İSTANBUL TEKNİK ÜNİVERSİTESİ

FEN-EDEBİYAT FAKÜLTESİ

GRADUATION PROJECT

MATLAB-based Nonlinear Optical Z-Scan Data Analysis Programming

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CONTENTS

ABSTRACT

This thesis presents a MATLAB-based application designed for analyzing experimental data from Z-scan measurements. Z-scan measurements are a critical technique for exploring nonlinear optical properties in materials, such as doped thin films and various types of glasses. The software's primary purpose is to aid in the importation and manipulation of raw data, allowing researchers to gain valuable insights into the optical characteristics of the materials under examination. The application features an intuitive user interface that simplifies the process of data manipulation, converting complex raw measurements into an easily analyzable format.

The software has advanced visualization tools that enable the graphical representation of scattering profiles. This allows for a direct visual assessment of sample behaviors under varying conditions. The application utilizes advanced fitting algorithms calibrated to align with theoretical models for phenomena such as open aperture Z-scan, closed aperture Z-scan, two-photon absorption and three-photon absorption processes. These algorithms accurately calculate critical material parameters, including the nonlinear absorption coefficient (β) and the nonlinear refractive index (n_2).

A MATLAB tool is available for this purpose, which integrates data importation, manipulation, and analysis in a user-friendly interface. This tool optimizes the research workflow. By streamlining these processes, the application not only enhances the efficiency and precision of nonlinear optical property studies but also contributes significantly to advancing the field of photonics research. The implementation of this application represents a significant step forward in the quest for a deeper understanding of nonlinear optical phenomena, offering researchers a powerful tool to expedite their discoveries in the realm of optical materials science.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to Assoc. Dr. Murat ERDEM, my thesis advisor, for his unwavering support and guidance throughout this research.

I cannot forget the incredible emotional support provided by my family, especially my grandparents, who have always believed in me.

MUHAMMED BEKTAŞOĞLU July, 2024

FIGURES

ABBREVIATIONS AND SYBOMLS

β	:	Nonlinear absorption coefficient
n_2	:	Nonlinear refractive index
Z	:	Rayleigh Range
L_{eff}	:	Effective Length of the Sample
α	:	Linear absorption coefficient
L	:	Thickness of the sample
i	:	Intensity of the incident laser beam
ω_0	:	Intensity of the incident laser beam
λ	:	Wavelength of laser

1. INTRODUCTION

Nonlinear optics is the study of the behavior of light in nonlinear media, where the response of the material to light is not directly proportional to the light intensity. This field has revolutionized the way we manipulate light, leading to advancements in a wide range of applications from high-speed communication to medical imaging. Understanding the nonlinear optical properties of materials is crucial for the development of devices such as lasers, optical switches, and modulators.

Z-Scan Technique: A Tool for Nonlinear Optics Exploration

The Z-scan technique is a simple yet powerful experimental method to measure the nonlinear optical properties of materials. It involves moving a sample through the focus of a laser beam and measuring the transmitted light intensity as a function of the sample position relative to the focal plane. This technique can distinguish between different types of nonlinearities, making it invaluable for characterizing materials for photonics applications.

The open aperture Z-scan method is used to measure nonlinear absorption, including phenomena like two-photon absorption and saturation absorption. In an open aperture setup, the entire transmitted beam is detected, allowing for the analysis of materials' absorptive nonlinearities without the influence of nonlinear refraction.

Contrastingly, the closed aperture Z-scan technique is utilized to assess nonlinear refraction. A small aperture is placed in the far field to partially block the transmitted beam. This setup enables the measurement of the phase distortion induced by the sample, providing insights into the refractive nonlinearities of the material.

Two-photon and three-photon absorptions are nonlinear optical process where photons are absorbed simultaneously, transitioning an electron from a lower to a higher energy state. These phenomena are crucial for applications requiring controlled light-matter interactions, such as in optical limiting and photodynamic therapy.

This thesis introduces a MATLAB-based application designed to simplify the analysis of experimental data from Z-scan measurements, enhancing the study of nonlinear optical properties in materials. By offering an intuitive platform for data manipulation, visualization, and fitting to theoretical models, this work contributes significantly to the field of photonics research. The application not only streamlines the experimental workflow but also provides a robust tool for the accurate characterization of nonlinear optical phenomena, thereby facilitating the advancement of optical materials science.

