Spectral imaging of Leonardo Da Vinci's Mona Lisa: An authentic smile at 1523 dpi with additional infrared data

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Abstract

Two photos of the famous Mona Lisa were taken in October 2004 to contribute towards improving the technical and scientific data of the masterpiece before moving it in April 2005. The capabilities of the multispectral system developed by the LUMIERE TECHNOLOGY Company within the scope of the European CRISATEL project have made it possible to achieve optimal spatial resolution on the masterpiece, the highest level of sharpness ever achieved in the field of infrared reflectography, and a level of accuracy regarding color information which cannot be achieved with traditional technologies. From ultraviolet to infrared, all the details enhance the intimacy of this masterpiece. The scientific utilization of this data will undoubtedly be a major breakthrough to achieve better knowledge of Leonard De Vinci's work. The remarkable nature of this masterpiece and its specific physical features have required appropriate parameterizations and preliminary tests which are described in this publication.

1. Introduction

High-resolution spectral imaging allows us to obtain new data in order to study fine art paintings. The main tools available include global spectrophotometry in the visible and near infrared as well as magnifying of the details of the painting. A portable nondestructive system makes it possible to produce high-fidelity color images and to consider virtual restoration. This technique has been used to improve knowledge of the world's most famous painting – the *Mona Lisa*. After a presentation of the masterpiece and relevant equipment, the first part of this article describes the course of the digitization session:

- Hardware setup.
- Preventive conservation.
- Camera settings and calibration.
- Image acquisition and processing.

In the second part, we assess the performance of digital signal transformation to spectral reflectance and suggest several potential applications regarding this digital original.

2. Painting

The *Mona Lisa* – which is exhibited at the Louvre in Paris, INV 779 – was painted between 1503 and 1506 by Leonard De Vinci. This masterpiece has always been linked with the Louvre, and more generally speaking with art. The perfect pictorial technique is one of the numerous elements that contribute towards the myth and give the masterpiece remarkable realism (rendering of the flesh). This oil painting is set on a thin poplar 77 cm × 53 cm wood panel support and now relocated – in April 2005 to the "Salle des États" – the largest room in the museum with its new protective enclosure and lighting. Extensive scientific and technical research was carried out prior to moving the masterpiece in order to check its state of conservation. Within the scope of this study and in addition to the usual experiments carried out by the French Museum Research and Restoration Center (C2RMF), the Louvre called in several external teams of scientific experts. Pascal Cotte and his team brought along their know-how in the field of high-definition multispectral digitizing of fine art paintings and took photos of this famous masterpiece with their equipment during the night of 19th October 2004.

3. Experimental

In addition to all the necessary precautions required when handling precious, fragile masterpieces, extremely minute and confidential experiments were carried out on this unique masterpiece. The equipment was set up in the photographic studio several days beforehand in order to design the stand dedicated to holding the painting and to carry out a series of preliminary tests. A substitute similiar-sized template based on the technical data mentioned in the archives of the work, was used to position the camera and lighting system.

3.1 Materials

The high-resolution spectral imaging system (see Figure 1) is based on a CCD sensor array of 12,000 pixels. An accurate step motor system makes it possible to move the sensor during 30,000 vertical lines and to achieve an optimal definition of 360 Mega-pixels for each channel. This 13-channel acquisition system uses Melles Griot interference filters in a half-cylinder and covers the visible spectral range with a 40-nm bandwidth and three additional IR filters with a 100-nm bandwidth. A last position without filters is dedicated to panchromatic acquisition and helps set up the hardware with quick image preview. The filter transmittance varies according to the angle of the incident rays. In order to minimize this spectral displacement, the camera is equipped with a 210-mm long focal length lens with a 10° field of view in addition to a mechanical filter orientation device preserving orthogonality at the optical axis. A set of motors controls the focus for each channel and the movement of the camera body in order to minimize the scale factor due to this individual focusing. A high-resolution scanning system equipped with a dedicated synchronized lighting system was developed and patented by LUMIERE TECHNOLOGY.

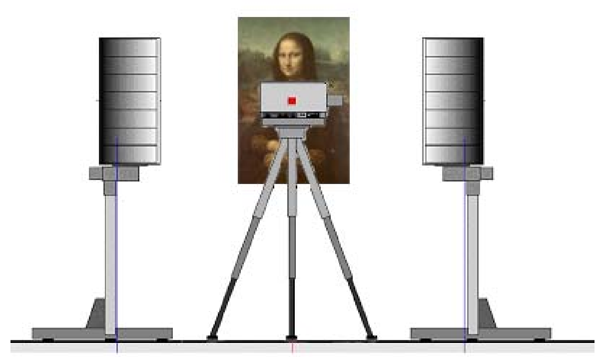

Figure 1: Installation of spectral imaging system.

