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Joint Investigation with Ground Penetrating Radar and Infrared Thermography as a Diagnostic Support for the Restoration of Two Wall Mosaics in the Church of St. Mary of the Admiral in Palermo, Italy

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Abstract: The church of S. Mary of the Admiral in Palermo, known as "La Martorana" and very famous for its Byzantine mosaics, has been a World Heritage site since 2015. The mosaic system of the church includes several groups of figures and scenes from the life of the Virgin Mary. From the western part of the ancient church only two mosaics survive, detached from their original position, and are now located in two internal chapels. On the occasion of several restoration works, these two mosaic panels were investigated with non-invasive techniques, in order to provide diagnostic support to the restoration and consolidation interventions. The investigations were aimed at detecting any air pockets that could cause the detachment of the tesserae or of possible differences between cement mortars under the tesserae. For this purpose, the integrated use of two non-invasive techniques namely infrared thermography (IRT) and ground penetrating radar (GPR) was considered. The joint analysis of IRT and GPR data allowed the interpretative uncertainties inherent in each technique to be reduced. Furthermore, for both techniques differentiated analyses were performed for layers at different depths under the mosaic surface. The results of these analyses were found to be more reliable regarding GPR data, compared to infrared thermography, the latter being more influenced by the reflectivity of the tesserae. However, the results partially confirmed the restorers' diagnosis, also allowing the identification of further critical areas that could be affected by deterioration or compositional differences in the layers supporting the mosaics

Keywords: mosaic; infrared thermography; ground penetrating radar; non-destructive test

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1. Introduction

Wall decoration using mosaics is widespread and witnessed in different types of historic buildings (e.g., houses, palaces, churches, etc.) and it is a technique that dates back to Mesopotamia in 3000 BC. In Greek, Roman, and Byzantine times, tesserae were widely used for the decoration of walls, pillars, ceilings, columns, and vaults [1–9]. In general, mosaics created on walls, domes, and vaults are more difficult to study than those placed on floors, due to the position and the often irregular geometric characteristics of the laying surface.

The Greek Orthodox church of St. Mary of the Admiral in Palermo, known as "La Martorana" (Figure 1), is one of the monuments of the site "Arab-Norman Palermo and the Cathedrals of Cefalù and Monreale", which UNESCO declared a World Heritage site in 2015. The church takes its name from George of Antioch, the Great Admiral of the Norman King Roger II, who founded it in 1143 [10,11]. Many scholars [12–14] date the completion of the church to a few years after its decoration but before the admiral's death (1151).

In 1435 the church of St. Mary of the Admiral was sold to the nearby Benedictine female monastery that Goffredo and Eloisa Martorana, ancient nobles of the city, had founded in 1193 and since then, for the Palermitans, this church is simply "La Martorana".

Figure 1. The northern facade of the church of St. Mary of the Admiral, called “la Martorana” in Piazza Bellini in Palermo.

The church is one of the most spectacular testimonies of the encounter between Islamic (Fatimid) architecture and Byzantine mosaic art [15]. In fact, George of Antioch brought Greek mosaicists from Constantinople to Palermo. The original structure of the Greek cross church with an atrium and a narthex has undergone substantial changes over the centuries both in architectural and artistic terms, producing the eclectic result that we admire today.

The floor is decorated with a cosmatesque motif, while the vaults are decorated with very small mosaic tesserae depicting saints and biblical scenes and the bell tower is embellished with lava stone inlays. Over the centuries the church has undergone changes and extensions, which include the choir, the frescoes, the Baroque façade, and the apse with the dome. The Baroque frescoes (by the artists Guglielmo Borremans, Antonio Grano, and Olivio Sozzi) have been added to the ancient mosaics while, in place of the ancient apse, the Baroque chapel was built by the architect Paolo Amato (1634–1714) and decorated with the famous Baroque marbles of Palermo [16].

The mosaic system of “La Martorana” church includes many figures, like the world famous “Christ Pantocrator”, and scenes from the life of the Virgin Mary. The demolition of the presbytery and the atrium, which took place between the 16th and 17th centuries, caused the loss of most of the mosaics placed on the eastern and western walls of the church [17]. Of these, only two wall mosaics from the western part of the ancient church survived: these were detached from their original position and relocated in two chapels marked in Figure 2.

The *Dedication* panel (Figure 3) represents George of Antioch prostrate in front of the Virgin Mary and invokes for him the protection of Jesus who appears in the upper right corner of the mosaic. The left half of the panel is occupied in all its height by the figure of the Virgin Mary, her head in three-quarters profile and slightly tilted to the right. In the upper right corner of the panel, Christ is depicted in a blue sphere in the form of a small half-length figure. The Virgin holds out her right hand towards George of Antioch who is kneeling at her feet. With her left hand she presents an open scroll with an inscription in verse: a plea that she addresses to her Son in favor of George of Antioch [18–20].

