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Research questions and analytical solutions

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Chapter 8

Advanced optical imaging methods for investigating manuscripts

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Introduction

This paper gives an overview of advanced optical imaging methods relevant to the study of manuscripts. While some of the methods covered are well established, others are very much in active development. ‘Optical’ in this context is loosely defined to cover the near ultraviolet, visible and the near infrared part of the electromagnetic spectrum. Optical imaging methods are in general non-destructive and can be applied *in situ*. They are non-invasive if care is taken to ensure a safe dosage of illumination during the imaging process. The examples given in this paper are biased towards work that the author has been involved in. This is by no means a comprehensive review. The aim of the paper is to illustrate how advanced optical imaging techniques can assist in the investigation of manuscripts.

Simple optical techniques are in use routinely by historians, curators and conservators in examining manuscripts. These include examination with a magnifying glass, a microscope and examination under UV light. For example, microscopic examination can reveal the individual paint particles on the surface of a miniature which can aid the identification of the paint mixture. Low powered UV light (black light or Wood lamp) can be used to detect faded writing and reveal the presence of organic material through UV fluorescence. UV light incident on a material can induce fluorescence emission in the visible and hence observable by eye. Visual observation using raking light (that is light applied at grazing incidence on the manuscript surface) is an effective method of revealing surface texture, e.g. indentation from writings on a previous page that is now missing.

Application of optical imaging methods to the examination of cultural heritage has a long history. Instead of visual observation, high resolution macro-photography has been used to reveal details. Infrared photography was used to examine paintings as early as in the 1930s (Lyon 1934). By the 1950s, it was a well established routine technique used in museums. In the 1960s, infrared imaging using a vidicon detector termed ‘infrared reflectography’, which is sensitive to longer infrared wavelength (up to 2 μm) than infrared photography (~ 900nm), was invented to provide better penetration of paint layers and clearer underdrawing images (van Asperen de Boer 1969).

In the following sections, we will concentrate on two types of advanced imaging techniques: spectral imaging and optical coherence tomography which is for non-invasive imaging of subsurface layers.

Spectral imaging: multispectral and hyperspectral imaging

A classic fibre optic UV-VIS spectrometer records the spectral reflectance of a single point (e.g. Bacci 1995). Multispectral and hyperspectral imaging are examples of spectral imaging where images of an object are obtained in a series of spectral windows such that spectra at millions of spatial points are collected simultaneously (see Fig. 1). The distinction between multispectral and hyperspectral imaging is rather blurred and very much discipline dependent. In general, hyperspectral imaging consists of more finely divided spectral channels (or windows) than multispectral imaging. For example, images taken in the visible spectral range at six evenly divided spectral channels (rather than three in the case of a colour image) would be called multispectral imaging rather than hyperspectral imaging. Multispectral imaging can sometimes refer to a set of images (usually scaled to the same size) taken at vastly different parts of the electromagnetic spectrum, e.g. three visible images in red, blue and green, an infrared image and an X-ray image of an object. For the rest of the paper, we will refer to multispectral and hyperspectral imaging together as spectral imaging.

Spectral imaging was first developed in remote sensing and astronomy. Since the early 1990s, it has found increasing applications in heritage science. In the case of paintings, multispectral imaging was first developed to increase the colour fidelity of the images for conservation monitoring. A number of EU projects have been dedicated to the design and implementation of high colour and spectral fidelity, high resolution scanning systems for the recording of museum paintings and other objects (e.g. Burmester et al. 1992; Saunders & Cupitt 1993, Lahanier et al. 2002, Liang et al. 2005). Spectral imaging enables rendering of colour accurate images of objects under any lighting conditions, unlike a normal tri-colour image which can only capture an accurate colour image under the specific illumination used at the time. Nowadays spectral imaging systems are capable of recovering the spectral reflectance per pixel of a painting with accuracy comparable to a fibre optics spectrometer for the purpose of colour rendering and pigment identification. Spectral imaging can also be used for qualitative inter-band comparison for detection of damage, past intervention, the presence of preparatory drawings and faded writing. This is particularly effective when comparing the UV and NIR images with those of the visible wavelength single band images or colour images. Since the eye is not sensitive to the UV and near infrared, these bands are most likely to reveal extra information.

Spectral imaging devices can be portable or fixed in a studio. For small objects such as manuscripts, it is convenient to use portable devices. For large maps and drawings in the collection of libraries, the problems with capturing large objects at high resolution is similar to those encountered in scanning large paintings. Traditionally, large paintings are scanned in studios using fixed scanners, however, the size of the studio ultimately limits the maximum size of painting that can be scanned. For example, the Vasari scanner at the National Gallery can scan paintings to a maximum size of 1 m x 1 m. A recently developed spectral imaging system PRISMS (Portable Remote Imaging System for Multispectral Scanning) for *in situ* scanning of large paintings such as wall paintings, has the flexibility of imaging paintings or other objects of any size at sub-millimetre resolution (Liang et al. 2007, 2008).

Classic multispectral imaging systems use interference filters of intermediate bandwidth (e.g. around 40-50nm) since the spectral reflectance of pigments are fairly smooth and devoid of sharp peaks. Recently, hyperspectral imaging using tunable filters such as Liquid Crystal Tunable Filters (LCTF) and Acousto-Optics Tunable filters (AOTF) have been developed for heritage applications in the 400 nm - 700 nm range (Hardeberg et al. 2002; Balas et al. 2003; Berns et al. 2005), the 650 nm - 1040 nm range (Mansfield et al. 2002) and in the 900-1700nm (Liang et al. 2010). The advantage of these tunable filter devices is ease of control, flexibility in the choice of filters and fast response (ms or ns). The disadvantage is the lower efficiency since both kinds of tunable filters are polarisation sensitive which means only half of the reflected light is recorded.

A review aimed at the conservation community is given in Fischer and Kakoulli (2006) and a more current review on the technology and applications to heritage science is due to be published (Liang 2010). Figure 1 shows an example of a spectral imaging setup for examining manuscripts.

