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# Multipurpose, dual-mode imaging in the 3–5 $\mu\text{m}$ range (MWIR) for artwork diagnostics: a systematic approach

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## Abstract

We present a multi-purpose, dual-mode imaging method in the Mid-Wavelength Infrared (MWIR) range (from 3  $\mu\text{m}$  to 5  $\mu\text{m}$ ) for a more efficient nondestructive analysis of artworks. Using a setup based on a MWIR thermal camera and multiple radiation sources, two radiometric image datasets are acquired in different acquisition modalities, the image in quasi-reflectance mode (TQR) and the thermal sequence in emission mode. Here, the advantages are: the complementarity of the information; the use of the quasi-reflectance map for calculating the emissivity map; the use of TQR map for a referentiation to the visible of the thermographic images. The concept of the method is presented, the practical feasibility is demonstrated through a custom imaging setup, the potentiality for the nondestructive analysis is shown on a notable application to cultural heritage. The method has been used as experimental tool in support of the restoration of the mural painting “Monocromo” by Leonardo da Vinci. Feedback from the operators and a comparison with some conventional diagnostic techniques is also given to underline the novelty and potentiality of the method.

*Keywords:* Thermal Quasi-Reflectography, thermography, nondestructive testing, artwork diagnostics

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## 1. Introduction

Optical methods are excellent tools in metrology and diagnostics [1, 2]. The main features of these techniques, namely the non-contact approach, the flexibility and the full-field measurement, make them very well suited

5 to artwork diagnostics. In particular, the full-field measurement was a key  
6 factor for their success and “imaging methods” are becoming more and more  
7 important, thanks to the rapid development of acquisition devices and image-  
8 processing algorithms and hardware. This impressive development led to the  
9 introduction and optimization of optical diagnostic techniques, both qualita-  
10 tive and quantitative [3, 4, 5, 6, 7, 8, 9, 10, 11], and to the wide diffusion of  
11 imaging investigative tools in the multidisciplinary field of cultural heritage,  
12 on which image-related sciences have a great impact [12, 13].

13 Infrared (IR) imaging is widely used in nondestructive analysis of paint-  
14 ings as it allows a non-contact and wide-field inspection in situ of their multi-  
15 layered features, namely the painting support, the pictorial layers, and the  
16 surface layers. Notable techniques are IR reflectography, which exploits the  
17 low scattering of the IR wavelengths up to  $2.5\ \mu\text{m}$  across the pictorial layers  
18 for imaging the features below the surface [14, 15] (e.g. preparatory draw-  
19 ings and repaintings), and IR thermography in the Long-Wavelength Infrared  
20 (LWIR) range (from  $8\ \mu\text{m}$  to  $12\ \mu\text{m}$ ), which exploits the thermal contrast at  
21 the object surface induced by heat waves propagation for retrieving infor-  
22 mation about the deep structures [16, 17] (e.g. internal defects and/or lack  
23 of homogeneity). Given the complexity of artwork’s materials and stratig-  
24 raphy, a comprehensive diagnostics usually requires a multi-technique ap-  
25 proach; thus, for example, thermography can be coupled to holography [18]  
26 or to reflectography [19] and imaging in different IR bands proved useful [20].  
27 Specific imaging methods can be tailored to extract information from the  
28 different matter-radiation interaction properties of the layers. The thermal  
29 quasi-reflectography (TQR) approach [21] takes full advantage of the surface-  
30 interacting capability of the Mid-Wavelength Infrared (MWIR) wavelengths  
31 (from  $3\ \mu\text{m}$  to  $5\ \mu\text{m}$ ) for imaging the pictorial layer in frescoes, where con-  
32 ventional IR reflectography is not effective, allowing the detection of features  
33 that are not imaged with traditional methods.

34 In this work a procedure, based on TQR, is proposed for IR diagnostics  
35 exploiting dual-mode acquisition in the MWIR range.

36 The paper is organized as follows: in Section 2 a schematic description  
37 of the proposed diagnostic procedure is given. Section 3 is devoted to the  
38 illustration of the basic features of TQR integrated in a dual-mode setup. In  
39 Section 4 the proposed procedure is treated in detail. In Section 5 the effec-  
40 tiveness of the procedure for the non-destructive analysis of mural paintings  
41 is shown in an exemplar case study: the notable restoration of the mural  
42 by Leonardo da Vinci of “Sala delle Asse” in the Sforza Castle in Milan,

43 Italy [22]. Feedback from cultural heritage operators and comparisons with  
 44 traditional diagnostic tools are also given to underline the novelty of the  
 45 method.

