

Chapter 3

Multispectral IR Reflectography for Painting Analysis



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1 InfraRed Reflectography (IRR)

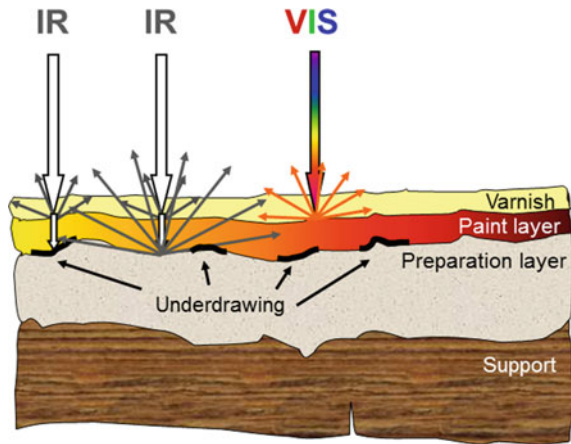
1.1 Fundamentals of IRR

InfraRed Reflectography (IRR) is a well-established diagnostic technique for the analysis of paintings that consists in irradiating the painting with an IR source and in detecting the back-scattered radiation in a wide spectral band with a suitable device [1, 2]. Thanks to the transparency properties of most pigments to the infrared radiation, it allows the visualization of features underneath the painting's surface (Fig. 1), such as the underdrawing (a preliminary sketch made by the painter on a preparation ground, prior to painting), the *pentimenti* (an underlying image in a painting providing evidence of revision by the artist), subsequent retouchings or repaintings (generally speaking, foreign materials added at a later stage for modifying the artwork's painting or structure), restoration intervention (the process of re-establishing the artwork legibility through selective removal of patina, consolidation of ancient materials and eventual reconstruction of missing pieces). The visibility of the underlying features depends on the paint layers' thickness and chemical composition, as well as on the chemical composition of the materials that form both the underdrawing and the preparation. If the preparation layer is characterized by a high reflectivity in the IR spectral range (a typical case is chalk-and-gypsum-based preparation) and the underdrawing is carbon-based, the visibility of the preparatory sketch is evident, whereas it decreases in case of iron-gallic inks or sanguine. Paints' transparency generally increases with the wavelength of the radiation used, reaching its maximum for most pigments around 1.7 micron.

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Fig. 1 Interaction scheme of visible and infrared radiation with a painting, sketched as a multilayer system



1.2 Traditional Devices for IRR

IR reflectography dates back to the '60s, and is based upon the fundamental work of Van Asperen de Boer [1, 2], who laid the theoretical and experimental bases for this technique, and introduced the use of PbS Vidicon cameras. Traditionally performed by means of image detectors like CCD or Vidicon cameras [3–7], IR reflectography has evolved with the first scanning device in the '90s [8]. The main advantages of imaging sensors are their ease of use, portability and fastness. On the other hand, output images are affected by geometrical distortion, due to the camera lens, requiring post processing. A rigorous calibration procedure is also necessary, to correct the non-uniform surface lighting [9, 10]. Vidicon has a good spectral sensitivity (up to 2.2 micron for PbO–PbS cameras) but its scarce light sensitivity demands for an intense illumination, which can induce a detrimental warming of the painting surface. Moreover, images are characterized by a very poor contrast due to the limited number (some tens) of grey levels, and are brighter in the centre and darker on the borders due to the non-uniform sensitivity of the detector's area. To obtain a high spatial resolution, the measured area must be very small (e.g. $10 \times 10 \text{ cm}^2$ to have a resolution of 4 pixel/mm, needed to resolve the finest under-drawing lines). The reproduction of a large panel requires, thus, the collection of several images (more than 100 for 1 m^2) that are successively combined in a mosaic. Because of the above mentioned intrinsic characteristics, the resulting reflectogram generally appears tiled, in many cases even after equalization [11]. The use of low-cost CCD detectors (Si based) does not meaningfully improve the quality of the reflectogram: they have higher intensity resolution and more uniform response than Vidicon. Nevertheless, they have a sensitivity limited to 1.1 micron, as a consequence the acquired images have a very scarce informative content. Special highly-priced CCD devices (InGaAs or PtSi arrays) can strongly improve the visibility of the underlying features, due to the extended spectral coverage.

