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Quantifying the Relative Thickness of Conductive Ferromagnetic Materials Using Detector Coil-based Pulsed Eddy Current Sensors

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TITLE:

Quantifying the Relative Thickness of Conductive Ferromagnetic Materials Using Detector Coil-Based Pulsed Eddy Current Sensors

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KEYWORDS:

Detector Coil, Ferromagnetic, NDE, NDT, Pulsed Eddy Current, Sensing, Signal Processing, Thickness Quantification

SUMMARY:

Here, we present a protocol to quantify the relative thickness (i.e., thickness as a percentage with respect to a reference) of conductive ferromagnetic materials using detector coil-based pulsed eddy current sensors, while overcoming the calibration requirement.

ABSTRACT:

Thickness quantification of conductive ferromagnetic materials by means of non-destructive evaluation (NDE) is a crucial component of structural health monitoring of infrastructure, especially for assessing the condition of large diameter conductive ferromagnetic pipes found in the energy, water, oil, and gas sectors. Pulsed eddy current (PEC) sensing, especially detector coil-based PEC sensor architecture, has established itself over the years as an effective means for serving this purpose. Approaches for designing PEC sensors as well as processing signals have been presented in previous works. In recent years, the use of the decay rate of the detector coil-based time domain PEC signal for the purpose of thickness quantification has been studied. Such works have established that the decay rate-based method holds generality to the detector coil-based sensor architecture, with a degree of immunity to factors such as sensor shape and size, number of coil turns, and excitation current. Moreover, this method has shown its effectiveness in NDE of large pipes made of grey cast iron. Following such literature, the focus of this work is explicitly PEC sensor detector coil voltage decay rate-based conductive ferromagnetic material thickness quantification. However, the challenge faced by this method is the difficulty of calibration, especially when it comes to applications such as in situ pipe condition assessment since measuring electrical and magnetic properties of certain pipe materials or obtaining calibration samples is difficult in practice. Motivated by that challenge, in

contrast to estimating actual thickness as done by some previous works, this work presents a protocol for using the decay rate-based method to quantify relative thickness (i.e., thickness of a particular location with respect to a maximum thickness), without the requirement for calibration.

INTRODUCTION:

The pulsed eddy current (PEC) sensing technique is perhaps the most versatile member of the family of eddy current (EC) non-destructive evaluation (NDE) techniques and has many applications in detection and quantification of defects, and the geometry of metals and metallic structures[1]. Thickness quantification of conductive ferromagnetic wall-like structures, having wall thicknesses of no more than a few millimeters to a few tens of millimeters, is a high demand engineering service in the field of structural health monitoring of infrastructure. Critical infrastructure made of ferromagnetic alloys that require this service are commonly available in the energy, water, oil, and gas industries. While PEC sensors can be designed following several architectures, the detector coil-based architecture was determined to be the most effective and commonly used in condition assessment of ferromagnetic materials[2-5]. Therefore, it is the detector coil-based PEC sensor architecture that sets the foundation to the problem of thickness quantification of conductive ferromagnetic materials.

The detector coil-based PEC sensor architecture is typically comprised of two concentrically wound, air cored, conductive coils[2-6] (typically copper coils). It is quite common to wind these coils to be circular in shape[2-6], but occasionally, rectangular shaped coils[6] have been used. From the two coils in the sensor, one behaves as an exciter coil while the other acts as the detector coil. In a PEC sensor, the exciter coil is excited by a voltage pulse—something that can be characterized as a Heaviside step function in principle. This pulsed excitation generates a transient magnetic field (called the primary field) around the sensor. When the sensor is placed adjacent to a conductive test piece (e.g., a conductive ferromagnetic wall-like structure), this transient magnetic field induces time varying eddy currents in the test piece. These eddy currents generate a secondary magnetic field (called the secondary field) that opposes the primary field. In response to the resultant effect of the primary and secondary fields, a transient voltage is induced in the detector coil—which becomes the time domain PEC signal of interest for this work.

The PEC sensor detector coil voltage decay rate (denoted as β) has been reported[6-8] to show the proportionality $\beta \propto \mu\sigma d^2$, when a signal is acquired placing a PEC sensor above a conductive ferromagnetic layer of magnetic permeability μ, electrical conductivity σ, and thickness d. Although this decay rate signal feature has considerable immunity to parameters such as sensor size, sensor shape, and lift-off[6-8], which makes the decay rate highly desirable for challenging NDE scenarios such as in situ pipe condition assessment[9-11], this feature must be calibrated (i.e., μ, σ of the material being inspected be estimated) to enable thickness (i.e., d) quantification. To enable conventional methods of decay rate-based thickness quantification[6,8], this calibration must be done by extracting calibration samples[6,8] or by involving eddy current-based material property characterization methods[12,13]. Alternatively, the complexity of calibration can be avoided by representing thickness in the form of relative thickness. Suppose an NDE exercise is carried out and β values are extracted from signals, then, the β value qualitatively representative of the maximum thickness point in the test piece is considered as a reference (i.e., $\beta_{ref} \propto \mu\sigma {d_{max}}^2$); then, the thickness of any other location can be represented as a percentage of the maximum thickness in the form $d/d_{max} = \sqrt{\beta/\beta_{ref}}$, presenting a relative thickness as the output, which is still useful qualitative information as an NDE output that also carries the simplicity of not having to calibrate for μ, σ. The protocol presented herein describes the steps to be followed to accomplish this.

Since the decay rate β shows generality to the detector coil-based PEC sensor architecture while showing immunity to parameters of the sensor design as well as lift-off[6-8,14], practitioners may use any detector coil-based PEC sensing system of their choice on a suitable conductive ferromagnetic material to perform relative thickness quantification following the protocol here. A PEC sensor design example for a conductive ferromagnetic material is available for interested readers[15]. The signals and results presented in this work were acquired using the PEC system developed by University of Technology Sydney[6,8]. The conductive ferromagnetic material used for representative results acquired by the PEC system is grey cast iron extracted from a pipe test-bed[9-11] in Sydney Australia.

It should be noted that the methods, results, and discussions presented in this publication explicitly focus on the use of the detector coil-based PEC sensor architecture's time domain signal's decay rate for thickness quantification of conductive ferromagnetic materials. The publication does not include a broader discussion on general conventions of PEC sensing principles and sensor configurations. Other published work[16-18] can be useful for readers to gain more insight about PEC sensor configurations other than the detector coil-based sensor architecture.

PROTOCOL:

1. Extracting the decay rate $\boldsymbol{\beta}$ from an available detector coil-based PEC signal

1.1. Express an available experimentally captured PEC signal (i.e., a time domain detector coil voltage (denoted as $V(t)$)) in the logarithmic form of $\ln[V(t)]$. A typical PEC signal expressed in the form of $\ln[V(t)]$ is shown in **Figure 1**.

1.2. Find a linear region in the form of $a < \ln[V(t)] < b, a, b \in \mathbb{R}$ as $t \gg 0$ such that the signal satisfies the condition $\ln[V(t)]|_{t \gg 0} \approx -{}^{1}\!/_{\beta}\, t + \alpha$ where $\alpha, \beta \in \mathbb{R}, \beta > 0$. As per the signal in **Figure 1**, $-3 < \ln[V(t)] < -1$, i.e., $a = -3, b = -1$ happens to be a satisfactory and practicable linear region.

1.3. As illustrated in **Figure 2**, fit the straight-line model $-{}^{1}\!/_{\beta}\, t + \alpha$ to the experimental signal data within the identified linear region $a < \ln[V(t)] < b$ and estimate the value of β.

2. Quantification of relative thickness

2.1. Suppose there are multiple signals (**Figure 3**) acquired from an NDE task performed on a conductive ferromagnetic test piece having varying thickness. First, identify a linear region common to all signals and extract β values. As per the signals in **Figure 3**, $-3 < \ln[V(t)] < -1$ seems to be an adequate and practicable linear region.

2.2. Select the maximum β value and label it as β_{ref} since the maximum β value should in principle correspond to the maximum thickness according to the $\beta \propto \mu\sigma d^2$ proportionality[6-8].

2.3. Express relative thickness percentage in the form $d_i\% = \sqrt{\beta_i/\beta_{ref}} \times 100\%$, where the index $i \in \mathbb{N}$ corresponds to the i^{th} measurement.

3. PEC_Signal_Processor installation

3.1. Locate the file **PEC_Signal_Processor.exe**. Double click the file and allow to execute.

3.2. When the interface below appears, click **Next**. When the interface pops up, specify the file location for installation, and tick the checkbox **Add a shortcut to the desktop** if a desktop shortcut is desired. Then click **Next**.

3.3. Specify the installation location for the required Runtime Environment, then click **Next**. If the required Runtime Environment is already installed, just click **Next**.

3.4. Read, and agree to prompted license terms and conditions. Then click **Install**.

3.5. Click **Finish** when installation is complete. The desktop icon will appear.

4. Preparation of signals

4.1. Ensure the PEC sensor outputs [raw signals, i.e., V(t)] are arranged as a table.

4.2. Copy the table containing signals to the desktop (or to a folder contained within the parent directory where the application is installed). For convenience, the desktop is recommended.

5. Executing the application

5.1. Double click the desktop icon to run the application. The interface will open.

5.2. Load signals by clicking on the **Load Signals** tab and select the file containing the signals in order to import the signals to the software interface.

5.3. Wait until the number of signals which is contained within the table containing raw signals appear in front of **Number of Signals =**.

5.4. Click on **Plot Signals** and observe the signals plotted in logarithmic scale.

5.5. Click on the **Zoom** tab and adjust the plot window for the linear region to be clearly visible.

5.6. After observation, decide on reasonable lower and upper margins for the linear region and enter the values in the editable text spaces.

5.7. Click on **Plot Margins** and wait for the margins to be plotted in green.

5.8. Click on **Extract Features** and observe how straight-line segments are plotted in red.

5.9. Click on **Calculate Relative Thickness** and observe how a histogram of calculated relative thickness values is plotted.

5.10. Click on **Save Relative Thickness** to save the calculated relative thickness values. Provide a filename and click **OK**.

5.11. Confirm filename by clicking **OK** again to confirm the filename. The relative thickness values will be saved as table on the desktop.

REPRESENTATIVE RESULTS:
Representative results within this section have been generated using the PEC signals provided as supplementary material with reference[8]; as mentioned above, the signals have been captured on grey cast iron samples extracted from the pipe test bed in Sydney Australia, whose location and vintage details are provided in references[9-11].

Figure 1 shows the typical shape of a time domain signal (expressed in the logarithmic form) captured from a detector coil-based PEC sensor while **Figure 2** shows an indicative linear region of the logarithmic signal as $t \gg 0$ from which the decay rate feature β is extracted. Multiple PEC signals are shown in **Figure 3**; a signal showing an indicatively maximum β value is included. Such a maximum β value can be used as the reference β values to quantify relative thickness using the equation $d_i\% = \sqrt{\beta_i/\beta_{ref}} \times 100\%$.

Table 1 shows some extracted β values along with relative thickness values that have been quantified using them. The results in **Table 1** have been produced for the 14 mm lift-off case presented in Figure 20 of reference[8]; the corresponding raw PEC signals captured on grey cast iron are available in the supplementary material provided with reference[8]. The first column of **Table 1** provides the actual thickness (in millimeters) of the grey cast iron test pieces on which the PEC signals were captured while the second column contains the corresponding β values.

The maximum β value (i.e., β = 0.010078491) is considered as the reference β value (i.e., β_{ref}). Provided in the third column are the corresponding relative thickness values resulting when quantified as $\sqrt{\beta_i/\beta_{ref}} \times 100\%$ and the last column lists the corresponding actual relative thickness values calculated using the actual thickness values listed in the first column. A plot of the actual relative thickness values against the relative thickness values calculated from PEC signals (i.e., calculated using β values) is shown in **Figure 4**. A correlation of over 99% between estimates and reality observed on this data set indicates the effectiveness of the relative thickness quantification method.

Figure 1: Typical shape of a PEC signal, i.e., induced detector coil voltage (i.e., $V(t)$) expressed in the form of $\ln[V(t)]$.

Figure 2: A representative linier region of a detector coil-based PEC signal expressed in the form $\ln[V(t)]$, as $t \gg 0$, from where the decay rate feature (i.e., β) should be extracted.

Figure 3: Multiple PEC signals resulting from an NDE exercise (performed on grey cast iron) displaying a signal indicatively showing a maximum β value, which should in principle qualitatively represent a maximum thickness according to the proportionality[6,15]: $\beta \propto \mu\sigma d^2$.

Figure 4: Correlation between Relative Thickness % quantified from actual thickness and Relative Thickness % quantified from β (based on measurements performed on grey cast iron).

Table 1: Some extracted β values along with quantified relative thickness of grey cast iron.

DISCUSSION:

A protocol to quantify the relative thickness (i.e., thickness as a percentage with respect to a reference) of conductive ferromagnetic materials using detector coil-based PEC sensors was presented. The main advantage of this method is the ability to overcome the calibration requirement (i.e., overcome the need to measure or estimate the magnetic permeability and electrical conductivity of the material being inspected to enable thickness quantification). The protocol involves logarithmic representation of the time domain PEC signal, identification of a linear region at the signal's later stages, fitting a straight-line to the linear region and extracting the decay rate (i.e., β), and quantifying the relative thickness with respect to a reference through the equation $d_i\% = \sqrt{\beta_i/\beta_{ref}} \times 100\%$, which cancels out the material properties (i.e., $\mu\sigma$) and produces a relative thickness due to the $\beta \propto \mu\sigma d^2$ proportionality. Experimental results (**Table 1** and **Figure 4**) show the effectiveness of the relative thickness quantification method from the protocol in this work.

Ensure the guidelines in Section 4 are followed when preparing data for import to the software interface. To avoid a heavy burden on computation and graphics hardware, arrange signals into multiple tables so that data files of smaller size can be processed separately. It is not easy to impose actual restrictions on the size of data files as that depends on the computation power available to users. A few trial and error tests are recommended to identify any file size restrictions that may apply according to computation power available to users. In terms of modifications, users may be able to program their own software packages with multiple, or any PEC signal processing algorithms of their choice, using any computation platform of their choice. A review of recently published PEC signal processing algorithms for thickness quantification of conductive ferromagnetic materials is available[19].

A crucial factor that will affect the accuracy of the estimated relative thickness values is the adequacy of the excitation strength. References[8] have reported how too little excitation strength can limit the depth of penetration reducing sensitivity to high thickness values while too much excitation strength can limit the sensitivity to low thickness values. This issue with the excitation strength means that if a particular thickness range of a particular material is assessed with an inadequate excitation strength, although the resulting decay rate might still be sensitive to thickness, it may be inaccurate in value to universally follow the principle $\beta \propto \mu\sigma d^2$, which may eventually result in erroneous relative thickness values quantified as $d_i\% = \sqrt{\beta_i/\beta_{ref}} \times 100\%$. This limitation needs to be taken note of by practitioners in situations where strict precision in quantitative NDE results matter. However, this does not become an issue in situations where quantitative outputs are not essential and qualitative representation of the test piece condition suffices. Since defining a procedure to tune the excitation strength without the use of calibration samples having known thickness is nontrivial, a good practice to counter any ambiguity with the excitation strength will be to collect signals under a range of excitation strengths. Such approaches will generate rich data sets that form bases for some advanced postprocessing and may be useful for NDE tasks performed by robotic means[10,11]. Further, the electrical and magnetic properties of certain inhomogeneous conductive ferromagnetic materials, such as grey cast iron encountered in some aged critical water pipes, display a considerable variance[8]. This variance imposes that the properties be different within a cohort of pipes, or at times even within a single pipe from one location to another, making calibration all the more challenging. Such variation in material properties will also act as a source of error for the method prescribed in this work when NDE is performed on such inhomogeneous materials.

Recent work has demonstrated frequent and continued use of PEC sensing for condition assessment of critical pipes[8-11,20-22]. Such works do tend to produce large amounts of PEC data and would benefit from signal analysis protocols and frameworks similar to the one presented in this work. In parallel to work on critical pipes, there has been an increased interest in research on condition assessment of concrete sewers as well in recent years[23-31]. Along with such work, PEC sensing technique has found use in condition assessment of steel reinforced sewers as well[32]. PEC signal analysis protocols such as the one presented in this work can be useful for analysis of the vast amounts of PEC data produced as a result of such condition assessment-related work.

Critical steps of the method can be listed as: (1) arranging raw PEC signals [*V(t)*] as a table; (2) loading the raw signals to the software interface; (3) plotting the signals in logarithmic scale and visualize (i.e., plot signals in ln[*V(t)*] form); (4) visually inspecting the plotted signals and identify a suitable linear range; (5) performing feature extraction; (6) performing relative thickness quantification; and (7) saving the results. Section 3 provides more detailed step-by-step guidelines to perform the tasks listed above.

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DISCLOSURES:

Authors have no conflicts of interest to disclose. Authors would like to recommend works[2,6-11] as additional reading material.

