collana **Problemi di conservazione e restauro. 50**

Il restauro dell'*Adorazione dei Magi* di Leonardo. La riscoperta di un capolavoro

a cura di Marco Ciatti e Cecilia Frosinini

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Indice

Presentazioni

Pre-restoration condition of superficial layers of the *Adoration of the Magi* by Leonardo da Vinci as seen by optical coherence tomography

Magdalena Iwanicka, Marcin Sylwestrzak, Anna Szkulmowska, Piotr Targowski *

Introduction

In the case of such a unique artwork as the *Adoration* only non-invasive analytical techniques may be used extensively. Among others, optical coherence tomography (OCT) has proven its usefulness for examination of works of art. The technique originates from medical diagnostics in which it is routinely used mainly in ophthalmology, but also in dermatology, gastroenterology, oncology etc. [1]. It is an optical interferometric technique with the specific advantage of being sensitive to changes in refractive index in the media under examination and to the presence of fine scattering centres. An OCT scan is further processed into a cross-sectional image (2D tomogram) of sub-surface structures of objects at least partially transparent to infrared (IR) radiation. The sequence of parallel scans can also be combined into volume data (3D cube). OCT offers high axial resolution: down to 1-2 µm with the total depth of imaging of about 1 mm and significantly less lateral resolution of about 15 µm with a large field of view up to 5 cm^2. OCT is, therefore, well suited to the imaging of structures composed of many layers parallel to the surface. An obvious disadvantage is the limited transparency of many media to the penetrating infrared beam. Nevertheless, OCT has been successfully employed for the examination of components of objects of cultural heritage, such as the varnish and glaze layers of easel paintings [2], stained glass [3], jade [4] and similar stones, manuscripts on parchment [5] as well as many others [6]. A review of such applications can be found elsewhere [7].

Methodology

During the examination, a portable ultra-high resolution spectral domain OCT system [8] was used. It was built at Nicolaus Copernicus University in Toruń, Poland for the FP 7 CHARISMA project. The instrument is equipped with a multi-diode superluminescent light source emitting in a band of 770-970 nm (near IR). The intensity of IR radiation on the object was not more than 800 µW and the beam was scanned over its surface at high speed. The axial resolution was 3 µm if measured in air. Since the axial resolution increases in the media, the varnish and paint layers were imaged with an axial resolution equal to 2,1 µm. The depth of imaging of this instrument was 1,3 mm and its lateral resolution was about 13 µm. In a single 3D measurement structural information from areas up to 17×17 mm^2 were acquired. The distance to the object from the most protruding element of the device (the working distance) was 43 mm. The signal from the instrument was converted to images (tomograms) using lab-made software. The most representative OCT results are tomograms (**fig. 2b** and following). They are usually presented in a false-colour scale: cool colours (from dark blue to green) depict low-scattering areas, while warm colours (from yellow to red) represent high-scattering or reflecting structures. Non-scattering media: air above the object, clear substances like glass and some varnishes, as well as areas not reachable by the probing beam, (i.e. below an opaque layer), are shown in black. In all of the tomograms presented here, the probing light approaches from the top (for the horizontal tomograms) or from the right (in the case of a vertical tomogram, **fig. 2b**), and thus the first, strongly reflecting and/or scattering layer is the surface of the painting (air-varnish interface). It must be noted that for better readability of the images, the in-depth scale is expanded in comparison to the lateral one as shown by scale bars. As it has been mentioned above, within the media (varnishes and glazes in this case) the axial dimensions of the structures are extended. Thus two axial scales are shown in all tomograms: one for the axial dimensions above the surface and one for axial dimensions within the medium imaged.

