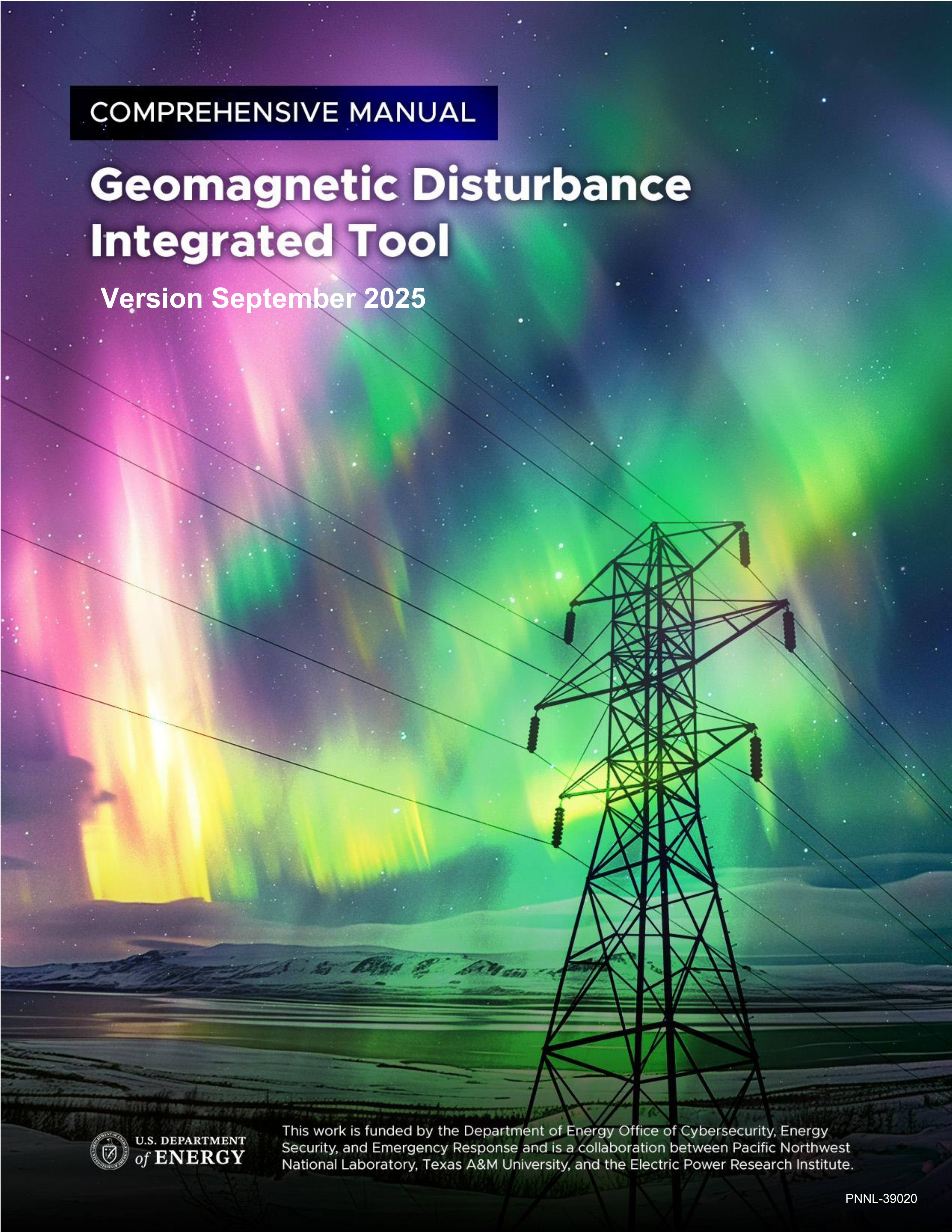

COMPREHENSIVE MANUAL

Geomagnetic Disturbance Integrated Tool

Version September 2025

U.S. DEPARTMENT of ENERGY

This work is funded by the Department of Energy Office of Cybersecurity, Energy Security, and Emergency Response and is a collaboration between Pacific Northwest National Laboratory, Texas A&M University, and the Electric Power Research Institute.

PNNL-39020

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1. (Schultz, A., Pellerin, L., Bedrosian, P., Kelbert, A., Crosbie, J. (2020-2023). "USMTArray South Magnetotelluric Transfer Functions". doi:10.17611/DP/EMTF/USMTARRAY/SOUTH. Retrieved from the IRIS database on Dec 03, 2024)
2. (Kelbert, A., Kelbert, A., G.D. Egbert and A. Schultz (2011), IRIS DMC Data Services Products: EMTF, The Magnetotelluric Transfer Functions, https://doi.org/10.17611/DP/EMTF.1).

Contents

1.0 GRAPHICAL USER INTERFACE

1.1 Getting Started

- **Launching the Graphical User Interface (GUI)**: To open the Geomagnetic Integrated Tool (GeoIT) GUI, double-click the executable file located in the tool package at:
  - \GeoIT-GUI\GeoIT V-Sept2025.exe
- **Interface Overview:** This action will launch both the GUI window and a console window (see Figure 1).
- While the GUI includes its own log panel for basic activity tracking, the console window provides more detailed logging information that may be useful for troubleshooting or advanced monitoring.

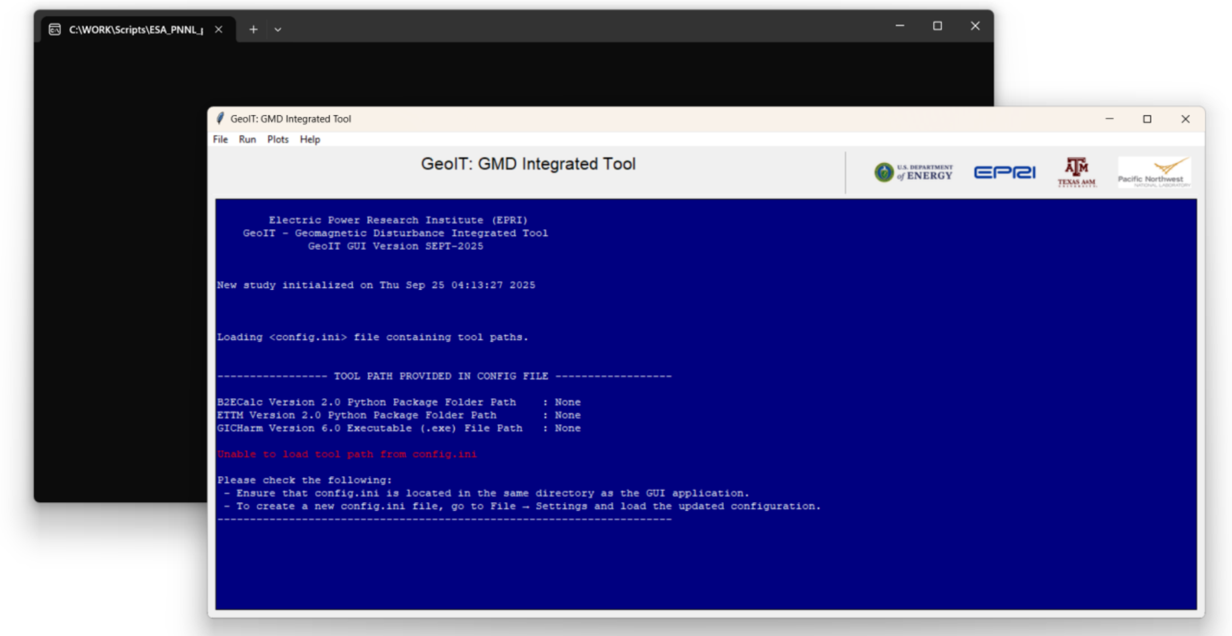

Figure 1. Getting Started—Dialogue Boxes as the Geomagnetic Integrated Tool (GeoIT) Graphical User Interface is Launched

1.2 GeoIT Home Screen

The GeoIT GUI base window (see Figure 2) includes the following components:

1. **Execution Log Window**: Displays real-time logs and status messages during tool execution.

- Menu Items:
  - File, Run, Plots, and Help
    - Help **Menu** Options:
      - **About**: Provides essential background information about the GeoIT tool.
      - **Documentation**: Links to all available documentation for the tool.

First-Time Use:

- **Initial Error Message**: When launching the GeoIT GUI for the first time on your computer, the **Execution Log Window** may display the following error: **"Unable to load tool path from config.ini"**
- **Loading Tool Paths**: First-time users must manually load the tool paths by navigating to **File** → **Settings**. Follow the on-screen instructions to populate the GeoIT configuration file with the available tool paths.
- **Saving Configuration**: Once the settings are loaded, a config.ini file is automatically saved. From this point onward, the GUI will use the saved tool paths unless the user chooses to reconfigure them via **File** → **Settings**.

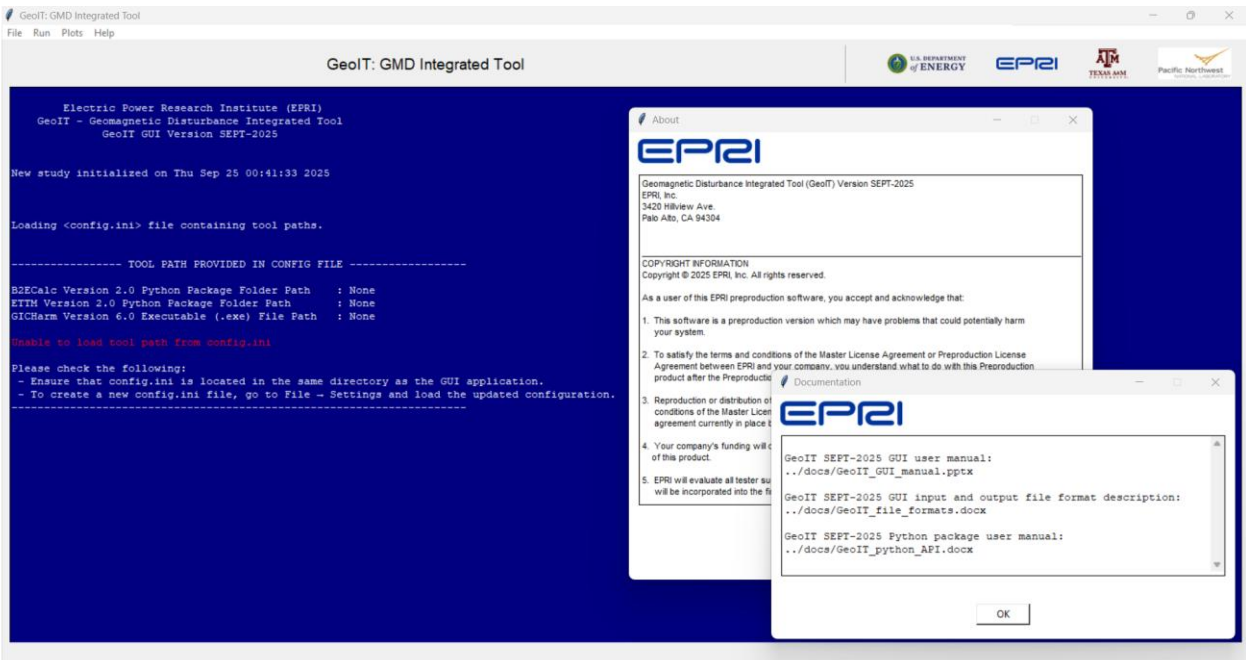

Figure 2. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Home Screen

1.3 File → Settings

To configure individual tool paths and dependencies follow the steps below (see Figure 3):

- Open Settings Window:
  - Click **File** → **Settings** to open the **Settings** window.
- Enter Tool Paths: Provide the paths for the following tool packages or executables. You can either enter the full path manually or click **Browse** to select from your directory.
  - B2ECalc Version 2.0 Python Package Folder Path
    - Path to the B2ECalc Python package. Screenshot shows folder contents.
  - **Register PowerWorld SimAuto 24**
  - PowerWorld SimAuto Registration Guide: https://www.powerworld.com/knowledge-base/registering-simauto

– **Electric Power Research Institute's Transformer Thermal Modeling (ETTM) Version 2.0 Python Package Folder Path**
  - Path to the ETTM Python package. Screenshot shows folder contents.
– **GICHarm Version 6.0 Executable (.exe) File Path**
  - Path to the GICHarm executable (GIC_harm_cmd.exe). Screenshot shows file location.
  - Note: This step must be completed to enable access to individual tool module options within the GUI.

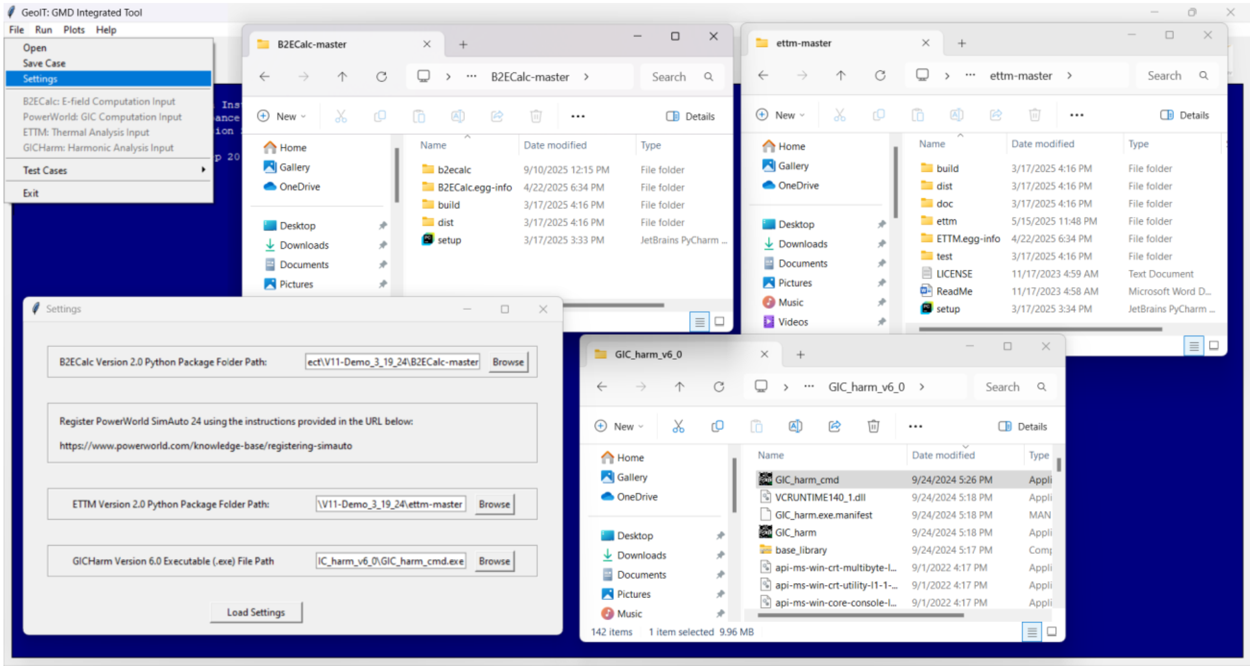

Figure 3. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate File → Settings

1.4 File → B2ECalc: E-field Computation Input

To open the input window for E-field computation using the B2ECalc module follow the steps below (see Figure 4):

- Navigate to **File** → **B2ECalc: E-field Computation Input**

Input Fields:

- **Time-Varying Field Data (IAGA 2002 Format):**
  – Under **Geomagnetic Field Input**, enter the full path of the geomagnetic field data file in IAGA 2002 format, or click **Browse** to select from your directory. Refer to GeoIT_file_formats.docx for details on the file format.
- **Earth Model Input:** Select one of the following surface impedance or transfer function options:
  – Fernberg 1-D conductivity model.

