

CHSOS, Cultural Heritage
Science Open Source

Dr. Antonino Cosentino

ANTONELLO, THE MULTISPECTRAL IMAGING (MSI) SYSTEM FOR ART

Learn Antonello, our low-cost Multispectral Imaging (MSI) system for Art Conservation professionals and Institutions. MSI is not invasive and it is successfully used in art examination to map and identify pigments, to localize retouches and to enhance the reading of faded documents.

Intro

Conservators and art historians need non-invasive methodologies to identify and map pigments on works of art and archaeology. These tools allow them to select appropriate conservation procedures, acquire information on the workshop practices, distinguish original sections from inpaints and to enhance visualization of faded pigments and inks.

Antonello is an MSI system composed of 18 bandpass filters for a full spectrum DSLR camera, covering the 400-925 nm spectral range. Using a DSLR camera rather than a monochromatic scientific camera has the advantage that the same camera can be used for other technical photographic methods, making the overall imaging equipment lighter, compact and affordable.

This tutorial is part of the MSI training module and explains step by step how to use the Antonello MSI system. The system is composed of **18 bandpass filters** whose labels clearly indicate their center wavelengths. This is the list of filters (center wavelength (nm)): 405, 430, 450, 467, 480, 500, 532, 560, 580, 610, 640, 671, 700, 730, 760, 840, 860, 920. The 18 filters are not equally spaced but have the same bandwidth (10 nm). The center wavelengths of these filters have been chosen in order to better represent the spectral features of historical pigments and they correspond to specific absorption or inflection points. See appendix A.

There is also the **filters adapter** to hold these filters on a 52 mm filter thread lens and the **MSI calibration card**. This system must be used on a full spectrum camera.

The system doesn't use selective illumination because it aims to be flexible and be used on large surface (wall paintings) as well as small one (manuscripts). Consequently it was chosen to use normal halogen lamps whose power can be adjusted to the specific size of the object to be documented.

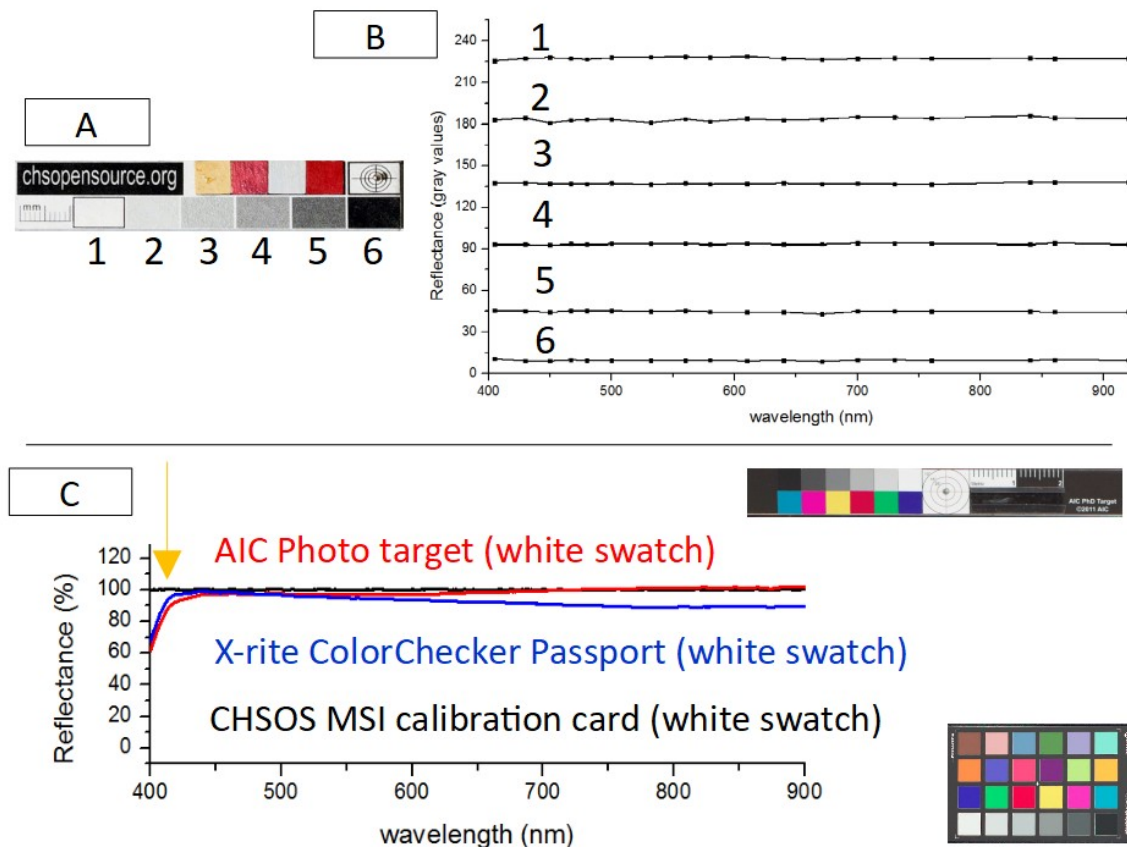
The CD-ROM contains the software and demo data which we will use during this training.

