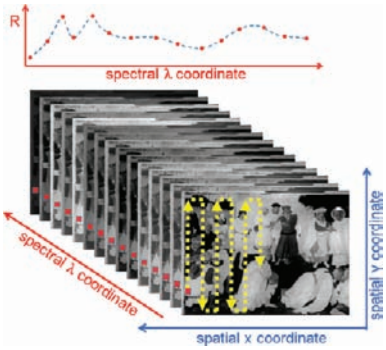
ACCOUNTS
of chemical research

Scanning Multispectral IR Reflectography SMIRR: An Advanced Tool for Art Diagnostics

CLAUDIA DAFFARA,* ENRICO PAMPALONI, LUCA PEZZATI,
MARCO BARUCCI, AND RAFFAELLA FONTANA
Istituto Nazionale di Ottica (CNR-INO), Largo E. Fermi 6, 50125 Florence, Italy

RECEIVED ON OCTOBER 30, 2009

CONSPECTUS



Spectral imaging technology, widely used in remote sensing applications, such as satellite or radar imaging, has recently gained importance in the field of artwork conservation. In particular, multispectral imaging in the near-infrared region (NIR) has proved useful in analyzing ancient paintings because of the transparency of most pigments and their varied reflectance changes over this spectral region. A variety of systems, with different detectors and filtering or dispersing technologies, have been implemented. Despite the recognized potential of multispectral NIR imaging, which provides information on both spectral and spatial domains (thus extending the capabilities of conventional imaging and spectroscopy), most of the systems currently used in art diagnostics have limitations. The technology is still in its early stages of development in this field.

In this Account, we present the scanning multispectral IR reflectography (SMIRR) technique for artwork analysis, together with an integrated device for the acquisition of imaging data. The instrument prototype is a no-contact optical scanner with a single-point measurement of the reflectance, capable of simultaneously collecting a set of 14 spatially registered images at different wavelengths in the NIR range of 800−2300 nm. The data can be analyzed as a spectral cube, both as a stack of wavelength resolved images (multi-NIR reflectography) and as a series of point reflectance spectra, one for each sampled pixel on the surface (NIR spectrometry).

We explore the potential of SMIRR in the analysis of ancient paintings and show its advantages over the wide-band conventional method. The multispectral option allows the choice of the most effective NIR bands and improves the ability to detect hidden features. The interband comparison aids in localizing areas of different pictorial materials with particular NIR reflectance. In addition to the analysis of single monochromatic images, enhancement procedures involving the joint processing of multispectral planes, such as subtraction and ratio methods, false color representation, and statistical tools such as principal component analysis, are applied to the registered image dataset for extracting additional information. Maintaining a visual approach in the data analysis allows this tool to be used by museum staff, the actual end-users.

We also present some applications of the technique to the study of Italian masterpieces, discussing interesting preliminary results. The spectral sensitivity of the detection system, the quality of focusing and uniformity of the acquired images, and the possibility for selective imaging in NIR bands in a registered dataset make SMIRR an exceptional tool for nondestructive inspection of painting surfaces. The high quality and detail of SMIRR data underscore the potential for further development in this field.

Introduction and Background

Near-infrared (NIR) methods have been increasingly used for noninvasive analysis of art objects and a number of different techniques are currently adopted for various tasks in this field. Since its introduction,[1] infrared reflectography (IRR) continues to be a well established technique for painting analysis, routinely utilized in any conservation laboratory as part of the diagnostic process before an intervention. Since most of the pigments are transparent to NIR wavelengths, this radiation allows features underlying the paint layer, such as retouching, underdrawings, and *pentimenti* (changes done by the artist himself during the

10.1021/ar900268t

painting composition process, dealing with either the drawing or the pictorial layer), to be revealed. Reflectographic imaging is performed by irradiating the artwork with NIR radiation and by detecting the backscattered radiation with suitable devices. According to the interaction properties of the painting materials in the employed spectral range and to the composition and thickness of the specimen, the distribution of absorbed and reflected radiation allows us to extract information about painting layers and artist's technique. Currently, different kinds of systems are available to acquire a NIR image, ranging from commercial to experimental apparatus, and response depends on the performance of the imaging device, as well as on the spectral band used.[2−9] Traditionally, reflectography is being performed in wide-band modality by acquiring the NIR image in a single large band, which corresponds to the spectral range of the device. The early systems using PbO-PbS vidicon cameras have sensitivity up to 2.2 μm, whereas updated Si-based CCD cameras are limited to 1.1 μm. More suitable systems use detectors InGaAs or PtSi with broader sensitivity.

Recently, the multispectral approach, widely used in remote sensing, has been proposed in NIR imaging of artworks and has found successful applications in this field.[10] Traditional wide-band IRR is improved by the multiband option, which allows the most effective range of wavelengths to be tailored to fit the specific case.[11,12] Spectral imaging technique allows the simultaneous collection of both spectral and spatial information thus enlarging the perspectives of IRR to new applications for the study of artists' materials. In combination with data from analytical techniques,[13,14] such as probe-based reflectance spectroscopy, it allows the nondestructive identification of particular pigments and provides information on their spatial distribution across the entire painting.[15−17]

Despite the recognized potential of this innovative method of investigation and the results achieved, most of the multispectral NIR imaging systems commonly used in painting diagnostics present limitations, and the technology for this specific application is still an open field. Various NIR multispectral devices based on different detectors and on a filtering or dispersing system are being used by a number of research groups.[15,18−23] Waveband selection is mostly achieved by means of a scheme of filters fitted with an infrared camera, which records the spatial distribution, and the set of multiband images is stacked as a sequence of acquisitions. Such systems suffer from systematic errors such as blurring of the multispectral channels, which affects the reliability of spectral data and require optical calibration.[24] When filters are tuned by mechanical systems, such as rotating wheels, the spectral image set is difficult to register.[25] Systems based on sensor array suffer from pixel-to-pixel biases, lens distortion, and nonuniform illumination and require proper correction procedures.[15,23] Detector size limits in practice the spatial resolution because of mosaicking.[26] Moreover, current multispectral devices used in conservation have limited spectral range, which is related to the available detector technology and cost. To cover a more extended NIR range, vidicon tube or a plurality of detectors are still being used instead of the most advanced solid-state detectors.[4,20] As a matter of fact, there is still a need for a specific developed technology in the spectral imaging of artworks covering the extended range of 800−2300 nm.

