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Hyperspectral imaging workflow for the acquisition and analysis of stained-glass panels

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ABSTRACT

Hyperspectral imaging has become a powerful technique for the non-invasive investigation of works of art. An advantage of this technique is the possibility to obtain spectral information over the entire spatial region of interest, allowing the identification and mapping of the constituent materials of the artefact under study. While hyperspectral imaging has been extensively used for artworks such as paintings and manuscripts, few works have been published on the use of this technique on stained glass. In this paper, a workflow for the imaging and analysis of stained-glass windows is proposed. The acquisition is carried out using a laboratory set-up adapted for transmittance measurement, which can support panels with a maximum size of around 50 x 50 cm. The image processing is carried out with two aims: visualization and chromophore identification. The results of this processing provide a foundation to discuss the potential of hyperspectral imaging for the scientific analysis of stained-glass windows.

Keywords: Hyperspectral imaging, Stained glass, Transmittance imaging, Cultural heritage.

1. INTRODUCTION

Hyperspectral imaging (HSI) has become a powerful technique for the non-invasive investigation of works of art. This technique offers the possibility to obtain spectral information over the entire spatial region of interest, allowing the identification and mapping of the constituent materials of the artefact under study. In the field of cultural heritage, HSI has been extensively used for non-invasive scientific investigation of artworks, especially paintings and manuscripts[1]. On the other hand, few works have been published on the use of this technique on stained glass[2-4]. The first application of hyperspectral imaging on this kind of artworks dates to 2011 and it was performed on the stained-glass windows of the Scrovegni Chapel (Padua); the panels were taken down and acquired in laboratory under controlled illumination, in transmittance and reflectance (double transmittance) mode. In transmittance mode, the light sources were simply placed at the opposite side of the camera, in a geometry similar to the one proposed in this paper. In double transmittance the camera and the lights were placed at the same side, and a scattering white support was placed below the stained glass to be scanned. The latter solution was exploited for stained-glass panels which could not be acquired vertically and yielded better results for light-colored glass pieces. From the imaging point of view, the paper does not provide any processed images; nonetheless, the authors were able to demonstrate that results from the two methodologies were complementary and able to identify most of the coloring agents (chromophores)[2]. Other two papers were published in 2019. The work of Palomar et al. explored for the first time the application of hyperspectral imaging in situ, exploiting the solar radiation as light source. The Art Nouveau stained glass from the Casa-Museu Dr.Anastácio Gonçalves in Lisbona were used as case study. The analysis showed promising results, especially when comparing and mapping the spectra of glass with same color and composition but with different transparency, despite the changing light conditions and the effect of external background (i.e trees) on the lighter colored glass[3]. The work of Perri et al, on the other hand, used an artistic stained-glass panel from 1969 as case study to evaluate the performance of a hyperspectral camera based on a Fourier transform approach. As for the previous paper, the acquisition was performed in-situ under natural light. With respect to the other paper the authors were able to demonstrate the ability of HSI in distinguishing and mapping different groups of blue colored glass within the stained-glass[4].

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From this brief review, it is already possible to frame some of the challenges that must be addressed during the acquisition of stained-glass windows. First, to deal with the transparency of the glass, it is necessary to have a set-up that can work for transmittance measurements and can be suitable for the size of the stained-glass under study. For in-situ analysis, solar radiation can represent an easy solution to avoid building complicated support for the light sources. However, as expressed in Palomar et al., the fluctuation of the light condition can affect the quality of the resulting spectra. In addition to this, the high dynamic range of the colored glass, and the complex interaction between light and glass represent other aspects that must be taken into consideration[5,6].

Nonetheless, HSI could still represent a valuable technique for the analysis of stained-glass windows. The possibility of documenting large areas non-invasively, could be an advantage with respect to point analysis traditionally used for identification of the coloring agents (chromophores) in the glass, such as such as UV-VIS-IR spectroscopy and X-Ray absorption spectroscopy (XAS/XANES)[7-9]. The potential contribution of this technique in the field of glass conservation has been discussed thoroughly in a paper recently published by this research group[5]. The aim of this paper is to implement concretely the ideas proposed in the previous paper, by presenting a workflow for the imaging and analysis of stained-glass windows. The acquisition was carried out employing a laboratory set-up adapted for transmittance measurements. In the current configuration, the set-up can support only panels with a maximum size of ca. 50 x 50 cm. Despite the size limitation, it can still be suitable for the investigation of single panels taken down for restorations.