Hardware

- 18 filters plus a 52 mm (filter thread) lens adapter
- TP-MSI calibration card
- CD-ROM

TP-MSI calibration card

The TP-MSI calibration card must be included in the scene we photograph for our MSI documentation. As shown in the figure below, this card has been designed to provide real flat gray tones. See in particular the absorption band in the violet region (405 nm) that other photography cards exhibit. This makes them not appropriate for MSI calibration.



A) TP-MSI calibration card. B) TP-MSI calibration card gray swatches reflectance spectra (gray values). C) Reflectance of white swatch of TP-MSI calibration card and of two color checkers for professional photography. See the absorption band in the violet region (close to 405 nm).

Software installation

Requirements: Windows 7 or upper operative system. There are no specific recommendations for the computer specs, it is clear that a faster computer will handle the computational work faster. A good starting set-up would be an i5 processor, 8 GB RAM.

ImageJ

ImageJ is the software that we will use to edit the raw spectral images and prepare them to be loaded into the actual MSI software, Hypercube. In the CD-ROM open the SOFTWARE folder and locate this folder “IMAGEJ FIJI + DCRAW + Antonello”. Copy this folder into the C drive. We recommend to copy it directly in the C drive main location, without sub-folders.

Go into this folder IMAGEJ FIJI + DCRAW + Antonello\fyji-win64\Fiji.app and locate the “ImageJ-win64.exe” double click and launch this executable. This software does not need installation. It is good practice to make a shortcut and put it on the desktop. The software could ask to run updates. It is better to avoid updates since they could have issues that would make the Antonello plugin not working. ImageJ needs the installation of Java Runtime Environment (JRE). This is also a free software. A copy of the latest JRE is in “SOFTWARE” folder.

Hypercube

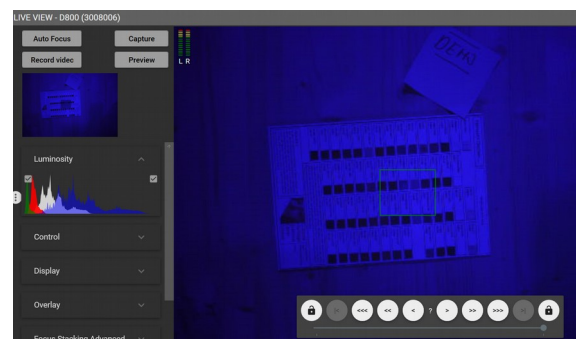
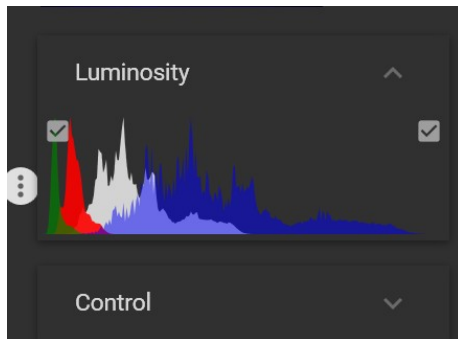
Hypercube is the MSI software we will use to make the actual MSI examination. In the CD-ROM open the SOFTWARE folder and locate this folder “Hypercube”. Copy this folder on the C: drive as we did for ImageJ. This software also just needs the folder to be copied, no installation required. Inside the “Hypercube” folder locate and double click on “Hypercube64.exe”. It is good practice to make a shortcut and put it on the desktop.

Scene and camera preparation

- *Antonello* works with any “full spectrum” camera sensitive from the near infrared to the near ultraviolet ranges of the spectrum (approximately the 360-1100 nm range). The camera must mount a lens with filter thread 52 mm (or less, using adapters).
- Screw on the filter adapter on the lens. The filters are hold in place by the magnets. Just gently push a filter out to interchange them. The label-side of the filters is the side that must face the scene.
- Add the **CHSOS TP-MSI calibration card** to the scene.
- Illuminate the scene with halogen lamps.

Shooting Raw Spectral Images

- The images must be shot in **raw** format.
- **Exposure time** is chosen for each spectral image so that the images are as bright as possible but not overexposed. It is important to expose correctly the photos so that the gray patches are distributed correctly across the gray space and are not too dark or overexposed. Tethering the camera to a laptop is recommended to better check the exposure and focusing. In order to choose the correct exposure, observe the live view histograms while shooting. The golden rule is to have the brighter channel well distributed, not overexposed. For example, if we are shooting with the 405 nm filter we expect that the Blue channel of the live view histogram is the more intense. Indeed, the image looks blue. We want to have this channel well distributed. If we are using the 532 nm filter, the green channel is the most bright and we want to select the exposure accordingly to this channel. Verify that there is not over exposure for the chosen channel. As a general rule, we expect shooting exposure in the order of 1-1/10 seconds. Only the first filter centered at 405 nm will require longer exposure since halogen lamps have poor emission in the violet region (up to 2 seconds).



Detail. Histogram. Blue is the brighter channel.

