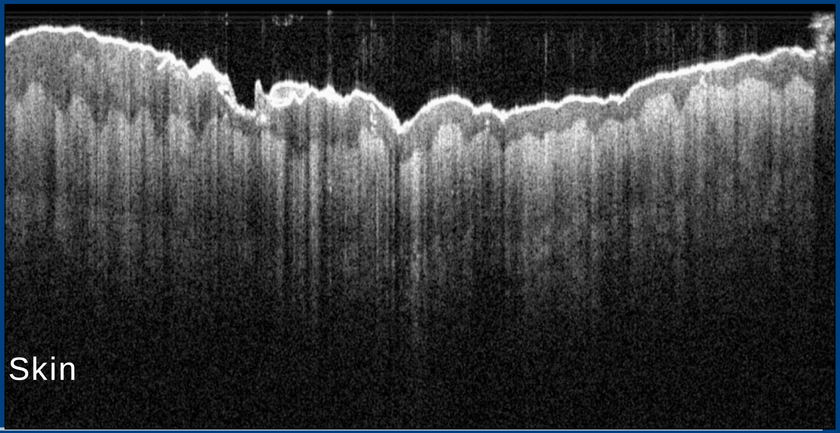
Optical Coherence Tomography

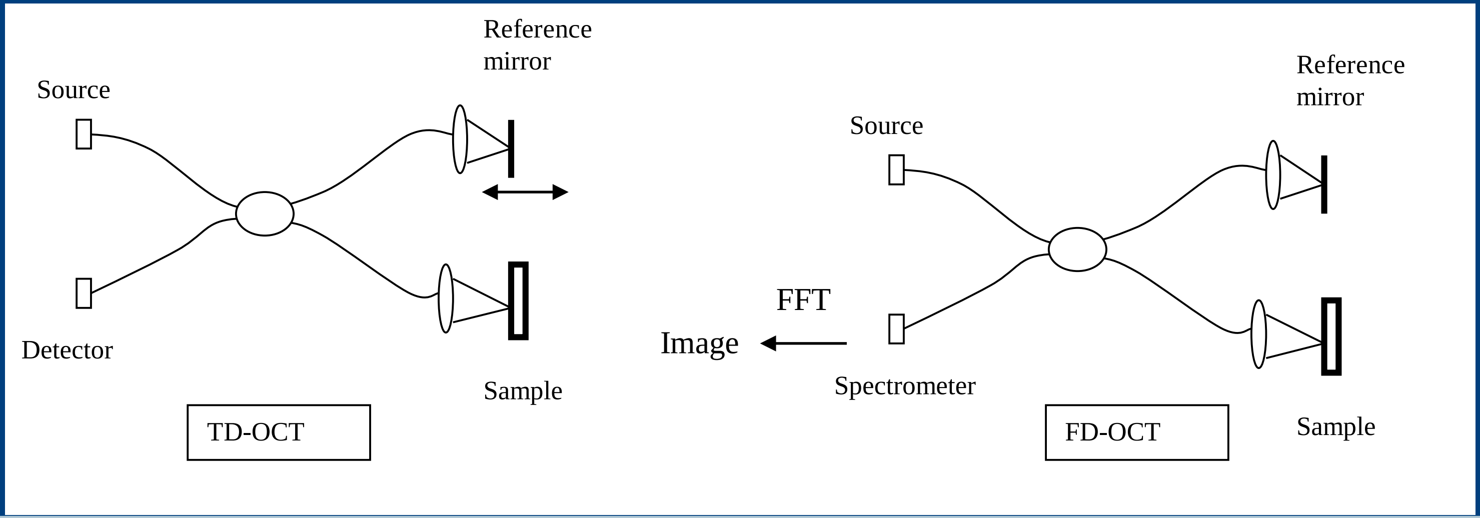
- Fast scanning Michelson interferometer – invented for in vivo imaging of the eye
- Axial resolution $\Delta z \propto \lambda_o^2/\Delta\lambda$ => need broadband laser for high resolution
- Transverse resolution given by the objective lens and the laser beam width

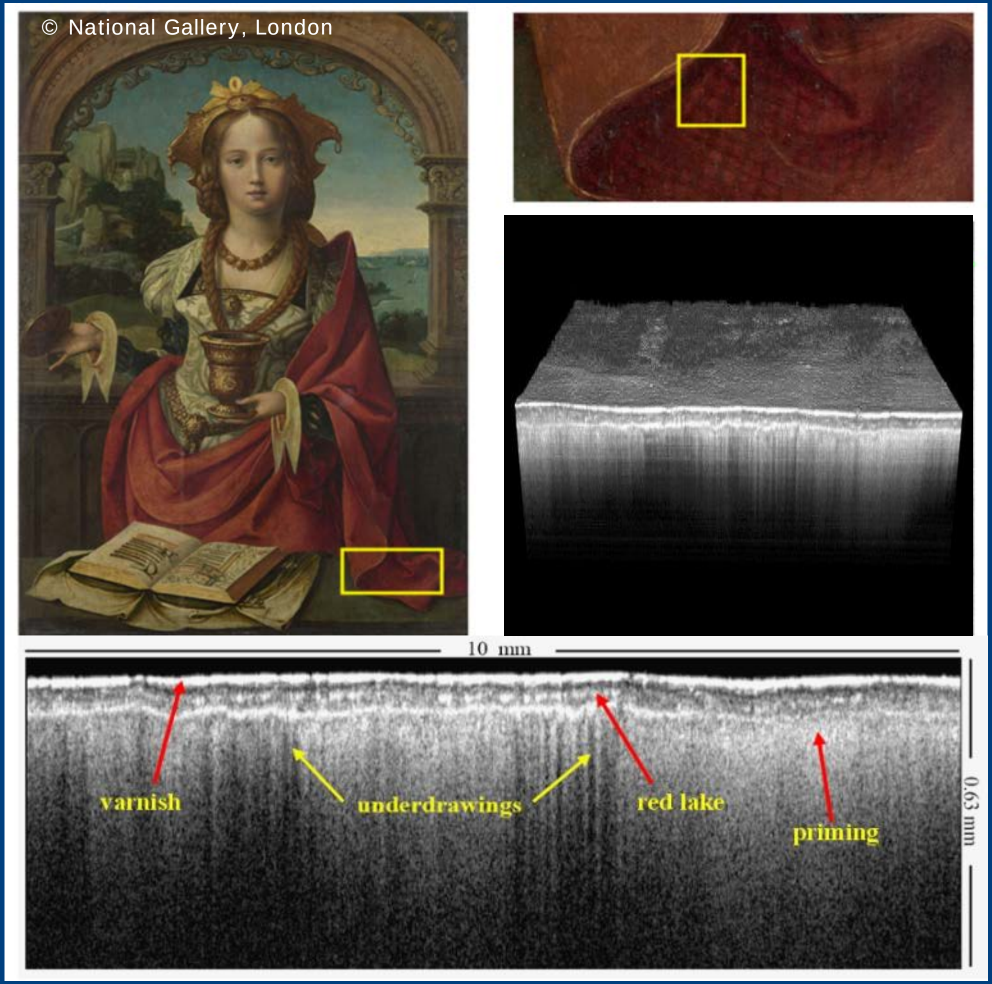




Types of OCT

- Time Domain OCT (TD-OCT) – scanning in depth by moving the reference mirror
- Fourier Domain OCT (FD-OCT)
  - Spectral Domain OCT – reference mirror fixed but the interference signal is registered as a function of wavelength through a spectrometer => FFT => image
  - Swept Source OCT – reference mirror fixed and depth scanning is achieved by sweeping through the source spectrum