In principle, with a single spectral imaging scan, one can obtain the spectral reflectance spectrum of any region in the image, derive the colour image for any given illumination (e.g. Tungsten or daylight), extract the infrared images at the appropriate spectral bands equivalent to infrared photography or infrared reflectography. Therefore, all the common imaging needs such as colour, infrared and false colour infrared images can be obtained with one set of calibrated spectral imaging data. With the appropriate UV light source and filters, the same spectral imaging device can also be used for UV fluorescence imaging.

Calibration of spectral images is crucial to obtaining quantitative scientific information. Usual calibration involves corrections for the thermal noise of the digital camera (dark correction), corrections for the inhomogeneity of the illumination and the pixel-to-pixel gain variation of the digital camera (flatfield correction), and finally corrections for the difference in throughput between the spectral bands (spectral correction). For dark correction, dark frames are taken with the lens cap on, at the same exposure time as the image to be corrected. Flatfield frames can be taken with a matt white or grey card at the same position as the target to be imaged through the same filter. An image of the target is calibrated by subtracting the dark frame and dividing by the normalised (i.e. divide the frame by the average pixel intensity) dark corrected flatfield frame. Spectral calibration is achieved by imaging a spectral standard (e.g. a Labsphere Spectralon white standard) through all the filter channels. For some systems it may be necessary to align and register the frames of various spectral bands. The software for both the hardware control and post-processing of the data is crucial for the effective use of a spectral imaging system. An open source image processing software VIPS/nip designed for heritage science applications has been used for the processing of spectral images given in this paper (Cupitt and Martinez 1996).

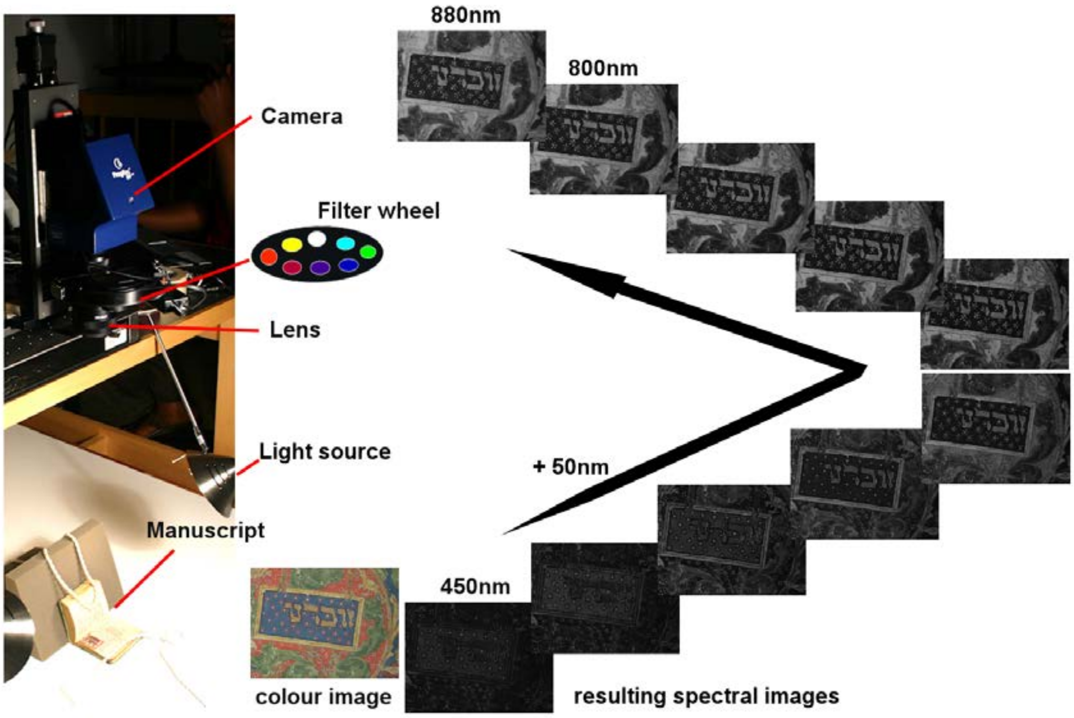


Figure 1. Left: A multipsectral imaging system (modified PRISMS) imaging a manuscript at the Bodleian. Right: the colour image and the series of monochrome images at wavelengths between 400nm and 880nm from which the colour image was derived.

Applications of Spectral Imaging

To illustrate the various applications of spectral imaging, examples and case studies will be given in the following sections. The spectral imaging instrument used in the following examples is a modified version of PRISMS, which is an in-house built instrument (Liang et al. 2008). PRISMS was originally designed for imaging large paintings from a distance using a telescope. It was adapted for imaging manuscripts by replacing the telescope with an appropriate lens and the whole imaging system attached to a motorised X-Y micrometer stage (Fig. 1). PRISMS uses interference filters for the spectral range of 400nm to 880nm with central wavelengths at 400, 450, 500, 550, 600, 650, 700, 750, 800 and 880nm. Each filter has a spectral bandwidth of 40nm except for the one at 880nm which has a 70nm bandwidth. The eye is not sensitive to light beyond 800nm. For the short wave infrared region between 900nm and 1700nm, PRISMS using an acousto-optic tunable filter (AOTF) where the central wavelength can be arbitrarily chosen between 900 and 1700nm and the bandwidth can vary between 10nm and 150nm.

Revealing faded writing

If the writing on a manuscript is invisible to the eye, it means that the ink is transparent at the visible wavelength or that the reflectance of the ink in the visible is similar to that of the substrate. The optical property of the ink may have very different characteristics outside of the visible range, hence near infrared or UV imaging can often reveal hidden or faded writing. Figure 2 shows an example of faded writing where it was barely visible by the naked eye but the signature of the owner of the manuscript showed up clearly in the 880nm near infrared spectral window.

