Agenda
Geomagnetic Disturbance Task Force (GMDTF)

August 14, 2019 | 8:30 a.m. – 4:00 p.m. Central

Exelon Headquarters
10 S. Dearborn St
48th Floor Meeting Room (48-NE-004)
Chicago, IL

Join WebEx Meeting
Access Code: 738 370 131
Dial-in: 1-415-655-0002 (US Toll); 1-416-915-8942 (Canada Toll)

Introduction and Chair's Remarks

NERC Antitrust Compliance Guidelines and Public Announcement

Agenda Items

1. **Welcome –** NERC Staff (8:30 – 8:40 a.m.)
2. **Space Weather Prediction Center Update** – Chris Balch, NOAA SWPC (8:40 – 9:00 a.m.)
3. **National Space Weather Strategy and U.S. Department of Energy Space Weather Initiatives** – John Ostrich, U.S. DoE (9:00 – 9:20 a.m.)
4. **NERC EMP Task Force Activities Update** – Rey Ramos, Southern Company (9:20 – 9:45 a.m.)

Break

5. **Update on Standards Development Project 2019-01 - Modifications to TPL-007** – Emanuel Bernabeu, PJM Interconnection (10:00 – 10:45 a.m.)
   a. Approaches for Performing GIC Calculations for the Supplemental GMD Event
6. **Transformer Fleet GIC Studies with Transformer Manufacturer Support** – Industry and Manufacturer Presenters (10:45 – 11:15 a.m.)
   a. Tennessee Valley Authority – Ian Grant
   b. PECO – Tony Franchitti
   c. ABB – Ramsis Girgis
7. **Industry Perspective: Planning for GMD Vulnerability Assessments in the Western Interconnection** – Doug Tucker, Staff Engineer, Western Electricity Coordinating Council (11:15 – 11:30 a.m.)

Lunch (11:30 a.m. – 12:30 p.m.)

8. **Discuss Draft GMD Data Reporting Instruction** – NERC Staff (12:30 – 1:00 p.m.)

9. **GIC Monitoring Equipment** – Gary Hoffman, Advanced Power Technologies (1:00 – 1:15 p.m.)

10. **EPRI GMD Supplemental Project Update** (1:15 – 2:00 p.m.)

    Status of Research Work Plan Activities – Bob Arritt, EPRI Project Lead

    Discussion of recently-published reports

    Improving Understanding of Characteristics of Geoelectric Field Enhancements Caused by Severe GMD Events, June 2019, https://www.epri.com/#/pages/product/3002016832/

    Review of Peer-Reviewed Research Regarding the Effects of Geomagnetic Latitude on Geoelectric Fields, June 2019, https://www.epri.com/#/pages/product/3002016885/

    Update on Harmonics Impact Assessment Tool (EPRI GICHarm) – Bob Arritt, EPRI

Break

11. **Research Community Topics** (2:15 – 3:40 p.m.)

    a. U.S. Magnetotelluric (MT) Array Status and Integration in Powerflow Studies – Adam Schultz, Oregon State University / Pacific Northwest National Lab (PNNL)

    b. Extreme Value Analysis of GIC Based On Historical Magnetic Field Data – Rishi Sharma, Iowa State University

    c. Texas Magnetometer Network – Komal Shetye, Texas A&M University

    d. Natural Resources Canada Research Update – David Boteler, NR Canada

    e. U.S. Geological Survey Research Update – Jeffery Love, USGS

12. **Participant Roundtable** (3:40 – 3:55 p.m.)

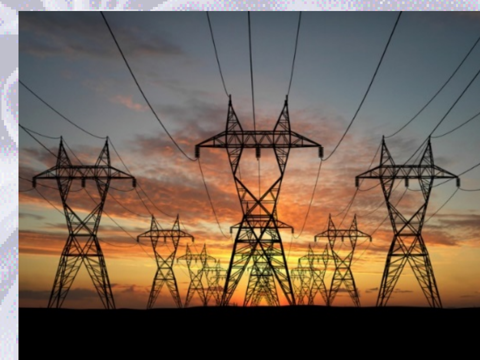
13. **Wrap up** (3:55 – 4:00 p.m.)

14. **Next In-Person Meeting – February 12, 2020 (T)**

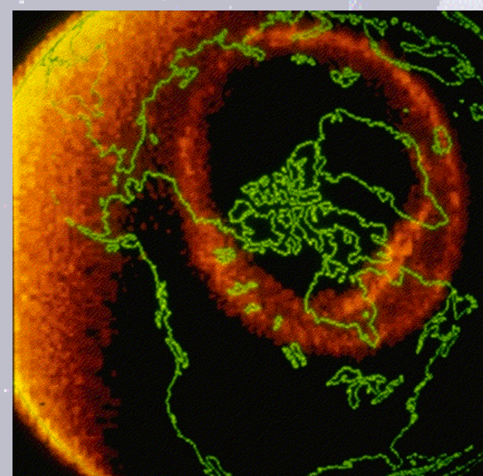
NOAA's Space Weather Prediction Center Report

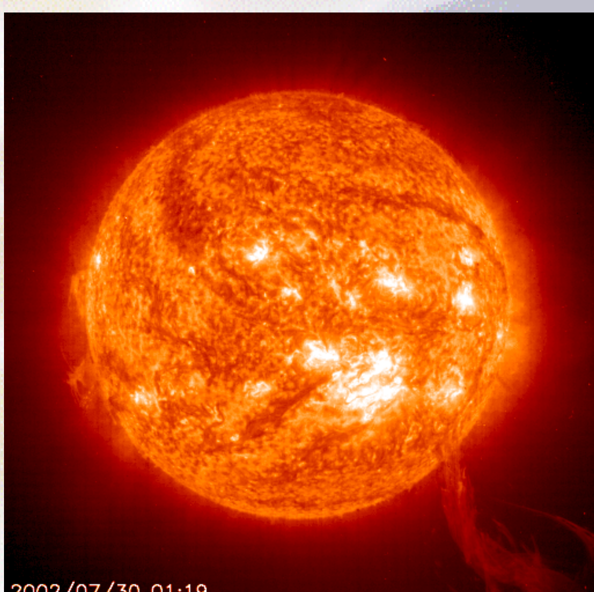
Outline

- Overview of SWPC's goals/objectives
- E-field Maps: current status & work in progress
- The work ahead for actionable maps: validation studies
- Input observatory network & invitation to participate
- Forecasting – initial steps



NERC GMDTF meeting
14 August 2019
Chicago, IL





Christopher Balch – NOAA/SWPC

Collaborators - Acknowledgements

- The near real-time E-field mapping project is a joint effort between
  - NOAA/SWPC (Balch, Millward, SWPC developers and system admins)
  - USGS Geomagnetism group (Anna Kelbert, Josh Rigler, Greg Lucas)
  - NASA/CCMC (Antti Pulkkinen)
- Technical advice from David Boteler/NRCAN is gratefully acknowledged
- Key data provider agencies are gratefully acknowledged:
  - U.S. observatories operated and maintained by USGS
  - Near U.S. observatories operated and maintained by NRCAN
- Magnetic field time-series interpolation algorithm (SECS) developed and made available courtesy of the Finnish Meteorological Institute
  - Amm & Viljanen, 1999; Pulkkien et al., 2003
- NSF's Earthscope USArray project & the IRIS Data Management Center are the source for improved Earth-conductivity specification (EMTF's)
- Past & Present validation collaborations: Dominion, CPI, PJM

NOAA/SWPC mission

- **Deliver space weather products & services to meet the evolving needs of the nation**
- **SWPC is one of NWS's national prediction centers**
- **Space Weather Forecast Office**
  - **staffed 24 hours x 7 days**
- **Synthesis of space weather data and information**
- **Nation's official source of space weather alerts, warnings and forecasts**



Geoelectric Field Modeling: Motivation

- To provide the Electric Power Industry a better indicator than a global index (e.g. Kp index/G-scale) to specify geomagnetic activity levels
- The Geoelectric Field – has been identified as the key space weather parameter that is needed:
  - Space Weather Workshop 2011:
    '…the best, most useful environment parameter…'
  - Referenced by industry standards (NERC/FERC)
  - National Space Weather Action Plan (SWAP) (OSTP 2015) highlights the Geoelectric field in Goal 1.1 (Benchmarks) & Goal 5.5 (Enhance Understanding). Recent executive order concerning '…resilience to electromagnetic pulses…'
- Advantages for using the Geoelectric Field:
  - Local-regional activity is characterized
  - Direct indication of induction risk by integrating along conductors (lines)
  - User actions can be more targeted: reduces unnecessary mitigation steps, improves the decisions made in response to space weather

Overview of Calculating GIC for non-uniform E-field

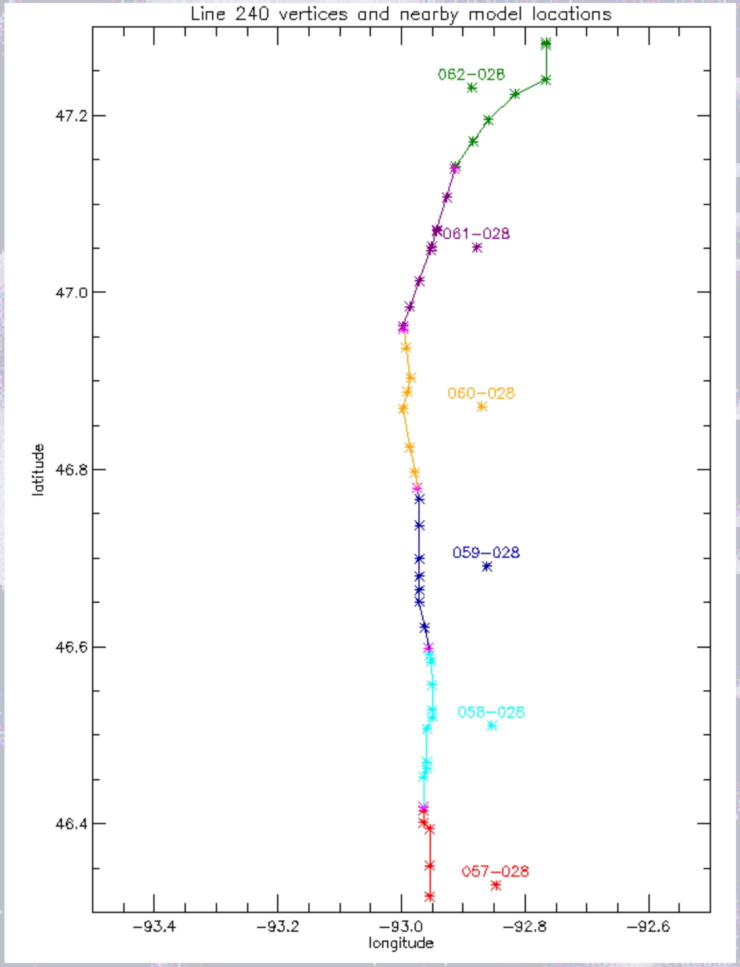
$v_{ij}^* = \int_i^j \boldsymbol{E} \cdot \boldsymbol{dl}$, *i.e. from node* i *to node* j

Combined with line resistance we find source currents between lines which can be translated into a net induced nodal current source at each node.

For example:

$J_A \stackrel{\text{def}}{=} j_{DA} - j_{AB}$

with $j_{DA} = v_{DA}^*/r_{DA}$ ***and*** $j_{AB} = v_{AB}^*/r_{AB}$



$\mathbf{J} = \mathbf{Y}^N\mathbf{V} + \mathbf{I}$, ***Kirchoff law***

Induced nodal current sources $\mathbf{J}$**:**

Outflows: to other nodes: $\mathbf{Y}^N\mathbf{V}$**, to ground:** $\mathbf{I}$

$\mathbf{Y}^N$ **is the 'nodal admittance matrix'**

Nodal voltages relationship to $\mathbf{I}$**:** $\mathbf{V} = \mathbf{Z}^e\mathbf{I}$,

$\mathbf{Z}^e$ **is the 'earthing impedance matrix'**

Combining:

$$\mathbf{J} = \left(\mathbf{Y}^N\mathbf{Z}^e + \mathbf{1}\right)\mathbf{I}$$

Inverting to solve for $\mathbf{I}$**:**

$$\mathbf{I} = \left(\mathbf{Y}^N\mathbf{Z}^e + \mathbf{1}\right)^{-1}\mathbf{J}$$

(See Lentinen & Pirjola, 1985 for original formulation, also see Boteler & Pirjola, 2017)

E-field maps data pipeline - today

USGS observatories (8)
B-field time series

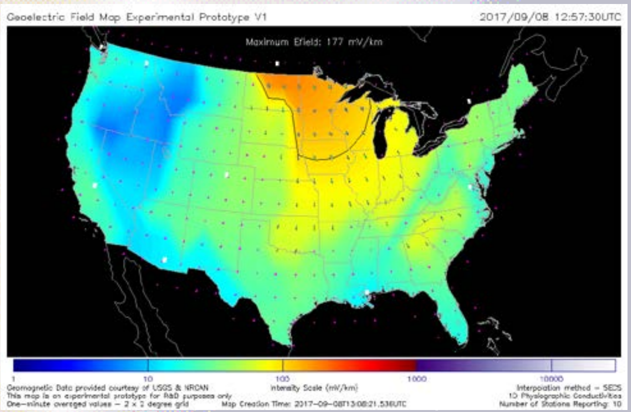
NRCAN observatories (5)
B-field time series

Detrending Algorithm

Interpolation Algorithm[†]
B-field on 0.5°x0.5° grid

E-field calculation: 2°x2° grid,
Fernberg 1D conductivities

E-field experimental products:
- *results in database*
- *graphical maps* **(public release Oct '17)**
- *gridded data files* **(available on request)**
- ***GeoJSON format for dissemination (June 15, 2018)***



Operational deployment for first version should be completed by September 30, 2019

[†] SECS - Amm & Viljanen, 1999; Pulkkinen et al., 2003

URLs
https://www.swpc.noaa.gov/products/experimental-geoelectric-field-1-minute
https://services.swpc.noaa.gov/experimental/products/lists/rgeojson.json ***(for list of geojson files)***
https://services.swpc.noaa.gov/experimental ***is the 'url' to prepend to the geojson filenames***

E-field maps data pipeline – test system

USGS observatories (8)
B-field time series

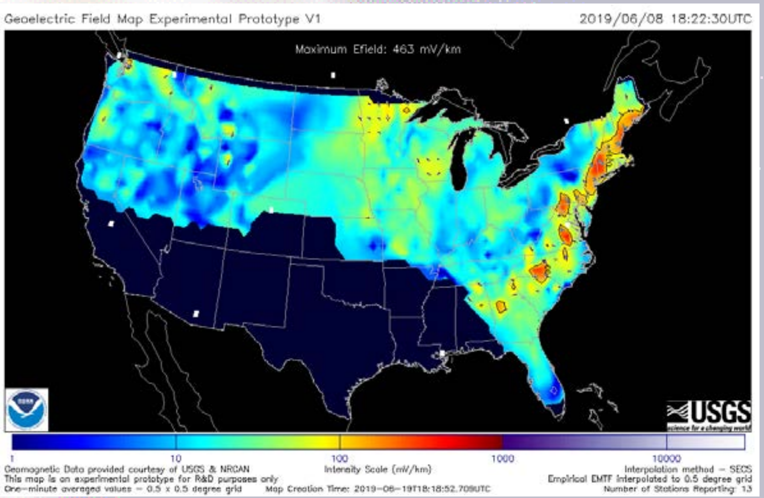
NRCAN observatories (5)
B-field time series

→ *Detrending Algorithm*

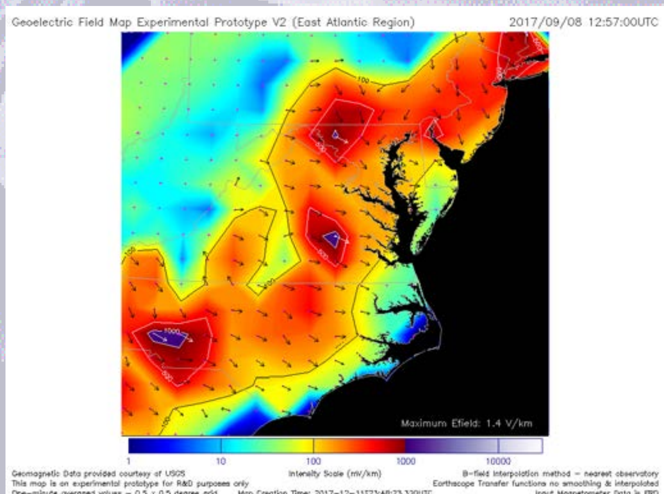
→ *Interpolation Algorithm*
B-field on 0.5°x0.5° grid
daily netcdf for archive

→ ***E-field calculation:***
-Earthscope Transfer Functions & (USGS for FL)
-Interpolate to 0.5°x 0.5° grid
-Gaps in coverage

→ ***E-field experimental products:***
-results in database
-graphical maps
-gridded data files
-daily netcdf for archive/repository
-GeoJSON format for dissemination

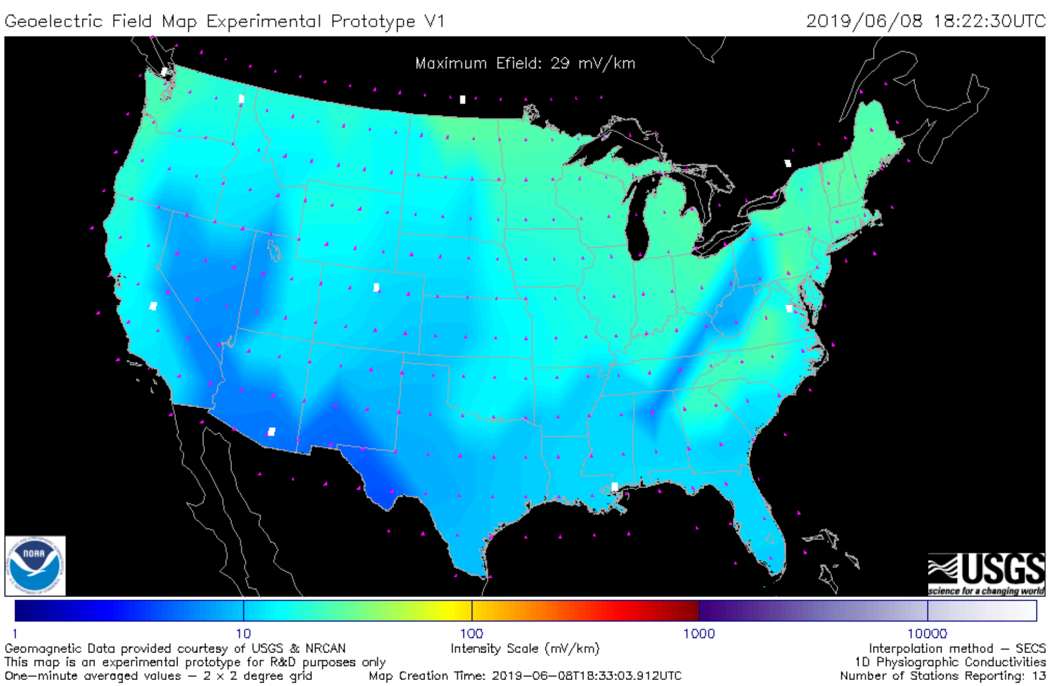


Scheduled to go operational in FY2020

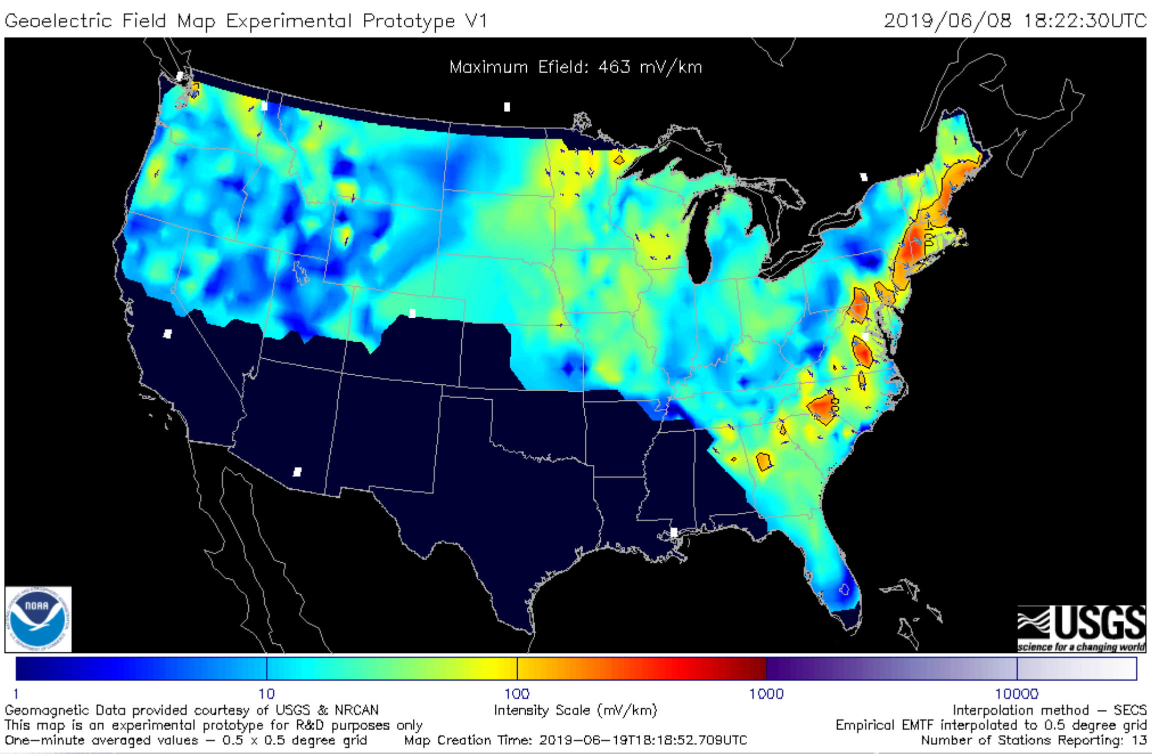


Recent Storm Comparison

Fernberg 1D model



June 8, 2019 Geomagnetic Storm



EMTF model interpolated to 0.5 x 0.5 degree grid

E-field maps data pipeline – in development

USGS observatories (8)
B-field time series

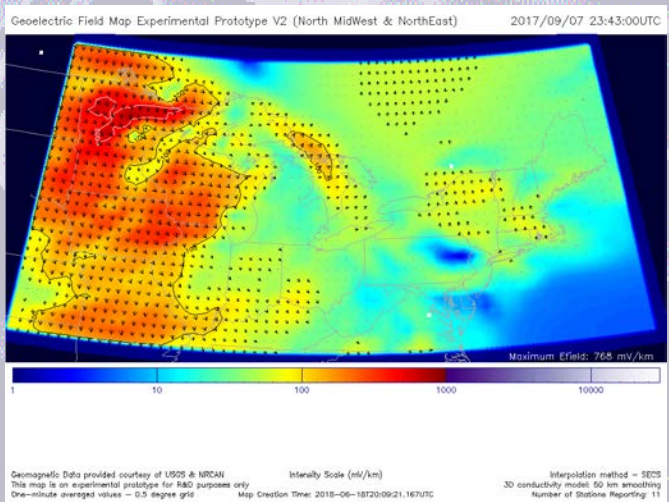
NRCAN observatories (5)
B-field time series

→ *Detrending Algorithm* → *Interpolation Algorithm*
B-field on 0.5°x0.5° grid

E-field calculation:
- *USGS 3D Model 0.1°x 0.1° grid*
- *Spatial Averaging to 0.5°x 0.5°†*
- *Gaps in coverage*

→ **E-field experimental products:**
- *results in database*
- *graphical maps*
- *gridded data files*
- *daily netcdf for archive/repository*
- *GeoJSON format for dissemination*

†Choice for spatial resolution is preliminary and may be changed depending on results of validation studies



E-field maps – in development
Joint US-Canada E-field map

- Partnership with NRCAN to develop US-Canada E-field map
- Northern boundary will extend up to 60 degrees latitude
- NRCAN space weather specifies conductivities for Canada
- Four high latitude magnetometers to be added:
  YKC, BLC, FCC, SNK
- Plans to improve data latency

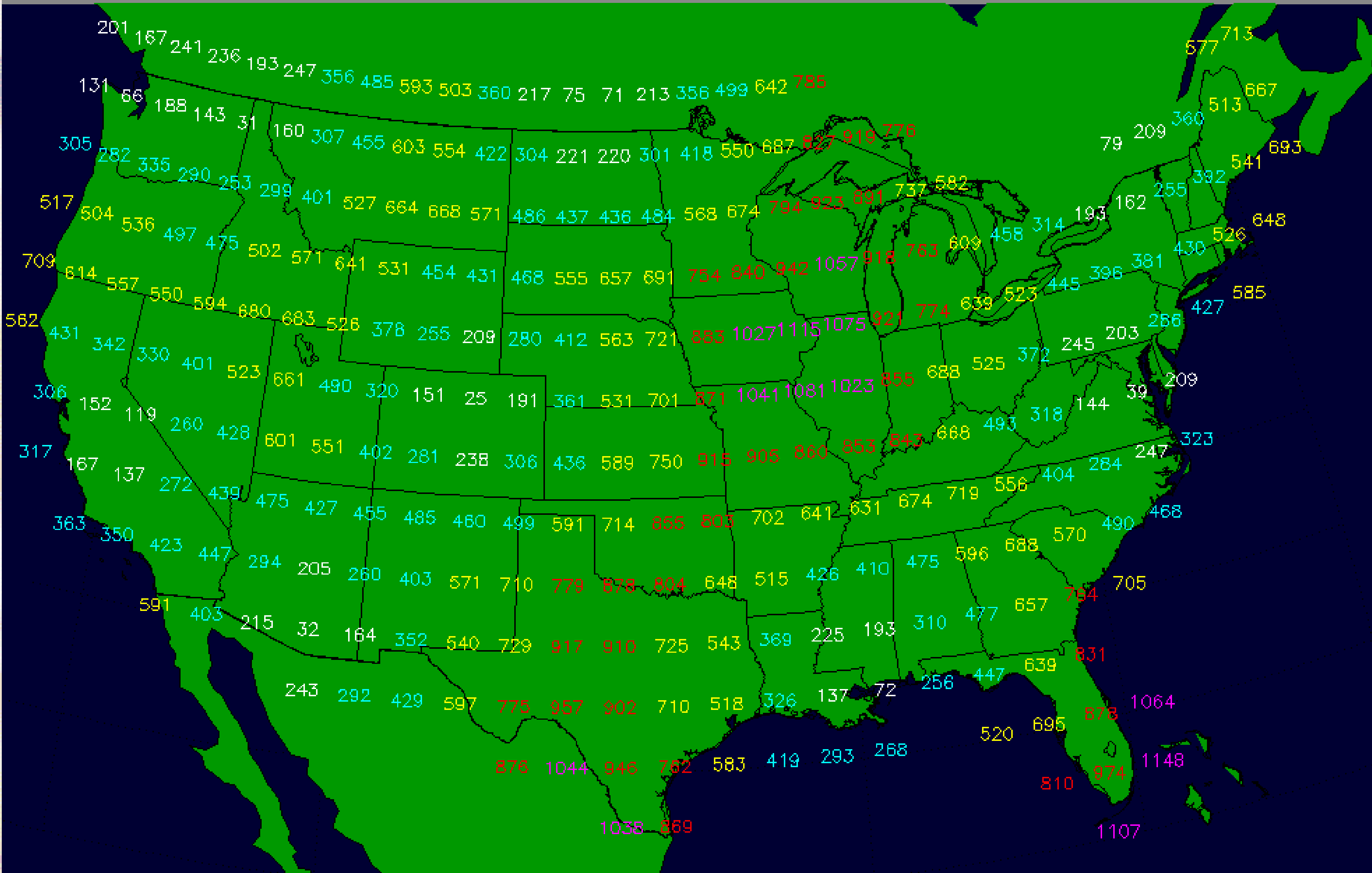
Is this Information Actionable? The Importance of Validation

- The Fernberg 1D models are the basis of the first version of these maps
- Comparing with the newer information from the MT surveys and based on comments from the research community, we expect some areas on the map may lack the accuracy that users require
- Therefore it is important for potential users of the information to run validation tests to check the usefulness of the results for taking actions
- We plan to do a comprehensive statistical comparison between the Fernberg 1D and the EMTF-based model to better characterize the ‘error bars’ in the former

Proposal for doing validation

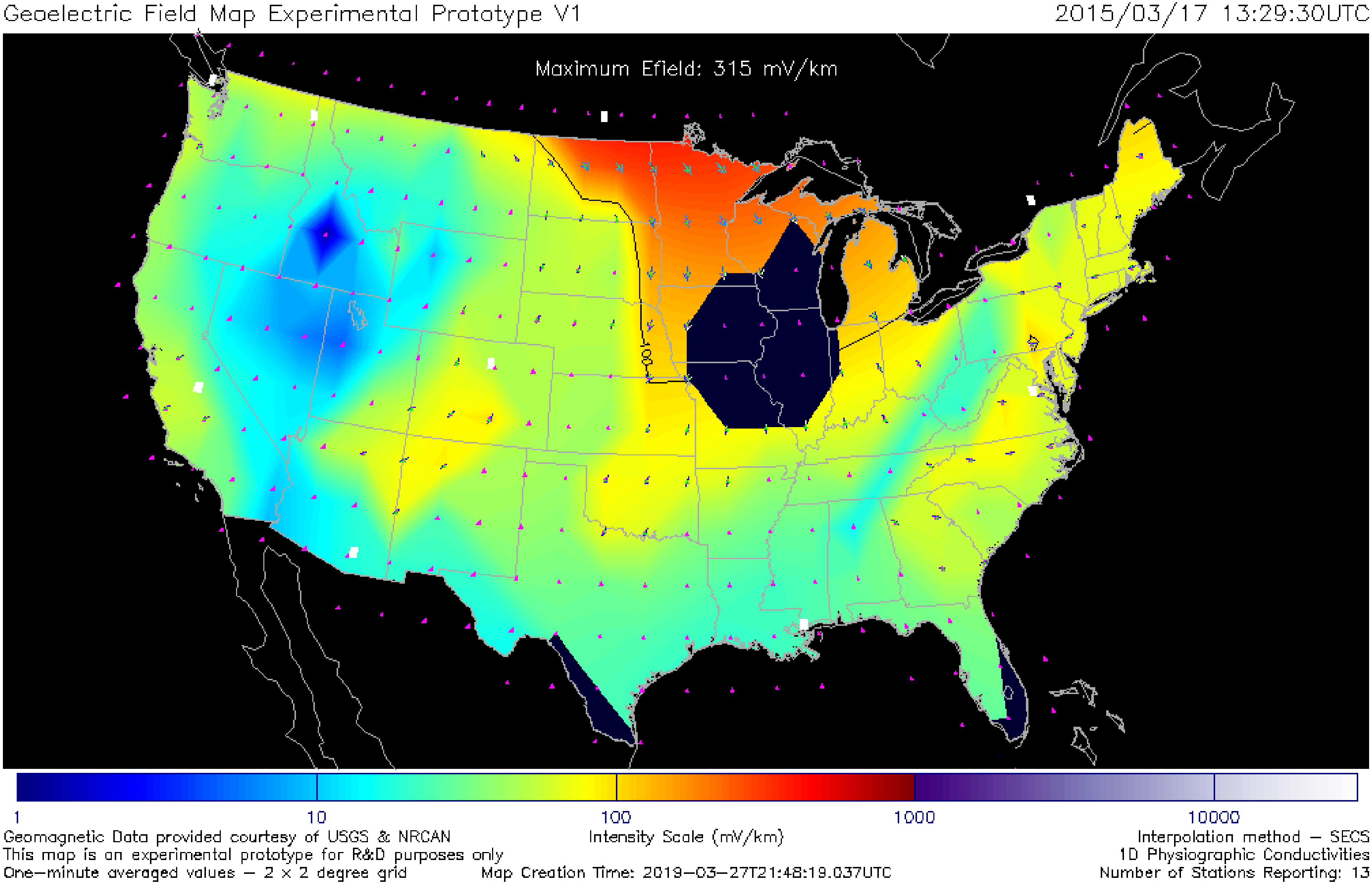
- **Government-Industry Partnership**
  - NOAA/USGS do E-field calculation for recent storms using varying conductivity specifications (has already been done for several storms)
  - Industry Partner carries out the integration of non-uniform E-field along their active transmission lines at the time of the storm to determine E-field imposed voltages
  - Industry Partner uses their grid model to calculate the currents – including currents at grounding neutrals
  - The calculated values can then be compared with actual measurements to check validity
- **We advise each regional entity to run these tests before using the information operationally**

Reminder: The Input Observatory Network is Sparse



Distances (km) of grid points to nearest observatory with 5 NRCAN and 8 USGS stations

Current Gap (Sites > 1000 km omitted)



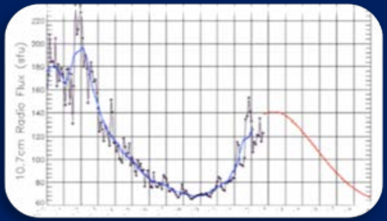
Options to Improve the Network

- Add more observatory data from
  - NASA/CCMC (initial steps)
  - Industry collaborations (open invitation)
  - DOE/SUNBURST…
  - NSF supported facilities…
- Key Requirements for the data
  - Maintain stable, continuous data flow with minimal delays
  - Mostly free from undesired artificial noise
  - Known directions for the components
  - Minimum cadence - one minute (averages) – (in the long term 10 second or faster cadence will be needed)
  - Only variations are needed for this application – not the absolute definitive values

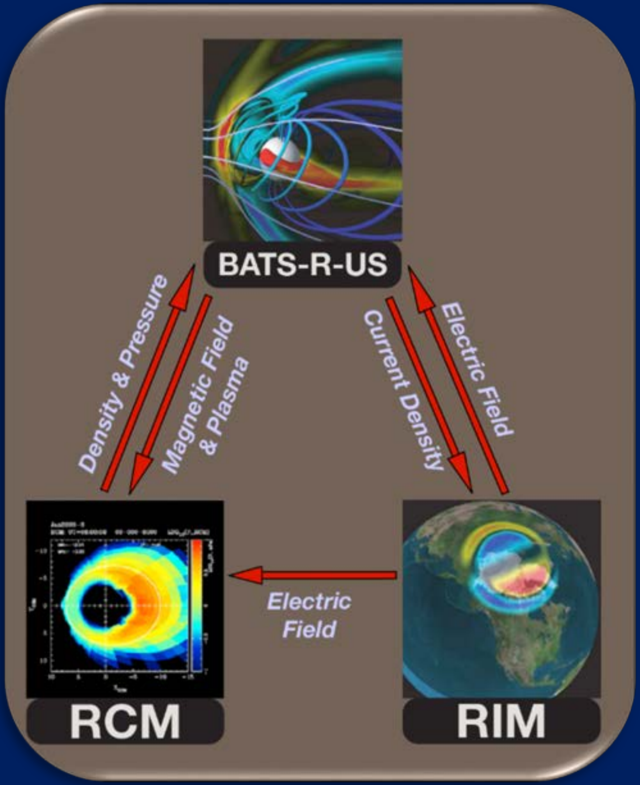
Forecasting:
Operational Geospace Model

Implementation at NWS

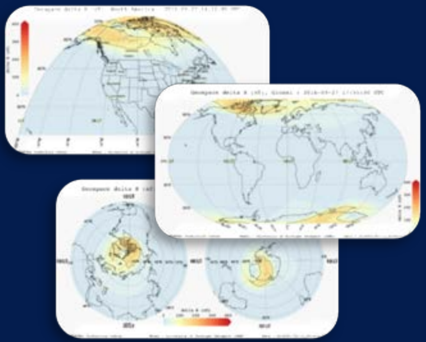
DSCOVR
Solar Wind Data:
V, n, T, B



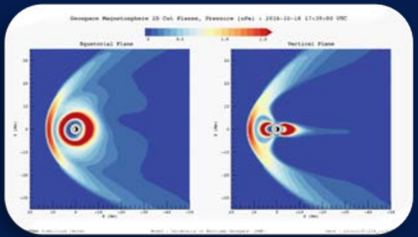
Solar F10.7 Radio Flux



Operational SWMF



http://www.swpc.noaa.gov/products

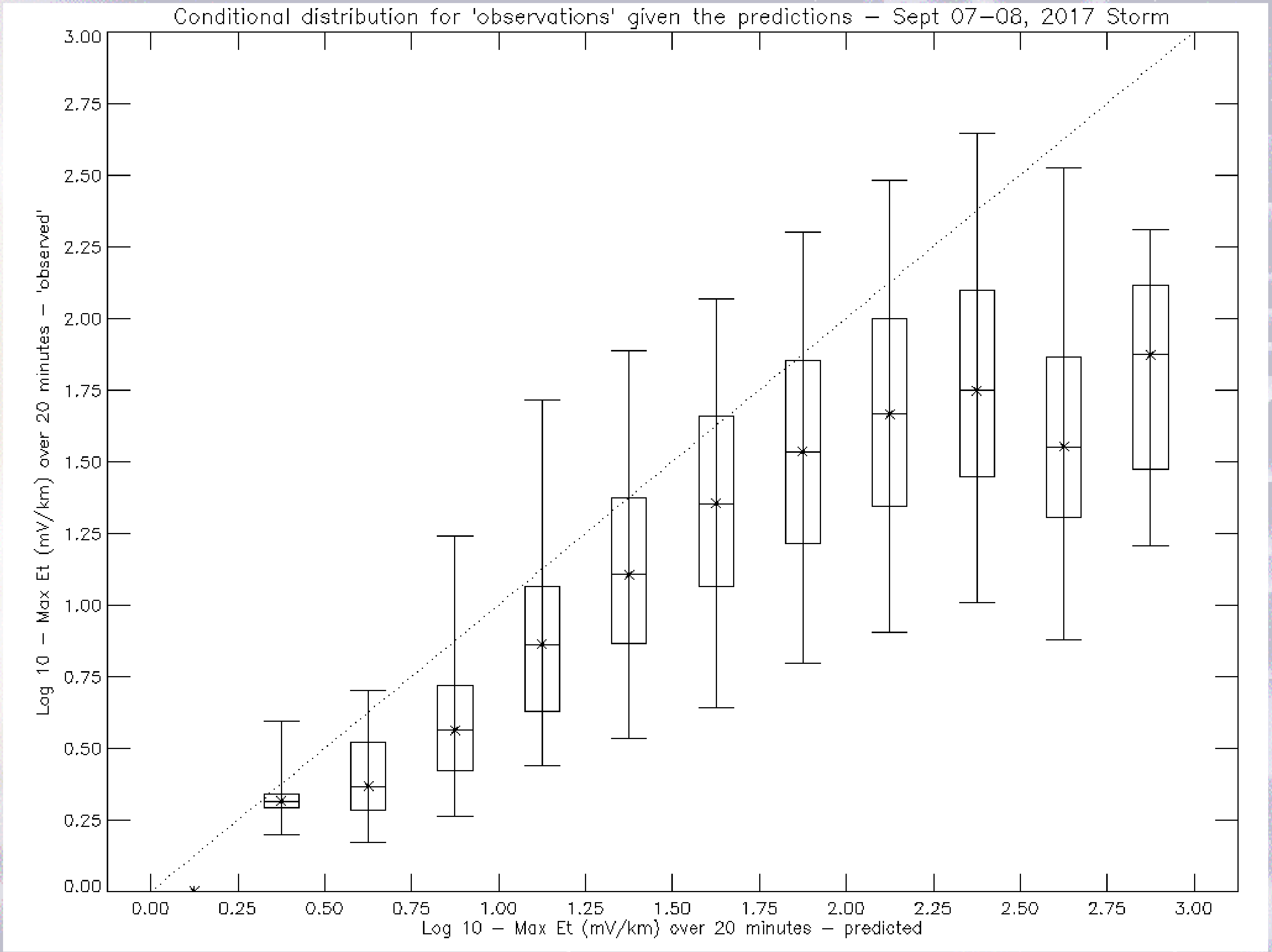


Predicts Geomagnetic Variations on a 2°x2° grid over lower 48 states

***SWPC** is looking at using the model output for the E-field predictions*

E-Fields: nowcast vs forecast

07-08 September 2017 storm



E-Fields: nowcast vs forecast

07-08 September 2017 storm

- Define an ‘event’ as |E| exceeding 100 mV/km over a 20 minute interval (for the September 07-08, 2017 storm)
- We compare predictions from Geospace with ‘observations’ from the ground-based mag calculation
- The 2x2 contingency table is shown below.
- There are more false alarms than hits, and there are a lot of misses
- The hit rate = 0.55 (hits over total events) is higher than the false alarm rate =0.14 (false alarms over total non-events) so at least the True Skill Statistic = 0.41 is positive
- Given that the forecast=yes, the probability of an event is ~27%
- Given that the forecast=no, the probability of an event is ~5%
- These results are limited to just one storm only – so further analysis is required to gain more confidence in this assessment
- There is likely sensitivity to choice of threshold

Fcst\Obs	Yes	No
Yes	748	2062
No	601	12720

Summary

Version 1 E-field products will be deployed on SWPC operational systems NLT than September 30, 2019

The next version for the E-field product uses improved conductivities (EMTF) and is running in test – deployment is planned for FY 2020

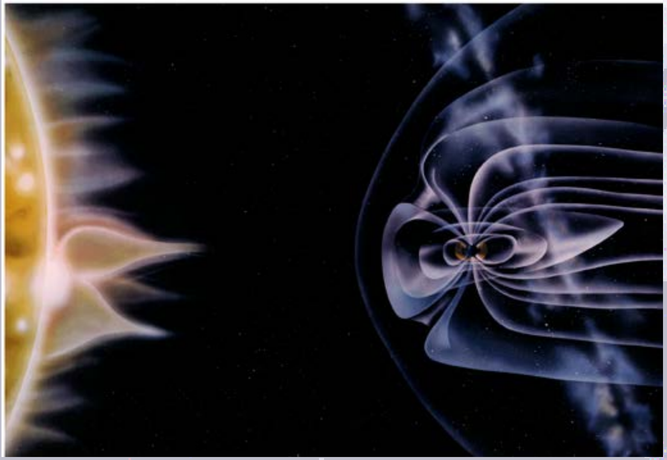
Joint US-Canada maps will be developed in FY 2020

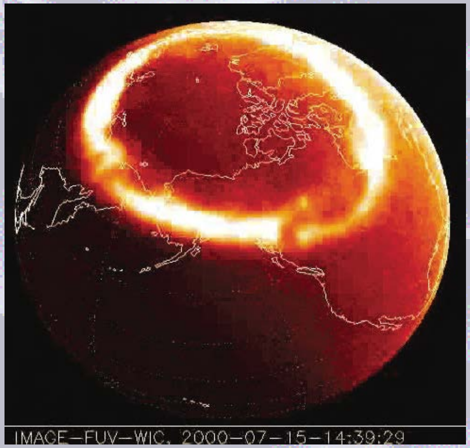
We invite users to work with us to run retrospective analyses for different map versions to test whether the maps provide actionable information

We will continue to evaluate regional forecast capability using the Geospace model

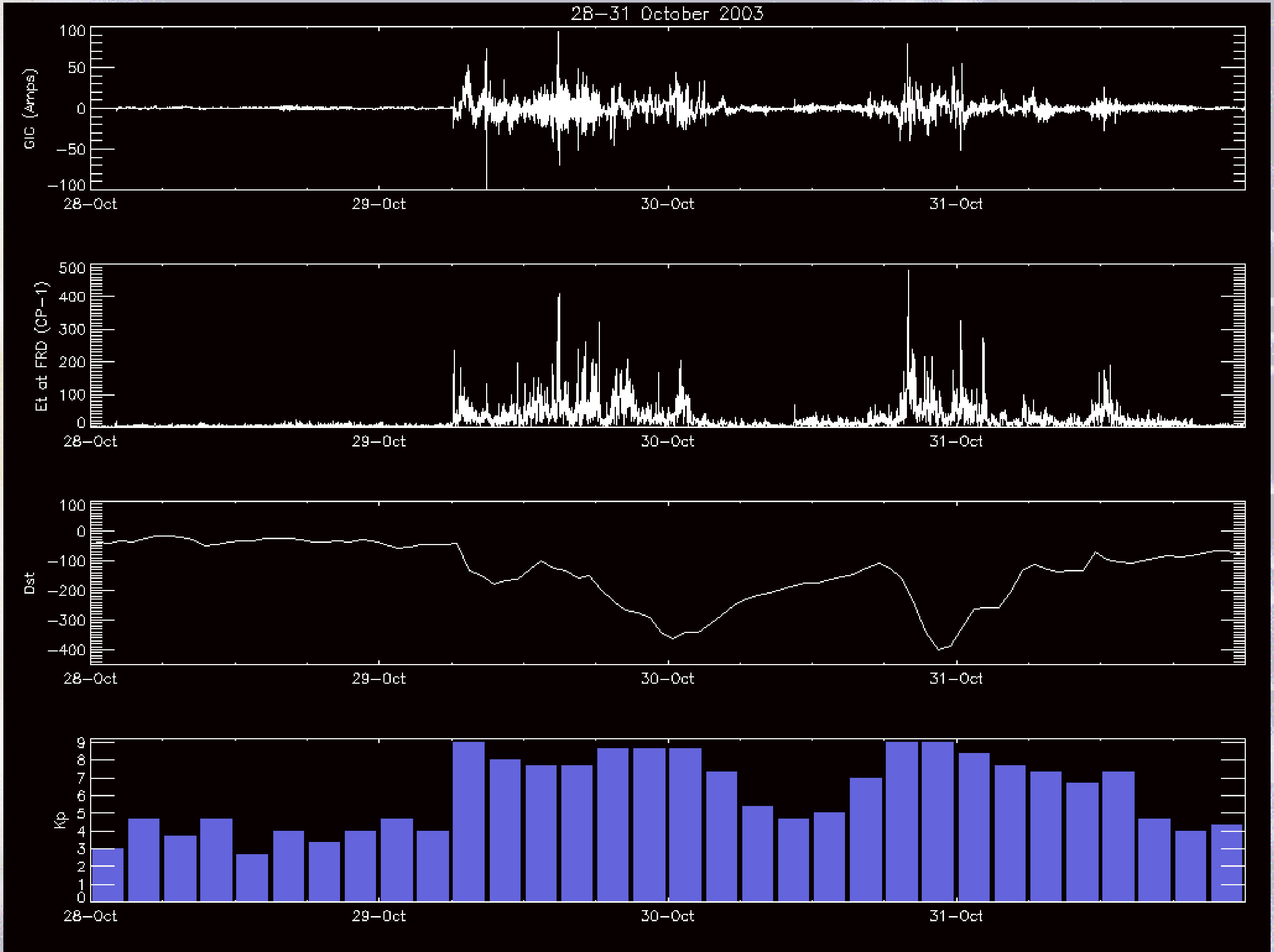
- Forecast skill is expected to improve with the newer model version
- Forecast products will provide summary measures over a (TBD) time interval – and will likely involve a probabilistic formulation

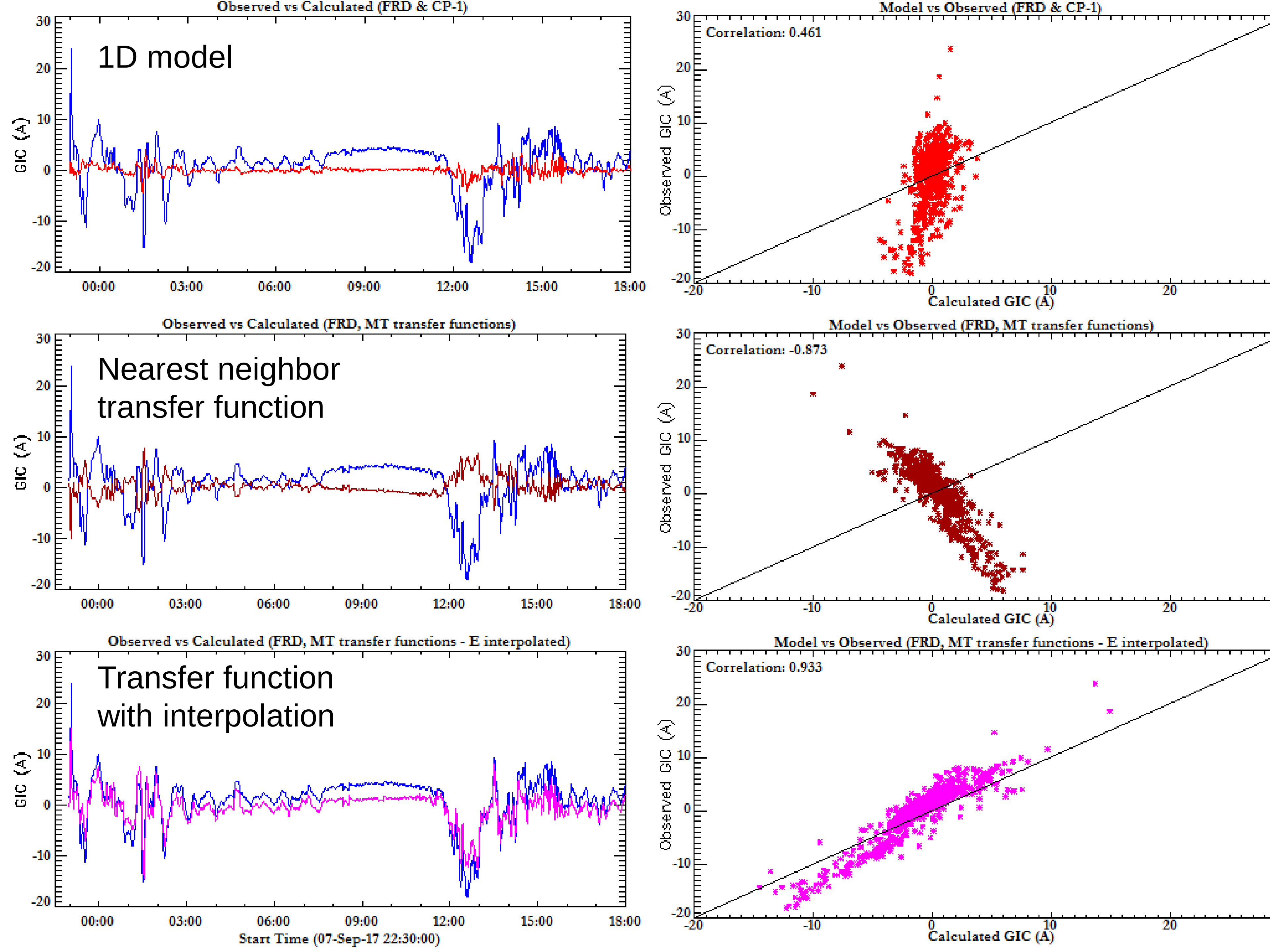
Questions?