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Figure 1

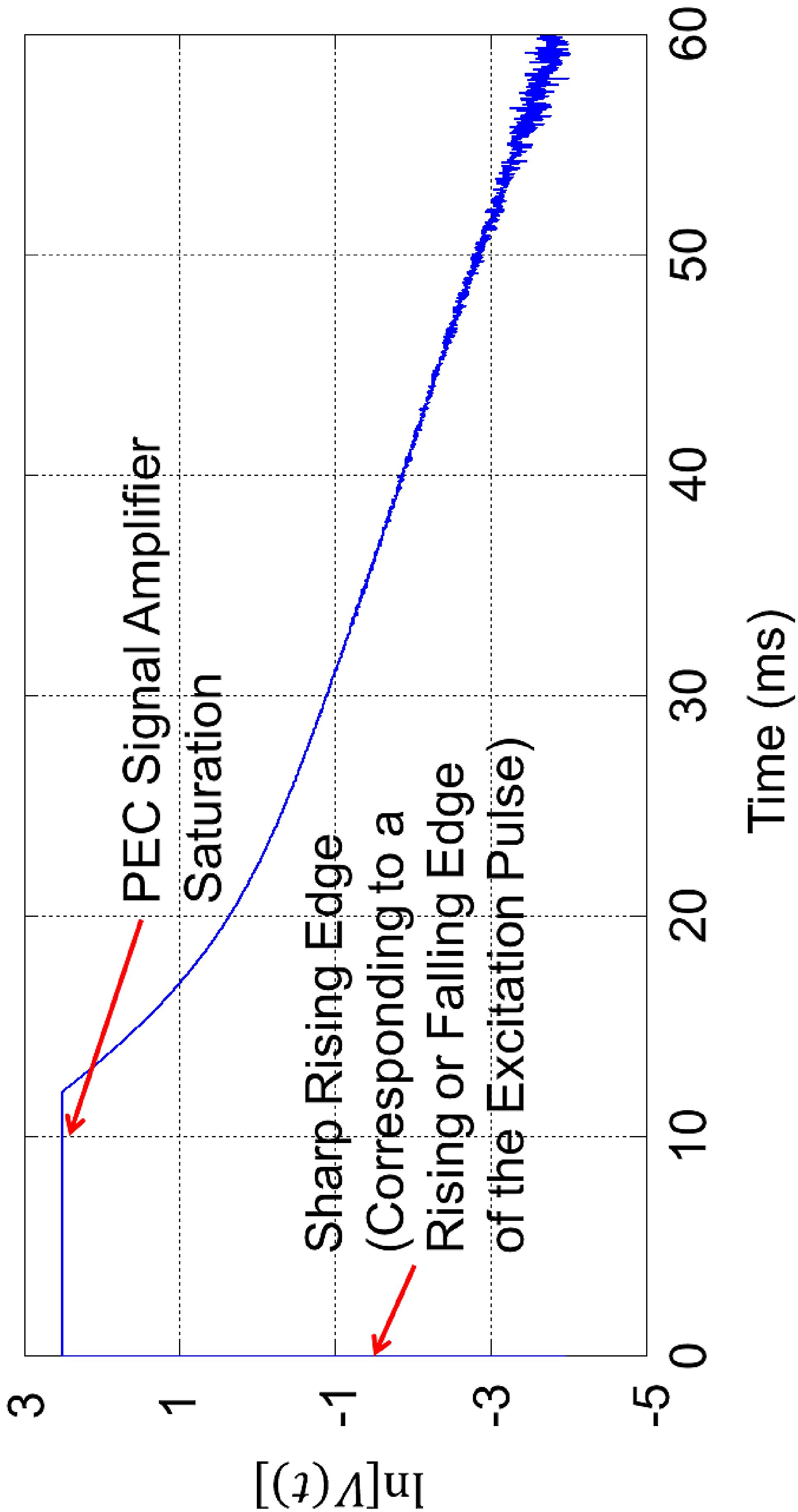
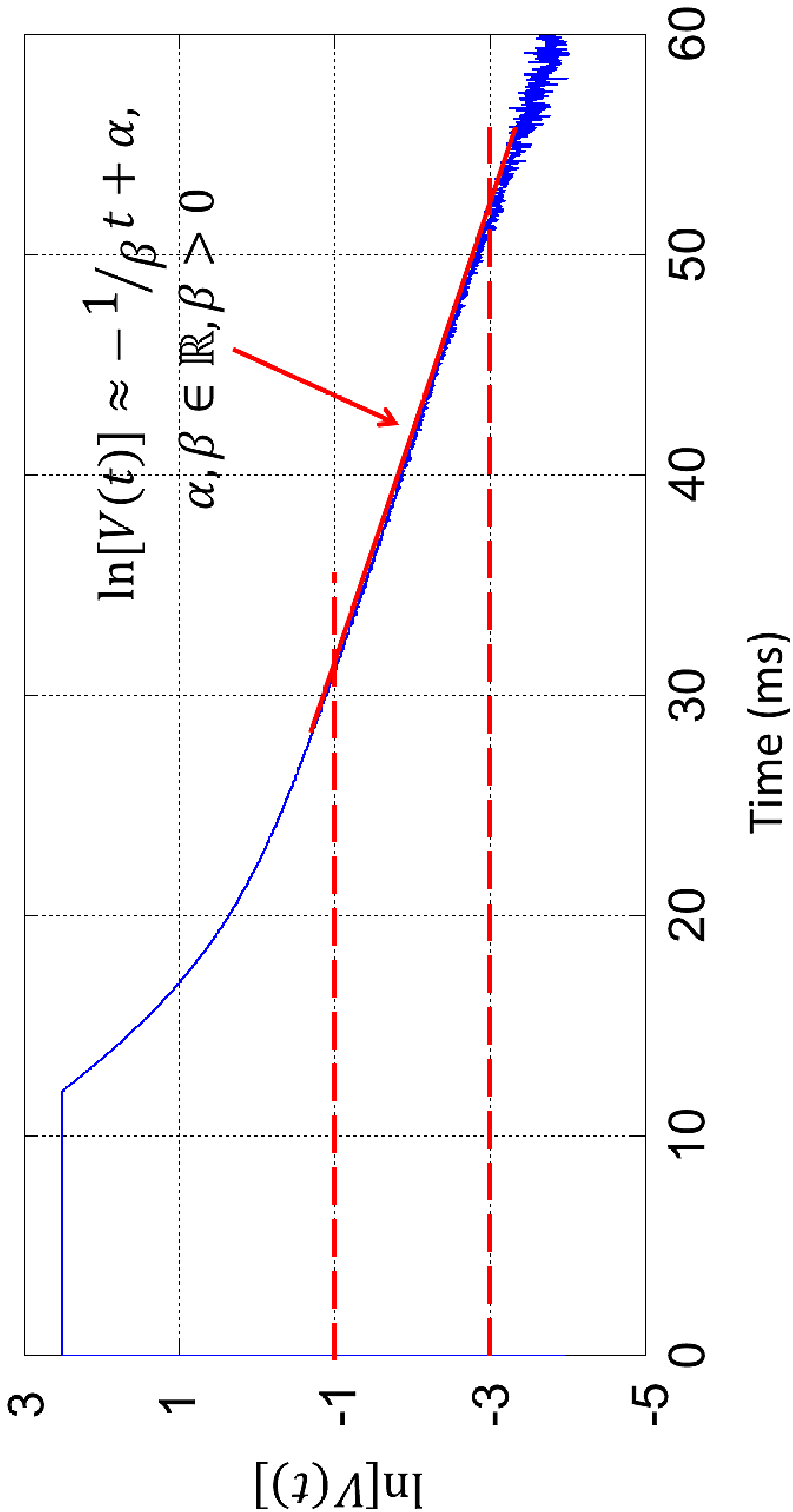

PEC Signal Amplifier
Saturation
Sharp Rising Edge
(Corresponding to a
Rising or Falling Edge
of the Excitation Pulse)
Time (ms)
ln[V(t)]
0
10
20
30
40
50
60
3
1
-1
-3
-5

Figure 2



$\ln[V(t)] \approx -{}^{1}/_{\beta}\, t + \alpha,$
$\alpha, \beta \in \mathbb{R}, \beta > 0$
Time (ms)
$\ln[V(t)]$
0
10
20
30
40
50
60
3
1
-1
-3
-5

Figure 3

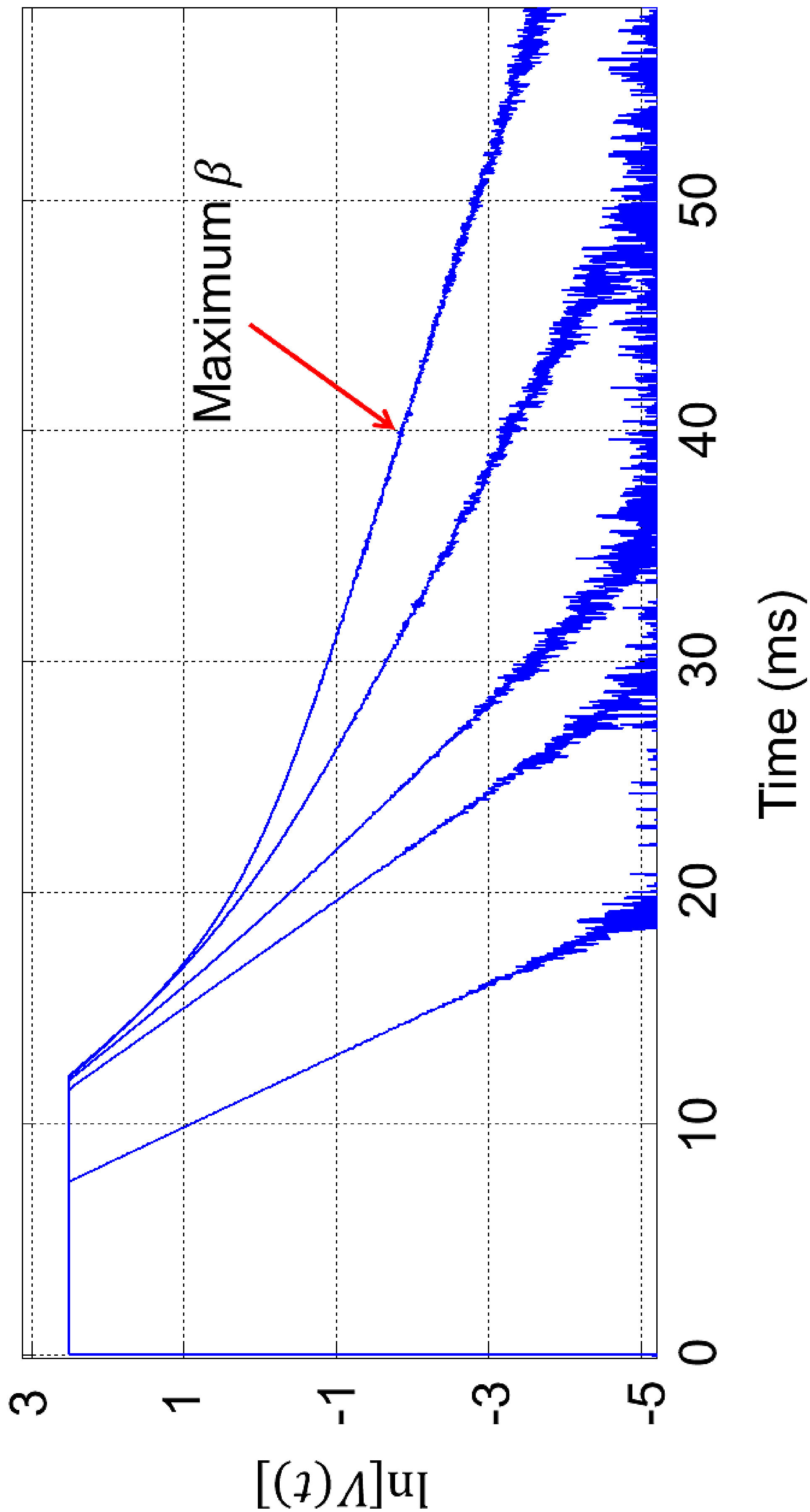
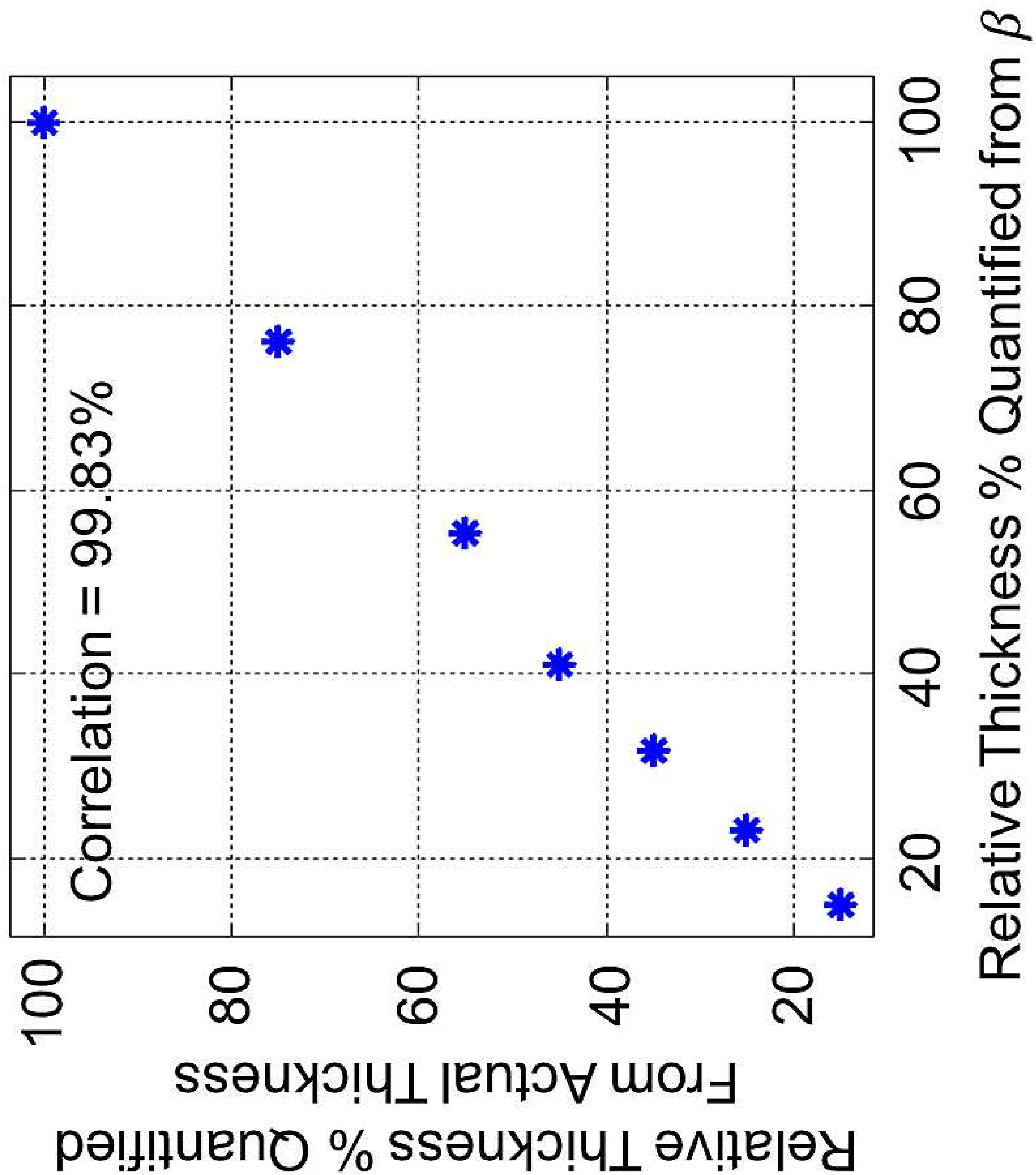


Figure 4


Correlation = 99.83%
20
40
60
80
100
Relative Thickness % Quantified from β
Relative Thickness % Quantified
From Actual Thickness

Actual Thickness of Test Piece (mm)	β Value Extracted from PEC Signal
3	0.000228395
5	0.000538137
7	0.001018941
9	0.001701758
11	0.003091023
15	0.005853939
20	0.010078491

Relative Thickness % Quantified from β
15.05379428
23.10728068
31.79631773
41.09141494
55.38005157
76.2125254
100

Relative Thickness % Quantified from Actual Thickness
15
25
35
45
55
75
100

Material
A Detector Coil-based PEC Sensing System.
A suitable conductive ferromagnetic material of varying thickness.
A computation platform for PEC signal processing
An application that can produce a table containing raw PEC signals (e.g., Microsoft Office Excel).

Description

The representative results in this work were generated using the PEC system developed by University of Technology Sydney (UTS), Australia and published in works[6,8]. This system may be accessible to readers via collaborating with UTS.

The representative results in this work were generated by acquiring PEC measurements on grey cast iron test pieces extracted from a pipe test-bed located in Sydney Australia, whose location and vintage details are available in references[9-11] The pipe test-bed as well as the extracted calibration samples may be accessible to readers via collaborating with UTS.

A computation platform in which the PEC signal processing algorithm can be coded and executed is required. In this publication, PEC signal processing was done using a software executable named "PEC_Signal_Processor", produced using MATLAB R2017b, Publisher: MathWorks, Natick, MA, USA.

Microsoft Office Excel (Office 16) was used for the work of this publication.

Relevant Supplier

N/A

N/A

MathWorks, Natick, MA, USA.

Microsoft Corporation, One Microsoft Way, Redmond, Washington, USA.

