Optical coherence tomography – a tool for high resolution non-invasive 3D-imaging of the subsurface structure of paintings

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Abstract

Optical Coherence Tomography (OCT) is an imaging technique originally developed for high-resolution 3D imaging of the human eye. In 2004, Targowski et al. and Liang et al. first reported its application to paintings, demonstrating that it was possible to produce cross-section images non-invasively with this technique. In 2005 Liang et al. explored further applications such as imaging of underdrawing at a resolution and contrast greater than that achievable with infrared reflectography. Since then the authors have been conducting a project to investigate systematically the potential of OCT as a new tool in the non-invasive examination of paintings and to design an OCT optimised for use in museums. This paper discusses recent developments in this work and presents examples of the use of OCT on paintings undergoing conservation treatment in the National Gallery, London.

Résumé

La Tomographie à Cohérence Optique (OCT) est une technique d'imagerie mise au point à l'origine pour une imagerie 3D à haute résolution de l'oeil humain. En 2004, Targowski et al. et Liang et al. ont été les premiers à faire part de son application sur les peintures, en démontrant que cette technique permettait de produire des images en coupe transversale, de manière non invasive. En 2005, Liang et al. ont exploré d'autres applications telles que l'imagerie des dessins sous-jacents à une résolution et un contraste plus élevés que ceux obtenus par la réflectographie infrarouge. Depuis, les auteurs ont mené un projet pour étudier systématiquement le potentiel de l'OCT comme nouvel outil pour un examen non invasif des peintures, et pour créer un OCT optimisé pour une utilisation dans les musées. L'article discute des récents développements de ces travaux et présente des exemples d'utilisation de l'OCT sur les peintures en cours de traitements conservatoires dans la Galerie Nationale de Londres.

Synopsis

La tomografía de coherencia óptica (TCO) es una técnica de imagen desarrollada originalmente para obtener imágenes tridimensionales de alta resolución del ojo humano. En 2004,

Keywords

optical coherence tomography, painting, imaging, cross-section, non-destructive, underdrawing, overpainting

Introduction

Optical Coherence Tomography (OCT) is an imaging technique originally developed for high-resolution 3D imaging of the human eye (Huang et al. 1991). Targowski et al. (2004) and Liang et al. (2004) first reported its application to paintings, demonstrating that it could produce cross-section images non-invasively. An increasing emphasis is placed on non-destructive methods in the field of cultural heritage science, but those currently routinely used cannot provide the information on stratigraphy and composition of the separate layers that can be achieved through analysis of cross-sections of paint samples. The ability to obtain the same information non-invasively would reduce the need to take samples, and also enable examination of any area of an object, providing a more representative view than a single cross-section. OCT allows 3D imaging, so that as well as cross-sections perpendicular to the paint surface, an *en-face* image from a plane parallel to the surface at a given depth can be extracted. Liang et al. (2005a) demonstrated that *en-face* OCT could be used to image underdrawing at a resolution and contrast greater than that achievable with current infrared reflectography equipment. An advantage over infrared reflectography and X-radiography is that it is

Targowski et al. y Liang et al. presentaron por primera vez su aplicación en las pinturas, demostrando que con esta técnica era posible producir imágenes de secciones transversales de una forma no invasiva. En 2005, Liang et al. investigaron otras aplicaciones, como la obtención de imágenes de una sinopia a una resolución y contraste mayores que los alcanzados con la reflectografía infrarroja. Desde entonces, los autores han estado llevando a cabo un proyecto para investigar sistemáticamente el potencial de la TCO como nueva herramienta en el análisis no invasivo de pinturas y para diseñar una TCO optimizada que pueda usarse en los museos. Este artículo presenta los avances recientes de este trabajo y ejemplos sobre el uso de la TCO en pinturas que están siendo restauradas en la Galería Nacional de Londres.

possible to image only the plane of interest, so that the paint lying on top and the priming layer below does not contribute to, or interfere with, the image.

An overview of OCT and the examination of works of art can be found in Targowski et al. (2006a). It has been used for dynamic monitoring of the drying of different varnishes and examination of differences in topography once dry (Liang et al. 2005b, Targowski et al. 2006a), as well as measurement of refractive indices of varnish and paint samples (Liang et al. 2005b, 2007a, 2007b). On paintings with several different varnish layers the high sensitivity of OCT enables the interfaces between them to be seen (Liang et al. 2005a). Gora et al. (2006) used a Fourier-domain OCT for monitoring laser ablation of varnish and Targowski et al. (2006b) showed it can be used for tracking canvas deformation caused by humidity changes.

