applied sciences

IMPACT FACTOR 2.838

CITESCORE 4.5

Article

Application of Sonic, Hygrometric Tests and Infrared Thermography for Diagnostic Investigations of Wall Paintings in St. Panfilo's Church

Sara Calandra, Irene Centauro, Stefano Laureti, Marco Ricci, Teresa Salvatici and Stefano Sfarra

Special Issue
Results of the II National Research Project of AIAr: Archaeometric Study of the Frescoes by Saturnino Gatti and Workshop at the Church of San Panfilo in Tornimparte (AQ, Italy)

Edited by
Dr. Anna Galli, Dr. Mauro Francesco La Russa, Dr. Maria Francesca Alberghina, Dr. Alessandro Re, Dr. Donata Magrini, Dr. Celestino Grifa and Dr. Rosina Celeste Ponterio

MDPI

https://doi.org/10.3390/app13127026

applied sciences

Article

Application of Sonic, Hygrometric Tests and Infrared Thermography for Diagnostic Investigations of Wall Paintings in St. Panfilo's Church

Sara Calandra [1,2], Irene Centauro [2], Stefano Laureti [3], Marco Ricci [3,*], Teresa Salvatici [2] and Stefano Sfarra [4]

[1] Department of Chemistry, University of Florence, 50019 Florence, Italy; sara.calandra@unifi.it
[2] Department of Earth Sciences, University of Florence, 50121 Florence, Italy; irene.centauro@unifi.it (I.C.); teresa.salvatici@unifi.it (T.S.)
[3] Department of Informatics, Modelling, Electronics and System Engineering, University of Calabria, 87036 Rende, Italy; stefano.laureti@unical.it
[4] Department of Industrial and Information Engineering and Economics, University of L'Aquila, 67100 L'Aquila, Italy; stefano.sfarra@univaq.it
* Correspondence: marco.ricci@unical.it

Featured Application: Non-destructive testing techniques, namely sonic pulse velocity, hygrometric tests, and infrared thermography, were employed for inspecting late XV-century frescoes to evaluate the state of conservation of the plaster-masonry structure.

Abstract: Prior to restoration work, the frescoes created at the end of the XV century by the painter Saturnino Gatti (1463–1518) in the apse of the Church of St. Panfilo in Villagrande di Tornimparte (L'Aquila) were the subject of a thorough diagnostic study involving several tests, from in situ non-destructive analysis to laboratory micro-destructive analysis on the collected samples. In this paper, we report the application of the sonic pulse velocity test, hygrometric tests, and infrared thermography to assess the state of conservation of the frescoes, i.e., the combined system of plaster and wall support. The complete analysis of the frescoes' state of conservation revealed significant insights. The integrity of the plaster was evaluated through sonic pulse velocity tests, which highlighted several areas of detachment or degradation phenomena. Hygrometric analysis described humidity variations, particularly near the boundary between the conch area and the church naves. Passive infrared thermography detected temperature inhomogeneities, emphasizing differences in the wall texture and the masonry structure. Moreover, by comparing sonic pulse velocity and passive thermography images, a certain degree of correlation between hot areas and slow areas in the presence of possible detachments was noticed. In addition, pulse-compression active thermography was applied in a few spots, and for the first time, to the best of our knowledge, the virtual wave concept was applied to the cultural heritage field. This strategy helps in better associating anomalies with depth. The measurement campaign was part of a research project conducted by members of the Italian Association of Archaeometry (AIAr), and the results were compared and integrated with those of other non-destructive and analytical methods.

Keywords: frescoes; non-destructive testing; heritage science; sonic pulse velocity; hygrometric tests; infrared thermography

check for updates

Citation: Calandra, S.; Centauro, I.; Laureti, S.; Ricci, M.; Salvatici, T.; Sfarra, S. Application of Sonic, Hygrometric Tests and Infrared Thermography for Diagnostic Investigations of Wall Paintings in St. Panfilo's Church. *Appl. Sci.* **2023**, *13*, 7026. https://doi.org/10.3390/app13127026

Academic Editor: Asterios Bakolas

Received: 4 May 2023
Revised: 2 June 2023
Accepted: 8 June 2023
Published: 11 June 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Archaeometry analysis is increasingly used as a preliminary step for restoration interventions on cultural heritage (CH) items such as historic frescoes. Over the years, several non-destructive testing (NDT) and micro-destructive methods have been tailored, combined, and used to support restoration interventions [1,2].

The state of preservation of a fresco and the choice of the most suitable restoration procedure depends on the evaluation of many aspects, from the historical analysis of the artwork to the study of execution technique and materials used, and to the analysis of the support. The latter is generally a complex stratified system characterized by different constituent materials and construction techniques. Assessing the state of health and preservation of such structures is not straightforward, as many parameters are unknown—for example, the thickness and the number of the various layers, the materials used, etc.

Among the NDT techniques, a few can penetrate the outer layers, the carbonated surface, and the painting layer, revealing info about the rough coat layer and the support, although possible detachments, the presence of water, and high humidity values can represent sources of structural damage and degradation phenomena that can affect the outer layers.

Sonic pulse velocity (SPV) is a method that uses elastic compression waves generated by a mechanical impact on the surface of a sample to investigate the materials in depth [3–6]. In the case of good adhesion between the painting layer and the underneath, and between the various layers in general, the elastic waves travel faster from the source point to the receiver points. Conversely, detachments, voids, and discontinuities of the plaster can hamper the propagation of the elastic waves, resulting in a lower sound propagation velocity.

In addition, by integrating the results of SPV tests with those obtained from other techniques, detachments, microfractures or lesions, and inhomogeneous areas can be distinguished [7,8]. A high level of humidity or the presence of water are two other aspects that can influence the measured velocity. While on the one hand, the presence of water affects the sonic velocity, causing a general increase [9], on the other hand, this is the main cause of the degradation of frescoes, leading to a general decrease of velocity [10]. To distinguish between a low velocity due to moisture/water or by detachments/weak adhesion, complementary information must be acquired.

Even if the hygrometric test (HT) measures the moisture level of the outer layer, usually a certain degree of correlation between surface and subsurface moisture is present. The moisture maps can then be superimposed on the SPV ones looking to highlight anomalous regions. Further, the moisture maps give helpful indications for the conservation and restoration of the painting layer.

Another NDT technique that is frequently used to assess the presence of water ingress and the distribution of moisture is infrared thermography (IRT), both in passive (mainly) and in active modalities [11–13]. Unlike HT, passive IRT produces images that give qualitative information on the wall under analysis, if the boundary conditions allow [14].