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Institution:	University of Technology Sydney
Title:	Research Fellow
Signature:	[signature] Date: 27/12/2018

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08/07/2019

Dear Panel of Editors,

Re: Manuscript titled "A Protocol for Quantifying Relative Thickness of Conductive Ferromagnetic Materials Using Detector Coil-based Pulsed Eddy Current Sensors".

Authors would like to make this opportunity to convey their heartiest gratitude to the editors and reviewers for their valuable comments to improve the manuscript, along with the editorial team's patience shown by providing time for authors to amend the manuscript.

Authors acknowledge all feedback received and have attempted to address every single comment. Herewith we present the amendments made to the manuscript.

Thank You,

Dr Nalika Ulapane.

(On behalf of Authors: Dr Nalika Ulapane and Dr Karthick Thiyagarajan)

Editorial Comments:

Comment 1: Please submit each figure as a vector image file to ensure high resolution throughout production: (.svg, .eps, .ai). If submitting as a .tif or .psd, please ensure that the image is 1920 x 1080 pixels or 300 dpi.

Author response: All images have been uploaded as .eps files.

Comment 2: Please upload tables as .xlsx files.

Author response: Table of materials has been uploaded as a .xlsx file.

Editorial Comments (General):

Comment 1: Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammatical errors.

Author response: Authors have checked the manuscript, proofing is expected to be done on the final version before publication.

Editorial Comments (Protocol Highlights):

Comment 1: Please bear in mind that theory/calculations in sections 1 and 2 cannot be filmed and must be highlighted.

Author response: Authors assume what the editors meant was to "remove the highlight"; as such, authors removed the highlight of Sections 1 and 2.

Editorial Comments (Discussion):

Comment 1: JoVE articles are focused on the methods and the protocol, thus the discussion should be similarly focused. Please ensure that the discussion covers the following in detail and in paragraph form

(3-6 paragraphs): 1) modifications and troubleshooting, 2) limitations of the technique, 3) significance with respect to existing methods, 4) future applications and 5) critical steps within the protocol.

Author response: Authors amended the "DISCUSSION" section as recommended. Authors have arranged the discussion section under subsections: (1) Summary of the work – this contains a summary and somewhat a significance of the presented work; (2) Troubleshooting and Modifications; (3) Limitations of the method; (4) Future Applications; and (5) Critical Steps of the method.

Editorial Comments (Figure/Table Legends):

Comment 1: Please expand the legends to adequately describe the figures/tables. Each figure or table must have an accompanying legend including a short title, followed by a short description of each panel and/or a general description.

Author response: Authors extended the figure and table labels so they provide a more adequate description of the figures.

Editorial Comments (Commercial Language):

Comment 1: JoVE is unable to publish manuscripts containing commercial sounding language, including trademark or registered trademark symbols (TM/R) and the mention of company brand names before an instrument or reagent. Examples of commercial sounding language in your manuscript are MATLAB Runtime, Excel. Please use MS Word's find function (Ctrl+F), to locate and replace all commercial sounding language in your manuscript with generic names that are not company-specific. All commercial products should be sufficiently referenced in the table of materials/reagents. You may use the generic term followed by "(see table of materials)" to draw the readers' attention to specific commercial names.

Author response: References to commercial names were removed from the text.

Editorial Comments (Table of Materials):

Comment 1: Please revise the table of the essential supplies, reagents, and equipment. The table should include the name, company, and catalog number of all relevant materials/software in separate columns in an xls/xlsx file.

Author response: Authors included supplier information for relevant material included in the "Table of Materials".

Editorial Comments (Originality of Figures and Tables):
Comment 1: If your figures and tables are original and not published previously or you have already obtained figure permissions, please ignore this comment. If you are re-using figures from a previous publication, you must obtain explicit permission to re-use the figure from the previous publisher (this can be in the form of a letter from an editor or a link to the editorial policies that allows you to re-publish the figure). Please upload the text of the re-print permission (may be copied and pasted from an email/website) as a Word document to the Editorial Manager site in the "Supplemental files (as

requested by JoVE)" section. Please also cite the figure appropriately in the figure legend, i.e. "This figure has been modified from [citation]."

Author response: All images and tables included in this manuscript were originally generated by the authors.

Comments from Peer-Reviewers:

Please note that the reviewers raised some significant concerns regarding your method and your manuscript. Please revise the manuscript to thoroughly address these concerns. Additionally, please describe the changes that have been made or provide explanations if the comment is not addressed in a rebuttal letter. We may send the revised manuscript and the rebuttal letter back to peer review.

Reviewer #1:

Manuscript Summary:

Comment 1: The work is interesting. More comparison of different PEC configuration and QNDE with reference are required.

A Sophian, etc. Pulsed eddy current non-destructive testing and evaluation: A review, Chinese Journal of Mechanical Engineering 30 (3), 500, 2017;
A Sophian, etc. Design of a pulsed eddy current sensor for detection of defects in aircraft lap-joints, Sensors and Actuators A: Physical 101 (1-2), 92-98, 2002.
P Li, etc. System identification-based frequency domain feature extraction for defect detection and characterization, NDT & E International 98, 70-79, 2018.

Author response: Authors included the highlighted paragraph shown below at the end of the introduction and cited the recommended references.

"It should be noted that the methods, results, and discussions presented in this publication explicitly focus on the use of detector coil-based PEC sensor architecture's time domain signal's decay rate for thickness quantification of conductive ferromagnetic materials. The publication does not include a broader discussion on general conventions of PEC sensing principles and sensor configurations. Works such as[16-18] can be useful for readers to gain more insight about PEC sensor configurations other than the detector coil-based sensor architecture."

Major Concerns:

Comment 1: More comparison and critical discussion are required.

Author response: As mentioned in the 'Author response' to the above comment, authors have mentioned in the Introduction about other PEC sensor configurations. In addition, authors have amended the "DISCUSSION" section amalgamating the comments received by the editorial team.

Minor Concerns:

Comment 1: Keywords need to be refined

Author response: Keyword "eddy current" was removed.

Comment 2: Abstract can be shortened

Author response: Authors shortened the "Long Abstract" to 280 words as opposed to 300 words that were there previously.

Comment 3: English proof read is expected

Author response: Authors amended the paper with care and expect to proofread the final version prior to publishing.

Reviewer #2:

Manuscript Summary:

Comment 1: Authors want to present a protocol to quantify the relative thickness of conductive ferromagnetic materials using Detector Coil-based Pulsed Eddy Current sensors without calibration.

Author response: Authors agree with the way the reviewer has comprehended the manuscript.

Major Concerns:

Comment 1: I don't know the interest to publish a software protocol as given. Here, authors present the application of the classical PET theory given by the equations. None relevant new theoretical or experimental information is given. It's just, as authors said, a very basic and classic protocol description with numerous software screenshots. I don't see, here, the interest for the community. They are no analysis or detail about the limit, precision of the method, etc. So, as such, the efficacy is not demonstrated...

Author response: Authors agree with the comment. Rather than presenting a novel theoretical result, the objective of this paper is to present a step-by-step guideline to describe a procedure to apply the existing PEC theory, for the interest of practitioners. As opposed to authors' previous work which dealt with quantification of actual thickness, in this publication authors describe to use the same principles, but for quantifying relative thickness instead of actual thickness which avoids the requirement for calibration. Authors have amended the "Long Abstract" to better emphasize that aspect.

Reviewer #3:

Manuscript Summary:

Comment 1: This paper proposes a method to evaluate thickness percentage of specimen with respect to the reference using pulsed eddy current technique. Though the method seems promising, the novelty to journal publication is missing in the context.

Author response: Authors agree with the comment. Rather than presenting a novel theoretical result, the objective of this paper is to present a step-by-step guideline to describe a procedure to apply the existing PEC theory, for the interest of practitioners. As opposed to authors' previous work which dealt with quantification of actual thickness, in this publication authors describe to use the same principles, but for quantifying relative thickness instead of actual thickness which avoids the requirement for calibration. Authors have amended the "Long Abstract" to better emphasize that aspect. Authors have written in the Long Abstract: "Motivated by that challenge, in contrast to estimating actual thickness as done by some previous works, this work presents a protocol for using the decay rate-based method to quantify relative thickness (i.e., thickness of a particular location with respect to a maximum thickness), eliminating the requirement for calibration."

Major Concerns:
Comment 1: What is the significance of figure 1, 2 and 3? All these figures represent similar information for the reader, I guess there is a scope to make it summarized and interpret in a surrealistic manner.

Author response: Authors extended the titles of the figures so they provide a more description of what is shown in the images. The message portrayed by the images should be clearer with the descriptive titles.

Comment 2: In the analysis, 7 different thickness were considered but, in the plot, it shows only 4 thickness, do the authors consider the same data for interpretation. please replace with relevant figures.

Author response: Since different datasets were captured from different locations and at different times, the signals are kept in different tables. To analyze different datasets, they must be imported separately. To avoid repetition, authors have shown processing of a single table containing 4 signals. But for completeness of analysis, authors have presented correlation for 7 thickness values in Figure 30.

Minor Concerns:
Comment 1: I encourage you to increase your innovations and give more description in key points of your technique i.e., relativity with reference to maximum thickness and evaluation if possible, find the expression for the relation along with the below recommendations.

Author response: The "INTRODUCTION" and "DISCUSSION" sections were modified substantially so that the contribution as well as the key points become more apparent. Some important sections that were modified are highlighted in the text.

Comment 2: Authors mentioned that designing approaches for PEC sensors for have been presented in previous works, if mentioned the reference it will be good for the reader.

Author response: Authors included the relevant references in the Long Abstract.

Comment 3: In the introduction, line no 4, the statement is confusing please rewrite the statement "Amongst the …monitoring of infrastructure".

Author response: The sentence of changed as shown below. Authors added some commas to make the sentence clearer.

“Amongst the applications, thickness quantification of conductive ferromagnetic wall-like structures, having wall thickness of no more than a few millimetres to a few tens of millimetres, is an engineering service that is of high demand in the field of structural health monitoring of infrastructure.”

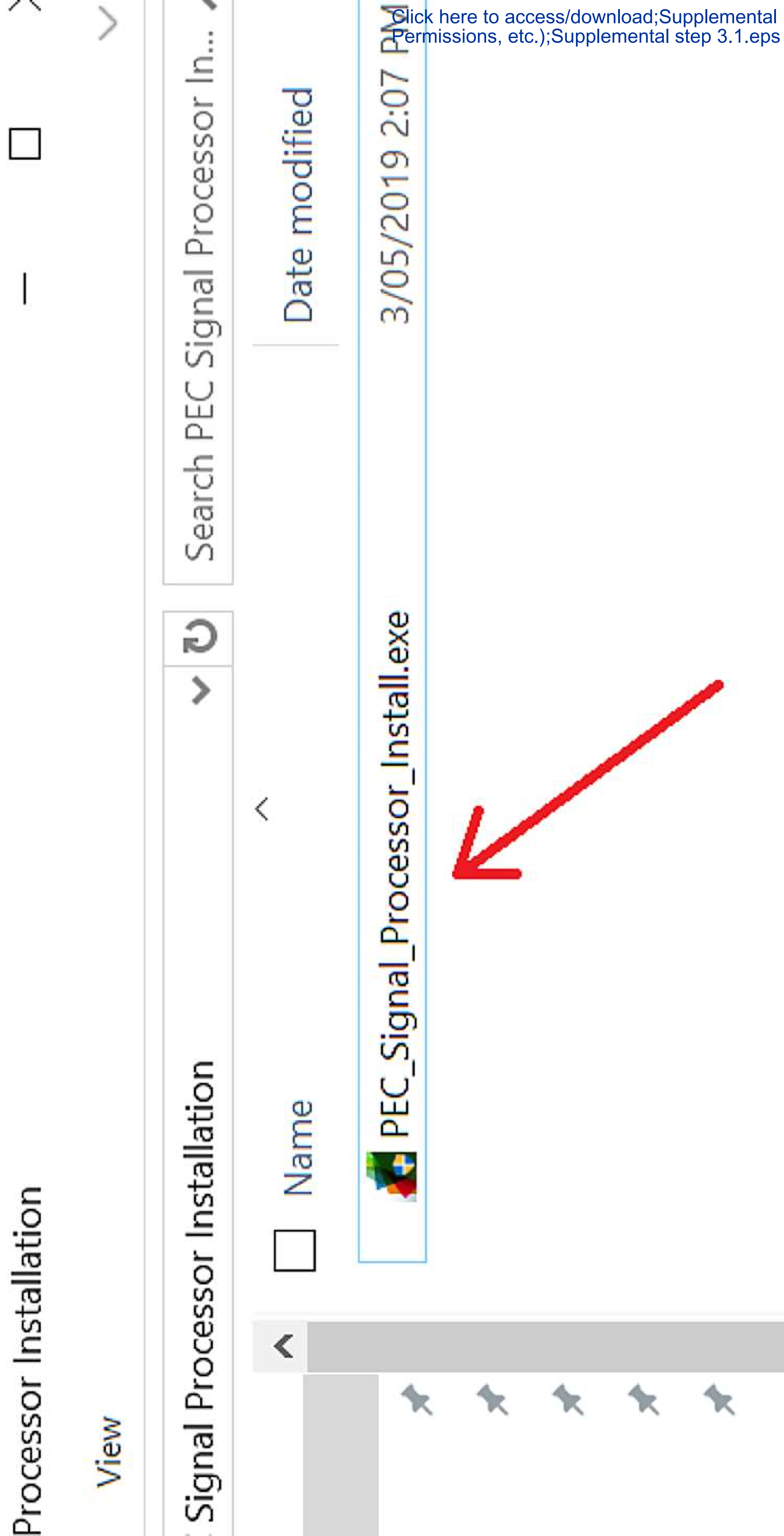
Comment 4: "The challenge faced by all such works has been the difficulty in calibrating sensors, especially when it comes to applications such as pipe condition assessment since measuring electrical and magnetic properties of pipe materials or obtaining calibration samples is difficult in practice". This paper proposes a protocol to evaluate thickness without any calibration specimens. Please describe the calibration methods and problems more explicitly, because the proposed method can achieve its novelty from this expression.

Author response: The relevant section was changed as shown in the highlighted text below for clarity and to better convey the contribution of this publication.

“However, the challenge faced by this method is the difficulty of calibration, especially when it comes to applications such as in-situ pipe condition assessment since measuring electrical and magnetic properties of certain pipe materials or obtaining calibration samples is difficult in practice. Motivated by that challenge, in contrast to estimating actual thickness as done by some previous works, this work presents a protocol for using the decay rate-based method to quantify relative thickness (i.e., thickness of a particular location with respect to a maximum thickness), eliminating the requirement for calibration. ”

Comment 5: I am pretty sure that there is a vast scope to improve this manuscript technically sound, in the discussion include more emphasis about your method more clearly. The entire manuscript needs to be reviewed for grammatical errors.

