2022 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
University of Calabria, Italy, October 19-21, 2022

Pseudo-noise pulse compression thermography of the Raffaellino del Colle "Sacra famiglia con San Giovanni Battista" during painting restoration.

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***Abstract* – Active thermography of panel paintings can retrieve useful information about the support and the preparation layer behind the pictorial one. The main challenges are obtaining such information by using low power excitation to avoid any possible alteration of the painting and processing it to gain insight about the stratigraphy of the artwork. Pseudo-noise active pulse compression thermography in combination with time- and frequency- domain analysis was used here to face these challenges. The procedure was applied to a panel painting from Raffaellino del Colle, a former Raffaello's pupil, owned by Galleria Nazionale dell'Umbria, during painting restoration at the Restoration Laboratory of the Tuscia University**

I. INTRODUCTION

Before proceeding with paintings restoration, several nondestructive and/or microdestructive analysis are usually done to acquire information about pigments, varnish, previous restorations, preliminary drawing, etc., and to evaluate the conservation status of the whole artwork. While a plethora of techniques are now available to inspect the pictorial layer and that underneath [1-3], just a few techniques can be used to extend the analysis to the preparation layer and up to the support. Traditional X-ray images and, recently, computer tomography (CT) can be used but some limitations exist: 1) CT reconstructs 3D high-resolution images of the sample but is not feasible for in-situ inspection of large items or it is only provided by custom equipment [4], 2) traditional X-ray images can scan large surfaces with the digital X-ray detectors, but they do not provide any information about the depth at which some feature is identified. In both the cases, in-situ measurements must fulfil safety procedures.

Optical coherence tomography (OCT) [5] and THz time-domain reflectometry and spectroscopy [6-7] can reconstruct a stratigraphy of a painting, but while OCT's inspection range is usually limited to some tens, up to hundreds of micrometres, THz can also reach the wood support. Anyway, both are point measures, so scanning large samples is a lengthy procedure and, in the case of THz the necessary equipment is often bulky and expensive, and mainly limited to laboratory analysis. NMR can also be used to scan surfaces and retrieve information at depths of several millimetres [8], but it is as well a point-measure system, and the stratigraphy can be reconstructed by processing the information about the chemical-physical composition through accurate calibration procedures. On contrary, beingly inherently an imaging procedure, active thermography (AT) can easily scan large surfaces, it does not require safety protocols and, with the recent increase in the camera performances, very high 2D resolution and framerate can be reached. Further, the thermal excitation is usually provided by light sources, so it is quite easy to tailor both the illuminated area, the power of the excitation, and to some extent also the frequency content of the thermal excitation and its electromagnetic spectrum. These features attracted a lot of interest on thermography for Cultural Heritage and represent a relevant benefit with respect other techniques.

However, differently from OCT and THz, the heat phenomenon is based on a diffusion process [9], so separating the response of different layers is not a trivial task, neither 3D tomographic methods based on attenuation measurement such those used for CT can be applied. Notwithstanding, by processing AT data useful information can be retrieved for paintings' inspection [10-11] and recent developments based on virtual wave theory open at a 3D imaging procedure of thermal data [12].

Here we will see how, by combining pseudo-noise (PN) pulse compression thermography (PuC) with time- and frequency- domain analysis, significant information about the painting structure can be retrieved.

The artwork inspected is the "Sacra Famiglia con San Giovanni Battista", a large (~ 150cm × 182cm) oil painting on panel dated approximately on 1560 (Italian renaissance) and attributed to Raffaellino del Colle, see Fig.1. The painting was an altarpiece in the church of SS. Giacomo e Filippo (formerly S. Agostino) in Perugia, and it currently belongs to the collection of the Galleria Nazionale dell'Umbria. The item had various conservation issues, related both to the support realization technique and

Fig. 1. Sacra Famiglia con San Giovanni Battista", Raffaellino del Colle, oil painting on panel (1560 ca)

previous restoration interventions. The goal of the thermography inspection was assessing the conservation state of the painting, focusing on analysing the preparation layers and the panel support for detecting and characterizing any anomaly.