2. THEORETICAL PERSPECTIVE

2.1. Open Aperture Z-Scan

$$Y = 1 - 2\left(\frac{(\frac{x}{z})^2+3}{(\frac{x}{z})^2+9}\right)\left(\left(\frac{x}{z}\right)^2+1\right)\left(\frac{bi}{2}\right)l \quad (2.1)$$

$$L_{eff} = (1 - e^{-\alpha L})/\alpha \quad (2.2)$$

$$\mathrm{z} = \frac{kw_0^2}{2} \quad (2.3)$$

$$k = \frac{2\pi}{\lambda} \quad (2.4)$$

2.2. Closed Aperture Z-Scan

2.3. Two Photon Absorption

$$1/(1 + \beta L_{eff}(i/(1 + (\frac{x}{z})^2)) \quad (2.)$$

$$L_{eff} = (1 - e^{-\alpha L})/\alpha \quad (2.)$$

$$\mathrm{z} = \frac{\pi w_0^2}{\lambda} \quad (2.)$$

2.4. Three Photon Absorption

$$1/(1 + 2\beta L_{eff}(i/(1 + (\frac{x}{z})^2))^2 \quad (2.)$$

$$L_{eff} = (1 - e^{-2\alpha L})/2\alpha \quad (2.)$$

$$\mathrm{z} = \frac{\pi w_0^2}{\lambda} \quad (2.)$$

Femtosecond and nanosecond nonlinear optical properties of alkyl phthalocyanines studied using Z-scan technique

3. PROGRAM MANUAL

3.1. Installation

3.2. User Interface

3.3. Data Import

The *Data Import* functionality is a critical component of the program that allows for seamless integration of measurement data into the application. To ensure efficient data handling, the application supports importing data through the following steps:

Multiple Independent Tabs:

The application is designed with five independent Input tabs, each capable of handling separate measurement data. This design enables concurrent processing of up to five distinct measurements within the same session, significantly enhancing productivity and multitasking capabilities.

Exclusive Use of Excel:

Data importation relies exclusively on Microsoft Excel files. Users are required to prepare their measurement data in an Excel file format before initiating the import process.

Data Format Specifications:

The data must be arranged in two columns, reflecting the dependency of Intensity on Z (mm) observed in Z-Scan configurations. It is crucial for the first column of data to reside in column A (representing Z(mm)), and the second column to be in column B (representing Intensity) within the Excel sheet.

Headers Flexibility:

The presence or absence of axis headers in the Excel file is accommodated by the application. The import process is designed to recognize and correctly handle data with or without these headers, providing flexibility in data formatting.

Single Observation Requirement:

Each Excel file should contain only the data for a single observation. This ensures clarity and prevents any potential confusion during the data analysis process. To maintain data integrity and simplicity, the Excel file should consist of a single worksheet. Data contained in secondary or multiple worksheets will not be recognized and hence should be avoided.

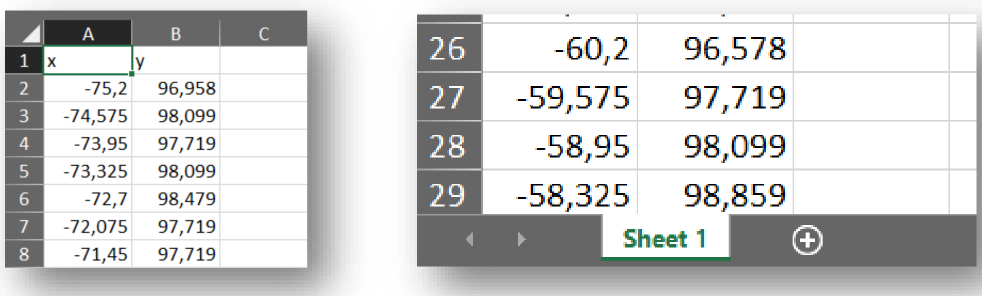

Figure 1: Sample Excel Spreadsheet Format

By adhering to the above guidelines, users can ensure a smooth and error-free data import experience into the application. To initiate the import, simply click on the green "Excel Import" button, conveniently located within each Input tab.

