J Infrared Milli Terahz Waves (2017) 38:380–389
DOI 10.1007/s10762-017-0365-2

Investigation of Layer Structure of the Takamatsuzuka Mural Paintings by Terahertz Imaging Technique

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Received: 13 September 2016 / Accepted: 24 January 2017 /
Published online: 10 February 2017

Abstract Terahertz imaging can be a powerful tool in conservation science for cultural heritages. In this study, a new terahertz imaging system was applied to the Takamatsuzuka mural painting of a blue dragon, and the condition of the plaster layer was diagnosed. As a result, the locations where the plaster layer appears solid on the surface but in actuality may have peeled off the underlying tuff stone were revealed and viewed as two-dimensional images.

Keywords Cultural heritage · Terahertz imaging · Layer structure · Takamatsuzuka mural painting

1 Introduction

The important subject of conservation science for cultural heritages is the scientific investigation of the materials and structures of cultural heritages. Obviously, there are many kinds of analytical methods for investigating the materials and structures of objects. However, for the investigation of cultural objects, there are usually some strong restrictions. One of them is that taking samples for investigation is prohibited and, in many cases, noninvasive methods are required because each cultural heritage is a unique object. Moreover, applying portable instruments is often required in case that the cultural heritage to be investigated cannot be transported. From these points of view, the terahertz imaging technique can be a powerful tool in conservation science.

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Taking the requirement of noninvasive methods into consideration, photons are candidate probes for analyzing cultural objects. For the investigation of the materials and structures of cultural objects, the energy of waves with various wavelengths (for example, X-rays, ultraviolet rays, visible rays, infrared rays, terahertz waves, and electric waves) has been used as probes.

Analytical methods using X-rays are among the most popular tools in conservation science. X-ray fluorescence analysis (XRF) and X-ray diffraction analysis (XRD) are used to identify the elements and crystal structures of the materials composing cultural objects, respectively [1]. Because of the relatively high transmittance of X-rays in materials, X-ray radiography is also a popular and conventional method of investigating the inner structure of cultural objects. On the other hand, infrared rays are used to search for rough sketches under paintings because of the high absorbance of infrared rays by charcoal and ink [2]. Because of their relatively low transmittance in materials, infrared rays are generally used to obtain information from the surface layer of cultural objects.

Terahertz waves cover the frequency range roughly from 0.1 to 10 THz (corresponding to wavelengths from 3 mm to 30 μm). The reflectance of terahertz waves is high at the boundaries of materials with different refractive indices. The transmittance of terahertz waves in materials shows intermediate characteristics between those of X-rays and infrared rays and can typically reach a depth of a few centimeters for organic materials. Therefore, terahertz waves are a suitable probe for investigating the layer structure beneath the surface of cultural objects [3]. In conservation science, there have so far been several investigations of cultural objects, for example, paintings [4, 5], folding screens, and building materials, using terahertz waves [6]. In this paper, the investigation of the layer structure of Takamatsuzuka mural paintings by the terahertz imaging technique is reported.

2 Takamatsuzuka Mural Paintings and Terahertz Imaging Technique

2.1 Takamatsuzuka Mural Paintings

In March 1972, the Takamatsuzuka tumulus was discovered in Nara prefecture, Japan. According to the results of excavation and research, it is considered to be a two-layer round barrow tumulus with the diameters of 23 m (lower layer) and 18 m (upper layer). In the tumulus mound, there was a stone chamber constructed of 16 tuff stone blocks. The interior of the stone chamber was about 2.7 m in depth from north to south, about 1.0 m in width from east to west, and about 1.1 m in height. Inside the stone chamber, the walls and ceiling were plastered; the depth of the plaster layer was typically a few millimeters. Mural paintings were drawn on the plaster, and they were designated as a national treasure in 1974. Figure 1a shows a photograph of the painting of a group of women drawn on the west wall. This photograph was taken soon after the painting was discovered in 1972.

After the excavation, discussions were conducted by a committee to decide how to conserve the mural paintings in the future. As a result of the discussions, in 1973, it was decided to conserve the mural paintings on site. In 1976, a conservation facility was constructed in front of the stone chamber so that the mural paintings would not be exposed to rapid fluctuations of temperature and humidity.

