Chapter

Reflectance Measurements on Cultural Heritage

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Abstract

Cultural heritage is a valuable and characteristic symbol of every country. It should be handled with care and it must be exhaustively investigated and measured with non-destructive techniques. In this chapter, we will talk about different reflectance measurement techniques to obtain the conservation state of the artwork. With this reflectance characterization, conservators, and curators could soon determine the best maintenance procedures for restoration purposes. Also, a new technique for lighting will be discussed, where the artwork can be also photonically restored illuminating with the correct light in the desired area of the artwork using a spectrally selective projection system.

Keywords: reflectance measurements, non-destructive, characterization, virtual photonic restoration, artwork, cultural heritage

1. Introduction

The color of an object depends on the reflectance properties of the object that are dependent on its physical and chemical composition. But also, color depends on the light source and the human being that views the object [1]. In this case, the light source and the observer who sees the artwork can vary but the reflectance of the artwork is inherent to it. Digitalizing artworks or paintings for color-accurate measurements is widely studied in the literature; usually, CIE color spaces must be considered to match reflectance and perceived color [2].

Spectral reflectance defines how a material reflects light when it hits the surface. The reflectance is a function of the incidence angle and the material itself. It can be quantified with different methods. The Commission Internationale de l'Eclariage (CIE) has a recommendation that comments on the practical methods for the measurement of reflectance and transmittance [3]. The best method to measure reflectance is the use of an integrating sphere. Classical colorimeters use this optical technique and are widely used in the industry, for example, in the automotive sector. The use of an integrating sphere needs contact with the surface, so it is not recommended in cultural heritage because of possible damage to the artwork. In this case, following the CIE recommendations and the geometric conditions, it is possible to use a light source and a spectrophotometer, **Figure 1**. This setup is

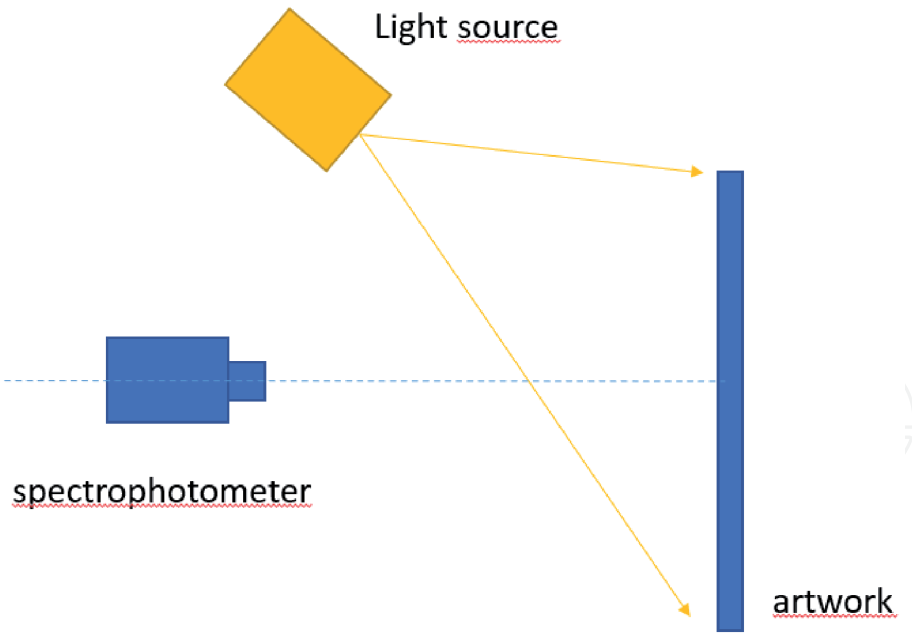

Figure 1.
Schematic setup for non-contact spectral reflectance measurements.

non-destructive for the artwork and requires a white diffuse reflectance standard, a stabilized light source, and a spectrophotometer, both of which should be positioned carefully at 45° or the desired angle to measure the reflectance.