Figure 2: The Excel Import Button

Once the "Excel Import" button is activated, a file selector will appear, guiding users to select and import the desired Excel file from the computer.

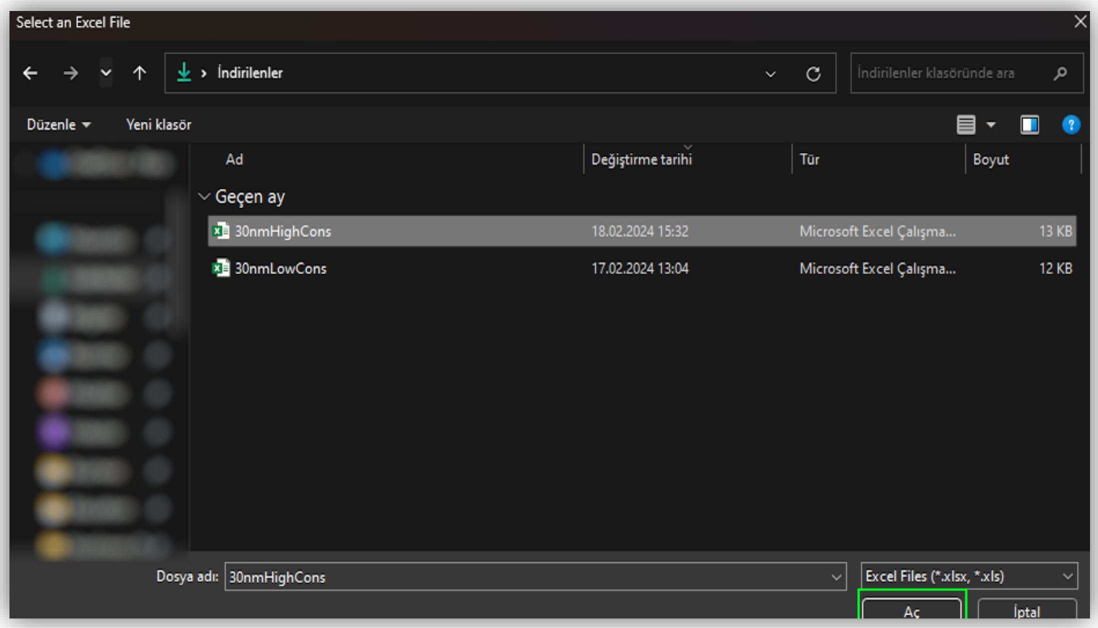

Figure 3: File Selection Dialog

When the Excel file is selected, the data it contains is automatically transferred to the 'Original Data Set' section within the application. The import process seamlessly populates the table with data from the file and organizes them under predefined column headings such as 'Z (mm)' for distance measurement and 'Intensity' for observed values.