46 **2. Multipurpose, dual-mode MWIR imaging in a nutshell**

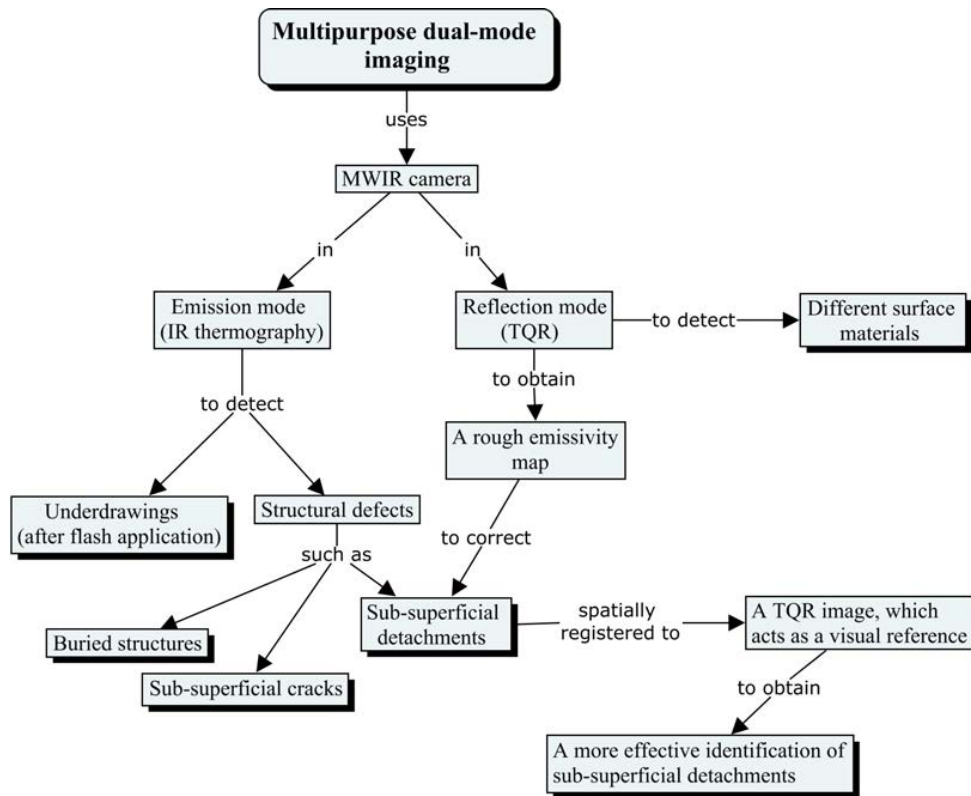


Figure 1: Schematic description of multipurpose dual-mode imaging.

47 The main concepts of the proposed dual-mode procedure are summarized  
 48 in Figure 1. Using a setup based on a thermal camera and multiple radiation  
 49 sources, two radiometric image datasets are acquired: the image in quasi-  
 50 reflectography modality and the thermal sequence in emission modality. The  
 51 dual-mode thermal stack is integrated to gain information.

52 The detection of structural defects by IR thermography is well described  
 53 in literature [16]. Regarding the possibility to discover underdrawings, IR

54 thermography after flash application [17] is not ideal: because of the low  
 55 resolution of IR cameras, a dedicated equipment results in a better choice [15,  
 56 19]. However, as all the measurements described in Figure 1 are taken by the  
 57 same recording device, images are spatially aligned and image fusion could  
 58 be easily accomplished. In the following, the focus is on a full exploitation  
 59 of TQR potentialities and on the detection of sub-superficial detachments by  
 60 IR thermography powered by TQR results.

### 61 3. The TQR imaging technique integrated in a dual-mode setup

62 The core of the TQR imaging modality is the observation that an object  
 63 with constant emissivity at room temperature has a very low emission in the  
 64 MWIR band; if the surface temperature is 293 K, it emits about 1% of its  
 65 thermal energy in the  $3\mu\text{m}$  to  $5\mu\text{m}$  range, as follows by the in-band Plank  
 66 radiant exitance. Therefore, by sending MWIR radiation, properly matched  
 67 with the thermal camera, and limiting any heating of the surface object,  
 68 the acquired signal is dominated by the reflected radiation. As shown in  
 69 [21], TQR imaging has the key feature to reveal details not detectable by  
 70 conventional techniques.



Figure 2: Dual-mode imaging setup.

71 In Figure 2, a sketch of the dual-mode acquisition setup is given. A  
 72 single thermal camera (geometry and optical configuration are fixed) is used  
 73 for recording dataset both in emission mode and in reflection mode. The  
 74 system employs multiple excitation sources. The heating sources, used for the  
 75 thermal stimulus in emission mode measurements, are two quartz tungsten  
 76 halogen lamps (1250 W). To prevent the transient cool down effect of the

77 sources, a shutter has been applied after their switch off. In the present setup,  
78 the shuttering is mandatory; in fact, the residual heat of the high temperature  
79 halogen bulb matches the spectral response of the MWIR sensor. This is of  
80 particular importance when inspecting painted surfaces that are not high in  
81 emissivity: indeed, the transient lamp cool down signal, reflected back, could  
82 dominate or affect the recorded signal in thermal inspection [23].

