TeraHertz imaging of hidden paint layers on canvas

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Abstract: We show terahertz reflection images of hidden paint layers in a painting on canvas and compare the results with X-ray Radiography and Infrared Reflectography. Our terahertz measurements show strong reflections from both the canvas/paint interface and from the raw umber/lead white interface, indicating sufficient refractive-index contrast. Our results show that X-rays cannot be used to image through the lead white pigment which effectively blocks the X-rays. Although Infrared Reflectography is capable of vaguely observing the hidden paint strokes from the canvas side, we show that only terahertz imaging is capable of providing information on the thickness of the hidden paint layers. Terahertz imaging is thus shown to be a powerful imaging method for art historians, conservators and conservation scientists.

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References and links
1. Introduction

What lies hidden under the surface of a painting? And what is the function of that substructure in the artwork? These questions are common to art historians, conservators and conservation scientists. First of all, the substructure of a painting provides insight into the genesis of the object. Underlying layers may include the underdrawing, underpainting and modifications to the original sketch. In a growing number of cases conservators have discovered abandoned compositions on paintings, illustrating the artists’ practice to re-use a canvas or panel and paint new compositions on top of existing ones.[1] All sorts of painterly effects can critically depend on the buildup of layers. This may include the translucent shine of colorful textiles, the suggestion of shadow in fleshtones or the convincing illusion of an object’s texture. All these effects can deliberately include (or exclude) the optical contribution of lower layers. Furthermore, the painting’s stratigraphy is of interest in conservation issues. This can include stability problems like paint discoloration, delamination of paint layers or the presence of intermediate varnish layers. The extent of such stability issues only becomes apparent after taking a depth profile of the paint layer. Over the past decades a number of optical techniques have been applied to study paintings and their substructure, such as X-ray radiography (XRR) and Infra-Red reflectography (IRR). Both techniques are complementary in their sensitivity to different painting materials, but also have drawbacks. Both methods project the complex and multilayered stratigraphy of a painting into a single, flat image. They convey little about the three-dimensional buildup of the painting. In order to understand the buildup of layers, researchers are therefore often required to take paint samples and prepare so-called paint cross-sections, which inevitably damages the painting. Another important disadvantage of the use of X-ray radiography is that the X-rays don’t easily penetrate layers of high density pigments, such as lead paint, which therefore obscure what’s underneath them. This is an important consideration, because lead white is ubiquitous in historical paintings.

Recently, it was shown how terahertz (THz) radiation can be used to identify paint pigments
by their unique spectral fingerprint at THz frequencies,[2, 3, 4, 5] and to observe hidden under-
drawings and paint layers embedded in wall paintings[6]. Terahertz radiation is electromagnetic
radiation containing frequencies roughly between 0.1 and 10 THz. In general, one of the adv-
antages of using terahertz radiation for imaging applications[7, 8, 9, 10, 11, 12, 13, 14, 15] is
that, in contrast to X-rays, THz radiation constitutes non-ionizing radiation and thus poses no
health risk or radiation damage to the object under study. Furthermore, terahertz imagers can
potentially be made portable, so that it can be used in situ in a painting gallery. It is, however,
not a priori clear that THz imaging can be used to image the multilayer stratigraphy of a paint-
ing, since this requires a sufficiently large refractive-index contrast between the various paints.
This notably applies to paint layers composed of relatively light elements that would be very
difficult to detect with x-rays, which are more sensitive to dense materials. In addition, it is
known that THz imaging can sometimes suffer from problems associated with changes in the
curvature of the front surface of an object. Changes in curvature can give rise to refraction-
and reflection-angle changes, and thus detection signal changes, which show up as image artifacts.