Author response: Authors checked the manuscript with care, and expect to proofread the final version prior to publishing. “INTRODUCTION” and “DISCUSSION” sections were modified substantially with the aim of better conveying the contribution of this publication.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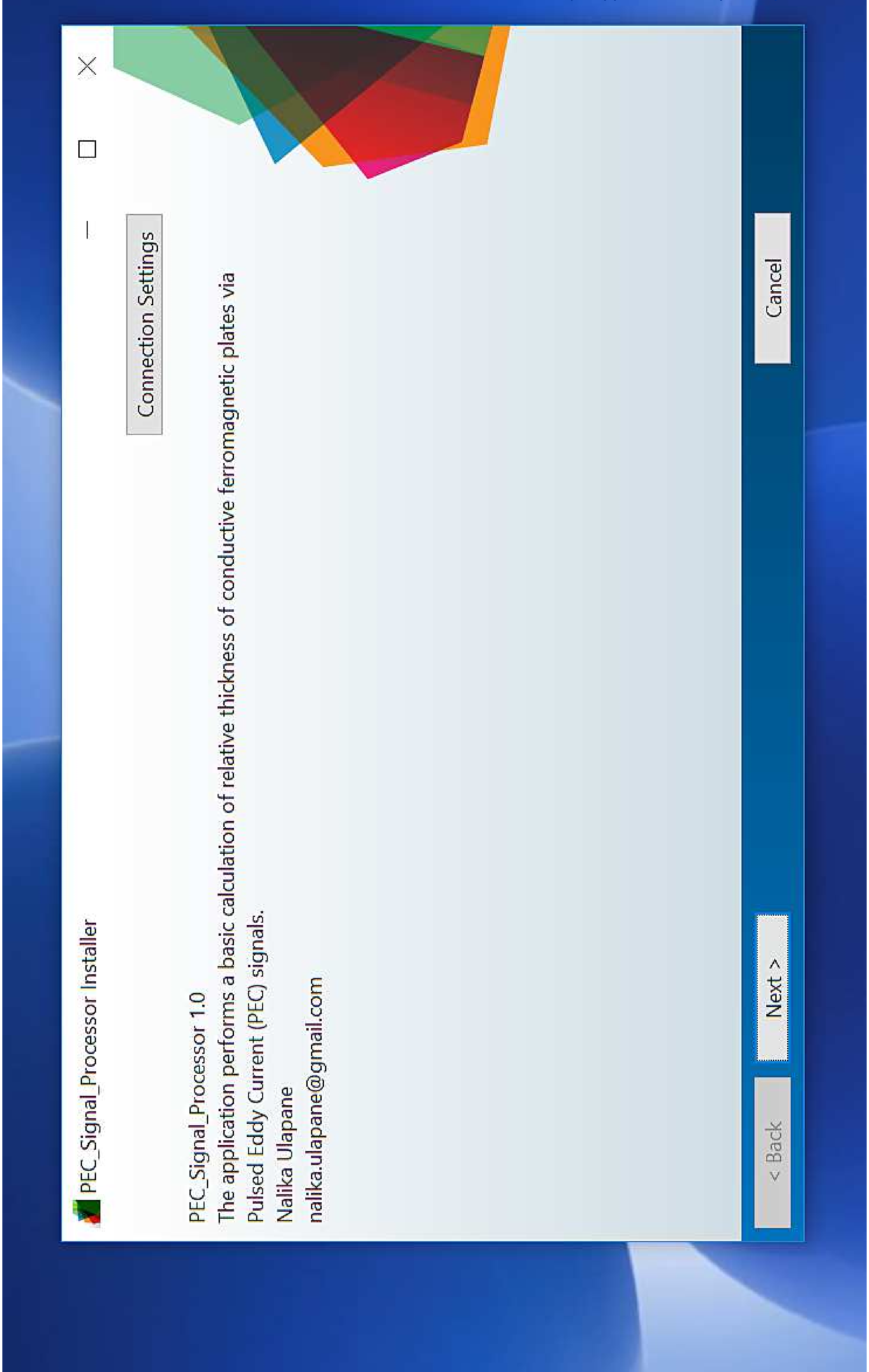
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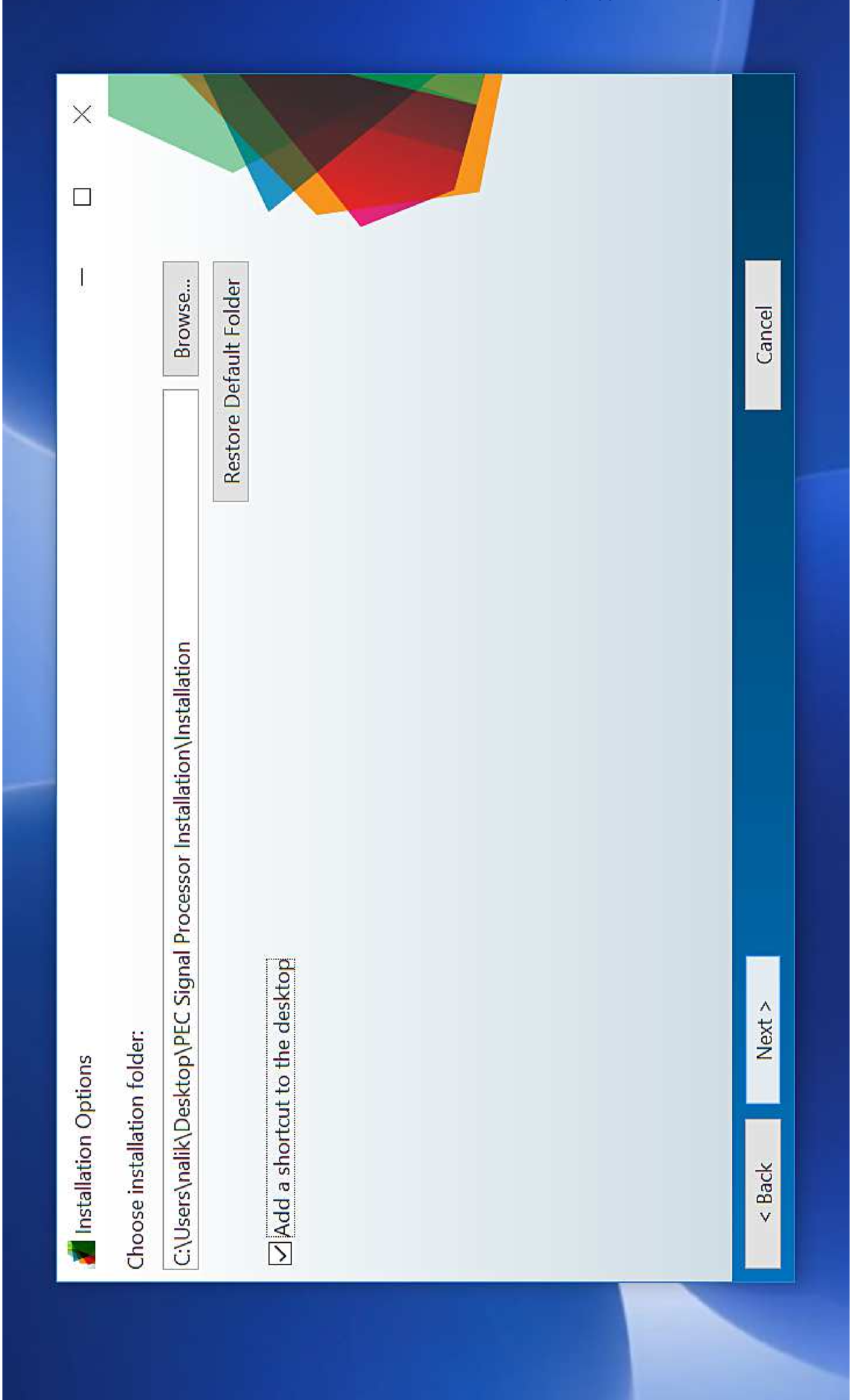
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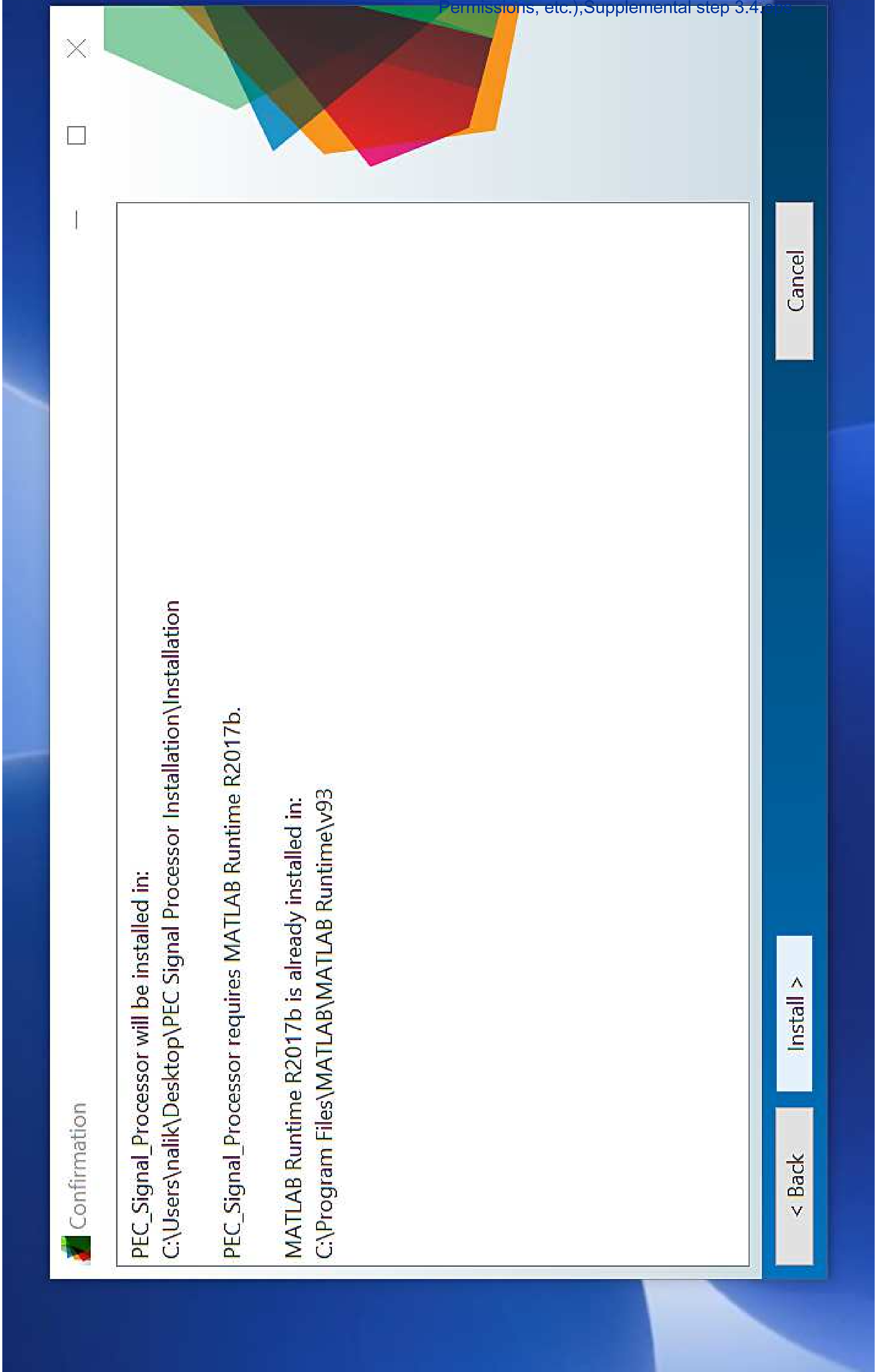
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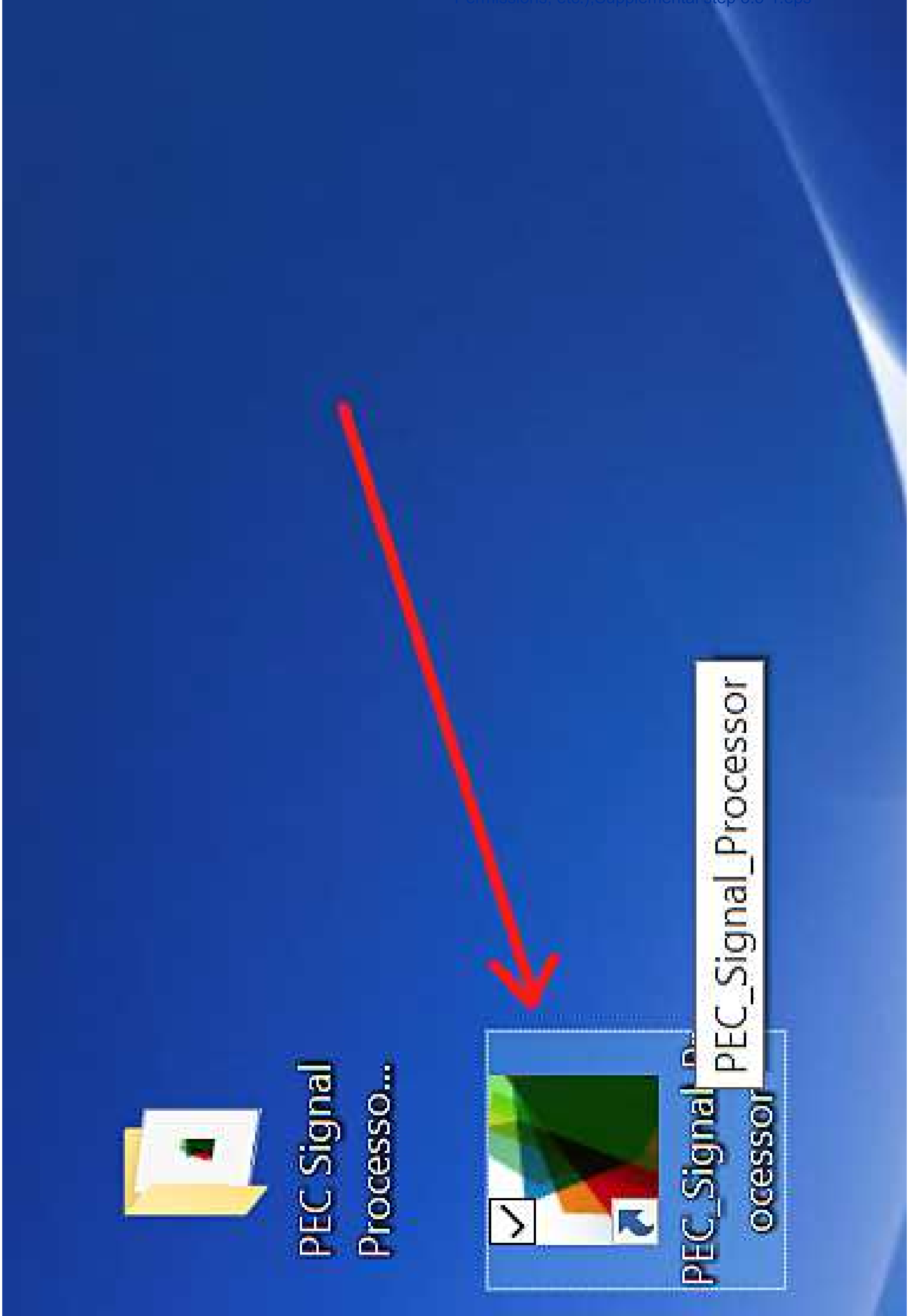
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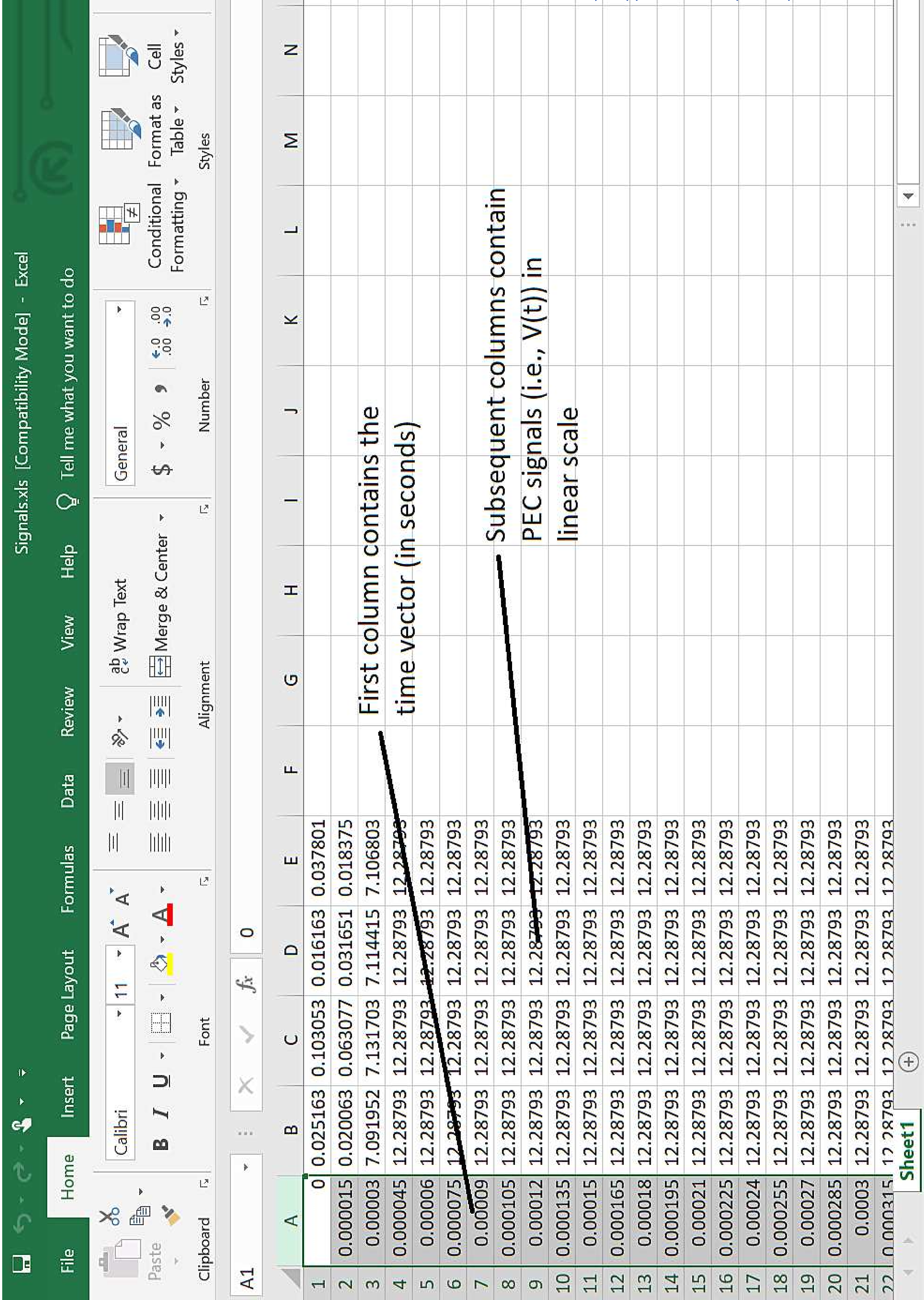