However, a great number of images must still be collected to reproduce a large painting with high spatial resolution. The mosaic realisation requests long calibration and clean-up operation of the acquired images, owing to the non-uniform lighting condition and the misalignment/distortion of collected images.

1.3 Scanning Device for IRR

High-resolution scanning reflectography was developed at the National Institute of Optics (INO, the actual INO-CNR), in Florence, at the beginning of the '90s. At that time, an innovative scanning device for imaging in the infrared spectral range was built, able to acquire a reflectogram with spectral sensitivity and tonal dynamics up-to-now unobtainable by any of the techniques traditionally used for IRR [8]. Besides that, single point detection together with simultaneous motion of in-built light sources, minimizes surface heating and bypasses the problem of uniform illumination. In the late '90s, its performances were improved and the scanner could simultaneously acquire the IR reflectogram and three R, G, B images that properly combined produced the colour image of a painting, which can be perfectly superimposed one on the other [12]. The point-by-point comparison between the reflectogram and the colour image of the painting, along with digital processing of the recorded images, such as IR false colour imaging [13], opened new possibilities in the IRR analysis.

2 Scanning Multispectral InfraRed Reflectography (SMIRR)

2.1 Concepts of SMIRR

Multispectral imaging is widely used in remote sensing applications, such as satellite or radar imaging, mainly for agriculture, forestry and weather mapping. It has recently gained importance in the field of artworks' conservation, in particular in the IR spectral region, having proved useful in analysing ancient paintings because of the varied reflectance of pigments over this spectral region.

Traditional reflectography, performed by acquiring the IR image in a single large band (wide-band modality) corresponding to the spectral range of the device, is improved by the multiband option, which allows the choice of the most effective wavelength for the specific case. Multispectral imaging in the IR allows the simultaneous collection of both spectral and spatial information enlarging, thus, the perspectives of IRR to new applications for the study of artists' materials. It consists in irradiating the painting surface with a broadband source and collecting the backscattered radiation within narrow spectral IR bands [14, 15].

2.2 Current Devices for Multispectral IRR

A variety of IR multispectral devices have been implemented, based on different imaging detectors with either filtering or dispersing element (Fig. 2) for waveband selection [16–21]. The output is a set of monochromatic images stacked as a sequence of acquisitions.

Systems based on imaging sensor suffer from pixel-to-pixel biases, lens distortion, non-uniform illumination and require proper calibration/correction procedures. Detector size limits the spatial resolution because of mosaicking. As previously said, multispectral devices currently used in conservation have limited spectral range, mainly due to the high cost of the available technology to cover an extended IR spectral range. Moreover, such systems are affected by systematic errors such as spectral channels blurring, chromatic aberration due to the objective lens, which affects the reliability of spectral data and require optical calibration. When filters are tuned by mechanical devices, e.g. rotating wheels, the spectral image set is difficult to register [22–24].

2.3 Scanner for Multispectral IRR

The upgrade of the wide-band scanner to the multispectral modality was carried out by the INO's Cultural Heritage Group in five years of the European project EuArtech (Access, Research and Technology for the Conservation of the European Cultural Heritage, 2004–2009) [25]. This scanning device (Fig. 3) was revolutionary in the field of infrared reflectography because it allowed to simultaneously acquire a set of 14 high resolution images at different wavelengths in the spectral IR region from 800 to 2300 nm [26–29]. Over such an extended spectral range chromatic aberration causes defocussing among the spectral images: a catoptric lens was then used to obtain a set of monochromatic images perfectly focused and superimposing. The instrument core is still single point detection performed by a purposely-designed fiber bundle whose ends are properly filtered. In the recent years, the scanner underwent further improvements consisting in the addition of

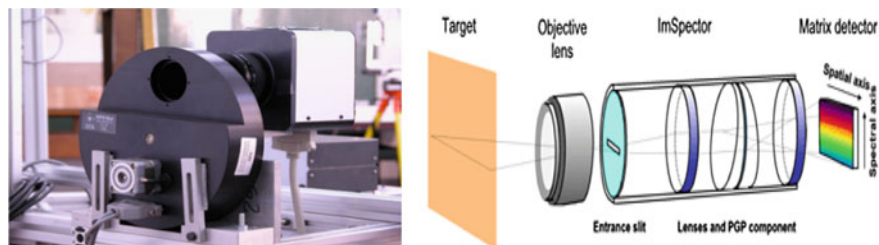


Fig. 2 Multispectral device based on (left) filter wheel and (right) dispersive system