Since data from *Adoration* was collected in 3D modality (usually 100 tomograms taken over the square area of 12x12 mm^2) another way of presenting data was also adopted. It allows mapping of the internal

1. *Adoration of the Magi*, locations where OCT data were collected. Yellow colour indicates places referred to in the text

structures with different scattering properties lying parallel to the surface of the painting. This method of data analysis, called *gate imaging*, is described in detail elsewhere [9]. Briefly: from the 3D data cube the slice of voxels of a given thickness (the width of the gate) has been extracted from a given depth (the depth of the gate) under the surface of the target. This way the slice is always parallel to the surface of the painting, independent of its tilt (which is necessary to avoid specular reflections of the probing OCT beam during imaging). The data from the given lateral position in the slice were then averaged and presented in the same false colour scale as OCT tomograms forming 2D maps.

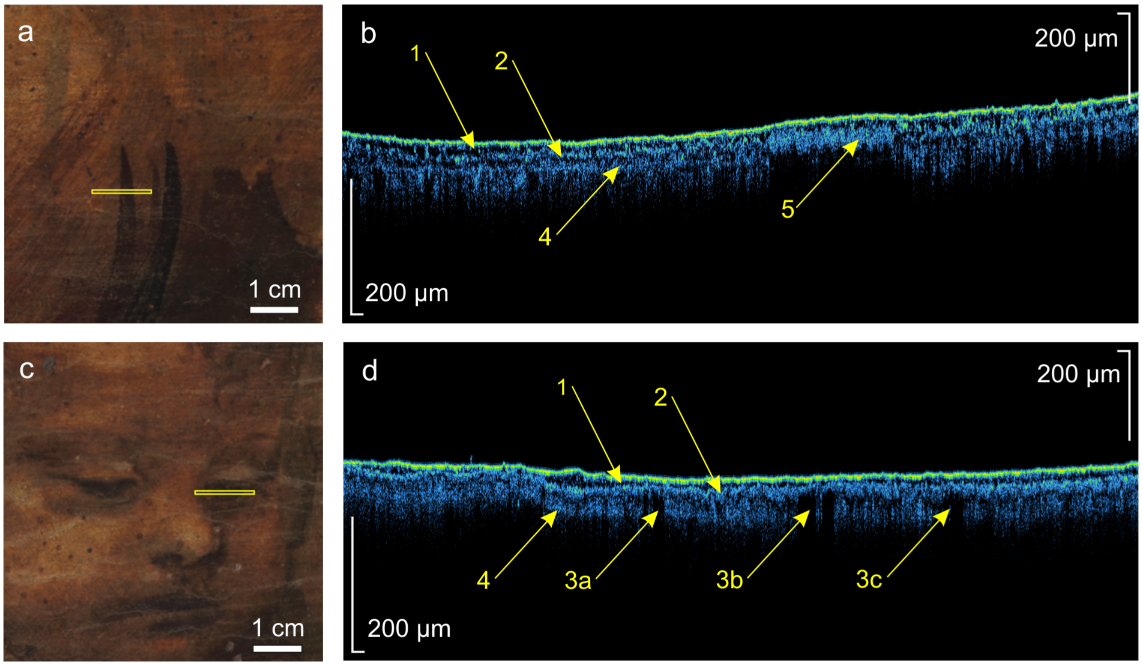
The tomography was performed at the Opificio delle Pietre Dure before the restoration began – between February 27 and March 1, 2012 – in 25 spots (**fig. 1**) at various locations on the painting for areas from 7x7 mm^2 up to 17x17 mm^2, as required.

The imaging sites were chosen to address specific restoration questions. The major issues were the number and thickness of varnish layers, the location of certain discoloured/blanched layers obscuring the painting, and the depth position and range of retouching.

Results

As mentioned above, the OCT technique is limited to the examination of transparent and semi-transparent structures. For paintings, the combination of three factors affects the layers' transparency in infrared: the thickness, the pigments used, as well as the pigment -to-binder ratio.