83 The non-heating sources, used for reflection mode measurements, are cus-  
84 tom designed as detailed in the following section.

### 85 *3.1. TQR sources*

86 The ideal TQR source should:

- 87 • exhibit a large, stable and smooth spectrum in the MWIR range;
- 88 • be capable of providing uniform irradiation over a large area, (e.g. FOV  
89 of 1 sqmt), thus enabling effective field measurements; exhibit a step-  
90 like emission, with rapid heat-up and cool-down;
- 91 • induce a heating on the target surface as small as possible. This is safe  
92 for artworks and a key issue in TQR to limit spurious contributions  
93 due to emission.

94 Since no source with these features is available in the market, it was  
95 specifically designed following [24]. The spectrum was modelled in grey-body  
96 approximation starting from the temperature and emissivity of filament, the  
97 transmission of the envelope, plus the emission of the envelope. Wien peak  
98 matches the MWIR in the range of temperature from 575 K to 975 K. This  
99 custom source was implemented starting from quartz elements with iron-  
100 chrome aluminium wire, which emit a large amount of MWIR, and polished  
101 aluminium reflectors. The elements were equipped with a thermocouple for  
102 monitoring the surface temperature. A suitable sapphire IR window was  
103 used to match MWIR band and to cut off unwanted thermal radiation. The  
104 system was controlled in power to maintain the same working temperature  
105 for the lamps. In the practice of TQR measurements, the emission of the  
106 MWIR source is then fine-tuned to the MWIR camera by optimizing the  
107 overall response on a lambertian certified reflectance target in-scene.

108 *3.2. TQR reflectance*

109 The MWIR reflectance, defined as the ratio of the incident and reflected  
110 radiant flux in the MWIR, is obtained as TQR measurement relative to a  
111 in-scene standard of known reflectance value. If  $S$  is the TQR radiometric  
112 image, the TQR reflectance is calculated point-wisely for the sampled pixel  
113  $ij$  as follows

$$R_{ij}^{\text{TQR}} = R_{\text{ref}} \frac{S_{ij}}{S_{\text{ref}}} \quad (1)$$

114 where  $R_{\text{ref}}$  is the certified reflectance of the standard (averaged in the MWIR)  
115 and  $S_{\text{ref}}$  the TQR measurement of the standard (averaged TQR image).  
116 The map  $R^{\text{TQR}}$  is the in-band diffuse reflectance in the MWIR, integrated  
117 spectrally by accounting the overall system response and angularly in the  
118 view collecting factor. Later, the issue of the quasi-reflectance approximation  
119 in the measurement is discussed.

120 The use of full-field calibrating panels is not practicable for in situ mea-  
121 surements of wall paintings; in our setup a partial-field target of 2 inches size  
122 is adopted. This may cause the spatial inhomogeneity in the surface signal  
123 to still affect the calibration of reflectance values. This issue is addressed  
124 later.

125 **4. Dual-mode MWIR imaging procedures**

126 The diagnostics is performed using the acquisition setup shown in Fig-  
127 ure 2. This setup gives, for each area, two spatially registered dataset: a  
128 MWIR image in the quasi-reflectography modality (TQR) and a thermal se-  
129 quence, in the thermography modality, after long-pulse heat stimulus. The  
130 measurement workflow can be summarized as follows:

- 131 1. TQR sources ON: record two TQR images, one with and one without  
132 a calibration target in scene;
- 133 2. TQR sources OFF; [Wait];
- 134 3. Start recording the thermal sequence;
- 135 4. Heat sources ON;
- 136 5. Heat sources OFF: shutter the heat sources and record the cooling.

137 As previously said, in a TQR measurement the recorded signal is dom-  
138 inated by the reflected radiation. As the reflectivity values depend on the  
139 materials and on the surface structure, TQR is very effective in differen-  
140 tiating surface elements [21, 23, 24]. Figure 3 shows the TQR ability to

141 detect different materials, binders and surface treatments in comparison to  
 142 IR standard reflectography. Lines were drawn with red pigment using dif-  
 143 ferent techniques. Figure 4 shows an example of TQR application to a real  
 144 artwork in situ.