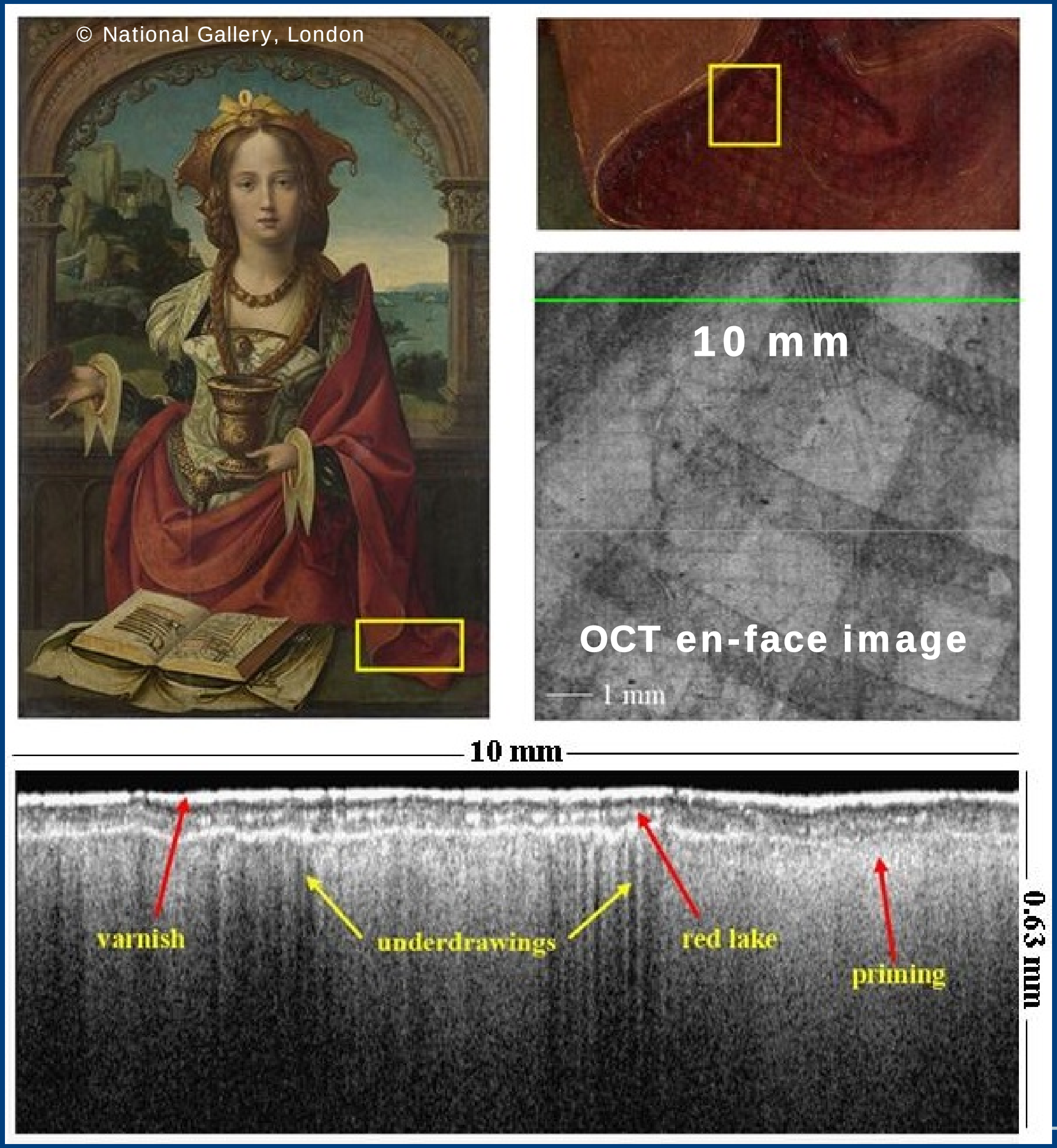


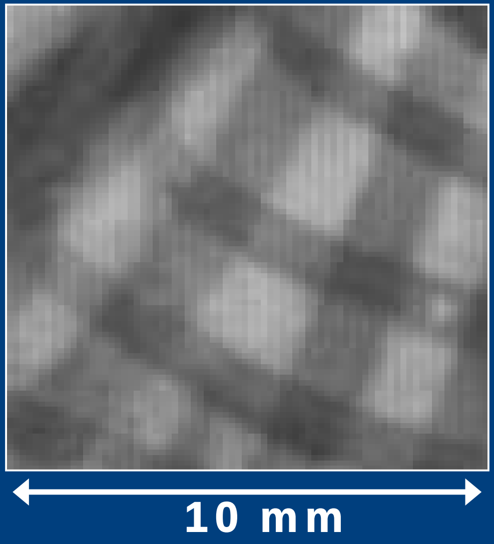


Workshop of the Master of 1518, The Magdalen (NG719), before 1524-6

OCT image of an en-face slice below the paint layers showing the underdrawings

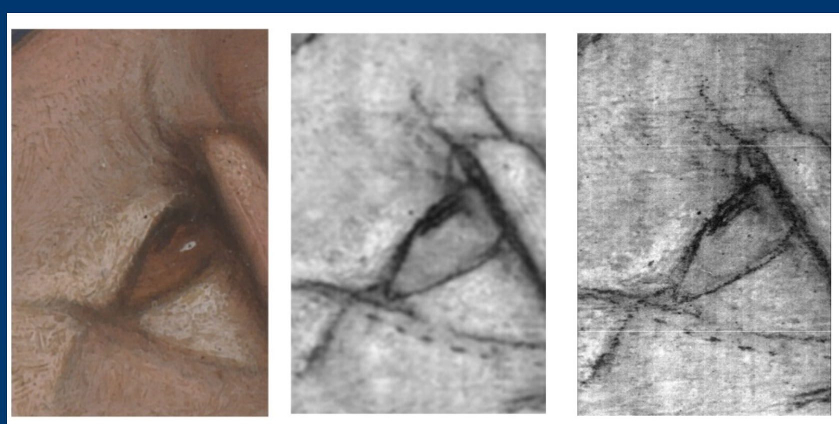
OCT virtual cross-section





Detail of infrared image (SIRIS high resolution InGaAS camera 900-1700 nm)

OCT imaging of underdrawings



Detail of the angel’s eye

SIRIS high resolution InGaAs camera (900-1700 nm)

OCT 930nm en-face image of the underdrawing

After Francesco Francia, *Virgin and Child with an angel* (NG 3927)

After Raphael, *The Madonna and Child* (NG 929), before 1600

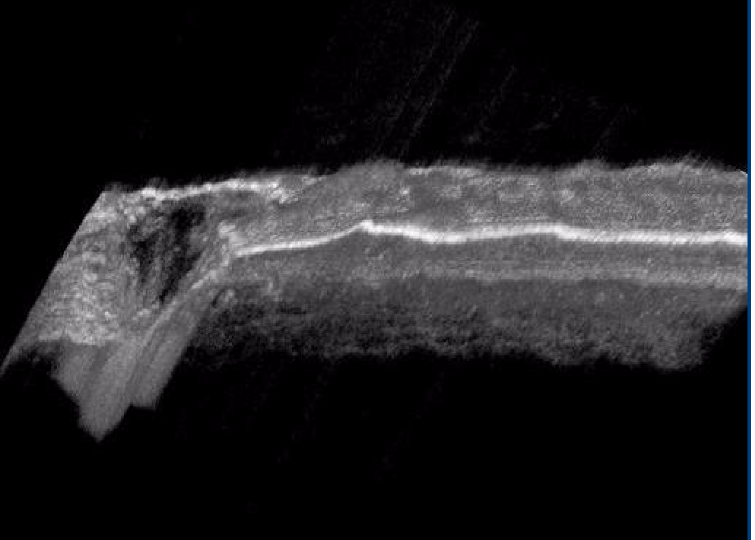
In-house built UHR OCT at 800 nm using a NKT SuperK versa:

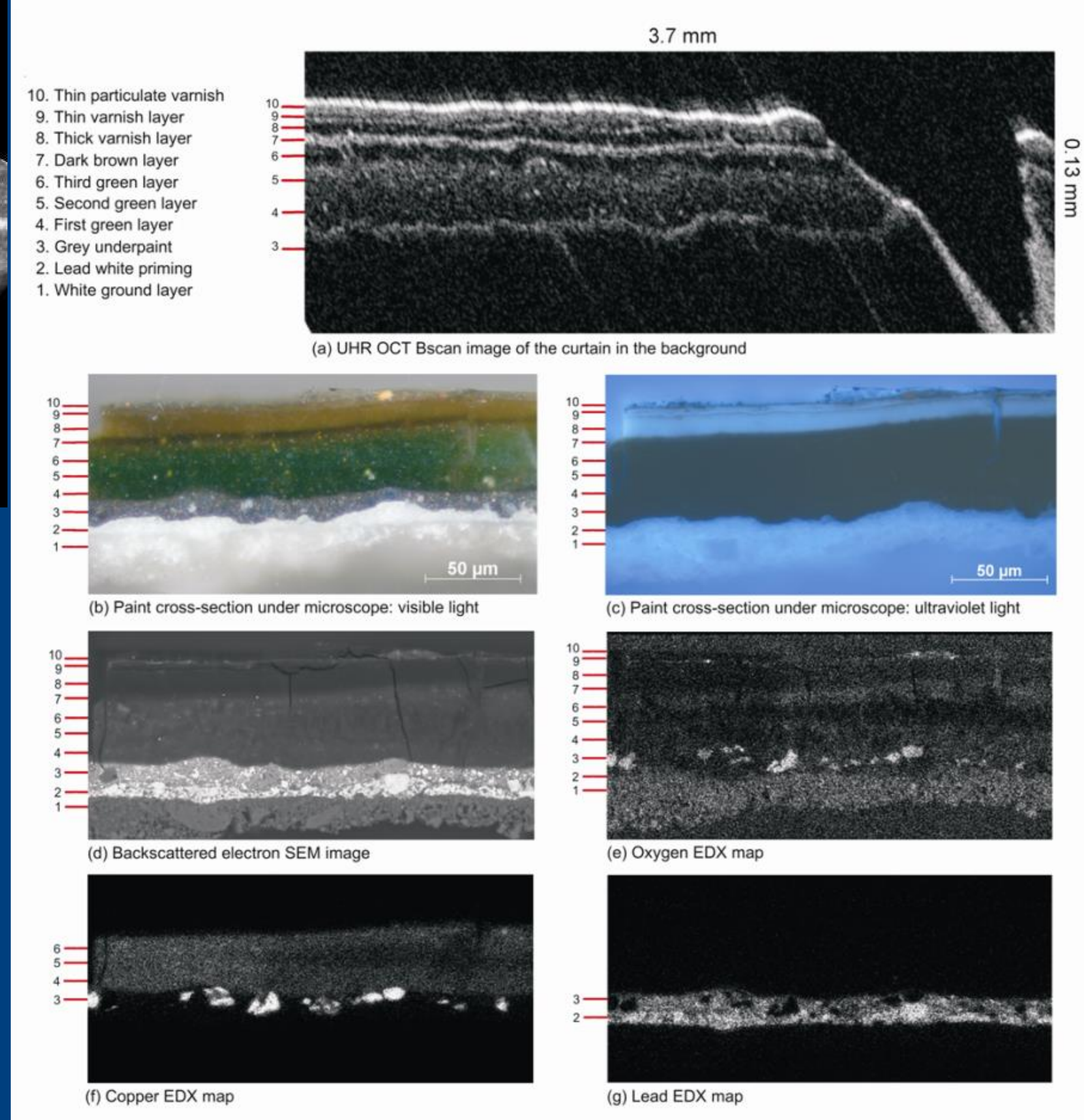
- depth resolution 1.2 μm in varnish and paint
- Sensitivity roll-off 2 dB over 1.2 mm
- Speed of acquisition ~40 μs per depth profile

=> 5 mm x 5 mm x 1.6 mm volume in 10s

- Power incident on object ~1 mW

Cheung, Spring, Liang, *Optics Express*, Vol. 23(8), pp. 10145-10157 (2015)





After Raphael, *The Madonna and Child* (NG 929)

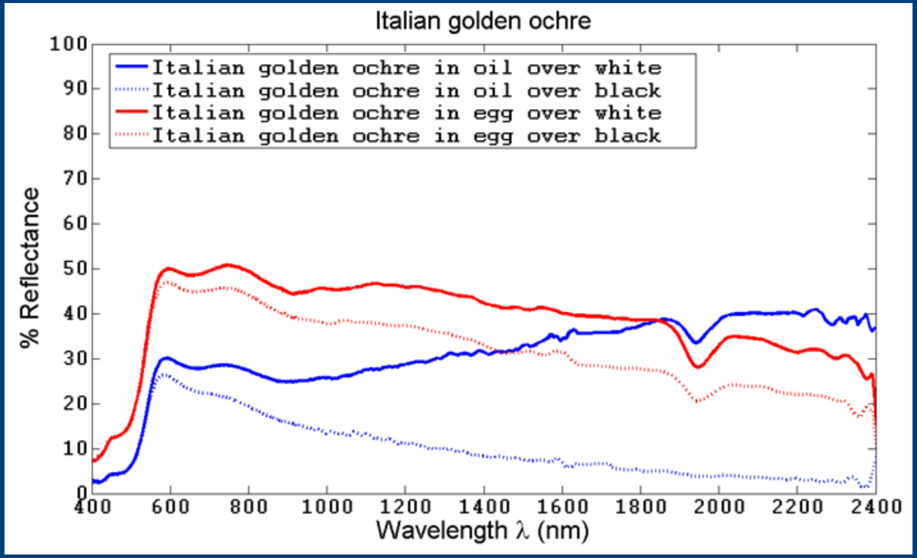
probably before 1600,Oil on wood, 87 x 61.3 cm

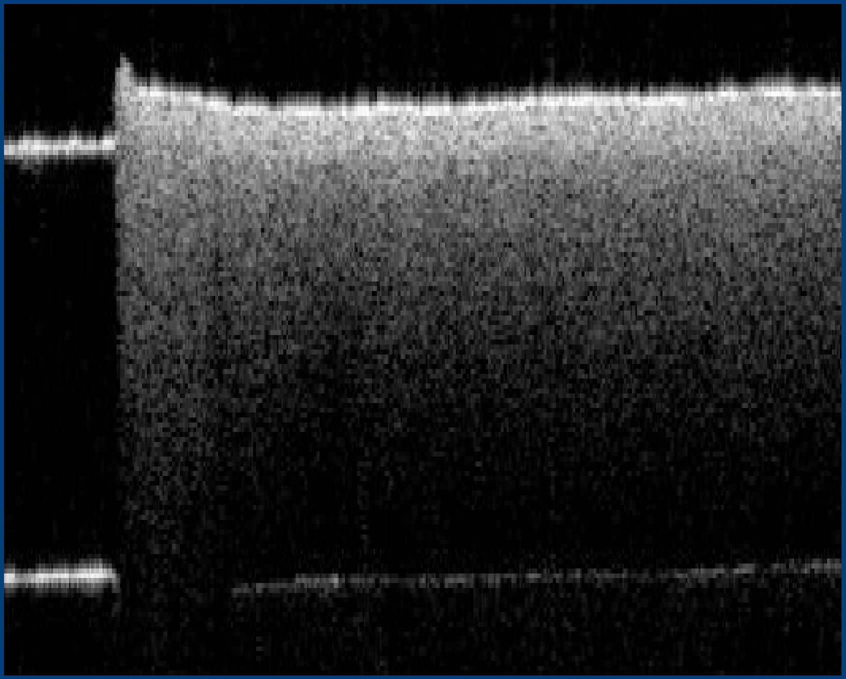
Cheung, Spring, Liang, *Optics Express*, Vol. 23(8), pp. 10145-10157 (2015)

Multiple Scattering masks layers

Transparent at 1300nm, but multiple scattering masked the layer

1300 nm

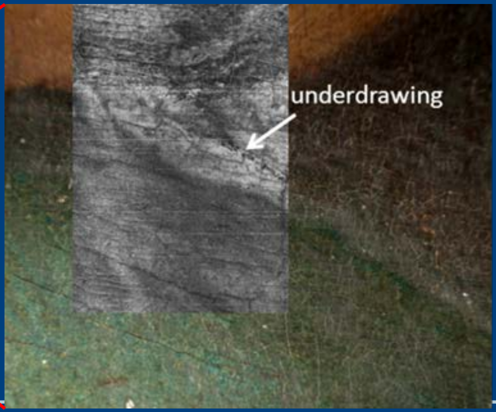




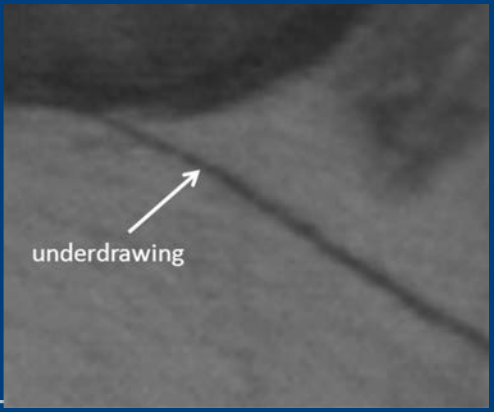
Underdrawing is not always seen with short wavelength OCT