This paper will discuss recent developments in a project investigating the potential of OCT for the non-invasive examination of paintings, to design an OCT optimised for use in museums. As part of this project, a commercial OCT instrument was used to examine a range of paintings in the National Gallery, London. As well as identifying possible practical applications that could be useful to conservators, this survey aimed to give a sense of the type of painting and circumstances under which OCT would be an appropriate imaging method. It will also inform the design of an OCT tailored to the study of paintings, indicating what depth range, sensitivity and resolution would be desirable. Some of the results that have been obtained so far will be presented here.

Principles of OCT

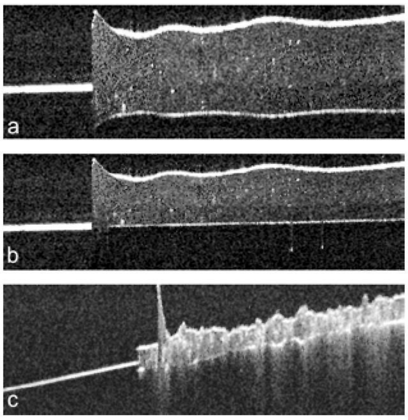

Figure 1. OCT cross-section images of paint on glass microscope slides: a) a transparent paint of rose madder in linseed oil; b) same as (a) but corrected for optical depth to show the true sample thickness; c) madder lake in egg tempera showing evidence for multiple scattering

Optical Coherence Tomography (OCT) is a fast, high-resolution 3D scanning Michelson interferometer. A near infrared source of very low power but high spatial concentration (small spot size) is generally used for illumination of both the reference mirror and the object. Interference fringes occur when the optical path of the backscattered light from within the object matches, within the coherence length, the optical path from the reference mirror, thus enabling depth determination. The depth resolution is therefore given by the coherence length, which depends on the bandwidth of the light source. The intensity at a point in the image corresponds to the strength of the backscattered light from the corresponding point inside the object (Figure 1). Mapping produces either cross-section images or *en-face* images at various depths; a series of these can be combined to give 3D information. The transverse resolution is determined by the numerical aperture of the objective lens. The depth range depends on both the type of OCT and the scattering properties of the material. It is particularly suited to the examination of translucent layers such as varnishes and glazes, although it has been shown that under certain circumstances it is capable of imaging the layer structure as far as the preparation layer.

Typical OCT speed of acquisition is at least a few frames per second. Most OCTs use superluminescent diodes (SLD), which can achieve a depth resolution of around 10 μm, although a depth resolution of the order of 1 μm has been achieved with expensive laser sources (Drexler 2004). Recently, preliminary results were shown from an inexpensive way of achieving 1 μm depth resolution (at the expense of sensitivity or speed) through a full field OCT using a tungsten halogen source (Gurov et al. 2007, Latour et al. 2007).

In this paper, an adapted commercial instrument 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 × 15 cm area, was used to examine paintings in the National Gallery. The instrument is small and portable, operating at a safe distance of around 1 cm from the paint surface.

A guide to interpreting OCT images

Although the OCT cross-section images appear deceptively similar to real cross-sections, there are crucial differences and it is important to combine knowledge about the instrument with an understanding of the behaviour of different types of paint when interpreting them.

Figure 1a shows an OCT cross-section image of a transparent paint, rose madder in linseed oil, on a glass microscope slide. On the left of the image where there is no paint, a bright straight line is seen at the interface between air and glass, since the glass surface is highly reflective; on the right the bright curved line shows the interface between air and paint and the pigment particles are seen as bright spots inside the paint because of the increased scattering at the pigment/medium interface; the fainter curved line at the bottom is the interface between the paint and the glass. OCT measures the optical depth rather than the physical depth; the ratio between these gives the refractive index of the paint. This explains why the interface between the paint and the glass in Figure 1a is not flat nor at the same level as the air/glass interface. Figure 1b shows the cross-section image after correction for optical depth.

Multiply-scattered light has a greater optical path length than singly-scattered light from the same depth. An example of this effect is shown in Figure 1c where madder lake in egg tempera is painted on a glass microscope slide. The air/paint and the paint/glass boundaries are clear, but the image also shows back-scattered light that appears to be from below the paint/glass boundary, indicating multiple scattering in the paint layer. The bright signal from below the paint/glass interface is clearly an artefact, but it also gives useful information about the optical properties of the paint. It indicates that madder lake in egg tempera scatters light more strongly than madder lake in linseed oil.