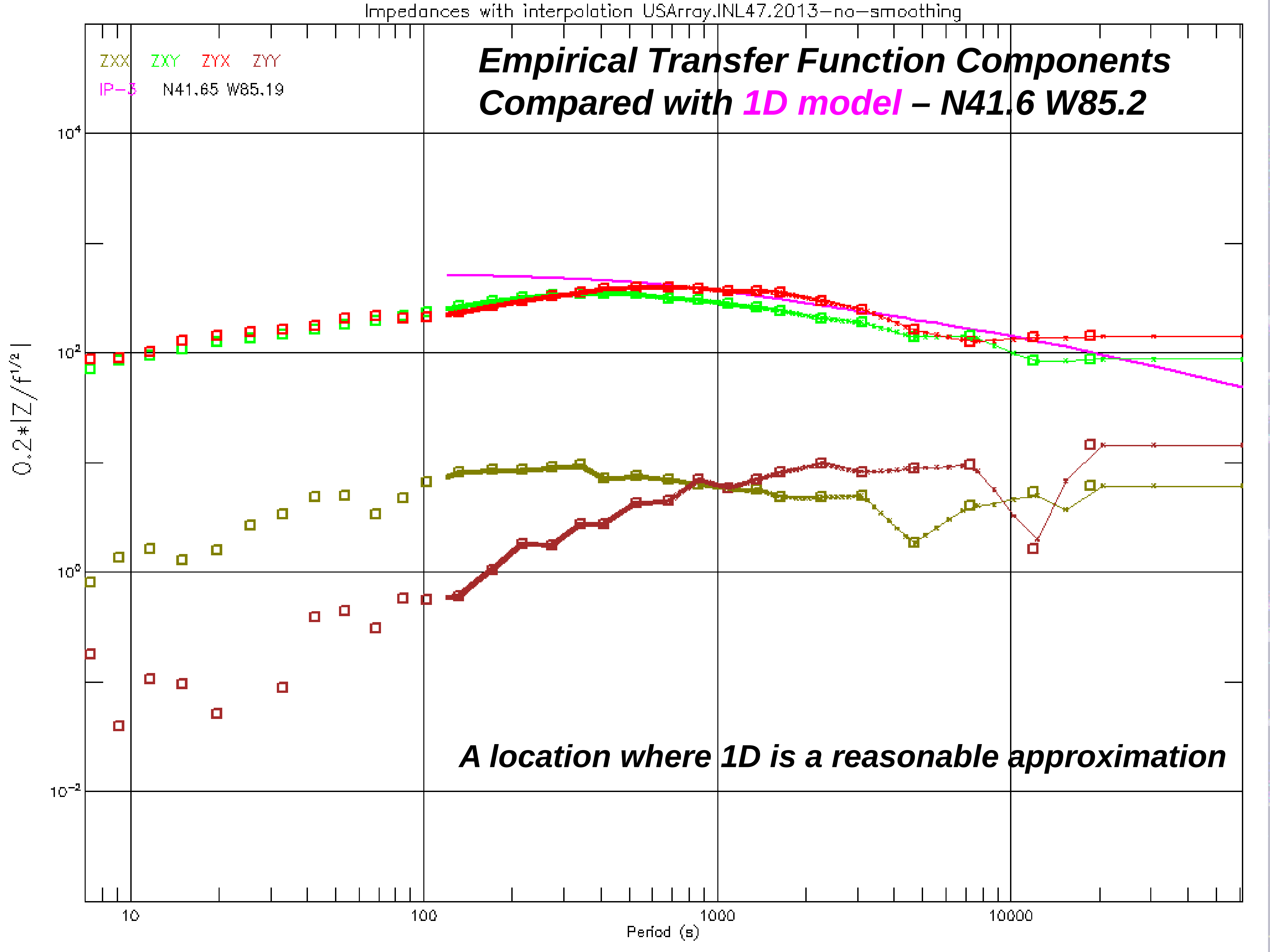


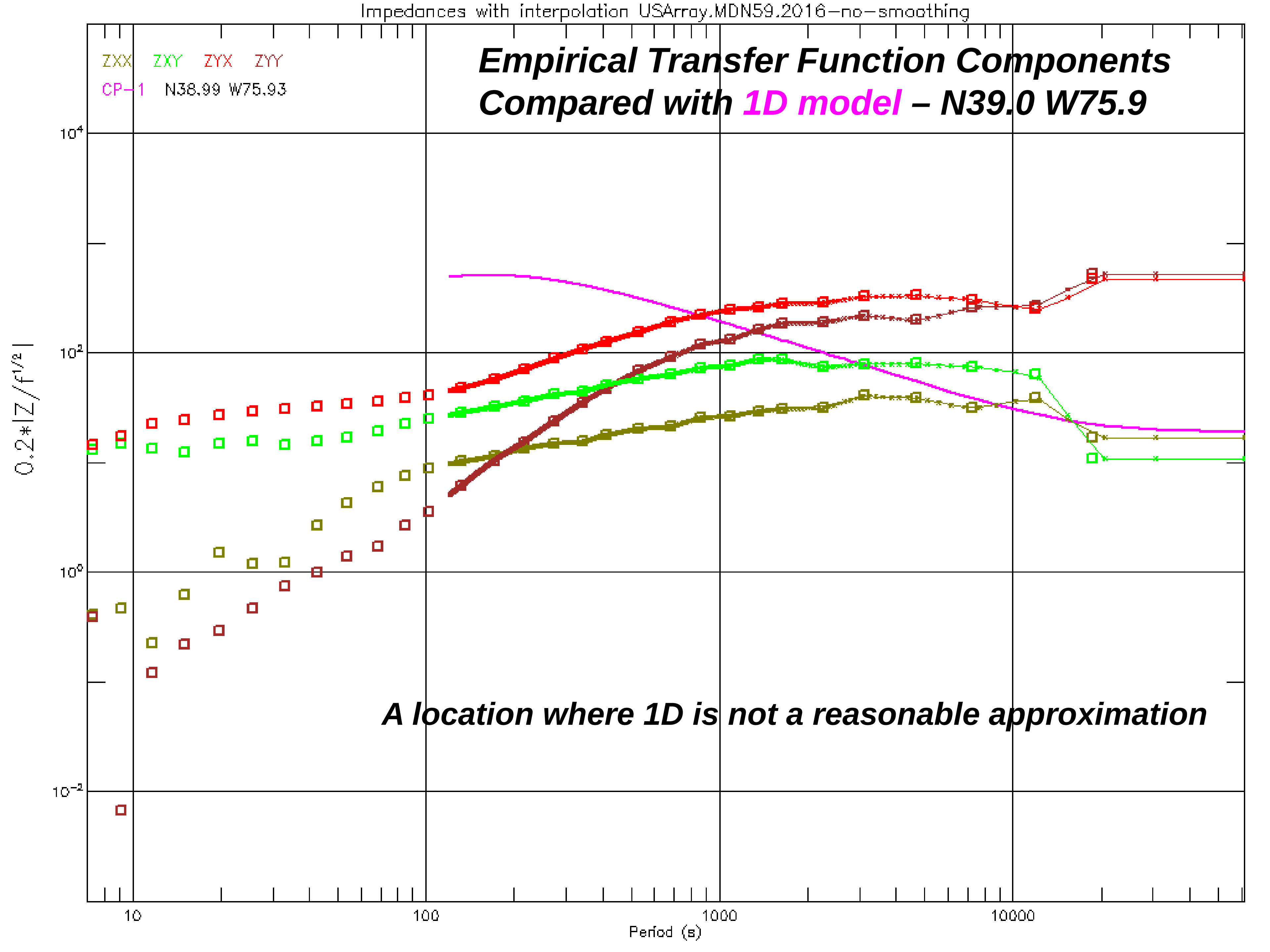


Comparison with the Storm Signatures

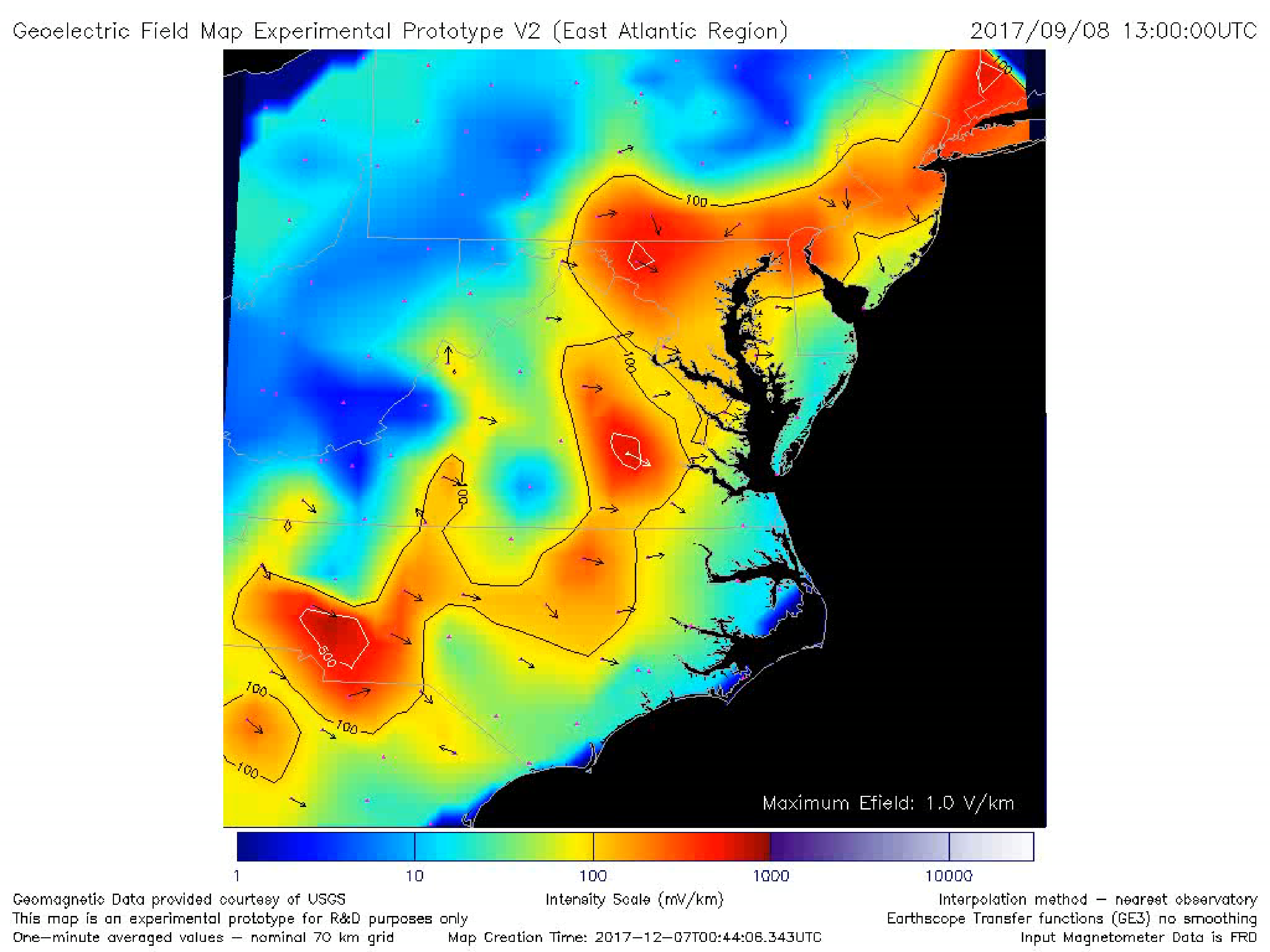



Observed vs Calculated (FRD & CP-1)
1D model
GIC (A)
Model vs Observed (FRD & CP-1)
Correlation: 0.461
Observed GIC (A)
Calculated GIC (A)
Observed vs Calculated (FRD, MT transfer functions)
Nearest neighbor transfer function
GIC (A)
Model vs Observed (FRD, MT transfer functions)
Correlation: -0.873
Observed GIC (A)
Calculated GIC (A)
Observed vs Calculated (FRD, MT transfer functions - E interpolated)
Transfer function with interpolation
GIC (A)
Start Time (07-Sep-17 22:30:00)
Model vs Observed (FRD, MT transfer functions - E interpolated)
Correlation: 0.933
Observed GIC (A)
Calculated GIC (A)

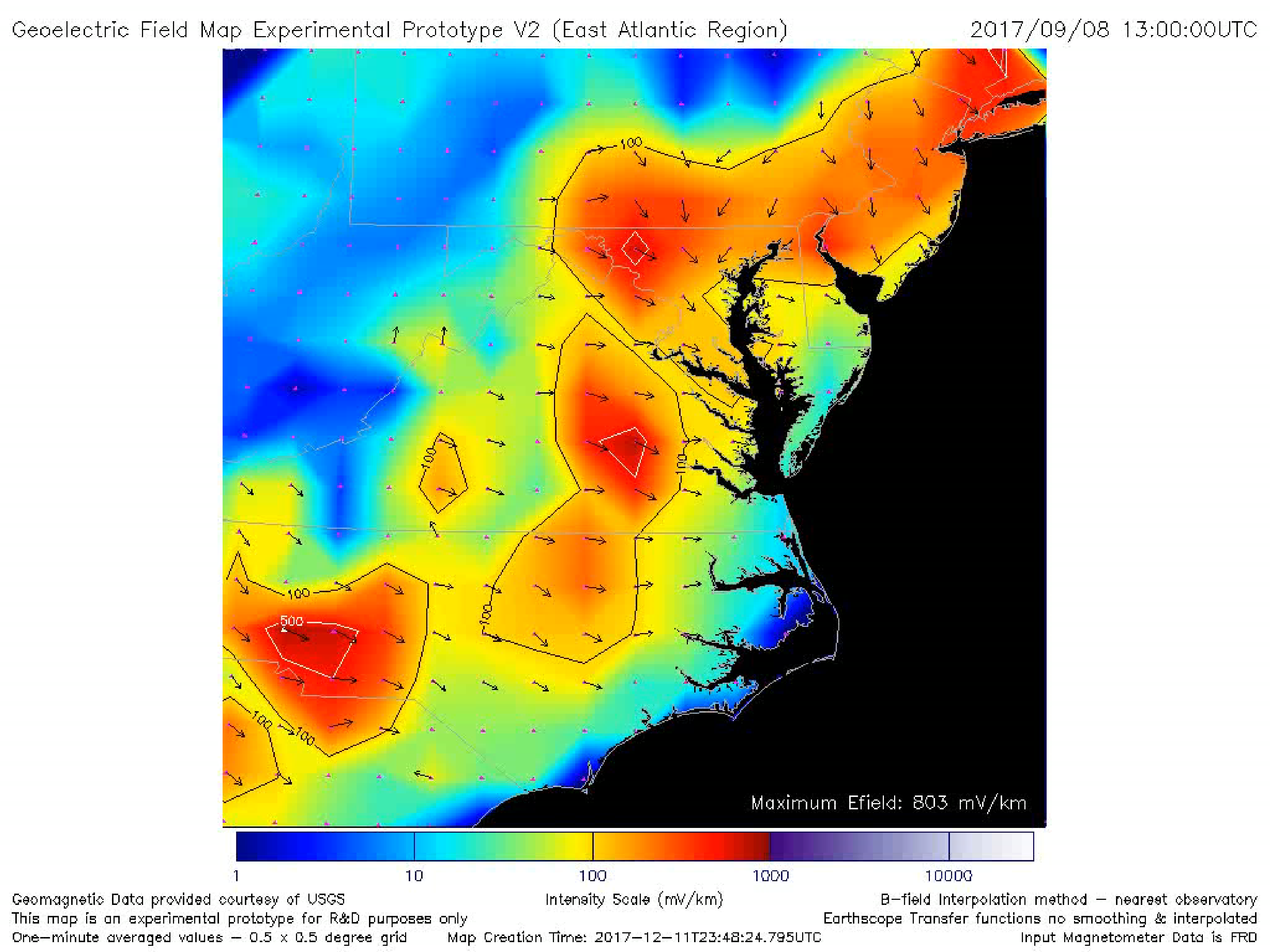

Impedances with interpolation USArray.INL47.2013-no-smoothing
ZXX ZXY ZYX ZYY
IP-3 N41.65 W85.19
Empirical Transfer Function Components
Compared with 1D model – N41.6 W85.2
A location where 1D is a reasonable approximation
10^4
10^2
10^0
10^{-2}
$0.2*|Z/f^{1/2}|$
10
100
1000
10000
Period (s)


Impedances with interpolation USArray.MDN59.2016-no-smoothing
Empirical Transfer Function Components
Compared with 1D model – N39.0 W75.9
ZXX ZXY ZYX ZYY
CP-1 N38.99 W75.93
A location where 1D is not a reasonable approximation
0.2*|Z/f^(1/2)|
Period (s)
10
100
1000
10000
10⁴
10²
10⁰
10⁻²

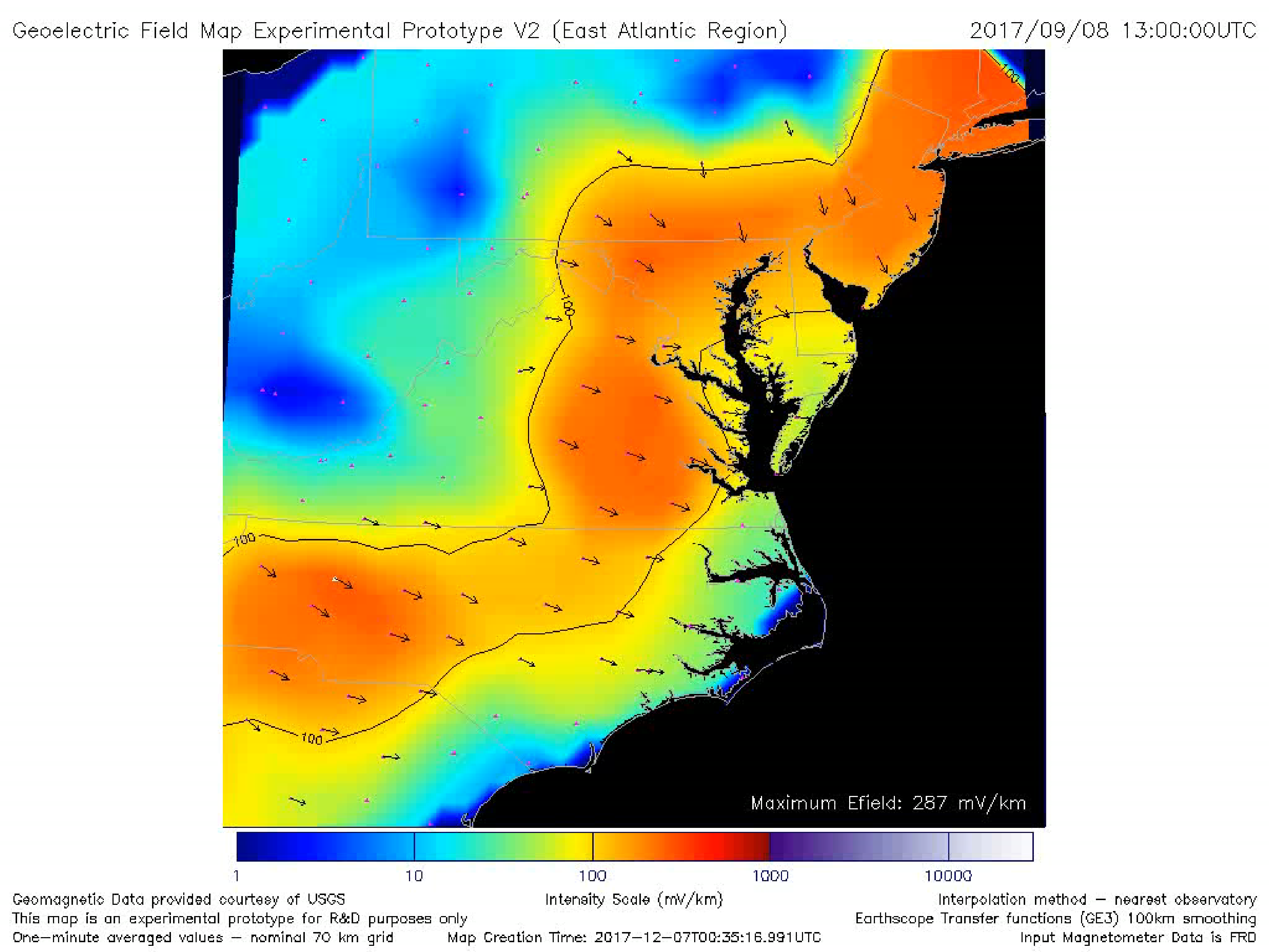
Using MT sites directly (irregular grid)



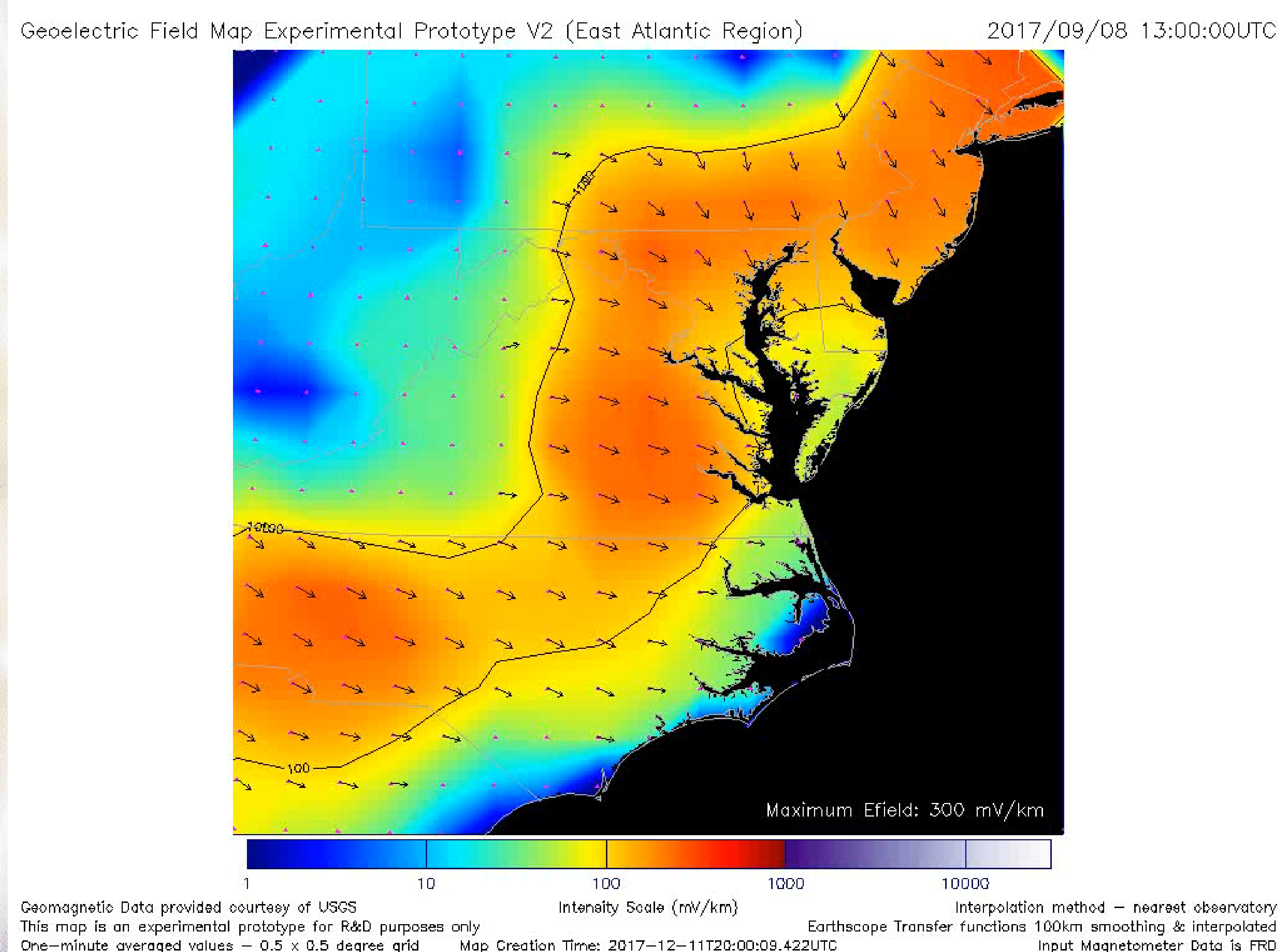
Interpolate from MT sites to 0.5° grid



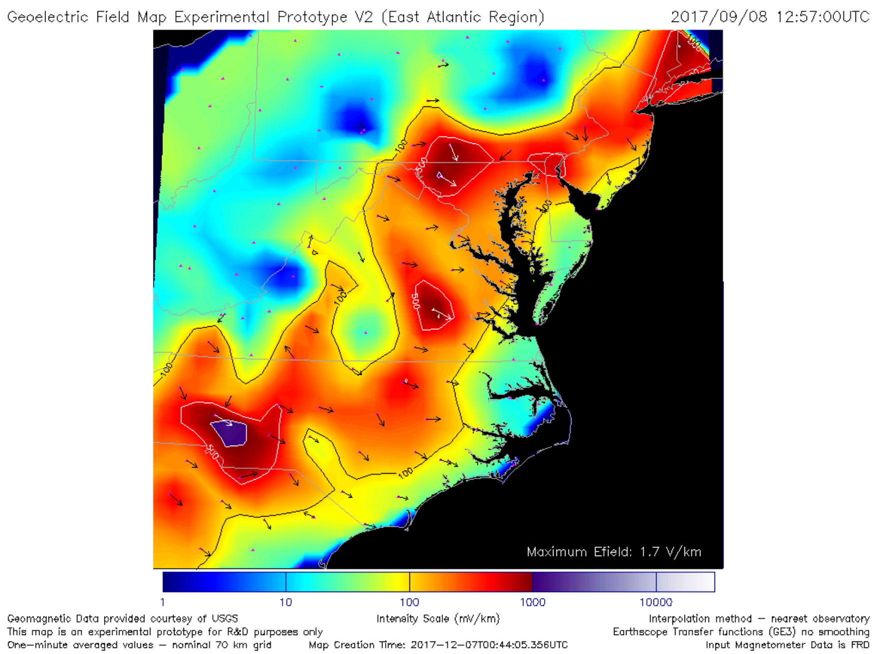
Irregular grid with 100 km smoothing

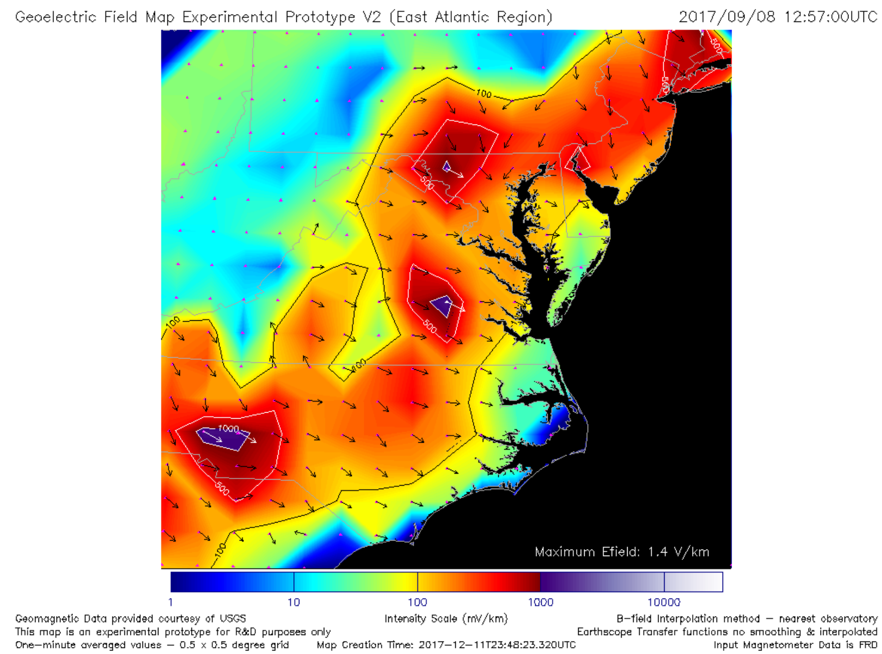


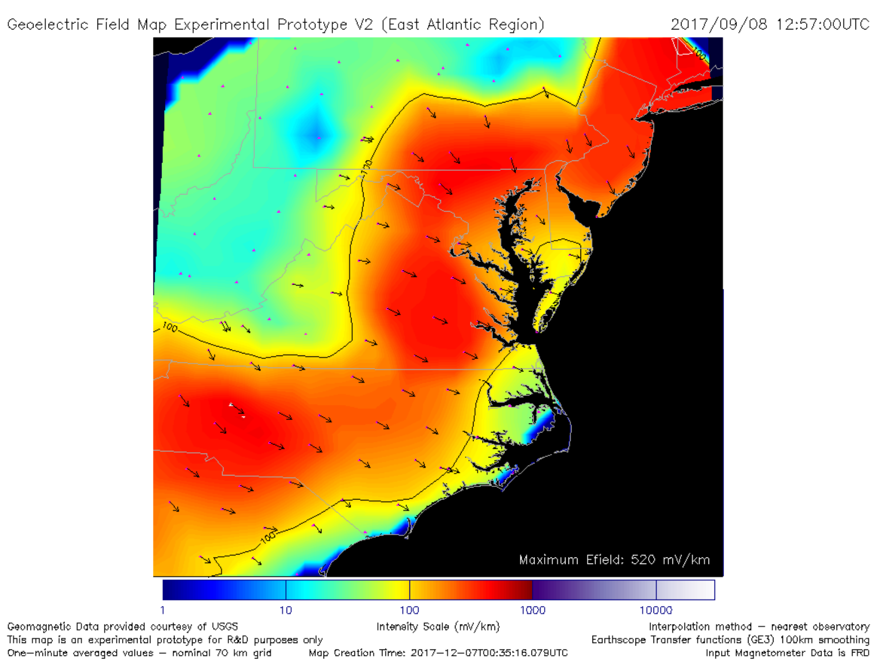
100 km smoothing on regular 0.5° grid

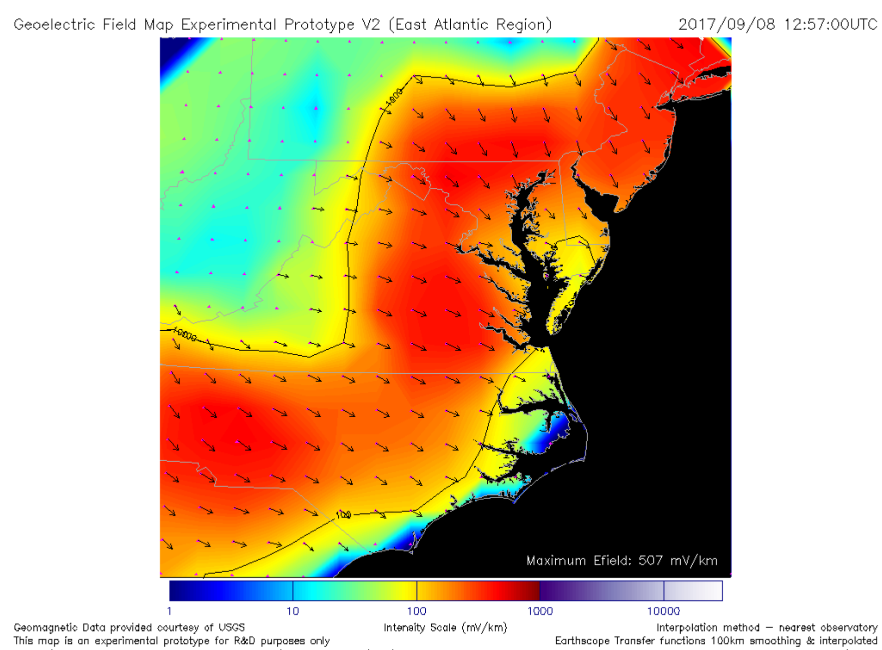


Side by side comparison









Data Dissemination via GeoJSON

- About GeoJSON
  - Adheres to a standard (RFC 7946): https://tools.ietf.org/html/rfc7946
  - Can be read by web and desktop GIS clients
  - Can be parsed as json, or by geojson libraries in a variety of languages
  - Could be returned by a geospatial data service (e.g. ESRI ArcGIS Online)
  - ASCII for human readability, compresses well when served with gzip enabled
- Sample data available from the September 2017 storm


```
{
  "type":"FeatureCollection",
  "features":[
    {
      "type":"Feature",
      "properties":{
        "Ex":-0.48,
"distance_nearest_station":1107.47,
        "Ey":-0.68,
        "quality_flag":5
      },
      "geometry":{
        "type":"Point",
        "coordinates":[
          -81.0,
          24.0
        ]
      },
    ...
```


- Each “feature” has properties (data) and geometry (coordinates)
- Can contain points, lines, multi-point lines, and polygons
- Human and machine readable ASCII - compresses well with gzip
- < 5 Kilobytes compressed for each minute

Sample Gridded Data

20170908T125730-10-Efield-2x2.dat (...or_1m\datadir_1m\2017\09\08) - GVIM

File Edit Tools Syntax Buffers Window Help

```
# product_filename         20170908T125730-10-Efield-2x2.dat
# time_tag                 2017-09-08T12:57:30.000
# product_generation_time  2017-09-08T13:06:44.658
# product_version          NearestMagFB1DLP
# cadence                  60
# n_stations               10
# n_station_models         45
# n_gridpts                283
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# last_insert_time         2017-09-08T13:06:35.347
# resolution               2x2
# grid_type                Geoelectric_Lower_48
# maximum_efield           210.34
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-81.00,24.00,-12.44,0.06,5,1107.47
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-81.00,28.00,-12.44,0.06,5,877.66
```

Geoelectric Field Calculation

- **Input – Geomagnetic Field (B-field) time series**
- **Earth conductivity acts like a frequency dependent filter:**
  - **The effect on input amplitude and phase depends on the frequency**
    - **High frequency fields have relatively shallow penetration (top-most layers), lower frequency fields have relatively deeper penetration (lower layers with different conductivity properties)**
- **Methods to determine the filter:**
  - **One-dimensional multi-layer models (conductivity varies with depth) allow the filter to be calculated numerically (but typically with limited accuracy) (EPRI-Fernberg models - 2012)**
  - **A magnetotelluric site survey (measures B-field and E-field together) allows the filter to be constructed empirically which incorporates all the effects of the 3D Earth conductivity (not available in all locations) (Earthscope-based models)**
  - **Earthscope MT data used with ModEM MT inversion code (Kelbert et al 2014) to generate high resolution 3D electrical conductivity model. (Enables interpolation between survey sites and also filters out near surface 'noise')**

U.S. DEPARTMENT OF
ENERGY
Cybersecurity, Energy Security, & Emergency Response

National Space Weather Strategy and Action Plan and U.S. Department of Energy Initiatives

John Ostrich, Program Manager, Risk and Hazard Analysis
U.S. Department of Energy
Cybersecurity, Energy Security, and Emergency Response

August 14, 2019

Office of Cybersecurity, Energy Security, and Emergency Response (CESER)

CESER MISSION

The Office of Cybersecurity, Energy Security, and Emergency Response (CESER) leads the Department of Energy's emergency preparedness and coordinated response to disruptions to the energy sector, including physical and cyber-attacks, natural disasters, and man-made events.

Infrastructure Security and Energy Restoration

The Infrastructure Security and Energy Restoration (ISER) Program is the lead for Emergency Support Function #12 (Energy) under the National Response Framework, and is the Energy Sector-Specific Agency for national efforts, in cooperation with public and private sector stakeholders, to enhance the preparedness, resiliency, and recovery of the U.S. energy infrastructure. **Three Resource Areas; Ten Programs**

Preparedness and Exercises

- **Goal:** *Lead Federal, State, and private sector partners to an enhanced level of coordination and preparedness for energy emergencies.*
- **Programs:**
  - Energy Sector Exercises
  - SLTT Energy Assurance
  - SSA Responsibilities
  - **Risk and Hazards Analysis**
  - International & Defense
  - Cyber Preparedness

Situational Awareness

- **Goal:** *Provide definitive situational awareness of power and fuel availability and infrastructure to support better prediction of, and recovery from, energy emergencies.*
- **Programs:**
  - Energy Sector Situational Awareness
  - Situational Analysis

Emergency Response and Recovery

- **Goal:** *Facilitate the response and recovery of the energy sector via coordination of private, state, local and federal activities and information sharing.*
- **Programs:**
  - Emergency Response
  - Cyber Incident Coordination

Cybersecurity for Energy Delivery Systems

Advance ***National Cyber Strategy*** goal to secure critical infrastructure, within the priority action area that calls for the Federal Government to work with the private sector to manage risks within seven key areas, including national security and energy and power.

Vision

Resilient energy delivery systems are designed, installed, operated and maintained to survive a cyber-incident while sustaining critical functions

Goals

1. Develop and improve tools for bi-directional, real-time, machine-to-machine information sharing

2. Research, develop, and demonstrate innovative tools and technologies to prevent, detect, and mitigate cyber-incidents in today's and future energy delivery infrastructure.

3. Build strategic core capabilities in the DOE National Laboratories to reduce the risk that a cyber-attack might disrupt energy delivery

Objectives

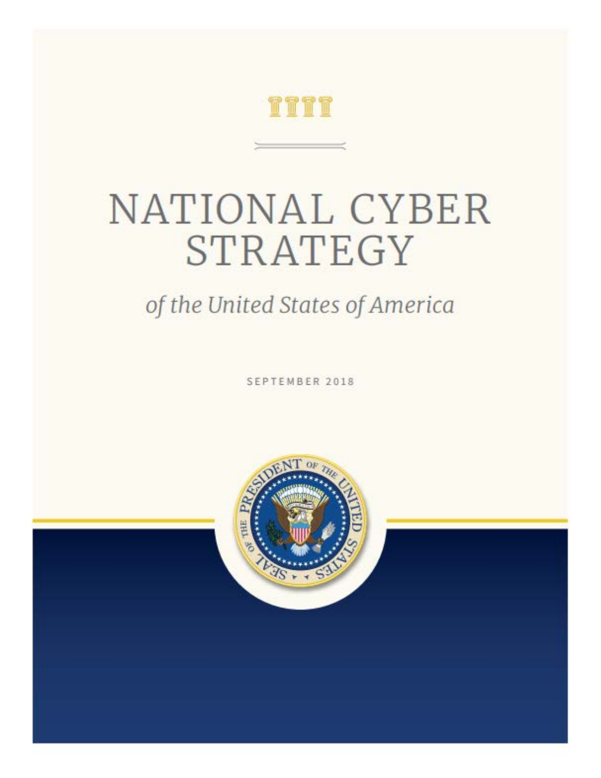
Increase timeliness and effectiveness of public-private bi-directional information sharing to detect and mitigate high-risk threats to energy infrastructure information technology (IT) and operational technology (OT) networks through the Cybersecurity for the OT Environment (CYOTE™) and Cyber Analytics Tools and Techniques (CATT™) projects.

Research, develop and demonstrate tools and technologies to:

- *Decrease the cyber attack surface*;
- *Provide for real-time automated continuous cybersecurity situational awareness*
- *Provide for automated response to a cyber incident* – adapt to survive.

- Quantify relative cyber-risk reduction
- Advanced threat mitigation through bi-directional, actionable, timely information sharing
- Quantum Key Distribution for energy infrastructure to reveal adversarial intrusion in real-time
- AI techniques, such as machine learning, for OT to automatically adapt and survive a cyber-attack

National Cyber Strategy



- First fully articulated national cyber strategy in **15 years**.
- Outlines actions to
  1. **Defend the homeland** by protecting networks, systems, functions, and data;
  2. **Promote American prosperity** by nurturing a secure, thriving digital economy and fostering strong domestic innovation;
  3. **Preserve peace and security** by strengthening the United States' ability— in concert with allies and partners — to deter and if necessary punish those who use cyber tools for malicious purposes; and
  4. **Expand American influence** abroad to extend the tenets of an open, interoperable, reliable, and secure Internet.

Executive Order on EMP

Section 5 (e) of the Executive Order states:

The **Secretary of Energy** shall conduct early-stage R&D, develop pilot programs, and partner with other agencies and the private sector, as appropriate, to characterize sources of EMPs and their couplings to the electric power grid and its subcomponents, understand associated potential failure modes for the energy sector, and coordinate preparedness and mitigation measures with energy sector partners

NATIONAL SPACE WEATHER STRATEGY AND ACTION PLAN

NATIONAL SPACE WEATHER STRATEGY AND ACTION PLAN

Product of the

SPACE WEATHER OPERATIONS, RESEARCH, and MITIGATION WORKING GROUP

SPACE WEATHER, SECURITY, and HAZARDS SUBCOMMITTEE

COMMITTEE ON HOMELAND and NATIONAL SECURITY

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

March 2019

OBJECTIVES of the NATIONAL SPACE WEATHER STRATEGY AND ACTION PLAN

1. **Enhance the Protection of National Security, Homeland Security, and Commercial Assets and Operations against the Effects of Space Weather**

2. **Develop and Disseminate Accurate and Timely Space Weather Characterization and Forecasts**

3. **Establish Plans and Procedures for Responding to and Recovering from Space Weather Events**

Improve the Understanding of and Assess Vulnerabilities of Critical Infrastructures and National Security Assets to Space Weather Events

- **Assess the vulnerability of priority critical infrastructure systems and national security assets to the effects of space weather and use the results to inform risk management**

- **Model the effects of space weather on space-, air-, and ground-based national critical functions and associated priority critical infrastructure and national security systems, assets, and networks**

- **Assess the cost of space weather effects on the operations and implementation of critical missions**

Develop and Test Technologies that Protect and Mitigate Critical Systems and Assets

- **Identify and prioritize R&D necessary to enhance the security and resilience of critical functions and national security assets to the effects of space weather**

- **Test, evaluate, and deploy technologies and devices to mitigate the effects of space weather on critical functions and assets**

- **Support the development and use of standards for improved resilience of equipment to space-weather events**

Improve Observations and Modeling for Characterization and Forecasting

- **Enhance current space weather models and develop improved modeling techniques for space weather**

- **Identify and release, as appropriate, new or previously underutilized data sets**

Ensure Timely Dissemination of Characterizations and Forecasts Useful to Consumers

- **Improve the effectiveness of space weather event notifications**

- **Develop and refine situational awareness capabilities**

Improve Planning for Space Weather Events

- **Develop, review, and update Federal response plans, programs, and procedures to address the effects of space weather**

- **Facilitate information sharing to inform and enhance the operation and restoration of critical infrastructure at greatest risk to the effects of space weather**

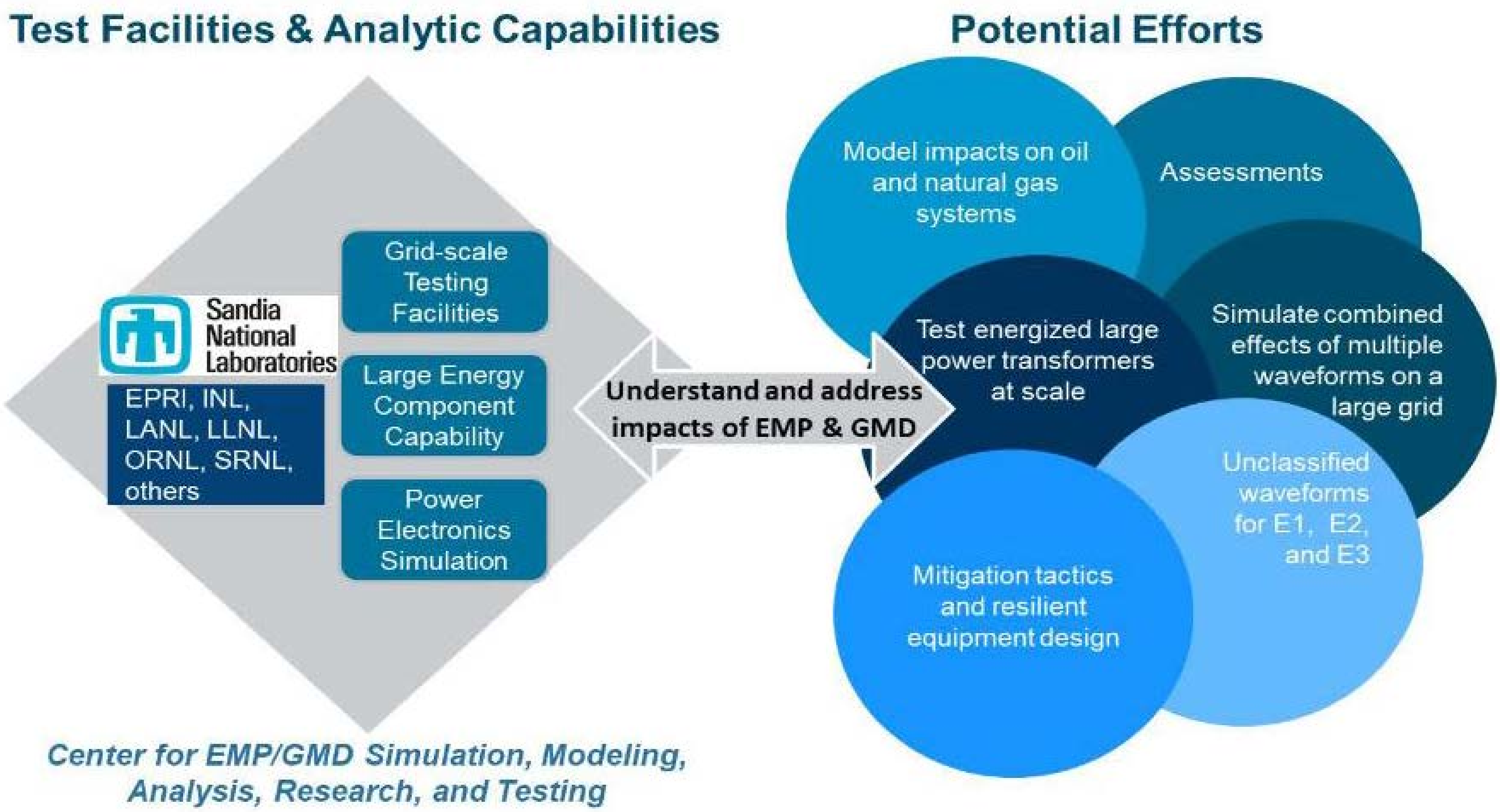
Test and Evaluate Plans and Procedures for Space Weather Events

- **Assess executive and statutory authority regarding the ability to direct, suspend, or control critical infrastructure operations, functions, and services before, during, and after space weather events**

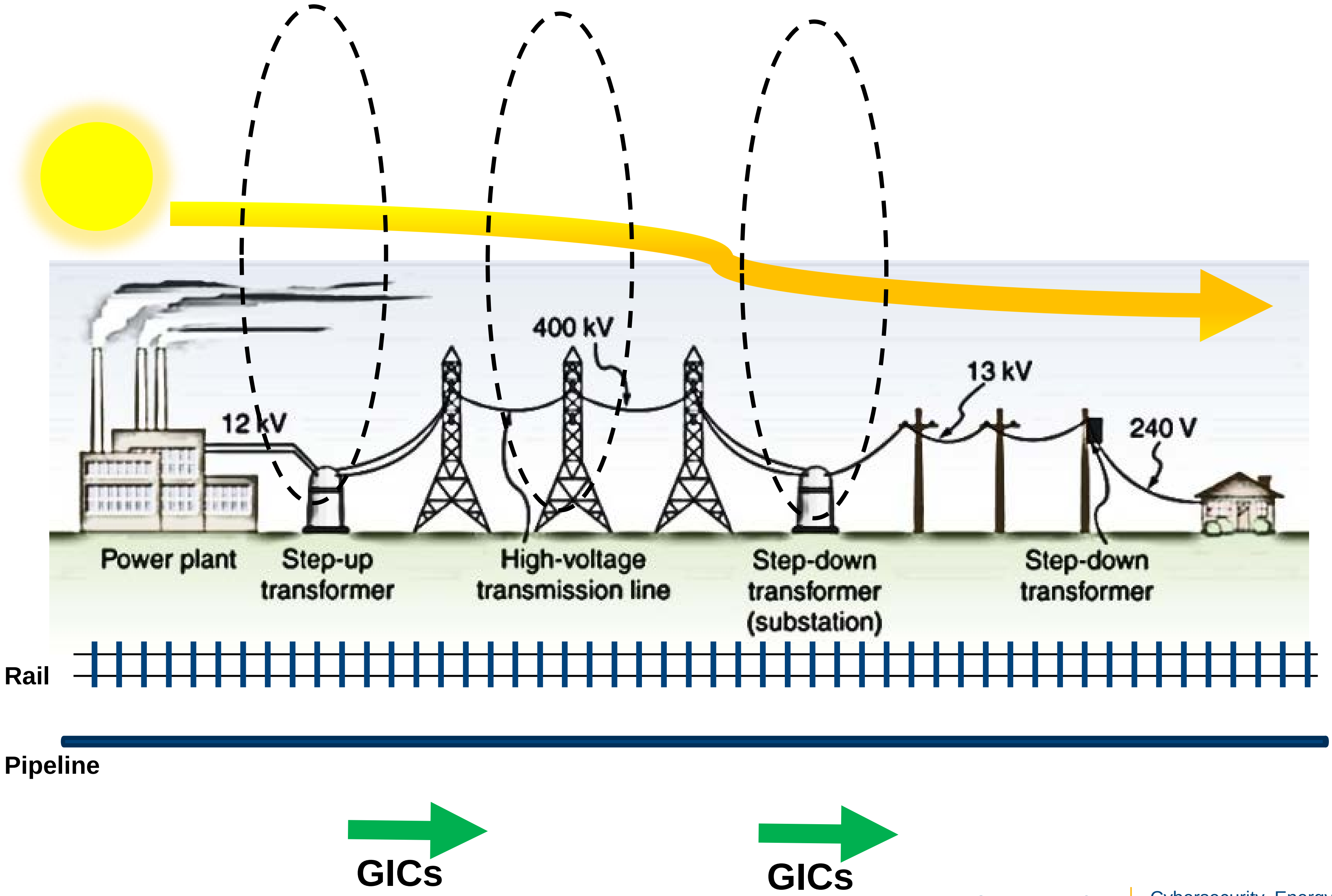
- **Exercise Federal response, recovery, and operations plans and procedures for space weather events**

DOE's Coordinated Path Forward to Address both EMP and GMD

To accomplish the goals of the Joint EMP Resilience Strategy and the new EO on EMP and the National Space Weather Strategy and Action Plan, DOE is building a new national program, **CE-SMART,** via a hub-and-spoke model



GMDs Induce Currents into Long Conductors



DOE Future Actions

- **Support National Space Weather Strategy and Action Plan**
  - DOE has a number of actions and deliverables

- **Develop and Implement CE-SMART**
  - Started in FY 2019
  - Center for EMP/GMD Simulation, Modeling, Analysis, Research and Testing

- **Mitigation and Protection**
  - Implement pilot program to field deploy mitigation or protection devices on grid

Questions?

John Ostrich, Program Manager, Risk and Hazard Analysis
Cybersecurity, Energy Security, and Emergency Response
U.S. Department of Energy

John.Ostrich@hq.doe.gov

Back up Slides – Impacts and Mitigations

Space Weather Effects

- **GIC Effects on Transformers:**
  - Causes half-cycle saturation with quasi-DC current
  - Significantly increases core noise and vibration
  - Creates harmonics
  - Increases absorption of reactive power
  - Causes voltage instability
- **GIC Effects on Other Parts of Bulk Electric System:**
  - May trip protective equipment
  - Could trip generators
  - Could result in grid imbalances
  - Interferes with precision timing devices

Potential Impacts on the Electric Grid from an Extreme Storm

- **Voltage Collapse is Biggest Concern Due to:**
  - Increase in Absorption of Reactive Power
  - Tripping of Generators and Other Equipment
- **Damage to Transformers from Heat and/or Vibrations**
- **Wear and/or Damage to Other Equipment**
  - Fuses and Breakers May Open
  - Bearings
- **Voltage Instability Can Lead to Power Quality Issues**
  - Lights Flickering
  - Damage to Customer Equipment?

Mitigation Current Systems

- **Adjust Protective Equipment to Reduce False Trips**
- **Have Ample VAR Compensation Available**
- **Reduce Load on Vulnerable Transformers**
- **Cool Transformers Prior to Arrival of GICs**
- **Reconfigure Grid to Reduce or Eliminate Movement of Electricity on Long Distance Transmission Lines**

Mitigation Future Options

- **Deploy new transformers with lower susceptibility to adverse impacts from GI**

- **Rely more on distributed energy resources**

- **Consider factors that affect strength of GICs when siting new substations:**
    - Latitude
    - Geology
    - Large Bodies of Water
    - Orientation of Transmission Lines
    - Adjust Protective Equipment to Reduce Trips

Current Protection and Cost to Enhance

- **Current Protection**
  - GIC blockers on transformer neutrals
  - Series compensation on transmission lines
  - Transformers with high GIC withstands
  - Protective device settings to prevent premature trips

- **Potential Protection Measures**
  - Transformers with higher GIC withstands
  - Configuring and building systems with less reliance on high voltage equipment and/or long distance power lines
  - Neutral resistive device
  - Low capacitance neutral blocker
  - Sacrificial MOV (surge arrestor) as a ground

Situational Awareness and Response

- **Situational Awareness**
  - Monitoring and Reporting Prior to, During, and After an Extreme GMD
- **Response**
  - Activation
  - Coordination with Partners
  - Damage Assessments
  - ESF-12 Roles and Responsibilities
  - DOE Responsibilities and Authorities

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EMP Task Force Status Update

Industry Outreach

Rey Ramos, Southern Company

GMD Task Force Meeting

August 14, 2019

RELIABILITY | RESILIENCE | SECURITY




Why is NERC Focusing on EMP?

- **October 9, 2018 |** The U.S. Department of Homeland Security (DHS) issued an EMP Strategy
- **March 26, 2019 |** U.S. Executive Branch issued an Executive Order addressing EMP
- **April 30, 2019 |** EPRI released Final Report on the impacts of HEMP to the BPS after completing a three year research project

Purpose

- **May 2019 |** NERC launched a Task Force to identify reliability concerns associated with EMPs and potential methods for promoting resilience
- The Task Force advises NERC, regulators, Regional Entities, and industry stakeholders to establish a common understanding of the scope, priority, and goals for the development of next-steps to address resilience to HEMP events

Collaboration with Government Agencies

- Task Force is an advisory team that collaborates with governmental authorities and industry members to provide leadership and guidance
- Associated with the Task Force to-date are the following U.S. government agencies:
  - Department of Energy (DOE)
  - Defense Threat Reduction Agency (DTRA)
  - DHS – Cyber Infrastructure Security Agency (CISA)
  - Federal Energy Regulatory Commission (FERC)
  - National Aeronautics and Space Administration (NASA)
  - Federal Emergency Management Agency (FEMA)
  - U.S. National Labs (Los Alamos, Sandia, Lawrence Livermore)

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Membership

Chair	Aaron Shaw	AEP
Vice-Chair	Rey Ramos	Southern Company
Members	John Babik	JEA
	Kenneth Braerman	Exelon Corporation
	Brian Evans-Mongeon	Utility Services
	Barry Gustafson	Xcel Energy
	Jason Marshall	Wabash Valley Power Association
	Arun Narang	Hydro One
	Thomas Popik	Resilient Societies
	Joe Sowell	GTC
	John Stephens	City Utilities
	Micah Till	Dominion Energy
	Randy Crissman	NYPA

Structure

- **Subgroup 1:** System Planning and Modeling
  - Provide guidance on how the industry might assess the potential impacts of EMP events on BPS reliability using the best available science recognizing the various BES designs across North America
- **Subgroup 2:** Critical Facility Assessment
  - Provide guidance to BPS owners and applicable NERC committees on how to appropriately identify and prioritize the types of facilities such as, but not limited to, power plants, substations, and control centers, that may have the highest priority with respect to EMP impact assessment and mitigation actions
- **Subgroup 3:** Mitigation, Response, and Recovery
  - The results of work from Subgroups 1 and 2 will be considered to provide guidance to BPS owners and applicable NERC committees on possible mitigation solutions, response plans, and recovery strategies

Phased Approach

Phase 1
- Strategic Recommendations

Phase 2
- Technical Committee Work

Phase 3
- Standard Drafting Team (if applicable)

Phased Approach (cont.)

