Hypercolorimetric multispectral Imaging and Pulse Compression thermography as innovative combined techniques for painting investigation: the case of a detached wall painting by Pastura

G Agresti¹, P Burrascano², G Calabrò¹, C Colantonio¹, L Lanteri¹, S Laureti¹, M Melis⁴, C Pelosi¹, M Ricci³, S Sfarra⁵

¹Department of Economics, Engineering, Society and Business Organization (DEIM), University of Tuscia, Viterbo, Italy
²Department of Engineering, Polo Scientifico Didattico di Terni, University of Perugia, Terni, Italy
³Department of Informatics, Modeling, Electronics and Systems Engineering, University of Calabria, Rende (CS), Italy
⁴Profilocolore S.r.l., Rome, Italy
⁵Department of Industrial and Information Engineering and Economics, University of L’Aquila, L’Aquila, Italy

Corresponding author: Claudia Pelosi pelosi@unitus.it

Abstract. This contribution focuses the attention on an innovative approach in diagnostics of paintings, based on the combine use of two imaging techniques named Hypercolorimetric Multispectral Imaging (HMI) and Pulse Compression Thermography (PuCT) applied to a 15th century wall painting, attributed to the Italian artist Antonio del Massaro, also known as Pastura. HMI technique is based on the simultaneous exploitation of the electromagnetic spectrum from the ultraviolet to the near infrared region. The acquisition, made under a standard metric, allows for characterizing the investigated surfaces in a more detailed way than the standard colorimetry. The system transforms any spectra in the range 300-1000nm into sevenfold hypecolorimetric coordinates. HMI guarantees very high radiometric (better than 95%) and colorimetric precision (better than ΔE = 2). PuCT is a thermography technique based on the use of coded modulated heating stimuli in combination with the pulse-compression technique. A PuCT scheme, based on coded LED excitation capable of optimizing the estimation of the impulse responses compared to the state-of-the-art PuCT literature has also been proposed. The combined use of HMI and PuCT recently revealed its potentiality in the investigation of important panel paintings by highlighting hidden details, mapping the conservation status, characterizing painting materials, etc. in a completely non-invasive way. Their combined capabilities are here tested on a wall painting representing the Madonna with the Child and the Saints Jerome and Francis, which was investigated during the restoration in the Laboratory in order to supply information about the materials and techniques.

1. Introduction

The diagnostic investigation of cultural heritage objects, through non-destructive and non-invasive techniques has become widely applied, due to the development of imaging methods that could supply information useful for conservators to choose the most appropriate intervention decision during a
restoration work [1-10]. The non-invasive imaging techniques are fundamental for obtaining a complete knowledge of the surfaces, for addressing the possible sampling of micro-chips of materials for laboratory analysis, and in case of impossibility to take samples from the investigated artworks [11-16].

A valid inspection approach for painting analysis relies on the integration of data collected from different imaging techniques, combining relative outputs through specific digital imaging processing tools. Imaging data integration can strongly support traditional analytical methods, yielding a comprehensive diagnosis of the painting state of conservation and reducing the ambiguities of information coming from a single diagnostic method [2,10,11,14,17].

In the present work, an innovative integrated analysis for painting diagnostics that combines InfraRed Thermography (IRT) [18-19], and Hypercolorimetric Multispectral Imaging (HMI) [20-22] is applied to a detached wall-painting, under restoration in the Laboratories of the five-year course in Conservation and Restoration of Cultural Heritage (LMR/02) of University of Tuscia [23].

The wall painting, specifically a lunette, depicts a Madonna and Child enthroned between the angels and the Saints Jerome and Francis (Fig. 1). The painting has been dated back to 1490 and it is attributed to the artist Antonio del Massaro, known as Pastura (1450-1519) [24-25]. Originally it was located in the convent of Santa Maria del Paradiso in Viterbo, a little city in Central Italy [24].

![Figure 1](image1.png)

**Figure 1.** The lunette with Madonna and the Child enthroned between the angels and the Saints Jerome and Francis (AD 1490) attributed to the painter Antonio del Massaro known as Pastura (1450-1519), before the restoration.