The paper is organized as follows: Section II introduces the theoretical background of thermography while Section III highlights the pros of the pseudo-noise pulse compression thermography (PN-PuCT) for paintings inspection. Section IV illustrates the experimental results while conclusions are drawn in Section V.

II. ACTIVE THERMOGRAPHY FOR PAINTINGS INSPECTIONS

To gain insight about the multi-layer composite structure of a painting, the AT approach must be used. Passive thermography, although can represent a quick method to detect macro anomalies, is not capable of giving any information about the depth of inspection.

In the AT scheme, a controlled thermal excitation is used and the thermal response of the sample to the stimulus is recorded for a certain time as a sequence of thermal images. By analysing the sequence, thermal signatures due to defects or just to the sample structure can be identified and their depth in the sample can be estimated by some theoretical considerations. In first approximation, the heat propagation in the sample can be considered as a 1-D phenomenon with the thermal front diffusing from the outer lighted surface to the inside of the painting and assuming a negligible contribution of lateral diffusion [13]. This is described by Eq.1

$$\frac{\partial^2\Theta(z,t)}{\partial z^2} - \frac{c\rho}{k}\frac{\partial\Theta(z,t)}{\partial \mathrm{t}} = -\frac{q(z,t)}{k} \qquad (1)$$

where $\Theta(z,t)$ is the temperature at a given depth z and time t, q(z,t) is the heating stimulus, c $[\frac{J}{kg\cdot K}]$ is the specific heat, ρ $[\frac{kg}{m^3}]$ is the density, k $[\frac{W}{m\cdot K}]$ is the thermal conductivity. The reciprocal of $\frac{c\rho}{k}$ is the thermal diffusivity $\alpha = \frac{k}{c\rho}\left[\frac{m^2}{s}\right]$.

The thermograms' sequence visualizes for each pixel the temperature of the outer surface $\Theta(z = 0, t)$ multiplied by a factor proportional to mean emissivity corresponding to the pixel area. By using light sources for heating the sample, we can assume a constant heating over all the surface and the light absorption happening just on a very thin outer layer. So, we can consider $q(z,t) = q(t)\delta(z)$, where $\delta(\cdot)$ is Dirac's delta function, which implies $q(z) = 0$ for z≠0 and ∀ t, and $q(t)$ is the excitation waveform.

The presence of an inner defect such a void, a gap, a painting elevation, etc., changes locally the thermal diffusivity causing local variations of the surface temperature. Hence, by analysing the radiation emitted by the inspected surface, the presence of a defect can be inferred. Further, since the heat diffusion is not instantaneous, defects located at different depths produce observable changes in the thermograms at different times. The information about the defect depth can be in principle extracted by a time-analysis of the emitted radiation. Similarly, local variations of the thermal properties due to the sample inhomogeneity affect the temperature of the inspected surfaces in time. For instance, the galleries of the woodworms change abruptly the density and the specific heat from wood to air, but also the rings of the wood are associated to a variation of the density (and sometimes of the moisture content), hence, of the specific heat.

The main issue in estimating the depth of a specific feature is the diffusion nature of heat: the heat flux in the sample caused by an external stimulus does not propagate but diffuses. This can be seen by analysing the so-called thermal waves (even being not waves), which are the solution of Eq.1 to a sinusoidal external heat source. Precisely, if $q(z,t)$= $q_0\cos(2\pi f t)\delta(z)$, the temperature profile $\Theta(\mathrm{z},t)$ in the sample is described by:

$$\Theta(\mathrm{z},t) = \Theta_0 e^{-\frac{z}{\mu}}\cos\left(\frac{z}{\mu} - 2\pi f t + \frac{\pi}{4}\right) \qquad (2)$$

where $\mu = \sqrt{\alpha/\pi f}$ $[m]$ is the thermal diffusion length.

Eq.2 is crucial to understand thermography inspection: μ quantifies both the decay of the temperature moving from the heated surface toward the interior of the sample, and the velocity of diffusion at a given frequency.

