Optical Coherence Tomography

14 November 2016

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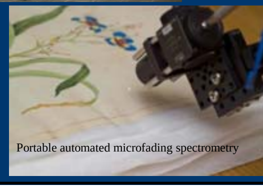
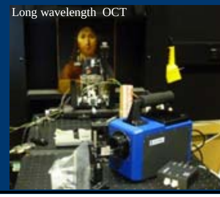
Imaging & Sensing for Archaeology, Art history & Conservation (ISAAC)

- Instrument development & data analysis (hardware + software)


Remote spectral imaging (PRISMS)


Ultra-high resolution OCT

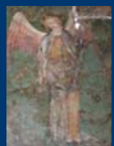

Portable automated microfading spectrometry


Long wavelength OCT

Imaging & Sensing for Archaeology, Art history & Conservation (ISAAC)

- Applications to art conservation, art history & archaeology

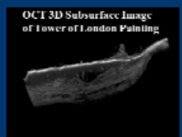

Rock art panel, Northumbria, UK


Byward tower wall painting


Manufacturing technique of Egyptian faience (British Museum)


Remote spectral imaging at Mogao cave 386


OCT monitoring water transport in rocks


OCT 3D Subsurface Image of Tower of London Painting


OCT virtual cross section of Egyptian Faience


Microfade of Mattise's Acanthes

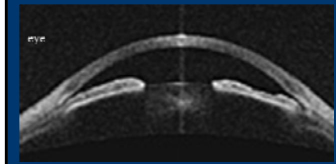
Overview

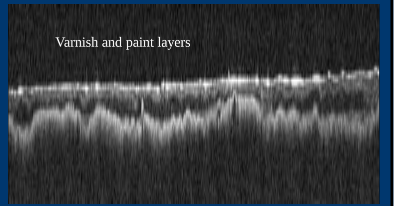
- What is OCT?
- How does it work?
- How to interpret an OCT image?
- Example applications of OCT to different conservation, art history & archaeology problems
- Types of OCT
  - Time domain versus Fourier domain
  - Raster scan versus full field/parallel scan
  - Functional OCTs: Polarisation sensitive OCT, Spectroscopic OCT, Doppler OCT
- Which OCT is right for your application?

What is OCT? How does it work?

Optical Coherence Tomography (OCT) – an imaging Michelson interferometer

- Designed for *in vivo* 3D scanning of the eye
- Needs a broadband laser for high depth resolution
- Capable of imaging subsurface microstructure of transparent and semi-transparent material in the NIR

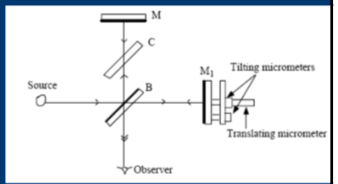




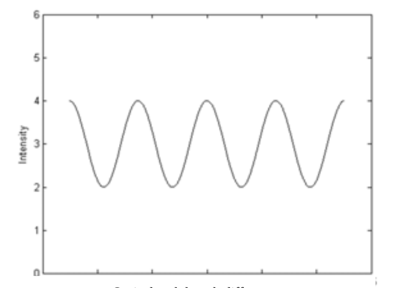
•1881: invented Michelson interferometer for the famous Michelson-Morley experiment to detect ether

• 20th-21st century: Michelson interferometer widely used in a variety of applications from spectroscopy to metrology, Astronomy, Chemistry, Biomedical research…

A. Michelson

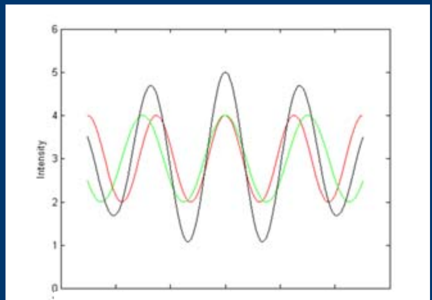


Interference of monochromatic light



Optical path length difference

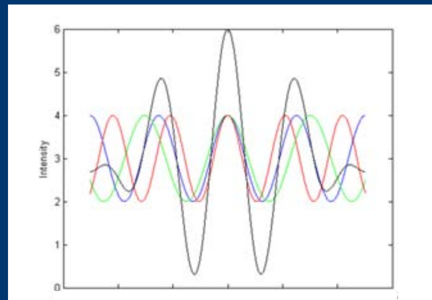
Fringes due to two monochromatic light sources of different wavelengths



Optical path length difference

Black curve is the sum of the two

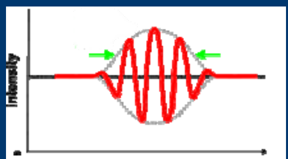
Fringes of 3 monochromatic light sources of different wavelengths



Optical path length difference

Black curve is the sum of the 3 fringes

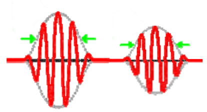
The broader the spectral bandwidth of the source, the narrower the fringe envelope



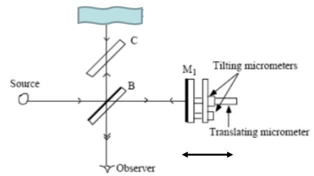
Optical path length difference

Metrology - distance measurements

- White light interferometer
  - Replace one of the mirrors with the object to be measured
  - Allow the second mirror to scan back & forth

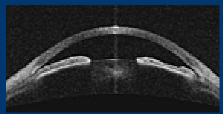


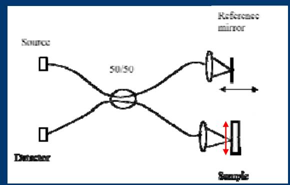
Optical path length difference



Optical Coherence tomography (OCT)

- Imaging white light interferometer
- Free space or fibre based Michelson interferometer using special light sources – broadband lasers (e.g. a superluminescent diode = SLD)
- Virtual cross-section or 3D subsurface volume imaging
- The name OCT was coined in 1991 and applied to the 3D imaging of the eye
- OCT has been applied to conservation/heritage science since 2004*

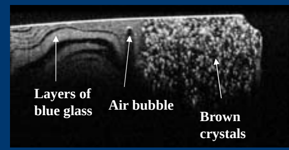




* Yang et al., Archaeometry, 2004
Targowski et al. Studies in Conservation, 2004
Liang et al. SPIE, 2004;
Liang et al. Optics Express 2005

OCT image of ancient Egyptian core formed glass

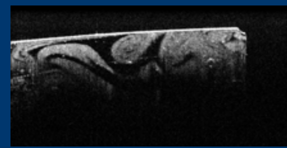
British Museum reference collection



1.6 mm

5 mm

A microscopy image of the cross-section at the broken edge



OCT virtual cross-section images

Liang et al. SPIE 2008

Resolution

- Advantage of OCT: depth resolution decoupled from transverse resolution
- Transverse resolution determined by

$$\Delta x = 1.22 \frac{\lambda}{D} f$$

where D is the diameter of the beam, f is the focal length

- Depth (axial) resolution give by

$$\delta z = \frac{2 \ln 2}{\pi n} \frac{\lambda_0^2}{\Delta \lambda}$$

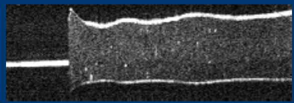
where λ_0, $\Delta\lambda$ are the central wavelength and bandwidth of the laser, n is the refractive index of the sample

How to interpret OCT images?