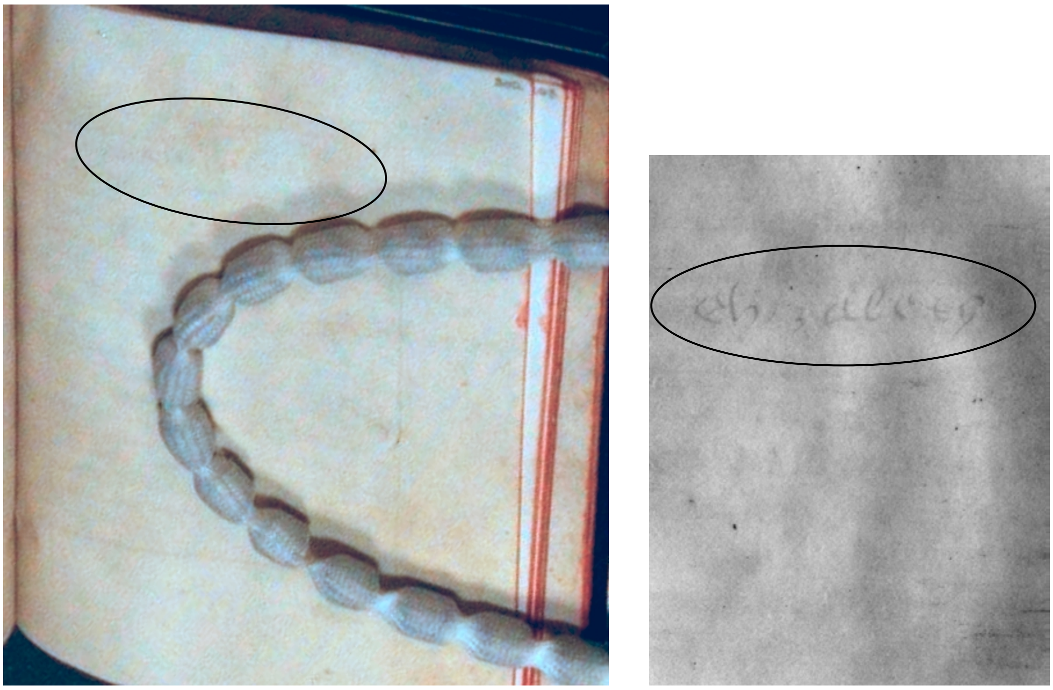


Figure 2. Left: Normal colour image of a page of MS Lat. Liturg. g.1. from the Bodleian library collection; Right: near infrared image (880nm spectral band) taken with a modified PRISMS of the corresponding area (circled in black) in the colour image on the left.

Identify preparatory drawings

Identification of preparatory drawings is important to our understanding of the production of illuminated manuscripts. Figure 3 illustrates an example of an image in the near infrared band of a spectral image cube (i.e. images of the same area in a series of spectral bands) showing clearly the preparatory drawing of some of the pictorial features that was different from the painted version (right hand side of Fig.

3b). One way to overcome the trade off between the resolution and field of view of an image is to mosaic a few overlapping high resolution images to create a larger image. For example, the images in Fig. 3c,d were created by mosaicing three separate images using the VIPS/nip software (http://www.vips.ecs.soton.ac.uk/). The mosaiced image in Fig. 3c shows that there were preparatory drawings showing the plan for the position of the text and the miniature.


(a) (b)

(c) (d)

Figure 3. a) An image from the 600nm spectral band of part of folio f83r of MS Opp. 776 from the Bodleian library collection; b) 880nm image of the same region in a); c)

a mosaic of three adjacent images of folio f83r at 880nm and d) colour image of the same region in c) derived from the mosaiced spectral imaging cubes obtained with a modified PRISMS.

Pigment and ink identification

Inks or paints that look alike in colour may not be the same material. Spectral imaging and their derived spectral reflectance are better at distinguishing between materials than colour information alone. Figure 4 illustrates an example where the blue on the mountain tops had the same colour but very different reflectance spectra in the near infrared.

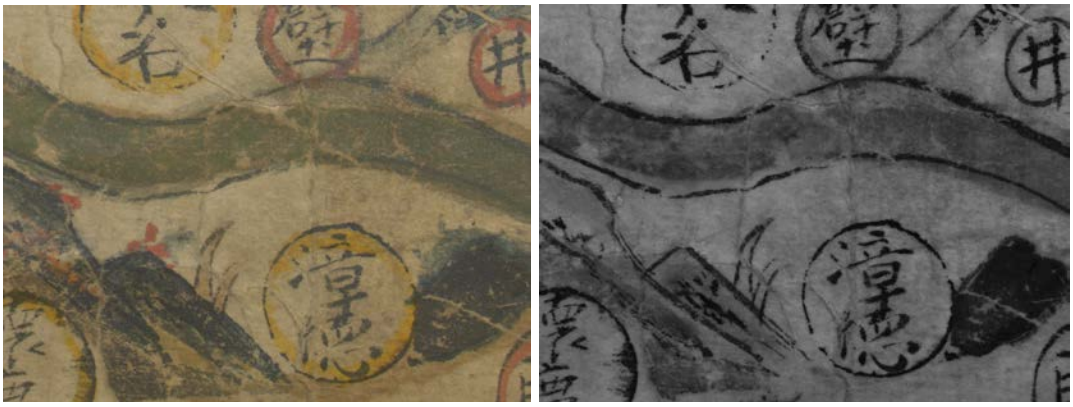


Figure 4. Left: colour image derived from multispectral images obtained with a modified PRISMS of a detail of the Seldon map (Bodleian library collection); Right: a near infrared image at 880nm of the same area showing that the blue mountain tops were painted with different materials.

A simple comparison of spectral reflectance obtain from spectral images can give an indication of whether the material used on different parts of a manuscript are the same or not. Figure 5 shows the pigment in Fig. 3d of the blue text is the same as the darker blue in the garment of the right figure in the miniature.