Phase 1

- Strategic Recommendations

(Example) Key Recommendation # __ | Collaboration and Coordination with Federal Government
Maintain an EMP Task Force within the ERO Enterprise Technical Committees to regularly coordinate and collaborate with governmental authorities to procure and effectively disseminate information needed by industry

- Collaborate with DHS to obtain the recommended unclassified E1 and E3 EMP environments (i.e., benchmark scenarios) that the industry needs to conduct vulnerability assessments...
- Consider the development of technology/alert systems to provide advance and/or post-event notices and information of HEMP events (location, altitude, etc.) to be used by the industry to take operational actions to reduce or recover from the impacts...

Key Task Force Milestones – Phase 1

June
- Numerous TF calls
- Face-to-face meeting (Washington DC)

July
- Numerous TF calls
- Charter development
- Technical workshop (ATL)

August
- Develop Strategic Recommendations
- Face-to-face meeting (ATL)
- Post for industry comment (30 days, end of August)

October
- Review industry comments
- Present recommendations with action items and next steps to appropriate committee

November
- Present recommendations to NERC Board of Trustees

Phase 2

Phase 1 - 2019 Deliverables

1. **Work Plan Schedule:** The task force shall develop a schedule for Phase 1 that will be reviewed and updated periodically.
2. **Meetings:** The task force shall convene in-person and/or conference calls to facilitate the discussion required to accomplish its mission and objectives.
3. **EMP Bibliography/Reference Document:** Publish an EMP bibliography/reference document for the electricity sector.
4. **Strategic Recommendations:** Develop and agree on a set of strategic recommendations that can be shared with the industry for review and comment.
5. **Post Strategic Recommendations for Industry Comments:** Post the strategic recommendations for industry review and comment.
6. **Review Industry Comments on Strategic Recommendations:** Consider industry comments on the strategic recommendations for inclusion in a Phase 1 report.
7. **Develop a Report with Recommendations:** Develop a report summarizing the findings of the task force that should include a prioritized list of recommended actions and/or next steps. The task force shall develop a resolution requesting endorsement of the report and its recommendations from NERC.

Task Force Activities To-Date

- May 20, Introductory call for task force
- June 12, Initial face-to-face meeting in Washington, D.C.
- July 25, NERC EMP Technical Workshop in Atlanta, GA
- **August 27,** NERC EMP Task Force Meeting (finalize strategic recommendations) in Atlanta, GA
- Industry outreach:
  - July 2 | North American Transmission Forum (NATF)
  - July 18 | Electricity Subsector Coordinating Council (ESCC)
  - August 7 | Northwest Power Pool (NWPP)
  - August 14 | NERC GMD Task Force… *[tentative]*
  - August 20 | North American Generator Forum (NAGF)… *[tentative]*
  - September 12 | Edison Electric Institute (EEI)… *[tentative]*
  - **Suggestions (?)**

EMP Task Force Webpage

- **Engage**: https://www.nerc.com/pa/Stand/Pages/EMPTaskForce.aspx

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About NERC | Governance | Committees | Program Areas & Departments | Standards | Initiatives | Filings & Orders | Newsroom

- One-Stop-Shop (Status, Purpose, Implementation Plans, FERC Orders, RSAWS)
- Reliability Standards
  - US Effective Dates
  - US Effective Date Status/Functional Applicability
  - Complete Set of Reliability Standards
  - Glossary of Terms
  - VRF Matrix
  - VSL Matrix
  - Functional Model
- Balloting & Commenting
- Reliability Standards Under Development
  - Projected Posting Schedule
  - Project Tracking Spreadsheet
  - Regional Standards Development
  - Reliability Standards Development Plan
  - Requests for Interpretations (RFIs)
  - Standard Authorization Requests (SARs)
  - Standard Drafting Team Vacancies
- Archived Reliability Standards Under Development
- Standards Committee
- Webinars
- Workshops
- Resources

Home > Program Areas & Departments > Standards > Electromagnetic Pulses Task Force

Electromagnetic Pulses Task Force

Task Force Resources
Related Files

Background

Protecting the Bulk Power System and assuring the effective reduction of risks to reliability are integral pieces of the Electric Reliability Organization (ERO) mission. NERC has launched efforts to identify reliability concerns associated with Electromagnetic Pulses (EMPs) and potential methods for promoting resilience. A task force was created in April 2019 to first identify key issues and scope areas of improvement for the industry. The task force will also submit, as necessary, best practices and reliability guidelines to the NERC technical committees for review and endorsement. If necessary, a SAR will be submitted to the Standards Committee by the end of the year.

In late April 2019, Electric Power Research Institute (EPRI) released another report which defined the EMP threat, assessed vulnerabilities/risks, and made mitigation recommendations, in addition to laying the groundwork for the technical basis to develop a potential standard. The EPRI report complements a Department of Energy (DOE) action plan that was released in January 2017 on EMP Resilience. The action plan identified five goals: 1) improve and share understanding of EMP threats, effects, and impacts; 2) identify priority infrastructure; 3) test and promote mitigation and protection approaches; 4) enhance response and recovery capabilities; and 5) share best practices across government and industry.

On March 26, 2019, the President of the United States issued an Executive Order on Coordinating National Resilience to Electromagnetic Pulses (EMP). The Executive Order calls for collaboration and information sharing among government agencies and private industry as appropriate to promote resilience to EMPs, particularly with regard to threat and vulnerability assessments. The Executive Order also directed the federal government to provide incentives as appropriate to "encourage innovation that strengthens critical infrastructure against the effects of EMPs through the development and implementation of best practices, regulations, and appropriate guidance." Various agencies were assigned different areas of focus. Of particular relevance, the Secretary of Energy was tasked to perform initial research and development and develop pilot programs that would identify potential failures modes, contingency preparedness, and mitigations with regard to the risk to the electric power grid. NERC will continue to work with DOE and EPRI to clearly understand EMPs, their effective mitigations, and the proper ways to engage industry.

Subscribe to EMP Task Force Distribution List
Select "NERC Email Distribution Lists" from the "Applications" drop-down menu and specify the list in the Description Box.

Questions and Answers

EMP Task Force Workshop Agenda

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Agenda
Electromagnetic Pulse Task Force (EMP) Workshop

July 25, 2019 | 8:30 a.m.–5:00 p.m. Eastern

NERC
3353 Peachtree Road N.E. Suite 600, North Tower
Atlanta, GA 30336

Dial-in Number + 1-415-655-0002 US Toll (Canadian Toll) + 1-416-915-8942
Access Code: 737 678 983 | Password: GzZvDeui | Join WebEx Meeting

Introductions and Opening Remarks (Jim Robb)

NERC Antitrust Compliance Guidelines and Public Announcement
NERC Participant Conduct Policy

Agenda Items

1. **EMP Task Force Introductions – Soo Jin Kim (15 minutes)**
   a. Overview of objectives and key deliverables
   b. Task Force charter overview – Aaron Shaw – American Electric Power (AEP)
2. **EMP Research Efforts**
   a. Randy Horton – Electric Power Research Institute (20 mins)
   b. Ross Gusstromson – Sandia National Labs (20 mins)
3. **Nuclear Effort Update – Scot Greenlee – Exelon Nuclear (20 mins)**
4. **Defense Efforts Panel – Aaron Shaw – AEP (1 hour)**
   a. Scott Backhaus – U.S. Department of Homeland Security
   b. Michael Rooney – Defense Threat Reduction Agency
   c. Colonel Douglas DeMaio – United States Air Force
5. **EMP Vulnerability Assessments – Rey Ramos – Southern Company (1 hour)**
   a. E3 EMP modeling capabilities – Scott Dahman – Power World
   b. Strategic recommendations
6. **Mitigations – Aaron Shaw – AEP (1 hour)**
   a. Identify realistic mitigation goals

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   b. Control Center and Substation Hardening Experience – Eric Easton – CenterPoint Energy
   c. Risk Analysis Example – Scott Adams – American Transmission Company
   d. Strategic recommendations
7. **Identifying Critical Assets – Ken Braerman – Exelon (1 hour)**
   a. Current approaches for identifying critical assets – Micah Till – Dominion
   b. Other industries: Natural Gas, Telecommunications, Water
   c. Strategic recommendations
8. **Feedback and Next Steps – Howard Gugel (1 hour)**

Agenda – Electromagnetic Pulse Task Force (EMP) Meeting – July 25, 2019 2

GMDTF – Update TPL-007-4

Project 2019-01 Modifications to TPL-007-3

Chicago

August 14, 2019

RELIABILITY | RESILIENCE | SECURITY




Agenda

1. *Project Status*
2. *Standard Updates*
3. *Implementation Guideline*
4. *Next Steps*

Status of Project 2019-01

- TPL-007-4 addresses FERC Order 851
  - Regulatory Filing Deadline of July 2020
- The Commission directs NERC to develop and submit modifications to Reliability Standard TPL-007-2:
  - (1) to require the development and implementation of corrective action plans to mitigate assessed supplemental GMD event vulnerabilities; and
  - (2) to authorize extensions of time to implement corrective action plans on a case-by-case basis.
- This is the formal initial posting
  - 45-day comment period
  - 10-day ballot period, August 30, 2019 – September 9, 2019

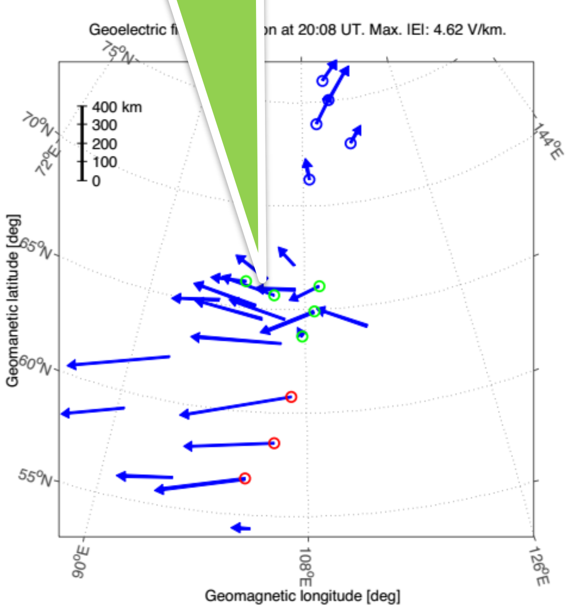
CAP for Supplemental GMD

- Requirement R11
- Requirement: Corrective Action Plans (CAP) for supplemental GMD event Vulnerability Assessment.
  - Same 2- and 4-year deadlines for non-hardware and hardware mitigation.
  - Requires prior approval of timeline extensions by Electric Reliability Organization (ERO).

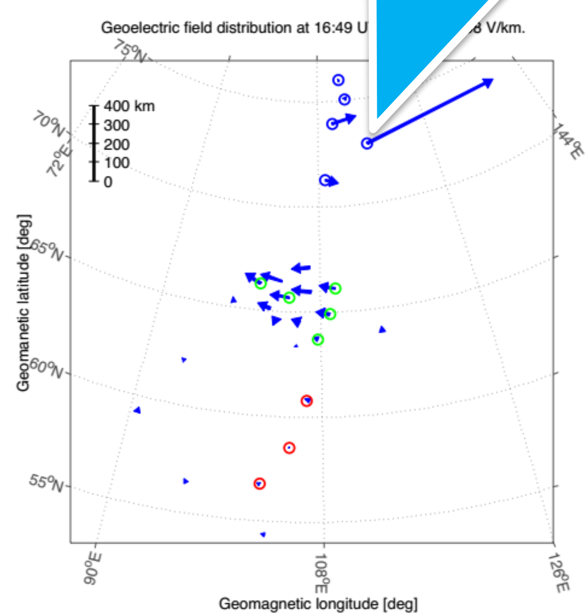
Benchmark vs. Supplemental

- Benchmark & Supplemental are complementary:
  - Different geoelectric field amplitude (Supplemental > Benchmark).
  - Different spatial characteristic (Benchmark > Supplemental).

Coherent **E**
BENCHMARK

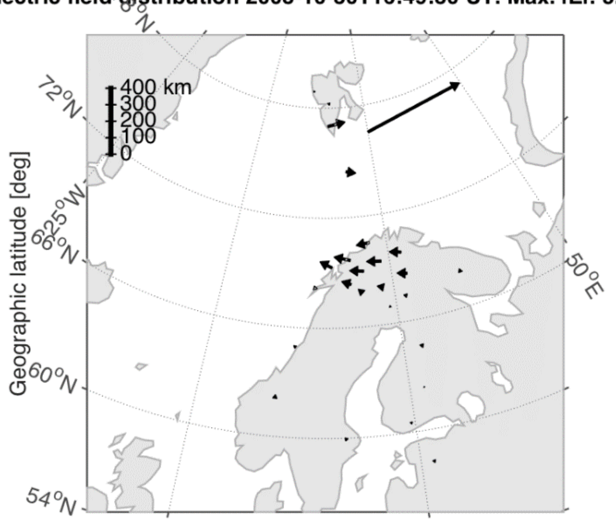


Local enhancement **E**
SUPLEMENTAL



Local Enhancement

Geoelectric field distribution 2003-10-30T16:49:30 UT. Max. |E|: 5.68 V/km.



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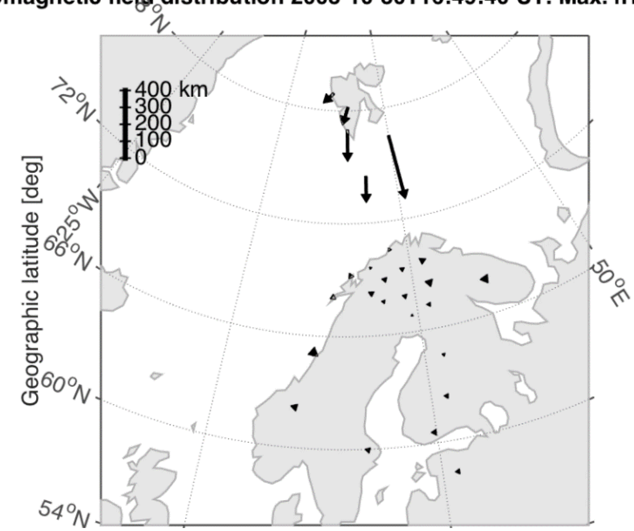

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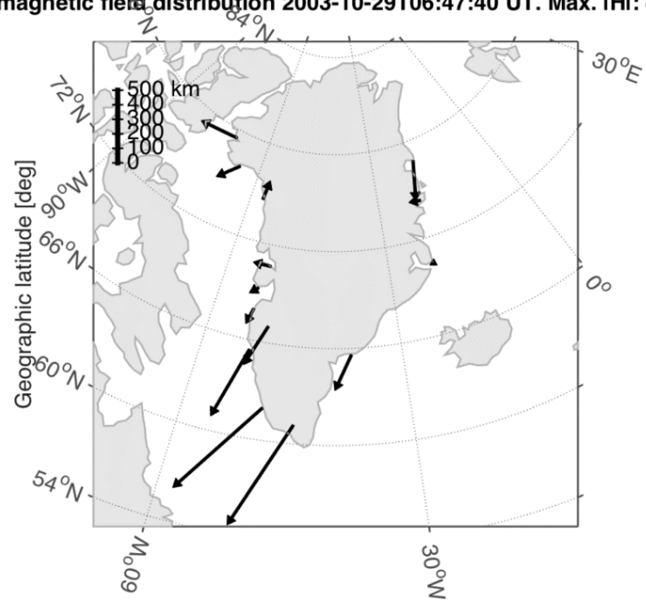
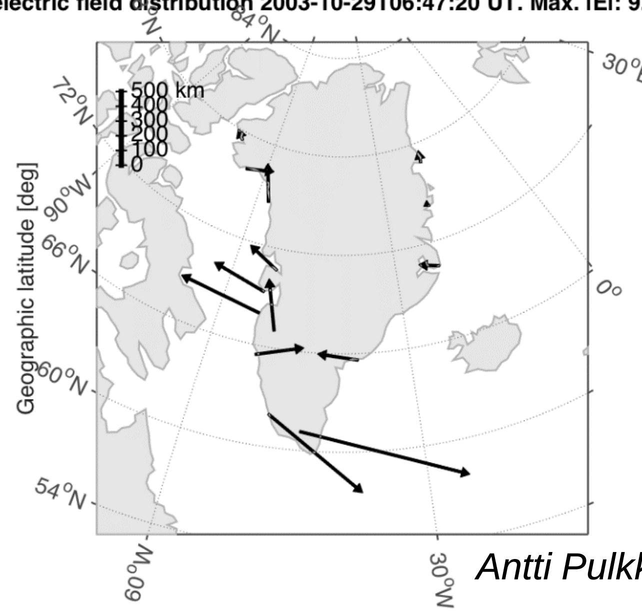


Geoelectric field distribution 2003-10-29T06:47:20 UT. Max. |E|: 9.31 V/km.

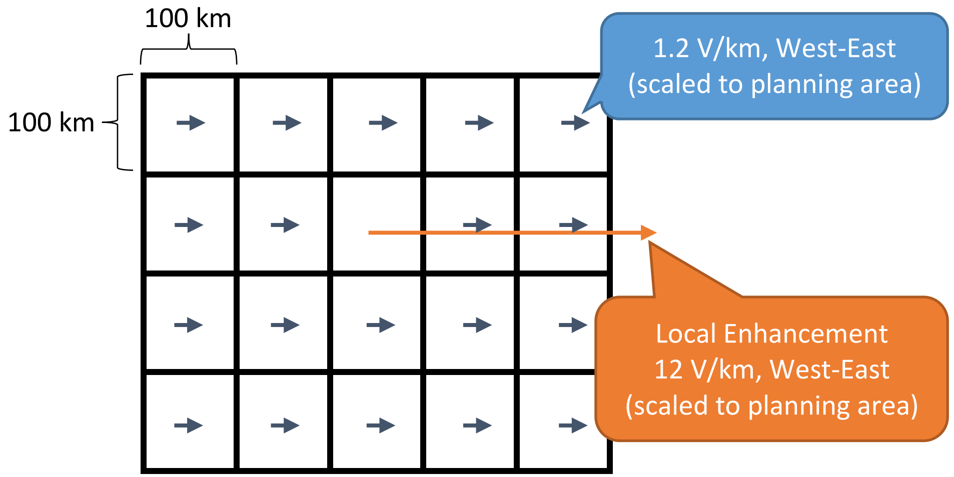


Antti Pulkkinen, et.al.

Implementation Guidance

- Standard maintains flexibility to apply the supplemental GMD event.
  - Guidance provides acceptable approaches and boundaries.

Spatial	Geoelectric Field		Position
	Inside	Outside	
Min 100x100 km	12 V/km West-East	Min 1.2 V/km West-East	Engineering judgment or systematically move



Case by Case Exception

- Applies to CAP for benchmark and supplemental events.
- Written into R7 and new R11.
- Standard of review is the same, “circumstances are beyond the control of the responsible entity”.
- Requires prior approval by the ERO.

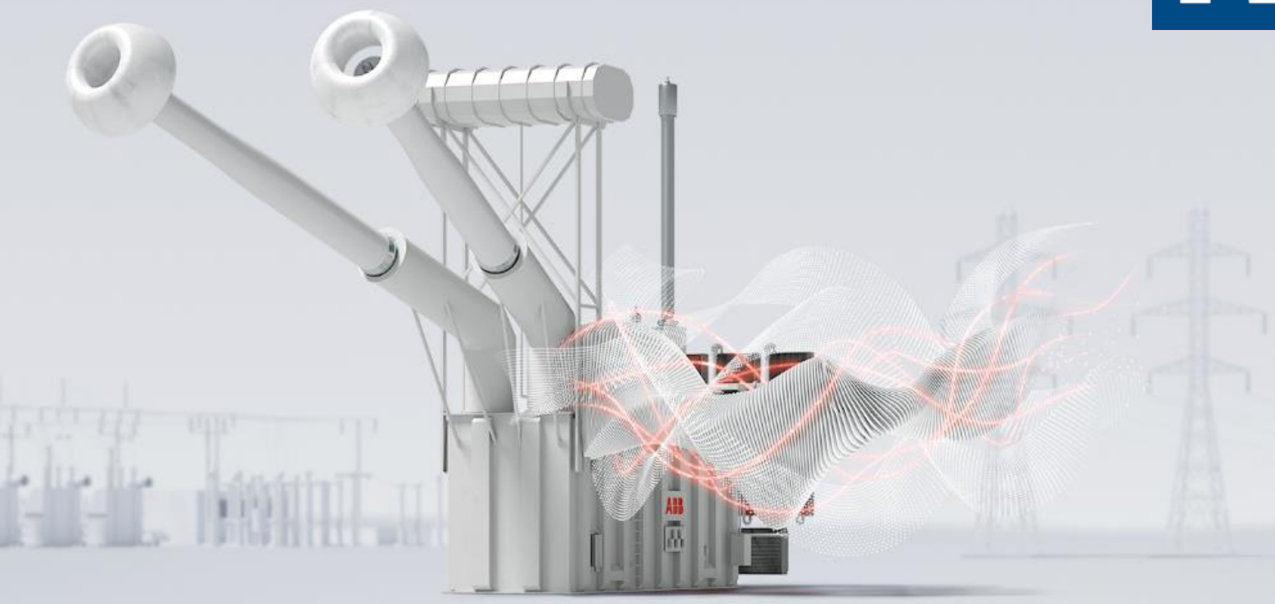
Canadian Variance

- Canadian variance addresses case-by-case extension process:
  - By replacing Requirement R7, Part 7.3 through Part 7.5 and Requirement R11, Part 11.3 through Part 11.5
  - With Canadian specific language to align with regulatory practices and processes within Canadian jurisdictions
- Written for Canadian entities to submit revisions to the Compliance Enforcement Authority or Applicable Governmental Authority

Next Steps

- Initial Ballot and Comment Period
  - June 26, 2019 – September 9, 2019
  - Project 2019-01 Page
- Respond to Comments
  - In-Person Meeting September 24-26, 2019 – Washington D.C.
  - October 2019

Questions and Answers



GIC Assessment of TVA’s fleet of 500 kV Transformers

Presenters: Ian Grant and Ramsis Girgis
August 14, 2019

Tennessee Valley Authority

Created in 1933 by the TVA Act

A federally-owned, self-financed corporation

Mission: Provide navigation, flood control, electric power, and economic development in the Tennessee Valley region

Largest public power system

Service Area:

- Parts of 7 states
- 80,000 square miles
- 9 million people

Primarily a wholesaler of power serving distributors and large industries.

What We Manage

16,156 miles of lines

508 substations/ switchyards

104,844 transmission structures on 237,398 right-of-way acres

1,321 individual interconnection & customer connection points

3,600-mile fiber network

to deliver

33,500 MW peak load

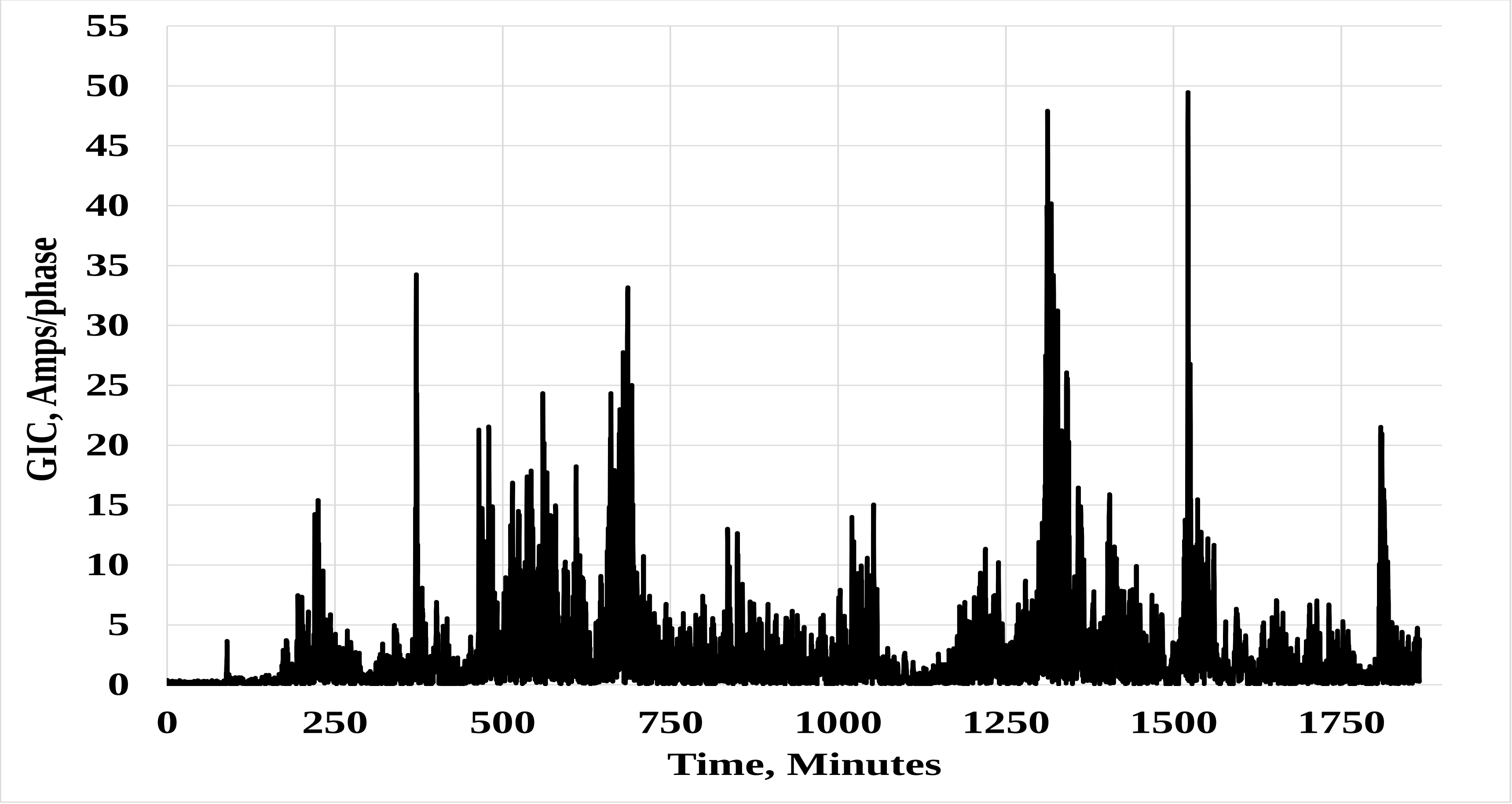
163 x10^9 kWh

DC System Modelling – 231 Transformers

- Winter 2016 base case
- Solve AC power flow
- Input substation/transformer/earth resistivity scaling region data
- Calculate GIC Values:
  - Constant electric field strength (8V/km), varying storm direction 0-360 degrees in 5 degree steps
  - Constant storm direction (15 degrees), increasing field strength up to 20V/km in 1V steps
    - 15 degrees was determined from step 1 to be worst case with all-ties-closed

Results of DC system modeling

- GIC Time Series, to be expected under Benchmark GMD event for all 500 kV transformers on the fleet



Development of ABB's GIC Magnetic and Thermal Universal Models

- ❑ Based on detailed modelling of a large number of transformers of different combinations of MVA and kV ratings, Core & Shell form, and Core types
- ❑ Allows performing the calculations in an order of magnitude less time
- ❑ Allows GIC assessment of transformers W/O Design information
  - ❑ Using Name Plate, Test Report, and Core type => Allows GIC Assessment of ABB, ABB Legacy, and Non-ABB Transformers
- ❑ Calculated values are sufficiently close to those of detailed calculations

ABB

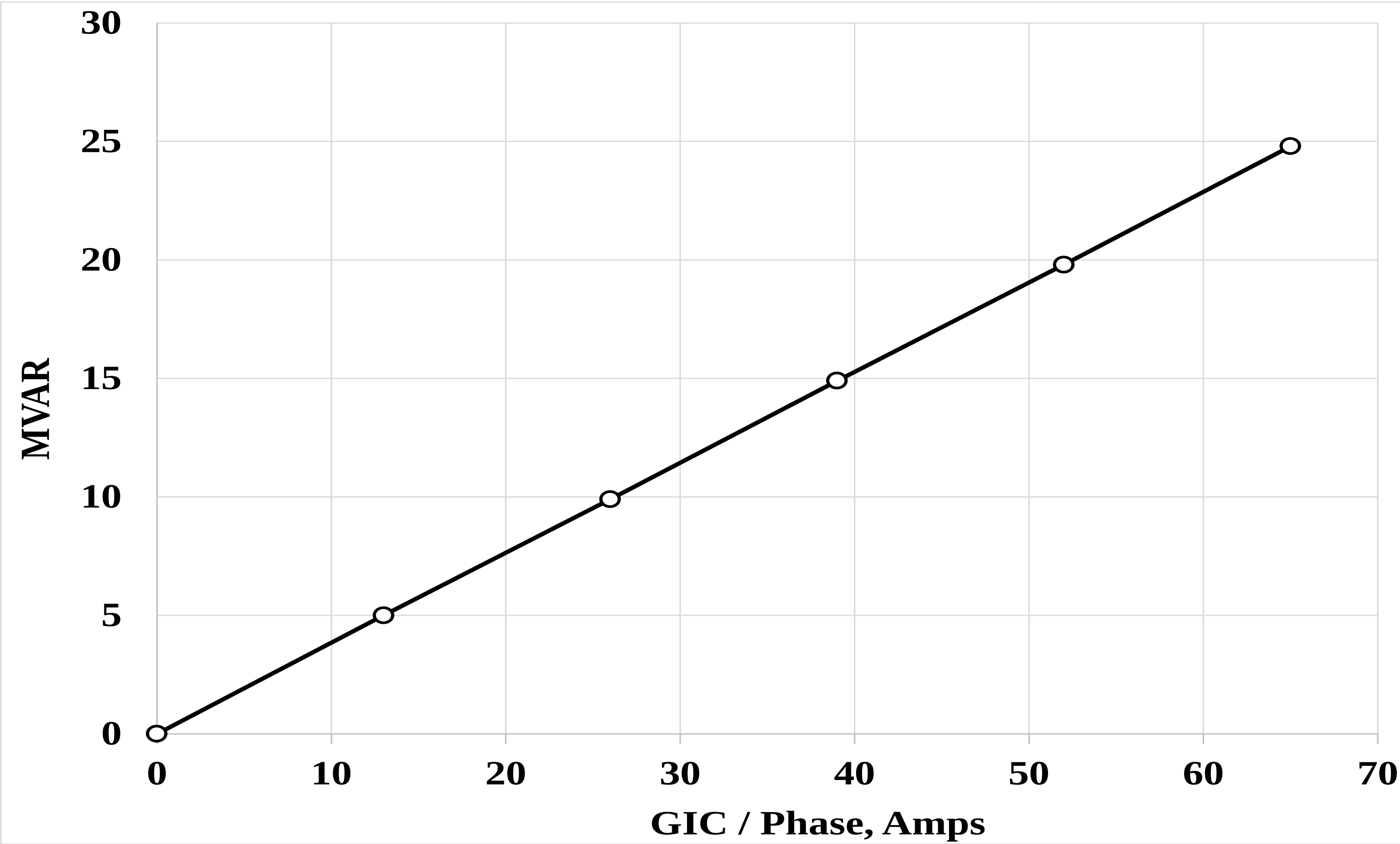
Calculation of values of the K Factor, Var Demand, and Current harmonics

- Developed Universal magnetic models for 8 different core types
  - 5 Core form, and 3 Shell form
- 4 Models for each core type
  - ⇒ K – factor => VAR Demand
  - ⇒ 2nd, 3rd, and 4th Current harmonics
- Calculations require MVA/ kV data, type of Transformer, and Core type

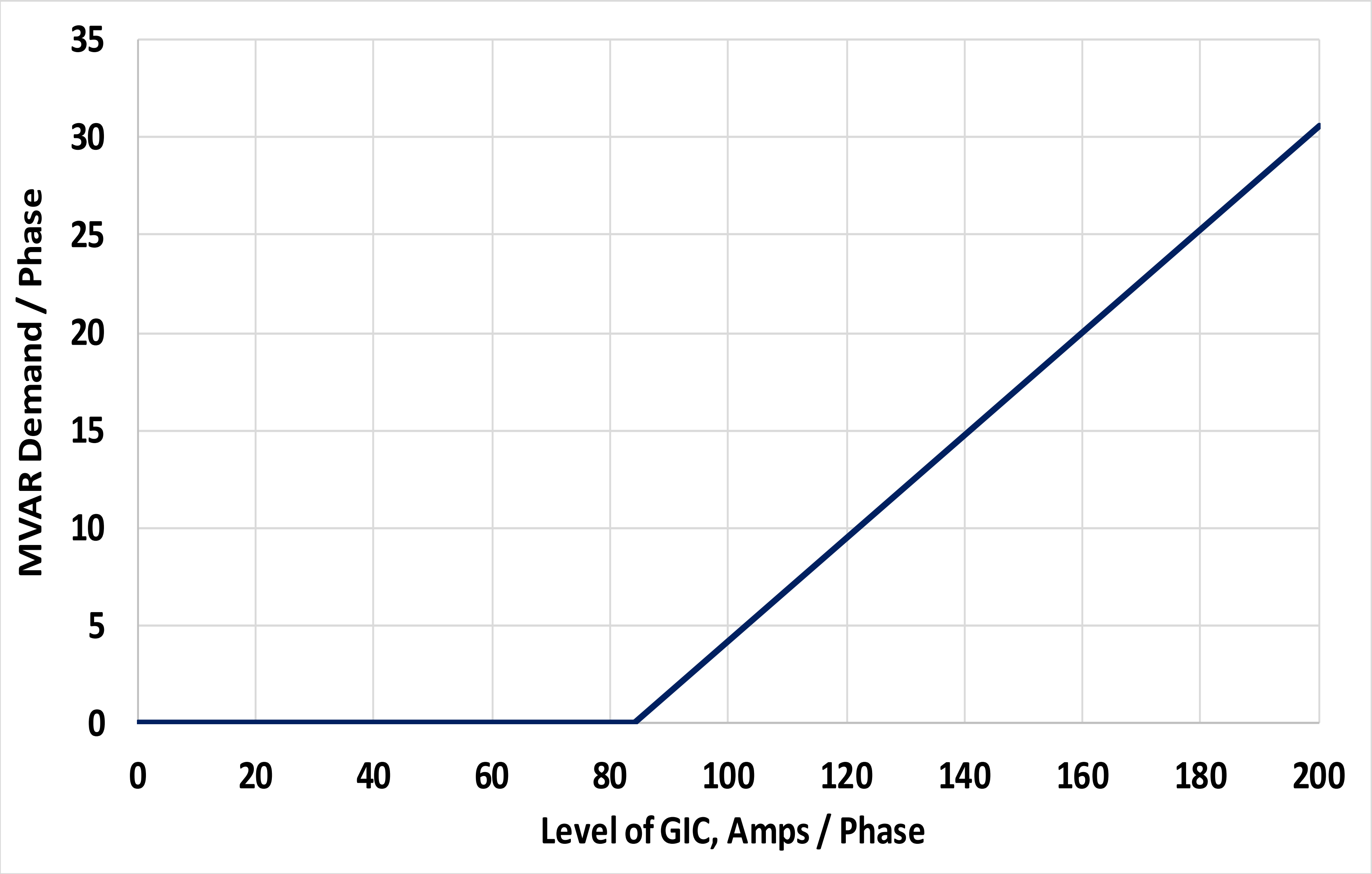
  * Calculates a specific value of the K factor for each transformer

  ** For 3-phase core form transformers with the 3-limb core type, calculates specific values for **Ics** & K factor

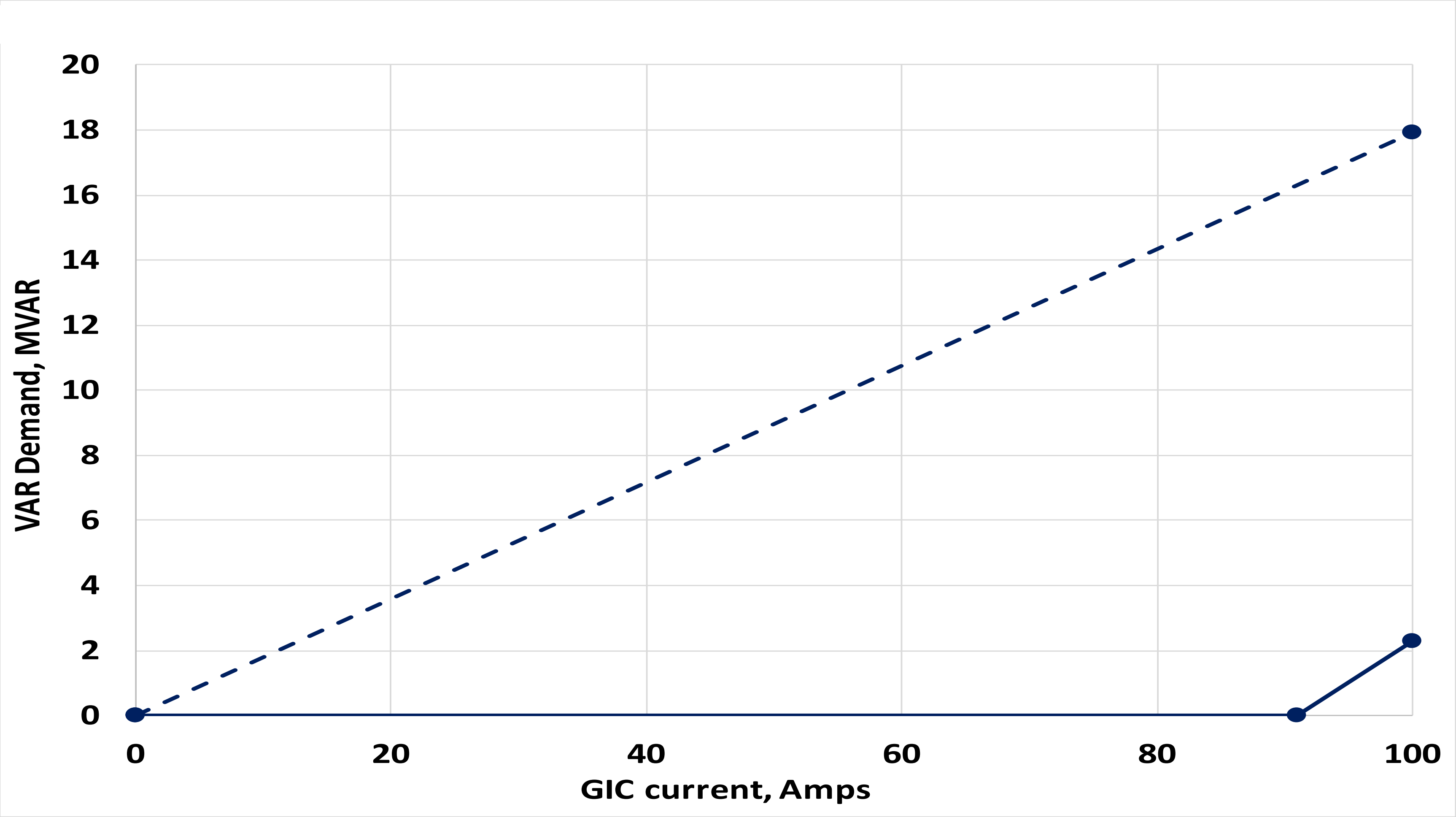
Calculated VAR demand for a 1 -phase Core form Transformer with a 3 -limb Core



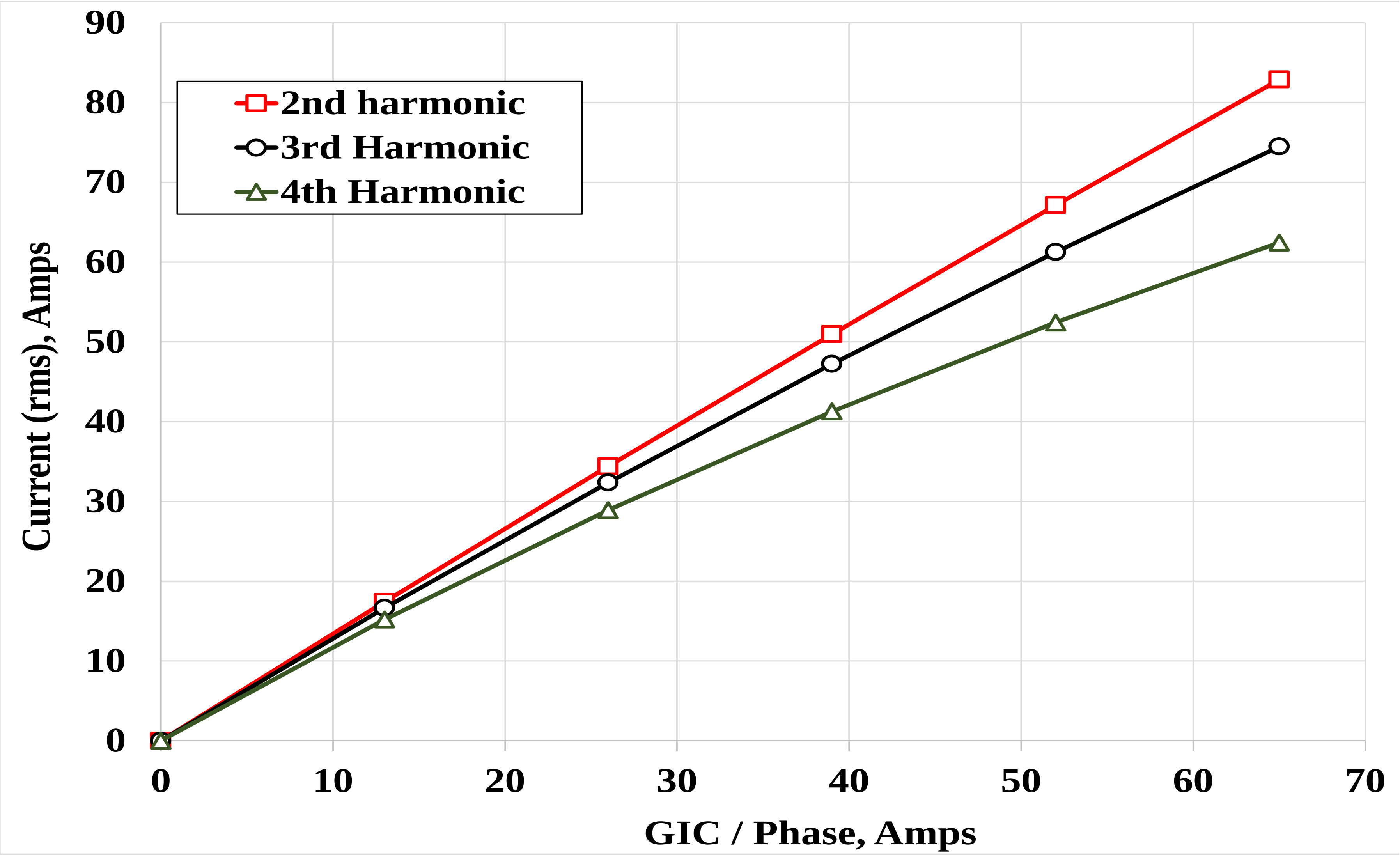
Calculated VAR demand for a 3 -phase Core form Transformer with a 3 -limb Core



Calculated VAR demand for a 3 -phase Core form Transformer with a 3 -limb Core



Calculated harmonic currents – 1-phase Core form Transformer with a 3-limb Core



Full results of GIC Magnetic Fleet Assessment – Extract

	Transformer Serial Number	Location	MVA	HV Rated Voltage kV	GIC, Amps/ Phase	MVAR	K factor	2nd Harmonic, Amps	3rd Harmonic, Amps	4th Harmonic, Amps
1			360	500	24	0	0.631	0	0	0
2			360	500	24	0	0.631	0	0	0
3			360	500	24	0	0.631	0	0	0
4			448	500	15	5.7	1.31	19.88	18.84	17.06
5			448	500	15	5.7	1.31	19.88	18.84	17.06
6			448	500	15	5.7	1.31	19.88	18.84	17.06
7			448	500	15	5.7	1.31	19.88	18.84	17.06
8			200	500	2	0	0.445	0	0	0
9			200	500	2	0	0.445	0	0	0
10			500	500	2	0.8	1.32	2.74	2.67	2.5
11			500	500	2	0.8	1.32	2.74	2.67	2.5
12			500	500	2	0.8	1.32	2.74	2.67	2.5
13			500	500	2	0.8	1.32	2.74	2.67	2.5
14			500	500	2	0.8	1.32	2.74	2.67	2.5
15			500	500	2	0.8	1.32	2.74	2.67	2.5
16			500	500	2	0.8	1.32	2.74	2.67	2.5
17			500	500	2	0.8	1.32	2.74	2.67	2.5
18			500	500	2	0.8	1.32	2.74	2.67	2.5
19			500	500	2	0.8	1.32	2.74	2.67	2.5
20			500	500	2	0.8	1.32	2.74	2.67	2.5
21			448	500	41	15.6	1.31	53	48.68	42.15
22			400	500	41	16.0	1.29	65.9	58.2	47.1
23			400	500	41	16.0	1.29	65.9	58.2	47.1
24			448	500	41	15.6	1.31	53	48.68	42.15

GIC Susceptibility Assessment per IEEE GMD Guide

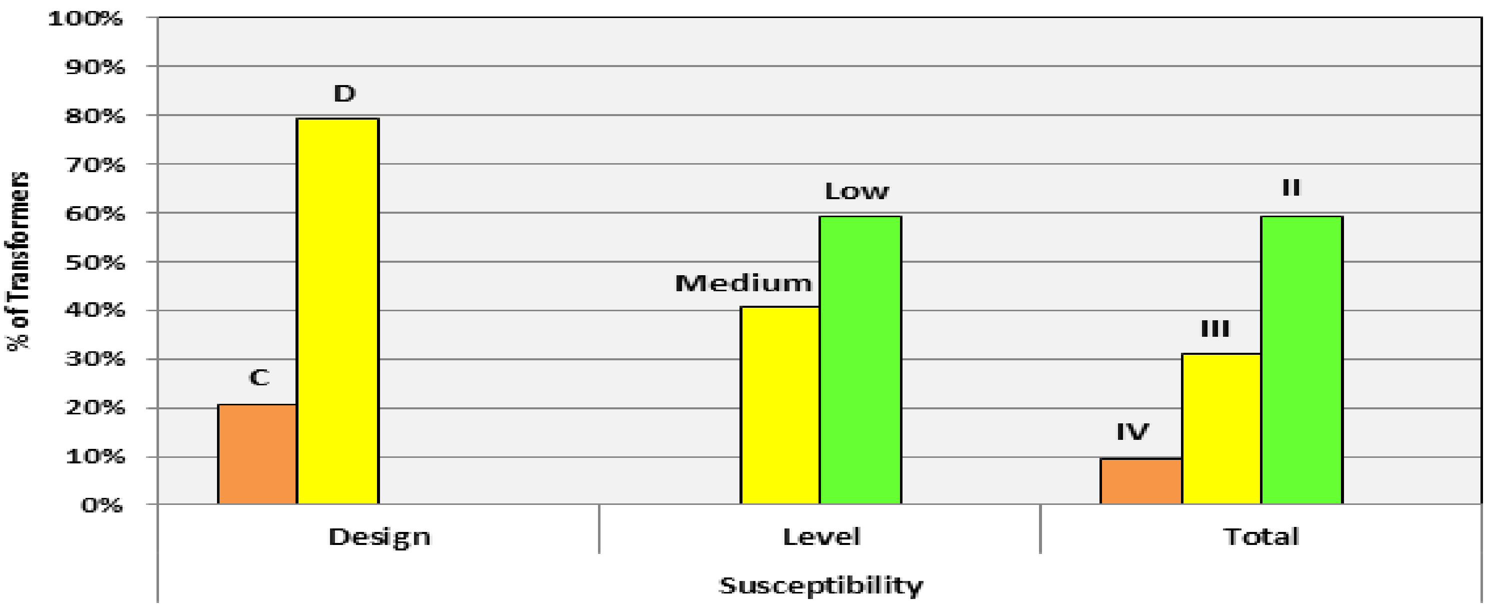
	GIC Exposure Level (Amps / phase)		
Design – Based Susceptibility	Low Exposure (≤ 15 Amp)	Medium Exposure (> 15 to < 75Amp)	High Exposure (≥ 75 Amp)
Not Susceptible (A)	I	I	I
Least Susceptible (B)	I	II	III
Susceptible (C)	II	III	III
Highly Susceptible (D)	II	IV	IV

- **Category – I**: No action may be needed
- **Category – II**: Only Magnetic Assessment is needed
- **Category – III**: Magnetic Assessment and Thermal Assessment of only the structural parts are needed
- **Category – IV**: Magnetic and Thermal Assessment of both windings and structural parts are needed

GIC Susceptibility Assessment of TVA's Fleet of 500 kV Transformers

- 231 large power Transformers in service
- Core-form and Shell-form transformers
- Mostly single-phase transformers, but some 3-phase transformers
- Autotransformers, 3-winding transformers, and GSUs
- 200 – 448 MVA Power Ratings
- Locations in 7 States

Summary of Results of Susceptibility Assessment



Number of transformers	Total Susceptibility Categories				
	IV	III	II	I	Total
Actual Count	22	72	137	0	231
% of Total	9.5%	31.2%	59.3%	0 %	100%

ABB Universal GIC Thermal Assessment Models

Developed for transformers of 8 different core types:

- ❑ Two Models for each core -type
  - ✓ One For S.S. Temperature Gradients and One for Thermal Time -Constants
  - ✓ For both windings and Structural parts

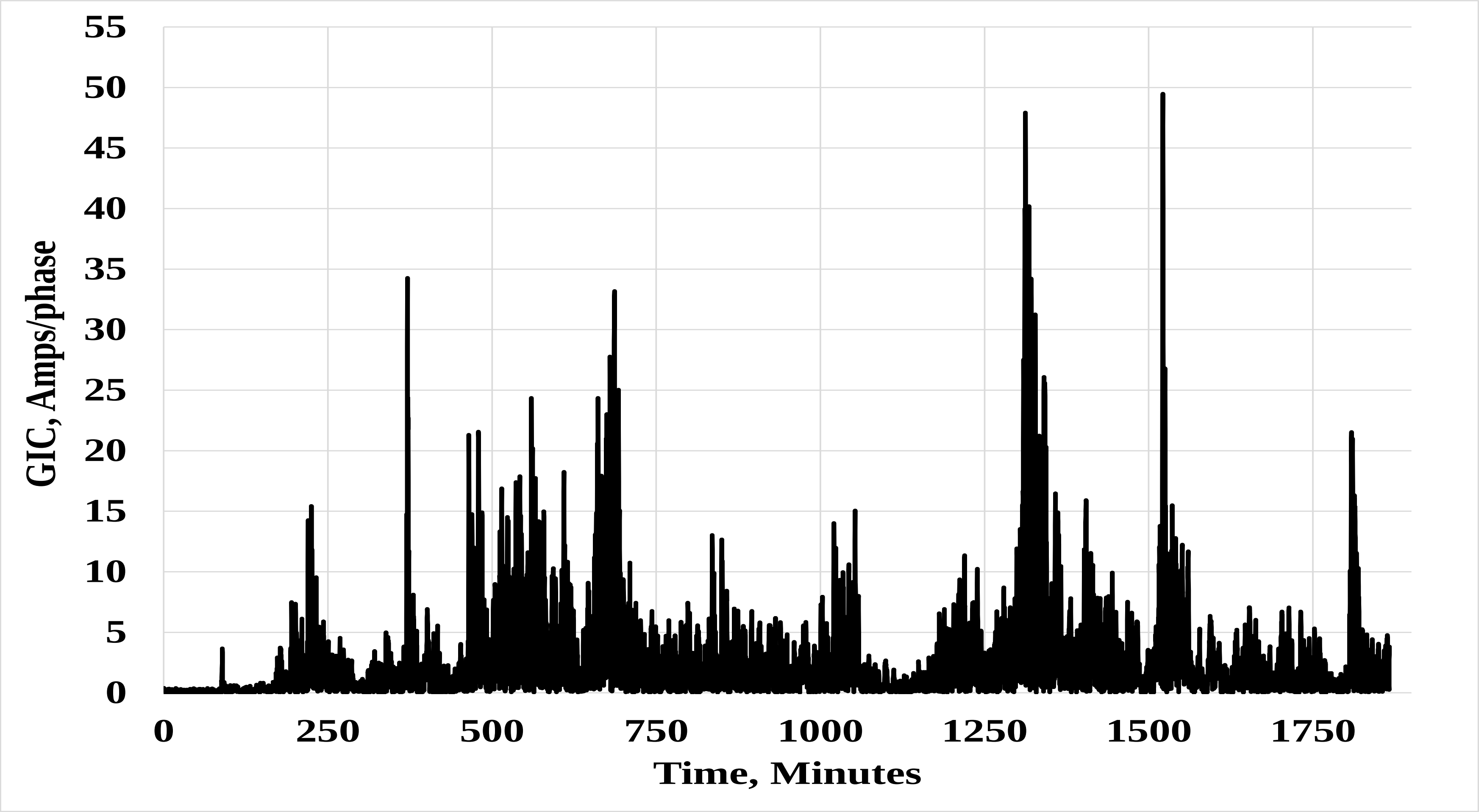
=> Hot Spot Temperature rises in Windings and structural parts corresponding to TPL 007 Benchmark GIC Signature (Time Series)

