Appl. Phys. A (2015) 121:981–986
DOI 10.1007/s00339-015-9303-0

Applied Physics A
Materials Science & Processing

INVITED PAPER

Analysis of a seventeenth-century panel painting by reflection terahertz time-domain imaging (THz-TDI): contribution of ultrafast optics to museum collections inspection

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Received: 27 February 2015 / Accepted: 15 June 2015 / Published online: 30 June 2015

Abstract Terahertz time-domain imaging (THz-TDI) has been applied for nondestructive visualization of a hidden painting and other subsurface composition layers of a seventeenth-century panel painting belonging to the National Gallery of Denmark. Plan-type and cross-sectional scans realized by THz have been compared with images obtained by X-radiography, thus helping in a deep understanding of the strengths and limitations of this technique for art diagnostic purposes and in defining its rule among the other complementary investigation tools for nondestructive inspection of art pieces.

1 Introduction

In the recent years terahertz time-domain imaging (THz-TDI) has started to find its place among examination techniques of artifacts and museum collections [1–3], and a growing number of investigations is now defining its position among investigation protocols currently used for cultural heritage investigation.

The technique already has shown its capability in returning stratigraphic and internal structural information noninvasively [3–9], and the potential of terahertz imaging techniques for noninvasive detection of wooden structure, hidden defects, such as knots and filled voids, has been proved for different wooden artworks [10–15].

In this study we will show the application of THz-TDI to image a hidden painting and other subsurface composition layers on the seventeenth-century (17C) panel painting *A Garden in front of a Country Seat* by David Teniers the Younger, belonging to the collection of the National Gallery of Denmark. Cross-sectional imaging (B-scans) has enabled a clear separation of the individual layers, thus offering visualization of the internal structure over large areas of the painting in a completely nondestructive manner.

Plan-type scans or C-scans realized by THz-TDI have been compared with X-ray radiographs of the same subject, thus adding information on the different responses and contrast mechanisms of the investigated materials at widely different regions of the electromagnetic spectrum used for imaging.

2 Materials and methods

2.1 The investigated panel painting

The investigated painting was *A Garden in front of a Country Seat* (National Gallery of Denmark collection—Fig. 1a) attributed to the Flemish artist David Teniers the Younger (17C, Oil on panel, 43 × 63 cm), a prolific artist of the mid-seventeenth century who worked in Antwerp and Brussels, where he was known for his genre scenes of peasant life.

The panel support of the painting had a horizontal grain direction and a thickness varying between 3 and 7 cm. Visual examination of the edges showed that the panel has at some point been trimmed along the sides. X-radiography

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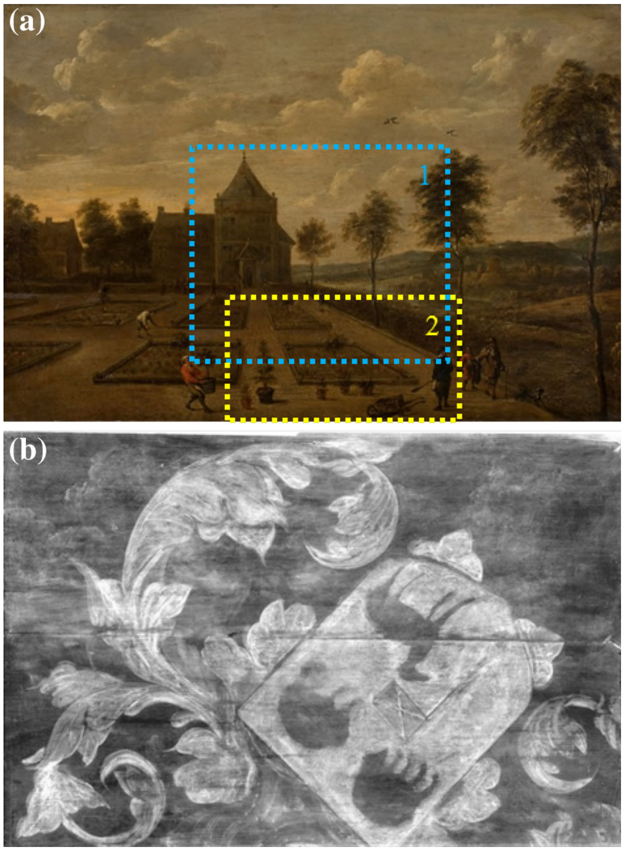