The paper is organized as follows: a detailed description of the acquisition set-up and the pre-processing steps is provided in Section 2, followed by the proposed image processing methodology, which is focused on two aspects of spectral imaging: image visualization and chromophore identification. With regards to chromophore identification, results from X-ray fluorescence spectroscopy (XRF) are shown and used to validate the information obtained with HSI. The results and the challenges related to stained-glass imaging are discussed in Section 3 and used to evaluate the potential of HSI for the analysis of stained-glass windows, before concluding.

2. EXPERIMENTAL

2.1 Case study

The test panel used for the experiment was originally prepared for camera calibration within the Fairford project[10] in 1996. The dimension of the panel is 515 x 405 mm and consist of an array of 10 x 10 rectangular glass tiles, each of size 45 x 35mm, held by 6mm lead calmes. The glass tiles consist of 80 colored and 20 clear glass tiles with grisaille paint and yellow silver stain in various textures. The central area of the rear surface of each tile has been ground away.

Figure 1: Test panel photographed on a light table. *Image credit Dr. Lindsay McDonald*

2.2 The acquisition set-up

The acquisition was carried out using a HySpex VNIR-1800 push-broom hyperspectral camera. The camera acquires 186 images in the visible and near infrared (VNIR) range 400–1000nm, with a spectral sampling of 3.26nm and a spatial resolution of 1800 pixels across the track. The camera lens has a fixed focusing distance of 30cm from the object, resulting in a linear field of view of around 8cm across the track. The HSI acquisition was performed in transmittance mode. In this configuration, the sample is positioned on a translational stage equipped with a diffusing panel, large enough to cover the field of view of the camera. A halogen lamp is positioned at around 7 cm from the stage, in correspondence with the diffuser panel, so that the light could shine through it and the stained glass (Fig 2). The image is recorded line by line by the line scanner, keeping the camera and the light source fixed, while the translational stage moves.

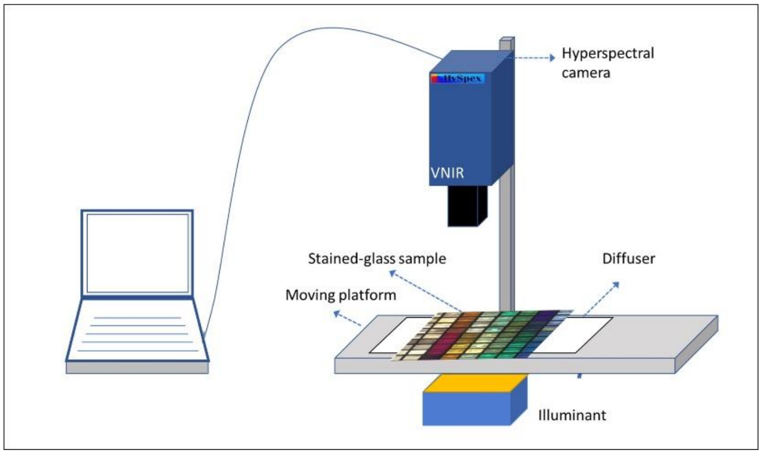

Figure 2: Schematic diagram of the transmittance set-up for the HSI system. The light source is positioned below a diffuser panel on top of which lays the stained-glass sample in direct contact. The transmitted light is collected by the camera.

3. METHODOLOGY

3.1 The image processing workflow

The spectral datacubes were collected in raw format and corrected to radiance through the HySpex-RAD software provided by the manufacturer. Sensor corrections and dark current subtraction was done at this stage. A total of 12 datacubes were recorded to cover the entire panel and later stitched together using the plug-in Pairwise Stitching[11] in ImageJ.

