Introduction to the Optical Coherence Tomography technique

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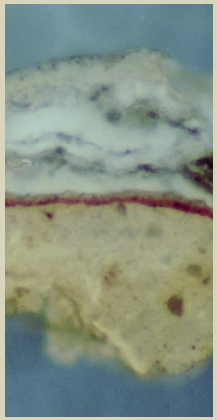
Why OCT? – an alternative to sampling

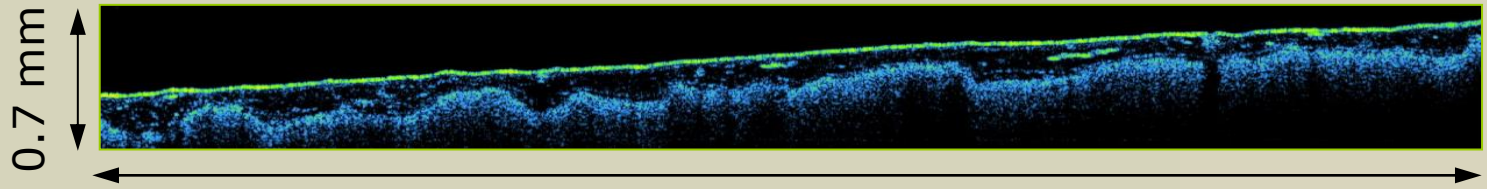
Why OCT? – an alternative to sampling

sample collection and examination (invasive)



~1mm

OCT tomogram (non-invasive)



up to 20 mm

- **no object preparation**
- **no limits as for the object size – *in situ* examination possible**
- **as many places of examination as desired**
- **duration of single examination: 0.2 – 6 s.**

The idea of OCT

OCT is essentially an optical radar

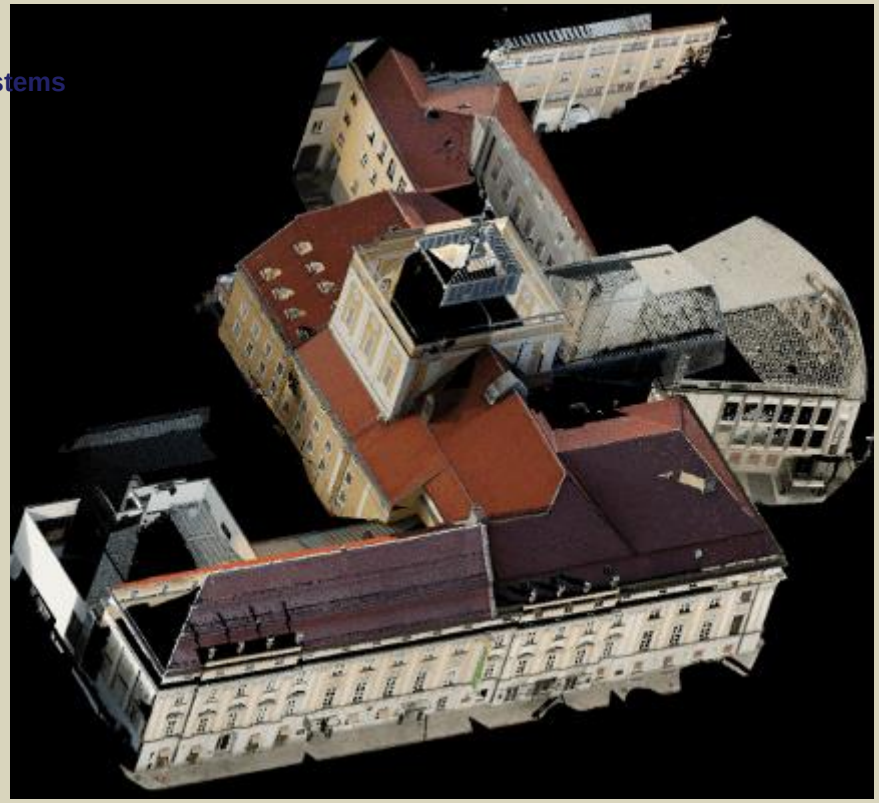
RAdio
Detection
And
Ranging

LIght
Detection
And
Ranging

The idea of OCT

LIDAR:

Model LMS-Z420i
RIEGL Laser
Measurement Systems
www.riegl.com

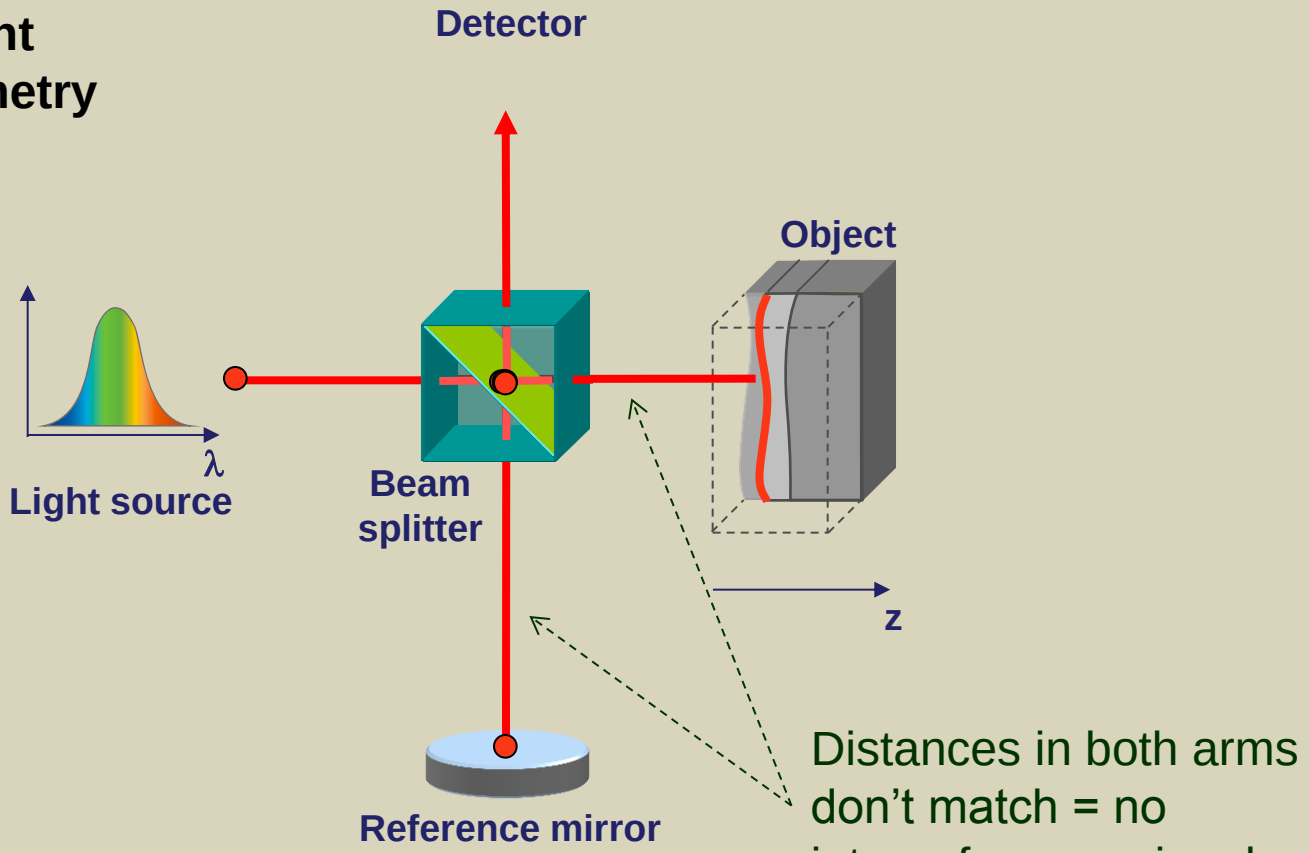


Distance scanning:
laser class 1, NIR, beam diverg. 0.25 mrad
range: 1000 m/350 m ($\rho \geq 80\%/10\%$)
Accuracy: 5 mm
Measurment rate: 12000 – 8000 pt/s
Position scanning:
Vertical: 0° do 80°, resolution 0.002°
Horisontal: 0° do 360°, resolution 0.0025°

$$2 \times \frac{5 \text{ mm}}{300\,000\,000\,000 \text{ mm/s}} = 32 \text{ ps}$$

How to measure distance with a better precision?

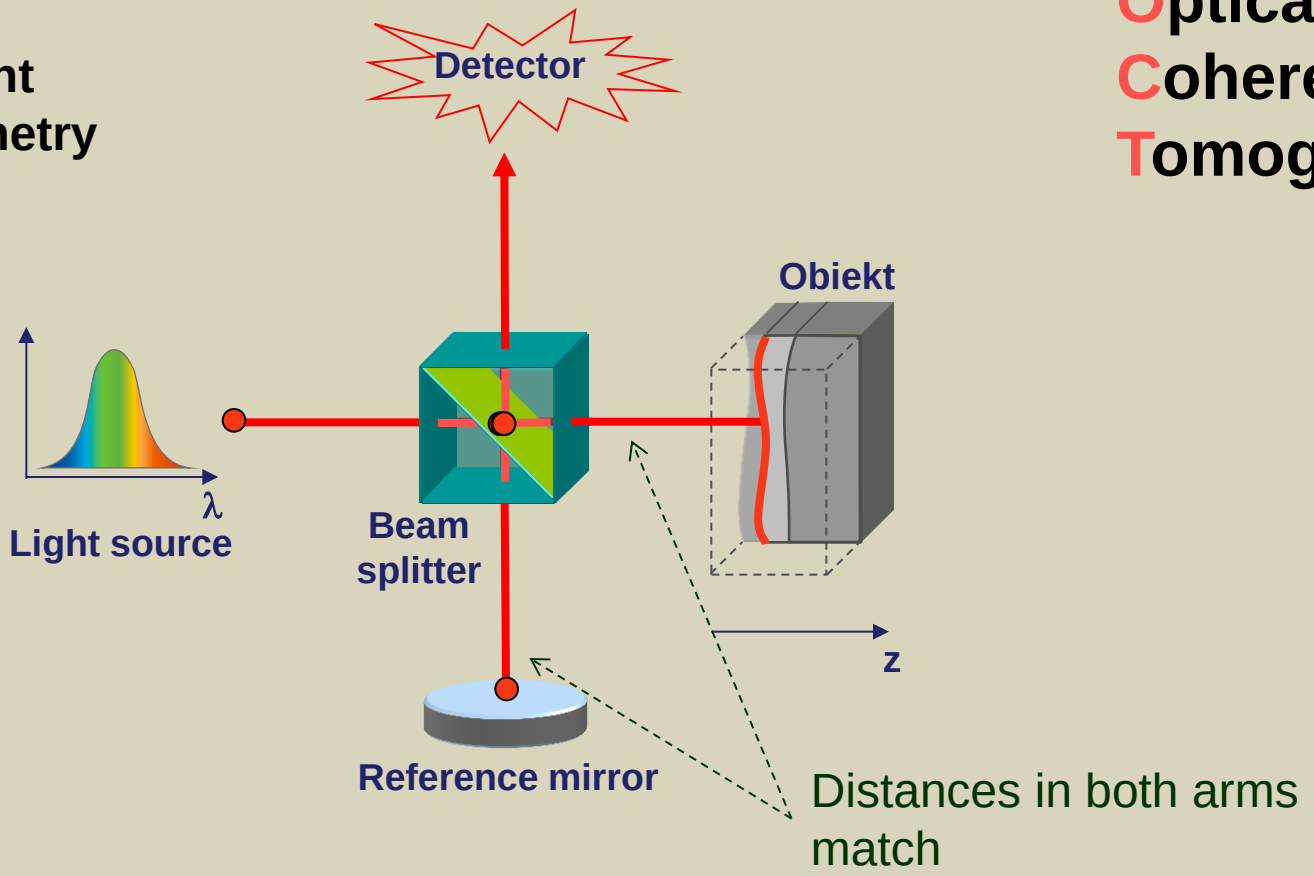
Answer:
White Light Interferometry



How to measure distance with a better precision?

Answer:
White Light Interferometry

Optical Coherence Tomography

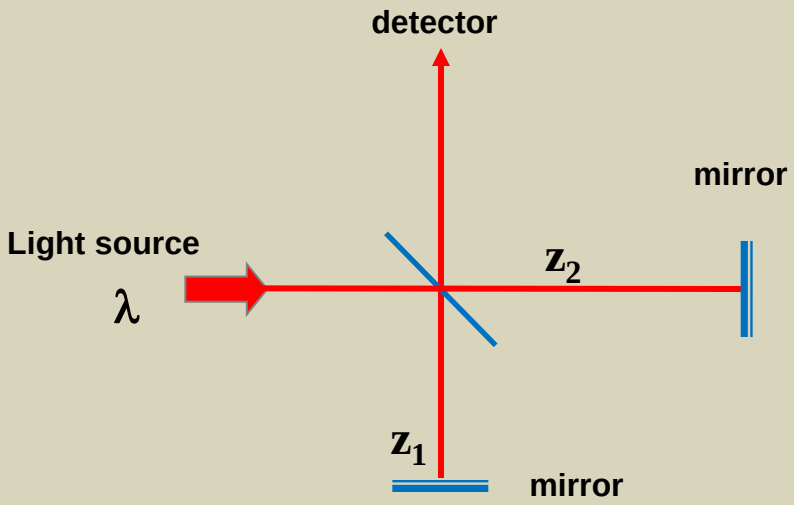


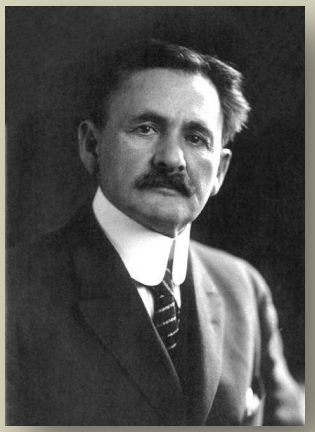
The Michelson interferometer

Major formula:

$$I_C = \left\langle \left[E_1(t) + E_1(t) \right]^2 \right\rangle = I_1 + I_2 + 2\sqrt{I_1 \cdot I_2} \cdot \cos(\Phi)$$

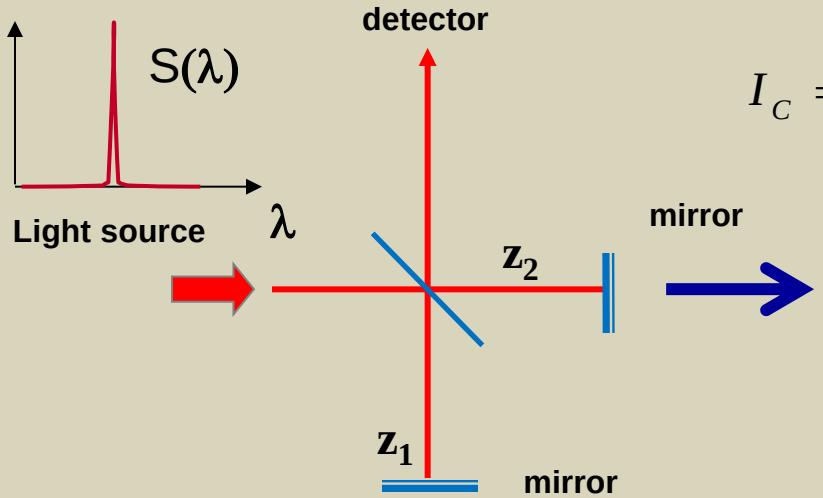
$$\Phi = \omega \cdot \Delta t = \omega \frac{2(z_2 - z_1)}{c}$$