The measurement process involves the use of a calibrated white diffuse standard that will be measured in the same position as the artwork. The spectral reflectance will follow the formula:

$$\rho(\lambda) = \frac{\phi(\lambda)_{out}}{\phi(\lambda)_{in}}, \tag{1}$$

where F_{out} is the reflected flux and F_{in} is the incident flux that must be obtained using the reference white that has a known spectral reflectance, so:

$$\phi(\lambda)_{in} = \frac{\phi(\lambda)_{out}}{\rho(\lambda)_{standardwhite}}. \tag{2}$$

Using this technique, the spectral reflectance of an artwork can be measured point by point, but a spectrophotometer measuring in this way has a circular relative measurement area of around 5 mm in diameter that depends on the used object lens and the focusing distance, as in the example of the spectral characterization in Picasso's painting *Guernica* [4]. Therefore, the utility of the measurement as a global characterization is low because part of the area of the painting is not covered by the measurements.

This measurement procedure can also be applied to sculptures, but there is a higher difficulty in establishing the correct illumination and detection angle than usually is recommended like angle 45° incidence and 0° detection. **Figure 2** shows a spectroradiometer being calibrated with a white standard. The system comprises a lighting ring and a portable spectroradiometer. The system is designed to light in a 3D annular way with 45° over the selected surface and receive light at a 0° angle for

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Figure 2.
Spectroradiometer with standard white at Pórtico de la Gloria.

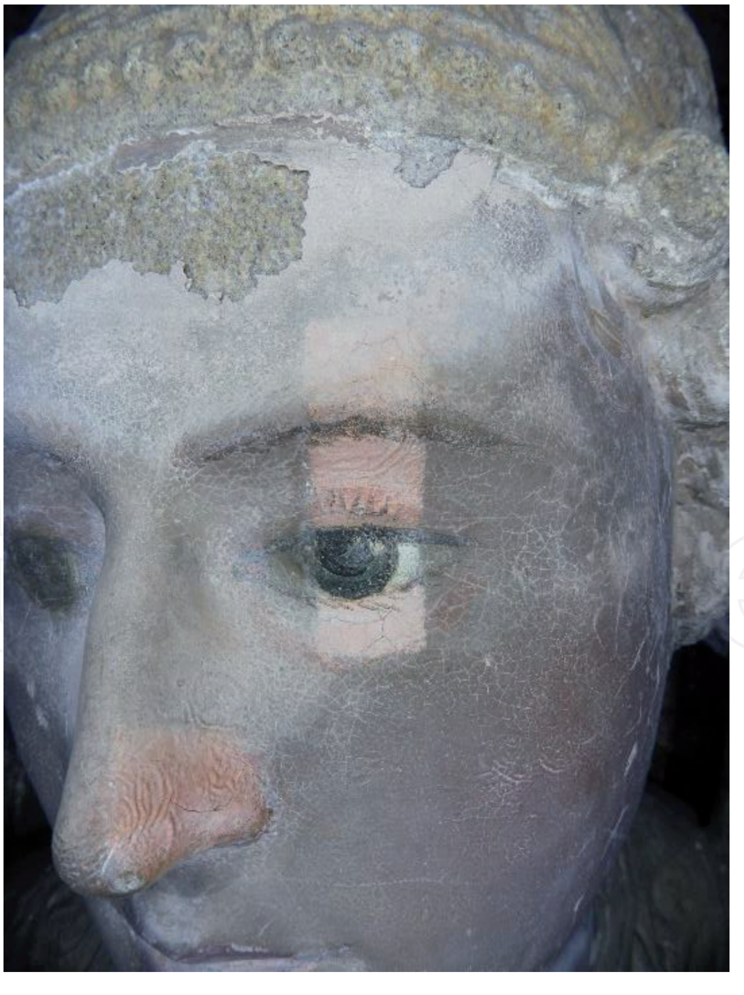

Figure 3.
Sculpture head with cleaned area in Pórtico de la Gloria. Santiago de Compostela.

spectroradiometric detection. The white diffuse reflectance standard had a reflectance of 0.75 over the visible spectrum, and if the same distance as in the sample is maintained, the absolute spectral reflectance is properly measured.

The system was used by the authors of this chapter to measure the Pórtico de la Gloria at Santiago de Compostela's Cathedral in Spain. One of the most complex problems in measuring spectral reflectance on sculptures is that the system must be not only aligned with every *x, y* point surface normal but also at the defined calibration distance. This setup was used to evaluate pigment cleaning over laser and chemical cleaning procedures. **Figure 3** shows the cleaning process that was done by Fundación Barrié, which was the leader and the funder of this project.