The rapidity of decay with the depth increases as the frequency increases, so for each frequency there is a maximum length of inspection over which the signal, i.e. the SNR, becomes too small. Such a distance is expressed by the thermal diffusion length μ, which depends nonlinearly on the frequency: at $z = 1\mu$ the amplitude is reduced of a factor e, at $z = 2\mu$ the amplitude is reduced of a factor e^2, so $z = 2\mu$ can be considered the maximum depth of inspection. From Eq.2, we can also assign a phase velocity $v_p(f)$ to the thermal front $\Theta(\mathrm{z},t)$:

$$v_p(f) = 2\pi f\mu \qquad (3)$$

Combining these arguments with the expression of μ, it is expected that different frequencies are likely to provide information from the outer surface up to different depths, and at different times. Lower frequencies penetrate more in the sample, but they have a lower depth resolution and phase velocity. As a rule of thumb, the optimal frequency $f^*(d^*)$ to inspect the sample at the depth d^* is given by:

$$f^*(d^*) \Rightarrow \mu(f^*) = d^* \Rightarrow f^* = {}^{\alpha\pi}/_{(d^*)^2} \quad (4)$$

while the time at which a defect/anomaly at depth d^* produces the largest difference on the emissivity of the inspected surface is expected to be:

$$t^*(d^*) = 2d^*/v_p(f^*) \Rightarrow t^* = {}^{(d^*)^2}/_{\alpha} \quad (5)$$

To summarize, in order to retrieve information of the thermal properties of a sample at different depths, a heat stimulus containing different frequencies must be chosen, and both time- and frequency- domain analysis should be preferably implemented. However, a stratigraphy cannot be directly reconstructed but it can be estimated by proper post-processing. In thermography applications for nondestructive evaluation (NDE), there are various excitation strategies working on a continuous range of frequencies and some other working in a discrete set. Not all of these are suitable for paintings inspection. It is also important to stress that, for a more accurate depth analysis the thermal properties of the sample should be known, and this is not the case of the paintings that have a very complex structure, but an analogous problem affects THz and OCT since the electromagnetic properties, and hence the velocity in the medium, are not known.

Further, even more important, the number and the type of the various layers is in general not known a-priori, and even sampling the item in a few points does not assure a complete identification of the whole painting structure. This is why an analysis of the thermal images made jointly by art historians, restorers and NDE experts is of utmost importance to optimally extract useful information starting from their technical knowledge and previous experience.

III. PSEUDO-NOISE PULSE COMPRESSION THERMOGRAPHY

As said, we need to excite the sample with a heat stimulus having components at several frequencies, to optimize the sensitivity and the resolution at different depths. We would also use an excitation signal that allows performing both time- and frequency- domain analysis. The simplest approach is using a flash-lamp to heat the sample. The flash duration is so short (a few milliseconds) that the heating can be considered instantaneous. This method is called pulsed-thermography (PT) and is one of the most used in AT for NDE.

Unfortunately, in the case of paintings inspection, especially for easel paintings, a strong limitation on the use of thermography exists: the maximum heat excitation power should be kept low enough to avoid any damage of the artwork, that could arise as an alteration of the pigments, thermal-induced mechanical stress (e.g. cracks in the pictorial layer), etc. PT is strongly affected by the limited peak power value since the SNR is proportional to it, and is it not routinely applied to easel painting analysis. Another common AT scheme is lock-in thermography, i.e. the use of a sinusoidal excitation, which allows the use of long low-power excitations, but for what mentioned above the information content about depth it provides is too small for analysing an easel painting. It is instead used on wall-painting mainly to detect possible detachments, even by using sun as heat source [14]. Many lock-in experiments could be done to trying collecting information at different depths, but the time-domain analysis cannot be retrieved. Being pulsed and lock-in the most used AT techniques, it can be understood why the potential of thermography for painting inspections has not yet fully exploited and why there is an enduring research effort on it.

