Electrochromic Optical Mapping System

USER MANUAL

1. INTERFACE USER MANUAL

This custom-developed interface enables users to process digital videos or images in order to extract spatially resolved optical information from large-area electrochromic devices. The analysis is based on corrected image data, preprocessed following the calibration protocol described in our previous work[1] using a ColorChecker chart to obtain accurate CIELAB coordinates. The user can define the active surface area of interest within each video or image, and the system will automatically generate color-coded maps corresponding to different electrochromic parameters over that region.

Specifically, the interface allows the calculation and visualization of:

- Transmittance homogeneity at λ_{max}
- Colorimetric homogeneity (ΔE maps)
- Optical contrast
- Switching speed (t_{90})
- Cycling stability (N_{80})

In addition to the spatial maps, the system can provide intermediate graphs and reconstructed transmittance spectra for each subdivided region, offering in-depth analysis of both instantaneous and time-dependent optical behavior.

The interface has been developed and executed in a local Python environment (Spyder IDE). Due to dependencies on graphical libraries such as tkinter, matplotlib.widgets, and video processing packages, this system cannot be run in online notebooks (e.g., Google Colab or Jupyter Lab). All necessary files, including the main Python script, are available in the GitHub repository provided in the following link:

https://github.com/antoniocs11/Homogeneity-spectrophotometer

This manual describes the functionality and workflow of the tool in detail, outlining input requirements, configuration steps, and the nature of the generated outputs.

The following subsection 1.1 describes the libraries needed to run the script, while subsection 1.2 describes the user interface created and instructions to use it.

1.1. Spyder software and required libraries

To open the corresponding programming environment, first download the "Anaconda" application (select the last version), available at the following address: https://www.anaconda.com/download , selecting your computer's operating system. Once installed, a set of programming environments are pre-installed, such as "Jupyter Notebook", "Spyder", "RStudio", and so on. In our case, "Spyder" will be used.

Before loading the system-related script, a set of extra libraries must be installed, as only some of them are installed by default. Below are the set of all libraries used and code to install them:

```
import cv2
import os
import datetime as dt
import pandas as pd
import numpy as np
from skimage.io import imread
from skimage.color import rgb2lab, lab2rgb
import matplotlib.pylab as plt
import matplotlib.cm as cm
import matplotlib.colors as mcolors
import tensorflow
import joblib
from keras.models import load_model
from matplotlib.backends.backend_pdf import PdfPages
from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg
from matplotlib.pyplot import figure
from tkinter import *
from pathlib import Path
from tkinter import filedialog
from PIL import Image
from colormath.color_objects import LabColor, sRGBColor
from colormath.color_conversions import convert_color
from scipy import signal
import csv
from tkinter import messagebox
import tkinter as tk
```

import matplotlib.colors as mcolors

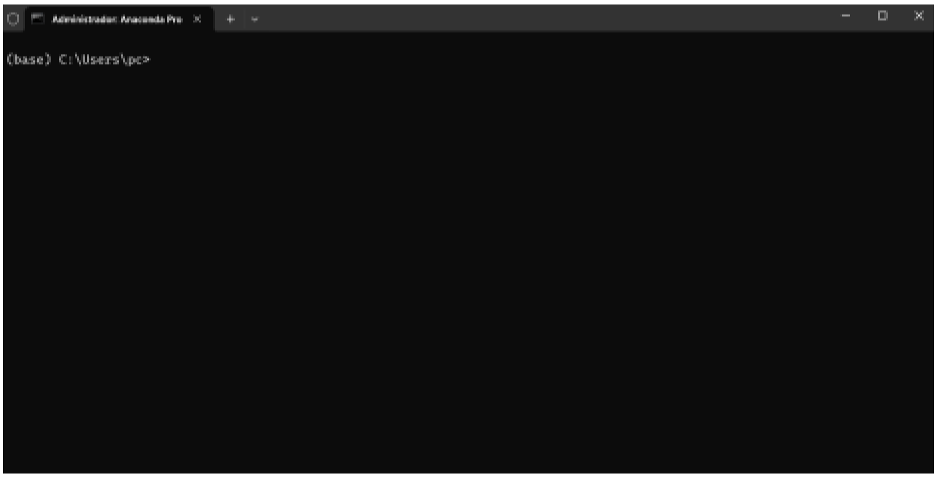
from matplotlib.colors import Normalize

from scipy.signal import find_peaks

from scipy.optimize import curve_fit

The vast majority of libraries are installed by default when installing anaconda software. However, there are several that must be installed manually. Regarding the ones used in this particular script, "tensorflow", "colormath" and "opencv" must be installed manually. The steps are described below:

- All libraries are installed in “Anaconda prompt”, which comes pre-installed with Anaconda. Therefore, the first step is to open this window:

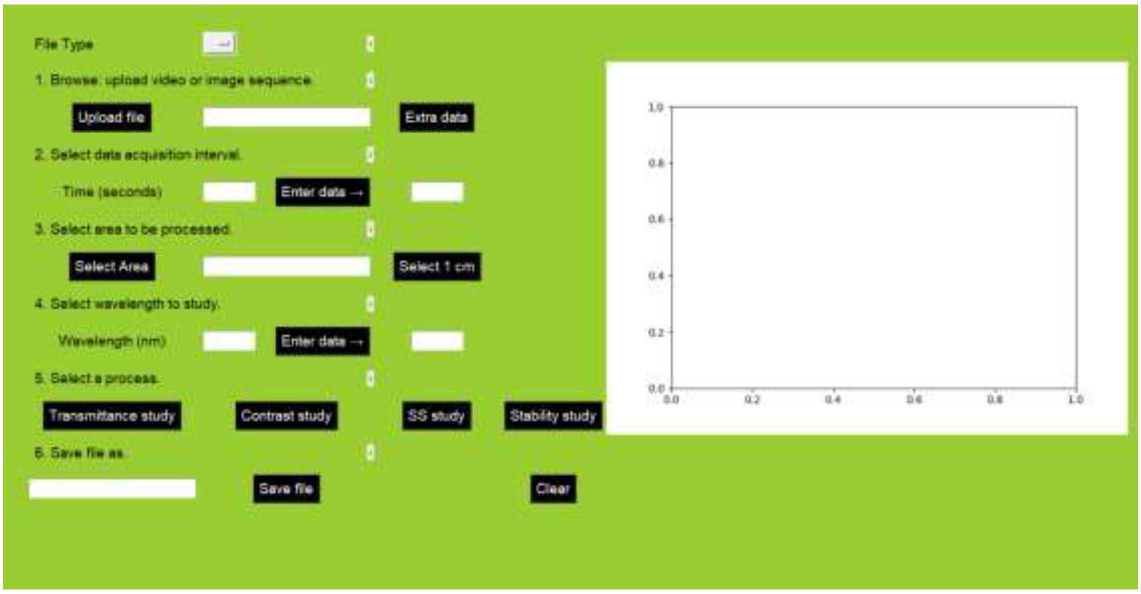


- “Tensorflow” library: this library is installed introducing the following command: “pip install tensorflow”.
- “Colormath” library: this library is installed introducing the following command: “conda install conda-forge::colormath”
- “Opencv” library: a file that includes this library must be downloaded. In the following link (https://www.youtube.com/watch?app=desktop&v=ZdMwt9ZZaSc) a video explaining how the installation takes place is shown. During the installation process, the user will download a file including the desired library, which will be saved in a specific folder. Subsequently, in Anaconda Prompt, this file will be installed, implementing the "Opencv" library to the software.