After the radiance correction, the datacubes were processed using the open-source software ImageJ. In order to transform the radiance data into transmittance, the image of the stained-glass sample is divided by the image representing a uniform transmitting surface. Usually, this step is performed by acquiring an image of the diffuser alone, under the same illumination condition and with the same size of the image as of the sample[2]. In the present case, only the translating stage moves, while the camera and the light source are kept fixed. Since the camera acquires line by line, it can be assumed that the signal collected and averaged from a few lines can be representative of the light distribution across the whole field of view[12]. For this reason, instead of collecting the reference over the entire area covered by the object, a small portion of the diffuser was always included in the image and used to calculate the reference spectrum. A new image can be created by transforming the spectrum extracted from the averaged lines into a single pixel, which size can be adjusted according to the dimension of the image to be corrected. During this step, it is crucial that all the 1800 across track pixel are included when averaging the lines from the reference, to consider the possible variation of the light distribution along the lines. The transmittance is calculated as follows:

$$T=\frac{S_{x,\lambda}-D_{x,\lambda}}{W_{x,\lambda}-D_{x,\lambda}} \tag{1}$$

where $S_{x,\lambda}$ is the signal relative to the light transmitted by the object and $W_{x,\lambda}$ is the signal relative to the light transmitted by the diffuser alone, at pixel location x, λ. Indices x, λ indicate respectively the spatial and the spectral dimension[2]. In this case the spatial dimension is represented by the 1800 pixel across the track and the spectral dimension is represented by the 186 spectral bands. It must be also specified that the camera acquires and subtract automatically the dark current. In practice, to calculate the transmittance it is only necessary to divide the object image to the reference one.

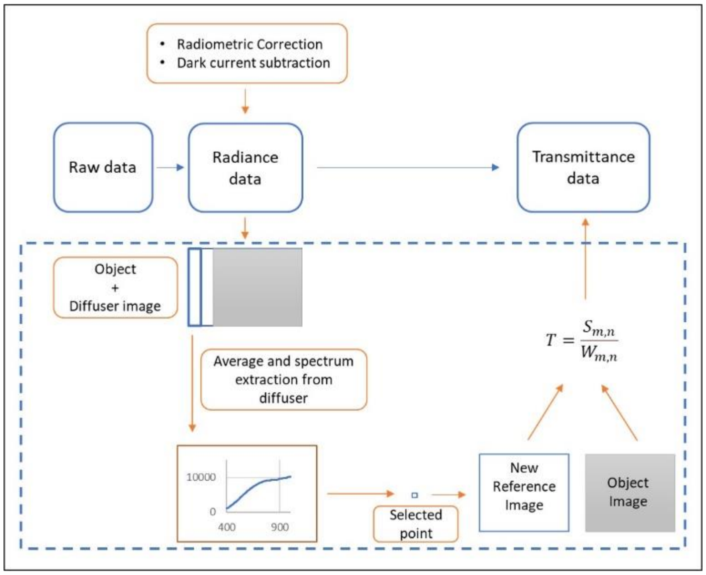

Figure 3: Schematic diagram of the workflow for HSI acquisition and preprocessing of the stained-glass panel.

3.2 Visualization: RGB and false color images

The first step for visualization of HSI is to extract the representative red, green and blue bands to reconstruct the color image. The default bands for red, green, and blue are 642, 549, 463 nm respectively. These bands are specified by the camera manufacturer and are usually stated in the header file of the datacubes. In ImageJ, the RGB image can be built by selecting the three bands and arranging them to create a new image made of three separated channels (red first, green and blue). These selected bands are transformed into a color image.

The false color image can be produced in a similar way. In this case, the two bands related to red (642 nm) and green (549 nm) are kept, and another band can be selected in the near-infrared region. Since there is no standard set for the choice of the infrared band, some trials are performed to understand which bands provide most information. Once the band are selected, they can be rearranged in a new image, putting first the image related to infrared, the red one and lastly the green one. The same procedure used to make the RGB image can be followed to create the false color image.

3.3 Visualization: color rendering

The color rendering of the HSI was performed in MATLAB using and adapting codes made available by Foster and Amano[13]. For the rendering, the CIE 1931-2° standard observer color matching function was used. The values for the daylight series standard illuminants were calculated using formulas retrieved from the Rochester Institute of Technology online repository of useful colorimetric data[14]. The values for the color matching function, as well as for the standard illuminant A, were obtained from the same repository. The datacube relative to the top left part of the panel (Fig.3) was used to perform the color rendering under different illuminants, while the entire panel was rendered only with D65, for comparison with the RGB image obtained through band selection (Fig 4a and 4b).