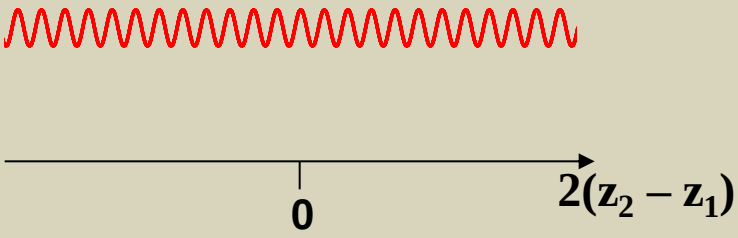
Albert A. Michelson (1852-1931)
- born in Strzelno, PL,
first American, awarded with Nobel
Prize in science (1907)

The monochromatic light interferometer



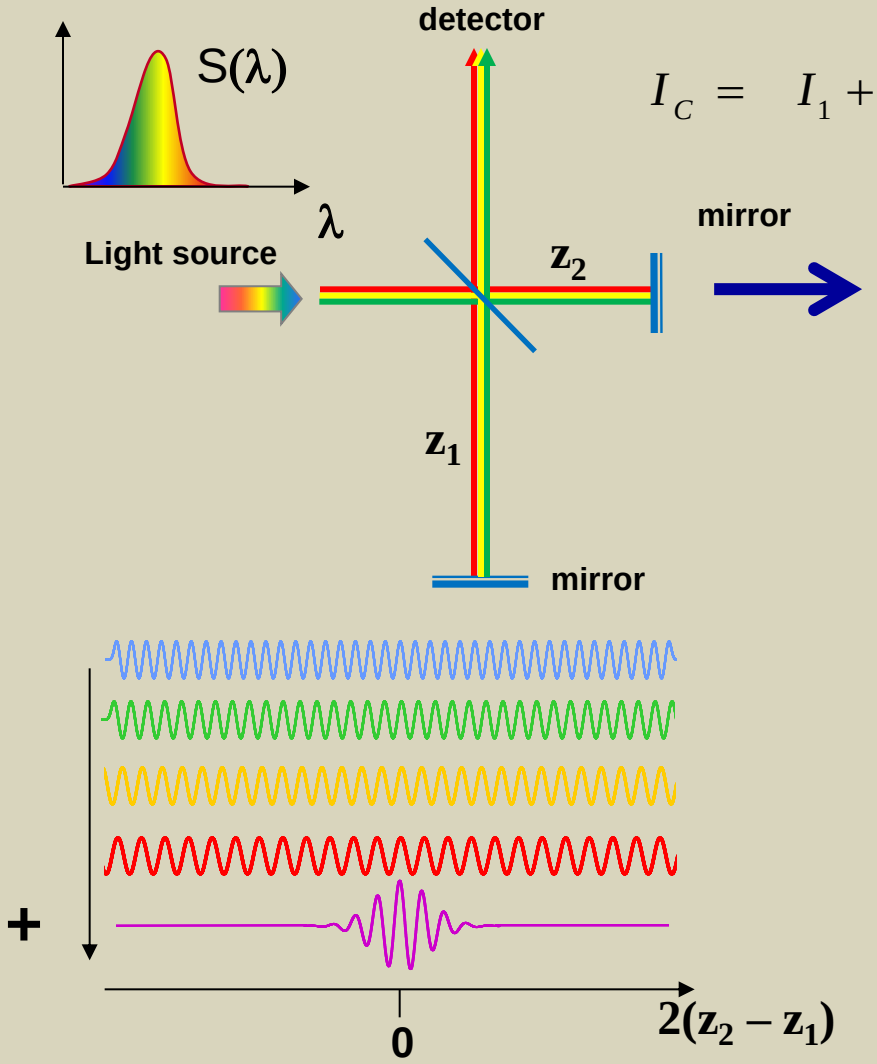
$$I_C = I_1 + I_2 + 2\sqrt{I_1 \cdot I_2} \cdot \cos\left[\frac{\omega}{c} 2(z_2 - z_1)\right]$$

If we use a monochromatic light (e. g. from a laser) and we will change a distance z_2, detector will detect many maxima – always when the difference between distances ($z_1 - z_2$) is a multiple of λ)



Albert A. Michelson (1852-1931) - born in Strzelno, PL, first American, awarded with Nobel Prize in science (1907)

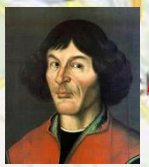
The white light interferometer



$$I_C = I_1 + I_2 + 2\sqrt{I_1 \cdot I_2} \cdot \cos\left[\frac{\omega}{c} 2(z_2 - z_1)\right]$$

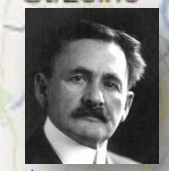
In OCT a polichromatic light is used. In this case combined interference signal occurs only for $z_1 = z_2$. This is because interference maxima coincide only if both distances are equal!

Albert A. Michelson (1852-1931) - born in Strzelno, PL, first American, awarded with Nobel Prize in science (1907)



✵1473

USA
1855

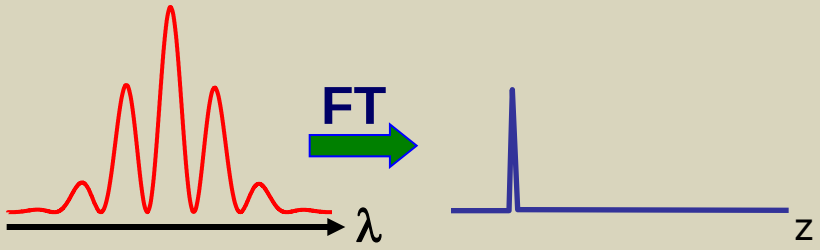


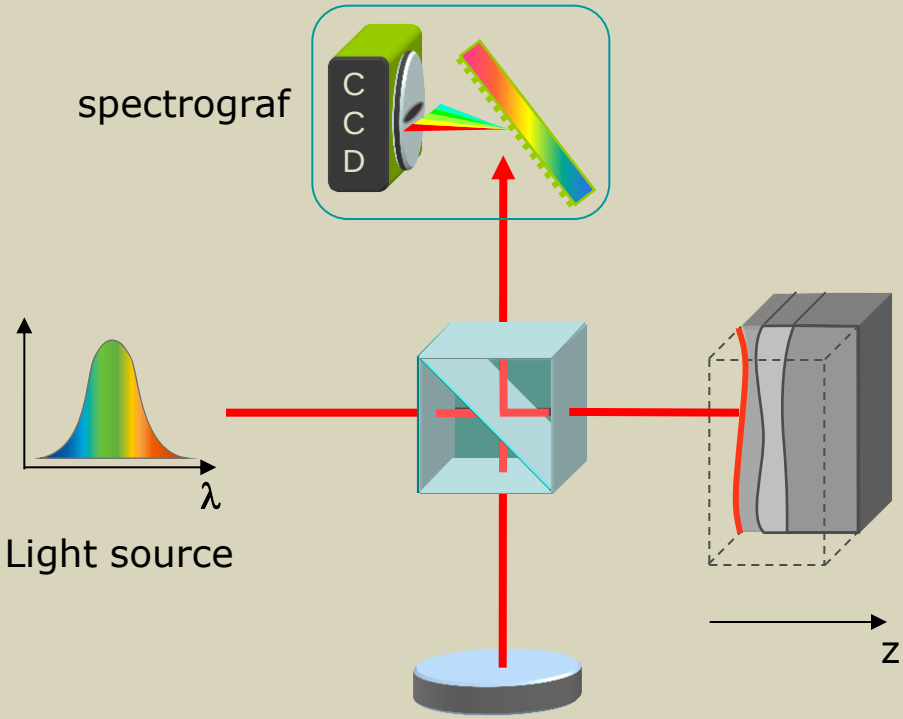
✡1852

Cracov
1491

How to do it faster?

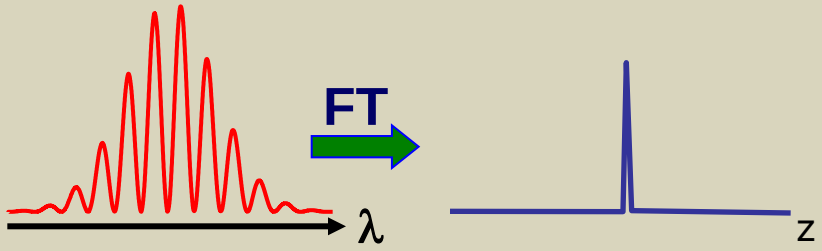
Spectral domain OCT
One of two Fourier domain methods

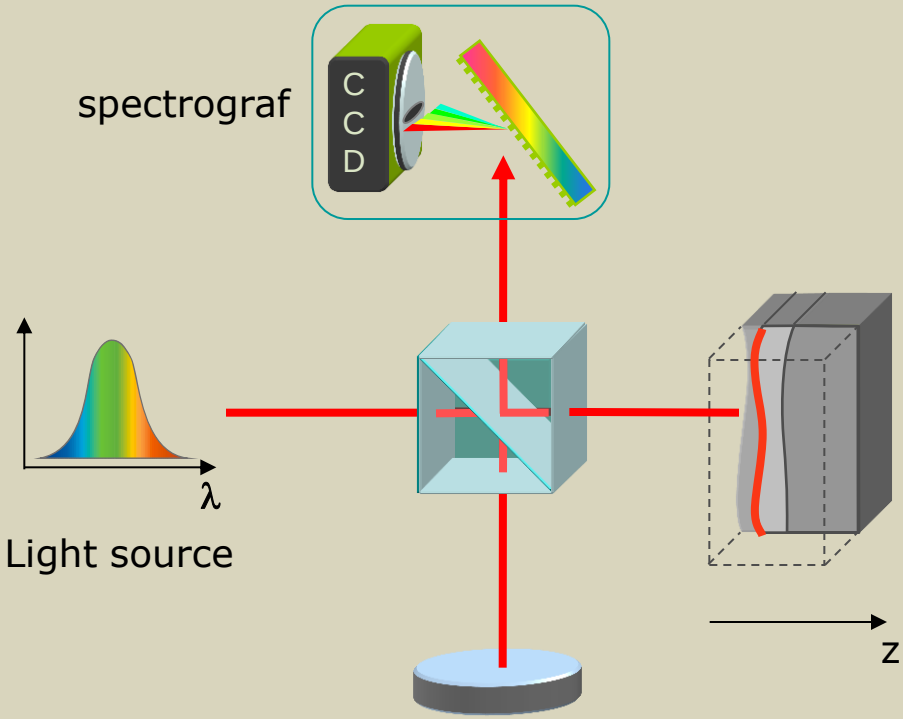




How to do it faster?

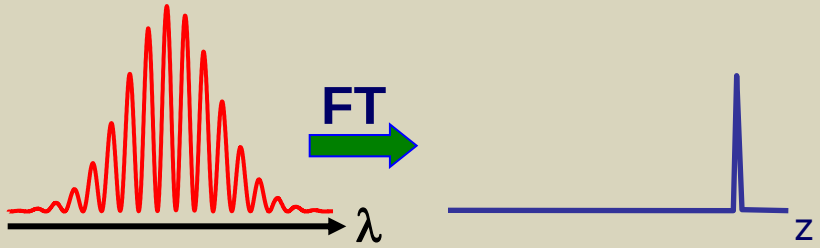
Spectral domain OCT
One of two Fourier domain methods

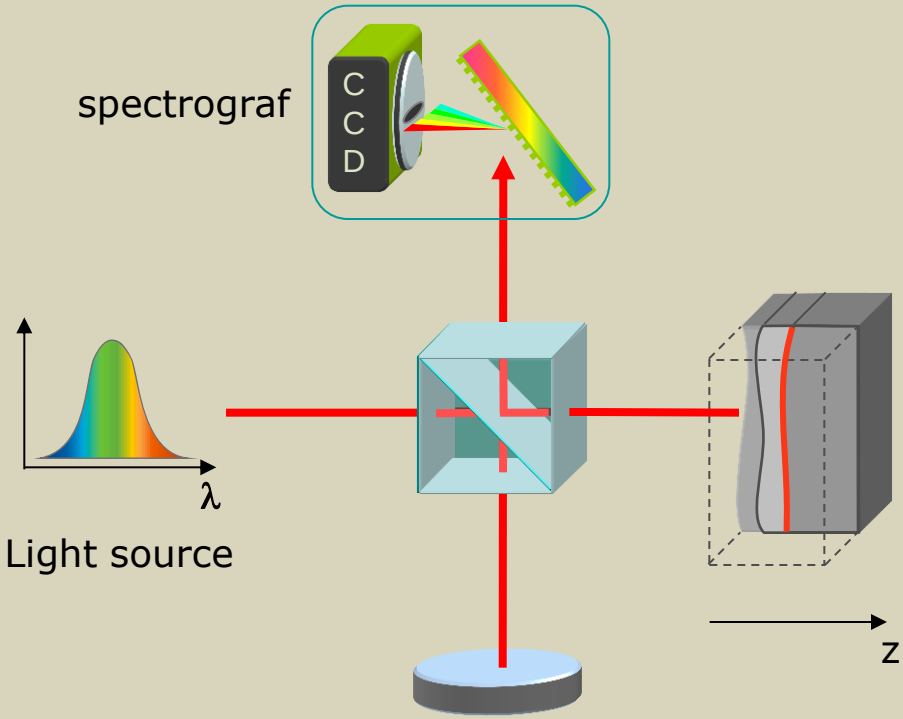




How to do it faster?

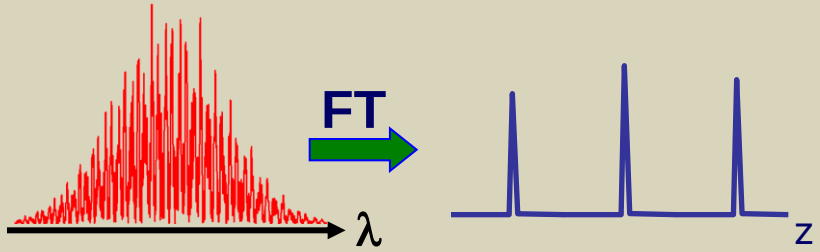
Spectral domain OCT
One of two Fourier domain methods

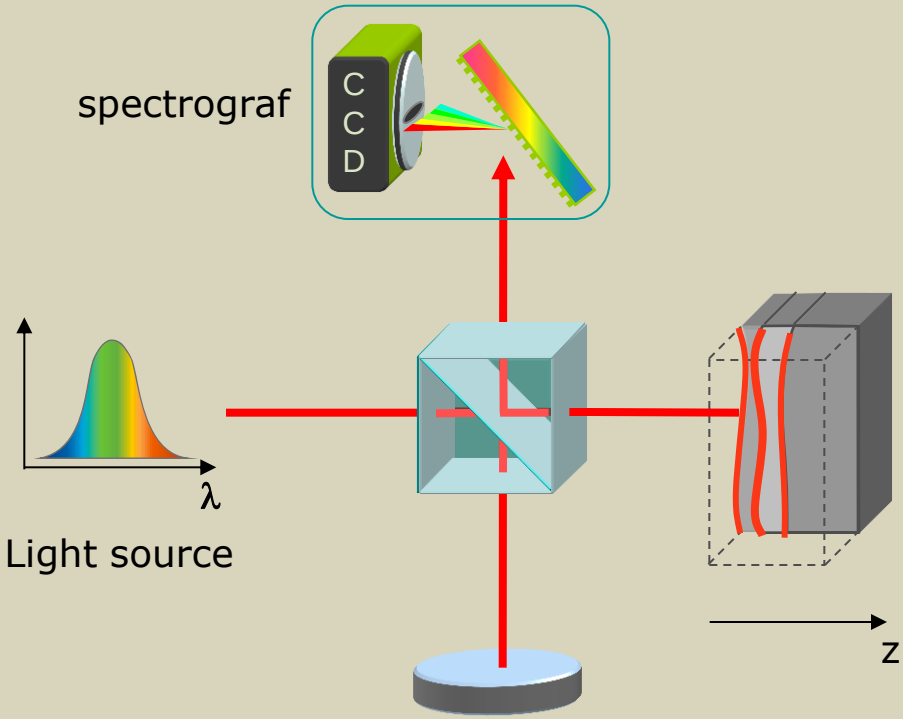




How to do it faster?