After the detachment, in 1912, the painting was transferred in the Civic Museum of Viterbo on the occasion of the opening of the new seat in Santa Maria della Verità church [24]. The detachment of the lunette was probably due to its bad state of conservation caused by exposure to weathering and vandalism [26]. In fact, in the photographs of the beginning of 20th century, large grouts were visible confirming the bad state and so the need for interventions [23].

The ancient restoration interventions, made with unsuitable materials and techniques (such as the mimetic reintegration), prevented correct readability of the artwork and of its original painting. So, it was decided, in accordance with the Superintendence and the responsible of the Civic Museum, to perform a restoration with the aim at recovering, as much as possible, the original appearance of the painting [23]. To reach this goal, the lunette was brought in the restoration laboratories of University of Tuscia in 2016 for starting the intervention.
The restoration work was supported by diagnostic investigation aimed at mapping the superimposed materials, the grouts, the lacunae and in general the non-original areas, well-visible under ultraviolet fluorescence photography (Fig. 2). The image under UV radiation showed diffuse blue fluorescence probably due to the presence of glue used for the detachment of the lunette. Grouts and cracks are also well-highlighted by the UV image [23].

Figure 2. The lunette with Madonna and the Child enthroned between the angels and the Saints Jerome and Francis (AD 1490) attributed to the painter Antonio del Massaro known as Pastura (1450-1519), under UV, before the restoration.

The surface material was sampled in order to perform Fourier transform infrared analysis to characterize its composition. This analysis revealed that the yellowed surface material was made of protein glue (Fig. 3). The main absorptions of glue can be observed in the infrared spectrum at cm$^{-1}$: 3289, 3064, 2930, 1660, 1542, 1373, 1313, 1246, 1033 [27-28]. The other absorptions in the spectrum of Figure 3 can be associated to calcium carbonate (1424 and 876 cm$^{-1}$) and gypsum (1152 cm$^{-1}$) [23]. This preliminary analysis has been fundamental to address the first cleaning choices of restorers to start the intervention.

After this, further investigation were performed by combining HMI and PuCT, supported by traditional XRF spectroscopy, in order to obtain information about the painting materials and the stratigraphic sequence combining possible original layers and new grounds added during the detachment of the lunette from the church of Santa Maria del Paradiso.

HMI and PuCT are two innovative techniques recently applied in combination to investigate panel paintings and whose theoretical principles have been widely reported in our previous research work [17, 29].
In the present work the two techniques were tested for the first time on a wall painting, which, due to the detachment from the original location, exhibits a peculiar stratigraphy and surface materials deserving investigation.

2. Experimental

2.1. Hypercolorimetric Multispectral Imaging
The HMI system consists of two main tools, i.e., SpectraPick for the image acquisition and calibration and PickViewer software for the image analysis [13, 17]. HMI acquisition was performed through a Nikon D810FR 36 Megapixel camera, modified to obtain full-range spectral reflectance measurements. Lighting was obtained by Nikon SB910 xenon flashes after removing their front plastic lenses, thus allowing also the UV wavelength to be emitted. The UV induced fluorescence (UVF) was then obtained by filtering the flashes light with a UV band pass filter with a cut at 380 nm, and UV-IR cut filter (400-700 nm) in front of the camera. As previously mentioned, a calibration step is needed before proceeding with HMI measurement. To this aim, the radiometric references consisted of a number of white patches surrounding the object and of 36 patches colour-checkers built using colour samples from the NCS – Natural Colour System®© catalog. The spectral reflectance of the references was accurately measured in the range 220-1050 nm in Profilocolore laboratory, with 0.7 nm accuracy (Instrument System Spectroradiometer CAS 140 CT and dark room). The calibration procedure has been executed as previously described [13, 17] and produced seven monochromatic images, 16 bit TIFF format, containing the spectral reflectance values at 350, 450, 550, 650, 750, 850 and 950 nm (i.e. IR1, IR2, IR3 respectively), and a single AdobeRGB TIFF 16 bit colour image. The achieved precision across the whole 36 megapixels image is higher than 95% on the spectral reflectance images and colour error less than CIE2000 ΔE=2 for the colour image [13]. The whole calibration and alignment process requires few minutes and can be performed in situ for an immediate results analysis. After the image acquisition and calibration processing, carried out using SpectraPick®, the multispectral images were processed through the HMI software PickViewer®, developed by