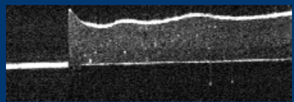
Physical & optical thickness - refractive index of paint layer

- OCT measures the optical thickness = (Refractive index) x (thickness)

Madder lake in linseed oil painted on a glass slide



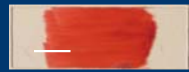
Raw OCT cross-section image



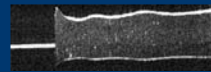
True cross-section image after correction for refractive index

Spring et al. ICOM-CC 2008

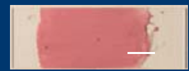
Optical scattering & absorption properties of paint limitation to penetration depth



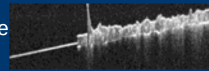
Single scattering



Madder lake in oil

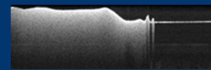


Single scattering ~ multiple scattering

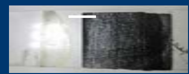


Madder lake in egg tempera

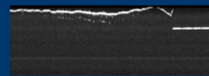
Multiple scattering dominates



Ti White in oil



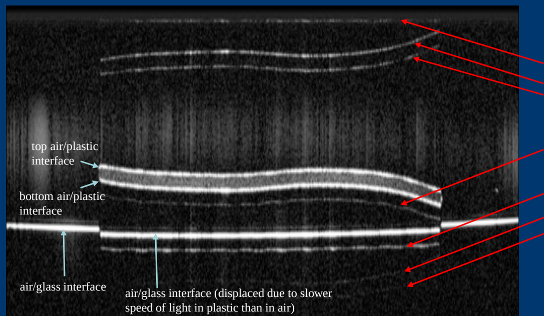
Absorption



Charcoal

Liang et al. Applied Physics B 2013

Ghost images or image artefacts



A transparent plastic sheet with a finite thickness placed above a flat glass surface

OCTs in ISAAC lab (those developed in our lab are in red)

Ultra-high resolution (UHR) OCT at 810 nm

λ_0 (nm)	δz (μm)	Δx (μm)	Speed (fps)	Penetration depth
810	1.2	7	50	Moderate
930	4.5	9	2	Moderate
1300	4	7-13	100	Moderately deep
1960	6	17	3	Deep

Commercial OCTs at 930 nm, 1300 nm

Long wavelength OCT at 1960 nm

Conservation applications

- Conservation assessment
- Monitoring cleaning of varnish
- Monitoring drying of varnish
- Detecting extent and area of loss
- Paint cross-section and degradation
- Early warning of glass degradation
- Degradation of enamel
- Revealing cracks in different depth
- Measuring speed of water transport in rocks

Gaspard DUGHET

Landscape with a Storm (NG 36)

Date: *c.*1653-54

Date entered National Gallery Collection: 1824

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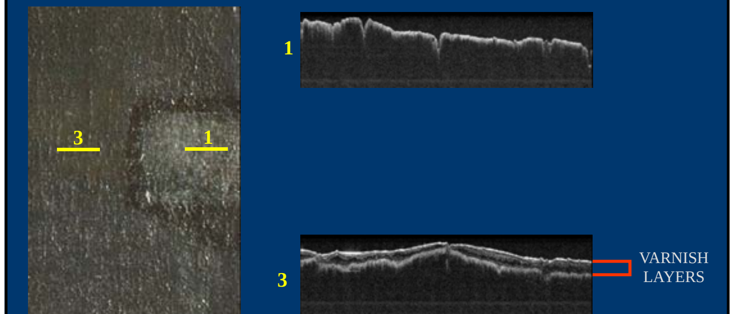
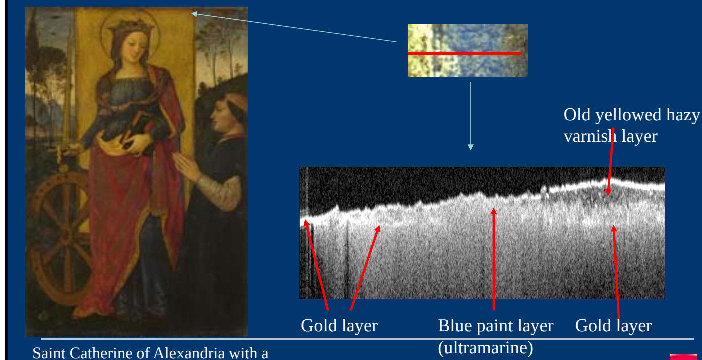


Monitoring cleaning of varnish

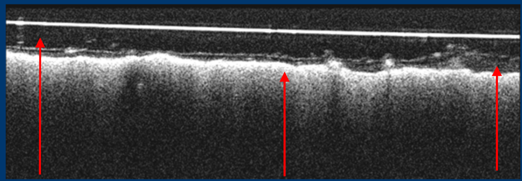
=> monitoring the cleaning of varnish with OCT



Saint Catherine of Alexandria with a Donor (1480-1500) by Pintoricchio (National Gallery No. 693)

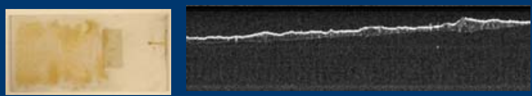
Liang et al. Conservation Science 2007

OCT imaging of layers of new and degraded varnish



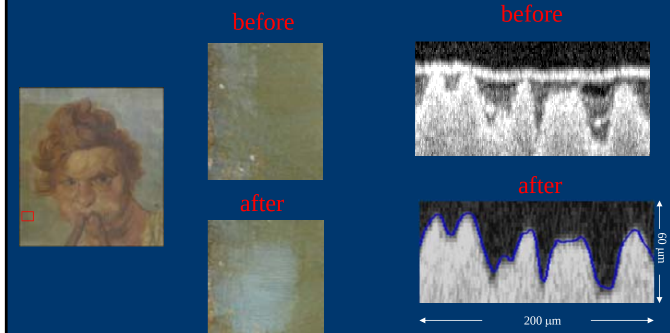
New mastic varnish | Pale blue paint | Old discoloured varnish

Mastic and boiled linseed oil varnish (1991)



Quantitative analysis of solvent cleaning of varnish

OCT can perform multilayer profilometry to 50 nm accuracy depending on surface roughness