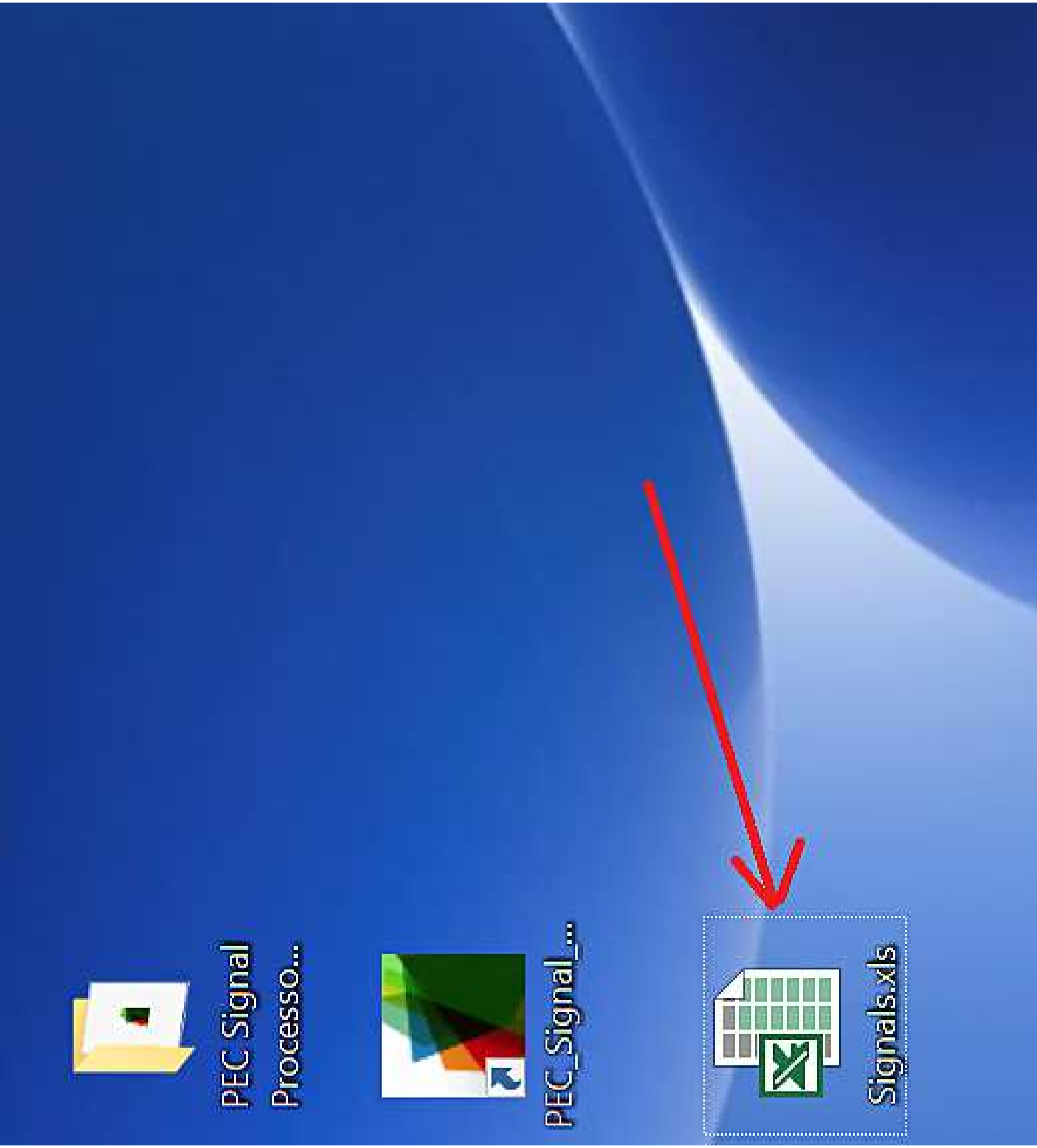
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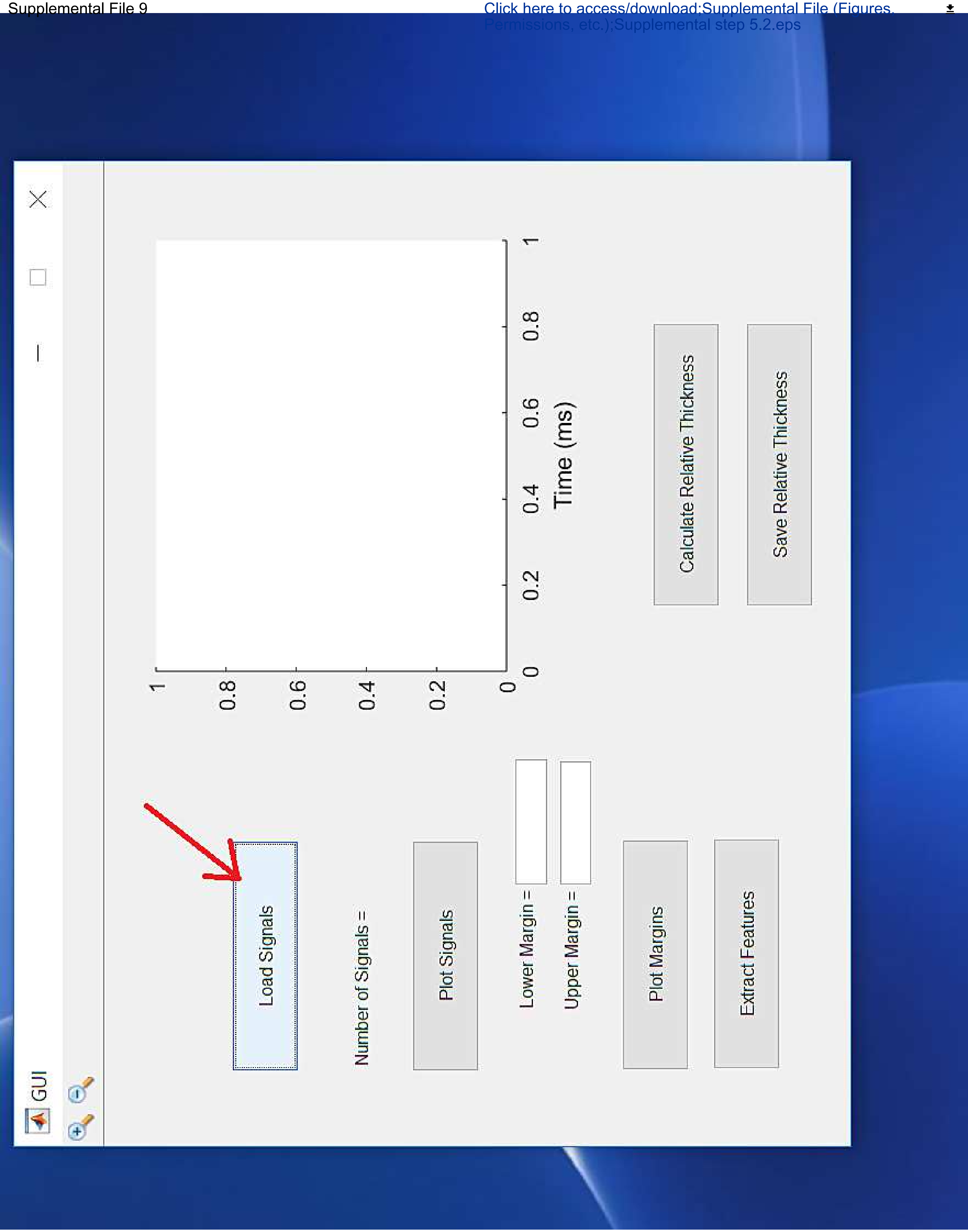
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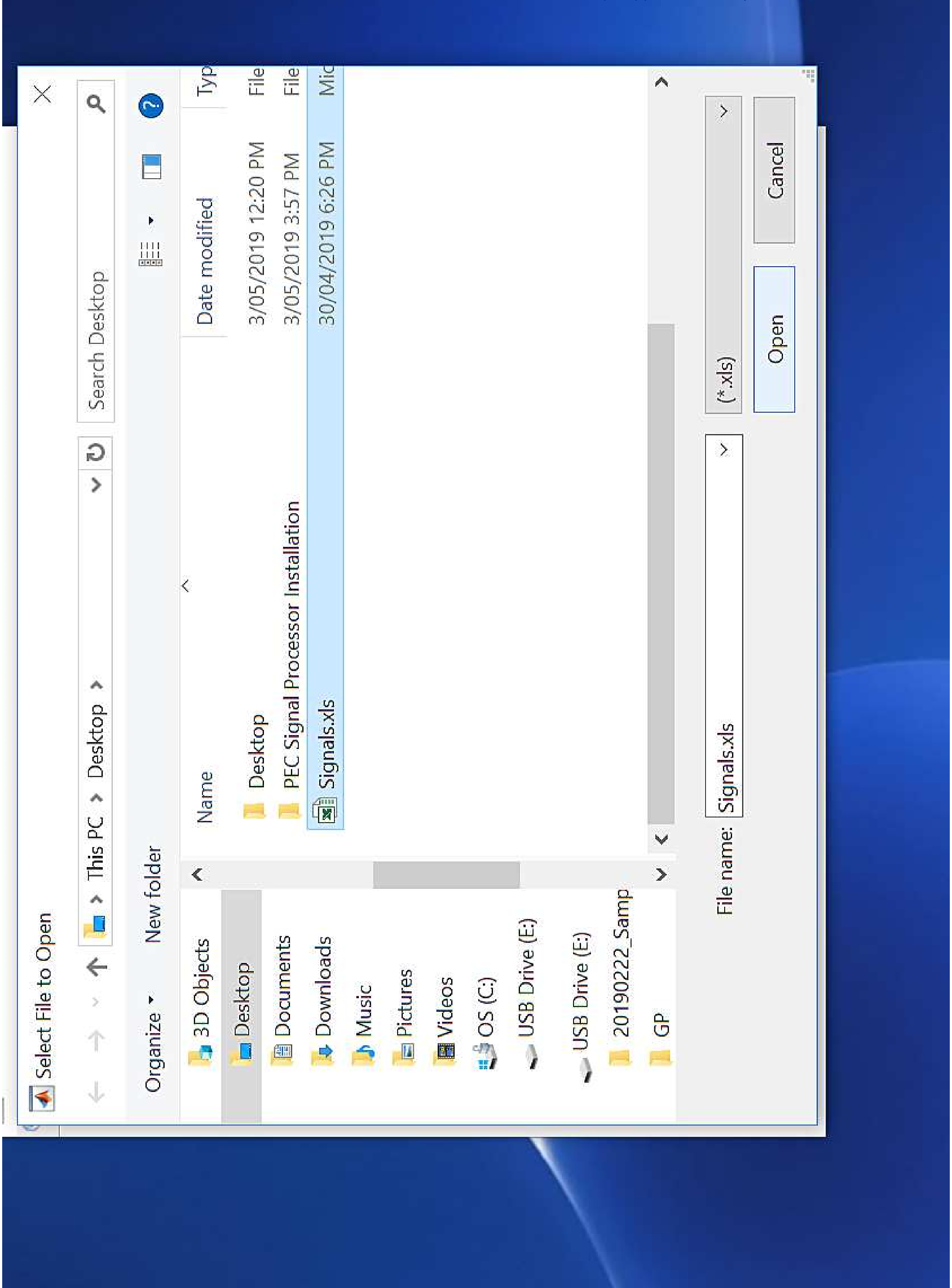
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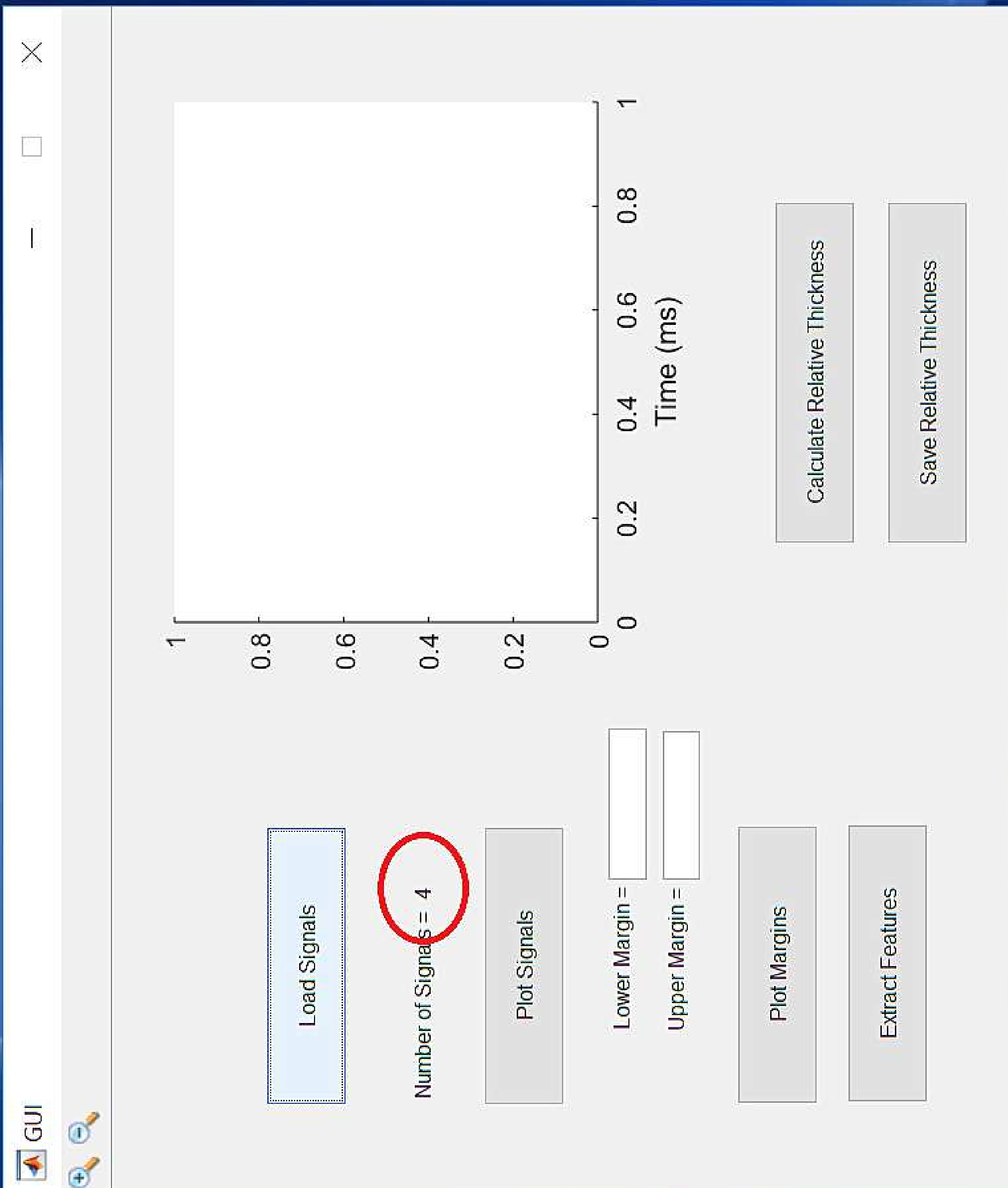
