Goya's artwork imaging with Terahertz waves

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Abstract: In this paper we use a Terahertz (THz) time-domain system to image and analyze the structure of an artwork attributed to the Spanish artist Goya painted in 1771. The THz images show features that cannot be seen with optical inspection and complement data obtained with X-ray imaging that provide evidence of its authenticity, which is validated by other independent studies. For instance, a feature with a strong resemblance with one of Goya's known signatures is seen in the THz images. In particular, this paper demonstrates the potential of THz imaging as a complementary technique along with X-ray for the verification and authentication of artwork pieces through the detection of features that remain hidden to optical inspection.

OCIS codes: (000.2170) Equipment and techniques; (040.2235) Far infrared or terahertz; (100.3010) Image reconstruction techniques; (110.6795) Terahertz imaging; (120.4290) Nondestructive testing.

References and links

1. K. Kawase, H. Hoshina, A. Iwasaki, Y. Sasaki, and T. Shibuya, "Mail screening applications of Terahertz radiation," Electron. Lett. **46**(26), S66–S68 (2010).
2. J. Chen, Y. Chen, H. Zhao, G. J. Bastiaans, and X.-C. Zhang, "Absorption coefficients of selected explosives and related compounds in the range of 0.1-2.8 THz," Opt. Express **15**(19), 12060–12067 (2007).
3. Y. Shen, T. Lo, P. F. Taday, B. E. Cole, W. R. Tribe, and M. C. Kemp, "Detection and identification of explosives using Terahertz pulsed spectroscopic imaging," Appl. Phys. Lett. **86**(24), 241116 (2005).
4. K. Yamamoto, M. Yamaguchi, F. Miyamaru, M. Tani, M. Hangyo, T. Ikeda, A. Matsushita, K. Koide, M. Tatsuno, and Y. Minami, "Noninvasive inspection of C-4 explosive in mails by Terahertz time-domain spectroscopy," Jpn. J. Appl. Phys. **43**(No. 3B), L414–L417 (2004).
5. A. J. Fitzgerald, B. E. Cole, and P. F. Taday, "Nondestructive analysis of tablet coating thicknesses using Terahertz pulsed imaging," J. Pharm. Sci. **94**(1), 177–183 (2005).
6. C. J. Strachan, P. F. Taday, D. A. Newnham, K. C. Gordon, J. A. Zeitler, M. Pepper, and T. Rades, "Using Terahertz pulsed spectroscopy to quantify pharmaceutical polymorphism and crystallinity," J. Pharm. Sci. **94**(4), 837–846 (2005).
7. J. A. Zeitler, P. F. Taday, D. A. Newnham, M. Pepper, K. C. Gordon, and T. Rades, "Terahertz pulsed spectroscopy and imaging in the pharmaceutical setting--a Review," J. Pharm. Pharmacol. **59**(2), 209–223 (2007).
8. C. Gendre, M. Genty, M. Boiret, M. Julien, L. Meunier, O. Lecoq, M. Baron, P. Chaminade, and J. M. Péan, "Development of a process analytical technology (PAT) for in-Line Monitoring of Film Thickness and Mass of Coating Materials During a Pan Coating Operation," Eur. J. Pharm. Sci. **43**(4), 244–250 (2011).
9. J. B. Jackson, J. Bowen, G. Walker, J. Labaune, G. Mourou, M. Menu, and K. Fukunaga, "A survey of Terahertz applications in cultural heritage conservation science," IEEE Trans. Terahertz Sci. **1**(1), 220–231 (2011).
10. M. Koch, S. Hunsche, P. Schumacher, M. C. Nuss, J. Feldmann, and J. Fromm, "THz-imaging: a new method for density mapping of wood," Wood Sci. Technol. **32**, 421–427 (1998).
11. M. Picollo and S. Porcinai, "Non-destructive spectroscopic investigation on artworks," Recent Res. Dev. Appl. Spectrosc. **2**, 125–135 (1999).
12. J. Labaune, J. B. Jackson, S. Pages-Camagna, I. N. Duling, M. Menu, and G. A. Mourou, "Papyrus imaging with Terahertz time domain spectroscopy," Appl. Phys., A Mater. Sci. Process. **100**(3), 607–612 (2010).
13. E. Abraham, A. Younus, J. C. Delagnes, and P. Mounaix, "Non-invasive investigation of art paintings by Terahertz imaging," Appl. Phys., A Mater. Sci. Process. **100**(3), 585–590 (2010).
14. G. P. Gallerano, A. Doria, E. Giovenale, G. Messina, A. Petralia, I. Spassovsky, K. Fukunaga, and I. Hosako, "THz-ARTE: Non-invasive Terahertz diagnostics for art conservation," in *Proceedings of IEEE of Infrared, Millimeter and Terahertz Waves*, (Pasadenca, CA, 1998), pp. 1–2.