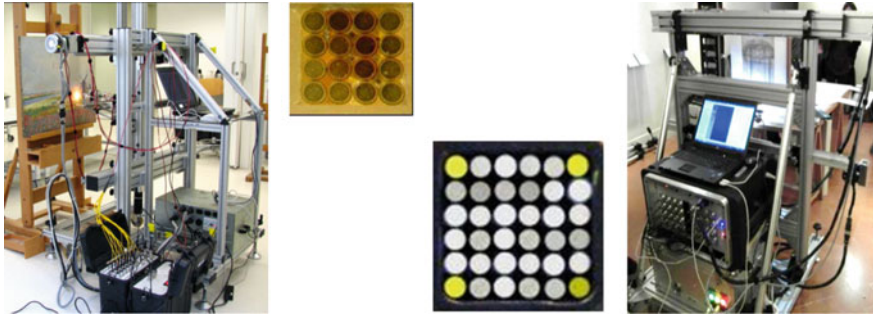


Fig. 3 Multispectral scanner for IR reflectography: version with (left) 16-fiber and (right) 36-fiber bundle; (middle) corresponding bundle sections, as seen at the optical microscope

both an autofocus system to keep the optical head at focus while scanning, and the R, G, B channels to provide the colour image perfectly superimposing with the reflectograms. In its last version [30], the instrument acquires 16 bands in the visible and 16 bands in the IR spectral range, this latter extended up to 2500 nm.

An XY scanning system moves an optical head that both illuminates the painting and collects the backscattered radiation carried to the detectors by means of a fiber bundle. The lighting system is composed of two low-voltage halogen lamps and two white LEDs (5° beam divergence, according to CIE suggestions for the 45°/0° configuration) and the irradiated area is about 5 cm² at the working distance of about 12 cm. The collecting optics is a catoptric system (depending on the scanner version, made of two faced spherical or two off-axis parabolic mirrors) working in a 2f–2f configuration to have a unitary magnification factor. The radiation scattered from the measured point on the painting is imaged on the fiber bundle, made of 16 or 36 fibers depending on the instrument version, assembled in square array (core/clad diameter 200/250 μm). The detection unit is composed of 3 Si and 13 InGaAs photodiodes (16-fiber bundle) or 19 Si and 13 InGaAs photodiodes (36-fiber bundle). Each detector is equipped with an interferential filter whose FWHM ranges from 50 to 100 micron in the IR and from 20 to 30 in the VIS range. The device allows continuous measurement of an area up to 1 m² with a sampling step of 250 micron, lasting about 3 h at the maximum acquisition rate of 2 kHz. In the acquisition phase our scanner is time-consuming compared with devices based on imaging sensors, but this time loss is recovered a posteriori because image data do not require any post-processing, being aberration-free and hardware registered.

Channels equalization was performed with certified standards with known reflectance. Raw 16-bit IR images are reconstructed point-by-point by associating to each pixel on the image plane the spectral reflectance factor $R(\lambda)$. The latter is computed based on both the intensity reflected by the sampled point on the painting surface I_{sample} and the in-scene reflectance standard I_{ref} with the formula:

$$R(\lambda) = \rho(\lambda) \frac{I_{sample} - I_{dark}}{I_{ref} - I_{dark}} \quad (1)$$

where $\rho(\lambda)$ is the certified value for the reflectance standard, I_{dark} is an image with closed optics and I_{ref} is acquired at the beginning of each scanning session.

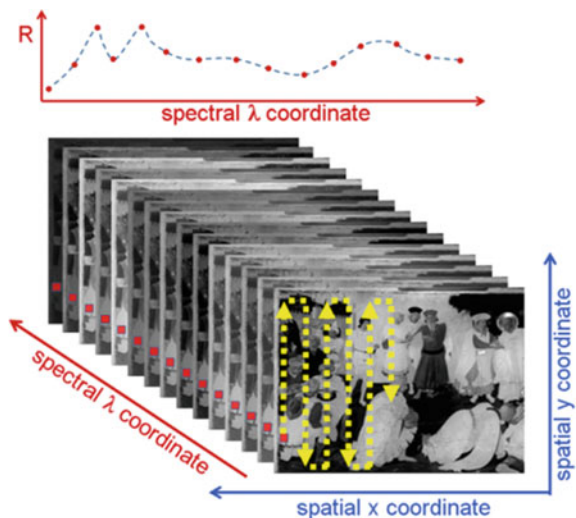
3 Applications and Results

3.1 Multispectral Data Processing

The stack of spectral images provides information in both the spectral and spatial domain (Fig. 4): the reflectance at each point of the multispectral image cube provides the spectrum of the pixel (IR spectrometry), whereas the slices correspond to images at different wavelength (multi-IR reflectography).