This lighting system is composed of two elliptical projectors with eight HQI metal discharge lamps and projects a combine narrow light beam synchronized with the CCD sensor displacement. The whole device enables levels of illumination of 100,000 lux to be achieved on documents while featuring excellent homogeneity over 3 meters in height. The advantage of this lighting system is developed in the part dedicated to preventive conservation of the masterpiece. The specific features of the system were described in previous publications[1].The camera is controlled by a dual-processor Macintosh G4. The camera and lamp controls use a serial connection and the image data is conveyed through low-voltage differential signaling (LVDS) from a proprietary PCI card.

3.1.1 Hardware set up

The copy stand used is a power-driven easel which was modified in order to hold the *Mona Lisa* by applying monitored pressure directly onto the wooden support. The oak frame – which was added in 1951 to reinforce the warped board – was specially removed for digitization processes (see Figure 2). The aim of the specific fastening is to enable positioning of the white calibrated patches and resolution targets required at the image resizing stage. That positioning stage is vital, given that the surface of the painting must be level with the resolution targets (see Figure 3). As this surface is not flat, technical – depth of field and focusing – and aesthetic choices – specular reflections management – were made based on photography-specific methods and Pascal Cotte's thorough knowledge of the specific behavior of the lighting system.

Figures 2 : Mona Lisa before installation .

Figures 3: Installation of Mona Lisa on a specific easel.

The distance between the painting and the camera depends on the size of the document to be digitized and the focal length of the lens. The image plane must be parallel to the object plane in order to ensure sharpness in the angles. Such an alignment is carried out using a laser placed on the imaginary object plane and pointed at the CCD's protection window, perfect geometry depending on the flyback position. The imaging configuration is equivalent to a 45°/0° adjustment on all the edges of the painting, thus making it possible to remove direct specular reflection. The specific features of the *Mona Lisa* – warped support and presence of varnish – required a modification of the geometry through less direct lighting. The angle varies between 57.5° and 66.5° compared with the optical axis depending on the area of the painting that is lit up (see Figure 4), thus minimizing specular reflections which had not been removed and reducing maximum lighting. The ideal would have been to take photos of the masterpiece in landscape format with the curvature running parallel to the focused light beam, but as a precaution and in order to avoid any pressure in the direction of the wood fibers, this option was not approved.

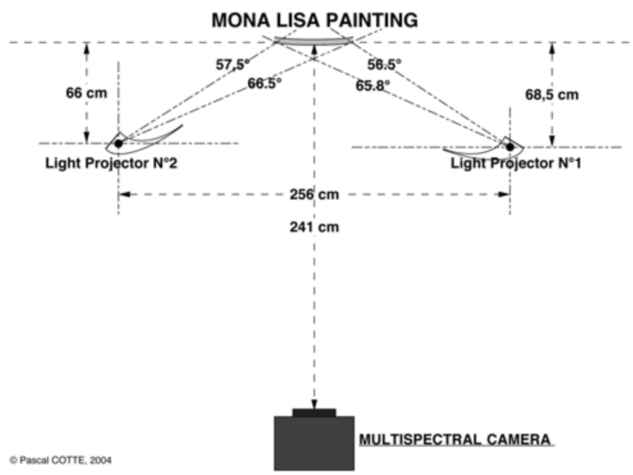

Figure 4: Camera and lighting system set up.

3.1.2 Preventive conservation

In addition to its portable nature, this new masterpiece analysis technique must protect the material's integrity. All the parameters linked with their potential deterioration have been studied. There are intensity illumination standards that apply to the exhibition of items in museums. These standards usually represent a balance between the limits of discernible details of an item and the latter's deterioration speed. The photochemical effects of light depend on other factors that may accelerate the process. The presence of oxygen – and therefore oxidation – plays a significant role in the deterioration processes and temperature speeds up chemical reactions. A large proportion of energy UV radiations also modifies the deterioration speed. The synchronized lighting system makes it possible to achieve a high level of illumination, but only on the part of the painting specifically required. Light acts through accumulation – deterioration will be the same whether the painting is exposed to a level of illumination of 100 lux during 5 hours or 500 lux during one hour. After having checked reciprocity with a high level of illumination on similar materials and observing no deterioration whatsoever, the lighting was adjusted in order to achieve a maximum level of illumination of 30,000 lux (see Figure 5).

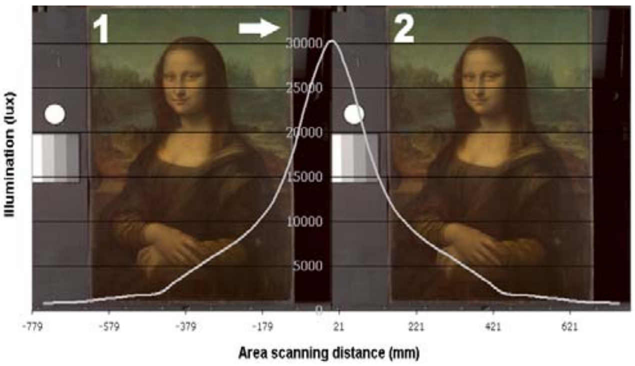

Figure 5: i(x) function, lighting distribution over the digitization area (1: beginning of the digitization process, 2: end of the digitization process, arrow: virtual shifting of the painting for fixed lighting).