Before opening the script and starting to run, it is necessary to save the file containing the neural network (Neural_network.h5) in the same folder where the program script is located.

1.2. User interface

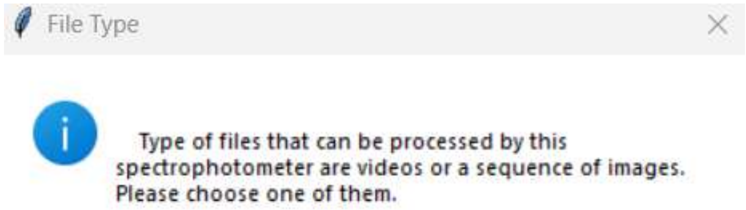
When the script is executed, The interface shown in the following image opens. There are six simple steps that the user will have to perform. Each one comprises, at the right side of the text area, a button with the letter "i" for information about that particular step.



FILE TYPE

The files that can be processed can be videos or image sets. The processing of these two types of files is different. Therefore, it is initially necessary to select which file type is going to be studied. First, click on the button that appears at the right of the text “File Type”. The user can select either “video” or “Image_sequence”:

The Info button will display this message when clicked:



1. Browse: upload video or image sequence.

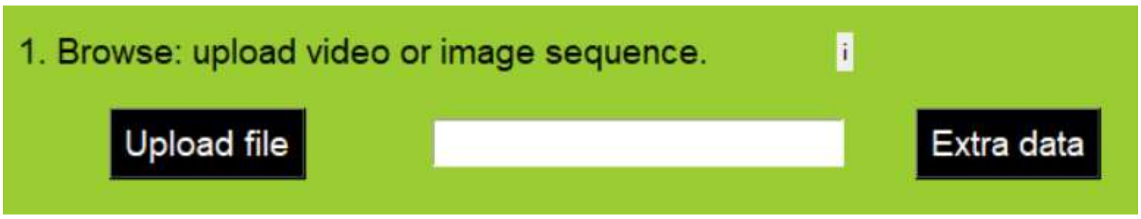
By clicking the "Upload file" button, the user can browse and load either a video file or a sequence of images for analysis:

- If a video is selected, it can be imported from any folder on the computer.
- If a sequence of images is selected, the folder containing those images must be located in the same directory as the main Python script. The sequence to be processed is determined by selecting a specific image—once selected, the system will process all subsequent files in that folder starting from the chosen one.

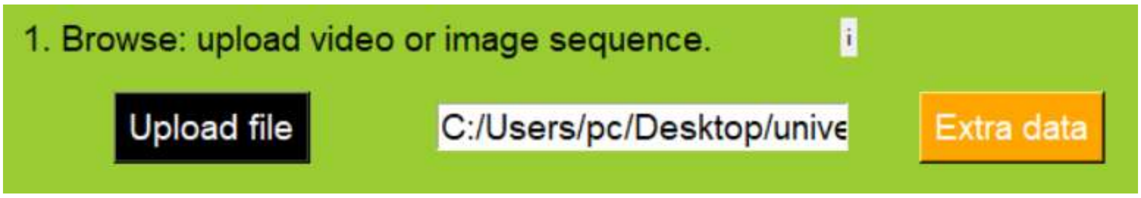
Once selected, the full file path of the uploaded video or image set will be displayed in the interface.

In addition, the user must now click the "Extra Data" button to define key processing parameters. Upon clicking, a pop-up window will request two inputs:

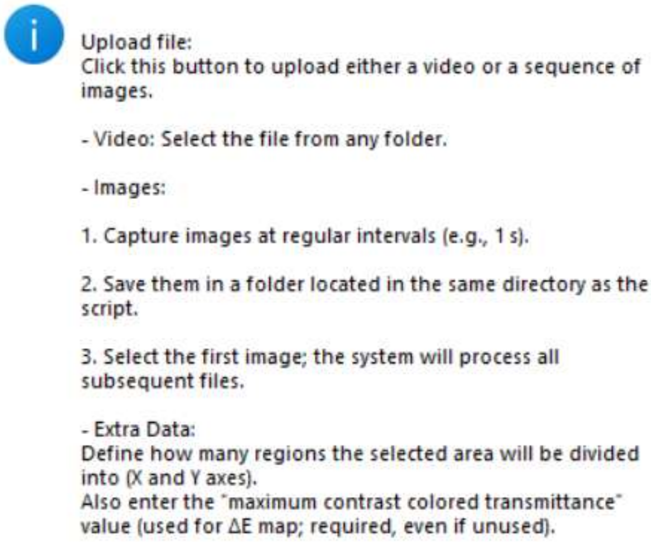
1. Number of divisions along the X and Y axes
These values define how the selected surface area will be segmented. For example, entering "10" for both axes will divide the area into 100 equal regions (10×10), and each region will be analyzed independently to build the final color maps.
2. "Maximum Contrast Colored Transmittance" value
This parameter refers to the expected transmittance (%) (at λ_{max}) corresponding to the optimal colored state of the material, as previously determined during film optimization. It is used exclusively to compute the colorimetric ΔE map comparing actual color coordinates to the ideal ones.
If the user does not intend to generate the ΔE map, any placeholder value may be entered (e.g., 10), but the field must not be left blank.



Furthermore, once these data had been completed, this button will change to orange colour (symbol to identify all these data have been completed).



In this step, the info button shows the following text:



2. Select data acquisition interval.

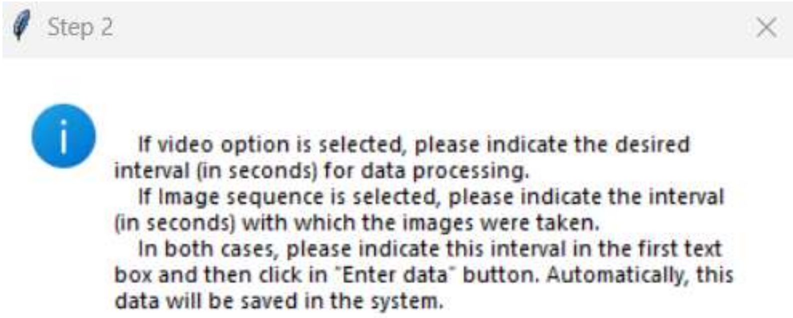
If video option is selected, the user will indicate the desired interval “t” (in seconds) for data processing. One frame every "t" seconds will be extracted from the video and processed.

If Image sequence is selected, the user will indicate the interval (in seconds) with which the images were taken.

In both cases, please indicate this interval in the first text box.

Then, click in “Enter data” button and, automatically, this data will be saved in the system. This data will appear in the second text box of the line.

In this step, the button related to information shows the following text:



3. Select area to be processed.

In this step, there are two buttons, first one to select the active area of the device to study (from the video or images) and the second one to reflect how many pixels are 1 cm.

