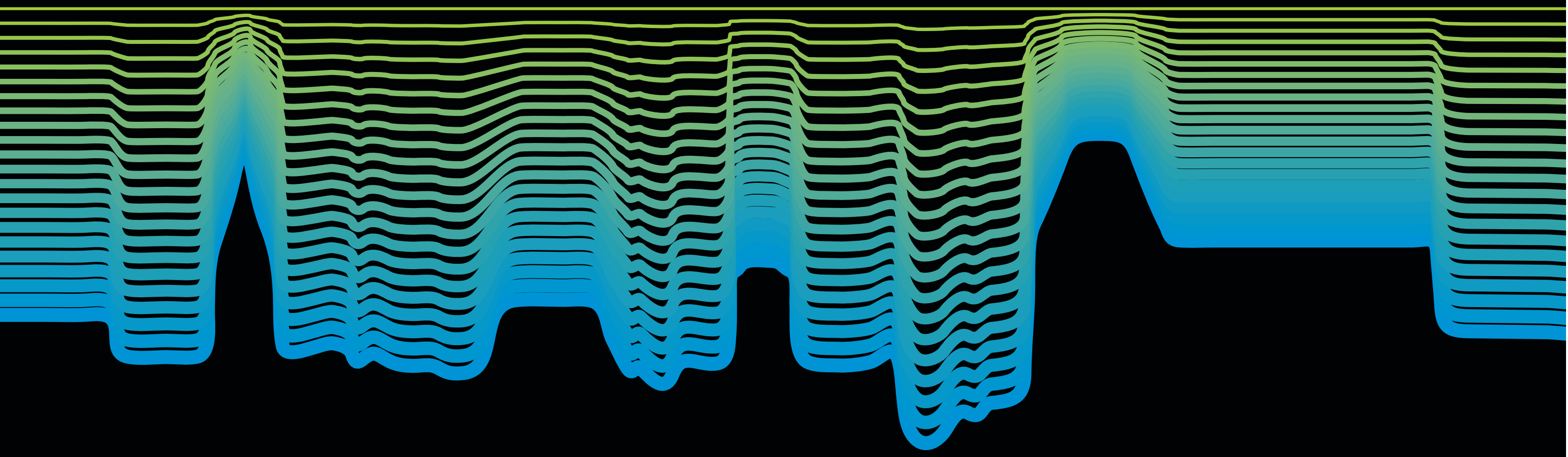
BOOK OF ABSTRACTS



CHARISMA

NEW TECHNIQUES FOR THE NON-INVASIVE INVESTIGATION OF THE SURFACE AND SUBSURFACE STRUCTURE OF HERITAGE OBJECTS.

25–26 June 2013

TRAINING ON APPLICATION OF OPTICAL COHERENCE TOMOGRAPHY (OCT) TO STRUCTURAL ANALYSIS OF HERITAGE OBJECTS.

27–28 June 2013

Co-organised by:
THE NATIONAL GALLERY, London, UK
NICOLAUS COPERNICUS UNIVERSITY, Toruń, Poland

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UNIVERSITAS NICOLAI COPERNICI TORUN
THE NATIONAL GALLERY
European Commission
CAPACITIES

BOOK OF ABSTRACTS

Edited by Marika Spring and Piotr Targowski

Events organised by The National Gallery, London and Nicolaus Copernicus University, Torun, Poland within the framework of CHARISMA (www.charismaproject.eu) integrating activity project co-funded by the European Commission within the action 'Research Infrastructures' of the 'Capacities' Programme – Grant agreement No. FP7-228330

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New techniques for the non-invasive investigation of the surface and subsurface structure of heritage objects

CHARISMA workshop organized by the National Gallery, London with Nicolaus Copernicus University, Toruń, Poland

PROGRAMME

Monday 24 June 2013
19:00 – 21:00 **Welcome reception** – Collegium Maximum, Pl. Rapackiego 1

Tuesday 25 June 2013
Location: Faculty of Mathematics and Computer Science, Nicolaus Copernicus University, Chopina Street 12/18, Toruń, Poland

9:00	Registration	
9:30	Opening remarks	
Session chair: Bruno Brunetti, CHARISMA project coordinator, University of Perugia		
10:00	*A systematic non-invasive optical investigation of wall paintings at a UNESCO world heritage site* **Haida Liang**[1], Andrei Lucian[1], Chi Shing Cheung[1], Bo Min Su[2] [1]School of Science & Technology, Nottingham Trent University, UK; [2]Dunhuang Academy, Gansu Province, China.	**13**
10:45	coffee break	
11:15	*Thermal Quasi-Reflectography, a new imaging technique for non-invasive analysis of artworks: principles and applications* **Claudia Daffara**[1], Dario Ambrosini[2], Luca Pezzati[3], Paola I. Mariotti[4] [1]Dept. of Computer Science, University of Verona, Italy; [2]DIIIE, University of L'Aquila, Italy; [3]INO-CNR, National Institute of Optics, Florence, Italy; [4]Opificio delle Pietre Dure, Florence, Italy.	**14**
12:00	*Of MOUSE and Men: Single-sided NMR in Cultural Heritage* **Tyler Meldrum** Institut für Technische und Makromolekulare Chemie, RWTH Aachen University, Germany.	**15**
12:45	lunch (provided on-site)	

Session chair: Heinz-Eberhard Mahnke		
14:15	*A CHARISMA round robin; comparison of non-invasive analyses and documentation methods for integration of results from multiple techniques on a single painting* **Marika Spring**[1], Rachel Morrison[1], Joseph Padfield[1], Magdalena Iwanicka[2], Łukasz Ćwikliński[3], Raffaella Fontana[4], Bernard Bluemich[5], Tyler Meldrum[5], Markus Kueppers[5], Wasif Zia[5], Paraskevi Pouli[6], Kristalia Melessanaki[6], Vivi Tornari[6], Demetrios Anglos[6] [1] National Gallery, London, UK, [2] Institute for the Study, Restoration and Conservation of Cultural Heritage, N. Copernicus University, Toruń, Poland, [3] Institute of Physics, N. Copernicus University, Toruń, Poland, [4] INO-CNR, Istituto Nazionale di Ottica, Firenze, Italy, [5] Institut für Technische und Makromolekulare Chemie, RWTH Aachen University, Germany, [6] Institute of Electronic Structure and Lasers (IESL), Foundation for Research and Technology–Hellas (FORTH), Heraklion, Crete, Greece.	**16**

15:00	*Laser tools in Cultural Heritage Science and Conservation; non-invasive analysis and management of cleaning interventions* **Paraskevi Pouli**, Kristalia Melessanaki, Vivi Tornari, Demetrios Anglos Institute of Electronic Structure and Lasers (IESL), Foundation for Research and Technology–Hellas (FORTH), Heraklion, Crete, Greece.	**17**
15:45	coffee break	
16:15	*Mid-infrared hyperspectral imaging of painting materials* **Costanza Miliani**[1,2], Francesca Rosi[1,2], Roland Harig[3], René Braun[3], Diego Sali[4], Alessia Daveri[5], Brunetto G. Brunetti[1,2], Antonio Sgamellotti[1,2] [1]CNR-ISTM c/o Chemistry Department, University of Perugia, Italy; [2]SMAArt, Chemistry Department, University of Perugia, Italy; [3]Bruker Optik GmbH, Ettlingen, Germany; [4]Bruker Italia S.r.l. uni personale, Milan, Italy; [5]Associazione laboratorio di Diagnostica per i Beni Culturali, Spoleto, Perugia, Italy.	**18**
17:00	*On site research on 'The Beanery' by Edward Kienholz with portable Fibre Optics Raman Spectroscopy* **Suzan de Groot**[1], Anna Laganà[2], and Sandra Weerdenburg[3], Thea van Oosten[4] [1]Conservation scientist, Cultural Heritage Agency of the Netherlands (RCE), Amsterdam, The Netherlands; [2]Freelance Modern Materials Conservator; [3]Conservator of Modern Objects / Head of Conservation, Stedelijk Museum Amsterdam, The Netherlands; [4]Conservation Scientist.	**19**
17:30	END OF THE SESSION	

Wednesday 26 June 2013
Location: Faculty of Mathematics and Computer Science, Nicolaus Copernicus University, Chopina Street 12/18, Toruń, Poland

Session chair: Suzan de Groot		
9:30	*Applications of Terahertz Imaging and Spectroscopy in Cultural Heritage* **Gillian Walker** School of Systems Engineering,University of Reading, UK	**20**
10:15	*Multiphoton microscopy: an efficient and promising tool for in situ study of historical artifacts* **Gaël Latour**[1]*, Jean-Philippe Echard[2], Marie Didier[2], Marie-Claire Schanne-Klein[1] [1]Laboratory for Optics and Biosciences (LOB), Ecole Polytechnique, CNRS, INSERM, Palaiseau, France; [2]Laboratoire de recherche et de restauration, Musée de la musique, Cité de la musique, Paris, France. *Currently at Laboratoire Imagerie et Modélisation en Neurobiologie et Cancérologie, Université Paris Sud, CNRS, Orsay, France	**21**
11:00	coffee break	
11:30	*Short poster talks*	
	Time-averaged digital speckle pattern interferometry for investigation of art objects surfaces **Leszek Krzemień** and Michał Łukomski Jerzy Haber Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Kraków, Poland	**29**
	Analysis of Ancient Paper Structure in Transmitted Light by Application of Different Microscopic Techniques. Examples from the Collection of the Kórnik Library of the Polish Academy of Science **Tomasz Kozielec**	**30**

	The Department of Paper and Leather Conservation, Nicolaus Copernicus University, Toruń, Poland	
	Preliminary physicochemical studies on a shield handle originating from the Przeworsk culture cemetery located in Czersk **Ewelina Miśta**[1] and Paweł Kalbarczyk[2] [1]National Centre for Nuclear Research, Otwock-Świerk, Poland; [2]Institute of Nuclear Chemistry and Technology, Warsaw, Poland.	**31**
12:30	lunch (provided on-site)	

Session chair: Costanza Miliani		
14:00	*Fusion of tomographic documentation of art objects based on electromagnetic radiation in the near and mid infrared area of the spectrum and ultrasonic microscopy. Application to Byzantine icons from Cyprus* **Georgios Karagiannis** ORMYLIA Foundation Diagnostic Centre, Greece	**22**
14:45	*Accelerators and X-rays in cultural heritage studies* **Heinz-Eberhard Mahnke** Fachbereich Physik and Excellence Cluster TOPOI, Freie Universität Berlin, Germany	**23**
15:30	coffee break	
16:00	*Optical coherence tomography for vulnerability assessment of sandstone in-situ* **Elizabeth Bemand** and Haida Liang School of Science & Technology, Nottingham Trent University, UK	**24**
16.25	*Macroscopic X-ray fluorescence analysis, a method for non-invasive imaging of painted works of art. Comparison with other methods and some case studies.* **Koen Janssens**[1], Mathias Alfeld[1], Geert van der Snickt[1], Joris Dik[2] [1]University of Antwerp, Belgium; [2]Delft University of Technology, The Netherlands	**25**
17:10	Final remarks	
17:20	END OF THE SESSION	

POSTERS

Training on application of Optical Coherence Tomography (OCT) to structural analysis

CHARISMA workshop organized by the Nicolaus Copernicus University, Toruń, Poland

PROGRAMME

Thursday 27 June 2013
Location: Institute of Physics, Centre for Quantum Optics, Nicolaus Copernicus University Toruń, Grudziądzka Street 5, Toruń, Poland

9:00	Opening remarks	
Session chair: Mei-Li Yang		
9:15	*Introduction to the OCT technique* **Piotr Targowski** Institute of Physics, Nicolaus Copernicus University, Toruń, Poland	**37**
10:00	*High resolution Fourier domain optical coherence tomography for resolving thin layers in painted works of art* **Chi Shing Cheung**, Haida Liang Nottingham Trent University, UK	**38**
10:20	*Application of Optical Coherence Tomography to the examination of varnish layers on the Ghent altarpiece* **Hélène Dubois** KIK IRPA - Royal Institute For Cultural Heritage, Brussels, Belgium	**39**
10:40	coffee break	
Session chair: Claudia Daffara		
11:10	*Next Generation OCT for Art Conservation, Art History & Archaeology* **Haida Liang**[1], Chi Shing Cheung[1], Masaki Tokurakawa[2], Jae M.O. Daniel[2], W. Andrew Clarkson[2], Marika Spring[3], Dawid Thickett[4] [1]School of Science & Technology, Nottingham Trent University, Nottingham, UK, [2]Optoelectronics Research Centre, University of Southampton, Highfield, UK, [3]Scientific Department, National Gallery, London, UK, [4]English Heritage, London, UK	**40**
11:55	*Laser ablation monitoring with OCT* **Paraskevi Pouli**[1], Kristalia Melessanaki[1], Magdalena Iwanicka[2], Łukasz Ćwikliński[3], Piotr Targowski[3] [1]Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, Heraklion, Crete, Greece; [2]Institute for the Study, Restoration and Conservation of Cultural Heritage, N. Copernicus University, Torun, Poland; [3]Institute of Physics, N. Copernicus University, Torun, Poland	**42**
12:15	*Ultra-high resolution, full-field, time domain OCT in the visible range and multi-spectral camera. Cross-checking and complementarity of the images* **Mady Elias** Evry University, France	**44**
13:00	lunch (provided on-site)	