A first solution proposed to overpass the limitations of pulsed and lock-in schemes was the use of binary pseudo-noise (PN) excitation combined with AR-MA modelling [15]: the PN excitations were used to excite an almost flat spectrum up to a certain cut-off frequency, which is defined by the update rate of the PN code, but with an arbitrary long signal. The AR-MA modelling was used to characterize the system response with a limited number of parameters. Despite the merits of this solution, AR-MA modelling was not capable of reconstructing accurately the system impulse response, and hence replacing the PT approach, but the method was used mainly for defect detection and imaging by compressing the information of thermal sequences on a few of AR-MA coefficients

More recently, pulse-compression thermography (PuCT) was proposed by some of the authors for painting inspection [16]. In that case, a frequency modulated chirp signal was used to span the desired bandwidth and the PuCT procedure was implemented to retrieve an estimate of the system response to a pulsed excitation. PuCT allows both time- and frequency- domain analysis to be carried out, increasing the information useful for estimating the stratigraphy of a paintings. However, PuCT protocols relying on chirp signals, both linear and non-linear [17], suffer from the so-called sidelobes that hamper the depth analysis in complex structures such as paintings, even if they do not significantly affect the defect detection. For suppressing the sidelobes, a PuCT protocol based on PN excitation signals was then developed and applied for paintings and CH inspections [18-19] by extending previous results in the field of ultrasonic NDE [20]. The reader is referred to [19-20] for the details of the pulse compression algorithm and to [18] for the experimental setup. In this paper we only report in Figure 2 the block diagram of the procedure, and in Figure 3 an example of its application. Note that, differently from previous works, we have also implemented here the Fourier-domain analysis on the PN output signal, see Fig.2.

IV. EXPERIMENTAL RESULTS

The painting was inspected by collecting 36 measurements on a regular grid. Each measure covers approximately an area of $25cm \times 25cm$ with a resolution of 256 × 256 pixels. The PN signal was a 23-bit Legendre sequence with a bit-rate of $0.5Hz$ [19-20]. The resulting excitation spectrum is almost flat up to $0.25Hz$.

The excitation signal contains two repetitions of the sequence for a total duration of $92s$ for each measurement, see Fig.2.

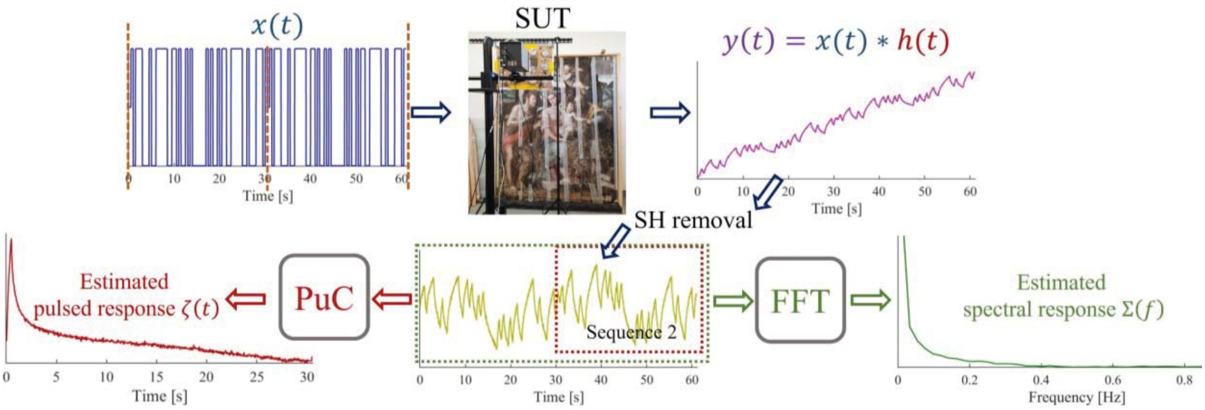

Fig.2 PN-PuCT procedure: a PN sequence $x(t)$ (two periods) excites the sample, the output $y(t)$ is processed to remove the step-heating contribution and then the resulting signal is: 1) processed with PuC to estimate the pulsed response in time-domain $\zeta(t)$; 2) processed with FFT to estimate the spectral response $\Sigma(f)$