- Need to find optimum spectral band for OCT

930nm OCT image overlaid



InGaAs NIR camera (900-1700 nm)

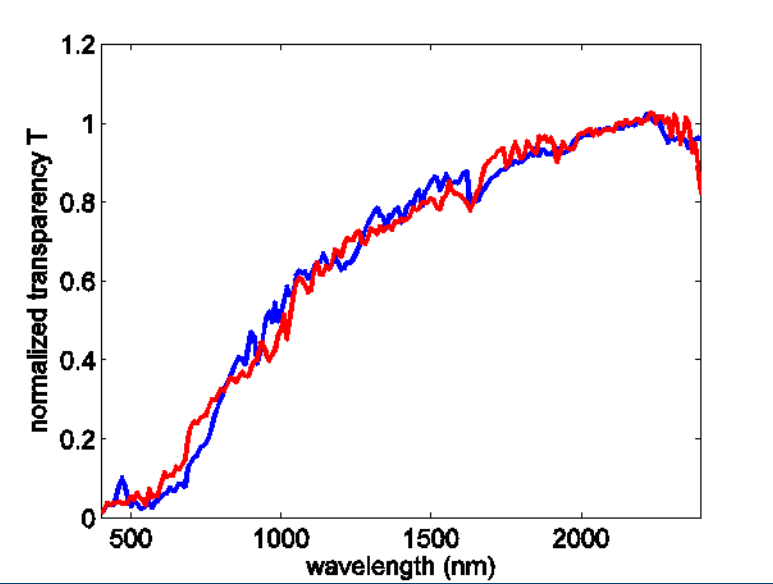


After Raphael, *The Madonna and Child* (NG 929)

probably before 1600,Oil on wood, 87 x 61.3 cm

Optimum Spectral Window for OCT imaging: 2.2 μm

- Scattering coefficient decreases with increasing wavelength
- Copper-based pigments, azurite, malachite and verdigris, have minimum transparency corresponding to absorption troughs between 0.7 and 1.0 μm;
- Cobalt pigments have minimum transparency corresponding to the broad absorption trough at 1.3–1.6 μm



Median spectral transparency normalized at 2.2 μm for pigments in use before the 19th century but excluding lake pigments.

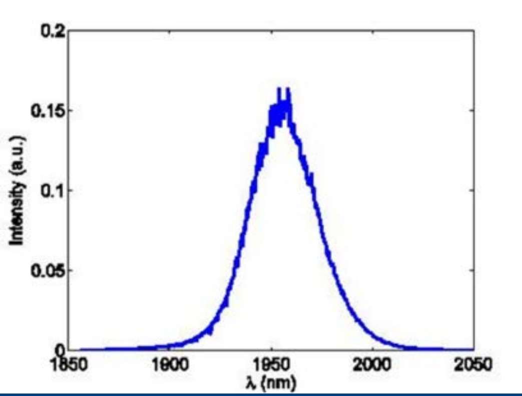
Blue – oil paint

Red – egg tempera paint

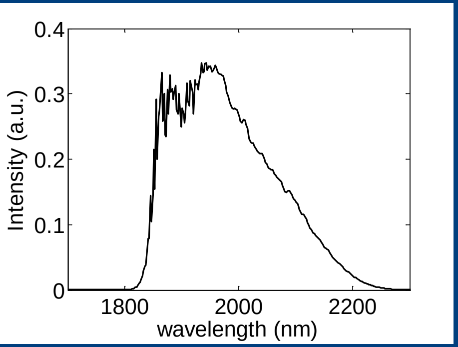
Liang et al. Applied Physics B, 2012

Broadband laser sources at 2μm wavelength

- Broadband Tm-doped superfluorescent fiber source generated through the process of amplified spontaneous emission (ASE):
  - very stable
  - Bandwidth 40 nm
  - OCT axial resolution 35μm

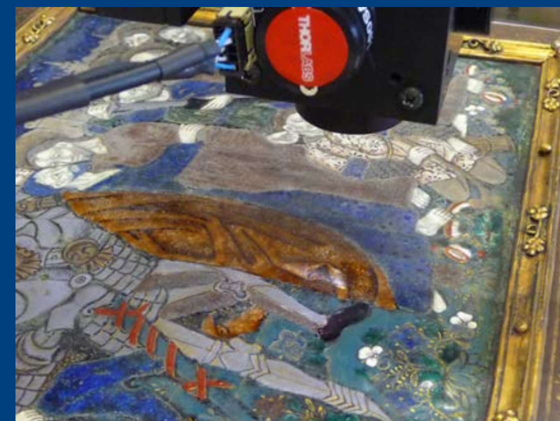


- Supercontinnum laser source generated by a pulsed source
  - Bandwidth >200nm
  - OCT axial resolution < 10 μm



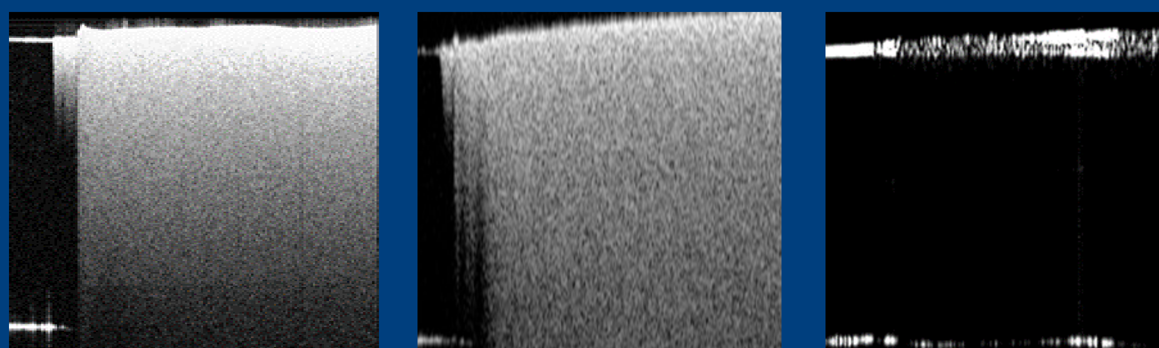
Long wavelength (2 microns) OCT

- First version: time domain OCT at 1960nm using ASE source (40nm bandwidth) => improved depth of penetration BUT rather slow, low axial resolution



5 mm

1.8 mm



930nm OCT

1300nm OCT

1960nm OCT

Paint layer on glass slide

Bottom of glass slide

Cheung, Daniel, Tukurakawa, Clarkson, Liang , Optics Letters, 34, 6509, (2014)

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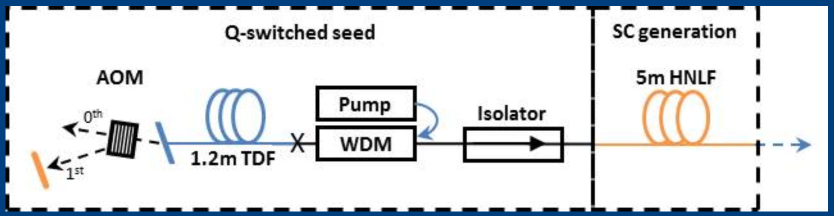
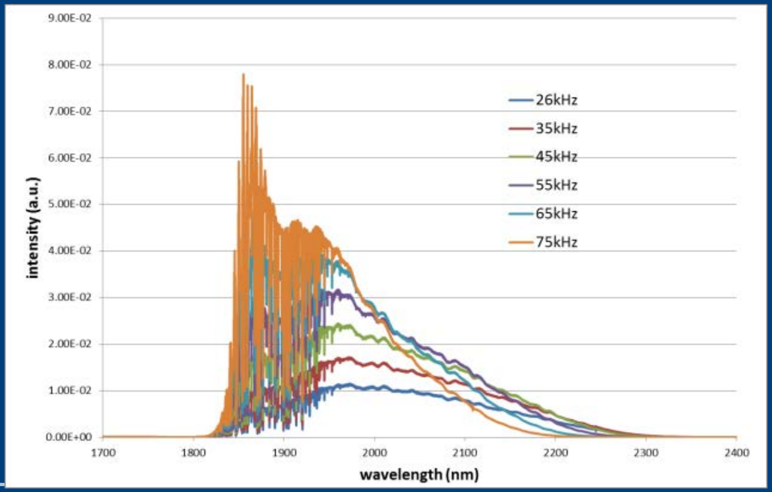
Broad band supercontinuum source