Fig. 1 **a** *A Garden in front of a Country Seat* by David Teniers the Younger, National Gallery of Denmark collection (17C, Oil on panel, 43 × 63 cm). The two areas scanned by THz-TDI are localized by *dashed squares* and, respectively, named 1 and 2 **b** X-radiograph of *A Garden in front of a Country Seat*

(Fig. 1b) further revealed that the artist had recycled an earlier painting for his composition, showing the existence of an escutcheon surrounded by ornamental scrolls underneath the present image. The coat of arms has heraldic bearings apparently in the shape of a flag and three different animals. A red layer observed in a few areas between the two paintings indicates that the artist most likely applied a new ground layer on top of the first painting (the coat of arms) before he painted the second composition.

2.2 Analytical instrumentation

2.2.1 THz-TDI

THz-TDI was performed with a Picometrix T-ray 4000 device, consisting of a femtosecond fiber laser coupled with 5-m-long umbilical cords to a photoconductive terahertz transceiver head mounted on an XY-scanning stage. The relevant areas have been scanned using a 320-picosecond (ps) measurement window, a time resolution of 0.078 ps. The THz source is linearly polarized, with a polarization extinction ratio of approximately 100:1. The system has a fundamental data acquisition rate of 100 scans/s and we employed a scan velocity of 12 pixel/s (6.7 scans averaged per pixel) in a reflection configuration at normal incidence. The raster scanning was performed with a resolution of 400 μm. The spatial step size was matched to the optical resolution of 300 μm at 1 THz (highest frequency considered here). The optical resolution was determined independently by a knife-edge scan of the THz beam profile [16].

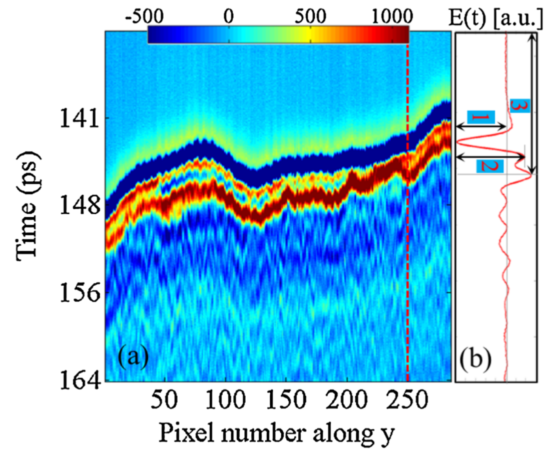

Fig. 2 **a** B-scan representing the electric field of the reflected THz signal as function of time, recorded along the scan line shown in Fig. 3d. The *dashed red line* is the waveform shown in Fig. 2b. **b** Waveform recorded at pixel (250, 250). The *horizontal axis* is the recorded electric field value, while the *vertical axis* represents the time delay (ps), and is in common with that of Fig. 2a. The *double arrows* represent, respectively, (1) the peak maximum absolute value used to plot Fig. 3c, (2) the peak-to-peak or peak-to-trough amplitude value used to plot Fig. 3d, and (3) the time delay of the pulse arising from the reflection at the paint materials/wooden panel interface, used to plot Fig. 3f

2.2.2 X-radiography

Digital X-radiography was carried out with an YXLON® MIR-201E X-ray tube and the exposure parameters 5 mA, 25 kV, 90 s. The radiography was performed on Dürr NDT CRIP3040108 digital image plates which were subsequently scanned at a resolution of 50 μm in a HD-CR 35 NDT laser scanner.