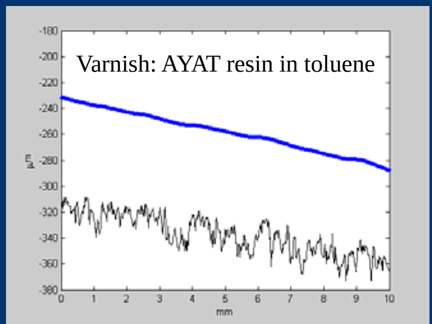


Blue line – paint surface before cleaning

Liang et al., SPIE, 2008

Dynamic monitoring of drying of varnish

– the quest for the perfect varnish



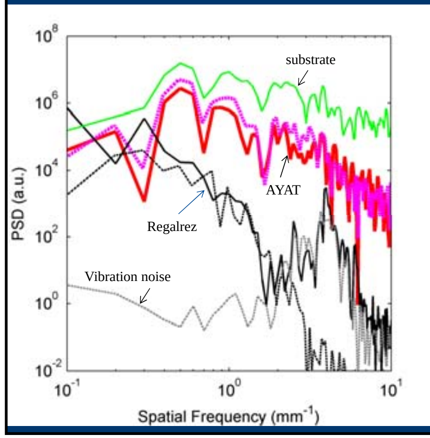
An ideal varnish

- has the right material properties (rheological properties) to form a dry layer with the right smoothness
- does not degrade easily

Monitoring the drying of varnish (blue profile) over a rough substrate (black profile)

Lawman & Liang, Applied Optics, 2011

Power spectrum of two varnish surfaces compared with models



Two varnishes:

I.AYAT polymer in toluene

II.Regalrez monomer in toluene

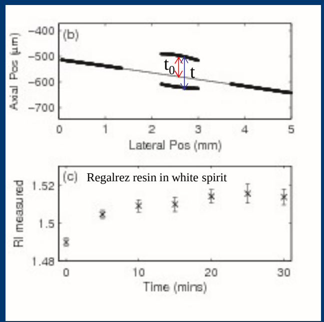
Applied to a rough substrate & measured with OCT (solid curves)

Model based on the lubrication approximation of the Navier-Stokes equation (dashed curves)

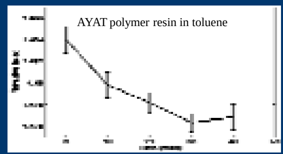
Lawman & Liang, Applied Optics (2011)

Dynamic monitoring of drying varnish

refractive index change as a measure of evaporation rate & concentration change

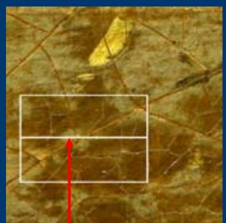


$$n = t/t_0$$

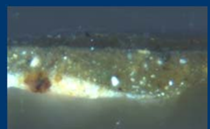


Lawman & Liang Applied Optics 2011

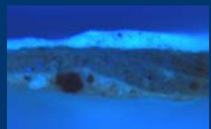
Aelbert Cuyp, *The Large Dort* (NG961), oil on canvas, about 1650