- *First button: "Select area"*

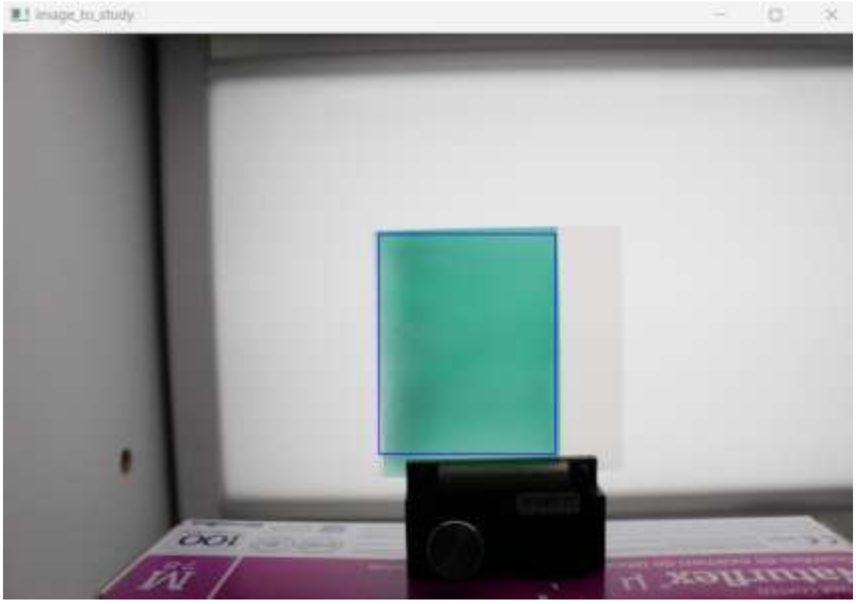
If the "video" option has been selected, note that the first step of the program will be the extraction of frames from the video. Simultaneously, it will save these frames in a folder called "data" that will be automatically created in the folder where the script is stored. Every time a new measurement is taken, the frames belonging to this folder will be automatically overwritten by the new ones. Due to this extraction intermediate step, this process could be slow (depending on the data acquisition interval selected).

If "image_sequence" has been selected, the system will directly open the image selected by the user. Remember to store this folder in the same address where the script is located. This process is immediate and should not take long.

In order to select the image area to be studied (whether in video or image sequence option), please, press the button "Select area". Then:

1. Wait until an image of the selected file appears in a pop-up window.

2. Then, with the left mouse button, select the upper left corner of the desired area of study.
3. With the right mouse button, please select the lower right corner, forming a rectangle corresponding to the area to be studied.



4. Press "ESC" key.
5. The process could take some time, mainly if the set of images is big or the video length is large. Please, wait until the process finishes. When the task is done, the next message will appear: "Process completed".

- *Second button: "Select 1 cm"*

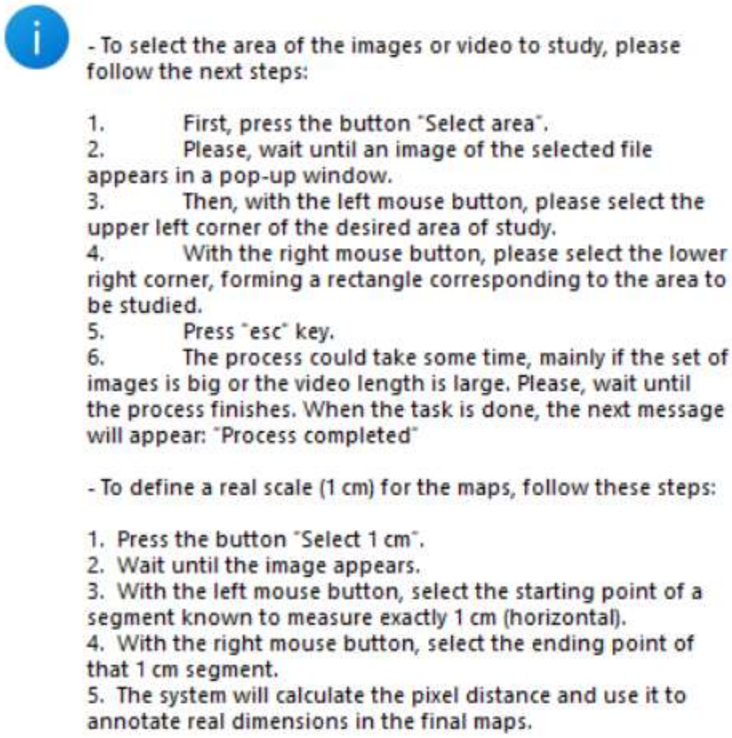
Additionally, to enable real-scale representation in the resulting color maps, click the "Select 1 cm" button:

1. A new pop-up window will display the same image as before.
2. Select the starting point (left mouse button) and the ending point (right mouse button) of a segment corresponding to exactly 1 cm in length on the horizontal axis.
3. The system will calculate the number of pixels between these two points (in X-axis) and use this reference to annotate real-world dimensions on the axes of all generated maps.

It is recommended that the reference image includes a visible scale marker or object of known size to perform this calibration accurately.

Furthermore, once these data had been completed, this button will change to orange colour (symbol to identify this reference has been taken).

In this step, the button related to information shows the following text:


- To select the area of the images or video to study, please follow the next steps:

1. First, press the button "Select area".
2. Please, wait until an image of the selected file appears in a pop-up window.
3. Then, with the left mouse button, please select the upper left corner of the desired area of study.
4. With the right mouse button, please select the lower right corner, forming a rectangle corresponding to the area to be studied.
5. Press "esc" key.
6. The process could take some time, mainly if the set of images is big or the video length is large. Please, wait until the process finishes. When the task is done, the next message will appear: "Process completed"

- To define a real scale (1 cm) for the maps, follow these steps:

1. Press the button "Select 1 cm".
2. Wait until the image appears.
3. With the left mouse button, select the starting point of a segment known to measure exactly 1 cm (horizontal).
4. With the right mouse button, select the ending point of that 1 cm segment.
5. The system will calculate the pixel distance and use it to annotate real dimensions in the final maps.

4. **Select wavelength to study.**

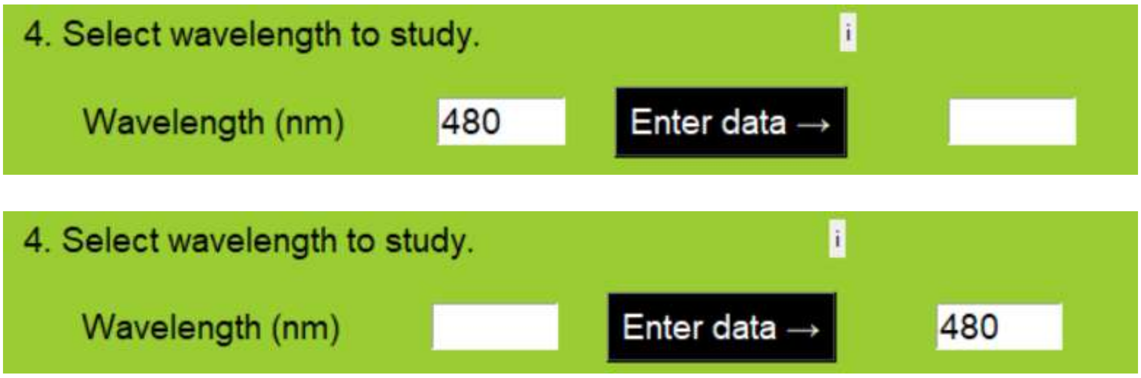
In all processing modes, the calculations are based on the transmittance at the material's maximum absorption wavelength (λ_{max}). Therefore, this parameter must be entered regardless of which analysis is selected later.