However, after consolidating the soil near the stone chamber in 2001, black mold was found outside and inside the stone chamber. In December 2001, black mold was also found on the mural paintings. The main causes were thought to be the consolidating work and a

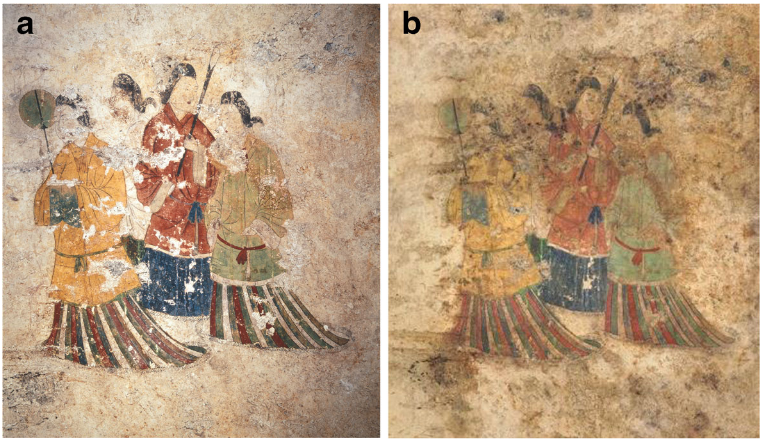

Fig. 1 Photographs of the painting of a group of women drawn on the west wall of the Takamatsuzuka chamber **a** taken when the paintings were discovered in 1972 (photo provided by Asuka village) and **b** taken just before the transfer to the renovation facility in 2006 (photo provided by Agency for Cultural Affairs, Government of Japan)

temperature increase [7]. Finally, for the conservation of the mural paintings, the committee decided (2005) to remove the stone chamber for restoration because the mold was an urgent problem. After the excavation in 2007, the stone chamber was disassembled and transported to the renovation facility constructed in Asuka Historical National Government Park, which is located near the Takamatsuzuka tumulus. Figure 1b shows a photograph of the same painting as that shown in Fig. 1a, but taken in 2006 just before the transfer to the renovation facility.

In the renovation facility, the temperature and relative humidity are kept at around 21 °C and 55%RH, respectively, and repair and cleaning have been conducted by restorers since 2007. In addition to repair and cleaning, it is important to understand the condition of the mural paintings, the plaster layer, and the tuff stone and to consider how to control the environment for the conservation of the mural paintings. For these purposes, several kinds of scientific investigations have been conducted, for example, microscope observations [8], digitizing scan visible images to record the current condition of the mural paintings, XRF [9], visible-light spectral analysis [10], and the investigation of the layer structure by the terahertz imaging technique.

2.2 Application of Terahertz Imaging Technique

One of the important components of the mural paintings is the plaster layer. When the stone chamber was in the tumulus, the relative humidity was almost 100%. Since the relative humidity surrounding the mural paintings became low after the transfer, the condition of the plaster layer might have changed. For example, its strength might have been reduced because of the reduced water content. In addition, there is the concern that the plaster layer might have peeled off because of its contraction. Care should be taken because peeling could occur even if the plaster appears to be rigid at its outer surface.

Actually, the locations of peeling were recognized by touch by restorers. However, it is also important to investigate the locations of peeling independently by scientific means, as an objective cross-check of the sense of the restorers. Terahertz imaging is a suitable method for noninvasive investigation of the condition of the plaster layer (whose depth is typically a few millimeters) and the locations of peeling.

3 Method

3.1 Instrument for Terahertz Imaging

In 2015, we selected the terahertz imaging system produced by Pioneer Corporation and, after some developments, applied it to the investigation of the condition of the plaster layer of the Takamatsuzuka mural paintings, as described in the previous section.

The system is composed of a THz scanner head, mechanical stage, system controller, and PC. As shown in Fig. 2, the THz scanner head is mounted on the mechanical stage, and the head is controlled to move two-dimensionally to scan the objects to be investigated. The pulse of a terahertz wave is emitted from the THz scanner head to the mural painting, and the reflected terahertz wave is detected by the THz scanner head. Then, the signal is processed by the system controller. One of the advantages of this system is that there is only one cable connecting the THz scanner head and the system controller. Therefore, it is considered that this is a safe system for the investigation of cultural objects.