230 microns



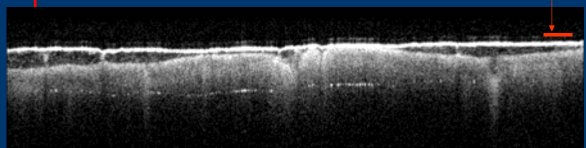
normal light



ultraviolet light

500 microns

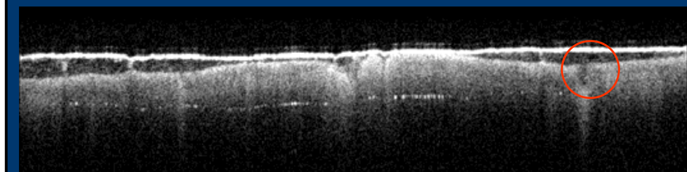
OCT cross section

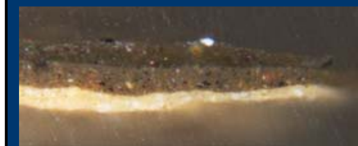


0.8 mm

10 mm

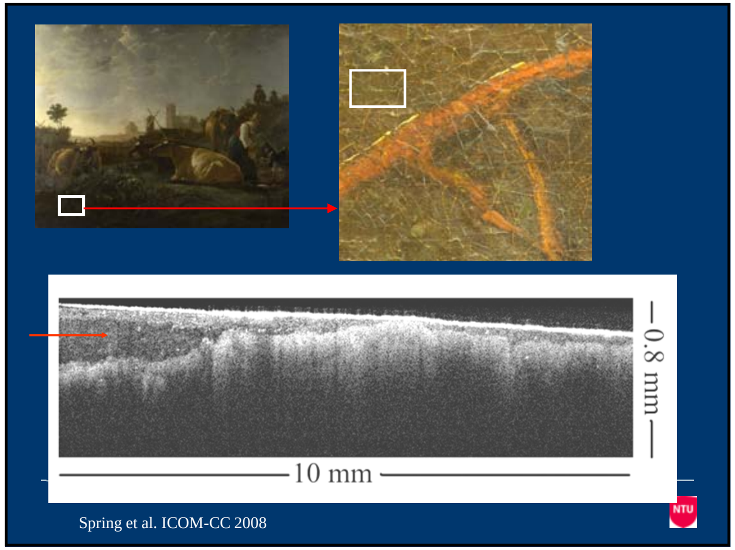
Spring et al. ICOM-CC 2008

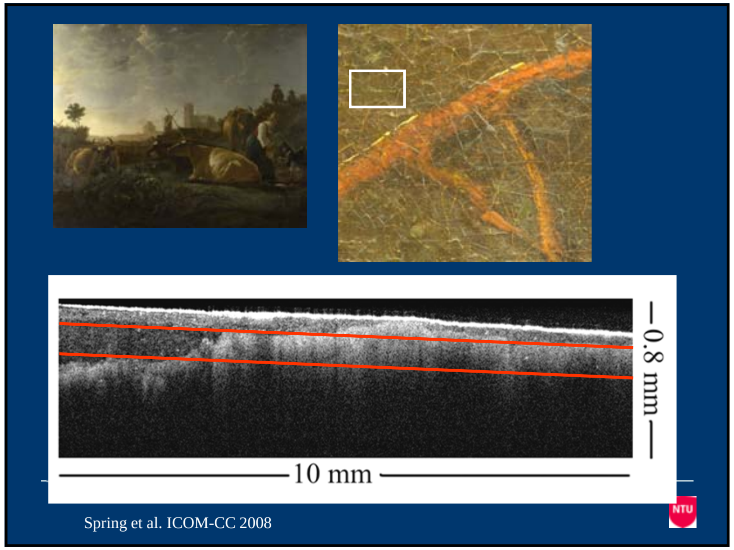


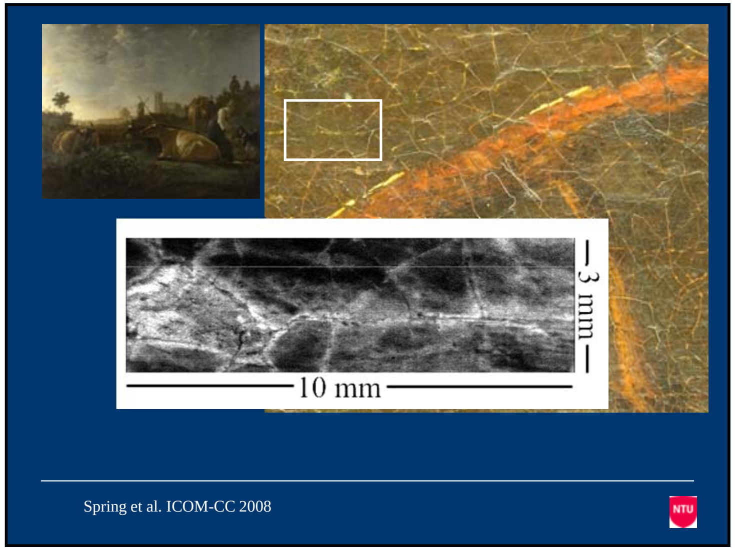


normal light

ultraviolet light

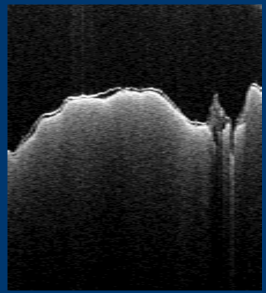

0.8 mm
10 mm
Spring et al. ICOM-CC 2008


0.8 mm
10 mm
Spring et al. ICOM-CC 2008


3 mm
10 mm
Spring et al. ICOM-CC 2008

UHR OCT imaging of modern painting: The Mellow Pad (1945-1951) by Stuart Davis



Brooklyn Museum
02/2016

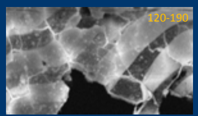
Ford et al., AIC, 2016 (in press)

OCT imaging of Mogao cave paintings in the Gobi desert along the Silk Road (UNESCO world heritage site)

- Depth resolved crack patterns

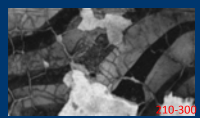

OCT in situ imaging of Mogao cave paintings in the Gobi desert along the Silk Road (UNESCO world heritage site)

OCT thin slices of G2

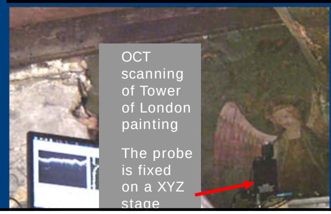


Surface cracks

Surface cracks + a few cracks underneath the surface

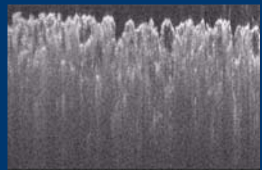

cracks underneath the surface

OCT Imaging of Wall Painting at Tower of London



Liang et al. SPIE, 2011

Monitoring water transport in rocks – probing vulnerability of rock art panels

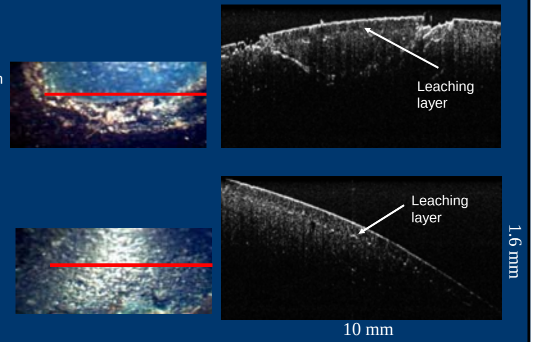


Rock art panels in Northumbria, UK

Bemand & Liang, Applied Optics 2013

Deterioration of ancient Egyptian glass

British Museum Collection

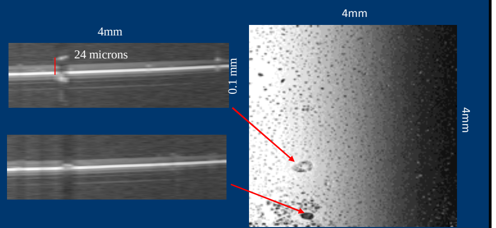


Liang et al, SPIE 7139, 2008

Degradation of cover glass for Daguerreotype – UHR OCT image

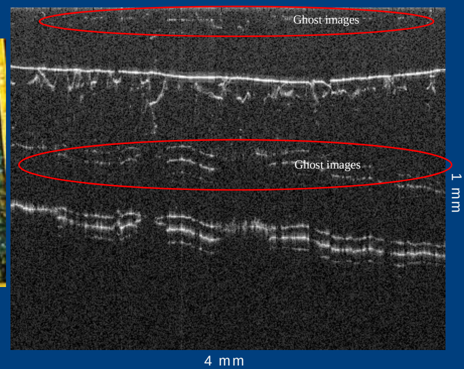
- 1839 Daguerre invented Daguerreotypes
- Down House displays six Daguerreotypes of the Darwin children with their original cover glass from 1842-1851

English Heritage



UHR OCT virtual cross-section image of enamel in English Heritage collection at Ranger House

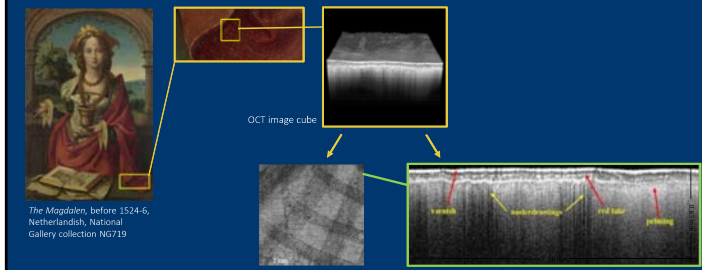
Imaging degradation of Limoges enamel



Art history applications

- Underdrawings
- Paint sequence
- Paper identification

Imaging underdrawing of paintings

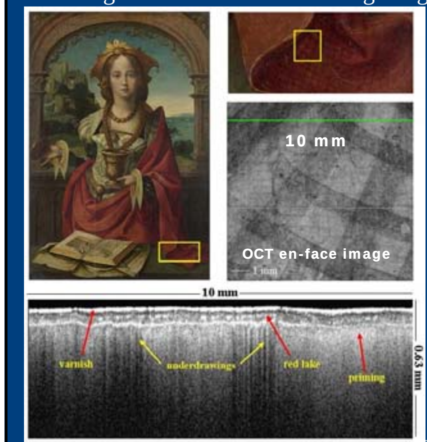


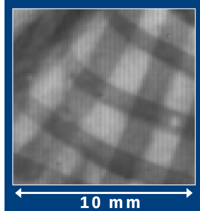
The Magdalen, before 1524-6, Netherlandish, National Gallery collection NG719

OCT image of underdrawing

OCT image of varnish/paint layers in cross-section

OCT gives the best underdrawing images

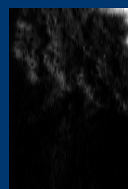




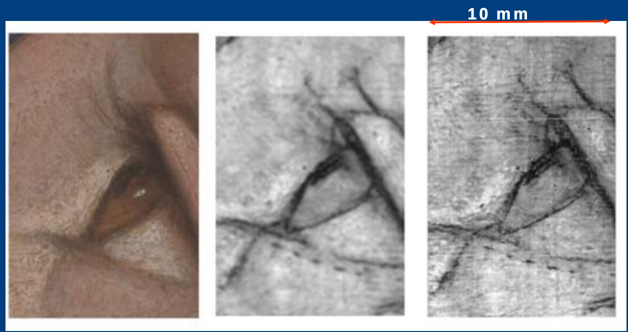
Detail of infrared image (SIRIS high resolution digital infrared camera 900-1700 nm)