Figure 3. Fourier transform infrared spectrum of the yellowed surface material. The photograph of the sampling point is also shown in the spectrum.
The PickViewer software provides powerful image processing tools able to reveal and achieve relevant information. It further allows gathering information on hidden data from the images acquired with SpectraPick system, containing spectral reflectance and colour coordinates for each of the 36 megapixels of the captured scene. Data are calibrated and are absolute, depending only on the spectral characteristics of the surface. Several kinds of analyses are possible with PickViewer, such as: add and integrate any other imaging data (fluorescence, X-ray, thermal etc.); multichannel images viewer; any pixel colorimetry and spectral reflectance read-out; mapping by: colour, spectra, arbitrary channels; principal components analysis; contrast enhancement through digital imaging processing algorithms; neural network based clustering; colour and spectral signature database; two ways mapping by database entry; any channel to RGB false colours visualization; channels math, indexes and normalised contrast; calibration and colour-checker test. Each relevant result can be saved as image in tiff, png or jpeg format. Results saved in tiff format can be reloaded as further derived channels and used combined with all the others [20].

2.2. Pulse Compression Thermography

The experimental setup used to implement the PuCT procedure is the same used and detailed in previous published papers together with the theoretical base of the technique [29-31]. In particular, the signal generation/acquisition was managed by LabviewTM software. Thermograms were collected through a Xenics Onca-MWIR (3.6–4.9µm)-InSb camera placed in reflection mode, having a resolution of 320×240 pixels, connected to a NI-1433 Camera Link Frame Grabber. The distance between the painting and the camera was of about 50 cm. Eight LED chips emitting in the visible spectrum were used as heat source with an operating total power of ~110 W. The coded excitation driving the LEDs was provided by a TDK Lambda GEN 750W power supply. The frame grabber and the power supply were synchronously driven by the signals provided by a National Instrument PCI-6711 Arbitrary Waveform Generation (AWG) board. Both the AWG board and the grabber were connected to a central PC/DSP Unit.

3. Results and Discussion

3.1. Hypercolorimetric Multispectral Imaging

The seven calibrated spectral bands were analysed in PickViewer software and some statistical processing tools were applied to the images in order to gain further diagnostic information. The IR2 band (850 nm) gave some details on the preparatory design of the scene (Fig. 4), as in the detail of the pentimento in the foot of Saint Jerome, where other outlines are visible on its left, and in the bottom left part of the Virgin’s blue garment, currently covered by restoration. Hidden details of pentimenti and original composition in HMI infrared image at 850 nm are indicated by the red arrows in the figure 4.

Infrared and ultraviolet false colour analysis (IRFC and UVFC, respectively) were obtained by combining calibrated R, G, B and IR/UV channels in order to hypothesize a non-invasive characterization of pigments based on their characteristic spectral behaviour (Fig. 5a-b). For the blue pigment of the Virgin’s garment, the use of azurite was hypothesized on the base of its characteristic deep blue colour in IRFC and opaque light green shade in UVFC. The sky and parts of the vest of the Virgin have a particular green colour in the visible; in IRFC they assume a light blue hue and a full brown colour in UVFC, making probable its attribution to malachite.

Considering the bad state of conservation of the artwork after a long exposition to weathering, a preferential degradation caused by humidity with a transformation of azurite into malachite or other green copper-based compounds, seems probable rather than the application of a green pigment in areas meant to be blue-coloured [32]. Portion of unaltered azurite are in fact clearly visible in the background sky behind the head of the Virgin as well as traces are appreciable in the lower edge of the sky.
In order to investigate this possibility in a non-invasive way, a map of spectral similarity was built on the base of the 7-bands curve of spectral reflectance measured in a 9×9 pixels area in the blue Virgin’s dress, as shown in PickViewer’s graphic user interface (GUI) in Figure 6. The output, shown on the right of the visible image in the software’s GUI, highlights a correspondence between the blue pigment of the vest of the Virgin and the one used to paint the sky, supporting the hypothesis of the use of azurite in all blue areas.