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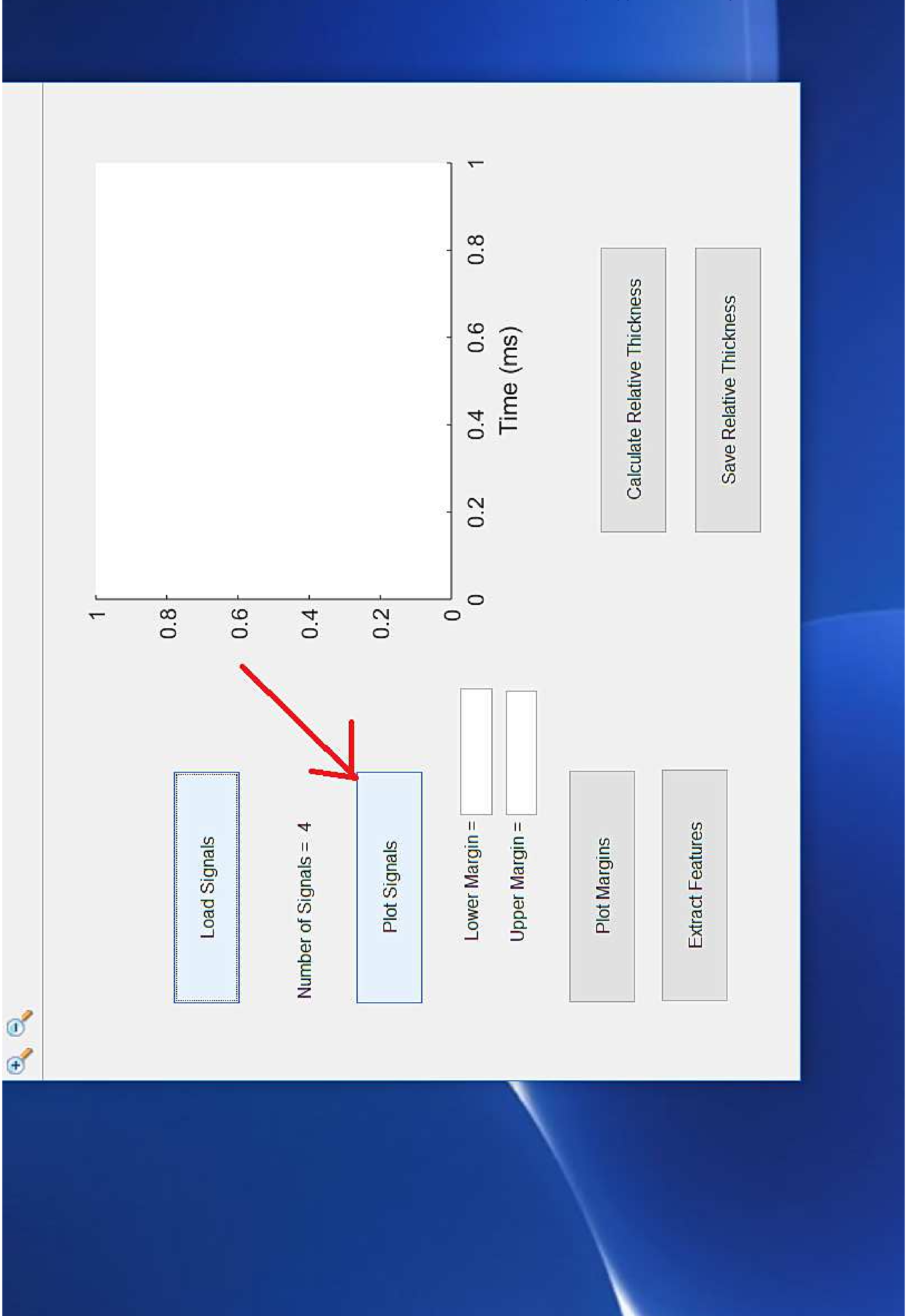
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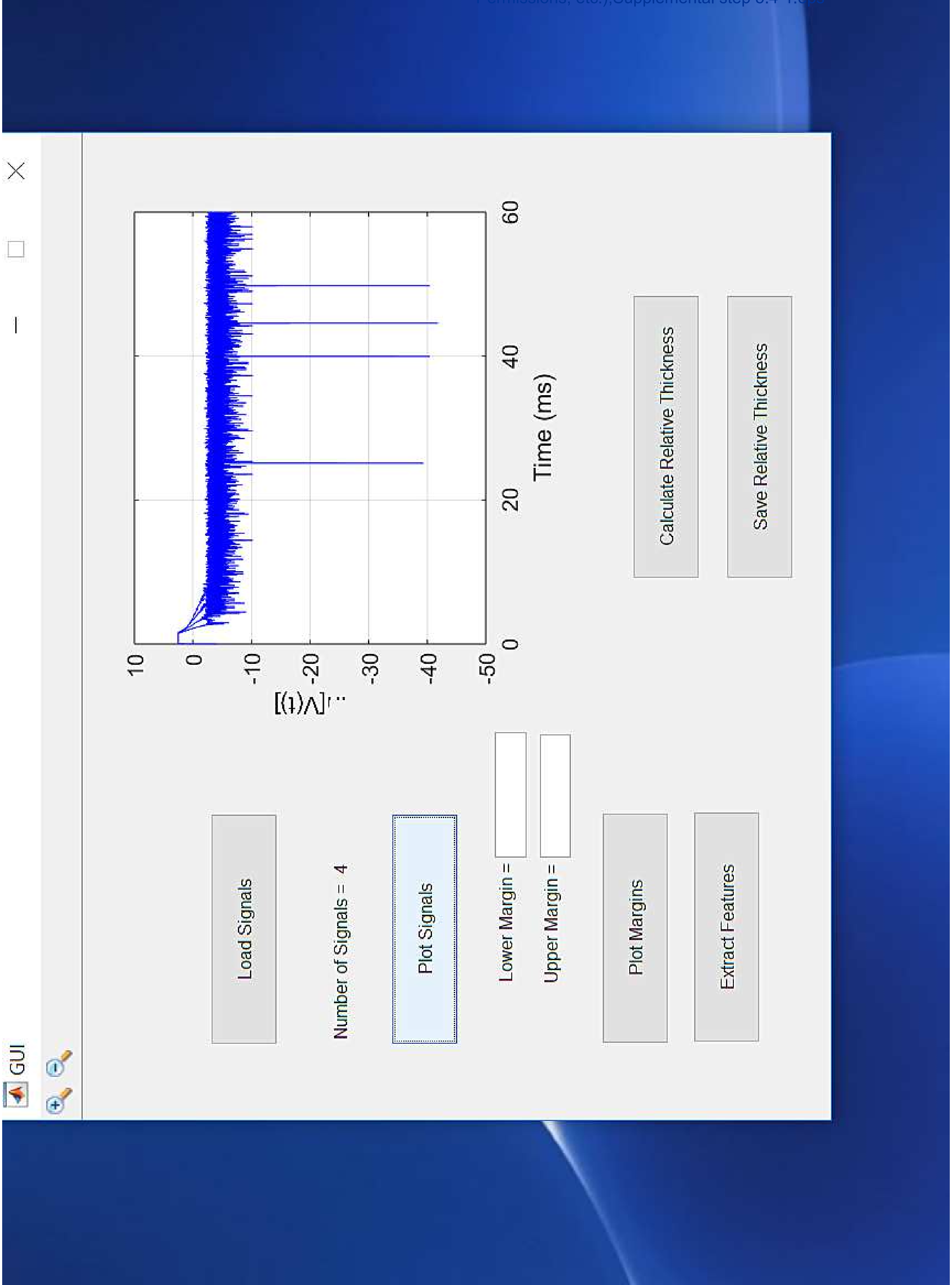
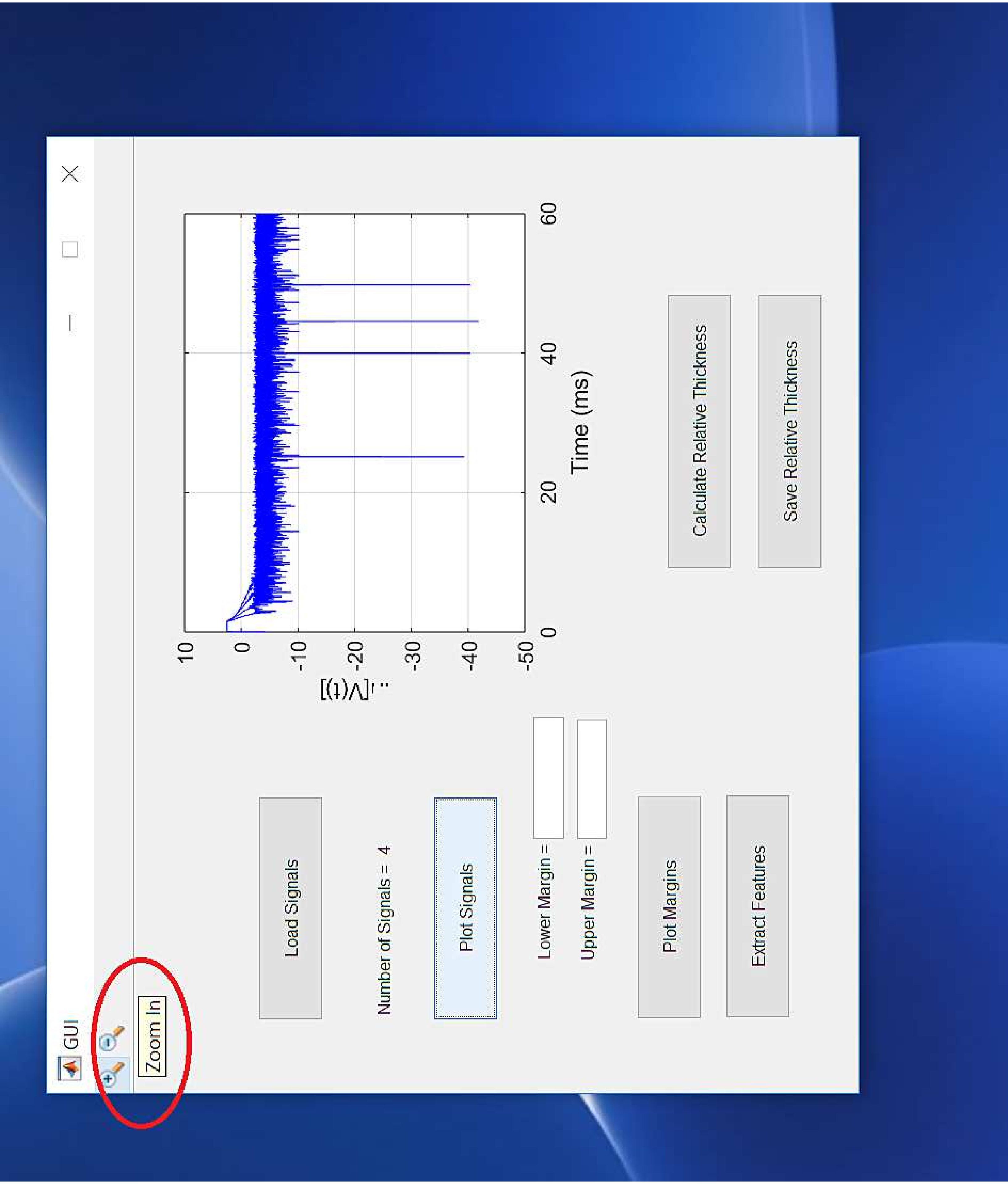
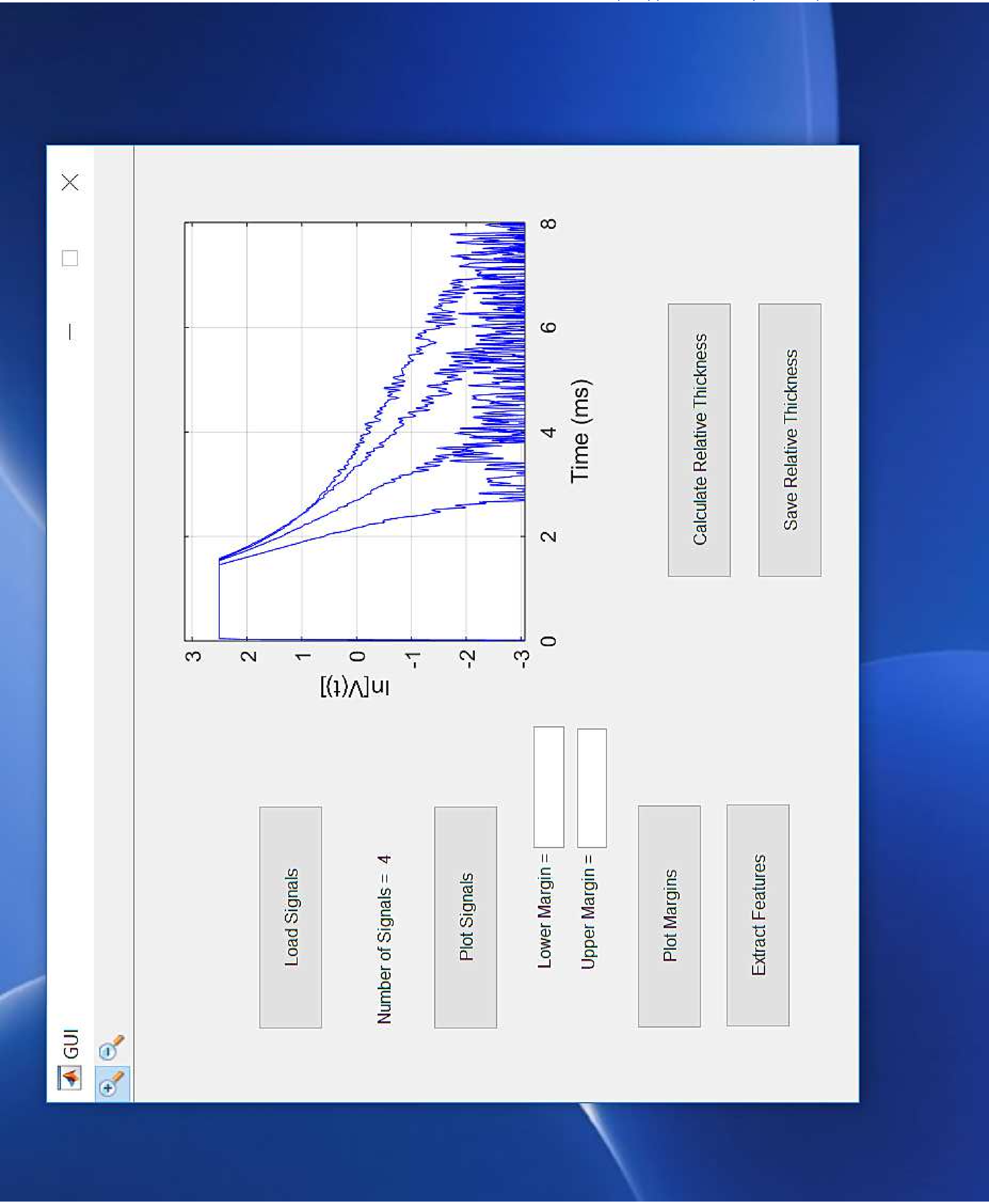
Supplemental File 13