This parameter can be calculated using the system created in previous research[1] with this same virtual spectrophotometer.

To enter this value, follow the steps below:

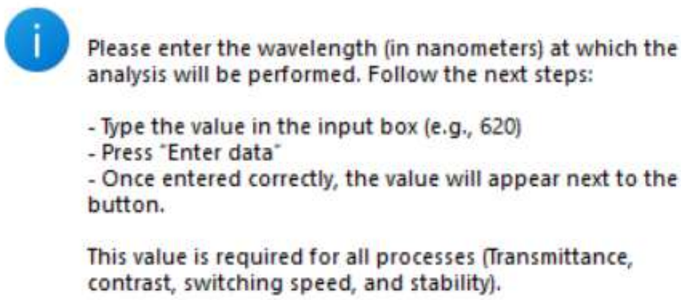
1. Locate the field labeled "Wavelength (nm)".
2. Enter the desired λ_{max} value in nanometers (e.g.: 480).
3. Click the button "Enter data" to confirm the input.

4. Once entered, the value will appear to the right of the button, indicating that the system has successfully registered it.



This wavelength will be used for all subsequent calculations and graphical outputs involving contrast, switching speed, and stability. Make sure the value corresponds to the correct λ_{max} for the specific material under study, as determined during initial film characterization.

In this step, the button related to information shows the following text:



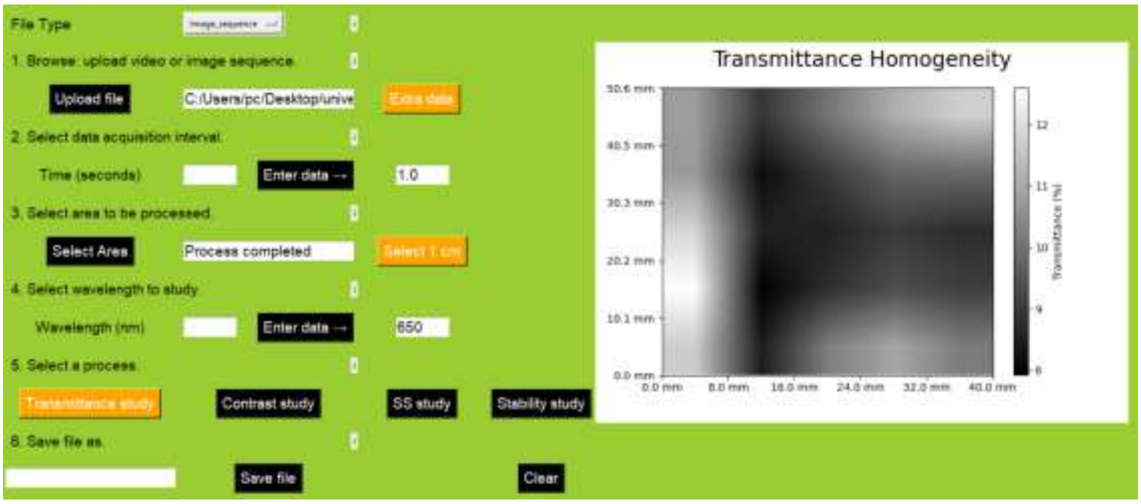
5. **Select a process.**

Once the region of interest and the working wavelength (λ_{max}) have been defined, the user must select the type of analysis to be performed. The interface provides four independent options, each corresponding to a specific electrochromic property:

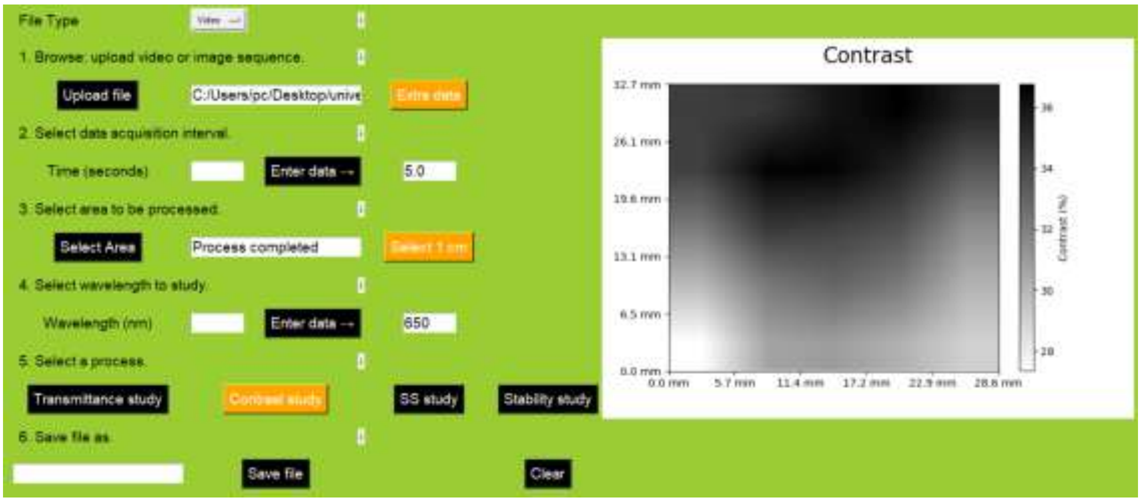
- **Transmittance**
- **Contrast**
- **Switching Speed (t_{90})**
- **Stability (N_{80})**

Upon selecting one of these options, the system will process all frames or images according to the chosen mode and generate a color-coded map representing the parameter of interest across the entire active surface. All maps are displayed to scale, with real-world dimensions labeled on the X and Y axes (based on the 1 cm reference selected earlier).

For the **TRANSMITTANCE** option, the system will only display the transmittance distribution map at λ_{max} across the selected surface. The colorimetric ΔE map (used for evaluating homogeneity with respect to the optimal colored state) is not shown at this point. This secondary map can be generated later by enabling the corresponding option in the interface.



By selecting the **CONTRAST** option, the system will calculate the transmittance difference at λ_{max} between the two optical states (colored and bleached) of the device, for each defined region of the selected surface. The resulting contrast map is displayed in the interface, representing the spatial distribution of ΔT across the active area. This visualization allows rapid assessment of switching performance uniformity.