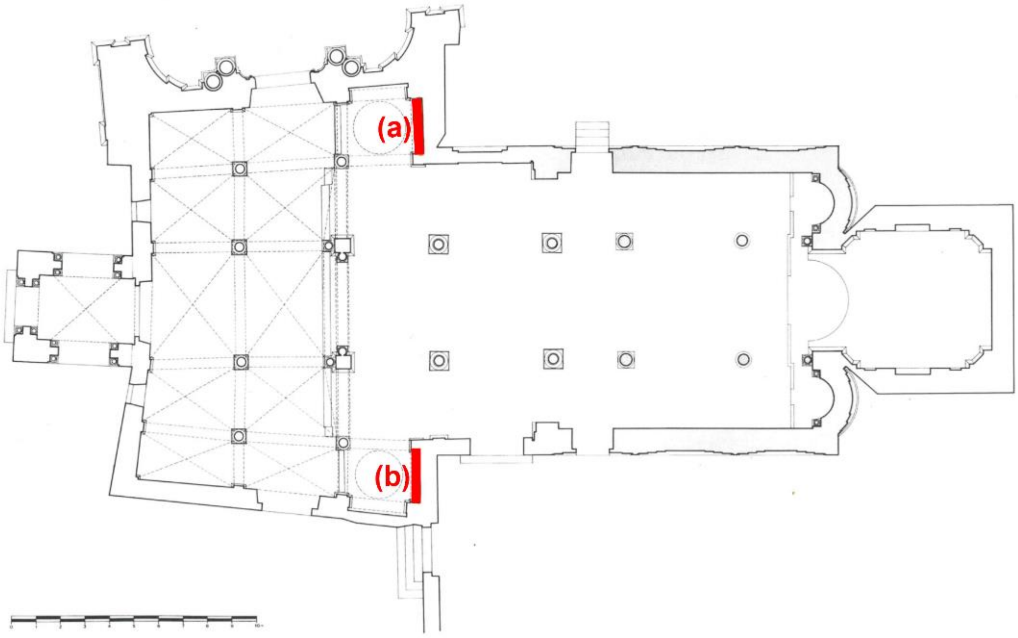

Figure 2. Plan of the church of St. Mary of the Admiral in Palermo. (**a**) Position of the Dedication panel; (**b**) position of the Coronation panel (authors modified after [14]).

Figure 3. Palermo, St. Mary of the Admiral, *Dedication* mosaic panel: George of Antioch prostrate at the feet of the Virgin Mary. The hatched lines indicate the areas affected by the risk of detachment of the tesserae, as previously indicated by the restorers.

The *Coronation* panel (Figure 4) represents Christ crowning Roger II. The king stands before his supreme leader, his head tilted reverently, his hands outstretched to him in a gesture of prayer. Roger wears the costume of a Byzantine emperor: a long blue tunic with gold clubs, a shorter overtunic adorned with a regular motif of gold cornflowers and the loros, the sash that covers it [21]. On his head he has an open, relatively high crown. The figure of Christ is taller and larger than that of Roger.

In Figures 3 and 4, the hatched lines indicate the areas affected by the risk of detachment of the tesserae, as previously indicated by the restorers.

Figure 4. Palermo, St. Mary of the Admiral, *Coronation* mosaic panel: Christ crowning Roger II. The hatched lines indicate the areas affected by the risk of detachment of the tesserae, as previously indicated by the restorers.

Radiocarbon analysis of a wooden sample of the rear panel of the Coronation mosaic [14] dates to the 18th century the rearrangement of both decorations inside two Baroque chapels [22]. In the 19th century, the architect Giuseppe Patricolo demolished the Baroque chapels [22], moving the two dedicatory mosaics to their current position on the eastern walls of the two lateral chapels.

In general, the wall mosaics were executed by placing different layers of preparation on the wall before the application of the tesserae which are generally made of glass, stone, nacre, or ceramic. A first layer of bedding mortar was applied over the wall, with or without aggregates [9] and on top of this another layer of lime mortar and various types of aggregates (sand, pozzolan, marble dust, etc.).

Detecting differences in the physical parameters investigated, possibly caused by changes in composition, number, and thickness of the layers, is useful for identifying the age of the mosaics and sometimes to distinguish the contributions of different mosaic artists. The physical anomalies may also be caused by alterations in the surface of the tesserae, presence of voids, humidity, water infiltration, efflorescence, and inhomogeneity in the underlying mortar layers. In fact, these problems can affect the conservation of the mosaic as they often lead to the detachment of the tesserae.

The advances in recent years of non-invasive techniques applied to the study of cultural heritage have opened new horizons in the field of heritage protection [23]. In fact, these techniques allow the increase of knowledge of the transformations that may have affected historical structures over the centuries, thus supporting and guiding restoration projects [24–30]. To minimize interpretative ambiguities, the joint use of different non-invasive techniques has often been proposed such as ground penetrating radar (GPR), terrestrial laser scanning (TLS) and infrared thermography (IRT) [31], unmanned aerial vehicle (UAV) photogrammetry and TLS [32], UAV photogrammetry and GPR [33], GPR, and electrical resistivity tomography (ERT) [34,35], GPR, IRT, and ERT [36].

The conservation, protection and restoration of mosaic decorations requires rapid and totally non-invasive diagnostic techniques, able to recognize previous restorations, replacements, and other changes that have occurred over time and, furthermore, quickly and effectively identify any anomaly caused by deterioration that can compromise the integrity of mosaics in the long run [37].

Among the non-invasive techniques that can be used for the study of wall mosaics, IRT, TLS, GPR, and ERT are to be considered. Their joint use often allows the information obtained to be integrated, resolving interpretative doubts.

The various vicissitudes of the church of St. Mary of the Admiral in Palermo, not always documented, have caused great difficulties in interpreting the origin of the tesserae and the various alteration and restoration interventions. Recently, diagnostic studies were carried out with non-invasive techniques and laboratory analyses to distinguish modern from medieval materials [38] with the aim of contributing to the reconstruction of the restoration phases of these mosaics, carried out between the 12th and the 20th century [39].

The most important restoration ever carried out on the Church of St. Mary of the Admiral took place between 2010 and 2012. The restoration involved both the church and the bell tower, internal and external walls, addressing both the static reinforcement of the walls and the vault of the choir, both the conservation of the very rich decorative system, from the eighteenth-century frescoes by Oliviero Sozzi and Guglielmo Borremans, to the mosaics in polychrome stones and glazes in glass paste, the Baroque marble of the altar, the ciborium in lapis lazuli and gilded wooden sculptures, the Baroque flooring, the majolicas of the choir.

In this context, non-invasive techniques were used to study the two above-described mosaic panels. The purpose of the investigations was to provide diagnostic support to the restoration and consolidation interventions of the two mosaic panels, with particular attention to the issues of detachment of the tesserae and of differentiation between cement mortars.

The diagnostic study involved the integration of two different non-invasive investigation methods: Infrared thermography (IRT) and ground penetrating radar (GPR). These techniques were preferred to the others because in fact they are the most expeditious and are easier to interpret.