- Open up the lens **aperture** (illumination should be kept as short as possible to avoid damage on the object). All the spectral images of the sequence must be acquired with the same lens aperture and lighting condition.
- Name images as 1, 2, 3,..18. Do not use other characters or there could be issues loading the images in ImageJ. This software, as well all based on Java, don't load files with spaces in the names.
- Shoot 18 spectral images changing the appropriate filters. As an example of this shooting procedure, the set of 18 raw images of pigments checker are stored in: Training data / folder “raw”

Editing raw spectral images

All the steps to edit the raw images to prepare them for loading on the MSI software Hypercube are automatized using the ANTONELLO macro (.ijm). This macro just do automatically what is described hereafter, making the process much more faster than proceeding manually. The Antonello macro is already copied into this location: IMAGEJ FIJI + DCRAW + Antonello\fiiji-win64\Fiji.app\plugins\Scripts\File.

To run the Antonello macro open ImageJ and click on "FILE. In the drop-down menu there is the "Antonello" macro. Click on it. The Antonello new window will ask to locate the folder with the raw images (we suggest to put them on the desktop). Then it asks to select the gray patches on the TP-MSI calibration card, starting from the white.

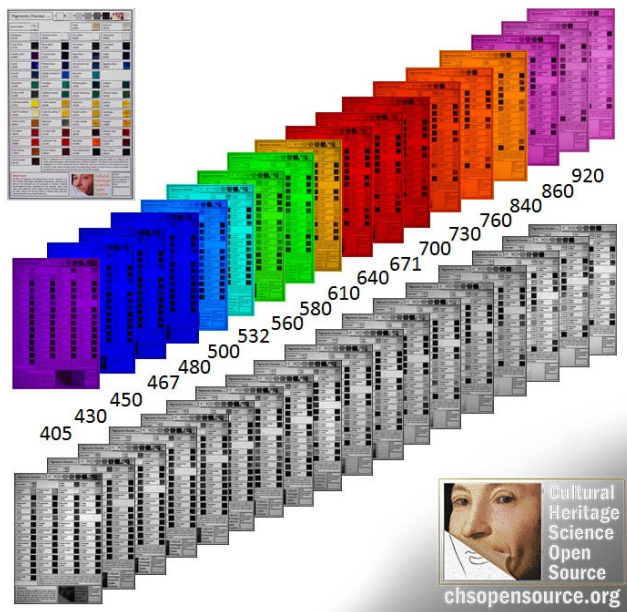
There is a demo video on this page <https://chsopensource.org/multispectral-imaging-system/> showing how to use the macro. The name of the video is "Automatic Spectral Raw Images Editing".

Description of the Antonello macro operations

This is a description of the steps done automatically by Antonello macro. By the way, there are many plugins for ImageJ available for free in the software webpage. To use them, download the plugin folder and copy the content into the PLUGINS folder of the ImageJ installation in your laptop.

1 Splitting Raw

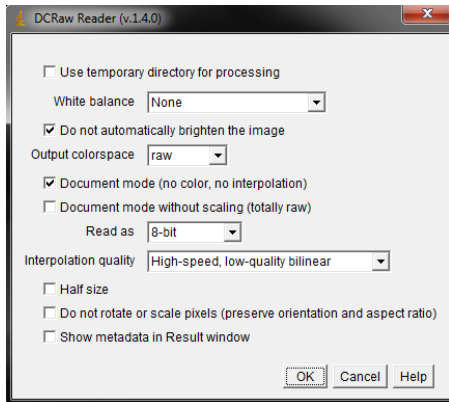
The photosensors of each pixel of a DSLR camera cannot distinguish the wavelength of the incoming light and they are covered with a CFA; tiny color filters placed over the pixels to select only red green or blue light. The CFA on the Nikon D800, as on the majority of digital cameras, implement the Bayer CFA scheme. The raw image is converted to a full-color image by a demosaicing algorithm run by the on camera image processor. This image cannot be used to reconstruct reflectance spectra. The raw images are split into their 4 (BGRG) components using ImageJ (Fiji distribution) and the DCRAW plugin. Based on the spectral response of the Bayer filter, the brighter split images are selected and the other are discarded.



Pigments Checker. Raw format spectral images and calibrated split components (gray values).

To perform this splitting manually, open the raw image in ImageJ using the DCRAW plugin, PLUGIN/ Input-Output / DCRAW reader (we cannot open a raw image by the usual FILE/open menu, we need to use DCRAW plugin). DCRAW is a C program created by David Coffin. Over 200 various raw formats are supported, including Adobe DNG. DCRAW allows to control how raw images are processed and this enables extracting sensor data that is lost when image is converted to a standard viewing format. The same plugin is used eventually to split the images into their native RGB components.

- From the new window use these parameters:



- Once the image is loaded (B/W mode) do: PLUGINS / NEW / MACRO and paste this code: This code will create the R G1 G2 and B images which you can save as TIF: FILE/ SAVE AS TIF.