Liang et al. Conservation Science 2007

OCT imaging of underdrawings



National Gallery Collection

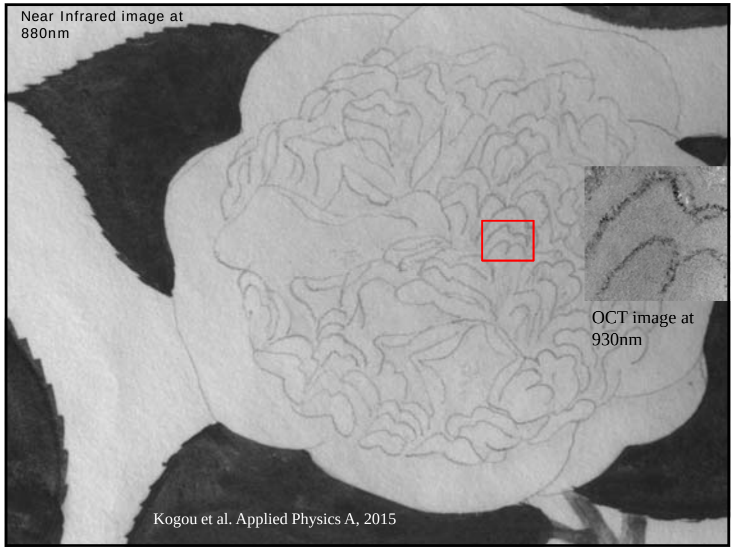


After Francesco Francia, *Virgin and Child with an angel* (NG 3927), Detail of the angel's eye

Detail of Infrared image (SIRIS high resolution digital infrared camera)

OCT en-face image of the underdrawing

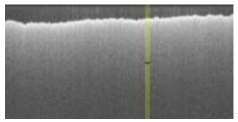
Spring et al. ICOM-CC 2008



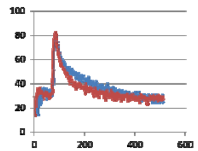
Paper classification

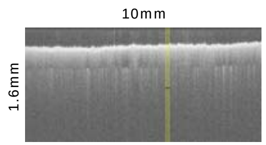
Royal Horticultural Society Reeves Collection of Chinese export watercolours

OCT depth profile

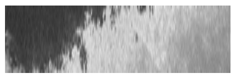


OCT cross-section image

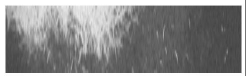




OCT cross-section image



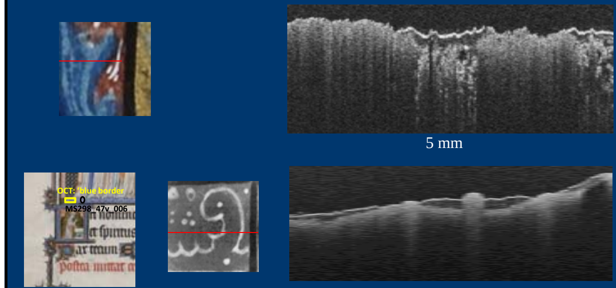
OCT surface image



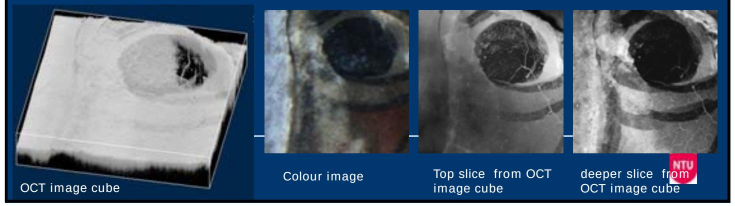
OCT surface image

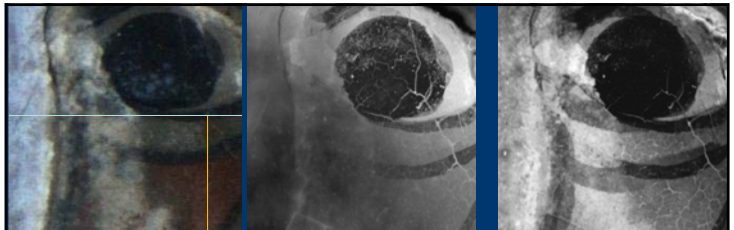
Manuscript on parchment from the Fitzwilliam Museum

- UHR OCT cross-section imaging of the paint thickness & sequence



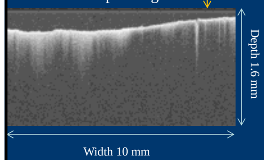
OCT in situ imaging of Mogao cave paintings in the Gobi desert along the Silk Road (UNESCO world heritage site)





colour image | OCT images: Top 200 µm slice | lower 200-650 µm slice

OCT images a virtual cross-section of the painting



Extracting ultra-high resolution underdrawing

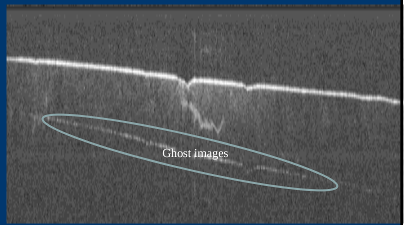
Separating underdrawing from final sketch

Archaeology applications

- Jade tool marks
- Faience microstructure
- Glass manufacturing

Identification of tool marks

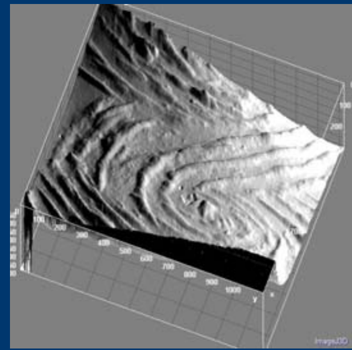
BM 1947,0712.515 , c. 2600-2200 BC, late Shijiahe culture 石家河文化, photo courtesy of British Museum



OCT virtual cross-section image

Identification of tool marks

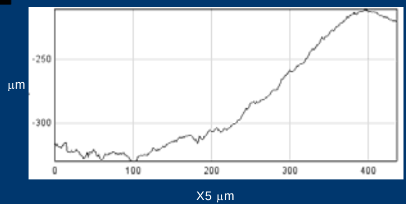
BM 1947,0712.515 , c. 2600-2200 BC, late Shijiahe culture 石家河文化, photo courtesy of British Museum



OCT imaging of ancient jade - tool marks

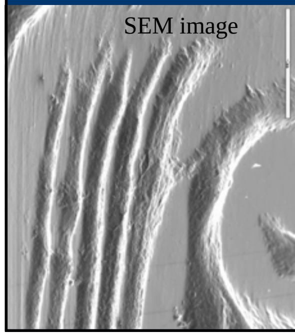
- Concave longitudinal profile => wheel cut