Supplemental File 14

Click here to access/download;Supplemental File (Figures, Permissions, etc.);Supplemental step 5.5.eps




GUI
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Plot Signals
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Upper Margin =
Plot Margins
Extract Features
ln[V(t)]
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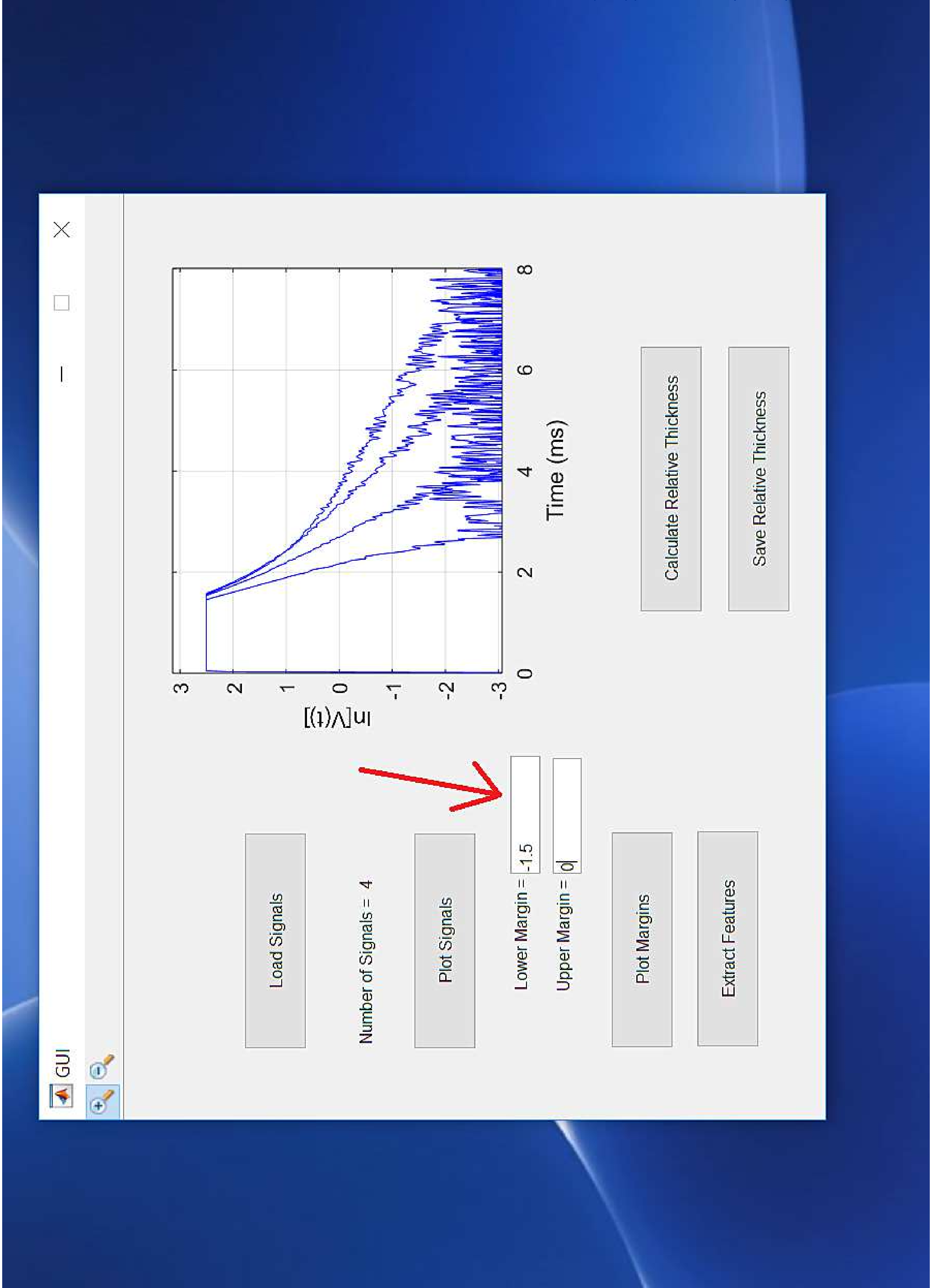
1
0
-1
-2
-3
0
2
4
6
8
Time (ms)
Calculate Relative Thickness
Save Relative Thickness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Extract Features
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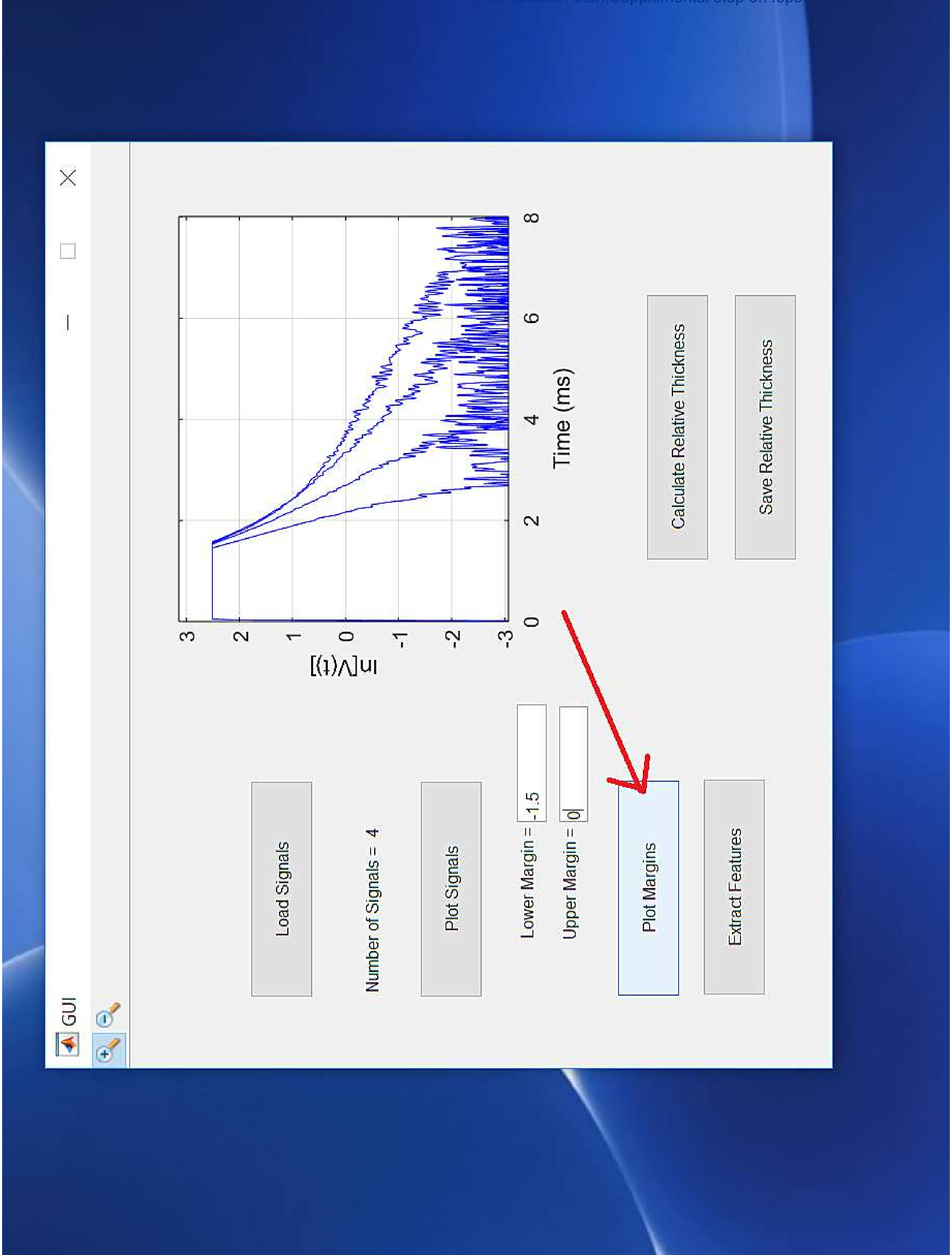
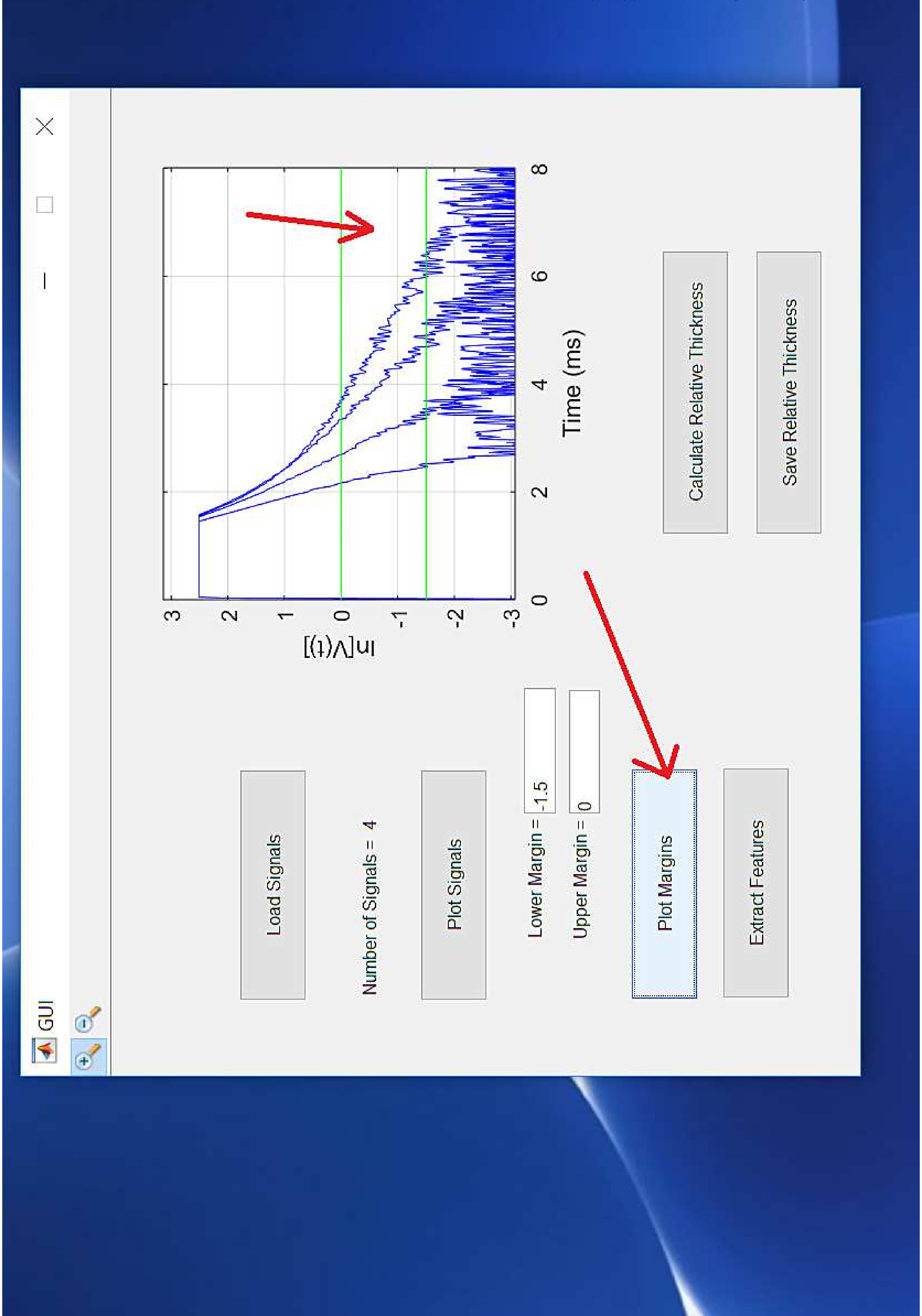
Time (ms)
Calculate Relative Thickness
Save Relative Thickness

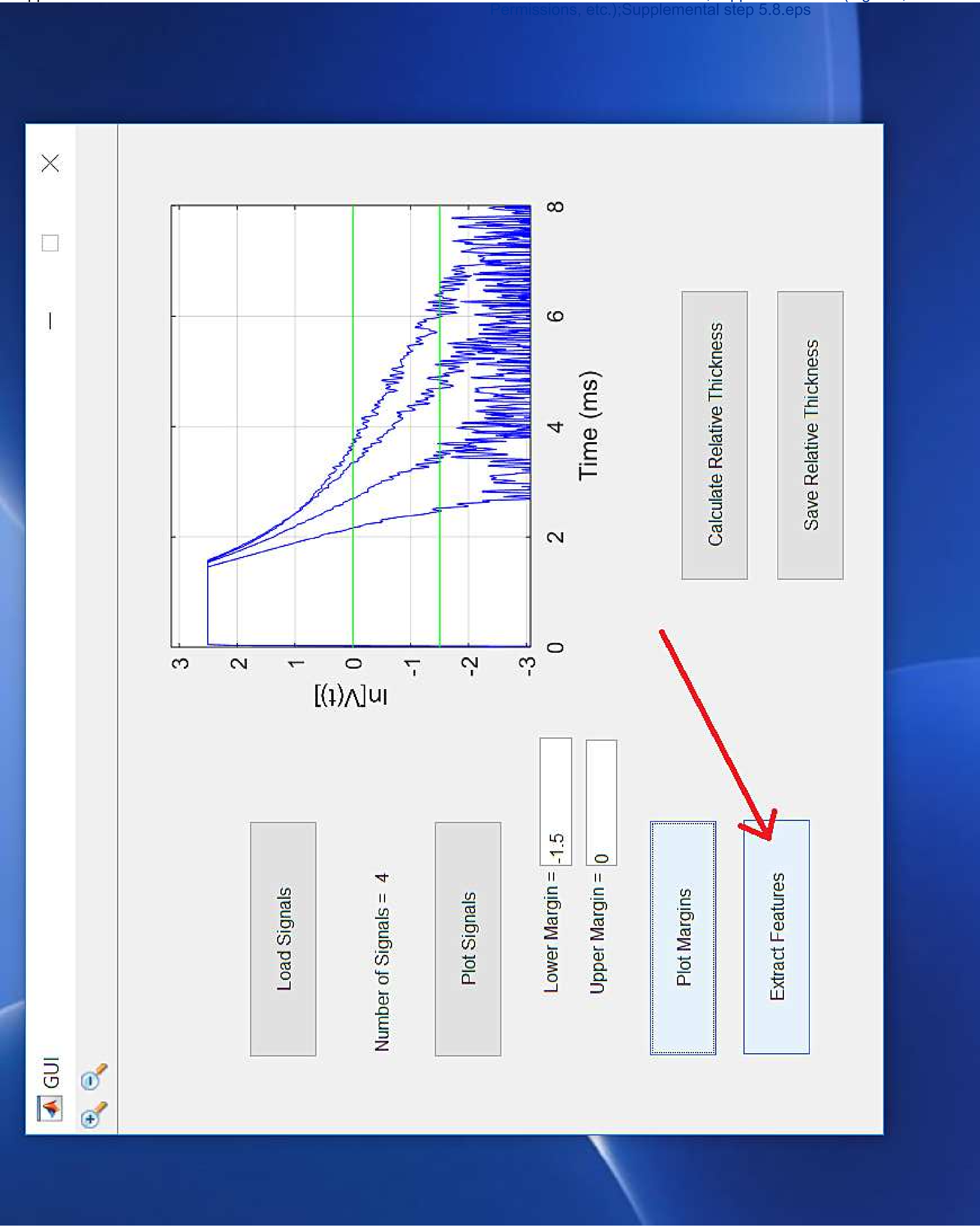
Supplemental File 17

Click here to access/download;Supplemental File (Figures, Permissions, etc.);Supplemental step 5.7.eps