***** splitting code*****

```
id = getImageID();
makeColorChannel("G1", 0, -1);
selectImage(id);
makeColorChannel("R", 0, 0);
selectImage(id);
makeColorChannel("B", -1, -1);
selectImage(id);
makeColorChannel("G2", -1, 0);

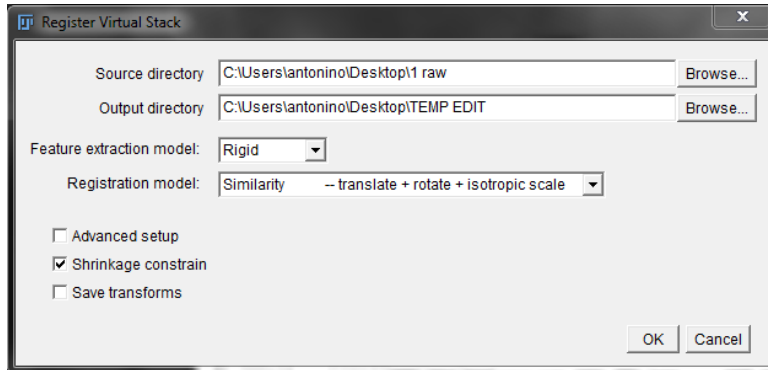
function makeColorChannel(name, dx, dy) {
    slices = nSlices();
    newWidth = getWidth()/2;
    newHeight = getHeight()/2;
    run("Duplicate...", "title=&name duplicate range=1-&slices");
    run("Translate...", "x=&dx y=&dy interpolation=None stack");
    run("Size...", "width=&newWidth height=&newHeight depth=&slices interpolation=None");
}
```

***** splitting code*****

2 Registration

Registration is the operation of aligning and scaling in order to make all the images overlap to each other. Registration is performed within ImageJ. The 18 spectral images are registered taking the first spectral image as a reference for all the others (differently than progressive methods which register one image to the previous).

- The plugin Register Virtual Stack Slices comes already installed under PLUGINS/REGISTRATION. This plugin takes one image and uses it as a reference. More info here: http://fiji.sc/Register_Virtual_Stack_Slices
- Choose these parameters:



- The plugin put the registered images in the destination folder.

3 In-scene calibration with TP-MSI calibration card

This step is applied to the registered images, discussed in the previous paragraph. The reflectance calibration of the spectral images is performed using the TP-MSI calibration card as in-scene reflectance standard. Its white, black and 4 gray patches are used to calibrate the images applying a multi-point 3rd degree polynomial calibration curve in ImageJ.

The gray card has 6 swatches: white, 4 grays and black. Their respective reflectance values are (%): 100, 80, 60, 40, 20, 5. The reflectance values are associated to gray values: 100:**230**; 80:**184**; 60:**138**;40:**92**; 20:**46**; 5:**11**. The pure white swatch is not associated to 255 in order to allow for white with higher reflectance to be recorded without overexposure.

To calibrate the images follow this procedure, repeat this procedure for each image of the sequence:

- Open the first image of the sequence (TIF format). Select a rectangle on each swatch of the MSI calibration card starting from the white and moving toward the black. Use the rectangle tool and take a measure pressing CTRL + m. The average gray value for the selected rectangle will be calculated and saved. Drag the rectangle to the first gray and repeat CTRL+m. Repeat this procedure for all the swatches. Proceed in the order from the white to the black. Again, no need to jot down these values, they are saved automatically in a new window in ImageJ.

1. Select the rectangle tool

3. Press CTRL + m . A new window will open showing the grey mean value of the area

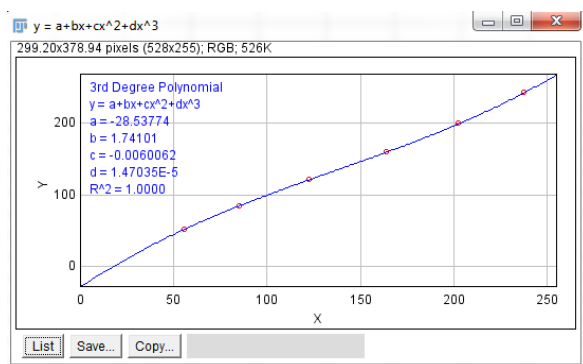
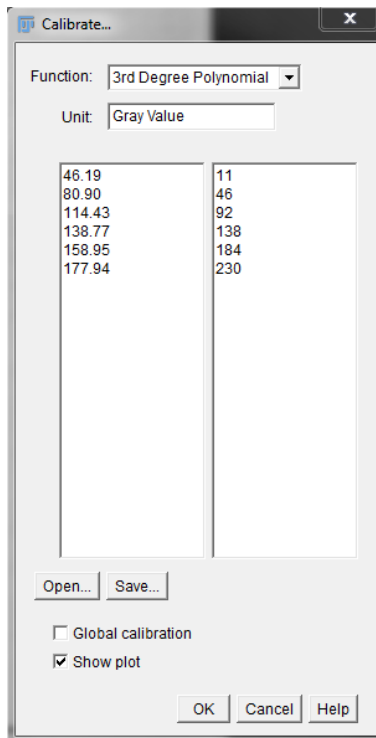
2. Drag a rectangle on the first swatch (white)