Session chair: Mady Elias		
14:30	*Using Optical Coherence Tomography to Examine the Structure of Ancient ChineseGlaze and Jade* **Mei-Li Yang** National Tsing Hua University, Taiwan	**46**
15:15	*Combined LIBS/OCT technique for examination of paintings* **Ewa A. Kaszewska**[1], Marcin Sylwestrzak[1], Jan Marczak[2], Wojciech Skrzeczanowski[2], Magdalena Iwanicka[3], Elżbieta Szmit-Naud[3], Demetrios Anglos[4,5], and Piotr Targowski[1] [1]Institute of Physics, Nicolaus Copernicus University, Torun, Poland; [2]Institute of Optoelectronics, Military University of Technology, Warsaw, Poland; [3]Institute for the Study, Restoration and Conservation of Cultural Heritage, Nicolaus Copernicus University, Torun, Poland; [4]Institute of Electronic Structure & Laser, Foundation for Research and Technology – Hellas, Heraklion, Crete, Greece; [5]Department of Chemistry, University of Crete, Heraklion, Crete, Greece	**47**
15:35	*From confocal microscopy to confocal OCT* **Raffaella Fontana[1]**, Marco Barucci[1], Enrico Pampaloni[1], Luca Pezzati[1], Claudia Daffara[2] [1]INO-CNR, Istituto Nazionale di Ottica, Firenze, Italy; [2]Università degli Studi di Verona, Verona, Italy	**49**
15:55	coffee break	
Session chair: Haida Liang		
16:25	*Assessing the potential of OCT for the non-invasive examination of varnish layers; a survey of paintings in the National Gallery London* **Marika Spring[1]** and Haida Liang[2] [1]The National Gallery, London, UK; [2]School of Science & Technology, Nottingham Trent University, Nottingham, UK	**52**
17:10	*Tracing of past restorations of 'Madonna dei Fusi' by Leonardo da Vinci (school)* **Magdalena Iwanicka[1]**, B.J. Rouba[1], P. Targowski[2], M. Sylwestrzak[2], Ewa A. Kaszewska[2], Cecilia Frosinini[3] [1]Institute for the Study, Restoration and Conservation of Cultural Heritage, Nicolaus Copernicus University, Torun, Poland; [2]Institute of Physics, Nicolaus Copernicus University, Torun, Poland; [3]Opificio delle Pietre Dure e Laboratori di Restauro, Firenze, Italy;	**53**
17:30	*Sweep Source Optical Coherence Tomography (SS-OCT) for the examination of dry and waterlogged "heritage" wood* **Dimitris Tsipotas[1]**, Alexandros Diamantoudis[2] [1]Technological Educational Institute of Larisa, Greece; [2]University Ecclesiastical Academy of Thessaloniki, Greece	**55**
17:50	*Parallel processing of OCT data for monitoring of restoration procedures* **Marcin Sylwestrzak,** Ewa A. Kaszewska, Magdalena Iwanicka, Łukasz Ćwikliński, Piotr Targowski Institute of Physics, Nicolaus Copernicus University, Torun, Poland	**57**
18:10	END OF THE SESSION	

Friday 28 June 2013
Location: Institute of Physics, Centre for Quantum Optics, Nicolaus Copernicus University Toruń, Grudziądzka Street 5, Toruń, Poland

Session chair: Marika Spring

9:00	*Examination of structure and properties of historic glass with OCT* **Piotr Targowski[1]**, Paweł Karaszkiewicz[2], Bogumiła J. Rouba[3], Dariusz Markowski[3], Ludmiła Tymińska-Widmer[3], Magdalena Iwanicka[3], Ewa A. Kaszewska[1], Marcin Sylwestrzak[1] [1]Institute of Physics, Nicolaus Copernicus University, Toruń, Poland; [2]Academy of Fine Arts, Kraków, Poland; [3]Institute for the Study, Restoration and Conservation of Cultural Heritage, Nicolaus Copernicus University, Toruń, Poland	**59**
9:20	*Examination of reverse painting on glass (Hinterglasmalerei) with OCT* **Magdalena Iwanicka[1],** Ludmiła Tymińska-Widmer[1], Bogumiła J. Rouba[1], Ewa A. Kaszewska[2], Marcin Sylwestrzak[2], and Piotr Targowski[2] [1]Institute for the Study, Restoration and Conservation of Cultural Heritage, Nicolaus Copernicus University, Toruń, Poland; [2]Institute of Physics, Nicolaus Copernicus University, Toruń, Poland	**60**
9:40	*Introduction to NCU OCT instruments* Tomasz Bajraszewski, Łukasz Ćwikliński, Iwona Gorczyńska, Michalina Góra, Ewa A. Kaszewska, Marcin Sylwestrzak, Maciej Szkulmowski, Anna Szkulmowska, **Piotr Targowski** Institute of Physics, Nicolaus Copernicus University, Toruń, Poland	**62**
10:00	*Introduction to Thorlabs OCT instruments* **Martin Krah** Thorlabs, Germany	**64**
10:20	coffee break	
10:50	hands-on training	
13:00	lunch (provided on-site)	
14:30	hands-on training	
16:00	coffee break	
16:30	hands-on training	
18:00	Final remarks	
18:10	END OF THE SESSION	

New techniques for the non-invasive investigation of the surface and subsurface structure of heritage objects

ABSTRACTS OF INVITED TALKS

A systematic non-invasive optical investigation of wall paintings at a UNESCO world heritage site

Haida Liang[1], Andrei Lucian[1], Chi Shing Cheung[1], Bo Min Su[2]

[1]School of Science & Technology, Nottingham Trent University, Nottingham NG11 8BS, UK
[2]Dunhuang Academy, Gansu Province, China

The Mogao caves near Dunhuang at the edge of the Gobi desert is a Buddhist temple site with a history that extends over 1000 years from the 4th C to the 15th C. There are 735 caves (492 with wall paintings) and 45,000 square metres of wall paintings at the site, which is an immense resource for the study of the history of art and architecture, religion, science and technology, politics and cultural exchange along the Silk Road. The wall paintings are vulnerable and therefore any examinations conducted for art conservation or historical and archaeological studies should preferably be non-invasive and non-contact.

In this paper, we show an example of a systematic in situ study of the wall paintings using a range of non-invasive optical imaging and spectroscopic instruments. PRISMS, the remote spectral imaging system developed in our group, has the capability of high resolution remote multispectral/hyperspectral imaging at distances of tens of metres making it convenient to examine ceiling paintings at a height of 11–12 m. Since these paintings have been in caves with very low natural lighting over the centuries, it is important to ascertain the stability of the paint to light before using strong illumination. While imaging is generally considered non-invasive, all imaging techniques need some sort of illumination which can potentially cause photo-chemical changes in the artefacts being examined. A microfading spectrometer developed in the group, which can monitor the change in spectral reflectance of a material while subjected to accelerated light ageing using a focused beam of light of high intensity at a tiny sub-mm sized spot, was used to examine the light stability of various paints in a cave before imaging. Spectral imaging revealed faded writings, preparatory sketches and allowed pigment identification. Optical coherence tomography (OCT) equipment was brought to this remote site for the first time. It was initially thought that unlike European paintings, East Asian paintings have very thin paint layers and higher pigment to binding medium ratios and would therefore not be suitable for OCT examinations. However, our results showed that OCT was very effective in separating the layers on which the preparatory sketches and the final sketches were drawn. This paper demonstrates through examples how a combination of these non-invasive imaging and spectroscopic methods can yield a wealth of information for conservation and art history.

Thermal Quasi-Reflectography, a new imaging technique for noninvasive analysis of artworks: principles and applications

Claudia Daffara[1.3], Dario Ambrosini[2], Luca Pezzati[3], Paola I. Mariotti[4]

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[2]DIIIE, University of L'Aquila, Via G. Gronchi 18, 67100 L'Aquila (IT)
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[4]Opificio delle Pietre Dure, Florence (IT)

Infrared imaging is widely used in heritage diagnostics allowing the non-invasive analysis of extended painted surfaces. Wide-field techniques and the selective use of an appropriate infrared band enable the mapping of many features both at surface and subsurface levels, according to the specific radiation interaction properties of the artwork materials. In particular, near-infrared reflectography, by exploiting the capability of the near-infrared spectrum (0.8-2.5 μm) to penetrate the different paint layers, is able to reveal hidden features such as preparatory drawings, pentimenti of the artist, or subsequent repaintings. It is well known that for the study of canvas and panel paintings, this technique is one of the most powerful tools in the hands of the art historian and the restorer. The more recent spectral techniques have further improved near-infrared imagery.

We have recently demonstrated a novel tool for artwork infrared imaging, named Thermal Quasi-Reflectography. The underpinning idea is to extract information from the mid-infrared energy (3-5 μm) reflected by the object, which is strongly related to the surface material properties. The thermal band is conventionally being used in non-destructive testing in relation to the emissive behaviour of the target object, and widely applied to artworks for the inspection of structural defects (inner support or paint delamination). Here the concept of classic thermography, where the radiation emitted by the surface is recorded and then correlated to the temperature distribution (the thermogram) is taken on reverse. Effectively, it is Thermal Quasi-Reflectography, in which the emitted radiation is minimized in order to properly record the reflected quote. The mid-infrared spectrum carries back information related to the absorption bands of the different materials of the pictorial surface. The result is the mid-infrared reflectogram, which allows the discrimination of many features in the pictorial layers, related both to the artwork materials and technique as well as deterioration of the artwork surface.

Thermal Quasi-Reflectography is very effective on mural paintings, where traditional reflectography is less effective due to the effect of the not-reflective plaster background. Examples of the results obtained on fresco models and on notable genuine artworks are shown. The technique provides the selective mapping of painting materials, finishing touches, and a clear detection of differently aged organic painting integrations. Different execution techniques, e.g. fresco or tempera, also exhibit different behaviours.

In this lecture, we trace the key-points of this new diagnostic method: 1) introduction of the basic principle and the instrumentation to enable operative measurements; 2) presentation of the main diagnostic results and discussion of the future potentialities.

Thermal quasi-reflectography is demonstrated to have strong potential, which surely underlines the need for further developments and applications in the field. An interdisciplinary effort is needed.

BASIC REFERENCES

1. C. Daffara, L. Pezzati, D. Ambrosini, "Thermal Quasi-Reflectography: a new imaging tool in art conservation," Optics Express 20 (2012).
2. C. Daffara, L. Pezzati, D. Ambrosini, D. Paoletti, R. Di Biase, P. I. Mariotti and C. Frosinini, "Wide-band IR imaging in the NIR-MIR-FIR regions for in situ analysis of frescoes," Proc. SPIE 8084 (2011).
3. J. Baxter, "Quasi reflectography", Nature Photonics 6, 572 (2012).

Of MOUSE and Men: Single-sided NMR in Cultural Heritage

Tyler Meldrum

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Nuclear Magnetic Resonance (NMR) is an extraordinary powerful technique for gathering detailed chemical and structural information on a wide range of samples. However, its utility is limited by its tremendous cost and requisite expertise, its fixed placement in a research lab, and severe limitations on sample sizes. New NMR devices, using permanent magnets, can circumvent many of the problems associated with typical NMR experiments. In particular, these devices are single-sided sensors, meaning they can probe samples in a non-destructive, contact-free manner, and they are portable, able to be taken to excavation sites and museums for in situ measurements of cultural heritage objects.

We introduce one single-sided NMR sensor, the NMR-MOUSE (**MO**bile **U**niversal **S**urface **E**xplorer), which has been used in the measurement of many objects of cultural heritage, including paintings, parchment, paper, frescoes, and building materials. The theory and technique of single-sided NMR is presented in context of heritage objects, including measurements of signal intensity, depth profling, relaxometry for the characterization of hardness of materials, and measurements of self-diffusion. In addition, some sample measurements on the curing of paint and the evaluation of the structure of different types of frescoes are presented.

A CHARISMA round robin; comparison of non-invasive analyses and documentation methods for integration of results from multiple techniques on a single painting

Marika Spring[1], Rachel Morrison[1], Joseph Padfield[1], Magdalena Iwanicka[2], Łukasz Ćwikliński[3], Raffaella Fontana[4], Bernard Bluemich[5], Tyler Meldrum[5], Markus Kueppers[5], Wasif Zia[5], Paraskevi Pouli[6], K. Melessanaki[6], V. Tornari[6], D. Anglos [6]

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[3]Institute of Physics, Nicolaus Copernicus University, Toruń, Poland.
[4]INO-CNR, Istituto Nazionale di Ottica, Firenze, Italy,
[5]Institut für Technische und Makromolekulare Chemie, RWTH Aachen University, Germany.
[6]Institute of Electronic Structure and Lasers (IESL), Foundation for Research and Technology–Hellas (FORTH), Heraklion, Crete, Greece.