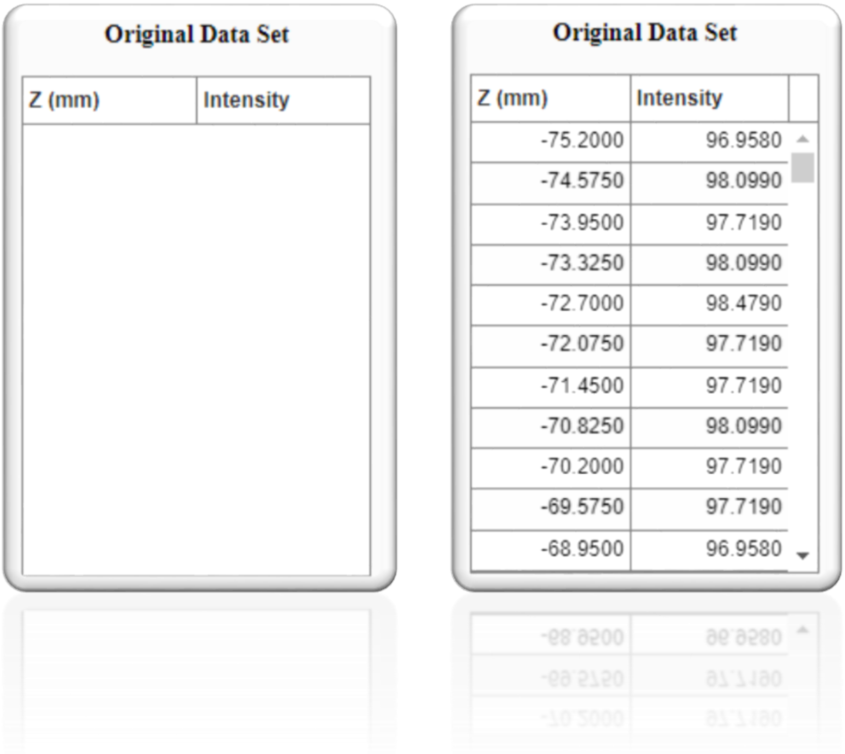

Figure 4: Importing Data Set to Original Table

It is also instantly displayed as a scatter plot on the graph. This visual representation provides an immediate and intuitive view of the data points, allowing users to assess the distribution and key patterns in their dataset before proceeding with further analysis

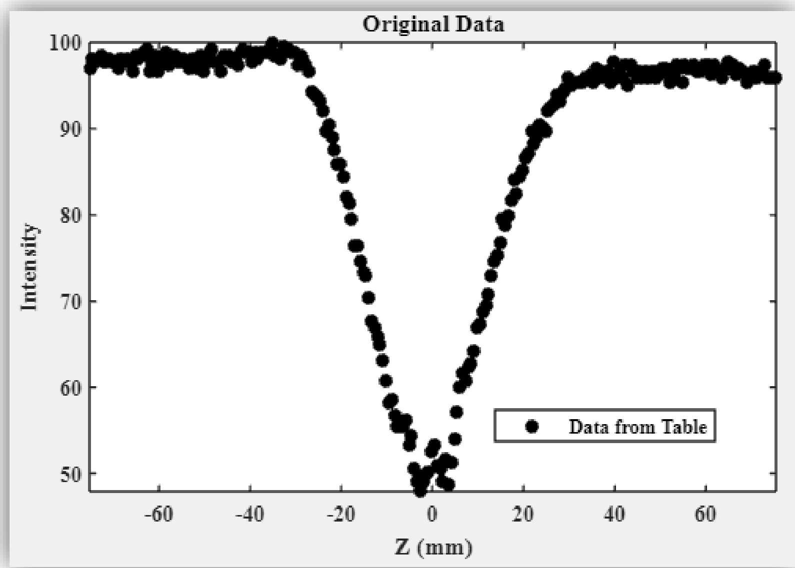

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Figure 5: Scatter Plot of Imported Data

3.4. Data Analysis and Processing

Following the successful import of data from Excel into the application, users can begin to manipulate and process the data for detailed analysis. This section of the manual guides you through the data manipulation features available after import.

Data Truncation for Focused Analysis:

At times, observational data may exhibit undesired behavior beyond a certain range. To address this, users can specify their range of interest by replacing the default -Inf and Inf values in the "Data Between -Inf < z < Inf" section with the desired numerical limits. Only the data within the defined range will be retained for subsequent analysis, allowing users to exclude any portion of data that might distort the fitting process.

Adjusting Data Alignment with Shift on x-direction:

The Z-Scan setup typically alters the distance starting from x = 0 mm. If the central point of the graph is to be aligned at x = 0 mm, users can achieve this by inputting a non-zero value in the "Shift on x-direction" field. This action will shift the Z(mm) values in the first column of the table, effectively re-centering the dataset around the desired midpoint.

Normalization of Intensity Data:

By engaging the Normalized button, the Intensity data is normalized to scale between 0 and 1. This feature is particularly recommended if the data has not been previously normalized, ensuring uniformity and comparability within the dataset.