4. Drag the rectangle to the next swatch and repeat step 3. Continue to the other swatches

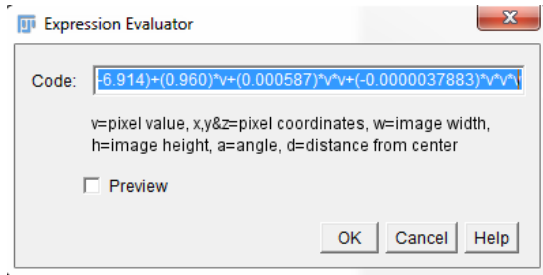
Area	Mean	Min	Max	Slice
19008	227.709	219	233	1

- Once all the swatches have been processed, select ANALYZE / CALIBRATE and add the reference value for the gray patches white:230; 1st gray:184; 2nd gray:138; 3rd gray:92; 4th gray:46; black:11.and choose 3rd degree polynomial. The parameters and the calibration curve is calculated and showed.

Note: the calibration curve can be saved. Select the calibration curve window and press File/ save (as txt). The curve is saved as a table.



- Select the spectral image to calibrate (i.e. the TIF image). In the menu press: Process/Math/Macro. Input the parameters into this formula (3rd degree polynomial): $v=(a)+(b)*v+(c)*v*v+(d)*v*v*v$
Note: the symbol “E-integer” like E-1, E-2, E-3, and so on, translates into adding a corresponding number of zeros. For example 2.324E-5 corresponds to 0.0000234. In any case, it can be input as it is, 2.324E-5, since the macro recognizes this format. We suggest to input at least 3 decimals.



Example of formula with actual parameters.

- Repeat the calibration procedure for all the spectral images. Now the images are ready to be input into Hypercube to build the spectral cube.

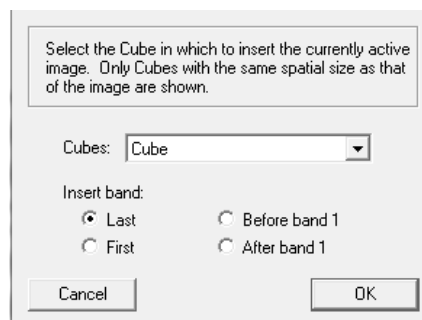
HyperCube

HyperCube imaging spectroscopy software is used for the analysis of the multispectral images we just created. HyperCube is a Macintosh and Windows application program specifically directed to the analysis and display of multi and hyperspectral images. In addition, HyperCube contains functions to perform arithmetic on images and data. For a detailed tutorial on this software read its manual, contained in the same folder of the software executable.

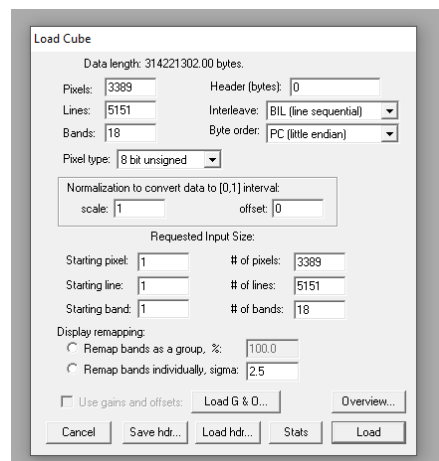
We provide here some basic instructions.

Build the Spectral cube

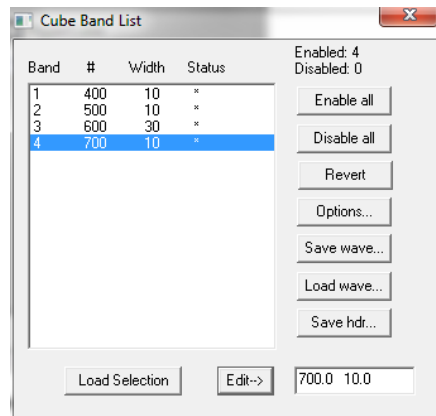
- Hypercube works with TIF and JPEG. Choose FILE/OPEN AS and open the first image of the spectral sequence.
- Choose IMAGE/CONVERT IMAGE/ PLANE TO CUBE
- Open the 2nd image of the sequence and choose IMAGE/ADD TO CUBE



- Repeat this procedure for all the 18 spectral images. We just created our first spectra cube. As an example of spectral cure, the one we created is stored in: Training data / folder "Cube". To open a cube choose FILE / OPEN and select the Cube file. A new window will appear, just click "load".



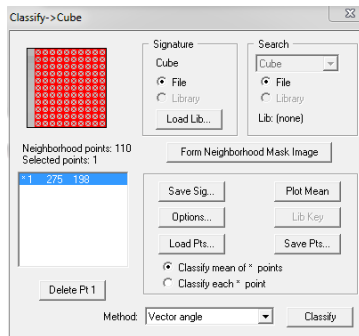
- We can add the center wavelength for each spectral image. Choose WINDOWS/SHOW BAND /LIST and insert the center wavelength for each band (width is not necessary).