The CHARISMA project (2009-2013), funded by the EU under the FP7 programme, is a consortium of 21 European institutions offering transnational access to various facilities, and including research and networking activities. Within one of the research work packages a number of instruments for the non-invasive analysis of the materials of cultural heritage objects are being developed, and the work is now in the phase of exploring and testing applications. Taking advantage of the fact that this work is taking place within one project, a 'round robin' exercise was planned, where a test painting was examined by some of these techniques in turn, as well as with more conventional methods.

The test painting was first documented and examined at the National Gallery. High resolution images in visible and ultraviolet light were made, and X-radiography and digital infrared reflectography were carried out. Some paint samples were taken and mounted as cross-sections to examine the layer structure. The pigments in the cross-sections were analysed by scanning electron microscopy with energy dispersive X-ray analysis, as well as attenuated total reflectance-Fourier transform infrared microspectroscopic imaging. These results served to give background information that would help to interpret the observations with the non-invasive techniques.

The painting has so far been examined using optical coherence tomography(OCT) (at Nicolaus Copernicus University, Torun, Poland), single-sided Nuclear Magnetic Resonance (NMR) (at RWTH Aachen University, Germany), confocal laser scanning microscopy(CLSM) (at INO, Florence, Italy) and laser induced breakdown spectroscopy (LIBS) as well as Digital Holographic Speckle Pattern Interferometry (DHSPI) (at FORTH, Heraklion, Greece). The aim was not for this exercise to be a rigorous scientific comparison, but instead to act as a case study for demonstrating the specifications of each instrument and to allow the exchange of knowledge between the partners in the project on suitable applications. This talk will discuss the preliminary results of the exercise.

These examinations produced many different images, as well as data in various forms, including not only spectra of specific points, but various technical images of the whole painting, images of the real paint samples, and a large number of 'virtual' cross-section images from OCT and CLSM. The subject of digital technical documentation systems that integrate the results from many types of analysis or imaging is a focus of one of the networking tasks in the CHARISMA project, and will be discussed in the second part of this talk. This networking task in CHARISMA is surveying the methods currently used by the partners, as well as bringing together knowledge of new initiatives on this subject that might be useful to this research community. The results from the round robin provided an ideal case study for testing ways of sharing and documenting the data, to act as a springboard for discussion of these issues.

Laser tools in Cultural Heritage Science and Conservation; non-invasive analysis and management of cleaning interventions

Paraskevi Pouli, Kristalia Melessanaki, Vivi Tornari, Demetrios Anglos

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Within the last two decades laser technology has been progressively established in cultural heritage study and conservation as it offers highly effective methodologies and versatile tools for material characterisation, structural assessment and cleaning. Non-invasive laser-based techniques are in this respect of high priority as they are able to illuminate complex diagnostic and analytical challenges, as well as to evaluate and monitor in-situ and in real-time the preservation condition of cultural heritage objects and monuments.

Specifically, laser spectroscopic techniques, such as Laser Induced Fluorescence (LIF), micro-Raman Laser Induced Breakdown Spectroscopy (LIBS), and Terahertz (THz) spectroscopy are employed to determine the chemical composition of materials in works of art and archaeological findings. Extensive research worldwide aims at the development of laser analytical methodologies and compact, portable and user-friendly instrumentation that will enable archaeologists, art historians and conservators to obtain information about cultural heritage objects, through chemical analysis of materials.

In parallel, laser interferometric techniques, such as holographic interferometry and speckle pattern interferometry, are increasingly being applied as non-destructive and non-invasive monitoring tools. Their ability to take full-field measurements remotely, fast and repeatedly, in combination with their high resolution (their detection limit is in the range of half of the operative laser wavelength i.e. 266 nm) have established laser interferometric techniques as structural diagnostic tools in preventive and active conservation of cultural heritage.

In this communication the portability and versatility of non-invasive laser based analytical and diagnostic techniques, together with their ability to operate synergistically with interventive actions (i.e. laser cleaning) in order to monitor and control their progress, will be presented and discussed.

Mid-infrared hyperspectral imaging of painting materials

Costanza Miliani[1,2], Francesca Rosi[1,2], Roland Harig[3], René Braun[3], Diego Sali[4], Alessia Daveri[5], Brunetto G. Brunetti[1,2], Antonio Sgamellotti[1,2]

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A novel hyperspectral imaging system (HI90, Bruker Optics), working in the mid-infrared range (1300–900 cm^{-1}) and recently developed for the remote identification and mapping of hazardous compounds, has been here applied for investigating painting surfaces. A painting by Alberto Burri, namely Sestante 10 (1982), has been investigated through the HI90 system, imaging the distribution of inorganic materials and binding media constituting the artworks. In order to validate the results obtainable by the imaging system previous tests on laboratory models were performed. Yellow, white and blue pigments painted with different binders (namely, egg, alkyd, acrylic and vinyl) were investigated by the HI90 highlighting the strengths of the device. Afterwards, the polychrome painting Sestante 10 was investigated in situ revealing the distribution of different extenders (kaolin, $BaSO_4$, $CaSO_4$) mixed with the various silica-based pigments and two different binders (acrylic and vinyl). The brightness temperature spectra collected by the HI90 system have been also compared with reflection point infrared spectra acquired by the conventional portable FTIR spectrophotometer R-Alpha (Bruker Optics) highlighting the good spectral quality of hypercube data produced by the new imaging system. This comparison also allowed evaluation of the spectral response and assignment from the reduced spectral range available by the HI90 imaging (1300–900 cm^{-1}), validating the reliability of the obtained chemical images. This study clearly highlights the high potential of the new hyperspectral imaging system and opens up new perspectives in the current scientific interest devoted to the application of mapping and imaging methods for the study of painting surfaces.

On site research on 'The Beanery' by Edward Kienholz with portable Fibre Optics Raman spectroscopy

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Edward Kienholz (1927–1994) made 'The Beanery' in 1965, basing it on his local bar, The Original Beanery on Santa Monica Boulevard in Los Angeles. It took Kienholz six months to consolidate and replicate the bar's content in an artwork. Everything in the installation is life size: from the figures (inspired by Kienholz's friends and acquaintances) to the bar, bottles of beer and spirits, ash trays, cash register, telephone book, and jukebox. Even the photos on the wall duplicate those of The Original Beanery. Remarkably, Kienholz gave each person in his bar a clock for a face, a reference to his fascination with time. The hands of the clock (the eyebrows) almost all remain at ten past ten – evidently, time has come to a standstill. Only the barman, modeled after Barney, the bar-owner at that time, has a face. Smelling and sounding like an actual bar, the installation is an evocative sensory experience that visitors are allowed to enter. 'The Beanery' is also something of a time capsule, the headlines of the 1964 newspaper in a newspaper dispenser at the door indicate that the United States is on the brink of war with Vietnam.

Acquired in 1970 by the Stedelijk Museum Amsterdam, The Beanery instantly became one of the collection's most popular artworks and was, in principle, to be permanently on display at the Stedelijk Museum or on loan to another museum. Smaller composite parts of the installation have been restored over the years, but comprehensive research into materials and techniques had not been conducted until now. A systematic analysis of the condition of the work was carried out by the Stedelijk Museum.

The biggest challenge to restoring 'The Beanery' is the layer of synthetic resin that Kienholz applied to the work, which he used to visually unify all the separate components. As time passed, the resin layer has strongly yellowed and is still sticky in places, attracting considerable amounts of dust and dirt. Because of the resin and the natural aging processes of the materials, the objects in 'The Beanery' are extremely vulnerable, the work has suffered mechanical damage caused by the members of the public walking through the installation.[1]

Besides questions about the composition and the condition of the synthetic resin there were questions about the composition of the adhesives used by Kienholz and about the composition of the many (sometimes vulnerable) objects present in 'The Beanery'.

Using a portable Raman system equipped with a Fibre Optic Probe many of the plastics in 'The Beanery' could be identified non-invasively. In case of the synthetic resin and the adhesives FTIR analyses using portable FTIR equipment provided complementary information.

After extended research into the materials and techniques, a condition report of the artwork, a review of the artist's intentions, and the identification of appropriate conservation materials and methods, 'The Beanery' could be restored, and has now taken its place among the artworks on permanent display in the historic building of the Stedelijk Museum Amsterdam.

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Applications of Terahertz Imaging and Spectroscopy in Cultural Heritage

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Terahertz (THz) radiation has been used for the analysis of cultural heritage since 2008 and has unique potential as it can penetrate up to one centimetre of opaque materials including plaster, wood and clay. The technique is non-contact, non-invasive and perfectly safe for the user and is now available portably and is capable of operating in diverse environments. Wall paintings can be analysed stratigraphically to determine the composition of layers of wall plaster, and in certain circumstances images of obscured sub-surface paintings recreated. Demonstrations will be provided from Churches and Cathedrals across Europe and an archaeological site in Turkey.

As THz imaging for cultural heritage is in its infancy, each new experimental mission provides its own challenges regarding the best way to process the data to achieve numerically reliable and easily interpretable results for the user. These include a new deconvolution technique that increases traditional limits of depth resolution and the facility to correct for uneven covering surfaces to interpret and recreate an image of the obscured painting beneath.

In addition the internal structure of other opaque artefacts can be used to determine the life history of the object.

Multiphoton microscopy: an efficient and promising tool for *in situ* study of historical artifacts

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Characterization of coatings (stratigraphy, composition) is of the utmost importance for the understanding and conservation of historical artifacts. Optical Coherence Tomography (OCT) has been for a few years a well-established as an *in situ* three-dimensional (3D) imaging tool.[1] In particular, full-field OCT allows 3D imaging with a micrometer scale resolution, necessary for the characterization of wood structure, the fine determination of the stratigraphy of thin layers and the imaging of scattering particles such as fillers or pigments.[2] Nevertheless, the discrimination of the various components is strongly limited with OCT despite some attempts in spectral selectivity[3] and spectros.[4]

Multiphoton microscopy (MPM), also called non-linear optical microscopy, appears to be a promising alternative imaging technique for investigating cultural heritage artifacts. This technique performs 3D imaging with micrometer-scale resolution based on an intrinsic optical sectioning. A key advantage of MPM is its multimodal capability with different modes of contrasts that are directly linked to the chemical nature of the materials. Two-Photon Excited Fluorescence (2PEF) is emitted by a wide range of materials in historical artifacts and spectral discrimination of different fluorophores is possible. Second Harmonic Generation (SHG) signals are emitted by non-centrosymmetric structures. We showed that plaster particles exhibit strong SHG signals when they are composed of bassanite crystals. SHG signal was also detected from crystalline cellulose within the wood cell walls.

Stratified layers composed of compounds widely used as artists' materials were studied by MPM and the different components were specifically detected and located within the stratigraphy. We were able to discriminate gelatin-based films from sandarac films and to perform 3D imaging of cochineal lake pigments. In the case of two stratified layers composed of cochineal lake pigments and plaster, the different fillers were clearly distinguished (2PEF versus SHG). This technique also allowed precise measurement of the thickness of each layer. Finally, we demonstrated that MPM can be used for *in situ* investigation of a historical violin. To conclude, this study demonstrates that multimodal MPM is an efficient and promising technique for 3D *in situ* investigation of historical artifacts and woods.

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Fusion of tomographic documentation of art-objects based on electromagnetic radiation in the near and mid infrared area of the spectrum and ultrasonic microscopy. Application to Byzantine icons from Cyprus

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Conservation science, after many years of research experience, provides us with significant tools in order to 'identify' art object bottom-up with high fidelity information. In particular, the internal structure – the stratigraphy – can be revealed, which provides important information related to the materials and the technique used for the creation of the object.

The materials and the technique are the components of the creation phase of the object but may have altered due to the time that has passed as well as due to restoration. Together these have influenced the object's appearance. The identification of all this knowledge related to the materials and their alterations caused by environmental conditions and light, their distribution on the surface and below, the techniques that have been used, as well as later significant interventions to the objects helps to understand the current state of preservation.

This information has been up to now been mainly acquired through analytical spectroscopic methods, which require a micro-sampling operation and time consuming work in the laboratory. Moreover, most of the time, the objects under study are highly valuable and therefore must not be subjected to any intervention. Consequently, non-destructive testing (NDT) tomographic techniques are valuable for revealing information about from the art object's paint layer structure (stratigraphy), beneath as well as on the surface, and can inform decisions about how to store and handle it.

The fidelity and the resolution of the information is an issue which relates to the potential for its exploitation. Do we need high resolution and high fidelity information which eventually cannot be traced in future measurements or do we need "lower" resolution or fidelity that still produces reliable information but will always be traceable?

Acquisition methods and case study on cultural Heritage

Remote sensing spectroscopic techniques, which reveal the interaction of the materials with external conditions and electromagnetic radiation in several wavelength bands, when used in a tomographic way can be targeted towards revealing subsurface information.