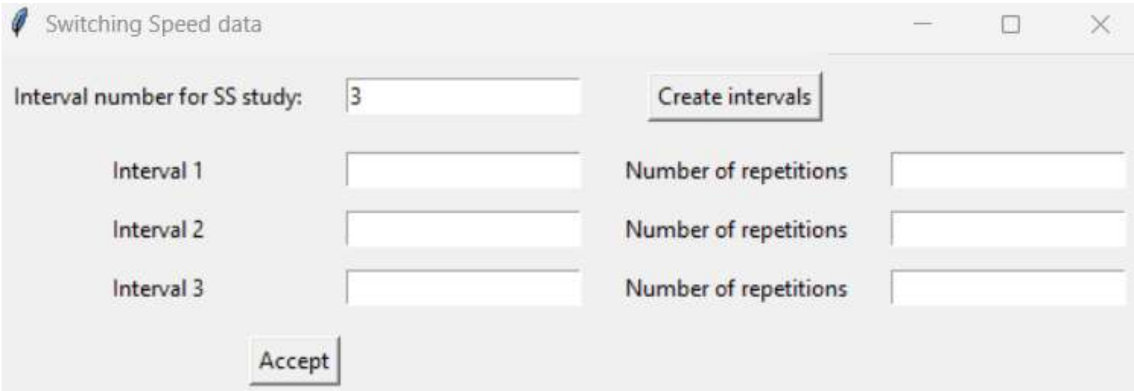


For **SS STUDY**, this option analyzes the device's kinetic response during a chronoamperometric experiment consisting of multiple potential steps of varying duration. Upon selecting Switching Speed, a new configuration window appears labeled "Switching Speed data".

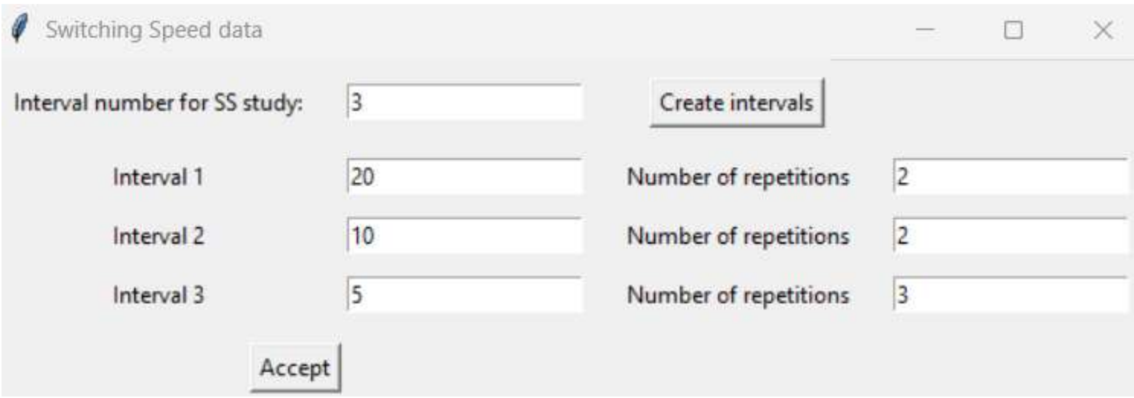
The user must:

1. Enter the number of distinct pulse durations applied during the test.

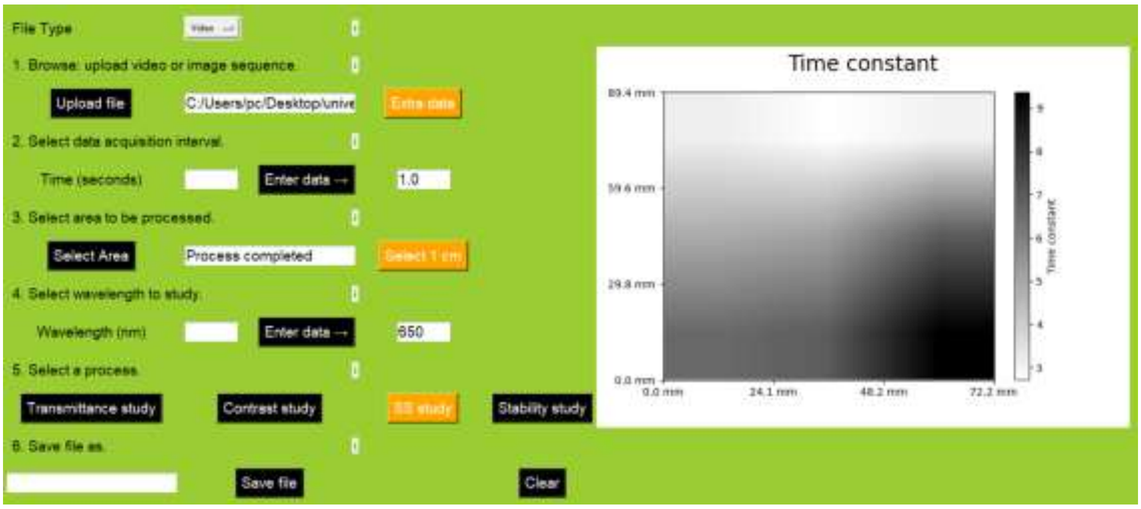
2. Click “Create intervals”.



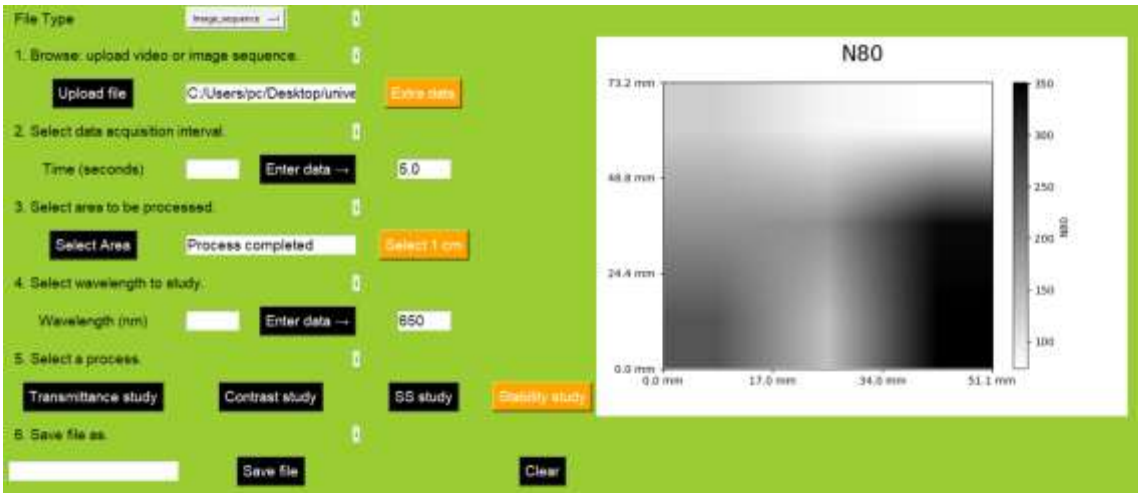
3. For each time interval (Interval 1, Interval 2, ..., Interval *i*), enter the number of time and repetitions corresponding to that pulse duration (e.g., 3, 5, etc.).



Internally, the system will use this information to detect the contrast associated with each pulse type, fit the resulting evolution curve, and calculate the t_{90} parameter for each region. After clicking “Accept”, the system will process the data and display a t_{90} color map across the selected area in the main interface plot.



The **STABILITY** process evaluates long-term performance through degradation analysis. After stability test, the system calculates the evolution of contrast over time and fits an exponential decay curve for each region. The resulting N_{80} map shows how many cycles each region can sustain before its contrast drops below 80% of the initial value. This allows for highly localized assessment of device durability.



Once any of the above processes is successfully completed, the corresponding button will change color to orange, confirming that the selected analysis has been carried out and the results are now available.

In this step, the button related to information shows the following text:

- Transmittance study: Shows the transmittance distribution at λ_max across the selected area.
No additional input is required.