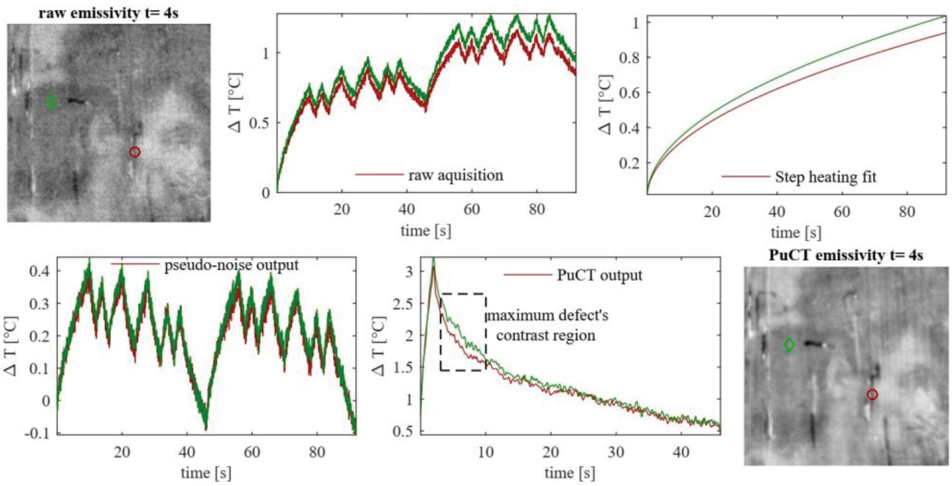

Fig.3 Example of application of the PN-PuCT procedure: the top-left image is the raw acquisition at t=4s, the bottom-right image is the output of the PuCT procedure at t=4s. The increase in resolution and sensitivity is evident. The plots represent the various steps of the procedures, the PuCT

The typical temperature increment of the painting surface due to PN excitation was around $1°C$, and always below $2°C$, see Fig.3. The processing procedure depicted in Figs. 2 and 3 was applied pixel-by-pixel for each measurement, and time- and frequency-domain analysis was implemented. The results of all the measurements were then combined to build up images of the whole inspected area. Figures 4 and 5 reports images at selected time and frequency values respectively; in particular Fig.4 reports the results of the PuCT procedure. It's worth to note that, after PuCT, the time-sequences can be considered as the response of the sample to an excitation having constant power and duration equal to the bit rate, i.e. $2s$. Thus, PuCT output exhibits a rise of temperature of the outer surface up to $2s$, followed by a cooling process, see. Fig.3. The maximum thermal contrast of the pictorial layer is then expected at $t = 2s$. Meanwhile, the layers underneath start to heat up due to diffusion, so hidden details reach the maximum contrast for larger times ($t > 2s$). In Fig.5 are reported the images of the PN output signal in frequency domain: for smaller frequencies all the structure details are simultaneously visible, from the pictorial layer up to the wood support. As the frequency increases, deeper features become invisible.

Figs. 4 and 5 have shown interesting results related to the executive technique. For shallow layers, up to $6s$ and above $40mHz$, the presence of gaps and elevations of the pictorial layer identifiable as completely black areas was highlighted (see $t = 4s$). Notably, also particular signs of horizontal and oblique stripes crossing throughout the painting are clearly visible. Such stripes reach the maximum contrast just after $2s$ and between 60 and $80mHz$, and they define a clear pattern of parallel lanes about $5 - 7cm$ wide each, with horizontal *ductus* in the central portion, and oblique in the right and left lateral bands, which reminds to the typical trajectory of a manual gesture. The most plausible hypothesis is that such pattern is the thermal image of the drafting of a basic preparatory layer by means of a scraper, perhaps a first saturation primer. The relative regularity of the lanes, revealed by the linear doubling along the parallel spreading, suggests in fact the typical gesture used to level and spreading of a semi-fluid preparation (oily primer?) with a flexible tool.