In this Account, we present a novel integrated device for multispectral imaging of paintings in the NIR spectral range up to 2300 nm. After the description of the acquisition system, some applications to the study of Italian masterpieces are reported with the aim of showing the potential of the technique.

Instrument and Method

Multispectral imaging in the NIR is carried out by irradiating the painting surface with a broadband source and collecting the backscattered radiation within narrow spectral NIR bands. The imaging method is based on point-by-point scanning of the surface. Reflectance of each sampled pixel is simultaneously acquired at different wavelengths and a set of multispectral images is constructed. Stacking multispectral images provides information in both the spatial and spectral domain that can be easily visualized for the analysis and further manipulation (Figure 1). Each point of the multispectral image cube can be extracted as a reflectance spectrum (NIR spectrometry), while the slices correspond to images at different wavelength bands (multi-NIR reflectography).

Multi-NIR Scanning Device. Scanning multispectral IR reflectography (SMIRR) is performed by using the multi-NIR scanner whose schematic diagram is shown in Figure 2. An optical head, moved by a scanning system, both illuminates the painting and collects the backscattered radiation that is carried to the detection unit by means of a fiber bundle. To avoid chromatic aberration, the collecting optics is a catoptric system made of two faced spherical mirrors with $f_\# = 3.75$ to have acceptance cones of about 15° (according to CIE suggestions for the 45°/0° configuration that we follow for the visible module, which is integrated in the device but is not treated in this Account). The EFL is 63 mm; the depth of field is about ±1 mm, and we work in a 2f−2f configuration to have a unitary magnification factor. The radiation scattered

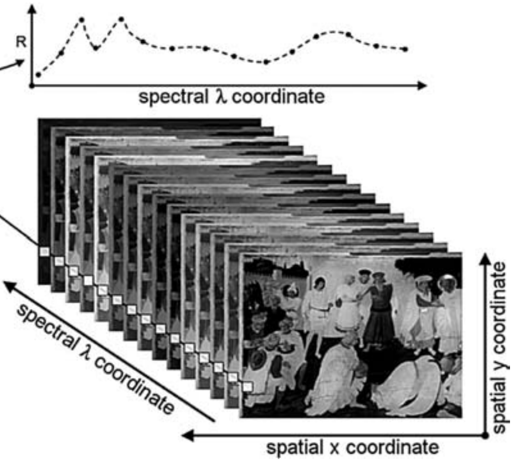


FIGURE 1. Sketch of the spectral cube consisting of as many image layers as NIR channels used. It can be analyzed as a set of wavelength resolved images (multi-NIR reflectography) or as a series of spatially resolved reflection spectra (NIR spectrometry).

from the measured point on the painting is imaged on the bundle made of 16 fibers assembled in square array with optical axes distance of 250 μm. Because the fibers have a 200 μm core and the magnification factor is equal to 1, the spot size at the painting is 200 μm for each channel (see Figure 2). The use of optical fibers allows separation of the optical head from the detection unit, thus minimizing the load on scanning stages. The lighting system is composed of two low-voltage halogen lamps, with ±5° beam divergence, and is stabilized in current. The irradiated area is about 5 cm^2 at the safe working distance of about 12 cm. Single point detection makes both the geometrical aberration negligible and the illumination uniform (the maximum fiber off-axis displacement is about 0.25°). Moreover, paint surface heating is minimized by scanning the lighting system.

The detection unit is composed of 3 Si and 12 InGaAs photodiodes, each fitted with an interferential filter. One InGaAs sensor covers the wide-band NIR range 800−1700 nm. The remaining sensors cover the multispectral NIR range 800−2300 nm split in 14 bands with spectral resolution ranging from about 50 to 100 nm. Last fiber is connected to the visible module, which is going to be integrated in the device but is not treated in this paper. The central wavelength of the channels are resumed in Table 1, together with the bandwidth of the corresponding filter. Channels equalization was performed with certified standards with reflectance from 99% to 2.5%.

The scanning unit is composed of two motorized XY translation stages orthogonally mounted, with a maximum stroke of 1 m and a precision less than 0.1 mm. The device allows continuous measurement of an area up to 1 m^2 with a spatial resolution of 0.5 mm. At an acquisition rate of 2 kHz and a sampling step of 250 μm, it takes about 3 h for maximum scanned area. The effect of motion blur due to electronic bandpass is negligible being less than 50 μm. In the acquisition phase our scanner is probably time-consuming compared with devices based on extended sensors, but this time loss is regained a posteriori because image data are aberration-free and hardware registered, thus saving postprocessing. The instrument has been assembled following the requirements for in situ measurement of paintings, namely, compactness, robustness, and transportability (Figure 3).

The device controlling software is a custom application capable of real-time acquisition through a user-friendly graphic interface. Main routines include that for controlling the scanning mechanics and that for acquiring synchronized multichannels data. Additional modules allow post processing of raw 16-bit imaging data for gray levels optimization. During the measurements, the images can be visualized in real-time for each of the spectral bands.

Multispectral Data and Processing. NIR images are reconstructed point-by-point by associating to each pixel on the image plane the intensity reflected by the sampled point on the painting surface. At each scanning section a reference image with a reflectance standard, I_{ref}, and a dark image with closed optics, I_{dark}, are acquired. Conversion to reflectance units is then made by using the in-scene reflectance standard with the formula

$$R_\lambda = \rho_{\mathrm{ref}} \frac{I_{\mathrm{sample}} - I_{\mathrm{dark}}}{I_{\mathrm{ref}} - I_{\mathrm{dark}}}$$

where R_λ is the spectral reflection factor, I_{sample} the detected radiation, and ρ_{ref} the certified value for the reflectance standard. This relation, generally used in the visible range, can be extended to the NIR range because up to 2.5 μm thermal emission is negligible. Reflectance accuracy for a single measurement was obtained using seven SphereOptics standards (2.5%, 5%, 10%, 25%, 50%, 70%, 99% diffuse reflectance) and resulted in the range 5−10% rms of white standard 99%.