2. Materials and Methods

2.1. Infrared Thermography

Infrared thermography (IRT) is a non-invasive method widely applied to cultural heritage studies [39–46], with several cases of applications to wall mosaics [39,46]. This telemetry technique determines the temperature of a surface by measuring the “black body” radiation emitted by each object as a function of its own temperature. Through the use of a thermal camera, it is possible, in fact, to perform non-destructive tests that do not cause alterations and do not require any contact between the equipment and the examined surface. The thermographic survey allows the evaluation and estimation of the thermal characteristics of the masonry structures, the detection of infiltration and dispersion of water, discontinuities due to different materials, the identification of pre-existing and currently hidden architectural elements (cavities, infill, and bracing), alterations on surfaces, detachments from the wall supports, wall textures and constructive facies, and discontinuity in the thermal insulation of buildings.

The thermal imaging camera is able to detect the temperature of the target by measuring the intensity of infrared radiation emitted.

The correlation between irradiation (q) and temperature (T) is given by the Stefan–Boltzmann law:

$$q = \varepsilon\ \sigma T^4, \tag{1}$$

where ε is the emissivity and σ is the Stefan–Boltzmann constant [47].

The non-destructiveness of IRT does not set limits on the number of acquisitions, which can be carried out in many areas and can be repeated over time for the verification and analysis of the structures during conservation and restoration interventions. Detection of non-visible structures is possible only if the difference in the properties of the materials induces a variable distribution of surface temperatures.

Thermographic techniques are divided into passive and active; in the first case, the measurement concerns the temperature assumed by the objects considered as isolated systems from the surrounding environment.

Active thermography, on the other hand, considers the temperature reached by the objects as a result of an external heating of the surface which, in general, is achieved through lamps or stoves. Discontinuities in the structure of the material can cause local variations in the thermophysical properties of the object. After applying the appropriate thermal stress to the investigated surface, these local variations can produce anomalies in the surface temperature distribution. A limit to this approach is caused by the different heat absorption from areas of different colors, so a thermal anomaly linked to an underlying detachment can suffer interferences with that caused by color change and consequently could be difficult to read.

In the case of mosaic panels, the thermal variations detected by the IRT can be caused not only by the different typology of the tesserae, but also by the presence of different materials under the decorative layer. Although this survey refers only to the first few centimeters below the decor, it is a perfect combination with the GPR method for identifying shallow voids (gaps) or moisture.

A FLIR System ThermaCAM™ P40 PAL thermal imaging camera was used for the thermographic surveys of the two mosaic panels preserved in the Martorana Church. This system guarantees a spatial resolution of 1.3 mrad and is sensitive to thermal radiation in the band between 7 and 13 microns.

The processing of the acquired images was carried out using the FLIR QuickReport and FLIR BuildIR software. In this case, the processing involved, in addition to the normal treatments for reducing noise and outliers, also the application of techniques for emphasizing the differences in temperatures, in order to identify probable differentiations and details in the investigated structure.

The thermographic survey conducted was both passive and active. The use of the active methodology has allowed clearer documentation of the areas affected by detachments or by the presence of different materials (generally due to the presence of layers of air between the support and the wall texture or anomalous areas consisting of different material than the surrounding areas). To this end, the surface was heated by diffused lighting using two halogen lamps for a duration of 20 min at a distance of about 1 m (Figure 5). The duration of the heating was limited by the conservation conditions of the panels, to avoid excessive thermal stresses that could damage the mosaics.

Figure 5. Palermo, St. Mary of the Admiral. Preliminary steps to the acquisition of thermographic images, with heating of the mosaic surfaces using halogen lamps: (**a**) *Dedication* mosaic panel; (**b**) *Coronation* mosaic panel.

2.2. Ground Penetrating Radar

Ground penetrating radar (GPR) is a geophysical method that uses EM waves, typically in the 10–3000 MHz frequency range, to map structures and objects underground or within walls [48]. The radar transmitting antenna emits an electromagnetic pulse which can be reflected, refracted, or scattered by a dielectric or magnetic discontinuity, and picked up by the receiving antenna. The depth of the target can be calculated from the time elapsed between the sending of the impulse and its reception. Variations in velocity and attenuations of the electromagnetic pulse, which cause reflections and refractions, are due to variations in electrical conductivity, dielectric constant, and magnetic permeability. These parameters mainly depend on the mineralogical composition, porosity, and water content. The resolution of the GPR is proportional to the band frequency of the antennas used. Consequently, the use of high frequency GPR antennas has increased in the last two decades in the field of diagnostics applied to cultural heritage [24,25,49–52]. To date, however, there are few bibliographic examples that show the application of GPR to mosaics, with the aim of localizing inhomogeneity, the presence of voids, mapping the moisture content [34], and analyzing the different layers of mosaic preparation [53].

The GPR surveys were performed using the Aladdin GPR system (IDS, 2006) consisting of a multi-channel central unit (3 channels) connected to two pairs of antennas with a frequency of 2 GHz.

GPR profiles were carried out by applying a sampling technique called RSAD (radar surface arrive detection), configuring the antennas in bipolar mode (i.e., two pairs of antennas perpendicular to each other. The use of the bipolar antenna made it possible to acquire data with different positions of the dipoles with respect to forward direction of each profile: parallel to the track line (perpendicular broadfire mode) and perpendicular to it (parallel broadfire mode).

Before the data acquisition phase, test profiles were acquired, aimed at optimizing the acquisition parameters. A time range of 2.6 ns was set, a Butterworth-type band-pass frequency filter (500–3000 MHz) was applied to the signal, to attenuate the spectral components of electromagnetic noise, and a horizontal stacking of 7 traces was considered to increase the signal/noise ratio, the average value of the relative dielectric constant ε_r was estimated both from the curvature of the reflection hyperbolas observed, and from calibrations carried out in situ with reflecting objects placed at a known depth. From these an average propagation velocity of about 0.08 m/ns was obtained and used for all the profiles, to convert times in depths. This also allowed to estimate the thickness of the mosaics: about 15 cm for the *Coronation* panel and about 11 cm for the *Dedication* panel.