Reconstructed Reflectance spectra

Once the spectral cube is ready you can explore some of Hypercube's handy functions.

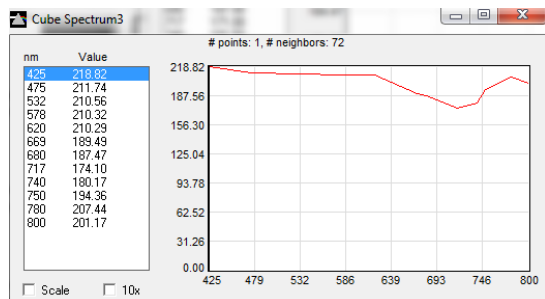
- **Spectra of selected points.** We want to visualize the reflectance spectrum of a point in the image. Select FUNCTIONS / PLOT SPECTRA (SELECTED POINT). Shift click on a point to see its reflectance graph. Uncheck "scale" to properly see all the reflectance spectrum intensity range (0-255). Also uncheck [0,1] (otherwise we do not see any spectrum because the scale is 0-1 (while we have gray values between 0-255)).
- **Dynamic plotting of reflectance spectra.** This is another plotting function as above but with dynamic updating based on the position of the cursor. FUNCTIONS / PLOT SPECTRA (dynamic). This function shows reflectance graph on the actual cursor position. As seen above for the selected points plot tool, uncheck "scale" to properly see all the reflectance spectrum intensity range (0-255). Also uncheck [0,1] (otherwise we do not see any spectrum because the scale becomes 0-1).
- **More precise reflectance spectra, averaging a large area.** Rather than just show the reflectance spectrum of a specific pixel, it is more precise to calculate the average spectrum from a number of pixels in the surrounding area. Go to FUNCTIONS / CLASSIFY / In the new window select a large number of pixels by CTRL + click the upper left corner and then SHIFT + click the bottom corner.



Choose “classify mean of * points” and then click “Plot Mean” to see the average spectrum from all the selected pixels.

Note that this “classify mean of * points” option will make the average also if you have more than one point selected in the image. This option should be used then just when we are selecting the same material.

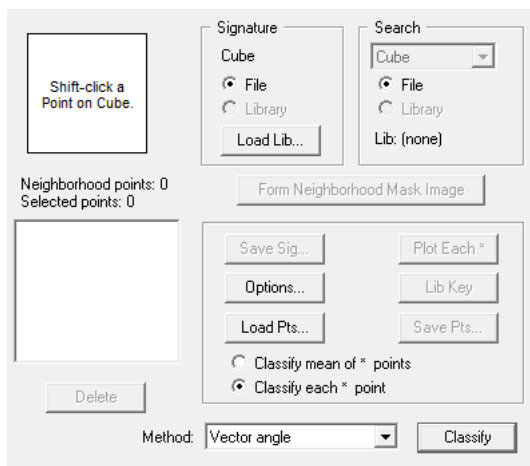
The spectrum can then be saved FILE / SAVE AS / library. The text file can then be opened and imported.







Instructed Classification

This is the procedure of mapping areas with the same reflectance spectra and making a false color map. Select CLASSIFY. The Classify window will open. Start to train the software by shift +click a point representative of the class and then use the average pixels selection procedure to add multiple pixels. If we are adding points representative of different materials, we need to select “Classify each* point “.

Click “classify”. A new window will show a false color map indicating the areas with the same reflectance spectra of the selected points. Add all the reference points that you want to classify to have a final map showing the distribution of these materials.



As an example, we use the cube created with the pigments checker and located in the “Training data” folder. Open the cube. We select points on lithopone, cobalt violet, and smalt. Be sure to select “Classify each* point “ and click “Classify”. The software will present an image as the one below. Lithopone is mapped with red, cobalt violet with green and smalt with blue.

Lithopone 46100		Titanium whi 46200
Lamp black 47250		Bone black 47100
Cobalt violet 45800		Prussian blue 45202
Smalt 10000		Phthalo blue 23050

Algorithms

There are a number of algorithms in the CLASSIFY section to choose from. We can start using the default “vector angle” with its standard options, as done for the example shown above. Depending on the application, other algorithms can be implemented. A useful one is “absolute difference”. The more classification points we select the better is the final classification. So, for example, if we select just lamp black, the algorithm could identify azurite and green earth as lamp black because they have all very dark and flat spectra. If we select lamp black, azurite and green earth, the software is able to recognize all of them. Compared to the other similar algorithms such as “Euclidean distance”, “absolute difference” produces less false classifications,

Vector angle and similar algorithms are based only on the “shape” of the spectrum. This approach represents an issue because with this algorithm lead white and lamp black are classified together because they have a flat curve, regardless of the fact that one is bright and the other is dark. So it is better to use “absolute difference” which takes into account “shape” and “brightness”. For these algorithms generally we have to apply the maximum threshold or very close to it.

We tested these latest algorithms for specifically locate the carbon based pigments, after selecting the lamp black as the classification point.

Euclidean distance. Even at maximum threshold not all the lamp black is selected and most of the other black are missed.