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15. E. Abraham, A. Younus, A. El Fatimy, J. C. Delagnes, E. Nguema, and P. Mounaix, "Broadband Terahertz imaging of documents written with lead pencils," Opt. Commun. **282**(15), 3104–3107 (2009).
16. K. Fukunaga and M. Picollo, "Terahertz spectroscopy applied to the analysis of artists' materials," Appl. Phys., A Mater. Sci. Process. **100**(3), 591–597 (2010).
17. P. Gassier and J. W. Bareau, *Goya: His Life and Work* (Thames & Hudson Ltd., 1971).
18. N. Glendinning, *Goya and His Critics* (Yale University Press, 1977).
19. M. Mena-Márquez and J. Wilson (private communication).
20. A. Canellas-López, *Las firmas y rúbricas del pintor Goya* (Real Academia de Nobles y Bellas Artes de San Luís, Zaragoza, 1991).
21. M. Riera and N. Hernández, (private communication, 2007).

1. Introduction

Terahertz (THz) radiation covers the part of electromagnetic spectrum between the microwave and far infrared bands (0.1 to 10 THz). THz has been extensively studied as a tool for spectroscopy in security [1–4] and pharmaceutical applications [5–8]. THz waves can also be used as a non-destructive evaluation tool because they can penetrate many materials (see through), such as plastic, paper, cardboard, canvas, and textiles, and their short wavelength allow generating images with spatial resolutions in the order of mm to sub-mm. For instance, THz imaging has been applied to study defects in insulation materials, composites, and in medical studies for cancer diagnosis. These features (e.g. see-through and sub-mm resolution) make THz technology particularly interesting in applications for artwork inspection. The use of THz radiation in the field of culture heritage inspection began in the late 1990 decade [9–11]. However, it has been during the past recent years that different types of studies have been reported, such as imaging of Egyptian papyrus, THz spectroscopy of ancient pigments, and THz imaging and layer analysis of paintings and archeological objects [12–16]. In this paper, we use a THz time-domain system to image and analyze the structure of the famous artwork "Sacrifice to Vesta" painted by Spanish artist Francisco de Goya y Lucientes (Fuendetodos 1746 - Bordeaux 1828) in 1771 [17,18]. In particular, this paper demonstrates the potential of THz imaging as a complementary technique along with X-ray and infrared (IR) imaging for the verification and authentication of artwork pieces through the detection of features that remain hidden to optical inspection. For this study we use a commercial Mini-Z THz time-domain system manufactured by Zomega Terahertz Corporation that can be used for both imaging and spectroscopy applications.