The spectral image cube was computed by means of algorithms developed in Matlab environment. We worked with the 16-bit data sets sampled by the instrument. The monochromatic images were analyzed separately, as well as jointly. Well-known methods, such as pixel-by-pixel subtraction and the ratio between pairs of single-wavelength images, were carried out to highlight changes in the reflectance of pigments from one wavelength to another. To explore the capability of the multispectral imaging, false color composites were elaborated with either single band or difference/ratio images in

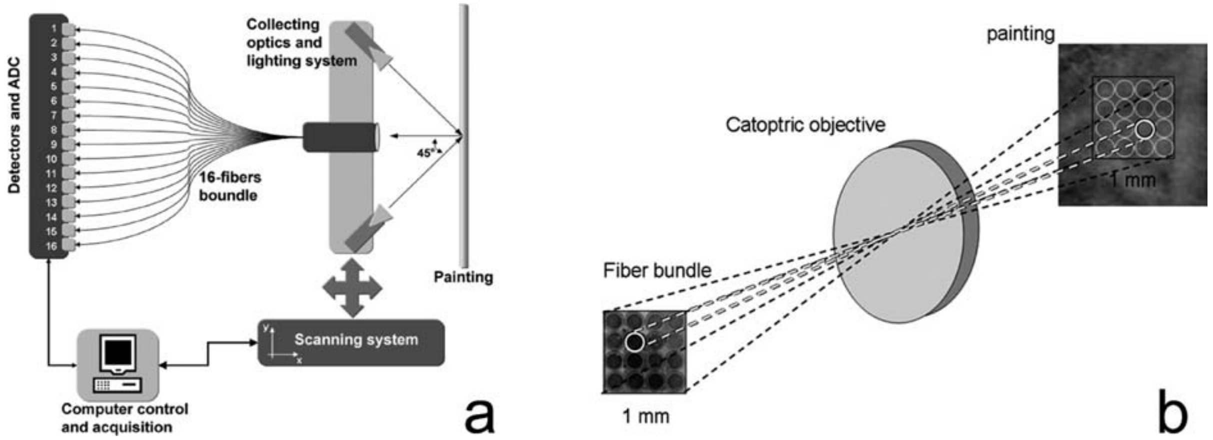


FIGURE 2. Schematic diagram of the multi-NIR scanning device (left). The instrument is a modular system composed of illumination/collection module, fiber bundle, detection module and scanning module which can be easily assembled (a). Sketch of multichannel acquisition of the painting (b). The single measure is carried out on a square array of sampled points that are simultaneously acquired through the fiber bundle.

TABLE 1. Central Wavelength and FWHM for the NIR Channels

CH	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
λ [nm]	wide (900−1700)	800	850	952	1030	1112	1200	1300	1400	1500	1600	1700	1820	1930	2265
$\Delta\lambda$ [nm]		10	67	67	55	66	66	90	90	90	90	90	100	112	590

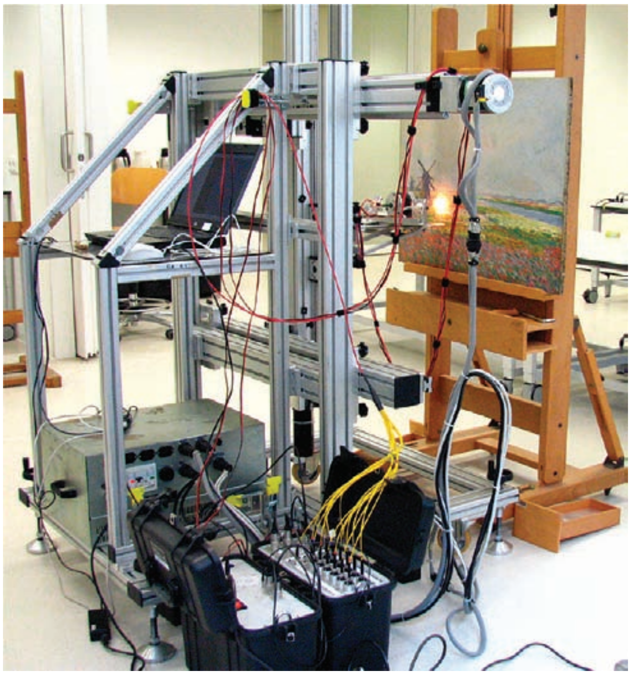


FIGURE 3. Multi-NIR scanning device during the demonstration measurements at the final meeting of the Eu-Artech project (Instituut Collectie Nederland ICN, Amsterdam, May 13th 2009).

both trichromatic RGB and quadri-chromatic CMYK spaces. The false color image, which includes all the information from the constituent monochromatic NIR images, is used to examine the features varying with wavelengths and to visualize information from more than one channel simultaneously. The spectral image cube was also processed using the well-known statistical method principal component analysis (PCA). PCA concentrates the significant features into a few representative images and makes somehow automatic the extraction of information enabling a straightforward interpretation of the results.[27] A false-color representation was also used to mix the images produced by the PCA transformations to display the painting characteristics in a useful and intuitively appealing way. Interband comparison and operation with different bands are possible thanks to the superimposing property of our images that do not require registration. Despite the drawback of being time and disk-space consuming, this approach has the advantage of being easy to use and of maintaining a visual correspondence with the painting. Moreover, it can be performed also with commercial software for image processing.

Application and Results

The multi-NIR scanner was evaluated on real artworks to test the system performance on field. First, measurements have been carried out at the INO Optical Metrology Laboratory hosted at the Opificio delle Pietre Dure (OPD) in Florence, one of the largest restoration facilities in Europe. The device was then moved to Italian and European museums for in situ diagnostics in the framework of the Eu-Artech project (2004−2009).[28] The multi-NIR scanner is part of the mobile instrumentation of the Charisma project (2009−2013)[29] and