The monochromatic images can be analysed separately, scrolling the λ -planes to study the transparency properties of the different coloured areas, as well as jointly, applying mathematical algorithms to enhance the visualization of features varying with wavelength. In particular, pairs of single-wavelength images were jointly processed to compute pixel-by-pixel subtraction and ratio to highlight changes in the reflectance of pigments from one wavelength to another. Standard IR false colour as well as colour composite images were elaborated with either single band or difference/ratio images in both trichromatic RGB and tetra-chromatic CMYK spaces to highlight the presence of retouching/integrations and to visualize the information from more than one channel simultaneously. Statistical methods such

Fig. 4 Scheme of spectral and spatial data output from multispectral measurement



as Principal Component Analysis (PCA) and Non-negative Matrix Factorization (NMF) were also applied either to concentrate significant features into a few representative images or to enhance the information content. It is worth noting that any operation with different bands is possible directly with the raw data thanks to the superimposing property and aberration-free characteristics of our images that do not require either registration or correction. This approach has proven to be easy to use as basic image processing can be performed also with commercial software. Moreover, maintaining a visual correspondence with the painting eases the interpretation of the results.

3.2 *Examples of Multispectral Applications and Analysis*

Many measurement campaigns on artworks were carried out both at the INO's Optical Metrology Laboratory hosted at the Opificio delle Pietre Dure (OPD) in Florence, one of the largest restoration facilities in Europe, and at Italian and foreign museums all over Europe. In fact, the scanner is part of the MOLAB (MOBILE LABORATORY), a facility that can be accessed by the scientific and the conservation community, after evaluation from a peer review panel, in the framework of the national E-RIHS.it [31] and IPERION CH EU-projects [32]. The results presented herein are intended to give an overview of both the applications of multispectral IR reflectography, with emphasis on the advantages over conventional reflectography, and the usefulness of the different analyses to evidence the potential of the multispectral approach.

Multispectral imaging may enable the analysis of features not detectable in the wide-band reflectography: according to the case study, it allows the choice of the most effective IR bands to enhance the presence of retouches/repaintings or, more generally, areas of painting materials different from the original. Moreover, the transparency properties of the pigments with wavelength can be analysed, together with the visibility of the drawing below them.

The potential of the multispectral approach is evidenced in Fig. 5 where the painting *Madonna with Child* by Cimabue is presented. Wide-band reflectography is compared with a few spectral images at different wavelengths. The two light spots on the Child's forehead, probably retouches, are clearly visible both in the wide-band reflectography and in the spectral images up to 1300 nm, whereas increasing wavelength beyond 1700 nm reveals details otherwise not visible such as the golden leaf that is marked out as a well-defined white area above the eye.

Depending on the case study, entering IR, i.e. increasing wavelength, can be most revealing or least revealing. The paintings in Figs. 6 and 7 are testimony of these two instances, respectively. For increasing λ , the Madonna's mantle in the painting by Giovanni di Paolo (Fig. 6) displays details not otherwise visible, whereas the *Adorazione dei pastori* by Beato Angelico (Fig. 7) shows nearly no difference.