Here, we show how terahertz time-domain spectroscopy (THz-TDS) can be used to image
the substructure of paintings on canvas. By monitoring the time delay between reflections off
different layers, the technique allows us to measure the optical thickness of these hidden lay-
ers, thus providing depth information. We illustrate this by presenting a THz reflection image
of a home-made painting on canvas which consists of several stripes of raw umber drawing
(rectangular patches) covered with lead white. Both paints were based on a linseed oil medium.
The stratigraphy of our paint sample thus reflects the practice of most 17th century painters,
who would first sketch a composition with umber or other iron-rich earth colours on a primed
canvas. In a second stage, this monochrome ‘underpainting’ would then be followed by a more
colourful final paint layer, usually a mixture of lead white and other pigments. Due to the con-
straints of conventional, X-ray based, imaging, such underpainting has been a rather elusive
aspect in art historical studies. It is therefore a prime candidate for the present feasibility study.
By performing the reflection measurements from the canvas side, which is relatively flat, we
reduce the reflection/refraction problems caused by the relatively strong curvature of the front
surface of the painting. To assess the capabilities of the technique, we compare our results with
infrared reflectography[16] and X-ray radiography images of the same sample. Our results show
that contrary to T-rays, X-rays don’t penetrate the lead white paint and can thus not be used to
image the underpainting.[17, 18] When using infrared reflectography from the canvas side, the
underpainting becomes vaguely visible, but no information on the thickness of the paint layers
can be obtained. Thus, we show that THz-TDS is a powerful technique in the analysis of the
substructure of a painting that can provide 3D information, such as paint layer thickness.

2. Experiments

Fig. 1(a) shows a schematic of the experimental setup. Broadband THz pulses, generated using
a photoconductive switch[19], are focussed onto the painting from the back. The direction of
the THz beam is perpendicular to the canvas. Using a mylar beamsplitter, the back-reflected
THz pulses are sent to a standard electro-optic detection setup[20] where every 20 ms, the THz
electric field is measured as a function of time.[21] The paint sample is raster scanned using a
computer controlled x-y translation stage and for each pixel, a full THz electric field transient of
20 ps duration is recorded. All data are collected by a digital signal processor (ADWIN Gold)
and stored on a computer for later analysis. The test painting (Fig. 1(b)) was prepared (4x4
cm²) from an industrially pre-ground canvas purchased from a artist’s supply store. We applied
six strokes of raw umber, consisting of raw, natural umber (supplier: Oud Holland). The strokes
of umber were painted in varying thickness, ranging from a translucent glaze to a thicker brush
stroke with surface texture. We then covered the canvas with a layer of lead white. This was
applied with a palette knife, such that neither the color nor the topography of the hidden pattern was visible to the naked eye. The choice of pigments and the paint stratigraphy in our sample thus resemble the typical 17th century painting practice. The first sketch of a painting, also known as underpainting, was painted in a monochrome tone, usually consisting of umber. The final, coloured paint was then applied on top of the underpainting. Note that all conventional imaging methods (infra-red reflectography, x-ray radiography) fail to visualize this particular type of underpainting.

In Fig.’s 2(a-c) we plot the measured THz electric field as a function of time, reflected off a metal mirror, off a location where the raw umber is located, and off a location in between raw umber patches respectively. Differences in arrival time between the pulse reflected off the metal mirror and the earliest arriving reflection off the air/canvas interface can be traced back to differences in the exact distances of the metal mirror and the canvas with respect to the focusing parabolic mirror. The oscillations after the main pulse in the reflection off the metal mirror, are caused by absorption by water vapor in the atmosphere. The measured THz pulses reflected off the canvas, consist of a number of major negative and positive peaks followed by more irregular oscillations. Again, the oscillations in the tail of the signal can partially be explained by the absorption of THz radiation by water vapor molecules in the ambient atmosphere. The initial major peaks and troughs are consistent with reflections off the front surface of the canvas, and
Fig. 2. (a) Measured THz electric field, reflected off a metal mirror. (b) Measured THz electric field as a function of time, reflected off a position on the canvas where one of the raw umber strokes is located. (c) Measured THz electric field as a function of time, reflected off a position in between two raw umber strokes. (d) Polarized light microscopic image of a cross section of the canvas approximately at the location where the reflected THz electric field shown in (b) was measured. (e) Polarized light microscopic image of a cross section of the canvas where the reflected THz electric field in (c) was measured.