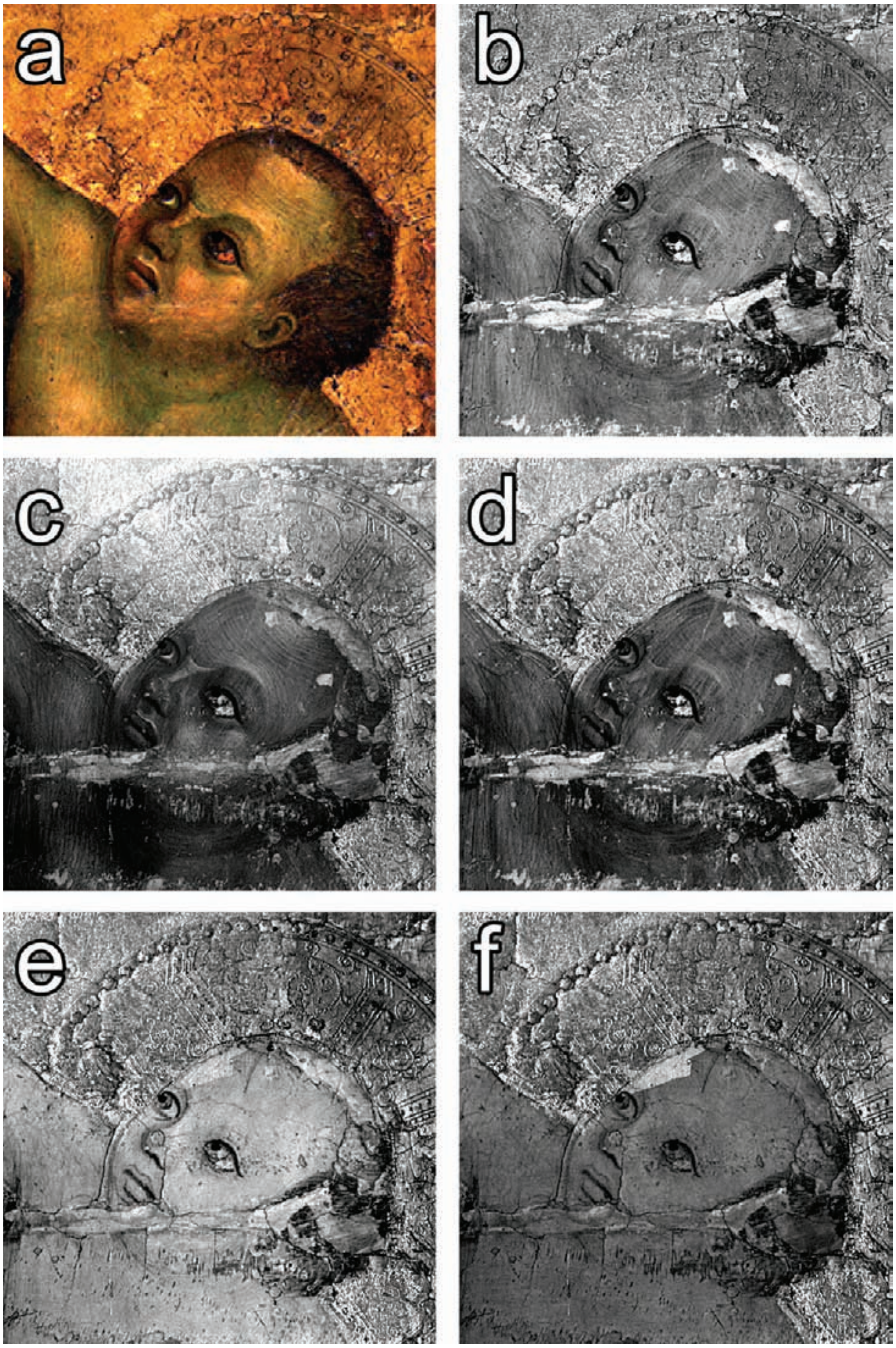


FIGURE 4. Cimabue, *Madonna con Bambino*, 13th century, Santa Verdiana Museum, Castelfiorentino (Florence, Italy). Detail of the Child's face at different wavelengths: (a) visible image, (b) wide 900−1700 nm channel, (c) CH2@850 nm, (d) CH6@1200 nm, (e) CH11@1700 nm, (f) CH14@2265 nm. Details, such as the mark of the golden leaf that appears as a white spot above the Child's right eye, appear more clearly with increasing wavelength and reach the best visibility in the 2265 nm image. On the contrary, the two little spots on the Child's forehead disappear at higher wavelengths.

can be accessed through its program by the scientific and the conservation community.

The preliminary results reported below are intended to give an application overview of the SMIRR technique with emphasis on the advantages over the conventional reflectography. Multispectral imaging enables the analysis of features that are not detectable in the wide-band reflectography, allowing the choice of the most effective NIR bands according to the different case study. Interband processing is used to enhance the presence of retouches and repaintings or, more generally, the

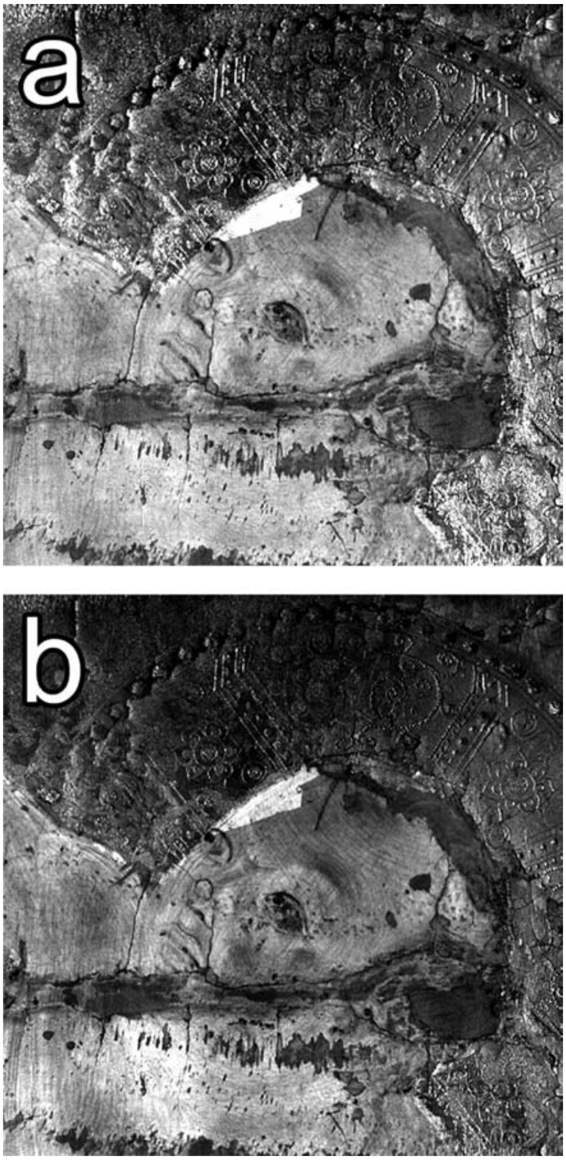


FIGURE 5. Cimabue, *Madonna con Bambino* (13th century). (a) Difference and (b) ratio images obtained with CH2@850 nm and CH14@2265 nm. Both elaborations allow the visualization of all the extracted information in a unique synthesized image plane: the golden leaf above the Child's right eye that appears with increasing wavelength, the two retouches on the Child's forehead that appear with decreasing wavelength, and the dark dots on the Child's chest that appear with increasing wavelength.

areas of different pictorial matter. This ability is well-known,[11,12,17] but it has not been fully explored with an integrated instrument in such an extended spectral range, 800−2300 nm.

