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Art Painting Diagnostic Before Restoration with Terahertz and Millimeter Waves

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Abstract Art painting diagnostic is commonly performed using electromagnetic waves at wavelengths from terahertz to X-ray. These former techniques are essential in conservation and art history research, but they could be also very useful for restoring artwork. While most studies use time domain imaging technique, in this study, a painting has been investigated using both time domain imaging (TDI) and frequency-modulated continuous wave (FMCW) system in the millimeter frequency range. By applying these systems to a painting of the eighteenth century, we detect and analyze the structure of some defects. This study underlines the differences between FMCW and TDI. We present the advantages and disadvantages of each technique on a real artwork.

Keywords Terahertz imaging · Art restoration · Painting · Time domain imaging · Frequency-modulated continuous wave

1 Introduction

Terahertz (THz) waves have shown their capabilities to analyze many materials like composite materials [1], explosives, polymers [2], biological samples, etc. [3]. These various examples show that it is possible to have both structural information of materials and also data about their chemical nature. The penetration properties of these waves were also used for analysis of

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art and heritage [4, 5]. A study of Egyptian papyrus [6] has shown the ability to differentiate several inks deposited on papyrus text. They have shown that the terahertz signal varies depending on the pigment ratio of the ink. This technique was also applied to manuscripts [7, 8] with a lead pencil, demonstrating a new way to investigate drawings under an ink or a painting layer. Another example is the analysis of a seal that has shown the ability to investigate the structure and see objects inside [9] and to provide complementary information about the conservation state of the samples such as defects and fractures that are detected with an estimation of their depth position. This technique was also applied to a wall painting [10, 11] and the authors showed that THz can reveal information about both the original work of the artist and the subsequent restoration works. Chiefly, terahertz time domain imaging (THz-TDI) has been used for several years to analyze paintings [12–14] due to (i) its penetration depth, complementary to X-rays, IR, and UV methods and (ii) the coherent detection of the THz field, so that both the temporal and spectral transmitted or reflected THz beams could be used to construct a contrast image step-by-step. While UV penetration length is limited to varnish layers, visible light to paint layers, and infrared to *imprimitura* layers, THz wave can see preparation layers [5]. This important property with respect to art painting materials is applied by several teams to access hidden layers [13–15].

While most of these works were performed using time domain systems based on a femtosecond laser, the growing number of source and sensor systems based on electronics allows performing imaging with millimeter and sub-millimeter waves efficiently. The rising of both power and frequency and the predictable drop of cost of these systems due to their massive use in the field of automotive industry through the FMCW radar, for instance, makes this approach interesting for art and heritage analysis [16]. Even if the FMCW approach cannot separate thin layers as precisely as THz-TDI, it can be used to detect structural defects analogously to what is done in the field of non-destructive inspection [17]. In this study, we applied both THz-TDI and millimeter wave FMCW imaging for the inspection and analysis of a painting prior to its restoration. The objective is to demonstrate the capability to detect several types of defects and to help on the diagnosis before restoration. That could concern the pictorial layer, paint, and varnish, and it is through the analysis of these layers that the causes of degradation and treatments are determined.

2 Setups and Painting

2.1 THz-TDI System

The time domain system used in this paper is a Teraview TPS 3000 spectrometer (cf. Fig. 1a, b). This setup allows measurements in reflection mode with a range of 30 × 30 cm and with a frequency from 0.1 to 3 THz. The spatial resolution depends on the frequency; it goes from 3 mm to 100 μm. The system is based on a Ti:Sapphire mode-locked laser-emitting short pulses (sub 100 femtosecond) at 800 nm with a power of 300 mW. This setup is embedded in a box and these pulses are split and guided out of the bow via two optical fibers to the 2D scanner. The first lifer is connected to a photo-switch generating the THz wave which is transmitted to the sample. The reflected terahertz signal is then focused to another photo-switch acting as a detector. Coherent detection methods allow the reflected or transmitted THz pulse profile to be measured and then it is possible to access to the dielectric properties without using the Kramers-Kronig relationship.