It is possible to understand how, similarly to SPV, IRT is sensitive to moisture, detachments, voids, cracks, weak adhesion, buried structures, etc.

In general, in thermograms, such kinds of defects are detected as a rise in the local temperature, whereas there is a decrease in moisture level. Combining SPV, HT, and IRT can help distinguish between moisture and detachments, voids, weak adhesion, and other defects.

It should be noted that some of the above-mentioned types of defects cannot always be detected, as the signal-to-noise ratio (SNR) of passive thermography images relies on temperature gradients due to environmental sources (i.e., different sun exposure) and on variations in the emissivity of materials. Active IRT is thus used to increase the SNR by exciting the sample under testing with a controlled heating source. By active thermography, larger sensitivities are obtained, even if the range of inspection is smaller than in passive IRT, and further depth-dependent information can be extracted, which is helpful to study the stratigraphy of the fresco support. In this way, a more qualitative moisture analysis can be carried out [15,16].

In this paper, we report the combined application of SPV, HT, and IRT to the frescoes created by Saturnino Gatti and his workshop between the years of 1491 and 1494 in the apsidal chapel of St. Panfilo Church in Villagrande di Tornimparte (L'Aquila). These frescoes illustrate key moments of Jesus' Passion. Moreover, the ceiling shows images of God, Angels, and the Blessed in Paradise, and represent a precious example of Italian Renascence art.

The measurement campaign was part of a research project conducted by members of the Italian Association of Archaeometry (AIAr), and the results were compared and integrated with those of other non-destructive and analytical methods. The scheme methodology of data/image acquisitions was affected by strict restrictions due to laws linked to the COVID-19 pandemic. The research groups worked in a disjointed manner, although guided by a protocol that described the main activities to do and the timelines.

The results of other non-destructive and micro-destructive analyses on the St. Panfilo's wall will be discussed in other articles of the Special Issue "Results of the II National Research project of AIAr: archaeometry study of the frescoes by Saturnino Gatti and workshop at the church of St. Panfilo in Tornimparte (AQ, Italy)". For in-depth details on the aims of the project, see the introduction of the Special Issue [17].

The paper is organized as follows: in Section 2, the methods used to collect and process experimental data are reported for SPV, HT, and IRT; in Section 3, the results are summarized. In Section 4 the results are discussed and conclusions are drawn.

2. Methods

2.1. SPV and HT Data Collection and Imaging Procedure

The sonic investigations exploit propagation in the material of elastic compression waves generated by a short elasto-mechanical impact on the surface to investigate the conditions in which the material is in its interior or to localize any inhomogeneities, voids, and defects in the investigated section [3–6,18].

The SPV is dependent on the physical-mechanical characteristics of the investigated material. Internal defects, voids, and lower density result in lower velocity values, indicating a poor state of conservation. On the contrary, high velocities indicate good characteristics and high homogeneity of the material.

The test involves the generation of elastic waves by using an instrumented impact hammer with a frequency range of 20 Hz–20 kHz through a punctual mechanical impulse, which is then read by an accelerometer. The value obtained in a sonic test is the time-of-flight (ToF), which is the time interval taken by the wave to pass through the material investigated. From the ToF and the length of the path investigated (L), the velocity of the wave (v) is estimated.

The instrumentation used for this study is a Novasonic U5200 CSD of IMG Ultrasuoni Srl, consisting of a hammer with a load cell in the impact head, the source of the acoustic wave. The time–amplitude function of the force applied in the impact is recorded through a detection system directly connected to the hammer [3,7].

The sonic test is performed in indirect mode; see Figure 1a in which the hammer and the accelerometer are placed on the same face. SPV was performed according to a specific survey scheme on the same regular grid of points (Figure 1b), following a horizontal line. The mechanical impulse point is kept fixed, moving the accelerometer horizontally at progressively increasing distances from the hammer.

By collecting measurements in a regular grid of points, SPV maps can be visualized to identify possible critical areas. These SPV maps represent velocity distribution. From the reference velocity of the investigated material in a good state of preservation, it is possible to consider the state of degradation of the frescoed masonry by comparing zones at different velocities. Since the SPV test involves acquiring large data, a management system for data collection and analysis on-site has been designed, adapting it to the specific survey campaign [3] (Figure 1c). Moreover, collected data were processed through GIS software for the graphical representation of the velocity distribution maps.

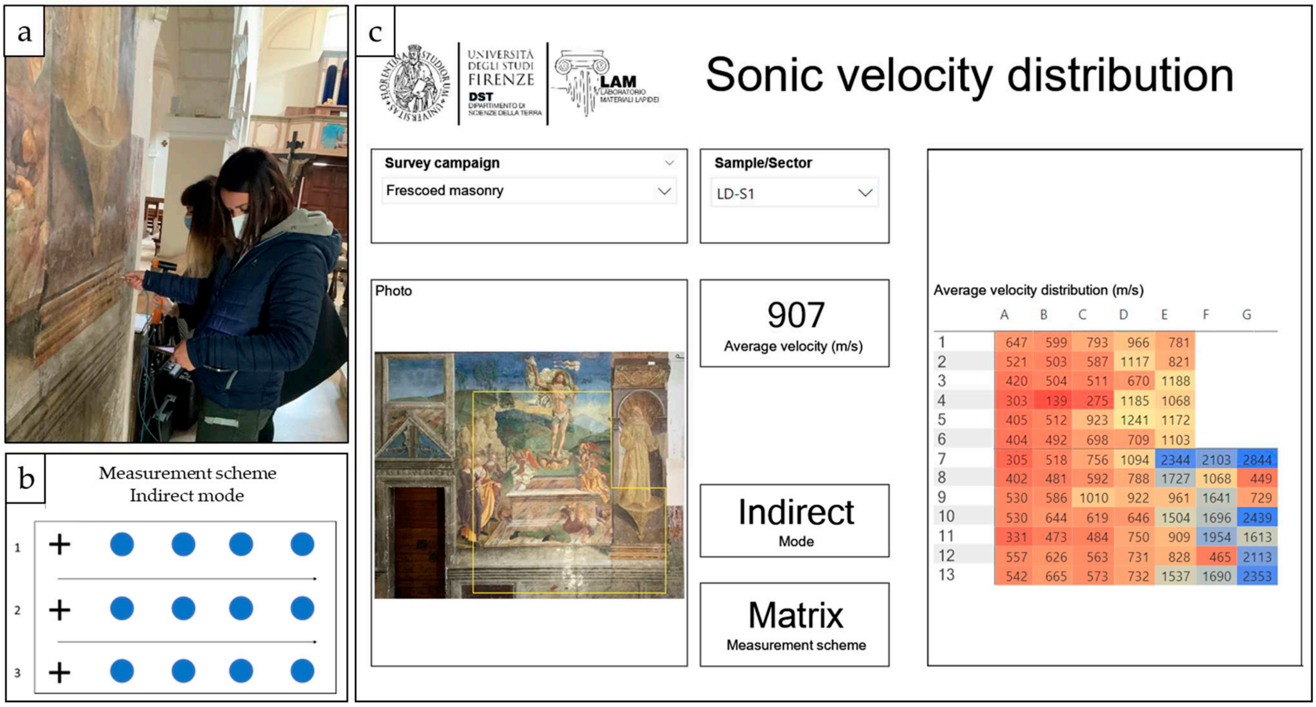

Figure 1. Sonic pulse velocity test: (**a**) on-site investigation, (**b**) measurement scheme performed in indirect mode. The + symbol indicates the hammer position, and the blue points represent the accelerometer position. (**c**) interactive report page to provide real-time verification of data and analysis.