To solve the problem of measuring only a small area, it is possible to measure multi- or hyperspectral data with high spatial resolution and also integrate spectral data into a 3D coordinate system [5]. This method uses a multi- or hyperspectral camera usually called a 2D spectroradiometer that needs to be calibrated to obtain good acquisition data [6].

Multispectral or hyperspectral imaging is based on a calibrated CCD that has a set of bandpass filters to obtain the hyperspectral data cube. These bandpass filters are usually installed in a rotational optomechanical wheel.

In this chapter, we will discuss the use of 0–45° reflectance measurement system applied to two Picasso paintings, one for control of the painting condition and the other one to determine the effects on restoration of eliminating a varnish layer that was added after the painting and was drawn by the artist. In the next section, we will introduce a novel design that has a matrix of CCDs with a bandpass filter in front of each one. This will be used for spectral reflectance measurements on Dali's painting *Dos Figuras,* which gives a better resolution on the painting spectral data. Finally, conclusions will be presented.

2. Reflectance measurements on Picasso's paintings *Guernica* and *woman in blue*

As commented in the introduction, spectral measurements can report and are part of the preventive conservation of cultural heritage. If the artwork has been measured during time pass you got a time photograph of conservation and deterioration with regard to color. But non-invasive techniques are required in order not to damage the artwork. In the first part of this section, we will describe a spectral measuring system and a lighting source that are designed for reflectance measurements in a large artwork painting (dimensions 7.77 m × 3.49 m) [4] with non-contact and non-invasive techniques.

Guernica was painted by the famous Spanish artist Pablo Picasso in the year 1937. The artist painted it to attract the world's focus to the Guernica Basque country town located in northern Spain. This village was bombed by the German and Italian army on April 26, 1937. The painting was charged to Picasso by the Republican government for the 1937 Paris' World Exhibit forum. This painting is related with the sacrifice of war and is considered by experts as a peace and anti-war symbol.

We will show a detailed matrix data of Picasso's *Guernica* paint by measuring reflectance factors in selected points located in rows and columns over the painting. After the measurement process, a database containing spectral and colorimetric data has been obtained. This database is georeferenced on the painting and could be useful in the future to track the conservative status development of this painting. This database also could be useful to optimize lighting when exhibited.

2.1 Measurement system configuration

A non-contact spectrometer, a lighting source designed for this task, and several additional instruments conform to the measurement system. Spectral

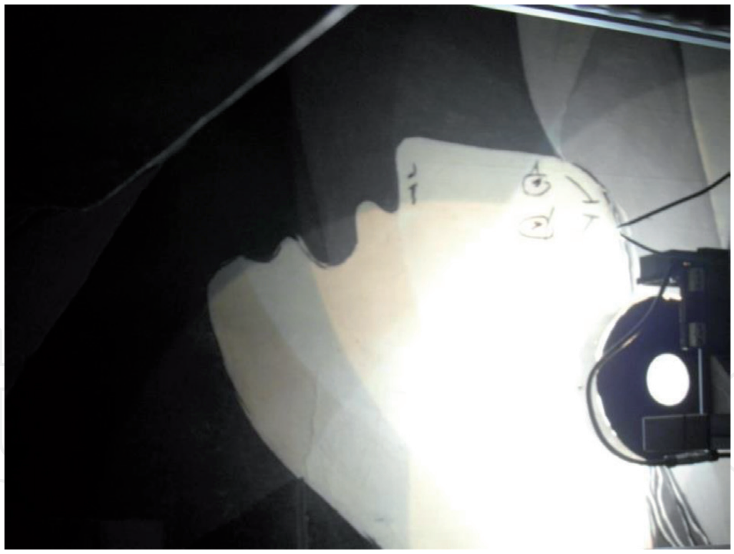

Figure 4.
Annular ring source for 35° lighting with a hole in the central area for spectroradiometric measurement.

measurements were taken between 400 and 780 nm every 4 nm with a Photo Research PR-655 spectroradiometer equipped with MS-75 accessory optical lens [7].