from the interface between canvas and paint layers. Reflections from the lead white/air interface are outside the time window of Fig. 2(b) and 2(c). This is because the lead white has an average thickness of more than 1 mm and, as we will show below, a refractive index of around 3.25. We emphasize that this is a limitation of our current setup only and not an intrinsic limitation of the method. With a longer scan length, the fourth peak can be visualized quite easily. The difference between the signals reflected off the two different locations is that the signal reflected off the location where the raw umber can be found contains three major positive peaks, whereas the signal from all other locations contains only two of which the second one is slightly broadened. This third positive peak is in fact the result of a reflection off the raw umber/lead white paint interface. It should, however, be noted that this picture may wrongly suggest that each positive peak can exactly be identified with a reflection from an interface. This is not true, however, since each reflection must consist of at least a single cycle electric-field pulse, having both a positive and negative going part. The reflection from the raw umber/lead white interface has partial temporal overlap with the reflection from the canvas/raw umber interface and the resulting interference gives the impression of a very narrow third positive peak. Regardless, the time separation between the second and the third peak can be used as a reasonable indication of the relative thickness of the raw umber paint layers. Fig.'s 2(d) and (2e) show microscope images, obtained using polarized light, of cross-sections of the canvas at approximately the same locations where the data in Fig.'s 2(b) and 2(c) were taken. The images reveal the structure of the canvas, the presence of a thin ground layer, a layer of raw umber and/or a thick layer of lead white. Although the exact nature of the ground layer is unknown, since the canvas was
Fig. 3. Refractive index of lead white (black) and raw umber (red), extracted from measurements of the transmitted THz electric field assuming an average sample thickness of 1.9 mm. The error bars give an indication of the uncertainty in the calculated values. The uncertainty is based on the results of several measurements at slightly different positions on the same sample.

purchased pre-grounded, we believe that we see an indication of the presence of the ground layer in Fig. 2(c) where the second peak appears broadened with respect to the first peak. This broadening may be the result of temporally overlapping reflections from the canvas/ground layer interface and the ground layer/lead white interface. The effect of the raw umber layer is a clear increase in the time separation between this second and third reflection. A fourth peak should be present, corresponding to a reflection between the ground layer and the raw umber but is not observed. We note that the presence of this reflection depends on the refractive index contrast between the (unknown) ground layer and the raw umber. If these refractive indices are comparable, only a small, or even, no reflection is expected. Qualitative information can only be extracted from our measurements once the refractive indices of raw umber and lead white are known. In theory, these can be obtained from the reflected pulses using Fresnel’s equations, but the different orientations of the paint surfaces, possibly reflecting some light outside the collection angle of the parabolic mirror used to collect the reflected THz pulses, make this difficult. For this reason, we have performed separate transmission measurements on specially prepared paint samples. Holes of 7 mm diameter were drilled through a metal plate and subsequently filled with paint. The paint initially rested on paper which helped absorb the linseed oil from the paint. The paint was allowed to dry for five days at temperatures of around 35 degrees centigrade, resulting in samples of approximately 1.9 mm thickness. The surface of these samples was not smooth, however, giving rise to a significant uncertainty in the exact thickness and, thus, the calculated refractive index of the paints. In Fig. 3 we plot the refractive index as a function of frequency of raw umber and lead white, extracted from measurements of the transmitted THz electric field through these samples. The lead white data only extends up to 1.5 THz due to a strongly decreasing transmission towards higher frequencies, presumably caused by scattering and/or absorption.[22] Besides providing useful THz refractive index information on the two paints used, the figure also emphasizes the large refractive index contrast between the raw umber and lead white paints. Within accuracy of the measurements, the refractive index shows little variation as a function of frequency. For raw umber, we find an average refractive index value of around 1.9 and for lead white a value of around 3.25. Using the values of the refractive index, we can now compare the hidden paint layer thickness obtained from the meas-
ured time separation between the second and third peak shown in Fig. 2(b), with the thickness of the ground layer and raw umber shown in Fig. 2(d). The measured time separation between the second and third peak in Fig. 2(b) is 1.3 ps. The thickness of the raw umber layer varies, but based on Fig. 2(d) we assume a thickness, averaged over the approximate diameter of the THz beam, of about 38 μm. Taking into account that the THz pulse propagates through the layer twice and using the refractive index of raw umber of 1.9, we arrive at an estimated time separation of about 0.5 ps, which is significantly less than the measured value. This can easily be explained, however, by closer inspection of the paint cross section in Fig. 2(d). The cross section clearly shows the presence of the ground layer which has a thickness somewhat larger than that of the raw umber layer. The combined thickness of the ground layer and raw amber is about 100 μm. Unfortunately, the nature of the paint used for the ground layer is unknown.