2. Setup and sample description

The painting, or sample, was inspected with a Mini-Z THz time-domain system configured for imaging in reflection geometry (Fig. 1(a)). The Mini-Z implements a pump-probe scheme to generate and detect the THz pulses. The pump beam generates the THz pulse and it is delayed respect the probe beam, which is used to detect the pulse. The Mini-Z includes a femtosecond laser that pumps a photoconductive antenna (PCA) to generate a THz pulse (pump beam). The THz pulse is focused onto the sample surface using a high-density polyethylene (HDPE) lens with 1" diameter and 1" focal length. The reflected beam is collected by the same lens and separated from the incoming beam by a beam splitter. The detection of the reflected beam is realized by electro-optical sampling with the probe beam. The shape and position of the pulses reflected from the sample are recorded in the time-domain in the so-called waveform. The temporal length of the waveform was set to approximately 30 ps (9 mm). This waveform provides information about the layered structure of a sample similar to the information provided by an ultrasound system.

Because the Mini-Z focuses the THz pulse on a single spot, the sample is set on a XY motorized stage so that the image can be generated in a raster scan mode. A manual micrometer controls the distance of the painting respect the Mini-Z in the perpendicular direction of the incident beam (Z-axis). A computer controls the stages and records the waveform at each position of the canvas, generating a cube of data. The scan duration depends on the desired resolution and the dimensions of the area being imaged and it can vary from a few hours to one week with waveform acquisition rates around 2 Hz. In this paper, the images are taken with a step size of 1 mm. Due to the dimensions of the painting and limited range of the XY stage, the painting was imaged in two half sections of 165 mm x 240 mm each. We measured one half first and then we rotated the painting to measure the other half. Furthermore, each section was imaged in eight different subsections of 82.5 mm x 60 mm so that the computer could handle the size of the data file being generated. The images from each subsection were stitched together to create the image of the entire painting. In the THz images, the two main sections can be identified through different contrast due to changes in the curvature of the painting that changed the maximum reflected power.

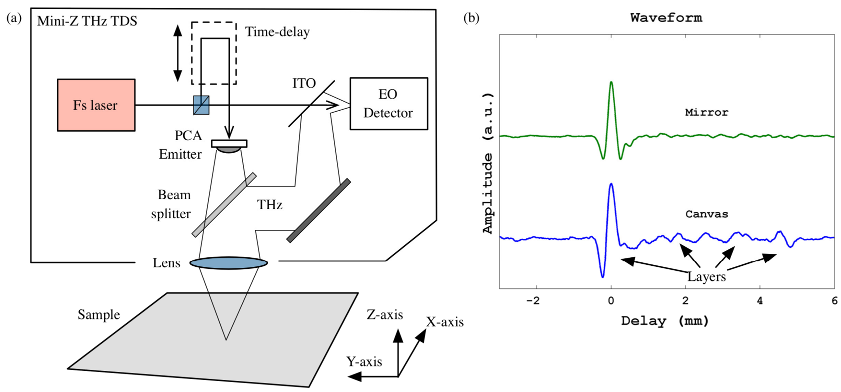

Fig. 1. Experimental layout.

Two analysis modes are possible with data provided by a THz time-domain system: structural and chemical. In the chemical analysis mode, the frequency components of the waveform (frequency-domain) can be analyzed via a Fourier transform. The spectrum of the waveform can provide information about specific resonances, or fingerprints, associated to particular pigments. In the structural mode, time of flight data is used to reconstruct the layered structure of the canvas and reveal features that are not visible because they are present at deeper layers of the sample. Figure 1(b) shows a waveform corresponding to a point in the canvas in which different layers are seen as replicas of the main peak. A waveform corresponding to the reflection of a perfect single surface (mirror) that does not contain such replicas is also shown for comparison. In this paper, we focus on the structural analysis by analyzing the amplitude of the THz pulse across the painting area. An analysis in the frequency domain was also performed to check the relationship between detected features and the resolution at different wavelengths. The usable bandwidth in the frequency domain analysis was up to 1.3 THz given the scattering properties of the canvas structure at high frequencies.

The title of the inspected artwork is “Sacrifice to Vesta” (Fig. 2(a)). This painting is an oil on a canvas with dimensions of 33 cm by 24 cm that has been published as a Francisco de Goya’s work in almost hundred art history publications and displayed in numerous exhibitions. This important work was painted by the young artist in 1771, almost certainly during his visit to Rome. “Sacrifice to Vesta” is one of the earliest known signed and dated work by Goya. In July 2007, a detailed investigation undertaken by leading Goya experts [19] endorsed the attribution to Goya. Currently, the paint belongs to a private collection.