3.4 Complementary analysis

In order to validate the results obtained from hyperspectral imaging, the elemental information on the composition of the glass tiles was studied by means of X-Ray Fluorescence (XRF) spectroscopy. The analysis was performed with a Thermo Scientific Niton XL3t handheld XRF spectrometer, equipped with a silver anode and a GOLDD detector. The analysis was performed in Cu/Zn mining mode, with 40kV voltage. The acquisition time for each measurement was 120s. The Niton

NDT software was used for the spectra interpretation. When possible, the XRF points were collected in the clearest areas of the glass tile.

4. RESULTS AND DISCUSSION

4.1 Visualization

Figures 4a and 4b shows the color images obtained by band selection and color rendering respectively. The rendered image can be considered an improvement with respect to the three bands RGB image as it allows a better visualization of darker glasses; however, it is worthy of mention that the rendering does not take into account other optical properties of glass (such as the refractive index for example), so it may not represent the real appearance of the glass tiles.

With regards to false color images, Figures 4c and 4d shows the results obtained by selecting two different bands in the infrared region, one at 811 nm (Fig. 4c) and one at 996 nm (Fig. 4d). Notice how the selection of the 996 nm band improves a little the visualization of very dark tiles and allows a better distinction of the green colored tiles.

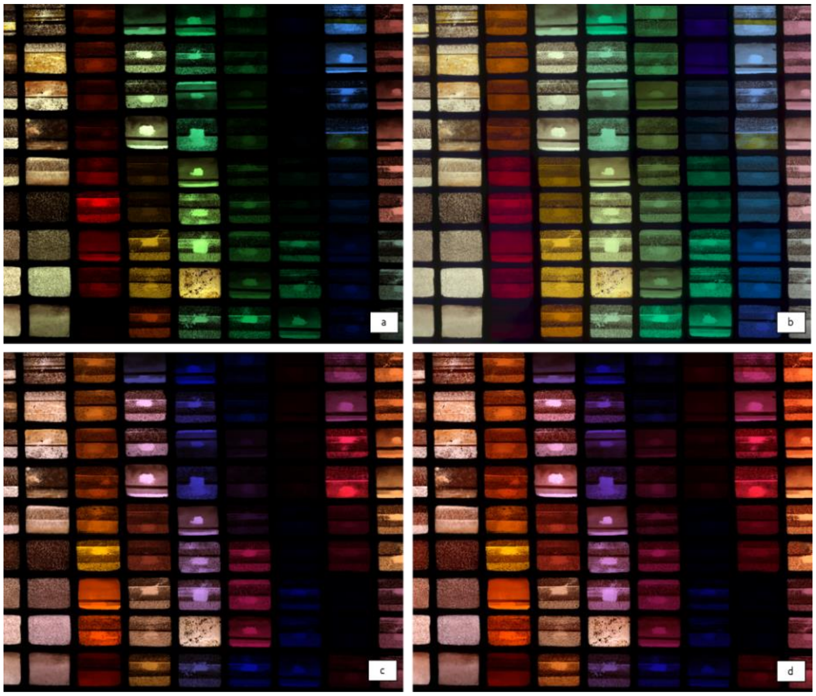

Figure 4: a) RGB color image obtained selecting three bands related to red (642 nm), green (549 nm), and blue (463 nm), from the HSI. Note that the last column and last row are missing as they were not included in the final stitching. b) RGB color image obtained using color matching function. c) false color image obtained selecting a band in the near infrared region at 811 nm d) false color image obtained selecting a band in the near infrared region at 996 nm.

4.2 Spectra interpretation

Looking at the false color image (Fig 4 and 6b), it is already possible to make a preliminary identification of glass made with the same coloring agents. Taking some of the green glass tiles as an example, it is possible to notice how their spectra match their similar color appearance in false color. (Fig. 6).

The second step in chromophore identification is to associate the characteristic peaks to the relative elements responsible for the color of the glass. This task is not easy and requires skills and expertise on glass-making techniques, as well as the mechanism behind the origin of color in glass.

A good starting point is to compare the results with the available literature for reference. It has been already mentioned that few works have been published on HSI applications on glass; nonetheless, one may take advantage of publications regarding the use of UV-VIS-IR spectroscopy, which is commonly used for the study of historical and archaeological glass. However, a simple comparison may not always be enough. While most of the spectral shapes can be easily identified, the variation in chromophore concentration, particle size, and furnace condition[3,15] can result in small differences between the spectra of the sample and those found in literature. In this case, comparison of the spectra obtained with published references suggests the presence of copper (Cu^{2+}) and chromium (Cr^{3+}) as main chromophores for both groups. The contribution of chromium seems to be higher in Group 2[2,3,7,15,16] as the two characteristic peaks at become more visible.