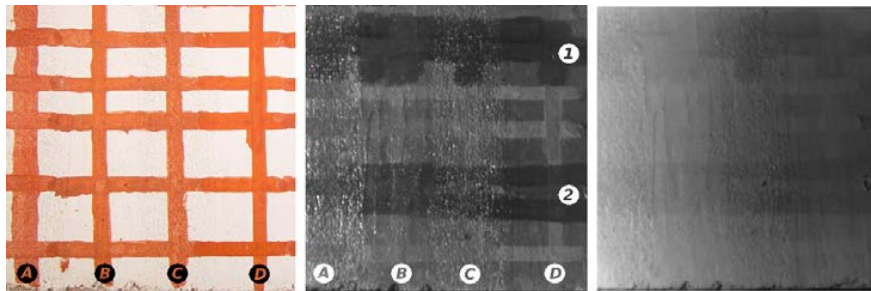


Figure 3: Fresco mock up: visible (left), TQR (center), IR (from  $1.2\mu\text{m}$  to  $2.5\mu\text{m}$ ) re-  
 flectography (right). Lines were drawn with iron oxide pigments red and yellow ochre  
 (color index PR 101 and PY 42) and different techniques. In columns: fresco (A); secco  
 with no binder in smooth (B) and rough (C) surface; secco with limewash (D). In rows:  
 different protective layers; vinyl coat (1) and rabbit-skin glue (2) have low MWIR re-  
 flectance. TQR is very sensitive to surface materials and roughness and differentiates  
 pigment-binder-protective layers where IR reflectography is not effective.

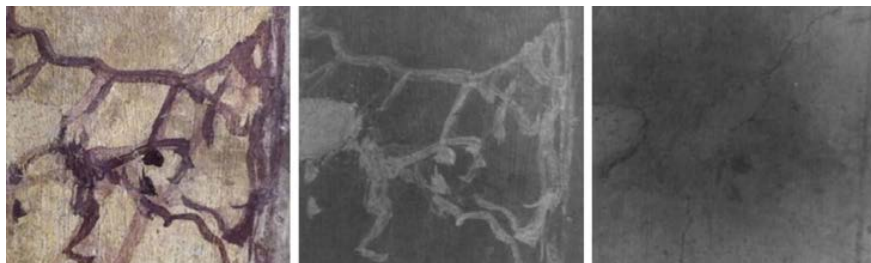


Figure 4: Detail of a 16th century Venetian fresco: visible (left), TQR (center), IR (from  
 $1.2\mu\text{m}$  to  $2.5\mu\text{m}$ ) reflectography (right). TQR is capable to map pigments in ancient  
 frescoes not detected by IR reflectography. The pigment with high TQR reflectance is  
 iron oxide based, likely hematite.

#### 145 4.1. TQR-based emissivity correction

146 The evaluation of the emissivity parameter is an important stage in IR  
 147 thermography and it is a particularly critical issue when the surface is het-  
 148 erogeneous. Common methods are based on the use of reference emissivities



149 (e.g. stickers, in thermal equilibrium with the surface) or on reference tem-  
150 peratures (e.g. contact measurements on the object). The TQR technique  
151 provides a noninvasive and non-contact alternative method to solve the emis-  
152 sivity problem in artwork diagnostics.

153 We assume the grey body approximation is valid, as in paintings diagnos-  
154 tics we usually deal with nonmetallic materials. Dependencies of emissivity  
155 from temperature range, wavelength, and angle are not relevant in the TQR  
156 setup. In our case, major parameters affecting the emissivity are the kind  
157 of material itself and the surface structure at micro-roughness level. Con-  
158 sidering that the MWIR wavelengths do not penetrate painting layers, i.e.  
159 that surface reflectivity can be given as reflectance, and taking into account  
160 the Kirchhoff's law and energy conservation for the incident radiation on an  
161 opaque body, we obtain an approximate estimation of the surface emissivity  
162  $\varepsilon$ , calculated point-wisely for the sampled pixel, from the values of the re-  
163 flectance map measured with the quasi-reflectography technique (Equation  
164 (1))

$$\varepsilon_{ij} = 1 - R_{ij}^{\text{TQR}}. \quad (2)$$

165 The Equation (2) is valid for an opaque surface under grey body approxima-  
166 tion. An example of the emissivity correction based on TQR is reported in  
167 Section 5. The TQR and the thermography images are affected by kind of  
168 aberrations that lead to different spatial resolutions, i.e the thermographic  
169 image is more blurred than TQR due to the features of thermal diffusion.  
170 This issue is taken into account by proper filtering the TQR image before  
171 calculating the emissivity correction map in Equation (2).

#### 172 4.2. TQR registration to visible orthophoto

173 The registration of multiple TQR images onto a visible reference or-  
174 thophoto is another crucial stage. Indeed, when large portions of frescoes  
175 are under restoration, a comprehensive high resolution map of emissivities  
176 overlapped to the visible fresco would increase the quality of the analysis per-  
177 formed by restorers, allowing a multi-modal inspection of different regions far  
178 apart. Moreover, the benefits of a registered multi-modal dataset onto a refer-  
179 ence orthophoto are not limited to the present days: future inspections  
180 with different techniques will also benefit of an aligned emissivity map.