OCT is particularly suited to the imaging of underdrawings, since it can produce an image at the depth at which the underdrawing is located. In addition OCT offers greater resolution and dynamic range than any direct imaging method. Figure 2 shows that the *en-face* OCT image of underdrawing on a test panel is far superior than even the images from the state-of-art infrared camera SIRIS using InGaAs technology (Saunders et al. 2006). The liquid droplets of the ink and the direction in which it is drawn can be seen in the OCT image.

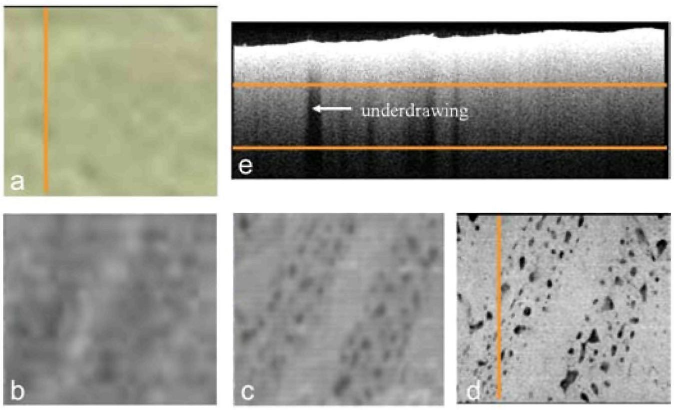

Figure 2. Near infrared images of a painted patch of two layers of lead-tin yellow over underdrawing of bone black in gum executed with a quill pen: a) colour image; b) Near infrared Vidicon image; c) Near infrared image from SIRIS, an InGaAs camera; d) 1300 nm OCT image, averaging the en-face *images between the horizontal lines in (e), where the underdrawing information is located; e) OCT cross-section image of a scan marked with a line in images (a) and (d)*

OCT imaging of paintings in the National Gallery, London

One of the paintings examined using OCT imaging was *A Distant View of Dordrecht, with a Milkmaid and Four Cows, and Other Figures*, by Aelbert Cuyp, dating from around 1650, which was undergoing conservation treatment. The old mastic resin varnish had yellowed considerably. There were also patches of a discontinuous brownish layer in some areas, as well as old brown discoloured retouchings. Samples were taken to investigate the composition and layer structure in these areas, as the status of the brownish layers was not immediately clear. Examination by OCT imaging at the same time gave the opportunity to consider how it could contribute to the technical examination being carried out in support of treatment, and the real cross-sections could be used to verify the interpretation of layer structure seen in the 'virtual' OCT cross-section images.

26 areas of the painting were examined using OCT. In each case a series of cross-section images were collected from an area 10 mm wide at intervals of 19 μm, scanning a length varying between 3 and 10 mm. The equipment is capable of scanning an area of 15 × 15 cm, but at the time was not yet automated to allow images to be acquired effectively from such a large area. The cross-section images were processed to produce a 3D cube, allowing *en-face* images at different depths parallel to the paint surface to be extracted. A corresponding series of video images was also collected at each point.

When the uppermost varnish had been removed there was still a patchy staining visible in some areas of the sky, particularly in the troughs of the brushstrokes. It was not clear whether this was the remains of an older surface coating or whether it was caused by an uneven change in the paint. A real cross-section showed a thin surface layer, fluorescent under ultraviolet light, measuring only around 5 microns in the area sampled. Figure 3a shows an image of the area of the sky examined with OCT. Figure 3b is made by averaging a series of *en-face* OCT images from below the surface, and shows the cracks clearly, locating the exact area imaged, as well as each individual cross-section image. In the OCT cross section (Figure 3c) there is a layer which appears dark at the surface of a highly scattering layer (which appears light), the lead-white-containing sky paint. The layer which is dark in the OCT cross-section is thicker in the hollows of the brushstrokes and in the centre of the image it can be seen to run over a crack in the paint and to continue across the top of the raised paint either side of the crack. The 295 closely-spaced OCT cross-section images that were collected give a better indication of the variation in thickness and distribution across the surface than can be gained from the real paint cross-section.