3. Results

Figures 2(b) and 2(c) show different superposition between optical and THz amplitude images varying the degree of transparency. In the THz images we have plotted the maximum amplitude value of the waveform for each pixel. Other possible images can be obtained by plotting the position of the peak of the waveform or generating sections at different depths of the sample. However, amplitude images already display a great deal of structure of the painting that is not obvious by optical inspection. The THz images exhibit a strong correlation with the visible image. Some elements and figures of the painting, such as the priest, the arm and the head of Vesta (the woman on the left) can be clearly recognized in THz images. Figure 2(b) shows a superposition of 50% visible 50% THz, and Fig. 2(c) corresponds to a 100% THz image with no visible image superposition. The difference in reflectivity in areas of the painting is related to the reflectivity of the pigments at the THz frequencies.

(a) Image in the visible. (b) 50% visible, 50% THz image. (c) 100% THz image.

Fig. 2. Composition of "Sacrifice to Vesta" at different transparency levels of visible and THz images.

The study of the THz images provides an insight on the painting technique and the detection of features that cannot be seen in the visible image. In particular, the THz image provides a "texture feel" of the painting in which the intensity of the stroke, the density of the pigments, and the structural features of the canvas all come together (Fig. 3). For example, in the left upper corner in the THz image, a horizontal line and an arc are clearly seen. The horizontal line is attributed to the interaction of the wooden frame with the canvas, and the arc corresponds to a type of mechanical defect common to almost any painting that is older than 60 years. These defects are caused by impacts during transportation, wrapping due to temperature and humidity changes, and weakening of the frame because of the action of fungi or insects. In the THz image we can also distinguish the main strokes that give shape to the figures in the artwork. However, the most surprising feature is found at the bottom right of the painting, which could correspond to Goya's signature. Goya signed his paintings with different signatures [20] and, one of them (Fig. 3(b)) could correspond to the observed traces. Enhancing the image on that particular area (Fig. 3(c)), we can clearly distinguish the "ya" and a feature in front of them that could correspond to the "G". However, the "o" cannot be detected. Figures 3(d) and 3(e) show the images resulting from computing the Fourier transform on the waveform and, therefore, provide the amplitude distribution at different frequency components. As expected, the alleged signature can be seen at high frequencies such as 0.8 THz (Fig. 3(d)) but it cannot be observed at the lower frequency of 0.46 THz (Fig. 3(e)) because lower frequencies are not able to resolve the feature due to longer wavelengths.

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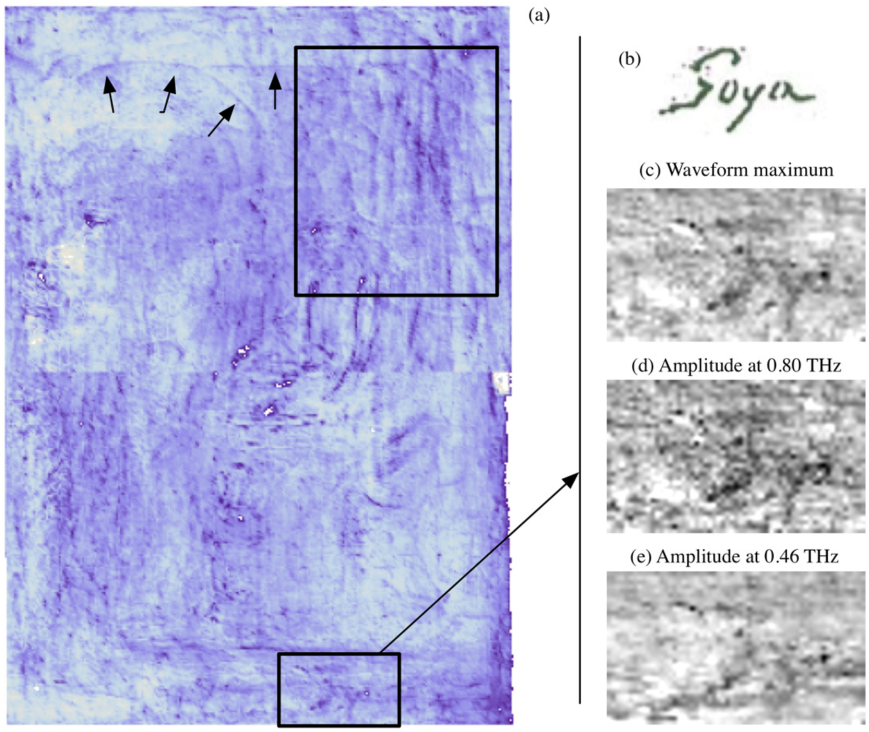