Figure 6: Temperature control during preliminaries tests.

The light beam enables maximum lighting on a width of 50 mm, then rapidly decreases to a value lower than 800 lux. The unit of the total exposure dose received by a document is in millions of lux per hour (Mlxh) and the unofficial standard sets the total exposure of a document to 0.36 Mlxh/year. Total exposure dose received by the masterpiece during the digitization session may be calculated. With full knowledge of the total amount of horizontal pixels – n – and total integration time – t – in ms, a total exposure dose in Mlxh is estimated as per the following formula:

$$DET = \int_{0}^{779} i(x) \times \frac{n \times t}{3600 \times 10^{6}} \times 2 \qquad (1)$$

i(x) represents the lighting distribution function on the digitization area. The residual lighting – except for the concentrated beam – is larger than the 779-mm digitization area. The masterpiece will be exposed to the entire lighting distributed over twice the digitization area. The total exposure dose obtained for shot No. 1 where n = 11,409 pixels and t = 480.5 ms is 0.020 Mlxh. The total exposure dose obtained for shot No. 2 where n = 20,000 pixels and t = 102.7 ms is 0.018 Mlxh. In comparison, when in its former protective enclosure, the *Mona Lisa* was exposed to a level of illumination of 180 lux lighting during 9 hours a day, i.e. a total of 0.00162 Mlxh. A photo of this masterpiece is therefore equivalent to ten days' exposure in the museum. We shall comment on this result in the part about applications. The spotlights include a preventive conservation device with heat filters at the front and a UV stabilizer directly integrated into the lamp bulbs. The microclimate of the room had been monitored in order to study the evolution of temperature and hygrometry. A series of sensors was placed in the latter and linked by radio waves to a central computer recording the data in real time. Furthermore, a sensor was placed on the easel in order to describe local fluctuations close to the painting. The balance between temperature (in °C) and relative humidity (RH) was only modified once, in the absence of the painting, when switching on the lighting equipment. After several minutes, adjustment of the air conditioning made it possible to work throughout the entire session at a temperature of 20.3°, with a RH of 50%. As a precaution, the maximum amount of people allowed in the room was limited to 4 during the entire photographing session. On several occasions, an additional temperature adjustment with an infrared thermometer (see Figure 6) was carried out on the painting itself and no increase of more than 1°C was recorded on the surface.

An ultraviolet radiation measurement was carried out using a radiometer. The processing features integrated into the HQI lamps enable the removal of UVB and UVC that may cause photochemical reactions at the surface of a document. A small quantity of UVA is present to enable digitization through the first filter, the transmittance of which ranges between 380 and 420 nm. The museum UV standards[2] are based on emission in the ultraviolet radiations of traditional incandescent lamps 60-80 μW/lumen between 300 and 400 nm with an accessibility level of 75μW/lumen. We recorded a maximum level of 40 $\mu W/cm^2$ at a level of illumination of 30,000 lux in the synchronized beam of the lighting system. Once converted, we obtained a value of 13.4 μW/lumen – i.e. approx. 6 times lower than the average value.

3.1.3 Targets

Three different targets (see Figure 7) are selected to evaluate system performances: the GretagMacbeth color checker DC target, the CRISATEL project's acrylic and oil Pébéo charts. The variety and homogeneity of pigments differ from one chart to another. The color checker represents a homogeneous part of the global color space. This makes it possible to compare performance with other spectral imaging systems using it as a standard. The acrylic Pébéo chart has 15 pure pigments among the 117 glossy applications, the remaining 102 being mixtures of pigments achieved from 38 pigments used during the 19^{th} and 20^{th} century. The oil Pébéo chart is similar to the former with modern pigments in an oil-based binder. The test charts were completed by Spectralon reflectance standards featuring the following characteristics: 99, 50, 28 and 12% reflectance and 99% Teflon white.

Figure 7: Targets used to evaluate performance and white calibrated patchs.

3.2 Method

During the stage following setup of the equipment, the camera is set using the control software. The aim is to reach a compromise in order to achieve optimal quality in a limited acquisition time, without being able to restart the experiments in the event of mistakes. A high-quality image must be sharp, preserve its initial geometry and feature a low level of noise. In order to achieve these goals, it is necessary to know the behavior of the camera and how each parameter (aperture, gain and integration time) influences the rendering. Once they have been set, the calibration stage records the levels of dark noise, inter-pixel differences, changing lighting and vignetting ($\cos^4$ fall-off) of the lens in order to enable relevant adjustment. Lastly, the masterpiece is placed on the easel for the image acquisition process, the meaning of which appears after appropriate processing.