- Supercontinuum source with 10-200 kHz repetition rate
- At 50 kHz pulse rate, 100 ns pulse width, average power ~0.5 W after spectral filtering
  - Pulse to pulse intensity variation ~ 1% (standard deviation) over the wavelength range ~1800-2200 nm
  - Pulse to pulse total intensity variation ~ 0.2%
- Compact in-house built Q-switch thulium fibre pump
- Low cost commercially available solid core germanium doped fibre for continuum generation





Cheung, Daniel, Tukurakawa, Clarkson, Liang, *Optics Express*, Vol. 23(3), pp. 1992-2001 (2015)

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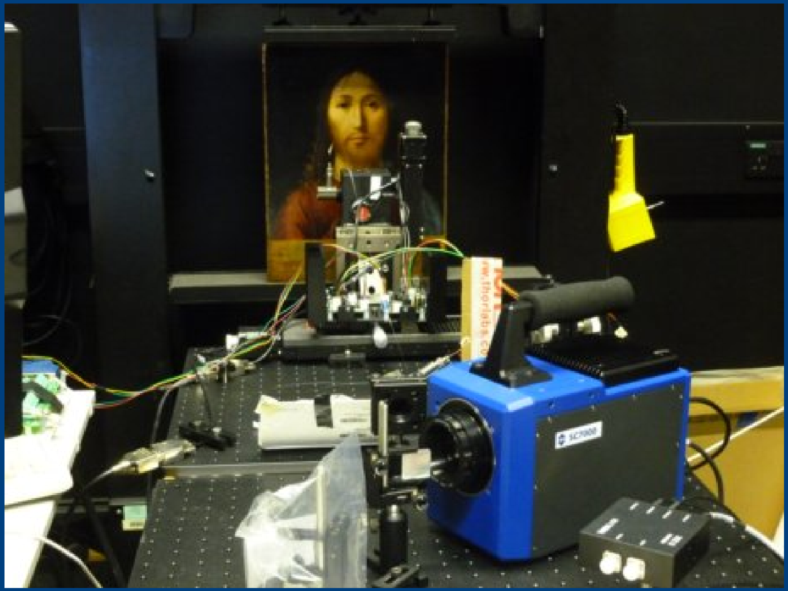
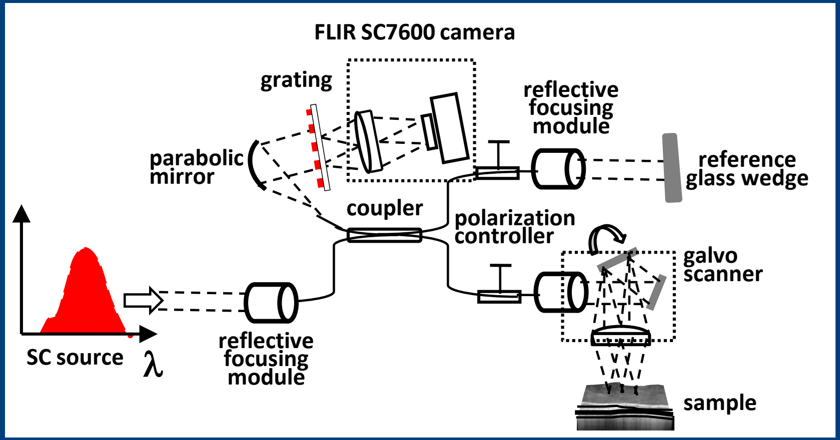
High resolution Fourier domain OCT at 1960 nm

- FDOCT using FLIR InSb camera (640x512 pixels) as detector
- Axial resolution ~ 6 microns (in paint and polymer)
- Incident power 1-2 mW
- Fast frame rate (2.7kHz) using 4x640 pixels

=> 6mm x 6mm area in 2 mins





Cheung, Daniel, Tukurakawa, Clarkson, Liang, *Optics Express*, Vol. 23(3), pp. 1992-2001 (2015)

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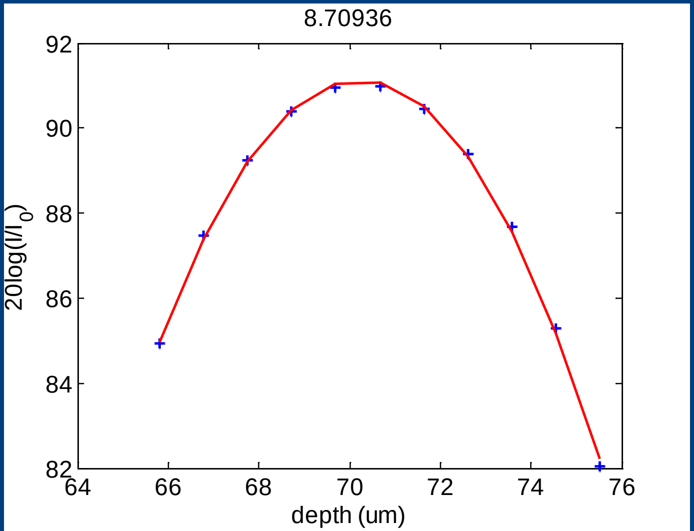
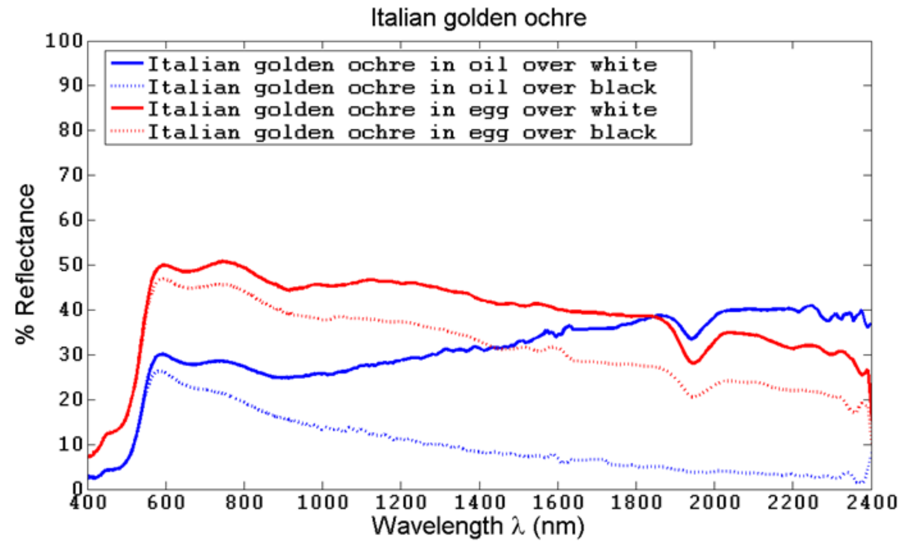
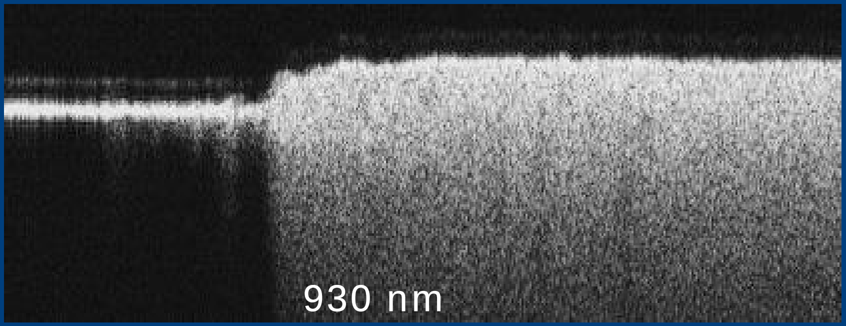
OCT axial resolution

