

RESULTS OF HYPERSPECTRAL ANALYSIS FOR THE CHARACTERIZATION OF MUDWALL. COMPARISON BASED ON NORMALIZATION

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ABSTRACT:

Currently, intervention in heritage is a task of social need. Non-destructive techniques are often used to carry out conservation and maintenance tasks. In the present. In this work we study the necessary calibration mode of a hyperspectral camera used in the characterization of the material to be conserved or to intervene. This camera is used to characterize the material according to its reflectance in different wavelengths. The result obtained is expressed as a function of the light condition at the time of the measurement. One of the most important phases of this technique is to normalize the values obtained in each take. This is conditioned by the intensity of light: the bigger it is, the bigger was reflectance value of a material at a given wavelength. This factor is corrected from patterns that are introduced in the scene. These patterns are elements whose reflectance values are known in the bands of the spectrum that the camera used registers. Likewise, they must reflect or absorb the maximum light (black and white reference, respectively) in order to delimit the maximum and minimum reflectance of each scene. These references will allow two scenes taken in different light conditions to be comparable. Therefore, the influence of black and white references on the scene is studied from the use of materials of different nature.

1. INTRODUCTION

In today's society there is a need to rehabilitate, conserve, maintain and spread the historical heritage built. The work of conservation and rehabilitation involves the study and analysis of the element built for the knowledge of the variables that define it. The variables to be controlled are different depending on the type of intervention or conservation that you want to make and the use of the element studied. When studying built heritage it is interesting to know variables of the type resistance of materials and structural elements, construction period, construction material, geometry, historical phases of remodeling, etc. For the knowledge of these variables, there are multiple techniques that have the capacity to offer values that characterize the patrimonial element. Among the possible study techniques, it is possible to differentiate between destructive and non-destructive techniques. The ideal in heritage intervention is to make the analyzes without altering it; that is, using non-destructive techniques. Also, it is natural to find functional buildings dated more than 10 centuries ago, this implies that the construction has gone through different phases. In these cases, it is fundamental to differentiate the constructive stages because these will be treated differently.

The work presented is carried out in Extremadura (Spain). It studies the application of BIM (Building Information Modeling) methodologies associated with the conservation of historical built heritage (HBIM). The research starts from the need to study heritage elements framed as defensive constructions and their current status for the development of a HBIM project aimed at conservation work. The research is framed in the project of regional interest HBIMEX developed by the NEXUS Research Group of the University of Extremadura. In this one a methodology based on BIM is developed for the conservation of the property heritage. It focuses on mudwalls from the Mozarab era whose fundamental building material is the wall.

The BIM methodology is based on the ability to have information of different nature arranged in a single digital computing environment. In this way, it is intended to link the geometry of the infrastructure with pathological damage, sensor readings, classification according to phase and time of construction or improvement, etc. All this starts from the premise of the study of the state of conservation through non-destructive techniques. To do this, the following techniques are used: terrestrial laser scanner, temperature and humidity sensors, thermal camera; sclerometer, ultra-sounds, fissurometer and hyperspectral camera. Each of the values obtained characterize the infrastructure according to a determined parameter.

Of all the techniques used, the hyperspectral camera is the technique that offers the most information. A hyperspectral camera is a device that allows to know the reflectance of a material for a certain light condition in different wavelengths of the electromagnetic spectrum. The number of wavelengths that allow a reading will depend on the sensor that is used in the data collection. It is considered that the rest of material characterization techniques will be auxiliary to the hyperspectral camera.

In this case, the object of study is the Torre del Horno, in the city of Cáceres and it is part of the wall of the same city. This mudwall, approximately 1.2 km long, was built in Mozarabic times (S. XII) although there is evidence at some point of it of foundations of a primitive wall of Roman origin. This infrastructure has evolved over the history adapting to the social needs of the time, wars, uses or conservation. This leaves a heterogeneous wall regarding of materials and construction phases. As the eras advance, it can be found areas reconstructed and enlarged with masonry walls (Figure 1 and Figure 2).