3.2 Measurement Conditions

The investigation of the layer structure of a Takamatsuzuka mural painting using the terahertz imaging system described in the previous section was conducted in the renovation facility from February 29th to March 2nd in 2016. In this study, the mural painting of a blue dragon was selected to be investigated. The visible image of this mural painting is shown in Fig. 3a. The mural painting had been on the east side of the stone chamber in the tumulus before it was dismantled.

In the renovation facility, the tuff stones were placed such that the mural paintings faced upward. The size of the mural painting that was investigated is 1160 mm by 910 mm. On the other hand, the THz scanner head can be moved over an area of up to 250 mm by 250 mm within the mechanical stage. Therefore, the area to be investigated was divided into 4 by 5 sections, and the measurement was conducted 20 times in total. As shown in Fig. 4, the THz scanner head, the mechanical stage, and the system controller were mounted on a frame produced expressly for the investigation of the Takamatsuzuka mural paintings. During the measurements, the THz scanner head was moved above the mural painting.

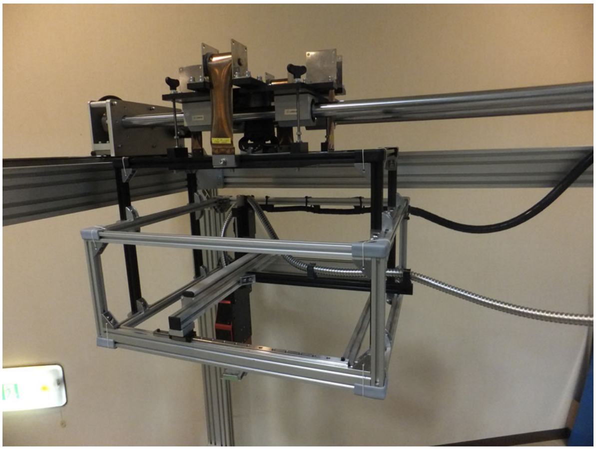

Fig. 2 THz scanner head of terahertz imaging system mounted on the mechanical stage

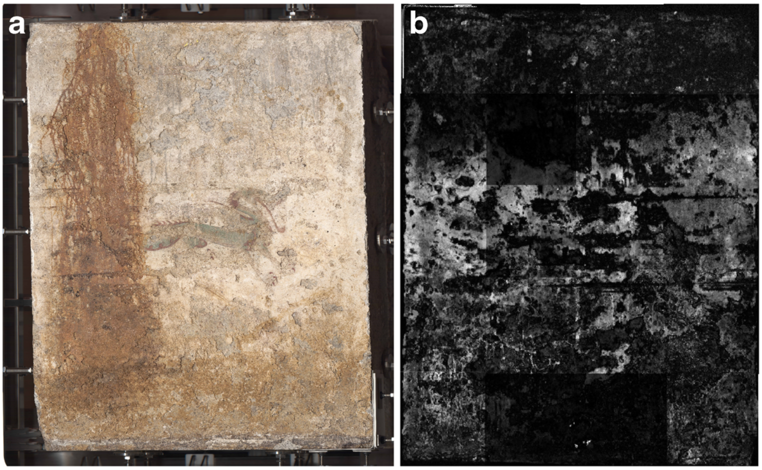

Fig. 3 Mural painting of blue dragon. **a** Visible image obtained using the digital scanner. **b** Terahertz image

A measurement pitch of 2 mm was selected. The velocity of the THz scanner head was set to 20 mm/s, taking safety into account. It takes about 1 h to scan each measurement area of 250 mm by 250 mm.