Although most pigments are impermeable to near-IR radiation when applied in thick layers, the paint layers in the *Adoration* have varied thickness which makes some of the veil-like paint layers accessible for OCT imaging. For instance, paint layers of different trans-



2. The OCT scan area for a brush stroke on the shoulder of a kneeling Magus (spot 11b in fig. 1) with the resulting tomogram (b) and (c-d) the same for the Child's eye (spot 25 in fig. 1). The probing light beam approaches from the top and the uppermost line is the surface of the painting; the tomograms show: (1) varnish, (2) paint layer, (3a, 3b, 3c) underdrawing, (4) ground layer, (5) thick brush stroke

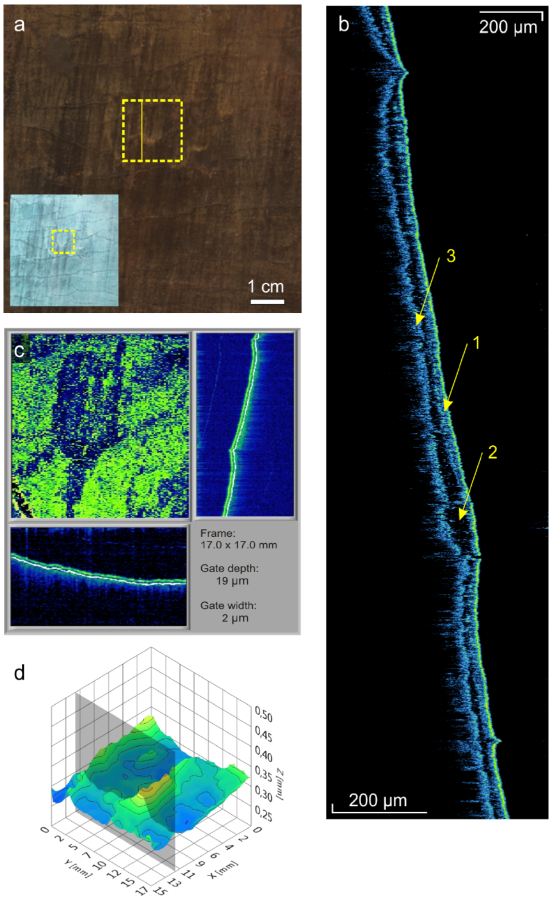
parency are discernible in the tomogram (**fig. 2b**). The dark brown brush stroke that is part of the drawing of a kneeling Magus' shoulder is painted with thick, opaque paint on top of one or two thin, hazy layers. In this case, the dark paint absorbs OCT probing light much more strongly that the adjacent light brown paint. The thickness of this layer cannot be determined with OCT unequivocally due to multiscattering, however from the OCT cross-section it is discernable that the surface of the paint is elevated here by about 15 µm. Below the surface, two (?) layers of varnish (again about 15 µm thick) are seen all along the cross section. These are supporting reasons for determining that this dark brown paint lies on top of the upper layer of the light brown glaze. This conclusion must however be made with due care.

In some cases even deeper pictorial layers are detectable. The underdrawing of the Child's eye (iris and pupil), executed in carbon black, is clearly visible in the OCT tomogram (**fig. 2d**) in the form of three dark areas (absorbing OCT's probing beam). The contour is covered with a layer of semi-transparent paint (about 10 µm thick) and two layers of varnish (together about 9-10 µm in thickness).

Two layers of varnish were found in most of the areas examined. They are especially visible if they have different scattering properties, e.g. due to blooming. For example, in spot 21 there is a droplet at the end of a drip of varnish that stopped and dried at the tent-shaped deformation of the paint layer (**fig. 3a**). As is shown in the image, the bottom edge of the droplet is lighter in visible light and shows stronger UV-induced fluorescence. In the area marked with a yellow square, the OCT data were collected as a series of 100 vertical scans, forming a 3D data cube. One of the tomograms collected over the droplet is presented in **fig. 3b**. It can clearly be seen that the droplet (thicker varnish layer) dried above the tent-shaped deformation. The two layers of varnish (upper – more scattering, and bottom – more transparent) are evident. The upper one is a thinner layer of the droplet which is formed mostly by the bottom one. Therefore it is justified to conclude that the fluorescence originates from this bottom varnish.