Evidence of the potential of the multispectral approach is given in the analysis of the Cimabue's painting *Madonna con Bambino*. In Figure 4, multi-NIR images and wide-band reflectography are compared to show how spectral segmentation beyond 1700 nm reveals retouches and details otherwise not visible. Enhancement procedures involving the joint processing of multispectral image planes, such as image subtraction and ratio methods, are applied to the registered data set for extracting hidden features. Such processing of image planes is straightforward because, as mentioned above, the multi-NIR scanner output is an high-quality data set (spatially registered, uniform illumination, aberration free). Difference/ratio images allows the visualization of all the extracted information in a unique synthesized plane, in addition to enhancing details that are scarcely visible in the monochromatic or in the wide-band images (Figure 5). In the difference image, the reflectivity variation between two bands is accentuated, thus allowing localization of areas of different materials. This is shown in the analysis of a XVI century wooden panel by an anonymous Italian painter (Figure 6). In a similar approach, false color representation with either single channels or difference/ratio images was used for the two paintings *La Gravida* by Raffaello and *Madonna con Bambino*, respectively, to differentiate regions which are then visualized in an effective and impactive way (Figures 7 and 8). PCA was profitably applied to a panel painting by Cosmè Tura for extracting the various score images. The first 91.9% score image contains the same information as the wide-band reflectography. The other three score images (5.5%, 1.9%, and 0.3%) combined in a false color representation improve the detection of details as shown in Figure 9.

Conclusion

An integrated imaging device operating in the extended NIR range 800−2300 nm has been developed with the specific application of scanning multispectral IR reflectography (SMIRR) of painted surfaces in mind. The multi-NIR scanner overcomes the limitations of most of the systems currently used for multispectral imaging. Point-by-point sampling for each of the NIR channels solves the problems related to the use of extended detectors and filter tuning and provides precise information in the spatial and spectral domain, namely, a metrically and optically corrected set of images that are mutually registered. As the potential of analysis of the multispectral data is enormous and involves many techniques, from the use of easy concepts to advanced mathematical tools, it is very important to start having high-quality data sets. Some applications to the analysis of ancient Italian masterpieces have been shown. The results show that the multispectral option together with the extended spectral range improve the traditional IRR technique.

SMIRR data can be analyzed both as multi-NIR reflectography and NIR spectrometry. In this work, emphasis was given to the former approach. The complex aspect of pigment mapping is not treated in this work and will be treated in the

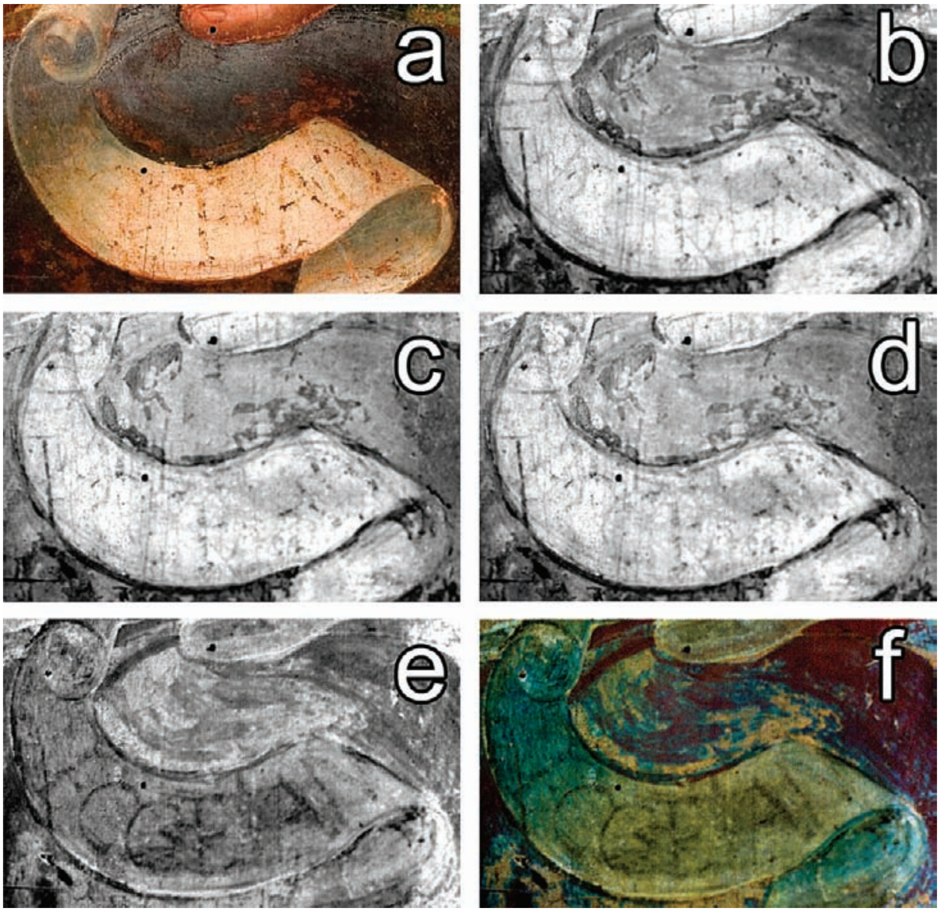


FIGURE 6. Anonymous Italian painter, *Madonna con Bambino*, XVI century, Gallery of Motti-Bardini Palace, Florence, Italy. Detail of the inscription "Ecce Agnus Dei": (a) visible image, (b) wide-band reflectogram 900−1700 nm, (c) CH13@1930 nm, (d) CH14@2265 nm, (e) CH14-CH13, (f) false color image in the CMYK space (C=CH3/CH2, M=CH7/CH5, Y=CH9/CH8, K=CH14/CH13; the K channel was inverted to enhance the inscription readability). In the difference image the reflectivity variation between two bands is accentuated thus allowing discovery of hidden details, such as the inscription that can be partially seen only in the visible image, but it is nearly invisible in the single IR images.

future. As far as pigment identification is concerned, the optical spectrometric techniques are restricted to particular cases because the reflectance response in a real artwork depends on several factors. Toward this aim and to provide an advanced and integrated diagnostics of paintings in the VIS-NIR spectrum, a version of the instrument including also the multi-VIS module is going to be implemented.