– **Updated 1-D response** transfer functions (RTFs).

– **Non-uniform (3-D) response**: USArray/USMTArray electromagnetic transfer functions.

- **Geographic Coordinates:** To define a uniform grid of geographic coordinates, provide the following values:

  – **From Longitude**: Longitude (in degrees) of the lower-left corner of the grid. Must be between −180 and 180.

  – **From Latitude**: Latitude (in degrees) of the lower-left corner of the grid. Must be between −90 and 90.

  – **Longitude Spacing**: Spacing (in degrees) between longitudes. Must be ≥ 0.1 and ≤ 360.

  – **Latitude Spacing**: Spacing (in degrees) between latitudes. Must be ≥ 0.1 and ≤ 180.

  – **Number of Longitudes**: Total number of longitudes in the grid. Must be a natural number.

  – **Number of Latitudes**: Total number of latitudes in the grid. Must be a natural number.

- Based on the above inputs, clicking **Plot Coordinates on US map** button will display the uniform grid of E-field evaluation coordinates on a map of the United States. For more advanced mapping, use **Plots → Map Plots → E-field Coordinate Map**.

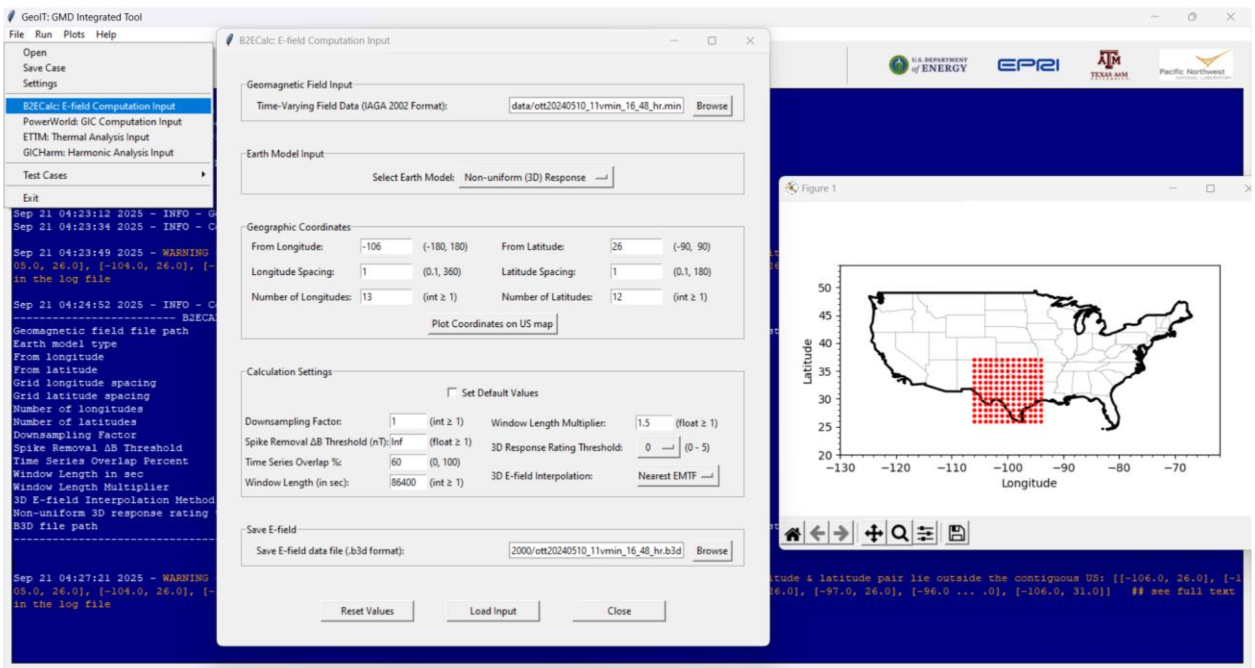

Figure 4. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate File → B2ECalc: E-field Computation Input

1.5 File → B2ECalc: E-field Computation Input (Continued)

- **Calculation Settings**: These settings allow modification of the computation algorithm parameters (see Figure 5):

  – **Set Default Values**: Resets all calculation settings to default.

- **Downsampling Factor**: Downsamples the input geomagnetic field data. Example: A factor of 2 changes a 1-second time series to 2 seconds. Must be a natural number.
- **Spike Removal ΔB Threshold (nT):** Removes data points where ΔB (difference between consecutive samples) exceeds the user-defined threshold.
- **Time Series Overlap (%)**: Percentage overlap between time series segments.
- **Window Length (sec)**: Length of each time series segment. Must be a natural number and ≤ total input data length.
- **Window Length Multiplier**: Multiplier for padding time series segments. Must be ≥ 1.
- **3-D Response Rating Threshold**: Filters electromagnetic transfer function (EMTF) impedances based on quality rating. Only those above the threshold are used for E-field computation.
- **3-D E-field Interpolation**: Sets the interpolation method for determining the E-field values at each location in the geographic coordinate grid. Applicable only for non-uniform E-fields. Choose one:
  - **Nearest EMTF**: Assigns the E-field value from the nearest magnetotelluric survey station.
  - **Inverse Distance Weighted Interpolation**: Uses Delaunay triangulation to find three nearby survey stations and applies inverse distance weighted (IDW) interpolation.

- **Save E-field Data File (.b3d format):** Enter the full path to save the E-field output in B3D format, or click **Browse**. Refer to GeoIT_file_formats.docx for format details.
- Control buttons:
  - **Reset Values**: Clears all input fields.
  - **Load Input**: Loads the input into the tool's working memory.
  - **Close**: Closes the input window.

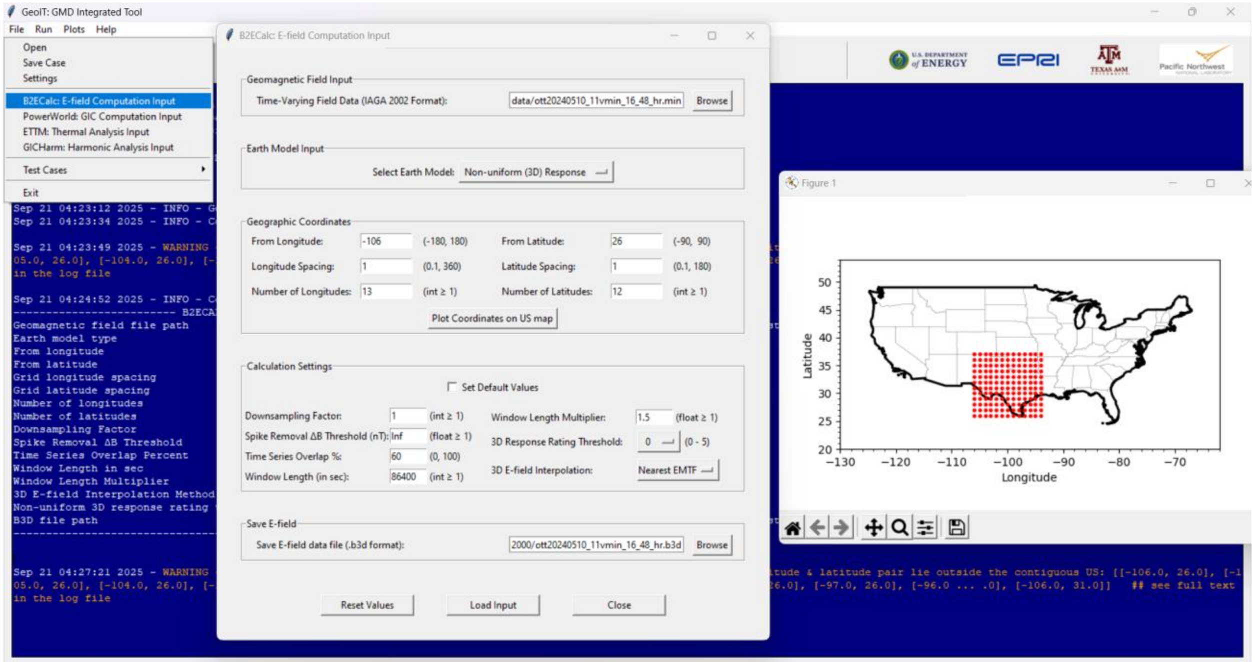

Figure 5. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate File → B2ECalc: E-field Computation Input (Continued)

1.6 File → PowerWorld: Geomagnetically Induced Currents (GIC) Computation Input

To configure and run GIC computations using the PowerWorld module follow the steps below (see Figure 6):

- Navigate to File → PowerWorld: GIC Computation Input to open the input window.

Input Fields:

- **Network Model Input:** Enter the full **PowerWorld Network Data Filepath (.pwb format)**, or click **Browse** to select from your directory. Refer to GeoIT_file_formats.docx for details on the required file format.
- **Geoelectric Field Input (Select One):** Check one of the following options:
  - **E-field From B3D File Saved Internally by the GeoIT GUI B2ECalc Module** uses the B3D file path specified in the Save E-field field of the B2ECalc input window.
  - **External B3D file path**: Allows use of externally computed E-field data.
- **Time Range Input** Specify the time range for which GICs are to be calculated:
  - Start Time (sec), End Time (sec) and Time Step (sec)
- **Save Results (Optional):** Check the **Save GIC results** box to save the output in pickle (.pkl) format. Enter the full path to the output file or click **Browse** to select a location. Refer to GeoIT_file_formats.docx for details on the output format.
- Controls Buttons:
  - **Reset Values**: Clears all input fields.
  - **Load Input**: Loads the input into the tool's working memory.

– **Close**: Closes the input window.

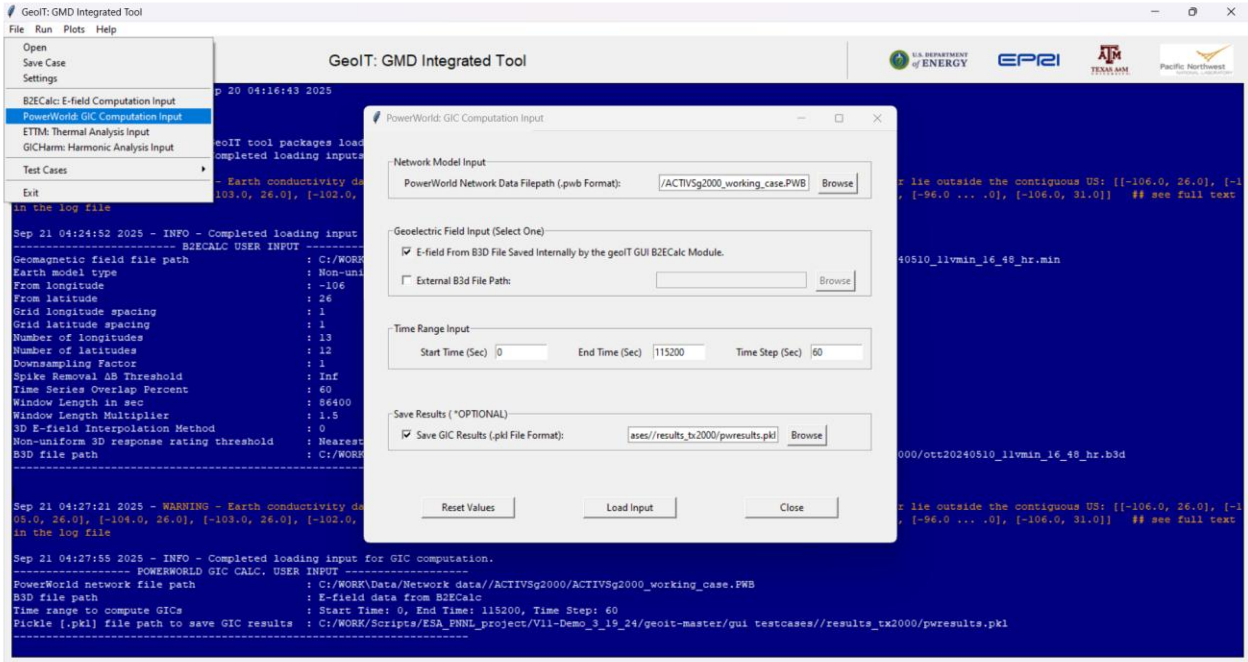

Figure 6. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate File → PowerWorld: GIC Computation Input

1.7 File → ETTM: Thermal Analysis Input

To configure and run transformer thermal analysis using the ETTM module follow the steps below (see Figure 7):

- Navigate to **File** → **ETTM: Thermal Analysis Input** to open the input window.

Input Fields:

- **ETTM Batch Input**: Enter the path to the ETTM batch analysis input Excel file, or click **Browse** to select from your directory. Refer to GeoIT_file_formats.docx for details on the required file format.
- **GIC Signature Input (Select One):** Check one of the following options:
  - – **GICs Calculated Internally Using the GeoIT GUI PowerWorld Module** uses GIC data stored in the tool’s working memory from the PowerWorld module.
  - – **Load External GIC (Options):**
    - ○ **GIC Signature (.xlsx)**: Enter the path to the external GIC signature Excel file or click **Browse**.
    - ○ **GeoIT GUI PowerWorld Module Output (.pkl)**: Enter the path to the previously saved PowerWorld results pickle file or click **Browse**.
- **Save Results (Optional):** Check the **Save ETTM Results to Directory** box to save all output files to a folder. Enter the folder path or click **Browse** to select the destination. Refer to GeoIT_file_formats.docx for details on the output file formats.

- Control buttons:
- **Reset Values**: Clears all input fields.
- **Load Input**: Loads the input into the tool's working memory.
- **Close**: Closes the input window.