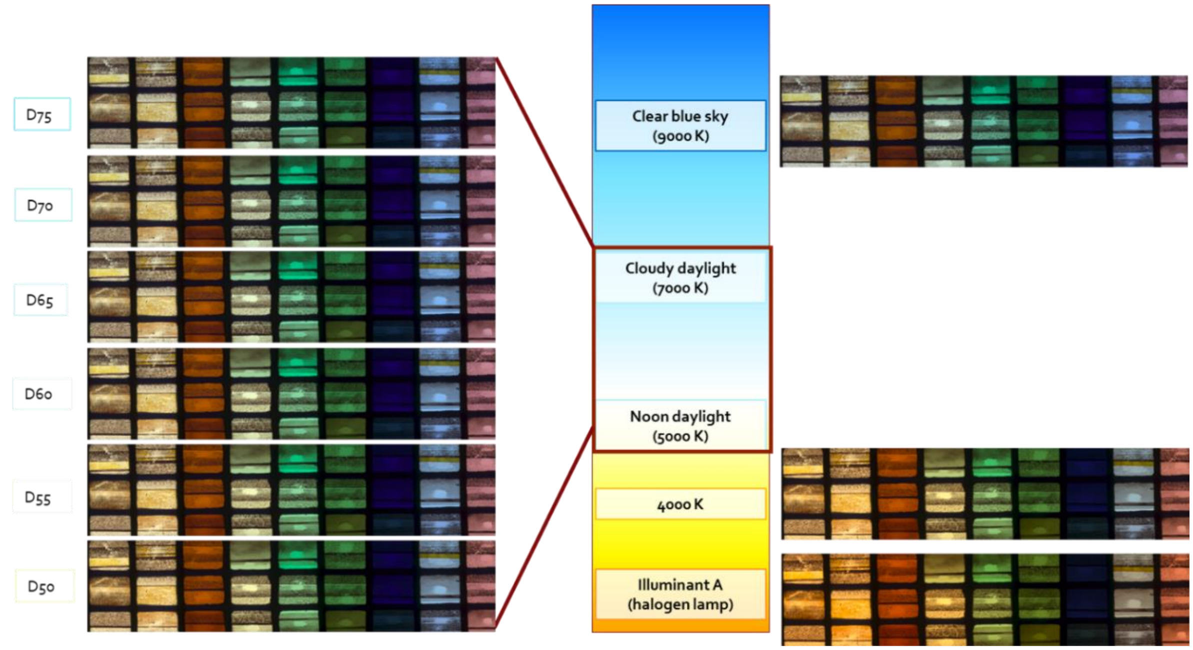

Figure 5: Top part of the stained glass rendered under different standard illuminants. The effect of the color temperature change can be observed best on the light blue and the pink glass on the right side of the rendered images.

In order to have a complete characterization of the glass composition, additional analytical techniques can be applied. Among those, XRF spectroscopy is widely used for the non-invasive characterization of the elemental composition of glass[5,7]. Presenting the complete results of XRF spectroscopy is beyond the scope of this paper, and a future publication is planned on this part of the research. However, considering the green glass taken as examples, it is already possible to mention that XRF confirmed the presence of copper and chromium as main chromophores in Group 1, with small addition of iron (Fe^{3+}). Regarding Group 2, the copper content seems to be lower in relationship with chromium and iron with respect to the Group 1. In Group 2, it is possible to make another distinction, between tiles 1D/9E and tiles 2, 3 and 4E. The differences between these two subgroups can be explained by the fact that tiles 1D and 1A seems to have a higher content of iron with respect to chromium, while for 2,3 and 4E it is the opposite. This assumption can help in providing a better interpretation of the VIS-NIR spectra: the small shoulder at around 400-450 nm which is present in all the samples, could suggests the presence of the absorption peak of Fe^{3+} (at 380 nm), which falls outside the range of the hyperspectral camera together with that of the Cr^{3+} (at 450 nm). In tiles 1D/9E, this shoulder is more pronounced, and could be correlated to a higher content of iron. On the other hand, the more defined small peak at around 680 nm in tiles 2,3,4E could be associate to the higher content of chromium versus iron[2,15,16].