ABB

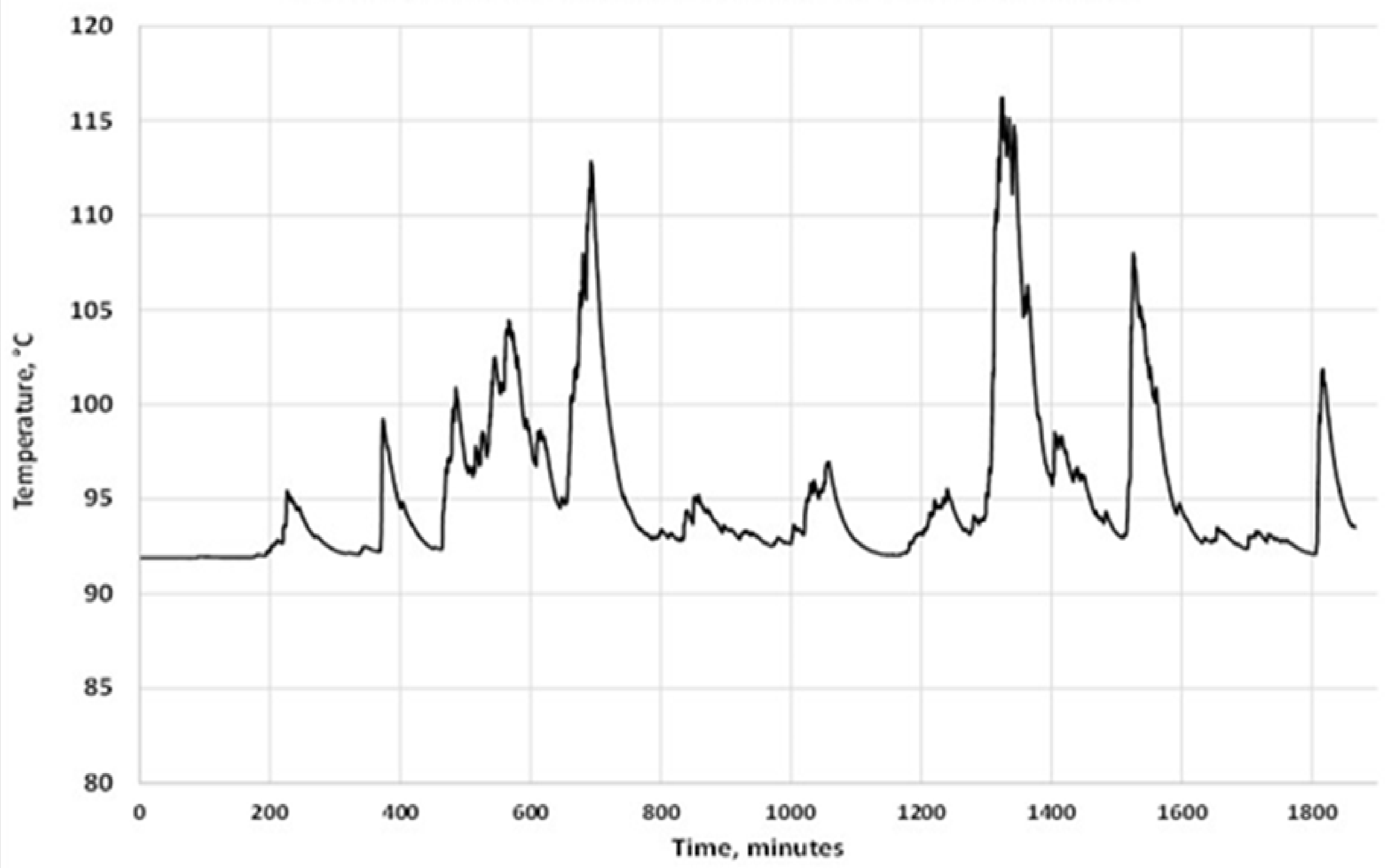
GIC Thermal Assessment of a fleet of Power Transformers – Data Required

- Data provided for Magnetic Assessment
- **Data available in Test Report**
  - Winding losses at full Load
  - Windings HS Temperature at full load
  - Top oil rise at full load
- **Design data (if Available)**
  - Mass of windings
  - Hot spot temperature of Tie plates for Core form transformers

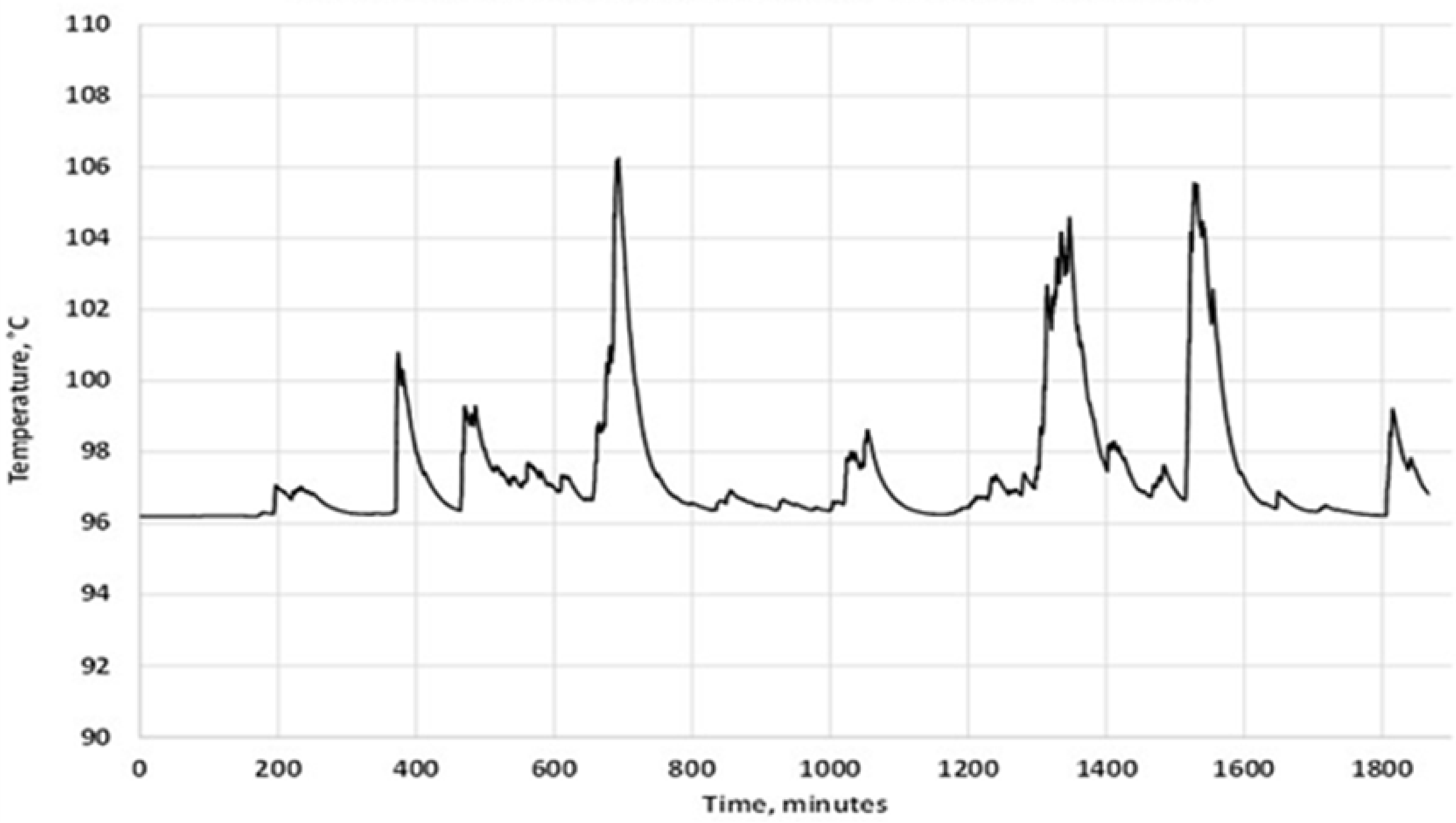
GIC Signature to be expected under Benchmark GMD event for one of the 500 kV transformers on the fleet



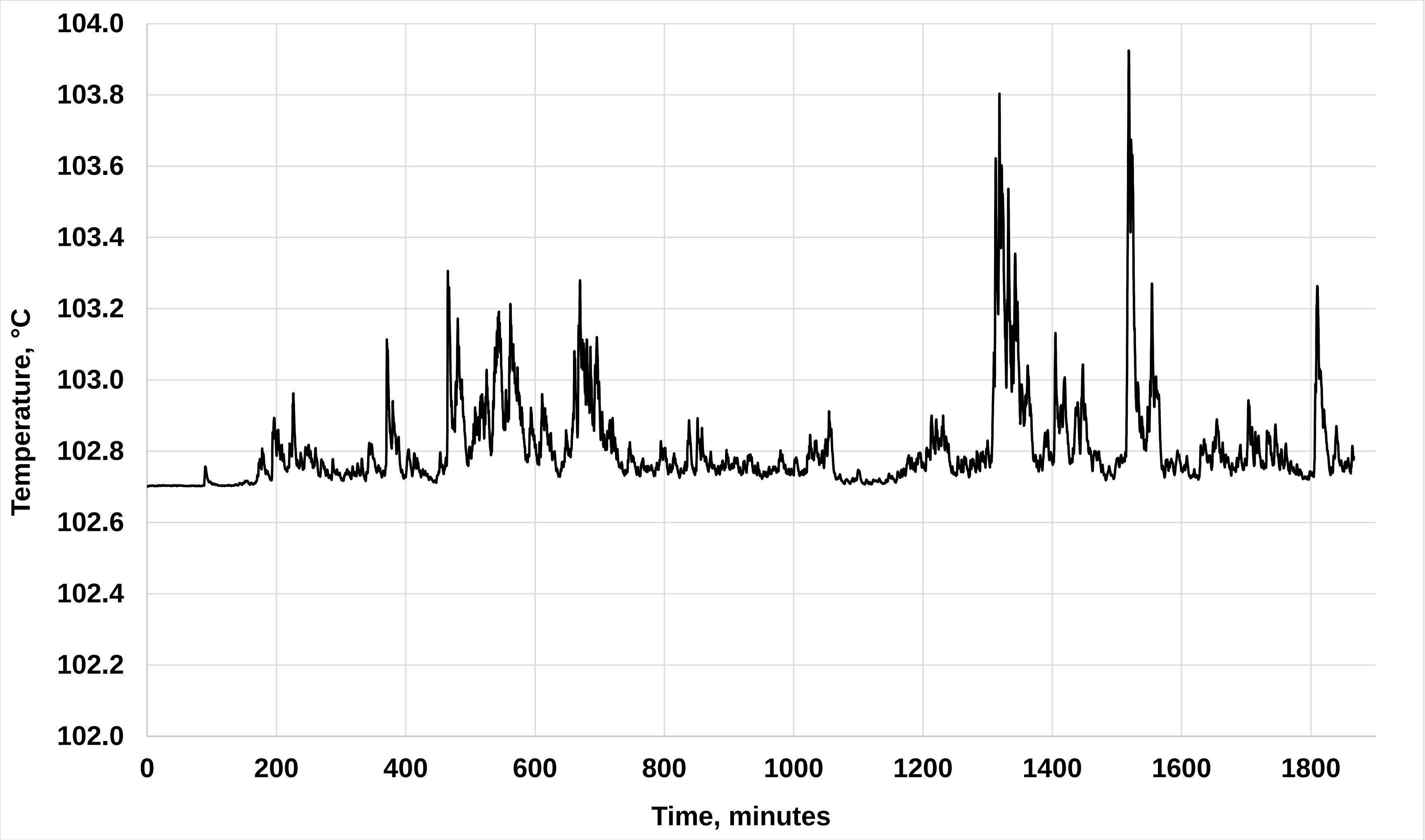
Calculated Flitch plate hot spot temperatures of transformers at one Generating station corresponding to Calculated GIC Signature



Calculated Tank wall hot spot temperatures of Shell form transformers at one Substation corresponding to Calculated GIC Signature



Calculated Winding hot spot temperatures of transformers at a Generating station corresponding to Calculated GIC Signature



Results of GIC Thermal Fleet Assessment Study – Extract

Transformer Serial #	Location	MVA	HV Rated Voltage kV	Peak GIC, Amps/ Phase	Maximum Winding Hot Spot Temp, °C	Maximum Structural Parts Hot Spot Temp, °C
[redacted]		448	500	37.9	100.6	113.3
[redacted]		448	500	37.9	100.0	106.0
[redacted]		448	500	16.2	108.9	115.7
[redacted]		448	500	16.2	94.3	120.0
[redacted]		448	500	16.2	96.2	124.7
[redacted]		448	500	16.2	96.2	124.7
[redacted]		448	500	16.2	96.2	124.7
[redacted]		448	500	16.2	109.6	98.7
[redacted]		448	500	16.2	109.6	98.7
[redacted]		250	500	22.9	106.2	130.1
[redacted]		250	500	22.9	106.2	130.1
[redacted]		250	500	22.9	106.2	130.1
[redacted]		250	500	22.9	106.2	130.1
[redacted]		480	500	14.4	97.6	94.5
[redacted]		480	500	14.4	97.6	94.5
[redacted]		480	500	14.4	97.6	94.5
[redacted]		448	500	32.5	97.0	124.9

ABB tool for GIC transformer fleet assessment

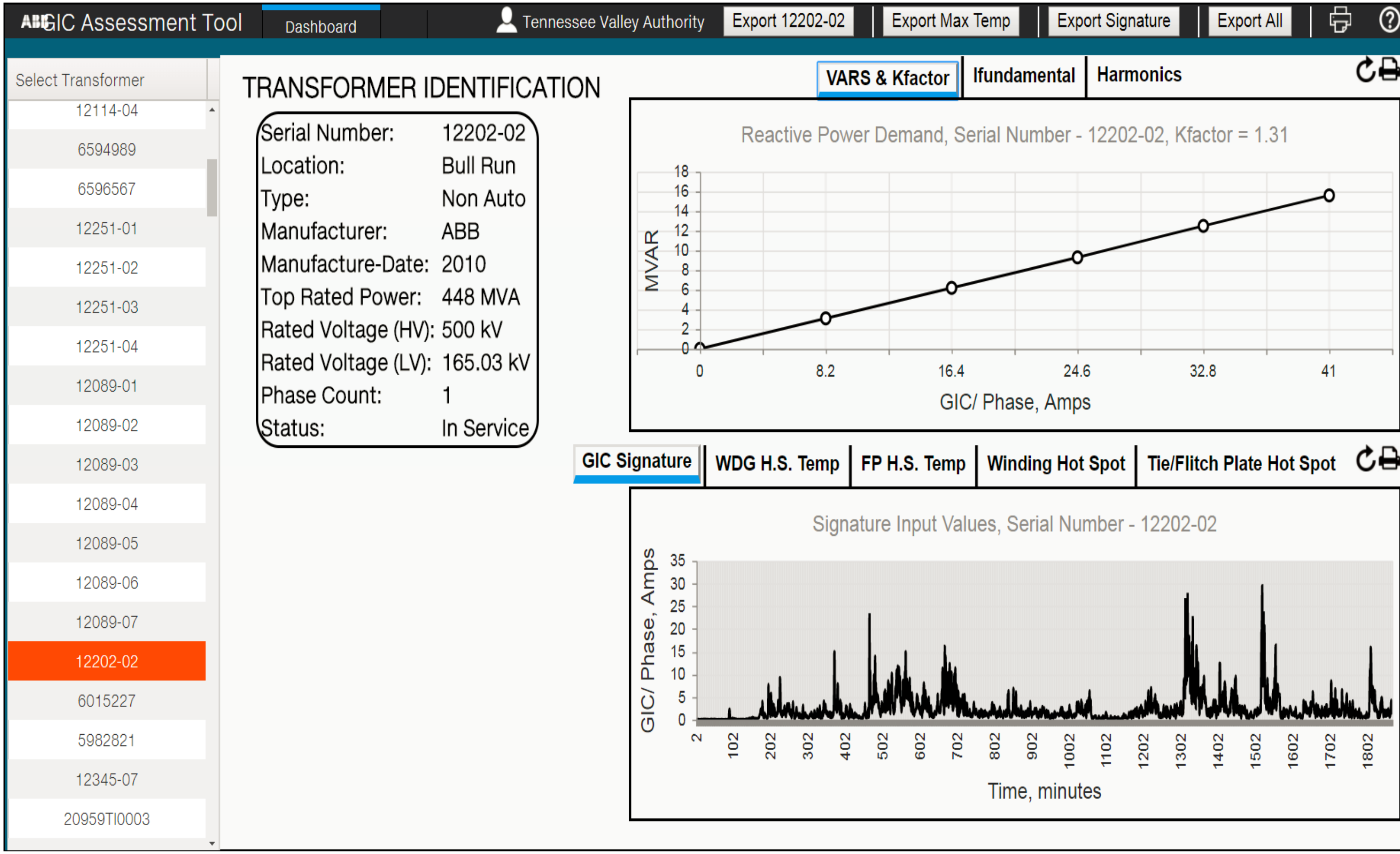
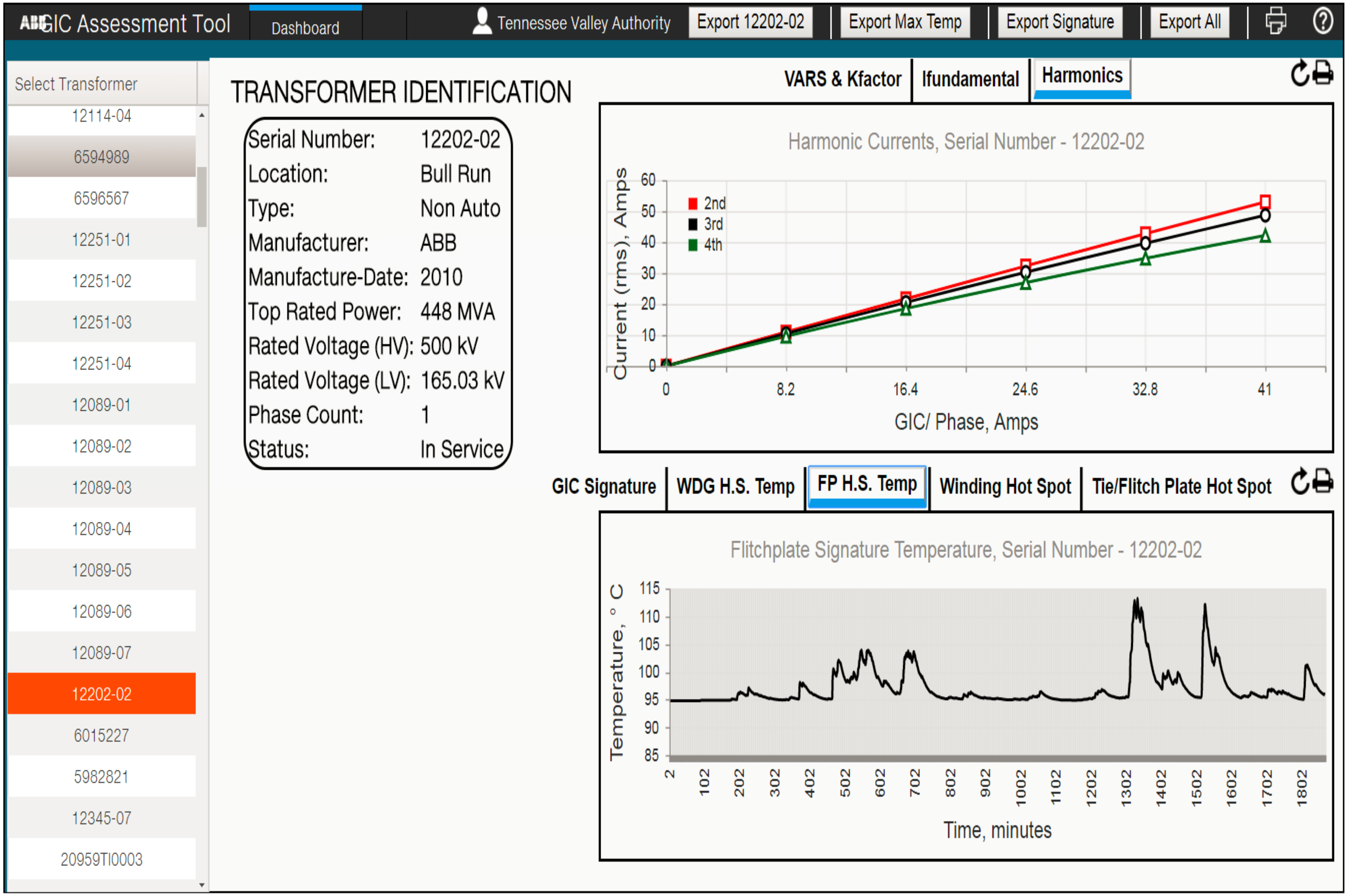


ABB tool for GIC transformer fleet assessment



What next for GMD at TVA:

- Extreme cases up to system collapse
- VAR Sensitivity of assumed vs calculated K
- Harmonic sensitivity with assumed vs calculated models
- Resistivity and grounding updates
- Magnetometer -based system models

Thank You

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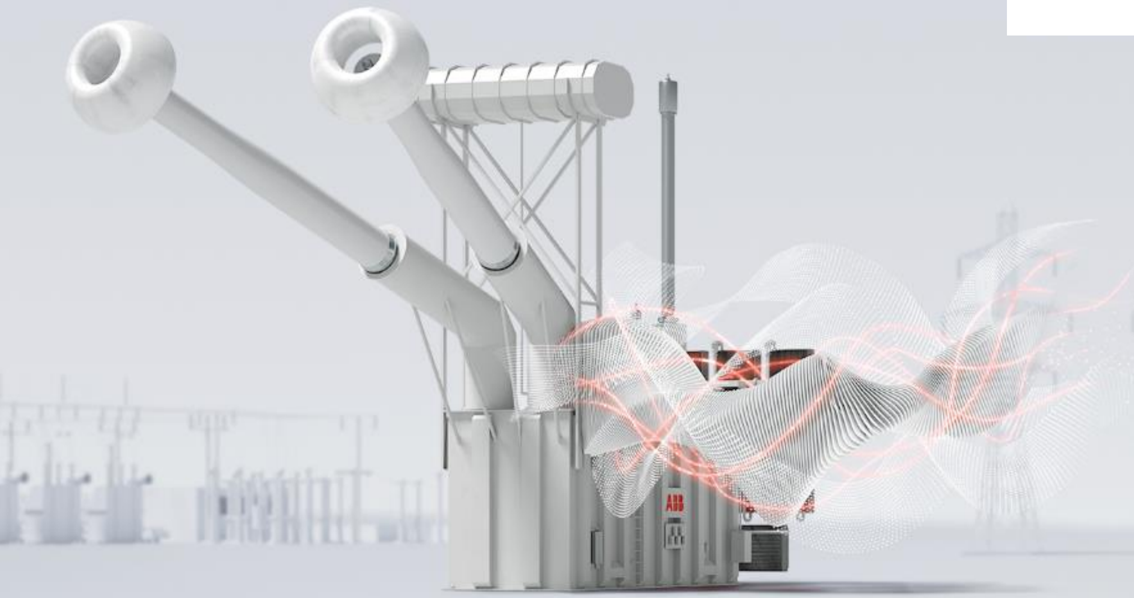


GIC Assessment of PECO’s fleet of Auto Transformers

Presenters: Tony Franchitti and Ramsis Girgis

August 14, 2019

DC System Modelling – 70 Transformers

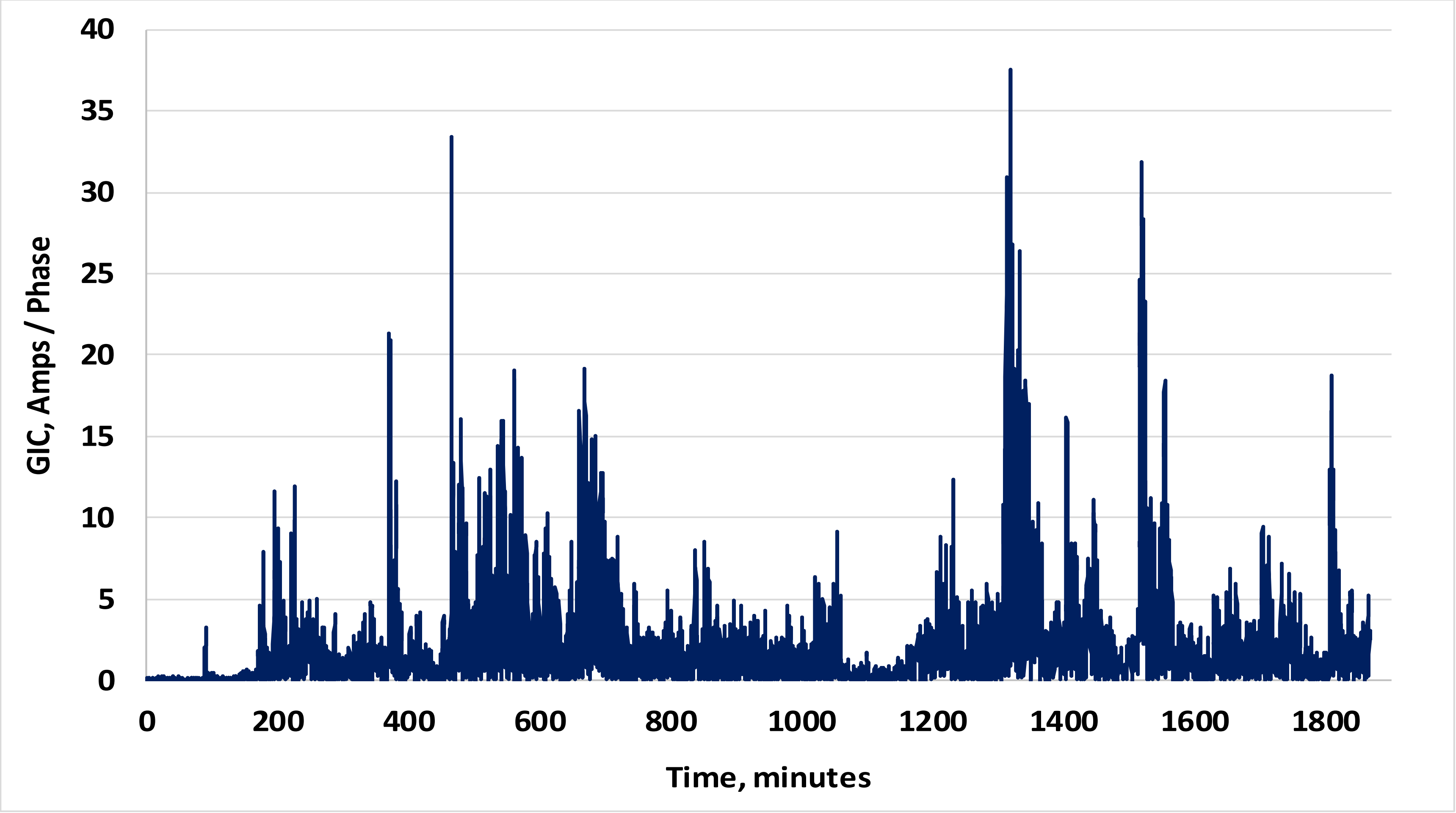
- 2016 Series PJM RTEP (2021 5-year) summer case
- Input substation data
  - Latitude, longitude, station grounding resistance & earth conductivity model
- Input transformer data
  - DC winding resistance, core type, K-factor, winding configuration
- Calculate maximum effective GIC values:
  - Benchmark GMD event (8V/km), varying storm direction 0-180 degrees in 10 degree steps

PECO's Fleet of Power Transformers

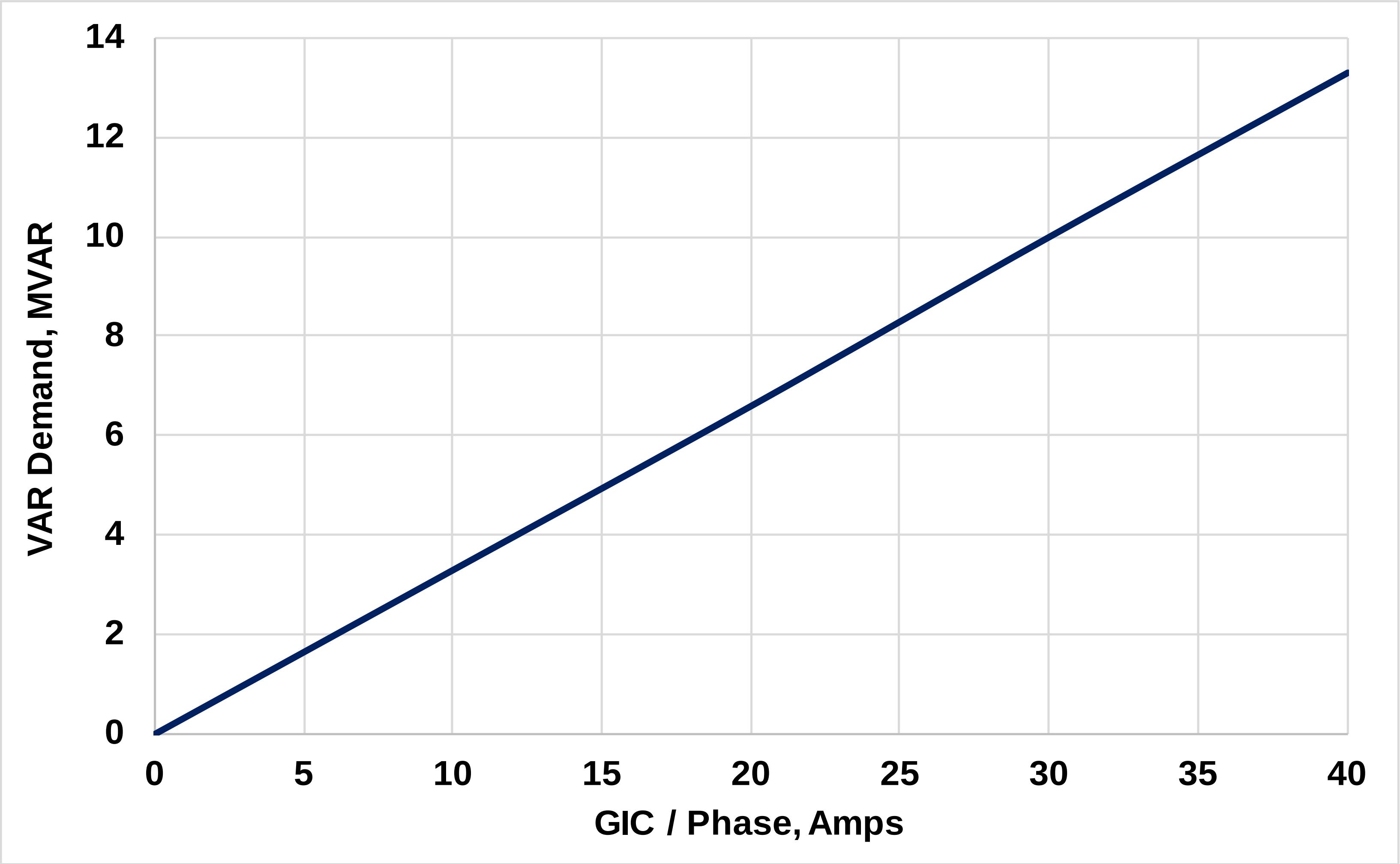
- ✓ 70 Auto Transformers
- ✓ 40 Different Designs
- ✓ High Voltage: 500 and 230 KV
- ✓ Low Voltage: 230, 138, and 69 kV
- ✓ Core form and shell form
- ✓ 7 Different core types
- ✓ ABB and ABB Legacy Manufacturers (GE, WH)
- ✓ 9 Non – ABB Manufacturers

Results of DC system modeling

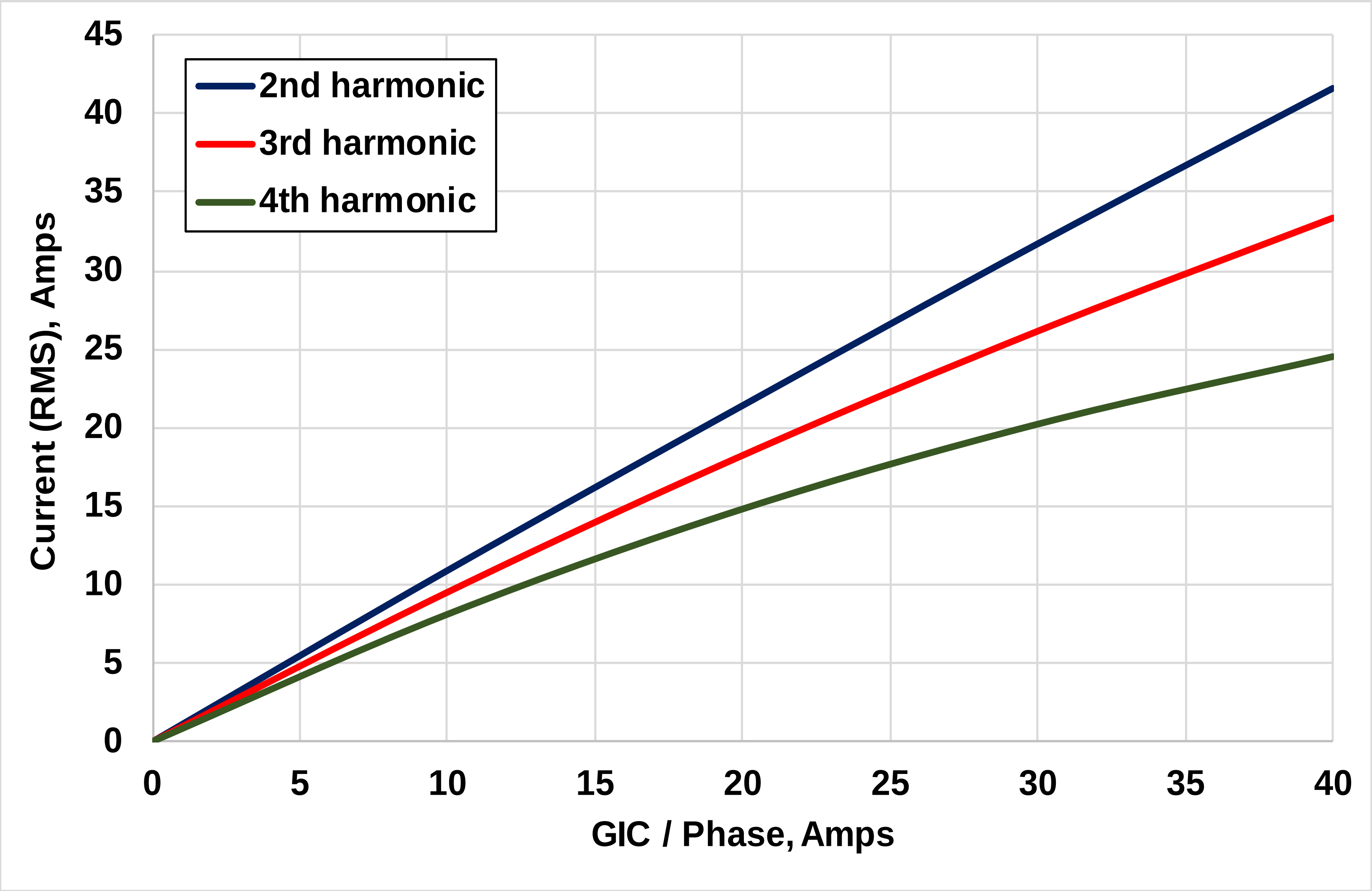
✓ Calculated GIC Time Series to be expected under Benchmark GMD event for 500 kV transformers at one Substation (Provided by PJM) With Highest GIC peak of 37.5 Amps / phase



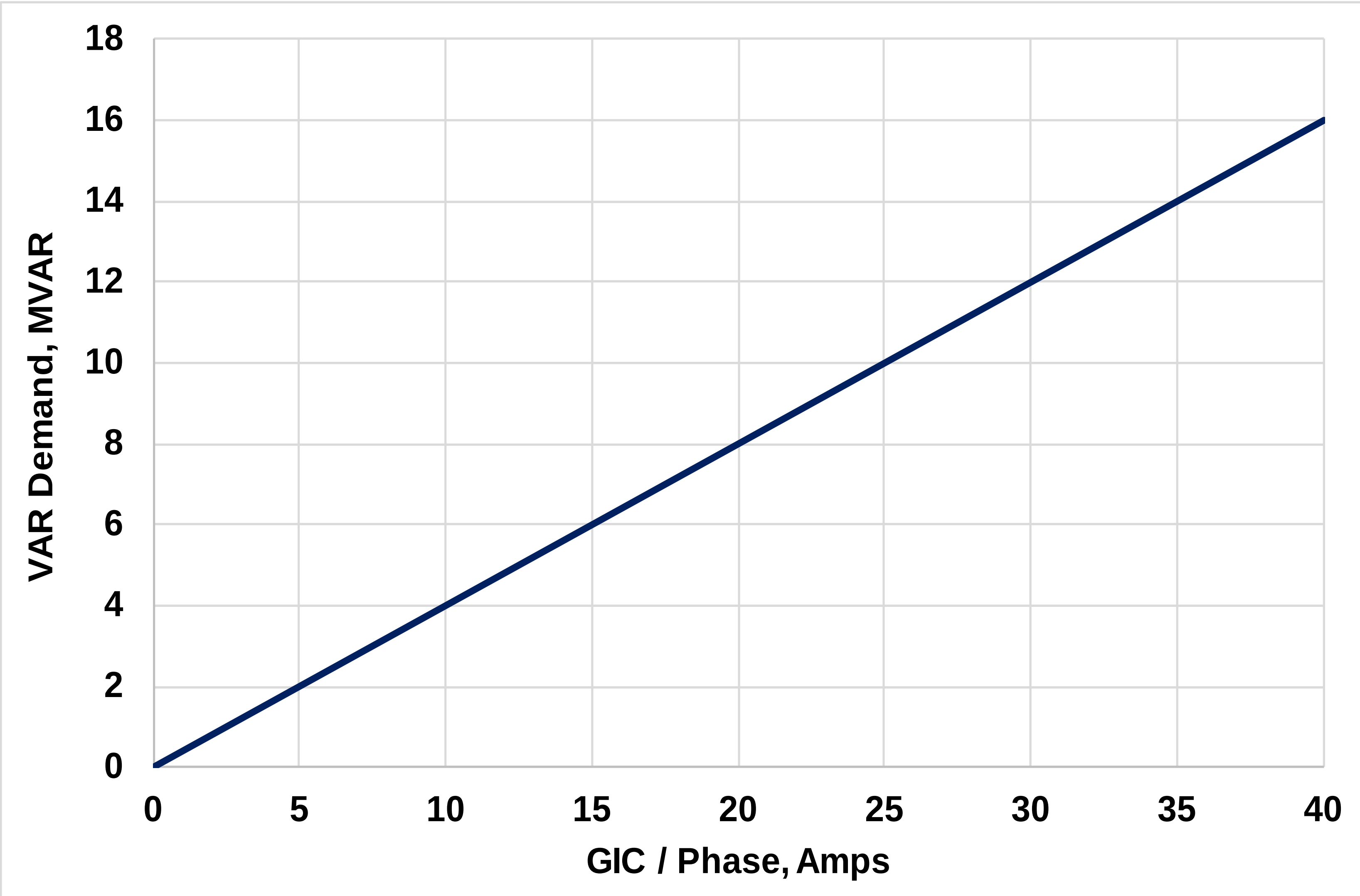
Calculated VAR demand for 1 -phase Core form Transformer with the 4 -limb Core



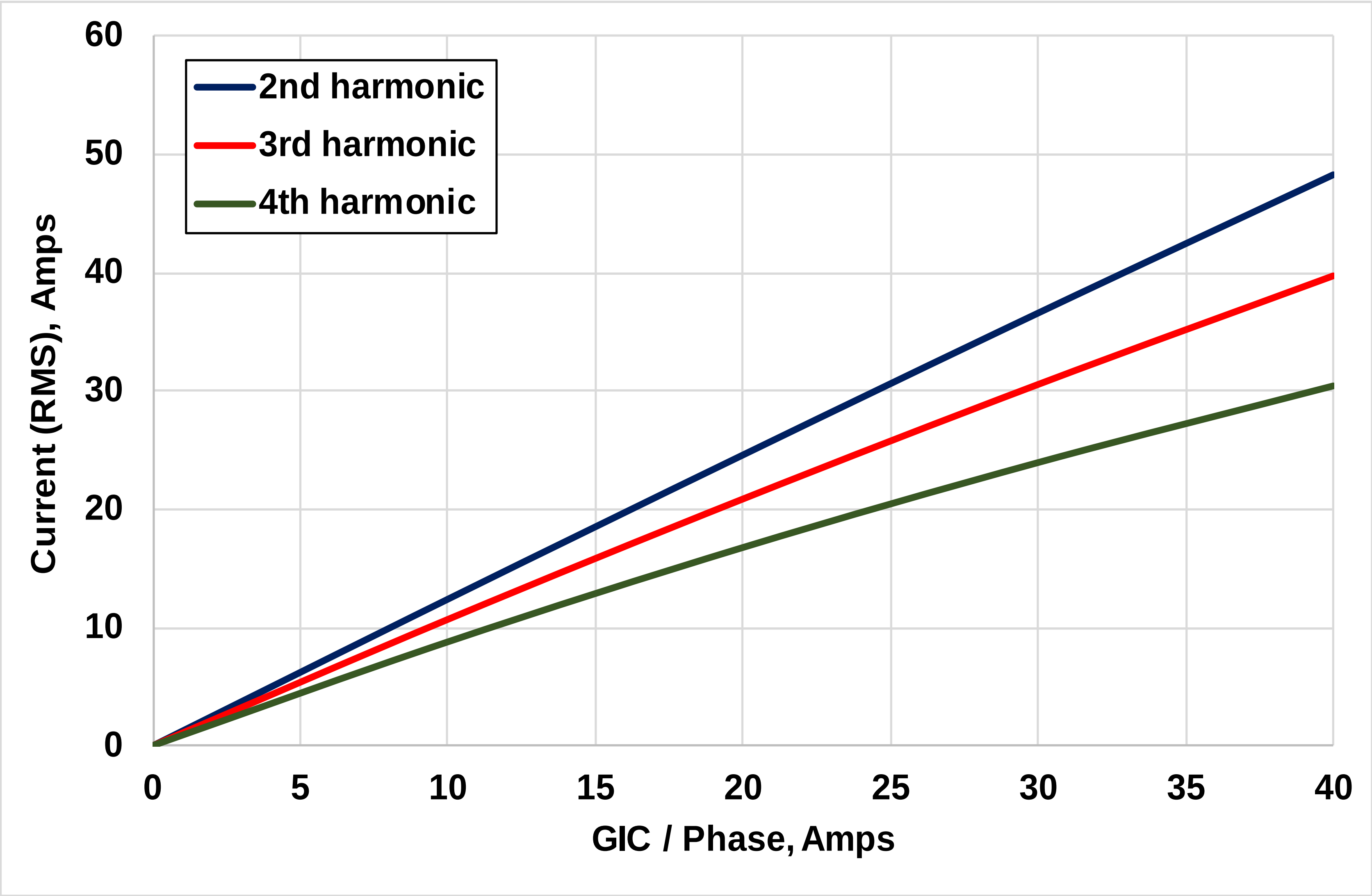
Calculated harmonic currents: 1 -phase Core form Transformer with the 4 -limb Core



Calculated VAR demand for a 1 -phase Shell form Transformer with the D – core



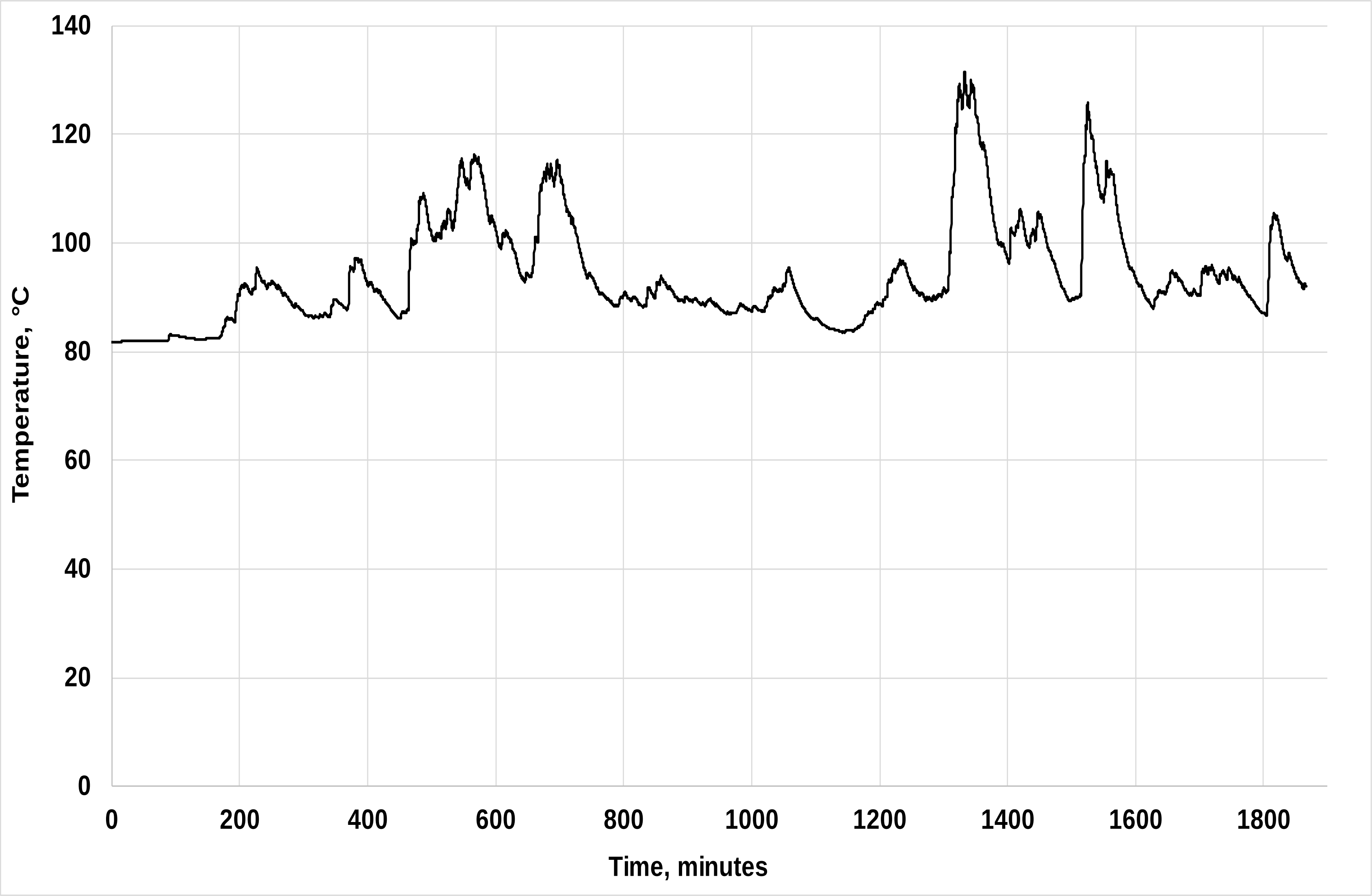
Calculated harmonic currents: 1 -phase Shell form Transformer with the D – core type



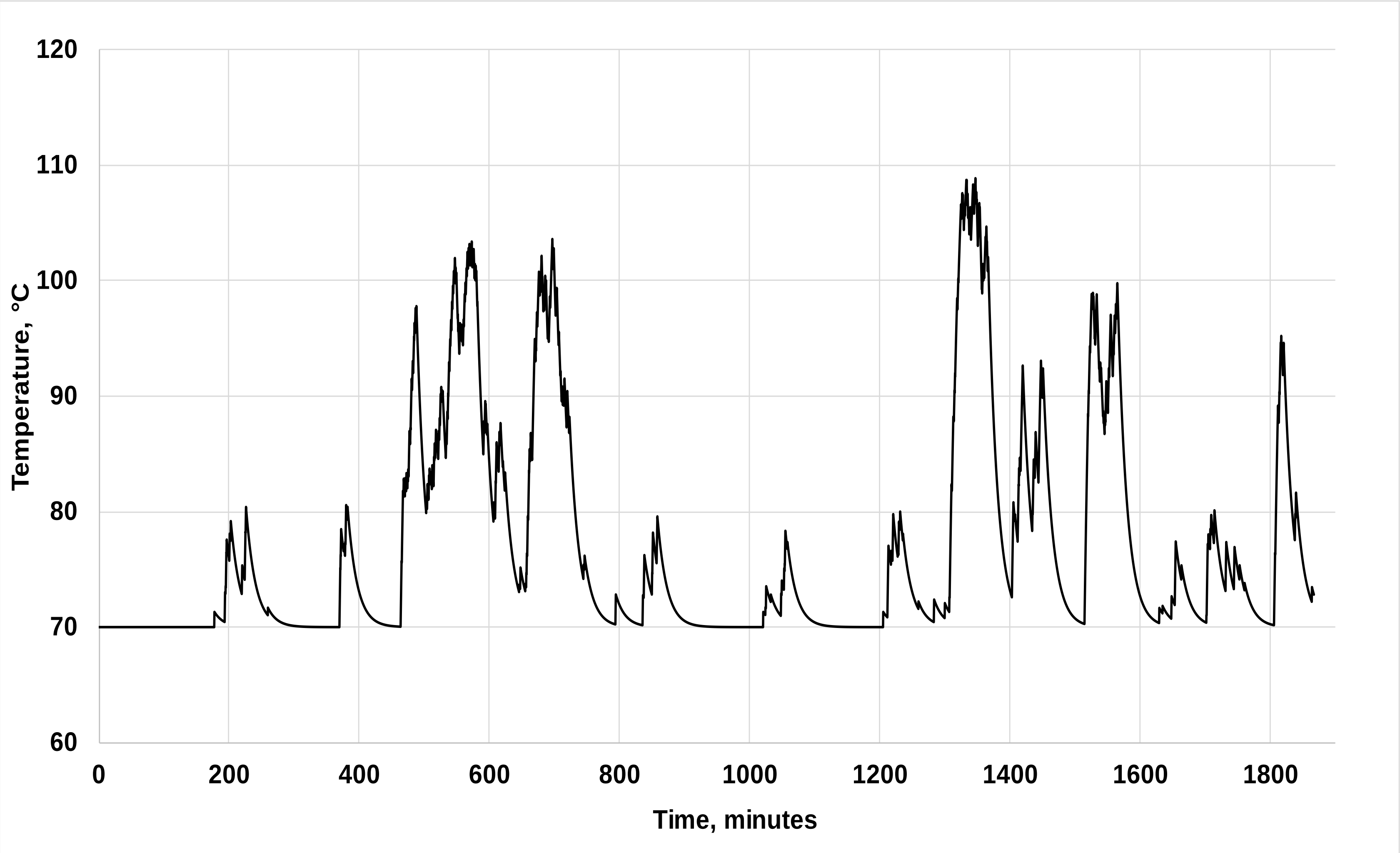
Full results of GIC Magnetic Fleet Assessment – Extract

Station	Spec.	HV, kV	MVA	GIC Current, A	I_{CS}, A	K-factor	VAR demand		Current Harmonic, Amps / Phase		
							MVAR	% of MVA	2nd	3rd	4th
XXXXXXXX11	XXX1	220	100	2.5	7.0	0.667	0.0	0.0 %	0.0	0.0	0.0
XXXXXXXX12	XXX2	220	100	7.3	4.7	0.706	0.7	0.7 %	1.1	0.9	0.6
XXXXXXXX13	XXX3	230	100	3.0	7.2	0.666	0.0	0.0 %	0.0	0.0	0.0
XXXXXXXX14	XXX4	220	100	4.9	7.0	0.667	0.0	0.0 %	0.0	0.0	0.0
XXXXXXXX15	XXX5	220	105	21.1	0.0	1.112	9.0	8.6 %	21.9	19.3	17.1
XXXXXXXX16	XXX6	220	110	3.9	7.3	0.659	0.0	0.0 %	0.0	0.0	0.0
XXXXXXXX17	XXX7	220	150	9.4	8.4	0.623	0.2	0.2 %	0.4	0.4	0.2
XXXXXXXX18	XXX8	225	168	16.3	8.9	0.608	1.8	1.0 %	2.5	2.7	1.6
XXXXXXXX19	XXX9	225	168	15.0	8.9	0.608	1.4	0.9 %	2.1	2.2	1.3
XXXXXXXX20	XXX10	225	168	9.2	8.9	0.608	0.1	0.0 %	0.1	0.1	0.1
XXXXXXXX21	XXX11	220	175	15.3	9.0	0.603	1.5	0.8 %	2.1	2.3	1.4
XXXXXXXX22	XXX12	225	200	8.2	6.0	0.656	0.6	0.3 %	0.9	0.8	0.5
XXXXXXXX23	XXX13	225	224	2.5	0.0	0.461	1.1	0.5 %	2.6	2.4	2.2
XXXXXXXX24	XXX14	218	200	8.9	5.8	0.661	0.8	0.4 %	1.2	1.1	0.7
XXXXXXXX24	XXX15	219	200	5.8	0.0	1.393	2.5	1.2 %	6.1	5.6	5.1
XXXXXXXX25	XXX16	512	217	12.4	0.0	1.259	4.6	2.1 %	15.0	13.2	11.3
XXXXXXXX25	XXX17	500	217	37.5	0.0	1.354	15.0	6.9 %	45.6	37.9	29.4