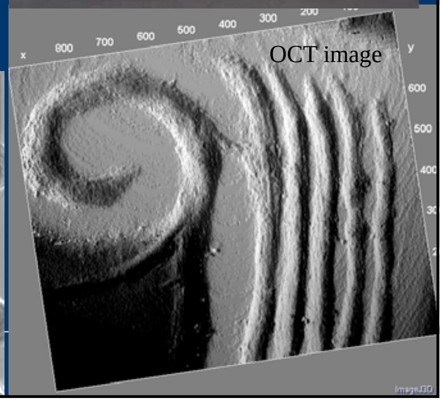
BM collection1973,0726.130 Ming/Qing dynasty, photo courtesy of British Museum



OCT as profilometer – surface profile plot

BM 1947,0712.507 Han dynasty

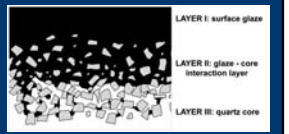


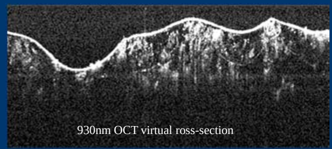


Method of manufacturing Egyptian Shabti

BMRL16323 – Egyptian Shabti
21st dynasty

1.5 mm





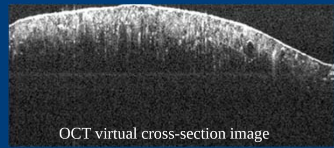
1.4 mm

6 mm

Penetration depth limited due to Cu pigment – can't see the core

Liang et al., Journal of Archaeological Science, 2012

BMRL 16322 – Egyptian Shabti Late Period

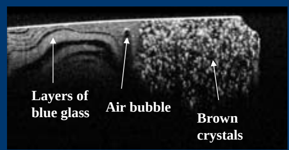


Liang et al., Journal of Archaeological Science, 2012

Non-invasive investigation of ancient manufacturing technique

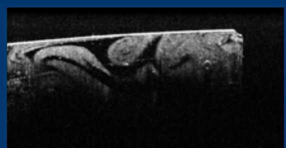
An image of the cross-section at the broken edge

Non-invasive OCT imaging of ancient Egyptian core formed glass from the British Museum. How are they made?



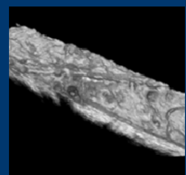
1.6 mm

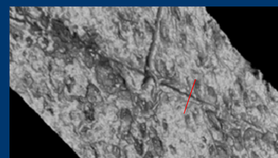
5 mm



Liang et al. SPIE 2008

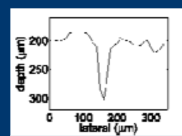
Manuscripts – Fadden More Bog bible leather cover (imaged while it was wet)





Follicles in leather

National Museum of Ireland collection



Profile of cut in the leather

Liang, BAR international series 2209, 2011

OCT laser safety

- The most light sensitive pigment realgar (fades in <1 min with microfade) was tested when the laser (central wavelength at 810nm) dwelled at the same spot for 400 times longer than it takes to collect an OCT image => no change in reflectance spectrum
- **OCT is safe** BUT make sure you block the laser when not imaging

	P (mW)	Spot size (μm)	t dwell (s)	I (W/cm^2)	Fluence (J/cm^2)
Microfade	2	500	60	1	60
OCT	1	10	1e-5	1.3e3	0.013
Raman	1	5	1	5.1e3	5100

Which OCT suits your application?

Consider

- Central wavelength
- Axial resolution
- Transverse resolution
- Speed of capture

Types of OCT

➢Raster scan, parallel or full field OCT
- Raster scan – most commonly used
- Parallel scan/full field – faster but problem with cross-talk

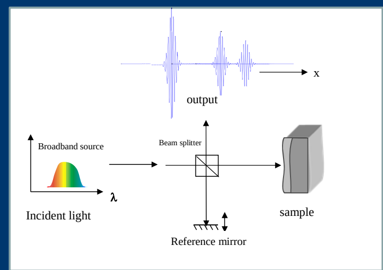
➢Time or Fourier domain
- Time Domain OCT (TD-OCT)
- Fourier Domain OCT (FD-OCT)

➢Functional OCT
- Spectroscopic OCT
- Polarisation sensitive OCT
- Doppler OCT

Time domain OCT

- Time Domain OCT (TD-OCT) – scanning in depth by moving the reference mirror

SLOW **Sensitivity constant with depth**



Fourier domain OCT

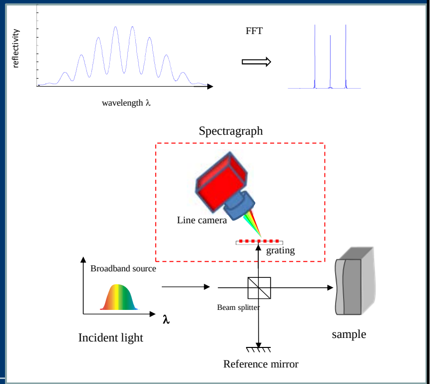
Spectral Domain OCT

Reference mirror fixed

- Spectral Domain OCT – the interference signal is registered as a function of wavelength through a spectrometer => FFT => image
- Swept Source OCT – the interference signal is collected by sweeping through the source spectrum => FFT => image

FAST **high sensitivity**

Sensitivity decreases with depth



Resolution

- Advantage of OCT: depth resolution decoupled from transverse resolution
- Transverse resolution determined by

$$\Delta x = 1.22 \frac{\lambda}{D} f$$

where D is the diameter of the beam, f is the focal length

- Depth (axial) resolution give by

$$\delta z = \frac{2\ln 2}{\pi n} \frac{\lambda_0^2}{\Delta\lambda}$$

where λ_0, $\Delta\lambda$ are the central wavelength and bandwidth of the laser, n is the refractive index of the sample

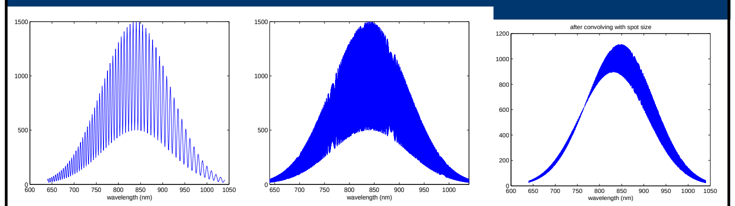
Depth range

- To achieve higher transverse resolution means shorter depth of field – depth range reduced

$$z_{\max} = \frac{\pi \Delta x^2}{\lambda} \qquad \Delta x = 1.22 \frac{\lambda}{D} f$$

- For Fourier domain OCT, the depth range is further limited by the spectral resolution of the spectrometer or the line width of a swept source
- Opacity of the sample is more often the limiting factor for depth range than instrumental depth range