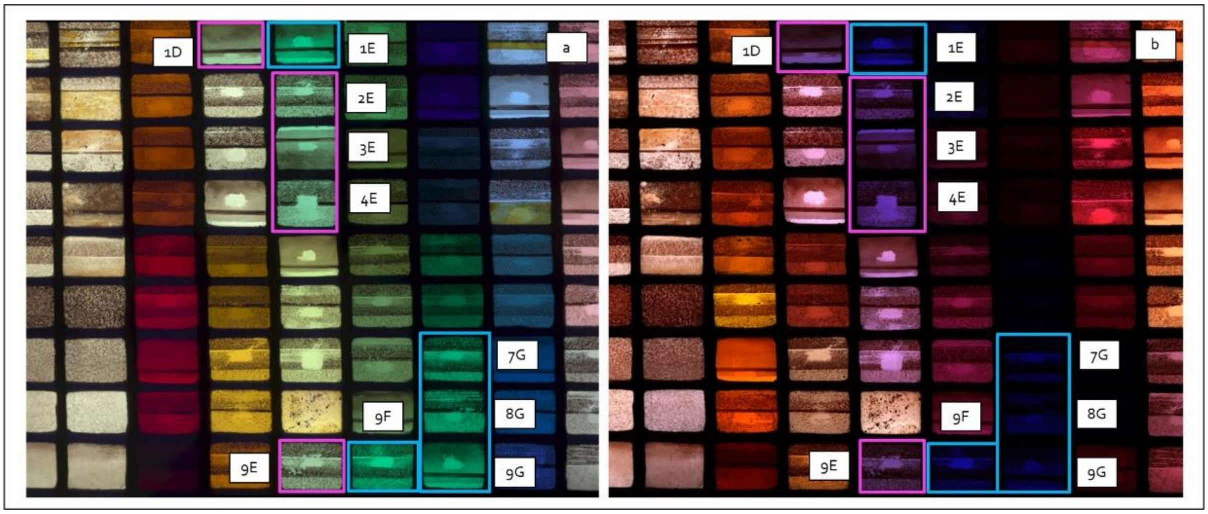

Figure 6: Comparison of color (a) and false color image (b) relative to some green glass.

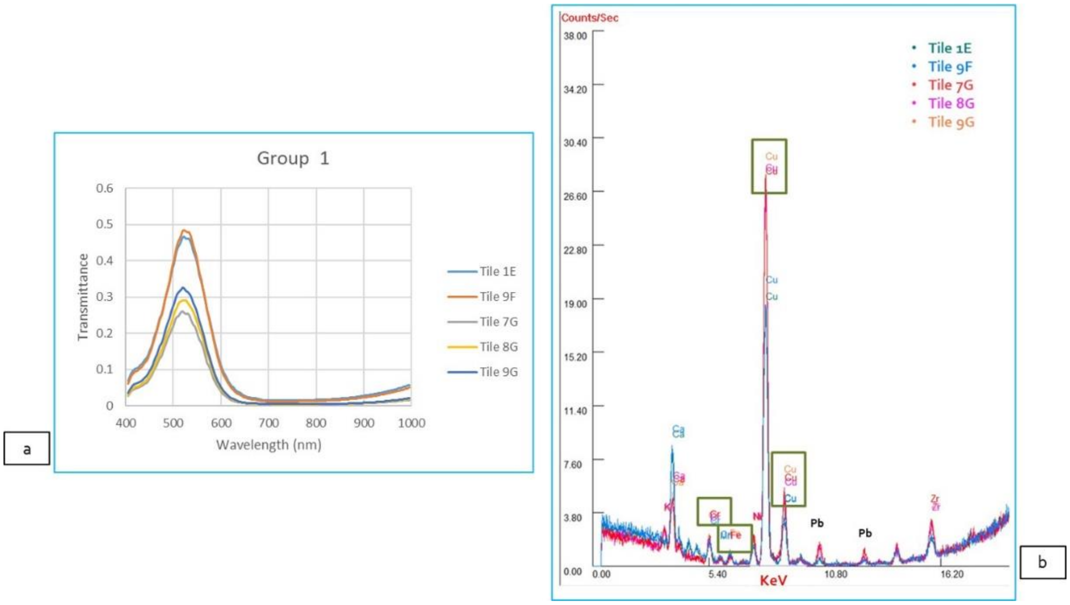

Figure 7: VIS-NIR spectra (a) and XRF spectra (b) of the green glass in group 1. XRF spectra confirm the presence of copper as main chromophore, as well as small quantities of chromium and iron.