3.2.1 Camera settings

Optical computing revealed a theoretical depth of field of 12.59 mm on the document with a diaphragm set to f/8. According to the technical archives relating to the masterpiece and by visually observing a curvature of approx. 8 mm of the poplar panel, it was decided to shoot again the fastest digitizations (five 520-680 nm filters) with an increased diaphragm at f/11. The depth of field increased and reached 19 mm. The lens is equipped with a symmetrical optical formula and the magnification ratio achieved is 10.5. The chromatic aberrations generate a different focusing value for each filter (see Table 1), focusing is carried out by shifting the lens using a power-driven gear. Using the ISO 16067 Target, we obtained a resolution indicator MTF (Modulation Transfer Function) equivalent to 51% for spatial frequency equivalent to16 lp mm^{-1} (8 pairs of B/W lp mm^{-1}) at 300 dpi. An extrapolation for the real *Mona Lisa* resolution (372 dpi) of 14.6 lines/mm instead of 16 gave an average MTF of 60%, and 99% with software processing.

Filters :	No filter	400	440	480	520
thickness (mm) :		6.48	5.32	5.3	5.05
Image-Lens distance (mm) :	229.8	232.4	231.8	231.7	231.5
Filters :	**560**	**600**	**640**	**680**	**720**
thickness (mm) :	3.75	4.11	3.8	2.58	4.5
Image-Lens distance (mm) :	231	231.2	231.2	231	231.8
Filters :	**760**	**800**	**900**	**1000**	
thickness (mm) :	4.59	4.8	4.45	4.58	
Image-Lens distance (mm) :	231.9	232.1	232.3	232.6	

Table 1: Image-Lens distance and thickness for each filter.

The lens-to-image distance variations were compared with that of the manufacturer's technical specifications (see Figure 8). We observed a decrease followed by an increase around a reference position placed at 560 nm. The differences observed are equivalent to the heterogeneous thickness of the filters, the standard deviation of which on all of the 13 filters is $\sigma = 0.90$. The maximum lens-to-image distance observed between filter 560 and filter 1000 is 1.6 mm.

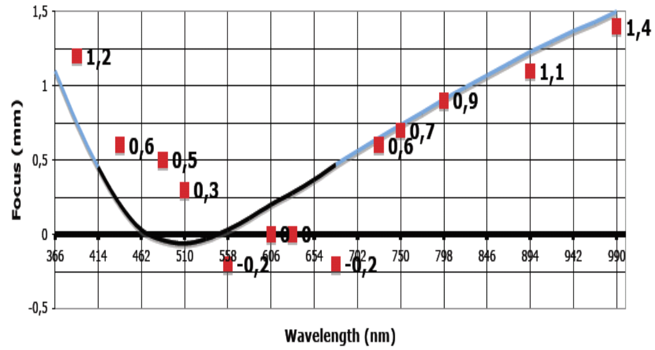

Figure 8: Focus position compare to a reference position (filter 560), black :Manufacturer's technical datas.

3.2.2 Gain

The electronic system of the camera is based on an integrated circuit dedicated to capturing images and includes signal conversion. Quantification is carried out by an analog-to-digital converter (ADC) on 12 bits. The available programmable gain amplifier enables an amplification range of –6 dB to 42 dB in linear progression.

Filters :	No filter	400	440 to 900	1000
Gain (dB) :	Variable	15	9	22

Table 2: Gain setting for each filter.

The choice of this setting (see Table 2) is a compromise to carry out digitization in a specific time slot while maintaining high quality. The relation between the gain level and standard deviation of the dark noise – described in the publications relating to the assessment of the camera[3] – makes it possible to set this optimal adjustment. Once the aperture and gain have been set, the system regulates – for a calibrated white target – an exposure time for each filter between 1.3 ms and 200 ms. For the sequence achieved at f/11, the exposure times were doubled and the gain settings retained.

3.2.3 Calibration

Once the parameters are set, the calibration phase may start in order to obtain the same level of response of the camera for each channel. Before placing painting on the easel, two extra digitization series are required. The aim of the first series is to record a white reference, the spectral nature of which is known and the size of which is similar to the scanning area. The second series is carried out when recording the response of the camera in the dark. A series of factors is determined and applied to the original image. Each of the images derives from a high-definition acquisition comprising the same amount of pixels as the images of the painting. The post-processing sequence starts by removing dark noise from the raw image, compensating inter-pixel differences and adjusting the lack of homogeneity of the lighting and the lens in order to obtain a calibrated image (See Figure 9).