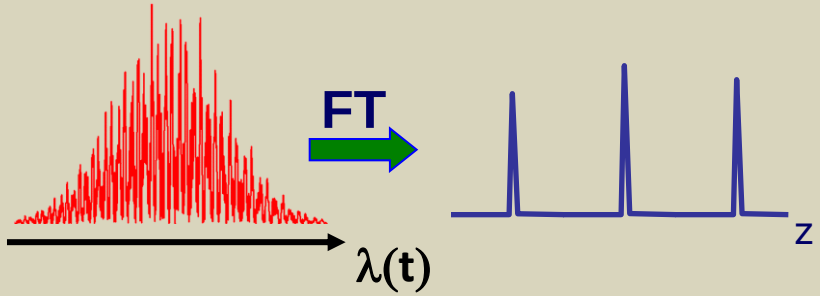
Spectral domain OCT
One of two Fourier domain methods

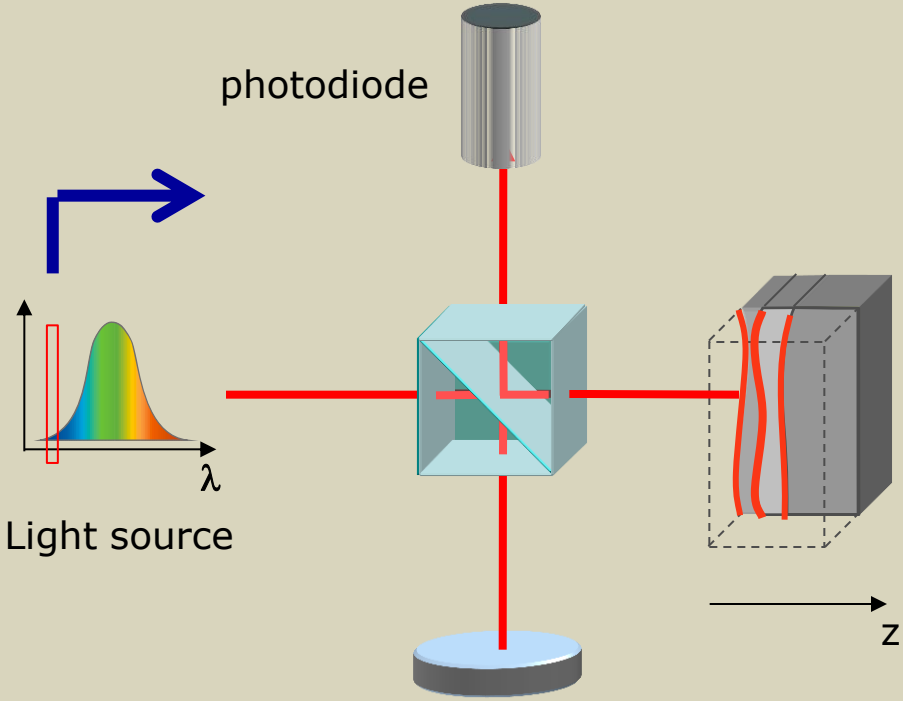




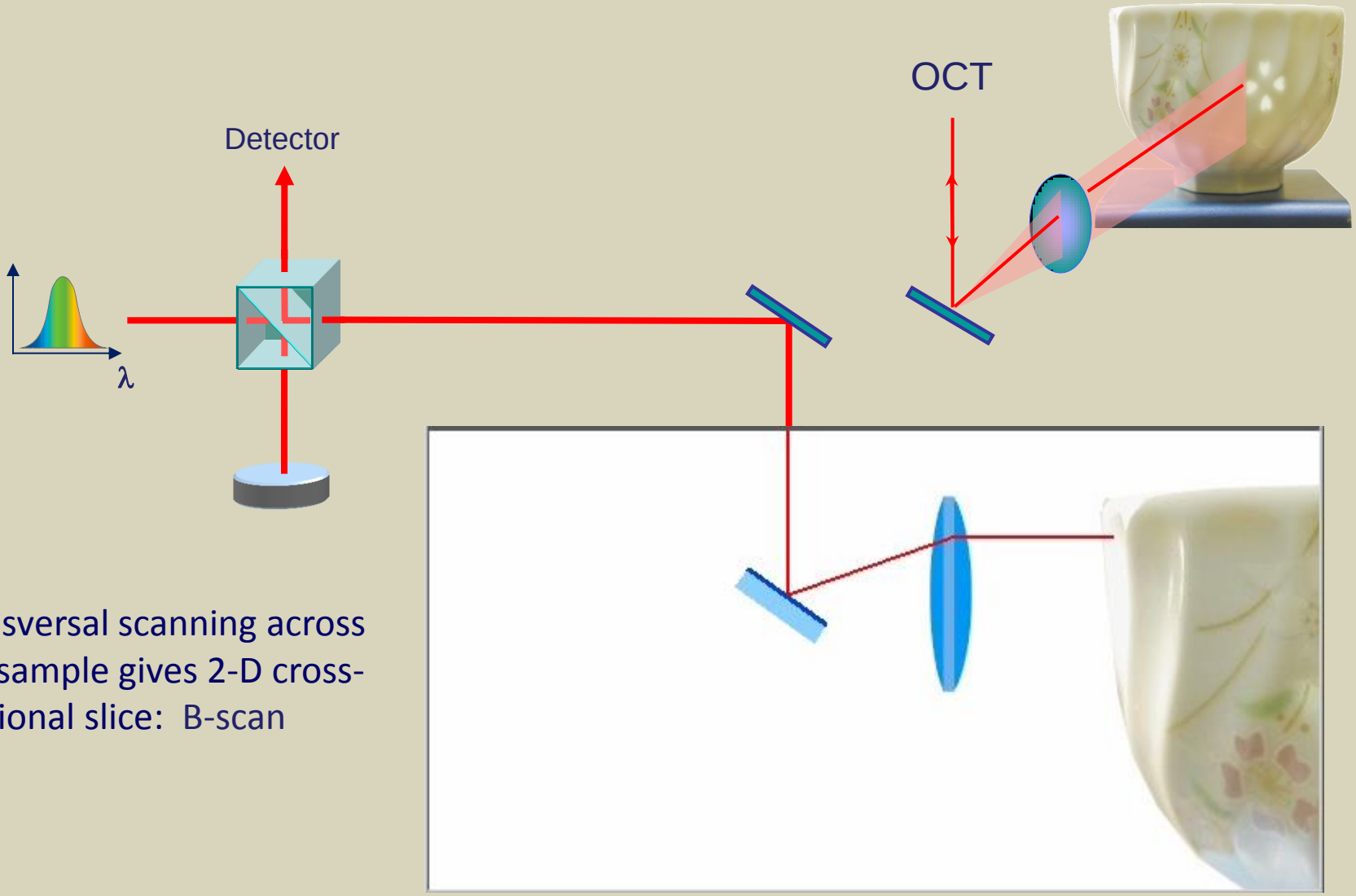
How to do it faster?