181 Unfortunately, the imperfect positioning of the camera in front of the  
182 wall, due to space limitation of the environment, the need of using a mosaic  
183 of images, the different spatial resolution between the visible orthophoto and

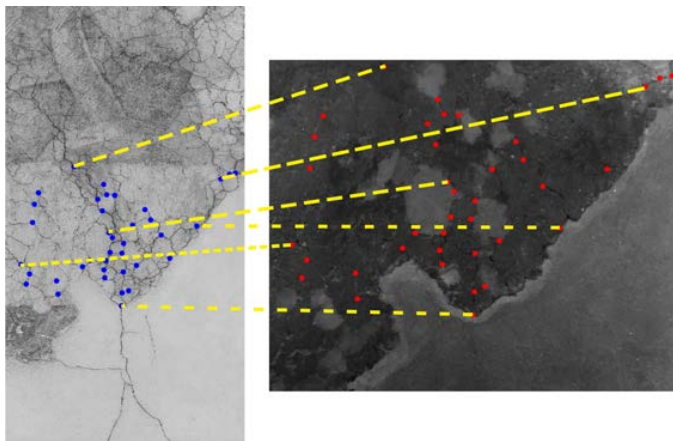


Figure 5: Registration of TQR frame onto orthophoto (and viceversa). In red the control points in TQR domain; in blue the control points in the orthophoto domain. The dashed yellow lines show the match between red and blue points.

184 TQR images, and the lack of control points helping the dual-mode regis-  
 185 tration, makes the projection problem challenging. However, some surface  
 186 features (craquelures, stucco works, etc ...) are still recognizable in both  
 187 visible and TQR images and manual identification of craquelures-like defects  
 188 can be used to drive the projective geometric transformation.

189 A procedure in Matlab, based on routines of the *Image Processing Tool-*  
 190 *box*, was adopted: control points were first selected via the *Control Point Se-*  
 191 *lection Tool cpselect.m*; then, the projective transformation was computed  
 192 via the routine *fitgeotrans.m*, to estimate the transformation mapping the  
 193 **moving** points (in TQR domain) onto the **fixed** points (in orthophoto do-  
 194 main), respectively the red and blue points in Figure 5. The only requirement  
 195 for a correct estimate of the transformation map is a well-distributed covering  
 196 of control points in the TQR frame.

197 Once that the transformation map is obtained, the inverse problem can  
 198 be solved, i.e. given a rectangular frame in the TQR domain, a rectangular  
 199 frame in the orthophoto domain can be obtained, in order to register the  
 200 region of interest from the orthophoto onto the TQR frame.

201 In an ideal dual-mode imaging experiment, the transformation mapping  
 202 TQR image onto the visible orthophoto will drive the same geometric regis-  
 203 tration of thermal images sampled at the same position in front of the wall  
 204 onto the visible orthophoto. However, an automatic dual-mode craquelure-

205 based registration process is left for future research.

### 206 4.3. Correction of TQR mosaic light inhomogeneities

207 The registered TQR mosaic could still suffer from nonuniform irradiance  
 208 because of the in situ setup and the limited working space (e.g. the use of  
 209 the partial field target and its incorrect displacement, the inaccurate position  
 210 of lamps, the change of the environmental temperature conditions). In such  
 211 situations, a post-processing intensity correction step would be desirable: a  
 212 suitable procedure is based on a drift-diffusion filter [25, 26] able to remove  
 213 constant shadows in images. Given a positive image  $f$  and a drift vector field  
 214 of the type  $\mathbf{d} = \nabla \log f$ , the steady state  $u$  is given by the time evolution of  
 215 the following linear equation

$$\begin{cases} \partial_t u = \Delta u - \operatorname{div}(\mathbf{d}u) \\ u(x, 0) = f(x) \\ \langle \nabla u - \mathbf{d}u, \mathbf{n} \rangle = 0 \end{cases} \quad (3)$$

216 where  $\langle \cdot, \cdot \rangle$  is the Euclidean scalar product and  $\mathbf{n}$  is the outer normal vector  
 217 on the boundary. Equation (3) has been named *osmosis filter*: indeed, when  
 218 the drift vector field vanishes on *shadow edges*, then steady state solutions are  
 219 shadowless, texture preserving, images. To sum up, such filter acts as a real  
 220 osmotic process, balancing different concentrations (light inhomogeneities)  
 221 through a semi-permeable membrane (shadow edges).