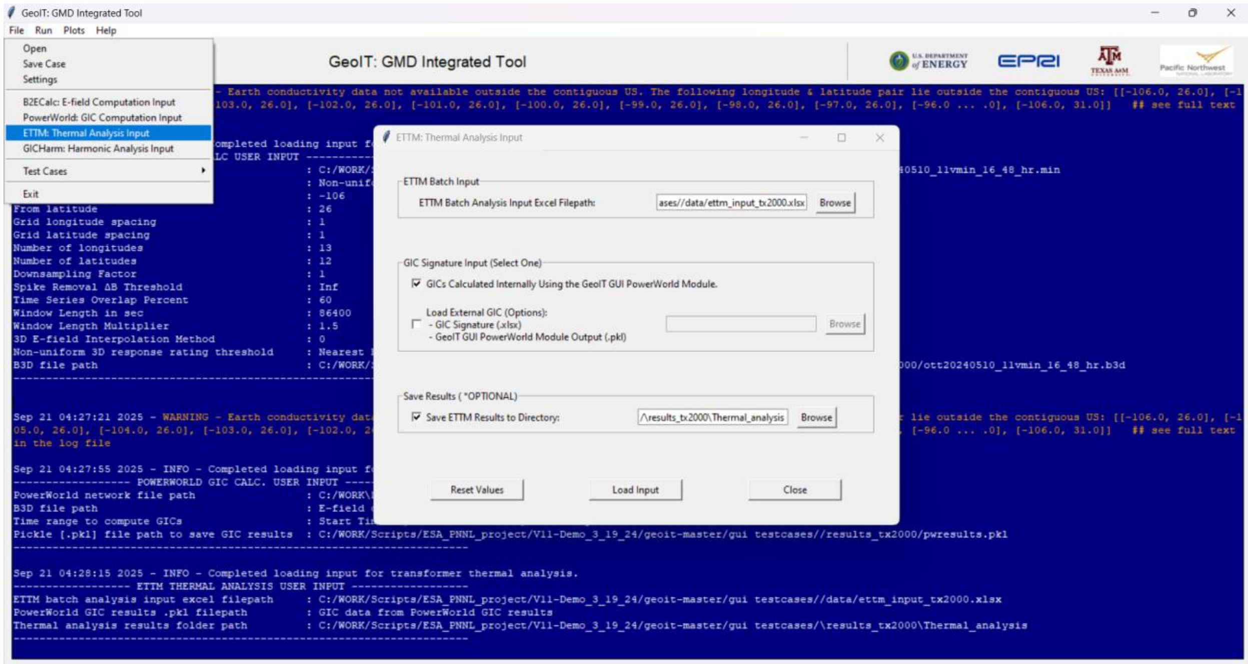

Figure 7. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate File → ETTM: Thermal Analysis Input

1.8 File → GICHarm: Harmonic Analysis Input

To configure and run harmonic analysis using the GICHarm module follow the steps below (see Figure 8):

- Navigate to **File → GICHarm: Harmonic Analysis Input** to open the input window

Input Fields:

- **Network Model Input**: Enter the path to the network model file in .dss format, or click **Browse** to select from your directory. Refer to GeoIT_file_formats.docx for details on the required file format.
- **GIC Scenario Input (Select One):** Check one of the following options:
  - **GICs Calculated Internally Using the GeoIT GUI PowerWorld Module** uses GIC data stored in the tool's working memory from the PowerWorld module.
  - **Load External GIC (Options):**
    - **GIC Scenario (.xlsx)**: Enter the path to the external GIC scenario Excel file or click **Browse**.
    - **GeoIT GUI PowerWorld Module Output (.pkl)**: Enter the path to the previously saved PowerWorld results pickle file or click **Browse**.

- **Time Samples**: Enter a comma-separated list of time samples for which harmonic analysis is to be performed. This field is not required if a GIC scenario Excel file is selected.
- **Save Results (Optional)**: Check the **Save GICHarm Results to Directory** box to save all output files to a folder. Enter the folder path or click **Browse** to select the destination. Refer to GeoIT_file_formats.docx for details on the output file formats.
- Control buttons:
  - **Reset Values**: Clears all input fields.
  - **Load Input**: Loads the input into the tool's working memory.
  - **Close**: Closes the input window.

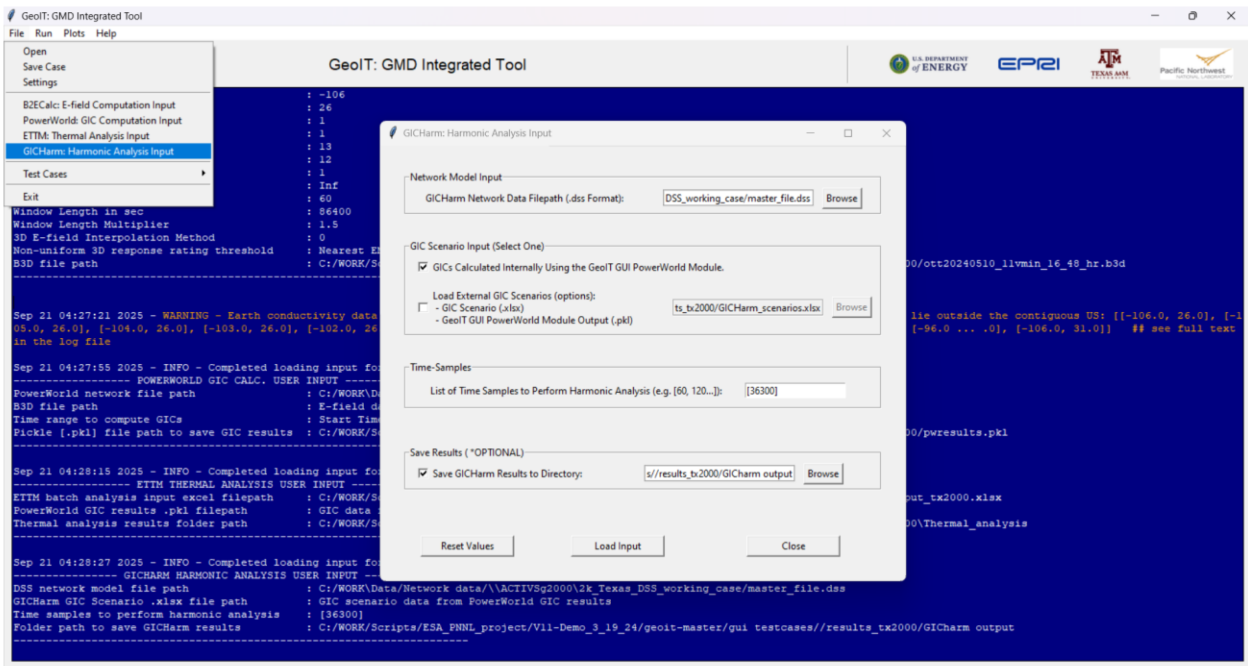

Figure 8. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate File → GICHarm: Harmonic Analysis Input

1.9 File → Save Case

This option allows users to save all input fields from every input window into a single JSON file.

Steps to Save a Case (Figure 9):

- Click **File** → **Save Case** to open the **Save GeoIT Case File** window. Enter a file name in the entry box.
- Click **Save** to store the case configuration. Refer to GeoIT_file_formats.docx for details on the JSON file format.

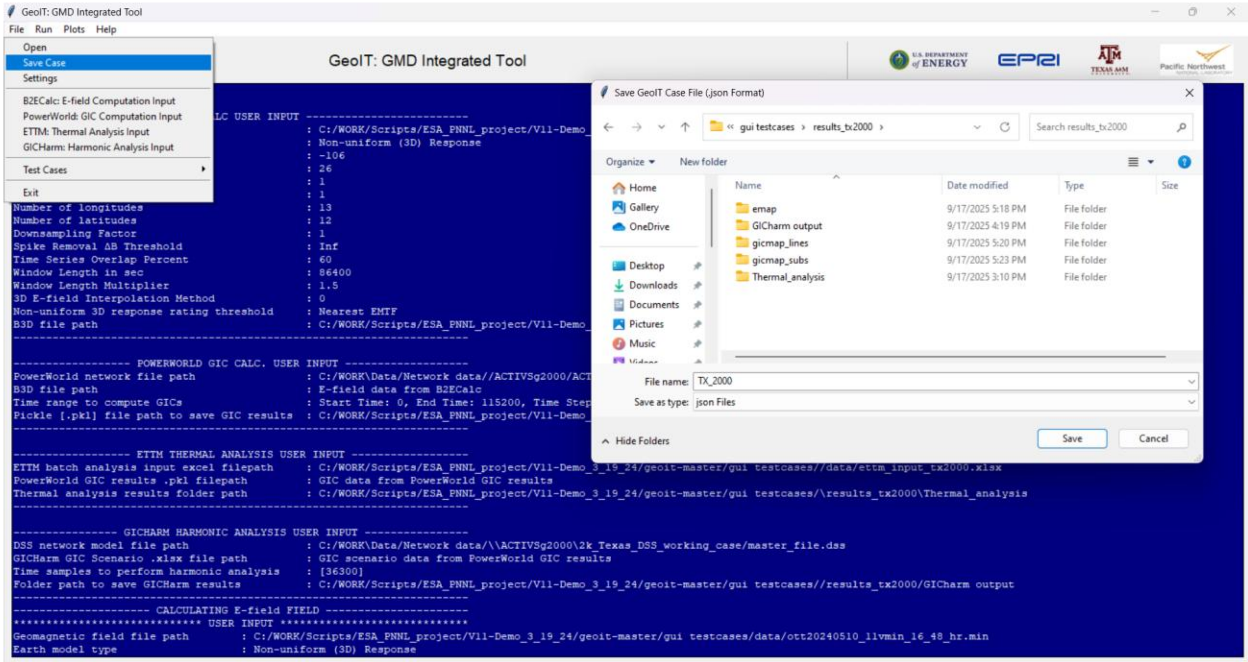

Figure 9. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate File → Save Case

1.10 File → Open Case

Navigating from File → Open Case (see Figure 10) allows users to load a previously saved JSON file to automatically populate all input fields across the tool input windows.

Steps to Open a Case:

- Click File → Open Case to open the Open GeoIT Case File window.
- Select a previously saved JSON file from your directory.
- Click Open to load the case configuration into all input windows. Refer to GeoIT_file_formats.docx for details on the JSON file format.

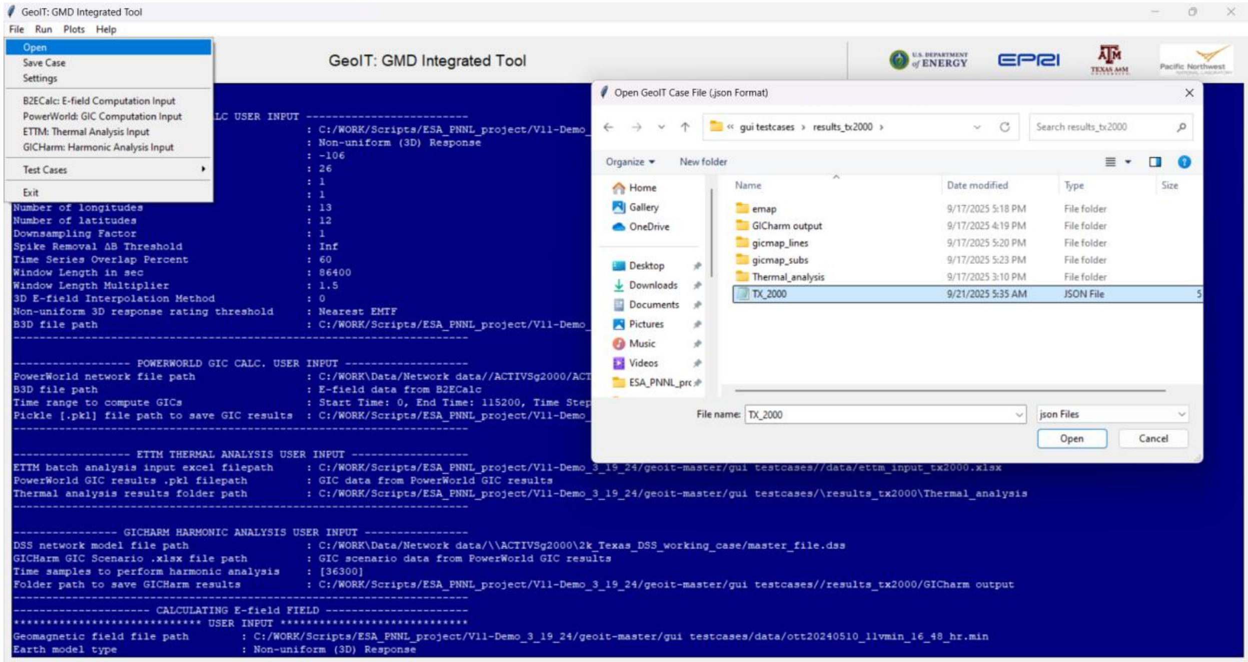

Figure 10. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate File → Open Case

1.11 Run → GMD Analysis

Navigating from Run → GMD Analysis (see Figure 11) allows users to perform a GMD analysis in sequence by selecting individual tool modules.

Steps to Run GMD Analysis:

- Click **Run** → **GMD Analysis** to open the **GMD Analysis** window.
- In the window, check the boxes for the tools you want to include in the analysis:
  - **Run E-field Computation**
  - **Run GIC Computation**
  - **Run Transformer Thermal Analysis**
  - **Run Harmonic Analysis**
- Click **Run GMD Analysis** to begin the computation.

Notes and Dependencies:

- If **Run GIC Computation** is checked but **Run E-field Computation** is unchecked:
  - You must provide an external B3D input file in the **PowerWorld: GIC Computation Input** window.
- If **Run Transformer Thermal Analysis** is checked but **Run GIC Computation** is unchecked:
  - You must load an external GIC input file in the **ETTM: Thermal Analysis Input** window.
- If **Run Harmonic Analysis** is checked but **Run GIC Computation** is unchecked:

- You must load an external GIC input file in the **GICHarm: Harmonic Analysis Input** window.