Sweep Source OCT
One of two Fourier domain methods



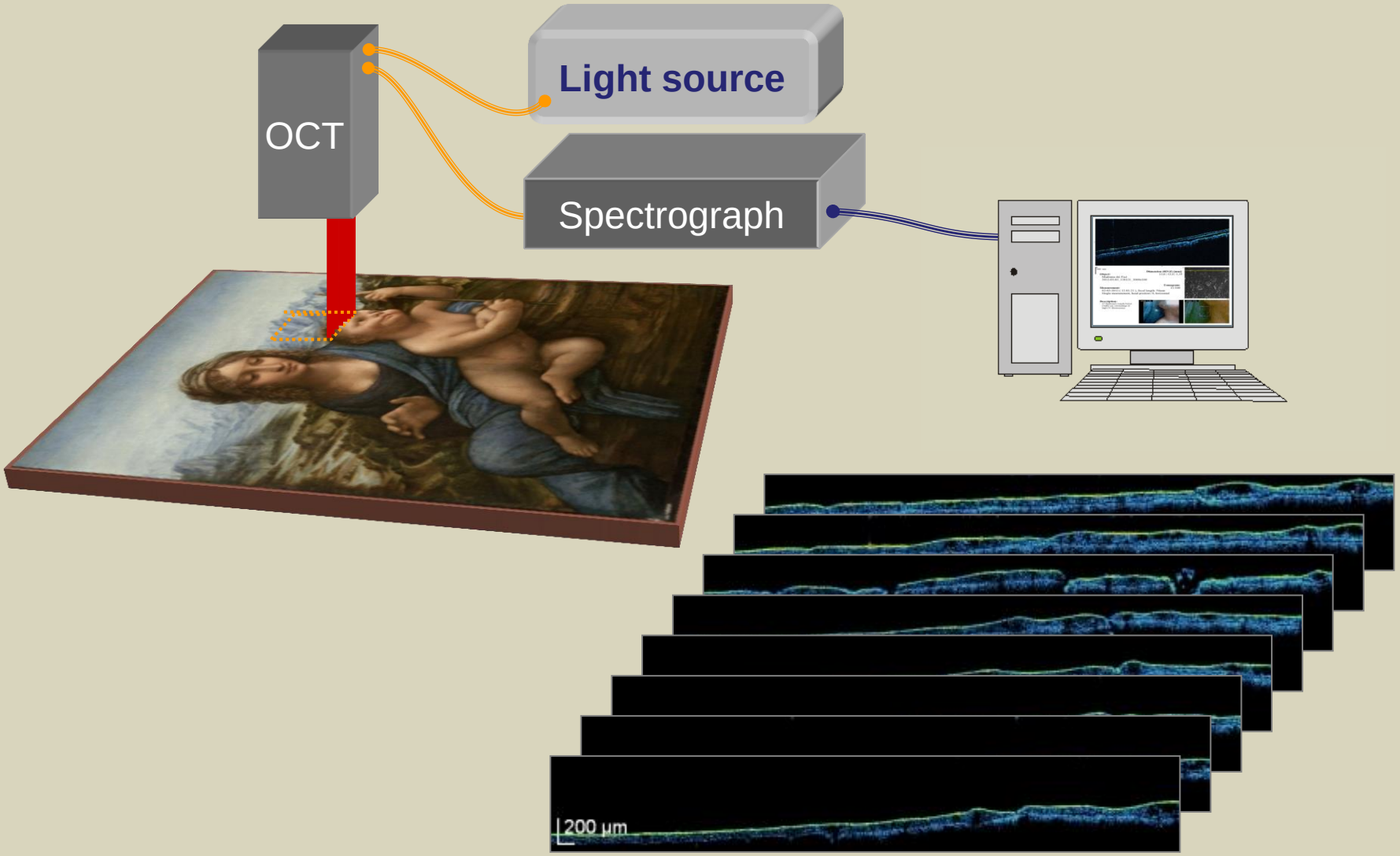


2D Scanning

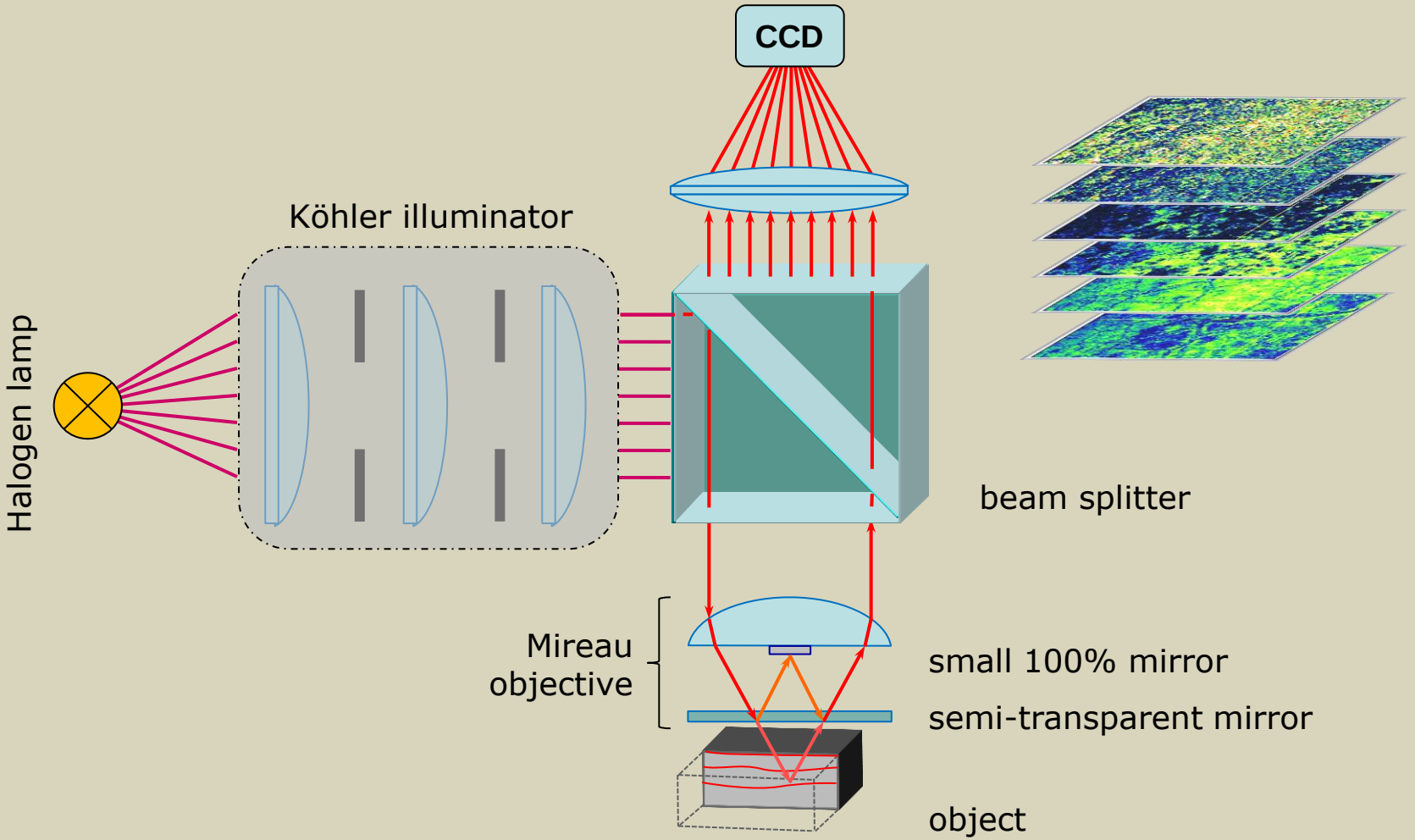


Transversal scanning across the sample gives 2-D cross-sectional slice: B-scan

Data collection modes



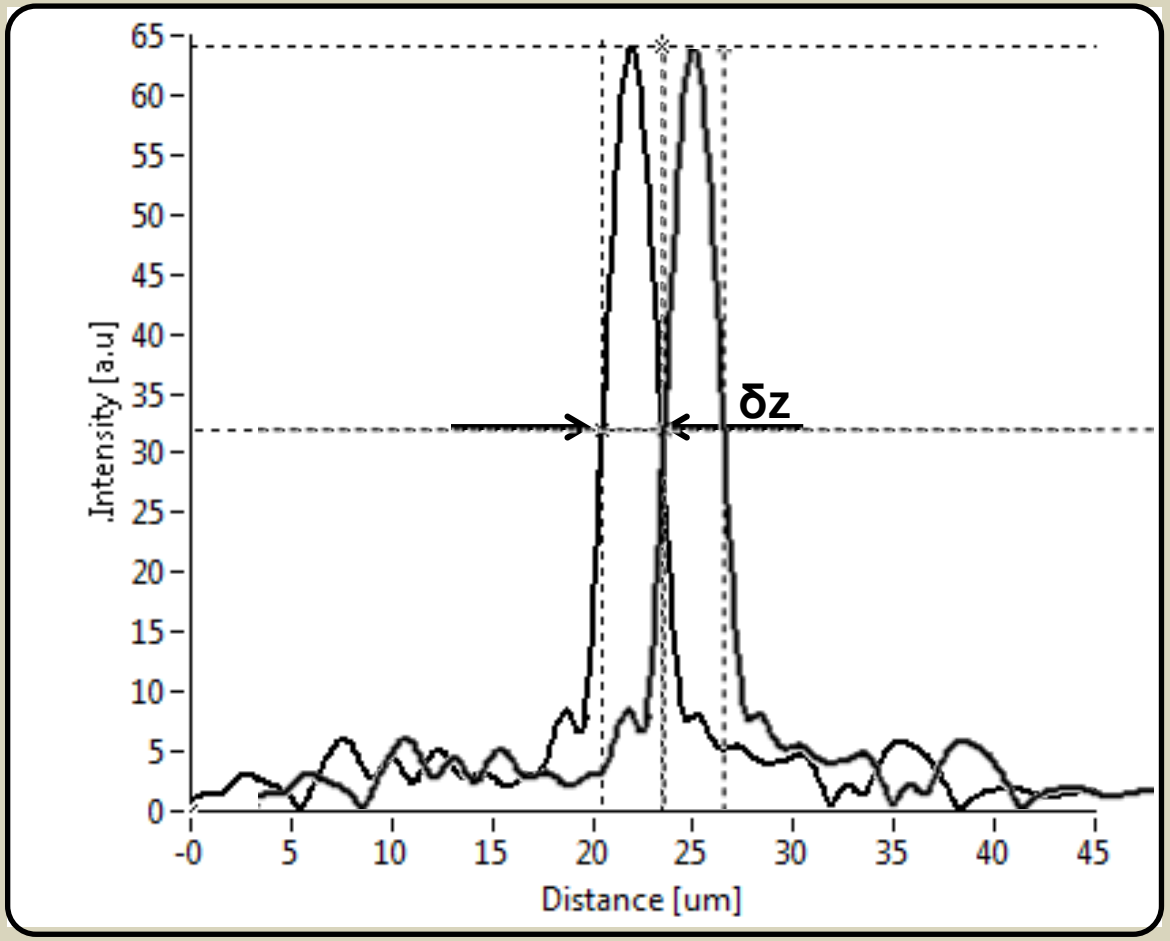
Another solution: Full Field OCT



✓ superb axial and lateral resolutions ≈1μm

✘ small field of view (<1 mm²)

Parameters of OCT systems – **axial resolution**



δz is an optical distance:
in material
of refractive index n_R :

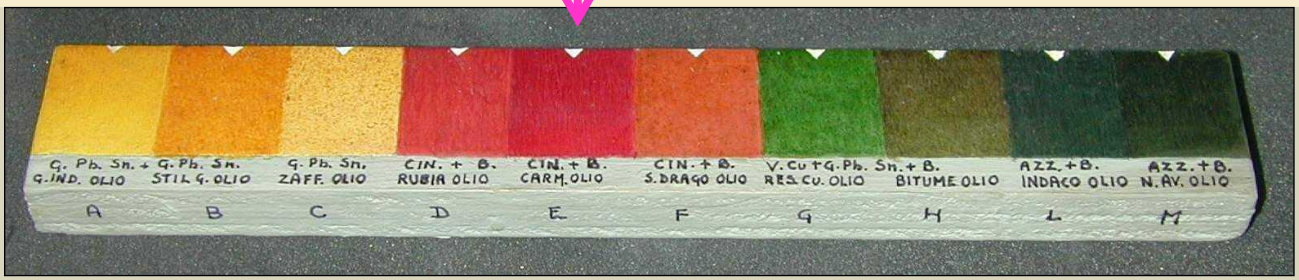
$$\delta z_{mat} = \frac{\delta z}{n_R}$$

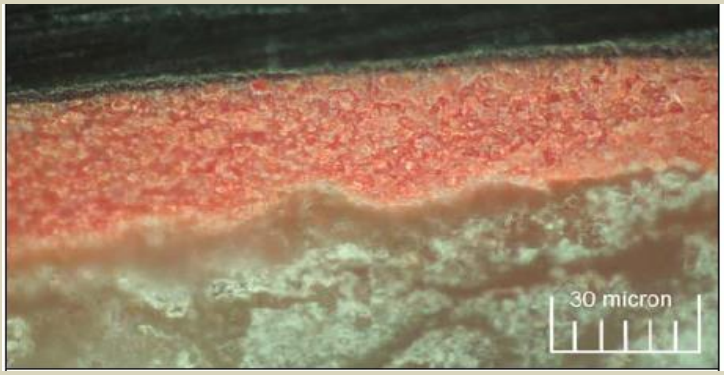
δz_{air} = 3.1 μm

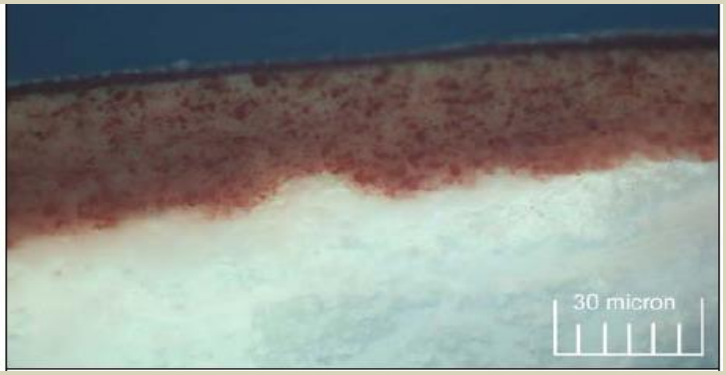
$\delta z_{n=1.4}$= 2.2 μm

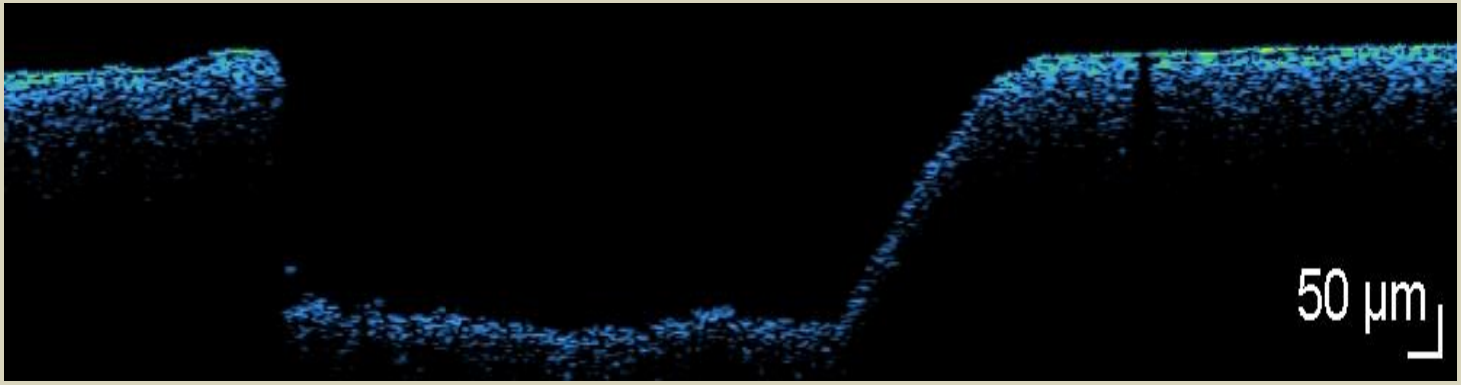
In practice:

Standard prepared by OPD





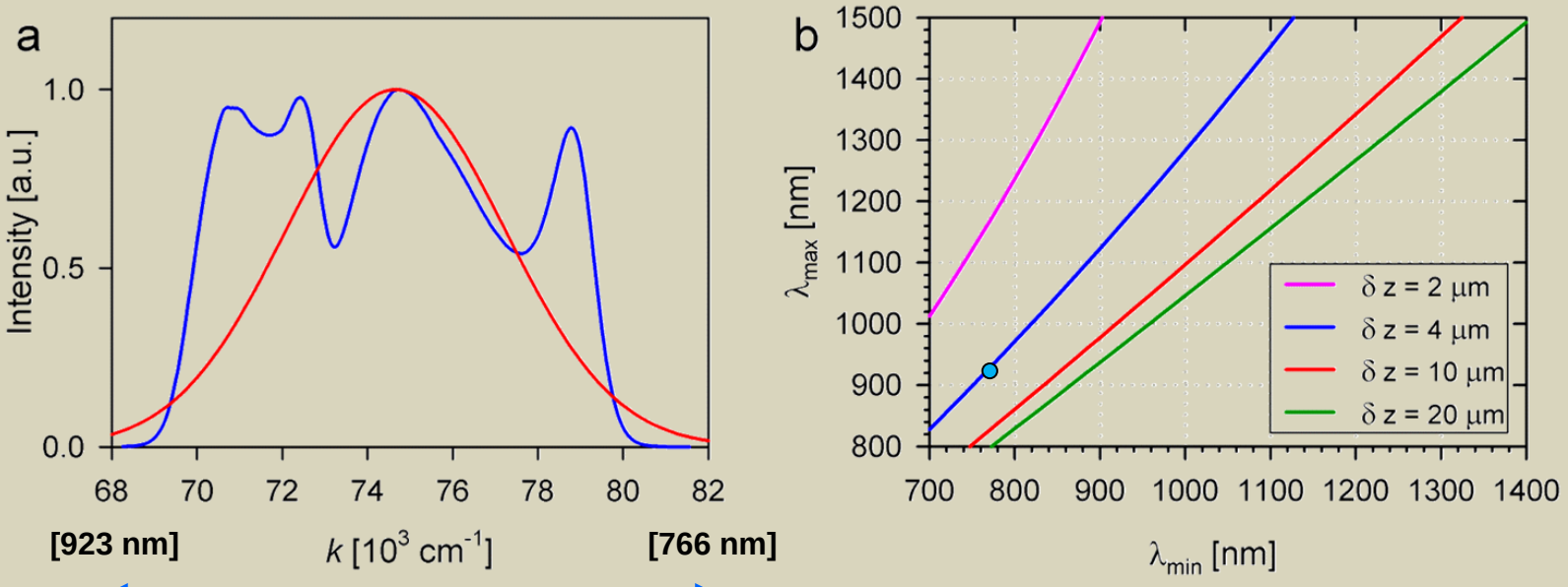




~4 µm of carmine over cinnabar + lead white, standard E

Axial resolution depends on **spectral width**

of the light source

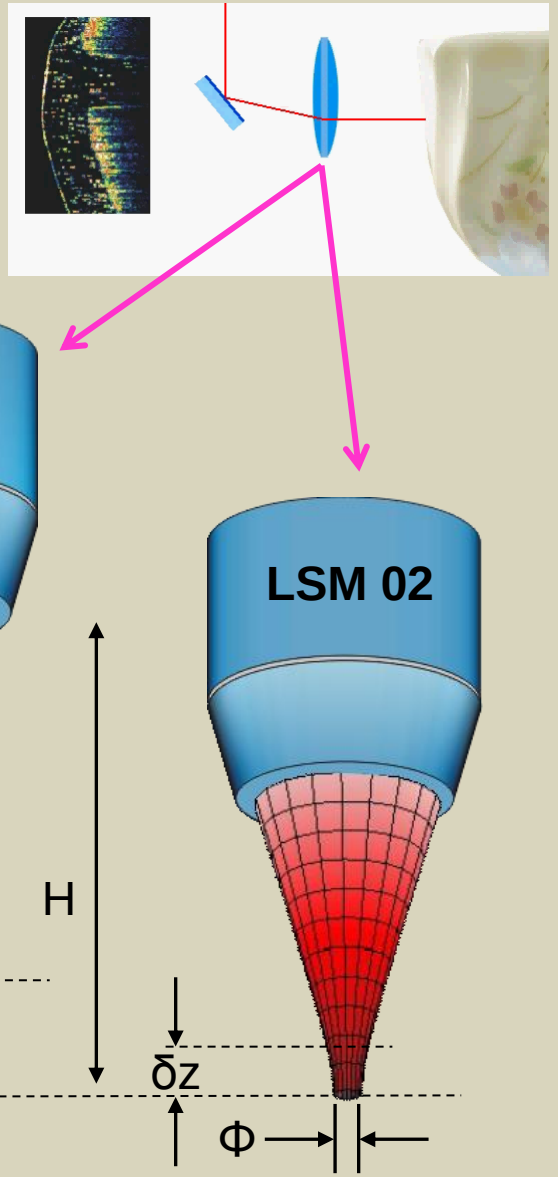


$$\delta z = \frac{1}{n_R} \frac{8 \ln 2}{k_{\max} - k_{\min}} \quad \text{or} \quad \delta z = \frac{1}{n_R} \frac{4 \ln 2}{\pi} \frac{\lambda_{\max} \lambda_{\min}}{\lambda_{\max} - \lambda_{\min}}$$