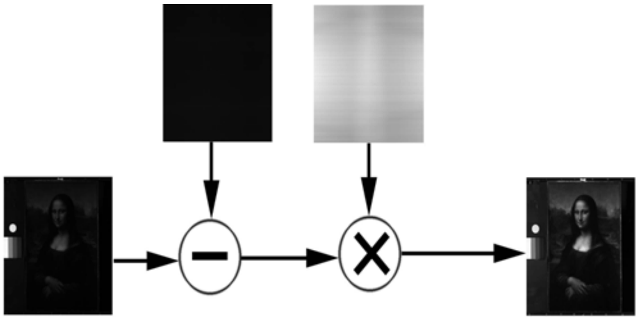

Figure 9: Calibration process diagram.

Image resizing is required in order to obtain an adaptive method taking into account inconstant distortions in the images – homothetic transformations, rotations and translations. The solution derives from 3D morphing techniques – i.e. homography. This method utilizes points of reference and resolution targets that are present in the various layers. The results achieved using this technique are excellent and the registration problems become invisible on the final images (see Figure 10).

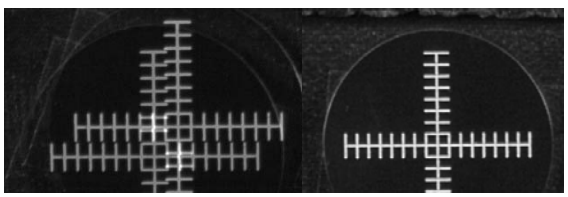

Figure 10: Resizing example.
Left : 2 layers without correction, right : corected image.

3.2.4 Image acquisition

After the essential calibration and setting phases, the system is ready to digitize works of art. A last validation phase was implemented with several masterpieces, among which a painting by Pierre Auguste Renoir. On 19th October, we had the honor of meeting Mona Lisa and taking photos of her authentic smile. The shots were taken in two phases: global frames of the entire masterpiece, followed by macro frames of the face (see Figure 11). The second series was not originally planned but was nevertheless carried out given the participant's enthusiasm further to the appearance of the first images on the screen. A first series of 18 shots (13 at f/8 and 5 at f/11) was conducted by the photographer Pascal Cotte and represents new documentary reference data on the masterpiece. The entire digitization session lasted 91 minutes. The second series required a modification of the system to accomodate extremely short remaining times available. The camera was moved closer until it stood 60 cm away from the masterpiece to capture the details of the face. It was then impossible to shift the lighting and therefore synchronize it automatically, given that the measurement configuration was beyond the tolerance permitted by the detection algorithm. Starting from a manual synchronization, a series of four shots was taken with the filters centered on 560, 800, 900 nm and a last one without filters. Each photo was taken with two spaced out focusing processes given that the depth of field was reduced and finding sharpness was tricky. The entire digitization session for this second image lasted 34 minutes and enabled a remarkable rendering of the details. The performances achieved during this photographing session are unique (see Table 3).

	Global:	Macro:
Resolution (dpi):	372	1523
Resolution (pixel per mm^2):	216	3627
Pixel size of image (µm):	68	16.7
Definition (Mpixel):	137	240
Scan area l x h (mm):	779 x 818.67	333 x 200

Table 3: System performance.

In order to translate these results into facts, we must imagine images displayed on a 1600 × 1200 standard definition 21″ screen. The global frame enables full-screen display (true size of the pixels) of a 81.6 mm × 108.8 mm area which would require 80 screens to be fully displayed. In full-screen mode, the macro frame would display a 20 mm × 26.72 mm area and require 130 screens for the image to be fully displayed.

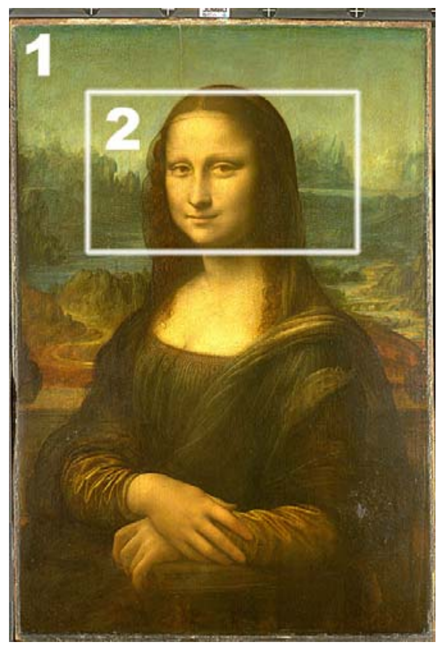

Figure 11: Mona Lisa global frame (1) and macro frame (2).