Figure 1. Walled city of Cáceres. Wall canvas preserved.
Source: © SPOT Image Copyright 2019, SIG of Cáceres

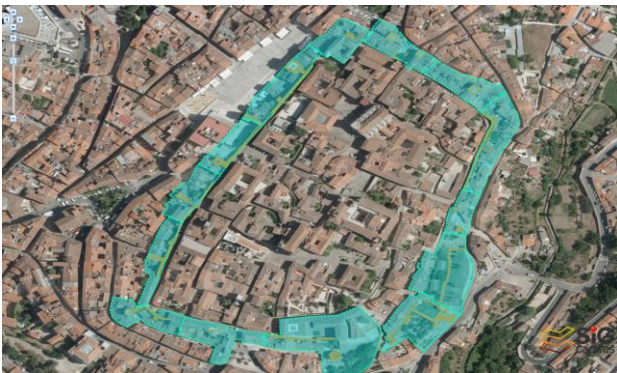


Figure 2. Walled city of Cáceres. Scope of original wall.
Source: © SPOT Image Copyright 2019, SIG of Cáceres

2. MATERIALS AND METHODS

In this work different black and white patterns are analyzed for the normalization of spectral images. The purpose is the characterization of materials in built heritage elements. For the development of the study, we worked with the Xenics Xeva-2164 hyperspectral camera with the Specim Inspector N17E spectrograph and the mirror scanner reading system (Xenics Infrared Solutions, Inc.). The equipment is characterized by:

- Have an passive sensor, which collects electromagnetic energy from the surface (Chuvieco, 1990).
- Have a sweep sensor, consisting of the oscillation of a moving mirror perpendicular to the direction of the trajectory (Chuvieco, 1990).

The system has an aperture lens from $f/1.4$ to $f/16$. The spectral range of the camera is 900 to 1700 nm. The sensor has a CCD size of 14.2 mm by 4.4 μm . The spectral resolution is 5 nm. The information obtained is presented in a cube of dimensions (rows * columns * bands). In the case of hyperspectral equipment used, the dimension of the results obtained is (320 pixels Rows * n pixels Columns * 256 bands). The number of pixels per column depends on the angle at which the mirror scanner is configured. It works with a turn of the mirror scanner of 25°, so the cube obtained is (320 pixels. * 361 pixels. * 256 bands).

The parameters of the sensor, the focal length used in the take just like the distance from the equipment to the wall determine the size of the ground pixel, that is, the reading unit in the studied wall. The pixel size of the sensor is 4.4 μm because the sensor dimension is 14.2 mm and contains 320 pixels. It known the focal

length of the lens used (16 mm), so the size of a pixel is calculated for a take distanced 1 m from the wall. For the exposed case, the ground pixel value is 2.77 mm (Figure 3).

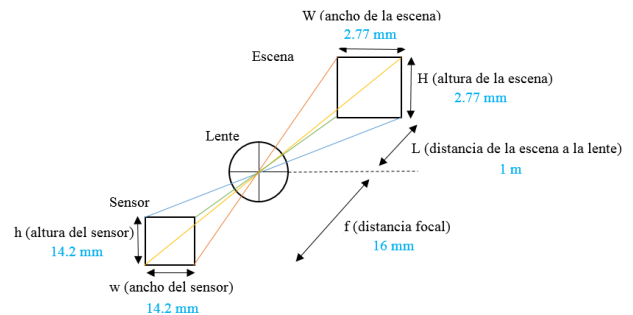


Figure 3. Representation of geometric optics

The sensor collects information from a scene on the axis perpendicular to the turn of the mirror to minimize the possible directional effects of illumination in the images (Jiménez, 2011). After collecting information, it stores it as a set of images. Each image represents a range of the electromagnetic spectrum, known as a band. These images combine, originating a three-dimensional image that is called hyperspectral cube or hypercube. (Sánchez, 2016).

The source of luminosity that has been used is the sun. That is why the captures must be made with little difference time between them so that they all have similar lighting conditions. The most relevant aspects related to lighting at the time of making the measurements are the angle of elevation of the sun, the atmospheric conditions at the time of capture and the type of solar radiation that the scene receives. (Valbuena, Castro, 2013)

The solar elevation angle must be 30° or 40° of inclination over the vertical. This reduces the thickness of atmospheric layers that alter the light source and prevents shadows from the objects that appear in the scene. Thus, it is advisable to take data two hours before and after midday, which may vary depending on the conditions that arise during the data captured. (Valbuena, Castro, 2013)

In terms of atmospheric conditions, measurements can be restricted to clear days with no clouds, fog, haze, etc. and where the air is pure. It is also convenient that there is little wind so that the scene is not altered to the moving the elements that intervene in the data collection or create dust. (Valbuena, Castro, 2013)