Absolute difference. We get a nice result with threshold 10. All the carbon based black are identified.

Template. This algorithm is too selective, so, even at the maximum threshold, only a part of the pigment of a single swatch is classified. Small differences in thickness are enough to rule out the same pigment, more than with the “absolute difference”.

Threshold sequence

It is possible to have the software prepare a sequence of the classification with different threshold values, so we can define which one is best for our task. We check the option “generate a sequence ” and we input the number of different values of the thresholds should be calculated between the input min and max.

Classify Options

Selected Method Parameters
Vector Angle (no param)
Theoretical best Tolerance: 0.000
Theoretical worst Tolerance: 3.142

Classification Match Criteria
 Threshold, Enter tolerance, [best,worst]:
 Percentage, Enter tolerance, [0,100%]:
 Equal distribution, Enter classes, [2,64]:
 Countable, Enter N closest, [1,32767]:

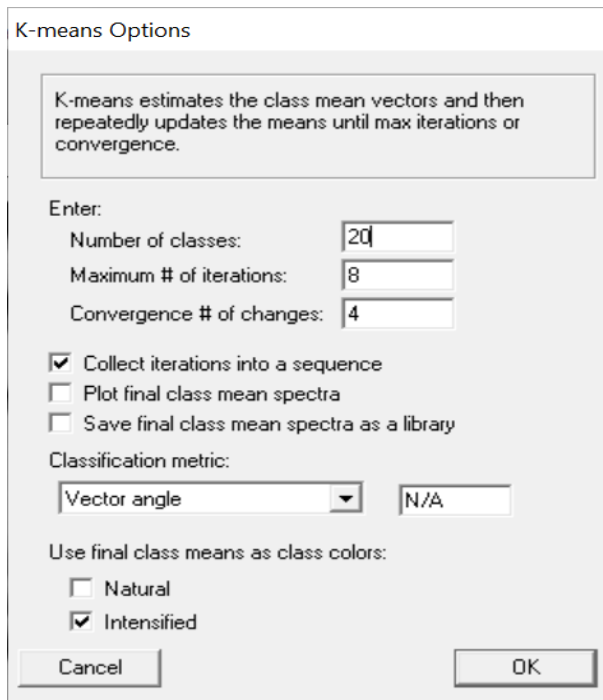
Classification Output(s)
 Color mask (black where no match)
 Color image (cube face shows where no match)
 Generate a sequence, Enter # of outputs:
Starting tolerance: ROC curve
Ending tolerance:

Library Parameters
 Closest library matches Lib:File match lists
 Ignore the Disabled Bands List in Library:Library searches
 Enable dynamic display in File:Library searches

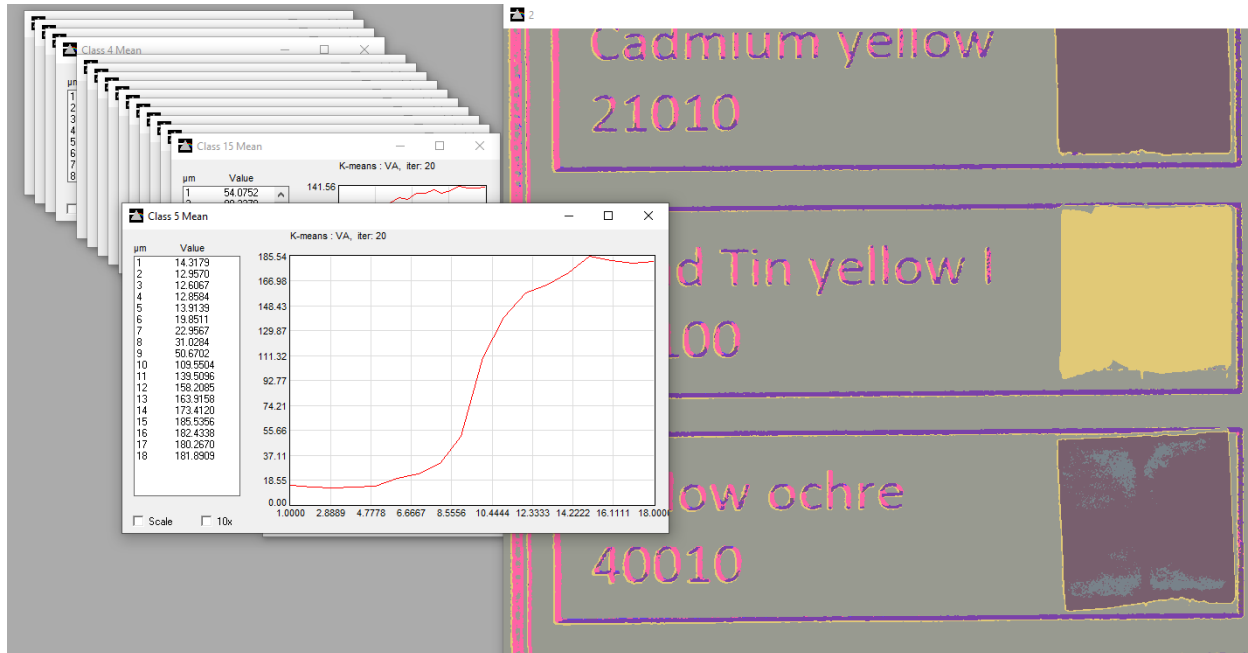
Pre-filter Spectra
 Enable spectral wavelet denoising