- Contrast study: Displays the contrast (ΔT at λ_max) for each region, calculated from the colored and bleached states.
Just click to run the process.

- SS study: Requires chronoamperometric data with potential steps of different durations:

1. Enter the number of pulse intervals, then click "Create intervals".

2. For each interval, specify the number of repetitions.

3. Click "Accept" to generate the t_{90} map.

- Stability study: Estimates cycling durability using image data from a multi-cycle experiment.
Click to obtain the N_{80} map showing the degradation behavior across the surface.

Once completed, each button turns orange to confirm successful processing.

6. **Save file as.**

After completing any of the analysis processes, the user has the option to export the resulting data and plots for further inspection or documentation. The system supports two output formats:

- PDF for graphical visualizations (e.g., color maps, contrast evolution curves)
- CSV for raw numerical data associated with each plot

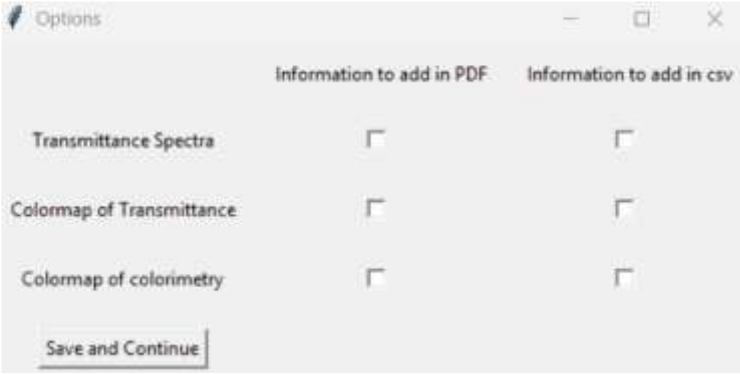
To initiate the export process:

1. In the "Save as" field, enter the filename you wish to assign to the exported files.
2. Click the "Save file" button.
3. A new window will appear, displaying a list of available plots and datasets, which depends on the previously selected analysis process.

In this new window, you can choose which results to export:

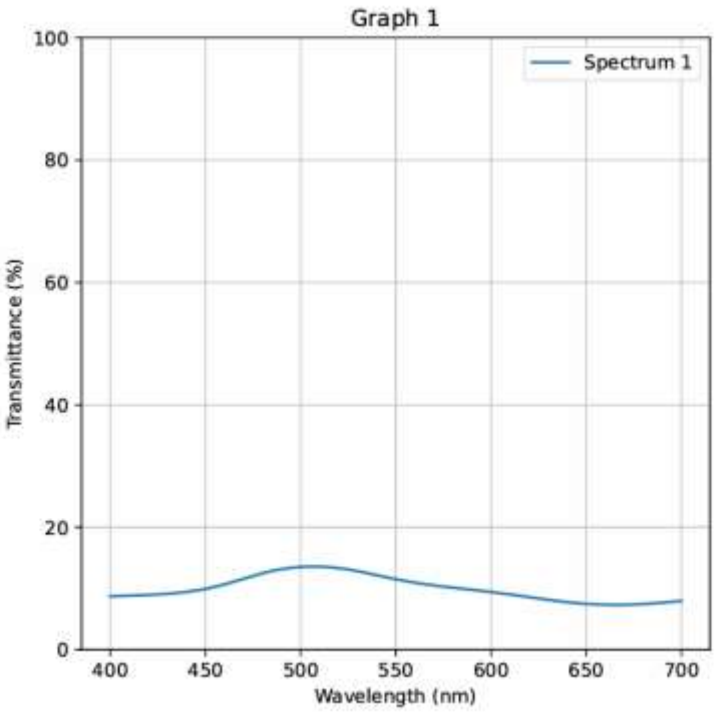
- Right-click on any item to select it. A checkmark (✓) will appear next to the selected entry.
- Repeat as needed for each figure or dataset you wish to export.
- When finished, confirm and the selected files will be saved in your local directory.

If the selected process is **Transmittance study**, the export window will display the following options:



1. **Transmittance spectra (400–700 nm)**
   One spectrum per region of the selected surface.

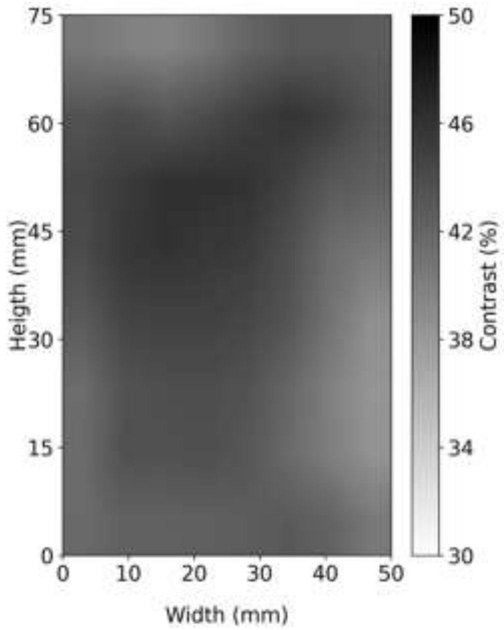
   - PDF: Plots of all spectra.



   - CSV: Numeric spectral data for each region.

2. **Colormap of Transmittance**
   Color map showing how transmittance varies across the surface (same as shown in the interface).

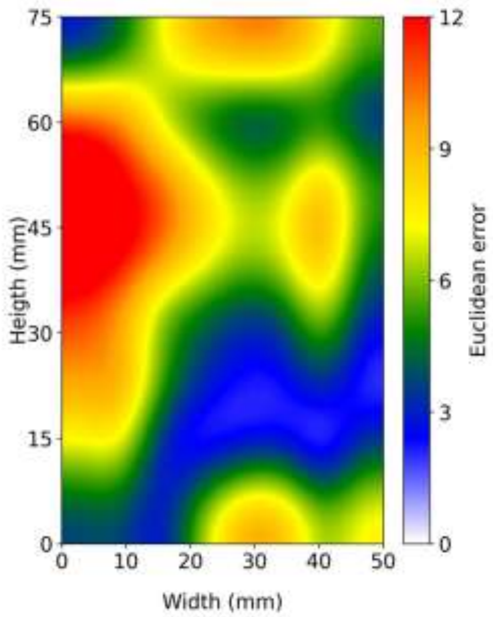
   - PDF: Color-Map image.



- CSV: Transmittance value per region.

3. **Colormap of colorimetry**
   Spatial map showing Euclidean color difference (ΔE) between actual color coordinates and the optimal colored state (as defined by the user).

   - PDF: Color-Map image.