Likewise, hygrometric tests (HT) of the area were performed punctually, following the SPV measurement scheme and data processing. HT was carried out using the instrument Protimeter MMS2 BLD8800 of Allemano Instruments, set on the "pin mode", to measure the surface moisture of the painting layer. The instrument measures the moisture content in WME% in non-conductive solid materials [19]. HT maps were generated by imaging the punctual values collected to highlight moisture distribution in the frescoed masonry. The environment measurements were conducted in the study area, with an indoor temperature of 7–12 °C and a relative humidity of 55–60%.

SPV and HT investigations were performed on the frescoed walls of the apsidal conch of St. Panfilo Church, selecting four areas (panels A, B, D, and E), widely described in [20].

2.2. IRT Data Collection and Imaging Procedure

The IRT tests were performed in both passive and active approaches (see [1]) by using a 640 × 480 thermal camera (7.5–13 µm, T660 FLIR System). Passive IRT (PIRT) was used to image frescoes' support walls and detect potential anomalies. PIRT uses infrared imaging to capture the natural temperature variations or mappings in materials and structures such as buildings [14]. Thanks to the rapidity of the passive IRT test, it was possible to collect images on the whole apse and structures close to it to evaluate the presence of possible areas with large inhomogeneities. For all the acquisitions, the visible RGB image of the area was also collected and superimposed to the thermogram to help interpret the thermal imprints; see Figure 2. During PIRT acquisitions, the thermal camera was handheld, and the target focused from a distance of around 6 m in a 4 °C and 55–60% RH environment.

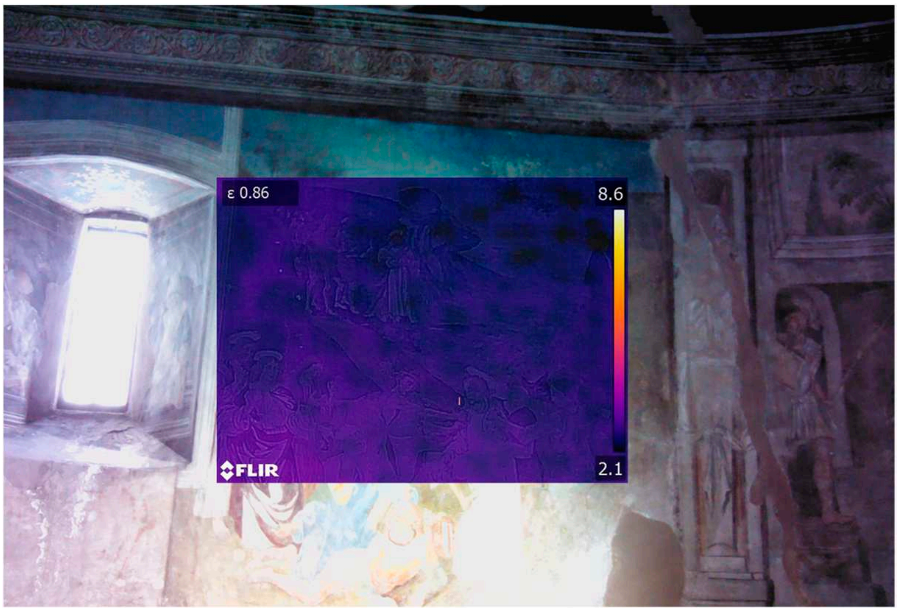

Figure 2. Example of passive thermography analysis used to identify the support wall texture. Stones with irregular shapes can be distinguished behind the fresco.

The active IRT was applied instead to some specific areas to acquire information at different depths. Two details of the frescoes' cycle were analyzed, as reported in the following section. The active IRT tests implemented exploited the pulse-compression thermography (PuCT) procedure introduced in [21] for the analysis of two Renaissance panel paintings and then further developed and applied to a variety of historical artworks and mock-ups; see, for example [22,23]. The peculiarity of the PuCT procedure is combining a long excitation time, such as in lock-in thermography, with the information content of pulsed thermography. This is made possible by using a pseudo-noise (PN) heat source (i.e., a heat source that is switched on and off following a PN signal) and by applying the pulse-compression procedure to the sequence of thermograms collected during PN excitation. In particular, the temperature time-sequence of each pixel is correlated with the PN input signal. After the PuCT, the results of a virtual pulsed thermography experiment are retrieved, and they can be further analyzed with standard thermography tools. In this way, a high value of SNR can be obtained by using even low-power excitations. In this work, an 8-LED system with a total electrical power of 400W was used to heat portions of the frescoes. The PN signal modulating the LED system was generated starting from a Legendre sequence of 31 bits, with a bit duration of 10s [22]. The overall duration of active thermography acquisitions was 620 s, i.e., approximately 10 min, and the thermogram acquisition rate was 2 frames per second, so each thermal sequence consisted of 1040 images.

3. Results

3.1. SPV and HT Results

The SPV and HT tests were performed on the frescoed walls of the apsidal conch of St. Panfilo's Church, selecting four areas characterized by fractures, infill of the underlying masonry, and near openings (doors and windows). For each panel, the SPV results are compared with the hygrometric one through maps obtained from data processing with GIS software. The point values have been interpolated to provide a 2D false-color map of the sonic velocity and hygrometric value distribution according to the Spline function. The maps in false color emphasize the different properties of the masonry and are shown in Figure 3.