Each GPR profile was elaborated to eliminate the coherent and incoherent noise present in the original data, applying in sequence a static correction, the background removal, and the Kirchoff migration. The latter is applied to a two-dimensional profile on the basis of an approximate estimate of a constant propagation velocity. In the specific case, a velocity equal to 0.08 m/ns was used. The purpose of the migration is to bring the reflections and diffractions back to the correct position of the object that generated them.

Having a dense grid of profiles is possible, after processing all the GPR sections, to rearrange the GPR data in time-slices (or depth-slices, which are conceptually equivalent). The time-slice technique [54] is now widely used for the analysis and representation of 2D GPR data acquired along parallel and equally spaced lines, in one direction or two perpendicular directions. This technique makes it possible to recognize the presence of any structures inside the wall with figurative comparisons.

For this study all the GPR profiles were acquired in one direction. In particular, 26 parallel profiles were acquired for the *Dedication* panel and 25 parallel profiles for the *Coronation* panel, for a total of 88 m per antenna. The spacing between the profiles was 5 cm (Figure 6).

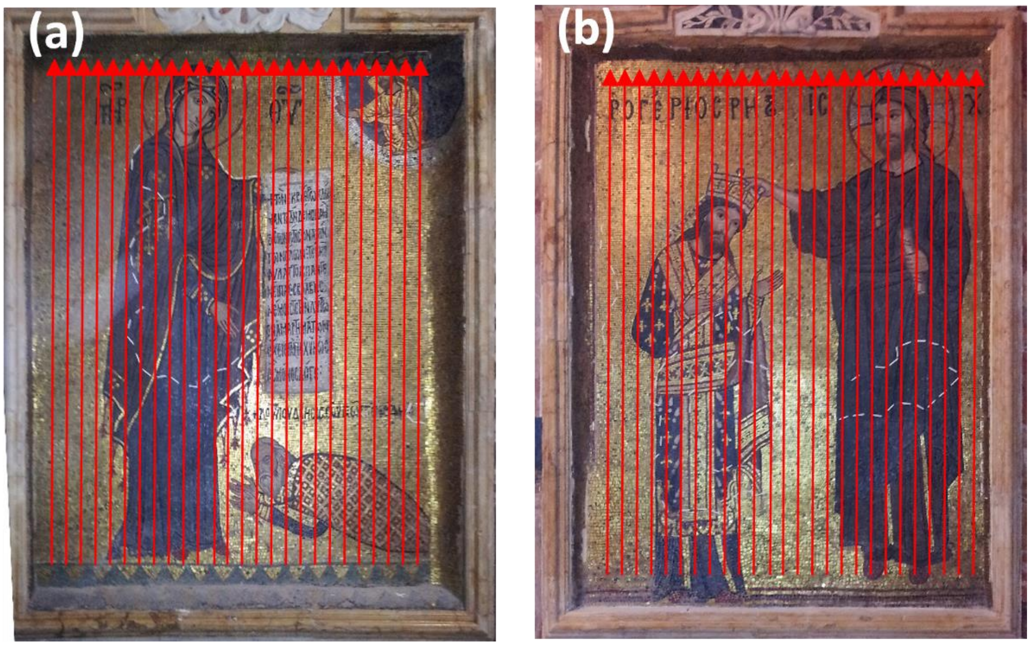

Figure 6. Palermo, St. Mary of the Admiral. Location of GPR profiles: (**a**) *Dedication* mosaic panel; (**b**) *Coronation* mosaic panel. The hatched lines indicate the areas affected by the risk of detachment of the tesserae, as previously indicated by the restorers.

For each of the two mosaics, the GPR profiles were used to construct the time-slices which were then transformed into depth-slices thanks to the estimated velocity of propagation of the EM waves. Considering the resolution virtually obtained by a 2 GHz antenna, we calculated a wavelength $\lambda = v/f = 4$ cm. Therefore, we considered the value $\lambda/2 = 2$ cm as the approximate value of the vertical resolution [55–57]. Consequently, we chose an average thickness of 2 cm for the depth-slices and the first three (up to 6 cm deep) were analyzed to identify any areas of detachment of the mosaic tesserae. Each depth-slice shows the maximum normalized amplitude of the electromagnetic signal within the analyzed data.

3. Results

3.1. Infrared Thermography

The survey was performed to obtain a thermal mapping of the surfaces aiming at detecting non-homogeneity due to humidity, detachment, and different types of materials.

The thermohygrometric values detected near the mosaic surfaces do not show differences with those recorded for the surrounding environment, so highlighting the absence of major evaporative phenomena regarding the studied mosaics, as already in the first analysis. In fact, any significant evaporations would alter the microclimate with a characteristic increase in the relative humidity of the air mass affected by the evaporation flow.

Generally, through thermography the areas with greater humidity below the analyzed surface, are distinguished from the dry ones because they appear colder, due to surface evaporation. The cooling of the surface is determined by the high latent heat due to the evaporation in progress, that is to the strong dissipation of thermal energy resulting from the passage of state of the water contained on the surface. The evaporative process is linked to the relative humidity and temperature of the environment, as well as to the concentration of water contained in the material, its chemical-physical characteristics, and the presence of soluble salts. Even in the case of active thermography, therefore, the heat supplied is used by the evaporative process. Consequently, the areas affected by humidity will show colder temperatures, returned in shades of blue in the thermograms.

On the other hand, during active thermography, i.e., with artificial heating, the areas affected by detachments, in the absence of evaporative flows, behave as insulators due to the air pocket, present between the detached surface and its support, which slows down the heat transfer to the underlying layers, thus appearing as warmer (red areas in the thermograms).