3 Results and discussion

The THz signal incident on the painting consists of a single cycle of the electric field, with a duration of approximately 1 ps. Figure 2 shows a representative data set obtained along a scan line of the image. The recorded return signals (Fig. 2b) show three main pulses arising from reflections at air/surface interface, at painting/wooden support and at one

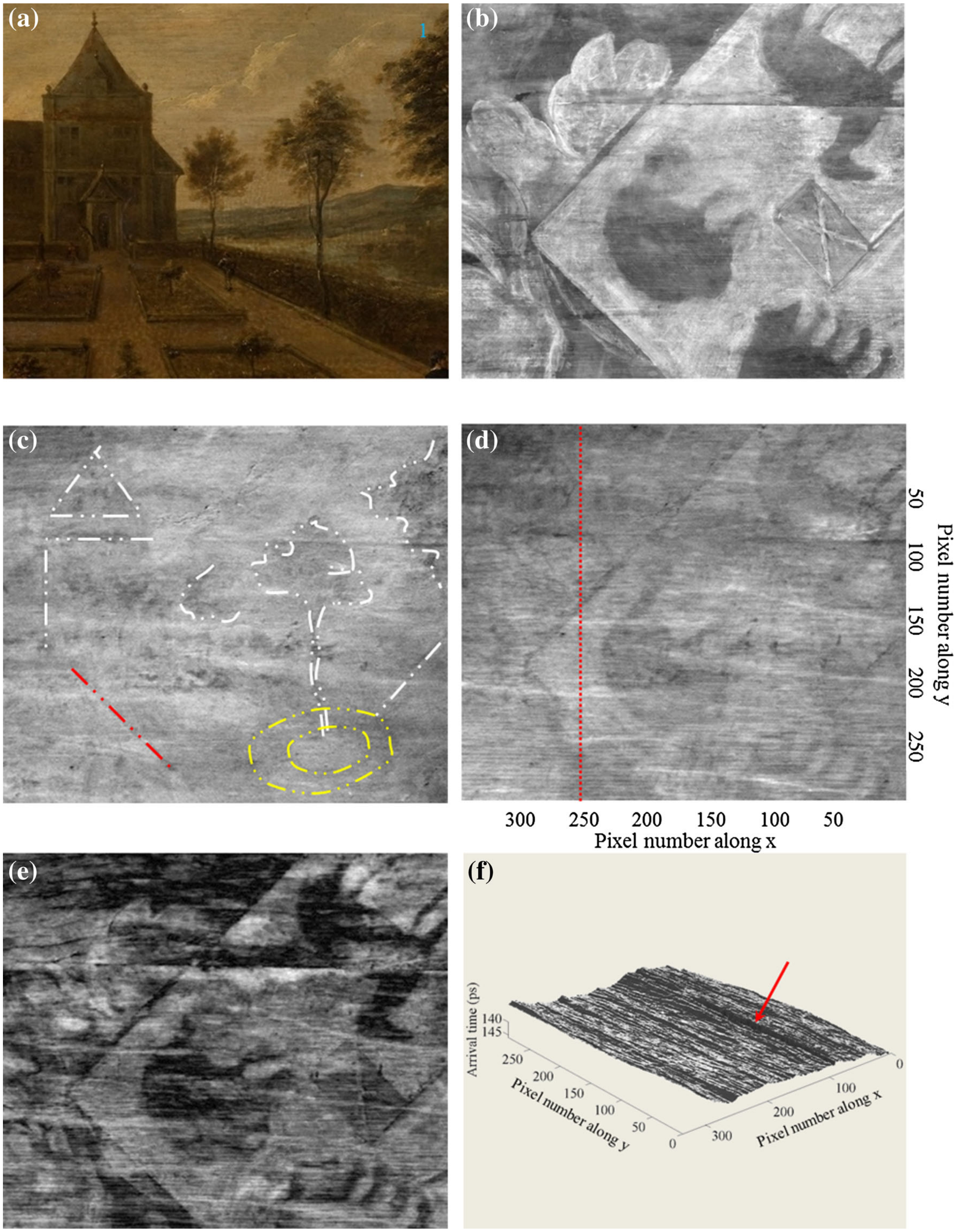

Fig. 3 **a** Scan area 1, located as indicated by the *blue dashed square* in Fig. 1a. **b** X-radiograph image of the same area. **c** THz time-domain parametric image plotted using the maximum value of the reflected electric field at each pixel. *White lines* indicate marks located on surface, *yellow lines* possible construction marks, and *red lines* feature of surface arising from subsurface components. **d** Peak-to-peak THz time-domain image. The *dashed red line* indicates the scan line used for the B-scan in Fig. 2a. **e** THz frequency-domain parametric image plotted by integrating the spectral amplitude over the 0.31–0.37 THz range, after Fourier transform of the region of interest isolated in the time domain by a window function. **f** Time-of-Flight (ToF) image clearly showing the wood grain and irregular structure, as well as the location of a crack in the wood panel supporting the painting, indicated by the *red arrow*