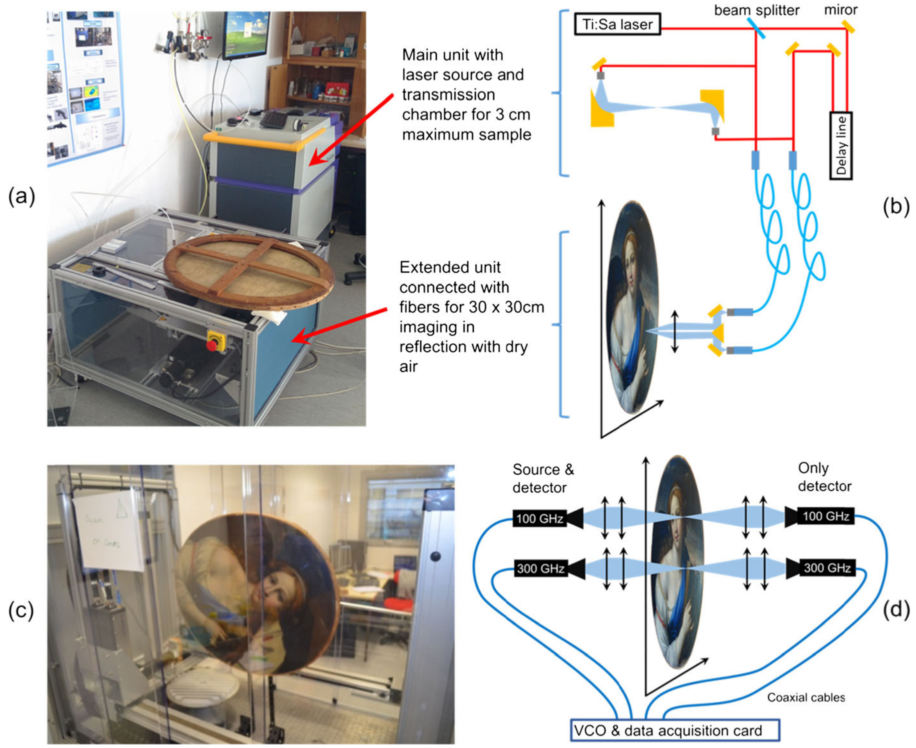

Fig. 1 **a** Photography of the THz-TDI system. We can see the painting placed on the reflection unit. **b** Optical scheme of Teraview TPS 3000 setup, with the main unit for transmission measurement and the extended unit for 30 × 30-cm reflection imaging. **c** Photography of the millimeter wave imaging setup. **d** Scheme of the millimeter wave imaging setup. The four measurements (transmission and reflection, 100 and 300 GHz) are performed simultaneously

2.2 Millimeter Wave Imaging Setup

The millimeter wave imaging setup is an all-electronic system able to measure signal in both transmission and reflection (cf. Fig. 1c, d). The system has two frequency ranges, from 75 to 110 GHz and from 220 to 330 GHz. Four heads compose the system: two both emitting and receiving and two only receiving signals. The output power is about 2 mW at 100 GHz and 60 μW at 300 GHz. The dynamic range is 70 dB at 100 GHz and 60 dB at 300 GHz. The image is produced by moving the head in a line with a maximum distance of 800 mm. Thus, the sample is raster scanned and the main advantage is the very large scanned area about 600 × 800 mm. The measurement time of one pixel is 240 μs, and a whole scan with best resolution lasts about 25 min. Each head works as a profilometer using frequency-modulated continuous wave to obtain a profile. The spatial resolution is about 5 mm in typical materials at 100 GHz and 2 mm at 300 GHz. The ability to see beneath the paint layer is illustrated in Fig. 2. We draw a triangle shape on a canvas with a pencil and add two rectangular spots of painting (sienna 520 and light green 425). We observe on the 100 GHz reflection image Fig. 2c that the pencil sketch appears clearly, including below the painting. Moreover, the ability to make a profilometric image will not be used for painting analysis because of the longitudinal resolution is not suitable in this case. In the remainder of this article, we will extract only an image from the maximum integrated signal.