3.2.5 Image processing : Digital signals to reflectance

From these 13 filters, the camera reflects 13 digital values for each pixel. A reflectance curve depending on the sampling interval needs to be defined on a minimum of 41 values in the 380-780 nm interval. An estimated reflectance curve from the camera is defined using 61 values in the 400-1000 nm interval. Several methods may be used to create these intermediate points: direct or indirect reconstruction and interpolation reconstruction. Direct reconstruction is based on a thorough knowledge of the acquisition system, the implementation of which is tricky due to the determination of the noise. Indirect reconstruction or acquisition reconstruction requires the presence on the images of a standard color test chart. A transfer function between the spectra measured on the test chart and the camera response is generated by extrapolation. Interpolation reconstruction solely focuses on the camera response and does not require any color test chart in the image but a white reference (see Figure 12). After standardization with this white reference standard, the camera is considered as a spectrum sampler that records a specific point of the curve once every 40 nm in the visible range. We must then interpolate to find the missing points.

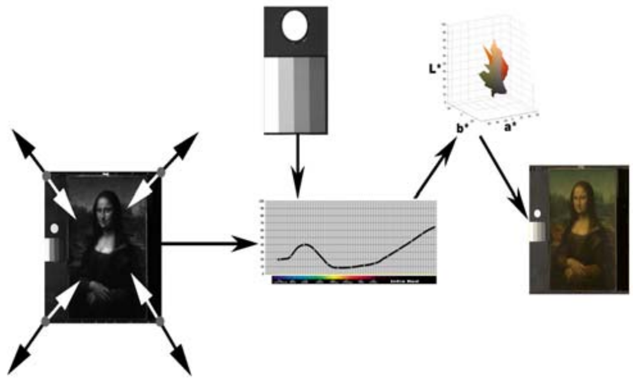

Figure 12: Reconstruction process diagram.

In the next part about color performance, we develop the methods used for taking photos of the *Mona Lisa*. Before presenting the results, we would like to explain several corrections that were carried out on the images before the full reconstruction. A series of defaults was observed: the specific orthogonality of the sensor was not observed and a 0.38° correction was implemented on all the images. The interference filters were measured once more to refine their dominant wavelength. In the case of interpolation reconstruction, we observed better performances after this correction. During the global photographing session, the entire scan area was not utilized. Centering framing solely on the scanning area enabled a faster digitization process. This function – which had never been utilized with the prototype camera– does not observe the sequential distribution of the image lines. All the information was available but in a muddle. After having assessed the defaults, the correction restored the scientific validity of the image. Finally, the variable measurement configuration – synchronized lighting – is an additional parameter that must be taken into account in order to optimize performance.

4. Results and applications

Once the images have been processed, the results are like rediscovering the masterpiece. Saving the images requires a 24-GB storage capacity. Through a 40 nm bandwidth followed by a 100 nm bandwidth in the near infrared, the portrait reveals new details (see Figure 13). The spectral reconstruction gives access to a high-fidelity digital color original, the performances of which are described in the next part. The nature of the data makes it possible to simulate the lighting of the masterpiece under various illuminants and to suggest virtual restorations. Lastly, the reading of spectral samples allows us to visualize and compare the reflectance curves with typical signatures of a spectra and pigment library. The high definition enables examination of each segment of the painting as a new independent entity, and makes it possible to retrace the pictorial technique and study the patchwork of cracks.

Figure 13: Each channel of spectral acquisition and a reconstruction with daylight illuminant (D65).

4.1 Spectral performance

We have described the test targets and reconstruction methods in the previous parts. The spectral data measured by spectrophotometry (d/8° geometry) and estimated by spectral imaging were compared with different indicators: RMS (Root Mean Square) and GFC (Goodness-of-Fit Coefficient). We used CIE equations of color difference ΔE_{00} and metameric index (D65 ▸ A, ΔE_{00}) in order to assess colorimetric accuracy using D65 and a 2° observer (see Table 4). We applied the interpolation method for the reconstruction given that the pigments used in the Pébéo or colorchecker DC test targets are not representative of the period during which the painting was achieved. On the other hand, the presence of synthetic pigments with highly-selective reflectance curves make these test targets useful for assessing the system performances by increasing the difficulty of the reconstruction.

Target :	**ΔE_{00}**	**RMS (%)**	**GFC**	**Metameric Index (ΔE_{00})**
Pébéo	2.13	4.8	0.996	0.39
Colorchecker DC	1.86	6.2	0.997	0.41

Table 4: Spectral and color accuracy with interpolation method.

The results obtained are really excellent given the complexity of the test target used as representative of the 19^{th} and 20^{th} centuries. The interpolation method offers performance stability were described in previous publication[5].The estimated spectral curves are very close to that measured and enable pigment identification. By comparison, here are – for information purposes – the performance values regarding indirect reconstruction of the aforementioned test targets: Colorchecker DC ΔE_{00} = 1.22 (0.12 – 8.1) and Pébéo ΔE_{00} = 1.24 (0.23 – 10.9). For the time being, indirect reconstruction cannot be applied to the Mona Lisa given that it requires a dedicated test target corresponding to the era of Leonard De Vinci which we will obtain over the next few months.