The droplet itself is quite visible in the gated OCT image (see methodology section for explanation). Here the signal was integrated from the thin slice located at a depth between 19 µm and 21 µm (**fig. 3c**). There is no doubt that the varnish forming the droplet is less scattering. Moreover, OCT enables a precise profilometry of the painting's surface (**fig. 3d**). The tent-shaped deformations and the droplet are clearly visible.

A similar varnish sequence is visible over the area of drying cracks (**fig. 4**). Again, two layers of varnish are discernible. The upper layer scatters more and is thicker than the bottom one. A drying crack (3 in **fig.**

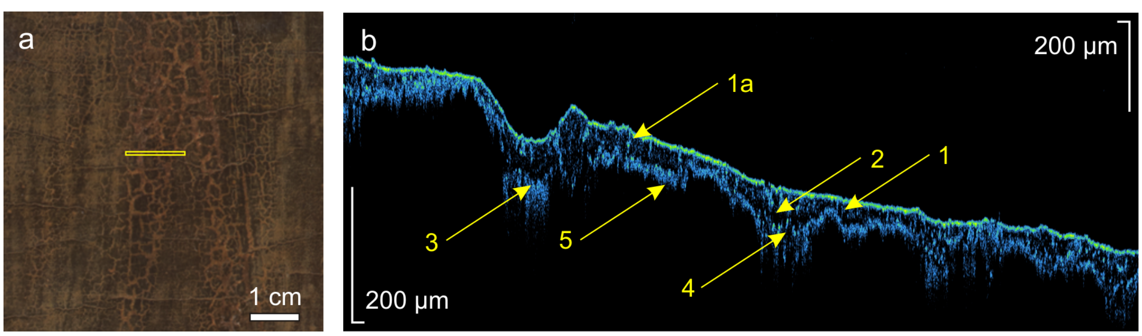


3. Results of examination of the area of the end of a varnish streak (spot 21 in Fig. 1): (a) Photos in visible light and of UV excited luminescence (insert); (b) One of the OCT tomograms collected from the yellow square shown in (a). Probing light approaches from the right; two layers of varnish – (1) scattering, (2) not scattering – and the surface of an opaque paint layer (3) are visible; (c) Gate imaging showing scattering properties of the varnish at a depth of 19 µm under the surface; (d) A precise surface map compiled from OCT data: x-axis increments towards the bottom of the painting; the grey plane indicates the location of the tomogram from (b)

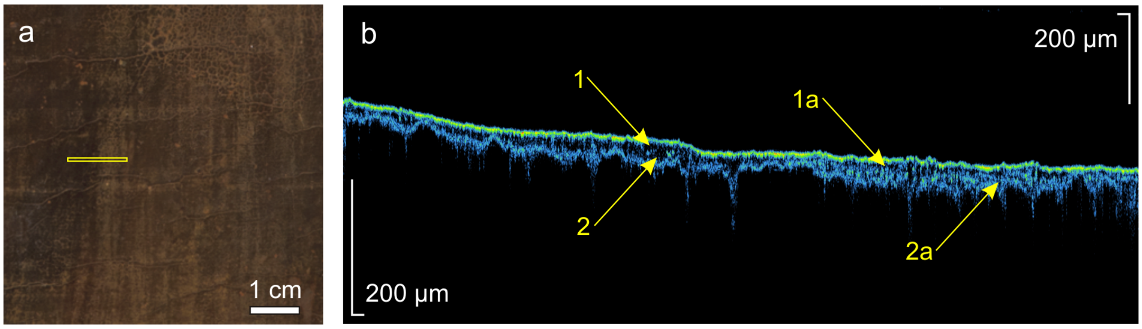
4b) is visible as a 100 µm deep and 1,4 mm wide valley continuing for another 55 µm, filled with varnish. Another crack (4) is completely filled with varnish, up to the level of the surrounding painting surface. Additionally, fine cracks (1a) – in the upper varnish layer only (1) – are visible.