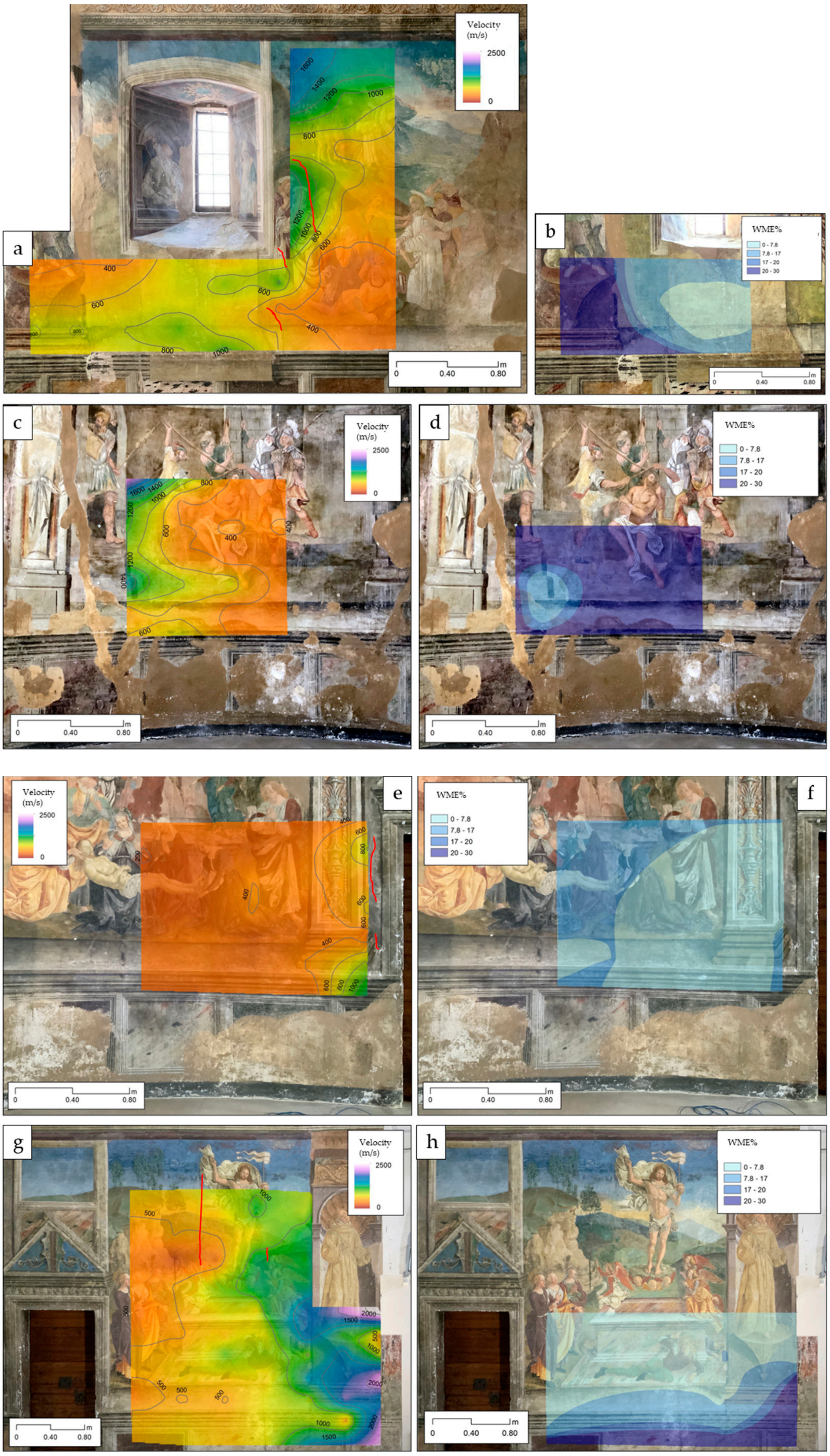

Figure 3. SPV and HT value distribution maps of (**a**,**b**) Panel A; (**c**,**d**) Panel B; (**e**,**f**) Panel D; and (**g**,**h**) Panel E. The plaster fractures are highlighted in red.

The sonic velocity of the walls ranges between 0 and 2500 m/s. In most cases, these values are related to the layer of painted plaster, thus being less representative of the underlying support masonry. False color maps highlight the different properties of the masonry. Higher velocity values correspond to well-cohesive plaster that is well-bonded to the masonry (areas from blue to purple in the maps), while lower velocity values indicate portions of detached or damaged plaster resulting from fractures (red areas).

In Figure 3a, the average velocity is about 700 m/s. The red area on the lower right shows lower velocities, which is due to both the detachment of the plaster and a large discontinuity that starts from the right edge of the window and cuts the masonry.

The HT values show that the humidity of the plaster increases towards the edge that delimits the conch area from that of the church naves (Figure 3b).

In Figure 3c, the average sonic velocity (v) is around 600 m/s, while in the right portion, average velocity values of about 370 m/s are recorded. These lower values are mainly due to a detached portion of the plaster that is located in the central portion of the investigated area. On the left side, however, where the plaster shows good cohesion to the masonry, the velocity is higher (average of 850 m/s).

In Figure 3d, the moisture values of the plaster are higher and more homogeneous (>20 WME%) than in the other areas investigated. This phenomenon is most likely due to the position of this area relative to the cardinal points; in fact, the wall is exposed to the sun only in the morning. The area corresponding to the detached portion of the plaster falls below 10 WME%, in accordance with SPV results.

In Figure 3e, the average sonic velocity is around 370 m/s. This area is affected by widely detached plaster. Moreover, a discontinuity is visible that divides the opening frame, probably made from stone, to the masonry and brings a variation of velocity; the right part has a higher velocity than the left side.

The results of the HT show that the moisture of the plaster increases going down (Figure 3f). In this area, the humidity value never exceeds 10 WME%, which can most likely be linked to the presence of numerous detached portions that allow air circulation. In addition, this wall of the conch communicates with the rooms of the rectory, so it is not directly exposed outside.

In Figure 3g, the left portion has lower sonic velocity values. On the right side instead, the velocity is higher (1500 m/s on average). This separation is found in the correspondence of a discontinuity in the coating plaster, as well as in the masonry itself (highlighted in red in Figure 3g). Figure 3h illustrates the HT values recorded, which indicate an increase in the moisture of the plaster in the lower right portion.

3.2. Passive and Active IRT Results

PIRT is useful to identify potential detachments, part of the wall structure, and a presumable humidity area. Figure 4 shows a part of the apse between two panels of the frescoes and precisely between the central one and that on the left (between panels A and B), which is the one with the worst degree of conservation and that was probably retouched in the past several times. A quite large and abrupt average measured temperature discontinuity between the central-right side of the apse and the left side can be seen, which was confirmed by the other images collected.