The painting layer of azurite used for the sky is applied over a coloured ground layer probably based on red earth (hematite) or charcoal black *(morellone)*, usually used for the application of azurite in wall paintings, as described in scientific literature [32].

From the UVFC image it can be seen different responses in the haloes of the characters that deserve a note. In fact, in this analysis, the haloes of Saints Jerome and Francis and of the two angels assume a violet hue, while those of the Virgin and Child turn into a vivid pink colour, suggesting the use of different materials. It is possible the presence of a *missione*, an adhesive oil/resin primer, used to allow the adhesion of gold on haloes and other parts in the wall paintings [33].

### 3.2. Pulse Compression Thermography

The reported results were obtained by applying pixelwise the pulse-compression algorithm over the acquired thermograms. A thorough description of the technique lies beyond the scope of this work, therefore the reader is referred to [17, 29-31] for a deeper understanding of the whole procedure.

Note that six thermal acquisitions were needed for testing as much as possible of the painting surface and assuring an enough spatial resolution of the captured thermograms. Those six contributions were then merged during the post-processing, so as to obtain a meaningful image of the selected area. However, the top-left acquisition was found to be corrupted, thus is not being shown in the images. Figure 7a depicts the results of the PuCT after 1 second from the beginning of the reconstructed thermal pulse, whilst Figure 7b shows the same but after 3 seconds.

It can be noted that detachments, gold coating and different restoration works appear as brighter area in Figure 7a and their signature is still present as time elapses – please compare marked area in Figure

---

**Figure 4.** HMI infrared image at 850 nm; hidden details of *pentimenti* and original composition are indicated by red arrows.
7a to the same in Figure 7b. As there is a direct link between the thermal responses of layers at deeper depths within the tested materials and the flow of time, signatures of potential deeper detachments/restorations/gluing are visible as vertical contrasted areas in Figure 7b and located with yellow markers.

Figure 5. Infrared (a) and ultraviolet (b) false colour images obtained through PickViewer®.
Figure 6. PickViewer® software’s GUI. On the left: visible image and red point highlighting the measurement of multispectral reflectance of possible azurite. On the right: multispectral similarity mapping of azurite.

The PuCT results are confirming what HMI discovered concerning the presence of gold in some parts of the painting.
In the figure 7b it is also well-visible the texture of the canvas that was used as new support, together with a mortar, for attaching the wall painting after the detachment.

Figure 7. Results of PuCT after 1 (a) and 3 seconds (b) from the beginning of the reconstructed thermal pulse.

4. Conclusions
In this work Hypercolorimetric Multispectral Imaging (HMI) and Pulse Compression Thermography (PuCT) have been tested on a detached wall painting representing the Madonna and the Child enthroned between the angels and the Saints Jerome and Francis (AD 1490), attributed to the painter Antonio del Massaro known as Pastura (1450-1519). The restoration work was the occasion for investigating the artwork in detail in order to study the materials, the construction techniques, the state of preservation and the stratigraphic pattern as consequence of the detachment operations performed at the beginning of the 20th century.
A preliminary investigation was carried out to have the basic information fundamental for the conservators to start the intervention, i.e. cleaning and removal of old grouts. Here, a synthesis of the main results of the first screening has been reported and discussed shortly in the introduction.
After this phase, it was decided to test the application of two innovative techniques, i.e., HMI and PuCT, whose great potentialities have been demonstrated on panel paintings, but they were never used before on wall paintings in combination.
HMI supplied relevant information about surface and immediately sub-surface layers in terms of possible pigment composition and distribution, and preparatory drawing/pentimenti, respectively. PuCT was able to study the detachments, grouting, gilding from the surface to the deep layers giving relevant information about the possible presence of discontinuity or deep grouts. Further processing of the acquired images will be possible also with the support of conservators that could address the choice of the most useful deepening to supply a valid aid to the intervention.

References:

[1] Aldrovandi A, Bertani D, Cetica M., Matteini M 1988 Multispectral image processing of paintings Stud. Conserv. 33 154–9.