Geometrical conditions are determinant on the measurement repeatability, and in this case, the instrument was placed 570 mm away from the painting surface. The relationship with instrument optical lenses makes that the measured area reach 23.7 mm^2. The lighting source was placed around the spectroradiometer in a ring-shaped form with an angular incidence of 35° with the normal vector of the measured area, **Figure 4**.

It must be noted that reflectance data are dependent on angular conditions; thus, obtained data for lighting at 35° could be different when lighting is at 45°. Therefore, system configuration should be maintained in the case of new measurements along time.

The source was made of four halogen light bulbs at 3500 K and eight white LEDs at 6500 K. The halogen light bulbs were selected to fill the spectra in the wavelengths that the LED has less flux to improve the spectral response of the system. The lighting system was powered by a current power supply to improve LED stability over time, and anyway during the measurement process lighting condition will be checked using the standard patron. **Figure 5** shows the spectral emission of the designed source used to light the measurement area.

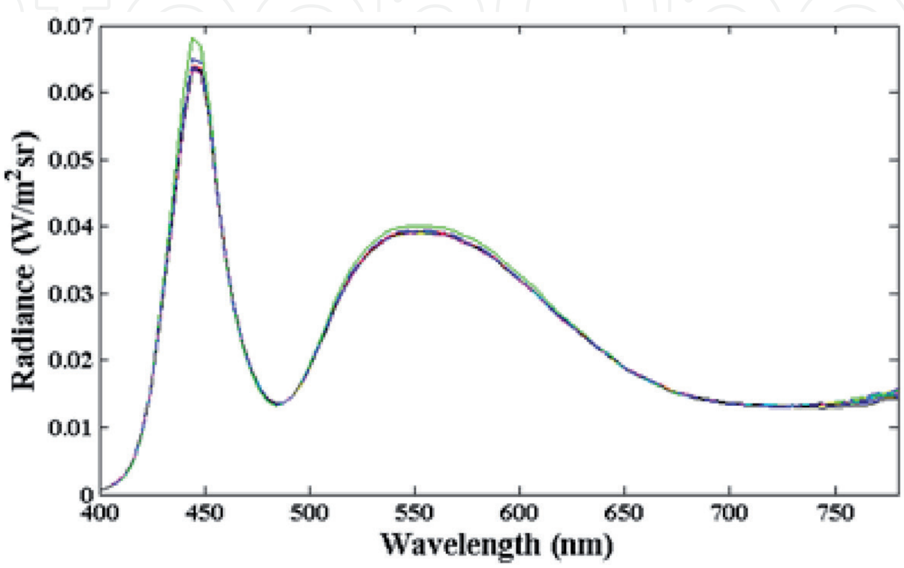

Figure 5.
Source spectral radiance (halogen+LED).

The use of a LabSphere white diffuse reflectance standard during the measurement permits us to obtain the reflectance factor at the desired x, y location. In this way, temporal changes on the source flux due to aging, current variation, or any other are considered in the reflectance calculation.

2.2 Cartesian displacement device

The painting dimensions required a large rail displacement system; in this case, XYZ Cartesian rails were developed with position accuracies of 25 microns on each axis. On board this rail, there were a platform that was moved by a computer system linked to the instruments. Onto this platform, the spectroradiometer with a CCD and a computer-controlled laser telemeter were installed. The laser telemeter was of higher importance because it permits to place the scientific instrument at a constant distance from the painting surface. As it was demonstrated after the painting surface has a topographical variation in the Z-axis making the surface non-flat, **Figure 6**. These deformations did not affect the measurement accuracy because the instrument was placed at a controlled distance all over the painting. The large dimension and weight of *Guernica* is part of this topographical issue that is not visually noted.

2.3 Color calibration

To ensure the correct calibration of the system, it is necessary to check performance all over the measurement process. One of the most used charts for color calibration is the GretagMacbeth ColorChecker (X-RITE). In this measurement process, the 24 chart samples were measured. Each sample spectral reflectance factor and the CIELAB Lab data were collected. For this calculation, CIE 1931 standard observer and D50 CIE illuminant were used. The instrument deviation in relationship to manufactured data was of ΔE = 1.16 CIELAB color units.