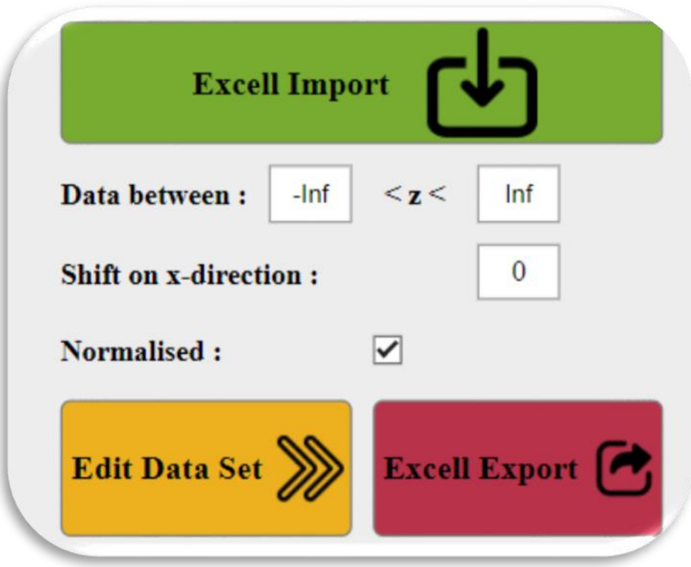

Figure 6: Data Manipulation Controls – The interface displays the main controls for data manipulation

Finalizing Data Manipulation:

Once the desired data manipulation has been completed, users can finalize their edits by clicking the **Edit Data Set** button. This action commits the changes and transfers the modified data to the **Edited Data Set** section, where users can visually confirm the updates to their data set, now ready for further processing or analysis.

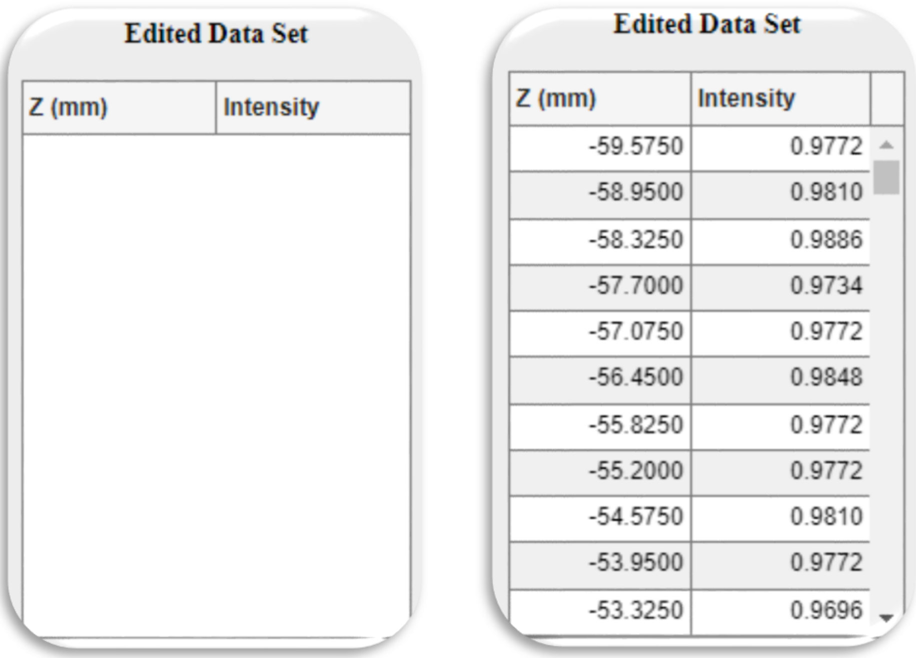

Figure 7: Edited Data Set Preview – This figure shows a sample of the Edited Data Set with two columns: Z (mm) and Intensity.

The prepared "Edited Data Set" serves as the foundation for fitting algorithms. The fitting function will interface with the "Edited Data Set" to perform regression or curve fitting, depending on the analysis required.

3.5. Determination of Fitting Method and Parameters

Creating a precise fit for your data is crucial to accurately interpret your experimental results. In this section of the application, you will select a fitting method and define parameters that match your experimental setup.

Selecting the Fitting Method:

Firstly, choose the fitting method that aligns with the type of data you have. You'll see options like:

- Open Aperture Z-Scan
- Closed Aperture Z-Scan
- Two Photon Absorption
- Three Photon Absorption

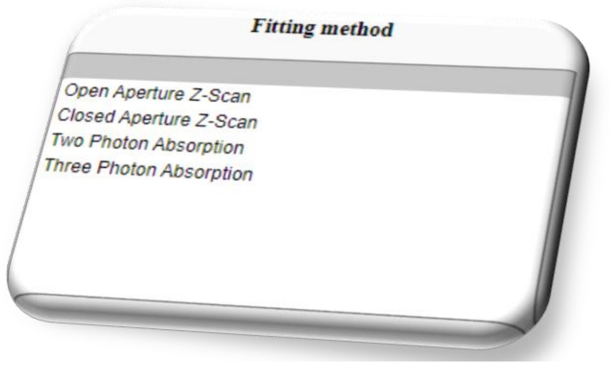

Figure 8: Selection Menu for Fitting Methods

After choosing the fitting method that best represents your experiment, the next critical step is to input the parameters that will be used to tailor the fit to your data.