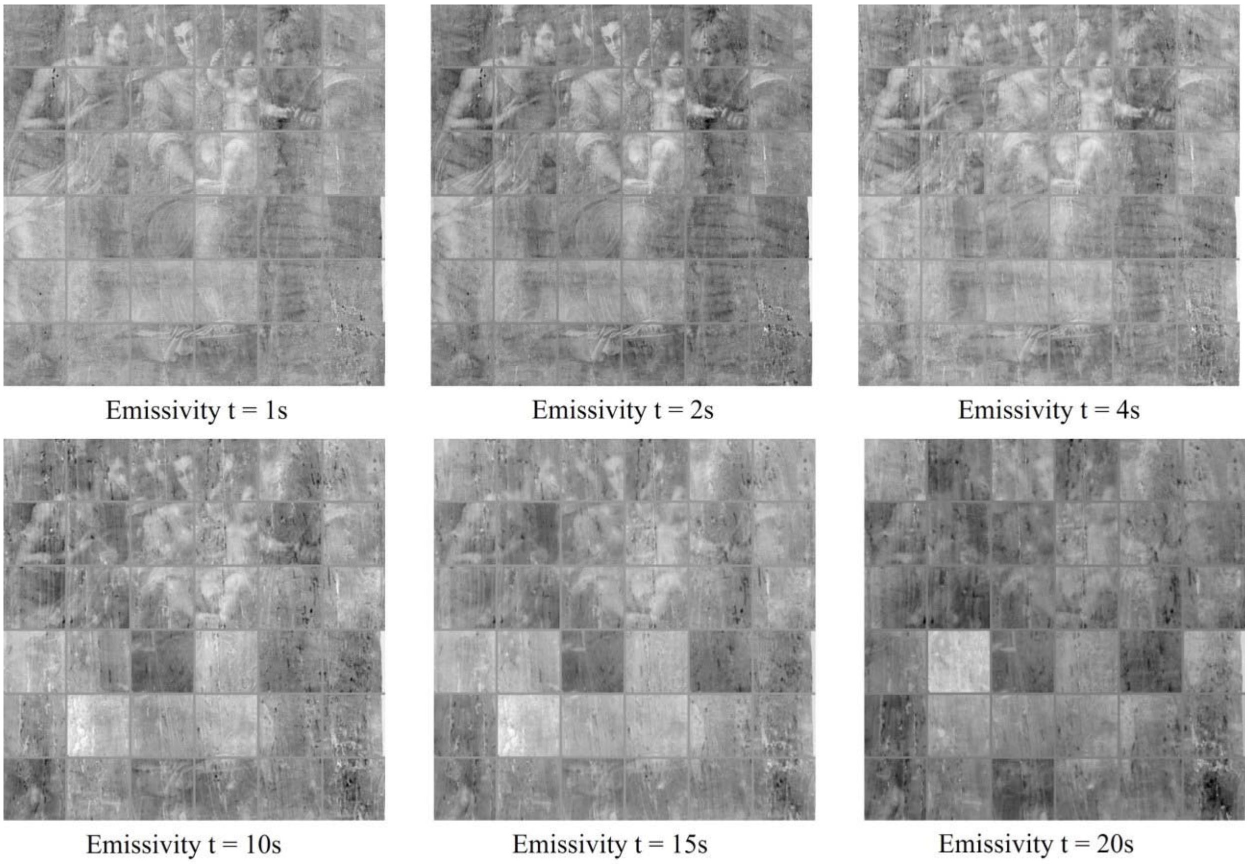

Fig.4 Reconstructed emissivity maps after pulse-compression at different times.