interface between these last two, respectively. Figure 2a shows the resulting B-scan.

The appearance of the relevant interfaces found has been imaged using different parameters, thus providing images containing different information. Comparing the visible appearance of the scanned area (Fig. 3a) and the THz image plotted using the signal global maximum of the reflected signal (peak absolute amplitude image, Fig. 3c), it may be noticed that the THz image indicates the location of marks used to trace the figure boundaries on the surface by the painter, and also reveal features which have no counterpart in the actual composition, probably construction marks as well as a mark arising from a subsurface layer. The absolute peak value has been used instead of the relative maximum value in order to take into account phase shifts through the painting materials sufficient to cause the waveform to invert [17]. Referring to the first back-reflected main peak, the change in the peak absolute value arises predominantly from scattering at the surface, rather than from the spectral properties of the paint material. In fact, lower peak values are recorded for positions on the painting where the optical path of the back-reflected signal increases and where the scattering angle changes abruptly with respect to that of the even surface. The deflection of the back-reflected signal causes beam decoupling at the receiver, thus reducing the recorded amplitude.

A pale appearance of the covered painting is already seen in the image formed by the THz signal peak-to-peak amplitude (Fig. 3d). The hidden painting is more visible by using this parameter since the peak separation occurred such that the point of the local maximum for the surface and the hidden painting occurs at the same time delay, where the reflection features of the hidden paint materials show significant differences [17], making the reading of the hidden composition possible. An acceptable reading of the hidden features is only obtained when integrating the spectral amplitude over a narrow THz frequency range (0.31–0.37 THz in Fig. 3e), obtained by Fourier transformation of the region of interest, windowed in time domain. In this case the contrast is enhanced by selecting the pulse arising from the reflection at the interface corresponding to the hidden painting and by choosing the frequency range where the subjects and the background composing the buried painting show the maximum difference in the reflectance spectrum.

Compared with the X-radiograph of the same scanned area (Fig. 3b), the THz image shows the features of the wood structure behind the composition more manifestly. The differences in wood density produce irregular dark and light banding that appears as longitudinal subtleties which are typical of the anisotropic structure of the wood.

Even if organic materials, such as cellulose, in general are not good absorbers of X-ray radiation, the prominent growth ring structures are usually recognizable depending on the direction of the radiograph relative to the grain of the wood [18, 19]. However, in this case the wood structure is mostly hidden by the more X-ray-opaque ground and paint layers, showing details of the painting composition clearer than in the THz images.

Contrarily, the interaction between terahertz and wood is influenced by numerous phenomena, related to the complex structure of wood, which include strong fingerprint absorption [20], as well as birefringence and attenuation that depends on the preferential fiber orientation within the wood, thus resulting in polarization-dependent optical properties [21, 22]. Wood absorption is particularly strong compared with other materials composing the painting due to the water still contained even in dry wood (free water and bound water), which results in a high refractive index, and thus a higher visibility in reflection THz images. On the opposite, the presence of water may be a complication for X-radiography [22]. Wood grains and irregular structures are clearly visualized by plotting the temporal position of the relevant peak [Time-of-Flight (ToF) image],

$$\Delta t = (1/c) \int n(z) dz \qquad (1)$$

where $n(z)$ is the refractive index sampled by the THz beam along its optical path, the integral is taken along the path, and c is the speed of light [23]. Since the wooden panel is fairly homogeneous, the presence of a crack and its extension is clearly imaged (Fig. 3f), thanks to the variation in the delay of the pulse.