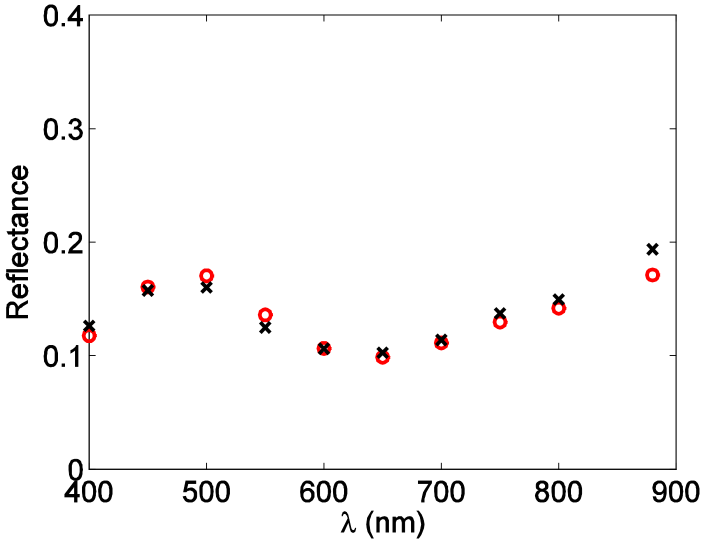


Figure 5. Spectral reflectance obtained from multispectral images taken with a modified PRISMS of the blue text (red circle) and the darker blue in the garment of the right figure (cross) in the miniature on folio f83r of MS Opp. 776 (see Fig. 3d).

The spectrum of an unknown pigment or ink can be compared with the spectrum of known pigments or inks from a reference library for identification. The positions of spectral features such as peaks and troughs are indicative of the pigment type. However, the amplitude of the spectral reflectance depends on the pigment to medium ratio. In the ideal case, the effect of concentration is just a constant shift in y-axis of the spectrum when spectral reflectance is expressed in terms of –log(K/S) where K/S is the ratio of absorption to scattering coefficient calculated from the spectral reflectance using Kubelka-Munk theory (Kubelka and Munk 1931). Hence it is customary to plot spectral reflectance in terms of –log(K/S) for the purpose of pigment identification. Figure 6 shows that the bright blue hat of the left figure in the miniature of Fig. 3d has a similar spectrum to that of natural azurite in linseed oil.

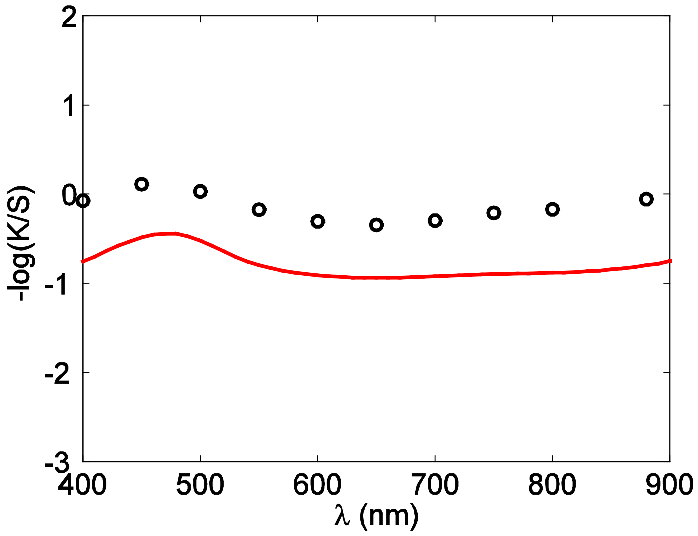


Figure 6. Spectrum of the bright blue hat of the left figure in Fig. 3d obtained with a modified PRISMS (black circle) is identified with a spectrum of natural azurite in linseed oil from a reference spectral library (solid red curve).

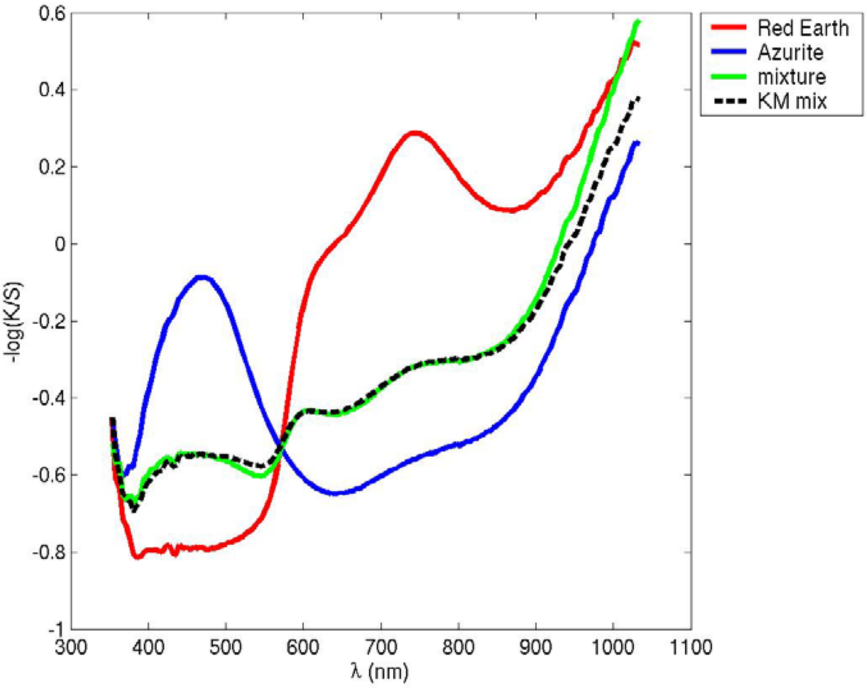


Figure 7. Measured spectrum of a mixture of two known pigments (red earth in solid red and azurite in solid blue) shown in solid green compared with the predicted spectrum of the mixture using Kubelka-Munk theory shown in dashed black.