2.4 Reflectance data

Reflectance data from 2201 points were measured with this technique. The time for measuring that number of points was around 10 h working at night for 3 days. The measurement process is slow due to the robot movement and the stabilization period where the system needs to stop before a measurement is made [8].

Figure 6.
Guernica topography matrix, data in mm.

These reflectance data along points were required by Museo Nacional Centro de Arte Reina Sofía in a specific format to have a valid reference for future inspection on the conservation state of the painting. As an example, **Figure 7** shows two of the selected points, one on white pigment and another one on black pigment. The circular black area in the zoomed images on the right (samples 7 and 1) is related to the measurement area as can be shown in **Figure 7**.

With the obtained data reflectance is calculated, **Figure 8** presents the spectral differences in two different samples. In this case, sample 1, which is mainly composed of a white pigment, has a higher reflectance than sample 7, which is measured over a black pigment.

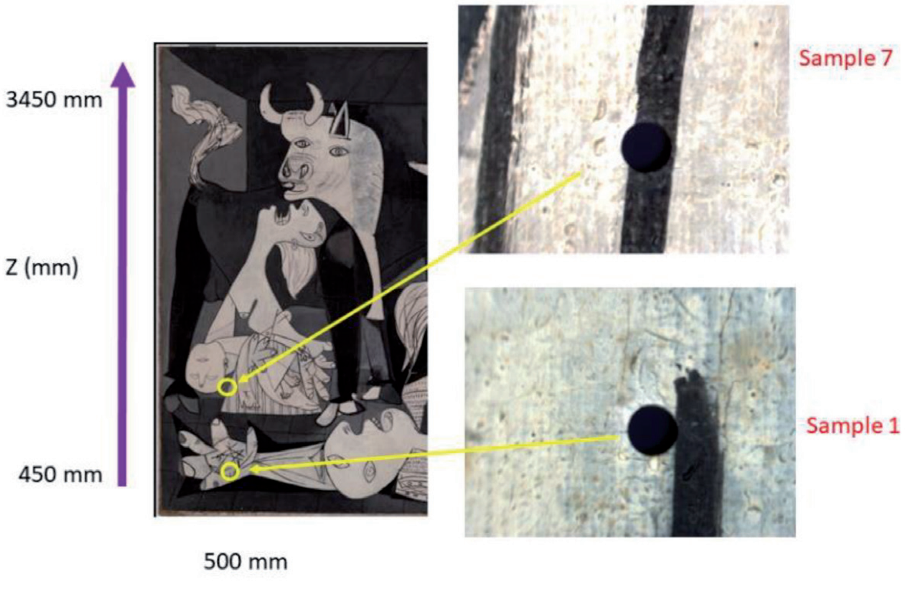

Figure 7.
Sample measurement area and detail for samples 1 and 7.