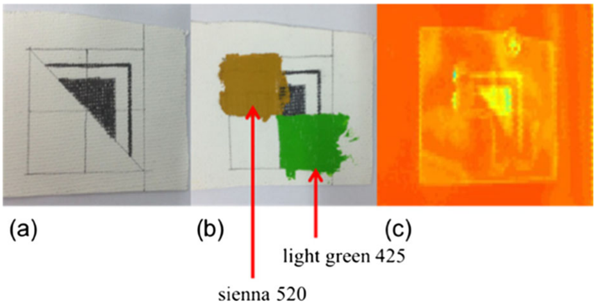

Fig. 2 **a** Pencil drawing on canvas. **b** Painting. **c** FMCW imaging in reflection at 100 GHz

2.3 The Painting

The investigated sample is an oil painting on canvas depicting a young erudite woman. This painting, coming from a private collection, has no visible signature but we can read an inscription on the back of the chassis "Hortense Mancini, niece du Cardinal Mazarin par Pierre Mignard". Its oval shape is not the original; additions have been made to evaluate from a rectangular shape to the oval final shape. The alleged dating of the work is the eighteenth century. The painting presented visible anterior restorations for a professional. The first is a relining. Then, a restored tear is visible. We can also note the small areas of deformation and warping (peeling of the painted canvas of relining of support) and see ancient painting and enlarging the canvas as well as a passage of a rectangular format in an oval format. Figure 3 presents a picture under visible light of the sample. The height is 78 cm and the width 62 cm. On the right, we show the 300-GHz reflection image of the painting.

3 Results and Discussion

3.1 FMCW Results

Figure 4 shows all the results obtained with the FMCW system. The FMCW system can provide images with different times of flight extracted from the phase shift between the

Fig. 3 On the *left*: photography of the painting with white light. We can observe at the right of the painting some cracks. On the *right*: 300-GHz reflection image of the painting. *Center*: image fusion between visible and millimeter wave. We note the excellent correlation between both and the precise localization of the different defects

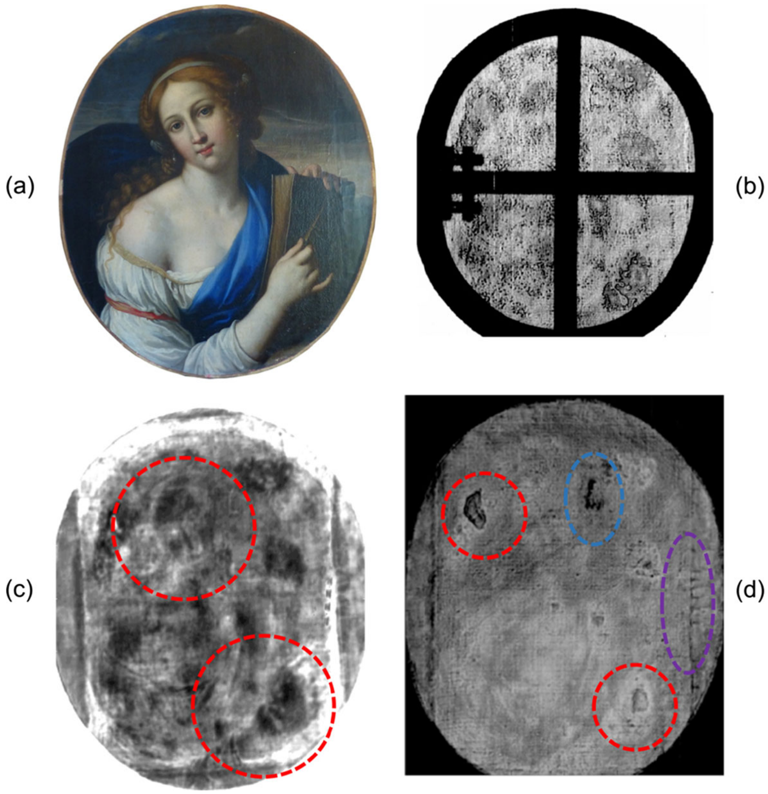

Fig. 4 **a** Visible image of the painting. **b** 300-GHz transmission image. **c** 100-GHz reflection image. *Red circles* highlight the face and the arm of the woman. **d** 300-GHz reflection image

transmitted signal and the received signal. However, in our case, we analyze a planar object. Thus, we cannot use this important property since the longitudinal resolution is about 1 mm. This depth resolution is inadequate to distinguish the different layers of a painting in that case. However, we can get interesting features of the picture by taking waveform intensity for each pixel. Moreover, we can get an absorption image providing data on the structural defects of the canvas in the transmission mode.