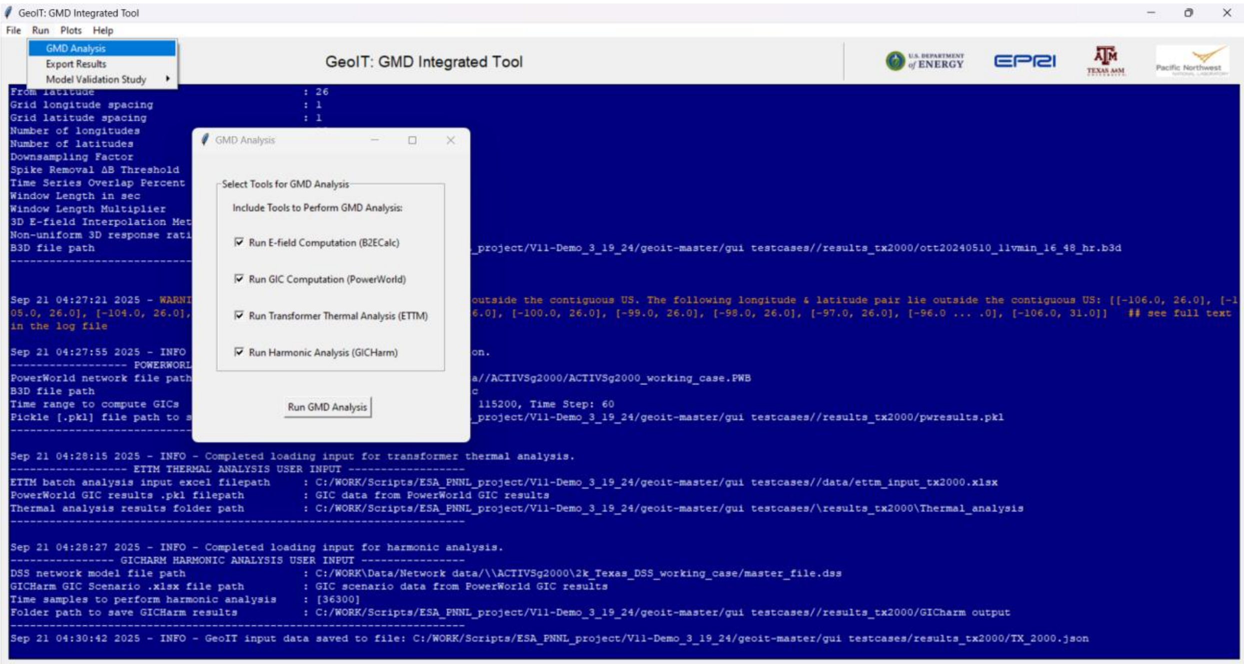

Figure 11. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Run → GMD Analysis

1.12 Autosaved Results

Each tool saves its results in directories specified in their respective input windows via autosaved results (Figure 12).

The screenshot referenced shows the following:

- Top-left: B3D output file generated using the **B2ECalc** module.
- Top-right: Pickle (.pkl) output file generated using the **GeoIT PowerWorld** module.
- Bottom-left: Thermal analysis output files generated using **ETTM**.
- Bottom-right: Harmonic analysis results folder generated using **GICHarm**.

Viewing Results in Excel Format:

- To view results from all tools in Excel format: Use the **Run** → **Export Result** option. The Excel files generated using **Export Result** are intended for viewing only. They cannot be used as input for subsequent tool runs.
- Performance Consideration**:** The file formats autosaved directly by each tool (e.g., B3D, .pkl) are optimized for computation speed. The Excel exports are optimized for human readability and analysis.

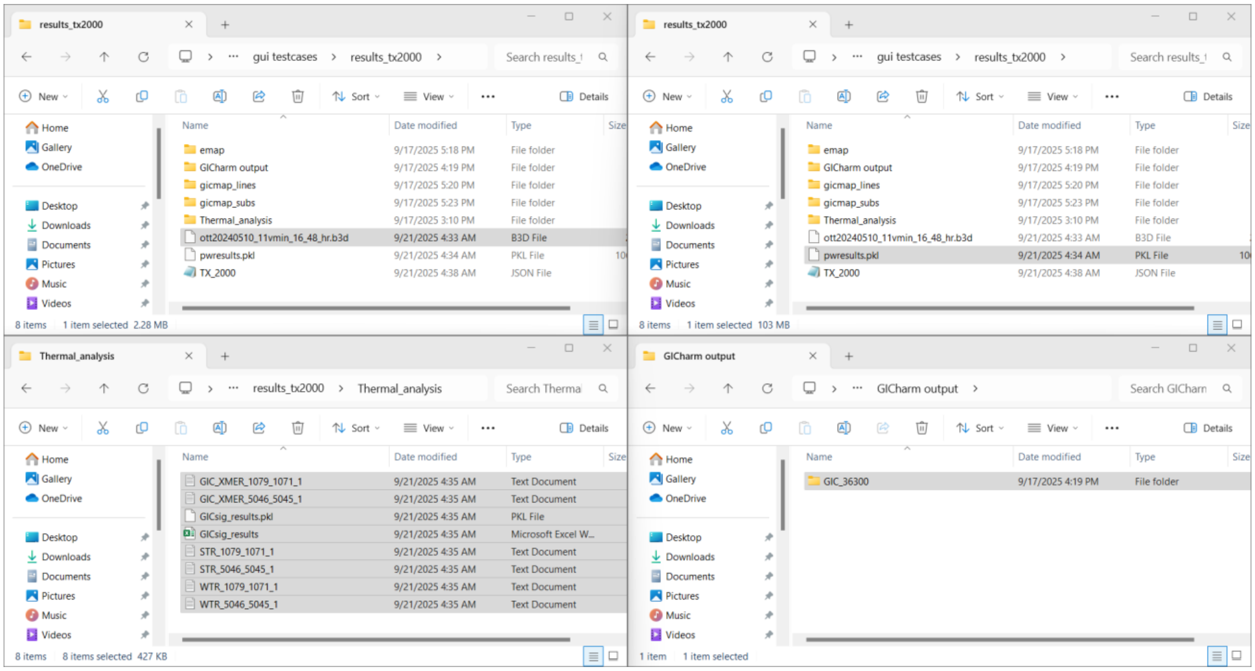

Figure 12. Autosaved Results on the Geomagnetic Integrated Tool (GeoIT) Graphical User Interface

1.13 Run → Export Results

Export Results feature allows users to export results from each tool in Excel format for easy viewing and analysis (Figure 13).

Steps to Export Results:

- Click Run → Export Result to open the Export Result window.
- Select the desired result type from the dropdown menu corresponding to each tool.
- Click Export to generate Excel files.

Available Export Options

- B2ECalc Results
  - Geomagnetic Field Input (nT)
  - Geoelectric Field (East: mV/km)
  - Geoelectric Field (North: mV/km)
  - Geoelectric Field (Mag: mV/km)
- PowerWorld Results
  - Transformer Neutral GICs
  - Transformer Effective GICs
  - Transmission Line GICs
  - Substation Neutral GICs

- ETTM Results: Winding Temperature and Structural Temperature
- GICHarm Results: Busbar THDv

Note: The Excel results generated here are intended for viewing only. They cannot be used as input for subsequent tool runs. Computation-optimized formats (e.g., B3D, .pkl) are saved automatically in respective directories based on respective tool inputs.

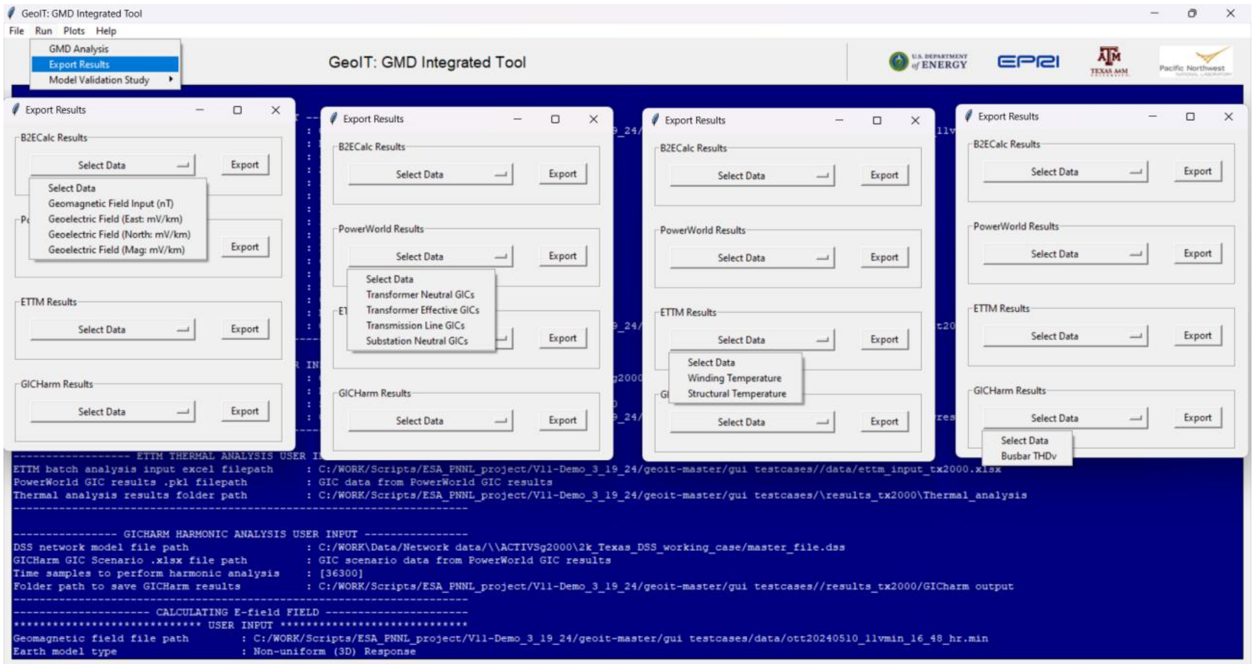

Figure 13. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Run → Export Results

1.14 Run → Export Results (Example)

This section illustrates how to use the Export Results feature with a practical example (Figure 14).

Example Workflow:

- Open the Export Results window by clicking Run → Export Result.
- From the dropdown menus, select one or more result types from any of the available tools. Example Selections (as shown in the screenshot):
  - Geoelectric Field (Mag: mV/km) — from B2ECalc
  - Transformer Neutral GICs — from PowerWorld
  - Winding Temperature — from ETTM
  - Busbar THDv — from GICHarm
- Click Export to generate the corresponding Excel files.

The screenshot shows the Excel files generated using the above selections displayed behind the **Export Results** window.

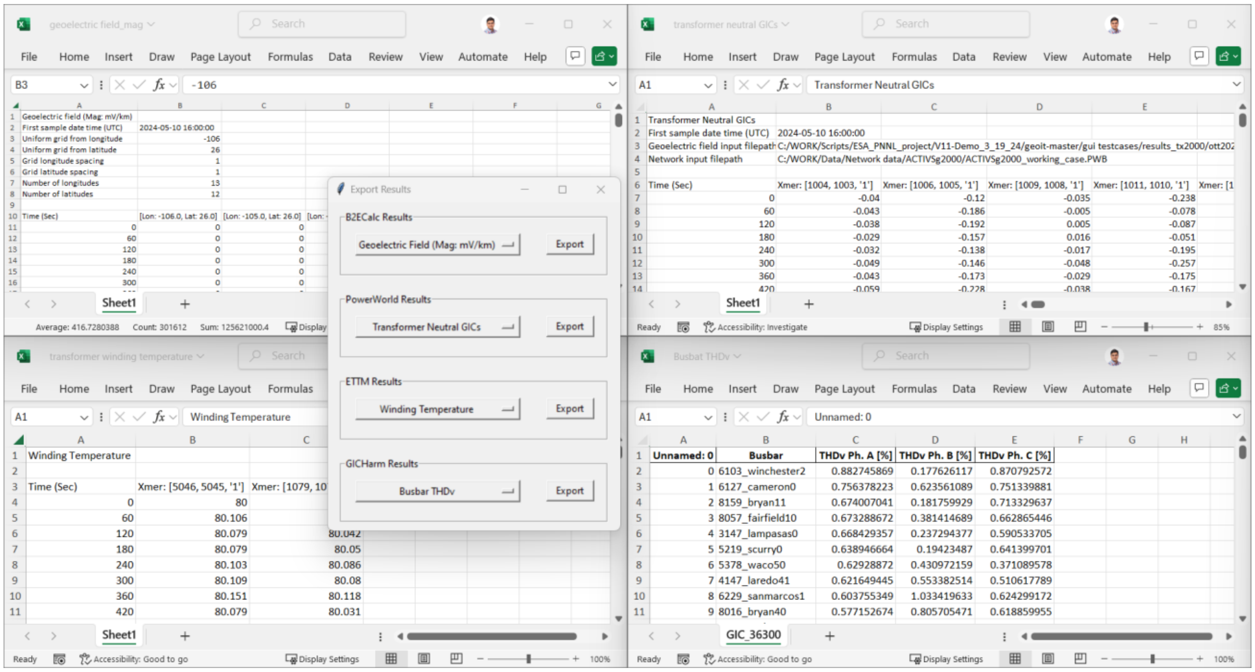

Figure 14. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Run → Export Results (Example)

1.15 Plots → Time-Series Plots

Navigating from Plots → Time-Series Plots (see Figure 15) allows users to perform a GMD analysis in sequence by selecting individual tool modules.

This feature allows users to generate time-series plots for various output variables from each tool*.

Steps to access are as below:

- Click Plots → Time-Series Plots to open the Time-Series Plots input window.

B2ECalc Plots: From the dropdown menu, select one of the following options:

- Geomagnetic Field Input (nT):
  - Click Plot to generate the time-series plot.
- Geoelectric Field (mV/km):
  - Enter the **Longitude** and **Latitude** of the location** for which the E-field must be plotted.
  - Click Plot.

* Exception is GICHarm which does not produce time-series results.

** The selected coordinate must lie within the region defined by the Geographic Coordinates input in the B2ECalc: E-field Computation Input window.

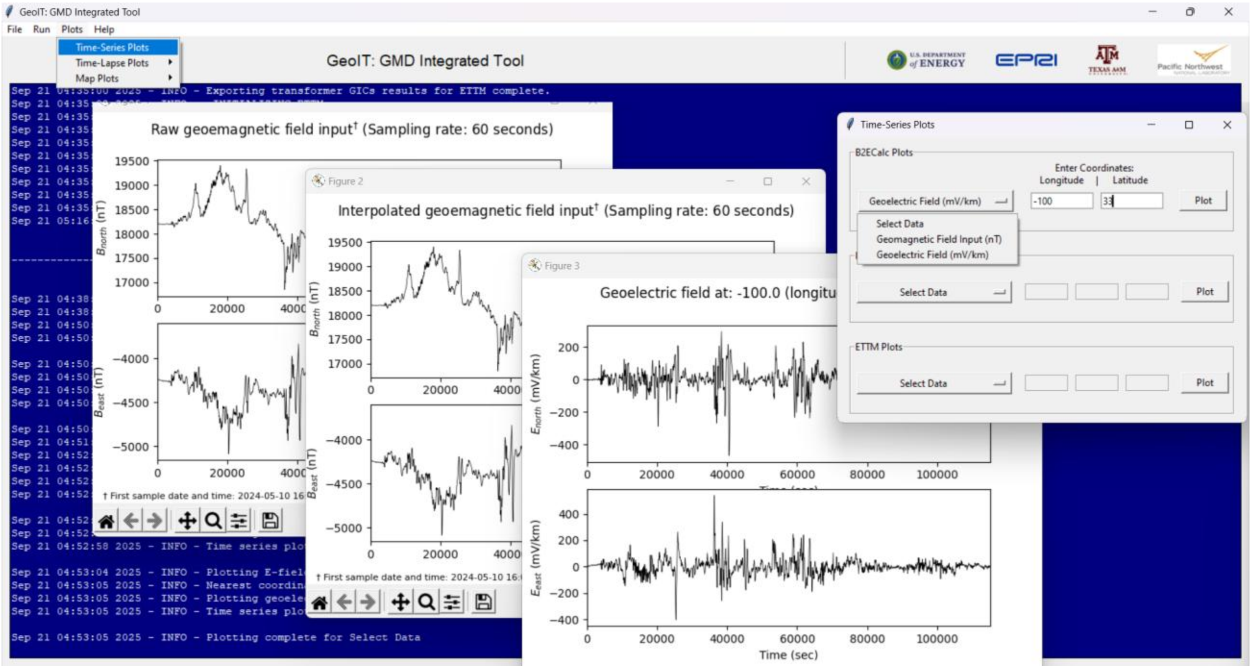

Figure 15. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Time-Series Plots

1.16 Plots → Time-Series Plots (Continued)

Refer to Figure 16.