4 Results

4.1 Condition of Plaster Layer

In this section, the results concerning the condition of the plaster layer obtained using the terahertz imaging system are presented. Figure 5 shows some examples of measurement points on the mural painting. In Fig. 5, the plaster layer is solid at point A, whereas the plaster layer has been lost and the surface of the tuff stone is exposed at point B. In addition, although the plaster layer appears solid on the surface at point C, the investigation using the terahertz imaging system revealed that the plaster layer may have peeled from the tuff stone, as

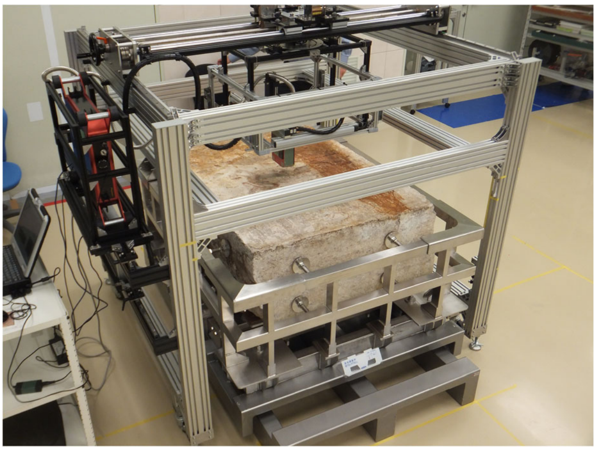

Fig. 4 THz scanner head, mechanical stage, and system controller mounted on the frame produced expressly for the investigation of Takamatsuzuka mural paintings

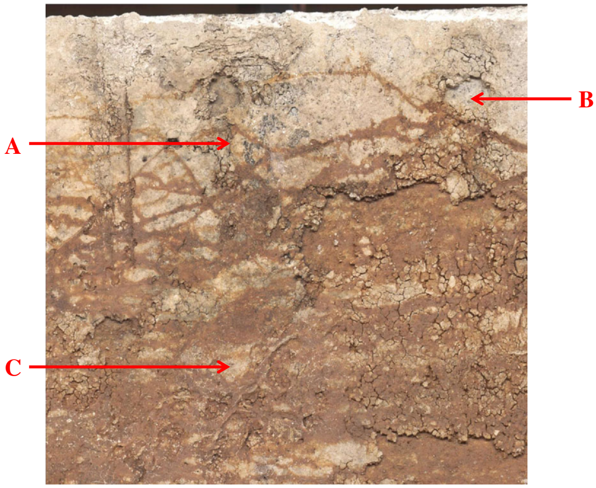

Fig. 5 Examples of measurement points on the mural painting

explained later. In the area shown in Fig. 5, the surfaces of the plaster and the tuff stone are flat and are parallel to the plane on which the THz scanner head is controlled to move.

Figure 6a shows the reflected terahertz pulse echo sequence for point A. Figure 6b shows the cross-sectional image along the scanning line including point A. On the other hand, Fig. 6c, d are the same as Fig. 6a, b, respectively, but for point B. In comparison with Fig. 6a, the reflected pulse shown in Fig. 6c is delayed by 30 ps, which corresponds to a distance of 4.5 mm in air. This time difference is due to the lack of the plaster layer at point B. From the cross-sectional image shown in Fig. 6d, the lack of the plaster layer at point B can again be recognized. In these figures,