When using a hyperspectral camera, the reflectance value of the material studied is obtained in different bands of the electromagnetic spectrum (spectral signature). Reflectance is defined as the ratio between the reflected and incident light intensity ratio of a sample. It is a dimensionless magnitude that is expressed with a number between 0 and 1. If the spectral signature of an element is 0, it means that it absorbs all the light that reaches it; if the spectrum is kept at 1, it means that it reflects everything. Similarly, we can speak of reflectance in percentage, from 0% to 100%. 0% indicates that the material absorbs all the light that reaches it and 100%, that reflects it in its entirety. A spectral signature represents the amount of reflected radiation with respect to the wavelength of this radiation. (Sánchez, 2016)

The information collected by the sensor is associated to a Digital Number (DN) for each pixel of each band. To obtain reflectance values that allow to study and compare the spectral signature of the different materials, it is necessary to normalize the data.

Normalization is a process that manipulates the contrast of the images, able of converting the values of DN to reflectance. Equation (1) presents one of the possible formulations for the calculation (Castaño, Moreno, 2015). This expression works with the pixels of higher and lower intensity of each band and with each pixel of that same band. Returns a value between 0 and 1 for each pixel.

$$R = \frac{DN - DN_{min}}{DN_{max} - DN_{min}} \quad (1)$$

where R = reflectivity value
 DN = Digital Number in the range of 0-255
 DN_{min} = Digital Number of the black reference
 DN_{max} = Digital Number of the white reference

One of the most important phases of the hyperspectral technique is to normalize the values obtained in each take. This is conditioned by the intensity of light that there is when capturing: the higher the light level, the higher is the intensity value of light reflected by a material at a certain wavelength. This factor is corrected from patterns that are introduced in the scene. These patterns are elements whose reflectance values are known and constant in the bands of the spectrum that the camera used registers. Likewise, they must reflect or absorb the maximum light (black and white reference, respectively) in order to limit the maximum and minimum reflectance of each scene. These references will allow two scenes taken in different light conditions to be comparable. For all this, in this work it study the influence of black and white references in the scene from the use of materials of different nature.

Takes have been taken with the hyperspectral camera at various distances from a scene. In the present work, takes have been taken at 0.5, 1, 3 and 4 m. Figure 4 shows the different black and white patterns to evaluate and compare the different values of reflected intensity offered by each material.



Figure 4. Black and white references used in the test

To carry out this study we have been used five white and three black patterns. Paper, methacrylate, polycarbonate, polytetrafluoroethylene (PTFE) and spectralon have been used as white patterns. Like black patterns, paper, methacrylate and polycarbonate. The finishing of all patterns is matte.

The acquisition of the takes was carried out with its own software developed by the NEXUS Research Group (belonging to the Polytechnic School of Cáceres, University of Extremadura), called ScanJai. This software synchronizes the rotation of the camera's mirror to form a hyperspectral cube. (Castaño, Moreno, 2015)

The analysis of the images has been done with the ENVI Classic® software version 5.0. The values obtained by the camera are DN values. It is necessary to normalize the cube to work with reflectance values. ENVI is able to make four types of normalization using an option called *Stretch Data: Linear, Equalize, Gaussian* and *Square Root*. We have chosen to work with the *Linear* equation because this function does not distort or apply correction to the input data of the cube. This type of normalization works with the highest and lowest pixel value in the scene, defining the dynamic range of the image. The pixel that has a higher value than the rest is assigned the value 1 while the pixel that has the lowest value of all is assigned a 0. (Harris Geospatial Solutions, Inc.)

The software allows to realize regions of interest (ROIs), these are selected areas of an image that are used for a particular purpose. When defining an ROI, the pixels of the image that are inside it are specified. If a region of interest is defined where the white and black reference are located, the normalization of the image will be based on them. We work with the highest and lowest pixel value that contains the ROI, defining the dynamic range of the image. The pixel that has a higher reflectance value than the rest is assigned the value 1 while the pixel that has the lowest value of all is assigned a 0. (Harris Geospatial Solutions, Inc.)

For the analysis of the results, different normalizations have been made depending on the existence or not of ROIs for the choice of black and white references.