This research has been funded by EU within the 6th Framework Programme, project EU-ARTECH. We are indebted with Dr Cecilia Frosinini of the Opificio delle Pietre Dure in Florence for giving us the possibility to apply the SMIRR technique on real artworks and with the restorer Roberto Bellucci for useful discussions and suggestions. Thanks to Sara Micheli and Dr. Mattia Patti for spending lots of hours looking after the multi-NIR scanner during measurements.

BIOGRAPHICAL INFORMATION

Claudia Daffara was born in Rome, Italy, in 1968. She studied theoretical Physics at the University of Padua and obtained a Ph.D. in Physics at the University of Bologna working in computational and applied physics. In 2003, she joined the Art Diagnostic Group at the National Institute of Optics CNR-INO in Florence, where she still works as researcher. Her research interests include radiation transport and imaging techniques for art diagnostics with major focus on data computation and modeling for 2D IR reflectography, thermography, and 3D microprofilometry confocal microscopy.

Enrico Pampaloni was born in Florence, Italy, in 1961. He studied Physics at the University of Florence, where he got his degree in 1989 and his Masters degree in Optics in 1992. From 1990, he has been a researcher at the National Institute of Optics CNR-INO in Florence. His principal research interests in the field of applied optics for Cultural Heritage are imaging techniques (IR reflectography, VIS-NIR multispectral

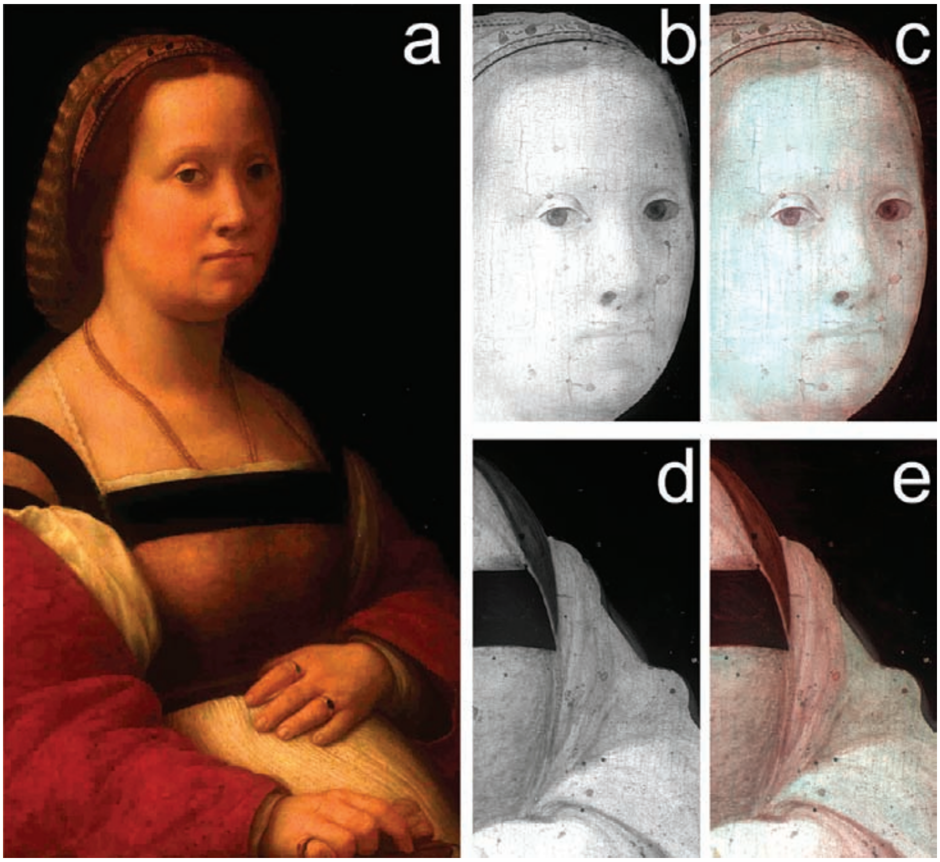


FIGURE 7. Raffaello, detail of *La Gravida*, Galleria Palatina, Palazzo Pitti, Florence, Italy. Visible image (a), wide-band reflectogram 900−1700 nm (b, d), and false color composite with CH14@2265 nm, CH5@1112 nm, CH3@952 nm (c, e). In the wide-band reflectogram, no relevant details come out, whereas the false color image enhances different materials both in the face and in the dress.

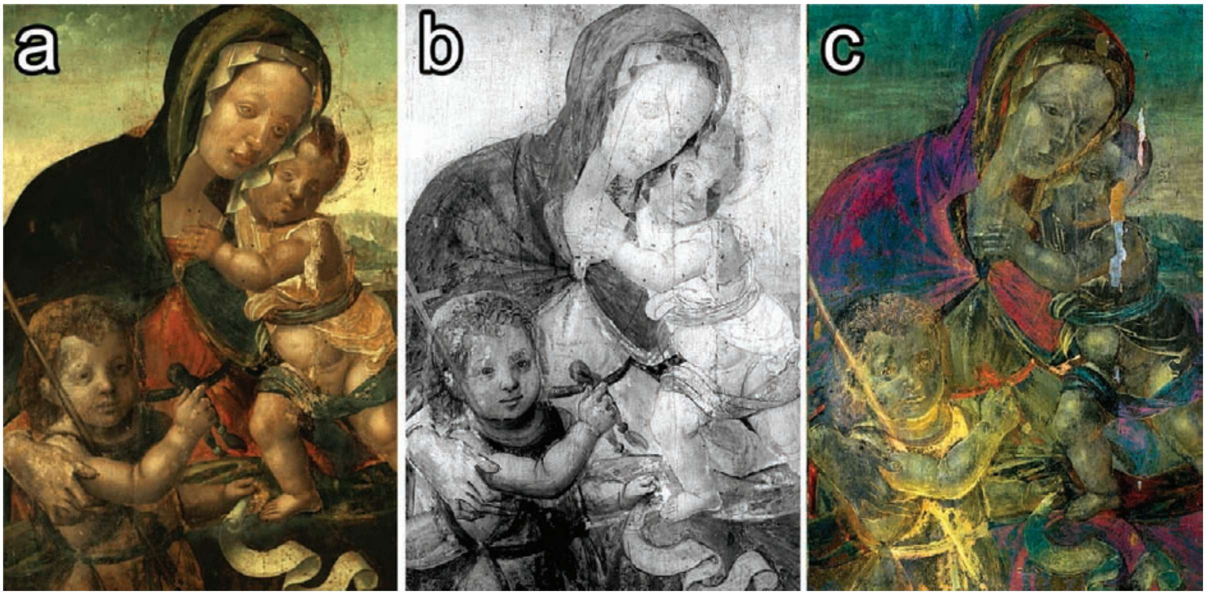


FIGURE 8. Anonymous Italian painter, detail of *Madonna con Bambino*, XVI century, Gallery of Motti-Bardini Palace in Florence. (a) Color image, (b) wide-band reflectogram 900−1700 nm, and (c) false color image obtained in the CMYK space using the ratio images CH3/CH2, CH7/CH5, CH9/CH8, CH14/CH13. False color image allows the visualization of all the extracted information in a unique synthesized image plane and differentiation of regions that are profitably visualized in an effective and impactive way. The presence of different pigments at the right shoulder of the Madonna's mantle are clearly visible.

imaging, UV-fluorescence, thermography), three-dimensional survey (time-of-flight laser scanning, laser-line scanning, and conoscopic microprofilometry), data analysis, and development of diagnostic methodologies.