PowerWorld Plots: From the dropdown menu, select one of the following options:

- **Transformer Neutral GICs**: Enter transformer **From Bus*, To bus*** and **Circuit*.**
- **Transformer Effective GICs**: Enter transformer **From Bus*, To bus*** and **Circuit*.**
- **Transmission Line GICs**: Enter line **From Bus*, To bus*** and **Circuit*.**
- **Substation Neutral GICs**: Enter **Substation Number*.**

Click Plot to generate the time-series visualization.

* Use the PowerWorld Simulator **Model Explorer** to obtain all necessary network component information.

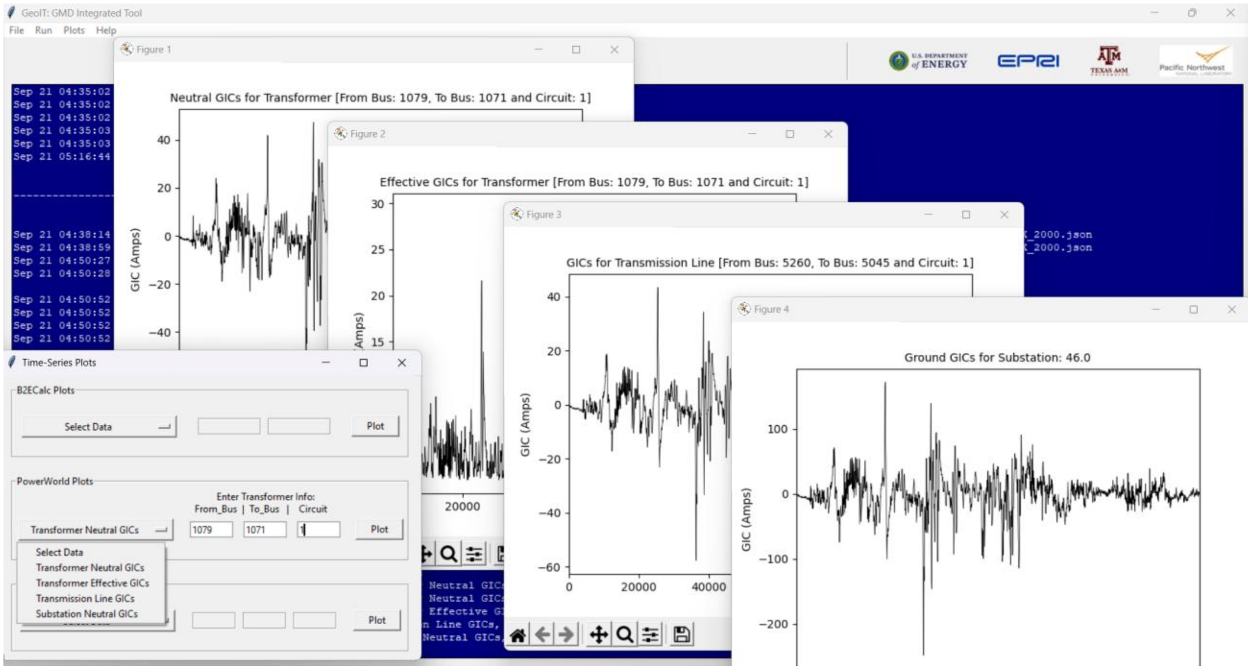

Figure 16. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Time-Series Plots (Continued)

1.17 Plots → Time-Series Plots (Continued)

Refer to Figure 17.

ETTM Plots: From the dropdown menu, select one of the following options:

- **Winding Asymptotic Response**
- **Winding Temperature Response**
- **Structural Asymptotic Response**
- **Structural Temperature Response**
- **Winding Temperature**
- **Structural Temperature**

Then enter:

- **From Bus*, To Bus*, Circuit***

Click **Plot** to generate the time-series visualization.

* Use the PowerWorld Simulator Model Explorer to obtain transformer identifiers.

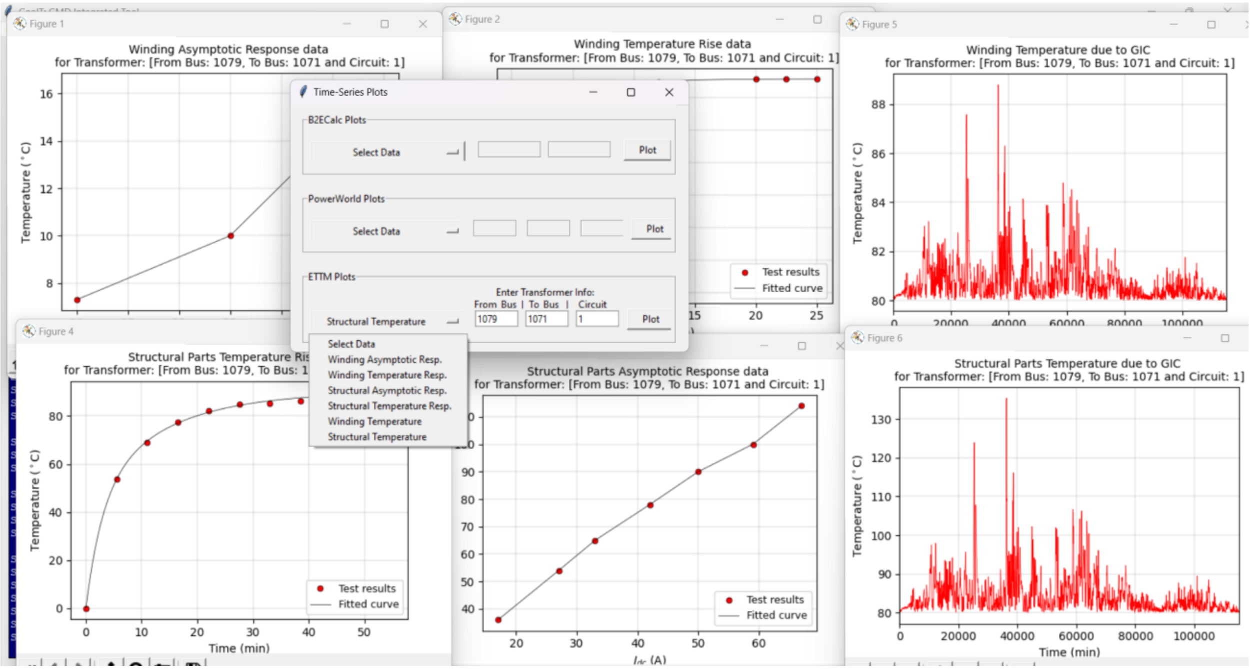

Figure 17. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Time-Series Plots (Continued)

1.18 Plots → Time-Lapse Plots

Navigating from Plots → Time-Lapse Plots (see Figure 18) allows users to perform a GMD analysis in sequence by selecting individual tool modules.

This feature enables visualization of output variables that change both spatially and temporally across the U.S. map.

Accessing Time-Lapse Plot Options: Click on **Plots** → **Time-Lapse Plots** to view the available options:

- **Geoelectric Field Map**
- **Line GIC Map**
- **Substation GIC Map**

Each of these options opens a dedicated input window with specific configuration settings.

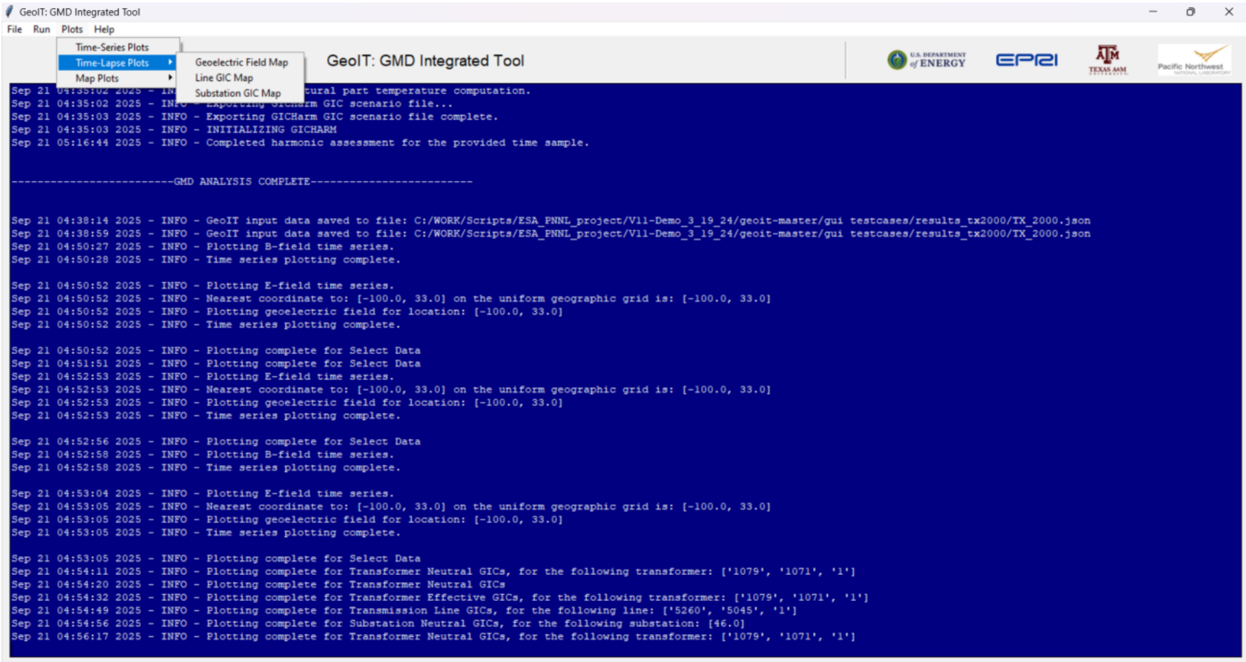

Figure 18. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Time-Lapse Plots

1.19 Plots → Time-Lapse Plots → Geoelectric Field Map

Click on **Plots** → **Time-Lapse Plots** → **Geoelectric Field Map** to open the input window (see Figure 19).

In this map plot, each region is color-coded by field magnitude, with quivers indicating field direction.

The input options are described below:

- Select Plot Type:
  - **Physiographic**: Plots the geoelectric field map for each physiographic region.
  - **Uniform Grid**: Plots the geoelectric field map using the E-field values at each uniform grid location.
- Colorbar Normalization:
  - **Logarithmic**: Color changes based on the logarithm of the field value.
  - **Linear**: Color changes linearly with field value.
- **E-field Unit**: Choose between **mV/km** or **V/km**.
- **Colorbar Ticks, Comma separated**: Enter a list of E-field values to define the colorbar ticks.
- **Quiver E-field Threshold**: Minimum field value required to display direction quivers.
- **Quiver Scaling Factor**: Float value to adjust the size of quivers.
- **Time Range, [Start Time, End Time]**: Specify the time window for plotting.

- **Generate E-field Time-lapse Images**: Click to generate the images.
- **Folder Path to Save E-field Time-Lapse Images**: Click **Browse** to select the save location.
- **Output Type**: Choose to generate **Images**, **Video**, or **Both**.
- **Animation Video Frames Per Sec**: Set the frame rate for video animation.
- **Save Time-lapse Images/Video**: Click to save the generated output.

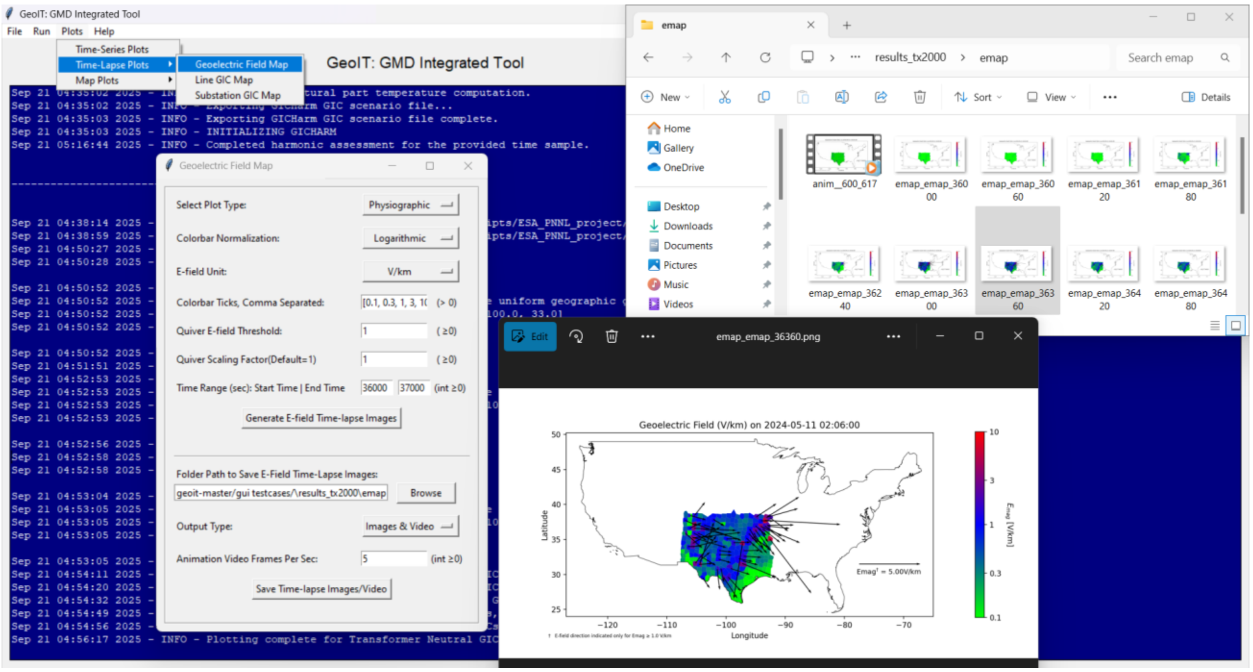

Figure 19. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Time-Lapse Plots → Geoelectric Field Map

1.20 Plots → Time-Lapse Plots → Line GIC Map

Click on **Plots** → **Time-Lapse Plots** → **Line GIC Map** to open the input window (see Figure 20).