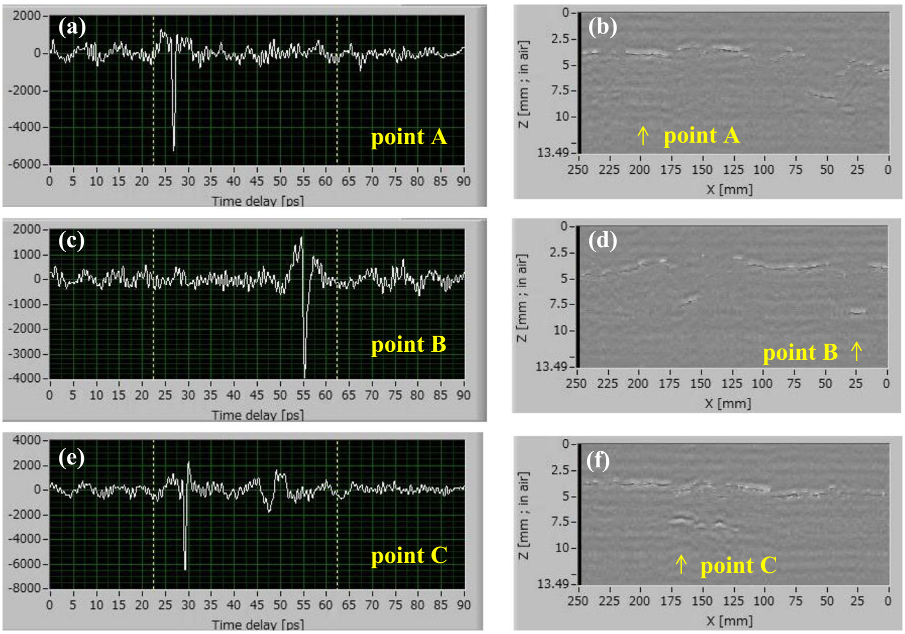

Fig. 6 **a** Reflected terahertz pulse echo sequence for *point A*. **b** Cross-sectional image along the scanning line including *point A*. **b**–**d** Same as (**a**) and (**b**), respectively, but for *point B*; **e**, **f** same figure for *point C*

the possible reflection at the boundary of the plaster and tuff stone cannot be observed probably due to the similar refractive indices of both materials and to the absorbance of the reflected pulse from the boundary through the plaster layer.

Figure 6e, f shows the reflected terahertz pulse echo sequence and the cross-sectional image for point C, respectively. In Fig. 6e, a large reflected pulse is observed at the same time as the one observed in Fig. 6a; therefore, this signal is due to the reflection at the surface of the plaster layer. This pulse is followed by another reflected pulse about 20 ps later. This pulse has a smaller height and is detected about 10 ps earlier than the reflected pulse observed in Fig. 6d, which originated from the surface of the tuff stone. Also in Fig. 6f, small reflected pulses are observed and displayed beneath the one due to the reflection at the surface of the plaster layer. One of the possible reasons for this phenomenon can be that the plaster layer had peeled from the tuff stone, creating an air gap between the plaster and the tuff stone. Note that the reflected pulse is broader in Fig. 6e probably due to the superposition of reflections at the interface of the plaster and air and at the interface of air and the tuff stone. The pulse was detected earlier because the refractive index of the plaster is higher than that of air, and the pulse height became smaller because of the absorbance while the reflected pulse was passing through the plaster layer.

The data obtained from this measurement includes the pulse height as a function of reflection time for each pixel (2 mm by 2 mm for this measurement). As indicated in Fig. 6a, c, and e, the information in the signals due to the reflection at the surface of the plaster layer can be extracted if the data of the earlier reflection time are extracted. Figure 7a shows the two-dimensional distribution of the absolute intensity integrated within the time interval from 10 to 40 ps in the same area as the one shown in Fig. 5. Upon comparison with Fig. 5, we can see that Fig. 7a indicates the two-dimensional distribution of the surface of a solid plaster layer. Figure 7b shows the two-dimensional distribution of the absolute intensity integrated within the time interval from 40 to 70 ps. In contrast to Fig. 5, this figure contains information about the two-dimensional distribution of the location without the plaster layer.

As shown in Fig. 6e, the reflection time at the location where the plaster layer has peeled from the tuff stone falls between the time due to the reflection at the surface of the plaster layer and the time due to the reflection at the surface of the tuff stone where the plaster layer has been lost. Figure 7c shows the two-dimensional distribution of the absolute intensity integrated within the time interval from 35 to 55 ps. This figure shows the location where the plaster layer appears solid on the surface but may in fact have peeled from the tuff stone, for example, point C indicated in Fig. 5. According to the restorers, the regions identified by this analysis method were almost consistent with the regions of peeling recognized by touch by them. Therefore, it can be concluded that the terahertz imaging technique is a suitable method for noninvasive investigation