For the comparative analysis of the spectra of the different patterns, normalization has been carried out, discarding create regions of interest. By not defining any ROI, the software selects the highest and lowest intensity pixels of the entire scene.

With the normalized cube the statistics of each black and white pattern used are studied. This is done by training neural networks with ENVI. So the pixels that make up the different materials that appear in the image are classified according to these, showing the statistics of each one. ENVI also offers an option to make statistics by the defining of ROIs that contain pixels of what you want to study (Harris Geospatial Solutions, Inc.). The reflectance of the materials varies depending on the distance at which you are working. To obtain a single reflectance value of each pixel, the arithmetic mean of the band-to-band value is calculated at the different distances. Three normalizations were necessary for the development of the research.

1. In a first calculation, the spectral signatures of the different materials that act as black and white patterns are studied. Each black and white pattern with which you have worked must have different spectral signatures. The white pattern that has a reflectance value greater than the rest and close to 1 and the black pattern that has a lower value close to 0 will be selected to work with them. The purpose is to establish which material returns greatest and smaller intensity to select the materials that should act as black and white references.
2. A second normalization is made creating an ROI which contain a sample of the white reference selected (the one that has a closest value to 1 in the first normalization) and the different black patterns. With the normalized cube the statistics of each black material are studied.

- In the third normalization an ROI is defined that contains a sample of the black and the white of references selected to normalize the hyperspectral cube (materials with maximum and minimum reflectances extracted from the previous calculations). This calculation allows to study the spectral signature of the mudwall that appears in the images (Figure 4).

All measurement processes cause noise in the obtained signals that can be reduced if they are filtered. The software Unscrambler® X version 10.4 is used to smooth the obtained spectral signatures. This software allows different types of smoothing to be applied but, in this case, the Savitzky Golay smoothing is used. The Savitzky-Golay filtering makes a polynomial least-squares adjustment through a mobile window inside the data in the time domain. (Savitzky, Golay, 1964). The bigger is the order of the polynomial, the bigger is the smoothing level that is performed, without attenuating the information. So this method allows to preserve important characteristics that contain the data. (Guiñón et al. 2007)

3. RESULTS AND DISCUSSION

Captures were made at 0.5 m, 1 m, 3 m and 4 m. The sensor collects information of a scene on the axis perpendicular to the turn of the mirror to minimize the possible directional effects of illumination in the images. (Jiménez Michavila, 2011). That is why the captures made at 0.5 m and 1 m are omitted, since it is not possible to achieve that all the patterns used are in the plane perpendicular to the camera and irregular effects are detected in the illumination of some patterns.

The light source that has been used is the sun because the measurements have been made in the field.. So that all the captures have similar light conditions were made with little difference of time between them. The solar elevation angle must be 30° or 40° of inclination on the vertical. This reduces the thickness of atmospheric layers that alter the light source and prevents shadows from the objects that appear in the scene. Thus, it is advisable to take data two hours before and after midday, although these hours may vary depending on the conditions that arise during the data collection. The measurements should be made on clear days with no clouds, fog, haze, etc. and where the air is pure. There must be little wind so that the elements that intervene in the scene that is captured do not move and dust does not occur (Valbuena, Castro, 2013)

In the first calculation, a comparative analysis of the spectra of the different patterns was carried out to determine the materials that should act as black and white references. For this, a normalization has been carried out, discarding regions of interest. By not defining any ROI, the software selects the highest and lowest intensity pixels of the entire scene. With the normalized cube the statistics of each black and white pattern used are studied. ENVI offers an option to make statistics by defining ROIs that contain pixels of what you want to study. (Harris Geospatial Solutions, Inc.). The reflectance of the materials varies depending on the distance at which you are working. To obtain a single reflectance value of each pixel, the arithmetic mean of them is calculated.

Examining all the signatures of the materials used for the white reference (Figure 5), as expected, the signature corresponding to the spectralon has higher intensity values than the rest of the white materials. This is because it is highly reflective and Lambertian throughout the electromagnetic spectrum (Jiménez, 2011). In addition, it is chemically inert, capable of providing

reflectance values up to 99 % and spectrally flat over the ultraviolet, visible and infrared spectrum, covering a wavelength range from 250 nm to 2500 nm. (Labsphere, Inc.). For this reason it is a material that is supplied to carry out tests of this type.