As mentioned above, this can be due to the position of the left side relative to the cardinal points, even if at the time of the measurement, the left side was exposed to the sun, but probably also to differences in the structure that affect the emissivity (e.g., materials, construction techniques, plaster characteristics, and later works such as the construction of the sacristy). This difference between the left and right sides is confirmed by the PIRT images shown in Figure 5 and collected over the same areas imaged with SPV and HT, reported in Figure 3. The subplots are named according to Figure 3.

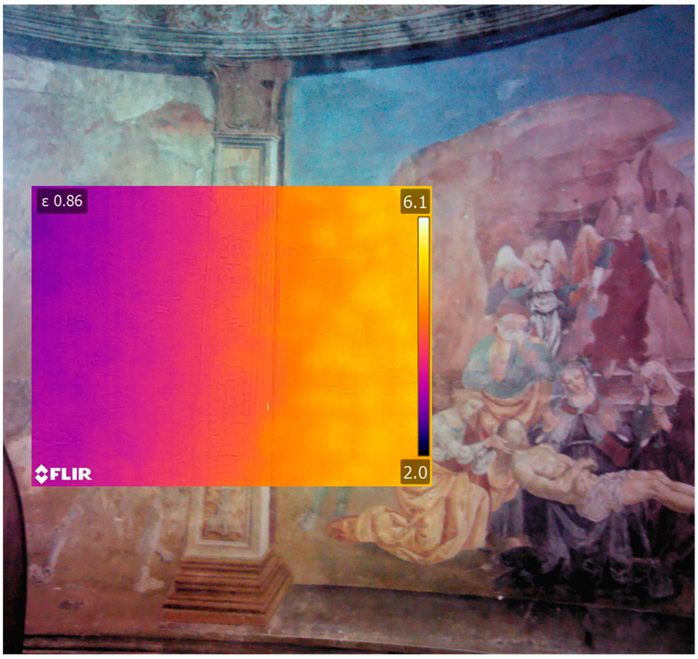

Figure 4. Passive IRT image of the attachment point of panels A and B. An abrupt discontinuity in the average emitted radiation can be seen.

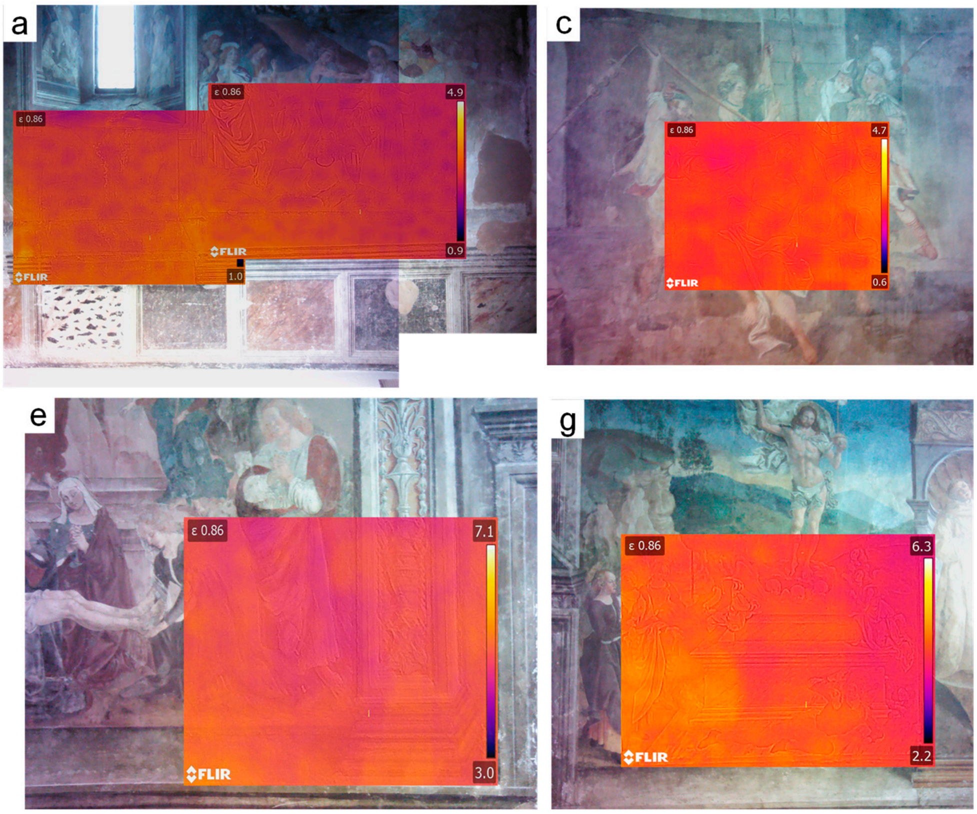

Figure 5. Passive IRT images of some frescoes' parts. The subplots (**a**,**c**,**e**,**g**) are named according to Figure 3.

In general, large temperature drops that could indicate large voids, anomalous moisture levels, or mass transfer (e.g., water) are not visible, even considering that the measurements were collected in the winter just after a huge snowfall (the church and all the area was covered by a thick layer of snow). There was also no evidence of severe inhomogeneities, moisture, or detachments, as the wall texture was visible in all the images, while large and long cracks were not. However, the wall texture was more visible on the left side of the apse, which is also less homogeneous with respect to the measured temperature.

The active IRT focused on two figures of the frescoes cycle. One is the figure that is going to be slaughtered in the second panel of the frescoes, starting from the left of the apse (panel A), and the other is the soldier lying at the foot of the tomb in the scene of the resurrection, which is in the first panel from the right (panel E). These two figures were chosen since passive IRT images evidenced some inhomogeneous spots on them, and further, for the soldier, the pictorial layer is significantly damaged, mainly scratched. In particular, the regions of interest (ROIs) were suggested by an art historian, Dr. Saverio Ricci, a renowned expert of the art master Saturnino Gatti.

The results of the PuCT experiments are reported in Figures 6 and 7. In particular, after the PuCT, virtual wave processing was applied [24]. These technique maps the time thermal signals, i.e., the intensity time trends of each pixel of IRT images, which are due to a diffusion process, into virtual signals associated to a propagation phenomenon, in which velocity is related to the thermal diffusivity. In this way, it is possible to estimate the depth corresponding to a specific image in the sequence after virtual wave application. This was made by assuming a thermal diffusivity of 0.3 mm^2/s. To the authors' knowledge, this is the first application of the virtual wave approach to the thermography inspection of CH.