Fig. 3. (a) Structural features in the THz image and signature area. (b) Known signature of the artist. (c) Alleged signature resulting from finding the maximum amplitude in the time-domain data. (d) Image of the alleged signature in the frequency domain at 0.8 THz. (e) Image of the same area in the frequency domain at 0.46 THz in which the alleged signature is not visible due to larger wavelength than that corresponding to 0.8 THz.

4. Discussion and conclusion

The painting has been inspected with X-Ray imaging. Figure 4 shows the X-ray image of the study reported in reference [21] from which the authors of the study conclude that the canvas is not damaged because no gashes neither tears are observed in the image. The authors of this study also claim that the X-Ray image shows modifications that the artist had done during the execution of the paint respect the final composition. They emphasize that vertical strip at the left of the female figure may indicate a correction in the position of the body, the face of the woman located at the center was initially conceived in three quarters while the final composition is nearly in profile. On the other hand, the THz image show wrinkles in the upper right corner that may indicate a slight deterioration of the painting. This deterioration may not compromise the integrity of the artwork at present time but it indicates that some sort of restoration or preservation operation may be required in the future.

In relation to the alleged signature, assuming that it was written using a pencil (basically carbon) and that the painting was covered by a top layer of finishing varnish that turned dark over time, it is expected that X-ray images cannot detect the signature because the atomic weight of carbon (signature) and the surrounding canvas and the paint is very similar. In this case, THz waves are more sensitive to molecular composition and to the different reflectivity of carbon and the surrounding canvas, which provides the mechanism for the detection of the signature.

Fig. 4. X-ray image in which alleged signature is not visible nor wrinkles and defects on the upper third sector.

IR images are not available for this painting. It could be interesting to perform IR imaging and compare the results with the THz images. IR radiation has less penetration than THz waves –IR typical penetration depth is around few tens of microns whereas THz waves can penetrate few millimeters–. In this sense, if the signature is nearby the surface, it may be possible that IR images may be able to recover it as well. However, if signature is located at deeper layers, IR might not be able to recover it.

Therefore, we conclude that the THz images provide complementary information to X-ray images and optical inspection because it can unveil features (hidden sketches and signatures, wrinkles, stroke style, etc.) that are less evident with other techniques. Again, it will be interesting to investigate this painting with IR and verify whether such feature can be detected as well. Characteristic and unique features recovered by a combination of X-ray, IR, and THz imaging can support evaluation studies of paintings in relation to authorship authentication, structural integrity assessment and restoration needs.

Besides the use of THz technology to analyze the structural properties of the paintings, THz technology has also the potential to study the chemical composition of the painting by analyzing the information provided by the waveform in the frequency-domain. However, the multiple layers of the canvas will generate multiple reflections that will be challenging to separate in order to perform a standard spectroscopic analysis. To overcome this challenge, specific waveform cleaning algorithms will need to be developed as well as the creation of a pigments spectroscopy database. These efforts are out of the scope of this paper.

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