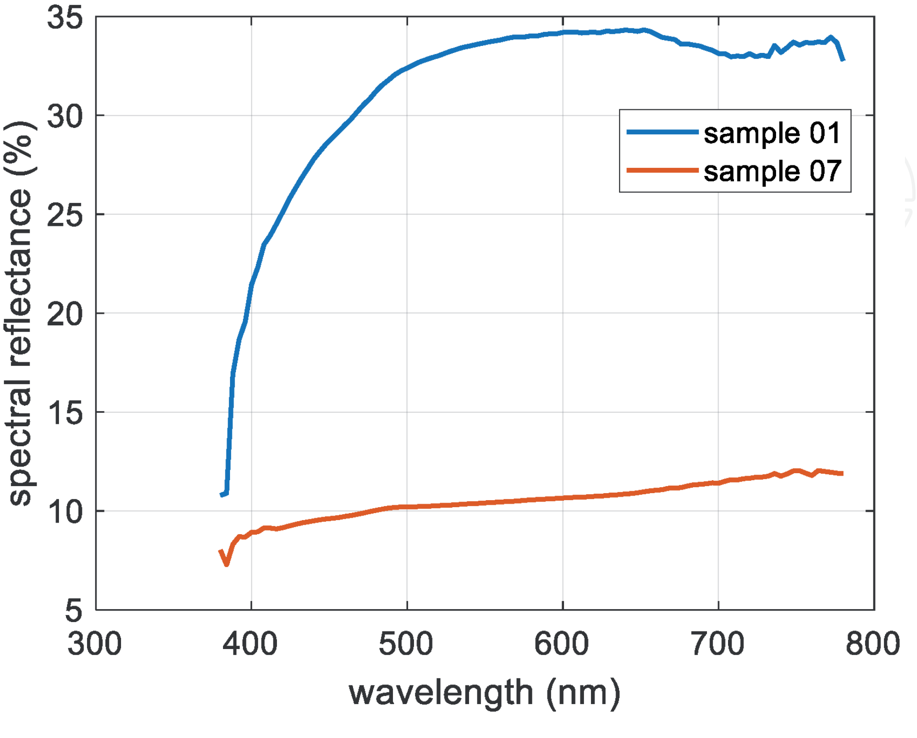

Figure 8.
Spectral reflectance for samples 1 and 7.

3. Reflectance measurement on Dali's painting *dos Figuras*

The project Photonic Restoration Applied to Cultural Heritage on Dali's painting *Dos figuras* (1926) is a competitive project subsidized by the Spanish Ministry of Science, Innovation and Universities. The project aim is to restore virtually with light projection the Dali painting "Dos figuras". This restoration will require and will be based on spectral measurement data.

This painting is in a bad state of conservation with some irreversible damage that prevents the painting from being appreciated in its original state, **Figure 9**. The Reina Sofía Museum has consolidated the canvas and stabilized the pigments to avoid further damage. But to maintain the painting, it was decided not to intervene anymore in a physical way after consolidation was done. Thus, this project opens the possibility to restore this painting virtually without physical intervention, just with light.

The project was divided into three phases: The first one is the study of the artwork and the process that has led to the actual conservation state (**Figure 10**); the second one is the characterization of the reflectance of the painting and the obtainment of 3D geometric data; the final phase consists in designing an algorithm to virtually restore the painting without physical intervention.

To characterize the painting, it is possible to use any of the reflectance methods commented in previous paragraphs. The example of the characterization of *Guernica* is a low-resolution method, therefore the UCM team (www.ucm.es/lightingandcolor) decided to improve the characterization resolution. In this way, a new design of a hyperspectral camera [9] with higher resolution and an interchangeable filter possibility was necessary.

3.1 Hyperspectral matrix camera

A hyperspectral camera is a system that can measure a hyperspectral cube of spectral data [10]. Typical scientific hyperspectral cameras have resolutions of around 1.4 MP. In the case of this painting, which is 2 m long, it implies approximately 1 × 1 mm square measurement resolution in the painting. This could be improved with higher sensor resolution. The designed CCD has 12 cameras, **Figure 11**, with a 12.3 MP

Figure 9.
Original state showing the painting and Dalí, year 1926.

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Figure 10.
Painting dos Figuras (1926), Salvador Dalí, year 2021.