It is remarkable that we can clearly distinguish on Fig. 4d tiny details of the artwork such as the face with the nose, eyes, and mouth. Also, the arm and the hand are visible with a significant change in dimension compared to the visible image. Then, we suspect the presence of a primary sketch under the final painting. We note the excellent painting correlation between both helping to localize precisely the different defects and different areas of interest that we will reveal by terahertz analysis.

Figure 4b displays the obtained transmission image at 300 GHz. The signal is not transmitted through the frame wood, so we can clearly see the shape of the frame. The irregular shape that is present on the left corresponds to the frame fastening system to stabilize the painting during the acquisition. Moreover, we can observe the presence of some splashed forms everywhere. They look like large droplets that are unrelated to the geometric forms of painting. One possibility is that these droplets correspond to the adhesive used for the relining (e.g., rabbit skin glue) during a previous restoration. This hypothesis is comforted by a visual inspection of the edges of painting which has confirmed that this painting has been glued on another canvas.

Figure 4c corresponds to the image in reflection mode at 100 GHz. One can discern the face and the arm of the woman inside the red circles. The contrast highlighting these parts from the rest of the painting comes from the differential of dielectric properties of the different painting colors used by the artist. Other different intensity areas can be observed but they cannot be associated with a clear defect or previous restoration changes. We can also clearly perceive a rectangular shape inside the rounded shape; we can clearly assume that it is correlated to the old chassis change to a rounded shape. This chassis change was accompanied by a repainted on the peripheral areas and so different material responses due to different aging and material compounds.

Finally, Fig. 4d corresponds to the image obtained in reflection at 300 GHz. This image has a better resolution than at 100 GHz and allows one to visualize defect details that were invisible at 100 GHz. These defects are circled with different colors. Red circles correspond to voids on the face and on the hand. The area surrounded in blue corresponds to a crack of the canvas and the purple zone corresponds to cracking of the canvas close to the extension of the recent enhancement of the painting to an oval shape. These different types of defects will be analyzed in more details using X-ray and THz-TDI.

3.2 Cracks

The right area of the painting shows the most significant cracks. This area was photographed with raking light in Fig. 5c. We can clearly see a rendering difference between two zones, one at the right and the other at the left. At the border between these two areas, we can observe crunches that we identify on the purple zone of Fig. 4d. They are visible in Fig. 5b which has been obtained with the THz-TDI system. This image was done using the maximum value of each waveform, meaning that an operator making no signal processing could easily get this image.

An analysis by time of flight to visualize a cross-section (B scan) of these cracks is given in Fig. 5d, e. The abscissa axis of the B scan shows the position of a pixel along the cut-line whereas the ordinate axis shows the THz signal (electric field amplitude) as a function of time. Let us remind that THz-pulsed imaging has the unique feature of providing a 3D “map” of the object by using the time of flight of the reflected THz pulses. In brief, a THz pulse is directed to the sample and the reflected beam is measured in amplitude and phase. The temporal situation of the reflected pulses directly indicates the presence of the interfaces along the propagation direction of the beam. In this way, by using the difference of time of flight from pixel to pixel, depth information of the 3D profiles of the object can be deduced. However, this new THz tomography tool relied on three hypotheses:

(1) Targets have no or small dispersion and diffraction properties.
(2) Reflection is weak so that multi-reflection can be ignored or suppressed.
(3) Refractive indexes are known and uniform within each layer.

Then, numerical calculations allow the determination of the thickness or the exact position of the defect.

In our work, Fig. 5e corresponds to a vertical cross-section at the position of the crack. We get a reflected signal with a delay of 7 to 12 ps with respect to the reference. There is a constant