4.2 Image rendering and infrared data

Spectral acquisition makes it possible to work out colorimetric coordinates for all illuminants (whether standardized or not) and observers. In the case of the *Mona Lisa,* this simulation is possible but the chromatic discoloration of the varnish – that acts like a filter on the perception of the painting – reduces the significance of the process. A first approach to minimize this effect is to carry out calculations for a daylight illuminant with a high

D95-type color temperature (black body: 9500 K). The simulation under several illuminants will pick up its full meaning after a virtual restoration dedicated to eliminating the yellowy influence of the varnish. In the part about preventive conservation, we have worked out the amount of days of exposure in the museum equivalent to the digitization of the painting. This result must be considered in context with the possibility of indefinitely using this digital original under a lighting that is impossible to consider in the museum. Reflectography in the near infrared makes it possible to look into the paint layer using a lower diffusion of the photons on the pigments. The new inaccessible information is as follows:

- Pentimento (see Figures 14 & 15).
- Underlying drawings (see Figures 16 & 17).
- Restoration works (see Figures 18 & 19).
- Underlying cracks.
- Overpainting.
- Discrimination of similar reflectance curves in the visible range.

The processing of infrared images in false colors enables easier highlighting of the differences between the visible and invisible image. The sharpness thus achieved cannot be compared with traditional systems and photographic emulsions sensible to infrared radiations are now practically entirely unavailable. The absorption of UV radiation can result in the reemission of photons in the visible spectrum, called fluorescence. Historical restoration can be more easily revealed when the camera and a UV lamp are used together on different varnishes.

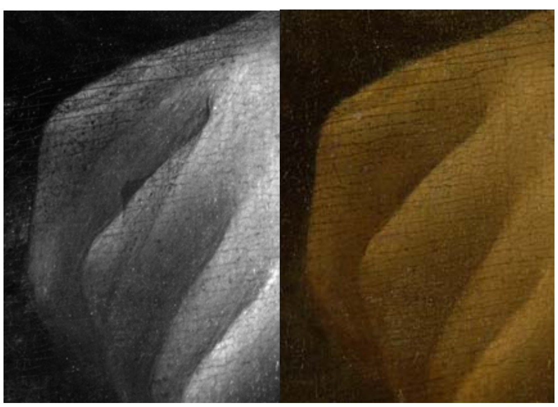

Figure 14&15: Infrared reflectography, overpainting (repaint).

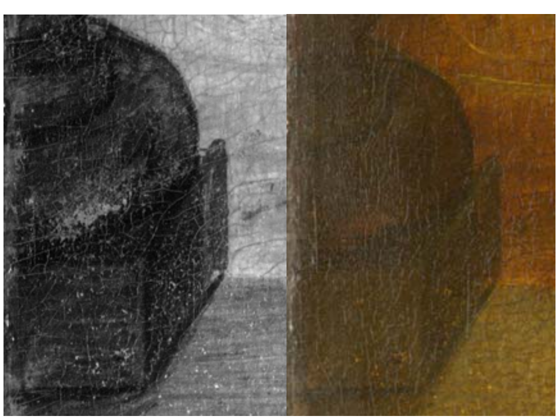

Figure 16&17: Infrared reflectography.

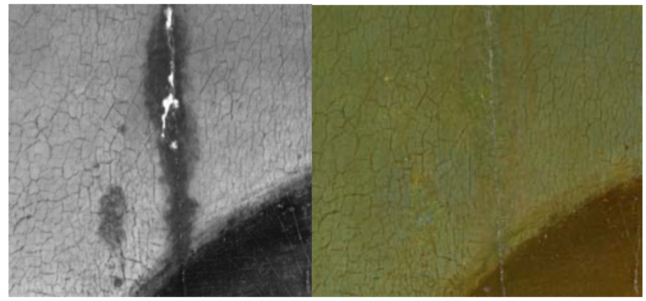

Figure 18&19: Infrared reflectography, overpainting (in paint).

4.3 Revajunating painting & pigment identification

The materials of this famous masterpiece have been modified over time and due to the conservation conditions. The wooden support has shrink and influences a type of crack presented hereafter. The features of the binder, pigments and varnish have changed due to their own ageing process or due to the interaction with other materials. We visually note the modification of the varnish applied as a protective layer during a restoration at the beginning of the 17^{th} century – probably to offset dampness problems. The loss of opacity of the lead white is an example of pigment modification. The binder also tends to turn yellow. In cooperation with restorers and curators, it is possible to consider restoration offers based on material knowledge and analysis. The period of the masterpiece – beginning of the 16th century – implies a limited range of pigments and mastic or rosin varnish. Based on measures of recreated and artificially-aged lead white, pigments and varnish, a varnish removal process of the painting has been carried out. The aim is to restore the initial spectral reflectance of a pure white pigment and monitor the global modification on other likely pigments in the painting. The results enable a better readability of the masterpiece with a restoration of the color ratios (sky, river, skin tone, dress), and the portrait and landscape thus recapture their full depth. The global modification must be considered as an intermediate phase prior to taking into account other effects in the paint layer such as the various thicknesses of the varnish and local interactions depending on the relevant materials. We are currently studying the various available restoration suggestions, in particular concerning the elimination of the varnish color, yellowing of the binder, specular reflections and cracks. Pigment identification is possible due to Leonardo Da Vinci’s fairly limited palette. The absence of a typical signature in that which is visible with a high proportion of earth and ochre pigments is offset by the additional infrared information. For example, samples in the sky make it possible to distinguish lapis lazuli and azurite pigments through a different bleeding in the red pigments and near infrared radiations (see Figure 20).