The second area scanned is shown in Fig. 4a. Even in this case, the THz image (the spectral amplitude integrated over the 0.38–0.43 THz range, after isolation of the proper pulse in time domain, Fig. 4c) shows interference due to the wood below the painting in a more prominent manner compared with the radiograph of the same region (Fig. 4b). It is likely that the change in the animal shape, resembling an additional head turned on the back, depends on these interferences instead of a significant compositional feature. The brushstrokes applied circularly around the animal figure are more evident in the THz image. Figure 4c shows a THz false-color image realized by visualizing the 0.38–0.43 THz band in red, the 0.34–0.37 THz band in green, and 0.28–0.34 THz band in blue.

This rendering helped in imaging a detail (Fig. 5c) which does not follow the structural lines of the wood and has no counterpart in the surface composition. Even if visible, the detail is barely notable in the X-radiograph image (Fig. 5a), also after contrast enhancement (Fig. 5b). Its dark appearance in the X-radiograph (i.e., low radiopacity) suggests that the material is composed of low-atomic-number elements. This is in contrast to the bright

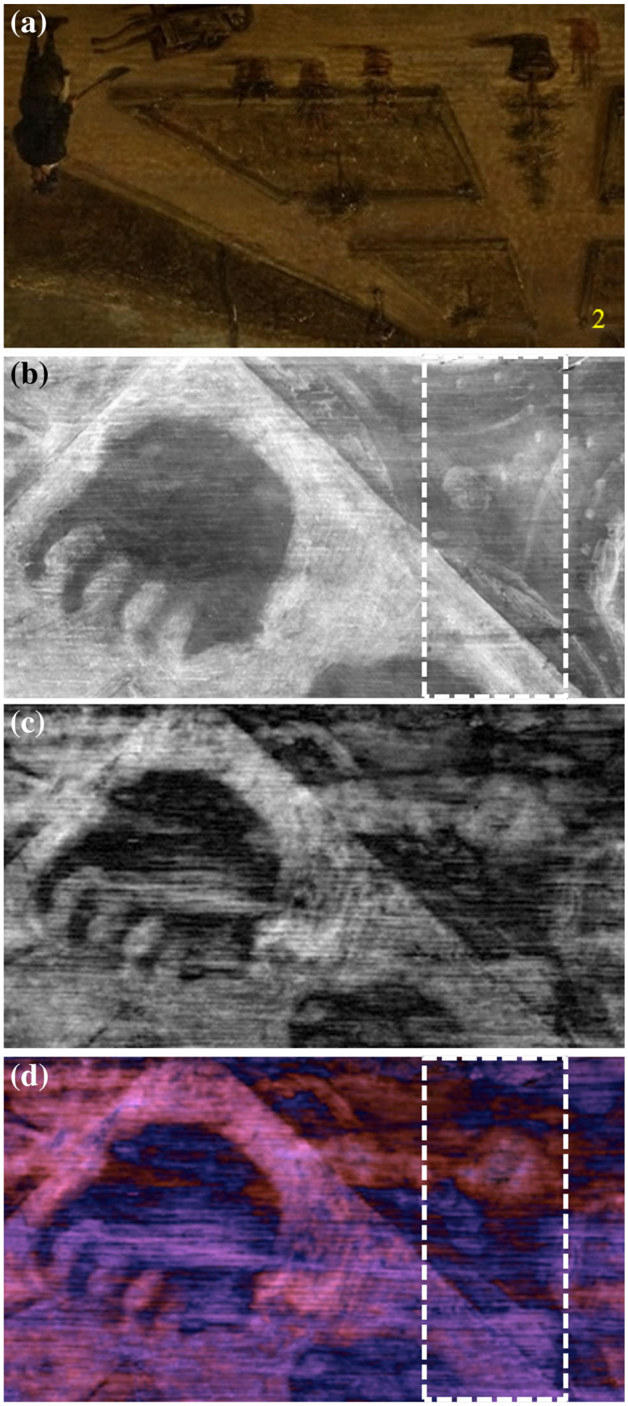

Fig. 4 **a** Scan area 2, located as indicated by the *yellow dashed square* in Fig. 1a. **b** Radiograph image of the same area. **c** THz frequency-domain parametric image of the integrated spectral amplitude over the 0.38–0.43 THz range, after Fourier transform of the region of interest isolated in the time domain by a window function. **d** False-color terahertz image realized with the 0.38–0.43 THz, 0.34–0.37 THz, and 0.28–0.34 THz bands represented as *red*, *green*, and *blue*, respectively

appearance of the same feature in the THz image. Excluding the connection between this signal and the wooden panel structure, this feature may be attributed to