Calculated Flitch plate hot spot temperatures of transformers at one Substation experiencing highest GIC peaks (37.5 Amps / phase)



Calculated Tank wall hot spot temperatures of Shell form transformers at one Substation experiencing highest GIC peaks (37.5 Amps / phase)



Results of GIC Thermal Fleet Assessment Study – Extract

Station	Spec.	HV, kV	LV, kV	MVA	# of Phases	GIC Current, A	Winding Hot -Spot, □C		Structural parts Hot -Spot, □C	
							NO GIC	At reported GIC	NO GIC	At reported GIC
XXXXXXXX11	XXX1	220	69	100	3	2.5	110.0	110.0	94.6	94.6
XXXXXXXX12	XXX2	220	138	100	3	7.3	71.8	71.8	80.0	80.0
XXXXXXXX13	XXX3	230	69	100	3	3.0	71.2	71.2	73.5	73.5
XXXXXXXX14	XXX4	220	69	100	3	4.9	94.6	94.6	85.3	85.3
XXXXXXXX15	XXX5	220	69	105	3	21.1	87.8	87.8	70.0	98.6
XXXXXXXX16	XXX6	220	69	110	3	3.9	109.7	109.7	97.4	97.4
XXXXXXXX17	XXX7	225	69	150	3	9.4	87.7	87.7	70.8	70.9
XXXXXXXX18	XXX8	225	69	168	3	16.3	88.0	88.0	81.0	82.8
XXXXXXXX19	XXX9	225	69	168	3	15.0	81.8	81.8	81.8	83.1
XXXXXXXX20	XXX10	225	69	168	3	9.2	81.8	81.8	81.8	81.8
XXXXXXXX21	XXX11	220	69	175	3	15.3	85.9	85.9	81.5	82.8
XXXXXXXX22	XXX12	225	138	200	3	8.2	85.4	85.4	66.5	66.9
XXXXXXXX23	XXX13	225	138	224	3	2.5	82.9	82.9	60.5	60.5
XXXXXXXX24	XXX14	218	138	200	3	8.9	83.1	83.1	80.3	81.0
XXXXXXXX24	XXX15	218.5	138	200	3	5.8	87.4	87.4	70	70.4
XXXXXXXX25	XXX16	512.5	230	217	1	12.4	77.4	77.4	72.8	80.7
XXXXXXXX25	XXX17	500	230	217	1	37.5	76.7	76.7	60.5	85.3
XXXXXXXX25	XXX18	512.5	230	243	1	37.5	75.0	75.3	81.8	131.6
XXXXXXXX25	XXX19	500	230	243	1	37.5	83.3	83.3	70.0	108.9

THANK YOU

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PECO®

An Exelon Company

ABB

GMD Assessments in WECC

August 14, 2019

Doug Tucker

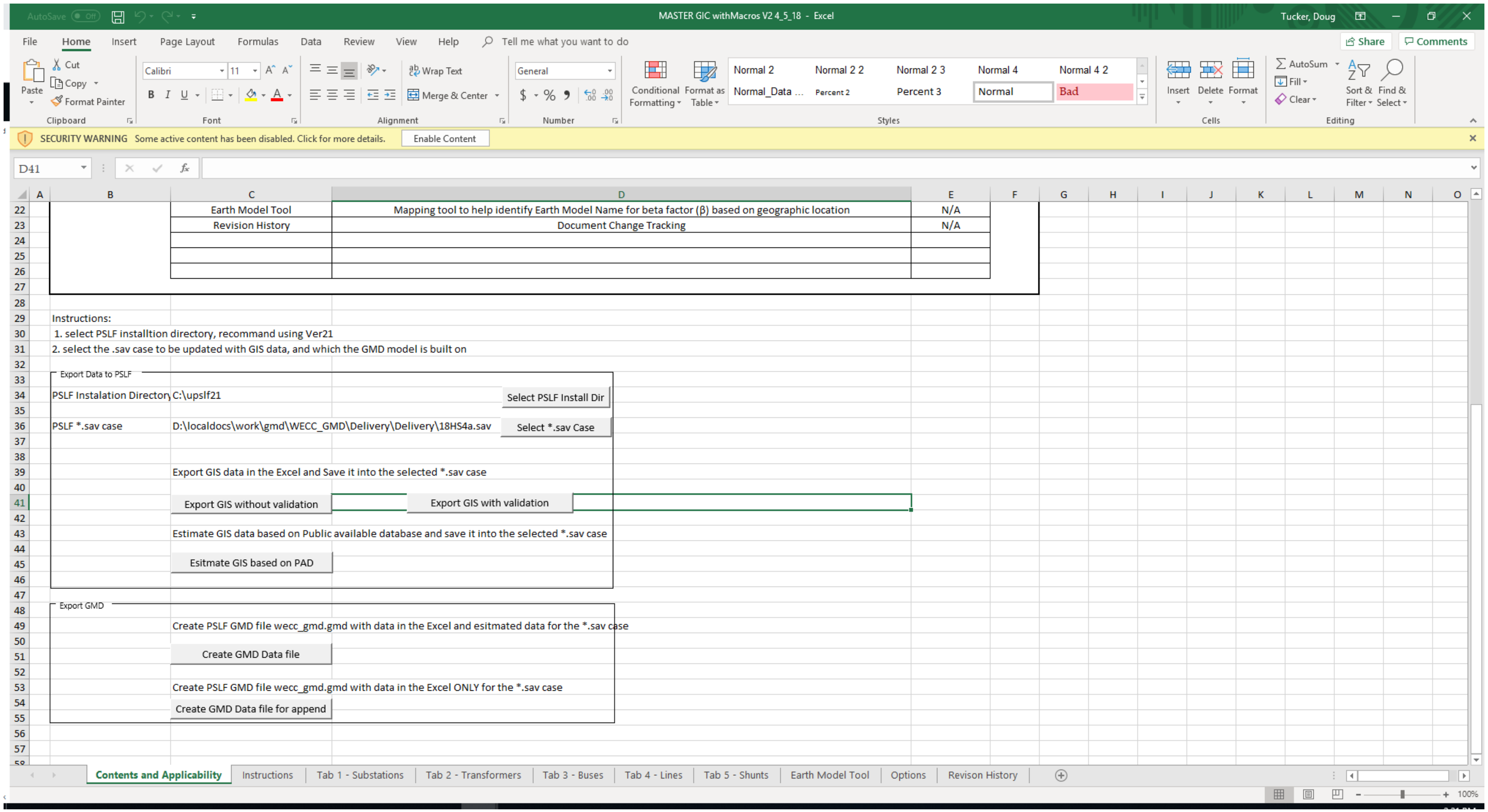
History

- As TPL-007 is being drafted
  - Stakeholders start discussing how to best meet the requirements
  - Decision to collect the data through the same process as interconnection wide base cases.
- Developed a “data collection spreadsheet”
  - Software vendors participated to ensure all data needed was collected
- Contracted with GE in 2017
  - Perform GIC assessment
  - Tool development
  - Training
- 2018 GIC assessments performed in house

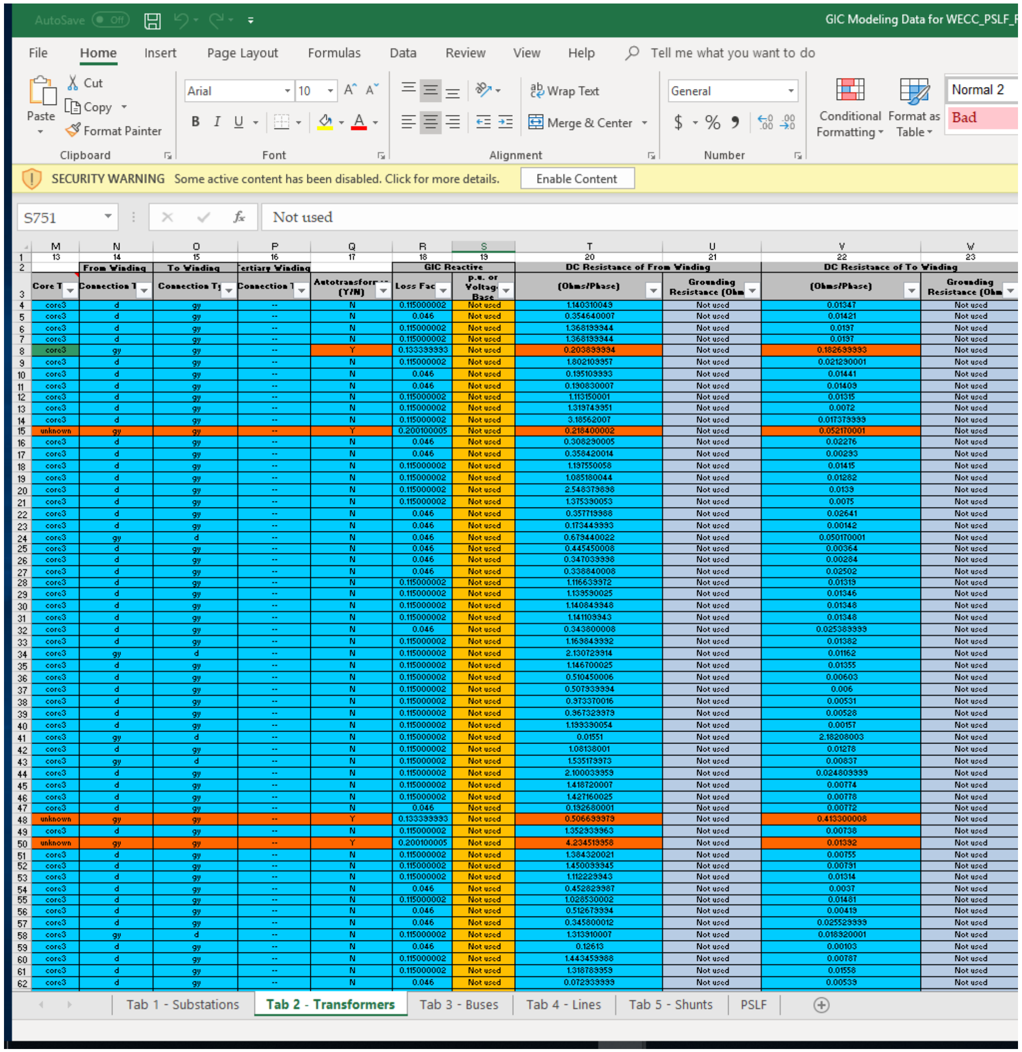
Data Collection in WECC

- Prepopulated spreadsheet with data from a recent operating base case
- GMD specific data added by data submitters
- At request of stakeholders the GMD data is made available only to registered entities
- Data provided is easily linked to any other base case

Creating GMD file



Comparison Tool



Building the Model

- Master GMD database
  - Only has the data collected from data submitters
- Missing data is populated with typically values
- GMD data base + typical data used for the benchmark and supplemental events
- Data made available in two forms
  - Spreadsheet
  - PSLF .gmd format

2017 and 2018 Results

- Transformers above 75 A/phase in Benchmark Event
  - 25 transformers (16hs3a) highest GIC flow 380 A/phase
  - 26 transformers (16lw1a) highest GIC flow 385 A/phase
  - 18 transformers (19hs3a) highest GIC flow 321 A/phase
  - 20 transformers (19lw1a) highest GIC flow 322 A/phase
- Transformers above 75 A/phase in Supplemental Event
  - 48 transformers (16hs3a) highest GIC flow 523 A/phase
  - 46 transformers (16lw1a) highest GIC flow 530 A/phase
  - 32 transformers (19hs3a) highest GIC flow 465 A/phase
  - 31 transformers (19lw1a) highest GIC flow 466 A/phase

Observations

- 2017 Simulations GIC flows were higher primarily because of old scaling factors (β) for Canada
- Few transformers outside of Canada exceed 75 A GIC
- Grounding Resistance affects GIC flows
  - GE used .1 ohm if it was not provided
- Data collection has improved case to case
- 2019 GMD data collection underway

Alberta's Scaling Factor

WECC

Electric Reliability and Security for the West

Contact:

Doug Tucker
dtucker@wecc.org

NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

GMD Data Reporting

Overview of Draft Data Reporting Instruction

Mark Olson, Senior Engineer
GMD Task Force Meeting
August 14, 2019

RELIABILITY | RESILIENCE | SECURITY



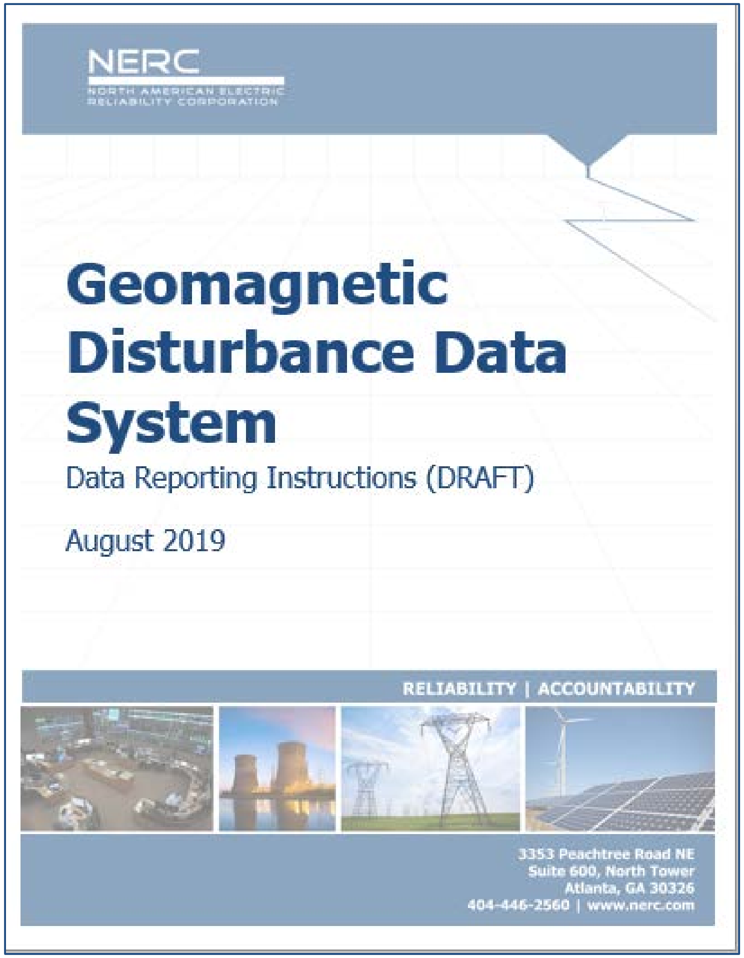

GMD Data Collection Background

- NERC Board approved Rules of Procedure Section 1600 data request for collecting GMD data in August 2018
  - Responds to FERC Order No. 830 directives for collecting data to "improve our collective understanding" of GMD risk
  - NERC developed the GMD Data Request with GMD Task Force (GMDTF) and technical committee input
- NERC is working to implement GMD data collection in 2020

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Data Reporting Instruction

- Data Reporting Instruction (DRI) is being developed by NERC
  - Assists NERC and reporting entities in fulfilling the GMD Data Request reporting requirements
  - Specifies processes, formats, and timelines for data collection
- NERC seeks feedback from the GMDTF on the draft DRI
  - Posting for comment in August



Intro Section: Who Must Report

- Transmission Owners (TO) and Generator Owners (GO) must provide information and data as indicated in the data request
- TOs and GOs that collect GIC data or magnetometer data are considered **Reporting Entities** for GMD events specified in the GMD Data Request and this instruction.
- The GMD data request applies to only U.S. responsible entities (*See* Order No. 830, n. 118).
  - Responsible entities in other NERC jurisdictions including Canada are encouraged to participate in order to obtain relevant GMD data for the North American Bulk-Power System.

Intro: What is Reported

- Reporting Entities will provide the following types of data for time periods during which GMD events KP_7 or greater
  - GIC data for designated GMD events
  - Geomagnetic field data for designated GMD events
- NERC will designate GMD events of interest in collaboration with space weather monitors (e.g., NOAA SWPC)
- Collection periods will capture entire GMD event

Figure: Data Collection Events

GMD Event Timeline

A GMD Event is predicted

- Space Weather monitors issue prediction (e.g., NOAA SWPC)
- Predictions issued 1-3 days prior to GMD event
- Warnings issued ~30 minutes prior to onset

A GMD Alert is Issued

- Space Weather monitors issue Alert (e.g., NOAA SWPC Alert message)
- Will indicate onset of GMD above threshold (e.g., K_P-7)

Return to normal (quiet)

- Dashboards (e.g., NOAA SWPC website) provide continuous information that will indicate when normal conditions have returned

NERC GMD Data Collection Event is Announced

- NERC Announces Start and End Date/Times for GMD Data Collection Period

NERC GMD Data Collection Period

Intro: When will reporting begin?

- NERC anticipates implementing GMD data reporting in Q3 2020
- Data for GMD Events of Interest must be reported at least annually by June 30 of each reporting year
- NERC will also collect historical GIC data for K-7 events dating back to May 2013 (one-time collection)

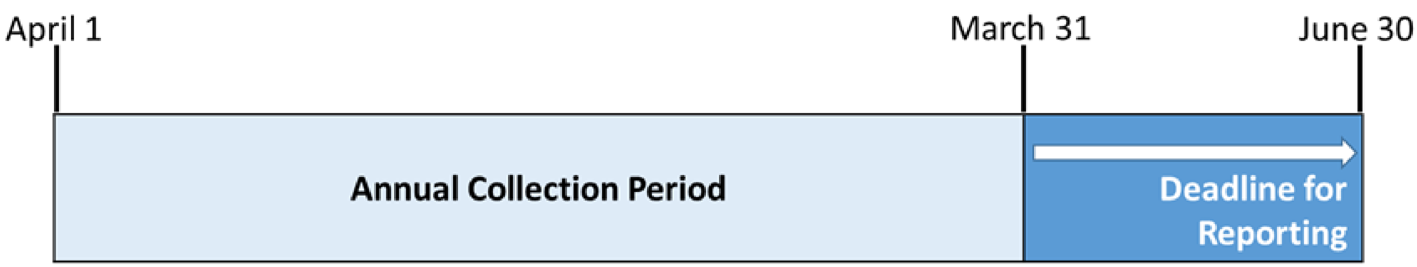
Chapter 1: Data Transmittal

- There are three types of data reported in the GMD Data System:
  - GMD Monitoring Equipment
  - GIC Data
  - Magnetometer Data

- The GMD Monitoring Equipment data must be submitted before reporting GIC data or magnetometer data for a GMD event

Chapter 1: Reporting Deadlines

- Data will be submitted to NERC through the GMD Data reporting application by the June 30 (annual reporting deadline)



Collection and Reporting Timeline

- If desired by the Reporting Entity, the requested data may be provided to NERC prior to the annual (June 30) deadline.

Chapter 2: GMD Monitoring Equipment Reporting

- This required information must be reported in the GMD Data Reporting System before submitting event data

GIC Monitor Information

Table : GIC Monitor Information		
Attribute	**Format**	**Excel**
NERC Compliance Registry (NCR) Number	Alpha-Numeric - 8	NCRID
Device ID	Numeric - 5	DeviceID
Device Manufacturer	Select (list)	GICManufacturer
Device Model No	Alpha-Numeric - 45	GICModel
Device Serial No	Alpha-Numeric - 45	GICSerial
Geographic Latitude	Numeric - 2 + 1 decimals	Latitude
Geographic Longitude	Numeric - 3 + 1 decimals	Longitude
Initial Operating Date	Date (yyyy/mm/dd)	InitialOperatingDate
Transformer Type	Select (list)	TransformerType
Neutral Connection	Select (list)	NeutralConnection

GIC Monitor Information

Table (continued) : GIC Monitor Information		
Attribute	**Format**	**Excel**
Fastest Data Sampling Rate Capable	Numeric - 4 + 3 decimals	SamplingRateCapable
Peak Value in Measurement Range	Numeric	PeakValueRange
Device Status	ID Request, Active, Inactive	DeviceStatus
Status Effective Date	Date (yyyy/mm/dd)	StatusEffectiveDate
Confidentiality Flag	Yes/No	Confidential
Confidentiality Effective Date	Date (yyyy/mm/dd)	ConfEffectiveDate
Confidentiality Expiration Date	Date (yyyy/mm/dd)	ConfExpireDate

Magnetometer Information

Table : Magnetometer Information		
Attribute	**Format**	**Excel**
NERC Compliance Registry (NCR) Number	Alpha-Numeric - 8	NCRID
Device ID	Numeric - 5	DeviceID
Device Manufacturer	Select (list)	GICManufacturer
Geographic Latitude	Numeric - 2 + 1 decimals	Latitude
Geographic Longitude	Numeric - 3 + 1 decimals	Longitude
Initial Operating Date	Date (yyyy/mm/dd)	InitialOperatingDate
Fastest Data Sampling Rate Capable	Numeric - 4 + 3 decimals	SamplingRateCapable
Magnetometer Orientation	Select (list)	MagnetometerOrientation
Device Status	ID Request, Active, Inactive	DeviceStatus
Status Effective Date	Date (yyyy/mm/dd)	StatusEffectiveDate

Chapter 3: GIC Data Reporting

- Table describes the data fields that are collected for each GIC monitor during each designated GMD Event.

Table : Sampled GIC Data Provided for Each GIC Monitor for GMD Event

Attribute	Description	Format
NERC Compliance Registry (NCR) Number	Code assigned to the Reporting Entity in the NCR	Alpha/Numeric - 8
GIC Monitor Device ID	Three-digit code assigned by NERC to this GIC monitor in the GMD Data Reporting System	Numeric - 5
Sample Date	Calendar Date that the data was sampled - Universal Time Coordinates (UTC)	Date (yyyy/mm/dd)
Sample Time	Time in UTC to the nearest whole second that the data was sampled	Time(hh:mm:ss)
GIC Measured	Measurement of GIC to the nearest tenth Amperes (A). Positive (+) and negative (-) signs indicate direction of GIC flow.	Numeric - 4 + 2 decimals

Chapter 3: GIC Data Reporting

- Data sampling rates should be at a continuous rate of between one sample per 10 seconds to one sample per second.
  - Sample rates up to 1 sample per minute are acceptable if required

Chapter 4: Magnetometer Data Reporting

- Table describes the data fields that are collected from each magnetometer during each designated GMD Event.

Table : Sampled Geomagnetic Field Data Provided for Each Magnetometer for GMD Event

Column ID	Description	Data Type
NERC Compliance Registry (NCR) Number	Code assigned to the Reporting Entity in the NCR	5-digits
Magnetometer Device ID	Three-digit code assigned by NERC to this magnetometer in the GMD Data Reporting System	3-digits
Sample Date	Calendar Date that the data was sampled - Universal Time Coordinates (UTC)	YYYY:MM:DD
Sample Time	Time in UTC to the nearest whole second that the data was sampled	HH:MM:SS (UTC)
Geomagnetic (B-field) measurement – North vector	Measurement of B-field (North Vector) to the nearest tenth nano-Tesla (NT).	4-digits, including tenths
B-field measurement – East Vector	Measurement of B-field (East Vector) to the nearest tenth NT.	4-digits, including tenths
B-field measurement – Vertical Vector	Measurement of B-field (Vertical Vector) to the nearest tenth NT.	4-digits, including tenths

Missing Data

- If data is not available from a devices for a designated GMD Event, the Reporting Entity shall submit a Missing Data report.

Table : Missing Data Report Fields		
Field	**Description**	**Data Type**
NERC Compliance Registry (NCR) Number	Alpha-numeric - 8	NCRID
Device ID	Numeric - 5	DeviceID
Start Date for Missing Data	Date (yyyy/mm/dd)	StartDateMissing
Start Time for Missing Data	Time(hh:mm:ss)	StartTimeMissing
End Date for Missing Data	Date (yyyy/mm/dd)	EndDateMissing
End Time for Missing Data	Time(hh:mm:ss)	EndTimeMissing
Data Narrative	Alpha-Numeric - 1000	DataNarrative

Restrictions on Disseminating Data

- If a Reporting Entity reasonably believes that any information required to be submitted under this instruction is Confidential Information, the Reporting Entity shall submit a request for Confidential Information treatment in accordance with FERC's guidance in Order No. 830.

Restrictions on Disseminating Data

- This request shall:
  - identify the information that the Reporting Entity reasonably believes contains Confidential Information;
  - identify the category or categories defined in Section 1501 of the NERC Rules of Procedure in which the information falls, including specific reasons why the information is believed to be Confidential Information;
  - if the information is subject to a prohibition on public disclosure in the FERC-approved rules of a regional transmission organization or independent system operator or a similar prohibition in applicable federal, state, or provincial laws, provide supporting references and details; and
  - if applicable, identify the time period after which the Reporting Entity would no longer consider the information to qualify for Confidential Information treatment (e.g., six months).

Restrictions on Disseminating Data

- If the request for Confidential Information treatment is granted, the entity shall mark the information as Confidential Information or Critical Energy Infrastructure Information as instructed in Section 1502.1 of the NERC Rules of Procedure prior to submission.
- NERC will handle the information in accordance with Sections 1500 and 1605 of the NERC Rules of Procedure for as long as the information is considered Confidential Information.

Next Steps

- NERC will post draft DRI to the GMDTF website in August and seek GMDTF comments
- NERC will continue development of reporting application and portal and incorporate GMDTF comments

Discussion

Reference Slides

GMD Data Collection Overview

- Data will be collected for GMD events that meet or exceed K_P-7
  - Historical events back to May 2013
  - Future events from implementation of data collection program
  - On average, 200 K_P-7 GMD events occur in 11-year solar cycle
- Transmission Owners and Generator Owners with GIC and/or magnetometer data are applicable entities
  - Non-U.S. entities are not obligated to participate but are encouraged
  - Reporting by an entity (e.g., EPRI) on behalf of applicable entities is acceptable
- NERC will make data available to researchers

Purpose of Collecting GMD Data

[The Commission] also direct NERC, pursuant to Sections 1500 and 1600 of the NERC Rules of Procedure, to collect and make GIC monitoring and magnetometer data available. We determine that the dissemination of GIC monitoring and magnetometer data will facilitate a greater understanding of GMD events that, over time, will improve Reliability Standard TPL-007-1. The record in this proceeding supports the conclusion that access to GIC monitoring and magnetometer data will help facilitate GMD research, for example, by helping to validate GMD models.

- Order No. 830 P 93

Data Request Background

- NERC Rules of Procedure (RoP) Section 1600
  - *Within the United States, NERC and Regional Entities may request data or information that is necessary to meet their obligations under Section 215 of the Federal Power Act, as authorized by Section 39.2(d) of the Commission's regulations, 18 C.F.R. § 39.2(d).* (P 1601)
- Data Request Elements
  - Describe why the data is needed, its use and collection method
  - Identify functional entity(ies)
  - Estimate the burden on reporting entities
  - Establish reporting criteria or schedule
- Process
  - 45-day public comment period on NERC's request
  - NERC Board approval required to issue data request to entity(ies)

What Data Will Be Requested

In addition, the Commission directs NERC, pursuant to Section 1600 of the NERC Rules of Procedure, to ***collect GIC monitoring and magnetometer data from registered entities****[*] for the period beginning May 2013, including both data existing as of the date of this order and new data going forward, and to make that information available.*

-Order No. 830 P 89

*does not apply to non-U.S. Entities

Historical Storms

- NERC will also collect historical GIC data for K-7 events dating back to May 2013 (one-time collection)

	Recommended for data collection (UTC)	
Kp	Start Observations	End Observations
K7	2013-03-17T03:00:00	2013-03-18T00:00:00
K7	2013-05-31T15:00:00	2013-06-01T15:00:00
K8	2013-10-02T00:00:00	2013-10-03T03:00:00
K8	2015-03-17T03:00:00	2015-03-18T06:00:00
K8	2015-06-22T03:00:00	2015-06-23T15:00:00
K7	2015-09-11T03:00:00	2015-09-11T18:00:00
K7	2015-09-19T18:00:00	2015-09-20T18:00:00
K7	2015-10-06T18:00:00	2015-10-06T09:00:00
K7	2015-12-20T03:00:00	2015-12-21T09:00:00
K7	2017-05-27T15:00:00	2017-05-28T15:00:00
K8	2017-09-07T21:00:00	2017-09-09T03:00:00
K7	2017-09-27T15:00:00	2017-09-29T00:00:00
K7	2018-08-25T18:00:00	2018-08-27T00:00:00

GIC Monitoring Applications

Gary Hoffman

Advanced Power Technologies

Discussion topics

1. GIC monitoring products
2. Key monitoring aspects
3. Advanced thermal modeling

Advanced Power Technologies

GIC Monitoring Solutions

ECLIPSE HECT

- GIC only (-500 to +500 A)
- Continuously outputs 4-20 mA
- Update time is less than 1 sec
- Automatic alarms for sensor disconnect or failure
- Range can be adjusted any where between -500 to +500

ECLIPSE

- GIC + Harmonic analysis
- Interface to analog outputs, DNP 3.0, Modbus, IEC61850
- Features our patented core saturation detection
- Advanced thermal modeling

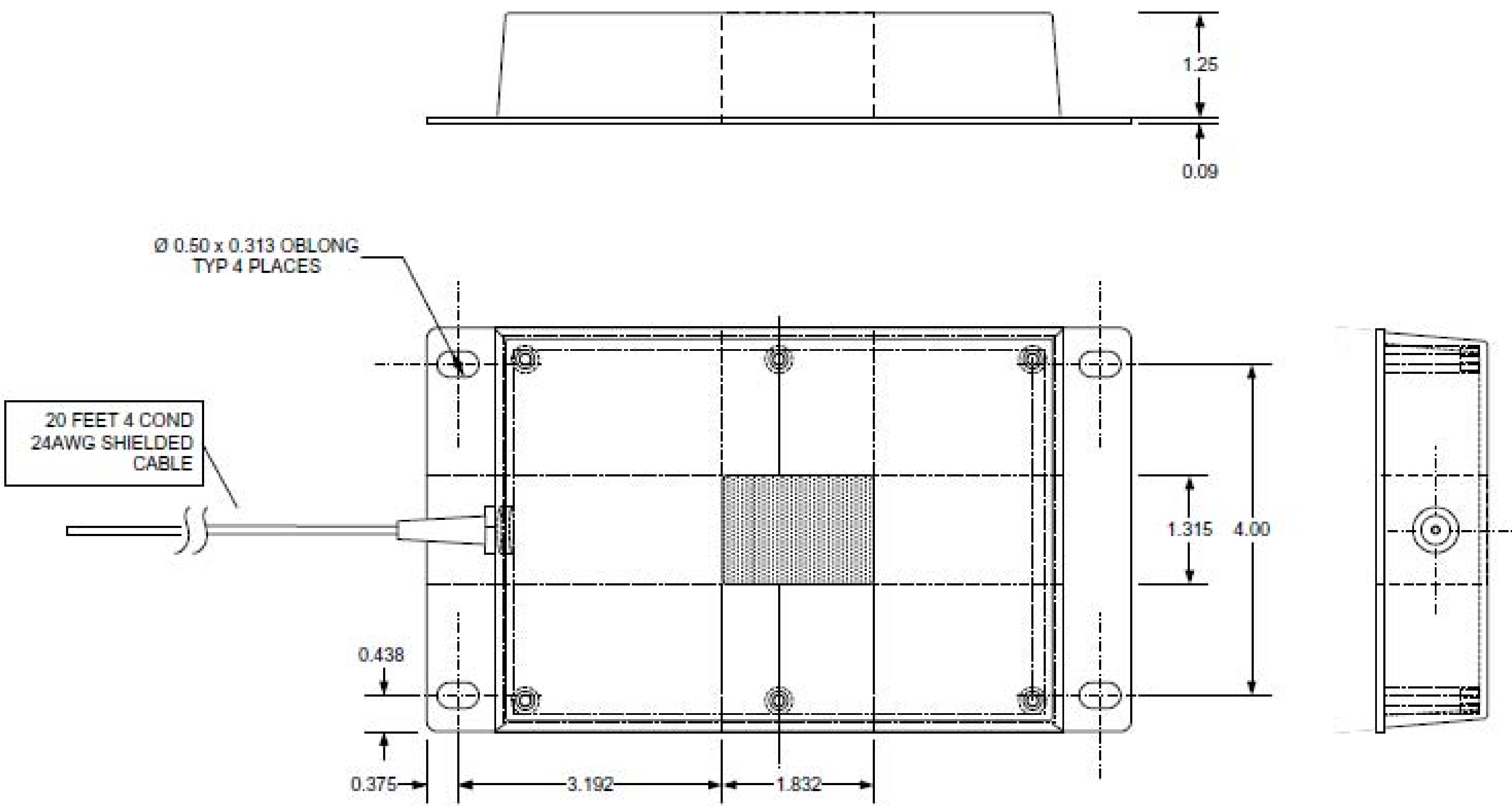
Lifetime Warranty ™

ECLIPSE Hall Effect Choices

- **APT makes Solid-Core & Split Core Hall Effect CT's**
- **Both products 100% potted and sealed to be waterproof**
- **Wide temperature range of -50° to 85° C**
- **Solid-Core CT allows conductor size up to 750 MCM or two 4/0000 conductors**
- **Split-Core CT allows conductor up to 4 inch ¼ inch thick rectangular bus**

Advanced Power Technologies

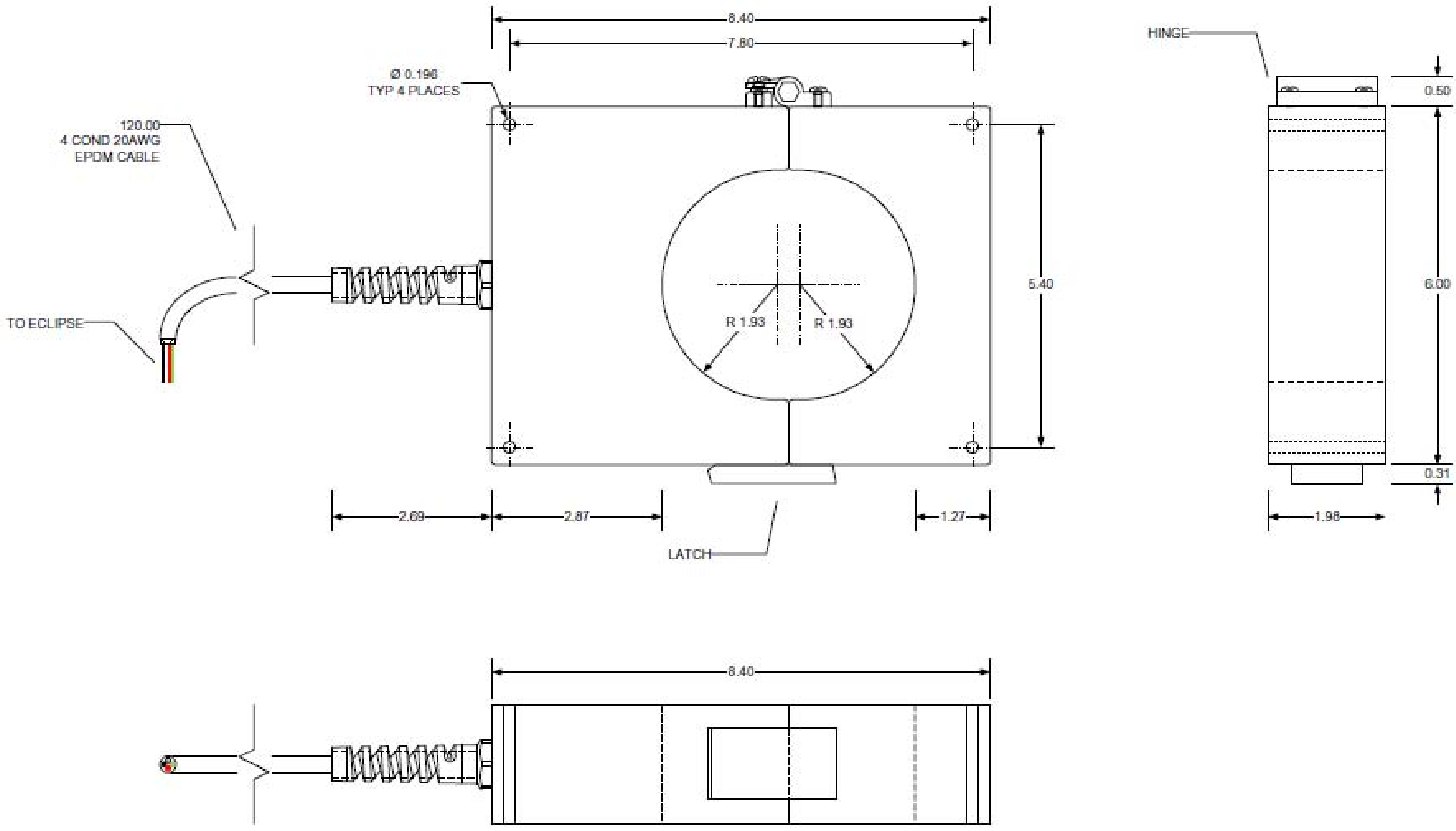
ECLIPSE solid core Hall Effect CT



Advanced Power Technologies

US Patent 9,018,962 Foreign Pat. Pending

ECLIPSE split-core core Hall Effect CT



Advanced Power Technologies

US Patent 9,018,962 Foreign Pat. Pending

ECLIPSE HECT advantages

- Quick and easy solution for GIC monitoring only
- Allows either Solid-Core or Split-Core Hall Effect CT to be used
- 4-20 mA output for monitoring GIC from -500 to +500 Amps dc
- Built-in sensor fail
- No settings other than auto-zero feature

Advanced Power Technologies

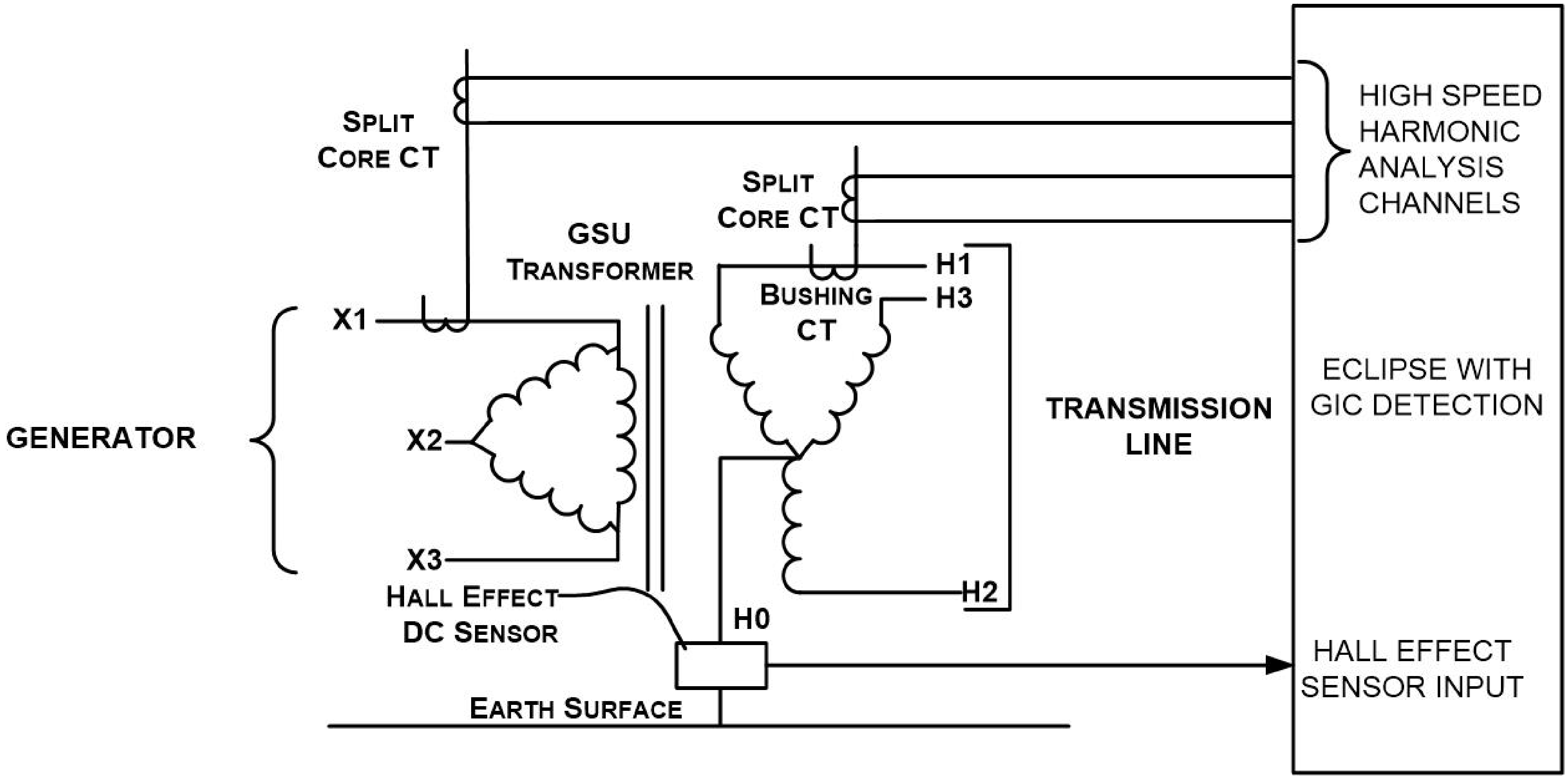
ECLIPSE Part-Cycle Core Saturation detection advantages

- The method used to accurately determine part-cycle core saturation detection is contained within IEEE C57.163-2015™
- If any utility wishes to employ the technology described in IEEE Std C57.163-2015™ they or their vendors will need to obtain a license to use on a reasonable and non-discriminatory (RAND) basis
- Allows utilities to deploy non-blocking detection schemes for vulnerable assets
- Advanced thermal modeling gives real time thermal information as the event evolves over time

Advanced Power Technologies

US Patent 9,018,962 Foreign Pat. Pending

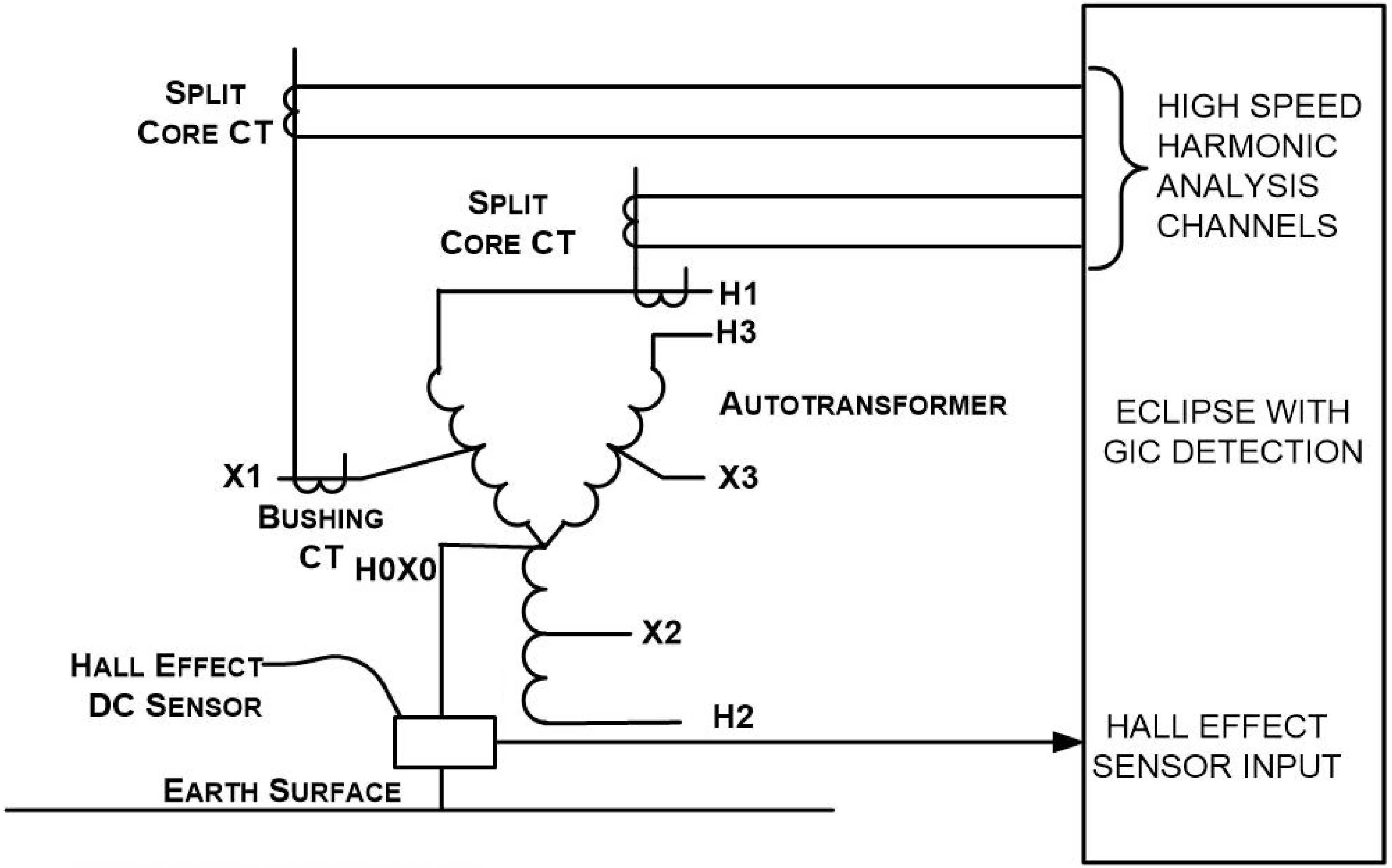
ECLIPSE GIC GSU core saturation detection



Advanced Power Technologies

US Patent 9,018,962 Foreign Pat. Pending

ECLIPSE GIC autotransformer core saturation detection



Advanced Power Technologies

US Patent 9,018,962 Foreign Pat. Pending

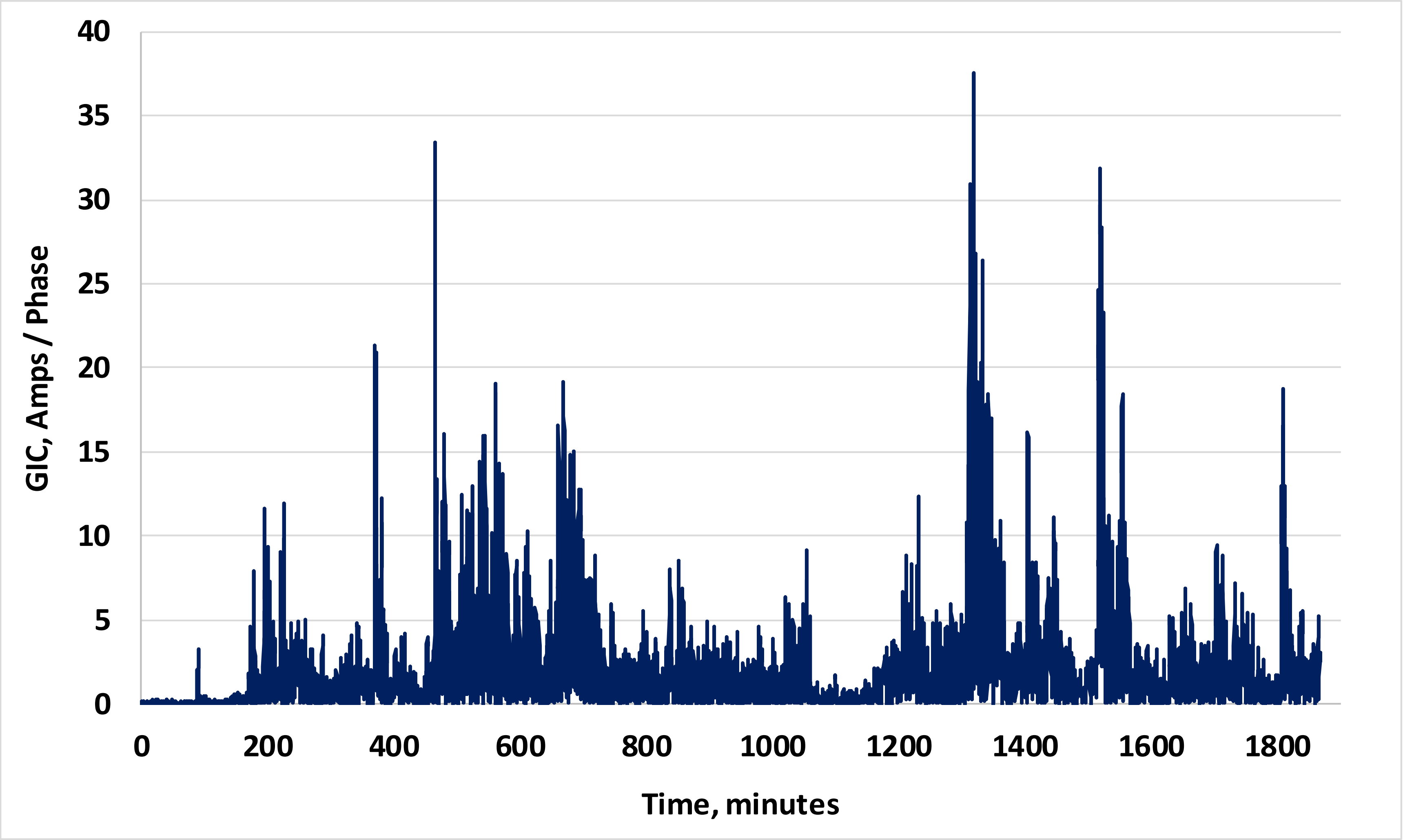
ECLIPSE Enhanced Thermal Modeling

- An ECLIPSE provided with programmed Encrypted Thermal GIC Models

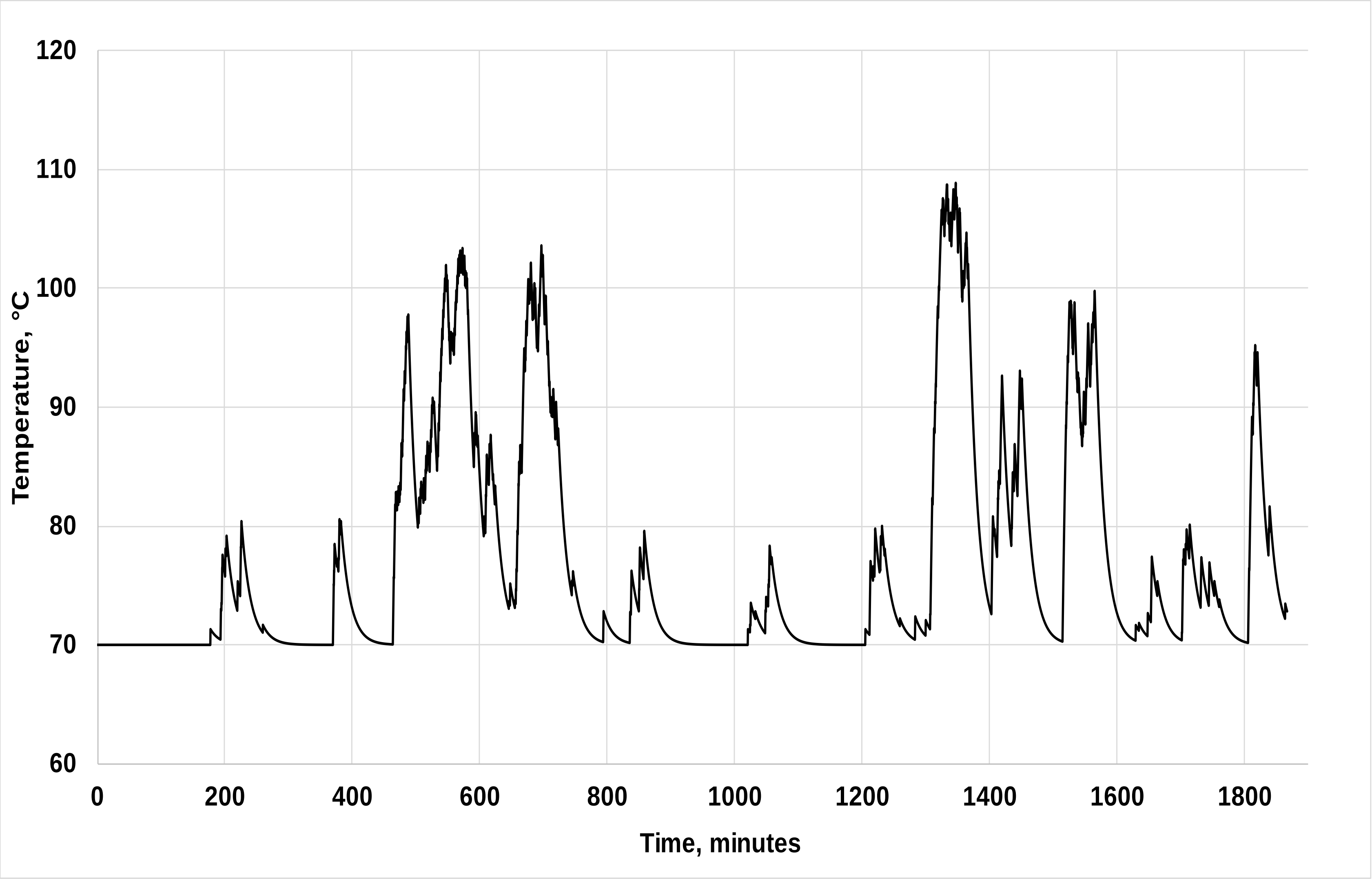
- The models provide calculated values of Windings and Structural parts hot spot temperatures corresponding to the monitored GIC signature, at the load the transformer is operating at