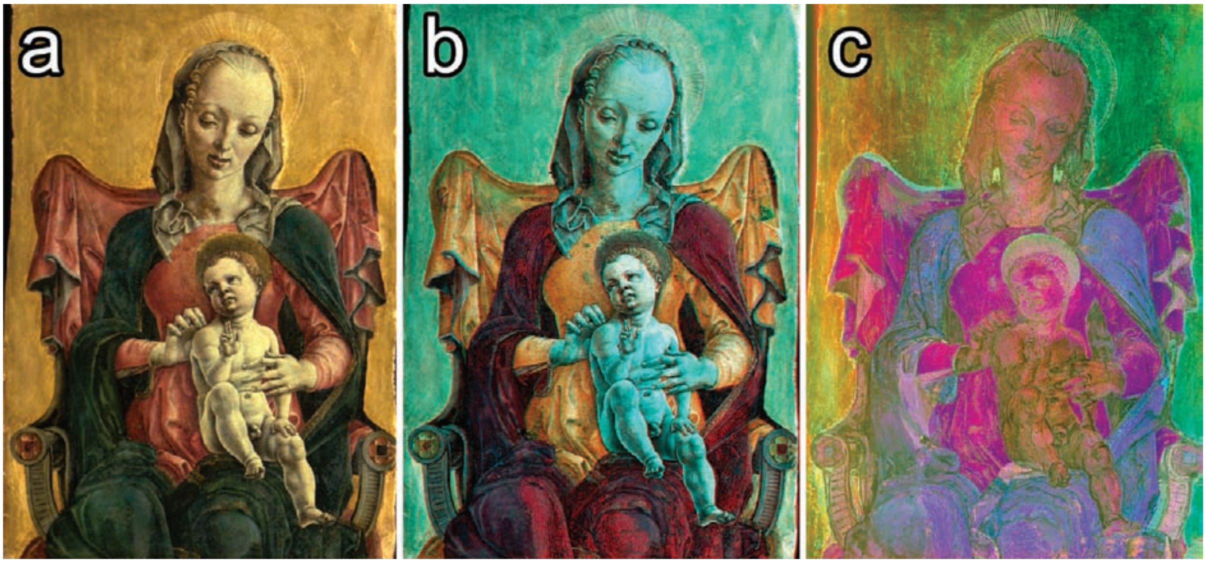


FIGURE 9. Cosmè Tura, *Madonna con Bambino*, Galleria dell'Accademia Carrara, Bergamo, Italy. PCA analysis is profitably applied to the multispectral data set for extracting the information: (a) visible image, (b) "standard" false color image, that is, made with wide-band IR, red, green images, and (c) false color image made with the 2nd, 3rd, 4th score images (5.5%, 1.9%, 0.3% information, respectively). Because the first score image contains the same information as the wide-band IRR, by combining the score images other than the first, we extract more features, such as the couple of light spot at the Madonna's neck side and the inhomogeneity in the background, the Madonna's right arm mantle, and the chair drapery on the back.

Luca Pezzati Born in Florence, Italy, on March 19th, 1964. He obtained his degree in Physics (1990) from the University of Florence and his specialization in optics (1995). Since 2003, he has been a Senior Researcher at the CNR-INO (National Institute of Optics of the National Research Council), which he joined in 1995 after having worked at the Officine Galileo in Florence. He has been the Coordinator of the *Gruppo Beni Culturali* (Art Diagnostic Group) of the INO since 1999 and Head of the INO Division in Lecce. He has managed many research projects in the field of optical technologies applied to Cultural Heritage. Among his research interests are optics applied to safeguard of cultural heritage, optical metrology, 3D-measurement of optical techniques, optical systems design, interferometry, phase-analysis techniques, and scientific software design. He is the author of many journal articles and conference proceedings.

Marco Barucci was born in Florence, Italy, in 1970. He studied physics at the University of Florence, where he got his Ph.D. on material science in 2004. He was a postdoctoral fellow until the end of 2008. Now, he is a researcher at the National Institute of Optics CNR-INO in Florence. His research interests include material characterizations for low temperature detectors and superconducting devices, optical techniques for material property analysis, and recently, development and realization of optic devices for the diagnostics of artworks.

Raffaella Fontana was born in Pavia, Italy, in 1964. She studied physics at the University of Florence, where she got her Ph.D. in 1997 and her Specialization School (Master-like) in Medical Physics in 1999. Subsequently, she was a postdoctoral fellow until 2003. Since then she has been a researcher at the National Institute of Optics CNR-INO in Florence. Her research interests include imaging techniques for the diagnostics of works of art, such as IR reflectography, VIS-NIR multispectral imaging, UV-fluorescence, confocal microscopy, and optical coherence tomography, thermography, as well as techniques for three-dimensional survey of objects, such as time-of-flight laser scanning, laser-line scanning, and microprofilometry.

FOOTNOTES

---

*To whom correspondence should be addressed. E-mail: claudia.daffara@ino.it. Phone: +39 055 23081. Fax +39 055 2337755. Web: http://arte.ino.it.

REFERENCES

1 Van Asperen de Boer, J. R. J. Infrared reflectography: A method for the examination of paintings. *Appl. Opt.* **1968**, *7* (9), 1711–1714.

2 Van Asperen de Boer, J. R. J. Reflectography of paintings using an infra-red vidicon television system. *Stud. Conserv.* **1969**, *14*, 96–118.

3 Bertani, D.; Cetica, M.; Poggi, P.; Puccioni, G.; Buzzegoli, E.; Kunzelman, D.; Cecchi, S. A scanning device for infrared reflectography. *Stud. Conserv.* **1990**, *35*, 113–117.