Many potentialities exist. One novel one is the use of tomographic techniques that can reveal bulk information combined with spectroscopic imaging techniques, providing the distribution of the materials within this bulk. Various kinds of waves can be used for this application, based on the latest technological means that are available, which are very well defined and interconnected as far as integration of their information is concerned. In the current case, we are presenting techniques based on both electromagnetic and mechanical waves, revealing information from the subsurface at a micrometer level. Novel applications on painted art objects will also be involved in this analysis, based on thermal emission and reflection phenomena. The resolution of the information can vary from macro (metres or centimetres scale) to micro (micrometers to nanometers) scale. At this point we reach the technological and practical frontiers where a thorough discussion is necessary to find a compromise between fidelity, reproducibility of measurements, portability of the infrastructure and non destructiveness.

Accelerators and X-rays in cultural heritage studies

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A review will be given on the use of accelerators in non-destructive or minimally invasive studies connected to our cultural heritage. It focuses on making use of the production and detection of X-rays as a general tool. At "small accelerators", the proton induced X-ray emission (PIXE), especially when combined with Rutherford backscattering spectroscopy (RBS), has been developed to a very versatile and powerful technique for near-surface investigations with μm resolution. It is well complemented by larger facilities, synchrotron radiation sources as well as medium energy ion accelerators for high energy PIXE. When high energy protons are used as inducing particles (with energies between about 20 and 100 MeV), elements deeply buried under several hundreds of micrometers of corrosion layers, can be identified, too. These techniques are complemented by X-ray fluorescence, which has recently been developed into a 3-dimensional micro analytical technique with a resolution of around 30 micrometers by employing multi capillary X-ray guiding lenses. The state-of-the-art methodology will be illustrated on examples from painted glass windows and luster ceramics closely related to basic research on nanometer sized metallic inclusions in glasses. Such metallic nanoclusters used for centuries in post Roman European culture are presently under intense research for photonic applications. Finally, the outlook will be given for a new generation under way of mono-energetic high-energy high-intensity X-ray sources being developed as "table-top" instrumentation with MeV-electron LINACS for complementary use of synchrotron radiation at GeV-electron or positron-storage rings in cultural heritage studies.

Optical Coherence Tomography for vulnerability assessment of sandstone in-situ

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Sandstone is an important cultural heritage material, in both architectural and natural settings, such as neolithic rock art panels. The majority of deterioration effects in porous materials such as sandstone are influenced by the presence and movement of water through the material. The presence of water within the porous network of a material results in changes in the optical coherence tomography signal intensity that can be used to monitor the wetting front of water penetration of dry porous materials at various depths. The technique is able to detect wetting front velocities from 1 cm s^{-1} to 10^{-6} cm s^{-1}, covering the full range of hydraulic conductivities likely to occur in natural sandstones from pervious to impervious. The OCT has recently been taken to the field to measure the hydraulic conductivity of historic gravestones in various states of weathering, demonstrating the ease at which the technique can be used for in situ measurements. The technique has the potential to monitor changes due to weathering over time and to determine depth penetration of conservation treatments and the effect of water proofing treatments on building and cultural heritage materials in situ.

Macroscopic X-ray fluorescence analysis, a method for non-invasive imaging of painted works of art. Comparison with other methods and some case studies

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Paintings from different historic periods (from Antiquity up to the time when photography was introduced) are considered to be valuable windows on the past. Via Pompeian frescoes, for example, we have a (partial) view on how Roman civil society functioned. The paintings of Brueghel show the life of ordinary citizens in the Low Countries of the 16th century, while those by Rubens and Rembrandt depict many aspects of society in the Golden age.

Hidden below the surface of many works of art, overpainted representations are present that provide additional information on the painter, the painting or its (preservation) history. Traditionally, a combination of X-ray radiography (XRR) and infrared reflectography (IRR) are used to examine the interior parts of paintings. We have recently developed a more powerful analytical method to visualize these hidden layers that is based on X-ray fluorescence (XRF) analysis, called macroscopic XRF (MA-XRF).

While initially, activities were conducted at synchrotron facilities by employing high energy, monochromatic primary beams of X-rays, more recently, several mobile MA-XRF scanners were constructed that made it possible to perform imaging measurements *in situ*. In this presentation, recent MA-XRF results obtained from paintings by Memling, Rembrandt, Flinck and Rubens will be discussed and some of these will be compared to (element specific) images obtained by other methods such as XRR and NAAR (Neutron Radiation Autoradiography). This will highlight a number of the advantages and limitations of this new imaging method

New techniques for the non-invasive investigation of the surface and subsurface structure of heritage objects

ABSTRACTS
OF POSTER PRESENTATIONS

Time-averaged digital speckle pattern interferometry for investigation of art objects surfaces

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The development and practical evaluation of a laboratory built, out-of-plane digital speckle pattern interferometer (DSPI) are reported. The instrument was used for non-invasive, non-contact detection and characterization of early-stage damage, like fracturing and layer separation, of painted objects of art. A fully automated algorithm was developed for recording and analysis of vibrating objects utilizing continuous-wave laser light. The algorithm uses direct, numerical fitting or Hilbert transformation for an independent, quantitative evaluation of the Bessel function at every point of the investigated surface. The procedure does not require phase modulation and thus can be implemented within any, even the simplest, DSPI apparatus. The proposed deformation analysis is fast and computationally inexpensive. Diagnosis of physical state of the surface of a panel painting attributed to *Nicolaus Haberschrack* (a late-mediaeval painter active in Krakow) from the collection of the National Museum in Krakow is presented as an example of an in situ application of the developed methodology. The test performed in the conservation studio showed that noisy environment, although affected the quality of the results increasing uncertainty of the reconstructed maps of surface vibrations, was not an obstacle to detect and characterize damage areas on a real work of art with sub-micrometer accuracy. It has been shown that the methodology, which offers automatic analysis of the interferometric fringe patterns, has a considerable potential to facilitate and render more precise the condition surveys of works of art.

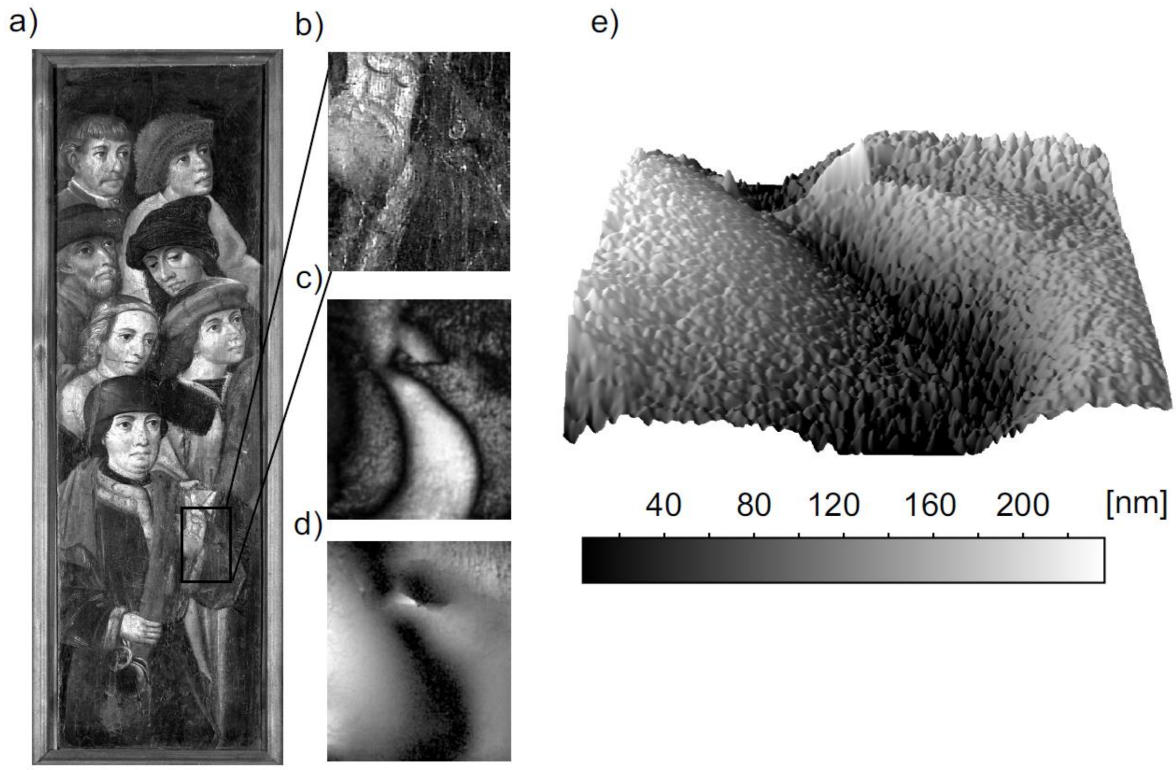

Figure 1. Analysis of the sound-induced (7.6 kHz) vibration of a decorative layer delaminated from a wooden support in central part of the investigated painting, (a) photograph of the painting; (b) magnification of the analysed area (c) raw interferogram; (d) two-dimensional map of vibration amplitude (e) enlarged and presented in 3D.

Analysis of Ancient Paper Structure in Transmitted Light by Application of Different Microscopic Techniques. Examples From Collection of The Kórnik Library of the Polish Academy of Science

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In general hand made or machine made paper is a product which shows a certain transparency. However, some kinds of paper found in museum, library and archive collections may reveal a more noticeable transparency (tracing papers, waxed paper negatives etc.). The degree of transparency of paper products depends on their thickness, technology production, pulp composition, additional substances applied and other agents. In this field stereoscopic microscopes with additional equipment offer many possibilities in non-invasive investigations of paper surface structure, as well as its look-through by scientists and conservators. Additional helpful tools are equipment for polarization (polarizer, analyzer) and the dark field condenser easily mounted in stereoscopic microscopes. They are very useful tools for obtaining much more information on antique paper structure without sampling in comparision with the results obtained by normal light applications. Beside fibers it is possible to determine the presence of additional inorganic and organic matters in paper structure.

In polarized light the presence of fillers can be detected and it is also possible to analyze their distribution within the paper, crack lines of overlayers, writing or painting inks distribution (or other media) on paper surfaces, as well as distribution of substances applied by conservators (cellulose derivatives, powdered erasers used for cleaning etc.). Moreover, in some cases it is possible to identify the types of fiber by analysing their morphological features and colours appearing during polarization. Application of polarized transmitted light allows the study of many paper features or degradation changes which can be emphasized much more in this configuration of lighting. Additionally, pictures of better quality can also be taken by applying another technique, reflected polarized light, during investigation of paper surfaces.

By using the dark field condenser it is possible to observe light paper structure (from white to greys) on a dark background. The image is reversed (like a negative) in comparison with an image obtained in normal transmitted light, where the dark outlines of fibers are visible in light field. The stronger contrast is also characteristic for the dark field technique.

An elaborated technique of simultaneous use of the black field technique and reflected light (low angle of reflection: ca. 10-20^{o}) serves to provide an additional interesting effect of a mixed image where the paper is observed in dark field but at the same time the structure of the surface is also visible.

Possibilities for analysing tracing papers, foxing stains, albumen, gelatin and salt paper prints are presented in the poster. The examples present mainly come from the photographic collection of The Kórnik Library of the Polish Academy of Science.

The research results are a part of the project "Identification of techniques, evaluation of the state of preservation, application of digital techniques of reconstruction and making of copies of valuable photographs from the collection of the Kórnik Library of the Polish Academy of Sciences". The project is realized under the programme "Exterius" financed by the Foundation for Polish Science".

Preliminary physicochemical studies in a shield handle originating from the Przeworsk culture cemetery located in Czersk

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The motivation for the analysis of the shield handle from the Przeworsk culture cemetery located in Czersk, a unique ancient metal object, was the possibility of gathering information which enabled understanding of ancient metallurgy processes. Elemental composition and structural variations that were evident visually in the shield handle were studied. The results were compared with tests carried out for the two fibulas on the areas that visually appeared silvered (in the bow). The following analysis is only the preliminary phase of the study. Because of the unique character of the object physico-chemical analyzes are planned and comparison with experimental smelting including chemical vapor deposition of specific bronze and silver corrosion layers will be performed. The analysis was carried using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) and neutron imaging (NI) techniques with preliminary imaging with scanning electron microscopy coupled to energy-dispersive X-ray analysis (SEM/EDS).

LA-ICP-MS provided information about the elemental composition of the alloy (Figures 1 and 2).

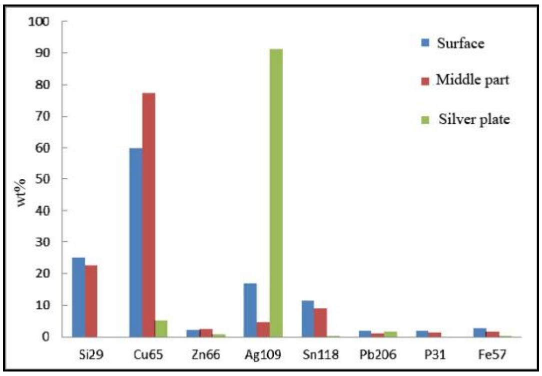

Figure 1. Results of the quantative polled analysis of the elemental composition of the main isotopes comprising three representative sampling points.