In our case, osmosis filter (3) is applied to a TQR mosaic made by many independent TQR samples, each one assumed affected by a constant light inhomogeneity and where TQR frame borders act as shadow edges. However, TQR mosaic of large size would slow down the post-processing so efficient numerical solver are needed for a fast in situ analysis [27]. The procedure adopted is based on Alternating Directional Implicit (ADI) splitting methods to split the finite difference matrix  $\mathbf{A}$  of Equation (3) along the spatial directions, which are solved separately. Following [28], Additive Operator Splitting (AOS) and Multiplicative Operator Splitting (MOS) In detail, for every iteration  $k$  and time-step  $\tau$  the AOS and MOS splitting methods read

as

$$\mathbf{u}^{k+1} = \frac{1}{2} \sum_{n=1}^2 (\mathbf{I} - 2\tau \mathbf{A}_n)^{-1} \mathbf{u}^k, \quad (\text{AOS})$$

$$\mathbf{u}^{k+1} = \prod_{n=1}^2 (\mathbf{I} - \tau \mathbf{A}_n)^{-1} \mathbf{u}^k, \quad (\text{MOS})$$

222 which are stable for any  $\tau$  and first-accurate in time. Also, standard proper-  
 223 ties of the continuous osmosis equations hold for the discretized model: the  
 224 Average Gray Value Conservation (AVG), the preservation of the positivity  
 225 and the convergence to a unique steady state. The importance of the AVG  
 226 preservation in real applications is emphasised since no information is lost  
 227 when osmosis filter is applied iteratively.

#### 228 4.4. The quasi-reflectography measurement

229 The systematic contribution of the surface thermal emission in the quasi-  
 230 reflectography approximation is analysed in order to evaluate the accuracy  
 231 of the measured reflectance  $R^{\text{TQR}}$ . For a given object temperature  $T_{\text{obj}}$  the  
 232 influence of the radiation emitted by a surface element increases when its  
 233 reflectance  $R$  decreases.

234 For the short measurement distance typical of the TQR setup ( $\sim 1$  m) the  
 235 attenuation due to ambient atmosphere is negligible; the radiometric chain  
 236 for TQR imaging that gives the radiation power incident on the detector  $\Phi_{\text{det}}$   
 237 in terms of the contributions reflected and emitted by the object is

$$\Phi_{\text{det}} = R\Phi_{\text{src}} + (1 - R)\Phi^{\text{bb}}(T_{\text{obj}}) \quad (4)$$

238 with  $\Phi_{\text{src}}$  the radiant power of the source incident on the surface and  $\Phi^{\text{bb}}(T_{\text{obj}})$   
 239 the blackbody radiant power at object temperature. All the contributions  
 240 include the dependences on the acquisition setup geometry and camera prop-  
 241 erties, which are fixed during the measurements; the detector signal is then  
 242 integrated over the wavelength in the MWIR band, accounting for the spec-  
 243 tral dependence of the specific system response and source. The calibrated  
 244 reflectance can be obtained after measuring the detector response on the refer-  
 245 ence reflectance target; supposing the target and the object at the same  
 246 temperature (i.e., avoiding any heating by the TQR source) and translating  
 247 in signal of the detector  $S$ , the actual point-wise reflectance is given by the

248 following

$$R_{ij} = R_{\text{ref}} \frac{S_{ij} - S_{ij}^{\text{bb}}(T_{\text{obj}})}{S_{\text{ref}} - S_{ij}^{\text{bb}}(T_{\text{obj}})}. \quad (5)$$

249 In the quasi-reflectance measurement the relative signal “error” due to  
 250 the emitted radiation, in regard to an ideal reflectance measurement, is

$$\frac{\Delta\Phi}{\Phi} = \frac{\Phi_{\text{det}} - R\Phi_{\text{src}}}{R\Phi_{\text{src}}} = \frac{1 - R}{R} \frac{\Phi^{\text{bb}}(T_{\text{obj}})}{\Phi_{\text{src}}} \quad (6)$$

251 which provides the accuracy of the TQR-measured reflectance. For a black-  
 252 body source picked at  $4\ \mu\text{m}$  ( $T = 724\ \text{K}$ ) and range of temperatures safe for  
 253 the artwork, we have for the MWIR in-band quantity  $\Phi_{\text{obj}}^{\text{bb}}/\Phi_{\text{src}} \sim 10^{-3}$  (Figure  
 254 6). The fraction of reflected radiation, i.e. the first term in Equation (4), with  
 255 regard to the total one received by the detector is depicted in Figure 7. The  
 256 graphic shows that in the range of working temperature the measurement  
 257 is performed in a very good reflectance approximation for different values of  
 258 the object reflectance (nonmetallic materials) and that such approximation  
 259 is stable under small variation of the object temperature.