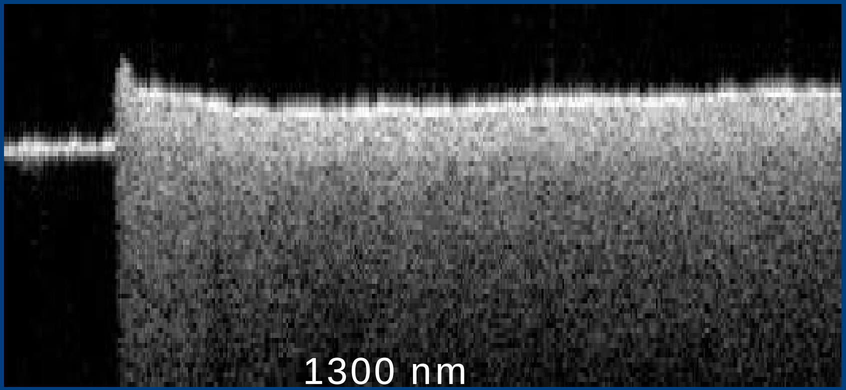
- 1840-2300nm spread over 640 pixels
- Spectral resolution ~1.4 nm (2 pixels) => depth range 1.2 mm
- Axial resolution 9 μm in air or 6 μm in paint (with Hann window)