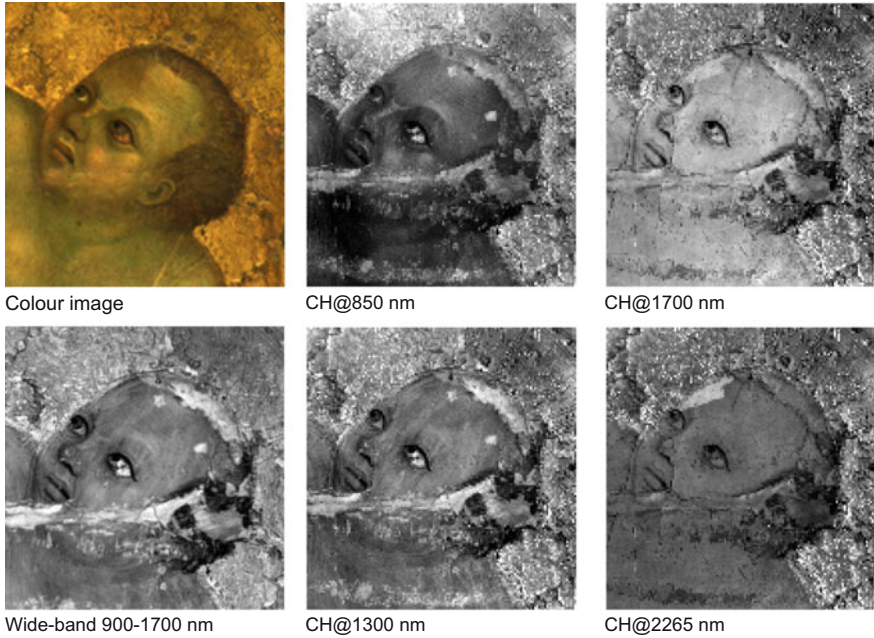


Fig. 5 *Madonna with Child* (Cimabue), detail of the Child's head. The wide-band reflectogram obtained with the very first scanner prototype is compared with the multispectral scanner's output at different wavelengths (CH@ = channel centered at)

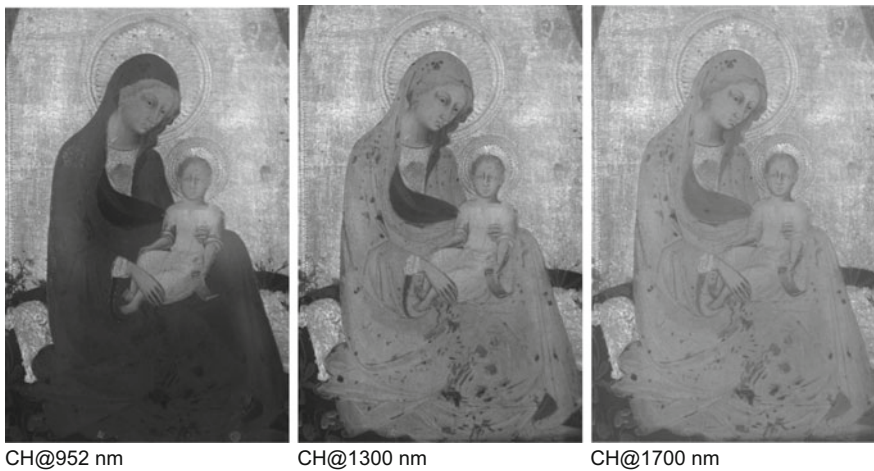


Fig. 6 Reflectograms (CH@ = channel centered at) of the *Madonna with Child* by Giovanni di Paolo, Harvard Center for Renaissance Studies, Villa I Tatti, Florence (IT)

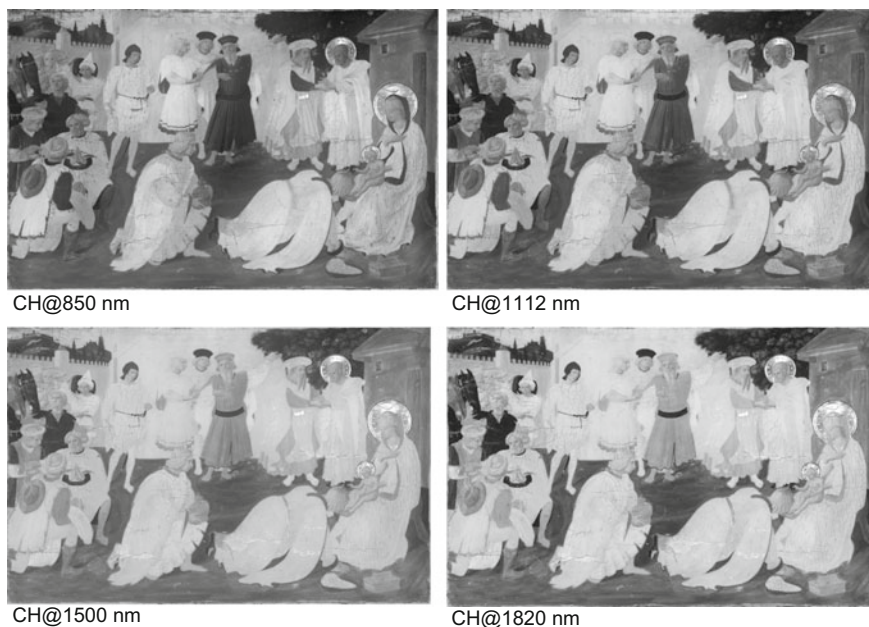


Fig. 7 Reflectograms (CH@ = channel centered at) of the Beato Angelico's *Adorazione dei pastori*, Tabernacolo dei Linaioli, Museo di San Marco, Florence (IT)