The absence of a clear signature reflection from the ground layer/raw umber interface suggests, however, that the refractive index of the ground layer is close to that of raw umber. Taking 1.9 as the value for the refractive index of the ground layer, we arrive at a calculated time separation between the second and third peak of 1.27 ps, which favorably compares with the measured value.

From these results we can try to predict the smallest absolute thickness that we can still measure using this method, again assuming a refractive index of 1.9. From Fig. 2(b), we estimate that two peaks separated by about 0.65 ps may still be identified as two separable peaks. This means that paints having a thickness of 50 μm, can still be measured in our method. Smaller thicknesses can also be measured, but this would require more elaborate signal processing to deconvolute the contributions of the closely spaced layers. Note that from the point of view of an art historian, it is not so much the knowledge of the absolute thickness of the paint layers that matters, but knowledge of the presence of the paint layer and the relative thickness of the paint layers, so that underpaintings may be visualized. Compared to the absolute thickness, variations in the thickness of a hidden paint layer can easily be determined, because they give rise to changes in the time-separation between the two peaks which are easily measurable. We estimate that changes in the time separation of 0.15 ps can still be measured which, again assuming a paint with a refractive index of 1.9, corresponds to changes in the paint thickness of about 12 μm. We note that typical paint layer thicknesses in historical paintings differ substantially. 16th century paintings were made with very thin paint layers (10-20 micron), providing barely enough opacity to hide lower paint layers. In the course of time, paint layer thickness increases, notably in the 17th and then the 19th century when Impressionists started to use thick, impasto paints in the millimeter thickness scale. As shown above, using THz imaging, the absolute thickness of a paint layer can only be determined when the paint and its THz refractive index are known.

In Fig. 4, we plot the THz electric field as a function of time, along two lines indicated in Fig. 4(a). The sign and strength of the field is indicated by the color, as shown by the scale. This type of plot immediately allows us to observe the arrival times of the reflected THz pulses along a line. The resulting curved wave fronts (in 1D) provide a quick view of the curvature and thickness of the canvas and paint layers along the indicated lines, information which is difficult to obtain using other non-contact imaging techniques. In Fig. 4(b), where we plot the field along a line where two patches of raw umber are present, two separate lines are visible, indicated by the vertical arrows. The lines correspond to two fairly closely spaced positive electric field peaks, very similar to the second and third peaks shown in Fig. 2(a): The left line corresponds to the reflection at the canvas/ground layer-raw umber interface, the right from the interface between the raw umber and the lead white paint. When we follow these down along the lines they are interrupted only roughly halfway at the location between the two patches, where they temporarily seem to merge into a single broader line in between the two patches. In contrast,
Fig. 4. (a) Photograph of the front surface of the painting on which the six raw umber strokes, hidden underneath the lead white, have schematically been drawn. The dashed lines represent the location of the line scans of which the results are shown in (b) and (c). (b) THz electric field (color coded) reflected from the canvas side of the painting, as a function of time and as a function of position along the line covering two raw umber strokes as indicated in (a). The two arrows at the top indicate the two maximum in the reflection from the canvas/ground layer-raw umber interface and the raw umber/lead white interface respectively. (b) THz electric field reflected from the canvas side of the painting, as a function of time and as a function of position along the line in between the raw umber strokes shown in (a). The arrow at the top indicates the peak electric field associated with a reflection from the canvas/lead white interface. In both (b) and (c), yellow indicates a positive electric field, black indicates a negative electric field.

when we plot the field along a line where there’s no raw umber (Fig. 4(c)), a single, fairly broad positive peak electric field is observed everywhere along the line, again similarly to the results shown in Fig. 2(b). An interesting feature of these results is that the position-dependent arrival time of the pulses reflected off all the interfaces, can be used to map the topography and curvature of the canvas and the paint layers. Incidentally, the differences between the lines shown in Fig.’s 4(b) and 4(c), shows that the raw umber patches have an effect on the curvature of the canvas.