Based on these considerations, it is possible to state that evaporative processes do not occur on the two mosaic panels. In fact, as detailed below, the thermographic survey highlighted the presence of detachments, or of material variation, highlighted in the thermograms by areas with higher temperatures than those of the surrounding areas.

After the heat source has been switched off, during the cooling phase, the areas affected by shallower detachments tend to cool down more quickly. In consideration of this, it was possible to qualitatively assess the extent of the detachments identified.

To obtain greater contrast and a better rendering of information, aimed at an easy localization of the detachments, the thermograms were highlighted with different thermal scales for each image. Furthermore, the thermographic image was superimposed in transparency on the corresponding photographic image.

On both panels the thermographic image preliminarily obtained without any thermal stress on the surface (passive thermography) did not return any anomaly, due to the absence of thermal differences between the constituent materials and the areas of alteration or detachment.

After heating the mosaic surfaces for 20 min with halogen lamps, thermographic images were acquired on both panels at different times: immediately after turning off the lamps (Figures 7a and 8a); after 2 min (Figures 7b and 8b); after 5 min (Figures 7c and 8c) and finally after 10 min (Figures 7d and 8d). This was carried out in order to obtain useful information to locate the detachments or evidence of different types of materials, also used in previous restorations. In all the following figures, the hatched lines indicate the areas affected by the risk of detachment of the tesserae, as previously indicated by the restorers. The higher temperature areas, however, may be indicative of areas affected by presumed detachments of greater depth, with large air bubbles between the support and the detached mosaic layer, or anomalous areas consisting of more insulating material different from the surrounding areas, or even restored areas with materials of different thermal characteristics.

3.1.1. Dedication to the Virgin

Observing the thermographic image acquired immediately after turning off the lamps (Figure 7a), the areas with the highest temperature (yellow tones) correspond in part to the area enclosed by the hatched line but extend by following a much wider perimeter. However, this area coincides with the part of the mosaic not characterized by golden tesserae. It is therefore probable that the latter reflected the electromagnetic waves more strongly causing less heating than the blue mantle of the Virgin and, in part, also of the white open scroll that she holds in her hand. The more consolidated areas, or those made up of more reflective material, are characterized by lower temperatures (blue colors). These areas, presenting more homogeneously on the right side of the panel, could disperse the heat more quickly and, in this case, this thermal behavior could suggest that they are better attached to the underlying layers, or, probably, they may have been heated less than the others and, in this second case, nothing can be said about eventual detachments.

By comparing the thermographic image acquired immediately after switching off with the subsequent thermograms recorded at different times (Figure 7b–d), through the cooling speeds of the different areas, it is possible to hypothesize the different depths of the detachments identified. In particular, the deeper detachments maintain their thermal difference for longer times compared to the surrounding areas. The more superficial detachments, on the other hand, return more quickly to equilibrium with the surrounding areas. The thermogram acquired 10 min after the end of heating (Figure 7d) no longer shows thermal differences such as to be able to highlight the discontinuities previously observed.