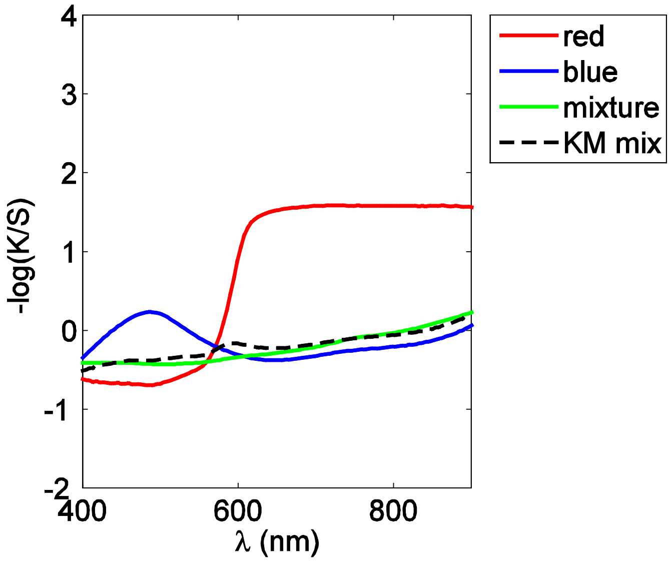


Figure 8. Model spectrum of mixture of natural azurite mixed with lead white (solid blue) with vermilion (solid red) in dashed black compared with the spectrum of the purple in the miniature below the figures in Fig.3d (solid green).

In the case of mixtures of pigments, it is still possible to identify the pigments using Kubelka-Munk theory which works very well for paints that are neither high in absorption nor very transparent (Liang et al. 2008). Figure 7 gives an example where the measured spectrum of the mixture of a red earth pigment and azurite corresponds well with the predicted spectrum from Kubelka-Munk theory. This method was used to identify the purple paint in the miniature of Fig. 3d, with a mixture of azurite and vermilion both of which were identified in other areas of the miniature or text.

Monitoring degradation

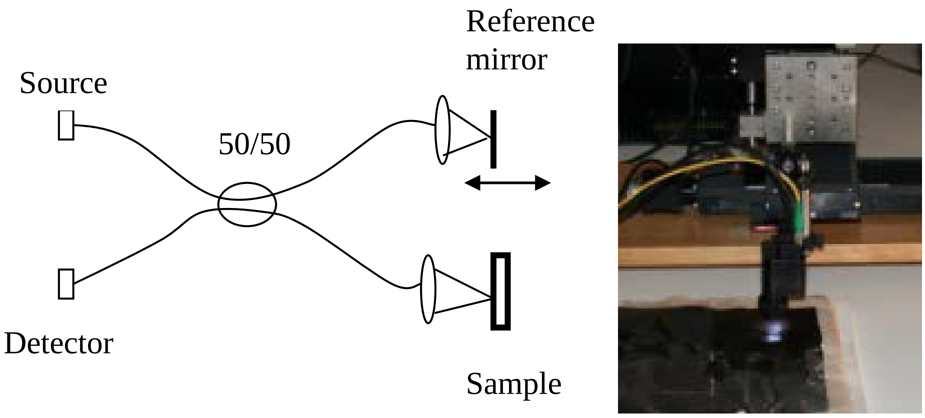
Long term monitoring of the degradation of the material is possible through measuring the spectral and colour difference over time. For such monitoring, precision calibration is necessary to observe the minute difference over time.

While spectral imaging is known in the heritage conservation and curatorial community, its application has not been fully exploited partly because of the cost of the equipment and lack of in-house technical expertise. However, the cost of a multispectral imaging system need not be more than that of an average microscope and with increasing hyperspectral imaging systems developed commercially for terrestrial use they will become more user-friendly.

Optical Coherence Tomography

Optical Coherence Tomography (OCT) is a high-resolution, fast, 3D scanning Michelson interferometer. A near infrared source is generally used for illumination of both the reference mirror and the object. The back scattered light from both the reference and object arms are brought together at the detector which records the interference between the back scattered light from the two paths (see Fig. 9 for illustration). Interference fringes of maximum contrast occurs when the optical path of the backscattered light from within the object equals to that from the reference mirror thus enabling depth determination. An equivalent explanation is that it measures the echo time of back scattered light from a certain depth within a sample. The image intensity corresponds to the strength of the backscattered light from the internal structure of the object. The interfaces between layers of strong mismatch in refractive index reflect the highest fraction of the incident light. For layered material, this enables the interfaces to be clearly delineated, and for inhomogeneous layers the scattering centres such as large pigment particles can sometimes be seen. OCT scanning is non-invasive, non-contact and often performed at a safe distance of ~1cm. OCT collects either cross section images or *en face* images at various depth, and a series of these can be combined to give 3D information of the surface and subsurface structure. The depth resolution depends on the spectral bandwidth of the illuminating source and the resolution in the other two axes 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.

OCT was first invented in the early 1990s for the *in vivo* examination of the eye. Considerable effort has been invested in the last twenty years on improving the resolution and speed of OCT for clinical and biomedical applications. OCT is becoming established as a routine instrument for ophthalmology. The application of OCT to conservation and archaeology is relatively recent (Yang et al. 2004, Targowski et al. 2004, Liang et al. 2004). Details of the various OCT applications to heritage science can be found in recent reviews (Targowski et al. 2006, Liang et al. 2008) and a list of articles on the subject can be found on http://oct4art.eu/. This is an emerging field of research and has potential to become one of the routine methods of examination in heritage science. Here we focus on the potential application of OCT to the study of manuscripts.