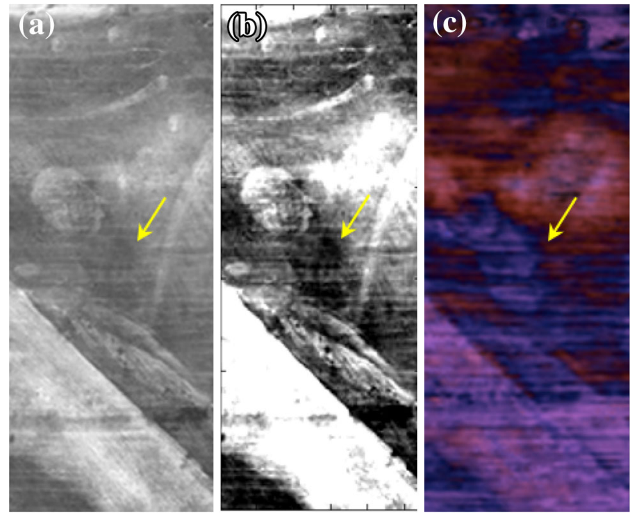

Fig. 5 **a** Detail of the X-radiograph, located as indicated by the *white dashed square* in Fig. 4b. **b** Detail of the X-radiograph after contrast enhancement. **c** Detail of the THz false-color image of the same area (*dashed line* in Fig. 4d)

the hand of the unknown artist of the heraldic motives or to the presence of restoration materials at this location. While the obtained terahertz false-color image cannot directly support the identification of the substance composing the detail, it helped in visualizing and localizing the feature within the concealed composition. It is auspicious that performing the hidden material mapping by means of THz-TDI will help in choosing the proper location for further spot analysis with other techniques for material identification.

4 Conclusion

Sections of the panel painting *A Garden in front of a Country Seat* by David II Teniers, National Gallery of Denmark collection (17C, Oil on panel, 43 × 63 cm), have been scanned using THz-TDI, offering an occasion to compare the results obtained by this technique with those obtained by the better developed X-radiography. Both X-radiography and THz-TDI were able to image an older painting hidden beneath the present painting.

The wooden structure of the panel was mostly hidden to radiographic imaging by the more X-ray-opaque ground and paint layers, while details of the painting composition were clearer than in the corresponding THz images.

We have shown that wood grains and irregular structure are better visualized by THz-TDI, especially by means of ToF plots, which also highlighted the presence of a crack and its extension on the wooden panel, while details of the hidden painting are optimally visualized by choosing the proper interval in THz frequency domain. The choice of the parameters used to image the THz data showed a significant influence on the information provided, and thus, we have been able to individually detail the surface profile, the wood grain, and the hidden paint layer. At the same time, the brushstrokes made circularly around an animal figure of the hidden heraldic composition are more evident in frequency parametric THz images compared with the X-radiograph. A feature, unrelated to the panel wooden structure and barely notable in the X-radiograph, has been detected by realizing false-color THz images, and can be attributed either to the unknown artist hand or to the presence of a material (including restoration material). While the THz false-color image alone cannot support a chemical identification of the substance composing the imaged detail, it helped in localizing the feature within the concealed composition. This may help in choosing the proper location of further spot analysis for material identification.

Information provided by the two techniques is thus complementary, and the study helped in defining THz-TDI as a useful tool among the other complementary investigation tools for art pieces inspection.

Acknowledgments The authors would like to thank the Conservation Department and The Centre for Art Technological Studies and Conservation—CATS—at the National Gallery of Denmark (Copenhagen, Denmark), for the fruitful collaboration during the study of *A Garden in front of a Country Seat*.

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