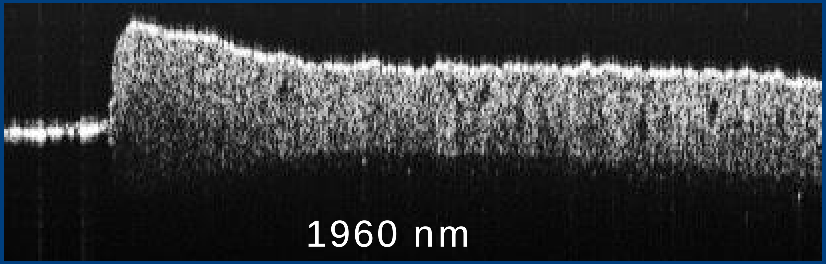


Italian golden Ochre

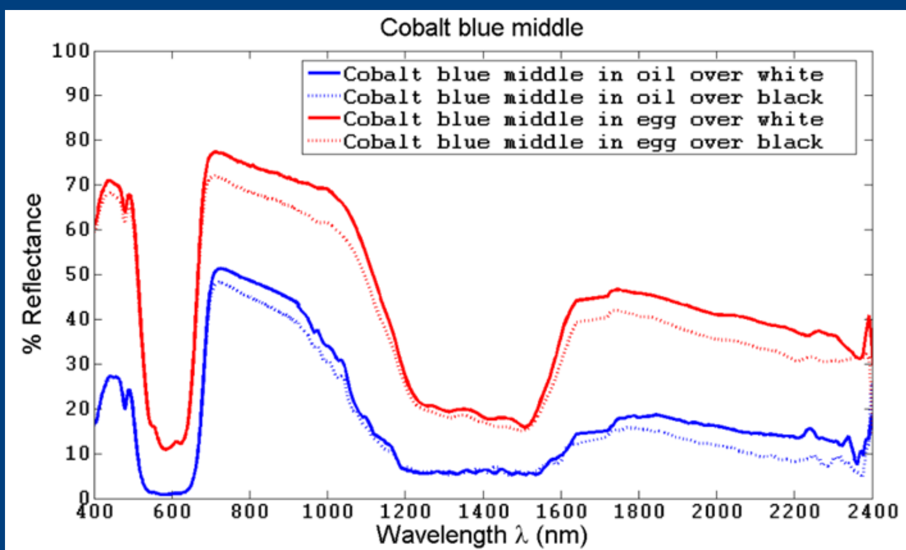


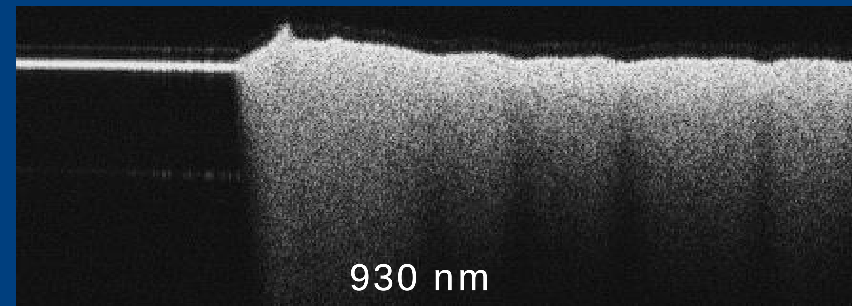


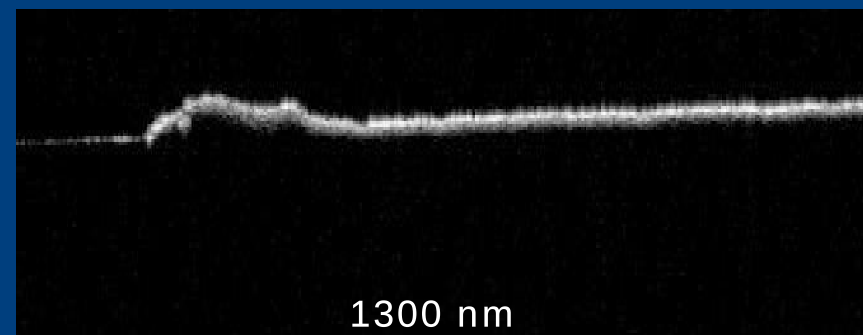


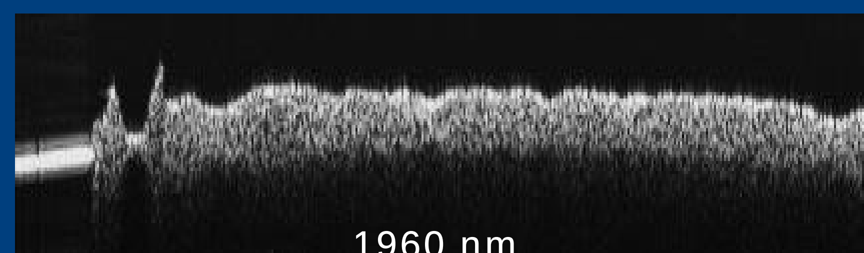


Cobalt blue in oil



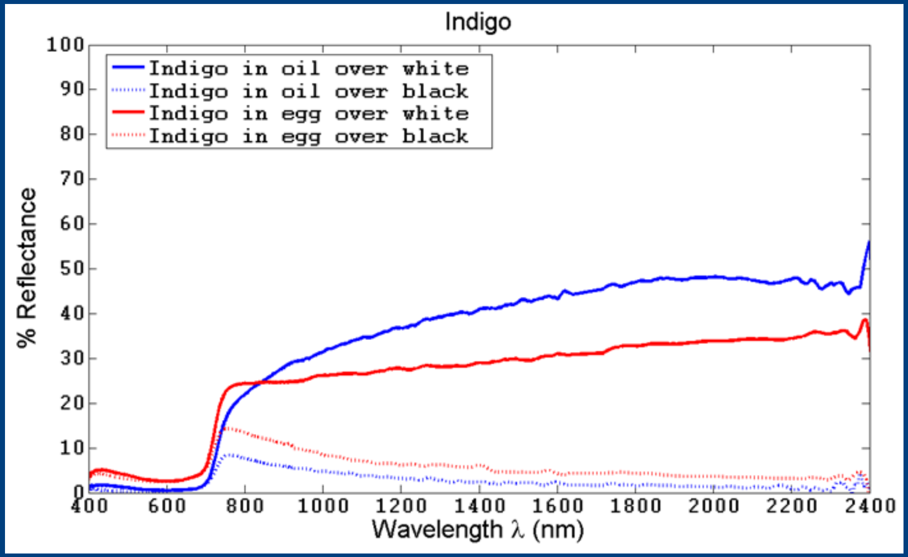


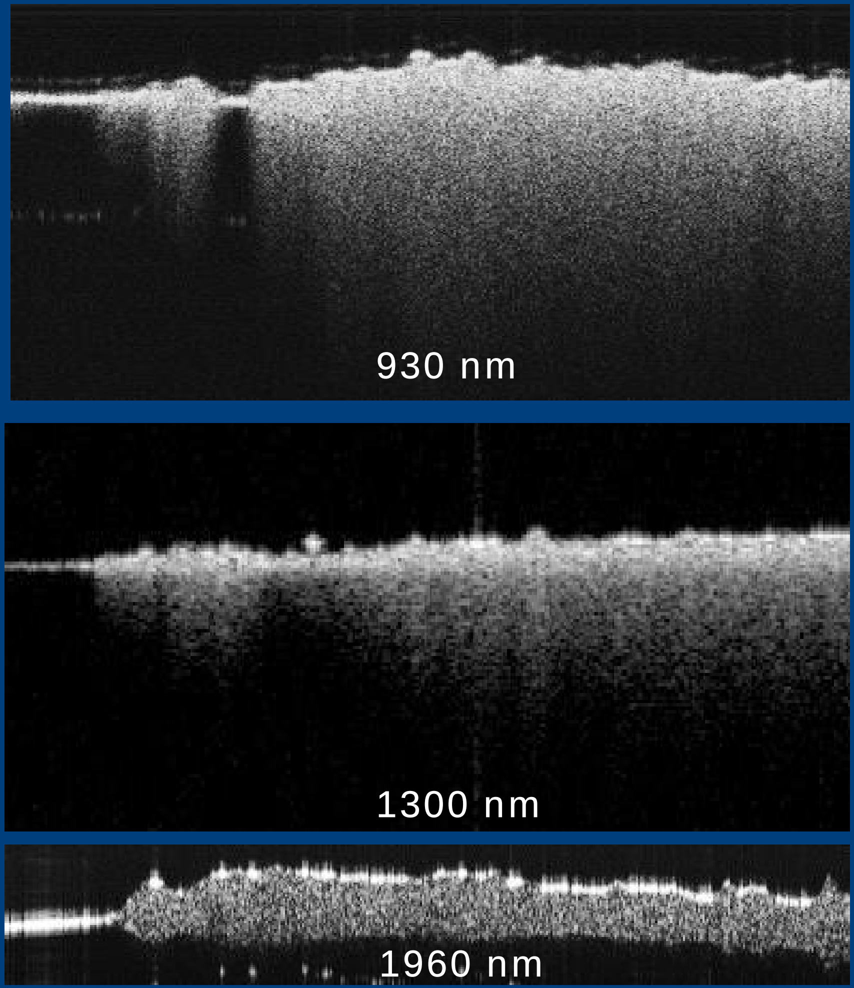


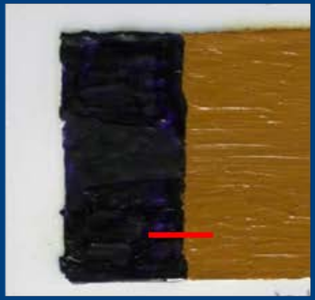


Indigo

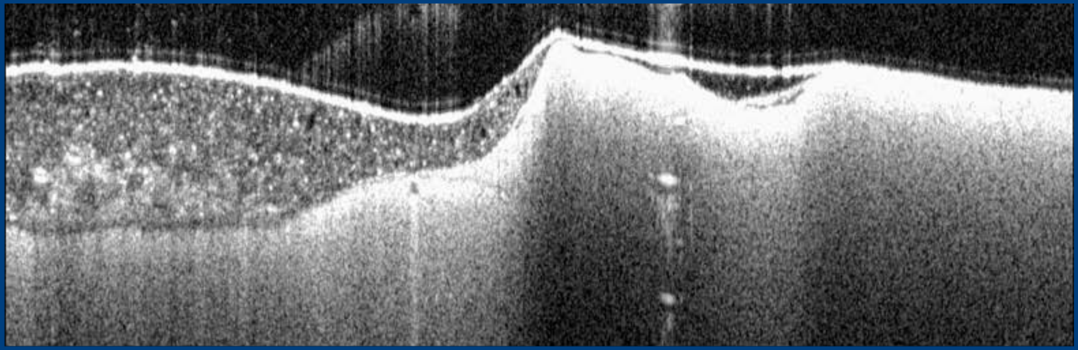

Indigo
KP 3600-A
W+N MnLO
50um
30/03/06


Indigo
Indigo in oil over white
Indigo in oil over black
Indigo in egg over white
Indigo in egg over black
% Reflectance
Wavelength λ (nm)
0
10
20
30
40
50
60
70
80
90
100
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400

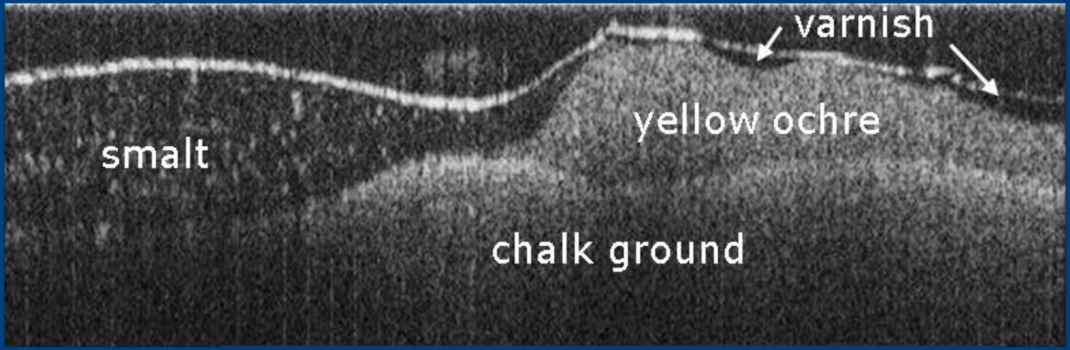

930 nm
1300 nm
1960 nm



Smalt (left) yellow ochre (right) oil paint on chalk ground



930 nm OCT cross-section image



1960 nm OCT cross-section image

2 micron OCT – best underdrawing image

Malachite,
lead white,
yellow lake
paint layers on
bone black
drawing

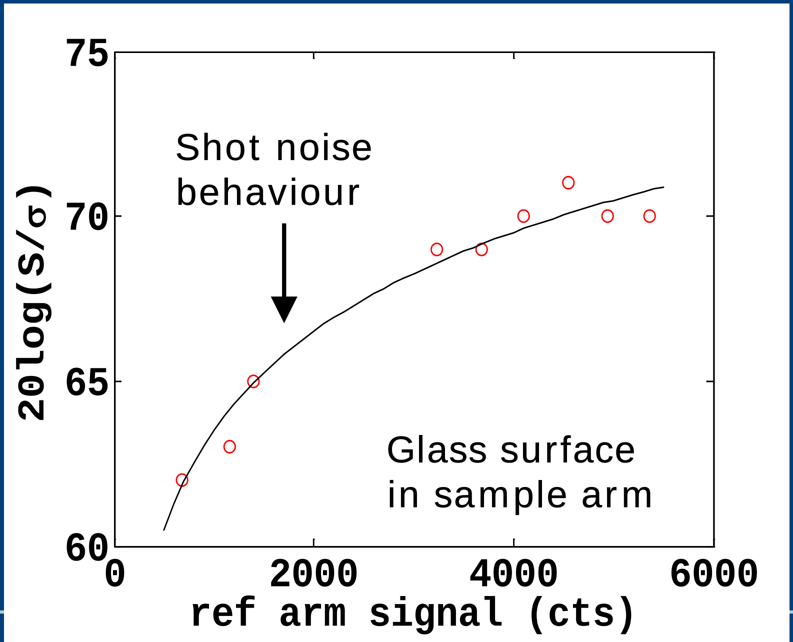
NIR InGaAs camera
900-1700nm

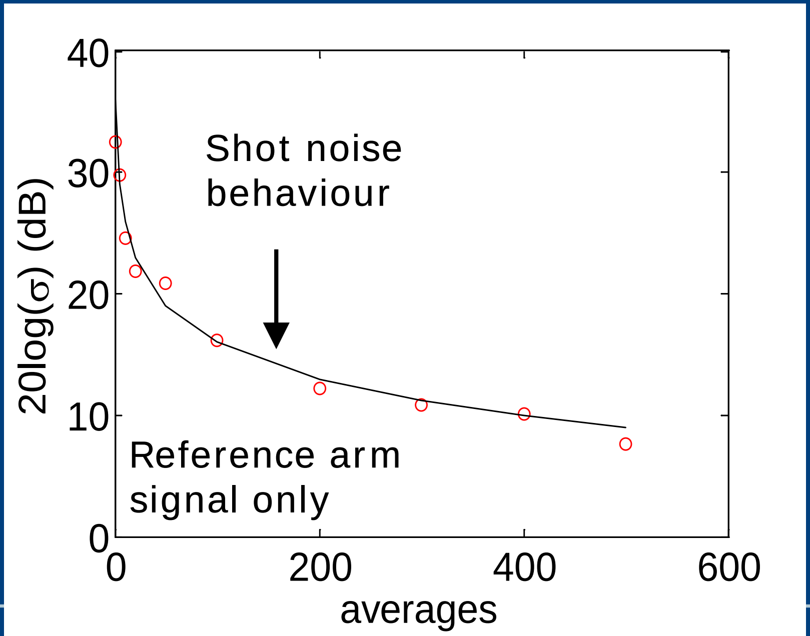
NIR InSb camera
1500nm -2500nm

1960nm OCT

Noise characteristics

- Camera noise – read noise and dark noise insignificant (possible integration time from 7 to 200 μs)
- Shot noise dominates