Evidence of the importance of the extended spectral range with respect to the current multispectral devices is given in Fig. 8. An architectural moulding, hidden under the dark background, becomes discernible at 1300 nm and it is clearly distinguished from 1700 nm, but the spolvero technique becomes evident at 2235 nm. None of these features would be detectable with standard devices such as CCD camera, with spectral sensitivity up to 1050–1100 nm (Fig. 9).

False colour representation with either single channels or difference/ratio images was used to differentiate areas that are then visualized in an effective way (Fig. 10).

PCA was profitably applied to a panel painting by Cosmè Tura: score images were extracted and analysed separately as well as jointly. The first score image T1 contains the same information as the wide-band reflectography. The following three score images T2, T3, T4, combined in a false colour representation, improve the detection of details as shown in Fig. 11.

As mentioned above, spectral segmentation allows the acquisition of pixel-by-pixel reflectance information that is closely related to the visual appearance of the reflectograms at the different wavelengths. In Fig. 12 an example of the study of pigment transparency is shown. In order to examine the features varying with wavelengths (pigment transparency and underdrawing visibility), the spectrum of cobalt blue, as measured with both FORS and our VIS-IR scanner, is presented together with the monochromatic images corresponding to the most representative wavelengths.

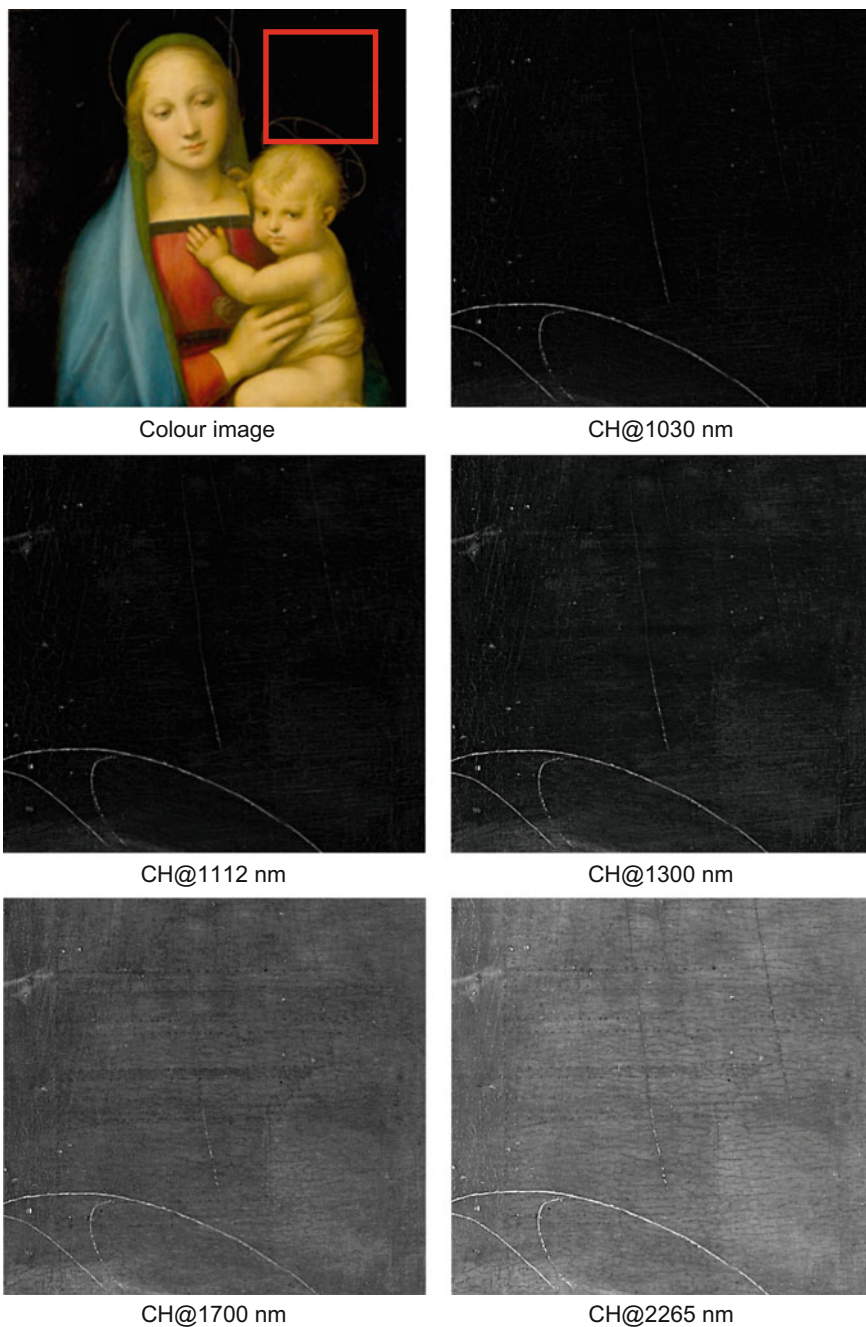


Fig. 8 Colour and reflectographic images (CH@ = channel centered at) of Raffaello's *Madonna del Granduca*, Galleria Palatina, Florence (IT)

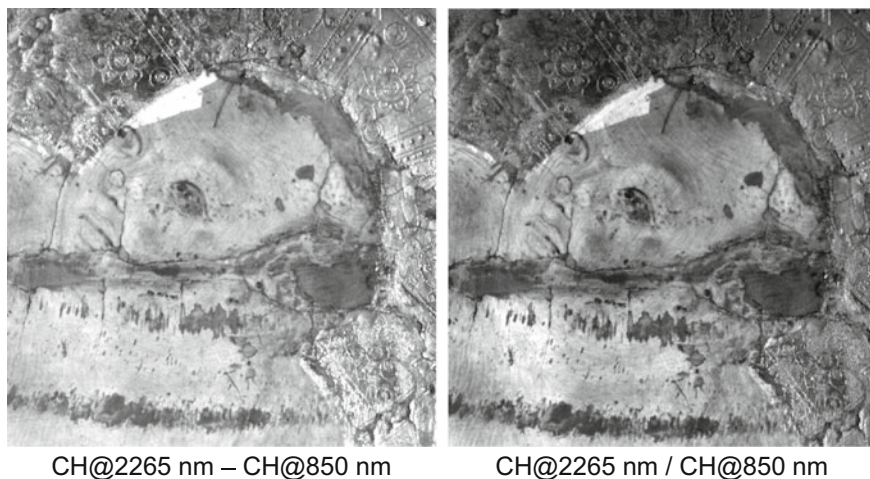


Fig. 9 Difference and ratio of the reflectographic images acquired on the *Madonna with Child* (Cimabue) painting (CH@ = channel centered at), detail of the Child's head. Florence (IT)