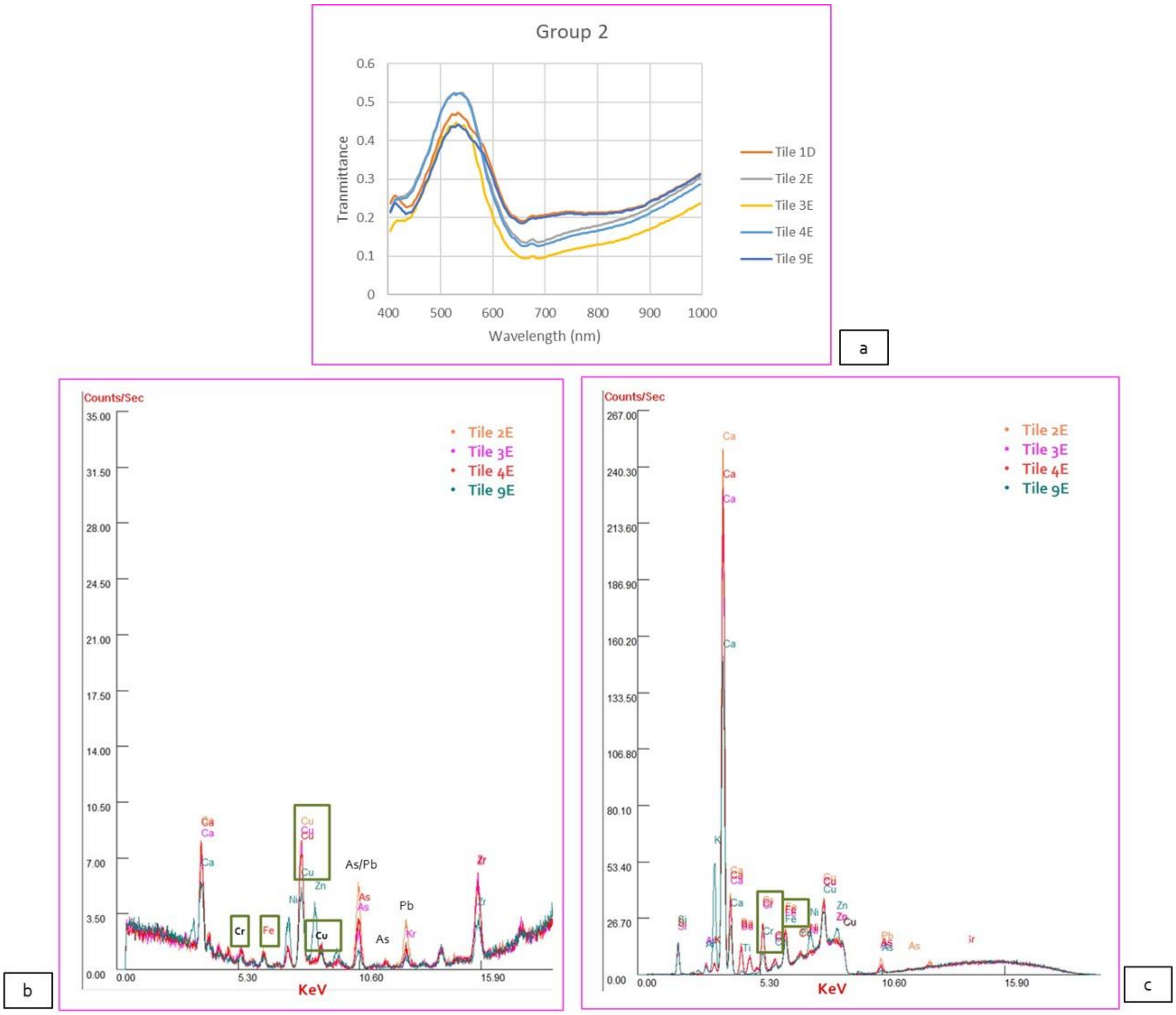

Figure 8: VIS-NIR spectra (a) and XRF spectra of the green glass in group 2 (b,c). XRF results from tile 1D are not available. The XRF spectra on the right (c) refers to the light element mode of the spectrometer, which allows a better distinction of the Cr/Fe ratio among the two sub-groups identified in group 2. It can be noticed that the tile 9E has a lower concentration of chromium with respect to the other three samples in the same group. This confirms that the lighter violet hue observed among the glass in group 2 are due to small difference in composition.