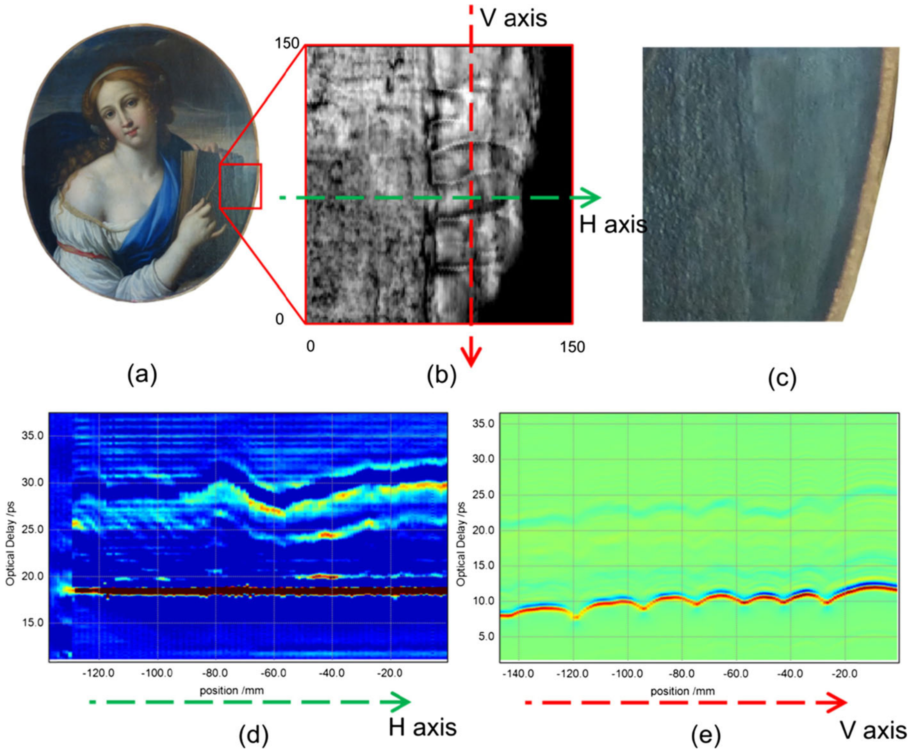

Fig. 5 Analysis of cracks with time domain system. **a** Visible photography. **b** THz time domain image with max peak size parameter. **c** Photography with white raking light. **d** B scan in the horizontal axis after flattening with alignment of waveform to maximum. **e** B scan in the vertical axis

slope from left to right that corresponds to the curvature of the canvas and oscillation behavior of roughly 3-ps period matching with cracks geometry. The equivalent distance $d = \frac{Vdt}{2}$ (where dt is the delay between the two reflected THz pulses and V the speed of light in the medium) is estimated around 0.45 mm; it corresponds to irregularities due to cracking. Temporal data were then numerically flattened, leaning on the position of the maximum. This digital process allows calibrating the maximum peak position and then analyzes the echoes coming from behind the first layer with a common time reference. Figure 5d corresponds to a horizontal cross-section after flattening. We can see that the maximum is now at 18 ps for all the positions and some echoes come from 25 ± 5 ps. We can observe an oscillation at position 75 mm corresponding to the border between the inner part of the painting (left) and outer part (right).

A complementary analysis was done using X-rays imaging. We can see frame wood details and nails on Fig. 6a, but cracks are not visible. One can see a vertical line at the left of Fig. 6a, which corresponds to the boundary between the new and old canvases (causing these cracks). Clearly, due to (i) the presence of the frame, (ii) the very small topological contrast, and (iii) the necessity to work at very low acceleration voltage, X-ray is not fully adapted to detect easily this kind of defect compared to FMCW and THz-TDI apparatuses. In counterpart, nails used to maintain the canvas are not detected by THz systems, demonstrating the complementarity of both techniques.

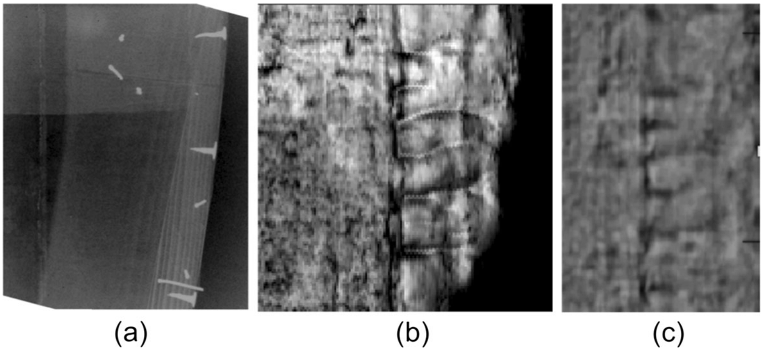

Fig. 6 **a** X-ray image, **b** THz-TDI reflection image, and **c** 300-GHz reflection FMCW image of the cracks area surrounded in purple in Fig. 4d

3.3 Empty Space: Detachment

Generally, some paintings are subject to a transfer, i.e., an operation of depositing the layer of paint to its original support for the transfer to a new medium. This extreme action is irreversible; it implies that the previous support and/or preparation were defective and that in any case a re-fixing, like any other form of consolidation, was not considered. It was probably the case of our artwork.