[2] Mairinger F 2004 UV-, IR- and X-ray-imaging Non-destructive microanalysis of cultural heritage materials eds. K H A Janssens and R Grieken (Antwerp: Wilson & Wilson Elsevier) pp 15–73.

[3] Schreiner M, Frühmann B, Jembrih-Simburger D, Linke R 2004 X-rays in art and archaeology: an overview Powder Diff. 19(1) 3–11.

[4] Saunders D, Billinge R, Cupitt J, Atkinson N, Liang H 2006 A new camera for high resolution infrared imaging of works of art Stud. Conserv. 51 277–90.

[5] Fischer C, Kakoulli I 2006 Multispectral and hyperspectral imaging technologies in conservation: current research and potential applications Rev. Conserv. 7 3–16.

[6] Kubik M 2007 Hyperspectral imaging: a new technique for the noninvasive study of artworks, Physical techniques in the study of art, archaeology and cultural heritage eds D Creagh and D Bradley (Amsterdam: Elsevier) pp 199–255.

[7] Delaney J K, Zeibel J G, Thoury M, Littleton R, Palmer M, Morales K M, de la Rie E R, Hoenigswald A 2010 Visible and infrared imaging spectroscopy of Picasso’s Harlequin Musician: mapping and identification of artist materials in situ Appl. Spectrosc. 64(6) 584–94.

[8] Adam A J L, Planken P C M, Meloni S, Dak J 2009 TeraHertz imaging of hidden paint layers on canvas Opt. Expr. 17(5) 3407–16.

[9] Fukunaga K, Picollo M 2010 Terahertz spectroscopy applied to the analysis of artists’ materials, Appl. Phys. A 100 591–7.

[10] Casini A, Bacci M, Cucci C, Lotti F, Porcinai S, Picollo M, Radicati B, Poggesi M, Stefani M 2005 Fiber optic reflectance spectroscopy and hyper-spectral image spectroscopy: two integrated techniques for the study of the Madonna dei Fusi Optical methods for arts and archaeology eds R Salimbeni and L Pezzi Proc. SPIE 5857 pp 178–84.

[11] Luciani G, Pelosi C, Agresti G, Lo Monaco A 2019 How to reveal the invisible: the fundamental role of diagnostics for religious painting investigation Eur. J. Sci. Theol. 15(3) 209–20.

[12] Lanteri L, Agresti G, Pelosi P 2019 A new practical approach for 3D documentation in ultraviolet fluorescence and infrared reflectography of polychromatic sculptures as fundamental step in restoration Heritage 2(1) 207-15.

[13] Colantonio C, Pelosi C, D’ Alessandro L, Sottile S, Calabrò G, Melis M 2018 Hypercolorimetric Multispectral Imaging (HMI) system for cultural heritage diagnostics: an innovative study for copper painting examination Eur. Phys. J. Plus 133 526.

[14] Pelosi C, Calienno L, Fodaro D, Borrelli E, Rubino A R, Sforzini L, Lo Monaco A 2016, An integrated approach to the conservation of a wooden sculpture representing Saint Joseph by the workshop of Ignaz Günther (1727-1775): analysis, laser cleaning and 3D documentation, J. Cult. Herit. 17 114-22.

[15] Lo Monaco A, Giagnacovo C, Falucci C, Pelosi C 2015 The triptych of the Holy Saviour in the Tivoli Cathedral: diagnosis, conservation and religious requirements, Eur. J. Sci. Theol. 11(2) 73-84.

[16] Pelosi C, Falucci C, Ardagna V 2017 Investigation of a medieval illuminated manuscript through non-invasive techniques, Eur. J. Sci. Theol. 13(2) 61-8.
[17] Laureti S, Colantonio C, Burrascano P, Melis M, Calabrò G, Malekmohammadi H, Sfarra S, Ricci M, Pelosi C 2019 Development of integrated innovative techniques for the examination of paintings: 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. 40 1-16.

[18] Zhang H, Sfarra S, Saluja K, Peeters J, Fleuret J, Duan Y, Fernandes H, Avdelidis N, Ibarra-Castanedo C, Maldague X 2017 Non-destructive investigation of paintings on canvas by continuous wave terahertz imaging and flash thermography, J. Nondestruct. Eval. 36(2) 34.