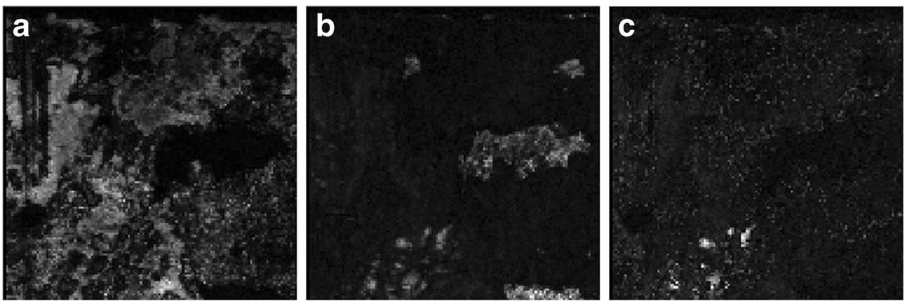

Fig. 7 Two-dimensional distributions of the absolute intensity integrated in the time interval (**a**) from 10 to 40 ps, (**b**) from 40 to 70 ps, and (**c**) from 35 to 55 ps

of the condition of the plaster layer and can be a scientific measure providing a cross-check of the sense of the restorers.

4.2 Information About Materials on the Painting

Figure 3b shows the terahertz image of the mural painting after combining 20 individual images obtained by integrating the absolute intensity over the whole time range recorded in the data. By applying the terahertz imaging system, there is a possibility of obtaining not only information about the layer structure of the plaster but also some information about the materials used in the mural painting.

For example, a gray material can be found in the upper part of this mural painting, as shown in Fig. 8a. This material has not yet been identified by other analytical methods, for example, XRF and visible-light spectral analysis. Figure 8b shows the terahertz image of the area shown as the red square in Fig. 8a. The pattern of the area with the gray material can be seen in Fig. 8b because the reflectance of terahertz waves is high at the surface of the gray material. There is a possibility that the terahertz imaging technique will provide some hints to investigate the chemical composition and physical properties of the gray material.

In this study, more information about the materials has been obtained. In this mural painting, there is a sun drawn in the upper part. Between the sun and the back of the blue dragon, ultraviolet spectroscopy revealed the existence of an unidentified material, as shown in Fig. 9a [11]. Although the material has again not yet been identified by other analytical methods, a pattern for this material was found by using the terahertz imaging technique, as shown in Fig. 9b.

5 Further Requests Concerning Terahertz Imaging Technology from Conservation Scientists

This is the first application of the terahertz imaging system produced by a Japanese company to the investigation of the Takamatsuzuka mural paintings. The instrument has been

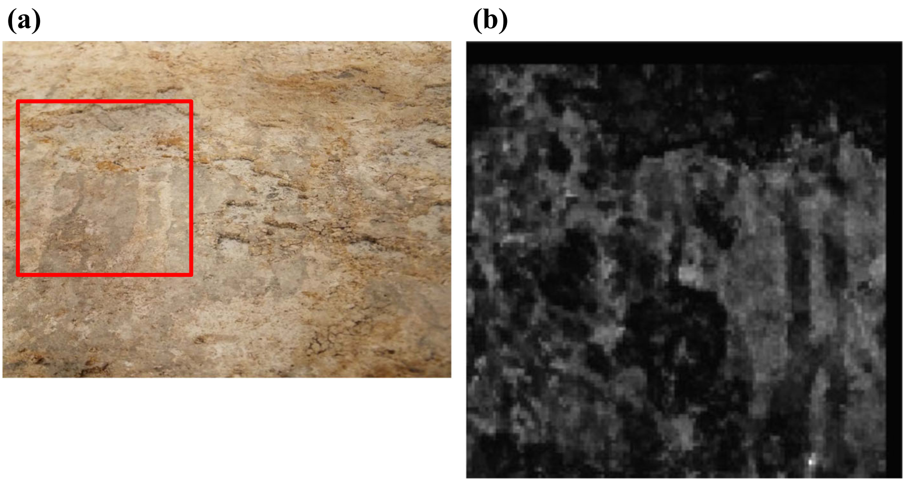

Fig. 8 **a** Photograph of the gray material (indicated by the *red square*) on the mural painting. **b** Its terahertz image