This feature visualizes the magnitude of GICs in transmission lines over time using a color-coded map.

Input Options:

- **Colorbar Normalization:**
  - **Logarithmic**: Colors change based on the logarithm of the GIC value.
  - **Linear**: Colors change linearly with GIC magnitude.
- **Colorbar Ticks, Comma Separated**: Enter a list of comma-separated GIC values to define the tick marks on the colorbar.
- **Time Range [Start Time, End Time]**: Specify the time window for which the map should be plotted.

- **Map Limits**: Define the plotting window on the US map by entering: **From Longitude, To Longitude, From Latitude** and **To Latitude**
- **Output Type**: Choose to generate **Images**, **Video**, or **Both**.
- **Animation Video Frames Per Sec**: Set the frame rate for video animation.
- **Folder Path to Save Line GIC Time-Lapse Images**: Click **Browse** to select the folder where the time-lapse images or video will be saved.
- **Generate Time-lapse Images/Video**: Click to save the generated output.

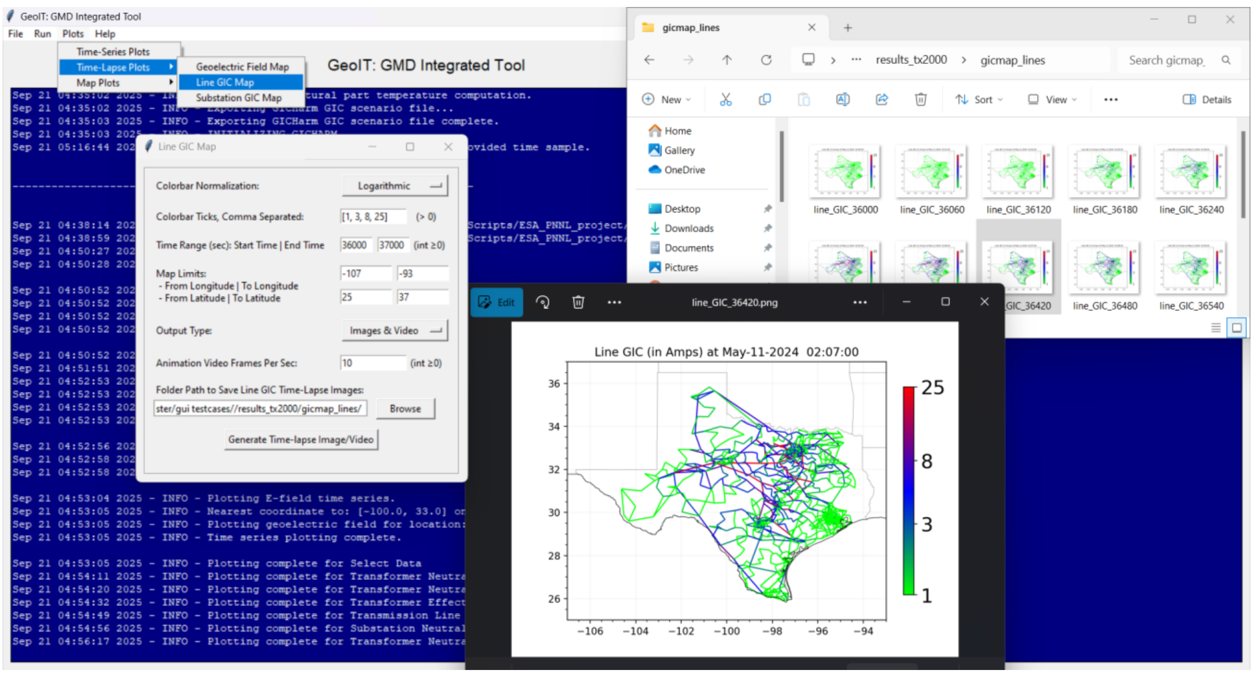

Figure 20. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Time-Lapse Plots → Line GIC Map

1.21 Plots → Time-Lapse Plots → Substation GIC Map

Click on **Plots** → **Time-Lapse Plots** → **Substation GIC Map** to open the input window (Figure 21).

This feature visualizes the magnitude of GICs at substations over time using red circle markers. The size of each circle represents the GIC magnitude.

Input Options:

- **Marker Scaling Factor:** A multiplier to scale the size of all circle markers in the plot.
- **Marker Reference GIC:** A reference GIC value used to define the legend marker size.
- **Legend Location:** Enter the **Longitude** and **Latitude** of the location where the legend should be displayed on the map.
- **Time Range [Start Time, End Time]:** Specify the time window for which the substation GIC map is to be plotted.

- **Map Limits**: Define the plotting window on the U.S. map by entering: **From Longitude, To Longitude, From Latitude** and **To Latitude**
- **Output Type**: Choose to generate **Images**, **Video**, or **Both**.
- **Animation Video Frames Per Sec:** Set the frame rate for the video animation.
- **Folder Path to Save Substation GIC Time-Lapse Images:** Click **Browse** to select the folder where the time-lapse images or video will be saved.
- **Generate Time-lapse Images/Video:** Click to save the generated output.

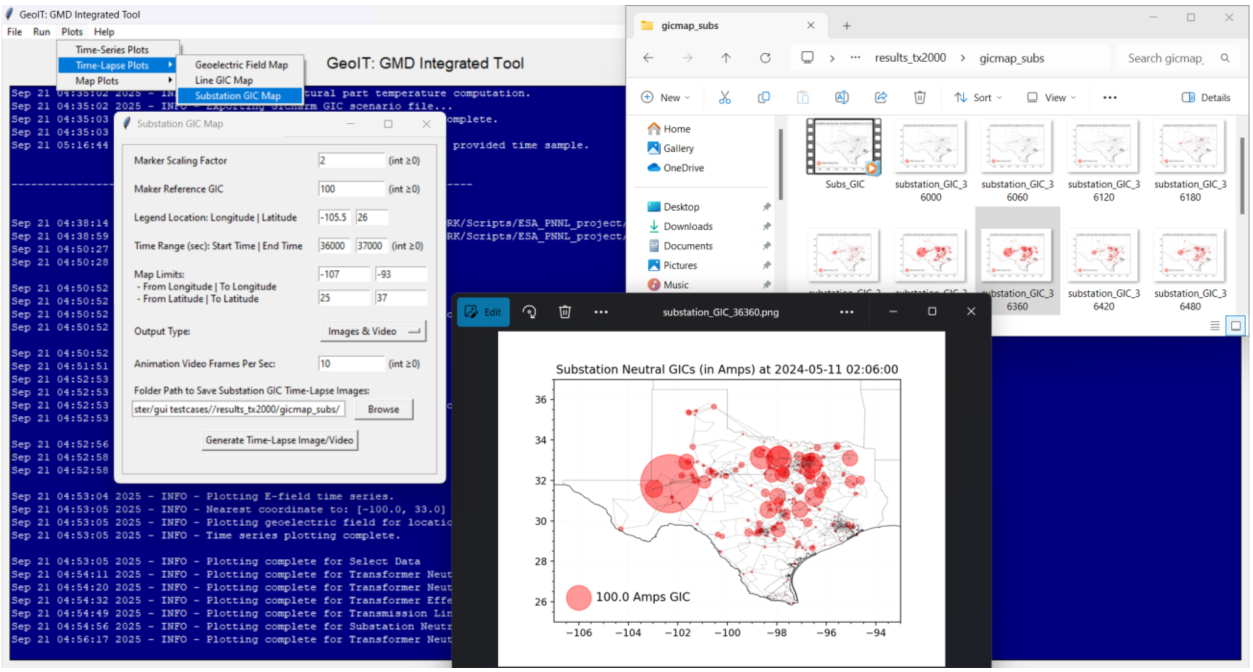

Figure 21. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Time-Lapse Plots → Substation GIC Map

1.22 Plots → Map Plots → E-field Coordinate Map

Click on **Plots** → **Map Plots** → **E-field Coordinate Map** to open the input window (see Figure 22).

Plot Feature Options:

- This feature allows users to visualize the uniform grid of E-field evaluation coordinates on a map of the United States, along with optional overlays for geological and survey data.

Check the boxes to include the following features in the map plot:

- **E-field Evaluation Coordinates:** Plots the uniform grid of coordinates based on inputs provided in the **Geographic Coordinates** section of the **B2ECalc: E-field Computation Input** window.
- **U.S. State Borders:** Adds State boundary lines to the map for geographic context.

- **Fernberg 1-D Conductivity Regions:** Overlays the physiographic regions defined by the Fernberg 1-D conductivity model.
- **Updated 1-D Response Regions:** Adds the updated 1-D ground response model physiographic regions to the map.
- **Non-uniform (3-D) Response Sites:** Displays all magnetotelluric survey station locations from the USArray, United States Magnetotelluric Array (USMTArray), and USMTArray-Conterminous United States (USMTArray-CONUS) projects. (updated April 2024).

Plotting the Map:

- After selecting the desired features, click the **Plot Coordinates** button to generate the map showing the uniform grid and overlays.

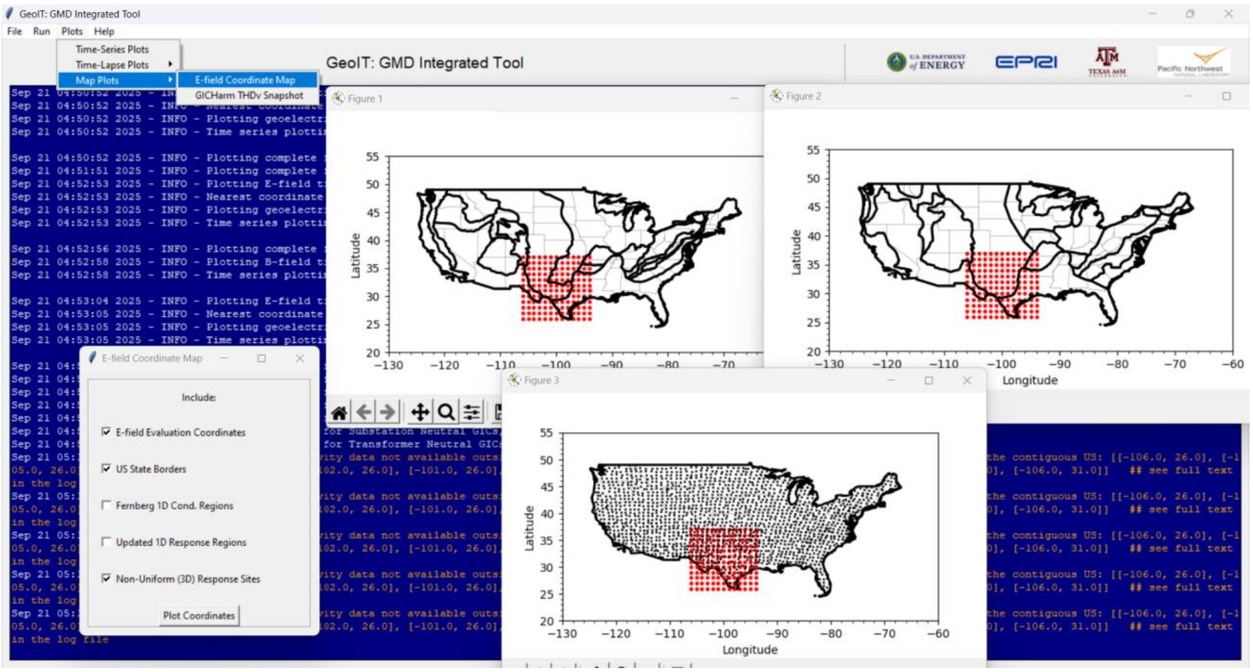

Figure 22. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Map Plots → E-field Coordinate Map

1.23 Plots → Map Plots → GICHarm THDv Snapshot

Click on **Plots** → **Map Plots** → **GICHarm THDv Snapshot** to open the input window (Figure 23).

This feature visualizes the Total Harmonic Distortion Voltage (THDv) at busbars using red circle markers. The size of each marker represents the magnitude of THDv.

Input Options:

- **Marker Scaling Factor:** A multiplier to scale the size of all circle markers in the plot.
- **Marker Reference THDv:** A reference THDv value used to define the legend marker size.

- Legend **Location:** Enter the **Longitude** and **Latitude** of the location where the legend should be displayed on the map.
- **Map Limits:** Define the plotting window on the US map by entering: **From Longitude, To Longitude, From Latitude** and **To Latitude.**
- **Phase Type:** Select the phase (**A**, **B**, or **C**) for which the THDv is to be plotted.
- **Open the thdv___Available_Busbars.csv File:** Click **Browse** to select the CSV file containing THDv data for available busbars.
- **Generate Snapshot:** Click this button to display the THDv snapshot plot.

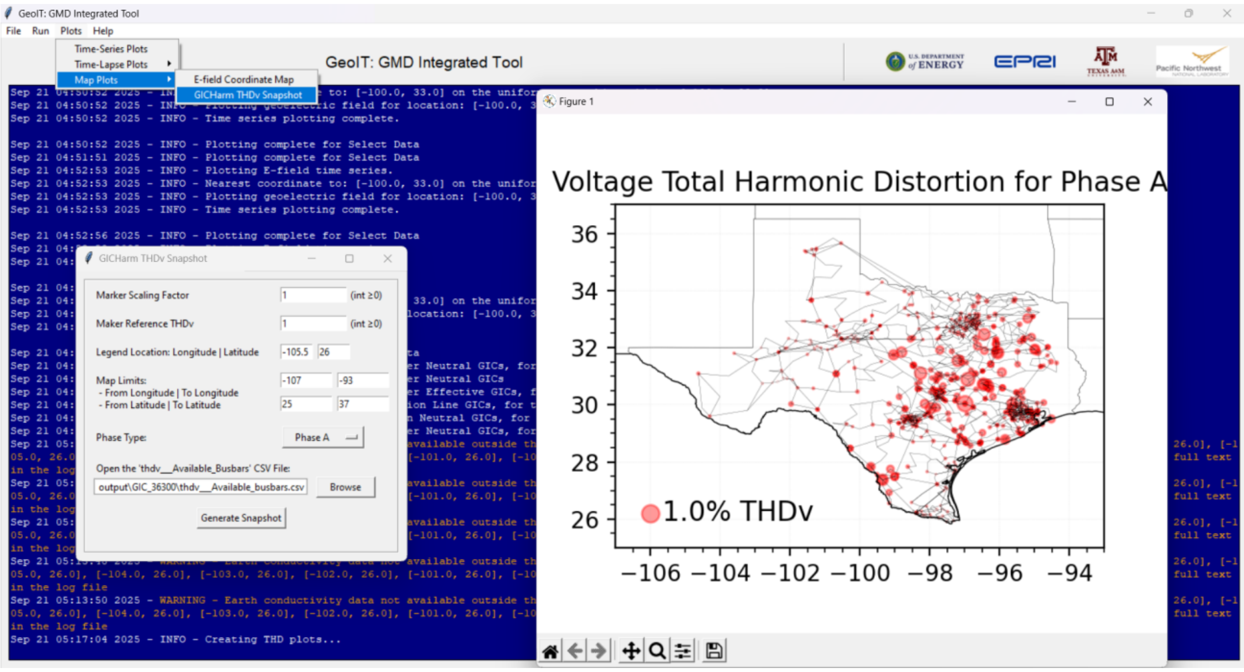

Figure 23. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Map Plots → GICHarm THDv Snapshot

1.24 Plots → Model Validation Study → GIC Comparison

To open the input window, navigate to **Plots** → **Model Validation Study** → **GIC Comparison** (Figure 24).