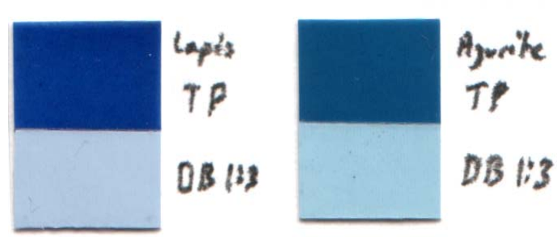

Figure 20: Targets used to distinguish blue pigments (Perego collection).

4.4 Analysis of cracks

After the Mona Lisa was stolen in 1911 at the Louvre, the masterpiece was found again in Florence in 1914. It was authenticated by comparing the patchwork of cracks with photos and the presence of the seal of the Louvre. This patchwork of cracks captured by the high-definition camera becomes a unique, fingerprint-type feature of the masterpiece which cannot be reproduced. Various types of cracks have been noticed in the painting (see Figures 21, 22 & 23), the examples illustrated in this publication being linked with the ageing of the lead white, the nature of the paint layer and the modification of the support features.

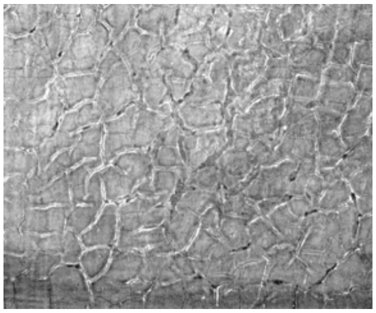

Figure 21: Cracks on lead white region (sky).

Figure 22: Horizontal cracks (veil).

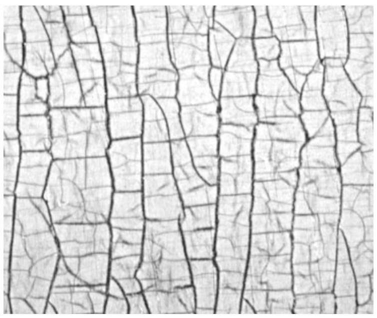

Figure 23: Vertical rectangular cracks (fronthead).

5. Conclusion

The photo of the *Mona Lisa* taken by Pascal Cotte gives significant substance to the curatorial file of the masterpiece using a nondestructive and portable technique. This unique system is capable of reproducing a masterpiece accurately and revealing details of its history. The description of the technical choices makes it possible to sum up the numerous precautions required during the digitization of fine art paintings. This system is currently the only commercially-available device dedicated to such use. Its main advantage lies in the fact that this digital original allows the Mona Lisa to be taken out of its showcase. This different point of view – usually kept for a privileged few – enables a new understanding of the masterpiece along with the opportunity to choose the lighting and restoration hypotheses. The accuracy of the details enabled by the high definition and easy navigation in a digital image bring forth a new way of studying it. This magnifying effect helps describe the artist's technique, cracks and accidents such as the stone that was thrown against the painting in 1952. The recording of the patchwork of cracks and of the color of the painting at a specific time represents a milestone in the life of the masterpiece. Indeed, a regular reassessment using this tool will enable quantification of the evolution of the materials over time and make it possible to plan conservation schemes where appropriate. By digitizing several of Leonardo Da Vinci's works and comparing them based on color and shape criteria, the multispectral data will have even greater significance. We have briefly described the numerous available applications in the last part. We will come back to each specific application in later publications to restore – besides the mythical painting – the original splendor Leonardo Da Vinci gave to his *Mona Lisa* thanks to his perfect technical know-how.

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Author Biography

Pascal COTTE is the founder and President of various companies specializing in digital imaging since 1980 and has designed and developed numerous R&D systems in the field of electronic imaging. He has invented 6-band and 13-band multispectral cameras and obtained numerous patents in the field of multispectral imaging and lighting systems. Pascal received his bachelor's degree at the French Lycée in Sao Paulo, Brazil. He then received post-graduate education in computers and electronics followed by optics, light and color in Paris. France.

Damien Dupraz received his engineering degree in photography from the Ecole Nationale Supérieure Louis Lumière, France in 2002. After one year in the French Museum Research and Restoration Center as color engineer, he began a Ph.D. in spectral imaging with Lumière Technology compagny and Paris VI University.