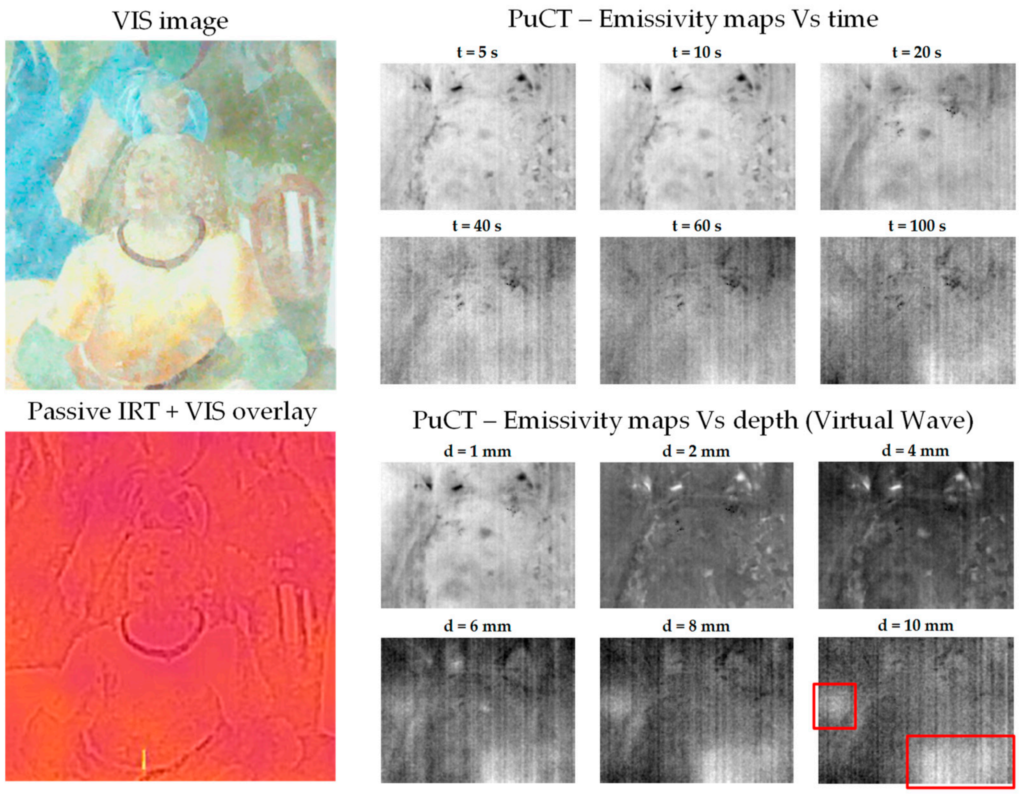

Figure 6. Results of PuCT and PuCT + virtual wave processing for the first area investigated. The red boxes in the bottom-right images indicate the shape of the bricks, which also barely visible in the passive IRT image (see Figure 5a). In the case of PuCT + virtual wave the bricks' shape appear from a certain value of depth and the maximum contrast is reached for a depth d = 10 mm.

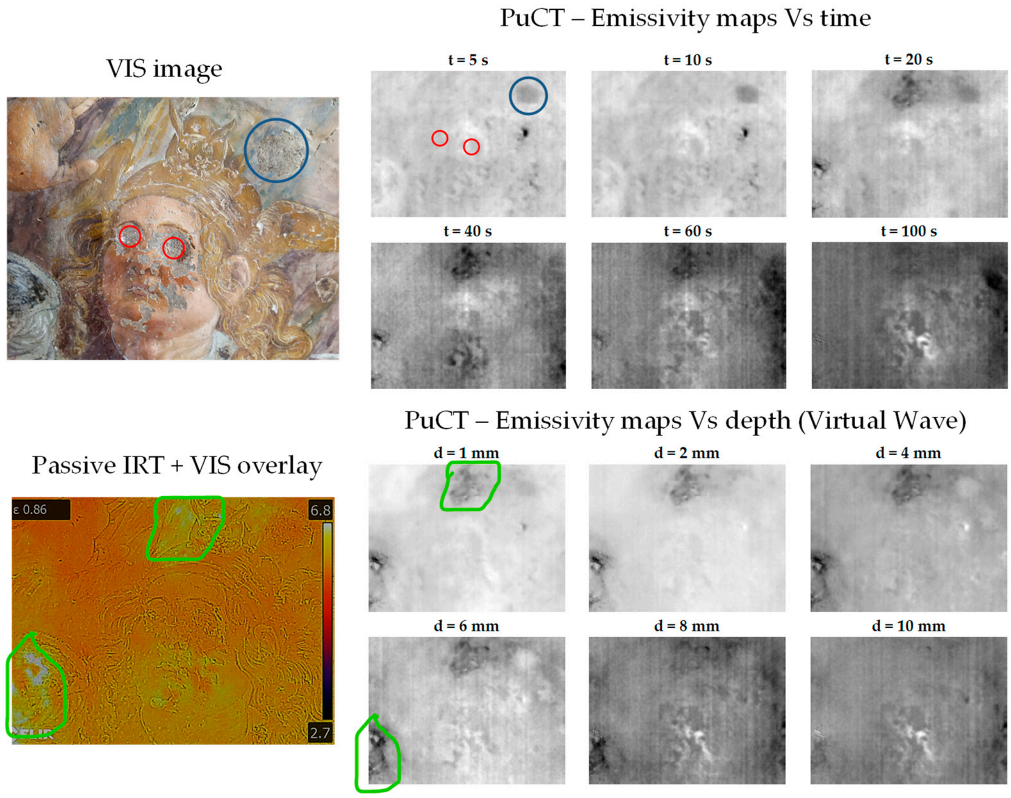

Figure 7. Results of PuCT and PuCT + virtual wave processing for the second area investigated. Blue and green curves highlight areas of specific interest. The blue circle indicates an area where a surface restoration intervention is visible. The thermal response is quite different indeed from the neighbor area especially at the initial times/depths, as expected from a surface inhomogeneity. The green curves indicate areas where there is no evidence of surface anomalies, but the thermal images highlight the presence of a thermal inhomogeneity under the surface.

Figure 6 reports the results for the first ROI. On the left, the VIS and the passive IRT images are shown, and the right shows some maps of the emissivity vs. time and emissivity vs. depth reconstructed after the PuCT and the PuCT + virtual wave processing.

In the time sequence of emissivity maps, the pictorial layer is maximally visible at the beginning, as expected. After some time, the maps are determined by the diffusion underneath the pictorial layer. However, the transition is smooth. After applying the virtual wave, the info is better associated with depth. In particular, the figure almost disappears beyond 2 mm, while other scratches and damages are visible up to 4 mm in depth. Further, the wall texture becomes clearly visible around 8–10 mm of depth; see the red rectangles in the right-bottom corner of Figure 6. This gives a measure of the plaster thickness and a better resolution than the passive IRT image can achieve. Note that a thermal diffusivity of 0.3 mm^2/s was assumed.