- Parameters of the models are calculated for the specific transformer on which the ECLIPSE is to be installed

Example GIC Signature



Calculated Structural Parts hot spot temperatures



THANK YOU

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Office: 314 679 4803 / Cell: 314 409 7080

Advanced Power Technologies

ABB

End

EPRI GMD Supplemental Project Status Update:

Furthering the Research of GMD Impacts on the Bulk Power System

Bob Arritt
Technical Executive

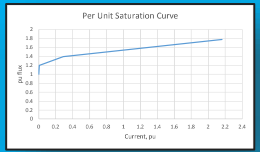
Chicago, IL
14 August 2019

GMD Research Work Plan

Highest Priority

Improved Earth Conductivity Models

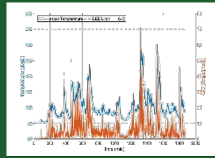
Improved Harmonic Analysis Capability



- EPRI Prioritization follows that of the FERC Directive
- Work to be completed in Q1 2020

Harmonic Impacts

Transformer Thermal Impacts



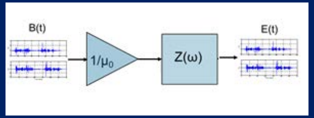
Spatial Averaging

$$E_{peak} = 8 \times \alpha \times \beta \text{ (V/km)}$$

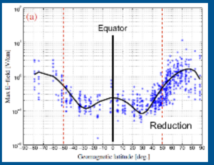
α= Geomagnetic Latitude Scaling Factors

β= Conductivity Scaling Factor

Geoelectric Field Evaluation



Latitude Scaling Factor



Lowest Priority

Released Material

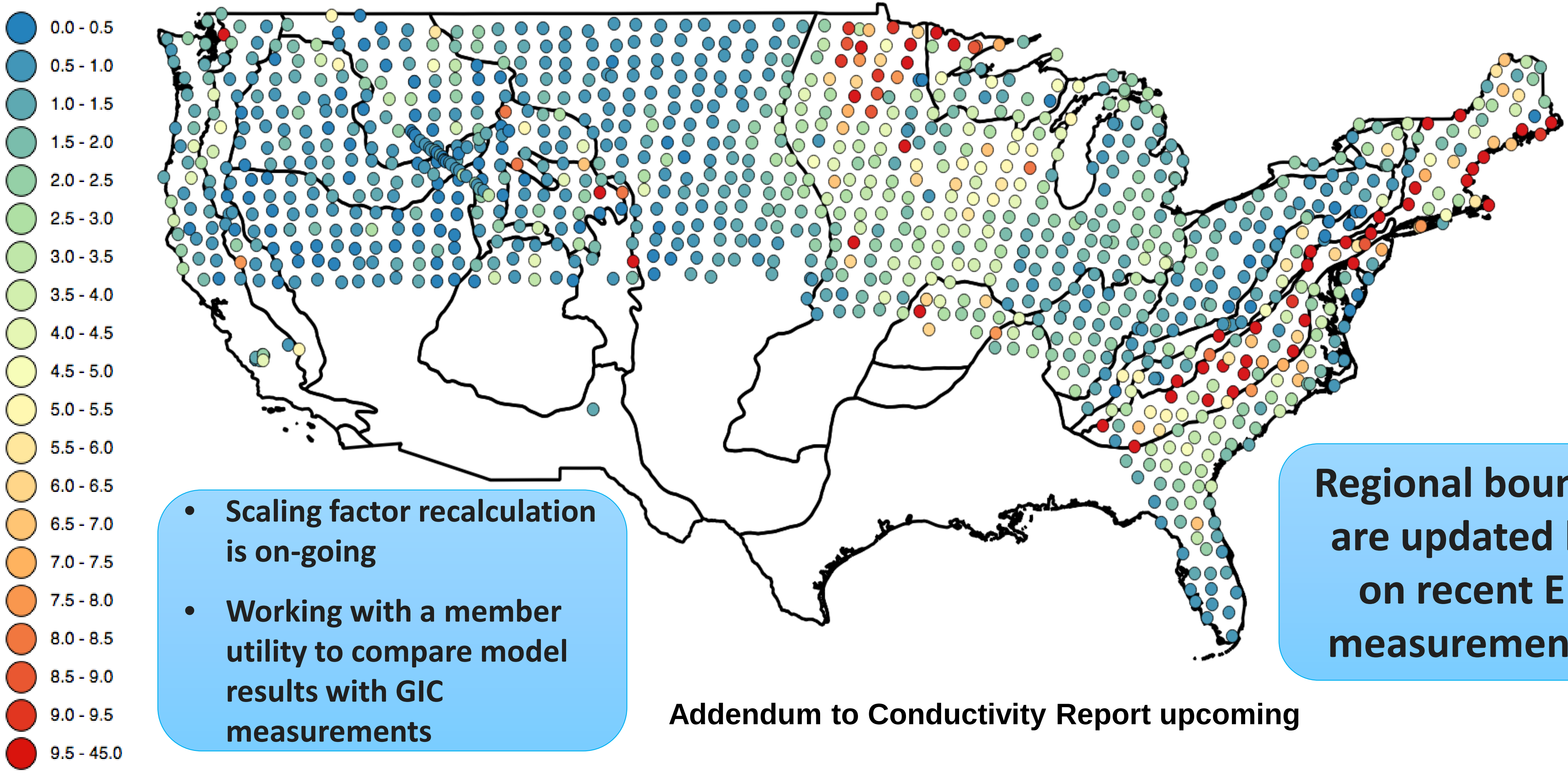
- Summary Whitepaper report on the present status of GMD research – Product ID# 3002013726
- Transformer Thermal Screening Tool – Product ID# 3002014059
- Tool Evaluation and Electric Field Estimate Benchmarking Results Product ID# 3002014853
- Improve Harmonics Analysis Capability Tool Product ID# 3002014854
- Transformer Vibration Analysis Product ID# 3002014855
- Use of Magnetotelluric Measurement Data to Validate/Improve Existing Earth Conductivity Models Product ID# 3002014856
- Improving Understanding of Characteristics of Geoelectric Field Enhancements Caused by Severe GMD Events: *Examining Existing Ground-Based Data* – ID # 3002016832
- Review of Peer-Reviewed Research Regarding the Effects of Geomagnetic Latitude on Geoelectric Fields: *Updated Based on the Latest Peer-Reviewed Research* – ID # 3002016885

Upcoming Material

- Transformer Thermal Modeling Report
- GIC Field Orientation for Transformer Thermal Impact Assessments
- Harmonic Impacts and Analysis Report
- Report of improved beta factors based on updated conductivity profiles, with evaluation of scaling factor ranges and sensitivities to differences in magnetic field input
- Guidance for Validation of GIC Models
- Non-uniform Field Modeling (Coastal Effects)
- Research results on (localized) benchmark and latitude scaling factors

Improved Earth Conductivity Models

Updated conductivity maps using new EMTFs

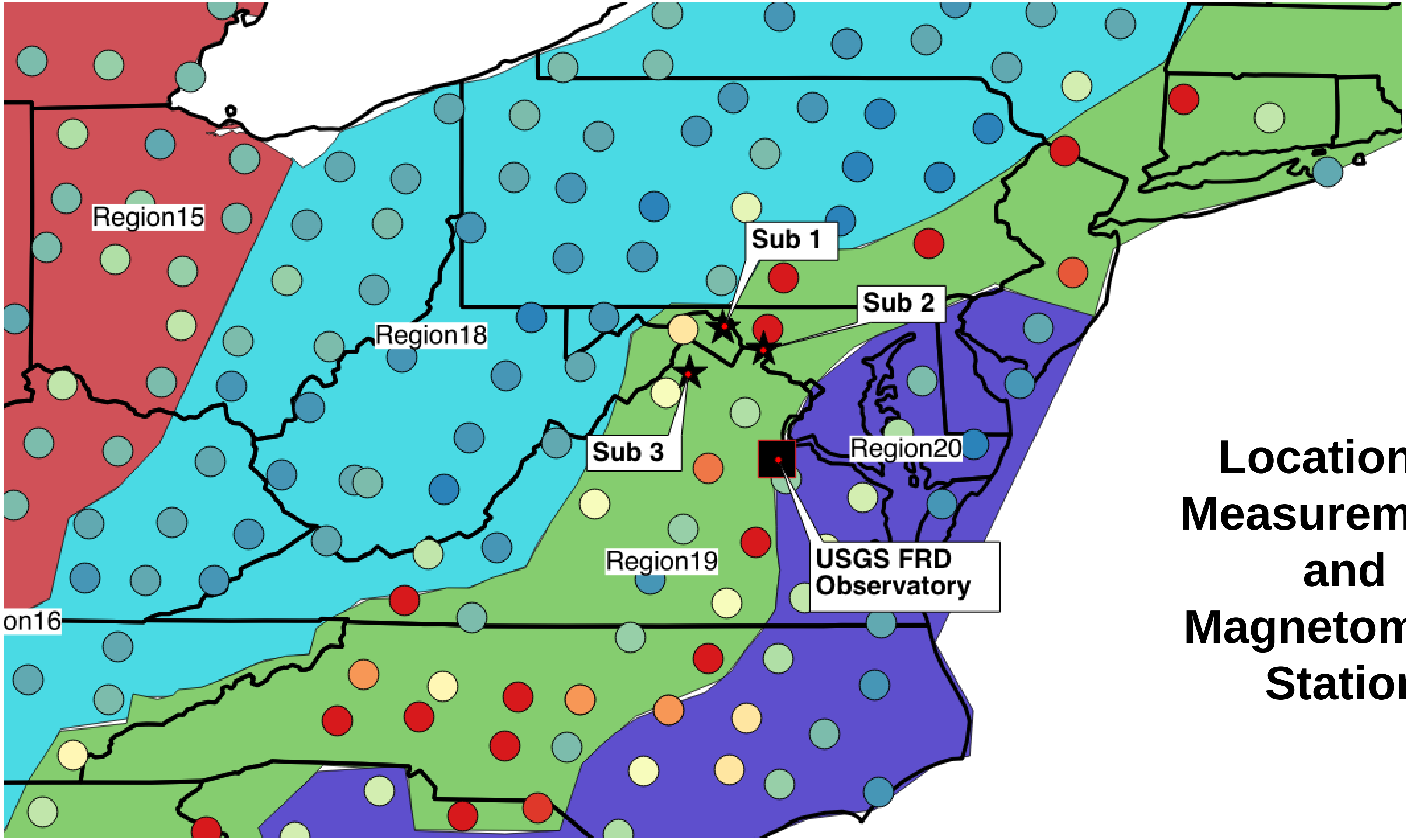


- Scaling factor recalculation is on-going
- Working with a member utility to compare model results with GIC measurements

Regional boundaries are updated based on recent EMTF measurement data

Addendum to Conductivity Report upcoming

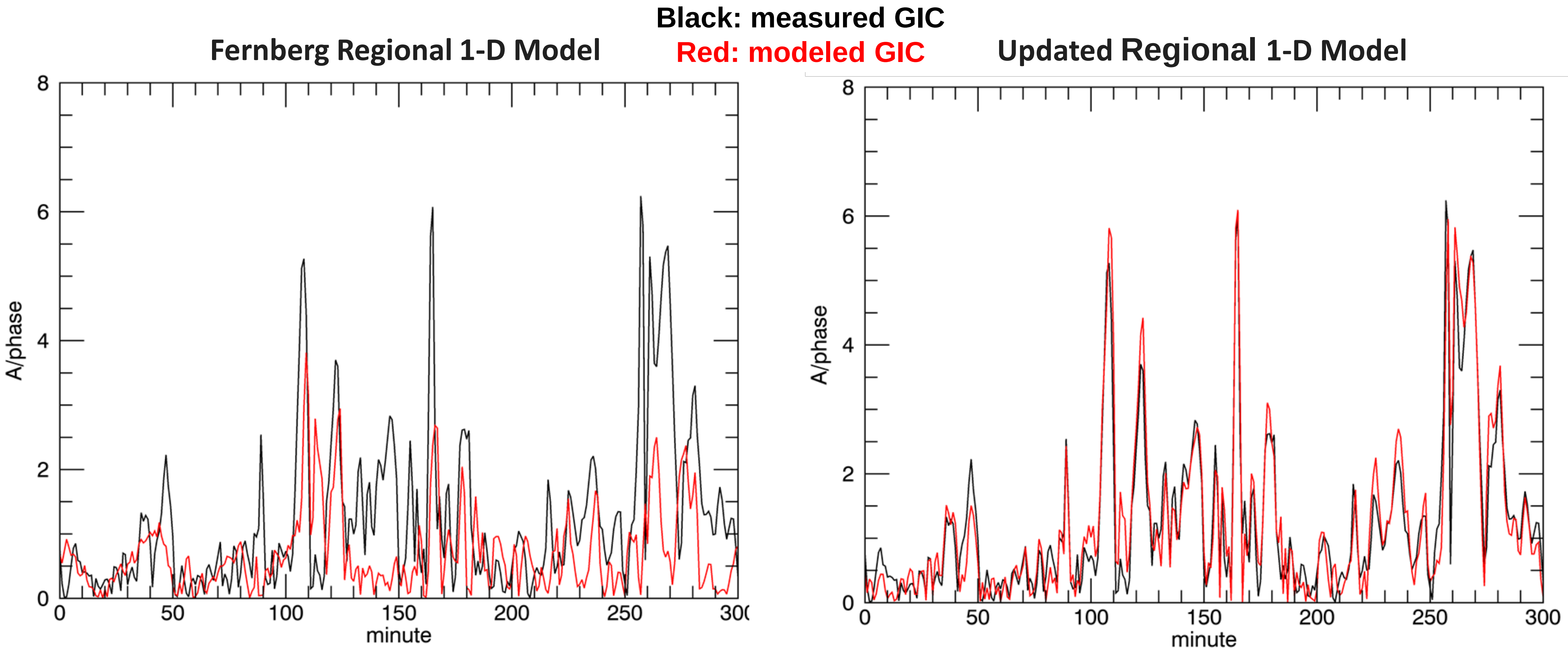
Examining the Impacts of Earth Model on GIC Estimates



Location of Measurements and Magnetometer Station

Region 19 updates improve GIC estimates

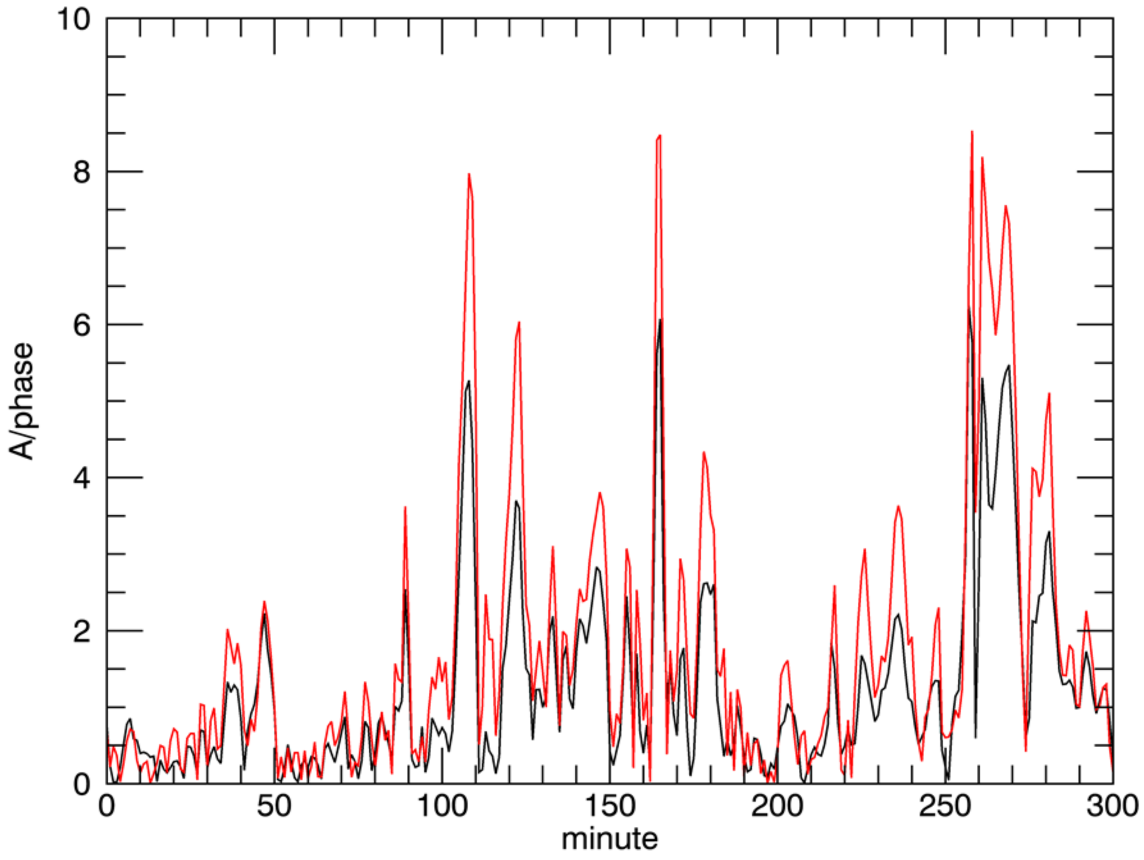
- Substation 1 – March 2015



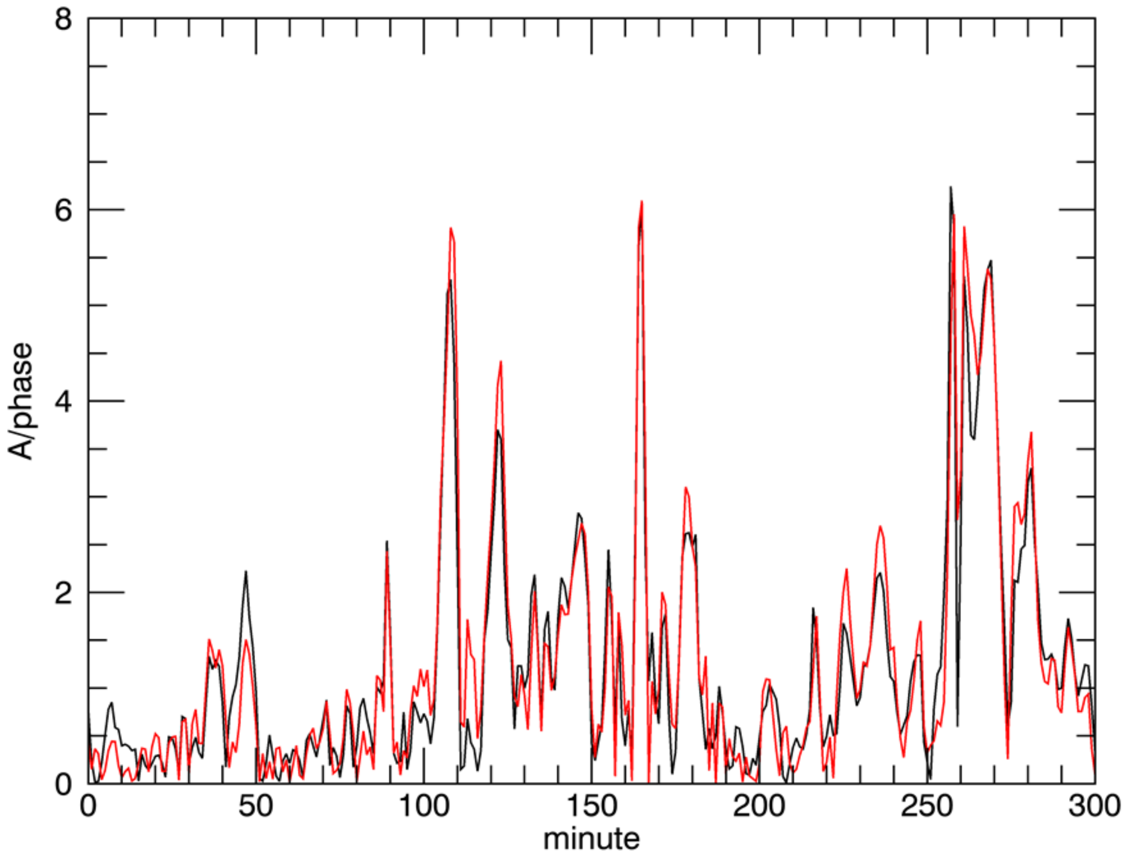
Differences between Regional (i.e. 1D) and Regionally non-uniform model (i.e. 3D)

Black: measured GIC
Red: modeled GIC

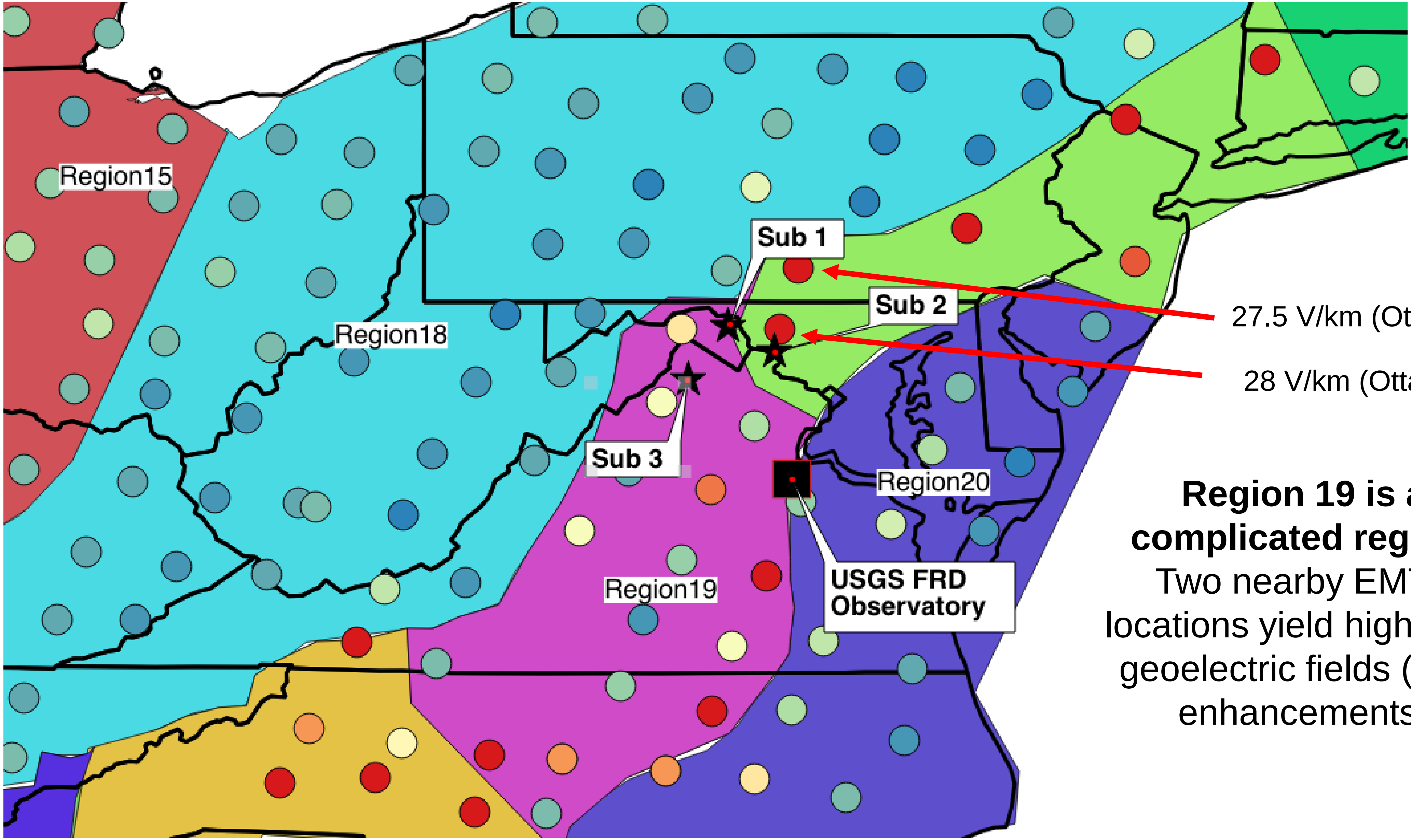
Non-Uniform 3-D Model



Updated Regional (i.e. 1D)

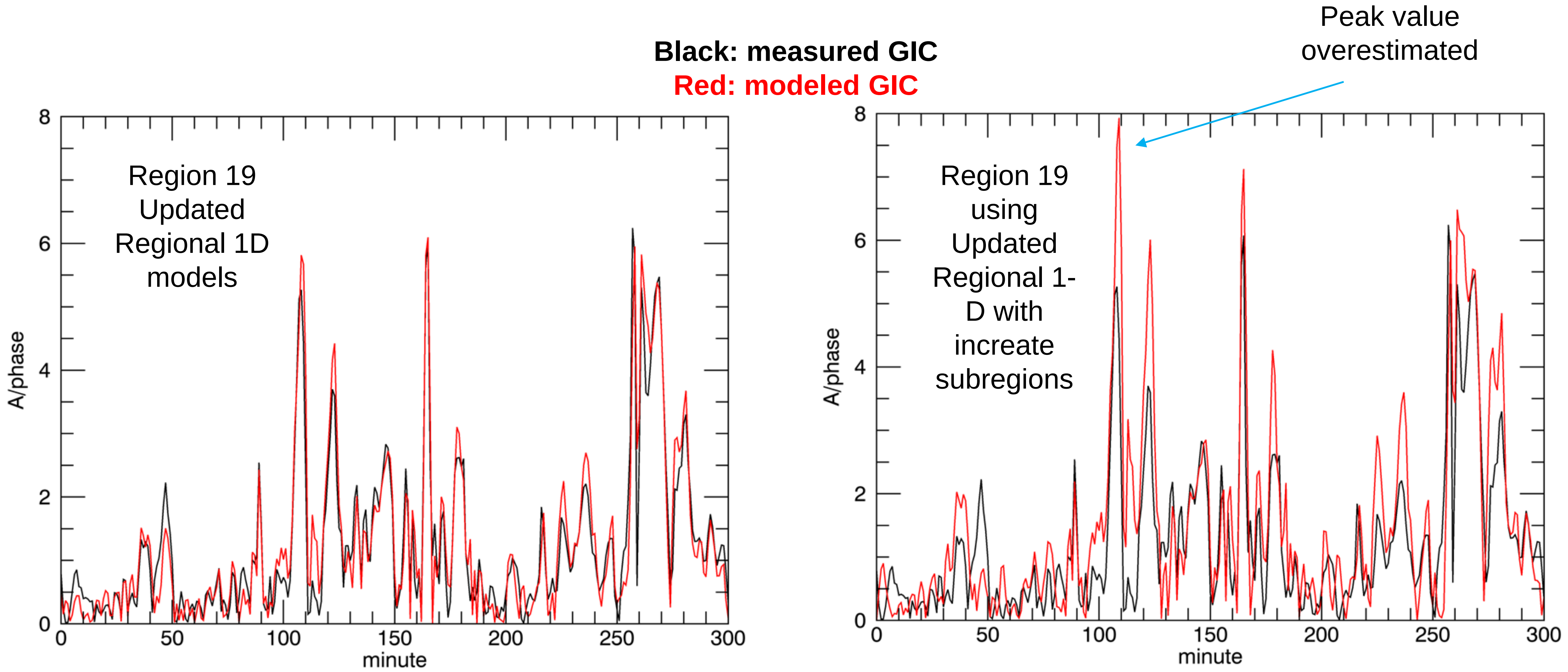


Additional Sub-regions



Region 19 is a complicated region:
Two nearby EMTF locations yield high peak geoelectric fields (local enhancements)

Using smaller Regional (i.e. 1D) results in responses closer to Non-Uniform model (i.e. 3D) – Sub #1



Examining the Impacts of Earth Model on GIC Estimates

- Updated Regional 1D models improve estimates
  - Regional 1D models were updated based on EMTFs in the region, as well as the boundaries
  - Region 19 is a difficult region to model because of localized ground responses and complex geology
  - Appears that localization more important than dimensionality.
- Continue to examine the observed differences between representations of ground response.
- GMD ground response – a three layered approach – regional vs local granularity
  - First layer: Beta scaling factors.
  - Second layer: Optimized regional 1D models.
  - Third layer: Non-uniform 3D or EMTFs

No matter which representation of ground response chosen to use, they should be based on the best available empirical information.

Improved Harmonic Analysis Capability

What Needs to be Examined in an Harmonic Analysis?

- Determine harmonic currents and voltages applied to equipment throughout the transmission grid
- Evaluate equipment and protection systems to identify:
  - Protection systems that are likely to falsely trip
  - Equipment in danger of possible failure during GMD
  - Operation of protection systems in proper response to the harmonic stress

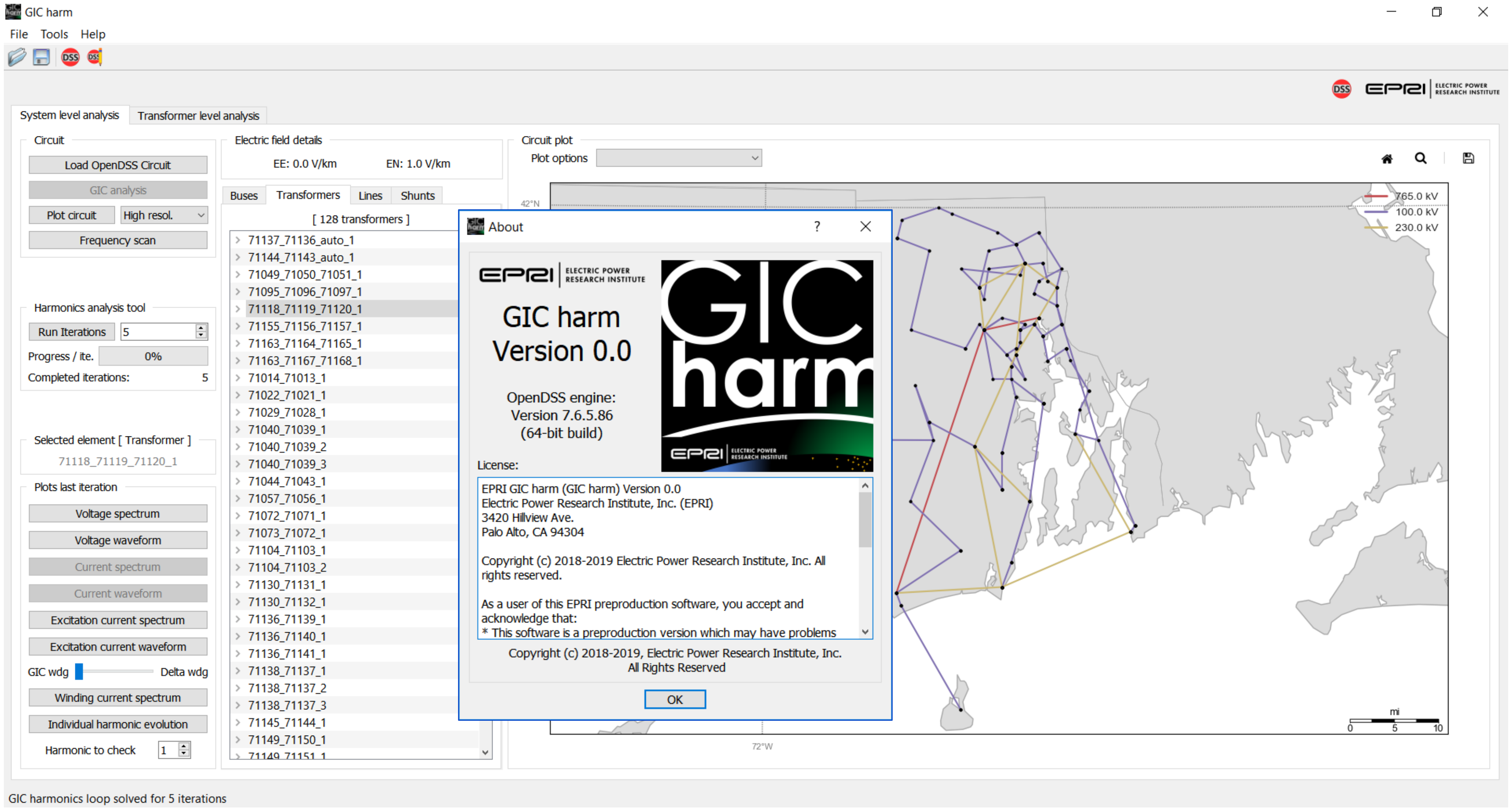
TPL-007. "*Protection Systems may trip due to the effects of harmonics. P8 planning analysis shall consider removal of equipment that the planner determines may be susceptible.*"

Harmonic Tool Beta Version

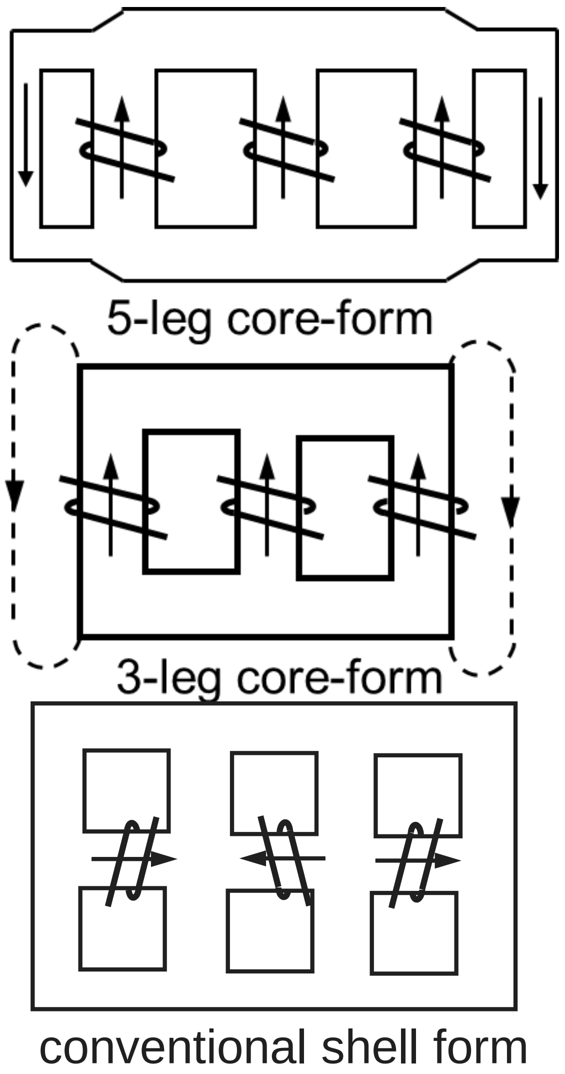
Available on epri.com Product ID# 3002014854

Capabilities of the beta version:

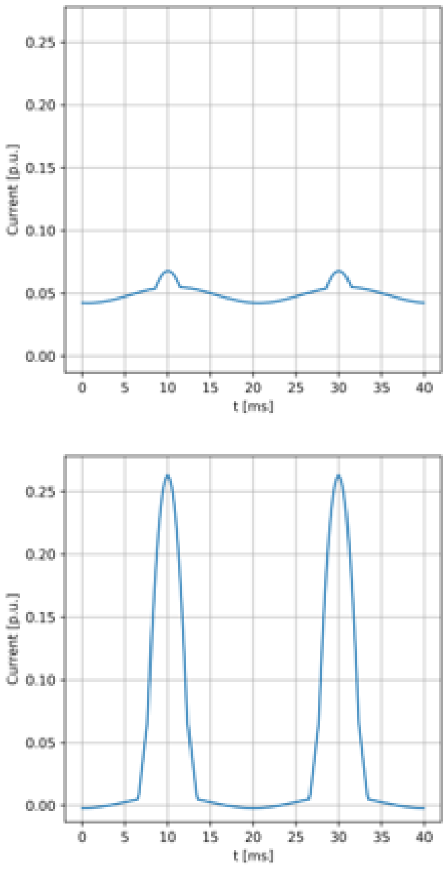
- Transformer level Analysis
- System level Analysis
- Built-in converter

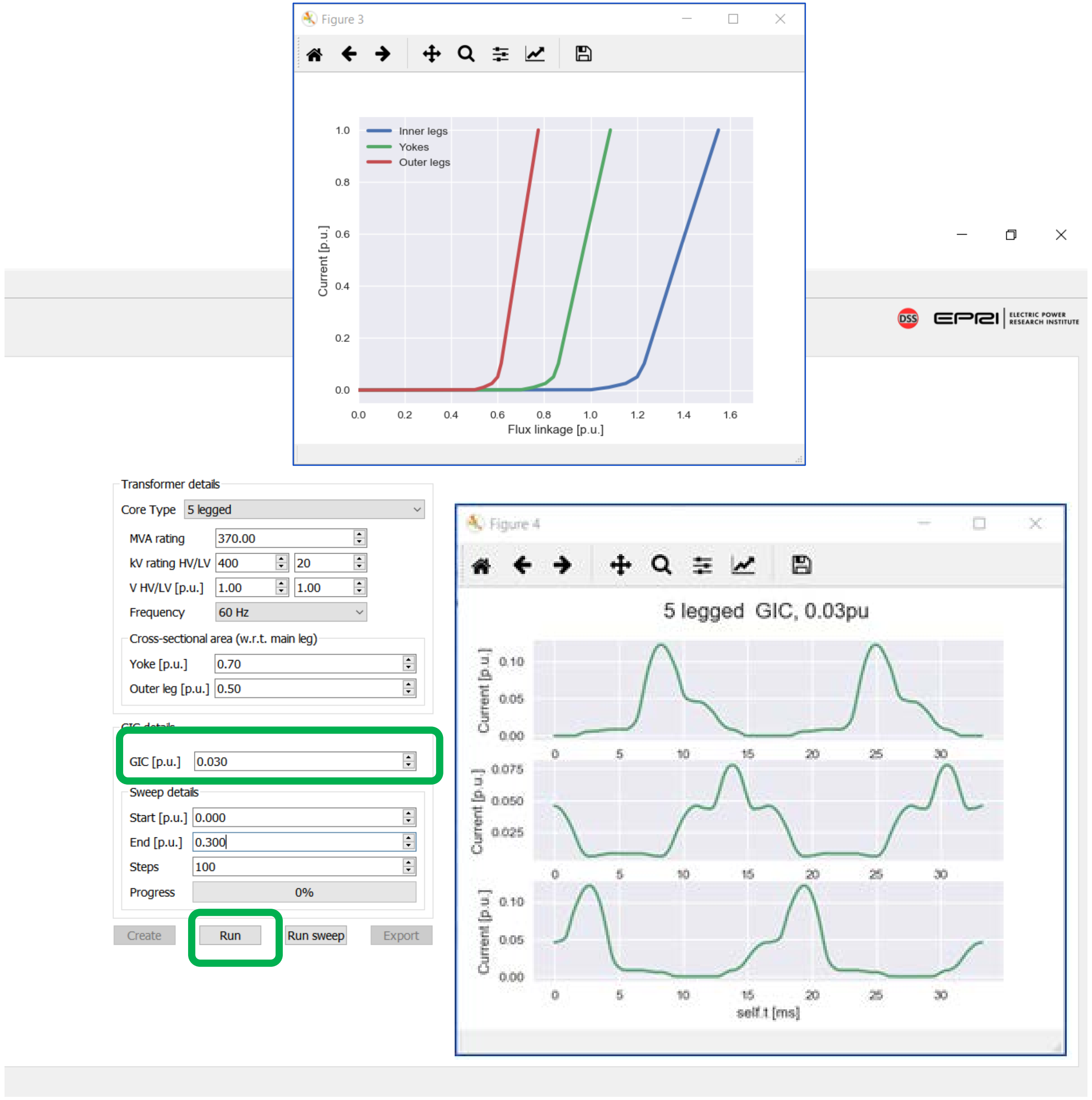


Transformer level analysis



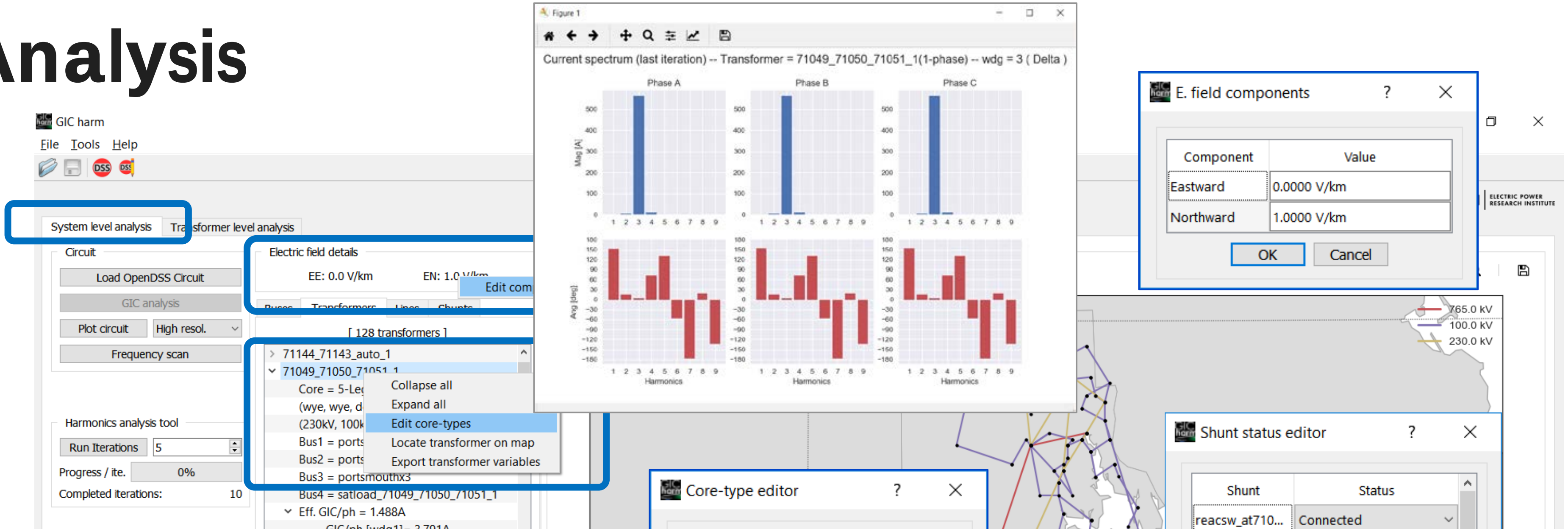
Magnetizing Current 40A GIC

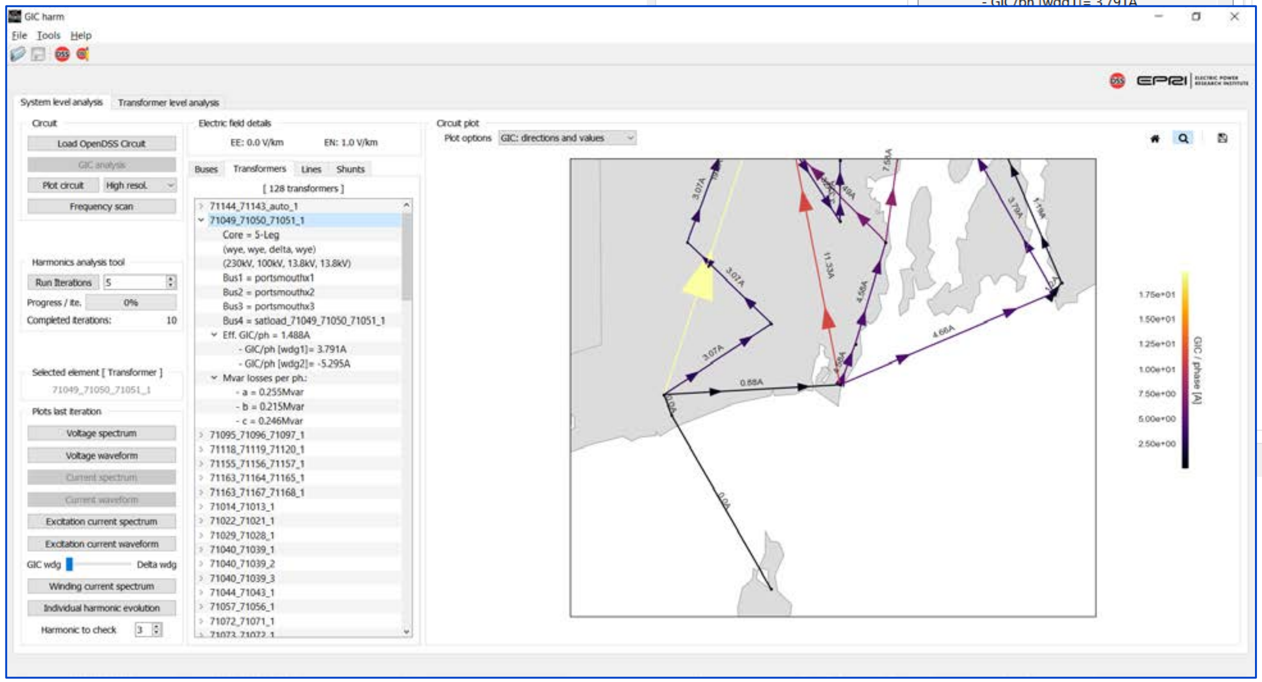


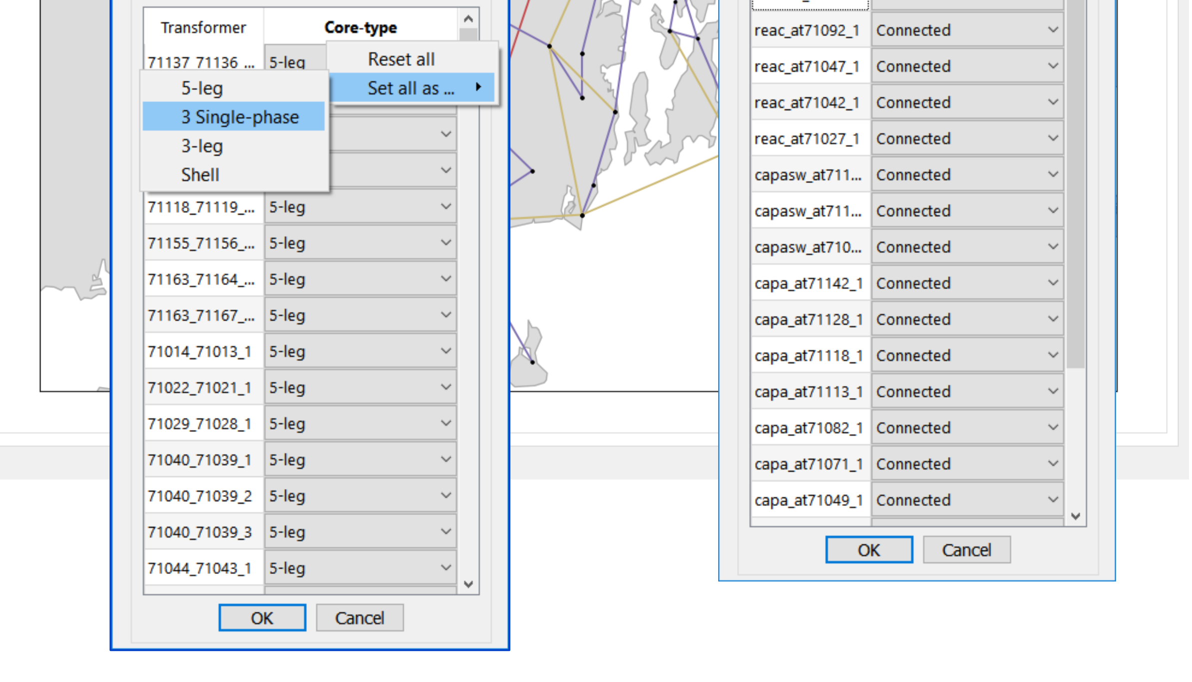


System Level Analysis

- Relevant details for buses, elements, and electric field
  - Buses
  - Transformers
  - Capacitors
  - Reactors
  - Generators



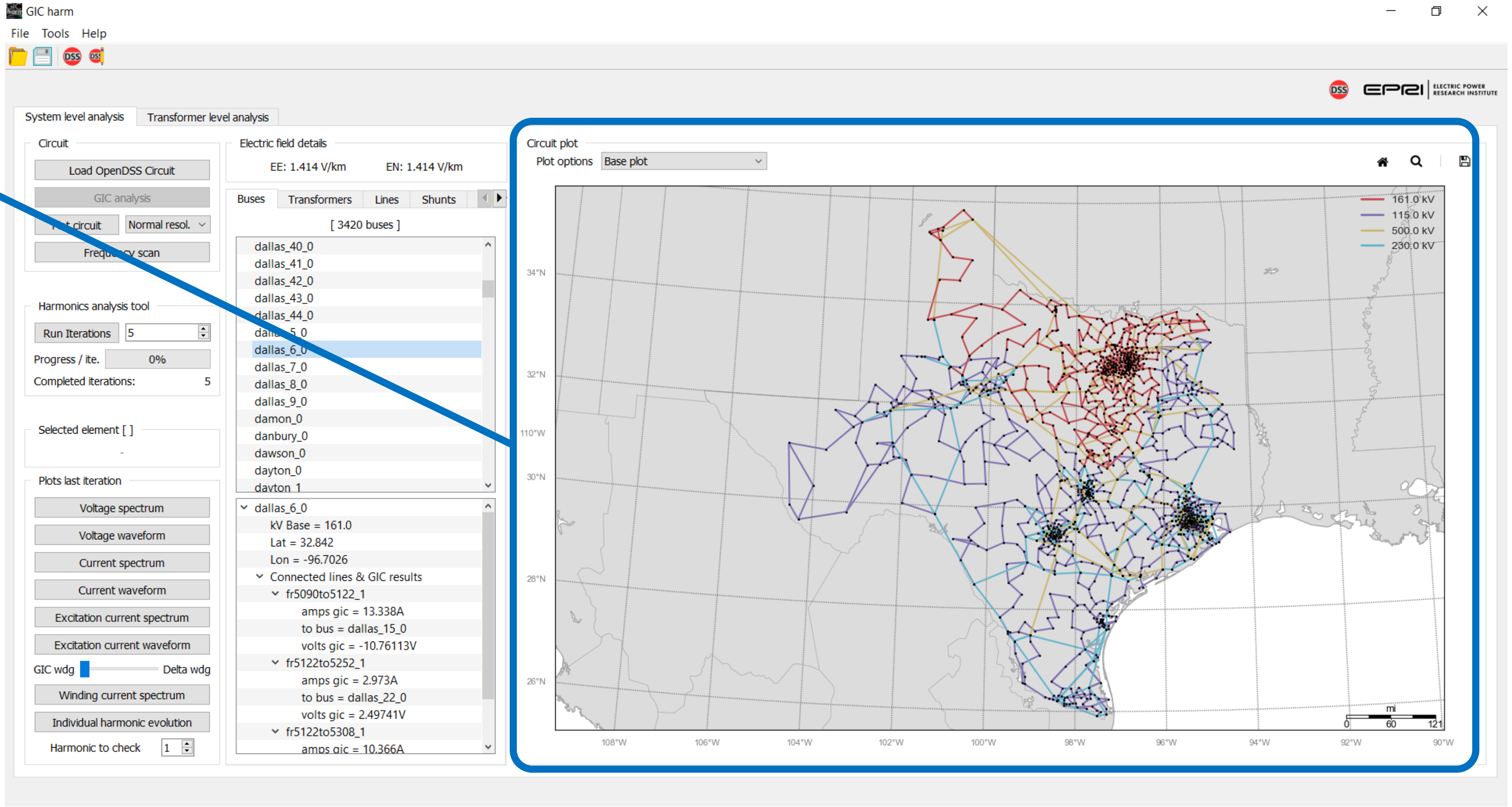




New Features GICharm

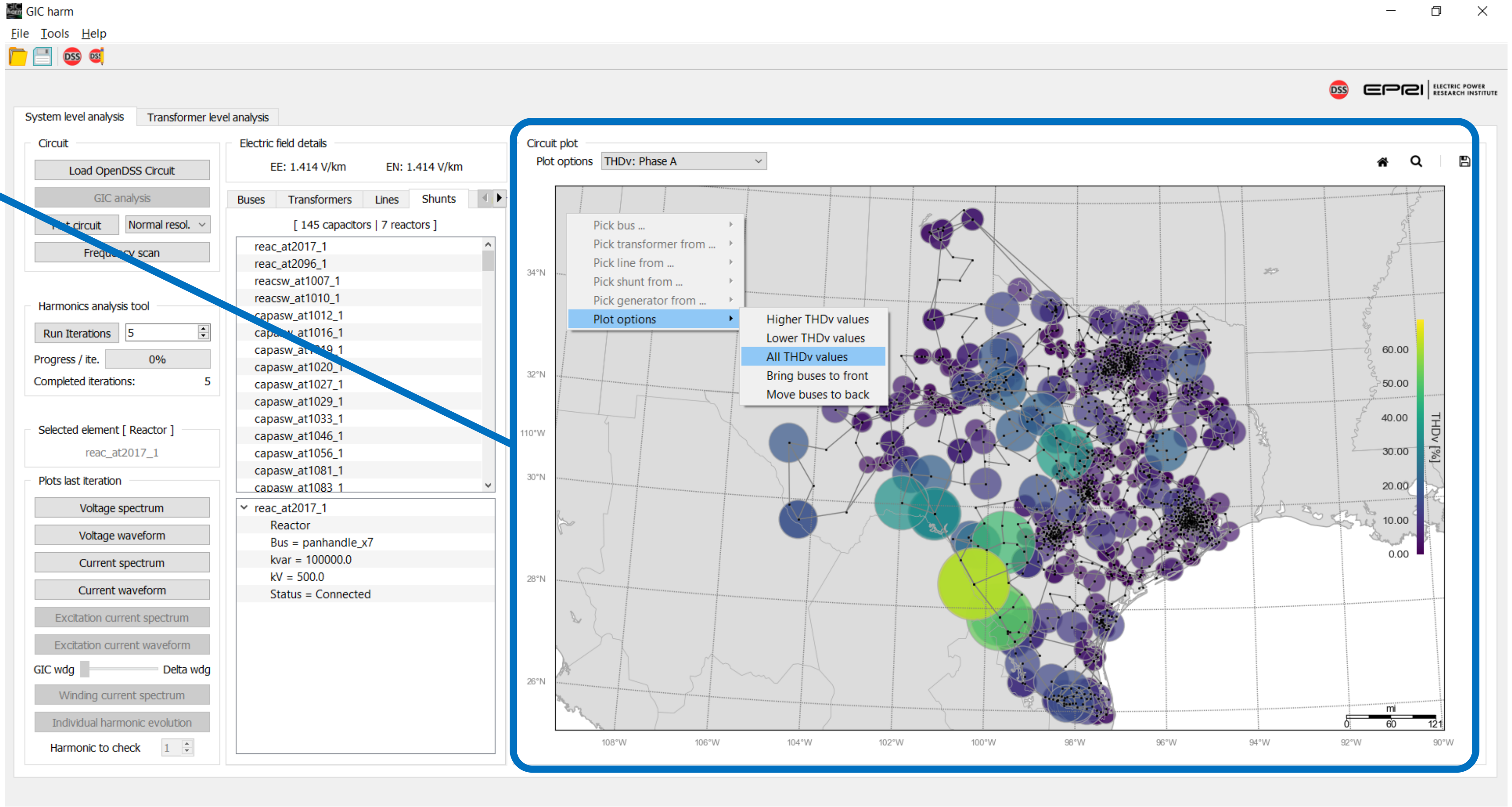
Changes to the interface to improve performance