This feature allows users to compare calculated GICs with observed GIC data from the SUNBURST network.

Input Options:

- Load Calculated Transformer Neutral GICs:
  - **Browse for GeoIT PowerWorld GIC Output (.pkl)**: Click **Browse** to select the .pkl file containing GIC data generated by the PowerWorld module.
  - **Specify Transformer**: Enter the transformer identifiers: From Bus*, To Bus*, Circuit*.

- **Add Time-Series**: Click this button to load the selected time series into the tool's working memory.

- Load Observed Transformer Neutral GICs:
  - **Load SUNBURST GIC Measurement .csv**: Click **Browse** to select the .csv file containing observed GIC data. Only the SUNBURST CSV format is supported. Data can be downloaded from: https://sunburst.epri.com/
  - **Add Time-Series**: Click this button to load the selected time series into the tool's working memory.
- Load multiple time-series by repeating above steps to load additional time-series data.
- Manage Loaded Time-Series: Use the **List of Loaded GIC File Names** at the bottom of the window to select or deselect time-series for comparison.
- Set **Common Sampling Rate (Seconds):** Enter a value to downsample all time-series to a common rate before comparison.
- **Plot/Compare GIC Time-Series:** Click this button to generate the comparison plot.

* Use the PowerWorld Simulator Model Explorer to obtain transformer identifiers.

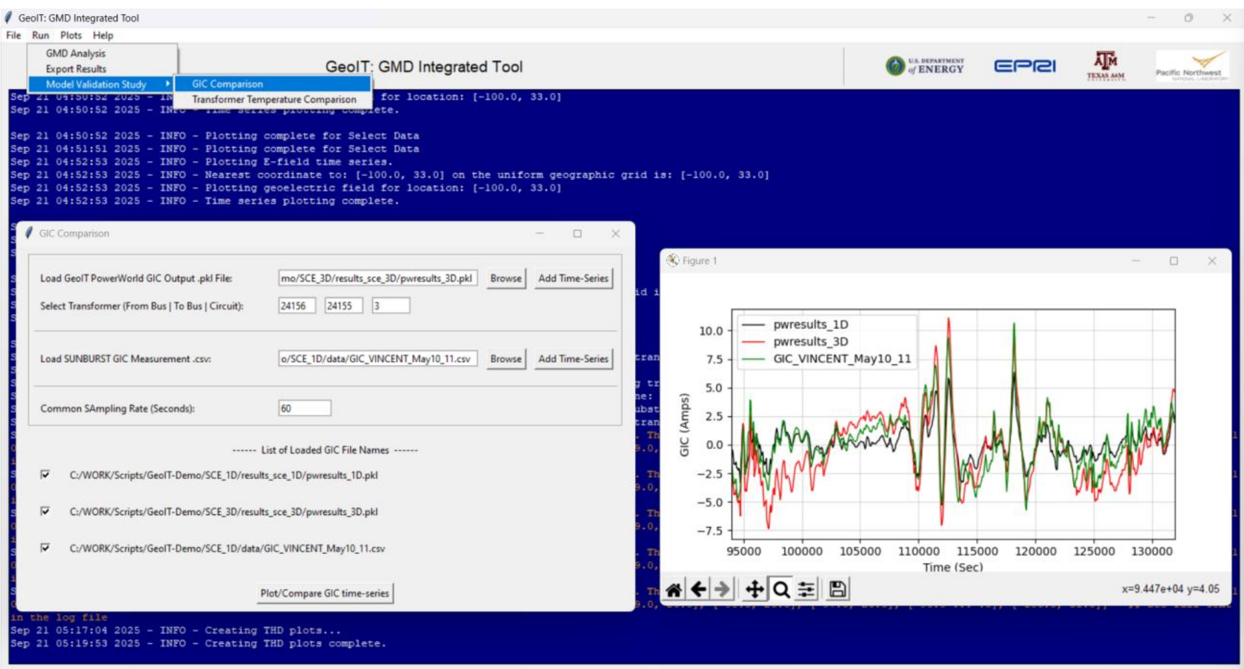

Figure 24. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Model Validation Study → GIC Comparison

1.25 Plots → Model Validation Study → Transformer Thermal Comparison

To open the input window, navigate to **Plots** → **Model Validation Study** → **Transformer Thermal Comparison** (Figure 25).

This feature compares multiple transformer temperature rise time-series.

Input Options:

- Load Transformer Temperature Rise Time-Series:
  - **Load Temperature Rise Time-Series .txt File**: Click **Browse** to select the .txt file generated by the ETTM module.
  - **Add Time-Series**: Click this button to load the selected time series into the tool's working memory.
- Load Multiple Time-Series**:** Repeat above step to load additional time-series data.
- Manage Loaded Time-Series: Use the **List of Loaded Temperature Rise File Names** at the bottom of the window to select or deselect time-series for comparison.
- **Set Common Sampling Rate (Seconds):** Enter a value to downsample all time-series to a common rate before comparison.
- **Plot/Compare Temperature Rise Time-Series:** Click this button to generate the comparison plot.

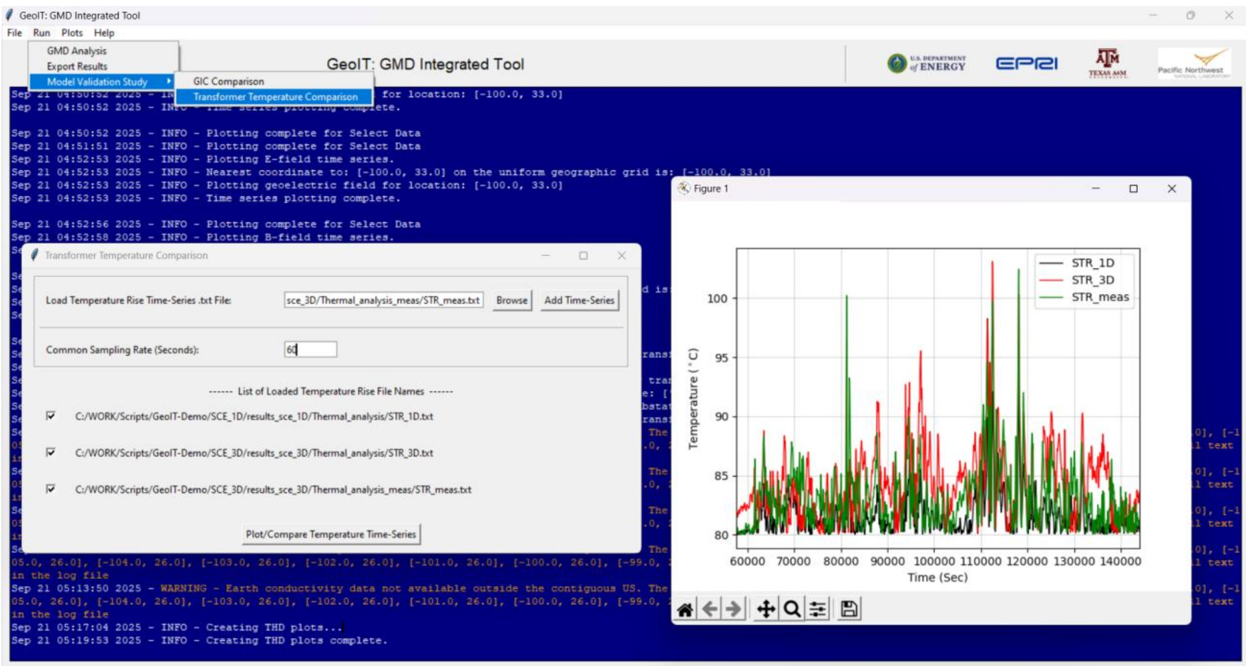

Figure 25. Geomagnetic Integrated Tool (GeoIT) Graphical User Interface Steps to Navigate Plots → Model Validation Study → Transformer Thermal Comparison

2.0 GEOIT WRAPPER (GIW) EXECUTABLE USAGE

2.1 System Requirements

The following items are required to use GeoIT executable:

- Windows 10 (64-bit).

- At least 100 MB free hard disk space.

- At least 2 GB of random access memory(RAM). Performance improves with more memory.

- Python 3.0 and above.

2.2 Python Executable Usage

Step 1: Install Python 3.0 or above and pip on your computer. Use instructions indicated here: https://www.python.org/downloads/

Step 2: To be able to use all features of the tools download the following EPRI and PowerWorld python packages.

- B2ECalc Version 2.0
- ETTM Version 2.0
- PowerWorld 23 with SimAuto Add-On
- GICHarm Version 6.0 executable

Step 3: Steps to run a GeoIT example.

Download the package folder.

1. The GeoIT wrapper executable is in folder: /GeoIT-Python-Wrapper/
2. **GeoIT-Python-Wrapper/Examples/example_tx2000.py** is the main script and **/Examples/input_tx2000.py** is its data input file.
3. Open **GeoIT-Python-Wrapper/Examples/input_tx2000.py** and make the following changes:

– Provide the folder path for the B2ECalc python package. Enter the folder path here:
   - 'b2ecalc_path': "b2ecalc/folder/path"

– Enter the "GIC_harm_cmd.exe" gicharm executable file path for the. Enter the file path here:
   - 'gicharm_exe': "gicharm/GIC_harm_cmd.exe"

4. To run the examples script examples_tx2000.py file from other folder locations, make sure to add the "geoit-master" folder to the system path using the commands below:

```
$ sys.path.insert(0, geoit_dir)
```

Step 4: Load results for further analysis using load_results.py python file (details indicated in Chapter: 1). To run this python script, you need to install the following python modules:

- Numpy 1.22.0
- Pandas 1.4.0
- Scipy 1.10.0

3.0 GEOIT WRAPPER (GIW) MODULE FUNCTIONS

3.1 Module 1: Geoelectric Field Computation Module

Key Function:

- **b2erun():** Computes geoelectric field using geomagnetic field data file path, Earth model input, geographic coordinate inputs and calculation settings.

Geoelectric Field Computation:

Geomagnetic field computation command:

```
$ giw.b2erun(b2e_input)
```

Parameter:

b2e_input {dictionary}, mandatory keys:

- b2ecalc_path{string}: Full folder path of the B2ECalc python package.
- bfilepath {string}: Full file path of the IAGA 2002 format geomagnetic field data file.
- em_type{integer}: Earth model type. The integer input and the corresponding surface impedance/ transfer function used are:
  - 1: Fernberg 1-D surface impedances.
  - 2: Updated 1-D RTFs.
  - 3: USArray/USMTArray EMTFs.
- geographic_cords{dictionary}, with keys:
  - from_lon {float}: From longitude. Values must be between −180 to 180 degrees.
  - from_lat {float}: From latitude: Values must be between −90 to 90 degrees.
  - lon_space {float}: Longitude spacing: Value limits [0.1, 360].
  - lat_space {float}: Latitude spacing: Value limits [0.1, 180].
  - lon_count {integer}: Number of longitudes: Must be a natural number.
  - lat_count {integer}: Number of latitudes: Must be a natural number.
- cal_setting{dictionary}, with keys:
  - dwnsmpl_fact {integer}: Downsampling factor. Must be a natural number.
  - spike_thres{float}: Delta B threshold to trim B-field spikes.
  - ts_overlap {float}: Time series overlap percentage. Value limits [0, 100].
  - window_len {integer}: Window length (in sec). Must be a natural number.
  - synth_win_mult {float}: Window length multiplier. Must be greater than 1.
  - emtfrting_thres {integer}: Minimum EMTF rating (1–5) for selecting EMTF model.
  - e_interp_meth {integer}: Non-uniform geoelectric field interpolation method. Options include:

   - 1: Nearest EMTF site location.
   - 2: Inverse distance weighted Interpolation.

- saveb3d_filepath{string}: Full file path of the output geoelectric field file.

Optional keys:

- mapplot_input {list}: Indicate this key to generate the geographic map plot.

Defined as:

$ mapplot_input: [state_border, fern_regions, rtf_regions, emtf_sites]

   - state_border {integer}: Plot state borders.
   - fern_regions {integer}: Plot Fernberg 1D conductivity physiographic regions.
   - rtf_regions {integer}: Plot update 1D ground response physiographic regions.
   - emtf_sites {integer}: Plots USArray and USMTArray project survey site locations.
     Each of the four parameters defined above take 0 or 1 as an input. Assign a value of 1 to include the plot, 0 otherwise.

- include_plot{list}: Indicate this key to generate the geomagnetic field time series plots.

Defined as:

$ include_plot: [raw_bfield, interpolated_bfield, downsampled_bfield]

   - raw_bfield {integer}: Plots the raw geomagnetic field time series.
   - interpolated_bfield {integer}: Plots the interpolated and processed geomagnetic field time series.
   - downsampled_bfield {integer}: Plots the downsampled geomagnetic field time series if downsampling factor (‘dwnsmpl_fact’) is equal not to 1.
     Each of the three parameters defined above take 0 or 1 as an input. Assign a value of 1 to include the plot, 0 otherwise.

- ‘location’{list}: Indicate this key to generate the geoelectric field time series plot at a given location defined by its latitude and longitude.

Defined as:

$ location: [location_longitude, location_latitude]

   - location_longitude {float}: Longitide of the location
   - location_latitude { float}: Latitude of the location

- timelapse_figprop {Dictionary}: Use this to generate the E-field time-lapse images.

The keys of this dictionary are indicated below:

   - mapplot_type {integer}: Map plot type.
      - Select 1 for E-field map for each physiographic region.
      - Select 2 for E-field map for uniform geographic grid coordinate.

- cbar_norm {integer}: Colorbar normalization.
  - Select 1 for logarithmic colorbar.
  - Select 2 for linear colorbar.
- e_unit {integer}: geoelectric field unit.
  - Select 1 for mV/km.
  - Select 2 for V/km.
- cbar_ticks {list}: Colorbar tick values.
- quiv_ecutoff {float}: E-field cutoff for plotting E-field quivers.
- quiv_scale{float}: E-field quiver scaling factor.
- time_range {list}: [Start time, end time] indicates start and end times for which the E-field maps are plotted.