A similar analysis was done for the soldier figure, the second ROI, which is reported in Figure 7. The pictorial layer is barely visible in the emissivity maps due to the large degree of degradation. The wall texture is not clearly visible as well, as found by passive IRT, but instead, some interesting features were found.

For example, there are two hot spots (green marks in Figure 7) on the top of the soldier's forehead, just on the rabbit's left on the hat, and on the right shoulder. These hot spots are also visible in the passive IRT image, and with the virtual wave approach, their depth can be better evaluated.

4. Discussion and Conclusions

The integration of humidity, sonic velocity, and thermal maps provided complementary information that enabled the estimation of various critical factors such as detachments, rising damp, percolation, humidity, and other inhomogeneities, which represent typical decay phenomena in wall paintings. This comprehensive analysis allowed for the identification of potential critical areas, emphasizing the need for targeted conservation and restoration procedures for the wall paintings of St. Panfilo's Church.

In particular, the SPV is useful to diagnose masonry in a non-destructive way and deepen the knowledge of the construction characteristics, evaluate the state of conservation, and provide important information for effective restoration interventions of masonry.

The maps in SPV and HT enabled conservation problems (e.g. surface warping, painting layer detachments, and humidity distribution) to be evidenced and provided indications about different properties of the infill wall. These investigations aimed at assessing the consistency of the plaster coating and locating the possible presence of detachments, discontinuities, and voids.

The SPV and HT tests highlighted how both microclimatic factors and the different exposure of the masonry to solar radiation have a significant influence on the conservation state of the frescoes. Thermal stress can be decisive in generating detachments and fractures in the painted plaster, as evident from Figure 3a,b. This area near the window is characterized by humidity inhomogeneities, which also affect the plaster, as indicated by the highly variable SPV values. On the other hand, the areas whose external walls are less exposed to sunlight (Figure 3c,d) show higher and relatively homogeneous humidity values.

Regarding passive and active IRT, these techniques give information that can complement the SPV and HT maps.

By comparing the passive IRT and SPV images, a certain degree of correlation between hot areas and slow areas in the presence of possible detachments is noticed (see Figures 3 and 5). In particular, in subplots "e" and "g", the hottest areas correspond to low-sound velocity areas in SPV images where possible detachments can be found.

In many IRT images, the wall texture is visible, and in such areas, the presence of relevant detachments can be excluded. The PuCT active IRT, combined with virtual wave processing, can give detailed information about the plaster thickness and a better resolution than the well-known passive IRT approach (see Figure 6). All these advantages may help the restoration tangibly because the thermal imprints are read like a sort of tomography.

Based on the integrated use of SPV, HT, PIRT, and PuCT techniques, several observations can be made regarding the conservation status of the frescoes:

- plaster cohesion: several detached areas or damaged plaster resulting from fractures were evidenced;
- moisture distribution: the HT tests reveal variations in humidity levels across different areas. The moisture values are generally higher and more homogeneous in those regions potentially influenced by the position of the area relative to the sun exposure. Detached portions of plaster exhibit lower moisture values;
- temperature variations: the passive IRT analysis shows temperature discontinuities between different sections of the apse, indicating potential variations in wall texture and masonry structure. These differences may be attributed to factors such as materials, construction techniques, or later interventions;
- structural integrity of frescoes: the presence of fractures, discontinuities, and infill of the underlying masonry is evident from the SPV and PuCT results. These structural elements can affect the overall stability and conservation of the frescoes.

The integration of SPV, HT, and IRT results demonstrated a smart way to inspect artistic and architectural heritage, and this test represents an important starting point to deepen the knowledge of the structures and direct further and targeted investigations and restoration interventions.

The types of defects in a complex system such as frescoed masonry vary greatly. Therefore, the combination of the different non-destructive techniques proposed in this paper is helpful in overcoming the limitations of individual methods and achieving a more reliable diagnosis of the state of conservation of the wall paintings, allowing a comprehensive and multi-scale approach to the restoration problem.

This approach provides a comprehensive and multi-scale analysis of these complex structures, offering a more reliable and detailed understanding of their construction characteristics and conservation status. Additionally, the study highlights the significance of combining these techniques to overcome the limitations of individual methods and achieve a more comprehensive diagnosis, paving the way for targeted and effective restoration interventions.

Further steps, such as image fusion and correlation, are desirable in future applications to improve the accuracy of the tests and the evaluation of the conservation status.

Author Contributions: S.C., I.C. and T.S. equally contributed to the conceptualization, methodology, and experimental analysis of SPV and HT; S.L., M.R. and S.S. equally contributed to the conceptualization, methodology, and experimental analysis of IRT. All authors contributed to the writing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was performed in the framework of the Project Tornimparte—"Archeometric investigation of the pictorial cycle of Saturnino Gatti in Tornimparte (AQ, Italy)" sponsored in 2021 by the Italian Association of Archeometry AIAR (www.associazioneaiar.com).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors want to thank the Proloco Tornimparte association, Giuseppe Spagnoli (University of L'Aquila), Saverio Ricci (Superintendence of Archaeology, Fine Arts and Landscape for the Provinces of L'Aquila and Teramo), and the mayor of the municipality of Tornimparte for their availability and support shown during the NDT campaigns. The authors are also grateful to LAM-DST-UNIFI for the technical and scientific support for the investigations, especially Carlo Alberto Garzonio.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zuena, M.; Baroni, L.; Graziani, V.; Iorio, M.; Lins, S.; Ricci, M.A.; Ridolfi, S.; Ruggiero, L.; Tortora, L.; Valbonetti, L.; et al. The techniques and materials of a 16th century drawing by Giorgio Vasari: A multi-analytical investigation. *Microchem. J.* **2021**, *170*, 106757. [CrossRef]
2. Sandu, I.; Dima, A.; Sandu, I.G.; Luca, C.; Anca Sandu, I.C.; Sandu, A.V. Survey on behaviour of interventions for probota monastery indoor frescoes conservation under environmental factors influence. III. Correlations between thermal, hygroscopic and sonic parameters. *Environ. Eng. Manag. J. (EEMJ)* **2004**, *3*, 561–567. [CrossRef]
3. Centauro, I.; Calandra, S.; Salvatici, T.; Garzonio, C.A. System integration for masonry quality assessment: A complete solution applied to Sonic Velocity Test on historic buildings. In *The Future of Heritage Science and Technologies: Materials Science*; Springer International Publishing: Cham, Switzerland, 2022; pp. 213–226.
4. Coli, M.; Ciuffreda, A.L.; Donigaglia, T. Technical analysis of the masonry of the Bargello'Palace, Florence (Italy). *Appl. Sci.* **2022**, *12*, 2615. [CrossRef]
5. Luchin, G.; Ramos, L.F.; D'Amato, M. Sonic tomography for masonry walls characterization. *Int. J. Archit. Herit.* **2020**, *14*, 589–604. [CrossRef]
6. Binda, L.; Saisi, A.; Tiraboschi, C. Investigation procedures for the diagnosis of historic masonries. *Constr. Build. Mater.* **2000**, *14*, 199–233. [CrossRef]
7. Calandra, S.; Cardinali, V.; Centauro, I.; Ciuffreda, A.; Donigaglia, T.; Salvatici, T.; Tanganelli, M. *Integration of historical studies and ND techniques for the structural characterization of the masonry walls in Palazzo Vecchio, Florence, In Diagnosis of Heritage Buildings by Non-Destructive Techniques*; Tejedor, B., Bienvenido-Huertas, D., Eds.; Elsevier: Amsterdam, The Netherlands, 2023.
8. Solla, M.; Gonçalves, L.M.; Gonçalves, G.; Francisco, C.; Puente, I.; Providência, P.; Gaspar, F.; Rodrigues, H. A building information modeling approach to integrate geomatic data for the documentation and preservation of cultural heritage. *Remote Sens.* **2020**, *12*, 4028. [CrossRef]
9. Besharatinezhad, A.; Khodabandeh, M.A.; Rozgonyi-Boissinot, N.; Török, Á. The Effect of Water Saturation on the Ultrasonic Pulse Velocities of Different Stones. *Period. Polytech. Civ. Eng.* **2022**, *66*, 532–540. [CrossRef]
10. Miranda, L.; Cantini, L.; Guedes, J.; Binda, L.; Costa, A. Applications of sonic tests to masonry elements: Influence of joints on the propagation velocity of elastic waves. *J. Mater. Civ. Eng.* **2013**, *25*, 667–682. [CrossRef]