In contrast to the situation shown in figures 3 and 4 where the layer of highly scattering varnish extends over the whole area of examination, there are also areas where optically altered vertical stripes, obviously not belonging to the composition of the painting, are clearly visible (**fig. 5a**). Comparison of tomograms in figures 3b and 5b indicates that the scattering varnish layer 2a in figure 5b is of similar thickness as layer 1 in figure 3. In this case, however, it constitutes the bottom layer. The left hand side of the area examined appears significantly darker. A possible explanation could be as follows: on the left side both layers of varnish are transparent (1, 2) and thus it is possible to differentiate them only thanks to the existence of some scattering centres at their interface. On the right side, the scattering bottom varnish (2a) is covered by a thin layer of transparent varnish (1a). In this area, the varnish significantly obscures the visual appreciation of the painting. The scattering centres are distributed homogeneously in the bulk of the varnish (2a), and indicate alteration of its structure, i.e. microcracks. These create a blanching effect [10] on a macroscopic scale, and are usually caused by exposure to excessive moisture. The vertical orientation of these areas suggests streaks of water running down the surface of the painting at some unidentified past time.

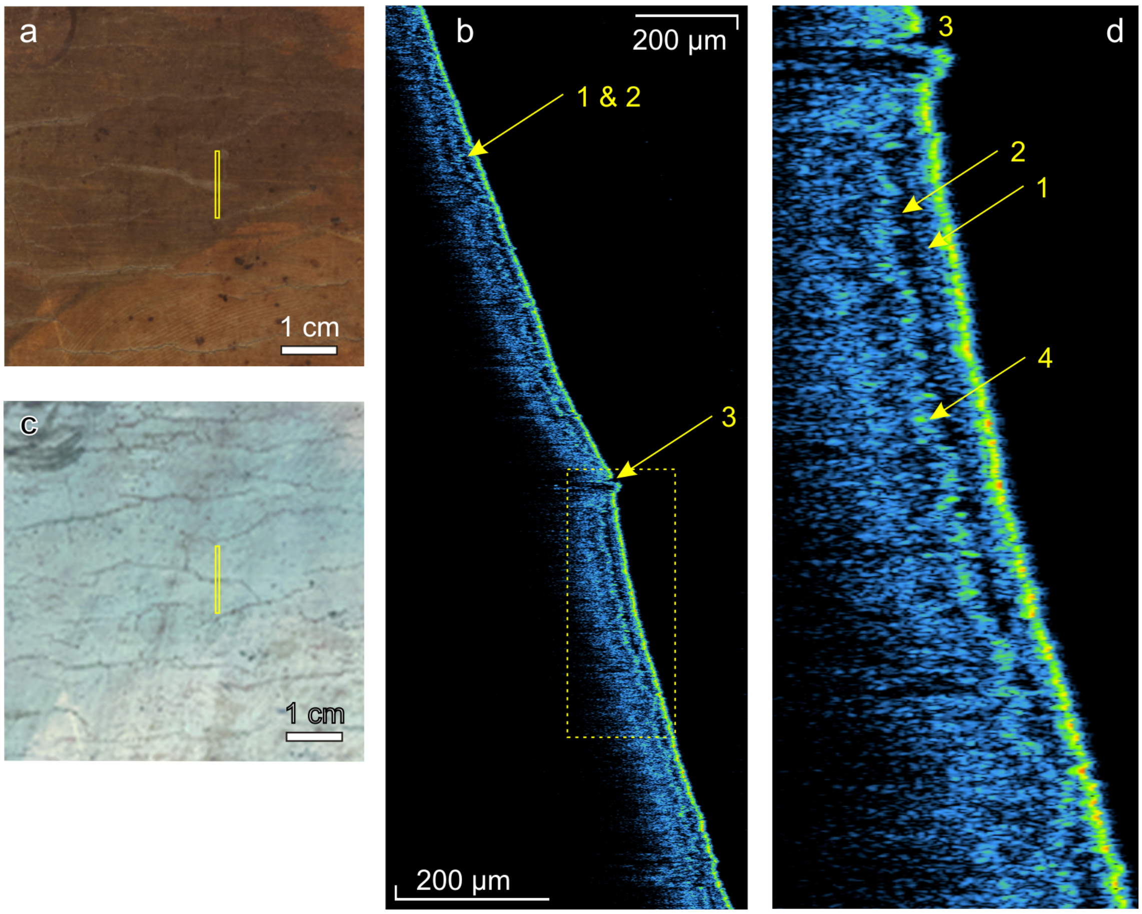
One of the issues raised by the restorers was the nature of specific whitish deteriorations running along some horizontal cracks (**fig. 6a**). UV-excited fluorescence (**fig. 6c**) imaging did not reveal the presence of any recent secondary layers. The OCT tomograms (**fig. 6b, d**) show a thin superficial layer of blanched varnish below the crack. It is reasonable