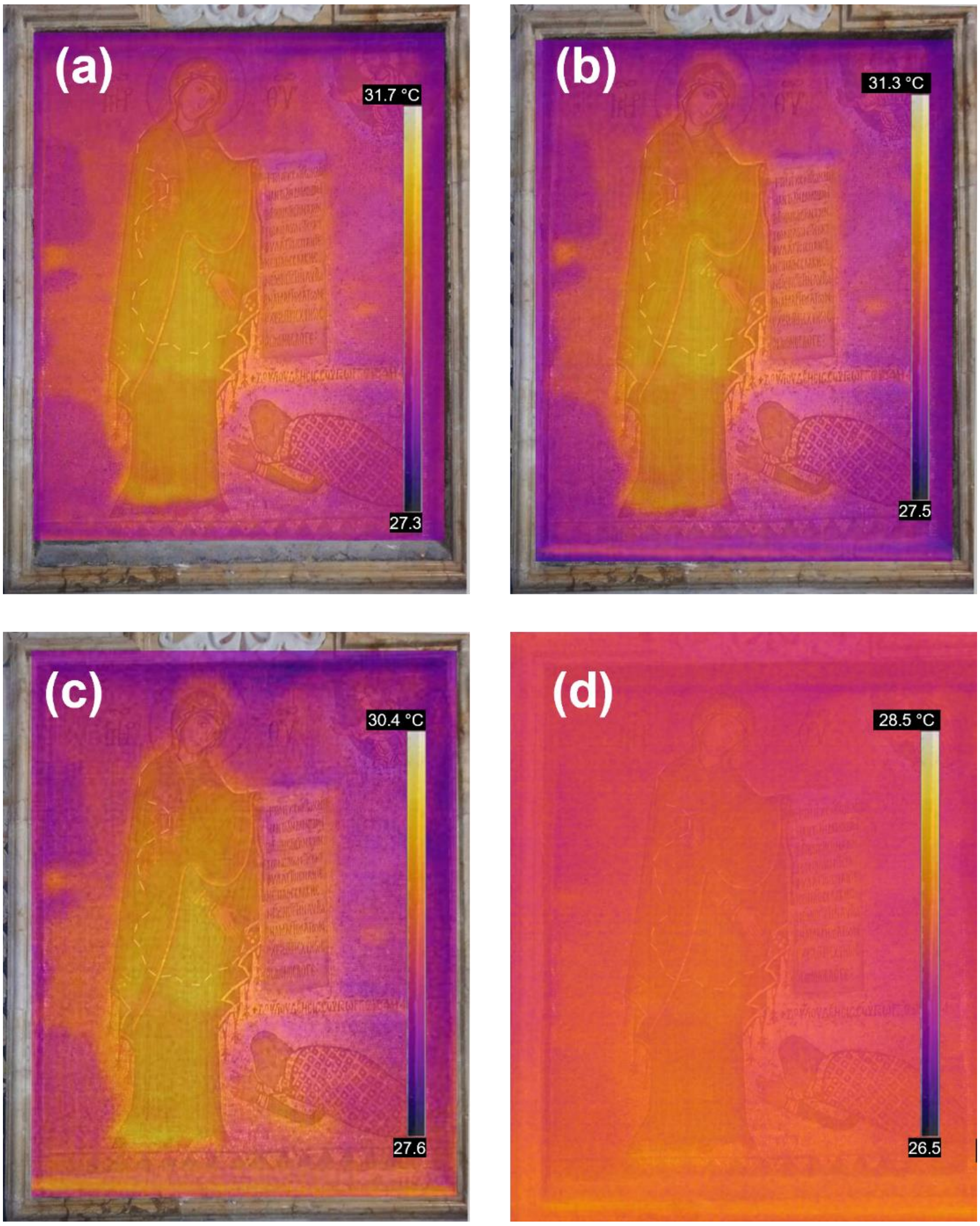

Figure 7. Palermo, St. Mary of the Admiral, *Dedication* mosaic panel. Thermographic images acquired (**a**) immediately after turning off the lamps; (**b**) after 2 min; (**c**) after 5 min; (**d**) after 10 min. The hatched lines indicate the areas affected by the risk of detachment of the tesserae, as previously indicated by the restorers.

3.1.2. Coronation of Roger II

Analyzing the thermographic image acquired immediately after turning off the lamps (Figure 6a), the areas in yellow tones can be affected by detachments of greater depth (i.e., areas in which there can be air pockets between the support and the detached mosaic layer) or consisting of more insulating material than the surrounding areas. These areas correspond in part, also in this case, to the areas surrounded by the hatched line, already localized by the restorers, but extend over a much larger area.

The more consolidated areas, or those made up of less insulating material, can be identified in the thermographic image acquired immediately after turning off the lamps (Figure 8a) for coloring in shades of blue (lower temperatures). This indicates that these areas, present more homogeneously in the upper central portion and in the lower part of the mosaic, disperse the heat supplied during heating faster. Consequently, it can be assumed that these areas are more cohesive with the underlying layers.

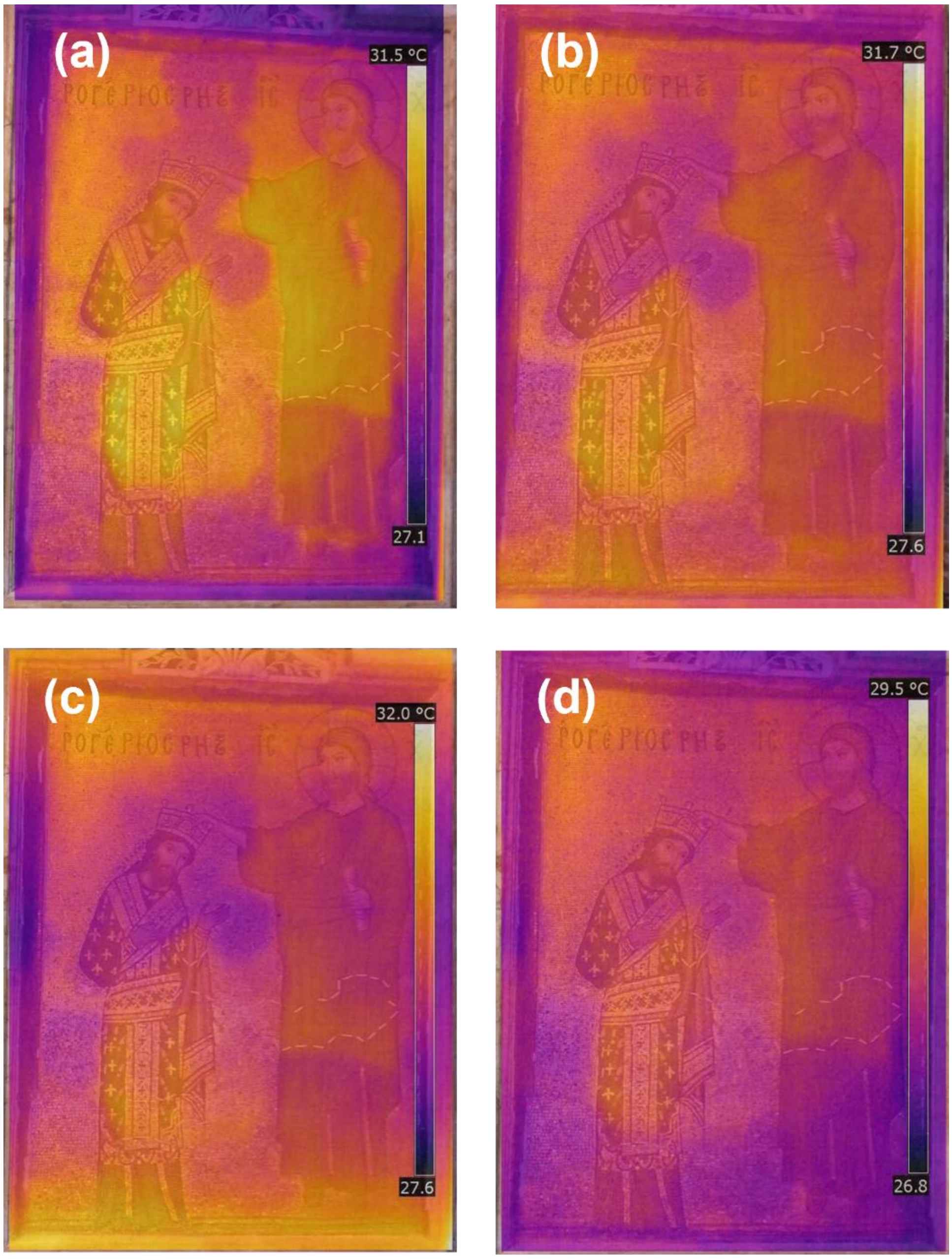

Figure 8. Palermo, St. Mary of the Admiral, *Coronation* mosaic panel. Thermographic images acquired (**a**) immediately after turning off the lamps; (**b**) after 2 min; (**c**) after 5 min; (**d**) after 10 min. The hatched lines indicate the areas affected by the risk of detachment of the tesserae, as previously indicated by the restorers.