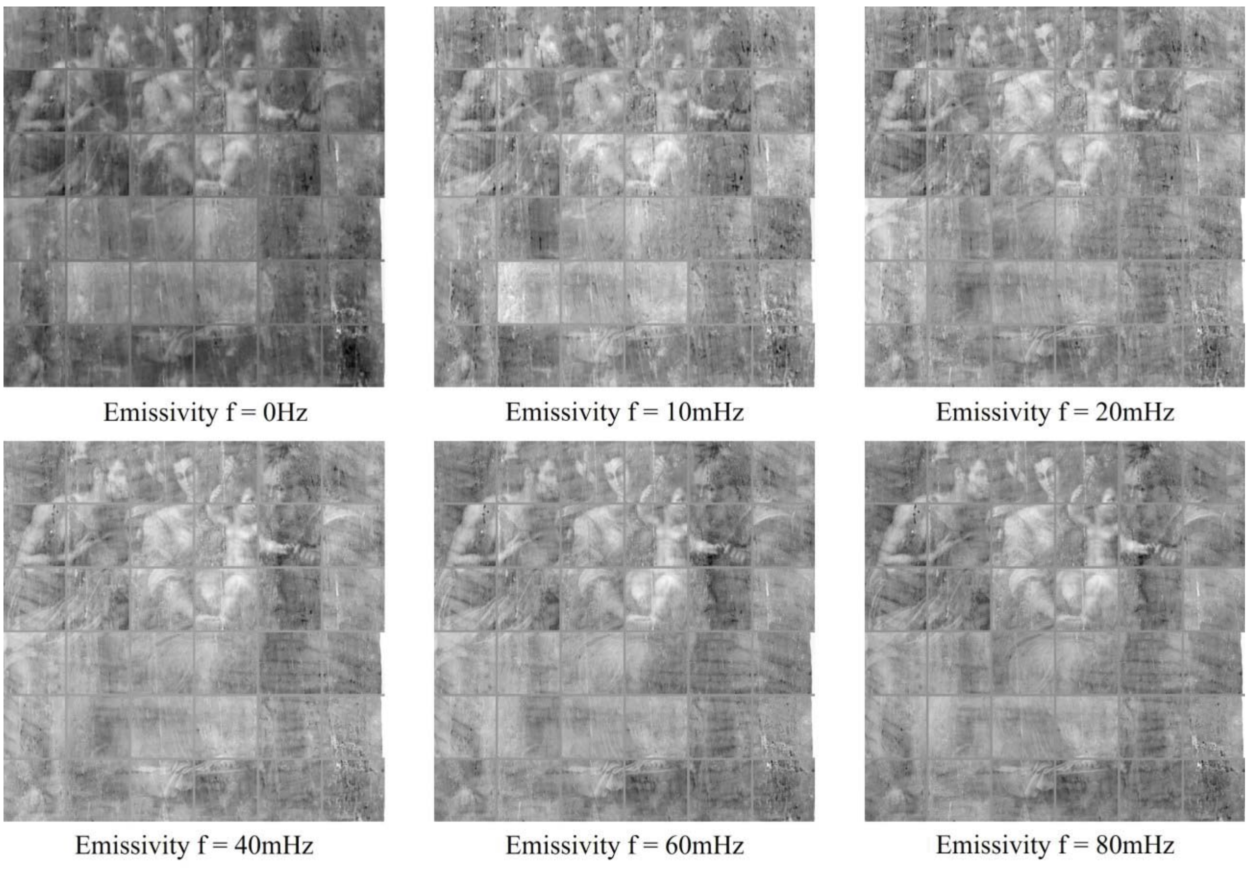

Fig.5 Reconstructed emissivity maps after pulse-compression at different frequencies.

PN-PuCT was also useful in investigating the anatomical characteristics of poplar wood boards, see images at $t = 10 - 15\, s$ and at $f = 10 - 20mHz$, showing the knots and the grain pattern, but it also highlighted elements relating to the execution technique for the construction of the support, such as the soft iron nails in the thickness of the planking inserted to a total corresponding to about half of the thickness. The images reconstructed at different times/frequencies show the presence of gaps and detachments placed at various depth levels which appear are totally dark. From the point of view of degradation, PN-PuCT allowed the particularly precarious and fragile state of the structure to be read, due to a massive presence of tunnels and woodworm holes. The latter start to be visible for $t = 2$, so just behind the pictorial layer, and become more relevant for $t = 4s$, when the grain of the wood is also clearly visible, allowing for feedback on the type of cutting of the boards and the more superficial tunnels. These defects become then particularly evident for $t \geq 10s$, $f < 20mHz$, and even more for $t = 20s$, where the pictorial pattern almost vanishes on thermal images, showing only the plank. Similarly, at $f = 10mHz$, the pictorial pattern become less visible while many woodworms' holes can be seen.

V. CONCLUSIONS

Pseudo-noise pulse compression thermography was applied to inspect an Italian renaissance oil painting on panel during its restoration. The analysis of the thermal sequences in both time- and frequency- domain allowed many details about the execution techniques and conservation status to be identified, thus providing useful information to the restorers. Starting from these results, further tailored processing for panel paintings analysis could be developed, e.g. by fusing time and frequency information to estimate the mean thermal diffusivity of the pictorial and preparation layers.

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