Automatic classification

It is possible to obtain an automatic classification of the cube without providing any point. We use the K-means method under the usual “classify” menu. The image below shows an example where the software was asked to segment the cube into 20 classes “Number of classes”. We can leave “maximum # of iterations” to 8, to avoid too long calculations. We can choose to check “Plot final class mean spectra” to have the spectra of these classes. As “classification metric” we suggest “euclidean difference”.



Remember to switch among the iterations to check which one works better. Below is an example of the mean class spectra produced for the automatic classification. Numbers indicate to what colors they refer.



The automatic classification does not produce the better result. For example, vermilion will not be distinguished from cadmium red and others reds. Since the software has to look at all the cube at once does not work well for pigments segmentation. Instructed segmentation is way more precise.

Select and Deselect a rectangle. Just left clicking and dragging the mouse allows to select a rectangle. To deselect DOUBLE click outside the rectangle.



4 Appendix A. Filters center wavelengths

Whites. Titanium white has a strong UV absorption band (filter at 405 nm) that goes until the violet region and distinguishes it from the other white pigments. Lithopone features the absorption bands (filters at 670 nm and 725 nm) in the red- infrared region due to its zinc sulfide component.

Blues. Prussian blue and cobalt violet have maxima in the blue region (respectively, filters at 450 nm and 700 nm). Maya blue and indigo have inflection points in the infrared (respectively, filters at 760 nm and 840 nm). Smalt features a maximum in the blue region (filter at 430 nm) and a large absorption band in the yellow region (filter at 580 nm). Phthalo blue has a maximum in the blue region (filter at 465 nm) and an absorption band in the infrared (filter at 920 nm). Cobalt blue features an inflection point in the green region (filter at 525 nm). Azurite and ultramarine large maxima in the blue region are covered by all the 5 filters already mentioned from 405 nm to 480 nm.

Greens. Malachite, verdigris and phthalo green have their maxima in the green region (respectively filters at 525 nm and 500 nm). Viridian has its inflection point in the infrared (filter at 760 nm). Green earth has weak absorption bands which cannot be resolved with this system and consequently it will produce a flat spectrum. Cadmium green is identified by its infrared fluorescence and no filter was selected for its spectral features. Cobalt green maximum is represented by the filter at 532 nm. The filter at 405 nm outlines the chrome green maximum in the violet region.

Yellows. Cadmium yellow has its sharp inflection point in the blue-green region (filter at 480 nm) while cobalt yellow has a weak absorption band in the red region (filter at 610 nm). Orpiment and saffron have their inflection point outlined by the filter at 532 nm. Lead tin yellow I has a sharp inflection point covered by the filter at 467 nm. Lead tin yellow II, naples yellow and gamboge inflection points are represented by the filter at 532 nm. Yellow and red ochre as well as sienna show an S-shape spectral feature with maxima at 600 nm and 770 nm and minima at 645 nm, 860 nm and 915 nm (respectively filters at 610 nm, 760 nm, 640 nm and 920 nm). Massicot has an inflection point at 450 nm (filter at 450 nm) and yellow lake reseda at 490 nm (filter at 500 nm). Realgar has its inflection point at 560 nm and a filter was added to cover it.

Reds. Vermilion, cadmium red, alizarin and madder lake have inflection points at 600 nm (filter at 610 nm). Lac dye spectrum is heavily dependent on the binders with an inflection point varying widely and so no specific filter was added for it. Carmine lake has an inflection at 630 nm (filter at 640 nm). Red lead has its inflection point at 575 nm (filter at 580 nm).

Browns and black. They don't have spectral features useful for their identification.

Center Wavelength (nm)	notes
405	Titanium white absorption; chrome green maximum
430	Smalt, malachite maxima
450	Prussian blue maximum, massicot inflection
467	Phthalo blue maximum (465), lead tin yellow I (465) inflection
480	Cadmium yellow inflection
500	Verdigris, phthalo green maxima; yellow lake R. (490) inflection
532	Cobalt blue inflection; cobalt green maximum; orpiment, lead tin yellow II (525), naples yellow (515), gamboge (535) and saffron inflections
560	Realgar inflection
580	Red lead (575) inflection

610	Cobalt yellow absorption (615); ochre (600) maxima, vermilion, cadmium red, alizarin, madder lake inflection
640	Ochre (645) minimum; carmine lake (630) inflection
671	Lithopone absorption (670)
700	Cobalt violet maximum
730	Lithopone absorption (725)
760	Maya blue, viridian (770) inflections; ochre (770) maximum
840	Indigo inflection (830)
860	Ochre minimum
920	Phthalo blue, ochre (915) minima

Table 1. 18 filters center wavelength and the respective pigments' spectral features that they outline.