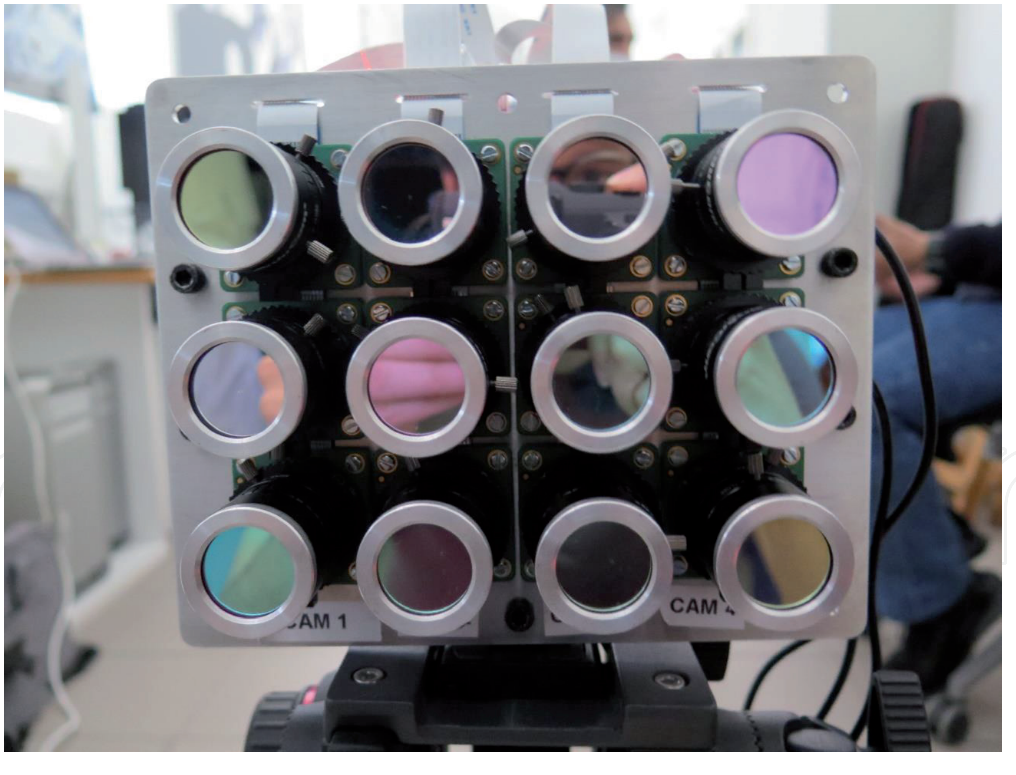

Figure 11.
Optical filter detail for hyperspectral camera.

sensor that provides a 0.3 × 0.3 mm resolution on the painting for spectral reflectance data. The hyperspectral camera can be suited with 12 narrowband filters selected depending on the measurement needs.

This camera is currently being calibrated on the group laboratory, **Figure 12**, using a calibrated reflectance standard and a stabilized LED light source. Also, for spectral reflectance measurements, a white background was previously measured and accordingly calibrated in spectral reflectance. This white background was made of a uniform rectangular piece of foamed PVC and once calibrated, it will be used to calculate spectral reflectance all over the picture area.

Hyperspectral system calibration is essential to obtain reliable measures and needs to be executed before any measure is made. In **Figure 13a**, comparison is made between a commercial system that measures each 4-nm band but only in a

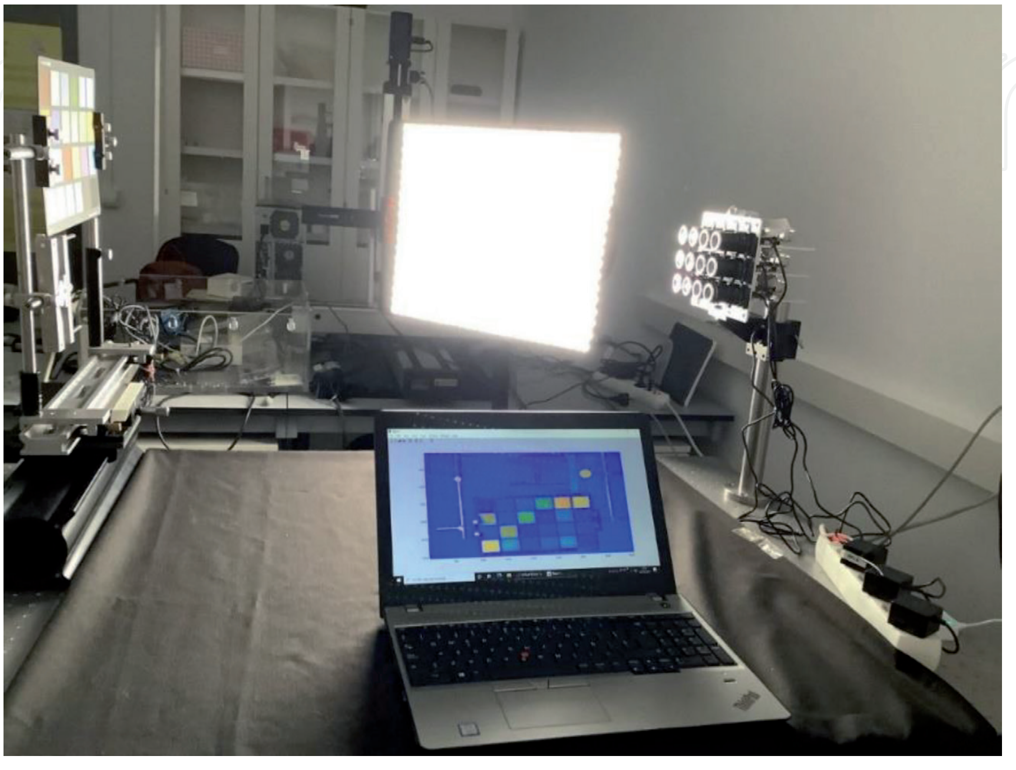

Figure 12.
Hyperspectral CCD calibration procedure.