One of the advantages of the current technique is that the time separation between reflections gives an indication of the relative thickness of the paint layers. This is shown in Fig. 5(a) where we plot the difference in arrival times between the reflections from the canvas/ground layer-raw umber interface (second peak) and the raw umber/lead white interface (third peak), as a function of position on the canvas. The image faithfully reproduces the position of five of the six strokes of raw umber, present under the lead white. It also shows that the separation between the second and third peak is different for the different strokes which were, in fact, painted with different thicknesses. Note that hints on the presence of the sixth stroke are observed, but this particular patch cannot clearly be identified since the raw umber paint layer at that location is
too thin to give two easily identifiable reflections off the two interfaces. The difference between the smallest (1.02 ps) and the largest (2.2 ps) time separation in Fig. 5(a) is 1.18 ps. If we assume that this change is purely caused by the raw umber with n=1.9, we can calculate that the thickest raw umber patch is, averaged over the diameter of the focused THz beam (∼0.75 mm FWHM), about 93 μm thicker than that of the thinnest-but-one patch. The ability to measure the optical thickness of the paint layers constitutes an invaluable source of information for art historians and art conservationists. We now proceed with a comparison of THz-TDS with two other existing techniques which can, in principle, be used to observe hidden paint layers: X-ray Radiography and Infra-Red Reflectography. In X-ray Radiography, a 2D image of the X-ray transmission of the paint sample is recorded. Results for our paint specimen are shown in Fig. 5(b). The Fig. shows that the overall X-ray transmission is, perhaps surprisingly, remarkably low and no clear features can be observed. The main reason for this is the presence of the lead-white paint which blocks the X-rays quite efficiently, making it very difficult to observe the raw umber paint strokes. This is a strong disadvantage of using X-rays since lead-white paint was widely used in historical paintings, in which it will overshadow the distribution of other pigments of lighter elemental composition, such as transition metals. In Fig. 5(c), we plot the 2D image of our paint sample, obtained using IRR. In IRR, high-resolution images are made in
the near infrared region (900-1700 nm) using a commercially available 320×256 pixel indium gallium arsenide area array sensor. Images were taken from both the front and the canvas side of the paint specimen, but only the reflection image taken from the canvas side showed features and is plotted here. The IRR image allows us to identify the raw umber strokes which are visualized through the canvas but with a limited contrast.

The spatial resolution of IRR is better than the spatial resolution our THz reflection image. This can be explained by the frequencies at which our setup operates. In general, for any far-field imaging system, the spatial resolution is fundamentally limited by the wavelengths used, which in the case of THz imaging range from 100 μm to several mm’s. Scattering and absorption in the painting further limit the bandwidth of the reflected pulses and thus give a rise to a limited spatial resolution which we estimate to be about 0.75 mm. However, contrary to THz imaging, IRR is not capable of providing 3D information, such as the optical thickness of the raw umber strokes shown in Fig. 5(a) or the curvature or interfacial plane between the different layers. The IRR contrast results from a higher reflectance of the surrounding lead white, rather than from the distinctive reflection signals of both interfaces of the umber layer itself.

3. Conclusion

We have shown how terahertz time-resolved reflectography can be used to image hidden paint layers in a painting on canvas. The method allows us to measure the optical thickness of these hidden paint layers, and to observe the paintings stratigraphy. The optical thickness of the hidden layers cannot be measured by either X-ray Radiography or Infrared Reflectography and our measurements thus show how terahertz time-resolved reflectography is a highly interesting non-contact technique for art historians and conservation scientists to learn more about what’s hidden under a paintings surface.