(a) (b)

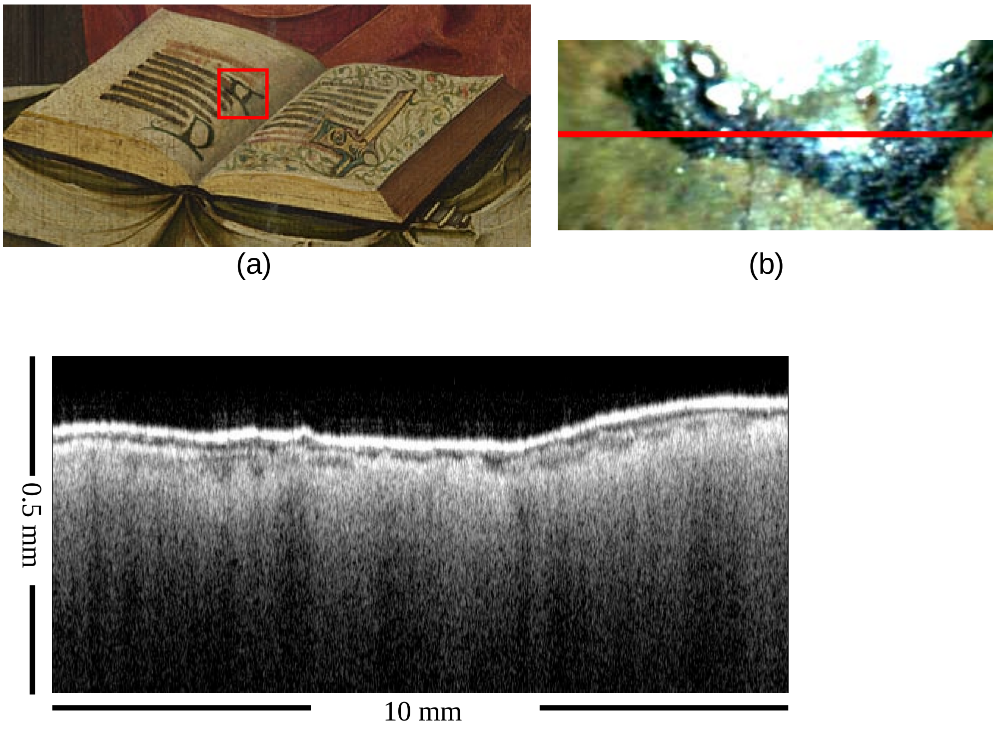
Figure 9. a) Schematic diagram illustrating the principle of OCT: light from the source is guided by an optical fibre and split into two paths using a 50/50 fibre couple, one towards the reference mirror and the other towards the sample; the back scattered light from the two paths are brought together and recorded by the detector; b) an OCT probe scanning the leather cover of the Fadden More bog bible.

Examples shown in this paper are obtained with a Thorlabs SROCT adapted by the author's research group at Nottingham Trent University. The OCT operates at a wavelength of 930nm, an axial resolution of 6µm, a transverse resolution of 9µm and a depth range of 1.6mm. The instrument is small and portable, capable of automatically scanning a 15cm x 15cm area and operating at a safe distance of around 1.5 cm from the object surface.

OCT applications

Imaging paint layers

OCT has been successfully applied to the examination of paint layer structures non-invasively (Liang et al. 2005; Spring et al. 2008). Figure 10c shows an OCT cross-section image of a varnish layer followed by a translucent paint layer in parts of the cross-section corresponding to the brown paint of the capital letter in the book depicted in the painting. Unlike paintings where it is possible to take small samples for analysis to find out the layer structure of the paint, it is generally not possible to take samples from illuminated manuscripts. OCT imaging may be the only possible way of obtaining information on the paint layer structure. The degree of scattering or absorption of the layers can help in identifying the material. The example shown in Fig. 10 is that of an easel painting rather than an illuminated manuscript, however, the paint used on illuminated manuscripts are often similar to easel paintings.



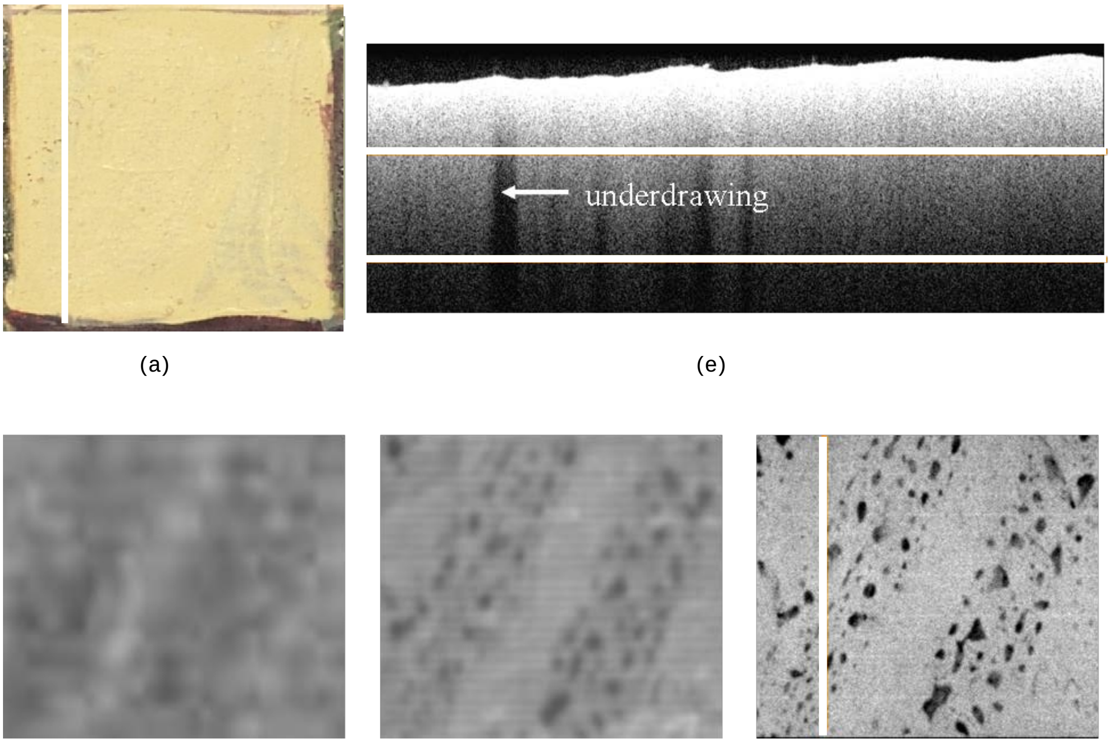
(a) (b)