- Circuit now remains plotted when testing scenario changes (i.e. changes in GMD electric field direction)
  - Circuit gets updated if new scenario affects visualization



Changes to the interface to improve performance

- New circuit visualization options
  - Depending on the plot view:
    - Hide buses and leave lines in front
    - Filter highest and lowest THD values
    - Filter highest and lowest fundamental voltage values



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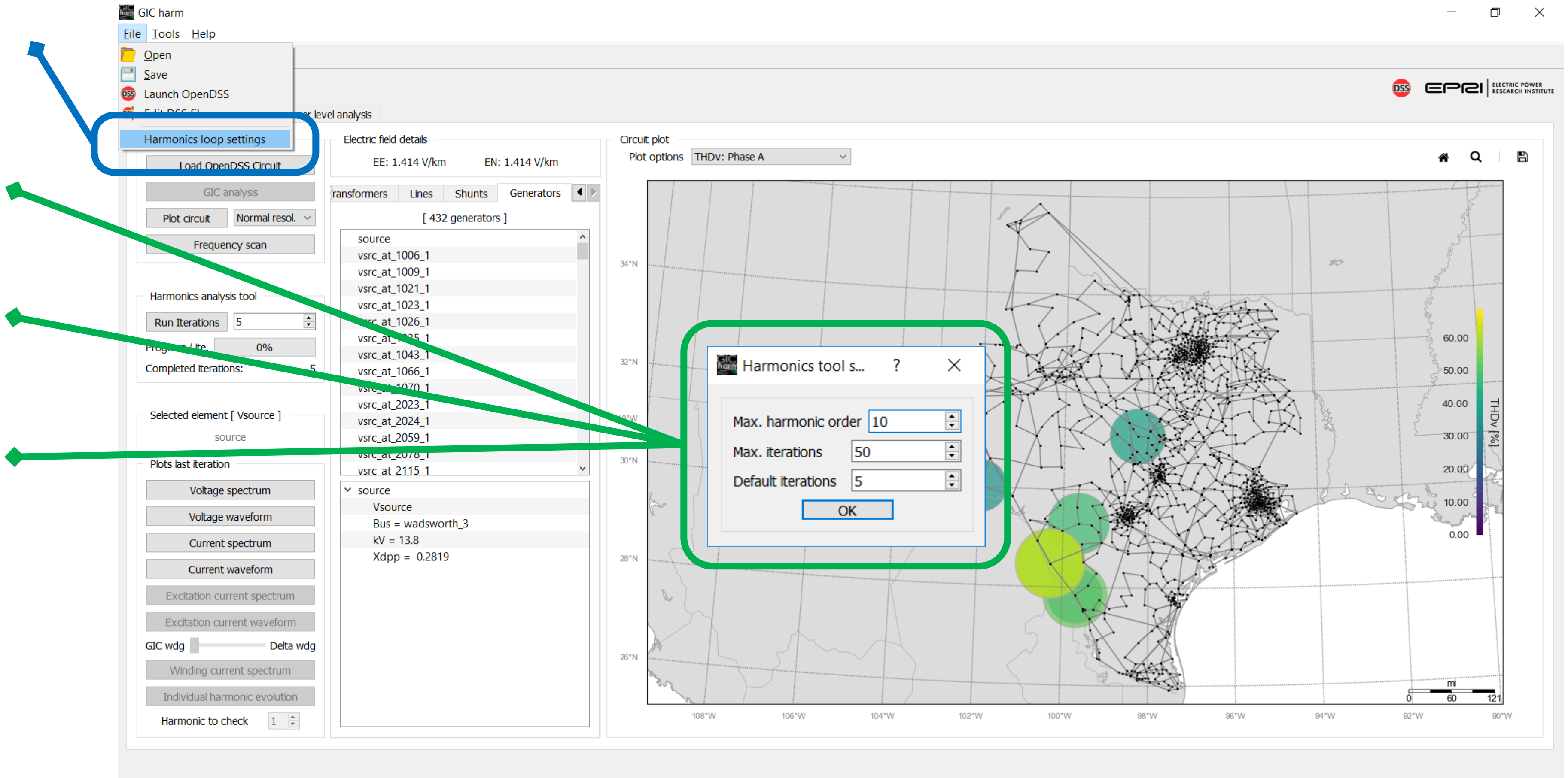
Changes to the interface to improve performance

- Dialog to edit harmonics loop default settings:
  - Highest harmonics order
  - Max number of harmonics loop iterations
  - Default number of single run iterations



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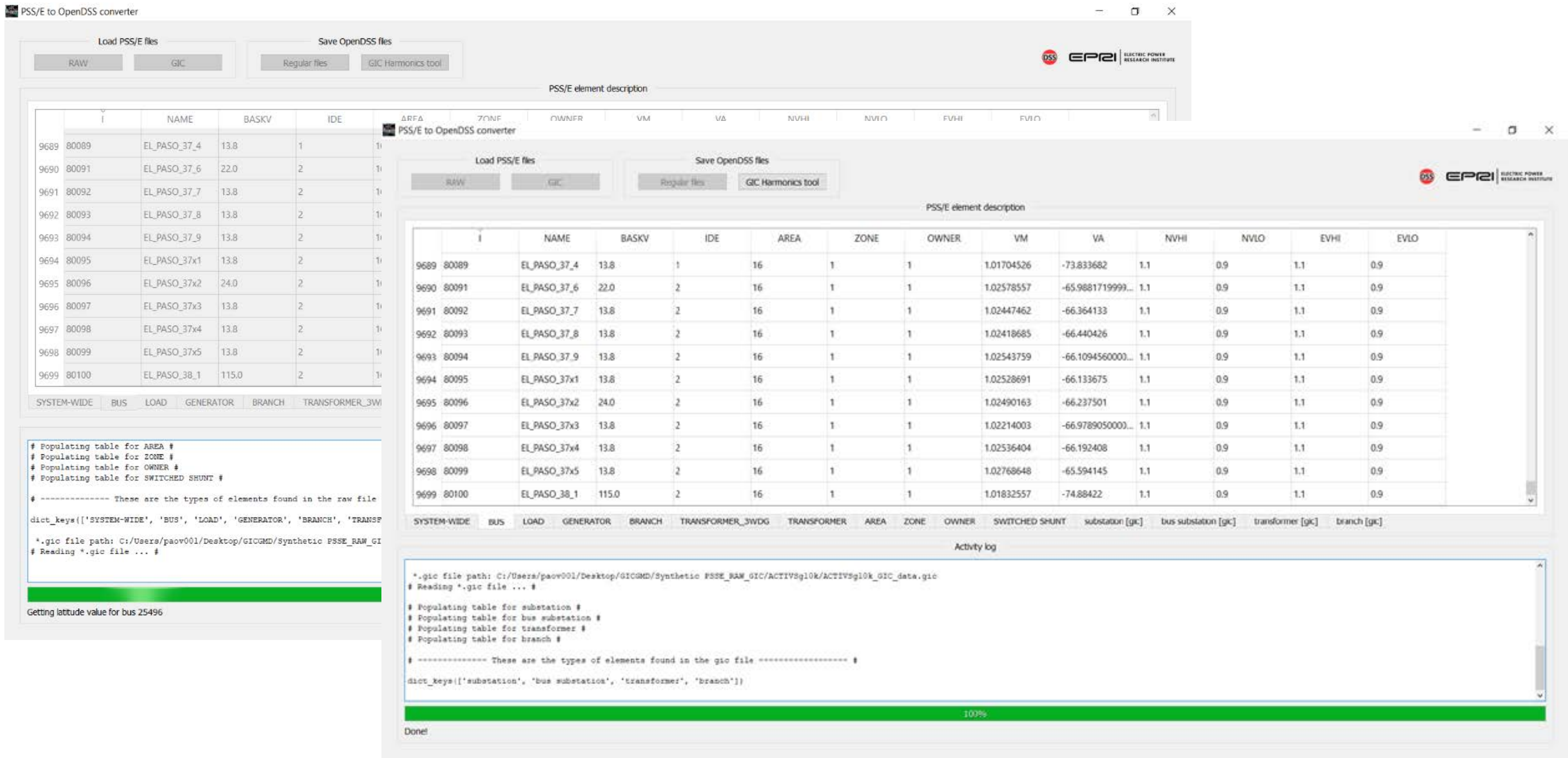
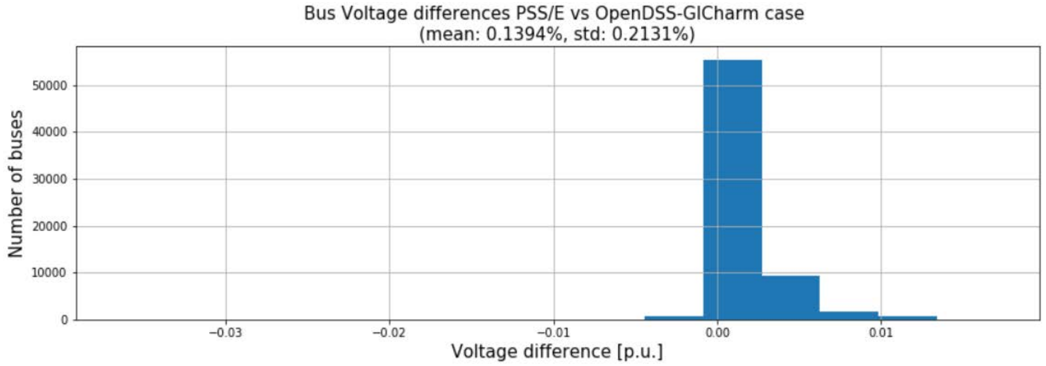
Improvements in PSS®E to OpenDSS converter

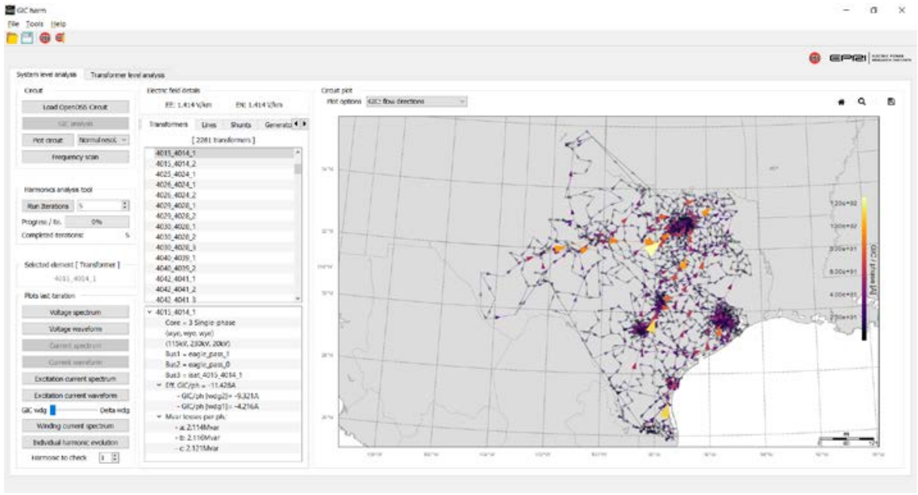
- Improvements to handle large cases
- Added progress bar and status bar feedback during:
  - Data import from PSS/E *.raw and *.gic files
  - Data cleaning after import
  - Data conversion to regular and GICharm *.dss files
- Improvements to the conversion itself
  - E.g. 70k buses case, voltage differences:
    mean = 0.0014p.u.
    Std = 0.0021p.u.

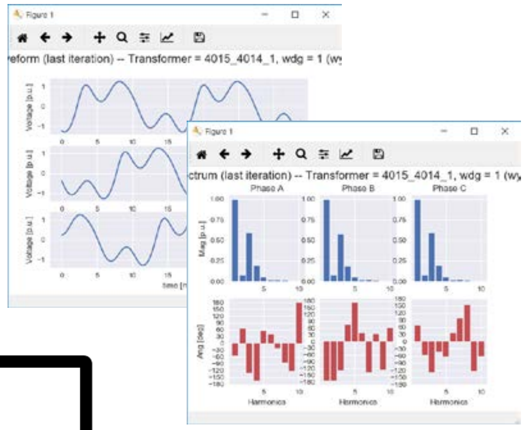




Data management: SQLite database & Serial files

- Transformer magnetic circuits are solved using parallel processing
  (more cores - higher speed)
  - For 2k buses case
    (ERCOT synthetic)
    - Laptop: 8 core - 16GB RAM:
      390 secs / Iteration
    - VM: 16 core - 32GB RAM:
      96 secs / iteration

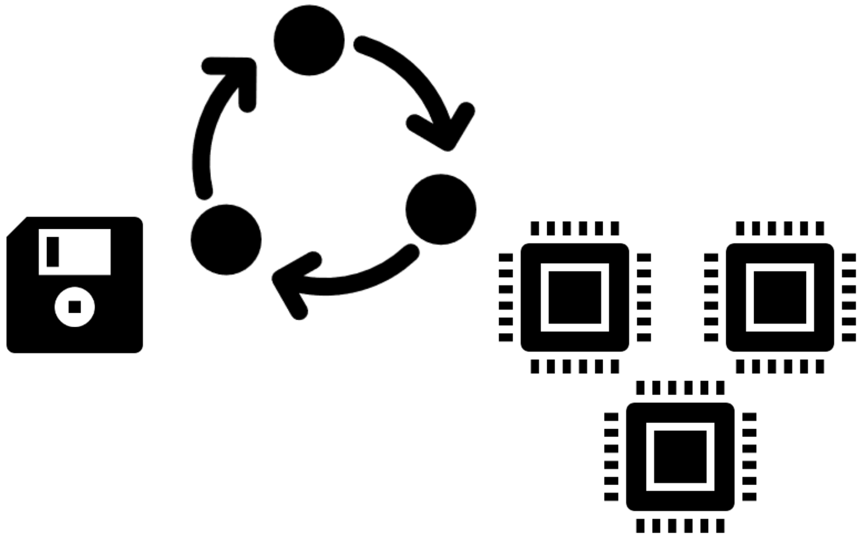




- Transformer data is kept in serial files on local disk

- Circuit data and visualization information is kept in SQLite local database

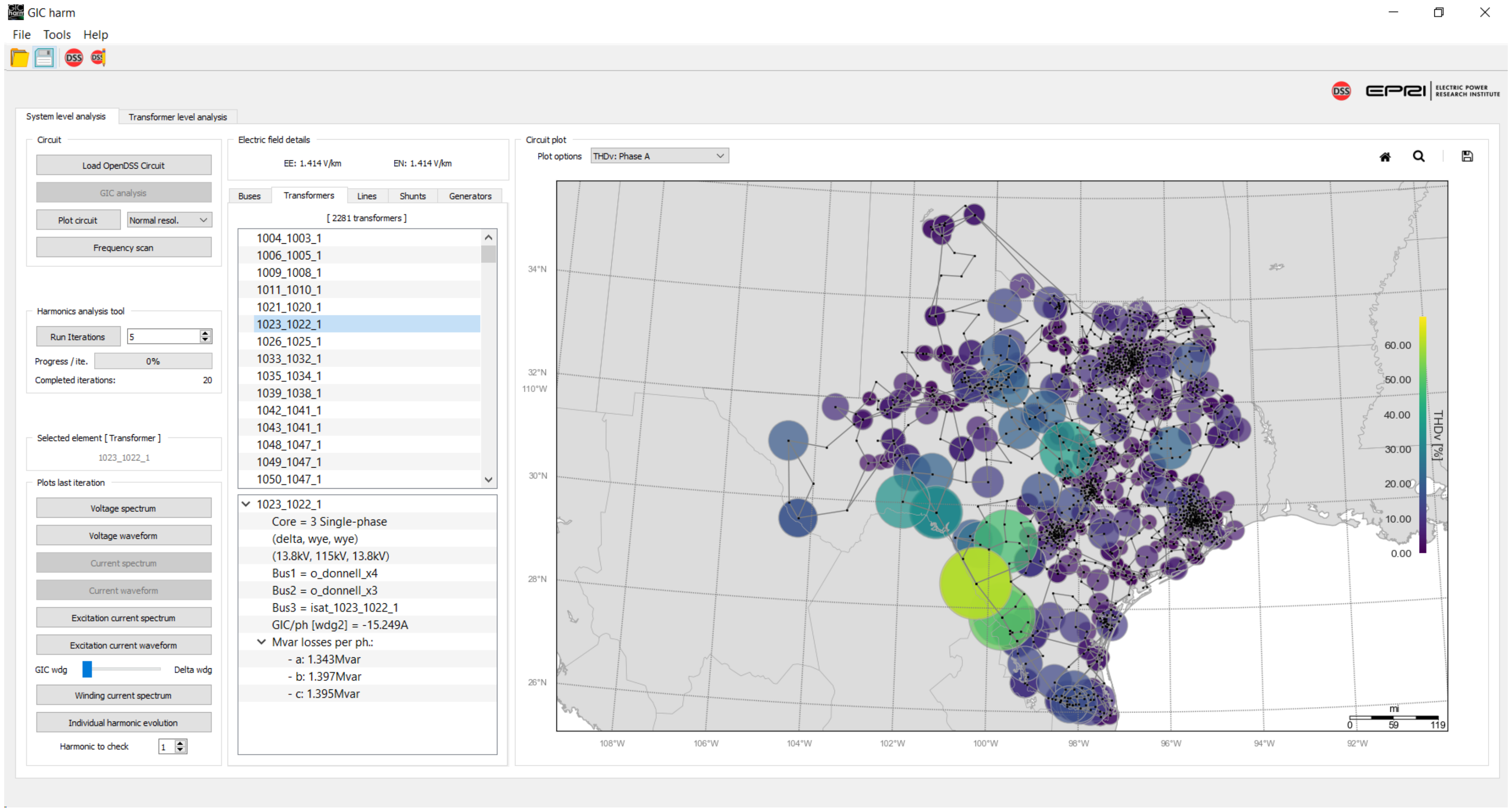
Name	Date modified	Type
EPRI_GIC_harm_db.db	8/8/2019 11:31 AM	DB File
1004_1003_1.pkl	8/8/2019 11:30 AM	PKL File
1004_1003_1_pass0.pkl	8/7/2019 10:13 AM	PKL File
1004_1003_1_pass1.pkl	8/7/2019 10:19 AM	PKL File
1004_1003_1_pass2.pkl	8/7/2019 10:27 AM	PKL File
1004_1003_1_pass3.pkl	8/7/2019 10:34 AM	PKL File
1004_1003_1_pass4.pkl	8/7/2019 10:42 AM	PKL File
1006_1005_1.pkl	8/8/2019 11:30 AM	PKL File



Tests with large cases

ERCOT synthetic case from Texas A&M

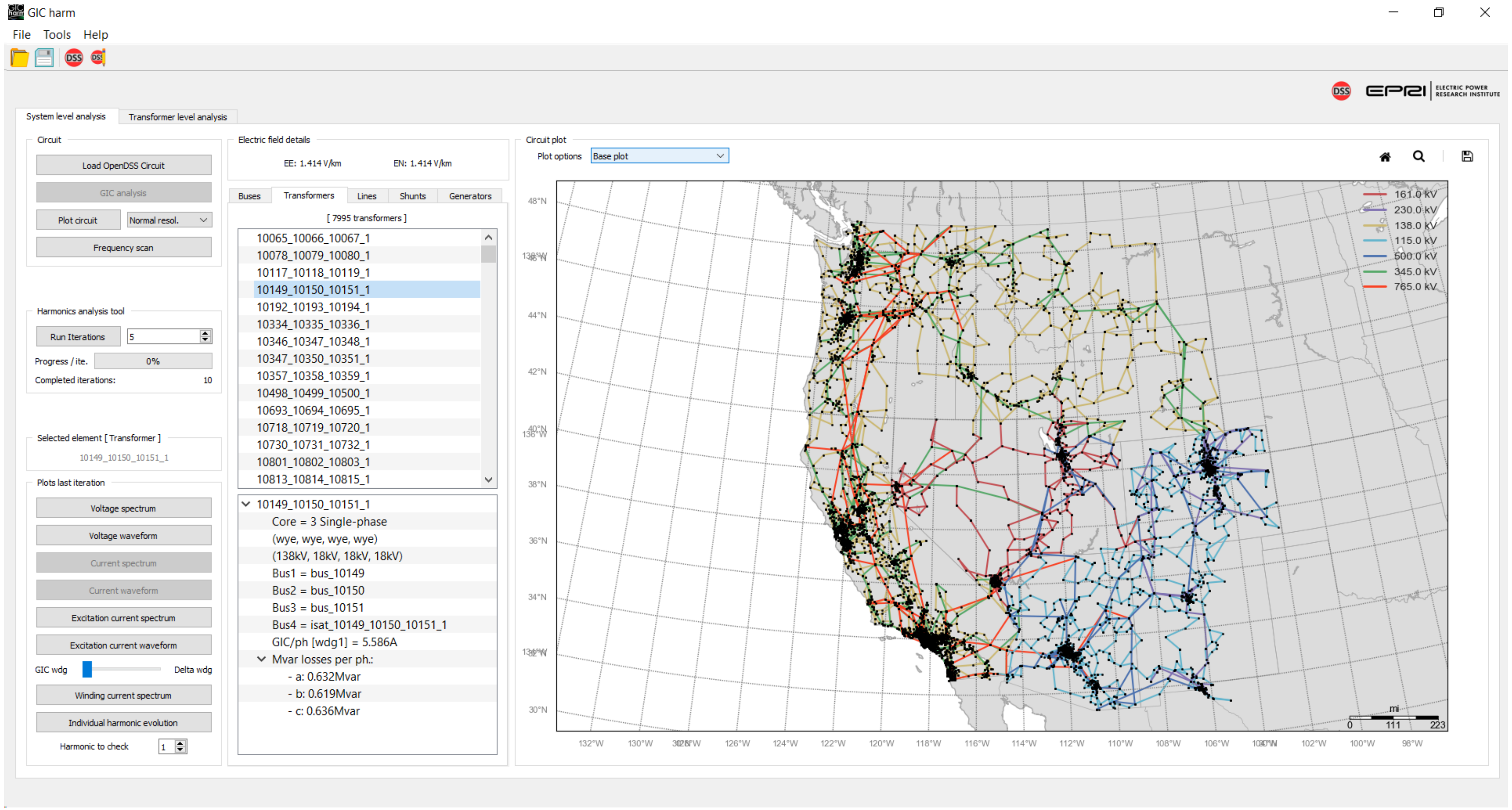
- 2k buses
- 861 Transformers
- 2,281 Transformers including added load transformers and GSUs



Tests with large cases

Western Interconnect synthetic case from Texas A&M

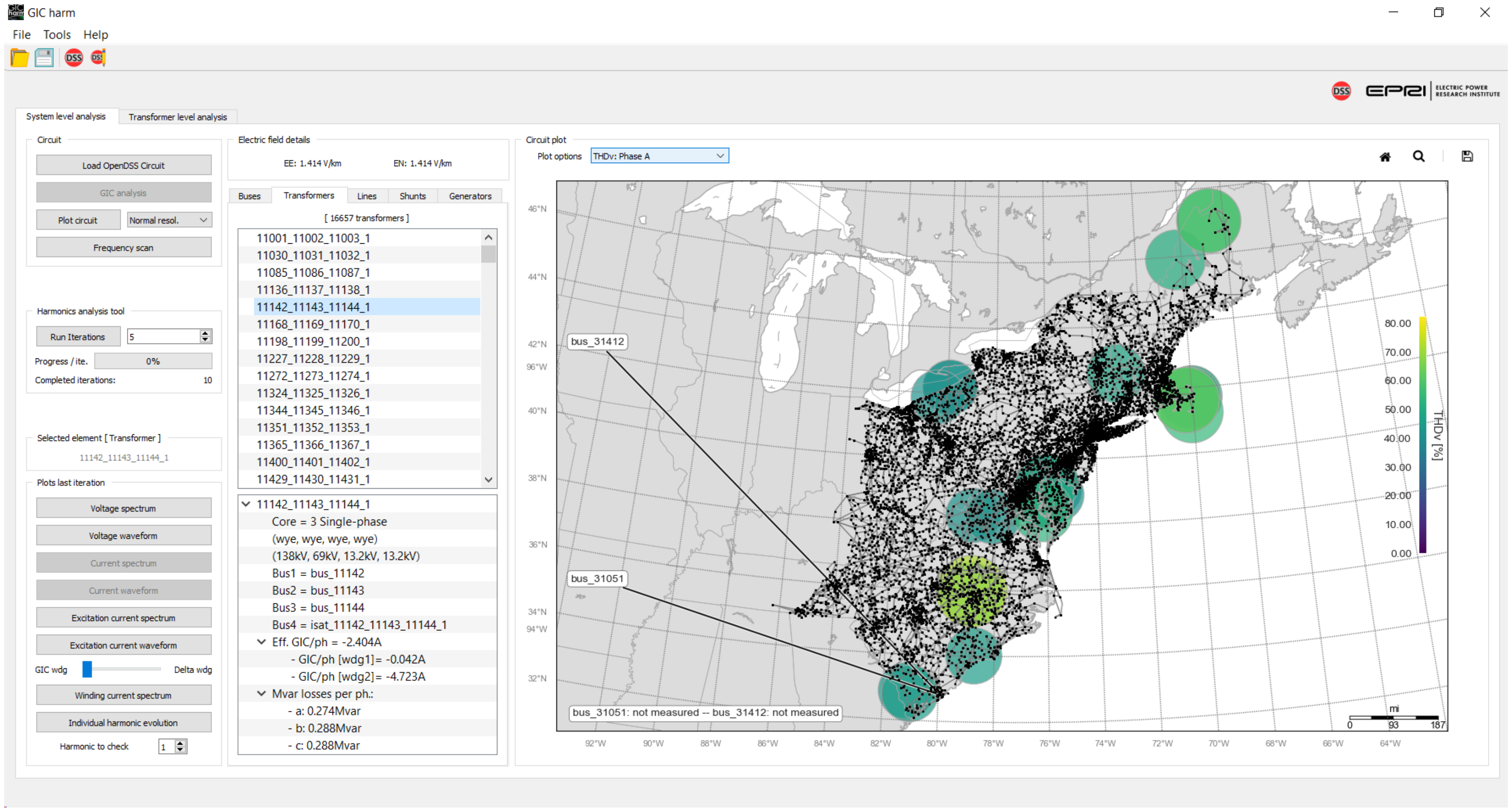
- 10k buses
- 2,380 Transformers
- 7,995 Transformers including added load transformers and GSUs



Tests with large cases

Eastern Interconnect synthetic case from Texas A&M

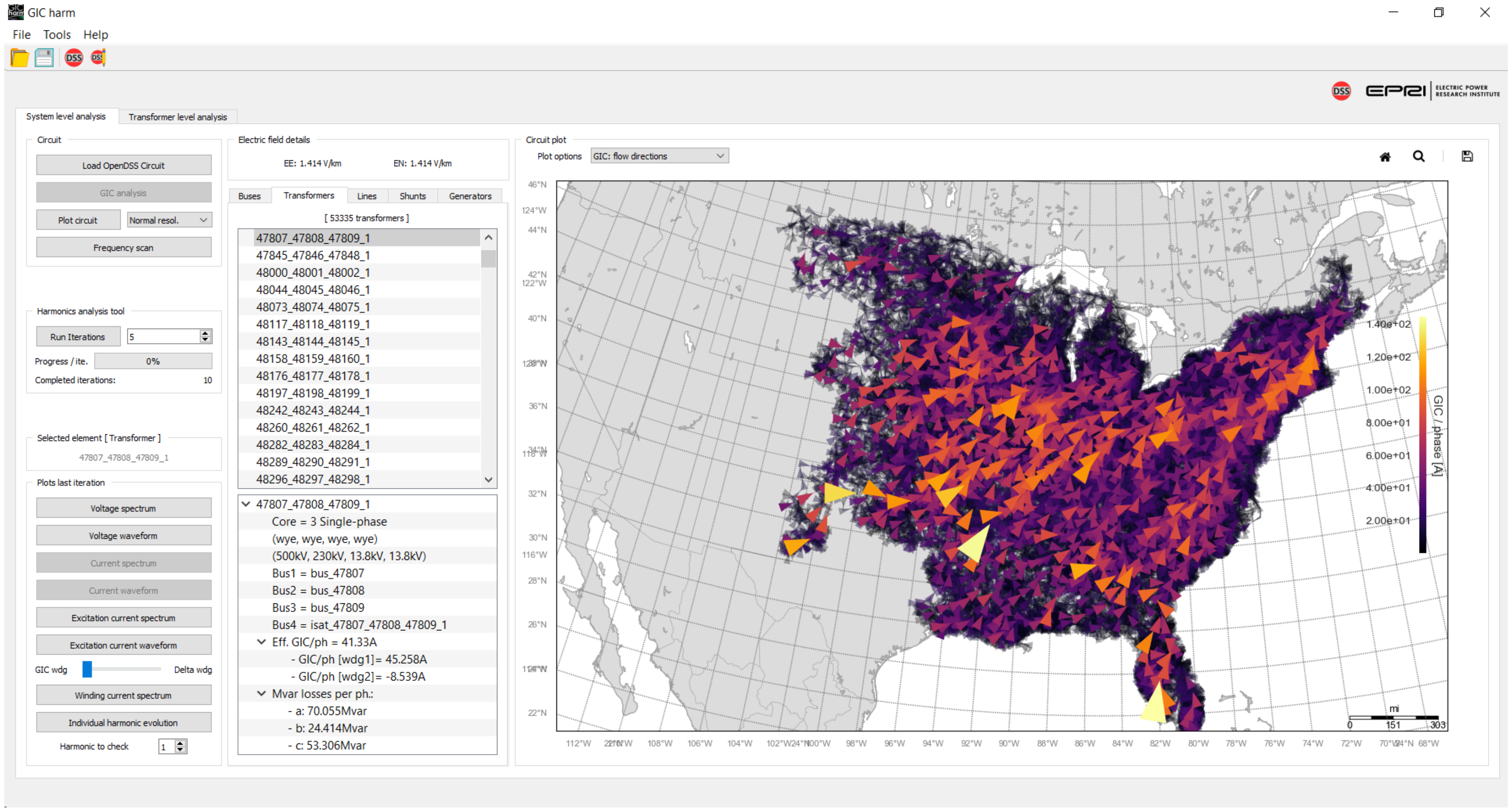
- 25k buses
- 6,030 Transformers
- 16,657 Transformers including added load transformers and GSUs



Tests with large cases

East and Mid West United States synthetic case from Texas A&M

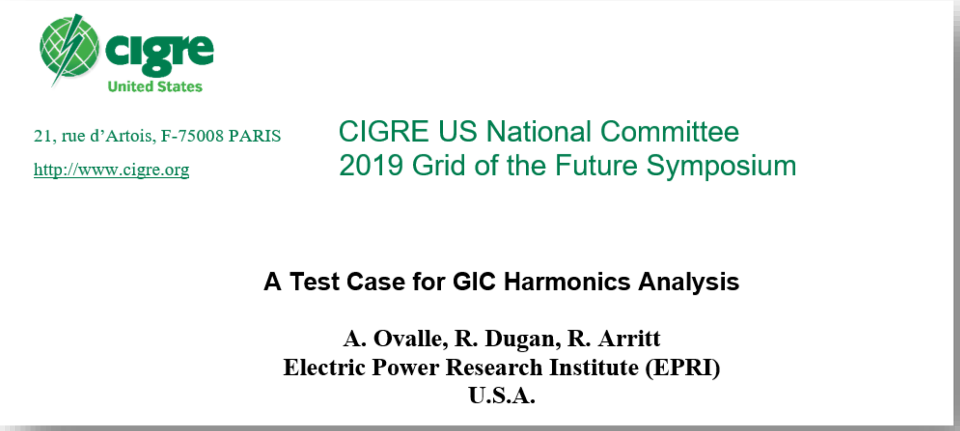
- 70k buses
- 12,655 Transformers
- 53,335 Transformers including added load transformers and GSUs



Benchmark case

Benchmark case submitted to CIGRE Grid of the Future Conference

- 3 bus case
- 3 transformers (3-leg, 5-leg and single-phase core topologies)

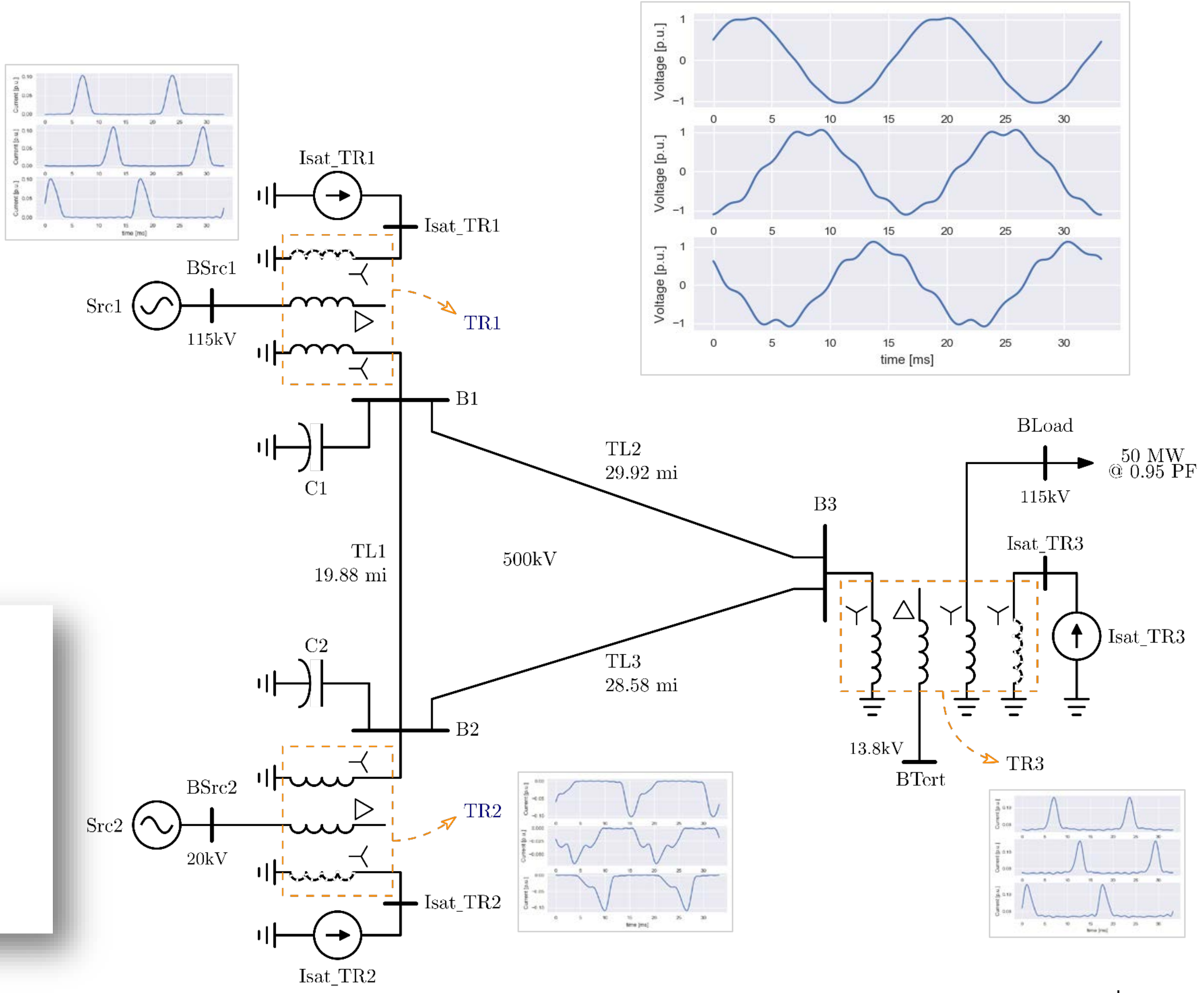

cigre United States

21, rue d'Artois, F-75008 PARIS
http://www.cigre.org

CIGRE US National Committee
2019 Grid of the Future Symposium

A Test Case for GIC Harmonics Analysis

A. Ovalle, R. Dugan, R. Arritt
Electric Power Research Institute (EPRI)
U.S.A.



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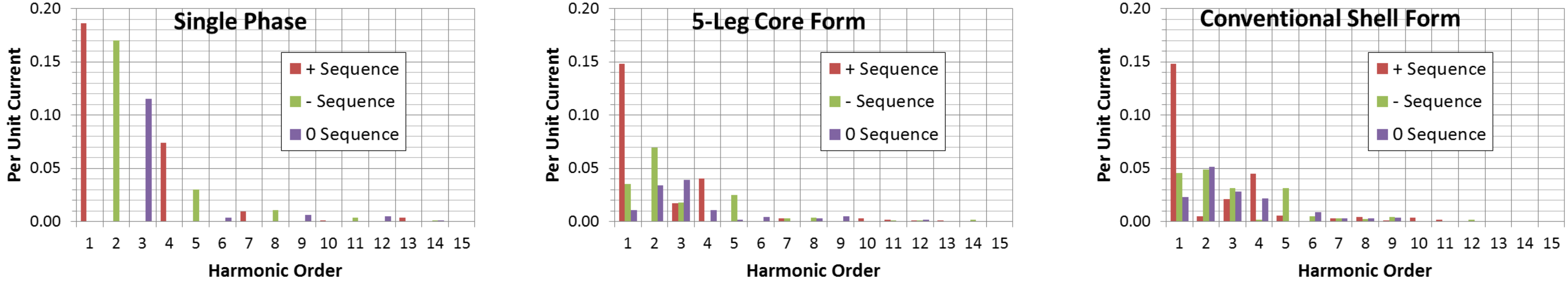
Harmonic Impacts

Harmonic Sequence Components



- Banks of 1-ph transformers follow conventional sequence component pattern
- Three-phase transformers do not follow this familiar pattern
  - Triplen (multiples of 3^{rd} order) harmonics not all zero sequence
  - Zero sequence has harmonic orders that are not triplens

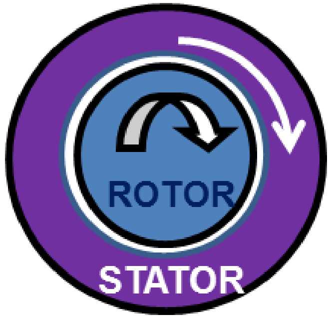
GMD harmonic analysis must model all sequence components
(or three-phase model with all mutual couplings)

Generators

- Harmonics cause generator rotor heating
  - Similar to fundamental negative sequence heating
  - Both positive and negative sequence harmonics
- Generator protections available today ignore harmonics
- Excessive rotor heating can cause catastrophic failure
  - Generator unavailable until rebuilt or replaced

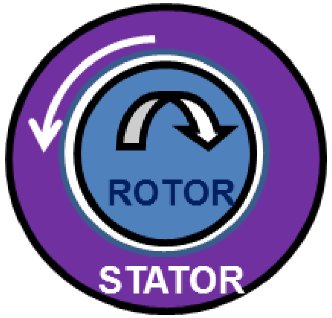
+ Seq. Harmonic

$f_{rotor} = f_{stator} - 60$



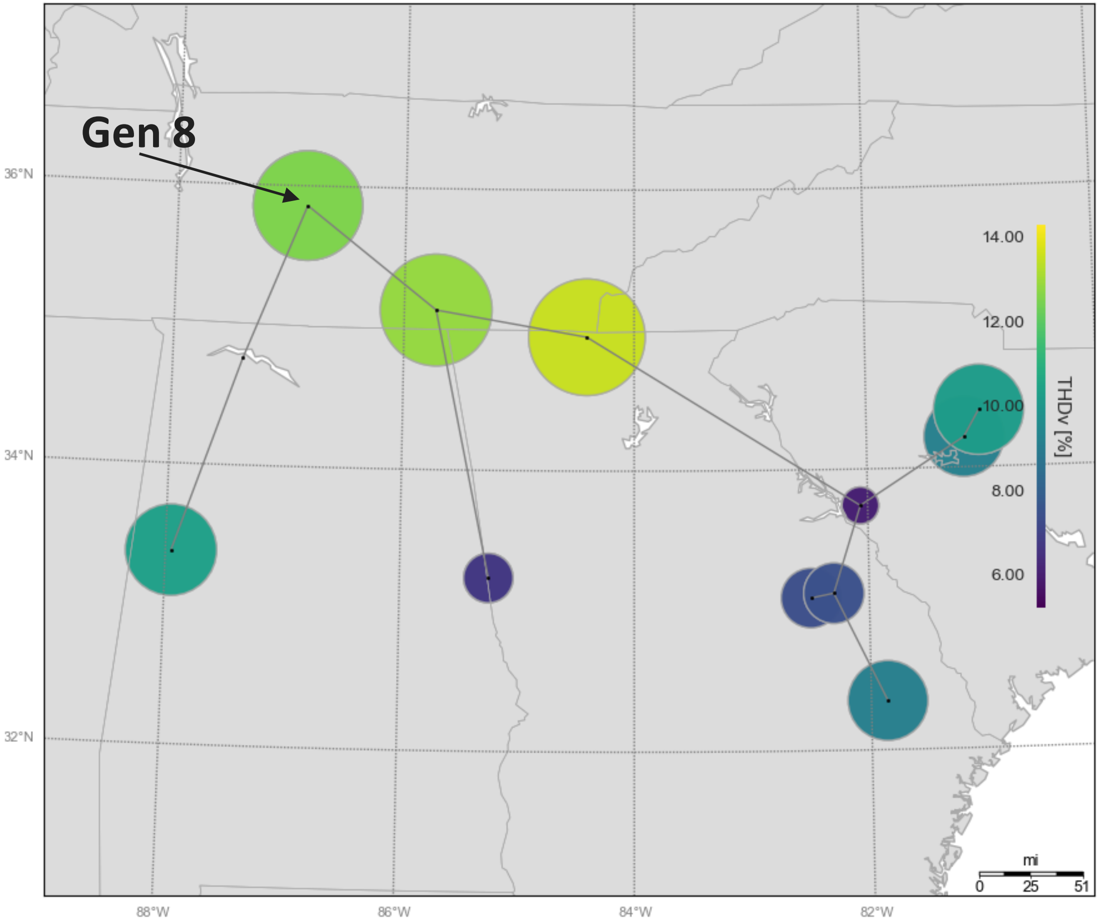
- Seq. Harmonic

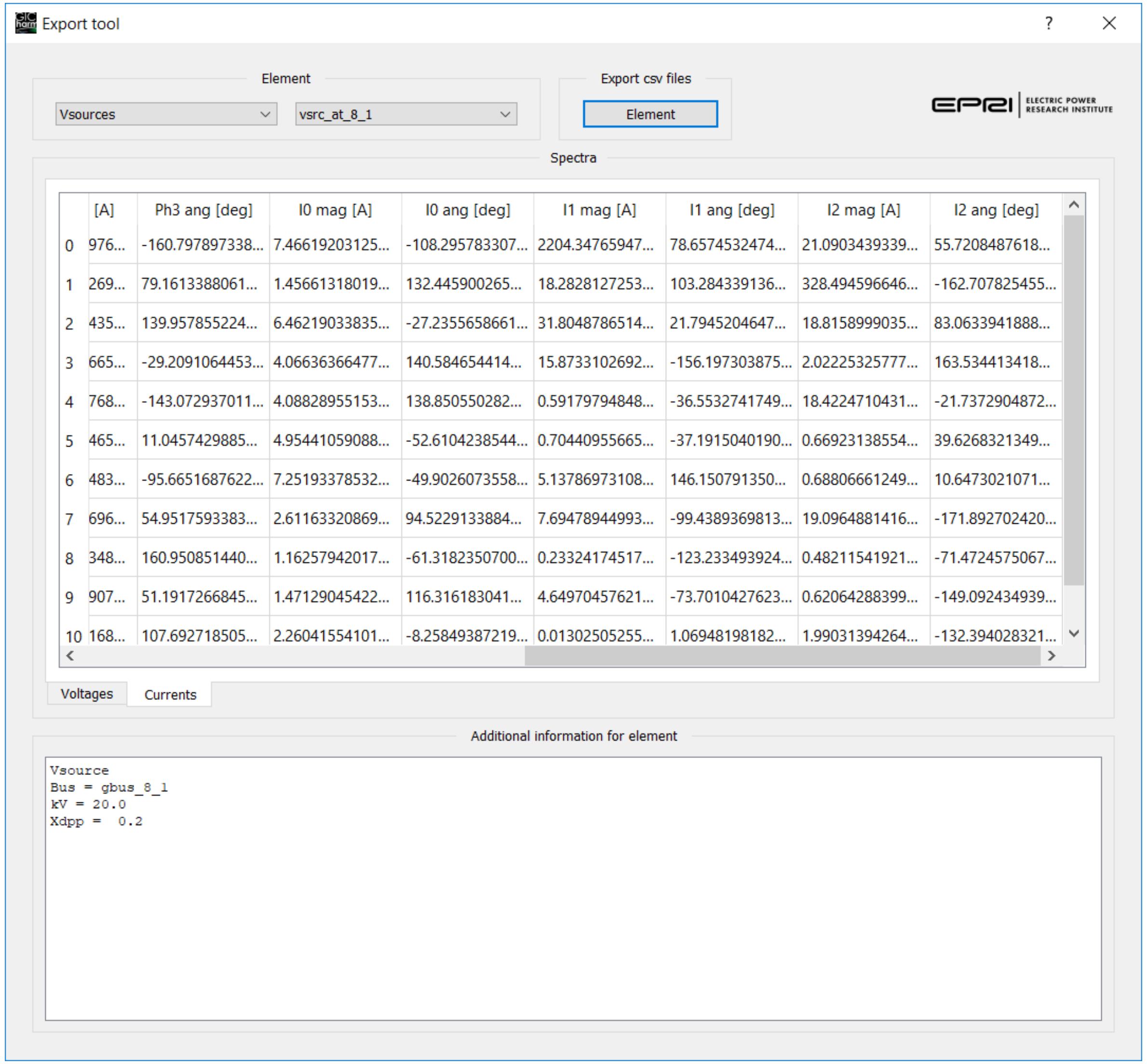
$f_{rotor} = f_{stator} + 60$



Generator Analysis Example

- Convert Harmonics to Sequence Components

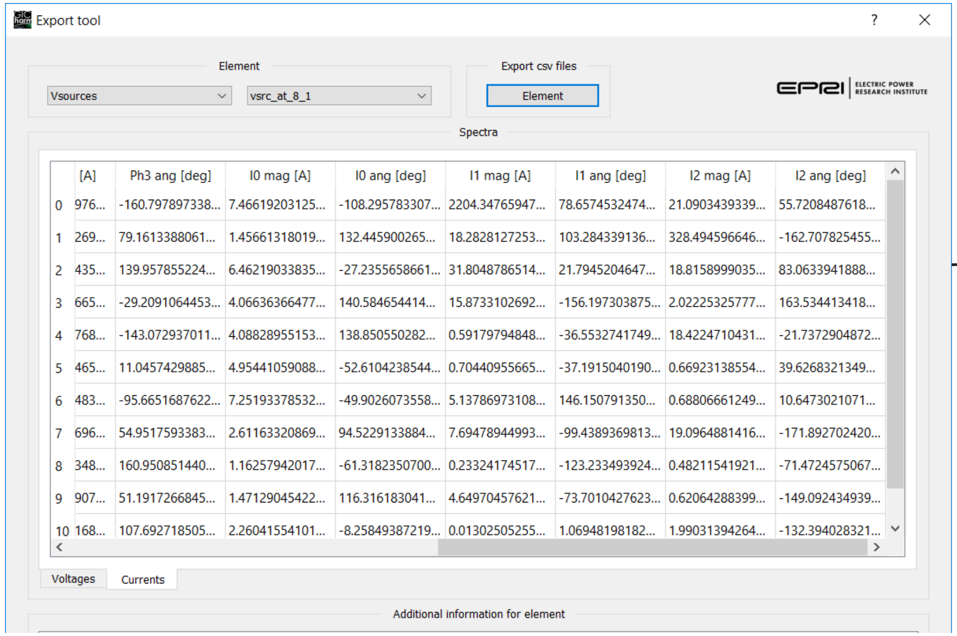




	[A]	Ph3 ang [deg]	I0 mag [A]	I0 ang [deg]	I1 mag [A]	I1 ang [deg]	I2 mag [A]	I2 ang [deg]
0	976...	-160.797897338...	7.46619203125...	-108.295783307...	2204.34765947...	78.6574532474...	21.0903439339...	55.7208487618...
1	269...	79.1613388061...	1.45661318019...	132.445900265...	18.2828127253...	103.284339136...	328.494596646...	-162.707825455...
2	435...	139.957855224...	6.46219033835...	-27.2355658661...	31.8048786514...	21.7945204647...	18.8158999035...	83.0633941888...
3	665...	-29.2091064453...	4.06636366477...	140.584654414...	15.8733102692...	-156.197303875...	2.02225325777...	163.534413418...
4	768...	-143.072937011...	4.08828955153...	138.850550282...	0.59179794848...	-36.5532741749...	18.4224710431...	-21.7372904872...
5	465...	11.0457429885...	4.95441059088...	-52.6104238544...	0.70440955665...	-37.1915040190...	0.66923138554...	39.6268321349...
6	483...	-95.6651687622...	7.25193378532...	-49.9026073558...	5.13786973108...	146.150791350...	0.68806661249...	10.6473021071...
7	696...	54.9517593383...	2.61163320869...	94.5229133884...	7.69478944993...	-99.4389369813...	19.0964881416...	-171.892702420...
8	348...	160.950851440...	1.16257942017...	-61.3182350700...	0.23324174517...	-123.233493924...	0.48211541921...	-71.4724575067...
9	907...	51.1917266845...	1.47129045422...	116.316183041...	4.64970457621...	-73.7010427623...	0.62064288399...	-149.092434939...
10	168...	107.692718505...	2.26041554101...	-8.25849387219...	0.01302505255...	1.06948198182...	1.99031394264...	-132.394028321...

Generator 8 Analysis Example

- 150 MVA, 20kV



Export tool

Element: Vsources | vsrc_at_8_1

Export csv files: Element

Spectra

	[A]	Ph3 ang [deg]	I0 mag [A]	I0 ang [deg]	I1 mag [A]	I1 ang [deg]	I2 mag [A]	I2 ang [deg]
0	976...	-160.797897338...	7.46619203125...	-108.295783307...	2204.34765947...	78.6574532474...	21.0903439339...	55.7208487618...
1	269...	79.1613388061...	1.45661318019...	132.445900265...	18.2828127253...	103.284339136...	328.494596646...	-162.707825455...
2	435...	139.957855224...	6.46219033835...	-27.2355658661...	31.8048786514...	21.7945204647...	18.8158999035...	83.0633941888...
3	665...	-29.2091064453...	4.06636366477...	140.584654414...	15.8733102692...	-156.197303875...	2.02225325777...	163.534413418...
4	768...	-143.072937011...	4.08828955153...	138.850550282...	0.59179794848...	-36.5532741749...	18.4224710431...	-21.7372904872...
5	465...	11.0457429885...	4.95441059088...	-52.6104238544...	0.70440955665...	-37.1915040190...	0.66923138554...	39.6268321349...
6	483...	-95.6651687622...	7.25193378532...	-49.9026073558...	5.13786973108...	146.150791350...	0.68806661249...	10.6473021071...
7	696...	54.9517593383...	2.61163320869...	94.5229133884...	7.69478944993...	-99.4389369813...	19.0964881416...	-171.892702420...
8	348...	160.950851440...	1.16257942017...	-61.3182350700...	0.23324174517...	-123.233493924...	0.48211541921...	-71.4724575067...
9	907...	51.1917266845...	1.47129045422...	116.316183041...	4.64970457621...	-73.7010427623...	0.62064288399...	-149.092434939...
10	168...	107.692718505...	2.26041554101...	-8.25849387219...	0.01302505255...	1.06948198182...	1.99031394264...	-132.394028321...