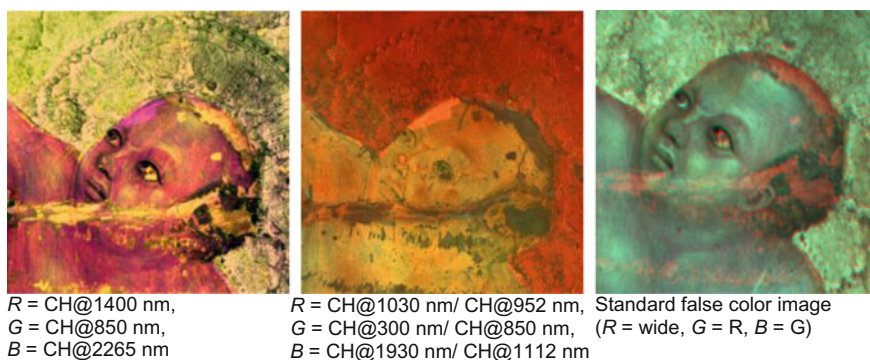


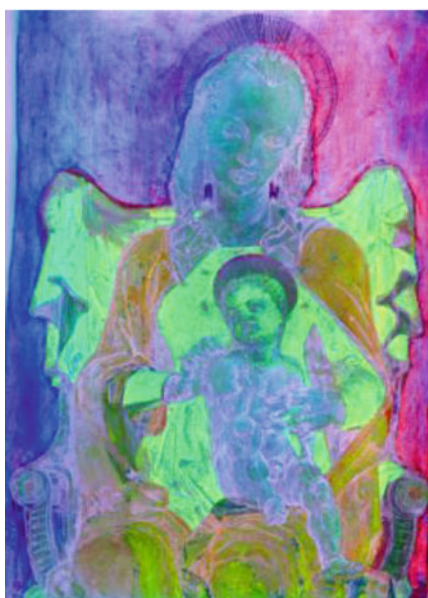
Fig. 10 Colour composite images with (left) IR bands; (middle) ratio images; (right) standard IR-false colour image of a detail of the Child's head (*Madonna with Child* by Cimabue, Florence, IT). (CH@ = channel centered at)



Wide-band reflectography



Score image T1



Colour composite image
 $R = T2, G = T3, B = T4$



Standard false colour image
 $R = \text{IR wide}, G = R, B = G$

Fig. 11 Virgin with child by Cosmè Tura, Galleria dell'Accademia Carrara, Bergamo

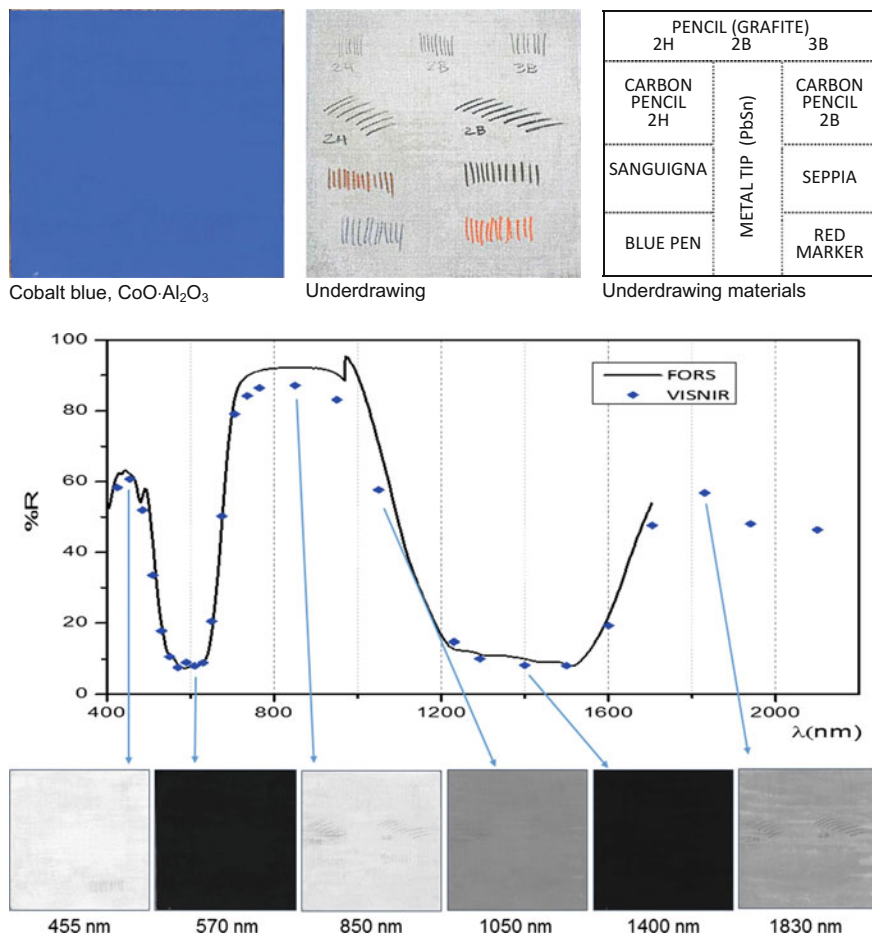


Fig. 12 (top) Sample of cobalt blue laid on underdrawings of different materials, (middle) corresponding spectrum as measured by multispectral VIS-IR scanner (blue diamonds) and FORS (black full line) and (bottom) related spectral images

4 Conclusions

Scanning multispectral infrared reflectography is presented herein. The output of the technology is a stack of monochromatic images, one for each selected wavelength, which can be analysed separately as well as jointly. Advantages over the traditional wide-band reflectography are presented by showing a few examples of applications on ancient paintings. The innovative multispectral scanner developed by the Cultural Heritage Group of INO-CNR allows for a straightforward processing of the spectral planes, without any image correction.

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