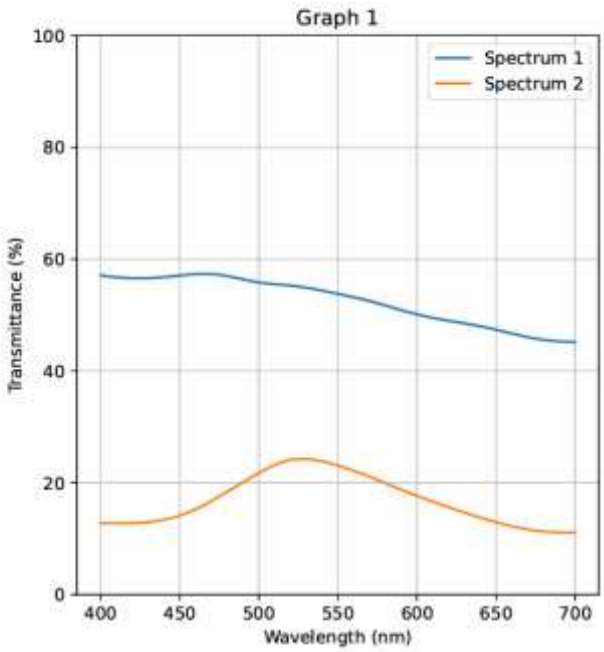
   - CSV: ΔE value per region.

If the selected process is **Contrast study**, the export window will display the following options:

1. **Transmittance Spectra:**

Bleached and colored spectra per region of the selected surface.

- PDF: Bleached and colored spectra per region.

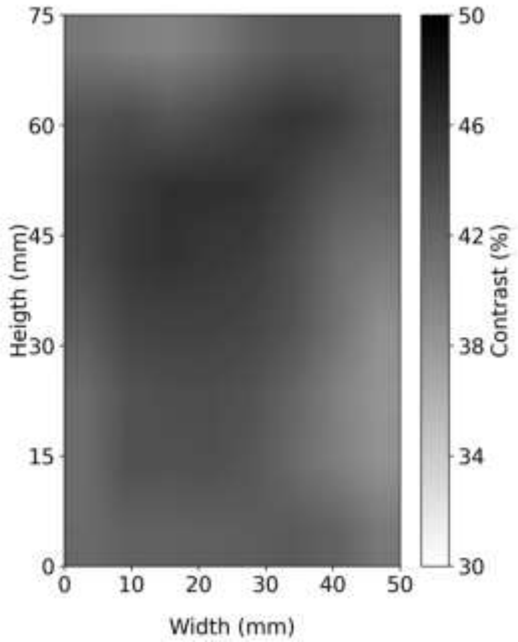


- CSV: Numeric spectral data for each region.

2. **Colormap of contrast.**

Color map showing how contrast varies across the surface (same as shown in the interface).

- PDF: Colormap of contrast.

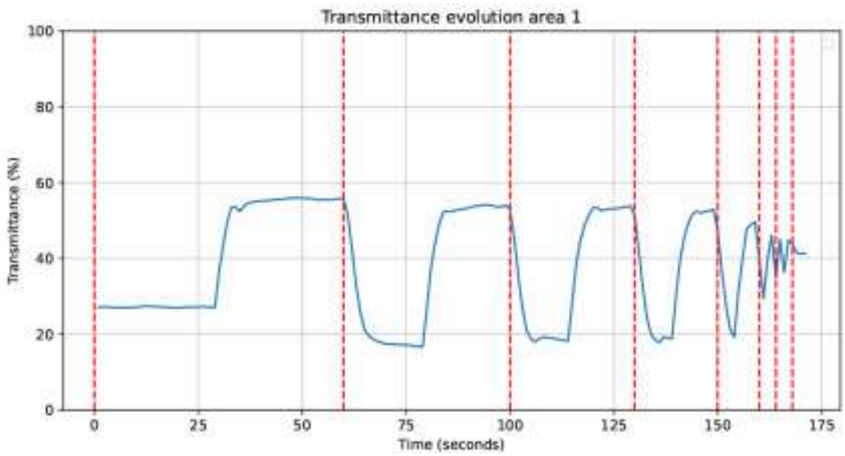


- CSV: Contrast value per region.

If the selected process is **SS study**, the export window will display the following options:

1. **Transmittance evolution**
   For each region, a plot showing the evolution of transmittance at λ_{max} over time during the chronoamperometric test.

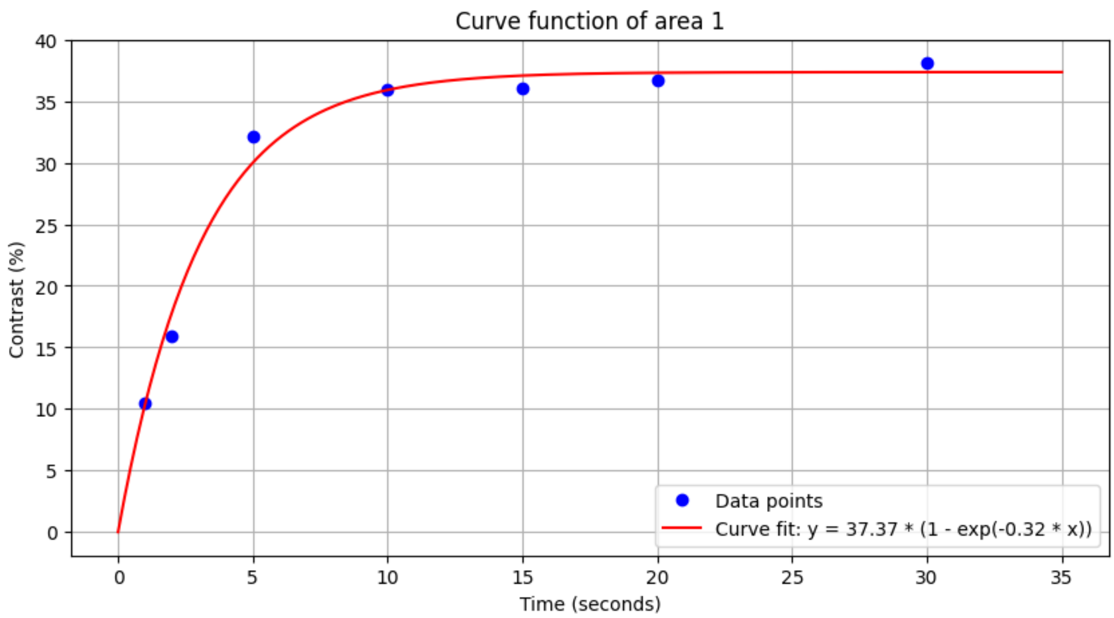
   - PDF: One plot per region



- CSV: Time and transmittance values

2. **Fitted function**
   For each region, the calculated contrast for each potential step, along with the fitted curve used to determine t_{90}.

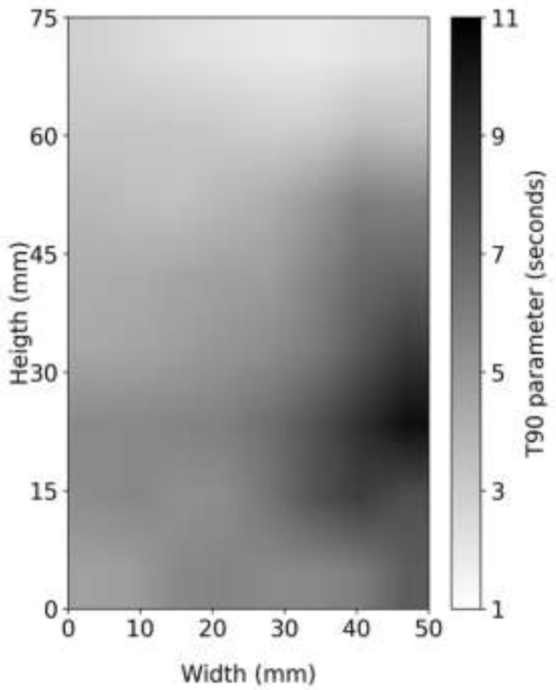
   - PDF: One plot per region



   - CSV: Pulse durations, contrast values, and fitted points

3. **Colormap of Switching speed parameter (t_{90})**
   Color map showing the distribution of the t_{90} parameter across the entire active surface (same as displayed in the interface).