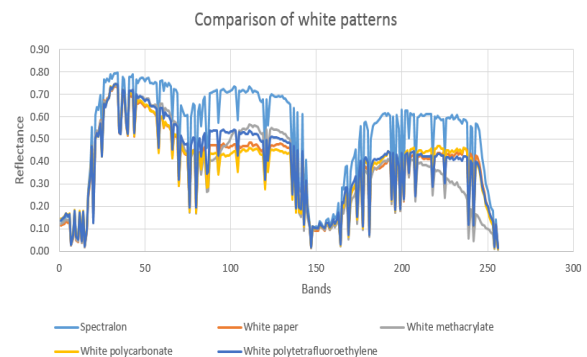


Figure 5. Comparison of the spectral signatures of the white patterns (normalization without ROIs).

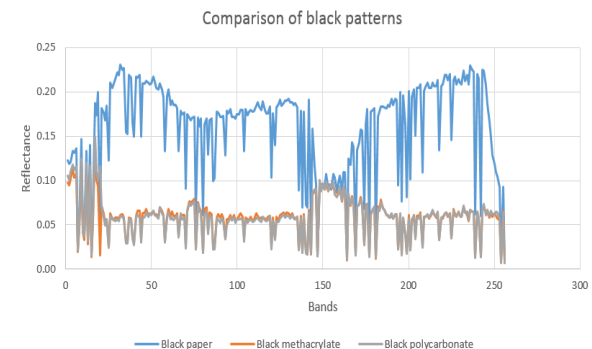


Figure 6. Comparison of the spectral signatures of the black patterns (normalization without ROIs)

As for the black patterns (Figure 6), the black methacrylate and the black polycarbonate have the similar reflectance. To determine which of them has lower values of reflectance and, therefore, will be selected to act as black reference material, the following procedure is followed.

Second, normalization is done by creating an ROI containing a sample of the white reference selected and the different black patterns. With the normalized cube the statistics of each black material are studied. The reflectance of the materials varies depending on the distance at which you are working. To obtain a single reflectance value of each pixel, the arithmetic mean of them is calculated (Figure 7).

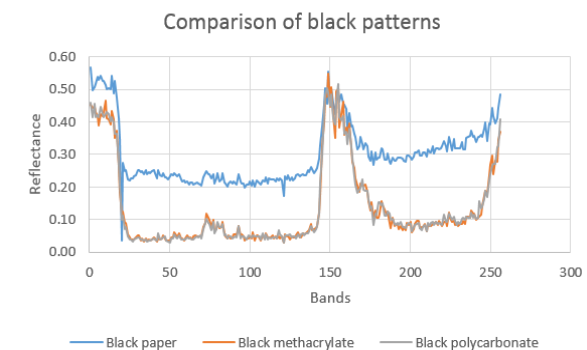


Figure 7. Comparison of the spectral signatures of the black patterns (normalization with ROIs)

Although the materials representing black methacrylate and black polycarbonate still have a similar spectral signature, methacrylate has a reflectance of 14% while polycarbonate has a 13% reflectance. Therefore, the latter is the one selected as the black reference pattern.

The reference materials that would be convenient to use each time that a capture is made with the hyperspectral camera are the spectralon and the polycarbonate. Figure 8 shows the captures made at 3 m and 4 m normalized using these reference materials (third normalization).



Figure 8. Normalization with respect to spectralon and polycarbonate to a) 3 m, b) 4 m

To obtain the spectral signature of the black (polycarbonate) and white (spectralon) reference patterns, an ROI is defined that contains a sample of the black and white of references selected. With the normalized cube the statistics of each of them are studied. ENVI calculates statistics by defining ROIs that contain spectralon and polycarbonate pixels. The reflectance of the materials varies depending on the distance at which you are working. To obtain a single reflectance value of each pixel, the arithmetic mean of them is calculated.

The spectral signatures of the black and white reference are analyzed with The Unscrambler X software. To reduce the noise of each signal, a smoothing of the spectral signatures of the black and white reference is made. For the white reference, a polynomial of order 3 and a window of 15 points were used (Figure 9); while the spectral signature of the black reference has been smoothed with a polynomial of order 1 and a window of 7 points (Figure 10).