We can see in Fig. 4d a black shape that appears to the left of the face. With a continuous wave system, it is very difficult to describe what kind of defects we are facing. Then, this defect was analyzed in more detail using the THz-TDI system. A 30-cm by 30-cm image was made with the Teraview system with a pitch of 1 mm. Each waveform for a pixel of the image contains 2048 measurements, which produced a file of 170 MB binary file. Each measurement is averaged 50 times to get a more accurate result, which has lengthened the scan time to 20 h.

It can be seen in Fig. 7a a superimposition of the visible image with the signal obtained in reflection mode at 300 GHz. Figure 7b shows the data obtained by raster scanning with the max peak size as a contrast parameter. This signal gives a fast picture presenting a lot of similitudes with the results in FMCW, but with a better resolution. The only difference relates to the intensity of the face that is darker with the THz-TDI system.

A B scan analysis is proposed in Fig. 7c. It may be noted firstly that the canvas has variations of flatness. In addition, it is observed in Fig. 7(c2) a spacing between the echoes corresponding to an air gap inside the canvas. This spacing is characteristic of a peeling off between the canvas with the paint layer and the latest canvas added during a previous relining. Moreover, Fig. 7(c3) does not show voids despite the presence of a dark spot on the time domain image. That demonstrates the necessity to analyze datasets using both the frequency and the time data in order interpret the THz-TDI images more precisely than with the FMCW data only. Figure 7(c5) shows no visible defect in the B scan at the rip located at the right of the head.

3.4 Rip at the Right of the Head

We can see on Fig. 4d an L-shaped structure at the right of the head (purple area). This area is shown in Fig. 8 with visible (a), X-ray (b), and THz-TDI (c) images. The analysis of THz-TDI pulsed and X-rays confirms the detection of the tear seen with FMCW imaging. Although the

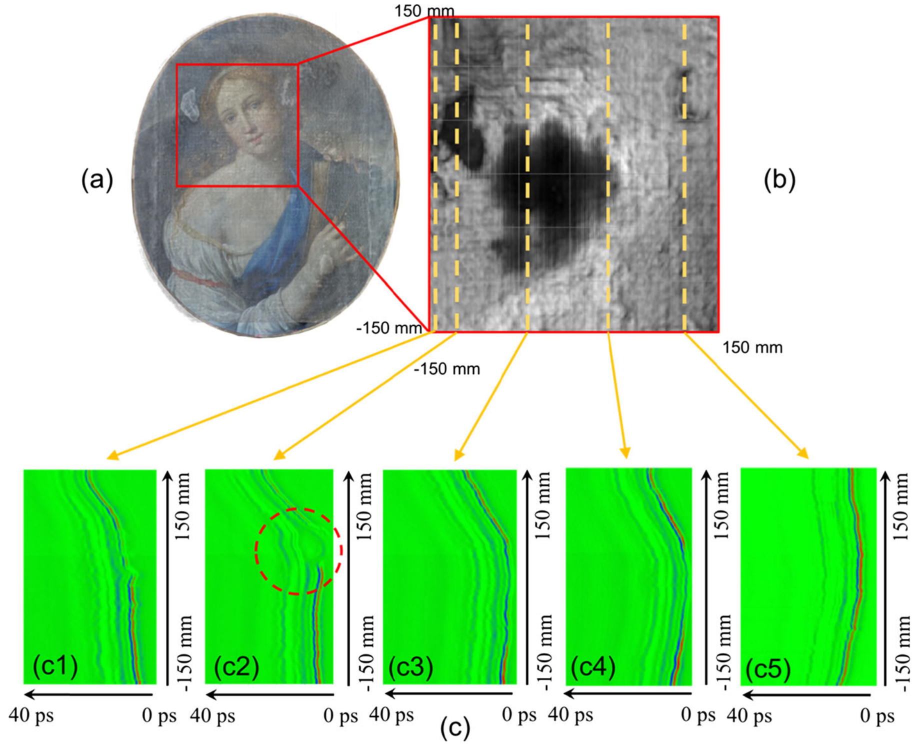

Fig. 7 Analysis of the void at the left of the head. **a** Superimposition of the visible image with the signal 300 GHz in reflection. **b** THz time domain image with max peak size parameter. **c** B scan in the vertical axis for five different positions. We can see a space in c2, which corresponds to the position of the void

THz-TDS picture brings a vision equivalent to FMCW, we have not observed remarkable signal echoes. Visible echoes on cross-section in Fig. 6(c5) are similar to cross-section in Fig. 6(c4). We can conclude that for this type of structural defect, FMCW imaging is quite sufficient to detect quickly this type of repair.