- saveanim_dat{Dictionary}: Use this to generate the E-field time-lapse images.
- The keys of this dictionary are indicated below:
  - name_prefix {string}: Prefix to add before the E-field map plot files.
  - dir_path { string }: Folder path to save the E-field map plots.
  - output_type {integer}: Output type.
    - Select 1 for E-field plots only.
    - Select 2 for E-field time-lapse video only.
    - Select 3 for E-field plots and time-lapse video.
  - fps{integer}: Time-lapse video frames per seconds.

3.2 Module 2: GIC Computation Module

Functions:

1. **gicrun()**: Runs the PowerWorld GIC computation and saves results.
2. **gic_plots ()**: Plots the GIC time-series results.
3. **linegic_tmlps():** Generates transmission line GIC time-lapse images.
4. **subsgic_tmlps():** Generates substation GIC time-lapse images.

GIC Computation:

This function loads the PowerWorld network data file.

```
$ giw.gicrun(pwrwrld_input)
```

Parameters:

pwrwrld_input {dictionary}, mandatory keys:

- network_filepath{string}: Full file path of the PowerWorld network data file.

- b3d_filepath{string}: Full file path of the geoelectric field input data file (in .b3d file format).
- time_range{dictionary}: The start time, end times and time step for which the GICs are to be calculated. The keys of this dictionary include:
  - start_time {integer}: Start time in seconds.
  - end_time { integer }: End time in seconds.
  - time_step { integer }: Time step in seconds.
- results_filepath{string}: Full path of the .pkl file where the user wants to save the PowerWorld results in a pickle format. Details indicated in Chapter 3.0.

GIC Plots:

Function to plot GIC time series.

```
$ giw.gic_plots(plot_param)
```

Parameters:

plot_param{dictionary}, mandatory keys:

- pw_results_path {string}: Full path of the PowerWorld results .pkl file.
- plt_type{string}: Choose from options below:
  - ‘xmer_effective’: To compute transformer effective GICs.
  - ‘xmer_neutral’: To compute transformer neutral GICs.
  - ‘line’: To compute transmission line GICs.
  - ‘subs_neutral’.” : To compute substation neutral GICs.
- device{list}: List to identify network component type:
  - If ‘xmer_effective’ selected, device = [from_bus, to_bus, circuit_number].
  - If ‘xmer_ neutral’ selected, device = [from_bus, to_bus, circuit_number].
  - If ‘line’ selected, device = [from_bus, to_bus, circuit_number].
  - If ‘subs_neutral’ selected, device = [substation number].

Line GIC Time-Lapse Plots:

Function to generate GIC time-lapse plots.

```
$ giw.linegic_tmlps(param)
```

Parameters:

param{dictionary}, mandatory keys:

- pw_results_path {string}: Full path of the PowerWorld results .pkl file.
- timelapse_figprop {dictionary}: Time lapse figure properties dictionary must have the following keys.
  - cbar_norm {integer}: Colorbar normalization.
    - Select 1 for logarithmic colorbar.
    - Select 2 for linear colorbar.
  - cbar_ticks {list}: Colorbar tick values.
  - time_range {list}: [Start time, end time] indicates start and end times for which the GIC maps are plotted.
  - xylim {list}: select US map corner point. List value is = [[from longitude, to longitude], [from latitude, to latitude]]
  - st_datetime{datetime}: Start date and time in Python datetime format, to include in plot titles
  - savedir{string}: folder location to store the time-lapse images
  - output_type {integer}: Output type.
    - Select 1 for GIC map plots only.
    - Select 2 for GIC time-lapse video only.
    - Select 3 for GIC map plots and time-lapse video.
  - fps{integer}: Time-lapse video frames per seconds.

Line GIC Time-Lapse Plots:

Function to generate GIC time-lapse plots.

```
$ giw.subsgic_tmlps(param)
```

Parameters:

param{dictionary}, mandatory keys:

- pw_results_path {string}: Full path of the PowerWorld results .pkl file.
- timelapse_figprop {dictionary}: Time lapse figure properties dictionary must have the following keys.
  - ‘scale_fact’{float}: Scaling factor to scale the size of circle markers.
  - ref_amps{float}: Reference GIC to scale the substation GIC legend marker size.
  - time_range {list}: [Start time, end time] indicates start and end times for which the GIC maps are plotted.
  - legend_loc{list}: Location [Longitude, Latitude] to place the reference GIC legend on the map.

- xylim {list}: select US map corner point. List value is = [[from longitude, to longitude], [from latitude, to latitude]]
- st_datetime: Start date and time in Python datetime format, to include in plot titles
- savedir: folder location to store the time-lapse images
- output_type {integer}: Output type.
  - Select 1 for GIC map plots only.
  - Select 2 for GIC time-lapse video only.
  - Select 3 for GIC map plots and time-lapse video.
- fps{integer}: Time-lapse video frames per seconds.

3.3 Module 3: ETTM Thermal Analysis Module

Module functions:

1. **gicexport_ettm():** Exports the PowerWorld GIC results in an ETTM input format.
2. **winding_temp()**: Performs the winding asymptotic response and winding test data curve fitting. Computes winding temperature rise for a given GIC signature.
3. **struct_temp()**: Performs the structural part asymptotic response and structural part test data curve fitting. Computes structural part temperature rise for a given GIC signature.

Export PowerWorld GIC results for ETTM:

This function exports the time series GIC data file for the transformer selected by the user. This file can be used by ETTM for transformer thermal analysis.

```
$ giw.gicexport_ettm(param)
```

Parameters:

param{dictionary}, mandatory keys:

- pw_results_path {string}: Full path of the PowerWorld results .pkl file.
- gic_export_ettm{dictionary}, with keys:
  - gicsig_folderpath{string}: Full folder path of the location where the user wants to save the GIC signature files.
  - select_xmer{list}: List of all transformers for which the user wants to save the GIC signature input files. This list is of the following format:

    ```
    $ 'select_xmer': [Transformer1_dat, Transformer2_dat, ….]
    ```

    Each of the transformer_dat follows the following format:

    ```
    $ transformer_dat = [from_bus, to_bus, circuit_number]
    ```

- from_bus {int}: Transformer from bus number.
- to_bus {int}: Transformer to bus number.
- circuit_number {int}: Circuit number.

Winding Temperature Calculation:

```
$ giw.winding_temp(ettm_input)
```

Parameter:

ettm_input{dictionary} has keys:

- WAR_filepath {list}: List of full file path of the winding asymptotic response table.
- GIC_ref_wind {list}: List of reference GIC at which the time series of temperature rise is given.
- WTR_ filepath {list}: List of full file path of the winding temperature rise test data table.
- GICsigdat_filepath {string}: Full file path of the input GIC .pkl (pickle) data file.
- init_wind_temp {list}: List of initial winding temperature value. In degree Celsius.
- export_windtemp {string}: Folder location to store the winding temperature rise data.

Structural Part Temperature Calculation:

```
$ giw.struct_temp(ettm_input)
```

Parameter:

- SAR_filepath {list}: List of full file path of the structural part asymptotic response table.
- GIC_ref_struct {list}: List of reference GIC at which the time series of temperature rise is given.
- STR_ filepath {list}: List of full file path of the structural part temperature rise test data table.
- GICsigdat_filepath {string}: Full file path of the GIC data file.
- init_oil_temp {list}: List of initial oil temperature value. In degree Celsius.
- export_structtemp {string}: Folder location to store the structural part temperature rise data.

Thermal Analysis Plots:

Function to plot thermal analysis results.

$ giw.ettm_plot(param)

Parameters:

param{dictionary}, mandatory keys:

- pw_results_path {string}: Full path of the PowerWorld results .pkl file.
- plt_type{string}: Choose from:
  - 'wind_asymp_resp': To plot winding asymptotic response curve fit.
  - 'wind_temp_resp': To plot winding temperature response curve fit.
  - 'struct_asymp_resp': To plot structural parts asymptotic response curve fit.
  - 'struct_temp_resp': To plot structural parts asymptotic response curve fit.
  - 'gic': To plot input effective GIC.
  - 'winding_temp_rise': To plot winding temperature rise.
  - 'struct_temp_rise': To plot structural parts temperature rise.
- xmer_id {list}: List to identify transformer. Value = [from_bus, to_bus, circuit_number].

3.4 Module 4: GICHarm Harmonic Analysis Module

Module functions include:

1. **gicexport_gicharm():** Exports the PowerWorld GIC results in an GIGHarm input format.
2. **run_gicharm()**: Runs harmonic analysis using a Python subprocess to run GICHarm.
3. **harmonic_mapplot():** Plots the voltage total harmonic distortion THDv on the US maps.

Export results for GICharm:

This function exports the GIC sequence excel file that can be used in GICHarm for harmonic analysis.

$ giw.gicexport_gicharm(param)

Parameters:

param{dictionary}, mandatory keys:

- pw_results_path {string}: Full path of the PowerWorld results .pkl file.
- gic_export_gicharm {dictionary}, with keys:
  - gicscenarios_filepath{string}: Full file path of the location where the user wants to save the GIC scenario csv file.
  - gicscenarios_timesamples{list}: List of all time samples whose GIC data the user wants to save in the GIC scenario excel file.

<u>GICHarm harmonic analysis:</u>

$ giw.harmonic_run(gicharm_input)

Parameter:

gicharm_input {dictionary}, mandatory keys:

- gicharm_exe_path {string}: Full file path of the GICHarm executable.
- model_filepath {string}: network model file in .dss format
- gicscenarios_filepath {string}: Full file path of the GIC scenarios excel file containing GIC data for different time samples.
- results_dir {string}: Directory to store the output results.

<u>Harmonics Map Plots:</u>

Function to generate GIC time-lapse plots.

$ giw.harmonic_mapplot(param)

<u>Parameters:</u>

param{dictionary}, mandatory keys:

- pw_results_path {string}: Full path of the PowerWorld results .pkl file.
- figprop {dictionary}: Dictionary indicating the time-lapse plot configuration.
  - THDcsv_filepath{string}: Voltage THD output file generated by geoit.run_gicharm().
  - plot_phase {string}: Select either ‘A’, ‘B’ or ‘C.’
  - ‘scale_fact’{float}: Scaling factor to scale the size of circles on the plot.
  - ref_THD{float}: Reference THD value to scale the THD legend marker size.
  - xylim {list}: select US map corner point. List value is = [[from longitude, to longitude], [from latitude, to latitude]]
  - legend_loc{list}: Location [Longitude, Latitude] to place the reference THD value legend on the map.
  - savedir {string}: folder location to save the plot.

4.0 OUTPUT PICKLE DATA FILES

This section describes the pickle file outputs and the data contained within them.

4.1 PowerWorld Output Pickle Data File:

The python file load_results.py indicates how to load the pickle data file. The format of the pw_results variable is indicated in Table 1 below:

Table 1. Powerworld Output Format

pw_results	PowerWorld Output Dictionary
	‘network_dict’	network data dicationary
		‘xmer’	transformer data dataframe
		‘substation’	substaion data dataframe
s		‘branch’	branch data dataframe
		‘line’	line data dataframe
		‘bus’	bus data dataframe
	‘gic_output’	GIC output dictionary
		‘xmer_effective’	transformer effective GIC dataframe
		‘xmer_neutral’	transformer neutral GIC dataframe
		‘xmer_frombus’	transformer from bus GIC dataframe
		‘xmer_tobus’	transformer to bus GIC dataframe
		‘line_from’	line GIC dataframe
		‘subs_neutral’	substaion GIC dataframe

4.2 ETTM GIC signature pickle data file:

The python file load_results.py indicates how to load the pickle data file. The format of the ettm_sig variable is indicated in Table 2.

Table 2. Electric Power Research Institute’s Transformer Thermal Modeling (ETTM) Geomagnetically Induced Current (GIC) Signature Format

‘ETTM_sig’	
	‘xmer_id_all’	List of all transformer [from_bus, to_bus, circuit]
	‘GICsig_filepaths’	List of GIC signature data files for each transformer

4.3 ETTM Winding and Structural Temperature Results Pickle Data File

The python file load_results.py indicates how to load the pickle data file. The format of the WTR_results and STR_results variable are indicated in Table 3.

Table 3. Electric Power Research Institute's Transformer Thermal Modeling (ETTM) Results Format

WTR_results/STR_results	**ETTM Results. List of Dictionary**
| 'WAR_data'	User provided winding asymptotic response test data.
| 'GIC_WTR'	User provided reference GIC at which the time series of winding temperature rise is given.
| 'WTR_data'	User provide winding temperature rise test data.
| 'WTR_fit'	User provide winding temperature rise curve fit data.
| 'SAR_data'	User provided structural part asymptotic response test data.
| 'GIC_STR'	User provided reference GIC at which the time series of structural temperature rise is given.
| 'STR_data'	User provide structural temperature rise test data.
| 'STR_fit'	User provide structural temperature rise curve fit data.
| 'GIC_dt'	GIC sampling rate (in minutes).
| 'GIC_time'	Time values of the input GIC time series (in minutes).
| 'GIC_current'	User provided GIC time series data.
| 'Initial_Temperature'	User provided initial oil temperature value in degree Celsius.
| 'Oil_Temperature'	User provided initial oil temperature value in degree Celsius.
| 'Import_WAR_Table_Data'	User provided winding asymptotic response test data.
| 'Import_WTR_Table_Data'	User provide winding temperature rise test data.
| 'Import_SAR_Table_Data'	User provided structural part asymptotic response test data.
| 'Import_STR_Table_Data'	User provide structural temperature rise test data.

WTR_results/STR_results	ETTM Results. List of Dictionary
| 't'	Time values for winding temperature rise time series (in minutes).
| 'y'	Winding temperature rise output (in degree Celsius).
| 't1'	Time values for structural part temperature rise time series (in minutes).
| 'y1'	Structural part temperature rise output (in degree Celsius).
| 'Hw'	Transfer function
| 'Hs'	Transfer function
| 'Idc_test_winding_ref'	User provided reference GIC at which the time series of winding temperature rise is given.
| 'Idc_test_structural_ref'	User provided reference GIC at which the time series of structural temperature rise is given.
| 'WAR_plot'	Contains the Matplotlib figure and axes of the winding asymptotic response curve fit plot.
| 'WTR_plot'	Contains the Matplotlib figure and axes of the winding temperature rise response curve fit plot.
| 'SAR_plot'	Contains the Matplotlib figure and axes of the structural part response curve fit plot.
| 'STR_plot'	Contains the Matplotlib figure and axes of the structural part temperature rise response curve fit plot.
| 'GIC_plot'	Contains the Matplotlib figure and axes of the input GIC time series plot.
| 'TRW_plot'	Contains the Matplotlib figure and axes of the winding temperature rise plot.
| 'TRS_plot'	Contains the Matplotlib figure and axes of the structural part temperature rise plot.
| 'xmer_id'	transformer ID