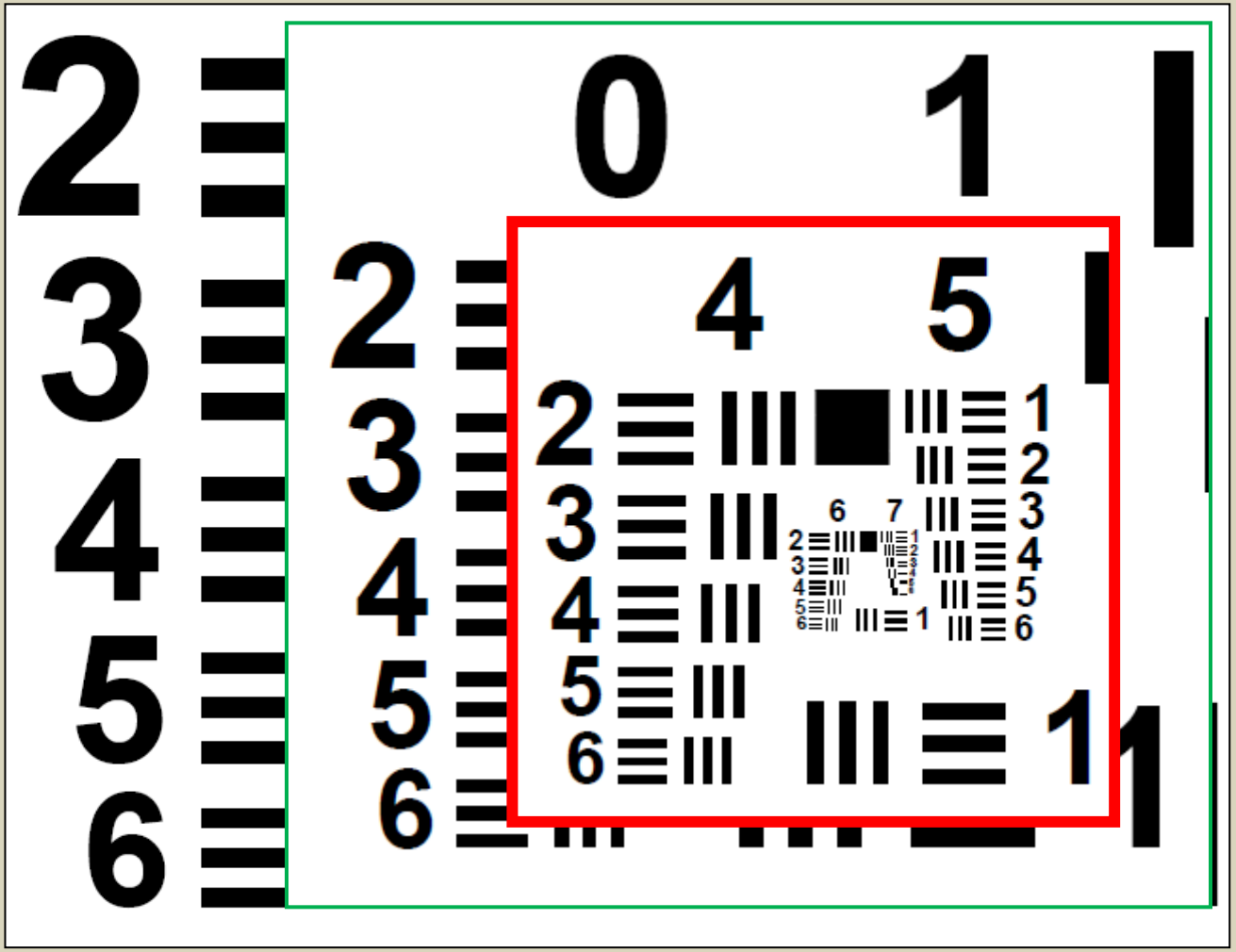
Lateral (in-plane) resolution depends on optics:

An example: the same OCT tomograph with two object lenses

- **LSM 04 objective**:
  - Lateral resolution Φ = 12.4 μm
  - Distance to object H= 43 mm
  - Scanned area = 17 x 17 mm
  - δz = 250 μm
  - f = 53.99 mm
- **LSM 02 objective**:
  - Lateral resolution Φ = 6.2 μm
  - Distance to object H= 7.5 mm
  - Scanned area = 5 x 5 mm
  - δz = 55 μm
  - f = 18.02 mm



How the lateral resolution is measured?



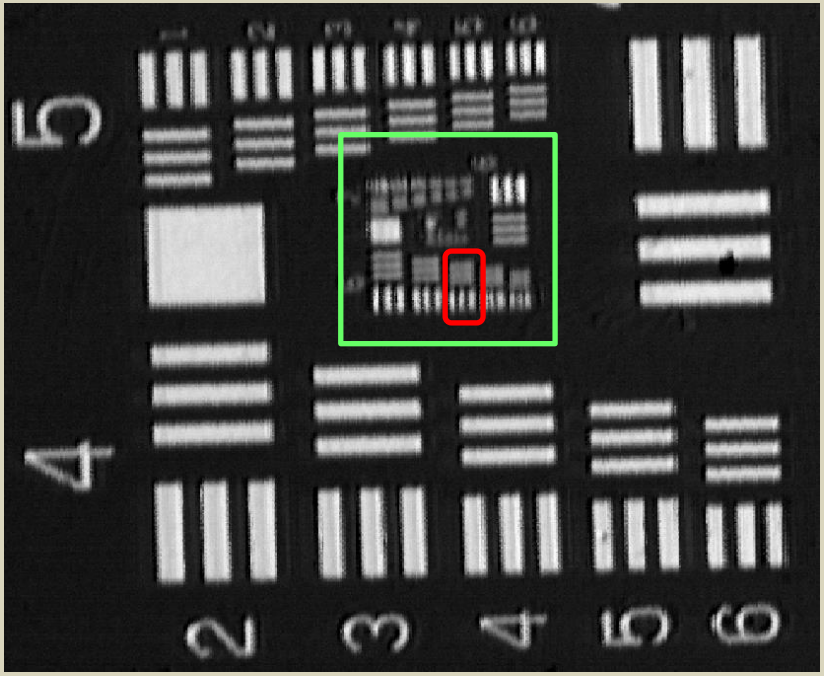
from:
0.25 line pairs/mm
= δx = 4mm

to
645 line pairs/mm
= δx = 1.6 μm

USAF Resolving Power Test Target 1951

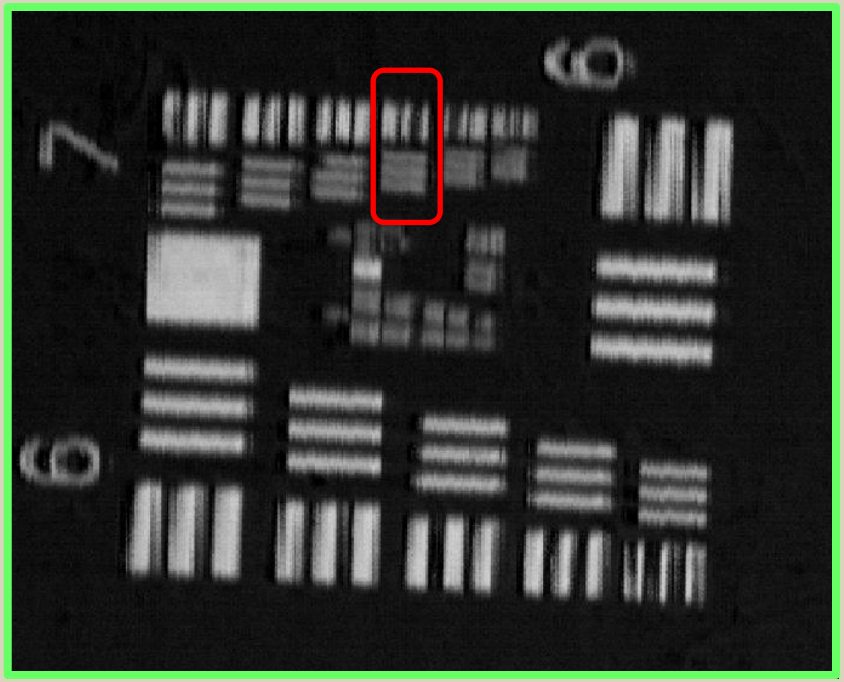
How the lateral resolution was measured?

LSM 04



#3 of group 6 (80.6 line pairs/mm)

LSM 02



#3 of group 7 (161 line pairs/mm)

USAF Resolving Power Test Target 1951

Other parameters:

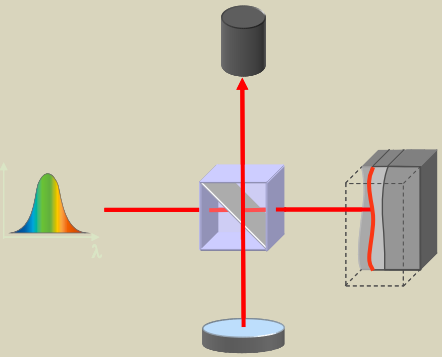
Range of examination:
the maximum thickness of the strata possible to image in one tomogram

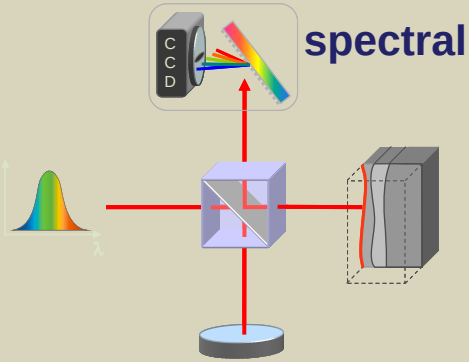
- TdOCT – in principle unlimited
- FdOCT:
  - SdOCT: limited to 2 – 4 mm (by No of pixels of the spectrograph)
  - SSOCT: up to few cm (quality of the laser line)

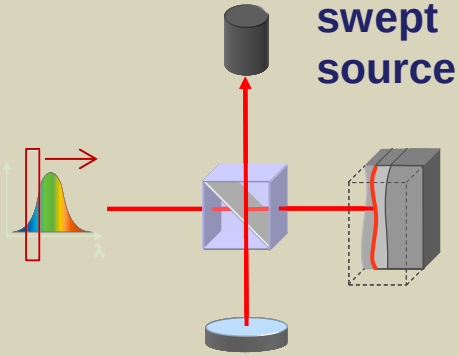
Sensitivity:
the maximum signal dumping in the object arm, still possible to detect
- expressed in dB: 100 dB: 0.000000001 of photons impinging the sample are still able to create an image.
SdOCT usually has sensitivities 20 dB higher than TdOCT
The higher the sensitivity, the less transparent layers can be selected

Power at the object:
usually less than 2 mW, either permanently scanned over object surface or spread over the examined area (FFOCT). Medical regulations may be used as indication of non-invasiness.

3 types of OCT tomographs





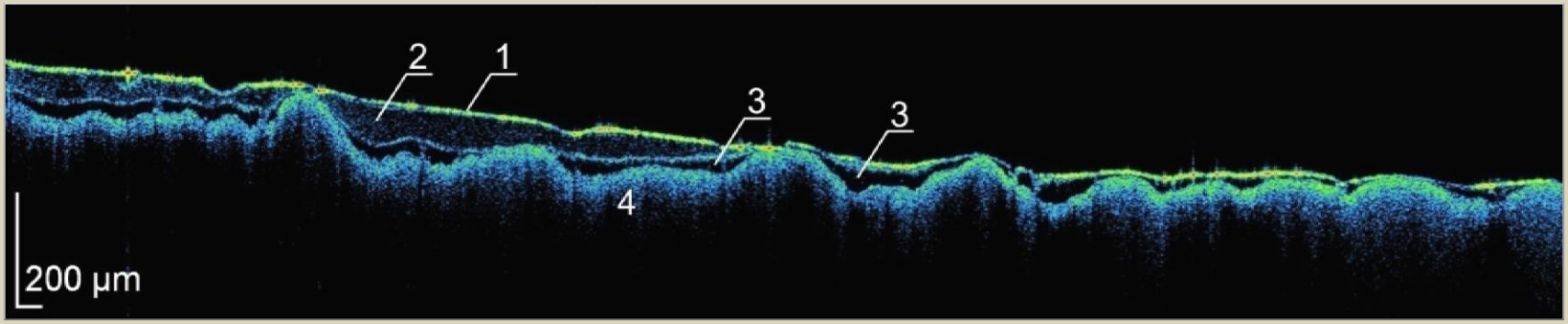


Time domain OCT

Fourier domain OCT

pro	✓ Unlimited depth of imaging ✓ Simple basic design	✓ Fast acquisition (3D imaging possible) ✓ High S/N (>100 dB)	✓ Very fast acquisition ✓ Adjustable resolution and depth of imaging ✓ high S/N ✓ λ up to 1.5 μm
contra	✘ Slow acquisition ✘ Moving parts in the optical delay line ✘ Artefacts (side lobes) for non-Gaussian source difficult to remove	✘ Limited depth of imaging(< 2mm) ✘ Sensitive to specular reflections ✘ Wavelength of operation limited by availability of CCD cameras (λ < 1 μm or €€€)	✘ Light sources still under development and expensive ✘ Sensitive to specular reflections (but less than SOCT)

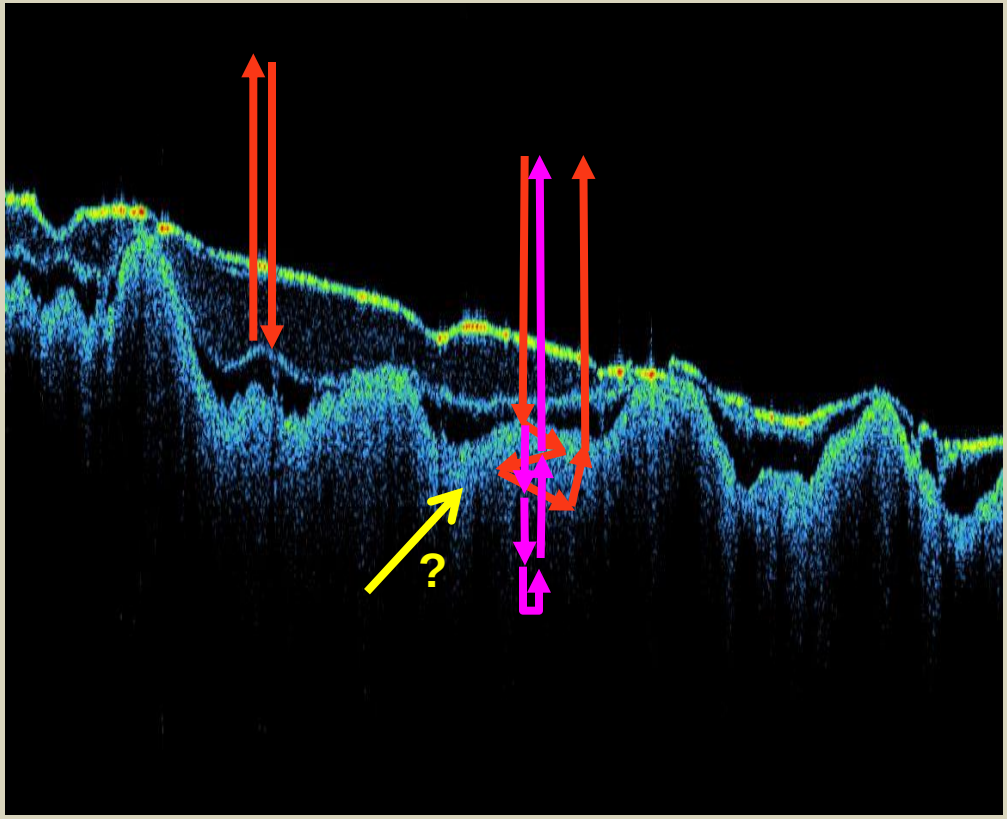
Sequence and thickness of layers



1 - the painting's surface
2 - layer of the varnish scattering probing light moderately
3 - transparent varnish
4 - opaque paint layer (end of penetration depth)

How to read the OCT tomograms?