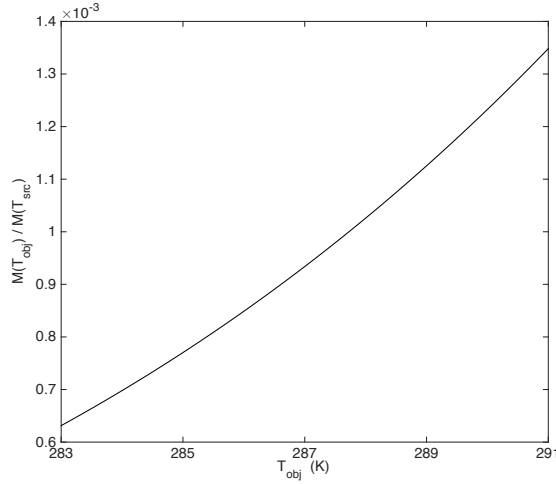


Figure 6: The quantity  $\Phi_{\text{obj}}^{\text{bb}}/\Phi_{\text{src}}$  computed as ratio of in-band blackbody exitance of different object temperatures and a MWIR source nominally picked at  $4\ \mu\text{m}$  ( $T = 724\ \text{K}$ ). At a room temperature ( $T_{\text{obj}} = 293\ \text{K}$ )  $\Phi_{\text{obj}}^{\text{bb}}/\Phi_{\text{src}} = 9.3 \times 10^{-4}$ .

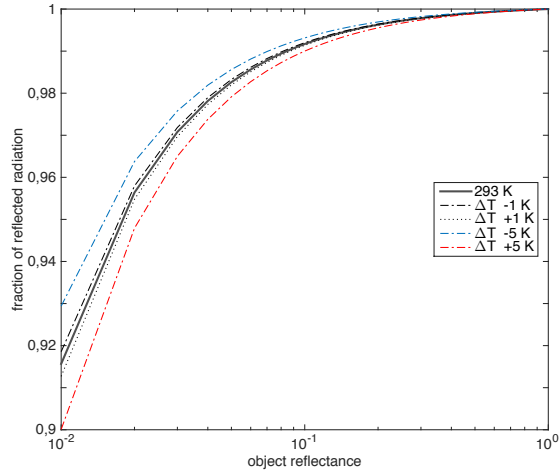


Figure 7: Fraction of the radiation reflected by the object in regard to total incident on the detector for different object reflectance at different object temperatures (semilog plot). Small variations of 1 degree that may occur during in situ measurement are not critical.

## 260 5. Experimental results and discussion

261 Dual-mode imaging in the MWIR was applied to support the restoration  
 262 intervention of the mural painting “Monocromo” by Leonardo da Vinci (Fig-  
 263 ure 8) in the period 2015-2016, with regard to the treatment of the surface  
 264 materials and the consolidation of the subsurface detaches [22]. Spatial res-  
 265 olution, full-field screening, and referentiation to the visible were asked by  
 266 the operators as mandatory factors for the effectiveness of the analysis.

267 The acquisition geometry was setup to obtain a sub-millimetric spatial  
 268 resolution ( $\sim 0.5$  mm).

269 Dual-mode imaging was performed by FLIR X6540sc camera, equipped  
 270 with a cooled InSb detector ( $640 \times 512$  array,  $15 \mu\text{m}$  pixel pitch) with MWIR  
 271 sensitivity and a NEDT of 20 mK. The lens was a 25mm with a FOV of  $22^\circ \times$   
 272  $17^\circ$ . The native ResearchIR Max 4 software was used in the recording phase.  
 273 Beside high sensitivity and accuracy, the camera enables full access to the  
 274 radiometric data at detector level. The reference standard for the calibration  
 275 of the TQR reflectance was an Infragold diffuse target by Labsphere of 2  
 276 inches size. The thermal sequence was acquired at 120 Hz after a 120 s long-  
 277 pulse heat stimulus.



Figure 8: Dual-mode measurement on Leonardo mural painting “Monocromo”, Sforza Castle, Milan.

278 The effectiveness of TQR imaging for the surface deterioration study is  
 279 shown in Figure 9. In this case, abundant crystallized salts (mainly sulphate  
 280 and nitrate salts) are detected thanks to the high MWIR reflectance. This  
 281 clear map of the salt patinas was not provided by the more traditional imag-  
 282 ing technique based on UV light. Surface treatments from past intervention  
 283 are well detected. Figure 10 reports an example of dual-mode imaging in  
 284 the MWIR showing the complementarity of the TQR and thermographic  
 285 measurement. In this case, the TQR detects the different surface patches  
 286 (stucco), while the thermography discriminates the presence of subsurface  
 287 consolidant (cement) from the cooling behaviour.