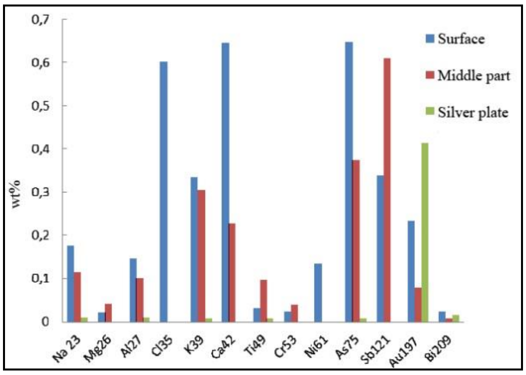

Figure 2. Results of the quantative polled analysis of the elemental composition of trace isotopes comprising three representative sampling points.

The base metal alloy of the object, onto which the silvered surface was applied, was interpreted as a bronze.

Elements responsible for the corrosion processes were detected, such as Cl and S (chloride corrosion and sulfide corrosion) and this fact can influence the shape of the surface silver ornamentation today, assuming the ancient preparation technique called fire silvering has been used.

In order to interpret the material layers the neutron imaging technique was used. Neutronography photos are shown in Figure 3 and 4.

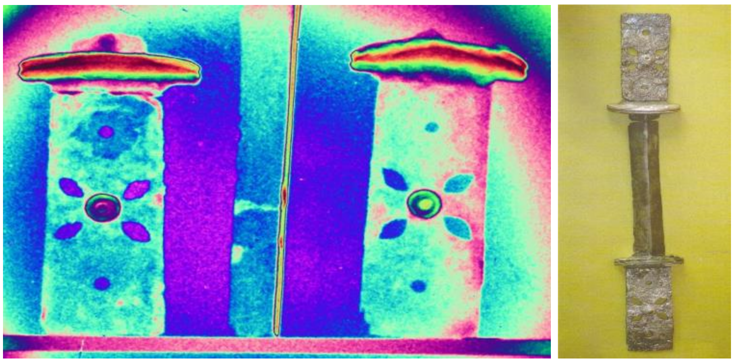

Figure 3. NI photos of silver pieces of the handle (right and left side of photo) and for the central component, front view. On the right is a normal photograph of the object

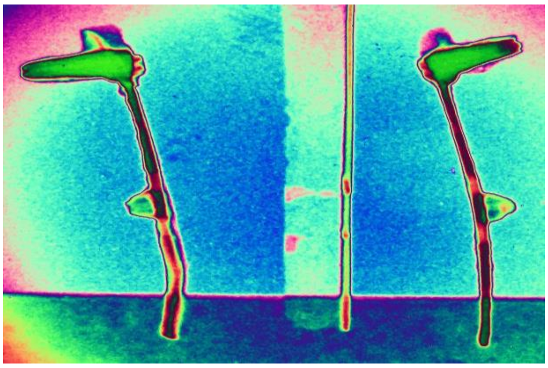

Figure 4. NI photos of silver pieces of the handle, side view.

Darkening of the image in this case is mainly due to the thickness of the irradiated layer. Inhomogeneities are visible within the silver plated areas, possibly associated with the degree of corrosion and heterogeneous object texture and with the thickness of the silver layer.

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The technology of red lake pigments and technique of application in Anton Möller's and Hermann Han's paintings - non-invasive optical microscopy, SEM-EDX and μ-XRD analysis on samples

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This poster discusses the painting technologies pertaining to red lake pigments and techniques of their application used in the Polish School of Painting, adding to what is already known from published analyses elsewhere, outside Poland. Complementary data on the Polish school enables the expansion of the data on the history of red organic dye production and on the paintings.

The analysis of the substrates in red lake pigments from 17th century Gdańsk paintings is presented in this paper. Three world famous panel paintings, two by Anton Möller and one by Hermann Han, were investigated. Different non-invasive analysis methods on one sample from each painting, such as optical microscopy (OM) under visible and ultraviolet light, energy dispersive X-ray microanalysis in a scanning electron microscope (SEM-EDX) and X-ray microdiffraction analysis (μ-XRD), enabled the determination of the substrate. The main goal of this study was to determine if μ-XRD can characterize the inorganic substrate in red lake layer cross-sections.

Keywords: Preparation of lake pigment dyestuffs; Substrates; X-ray microdiffraction analysis μ-XRD of cross-sections; Energy dispersive X-ray microanalysis in the scanning electron microscope SEM-EDX

Training on application of Optical Coherence Tomography (OCT) to structural analysis

ABSTRACTS

Introduction to the OCT technique

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In this contribution the Optical Coherence Tomography (OCT) technique will be presented. Firstly, for audience not familiar with this analytical method, a brief introduction will be given and the physical background will be explained at non-specialist level.

Specifically, two essential configuration of OCT systems:

- Time domain OCT
- Fourier domain OCT (further specified as Spectral domain OCT or Swept Source OCT)

will be described with the emphasis on advantages and disadvantages of these configurations for specific tasks within examination of cultural heritage object.

Then the major parameters of the OCT instruments will be defined:

- axial resolution,
- lateral (in-plane) resolution,
- spectral properties of the probing light (central wavelength and bandwidth),
- power of light at object,
- imaging range,
- sensitivity,
- time of examination.

and discussed with emphasis on their importance for applications in art conservation/restoration practice.

Then the data acquisition protocols and modes of presentation will be discussed.

Using examples from model as well as real objects a key for interpretation of OCT tomograms will be given and exemplary tomograms will be discussed including common distortions and other artifacts of OCT imaging. Among others it will be shown how to distinguish scattering and absorbing layers, find a metal foil layer in the structure, and differenciate a distortion of layer structure caused by light refraction from a real one.

Finally, an overview of applications to be presented in further lectures will be given.

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Ultra-high resolution Fourier domain optical coherence tomography for resolving thin layers in painted works of art

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Optical Coherence Tomography (OCT) is an imaging technique based on the Michelson interferometer. The sample is illuminated by a source of focused light and the scattered light is collected, processed and an image is displayed. The technique is non-invasive, non-contact and capable of imaging subsurface structures in 3D, making the technique a very useful diagnostic tool for visualization of internal microstructure. Improvement in OCT resolution can significantly increase our knowledge about the structure and composition of the material.

Scientific examination of works of art is essential for conservation, preservation and understanding of material change. In heritage and conservation, OCT technique has found applications in the examination of paintings, jade, ceramics, ancient glass, enamel, parchment, faience and other historical objects.[1,2] It has also been used for dynamic monitoring of the wetting and drying of different varnishes, real time monitoring of varnish removal using solvents and laser ablation of varnish layers as well as tracking of canvas deformation due to environmental changes.[3] Besides the visualization of the stratigraphy of paint and varnish layers, application of OCT to paintings has shown to be the most sensitive technique for revealing preparatory drawings beneath paint layers owing to its high dynamic range and depth selection capabilities.

While current OCTs have shown potential in this field, the best resolution commercial OCT at any wavelength is rarely better than 5µm in air. Currently depth resolution of OCTs used in these applications cannot compete with microscopic examination of sampled paint cross-sections. Conventional microscopic examination of paint cross-sections has resolution approaching 1µm. Since the depth resolution of OCT is proportional to the source bandwidth, ultra wide bandwidth light sources allow greater depth resolution to be achieved. It is known that some varnish and paint layers can be as thin as a few microns. By using a supercontinuum source (NKT SuperK Versa), we have developed a spectral domain OCT at 815nm for high depth resolution imaging of varnish and paint layers. The theoretical depth resolution of 2.2µm in air (or ~1.5µm in varnish) is achieved and it is shown to be able to resolve thin varnish layers.

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Application of Optical Coherence Tomography to the examination of varnish layers on the *Ghent altarpiece*

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The *Altarpiece of the Adoration of the Lamb (*The *Ghent Altarpiece*) painted by the Van Eyck brothers and finished in 1432 for Joos Vijdt is thought to be one of the most influential old master paintings in Europe. The quality of the execution, the exceptional rendition of light, space and materials and the monumentality of the altarpiece are exceptional. It is conserved in the Saint Bavo Cathedral in Ghent, the church housing the chapel funded by the donor.

The altarpiece is undergoing an extensive conservation-restoration treatment from 2012 to 2017, following the conclusions of the urgent conservation treatment and diagnostic study from 2010. The work is carried out by the Royal Institute for Cultural Heritage (KIK-IRPA, Brussels) in one of the exhibition halls at the Ghent Museum of Fine Arts. Only a third of the panels is removed for treatment at any one time, the rest of the polyptych remaining on view in Ghent's Saint Bavo Cathedral. The public can follow the progress of the restoration at the museum through a large, transparent window.

The altarpiece has undergone many restorations throughout its eventful history, marked by civil unrest, wars and thefts. Little is known about the nature of the early restorations that are mentioned in historical literature and in archives. A cleaning intervention carried out before 1550 is said to have caused damage to the paintings, and several other treatments are known to have taken place since the sixteenth century. The altarpiece was dispersed at the end of the eighteenth century and the different parts underwent diverse alterations and restoration campaigns.

In 1951, the last complete treatment of the paintings since their reunification in 1923 comprised the structural stabilization of the wooden supports, consolidation of the paint layers and selective cleaning of the paintings.

Since 1951, the paintings have been revarnished at least four times. The numerous layers of varnish, retouching and overpaint have severely degraded over time and distort the perception of the paintings. Varnish removal is necessary to remedy this problem and to allow for the consolidation of the fragile paint layers.

The first phase of the conservation campaign that started last year involves varnish removal. The complexity of the material history of the paintings implies that both their condition and varnishes differ considerably. The number of varnish layers, their relative thickness, colour and evenness vary.

Optical Coherence Tomography was applied early 2013 to support the characterization of the varnish layers to guide the cleaning. The portable system used for this study was built especially for the examination of cultural heritage objects under 7FP *Charisma* project at N. Copernicus University in Torun, Poland. It is high resolution custom designed Fourier domain OCT instrument with the spectrograph used as a detector. The axial (in-depth) resolution is 3 µm in air (2.2 µm in varnish). The instrument utilizes the superluminescent multi-diode light source emitting in band 770 nm–970 nm with the intensity at object less than 800 µW. The axial imaging range is 1.4 mm and sensitivity 98 dB. Volume data acquisition with protocol used in this case (100 B-scans comprising 3000 A-scans each) takes 12 s. The system is equipped with two standard video cameras for the precise documentation of the position of examined area at the object.

In connection with other examination techniques, it contributed to the understanding of the complex cleaning issues. This paper will describe the circumstances of the examination and discuss the contribution of OCT to the project.

Next Generation Optical Coherence Tomography for Art

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In the last 10 years, Optical Coherence Tomography has been successfully applied to art conservation, art history and archaeology.[1] OCT has the potential to become a routine non-invasive tool in museums allowing cross-section imaging anywhere on an intact object where there are no other methods of obtaining subsurface information. While current OCTs have shown potential in this field, they are optimised for biomedical applications. Some major limitations are: (i) lower depth resolution compared to conventional microscopic examination of paint cross-sections; (ii) limited probing depth through highly scattering paint.

Increasing the depth resolution involves broad band sources and increasing the probing depth needs sources at longer wavelength than conventionally used in biomedical imaging. To achieve this, two new OCT systems have been built in our current project so that when used in conjunction, they would aim to match the information from conventional invasive microscopic examination of sample cross-sections (tiny samples removed from objects):

1. A 2000nm OCT optimised for deeper penetration suitable for imaging cultural heritage objects consisting of highly scattering materials. This would allow improved imaging of highly scattering or absorbing paint layers and underdrawings beneath them (at higher transverse resolution than conventional infrared imaging), as well as pigmented objects such as coloured enamels and glass with opacifiers. A recent survey of the transparency of historical artists' pigments over the spectral range of 400nm – 2400nm has shown that the optimum spectral window for OCT imaging of paint layers is around 2200nm.[2] Excluding the lake pigments (which are all highly transparent at wavelength >600nm) in the sample of 45 historic artists’ pigments studied, over 30% of the paint samples are >5 times more transparent at 2200nm than at 800nm, and ~25% of the paint samples are >2 times more transparent at 2200nm than at 1500nm. Off-the-shelf OCT sources are commonly found around 800nm, 1000nm, 1300nm and 1500nm and few OCT systems have been built beyond 1300nm. The development of long wavelength OCT requires the development of novel broadband sources at such wavelength. Two types of novel sources, a superfluorescent fibre source[3] and a swept (tuneable) laser source were developed.[4] An OCT at 1950nm has been developed and shown to reveal layer structures of both highly scattering paint such as Titanium white and highly absorbing paint such as Prussian blue.[5] These were not possible with shorter wavelength OCTs.