   - PDF: Map image

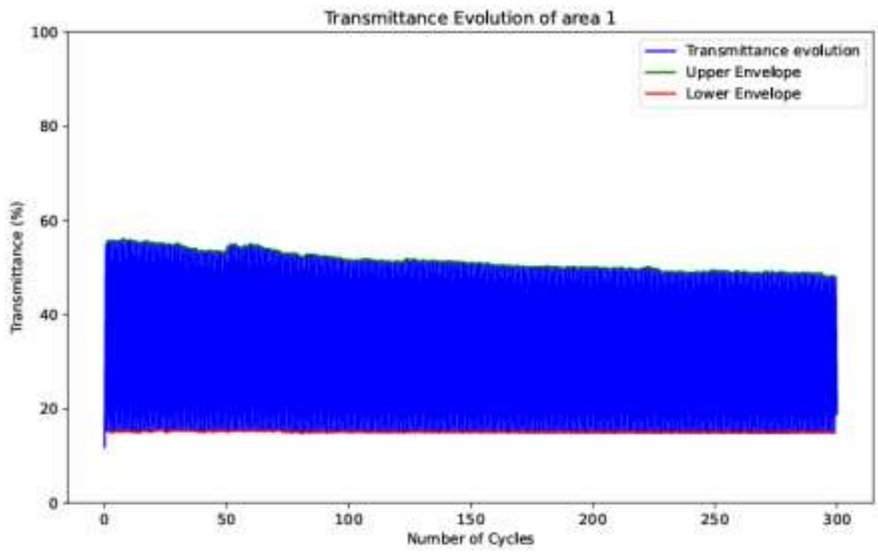


- CSV: t_{90} values per region

If the selected process is **Stability study**, the export window will display the following options:

1. **Transmittance evolution**
   For each region, a plot showing the evolution of transmittance at λ_{max} over time during the stability test.

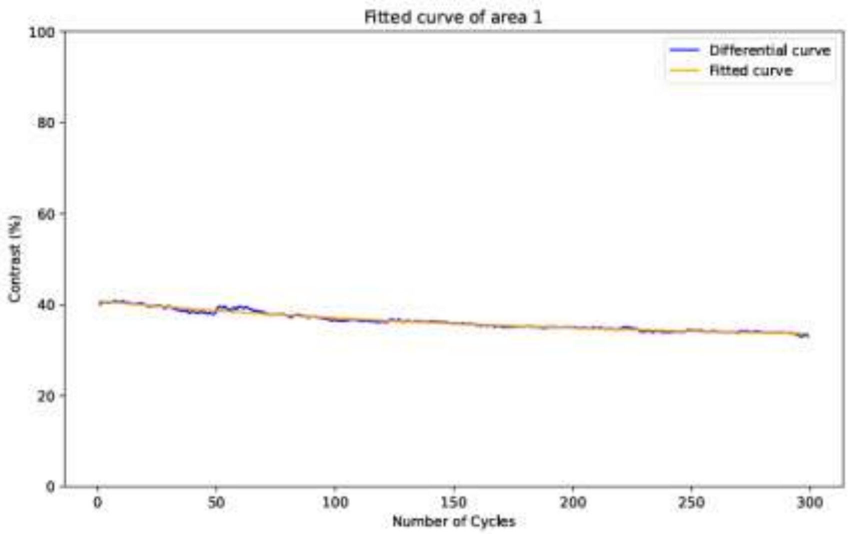
   - PDF: One plot per region



- CSV: Time and transmittance values

2. **Fitted function**
   For each region, the calculated contrast evolution, along with the fitted curve used to determine N_{80}.

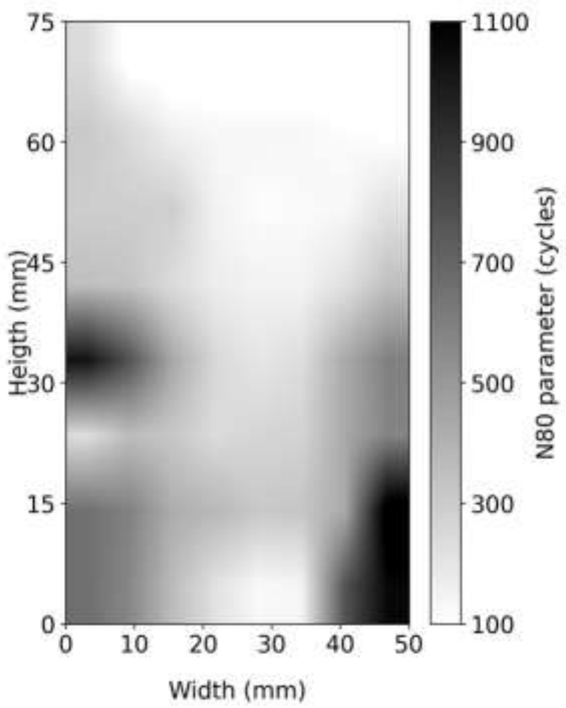
   - PDF: One plot per region



   - CSV: Cycles, contrast values, and fitted points

3. **Colormap of stability parameter (t_{90})**
   Color map showing the distribution of the t_{90} parameter across the entire active surface (same as displayed in the interface).

   - PDF: Map image



- CSV: N_{80} values per region

When the files have been generated and saved, the message “saved” will appear.

All selected files will be saved with the chosen name in your local directory (same to the script).

The clear button deletes all data added while using the interface so that you can start processing new data.

In this step, the button related to information shows the following text:

To save data or plots, enter a filename in the "Save as" field and click "Save file". A new window will appear where you can choose what to export.

- Right-click on each item to select it (✓ will appear).
- PDF: saves the figure
- CSV: saves raw data

Available options depend on the selected process:

1. Transmittance study:

- Transmittance Spectra (400–700 nm)

- Transmittance map at λ_max

- ΔE color difference map

2. Contrast study:

- Bleached and colored trasnmittance spectra

- Contrast map (ΔT at λ_max)

3. Switching Speed study (t_{90}):

- Transmittance over time

- Contrast vs. pulse duration + fit

- t_{90} map

4. Stability study(N_{80}):

- Transmittance over cycles

- Contrast decay + exponential fit

- N_{80} map

All selected files will be saved with the chosen name in your local directory (same to the script).

The clear button deletes all data added while using the interface so that you can start processing new data.

Enjoy your new Electrochromic Optical Mapping System!!

References

(1) Cánovas-Saura, A.; Serrano-Luján, L.; Beltrán, V.; Padilla, J. Neural Network-Based Digital Camera Spectrophotometer: Application to Chromogenic Technologies Characterization. *ACS Appl. Opt. Mater.* **2024**, acsaom.4c00180. https://doi.org/10.1021/acsaom.4c00180.