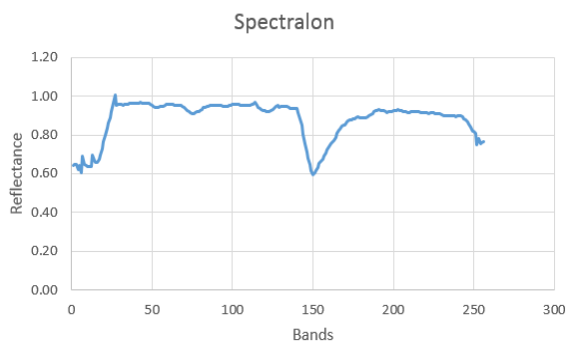


Figure 9. Spectral signature of the reference white

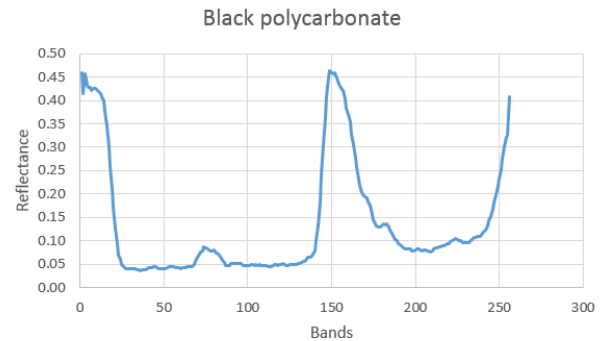


Figure 10. Spectral signature of the reference black

The spectral signature corresponding to the white reference (spectralon) presents the maximum intensity values that can be obtained, with 88% reflectance. This material is used to carry out this type of tests because it is capable of providing reflectance values of up to 99%, being chemically inert and spectrally flat from 250 nm to 2500 nm (Labsphere, Inc.).

The spectral signature of the black reference (polycarbonate) is inverse to that of the white reference. That is, the part of the spectrum that the spectralon reflects with highest intensity is absorbed by the polycarbonate and the part of the spectral signature of the spectralon that presents higher absorption is reflected by the polycarbonate. The first and last bands are usually ignored because they keep aberrations. Black polycarbonate has a reflectance of 13%.

It may be the case of not having a white reference, calibrated and well characterized as the spectralon. Polytetrafluoroethylene is a diffusing and reflecting substance, commonly known as Teflon. In addition, it is a washable material and insensitive to changes in humidity. That is why in many occasions the spectralon is replaced by a white pattern of PTFE. Both materials have a spectral signature and similar absorption peaks because the PTFE is the material used to manufacture the spectralon. The polytetrafluoroethylene receives a treatment that gives it higher reflectivity, giving rise to the spectralon. (Coca, 1999)

In addition, Figure 5 shows how polytetrafluoroethylene is the second material that offers higher intensity values. For this reason, it will be used in place of the spectralon to collect data with the hyperspectral camera.

To achieve its spectral signature, the hyperspectral cube is normalized by defining an ROI containing a black and white sample of references selected (polytetrafluoroethylene and polycarbonate, respectively). Once normalized, the statistics of each of them are studied. An ROI containing the PTFE pixels is defined. Then, the arithmetic mean of the reflectance values of each pixel is calculated to be able to characterize it. To reduce signal noise, we used a polynomial of order 1 and a window of 13 points (Figure 12).

In Figure 12 the spectral signatures of the spectralon and polytetrafluoroethylene are shown to visualize the differences and similarities between both.

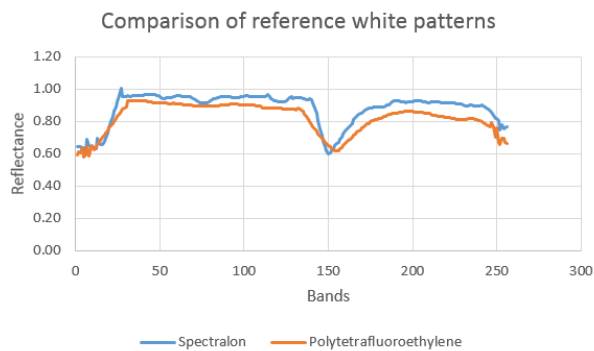


Figure 12. Comparison of the spectral signatures of the spectralon and polytetrafluoroethylene. Normalization in both cases with polycarbonate as reference black.

The spectral signature of PTFE keeps a reasonable resemblance to the spectral signature of the spectralon. The first has a reflectance of approximately 82% with respect to the 88% reflectance that the spectralon presents.