2. An 800nm OCT optimised for imaging at high depth resolution: targeted towards applications where the highest resolution is required but the material is relatively transparent, such as imaging of multiple thin varnish layers on painting surfaces, gel layers on degraded glass or glazes on the surface of ceramics and enamels. Since OCT depth resolution is determined by the source spectrum (specifically it is proportional to wavelength squared and inversely proportional to the bandwidth), to achieve the same depth resolution a source at 2000nm would need to have a bandwidth ~6 times broader than the one at 800nm which is technically very challenging. The opposing demands of resolution and penetration mean that we need to build two OCTs to cover

the different requirements of the various questions being investigated when imaging cultural heritage objects. An ultra-high resolution OCT at 810nm with depth resolution of 1.2 micron in varnish or glass has been developed and shown to be able to resolve thin varnish layers at similar resolution to invasive microscopic examinations currently employed in museums.[6]

A number of examples of OCT imaging of different materials using the two new OCTs will be shown to illustrate the new approach.

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Laser ablation monitoring with OCT

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Cleaning interventions are irreversible and thus call for exceptional attention as regards their monitoring and control. This gets particular important for laser assisted removal of overlayers from paintings[1,2] given the sensitivity of pigments and paint materials to laser radiation.[3,4] In this respect the development and adjustment of analytical and diagnostic techniques that will reliably monitor and control the laser cleaning process is crucial.[5,6]

Towards this aim the role of OCT as a monitoring and diagnostic tool was investigated and will be herein presented. OCT, allowing sub-surface imaging of translucent or opaque materials, offers important advantages given its sub- micrometer resolution and the ability to obtain 3D information of the surfaces under investigation.[7-9] The synergistic action of OCT and laser ablation were studied on a painted test panel supplied by the National Gallery in London in the framework of the CHARISMA project. The painting surface was investigated with OCT prior its laser ablation treatment and reference data of different areas with various surface morphologies and varnish thicknesses were recorded. A series of laser ablation tests have been then performed aiming to optimize the laser cleaning methodology and these results were applied in larger areas with the objective to achieve different cleaning levels. OCT measurements post ablation allowed to estimate the extent of varnish removal and to evaluate the cleaning process. The results of this synergistic study will be presented and discussed with emphasis to the potential of using OCT as a monitoring and controlling tool in laser ablation of aged varnish layers from paintings.

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Ultra-high resolution, full-field, time domain OCT in the visible range and multi-spectral camera. Crosschecking and complementarity of the images

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In order to increase the knowledge on works of art for restorers and art historians, we present two instruments allowing non-destructive measurements and whose results are complementary. We begin by a short description of both devices, already developed since four years[1, 2]. We shall here insist on the new improvements of each method. Images on an oil painting, a portrait of the Austrian painter Franz Schrotzberg (1811-1889), with several restorations, will be presented and compared [3, 4].

The OCT instrument built at INSP works in the visible range in order to obtain a micrometric accuracy in the three directions. The system is based on a Linnik interferometer, which allows full-field recording, without lateral sweeping. Both arms are then gathered in a Mirau interferometric objective leading to record in-face images 200µmx 200 µm each 40 nm in depth. Recent improvements deal with the instrument and the signal processing:

- A new Mirau with four different beam-splitters allows increasing the contrast of the interferograms.
- The signal processing has been modified in order to increase the signal to noise ratio: the Larkin algorithm used initially has been replaced by a first band-pass filter followed by the demodulation of the interference career and at last by a second band-pass filter.

The OCT results thus lead to quantitative information with ultra-high resolution, in lateral or transverse 2D images or 3D reconstructions. Surprising images of Schrotzberg’s portrait will be presented.

The multi-spectral camera built by Lumière and Technology [5] contains 13 interferential filters from 440 to 900 nm, a CCD of 12 000 pixels on each line and 20 000 lines. So that 240 millions of pixels are recorded for each wavelength and allows spectra reconstruction. The Schrotzberg’s portrait was recorded with 354 dpi, the size of the digital painting was 4323 x 5370 pixels with a pixel lying around 70 μm^2. The following new developments are listed here:

- Compatibility between the reflectance spectra recorded with the camera and those belonging to our spectra date-bases of pigment and dye references. Pigment, dye and pigment mixture can then be identified 6, 7.
- Virtual unvarnishing of the painting
- Visualization of touching-up thanks to the difference of images at different wavelengths, using different algorithms such as numerical derivate, minimum of entropy or weighting of images.

The multispectral camera leads to qualitative information that can be crosschecked to OCT results, such as the network of micro-cracks and the depth of each crack.

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Using Optical Coherence Tomography to Examine the Structure of Ancient Chinese Glaze and Jade

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The ancient Chinese primary used two mineral materials, nephrite and jadeite, to carve objects into specific forms for ceremony or dressing. Nephrite has been used for more than five thousand years, whereas jadeite came into use very late, beginning in the seventeenth century. Therefore, in general, archaeological jade in China was made of nephrite. Nephrite is a fibrous aggregates twinned by long, bladed crystals. However, the natural variation of structure in jade caused by the loss of certain elements from its composition results in a loose structure after being buried for a long period.

The glaze is a glass melt coated on the surface of a vessel. Chinese high-temperature glazes usually consist of three major phases (components): homogeneous glass phase, liquid-liquid phase separation phase and crystallization phase. They form the specific structure of the glaze matrix. However, the variety of glaze structure has an immediate relationship with the individual recipe and heat treatment process. Therefore, the structure actually reflects the ceramic manufacturing technology.

Optical Coherence Tomography (OCT) presents structure characteristic and establishes the structure model of glaze or jade samples that aid the authentication of museum collections[1]. In addition, the OCT image provides crucial information related to the variation of structure that is important not only for conservation scientist to treat the deterioration of archaeological materials or artworks[2], but also for the art historian to understand the history of each ceramic or jade object[3].

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Combined LIBS/OCT technique for examination of paintings

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In this contribution results on simultaneous use of Laser Induced Breakdown Spectroscopy (LIBS) and Optical Coherence Tomography (OCT) for depth-resolved elemental analysis of stratigraphy of multilayer paintings will be presented. The LIBS is a technique based on atomic emission from the cooling plasma plume generated by a laser pulse focused on the material under investigation. The spectral analysis of the fluorescence emission from the plasma permits for identification of chemical elements of the target. In the modality of this technique called the LIBS stratigraphy, consecutive laser pulses with energy adjusted at low level to ensure ablation of a thin layer of material in one shot are applied to the same place. As a result the elemental concentration profiles as a function of a number of laser pulses are obtained. The disadvantage of this technique lays in lack of information on the depth from which certain spectrum is collected and thus the absolute determination of layer thicknesses is not possible. Moreover, since the ablation rate is not constant for different strata within the structure of a painting, the obtained profile, if presented as a function of the laser pulse number, is distorted nonlinearly. This drawback may be overcome by means of OCT, used here mostly as a technique for profile imaging with micrometric resolution. Combining a high spatial resolution OCT instrument with a high spectral resolution LIBS system enhances significantly the quality and accuracy of stratigraphic analysis. The experiment was conducted essentially as follows: firstly the surface profile of the target was obtained with OCT 3D scanning, then the laser pulse was applied and fluorescence spectrum of generated plasma was collected. After that the OCT scan of the crater was performed followed by the next laser pulse. The procedure was completed when the final OCT scan was collected after the last laser pulse.

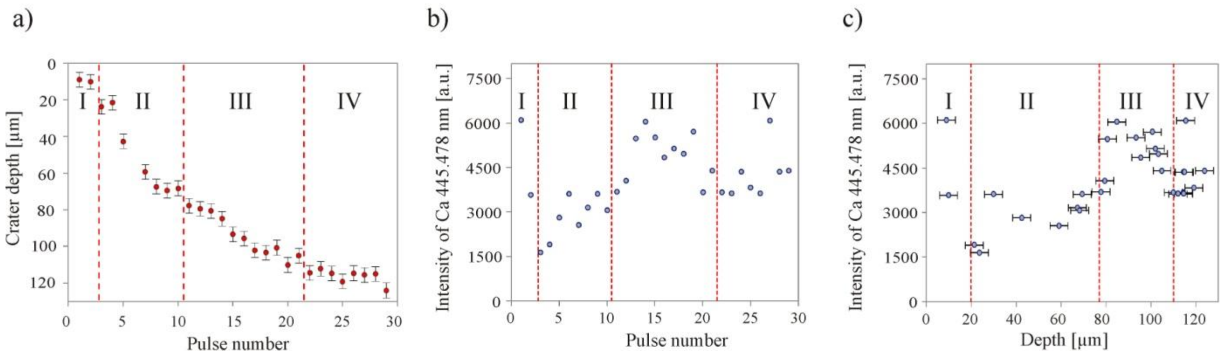

Figure 1. OCT and LIBS data obtained from historic painting on canvas; a) Ablation crater depth versus pulse number as determined by OCT. Notice ablation rate change between layers (dashed lines); b) Intensity of a calcium spectral line determined from the plasma emission signal shown as a function of LIBS laser pulse number; c) Intensity of the same calcium spectral line shown as a function of depth of origin as determined with OCT.

This novel approach enables the precise in-depth scaling of elemental concentration profiles and the recognition of layer boundaries by estimating the corresponding differences in material ablation rate. Additionally, the latter is supported, within the transparency of the object, by analysis of the OCT cross-sectional views. The potential of the method will be illustrated by presenting results on the detailed analysis of the structure of a historic painting on canvas performed to aid its planned restoration.

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From confocal microscopy to confocal OCT

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Confocal microscopy is a well-established technique in many fields, ranging from the biomedical to the engineering one, because of both its ability to image subsurface features selectively in depth and the improved lateral and axial resolution over conventional microscopes. A confocal microscope is a diffraction-limited scanning spot microscope in which both the light source and the detector usually take the form of micrometer scale pinholes. An image of an object is built up in a pointwise fashion by scanning the diffraction-limited spot across the surface of the object in a technique similar to that used in scanning-electron microscopy. The basis of operation of the confocal microscope is now well documented in the literature.[1-10]

The concept of confocal microscopy was described in 1961 by Minsky[11], but it was not until 1968 that the first practical instrument was built[12], and it is only in the last decade that confocal microscopy has become popular, particularly thanks to the use of optical fibers.[13,14] Although a number of commercially available confocal microscopes are now on the market, the technology is young and still evolving.

OCT is a relatively new high-resolution imaging technique which provides high resolution tomographic images of semi-transparent objects. The OCT technique was invented in the mid-1990s by Huang et al.[15], and since then has been widely applied in medicine and biomedical field for probing biological tissues.[15-17] It uses visible or infrared light to provide non-invasive cross-sections of partially transparent or scattering media.

Either commercial sources, such as superluminescent diodes,[18] or laboratory-based solid state lasers can be used,[19, 20] being the axial resolution determined by the bandwidth of the source. This latter generally falls into the range from 1 to 10 µm, even though the lateral resolution is significantly lower, usually no better than a few tens of micron, making the technique particularly well suited to inspect the internal structure of stratified objects.

Both techniques are harmless to all known types of artworks because the examination is non-contact, it does not require any preparation of the object examined and light of low intensity is utilized. The increasing emphasis on non-destructive testing in conservation and the demand for thorough characterization of artworks *in situ* can be met through the application of portable diagnostic methods such as OCT and confocal microscopy.

Up to now Optical Coherence Tomography has been successfully applied in the Cultural Heritage field for measuring the varnish thickness[21-30] whereas confocal microscopy is at its very early stages in this field, and no report can be found in literature of the use of confocal microscopy in cultural heritage field.

When measuring a highly reflective surface the microscope results in a marked intense signal that often hides the signal which comes from underlying surfaces. We decided, then, to modify the instrument transforming it in a confocal-OCT device: the optical launching/receiving system is the one of the confocal microscope but we put upstream a fiber optic coupler and we used a broad-band SLED.

This configuration, besides increasing the depth resolution, has the advantage to allow to maximize the signal scattered by the internal interfaces, where generally speaking there is a low refractive index variation and a huge diffusion.

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Assessing the potential of OCT for the non-invasive examination of varnish layers; a survey of paintings in the National Gallery London

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Optical coherence tomography (OCT) has shown the potential to be a useful technique for the non-invasive examination of the surface and subsurface structure of cultural heritage objects.[1,2] On paintings it can provide 'virtual' cross-section images anywhere on the surface that give information on the paint and varnish layer structure. It offers the possibility of contributing to examinations carried out in support of conservation treatments, and could be particularly effective in extending knowledge of the structure when used in conjunction with what is known from real paint cross-sections.