By comparing the thermographic image acquired immediately after switching off with the subsequent images acquired at different times (Figure 8b–d), through the cooling rates of the different areas, it is possible to provide qualitative information on the different depths of the detachments identified. In particular, the deeper detachments, which here correspond to the characters depicted in the mosaic, maintain their thermal difference for a longer time than the surrounding areas. The more superficial detachments, on the other hand, reach thermal equilibrium with the surrounding areas more quickly.

Finally, the thermogram acquired 10 min after the end of heating (Figure 8d) highlights how even the areas initially characterized by the highest temperatures have almost completely cooled, no longer showing thermal differences such as highlighting the discontinuities previously observed.

3.2. Ground Penetrating Radar

The GPR profiles were used to obtain three depth-slices relating to the first 6 cm of depth (one every 2 cm of thickness). The images show the maximum normalized reflection amplitudes of the electromagnetic signal. GPR results are not particularly influenced by the color of the cards. From this it can be assumed that there is a better correspondence between the anomalies highlighted and the possible areas of deterioration of the mosaics. Consequently, the anomalies highlighted can be matched with less uncertainty with the possible detachment areas of the tesserae.

3.2.1. Dedication to the Virgin

In the Dedication to the Virgin mosaic the calculated depth-slices do not seem to show a correspondence between the high amplitude anomalies and the areas identified by the restorers as possible detachment zones of the mosaic tesserae.

The depth-slice relating to the thickness between 0 and 2 cm (Figure 9a), does not show substantial anomalies, with the exception of small areas on the left side of the panel and in correspondence with the face of the figure of the Virgin.

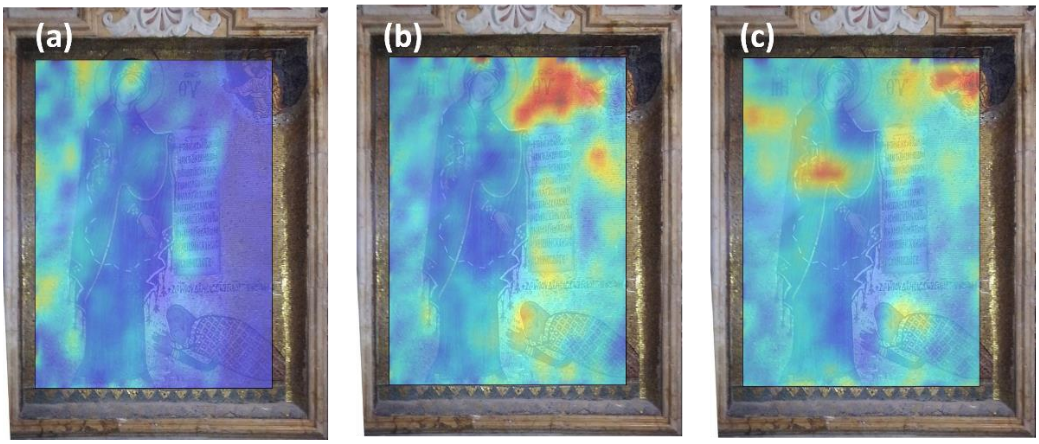

Figure 9. Palermo, St. Mary of the Admiral, *Dedication* mosaic panel. Depth-slice of the normalized reflection amplitudes relative to the following depths from the acquisition surface: (**a**) between 0 cm and 2 cm; (**b**) between 2 cm and 4 cm; (**c**) between 4 cm and 6 cm.

On the other hand, in the depth-slice between 2 and 4 cm of thickness (Figure 9b), some anomalies are highlighted that could be linked to a detachment of the tesserae not identified by the restorers. In particular, there is a strong anomaly in the upper part of the panel with a considerable extension.

Finally, in the depth-slices relating to the thickness between 4 and 6 cm (Figure 9c), various anomalies are highlighted, which persist in the upper part of the panel. There is also an anomalous area in the Virgin's mantle, within the area identified by the restorers as a possible detachment.

3.2.2. Coronation of Roger II

In the Coronation of Roger II mosaic the calculated depth-slices show numerous anomalies characterized by high reflection amplitudes.

The depth-slice relative to the thickness between 0 and 2 cm (Figure 10a), presents some small anomalies on the left side of the panel, which are highlighted at greater intensity in the depth-slice between 2 and 4 cm thick (Figure 10b). In fact, there is a strong anomaly in the upper part on the left of the panel which continues to be present also in the depth-slice relative to the thickness between 4 and 6 cm (Figure 10c). Although this anomaly does not correspond to the areas identified by the restorers, it has been reported as an area to be controlled for its persistence and intensity.

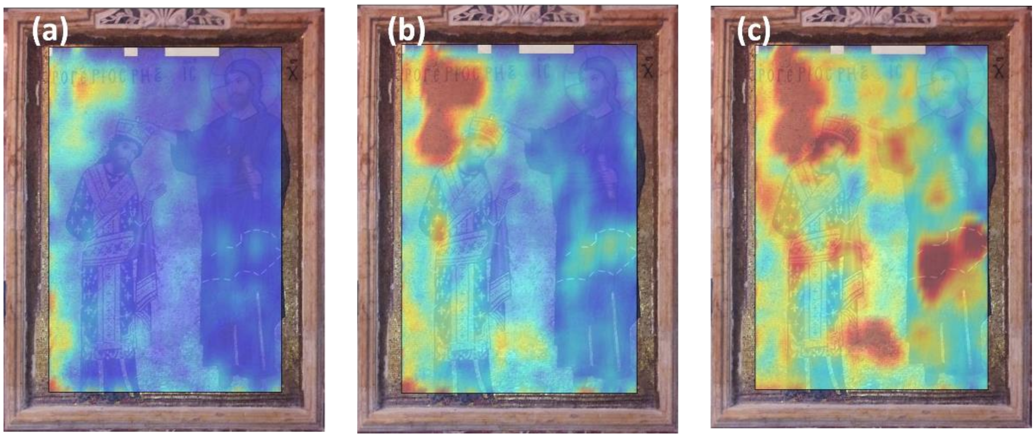

Figure 10. Palermo, St. Mary of the Admiral, *Coronation* mosaic panel. Depth-slice of the normalized reflection amplitudes relative to the following depths from the acquisition surface: (**a**) between 0 cm and 2 cm; (**b**) between 2 cm and 4 cm; (**c**) between 4 cm and 6 cm.