Fourier domain OCT
Spectral resolution limits effective depth range



Top interface

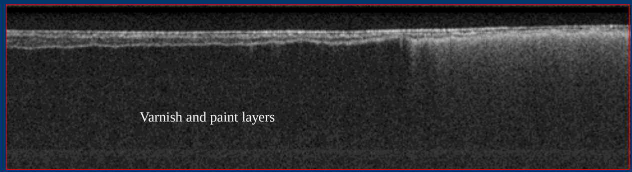
Bottom interface

Bottom interface with limited spectral resolution => fringe contrast reduced

Special feature of OCT

- Depth resolution decoupled from transverse resolution
  - Transverse resolution determined partly by the objective lens
  - Depth resolution determined by source spectral bandwidth
  - Most layer structures are smooth but thin

  ⇒ high depth (axial) resolution is important
  ⇒ *no need for very high transverse resolution*
  ⇒ *better to have large x-y-z field of view*



1.6 mm

10 mm

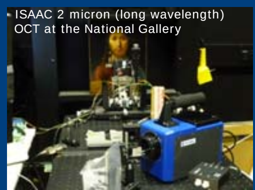
Speed of capture

- Fourier domain OCT is much faster than time domain OCT for the same sensitivity, current speed for capturing an image cube of 500 x 500 depth profiles => 10s to 3s
- BUT for the same OCT the longer exposure time (slower) images are better quality than the images captured with faster speed
- For Fourier domain OCT the maximum speed of capture is determined by the camera readout speed
- For most applications in heritage science speed of capture is a secondary consideration

New Generation OCT for Heritage Science

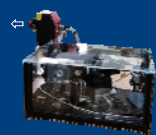
- Increase depth resolution towards 1μm while maintaining high sensitivity & dynamic range
  - Axial resolution $\Delta z \propto \lambda_0^2/\Delta\lambda$ => broadband laser (BW~200 nm) at short central wavelength (~800 nm)
- Increase depth of penetration
  - OCT at longer wavelength (~2μm) to reduce scattering

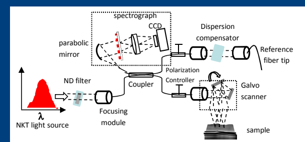

ISAAC Ultra-high resolution OCT at the National Gallery


ISAAC 2 micron (long wavelength) OCT at the National Gallery

Ultra High Resolution (UHR) Fourier Domain OCT at 810nm

- Depth **resolution 1.2 μm** in varnish and paint
- Transverse resolution **7 μm**
- Speed of acquisition ~40 μs per depth profile
  => **20 ms per cross-section image**
  => 5 mm x 5 mm x 2 mm volume in 10s
- Power incident on object ~1 mW

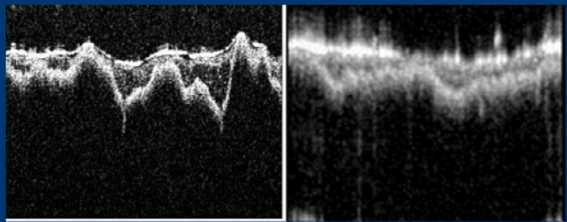




Cheung, Spring, Liang, **Optics Express**, Vol. 23(8), pp. 10145-10157 (2015)

Ultra-high resolution OCT

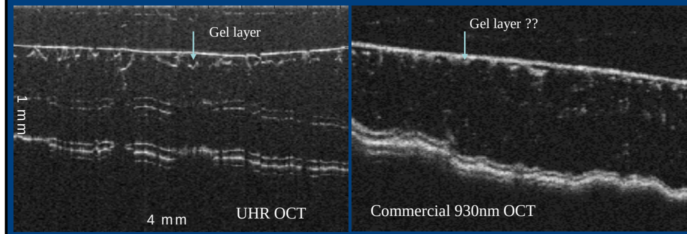
Ultra-high resolution OCT ~1 micron resolution
An image cube in 10s



UHR OCT   Commercial 930nm OCT

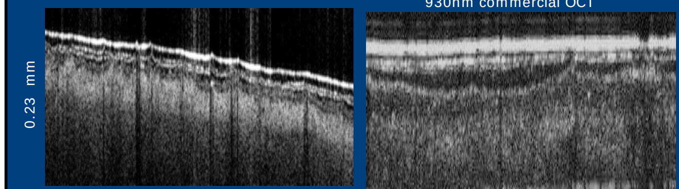
UHR OCT virtual cross-section image of enamel in English Heritage collection at Ranger House

- Difficult to see the gel layer without high axial resolution

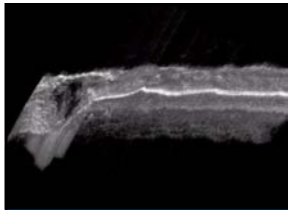


Importance of resolution

815nm UHR OCT   930nm commercial OCT

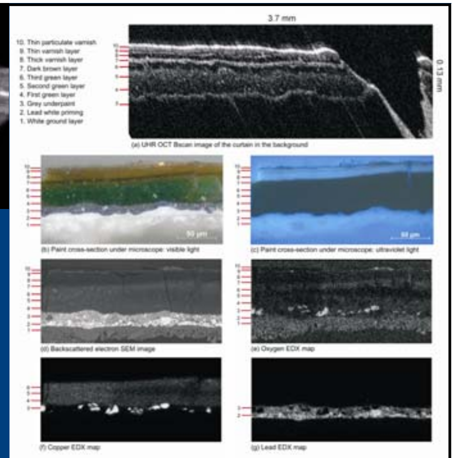


4.1 mm



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

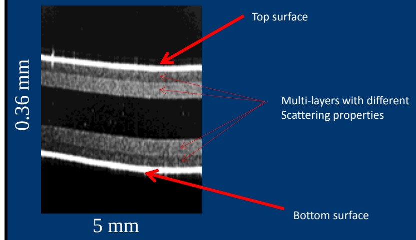
probably before 1600,Oil on wood, 87 x 61.3 cm



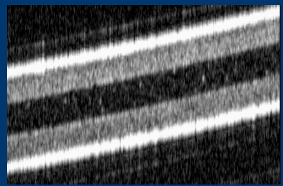
Cheung, Spring, Liang, **Optics Express**, Vol. 23(8), pp. 10145-10157 (2015)

Importance of Sensitivity

Ultra-high resolution 810nm OCT



930nm OCT
=> not all the layers are seen (3 instead of 5 layers)



What resolution do you need?