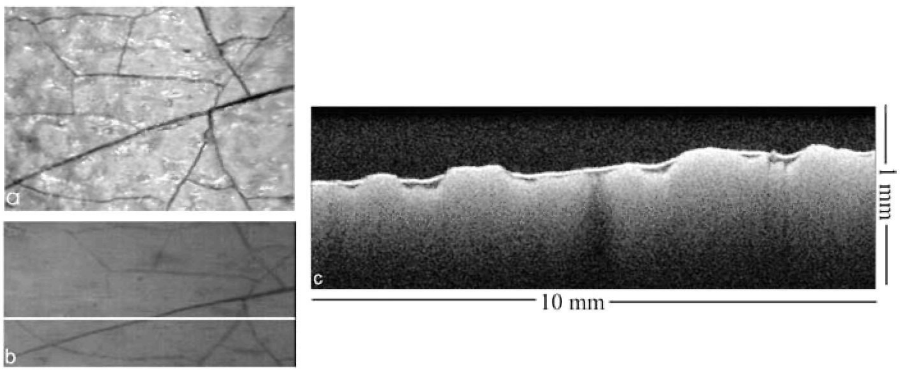

Figure 3. Aelbert Cuyp, A Distant View of Dordrecht, with a Milkmaid and Four Cows, and Other Figures: *a) Image of the area of the sky examined by OCT; b)* En-face *OCT image; c) OCT cross-section. The line in (b) indicates its location*

Figure 4a shows an area in the foreground of the painting where a patchy brown translucent surface layer is present. It is particularly visible in this area because it lies over yellow-green paint. This area was examined by OCT and a sample was also taken (Figures 4d and e). The real cross-section shows that the paint consists mainly of yellow lake (with a calcium carbonate substrate) mixed with a small amount of lead white (basic lead carbonate), Kassel earth and vivianite (hydrated iron phosphate). The strong fluorescence in ultraviolet light of the brown surface layer suggests that it is the remains of an old varnish; this was confirmed by Gas-Chromatography – Mass-Spectrometry.[1]

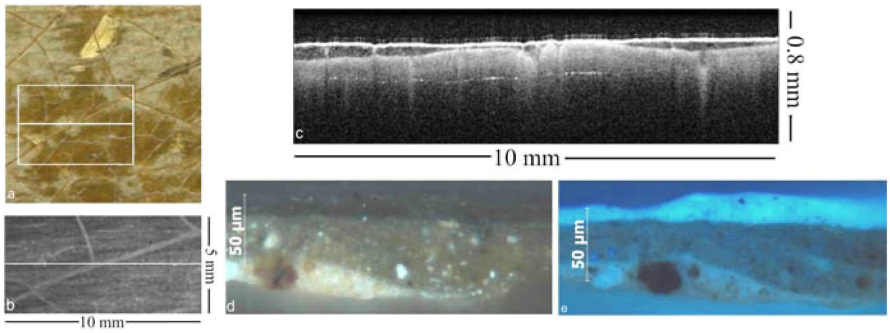

Figure 4. a) Detail of the lower right foreground of the painting by Cuyp showing the patchy brown layer on the surface. Photo © The National Gallery, London; b) en-face *OCT image of the area marked by a box in image (a); c) OCT cross-section through the line marked in (a) and (b); d) Cross-section from an area of the foreground where there is a translucent brown layer on the surface: normal light; e) Cross-section in (d) in ultraviolet light*

The results of OCT examination of a similar area are shown in Figure 4. Below the bright white line in the OCT cross-section, caused by the first surface reflection at the air/paint interface, is a layer which appears dark, corresponding to the brown translucent residual varnish seen in the real cross-section. The OCT cross-section shows that it varies in thickness between 15 and 75 µm in the area of the painting examined, consistent with the thickness of 20 µm measured from the real cross-section. The dark layer corresponding to the old varnish can be seen to run over a crack in the paint layer at the right and in the middle of the OCT cross-section, further evidence that it is not an original layer. A patch in the middle of the detail of the surface (Figure 4a) appears much greener, and the residual brown varnish can be seen to be much thinner in the middle of the OCT cross-section image.