Entering the Parameters:

Inputting parameters in the application is flexible, you do not need to fill in every field. The program is designed to work with either direct inputs from you or to calculate necessary values based on the information you provide. Here's how you decide which parameters to enter:

If you input the sample's thickness (L) and the linear absorption coefficient (α), the application will automatically compute the effective length of the sample (L_{eff}). In this case, you should not enter L_{eff} directly because the application calculates it for you.

Conversely, if you prefer to provide L_{eff} directly based on your calculations or knowledge, you should then leave the L and α fields empty. The app is set up to prevent contradictory inputs.

For the wavelength (λ) and beam waist (ω_0), inputting values will automatically restrict you from entering the Rayleigh range (Z) as the program is designed to prevent the simultaneous input of these parameters. If you instead choose to enter a value for Z first, the application will then disable the entry fields for λ and ω_0 to ensure the consistency of data required for the fitting process.

To perform a fit, the application must have an L_{eff} value. It can be either calculated by the app or input directly by you. Also, at least one of the following parameters must be provided for the fit to proceed: Z, i (Intensity), or β (Nonlinear absorption coefficient). Without at least one of these, the fit cannot be performed.

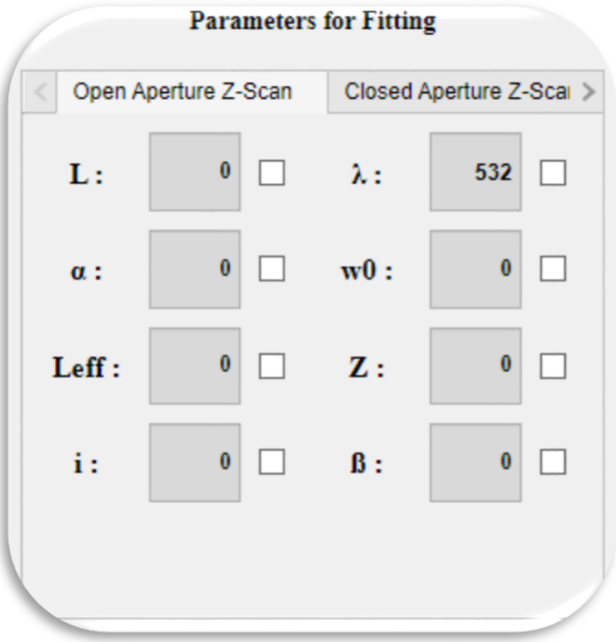

Figure 9: Fitting Parameters Input – A graphical user interface presenting a set of input fields for parameters used in fitting procedures

3.6. Obtaining Graphical Output

After selecting the fitting method and entering the necessary parameters, it is crucial to ensure that data manipulation has been completed. This means that the "Edit Data Set" button must have been clicked to prepare the data in the "Edited Data Set" section.

If there are no issues with adhering to the rules for fit parameters, clicking on the **Get the scattering and fitting** checkbox initiates the application's calculation process.

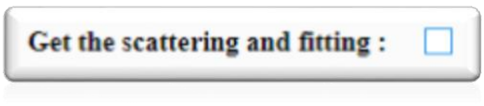

Figure 10: Scattering and Fitting Selection – An interface checkbox element

The algorithm then proceeds to plot the optimal fit and scattering graph within the "Edited Data" graph and displays the results under the "Fit Data Set" section.

With these steps, the results are successfully obtained, showcasing the application's capability to seamlessly integrate data manipulation, parameter setting, and fitting processes to produce and display the fitting and scattering data comprehensively. This streamlined approach facilitates an intuitive and efficient analysis workflow, enabling users to derive meaningful insights from their data with ease.