11. Garrido, I.; Lagüela, S.; Fang, Q.; Arias, P. Introduction of the combination of thermal fundamentals and Deep Learning for the automatic thermographic inspection of thermal bridges and water-related problems in infrastructures. *Quant. InfraRed Thermogr. J.* **2022**, 1–25. [CrossRef]
12. Rocha, J.H.A.; Santos, C.F.; Póvoas, V. Evaluation of the infrared thermography technique for capillarity moisture detection in buildings. *Procedia Struct. Integr.* **2018**, *11*, 107–113. [CrossRef]
13. Kim, C.; Park, G.; Jang, H.; Kim, E.J. Automated classification of thermal defects in the building envelope using thermal and visible images. *Quant. InfraRed Thermogr. J.* **2022**, 1–17. [CrossRef]
14. Larbi Youcef, M.H.A.; Feuillet, V.; Ibos, L.; Candau, Y. In situ quantitative diagnosis of insulated building walls using passive infrared thermography. *Quant. InfraRed Thermogr. J.* **2022**, *19*, 41–69. [CrossRef]
15. Davin, T.; Serio, B.; Guida, G.; Pina, V. Spatial resolution optimization of a cooling-down thermal imaging method to reveal hidden academic frescoes. *Int. J. Therm. Sci.* **2017**, *112*, 188–198. [CrossRef]
16. Cadelano, G.; Bison, P.; Bortolin, A.; Ferrarini, G.; Peron, F.; Girotto, M.; Volinia, M. Monitoring of historical frescoes by timed infrared imaging analysis. *Opto-Electron. Rev.* **2015**, *23*, 102–108. [CrossRef]
17. Galli, A.; Alberghina, M.F.; Re, A.; Magrini, D.; Grifa, C.; Ponterio, R.C.; La Russa, M.F. Special Issue: Results of the II National Research project of AIAr: Archaeometric study of the frescoes by Saturnino Gatti and workshop at the church of San Panfilo in Tornimparte (AQ, Italy). *Appl. Sci.* **2023**. *to be submitted*.
18. Valluzzi, M.R.; Cescatti, E.; Cardani, G.; Cantini, L.; Zanzi, L.; Colla, C.; Casarin, F. Calibration of sonic pulse velocity tests for detection of variable conditions in masonry walls. *Constr. Build. Mater.* **2018**, *192*, 272–286. [CrossRef]
19. Santo, A.P.; Agostini, B.; Garzonio, C.A.; Pecchioni, E.; Salvatici, T. Decay Process of Serpentinite: The Case of the San Giovanni Baptistery (Florence, Italy) Pavement. *Appl. Sci.* **2022**, *12*, 861. [CrossRef]
20. Lanteri, L.; Calandra, S.; Briani, F.; Germinario, C.; Izzo, F.; Pagano, S.; Pelosi, C.; Santo, A.P. 3D Photogrammetric Survey, Raking Light Photography and Mapping of Degradation Phenomena of the Early Renaissance Wall Paintings by Saturnino Gatti—Case Study of the St. Panfilo Church in Tornimparte (L'Aquila, Italy). *Appl. Sci.* **2023**, *13*, 5689. [CrossRef]
21. Laureti, S.; Colantonio, C.; Burrascano, P.; Melis, M.; Calabrò, G.; Malekmohammadi, H.; Sfarra, S.; Ricci, M.; Pelosi, C. Development of integrated innovative techniques for paintings examination: The case studies of The Resurrection of Christ attributed to Andrea Mantegna and the Crucifixion of Viterbo attributed to Michelangelo's workshop. *J. Cult. Herit.* **2019**, *40*, 1–16. [CrossRef]
22. Sfarra, S.; Laureti, S.; Gargiulo, G.; Malekmohammadi, H.; Sangiovanni, M.A.; La Russa, M.; Burrascano, P.; Ricci, M. Low Thermal Conductivity Materials and Very Low Heat Power: A Demanding Challenge in the Detection of Flaws in Multi-Layer Wooden Cultural Heritage Objects Solved by Pulse-Compression Thermography Technique. *Appl. Sci.* **2020**, *10*, 4233. [CrossRef]
23. Ricci, M.; Laureti, S.; Malekmohammadi, H.; Sfarra, S.; Lanteri, L.; Colantonio, C.; Calabrò, G.; Pelosi, C. Surface and interface investigation of a 15th century wall painting using multispectral imaging and pulse-compression infrared thermography. *Coatings* **2021**, *11*, 546. [CrossRef]
24. Burgholzer, P.; Thor, M.; Gruber, J.; Mayr, G. Three-dimensional thermographic imaging using a virtual wave concept. *J. Appl. Phys.* **2017**, *121*, 105102. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.