- Scattering intensity is encodded in false colours:
- Single scattering / multiple scattering:



High scatter

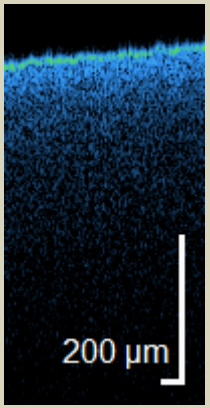
← varnish/air interface

← paint

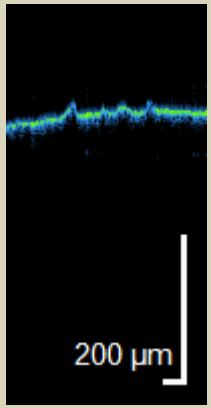
← glazes/pigmented varnish

← air, glass or transp. varnish

Low scatter



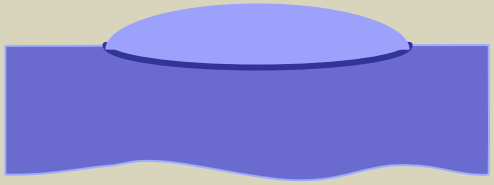
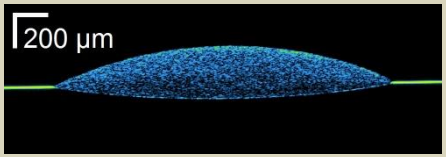
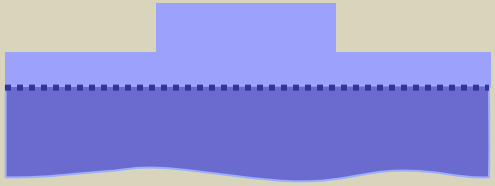
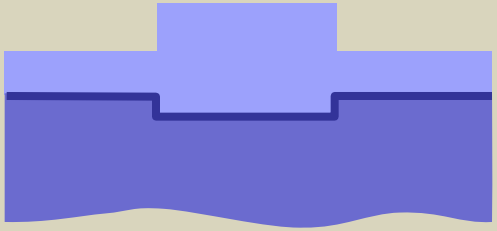
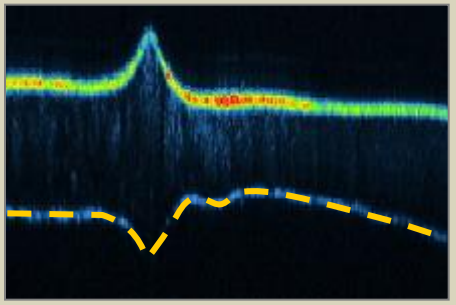
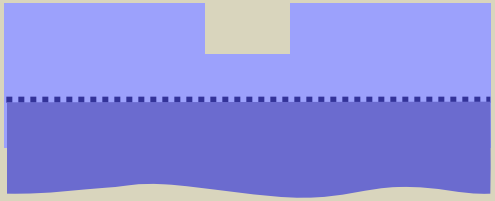
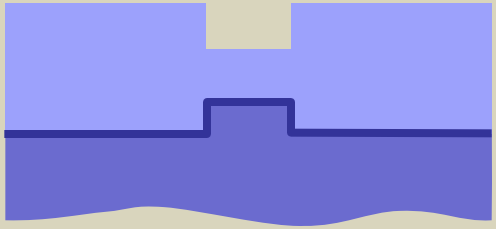
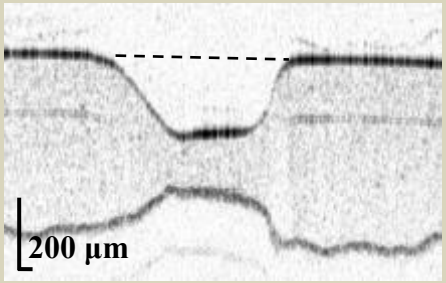
Cobalt Blue (Coelina)



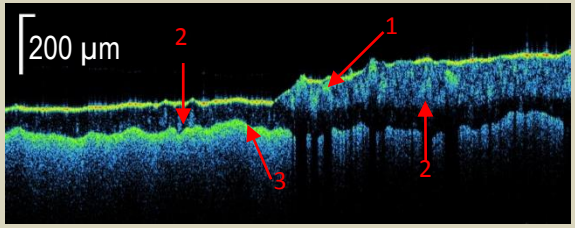
Prussian Blue (Milori)

How to read the OCT tomograms?

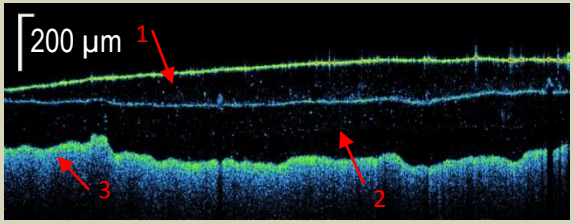
All in-depth distances are optical ones: depend on refractive index

object:	is imagined as:	example
 $n_R=1$		
		
		

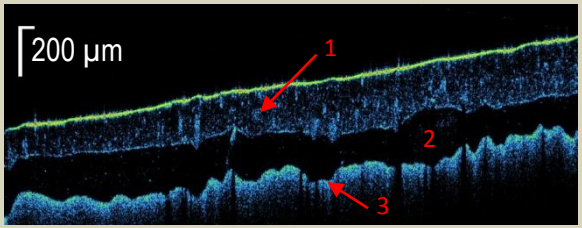
How to read the OCT tomograms?



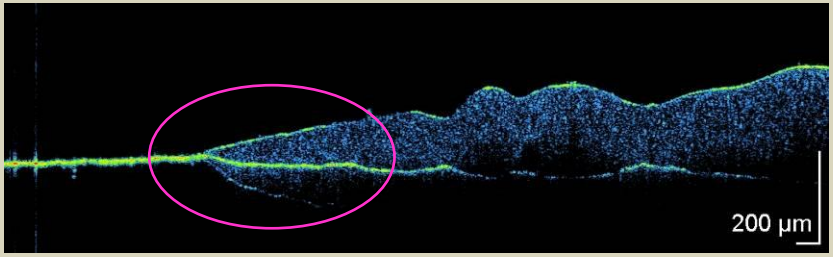
from the top: Indigo genuine (1), Alizarine Crimson Dark(2), Oil priming (3).

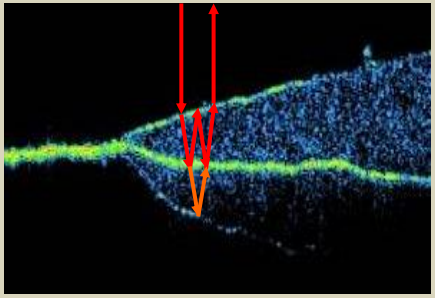


From the top: oil varnish (1), Second layer of oil varnish with surface dirt (soot) (2), Oil priming (3).



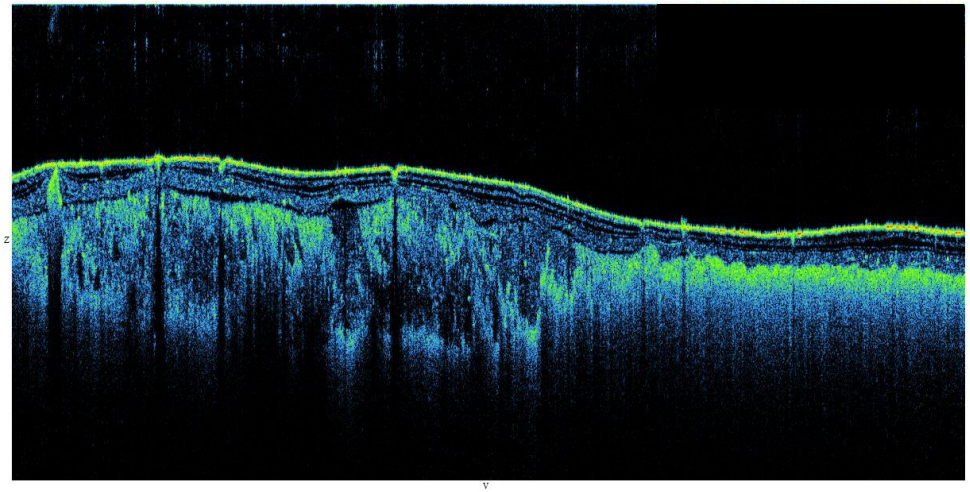
From the top: Alizarine Crimson Dark(1), Second layer of oil varnish with surface dirt (soot) (2), Oil priming (3).





Gold foil partially covered by cinnabar. Double reflection atrefact is clearly visible

Example of the structure of easel painting



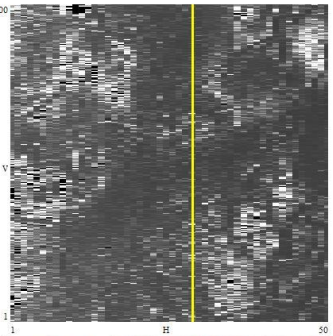
200 um

Dimension (H|V|Z) [mm]:
10,0 | 10,0 | 1,18

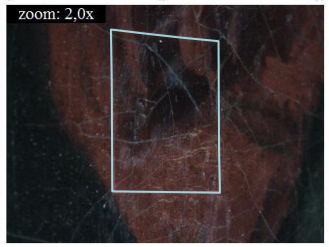
Object:
Portret sir Jamesa Wylie 2012
2012-10-22_151533_6000x50

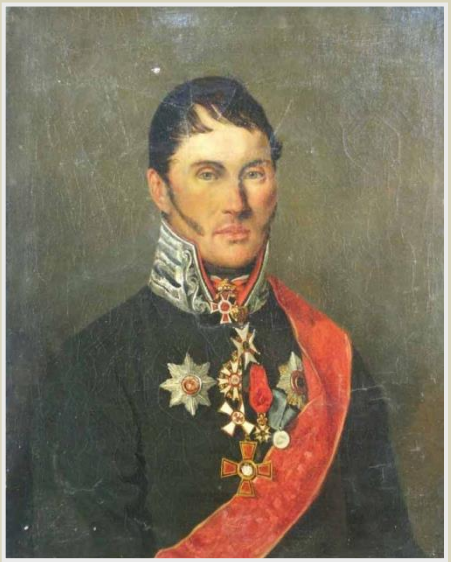
Tomogram:
22/50

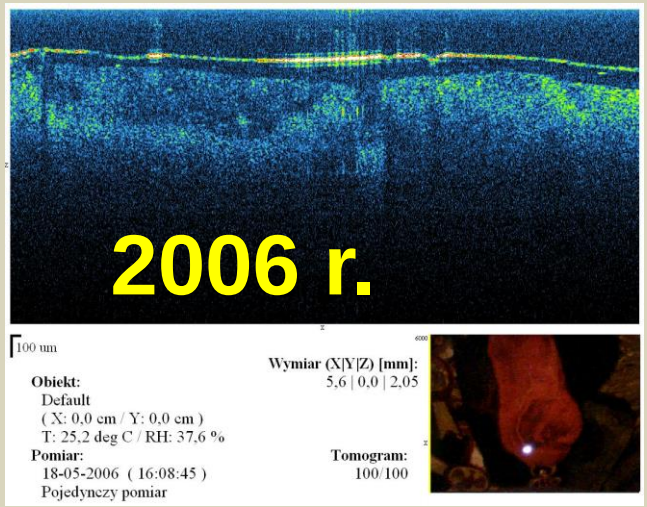
Measurement:
22-10-2012 (15:15:33), focal length: 54mm
Single measurement, head position: 9, vertical



Description:
miejsca badane w 2006 r.uzupełnienie w. mal. na szarfie





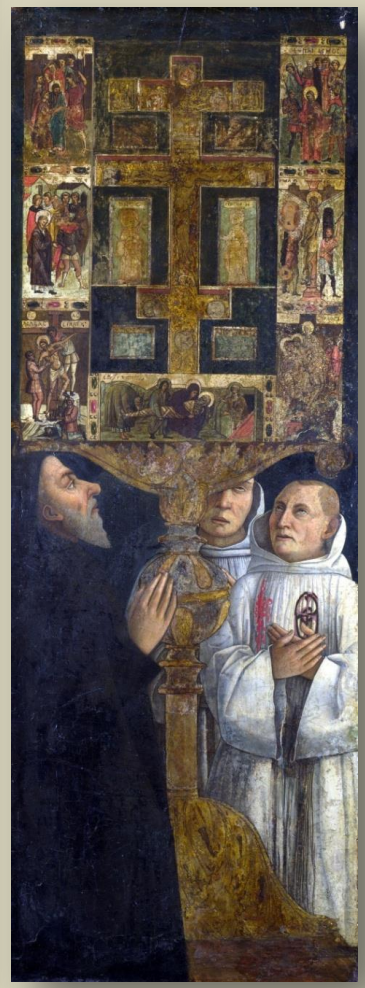


OCT for art conservation

- structure examination:
  - ✓ sequence and thickness of varnish and glaze layers of easel paintings
  - ✓ examination of underdrawings
  - ✓ absolute LIBS stratigraphy
  - ✓ destruction processes of historic glass
  - ✓ structure of objects with glass support
  - ✓ structure and surface morphology of glazed ceramics
  - ✓ structure of jades and similar materials
  - ✓ volume rendering – 3D maps and profilometry
- real-time monitoring:
  - ✓ monitoring of cleaninig procedures, both chemical and by laser ablation of varnish
  - ✓ tracking of canvas deformations under environmental stress

Exemplary result: *Reliquary of Cardinal Bessarion*

In 1438 Bessarion (1403 - 1472) was sent by the Emperor John VIII Palaeologos to the Council of Ferrara/ Florence to plead for western support in Constantinople 's final struggle against the Ottoman Turks. Despite the failure of his mission Pope Eugenius IV recognised Bessarion's constructive role in the deliberations by making him a cardinal… [Wiki]

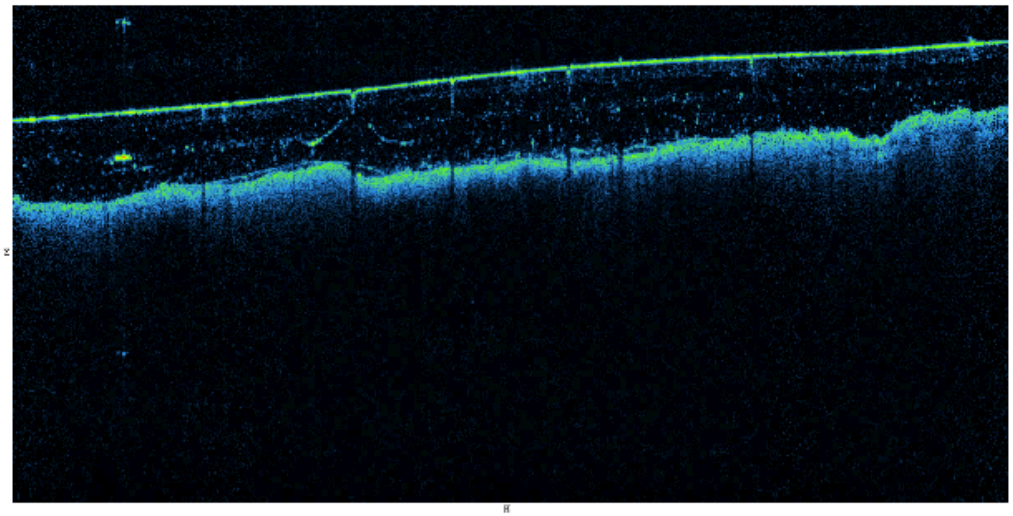


Gallerie dell'Accademia, Venice, Italy

Gentile Bellini, 1472-3, National Gallery, London

Photo:OPD

Reliquary of Cardinal Bessarion



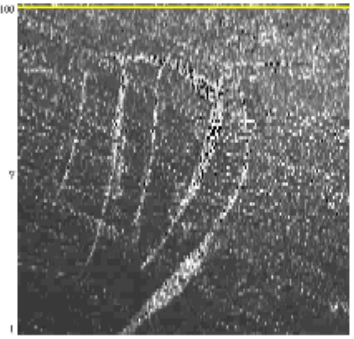
200 um

Dimension (H|V|Z) [mm]:
8,0 | 8,0 | 1,50

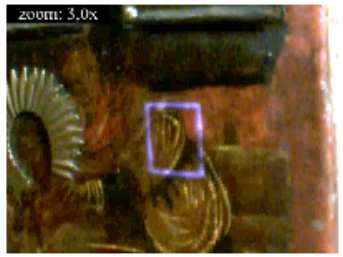
Object:
Reliquary of Cardinal Bessarione
2012-03-02_125702_3000x100