4.3 Challenges

One of the challenges to take into consideration when performing transmittance measurements regards the typology, shape, and positioning of the light source within the set-up. In the current set-up, a powerful halogen lamp is used as the light source, at a close distance to the diffuser. Due to the structure of the halogen lamp, the light distribution is non-uniform on the diffuser, which causes inhomogeneity in the light distribution along the scanned line. Another issue related to the light source is the amount of heat produced by halogen lamps, which can represent a risk for historical objects. A solution that could partially solve both problems would be to keep the light source at a longer distance from the diffuser. It has been noticed during the experiment that the light can be focused into a narrow, homogeneous stripe if the lamp is placed at a distance of around 30 cm from the diffuser. Moreover, the longer distance will also reduce the heat on the surface of the diffuser, and consequently, the stained-glass panel. However, it must be considered that the intensity of the light source could be reduced by this change. Research related to these topics are currently in progress out to better understand the effects of distancing the light from the diffuser on the results.

Another challenging aspect is the transmittance properties of the colored glass and the way these properties influence the result. In many stained-glass panels, it is common to see very dark and very light glass placed close to each other to create striking light effects. This situation may represent an issue when searching for a satisfying exposure time, resulting often in an underexposure of the darker glass. Moreover, in some cases, even glass tiles that appears light colored can show a low transmittance. Increasing the exposure time of the camera may be a solution, but in general it has been observed that it barely improves the results for very dark glass, with the added disadvantages of slowing down the acquisition time and saturating the diffusing panel, as well as the lighter colored glass signals. For this reason, during the experiment the exposure time was set by taking into consideration only the illumination condition of the diffusing plate. Figure 3 shows that in many cases it is possible to obtain a sufficiently good signal even for very dark colored glass.

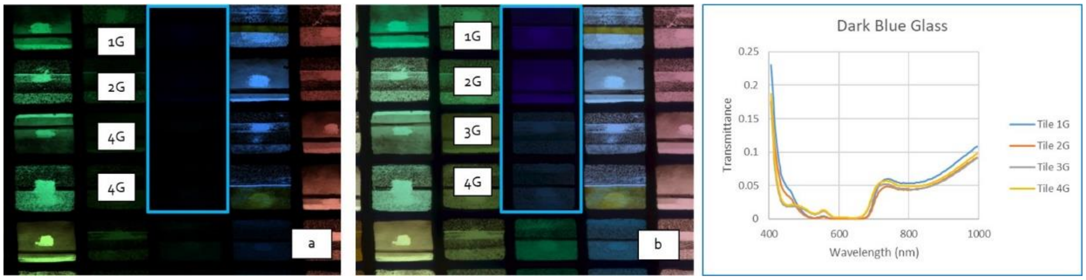

Figure 9: Despite the low transmittance of the very dark glass, the signal obtained provides enough information on the nature of the color in the glass. This can also be noticed by looking at the difference between the three-band RGB image and the spectrally rendered color image, where the blue color can be better appreciated.

5. CONCLUSION

In this paper, a workflow for the hyperspectral image acquisition and analysis of stained-glass windows has been proposed. For the purpose of the research, a test panel has been analyzed using a laboratory set-up adapted for transmittance measurements. Challenges related to the characteristics of the set-up and the optical properties of stained-glass, have been discussed as well. While these challenges can be addressed in different ways, the results obtained showed that hyperspectral imaging technique can be helpful for simultaneous documentation and analysis of stained-glass windows. In addition to the improvement of the current set-up, future works will be focused on two aspects: a better characterization of the coloring agents used in the different tiles of the panels and creation of spectral libraries, and application of classification algorithms for chromophore mapping purposes.

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