Much work is underway on further developments in OCT instrumentation, tailoring the specifications of various systems so that they are suitable for a variety of cultural heritage applications.[3] Also very important is parallel work investigating how the materials on cultural heritage objects behave when examined with this relatively new emerging technique. Studies have already been carried out on the properties of reference samples with different pigments and binding media,[4] and a limited number of case studies on individual works of art have been published.[5]

This talk will describe the observations made during a much broader survey with OCT of paintings in the National Gallery, London, chosen because they had a well recorded conservation history, with multiple layers of varnish applied over a very long period of time. In some cases the paintings were undergoing conservation treatment and so real paint cross-sections taken to support treatment decisions were available for correlation with the OCT cross-sections. An adapted commercial instrument was used, operating at a wavelength of 930 nm, an axial resolution of 6 μm, transverse resolution of 9 μm and depth range of 1.6 mm, capable of automatically scanning a 15 cm x 15 cm area. The instrument is small and portable, operating at a safe distance of around 1.5 cm from the paint surface. The study gave an overview of the behaviour of many different naturally aged varnishes on real paintings when examined by OCT, useful information for the design of the specifications of future OCT instruments, especially in terms of desirable depth resolution, and also provided further insight into how OCT can be used as one of the tools for examination of paintings during conservation treatment.

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Tracing of past restorations of 'Madonna dei Fusi' attributed to Leonardo da Vinci

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"Madonna dei Fusi" ('Madonna of the Yarnwider') is a spectacular example of Italian Renaissance painting, attributed to Leonardo da Vinci, possibly with aid of one of his pupils. It was probably executed between the years 1501–1507. The exact history of the picture could be traced down since its purchase by Henry Petty-Fitzmaurice, the 3rd Marquess of Lansdowne in 1809.[1] Since then it was restored at least twice, but previous attempts cannot be excluded. The painting was previously extensively examined with various non-invasive techniques.[2-6]

The aim of this study[7] is to give an account of past restoration procedures. The evidence of a former retouching campaign will be presented with cross-sectional images obtained non-invasively with Optical Coherence Tomography (OCT). Specifically, the locations of overpaintings/retouchings with respect to the original paint layer and secondary varnishes will be given.

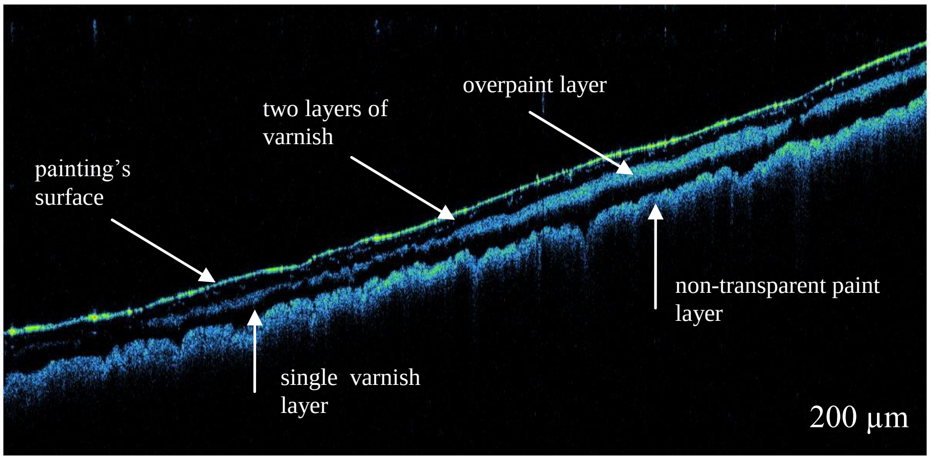

Figure 1 Exemplary result of the OCT examination. The overpaint layer is clearly visible between layers of varnish.

Interestingly, these alterations are not clearly distinguishable with the UV-excited fluorescence, probably due to the fact that the overpaint layer is covered with two layers of strongly fluorescing varnish.

In the contribution the procedure for extracting maps of alterations from the OCT data will be presented. Additionally, the evidence of a former transfer of the pictorial layer to the new canvas support by detecting the presence of its structure incised into paint layer will be shown.

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Sweep Source Optical Coherence Tomography (SS-OCT) for the examination of dry and waterlogged "heritage" wood

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OCT has been under development over the past few years in increasing numbers of applications for the diagnosis of art objects, such as stratigraphic applications, varnish layer analysis, other structural analysis and profilometric applications.[1-9] Nevertheless, present and potential applications of OCT to diagnostics and documentation of art objects, are still seeking for a subject best served by the method and further significant progress will only be possible if the method becomes widely adopted by conservation scientists and researchers.[5,9]

In this project, a Thorlabs-OCS1300SS sweep source optical coherence tomography (SS-OCT) setup with a single photodiode was used. The central wavelength of the setup is 1325 nm with a spectral bandwidth of 100 nm. The coherence length is 6 mm and the maximum imaging depth, depending on the refraction of the material, is 2 to 3 mm.[10]

Scanning was performed on dry and waterlogged fresh and archaeological samples without processing or sectioning as well as samples thin-sectioned by hand with a razor blade. Since cross-sectional images are generated by measuring the echo time delay and intensity of light reflected or backscattered from the internal structure[11], moisture content seems to play a fundamental part in imaging. 2D and 3D imaging was exported by Thorlabs 3D Builder, "3D swept display" software.[12]

High resolution, detailed cross-section views of the samples were provided in all planes - Transverse (TR), Radial (RAD), Tangendial (TAN)- allowing surface topography and internal anatomical information, such as growth rings boundaries, pores, rays, patterns, tyloses etc., to be differentiated. Dimensions measured were used to export qualitative and quantitative anatomical information.

3D imaging enabled the sample to be interpreted in 3D space, which strongly influenced its topographical representation and illustrated quantitative morphometric investigation of wood surface and structure. Export of animations is also supported.

Data processing of 2D and 3D imaging was also used to support quantifications based on the analysis of real physical parameters. Thus, physical properties like moisture content and water movement, as well as their associated effects were most likely visualized and quantified. Variations associated with them through time, such as changes in thickness, width, distances between characteristic points, volume of chosen structures etc., possibly assessed values of specific physical parameters. Results were displayed as contour maps, with labeling associated to the various changes.[13]

Except successive 2D images in time, high speed SS-OCT enabled 4D imaging (3D in time). This approach probably offered opportunities to monitor dynamic changes in wood properties and structure, p.e. due to drying. Examples of 4D can only occur though, when an entire scanning protocol is repeated in time, giving real-time volumetric reconstruction of the structure.[13]

Statistical Parametric Mapping (SPM) data analysis was carried out with the Free - Open source software "Gwyddion 2.31", (covered by GNU General Public Licence), developed by the Czech Metrology Institute as a modular program for 2D and 3D data analysis.[14]

2D or 3D contour maps obtained from SPM analysis of 3D OCT data have two basic advantages: first they enable a quick assessment of the condition of the structure without the necessity of studying cross-sectional images successively. Second, each of the contour maps is created based on a physical value, thanks to which the statistical specificity of a given analysis can be increased.[13]

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Parallel processing of OCT data for monitoring of restoration procedures

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Optical Coherence Tomography (OCT) is a method of non-contact and non-invasive imaging of the internal structure of objects. It originates from medicine, but now it is also routinely used in many non medical examinations.[1] OCT allows for analyzing with micrometer-level axial resolution of the internal structure of the works of art, especially easel paintings.[2,3] Additionally, the OCT may be used for real-time monitoring of technological processes. As examples taken from the cultural heritage filed may serve some conservation treatments[4] including laser ablation of varnish.[5]

In Spectral OCT systems utilizing CPU for data processing the main limitation for real-time imaging lays in the time of data processing, which usually takes more time than the acquisition. Utilizing a General-Purpose computing on Graphics Processing Units (GPGPU) for massively parallel processing of the OCT data gives a solution this problem – it allows to overcome the limitation of processing time and to visualize cross sectional images faster than to acquire data.

The presented results were obtained with a computer workstation equipped with Intel® Core™ i7 920 (2.67 GHz) CPU, 6 GB RAM memory and low cost, game-designed graphic card: NVIDIA® GeForce® GTX 580 with 3 GB device memory, featuring the Fermi architecture. It controls a laboratory-made, high resolution Spectral domain OCT system, which is equipped with a Superlum Broadlighter Q870 with central wavelength λ_c = 870 nm and full spectral width at half maximum $\Delta\lambda$ = 200 nm. This source provides axial resolution Δz = 3 μm.

The software for instrument control and parallel data processing was developed under Microsoft® Windows™ 7 Professional x64 operating system and written in C++ programming language. All procedures for parallel processing in GPU were compiled with NVIDIA® CUDA™ compiler version 4.0. The OpenGL® 4.0 Library was used for 2D/3D visualization of the results.

The developed software is capable of processing about 1 000 000 spectra (2048 points each) per second (Fig. 1). The processing and visualization is faster than acquisition, therefore the same data is reprocessed several times until a new data occurs. It allows for on-line adjustments of data processing (e.g. dispersion compensation) and display (e.g. rotation angle, zoom) parameters. The frame rate of reprocessing (with rendering) and the total frame rate when new data is transferred to the GPU are presented in Table 1.

The developed software may be utilized for real-time monitoring of various, dynamic processes. One of them is laser ablation of varnish (Fig. 2). The effectiveness of the process depends strongly on the properties of the ablated layer and the thickness of removing varnish. Since the thickness of an ablated layer changes rapidly form point to point, safe removing of varnish without any control is almost impossible. This drawback may be overcome by real-time monitoring of this process with high-resolution, fast OCT system.

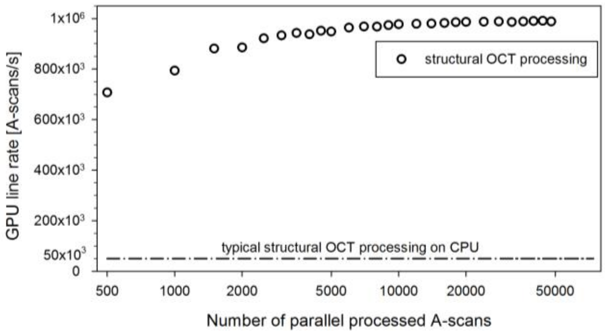

Fig. 1. GPU line rate for structural OCT imaging as a function of the number of A-Scans

Table 1. Frame rate of processing and visualization of the OCT data (with and without transfer of new data)

Protocol	No. of A-scans	Frame rate of reprocessing and visualization	Total frame rate (data transfer, processing and visualization)
Cross 2x2000	4 000	120 fps*	45 fps
Cross 2x4000	8 000	87 fps	22 fps
4 slices 4x2000	8 000	87 fps	22 fps
4 slices 4x3000	12 000	62 fps	15 fps
3D 100x100	10 000	21 fps	13 fps
3D 140x140	19 600	13 fps	6 fps

*Limited by screen

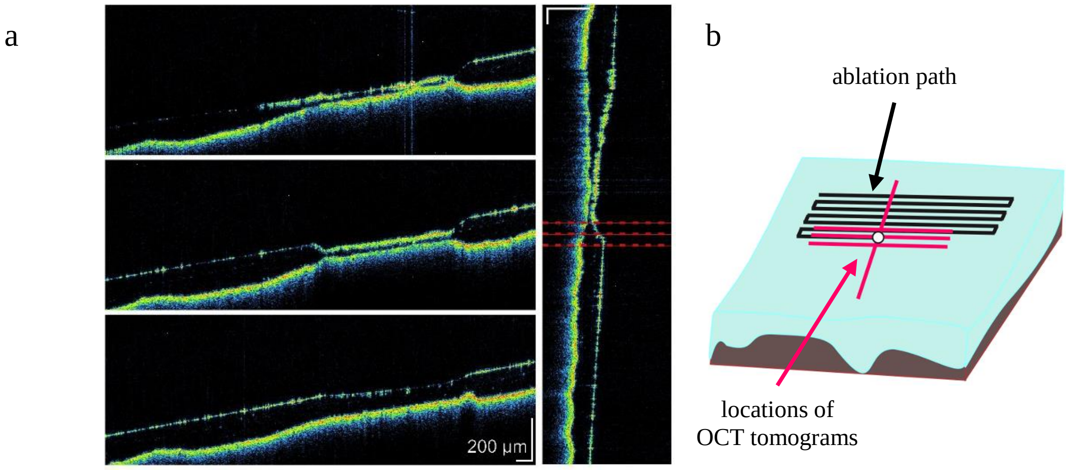

Fig. 2 a: A screen shot registered during real-time OCT imaging of varnish ablation process
b: locations of OCT tomograms (red lines) and ablation path (black lines)

The ascendancy of the processing speed over acquisition of the data allows for processing of the same data set several times in order to optimize parameters of numerical analysis and/or visualization conditions in a real-time. Alternatively, to avoid reprocessing of the data and to better utilize the computational power of the graphic card, the GPU processing opens a gate for implementation time-consumed algorithms previously executed in post-processing only. Now, some of them may work in real-time, and may create a new applications of the OCT technique, especially if the development of GPU technology continues to be as rapid as at present.