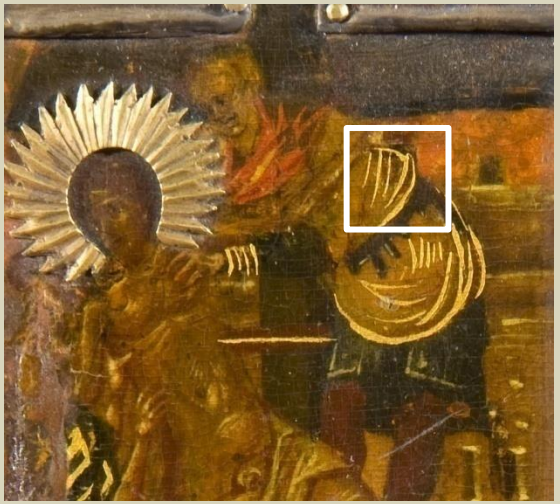
Tomogram:
1/100

Measurement:
02-03-2012 (12:57:02), focal length: 54mm
Single measurement, head position: 0, horizontal

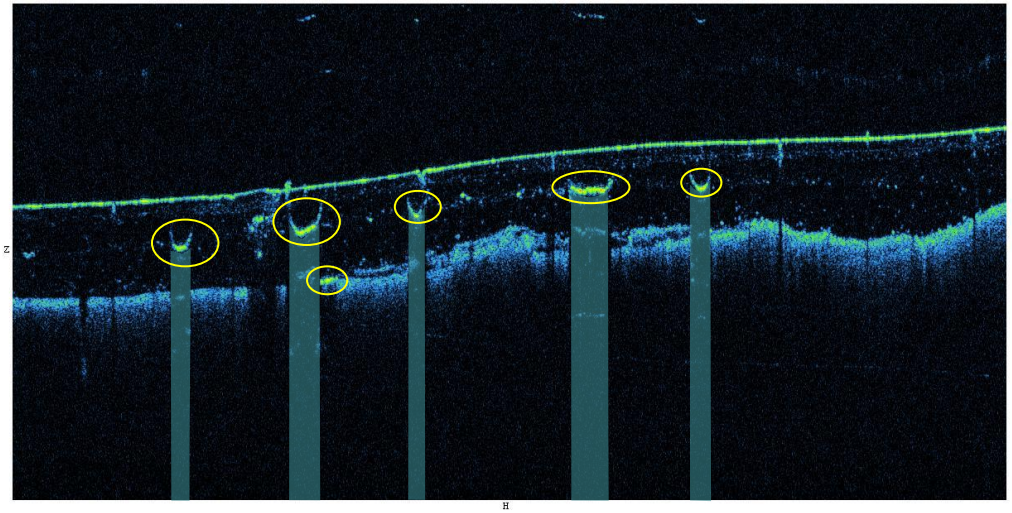


Description:
†1, Salita alle Croce,
superimposed drawing in gold
(area 2 - microphoto)





Reliquary of Cardinal Bessarion



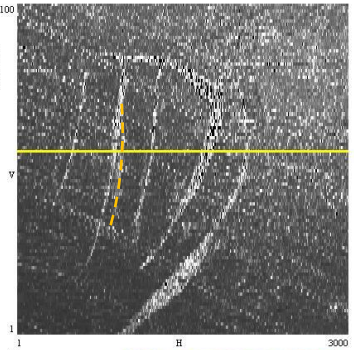
200 um

Dimension (H|V|Z) [mm]:
8,0 | 8,0 | 1,50

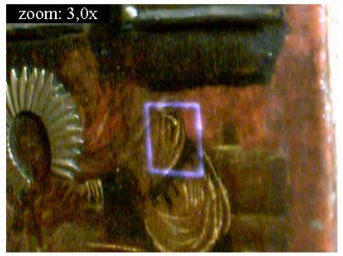
Object:
Reliquary of Cardinal Bessarione
2012-03-02_125702_3000x100

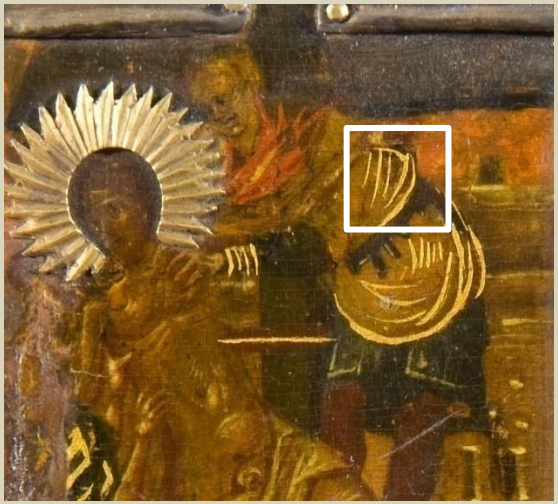
Tomogram:
44/100

Measurement:
02-03-2012 (12:57:02), focal length: 54mm
Single measurement, head position: 0, horizontal

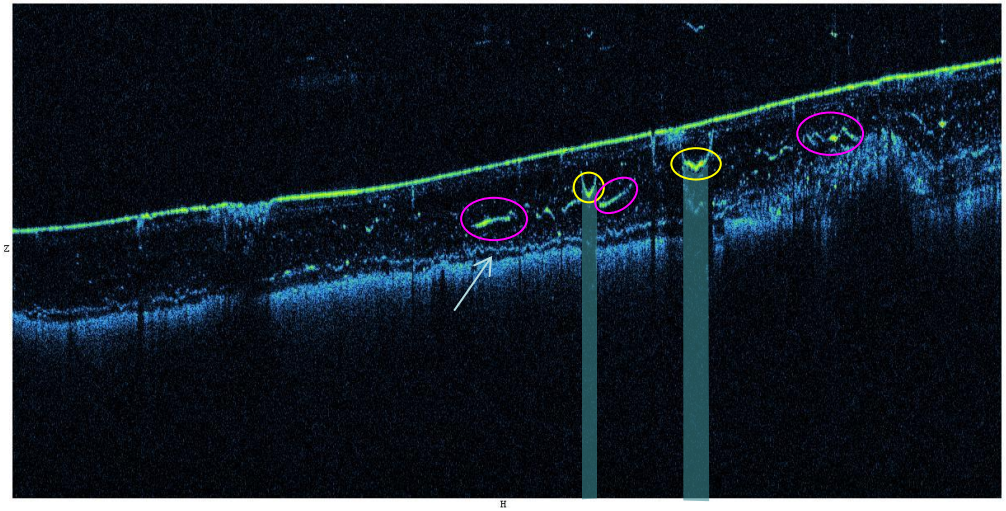


Description:
#1, Salita alle Croce,
superimposed drawing in gold
(area 2 - microphoto)





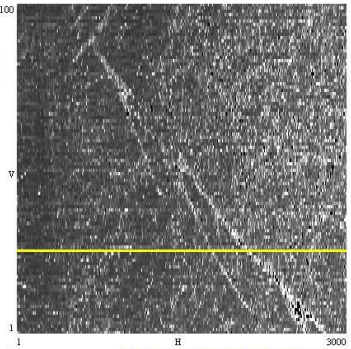
Reliquary of Cardinal Bessarion



200 um

Dimension (H|V|Z) [mm]:
12,0 | 12,0 | 1,50

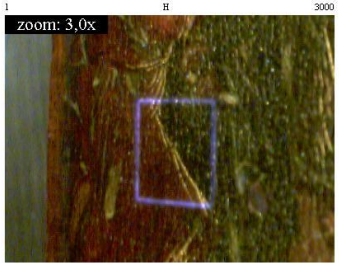
Object:
Reliquary of Cardinal Bessarione
2012-03-02_155625_3000x100

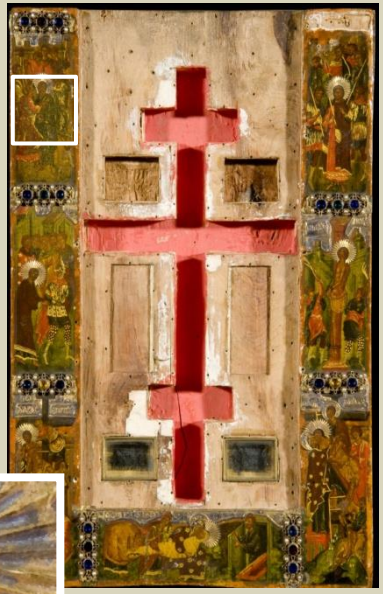


Tomogram:
74/100

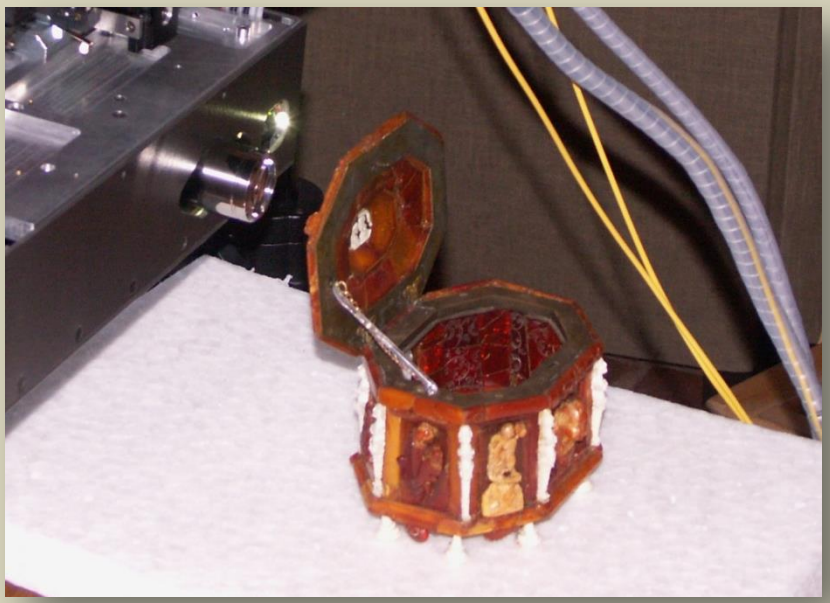
Measurement:
02-03-2012 (15:56:25), focal length: 54mm
Single measurement, head position: 0, horizontal

Description:
#6, Judas's betrayal, internal fractures (?) in varnish





Examination of amber artworks

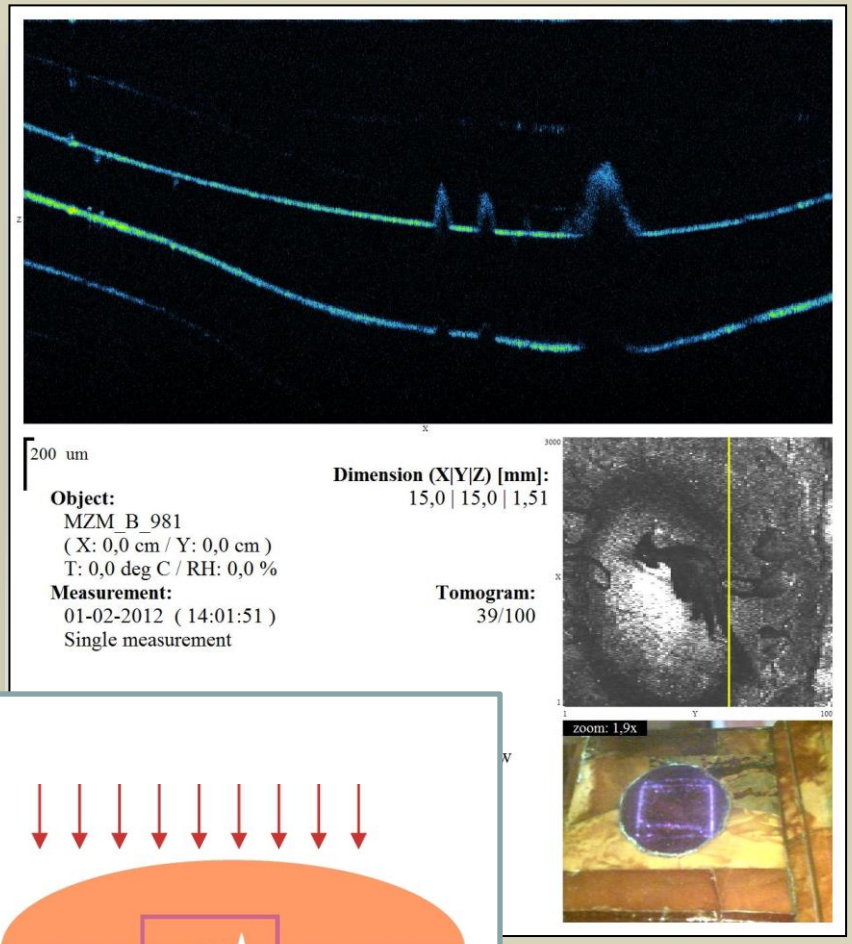


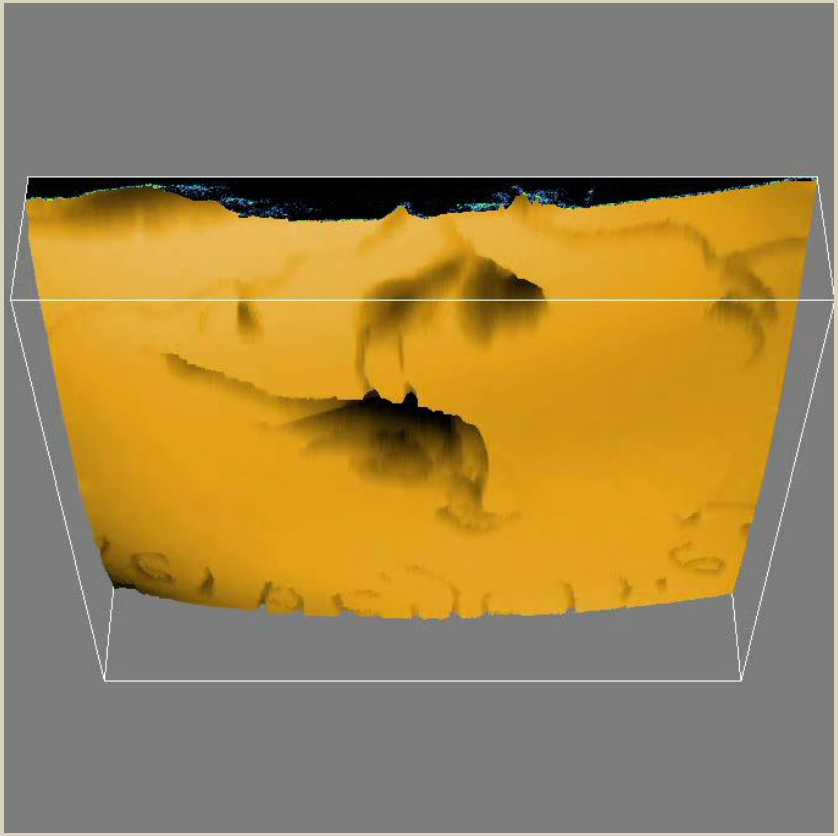
Teutonic (German Order) Knights' Castle in Malbork, PL