4. The OCT cross-section in the area of drying cracks (spot 19 in Fig. 1). Two layers of varnish (1, 2) are seen over the opaque paint layer (5). One crack (3) is partially filled with varnish whereas the other one (4) is filled completely. Fine vertical cracks (1a) in the upper varnish are also discernible



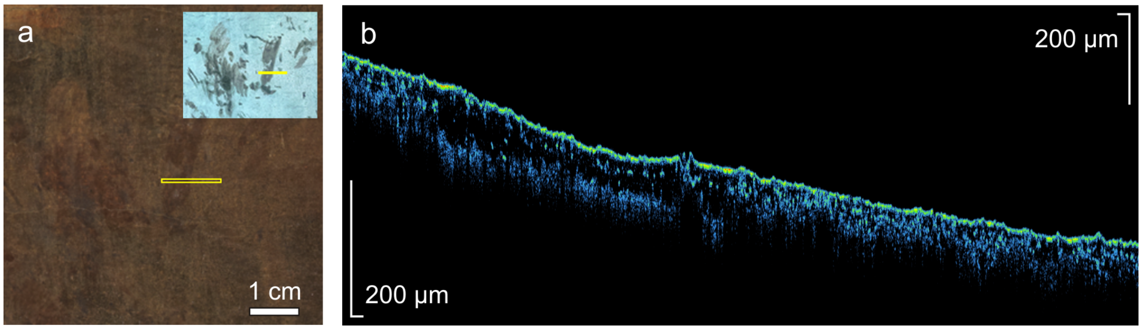
5. Result of OCT imaging of the area with blanched stripes of varnish (spot 22 in fig. 1): (1,2) – two layers of clear varnish, (1a) – transparent thin upper layer of varnish, (2a) – blanched layer of bottom varnish



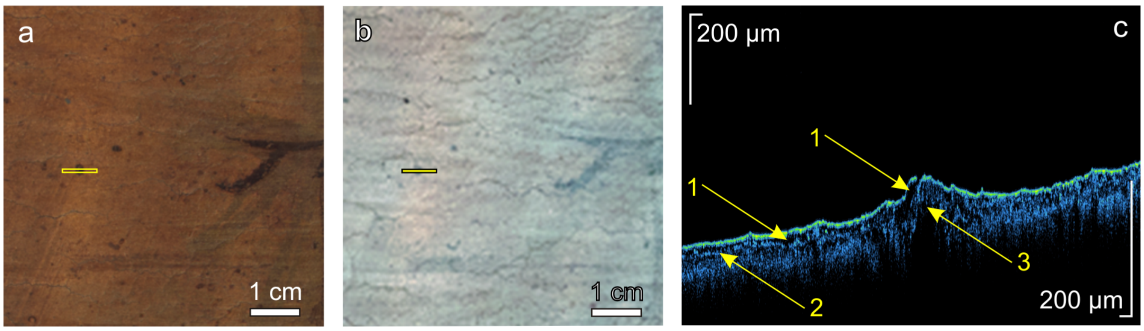
6. Result of OCT imaging of the region around a crack (spot 18 in fig. 1): (a, c) VIS/UV photos; (b) OCT cross-section with two layers of varnish (1 & 2) discernible in the area below the crack (3) as a blanched upper layer (1) and a transparent bottom one (2), on top of paint layer (4); (d) enlarged view of the area marked with a dashed rectangle

to assume that it was caused by increased water concentration at the crack. It must be noted, however, that there is no trace of delamination of the varnish layer(s) in this area. Such an internal lateral crack, if existing here, would have been exquisitely visible in the OCT examination (compare detail 1a in **fig. 4b**) due to the rapid change of refractive index at the media/air interface within a delamination [11].