In the last two depth-slices (Figure 10b,c), an anomaly in the tunic of Christ is also identified, corresponding to one of the areas identified by the restorers as a possible detachment area of the tesserae. The intensity of this anomaly is higher at greater depth, but it is also clearly evident in the depth-slice between 2 and 4 cm.

These two areas also correspond to two hot thermal anomalies, confirming the possibility of the presence of the detachment of the tesserae.

Finally, a third anomaly occurs in the lower part of the panel, between the figure of Christ and Roger II, which has been indicated as an area to be controlled.

4. Discussion

The comparison between the depth-slice technique in GPR data processing and the time-lapse analysis of the thermographic images after the lamps are turned off, can help to understand if the anomalies identified with the different methods are attributable to the same causes. The choice of the thickness of the depth-slice is substantially linked to the vertical resolution of the GPR data, the latter being linked to the bandwidth of the antenna [58]. In this case, the use of 2 GHz antennas and an estimated wavelength of 4 cm made it possible, considering a vertical resolution of about $\frac{1}{2}$ of the wavelength, to derive depth-slices with a resolution of 2 cm. On the other hand, the choice of the time-lapse for the tomographic images has been linked to the experience and to the execution of preliminary tests that made it clear that a time longer than 10 min after the lamp switch off returned practically homogeneous thermal images, therefore without information.

The aforementioned approach made it possible to highlight several anomalies which, in the case of a good correspondence between the two methods, could strengthen the interpretation in support of that obtained from the observations of the restorers regarding the risk of detachment of the mosaic tesserae.

In the Dedication to the Virgin panel, there is no correspondence between the hot thermal anomalies and the presence of high reflection amplitudes in the GPR data. Indeed, the thermal analyses show a good correspondence with the area delimited by the restorers as suspected of the presence of detachment. However, the presence of the golden tesserae could have compromised the results of the IRT, not highlighting sufficiently any other anomalous areas that are instead identified by the GPR.

In the Coronation of Roger II panel, the hot thermal anomalies instead seem to show a good correspondence with the anomalies with a high amplitude of reflection of the GPR signal and, in one case, also with the areas highlighted by the restorers. However, the GPR data show other anomalies with the same behavior that were highlighted to the restorers for the restoration intervention.

In addition, in this case the different reflectivity of the golden tesserae compared to the darker ones could have influenced the results of the IRT, but the golden tesserae are present in lower quantity and probably for this reason there is a better correspondence between the results of the two techniques used. The results therefore seem to suggest that although the electromagnetic signal is attenuated by the presence of metal surfaces such as golden tesserae, this appears to cause greater problems for the IRT technique than for GPR.

5. Conclusions

One of the issues to be solved preliminarily, before carrying out the conservative restoration on the mosaic panels, was to preliminarily identify possible critical areas of the mosaic panels, susceptible to problems of detachment of the tesserae, caused by the presence of gaps between the support layers. To this end, the visual analysis carried out by the restorers had allowed us to circumscribe some problematic areas.

The combined use of ground penetrating radar and infrared thermography was considered because these two techniques are among the most expeditious ones for the study of mosaics. In fact, GPR is an optimal technique for revealing deep wall structural defects, and it allows a quantitative analysis useful for estimating the exact depth of the defects. However, it needs to be considered that GPR surveys must be performed with the antennas in contact with the tesserae. Furthermore, the acquisition is performed for parallel lines, and this produces a lower resolution if compared to that of other techniques used in physics for cultural heritage. Another critical issue is the attenuation of the transmitted signal if moisture, salts, highly conductive materials, are present near the surface.

On the other hand, the IRT allows a non-contact and full-field acquisition, instant visualization of the results, and their easy interpretation. For these reasons it can be coupled to other techniques for complementary information. However, the limitations and issues of the IRT are the low informativity if thermal gradient is not present and above all the influence of thermal emissivity values of the tesserae (Chaban et al., 2020). In fact, the background areas of the mosaics, covered with golden tesserae, showed lower temperatures and a more homogeneous trend than the human or divine figures.

The previously discussed results showed that the integrated use of these two non-invasive techniques applied to the diagnosis of the conservation status of the mosaic panels allowed the reduction of the interpretative uncertainties typical of each technique, if used alone, and to reliably identify some critical areas not immediately visible.

Furthermore, their integrated use allowed the improvement of the diagnosis derived from the visual analysis, confirming it for some areas, but, in addition, identifying other areas potentially subject to detachment, not previously indicated by the restorers.

The use of the depth-slice technique, applied to the GPR data processing, allowed visualization of the electromagnetic reflectivity trend in slices at different depth intervals. Similarly, the comparison between thermographic images acquired in time-lapse allowed us to hypothesize an anomalous area with a differentiated depth. However, in GPR the reliability of the depth estimate is linked to a good preliminary estimate of the permittivity of the materials, while in IRT it is not easy to quantify the dependence between the cooling time and the depth investigated.

Nevertheless, the results confirmed, albeit partially, the incomplete diagnoses carried out by the restorers and preliminarily traced on the mosaics, and also in identifying further critical areas possibly affected by deterioration or compositional differences in the layers underlying the level of the tesserae.

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