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Examination of structure and properties of historic glass with OCT

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In this contribution the application of Optical Coherence Tomography (OCT) for investigations of various glass artifacts will be presented. Since the OCT technique relies on multispectral interference of infrared light, it is well suited for examination of transparent and semi-transparent structures like archeological and stained glass, especially if collection of the sample is not possible.[1-6]

Among applications of OCT to the stratigraphy of glasses, the most important seems to be utilization of OCT for identification and characterization of leached and hydrated glass surface layers.[4] Particularly, the range of in-depth corrosion may be determined this way. The method is simple and not limited by neither sample preparation nor object size. Therefore it could be useful for a quick screening of museum collections as well as stained glass windows to identify possible threat to so called unstable glass from the storage conditions. Examples of OCT cross-sectional images useful for evaluation of the extent and character of atmospheric corrosion of stained glass and for identification of the surface layer of glass affected with crizzling will be given.[5,6]

Another application concerns the utilization of the OCT imaging for examination of multilayered structures on glass support like paintings on glass, photographs and similar collage techniques. First example of this kind will be a 19th c. glass window painted with annealed colors.[2] In this case the thickness of color glass may be determined even if this layer is opaque for light used for the examination. This was possible by a additional examination through the whole glass support – the unique method available only for the transparent base. Another example to be presented is late 19th c. photographic collage.[6] This item is composed of the black and white photograph glued with its front side to the partially painted glass plate. Delamination of the glass-paper structure and splitting of the glass caused by a contraction of the animal glue used may be conveniently inspected with aid of the OCT technique.

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Examination of reverse painting on glass (*Hinterglasmalerei*) with OCT

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Since 18th century the *Hinterglasmalerei*, also known as reverse painting on glass, has been popular in folk art of Central and Eastern Europe. In this technique a plate of glass is used not only as a support for the paint layers, but also as a front surface of the painting, shiny and impermeable. As a result of this approach the process of painting has to be performed in order opposite to the classical painting techniques. The layers which are intended to be viewed as finishing details (like glazes and highlights) are in fact painted in the first place, and followed by adding opaque background paint. Lack of access to the layers of painting crucial to its esthetics, together with seldom predictable materials used by the artists, hinders both inspection and conservation treatment.

Its ability of remote sensing renders Optical Coherence Tomography especially convenient for examination of reverse painting on glass. By means of the OCT, uniquely to other examination methods, layers closest to the viewer are most convenient to investigate. Moreover, the inspection is possible without dismounting the picture from the frame and protective back cover. In this experiment a Spectral OCT instrument of 4 μm axial resolution and 100 dB sensitivity was utilised.

In the figure a cross-sectional view through the fragment of 19th century folk painting is presented showing different types of damages specific for this kind of artwork. Light approaches the object from the top and propagates through the supporting glass (1). Then the multiple semitransparent paint layer (2) or strongly absorbing contour paint (3) is expected. However, in this case the adhesion of this layer to glass is quite poor and the paint is detached in many places. Some detachments are filled with consolidation adhesive (4) remaining after some previous conservation treatments, whereas the others, presumably developed later, are empty and form blisters (5). The process is dynamic and new detachments (seen as strong boundary lines between glass and paint layer) are visible at right hand side of the image.

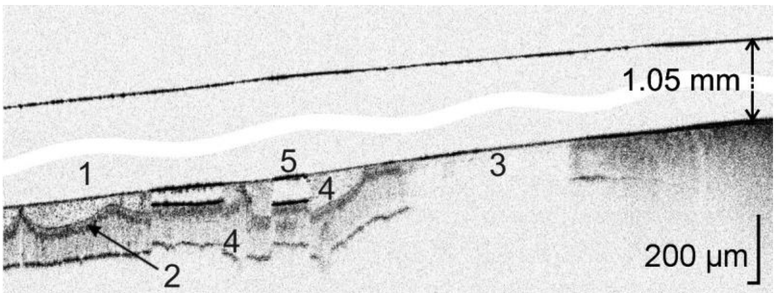

Fig. 1. An example of OCT tomogram of reverse painting on glass. Glass thickness is reduced for tightness of the picture. See text for description.

In this contribution results of examinations of 19th century folk painting will be discussed with emphasis on applicability of OCT to resolving specific problems related to conservation of this object. Furthermore, the application of OCT as a monitoring tool for assessment of various consolidation techniques will be presented.

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in *Proceedings of the international conference LACONA VIII: - Lasers in the Conservation of Artworks, Sibiu, Romania, September 17 - 21, 2007*, R. Radvan et al. eds, (CRC Press, Taylor & Francis Group, London 2011), 209-214.

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Introduction to NCU OCT instruments

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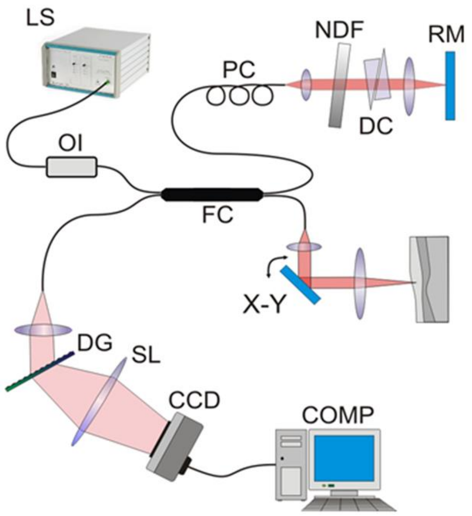
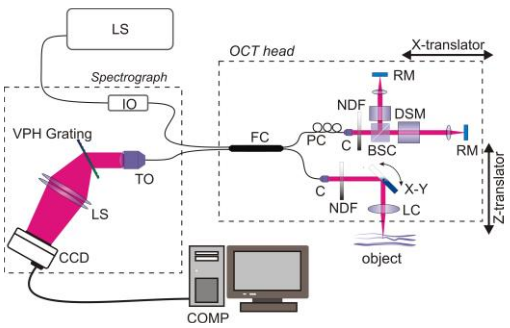
Both instruments to be used in hand-un training were built in the Institute of Physics, Department of Physics, Astronomy and Informatics N. Copernicus University firstly under grants on Polish Ministry of Science and Higher Education (Instrument I) and then under EU Community's FP7 Research Infrastructures programme under the CHARISMA Project (Grant Agreement 228330 – Instrument II).

Instrument I (developed by: IG, MG, TB, MSz, PT)



- Instrument type: spectral domain OCT
- Detector system: diffraction grating spectrometer with linear CCD detector
- Light Source: Broadlighter D855 (Superlum, Ireland) 780 – 920 nm
- Power at object: 600 – 1500 μW
- Axial (in-depth) resolution in varnish.: δz = 4.5 μm
- Transverse (in-plain): δx ~15 μm
- Sensitivity: 108 dB (80 – 110 dB)
- Distance to the object: 65 mm
- Field of view: 20 x 20 mm
- A/D converter: 12 bits
- Acquisition rate:
  - 40 μs/A-scan
  - 0.2 s / 2D image (cross section, 5000 A-scans)
  - OCT movie: 16 frames/s x 1200 A-scans
  - real time monitoring: 2 frames/s x 400 A-scans

Instrument II (developed by: ASz, MSz, MS, ŁC, EAK, PT)



- Instrument type: spectral domain OCT
- Detector system: diffraction grating spectrometer with linear CCD detector
- Light Source: Broadlighter Q-870-HP (Superlum, Ireland) 770 – 970 nm
- Power at object: 800 μW
- Axial (in-depth) resolution in varnish.: δz = 2.2 μm
- Transverse (in-plain): δx= 6.2 / 12.4 μm
- Distance to the object: 43 / 7.5 mm
- Field of view: 17 x 17 mm / 5 x 5 mm
- Sensitivity: 100 dB
- A/D converter: 12 bits
- Acquisition rate:
  - 40 μs/A-scan
  - 0.2 s / 2D image (cross section, 5000 A-scans)

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description of instrument I

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description of Instrument II

1. Piotr Targowski, Magdalena Iwanicka, Marcin Sylwestrzak, Ewa A. Kaszewska, Cecilia Frosinini "OCT structural examination of 'Madonna dei Fusi' by Leonardo da Vinci" Proc. SPIE **8790** (2013)

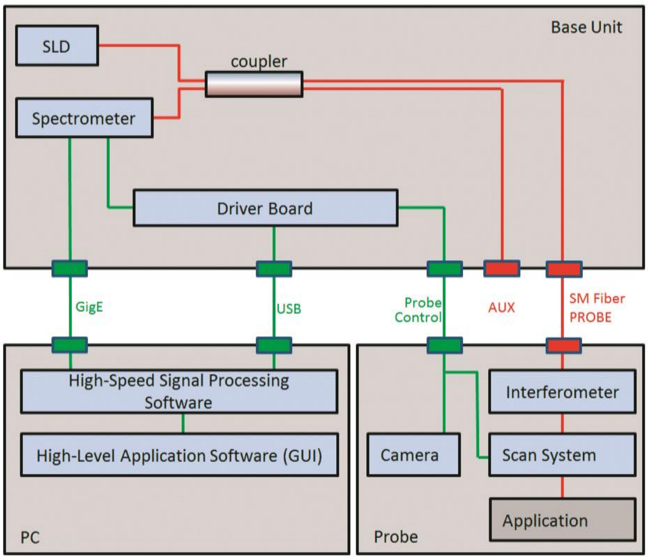
Introduction to Thorlabs OCT instruments

Martin Krah

Thorlabs, Germany

GANYMEDE HR

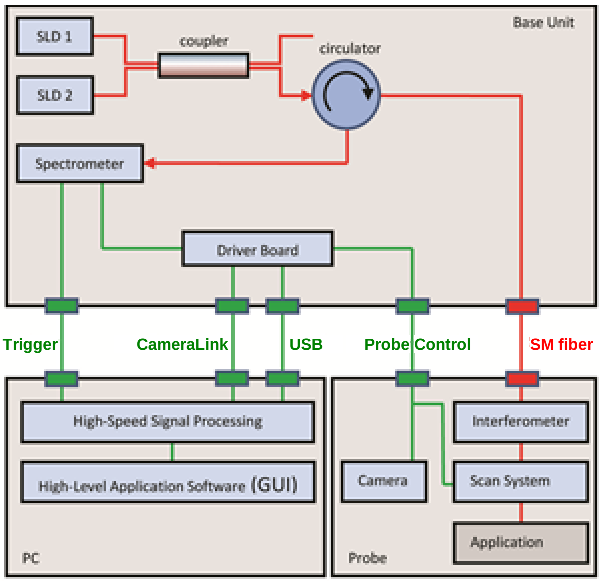
- Instrument type: Spectral Domain OCT
- Detector system: Diffraction Grating Spectrometer with linear CCD detector
- Light Source: SLD 800nm – 1000nm
- Power at object: 1.5mW typical
- Axial (in-depth) resolution in varnish.: δz =2.3 μm
- Image depth in air: 2mm
- Transverse (in-plain): δx ~4μm / ~8μm (LSM02-BB/ LSM03-BB)
- Sensitivity: up to 91dB
- Distance to the object: 7.5mm / 25.1mm
- Field of view: 6mm x 6mm / 10mm x 10mm
- A/D converter: 12 bits
- Acquisition rate:
  - 33μs - 800μs / A-scan
  - ≥ 0.17 s / 2D image (cross section, 5000 A-scans)
  - real time monitoring: 29 frames/s x 512 A-scans

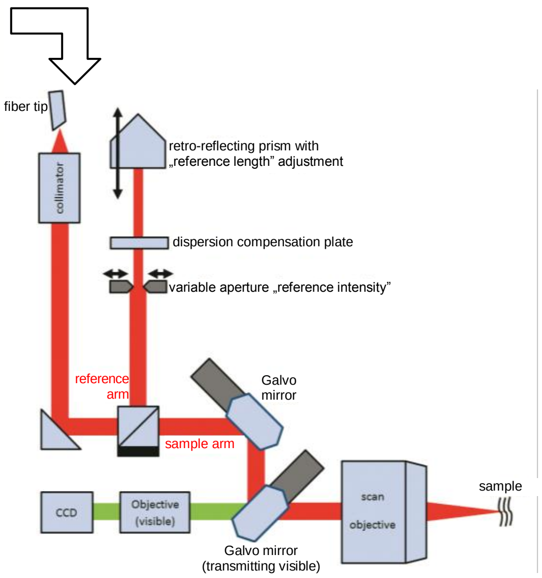


CHARISMA: Cultural Heritage Advanced Research Infrastructures: Synergy for a Multidisciplinary Approach to Conservation/Restoration, Grant Agreement 228330

TELESTO

- Instrument type: Spectral Domain OCT
- Detector system: Diffraction Grating Spectrometer with InGaAs Diode Array Detector
- Light Source: SLD 1230nm – 1420nm
- Power at object: 4.5mW typical
- Axial (in-depth) resolution in varnish.: δz =4.3 µm
- Image depth in air: 2.5mm
- Transverse (in-plain): δx ~6.7µm / ~13µm (LSM02 / LSM03)
- Sensitivity: up to 106dB
- Distance to the object: 7.5mm / 25.1mm
- Field of view: 6mm x 6mm / 10mm x 10mm
- A/D converter: 12 bits
- Acquisition rate:
- 11µs - 181µs / A-scan
- ≥ 55ms / 2D image (cross section, 5000 A-scans)





NOTES