The OCT images of the edge of a branch at the left of the painting illustrate that the original brown translucent paint appears different from the brown translucent surface accretions, and can therefore be distinguished from it (Figure 5). In the *en-face* image, the brown branch can be seen as a darker patch, because of its stronger absorbance at 930 nm than the surrounding paint. This is also why, in the cross-section image, the paint of the branch (at the left) appears darker than the paint at the right (below the scattering that occurs at the surface of the layer). A brown patch which appears to run over the cracks is visible towards the bottom right of the visible image (Figure 5a). A second OCT cross-section (Figure 5d) from near the bottom of the area scanned confirms that this is a later surface accretion, as a dark layer can be seen at the right of the image running over a crack in the layer below. The *en-face* image is from a plane below the accretion; the crack is visible

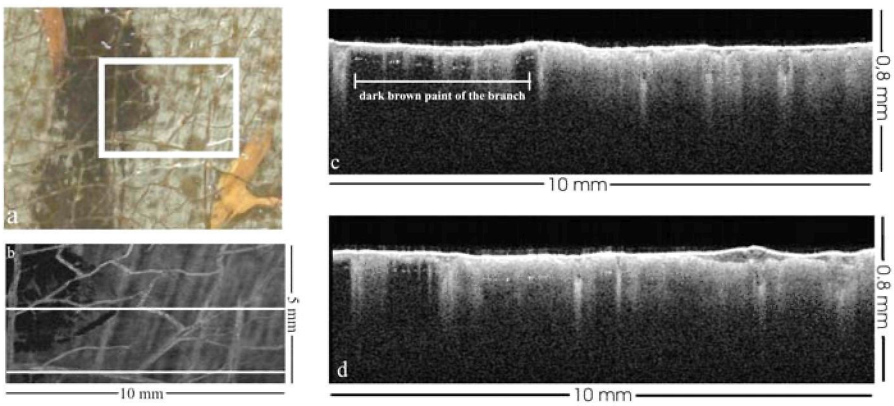

Figure 5. a) Detail of a branch at the left of the painting. Photo © The National Gallery, London; b) en-face *OCT image of the area in the box in image: a); c) OCT cross-section through the line in the centre of image (b); d) OCT cross-section through the line near the bottom of image b)*

confirming observations from other images, but it also demonstrates that the accretion is covering paint rather than a loss.

In another area of the foreground there were remnants of overpaint from previous restoration campaigns. A sample (Figures 6a and b) was taken from the edge of a crack and at the left of the cross-section multiple varnish and overpaint layers can be seen where they remain in the crack. Under ultraviolet light these are almost all fluorescent, but some contain pigment and are probably overpaint with a resinous binding medium, while one layer is more fluorescent, does not contain any particles, and is probably varnish. In the OCT cross-section from a similar area a comparable series of layers can be seen on top of the highly scattering paint, at the left of the image (Figure 6c), including a darker, less scattering layer which could be varnish and which appears cupped.

Figure 6. a) Cross-section from the foreground of the painting by Cuyp, with a crack at the left in which there are several varnish and overpaint layers, normal light; b) Cross-section in ultraviolet light; c) OCT cross-section of a similar area with multiple varnish and overpaint layers visible on the paint surface at the left of the image

The OCT images from an area just above a branch running diagonally across the painting at the left included an area of paint loss covered with varnish and overpaint (Figure 7). At the left of the OCT cross-section image this can be seen as a hollow filled with overpaint, which also extends across the rest of the cross-section. The *en-face* image, taken from below the surface, clearly shows the area of loss at the left (which is hidden by overpaint in the normal light image). The X-radiograph of this painting confirmed that there was a small loss in this area, but it is dominated by the thick lead-white-containing priming layer, and in general it is difficult to see the upper paint layers, losses in them and overpaint. This illustrates the advantage of OCT in a case such as this where an *en-face* OCT image can be extracted from a certain depth range, so that the priming layer is not included in the image.

The ability to produce *en-face* images which do not include the paint is one of the reasons why underdrawing can be imaged so effectively using this technique, as demonstrated with the test panel described above. The SIRIS digital infrared camera had shown that *The Virgin and Child with an Angel*, ascribed to Francesco Francia (NG 3927), has detailed underdrawing which includes pouncing as well as lines which appear to have been drawn with a