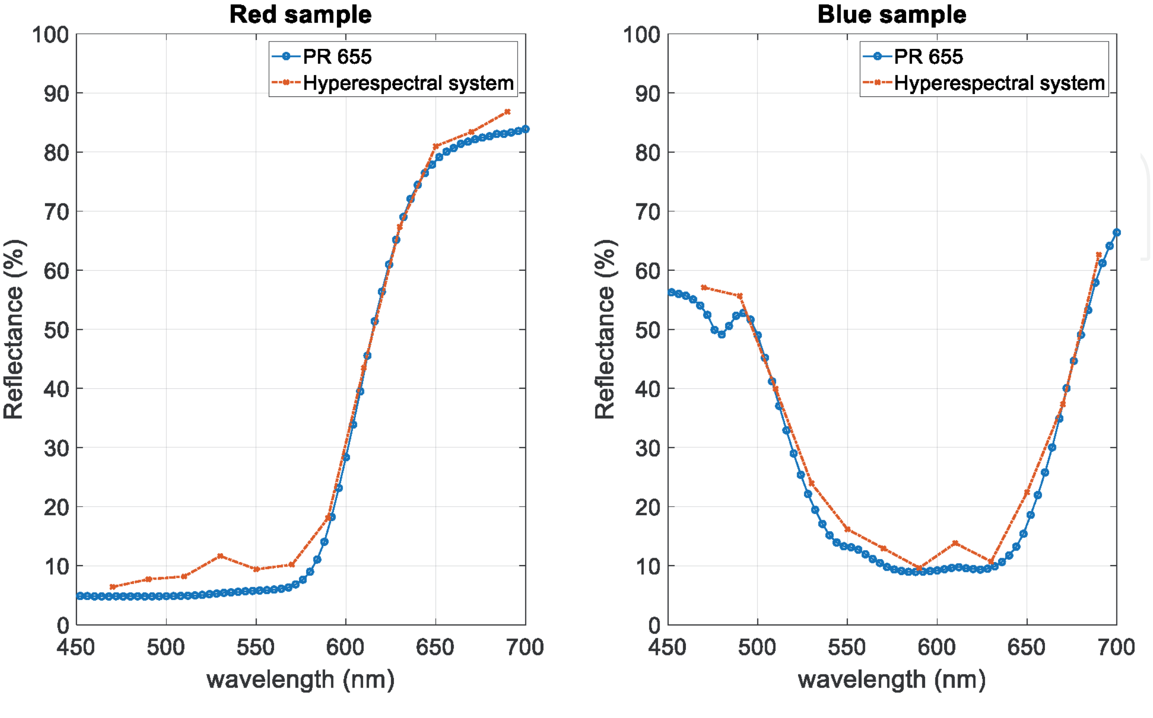

Figure 13.
Reflectance comparison between commercial PR655 spectroradiometer and custom made 12 filters hyperspectral system.

5-mm area and the hyperspectral system that measures each 30-nm band but the measurement area is 0.3 mm.

4. Conclusions

Cultural heritage conservation is having a new paradigm with new optical techniques. Moreover, the conservation procedure can be improved with the help of reflectance spectral measurements. In the case of deteriorated artworks, the spectral characterization is useful for having an objective "photography" of the current state of the pigments. Instrument resolution is also of high importance because of the higher resolution, more accurately data are collected on the artwork for future review. These data could lead us to virtually restore an artwork with previous data and with the curator and restorer help. As a conclusion, the reflectance measurement system must be chosen according to experimental necessities, and some experiments will require wavelength precision and others will require a small area detection. Color changes due to artwork deterioration or changes in lighting conditions are easily calculated with spectral reflectance data.

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Appendices and nomenclature

CIE	Commission Internationale de l'Eclariage

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