Supplemental File 18

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Upper Margin = 0
Plot Margins
Extract Features
Calculate Relative Thickness
Save Relative Thickness
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Time (ms)
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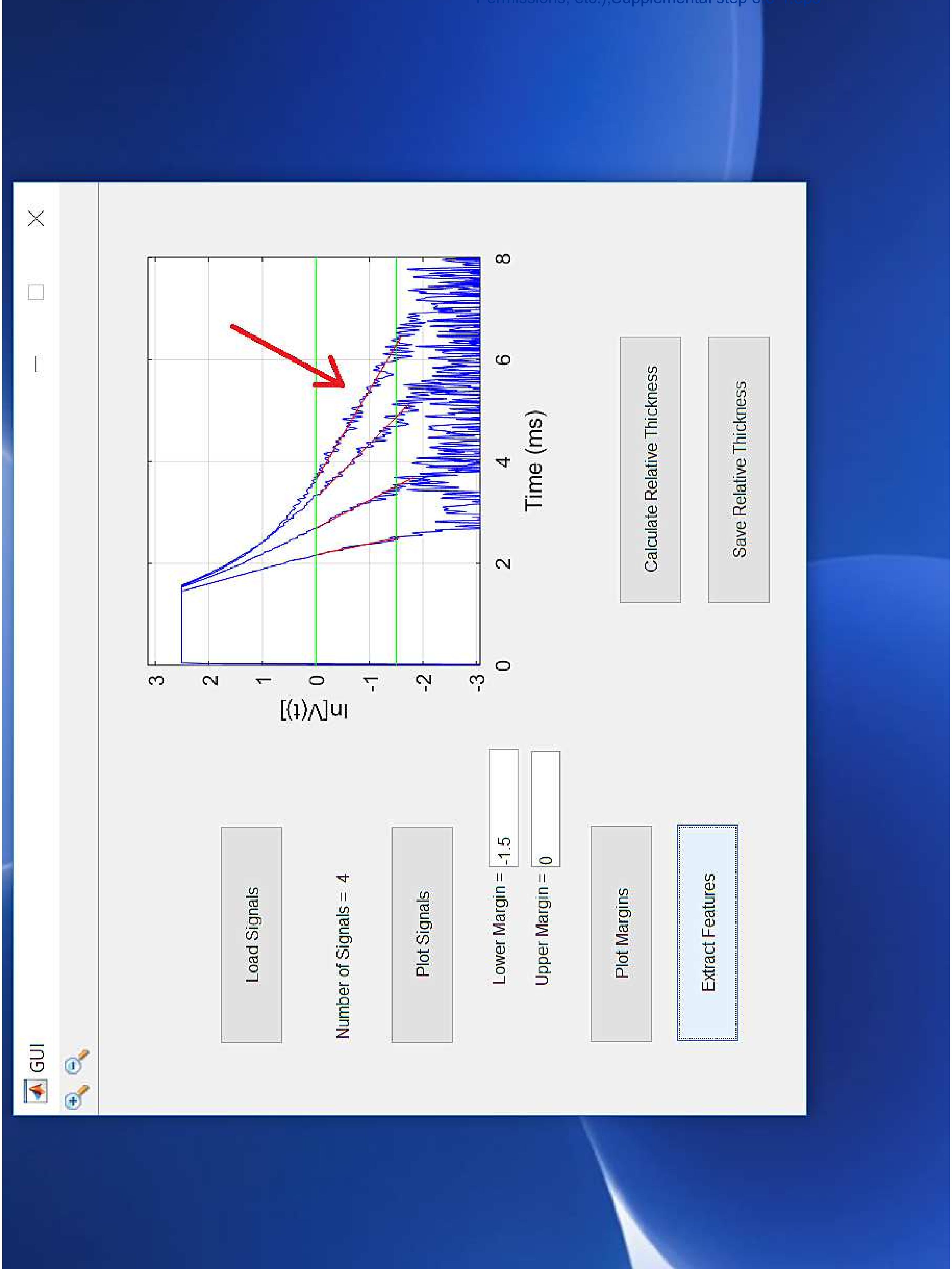
2
1
0
-1
-2
-3
0
2
4
6
8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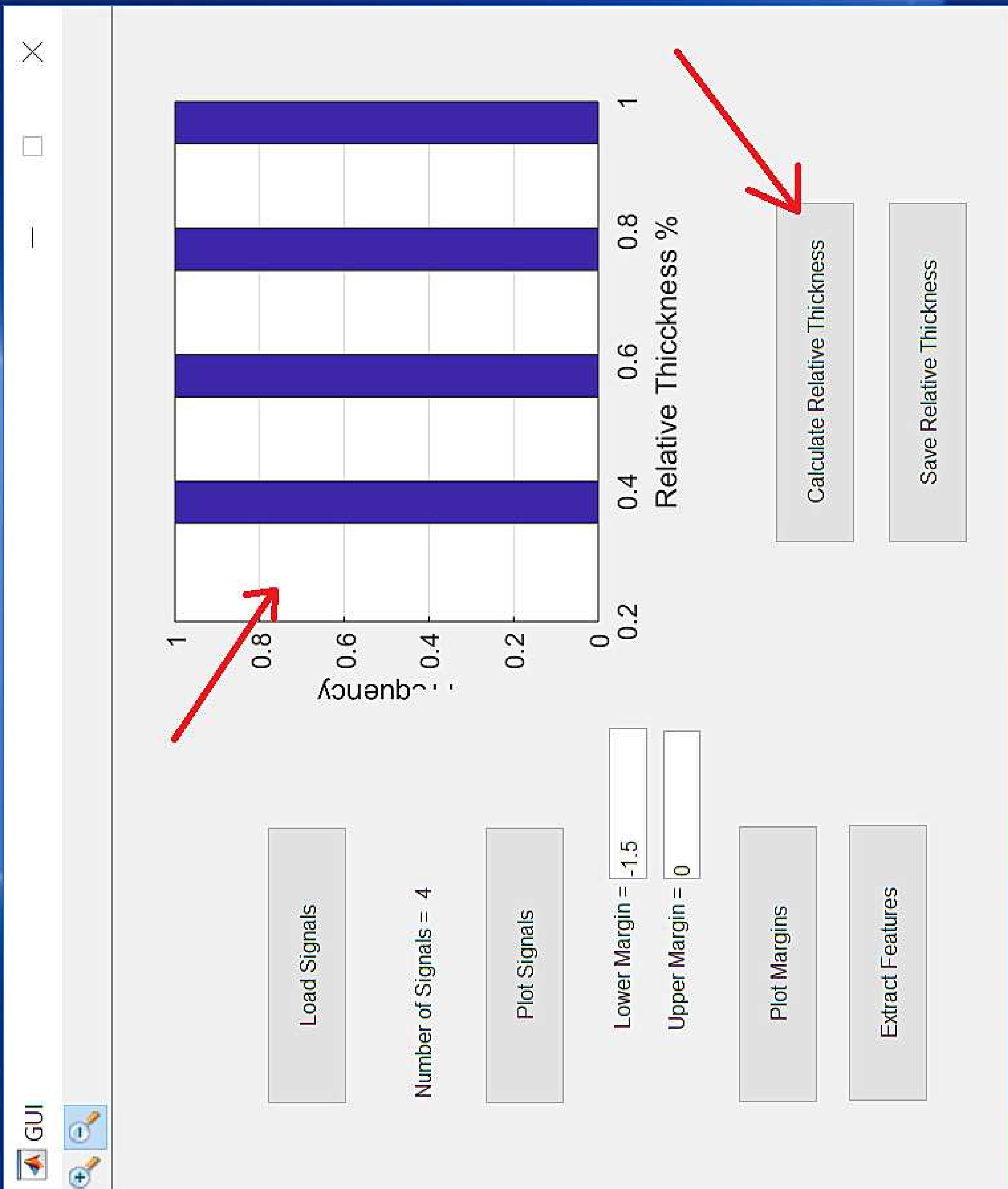
Upper Margin = 0
Plot Margins
Extract Features
ln[V(t)]
Time (ms)
Calculate Relative Thickness
Save Relative Thickness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Plot Signals
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Upper Margin = 0
Plot Margins
Extract Features
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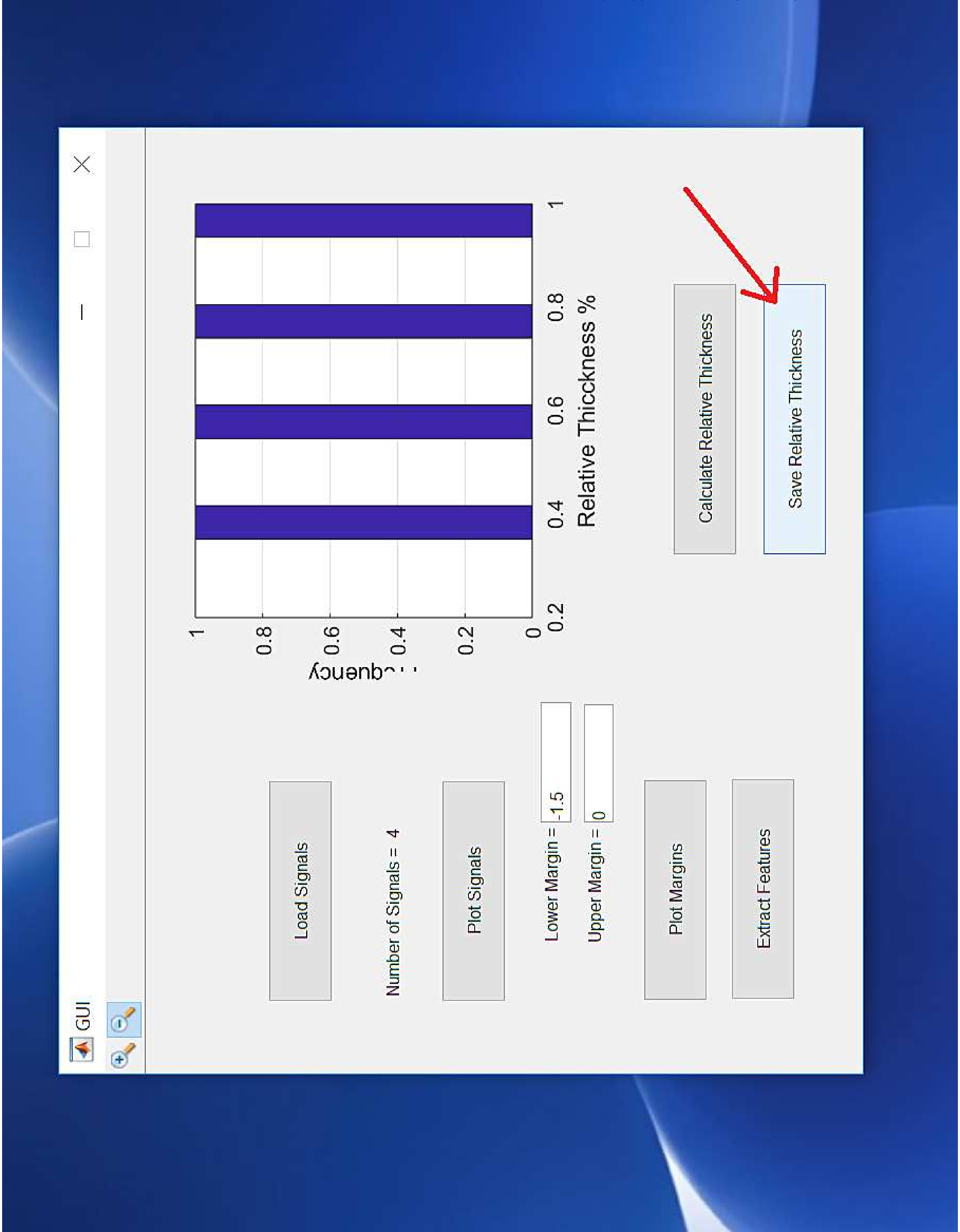
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
Relative Thicckness %
Calculate Relative Thickness
Save Relative Thickness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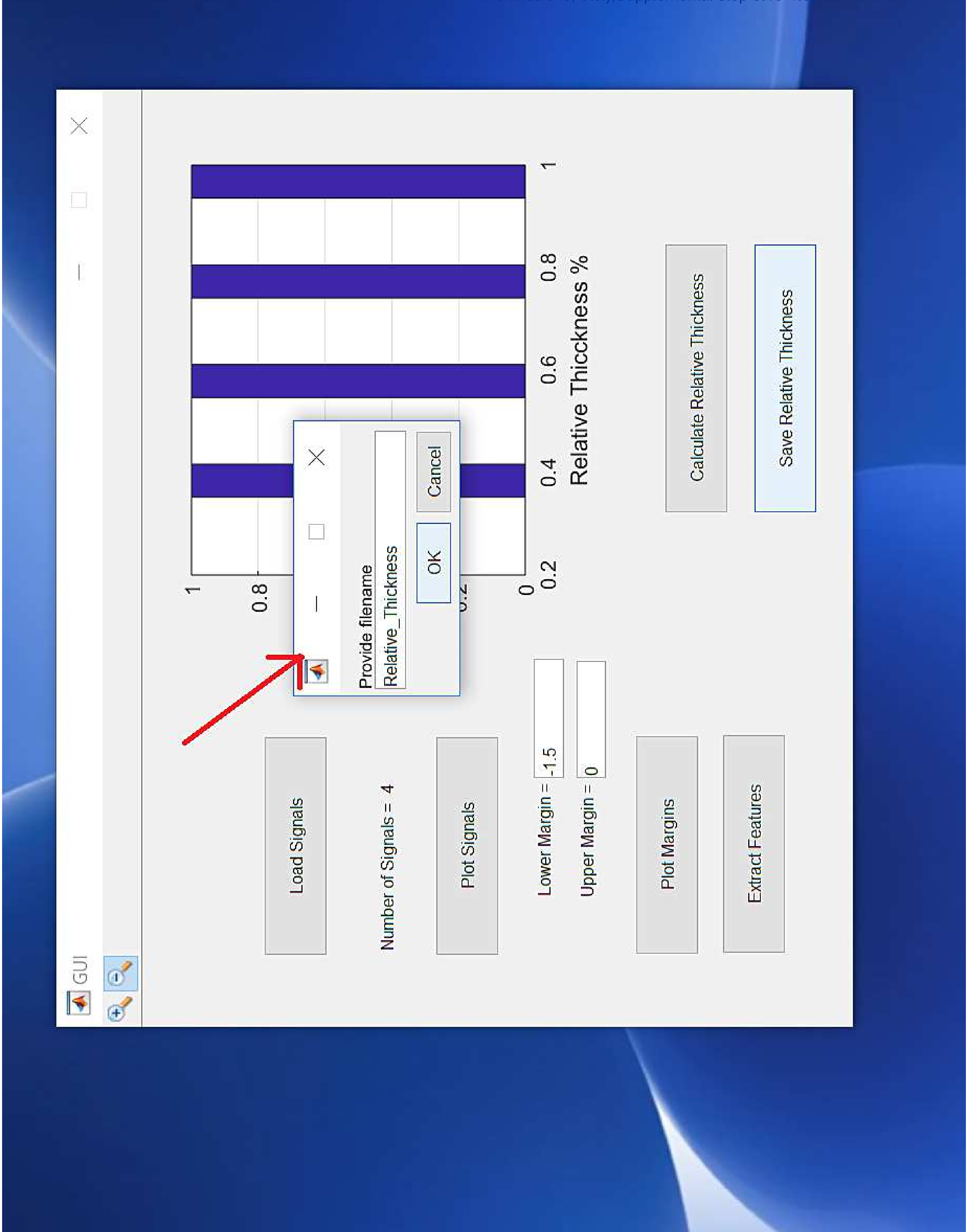
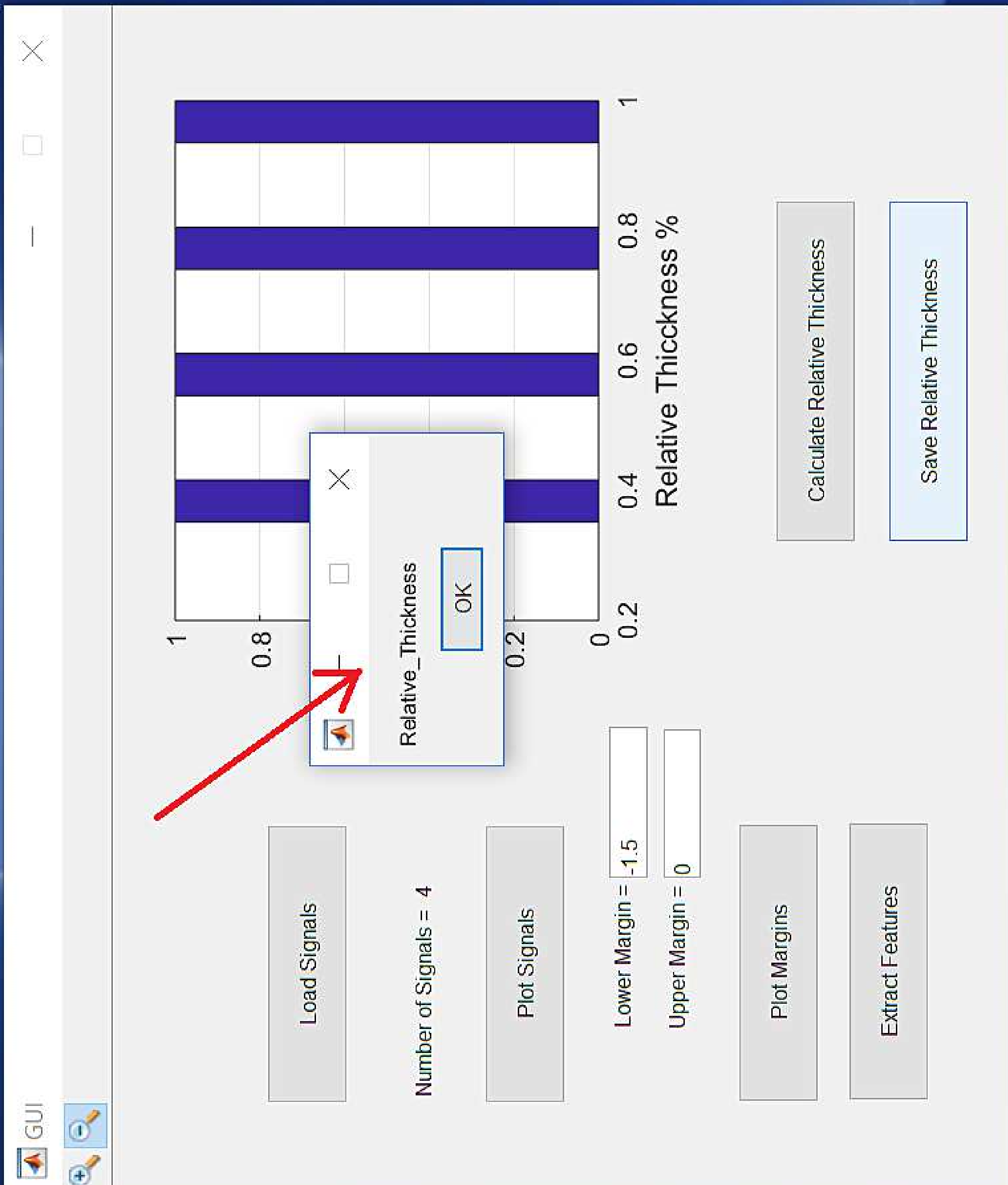
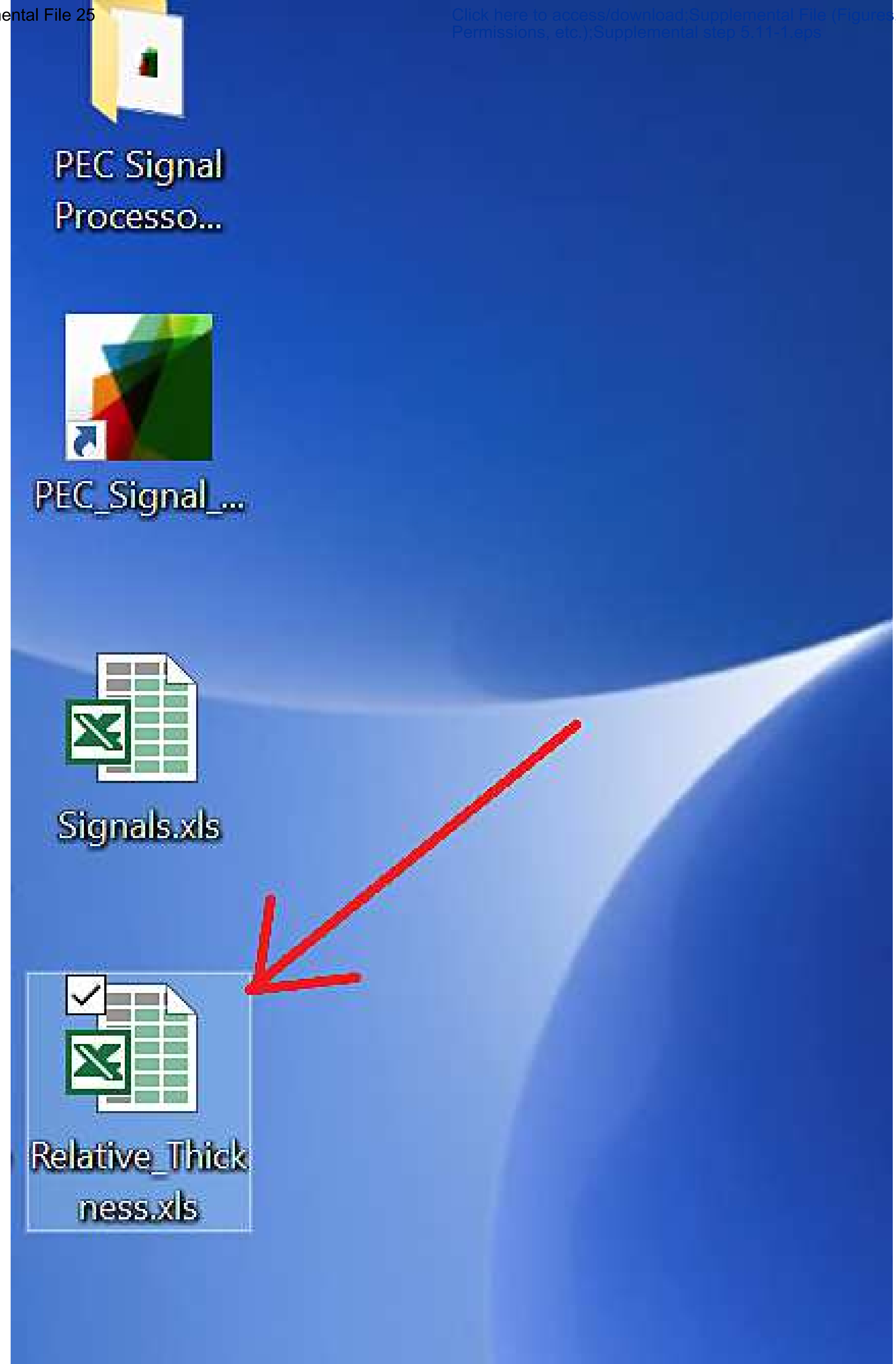
Relative Thickness %
Calculate Relative Thickness
Save Relative Thickness

Supplemental File 23



Supplemental File 24




PEC Signal
Processo...
PEC_Signal_...
Signals.xls
Relative_Thick
ness.xls