In the area of the standing man's shoulder, UV excited fluorescence imaging indicated the presence of contemporary retouchings (**fig. 7a**). In the OCT tomogram, this area (left side of **fig. 7b**) was transparent down to 100 μm. Although the secondary paint was



7. OCT examination of the area of contemporary retouchings (spot 12 in fig. 1)



8. OCT imaging of the area (spot 17 in fig. 1) of one of the dark round deposits: (1) two (?) varnish layers; (2) semi-transparent paint layer; (3) protruding deposit strongly absorbing IR radiation

too thin to be visible as a separate layer in the OCT cross-section (it was probably below 2 µm, the instrument's axial resolution in paint media), the body of the filling material is transparent, indicating the possible use of wax putty. The filling was applied in two layers and did not even out the painting surface properly.

Another deterioration specific to the *Adoration* was the presence of dark round deposits of 1-2 mm in diameter. They visually affected many areas of the painting, especially light coloured ones. These features were scanned with OCT in a few different areas (spot 17, see **fig. 8**, as well as spots 1, 7, 9) yielding the same conclusion. They are highly IR-absorbing protruding deposits (3 in **fig. 8**c) located under the varnish layers (1).

Conclusions

The *Adoration of Magi* by Leonardo da Vinci is unique not only from the obvious artistic point of view but also due to its structure – as an unfinished masterpiece. The few, thin layers make it a challenge for structural examination by means of OCT. Nevertheless, the analysis of all tomograms collected leads to the following general conclusions.

The structure of paint layers is seen in this examination to a limited extent due their partial opacity, as is usual with OCT. Nevertheless, in many areas one is able to follow Leonardo's specific painting technique of building the form with thin, veil-like layers (**fig. 2b**, **fig. 6**, **fig. 8**). Deep shadows and dark brown brushstrokes, on the other hand, strongly absorb the OCT infrared probing beam. In some areas, even the preparatory drawing with carbon black (**fig. 2d**) can be detected under semi-transparent paint.

In the majority of tested areas there are two layers of varnish. These may be difficult to distinguish in a single cross-section in which they are often visible only locally. However, the analysis of a series of adjacent cross-sections strongly supports this conclusion. It must be also noted that very thin layers (under about 2 µm), if present, might have been overlooked due to the limitation of the axial resolution of OCT. The overall thickness of the varnish in most cases varies from 10 µm to 20 µm.

In addition to general conclusions about the varnish layer structure, several specific issues regarding the state of preservation of the painting were addressed during the imaging. Discolouration (in the form of vertical stripes) in the area of the mantle of the standing man (**fig. 5**, confirmed also at spots 8, 20 in **fig. 1**) corresponds to strong scattering in the bulk of the thick varnish layer visible in the OCT tomograms, which indicates the phenomenon of varnish blanching. In the same area of the composition, two layers of varnish with different properties have been identified (**fig. 4**). The upper one contains more scattering particles compared to the bottom one. Both layers fill in drying cracks of the paint layer. At the spot shown in **Fig. 3**, a similar structure of varnish layers is visible in the tomograms. The OCT scanning was performed over the droplet at the end of a drip of varnish (strong UV excited fluorescence). It is evident, that the droplet is formed from the bottom layer of varnish. Whitish matt borders around certain cracks (**fig. 6**) correspond to blanching of the top layer of varnish, possibly caused by accumulation of condensation water at the crack.

The latest retouchings (black in UV excited fluorescence imaging) are transparent in OCT examination, as well as two thick layers below – possibly a wax putty (**fig. 7**).

The position of frequently occurring dark round deposits was determined; they are covered with varnish (**fig. 8**, confirmed also at spots 1,7,9 in **fig. 1**).

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