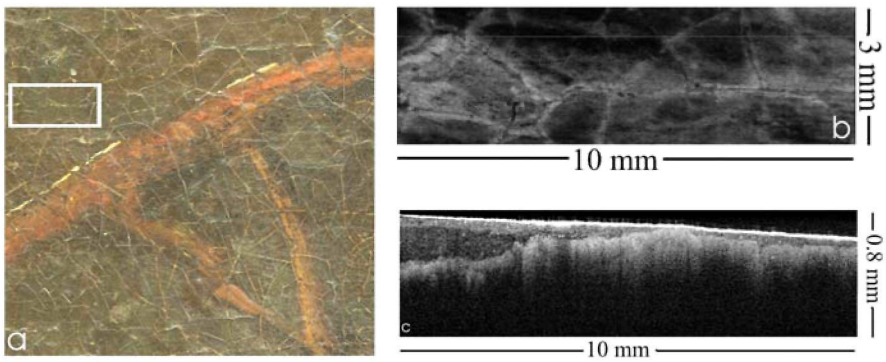

Figure 7. a) Detail of a branch in the left foreground of the painting by Cuyp. Photo © The National Gallery, London; b) en-face *OCT image showing a loss in the paint at the left; c) OCT cross-section from the line marked on image (b), showing the loss filled with what appears to be overpaint at the left*

dry medium. The high resolution and dynamic range of the OCT image of the angel's eye is immediately evident when compared with that from the SIRIS camera (Figure 8). This is particularly useful when considering the nature of the medium used for the drawing, as it is often the quality of the lines that gives this information.

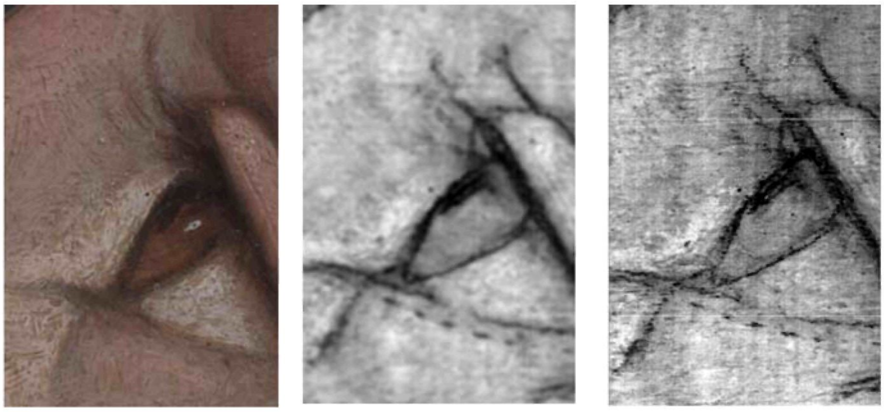

Figure 8. a) Francesco Francia, The Virgin and Child with an Angel *(NG 3927), detail of the angel's eye. Photo © The National Gallery, London; b) Infrared image of the same region using the SIRIS camera; c)* En-face *OCT image at 930 nm; the size of the area on the painting is 10 by 15 mm*

Conclusion

OCT imaging shows great promise for the examination of paintings, and could be a useful tool for answering questions that arise during conservation treatment. Particularly valuable is its ability to reveal the layer structure of a painting, including both paint and varnish, in a non-invasive manner. This allows many more areas of the painting to be examined than would be possible by conventional sampling methods, but it is likely to be most effective when used in combination with the information gained from sampling to provide a more representative view. Acquisition of 3D information broadens even further the range of possible applications, making it a technique that could extend and complement the imaging techniques currently available.

The examinations carried out with a commercial OCT system presented here demonstrated its potential and will contribute towards the design of an OCT system specifically suited to the examination of paintings. It may be possible to obtain layer structure to a greater depth and higher resolution by varying the parameters of the instrument such as wavelength and bandwidth of the light source. A systematic study of the transparency of pigments as a function of wavelength has been conducted for around 50 historic pigments in linseed oil and egg tempera, and the best spectral window for OCT was found to be ~2.2 μm (Peric et al. 2007, Liang et al. 2007b). Multi-wavelength OCT, which could provide spectral information on the paint layers, is also being explored (Liang et al. 2007b), as well as measurement of optical parameters such as refractive index and scattering properties by OCT, which have the potential to provide information on the composition of the layers.

Acknowledgements

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Note

1 GC-MS analysis detected heat-bodied linseed oil, as well as degraded pine and oxidised triterpenoid resin components consistent with a degraded oil-resin varnish. The fatty acid methyl ester ratios were: P/S = 1.5; A/P = 2.5; Sub: Az = 1:2.3. Significant quantities of 7-oxodehydroabetic acid methyl ester and 7-oxo, 15–OH–dehydroabetic acid methyl ester were detected. Several oxidised components of the dammarenone type were also seen, suggesting the presence of an aged triterpenoid resin, possibly dammar.

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