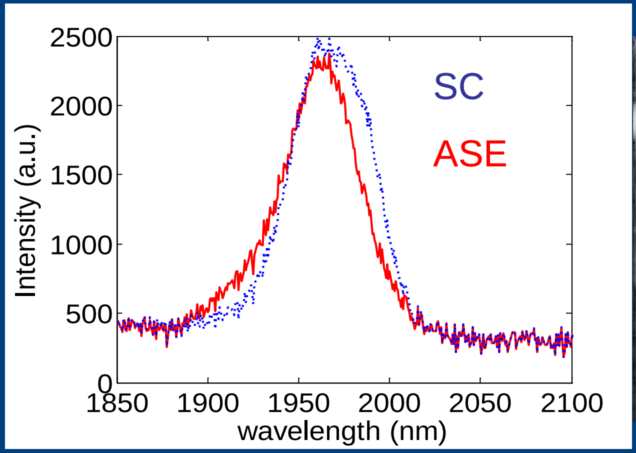




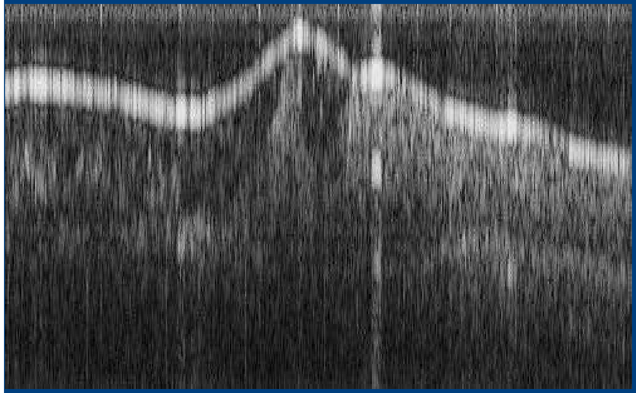
increase ref arm signal by increasing the number of pulses or integration time

Source comparison – ASE versus SC at 2 microns

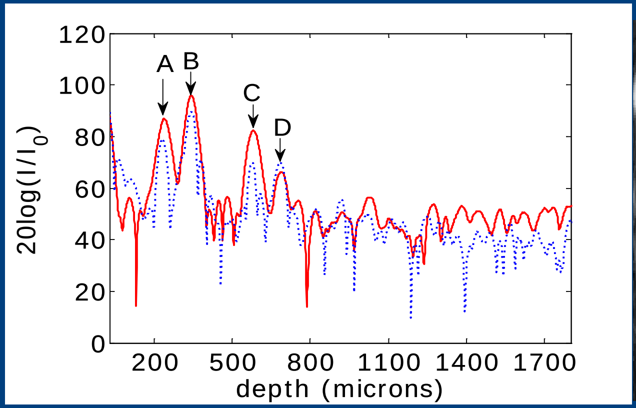
Single pulse: ASE source more stable than SC source => 10 dB advantage



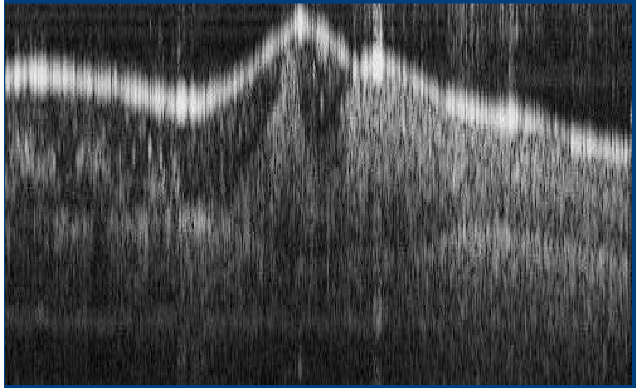
(a)



SC source



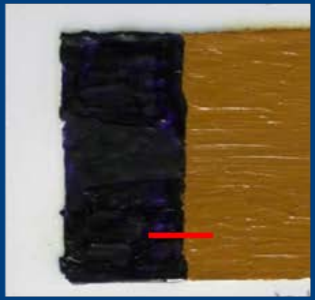
(b)



ASE source

Source comparison – preliminary qualitative comparison

Comparing ORC SC source with 50 kHz repetition rate and newly available commercial SC source (SuperK EXTREME EXW-12) with ~80 MHz repetition rate



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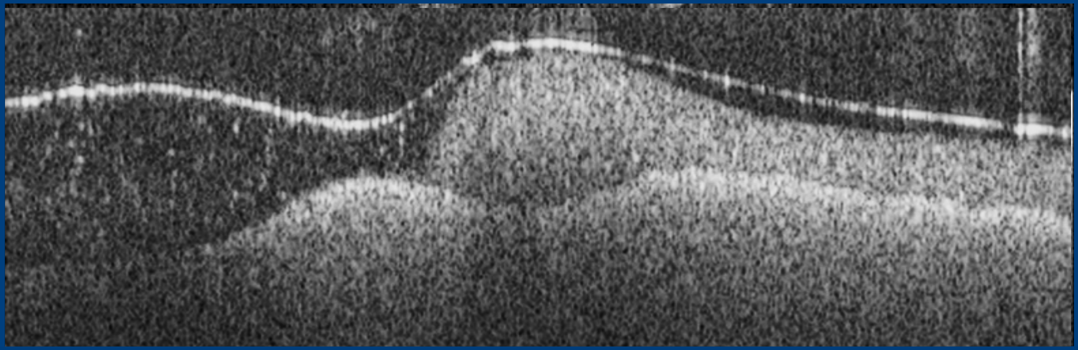
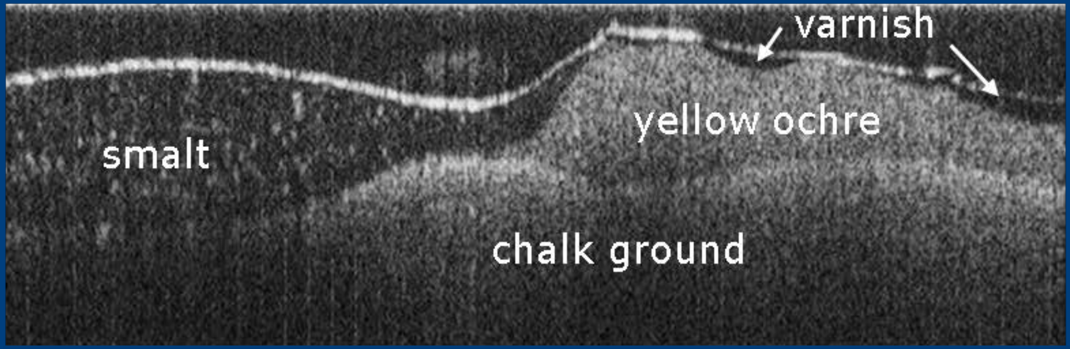


2 μm OCT cross-section image using commercial SC source



2 μm OCT cross-section image using in-house built SC source

Conclusions

- 1960nm OCT demonstrates the dramatic improvement in penetration depth over shorter wavelength systems
- Can achieve similar improvements when applied to other materials with low water content
- The supercontinuum source based Fourier domain OCT at 1960nm has been demonstrated with axial resolution ~6 microns in paint
- FDOCT speed of capture – depth profile (A-Scan) at 2.5kHz (or ~5 fps for cross-section images)

Acknowledgements

- Funding from the UK Engineering & Physical Science Research Council and Arts & Humanities Research Council, Science & Heritage Programme (AH/H032665/1)
- Gooch & Housego plc. for 2um fibre couplers
- National Gallery for paint samples
- Funding from NTU for FLIR camera