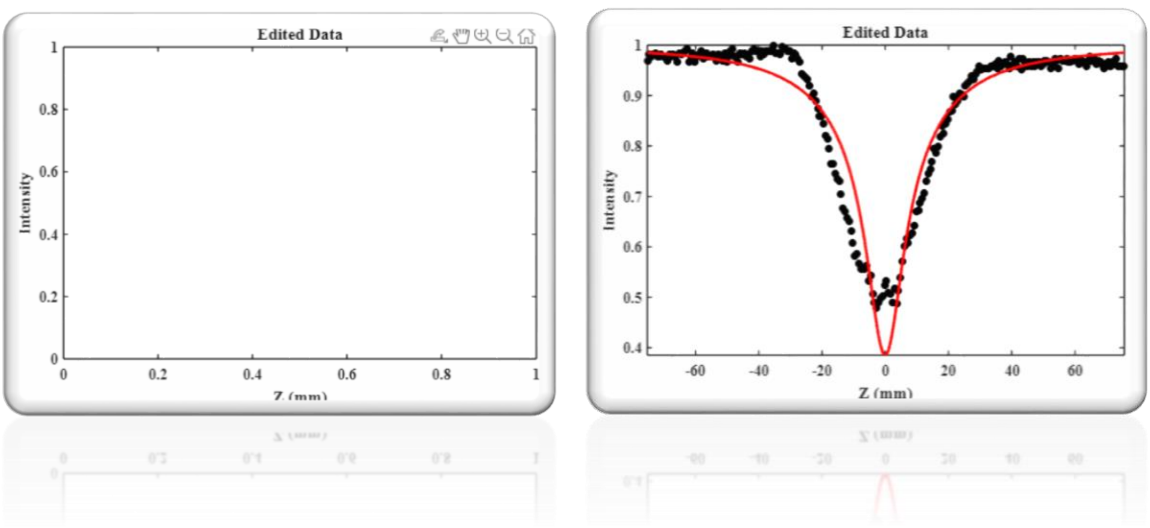

Figure 11: Edited Data Graphs – The left graph displays an empty plot titled "Edited Data", prepared for data visualization. The right graph shows intensity data as a function of Z (mm), with a fitted curve overlaid on the scatter plot, demonstrating the results

Once the fitting process is complete, the coefficient of determination, R^2 , which illustrates the compatibility between the scattering and fitting data, can be found in the lower right corner of the application. This R^2 value is updated upon the completion of the fitting process, providing a quantitative measure of how well the fitted curve matches the original data points.

Figure 12: Coefficient of Determination Display

The context menu may be accessed by right-clicking on the chart. Within this menu, adjustments to the axis titles and chart title can be made. This context menu serves as a portal to various properties of the chart, typically initiated by a right-click action. It provides a convenient means to modify

Figure 13: Chart's Context Menu

After completing the data import and manipulation process, and once the fitting curve has been applied to your dataset, you will have a comprehensive set of data ready to be utilized for further analysis, reporting, or presentation. To facilitate this transition, the application provides an "Excel Export" feature,

Figure 14: The button is used to export all processed data, including the original dataset, the manipulated entries, and the results of the fitting analysis, to an Excel file for further use and sharing.

3.7. Comprehensive Analysis and Export Features

4. APPLICATION AND RESULTS

4.1. Application Scenarios

4.2. Analysis of Results

4.3. Case Study

5. CONCLUSION

REFERENCES

ATTACHMENTS

BIOGRAPHY

Muhammed was born in Istanbul in the year 2000. He spent his childhood and teenage years and completed his primary, secondary, and high school education in Sariyer, İstanbul. In 2018, he commenced his studies in Physics Engineering at Istanbul Technical University, where he had the opportunity to merge theoretical knowledge with practical application.

Additionally, he participated in the Erasmus exchange program at Umeå University in Sweden, in the third year of the study, further broadening his academic and cultural perspectives.

During his university studies, Muhammed gained professional experience by working as a full-stack web developer and system analyst at Turkish Airlines and Amadeus IT Service. These experiences helped enhance his passion and skills in technology and software.

Currently, in the final year of his undergraduate degree, he is engaged in significant research in the field of optics, collaborating with his advisor, Assoc. Dr. Murat Erdem.