4 Walmsley, E.; Fletcher, C.; Delaney, J. Evaluation of system performance of near-infrared imaging devices. *Stud. Conserv.* **1992**, *37*, 120–131.

5 Saunders, D; Billinge, R.; Cupitt, J.; Atkinson, N.; Liang, H. A new camera for high-resolution infrared imaging of works of art. *Stud. Conserv.* **2006**, *51*, 277–290.

6 Consolandi, L.; Bertani, D. A prototype for high resolution infrared reflectography of paintings. *Infrared Phys. Technol.* **2007**, *49* (3), 239–242.

7 Gargano, M.; Ludwig, N.; Poldi, G. A new methodology for comparing IR reflectographic systems. *Infrared Phys. Technol.* **2007**, *49* (3), 249–253.

8 Daffara, C.; Gambino, M. C.; Pezzati, L. Performance analysis of imaging systems for NIR reflectography. *Proceedings of the 2nd International Topical Meeting on Optical Sensing and Artificial Vision (OSAV 2008)*, St. Petersburg, Russia, May 12—15, 2008; International Commission for Optics: Boca Raton, FL, 2008; pp 307—314.

9 Falco, C. M. Invited Article: High resolution digital camera for infrared reflectography. *Rev. Sci. Instrum.* **2009**, *80*, 071301.1—9.

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

11 Walmsley, E.; Metzger, C.; Delaney, J. K.; Fletcher, C. Improved visualization of underdrawings with solid-state detectors operating in the infrared. *Stud. Conserv.* **1994**, *39*, 217–231.

12 Fontana, F.; Bencini, D.; Carcagni, P.; Greco, M.; Mastroianni, M.; Materazzi, M.; Pampaloni, E.; Pezzati, L. Multi-spectral IR reflectography. *Proc. SPIE* **2007**, *6618*, 661816.1–12.

13 Mansfield, J. R.; Sowa, M. G.; Majzels, C.; Collins, C.; Cloutis, E.; Mantsch, H. H. Near infrared spectroscopic reflectance imaging: supervised vs. unsupervised analysis using an art conservation application. *Vib. Spectrosc.* **1999**, *19*, 33–45.

14 Bacci, M. UV-Vis-NIR, FT-IR, and FORS spectroscopies. In *Modern Analytical Methods in Art and Archaeology*; Ciliberto, E., Spoto, G., Eds.; Wiley Interscience: New York, 2000; pp 321−362.

15 Baronti, S.; Casini, A.; Lotti, F.; Porcinai, S. Multispectral imaging system for the mapping of pigments in works of art by use of principal-component analysis. *Appl. Opt.* **1998**, *37* (8), 1299–1309.

16 Casini, A.; Lotti, F.; Picollo, M.; Stefani, L.; Buzzegoli, E. Image spectroscopy mapping technique for non-invasive analysis of paintings. *Stud. Conserv.* **1999**, *44*, 39–48.

17 Delaney, J. K.; Walmsley, E.; Berrie, B. H.; Fletcher, C. F. Multispectral imaging of paintings in the infrared to detect and map blue pigments. In *Scientific Examination of Art: Modern Techniques in Conservation and Analysis*; National Academies Press: Washington, DC, 2005; pp 120−136.

18 Mansfield, J. R.; Attas, M.; Majzels, C.; Cloutis, E.; Collins, C.; Mantsch, H. H. Near infrared spectroscopic reflectance imaging: a new tool in art conservation. *Vib. Spectrosc.* **2002**, *28*, 59–66.

19 Balas, C.; Papadakis, V.; Papadakis, N.; Papadakis, A.; Vazgiouraki, E.; Themelis, G. A novel hyper-spectral imaging apparatus for the non-destructive analysis of objects of artistic and historic value. *J. Cult. Herit.* **2003**, *4* (1), 330–337.

20 Bacci, M.; Casini, A.; Cucci, C.; Muzzi, A.; Porcinai, S. A study on a set of drawings by Parmigianino: integration of art-historical analysis with imaging spectroscopy. *J. Cult. Herit.* **2005**, *6* (4), 329–336.

21 Liang, H.; Saunders, D.; Cupitt, J. A new multispectral imaging system for examining paintings. *J. Imaging Sci. Technol.* **2005**, *49* (6), 551–562.

22 Karagiannis, G.; Salpistis, C.; Sergiadis, G.; Chryssoulakis, I. Non-destructive multi-spectral reflectoscopy between 800 and 1900 nm: An instrument for the investigation of the stratigraphy in paintings. *Rev. Sci. Instrum.* **2007**, *78* (6), 065112.1−7.

23 Delaney, J. K.; Zeibel, J. G.; Thoury, M.; Littleton, R.; Morales, K. M.; Palmer, M.; de la Rie, E. R. Visible and infrared reflectance imaging spectroscopy of paintings: pigment mapping and improved infrared reflectography. *Proc. SPIE* **2009**, *7391*, 739103.1–8.

24 Mansouri, A.; Marzani, F. S.; Hardeberg, J. Y.; Gouton, P. Optical calibration of a multispectral imaging system based on interference filters. *Opt. Eng.* **2005**, *44* (2), 27004.1–12.

25 Gat, N. Imaging spectroscopy using tunable filters: A review. *Proc. SPIE* **2000**, *4056*, 50–64.

26 Corsini, M.; Bartolini, F.; Cappellini, V. Mosaicing for high resolution acquisition of paintings. In Proceedings of the 7th International Conference on Virtual Systems and Multimedia (VSM'01), Berkley, CA, October 25−27, 2001; IEEE Computer Society: Washington, DC, 2001; pp 39−48.

27 Bonifazzi, C.; Carcagni, P.; Fontana, F.; Greco, M.; Mastroianni, M.; Materazzi, M.; Pampaloni, E.; Pezzati, L.; Bencini, D. A scanning device for VIS-NIR multispectral imaging of paintings. *J. Opt. A: Pure Appl. Opt.* **2008**, *10*, 064011.1−9.

28 EU-ARTECH: Access Research and Technology for the Conservation of the European Cultural Heritage, European Project 2004−2009, Contract no. RII3-CT-2004-506171, www.eu-artech.org.

29 CHARISMA: Cultural Heritage Advanced Research Infrastructures: Synergy for a Multidisciplinary Approach to Conservation, European Project 2009−2013, Grant Agreement no. 228330.