[19] Maldague X 2001 Theory and practice of infrared thermography for nondestructive testing. Wiley series in microwave and optical engineering (Hoboken: Wiley) p 684.

[20] Melis M, Miccoli M, Quarta D 2013 Multispectral hypercolourimetry and automatic guided pigment identification: some masterpieces case studies Optics for Arts, Architecture, and Archaeology IV, eds L Pezzati and P Targowski, Proc. of SPIE 8790 pp 1-14.

[21] Samarelli M, Melis M, Miccoli M, Egarter Vigl E, Zink A R 2015 Complete mapping of the tattoos of the 5300-year-old Tyrolean Iceman. J. Cult. Herit. 16 753-8.

[22] Melis M, Miccoli M 2013 Trasformazione evoluzionistica di una fotocamera reflex digitale in un sofisticato strumento per misure fotometriche e colorimetriche Proc. Colore e Colorimetria contributi multidisciplinari (Firenze) vol IX A eds M. Rossi and A. Siniscalco (Santarcangelo di Romagna – RN: Maggioli Editore) pp 28-38.

[23] Gittins M, Agresti G, Catalano M I, Pelosi C, Pogliani P 2017 La lunette raffigurante Madonna con Bambino in trono tra gli angeli e i Santi Francesco e Girolamo staccato dal convento di Santa Maria del Paradiso per il Museo Civico di Viterbo: fortuna dell’opera e storia conservativa alla luce dell’ultimo restauro (2016-2017), Proc. XV Congresso Nazionale IGIIC Lo Stato dell’Arte (Bari) (Firenze: Nardini Editore) pp 461-468.

[24] Ricci C 1912 Antonio da Viterbo detto il Pastura e il Appartamento Borgia Per l’inaugurazione del Museo Civico di Viterbo (Viterbo: Agnesotti) pp 23-27.

[25] Zucchi A 1983 L’attività viterbesi di Antonio del Massaro detto il Pastura Il Quattrocento a Viterbo eds M. Calvesi, R. Cannatà and C. Strinati (Milano: De Luca) pp 222-239.

[26] Rinaldi S 2004 I dipinti del Museo Civico di Viterbo. Censimento conservativo in omaggio a Michele Cordaro (Todi: Ediart) p 75.

[27] Derrick M R, Stulik D, Landry J M 1999 Infrared Spectroscopy in Conservation Science (Los Angeles: The Getty Conservation Institute) p 235.

[28] Meilunas R J, Brentsen J G; Steinberg A. 1990 Analysis of Aged Paint Binders by FTIR Spectroscopy, Stud. Conserv. 35 33-51.

[29] Laureti S, Malekmohammadi H, Khalid Rizwan M, Burrascano P, Sfarra S, Mostacci M, Ricci M 2019 Looking Through Paintings by Combining Hyper-Spectral Imaging and Pulse-Compression Thermography, Sensors 19(19) 4335.

[30] Silipigni G, Burrascano P, Hutchins D A, Laureti S, Petrucci R, Senni L, Torre L, Ricci M 2017 Optimization of the pulse-compression technique applied to the infrared thermography nondestructive evaluation, NDT&E Int. 87 100–10.

[31] Laureti S, Sfarra S, Malekmohammadi H, Burrascano P, Hutchins D A, Senni L, Silipigni G, Maldague X P V, Ricci M 2018 The use of pulse-compression thermography for detecting defects in paintings, NDT&E Int. 98 147–54.

[32] Cavallo G 2009 Alteration of azurite into paratacamite at the St. Alessandro Church (Lasnigo, Italy), Conservar Patrimônio 9 5-11.

[33] Sandu ICA, Afonso LU, Murta E, De Sa MH 2010 Gilding Techniques in Religious Art between East And West, 14th–18th Centuries, Int. J. Conserv. Sci., 1(1) 47-62.

Acknowledgments
Authors wishing to acknowledge assistance from restorers and art historians of LMR/02 course, specifically Dr. Mark Gittins and Dr. Paola Pogliani, that allowed us to perform the investigation of the lunette. The authors acknowledge fruitful discussions with Dr. Saverio Ricci about the history of the artwork inspected.