(c)

Figure 10. a) A region of the painting *The Magdalen* by an anonymous Netherlandish artist (National Gallery, London N00719), the red box indicates the area scanned with OCT; b) detail capture by the monitoring camera attached to the OCT showing the scanned area; c) OCT cross-section image taken from the position indicated by the red line in b). The image is 0.5mm in depth and 10mm across the surface of the paint, the top bright interface is the air/varnish interface, the dark brown paint of the letter shows up as an extra paint layer.

Imaging of preparatory drawings

OCT is suitable for high resolution and high dynamic range imaging of preparatory drawings beneath the paint layers. Since OCT collects 3D subsurface volume images, it can distinguish between paint layers and drawing layers. It is the ability to extract only the layers with underdrawing information that enables it to provide the best dynamic range images of underdrawings compared to direct imaging methods described earlier. The high resolution of OCT makes it best suited to imaging fine features of underdrawings. The OCT image of underdrawings in Fig. 11d is extracted from the 3D volume image and it shows the fine details of the underdrawing. It is possible to determine that the drawing material was liquid based, and from the droplet shape the direction of the stroke can be deduced.



(a) (e)

(b) (c) (d)

Figure 11. 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) digital near infrared image from an InGaAs camera sensitive to the spectral range between 900 and 1700nm; d) 930 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 leather & parchment

OCT has been used in biomedical applications to examine human skin and it was found that in some cases it was possible to detect the birefringence of the skin which in turn allows measurement of the orientation of the collagen. Gora et al. (2006) used a polarisation sensitive OCT to examine parchment and found that the birefringence decreased somewhat as the parchment aged. OCT imaging of paper was used to estimate the filler content of paper (Alarousu et al. 2005).

A case study is presented here of an OCT examination of the leather cover of the Fadden More bog bible in the collection of the National Museum of Ireland. Carvings into the leather cover were found by visual examination but it was faint and difficult to see (Fig. 12a). A 3D rendering of a small piece of the OCT scanned leather cover shows both the details of the cut into the leather and the follicles (Fig. 12b,c). The shape of the follicles and their inclination can help identify the type of skin used to make the leather. Averaging a number of slices parallel to the surface gives a clear image of the surface features and the carving patterns (Figure 12e). The dark patches correspond to regions that were painted with a material (or the degraded material) that strongly absorbs light at 930nm (the operating wavelength of the OCT). The cross-section image obtained from the OCT show the cross-section of the follicles and the carvings (Figure 12d). Figure 12f shows the surface profile of the leather near a carved feature extracted from an OCT cross-section image using a surface fitting algorithm. The cuts appear to be as deep as 100 microns and about 50 microns wide at the surface which gives information on the tool used for the carving.