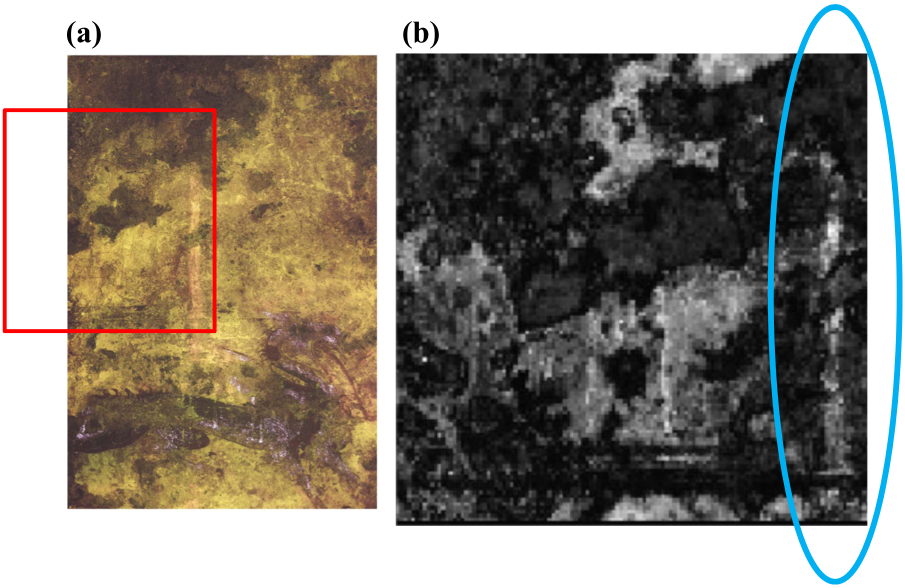

Fig. 9 **a** Image obtained by ultraviolet spectroscopy. **b** Terahertz image of the area indicated as the *red square* in (**a**). The unidentified material between the sun and the blue dragon is indicated by the blue circle in (**b**)

customized to cope with the investigation of cultural heritage. One of the advantages of this instrument is that the mechanical structure of the whole system is simple, and it is sufficiently safe for conservation scientists to conduct noninvasive measurements (Section 3.1). Another advantage is that the software programs for controlling the measurements and for data analysis are also simple, making it easy to operate the system even for conservation scientists. On the other hand, one of the drawbacks is that the maximum measurement range of reflection time is only 90 ps, which is relatively short compared with those of other terahertz imaging systems used for other investigations of cultural objects [4]. This is a trade-off with the simplicity of the system, but it would be useful if the system could be improved to enable deeper measurements without reducing the convenience to users.

When Fig. 7 was produced, the data within a specified time range were extracted and the absolute intensities were integrated. Therefore, in principle, three-dimensional images similar to those obtained by X-ray computed tomography can be constructed by combining two-dimensional images produced in subsequent time ranges. Such a study has already been started [12]. Instruments with the function of creating such three-dimensional images would be convenient for conservation scientists because it would be possible to diagnose the layer structure of cultural objects and to conduct more effective discussions with restorers.

6 Summary

Terahertz imaging can be a powerful tool in conservation science because, for the investigation of cultural heritages, noninvasive methods and/or portable instruments are usually required. The transmittance of terahertz waves shows intermediate characteristics between those of X-rays and infrared rays, and typically can reach a few centimeters for organic materials.

Therefore, terahertz imaging is a suitable method for investigating the layer structure beneath the surface of cultural objects.

In this study, a new terahertz imaging system was applied to the Takamatsuzuka mural painting of a blue dragon and the condition of the plaster layer was diagnosed. As a result of analyzing the data for the pulse height as a function of reflection time for each pixel, the locations where the plaster layer appears solid on the surface, but may in fact have peeled from the tuff stone, were revealed and viewed as two-dimensional images. The locations extracted in this manner were almost consistent with the regions of peeling recognized by touch by the restorers. Therefore, it can be concluded that the terahertz imaging technique is a suitable method for noninvasive investigation of the conditions of a plaster layer and can be a scientific measure providing a cross-check of the sense of restorers.

It would be more convenient for conservation scientists if the system was capable of deeper measurements without reduced convenience to users and if the function of three-dimensional imaging will be available in its software.

Acknowledgements The authors would like to thank the technical staffs of Pioneer Corporation for their cooperation in customizing the terahertz imaging system and for technical support.

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