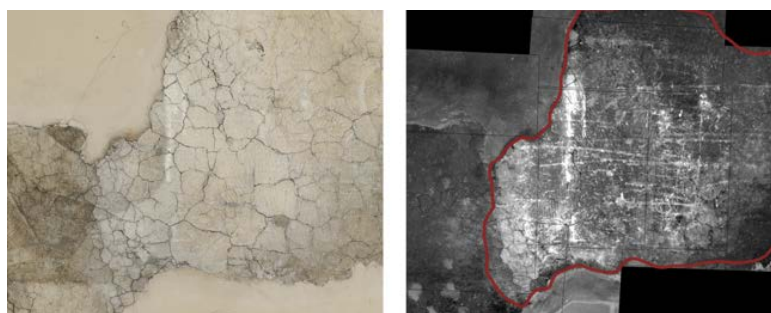


Figure 9: A fresco detail; visible and TQR image (mosaic), mapping the surface salt decay. The region with the crystallization is outlined in red.



Figure 10: Example of dual-mode imaging for diagnostics in a fresco detail: visible (left); TQR measurement (center); alpha fusion image between TQR and thermogram after the lamps switch-off (right).

288      Figure 11 depicts the TQR workflow for a frame acquired on the Leonardo  
 289 painting according to Sections 3 and 4. The result is a spatially aligned  
 290 dataset with the TQR calibrated reflectance, the emissivity map, and the  
 291 visibile image of the corresponding region. Figure 12 shows as result the mo-  
 292 saic of emissivity obtained from three TQR frames, computed by applying  
 293 the image osmosis filter with AOS splitting method. As shown in the results  
 294 in Figure 13, the mosaic of the thermographic frames is obtained from the  
 295 TQR allowing to solve in precise way the crucial issue of referencing thermog-  
 296 raphy to the visible. In this specific work, the dual-mode MWIR technique  
 297 has allowed to produce a considerably large map of the Leonardo wall with  
 298 surface and subsurface features referenced at sub-millimetric accuracy that  
 299 represented a valuable tool for the operators during the intervention.

## 300 6. Conclusions

301      This paper was devoted to a systematic approach of a multipurpose, dual-  
 302 mode imaging in the MWIR ( $3\mu\text{m}$  to  $5\mu\text{m}$ ) range, in which the features of  
 303 IR thermography enrich the powerfulness of thermal quasi-reflectography  
 304 (TQR).

305      The main advantages of the proposed procedure are:

- 306      • the acquisition of complementary surface and sub-surface information  
 307          with an imaging setup based on a single camera;
- 308      • the use of TQR map for registering the thermographic images, which  
 309          are “blurred” due to heat diffusion, onto the visible images;





Figure 11: TQR workflow for the single frame: TQR raw radiometric image (top-left); TQR golden target in-scene (top-middle); target segmentation (top-right). TQR calibrated reflectance (bottom-left); emissivity map obtained from TQR (bottom-middle); visible orthophoto (bottom-right) spatially aligned to TQR. For visualization purposes only, the colormap has been fixed to the data range without the target in figure top-left and top-middle.



Figure 12: From left to right: mosaic of three emissivity frames; light corrected emissivity mosaic following [28]; visible orthophoto.

- 310 • the possible use of the quasi-reflectance map, acquired by the TQR
- 311 modality, for a simple yet effective emissivity correction in support of
- 312 the thermographic analysis.

313 TQR performance was enhanced by designing a custom source and by

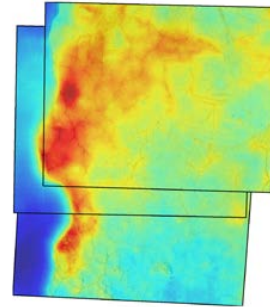


Figure 13: Example of TQR-thermal integration for defect detection on mosaic in Figure 12: TQR reflectance mosaic (left); radiometric thermal measurement after switching off the lamps (center); alphaColor image between radiometric thermal measurement and visible orthophoto (right) showing the precise localization of the detachment. Left and central mosaic have been post-processed as in [28] for light inhomogeneity correction.

314 defining suitable measurement procedures.

315 Dual-mode imaging was validated on a notable case study: the restoration  
 316 of the mural painting by Leonardo da Vinci of “Sala delle Asse” in the Sforza  
 317 Castle in Milan, Italy. The method was capable to provide high resolution  
 318 maps of the painting surface as well as maps of the sub-surface defects refer-  
 319 entiated to the visible by the TQR investigation. The results were validated  
 320 in situ by expert restorers, which confirmed the uniqueness and importance  
 321 of the proposed diagnostic method.

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### 330 Data Statement

331 The data leading to this publication are sensitive; restricted access is sub-  
 332 jected to the approval of Castello Sforzesco’s administration “Soprintendenza  
 333 Castello, Musei Archeologici e Musei Storici”, Milan.

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