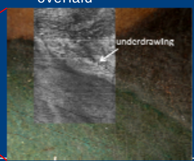
- Depends on the features you want to image
- High resolution is not always the best - if the features of interest is diffuse, high resolution may not be the best

Importance of wavelength for depth of penetration

After Raphael, *The Madonna and Child* (NG 929) probably before 1600,Oil on wood, 87 x 61.3 cm

- Need to find optimum spectral band for OCT

930nm OCT image overlaid



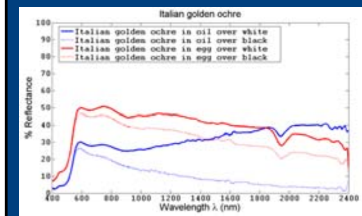
InGaAs NIR camera (900-1700 nm)

Liang et al. Applied Physics B, 2013

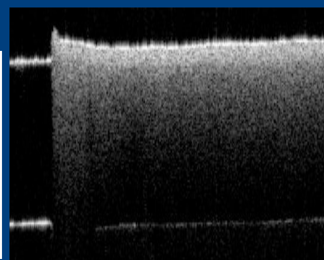
NTU

Multiple Scattering masks layers

Transparent at 1300nm, but multiple scattering masked the layer



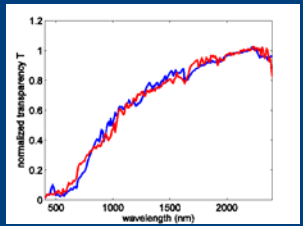
1300 nm



NTU

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

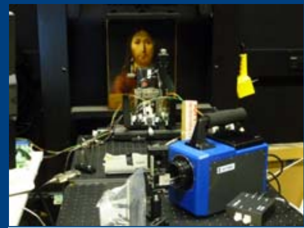
Red – egg tempera paint

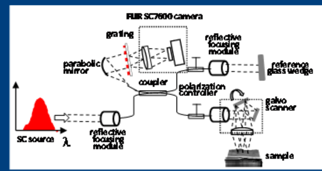
Liang et al. Applied Physics B, 2013

High resolution Fourier domain OCT at 1960 nm

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

=> 6mm x 6mm area in 2 mins

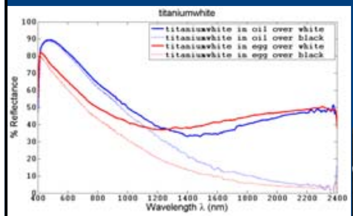


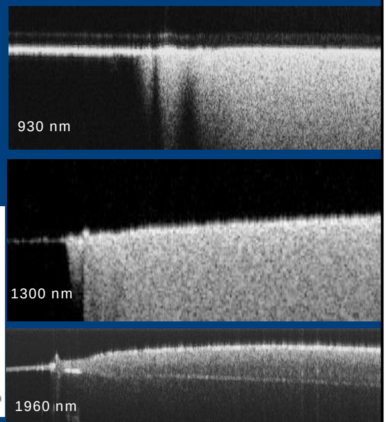


Cheung et al., Optics Express, Vol. 23(3), pp. 1992-2001 (2015)

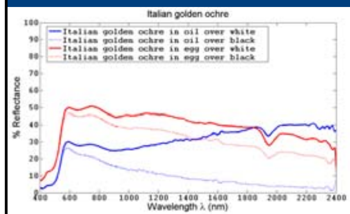
Liang et al. SPIE Vol. 9527, 952705 (2015)

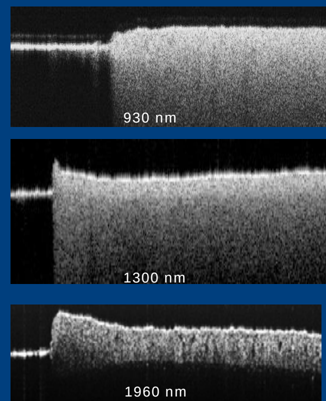
Ti White



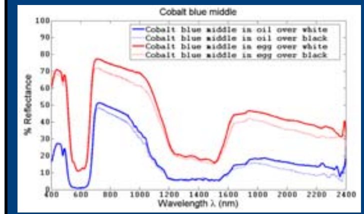


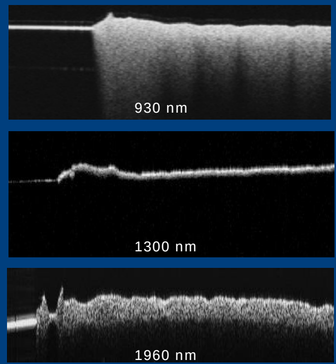
Italian golden Ochre



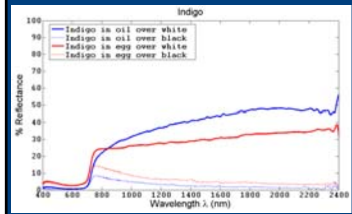


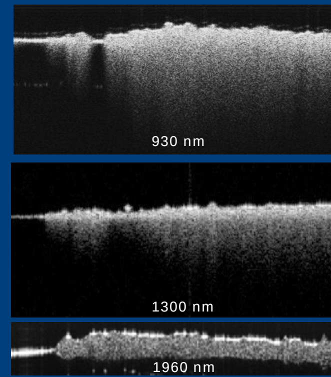
Cobalt blue in oil



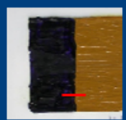


Indigo

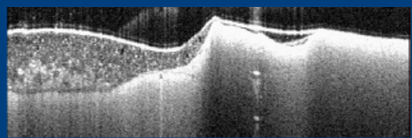




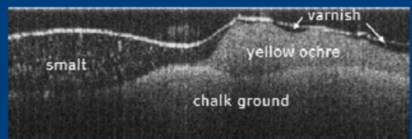
Long wavelength OCT for deeper penetration



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



930 nm OCT cross-section image



Long wavelength (1960 nm) OCT cross-section image

Cheung et al., Optics Express, Vol. 23(3), pp. 1992-2001 (2015)

2 micron OCT – best underdrawing image

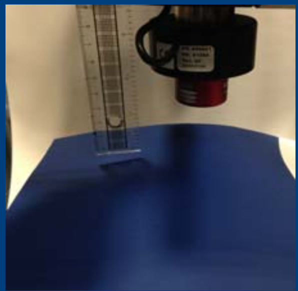
Malachite, lead white, yellow lake paint layers on bone black drawing

NIR InGaAs camera 900-1700nm

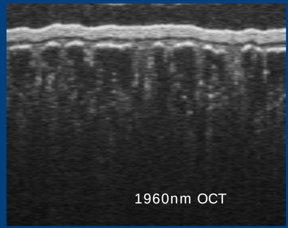
NIR InSb camera 1500nm -2500nm

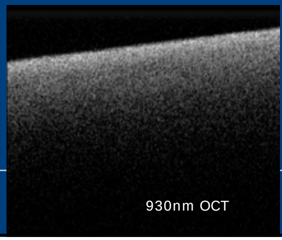
1960nm OCT

Composite textile



Working distance of 4cm





Which wavelength do you need?

- Long wavelength for deeper penetration into highly scattering material
- Shorter wavelength for transparent material that require high resolution

References

- Free download of full text for all the papers published by my group http://llr.ntu.ac.uk/rpd/researchpublications.php?pubid=18ea0ae3-8395-4d09-b763-637da94f532a or go to my web profile https://www.ntu.ac.uk/staff-profiles/science-technology/haida-liang and click on ‘go to Haida Liang’s publications’
- For all OCT publications in heritage science see http://www.fizyka.umk.pl/~oct4art/

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- Victoria & Albert Museum: Lucia Burgio & colleagues
- Royal Horticultural Society: Charlotte Brooks & colleagues
- Historic Royal Palaces: Jane Spooner & colleagues
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