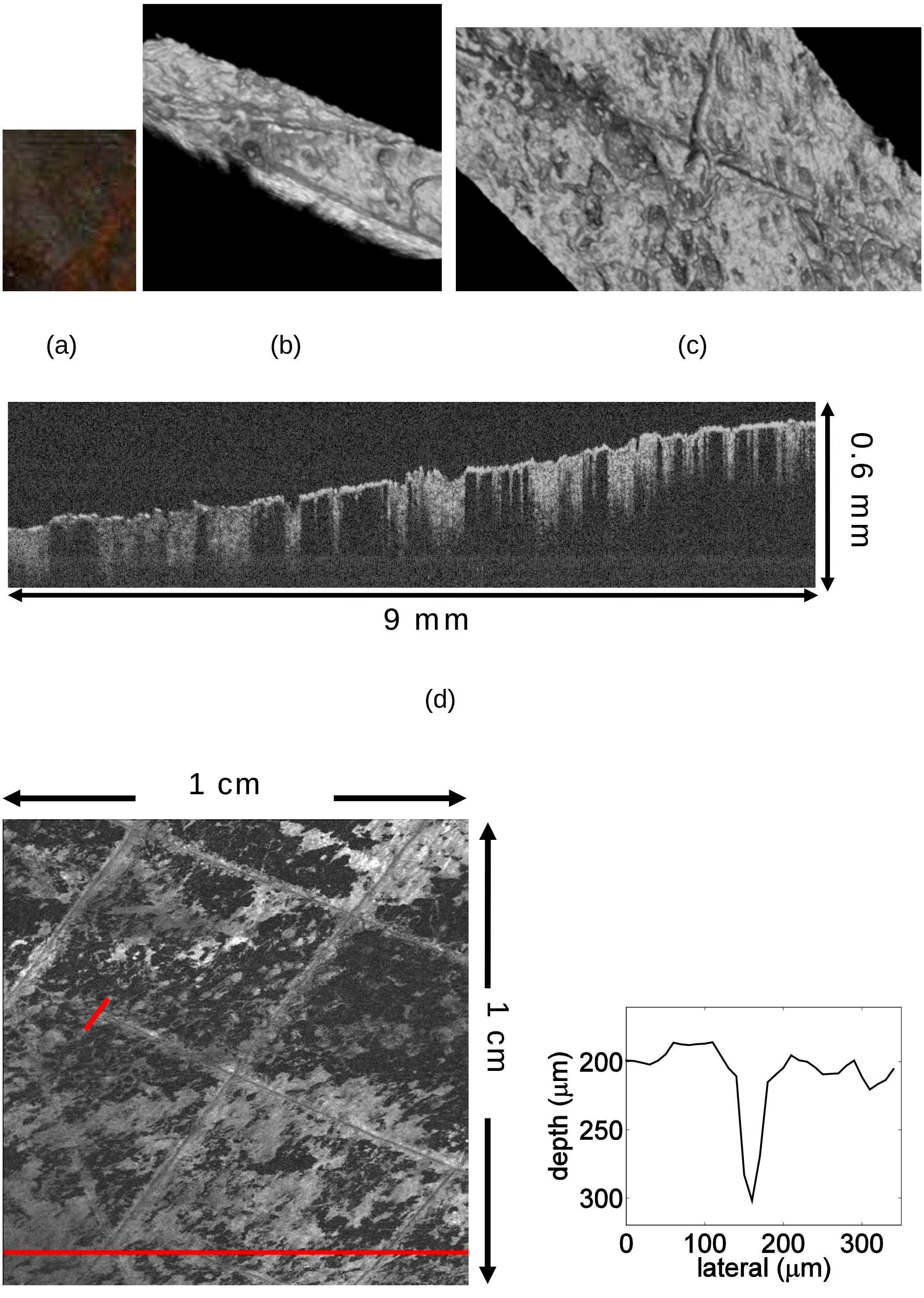


Figure 12. a) A detail of the leather cover of the Fadden Moe bog bible showing very faint marks (courtesy of National Museum of Ireland); b) a 3D rendering of a small volume of the OCT image cube showing follicles and cuts into the leather; c) a zoomed in 3D view of another small area of the leather cover giving a magnified view of the cuts into the leather; d) an OCT cross-section image of the region around the

red line in e) showing surface cuts, follicles and areas with surface paint (regions where it is dark beneath the surface); f) profile of the leather surface showing one of the cuts in the leather at the position of the short red line segment in e).

In summary, OCT provides a non-invasive method of probing the depth structure of materials which could be used to examine paint layers on miniatures, to obtain high resolution surface profiles for the identification of tool marks, to image the 3D structures of follicles in skins and to obtain depth resolved high resolution image of preparatory drawings. In addition, absorption and scattering properties of the material could be used as an aid for material identification.

Determining light-fastness for display strategy

It is worth mentioning another optical technique, microfading spectrometry (or microfadometer), which is not an imaging technique and is not non-invasive but micro-destructive (Whitmore et al. 1999; Lerwill et al. 2008). Given the vulnerability of manuscripts to light, there is always a trade off between optimum light level for display and light induced degradation. A microfadometer illuminates a tiny spot of ~0.2-0.4 mm in diameter with a high intensity lamp for in situ accelerated light aging which is monitored by a fibre optic spectrometer. The time required to fade a spot to a colour difference of a few ΔE gives an indication of the light-fastness of the material. Since the faded spot is so tiny, a small colour difference in such a spot is not noticeable with the naked eye. Such *in situ* microfading can be used to inform the long term display strategy of manuscripts. For example, it may be better to display certain pages in a manuscript rather than another with more vulnerable pigments. Figure 13 shows a portable microfadometer fading a paint sample, and Fig. 14 shows the result of fading blue wool standards over 15 minutes.

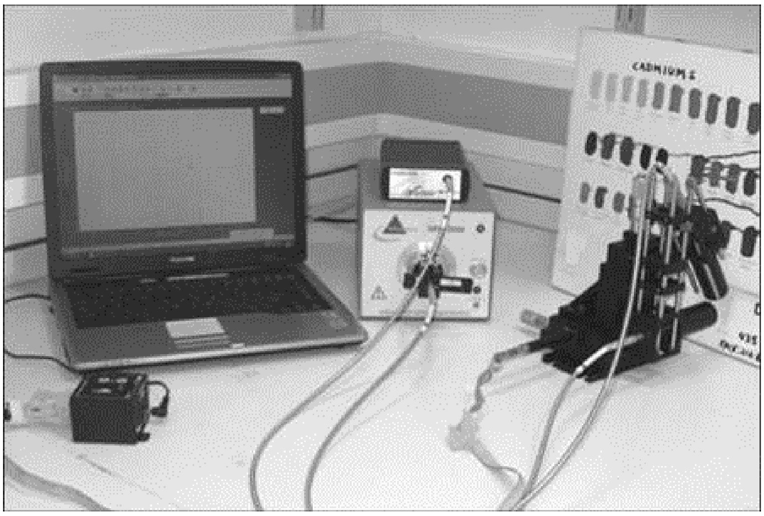


Figure 13. A microfading spectrometer (microfadometer) fading a sample of paint (Lerwill et al. 2008).

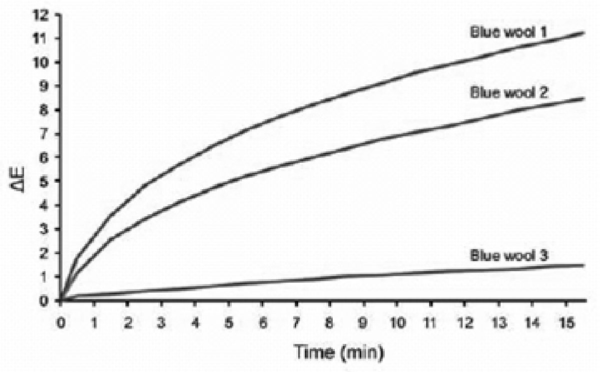


Figure 14. Colour difference as a function of time for the fading of blue wool 1, 2 and 3 using the microfadometer shown in Fig. 13.

Conclusions

Advanced optical imaging techniques such as spectral imaging and optical coherence tomography are capable of providing information on spectral reflectance and other optical properties of material useful for material identification and monitoring of degradation, revealing hidden writing and preparatory drawings, giving depth resolved 3D images of subsurface layers and microstructure of paint and substrates such as leathers and parchment. The non-invasive nature of these optical imaging methods makes them powerful tools for scientific examination of manuscripts.

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