In this case, the spectral signature of the black polycarbonate is very similar to that obtained by normalizing an image as a function of the spectralon. To reduce the noise of the signal, the same parameters were used as in the spectral signature obtained when normalizing with respect to the spectralon: a polynomial of order 1 and a window of 7 points (Figure 13).

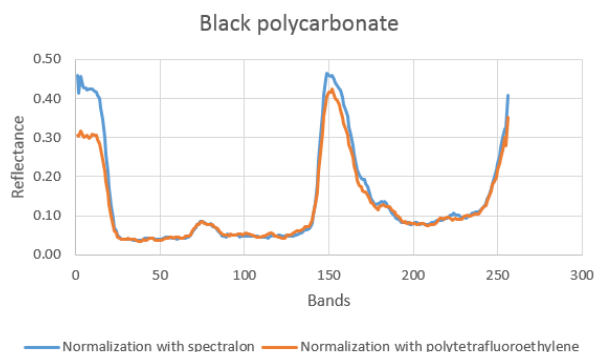


Figure 13. Comparison of the spectral signature of black polycarbonate with respect to spectralon and polytetrafluoroethylene

To study the mudwall characterization, images captured at different distances are normalized, using an ROI containing a sample of the black and white reference. The mudwall statistics are studied with the normalized cube. To do this, an ROI containing mudwall pixels is defined and the average of the values obtained is calculated to represent it.

The hyperspectral images are normalized twice in each distance. In each normalization one of the two white reference selected (spectralon or polytetrafluoroethylene) and black polycarbonate is used. Both signals are filtered using The Unscrambler X software. The spectral signature of the mudwall obtained in both normalizations is smoothed by applying a polynomial of order 1 and a window of 21 points. Figure 14 shows the differences of the mudwall spectral signature depending on the white reference used in the normalization.

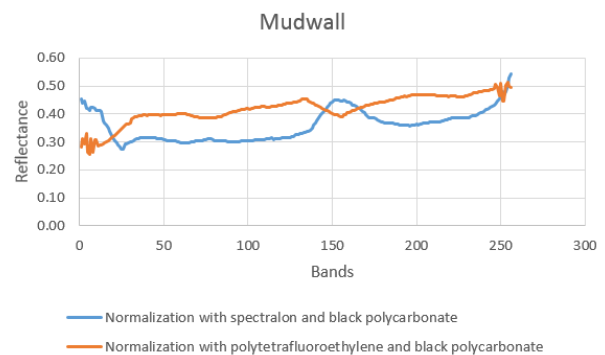


Figure 14. Spectral signature of the mudwall of the Torre del Horno according to the reference patterns: spectralon and polytetrafluoroethylene as reference white and polycarbonate as reference black in both cases.

Figure 14 shows the influence of the use of different black and white patterns in obtaining the spectral signature of an element when you work with a hyperspectral camera.

4. CONCLUSIONS

From the results obtained it is determined that the pattern that reflects the most intensity of light is the spectralon. This material, according to the manufacturer, has a reflectance value of 99%, being spectrally flat on the ultraviolet, visible and infrared spectrum; so it is a material that is supplied to carry out tests of this type for offering the highest values of diffuse reflectance (Labsphere, Inc.). With our equipment and in the conditions in which the captures have been taken, a result of 88% reflectance has been obtained. Despite being a value of 11% lower reflectance than that provided by the commercial house, it has always been the material that has had the greatest intensity in the capture. As the most reflective material, it is selected as a white reference.

Analyzing the spectral signatures for the black reference it is observed that the one that less intensity of light reflects, and therefore, can be used as black reference, is the black polycarbonate.

The spectral signature of black polycarbonate is inverse to the spectralon. That is, the part of the spectrum that the spectralon reflects with highest intensity is absorbed by the polycarbonate and the part of the spectral signature of the spectralon that presents higher absorption is reflected by the polycarbonate.

The black and white reference must always appear in the scene to be captured with the hyperspectral camera. This allows two scenes taken in different light conditions to be comparable.

In case of not having spectralon, Teflon is the best alternative as reference target since the former has 88% reflectance with respect to 82% of polytetrafluoroethylene.

Finally, it can be said that the black and white reference patterns that are used to make the captures with a hyperspectral camera influence the spectral signature that characterizes a certain element.

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Xenics Infrared Solutions, Inc. <https://www.xenics.com/>