Exemplary result from miniature lace bench

Co-operation: prof. Jadwiga Łukaszewicz

Exemplary result from miniature lace bench

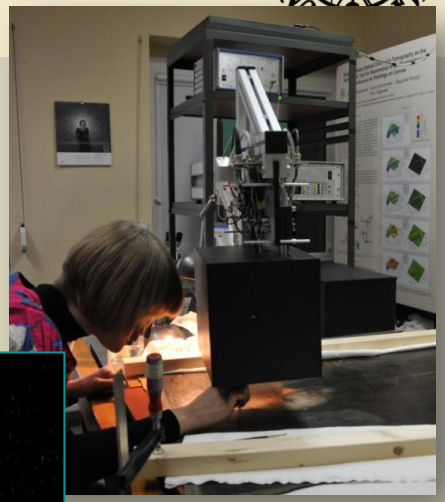


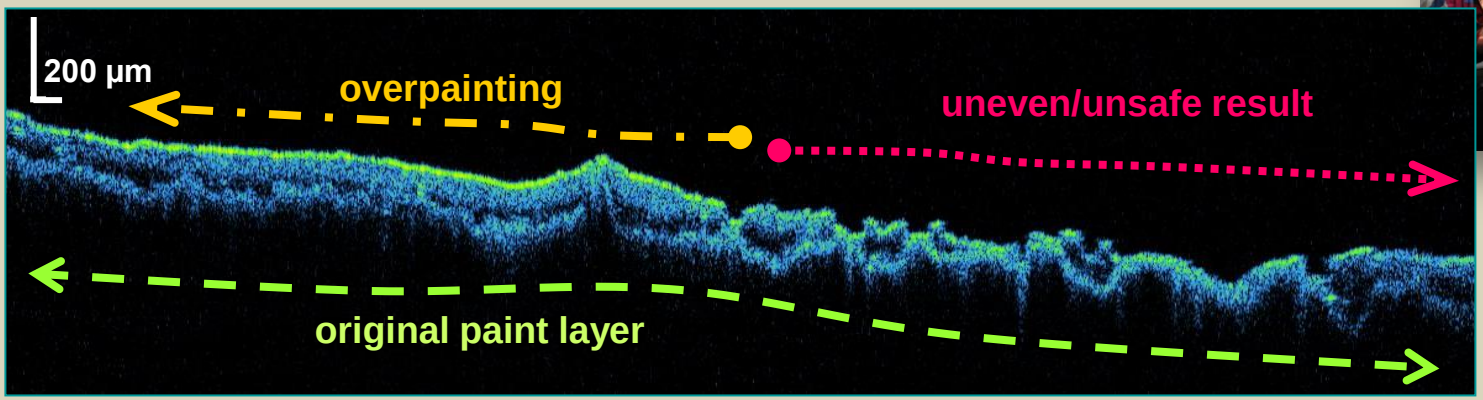


Co-operation: prof. Jadwiga Łukaszewicz

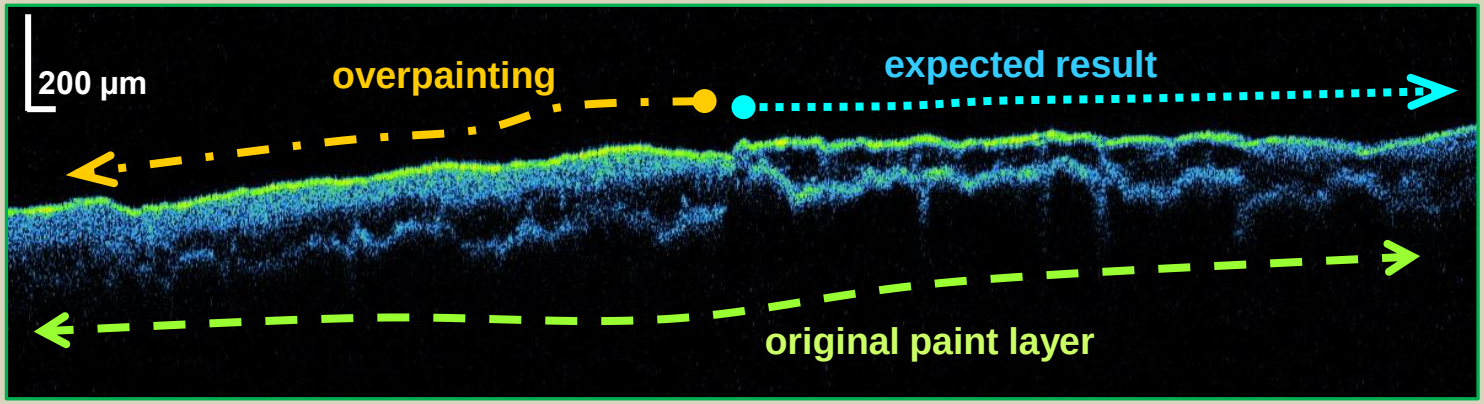
Monitoring of restoration treatment

Testing various solvent compositions for overpaint removal





isopropanol, water and ammonium (9:1:1) applied with cotton swabs



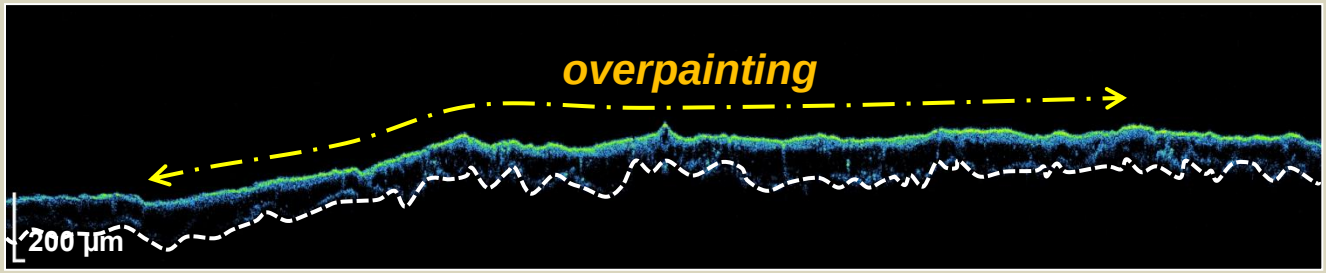
ethanol and white spirit (1:1) applied with cotton swabs

Result: choosing best working solvent composition

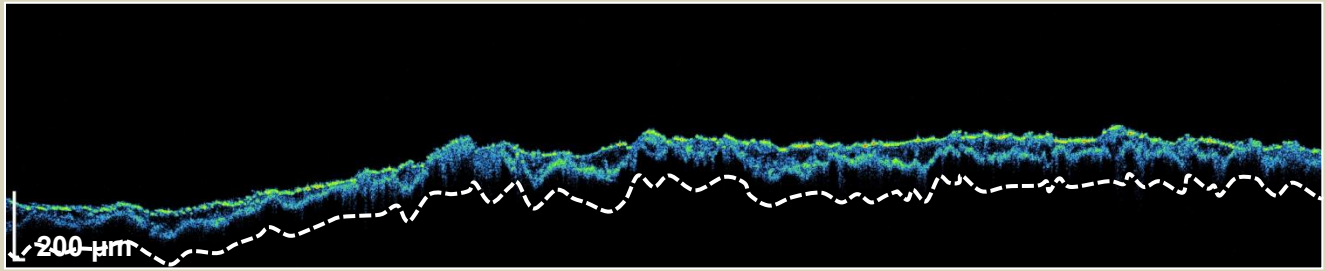
Testing means of application

Another set of OCT monitored trials was performed in order to evaluate the effect of using previously chosen solvent composition, but with different removal procedures (such as rolling with a cotton swab, brushing, exposition to poultices, mechanical removal with a scalpel, and their combinations).

Before treatment



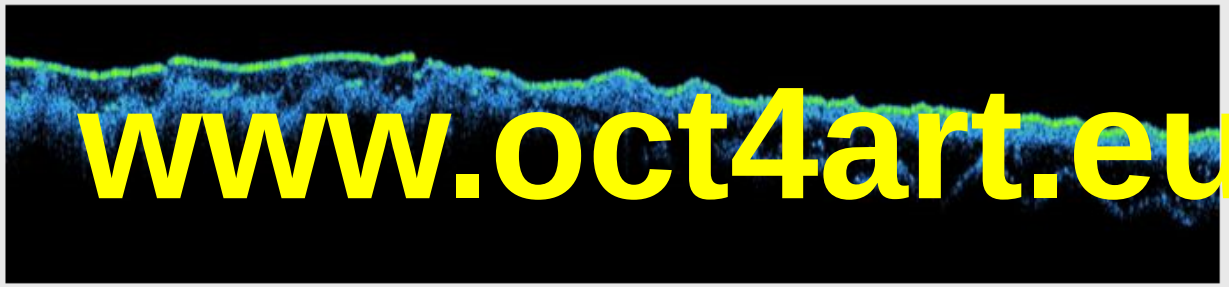
After treatment



Result: choosing optimal cleaning procedure:
(3 minute poultice exposition + final solvent treatment with a cotton swab)

OCT4ART

Optical Coherence Tomography for Examination of Works of Art



welcome
publications on oct4art
oct4art at conferences
oct4art community
workshop on oct4art Torun 2008
usefull links on OCT or Art
contact

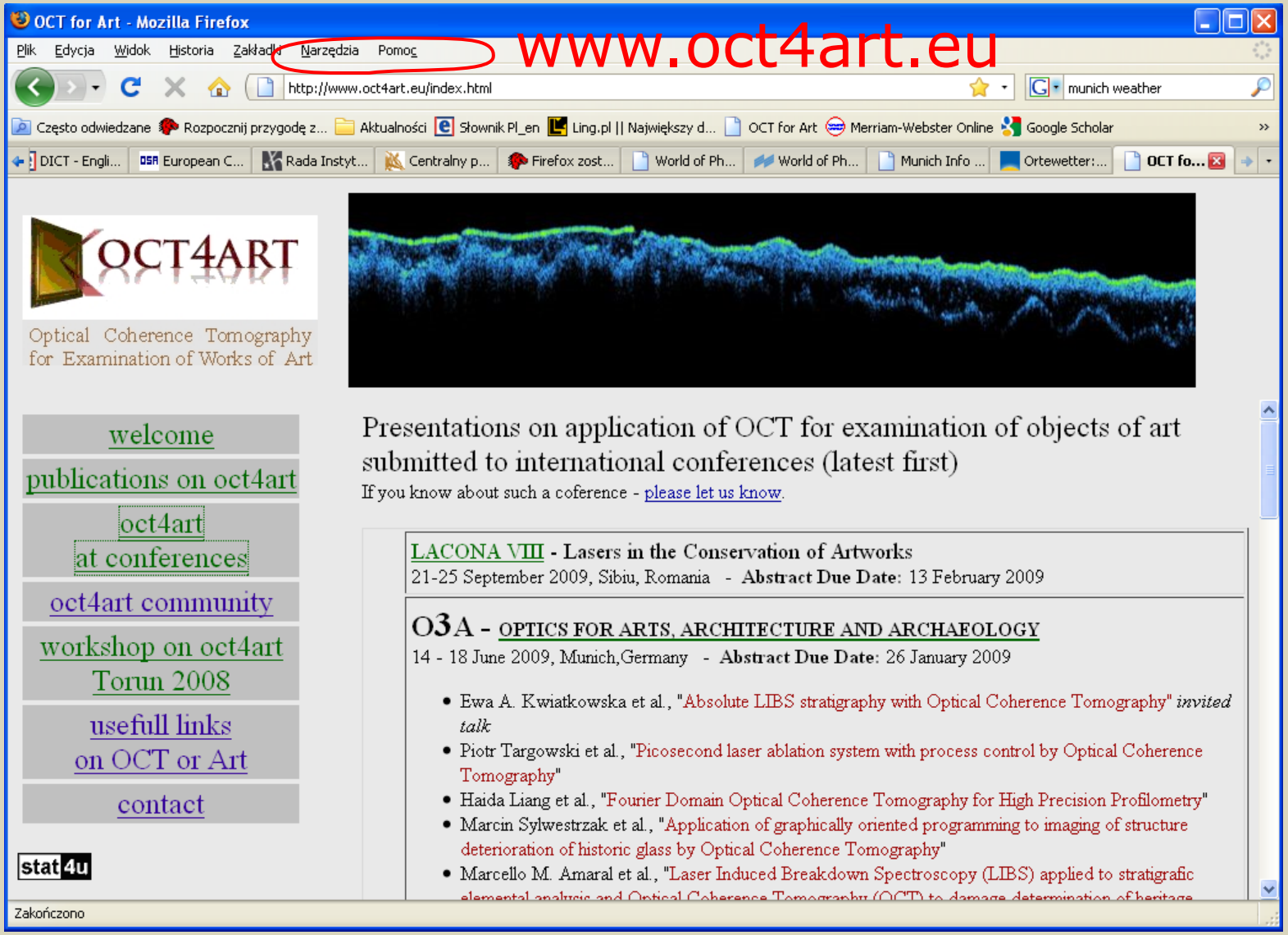
Complete list of papers published on OCT for examination of artwork

If you know about a paper not listed here, please let us know:
add an article in journal, add a conference paper, or just send me an e-mail.

Papers are listed in reverse chronological order:

71. S. Lawman, H. Liang, " High precision dynamic multi-interface profilometry with optical coherence tomography" Applied Optics **Article in press**, (2011) PDF
70. R. Lange, H. Liang, H. Howard, J. Spooner, "Optical coherence tomography and spectral imaging of a wall painting" in SPIE Newsroom, DOI: 10.1117/2.1201107.003778, (2011) PDF
69. M. Elias, N. Mas, P. Cotte, "Review of several optical non-destructive analyses of an easel painting. Complementarity and crosschecking of the results" Journal of Cultural Heritage **Article in press**, DOI: 10.1016/j.culher.2011.05.006, (2011) PDF
68. E. Bemand; M. Bencsik, H. Liang "OCT and NMR for non-invasive in-situ monitoring of the vulnerability of rock art monuments" Proc. SPIE **8084**, DOI: 10.1117/12.890084, 80840H (2011) PDF
67. M. Iwanicka, E.A. Kwiatkowska, M. Sylwestrzak, P. Targowski "Application of optical coherence tomography (OCT) for real time monitoring of consolidation of the paint layer in *Hinterglasmalerei* objects" Proc. SPIE **8084**, DOI: 10.1117/12.890398, 80840G (2011) PDF
66. H. Liang, R. Lange, H. Howard, J. Spooner "Non-invasive Investigations of a Wall Painting using Optical Coherence Tomography and Hyperspectral Imaging" Proc. SPIE **8084**, DOI: 10.1117/12.890088, 80840F, (2011) PDF
65. H. Liang "Advanced Optical Imaging Methods for Investigating Manuscripts" in *The Technological Study of Books and*

OCT in the Web - conferences



Thank you for your attention