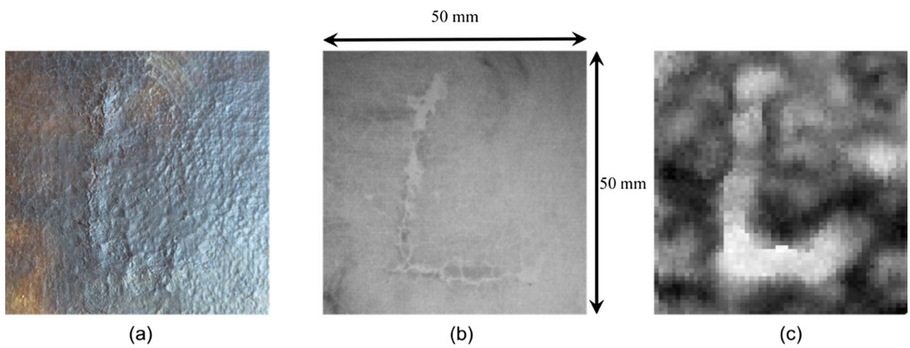

Fig. 8 Images of the rip at the right of the head. **a** Visible photography. **b** X-ray image. **c** THz time domain image axis after flattening with alignment of waveform to maximum and using a slicer

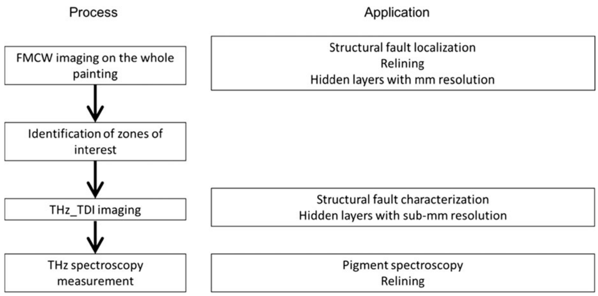

Fig. 9 Proposed process flowchart using terahertz pulse FMCW and technologies, taking into account their advantages and disadvantages in terms of resolution, analysis capacity, and speed

3.5 Methodology for THz Testing of Paintings

Finally, TDS systems allow for spectral measurements and analyze pigments but they need more time for raster scan the total surface of an artwork. They also bring topological information and are able to extract multilayered structures [18]. These properties are summarized in the proposed process flowchart in Fig. 9. The left part corresponds to the process type, from the fastest to the slowest, and the right part correspond to application. The FMCW techniques have a potential to be exploited for the rapid analysis of painting and defect detection. It can be used as a first step in THz art process flowchart and then completed with THz-TDI and spectroscopy on restricted surface of interest.

4 Conclusion

We demonstrate that THz and millimeter wave imaging are useful in the framework of art restoration. THz-TDI and FMCW allow obtaining complementary results compared to X-rays and infrared. Even if THz-TDI and FMCW rely on the same physical domain, we can see that longitudinal and lateral resolution, origin of contrast, and results vary as a function of the topology of the experiment (transmission or reflection) and the frequency. Images produced with FMCW systems allow to have a quick diagnosis of a 1-m^2 painting even if the resolution is limited. However, in our case, it is sufficient to resolve numerous defects and it is useful to localize structural defects on the canvas, to detect a relining and see hidden layers with a resolution of a few millimeters. This technique can be used upstream of TDS techniques which have a better resolution and offer cross-sectional analysis capabilities using the time-of-flight approach. At least, one important advantage of imaging with a single-frequency source is the ability to select the source wavelength in order to optimize the imaging capability. Three hundred gigahertz is a good tradeoff between depth penetration and resolution. Moreover, recent advances in semiconductor optoelectronics and QCL sources, for example, will induce the existence and choice in terahertz frequency. The terahertz field is likely to be an efficient tool for restoration of artwork.

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