Voltages | Currents

Additional information for element

Harmonic Order on Rotor Reference Frame (n)	I^{+}_{n+1} (p.u.)	I^{-}_{n-1} (p.u.)	$\sqrt{\frac{n}{2}\cdot\left(I^{+}_{n+1}+I^{-}_{n-1}\right)^2}$
1	0.0084	0	0.000050
2	0.0147	0.0097	0.0006
3	0.0073	0.1517	0.0310
4	0.0003	0.0087	0.0001
5	0.0003	0.0009	0.0000
6	0.0024	0.0085	0.0002
7	0.0036	0.0003	0.0000
8	0.0001	0.0003	0.0000
		Sum=	0.0320
		I2eq=	**0.1788**

Below I2eqv screening threshold of 0.267

I^2eqv= 0.1788

Harmonic	I Mag
1	2.2E+03
2	3.3E+02
3	4.4E+01
4	1.7E+01
5	1.9E+01
6	1.1E+00
7	4.7E+00
8	2.3E+01

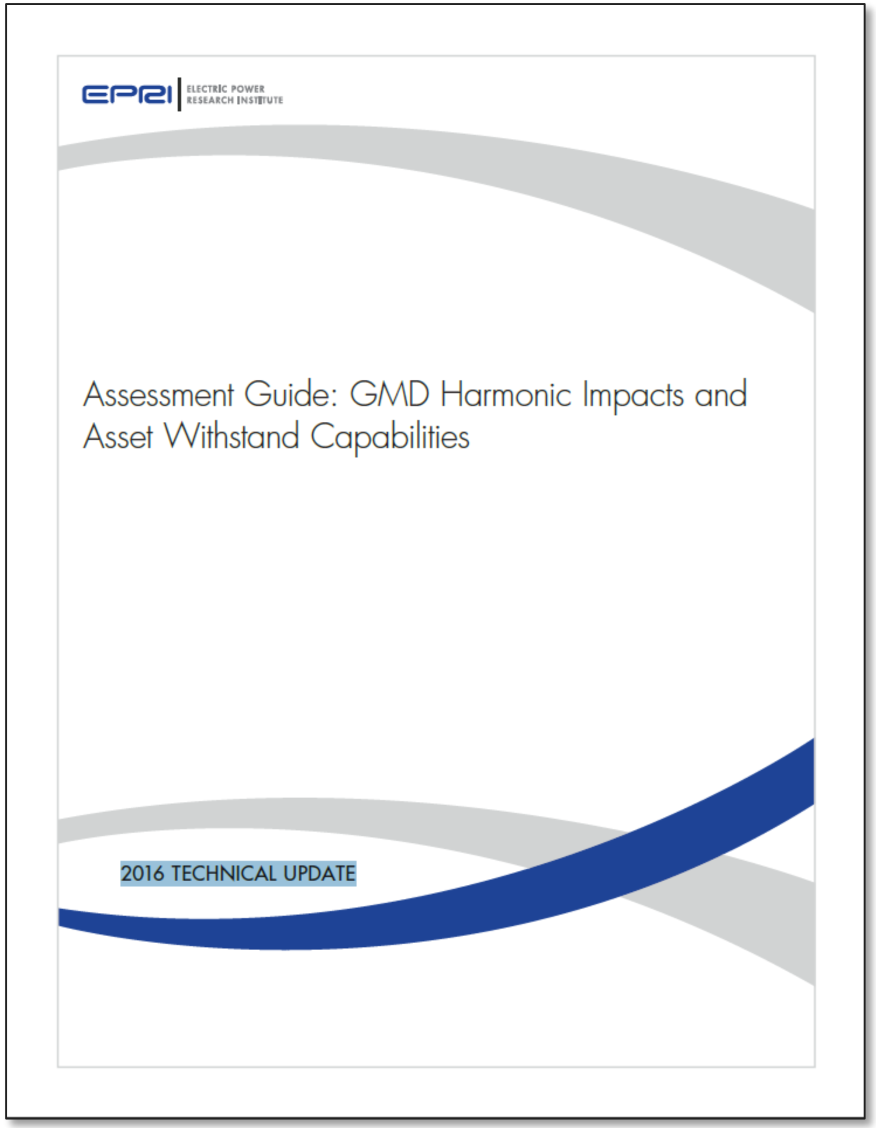
Exceeds THDi screening threshold of 0.107

THDi= 0.153

Source: Assessment Guide: GMD Harmonic Impacts and Asset Withstand Capabilities # 3002006444

Update Assessment Guide: GMD Harmonic Impacts and Asset Withstand Capabilities

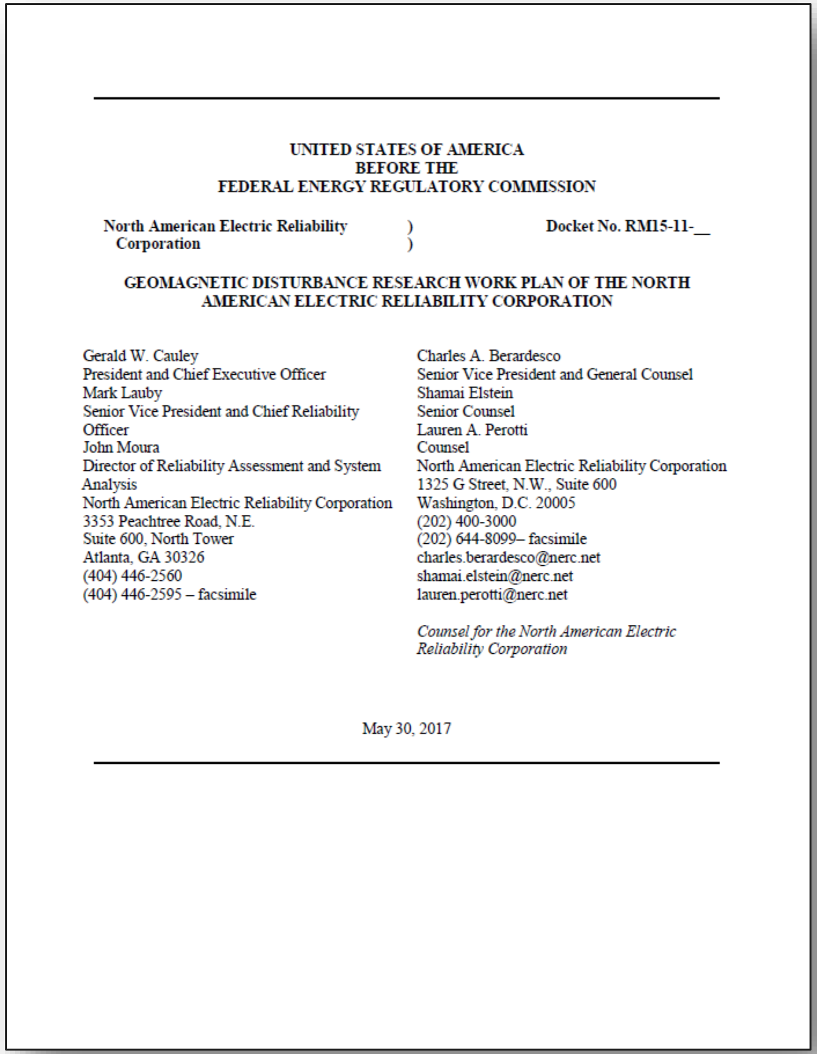
- 2016 Publically Available Report
- Report # 3002006444
  - www.epri.com
- Update Guide
  - Documentation of GICHarm
    - System Requirements
    - Examples
  - Update Generator Harmonic Impact Chapter



Transformer Thermal Impacts

Research Goals

- Assess the 75A transformer thermal screening criteria provided in TPL-007 and provide recommendations for improvement if deficiencies are found.
- Study tertiary winding harmonic heating and determine if this impacts the thermal screening criteria.
- Study Field Orientation for Transformer Thermal Impact Assessments
- Determine the impacts of vibrations on power transformers and determine if this causes damage to the mechanical integrity of the transformer.



UNITED STATES OF AMERICA
BEFORE THE
FEDERAL ENERGY REGULATORY COMMISSION

North American Electric Reliability Corporation) Docket No. RM15-11-__

GEOMAGNETIC DISTURBANCE RESEARCH WORK PLAN OF THE NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

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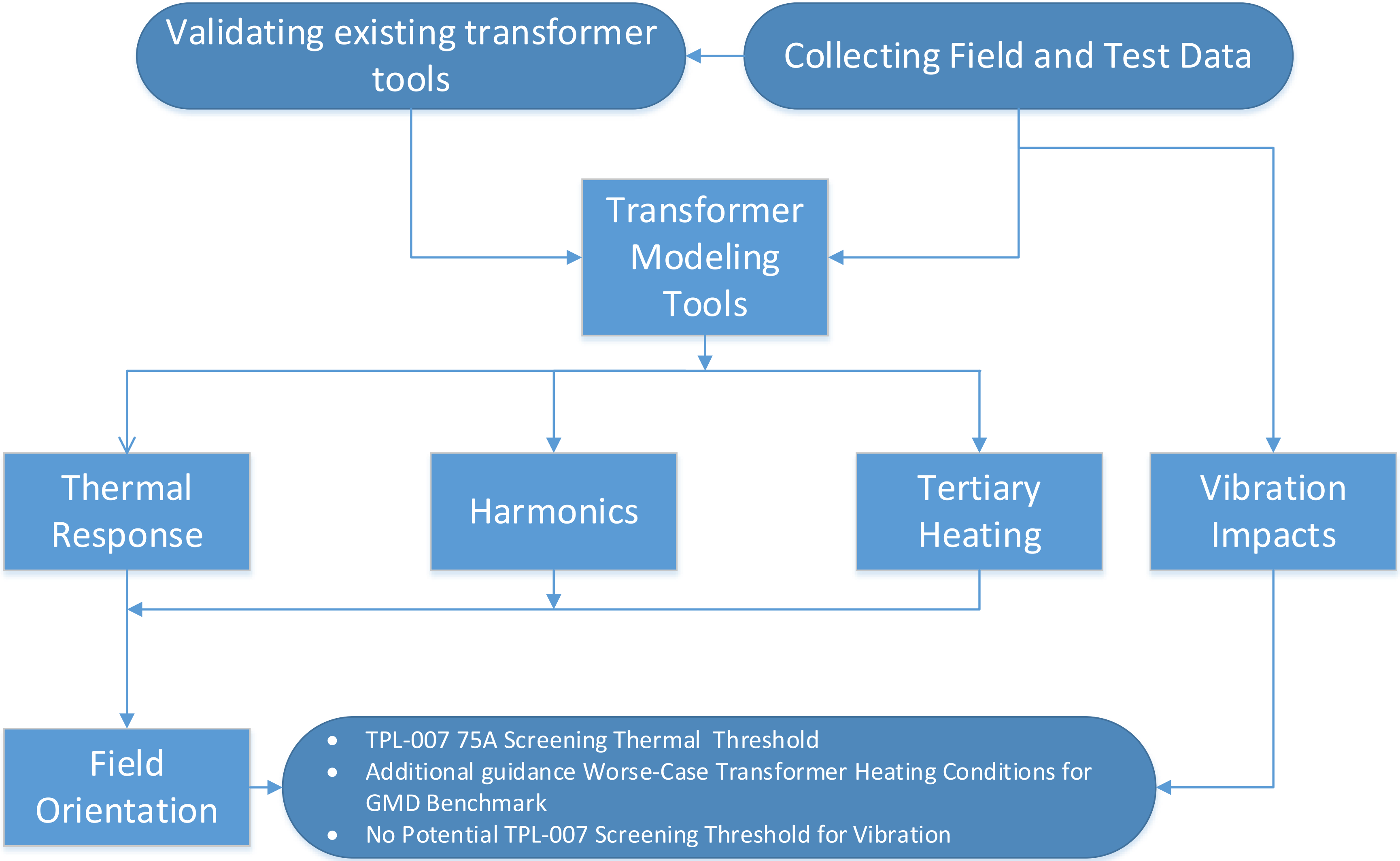
Counsel for the North American Electric Reliability Corporation

May 30, 2017

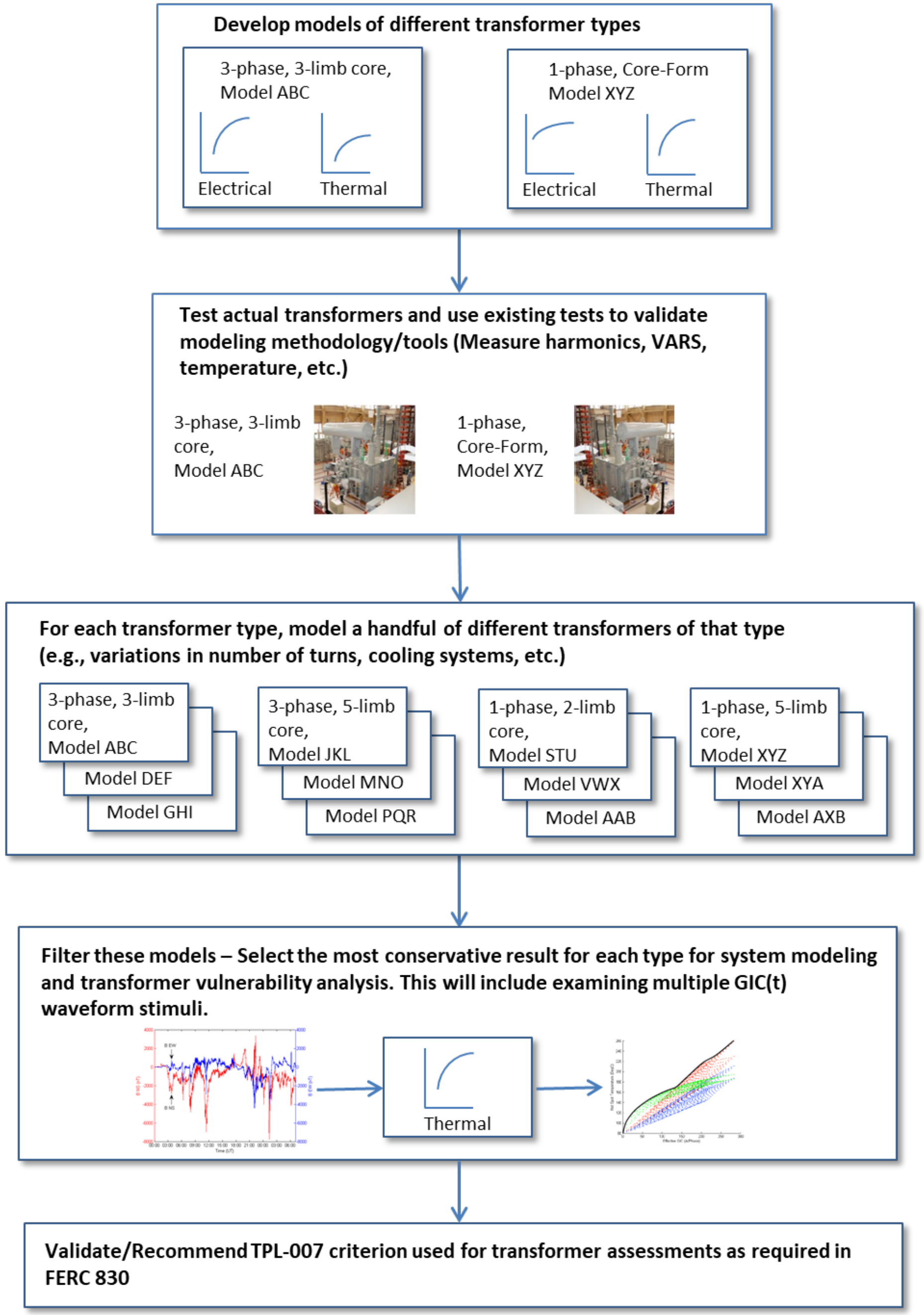
Schedule and Work Plan Flow

- Vibration Work Completed
  - On-going Monitoring
- Thermal Evaluation near completion
- Beginning field orientation work to inform screening criteria
- Complete Tasks by Q2019 wrap-up by Q1 2020



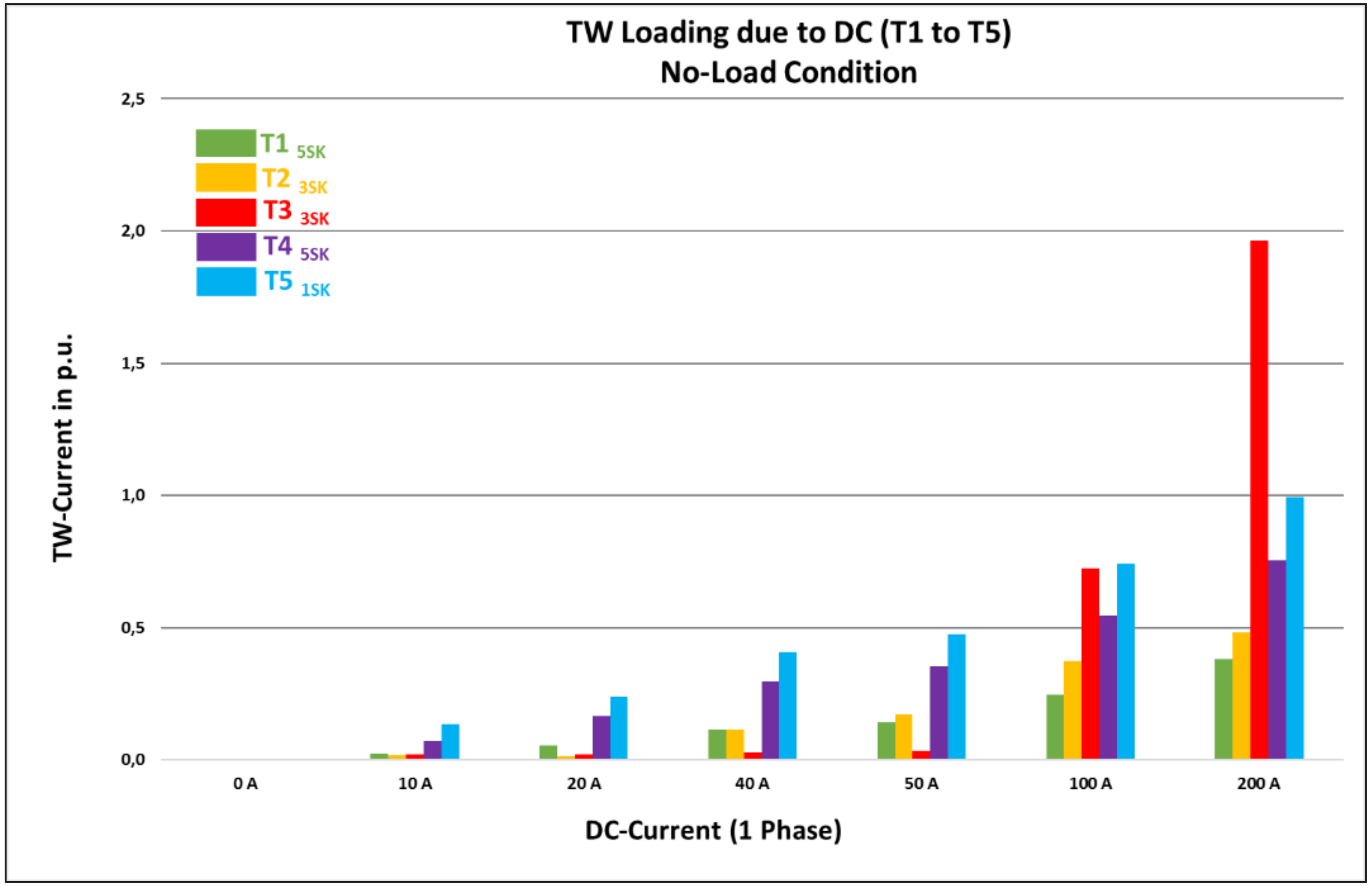
Approach

- Analyzing electrical and thermal models for a reasonable number of primary design types of transformers.
- Analyzing Impacts of tertiary heating
- Identifying relationships of conservative engineering simplification of multiple design variations to ensure screening criteria is all encompassing.



Tertiary Loading Due to GIC

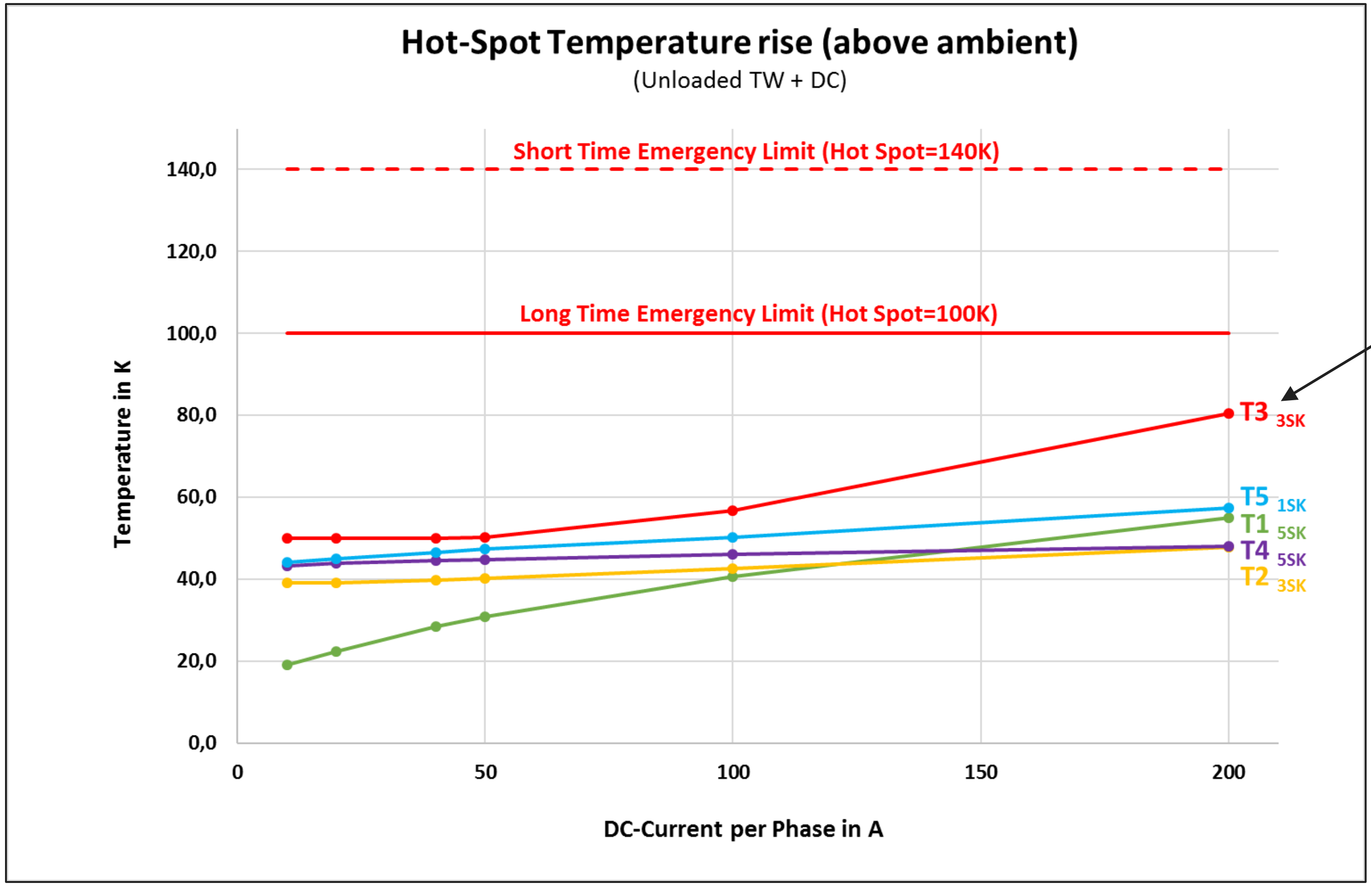
- Increase of tertiary circulating current due to GIC (T1 to T5, RMS value in per unit of nominal value)



Per unit values do not have a significant meaningfulness to evaluate whether a critical hot spot temperature is reached with GIC. The reason is, that the windings have to meet short-circuit ratings and are thus oversized. Therefore, the real thermal capability of winding is significantly higher.

Tertiary Heating

- Hotspot temperature rise with DC (above ambient, unloaded tertiary condition, all transformers)



3-phase, core-form, 3-Limb

With the tertiary winding loaded, the critical temperatures is not reached with an additional DC level up to 200 A DC per phase in the high-voltage winding.

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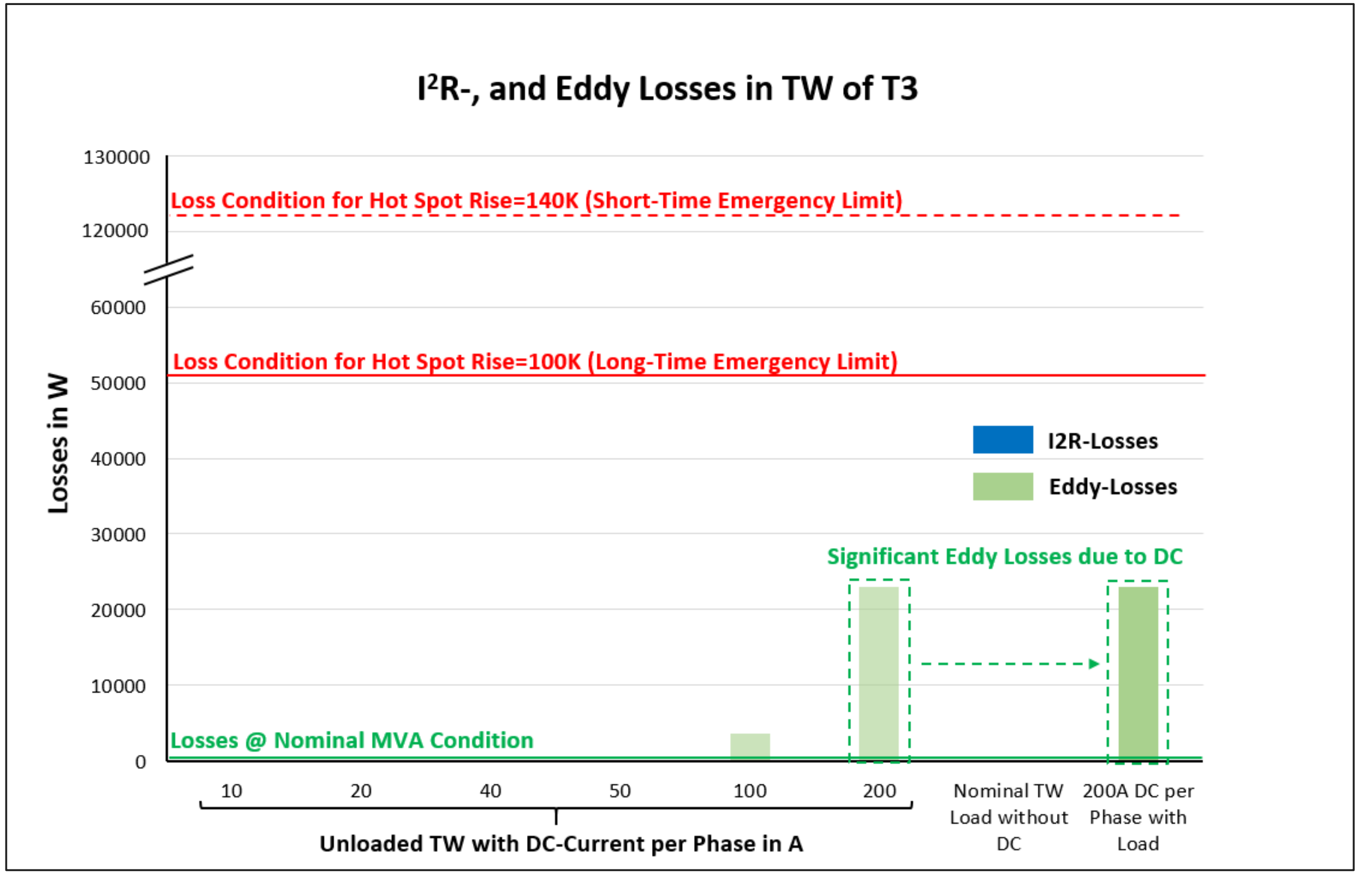
Tertiary Heating

- T3 transformer Eddy-Losses dominate the I^2R Losses with fully-loaded tertiary
  - Does not use a Continuously Transposed Conductor in the tertiary winding



Eddy-Losses dominate the I2R Losses with fully-loaded tertiary.

Tertiary Heating Conclusions

- Losses in the tertiary winding increases due to the increased harmonics, eddy losses increase significantly compared to the nominal condition without DC.
- Study shows, that no critical steady-state temperatures are reached, even with 200 A DC per phase in the high-voltage winding.
- This study shows, that the nominal condition of losses (nominal rating) can be easily exceeded due to GIC.
- The tertiary winding in transformer T3 shows a much higher eddy loss increase as the other studied.
  - Main reason is that this winding does not use a Continuously Transposed Conductor (CTC) in the tertiary winding. This type of winding design may occur in older transformers with low tertiary winding rating compared to the main winding rating.
- Looking to investigated in more detail different transformer designs with different tertiary winding ratings and e.g. GIC sensitive single-phase and three-phase, 5-limb, core-type transformers.

Thermal Heating

- 42 additional transformers examined of different core designs, winding geometry, voltage levels, etc

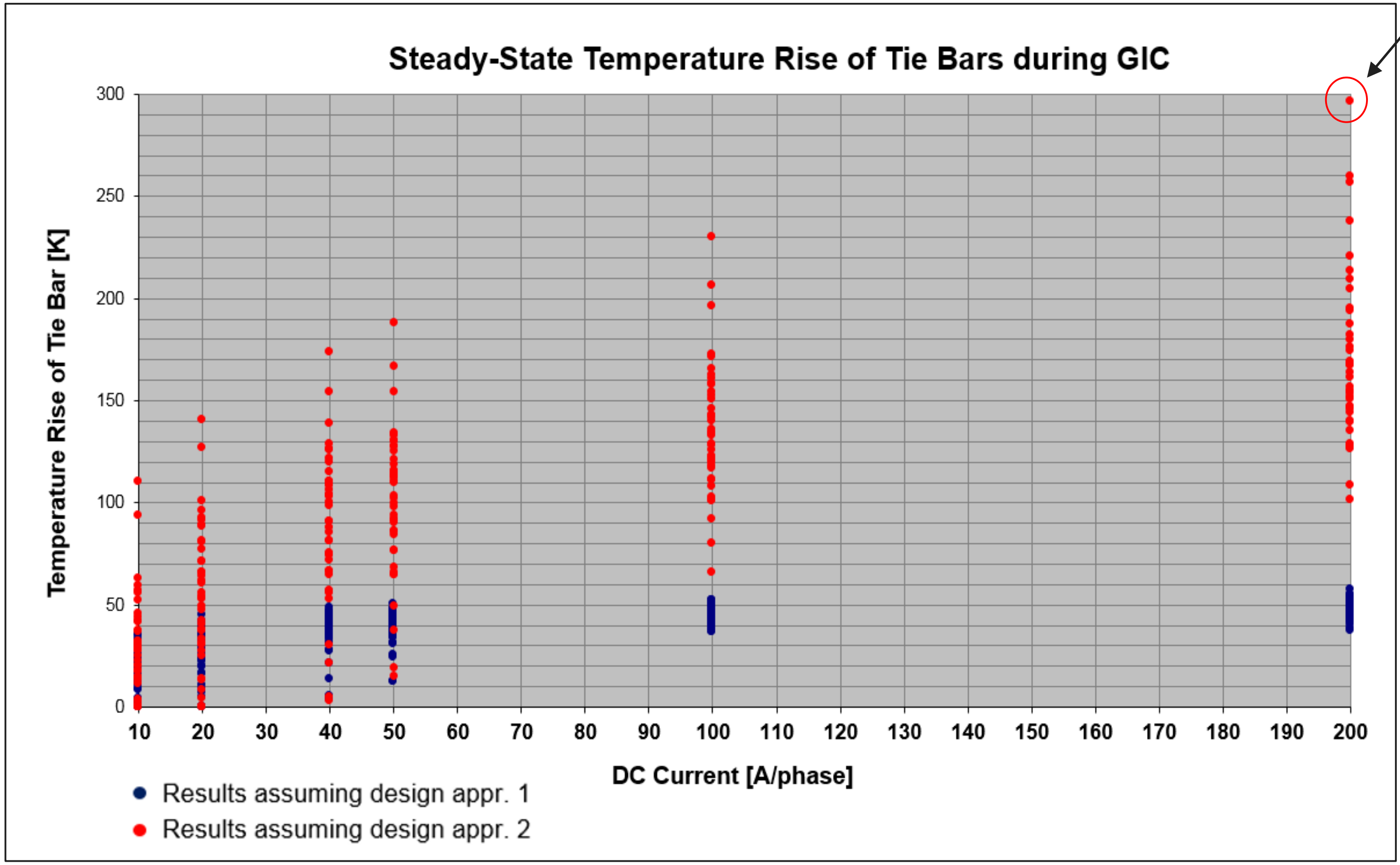
Transformer No.	Core Type	HV rating	HV voltage	Type
-	-	MVA	kV	-
T1	1	92	526	GSU
T2	1	374	525	Auto
T3	2	500	525	Auto
T4	3	300	525	Auto
T5	3	560	525	Auto
T6	4	292	500	Auto
T7	4	672	500	Auto
T8	4	460	525	Auto
T9	5	840	500	Auto
T10	5	300	525	GSU
T11	2	100	735	GSU
T12	4	373.33	765	Auto
T13	4	750	746	Auto
T14	1	167	400	Auto
T15	1	360	420	Auto
T16	2	121,33	433	GSU
T17	2	94	410	GSU
T18	3	750	420	Auto
T19	3	160	400	GSU
T20	4	570	405	GSU
T21	5	450	405	TRA
T22	5	310	400	GSU
T23	5	910	420	GSU
T24	1	100	335	Auto
T25	1	133.33	345	Auto
T26	3	120	275	TRA

Transformer No.	Core Type	HV Rating	HV Voltage	Type
-	-	MVA	kV	-
T27	3	500	275	Auto
T28	3	200	330	Auto
T29	4	500	345	GSU
T30	5	500	345	Auto
T31	5	800	345	Auto
T32	5	315	345	GSU
T33	1	133.33	230	Auto
T34	1	66,6	231	Auto
T35	2	100	230	GSU
T36	3	160	230	Auto
T37	3	290	230	GSU
T38	3	420	230	Auto
T39	4	300	242	GSU
T40	4	466	240	GSU
T41	5	240	225	GSU
T42	5	560	230	Auto

1) Single-phase, core-form, three-limb
2) Single-phase, core-form, two-limb
3) Three-phase, core-form, three-limb
4) Single-phase, core-form, four-limb
5) Three-phase, core-form, five-limb

Temperature Rise of the Tie Bar

- Provided steady-state temperature rises



100 MVA, Single-phase Auto, core-form

Transformer has a very high number of turns in the high-voltage winding (N=1467), which is one reason for the extremely high temperature rise. E.g. 25 A DC in a transformer with 1000 turns causes approximately the same DC excitation as 50 A DC in a transformer with 500 turns. This means not the DC level is relevant, it is always the DC current multiplied with the DC carrying turns.

Mechanical Heating

- Thermal-time constants and steady-state temperature values provided for each transformer type.

SIEMENS

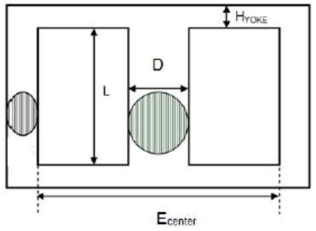
General data

Transformer data

The general data of the transformer under investigation is shown in the following table and figure where the basic geometry of the core and the main technical information are demonstrated.

Table 1: General transformer data

Project name	T24
Transformer type	Auto
Rated power	100 MVA
Number of phases	1
Voltage levels	335/√3 kV // 136/√3 kV // 13.8 kV
Winding affected by DC	HV
Core type	1



L [mm]	2276
D [mm]	644
H yoke [mm]	320
E center [mm]	2060
A limb [m2]	0.286286
A yoke [m2]	0.144462

Figure 1: Sketch of core geometry

Air core inductance of HV winding: 0.9352 H

SIEMENS

DC levels overview

The report contains steady-state results for the electrical and thermal response of the transformer for following DC levels per phase:

- 10 A
- 20 A
- 40 A
- 50 A
- 100 A
- 200 A

Thermal behavior under DC

Steady-state temperatures for different DC levels

The thermal behavior of the tie bar is calculated based on the following top and bottom oil temperature condition in the transformer tank.

Table 2: Temperature condition in the transformer tank

Bottom oil temperature [°C]	70
Top oil temperature [°C]	90

The calculated steady-state tie bar hotspot temperature rises above the Topoil temperature for different DC levels are listed in the table below and demonstrated in following graphic.

Table 3: Steady-state tie bar hotspot rise with DC

DC level per phase [A]	Tie bar hot spot rise [K] "Design 1"	Tie bar hot spot rise [K] "Design 2"
10	35.5	110.5
20	38.4	140.5
40	41.8	173.5
50	45.7	188.0
100	46.6	230.0
200	53.1	296.6

SIEMENS

Graphical result for steady state temperatures for different DC levels

Figure 2 shows the steady-state hotspot rises for two different tie bar designs for different DC levels.

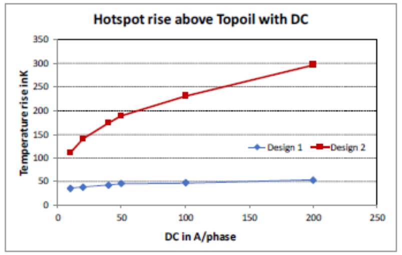


Figure 2: Tie bar hotspot rise above Top oil

Transient temperature behavior during a GIC profile

Figure 3 and Figure 4 show a DC profile and the corresponding thermal responses of the heating of both tie bar designs.

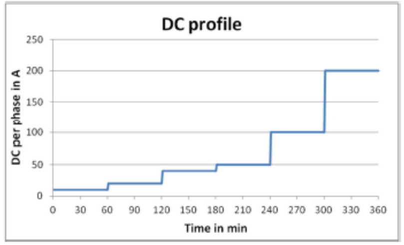
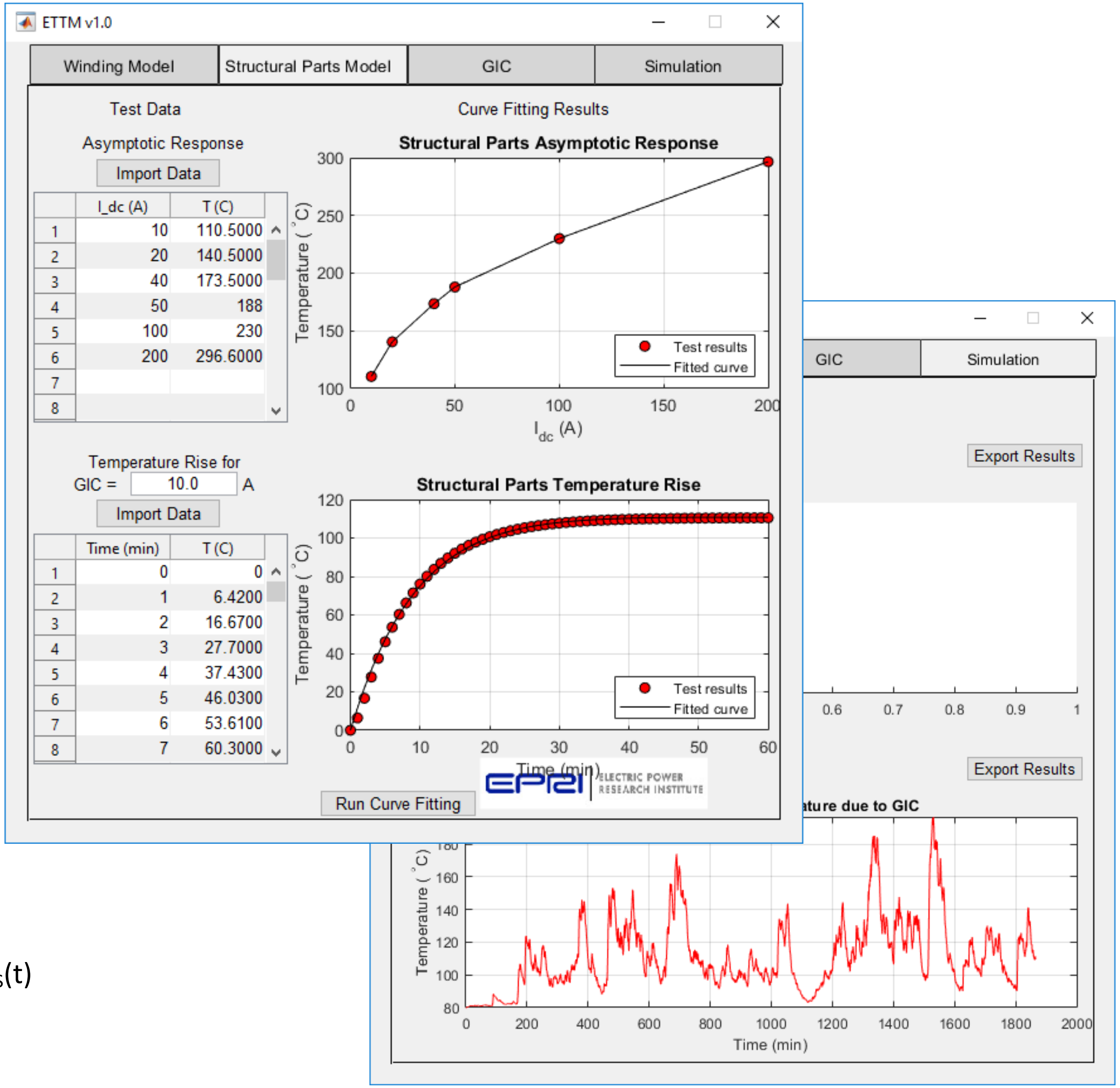


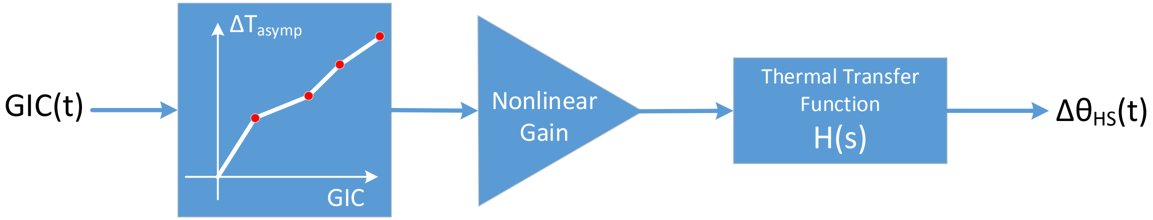
Figure 3: DC profile

EPRI ELECTRIC POWER RESEARCH INSTITUTE

GIC Transformer Thermal Analysis Tool

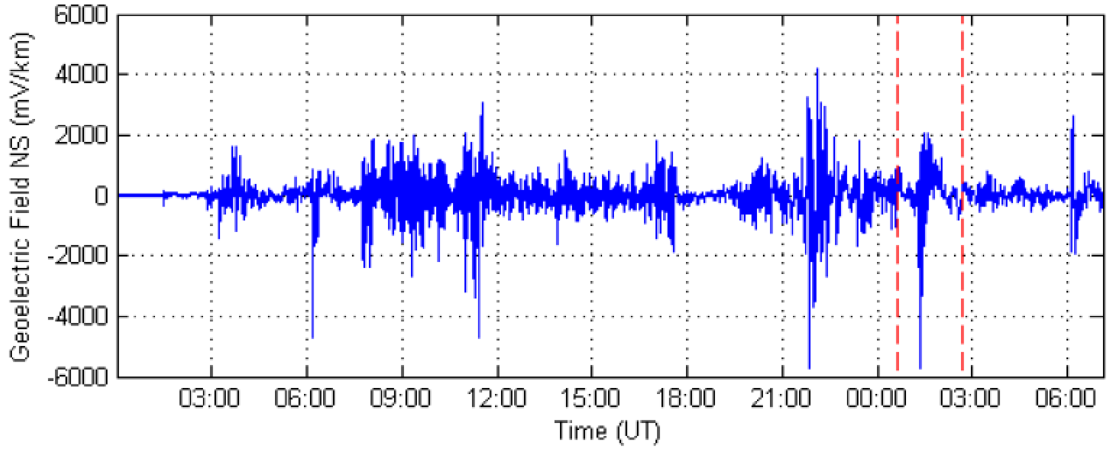
- Fit a transfer function to measurements or simulation data that represents the thermal behavior of the transformer
- Compute Temp(t) using the simulation model and GIC(t)
- Compare maximum hotspot temperatures with e.g. IEEE Std. C57.91 thresholds

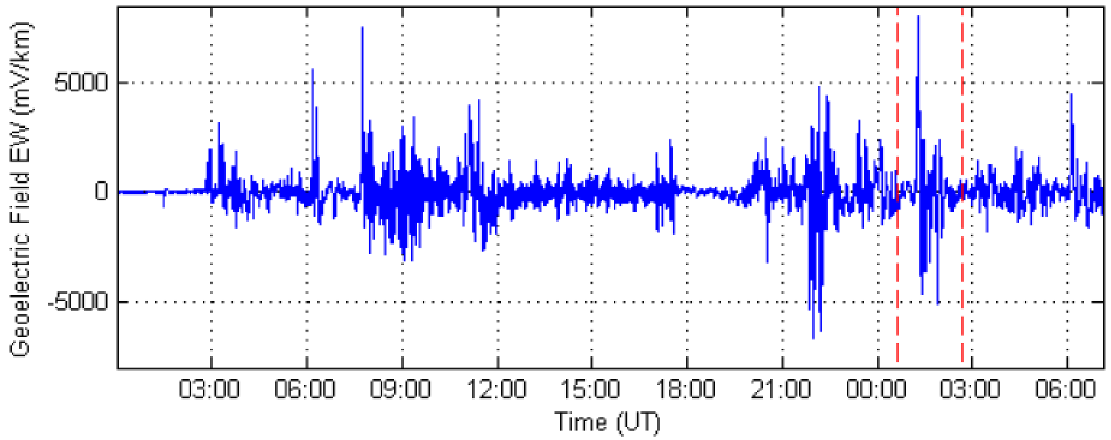




Study GIC Field Orientation for Transformer Thermal Impact Assessments

- The question motivating this research project is: what happens if the orientation of the geoelectric field is different from the orientation of the 1989 GMD event?
- What is the impact of other benchmark waveforms?

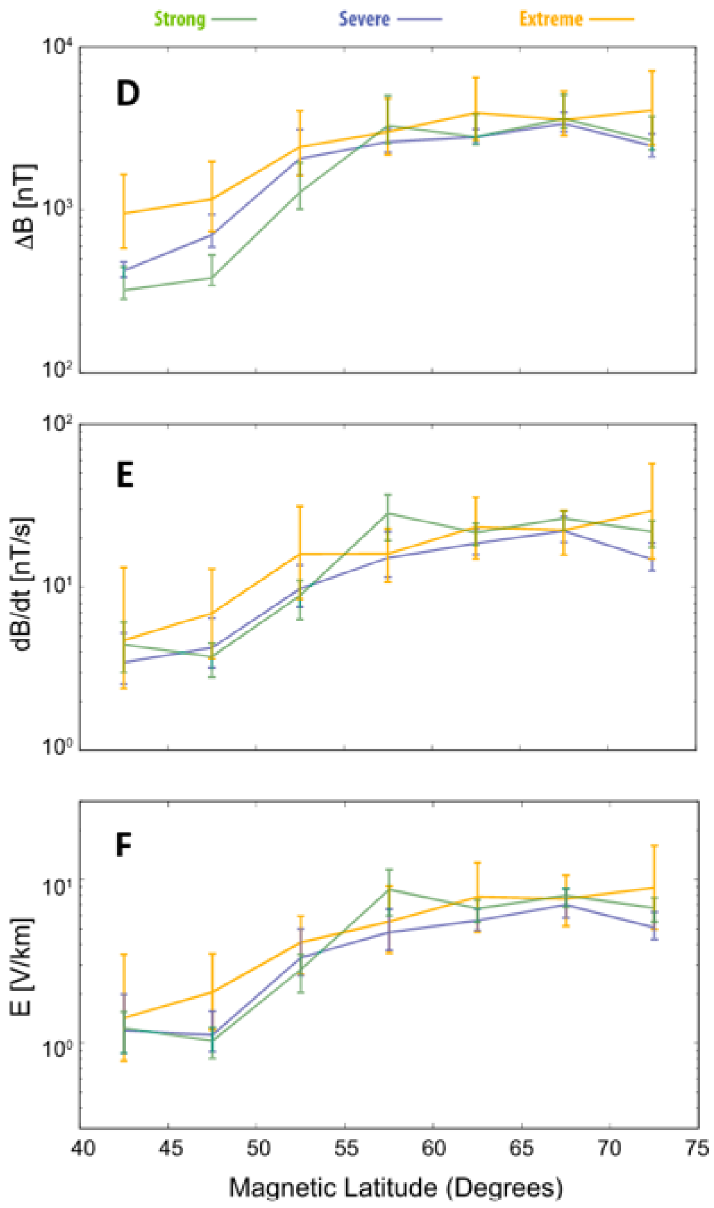


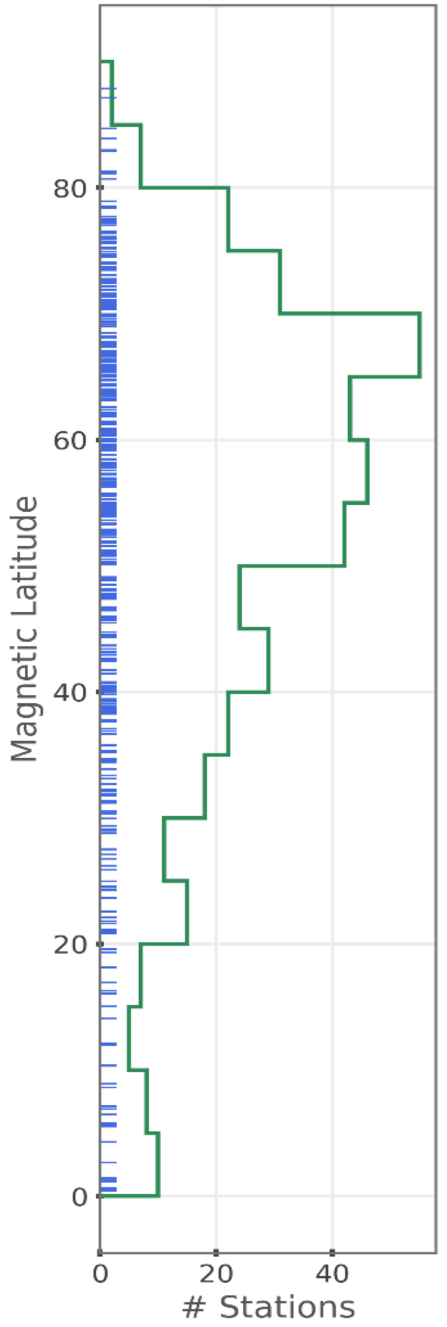


Spatial Averaging and Latitude Scaling Factor

Recently Released Reports

- Improving Understanding of Characteristics of Geoelectric Field Enhancements Caused by Severe GMD Events: *Examining Existing Ground-Based Data* – ID # [3002016832]
- Review of Peer-Reviewed Research Regarding the Effects of Geomagnetic Latitude on Geoelectric Fields: *Updated Based on the Latest Peer-Reviewed Research* – ID # [3002016885]



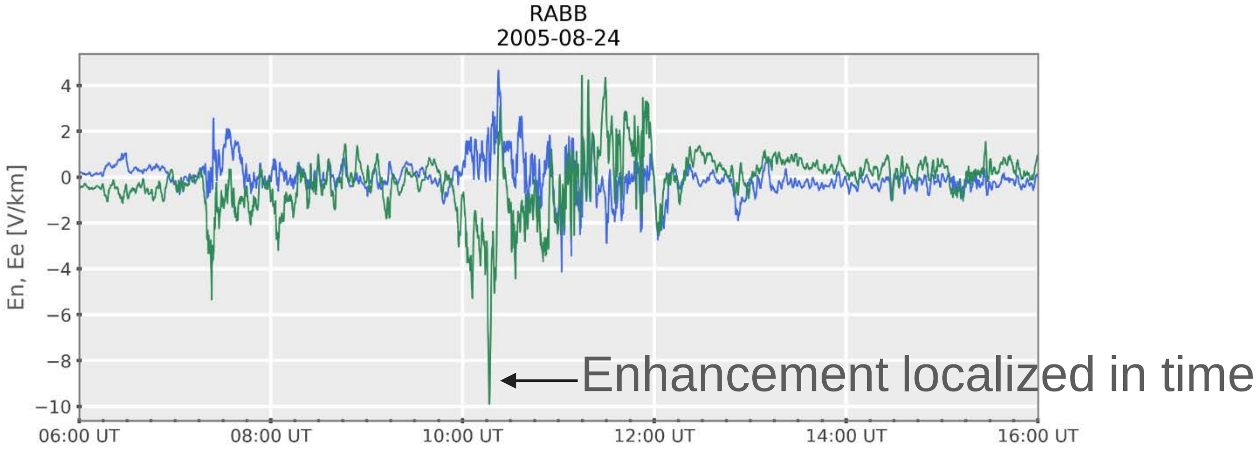


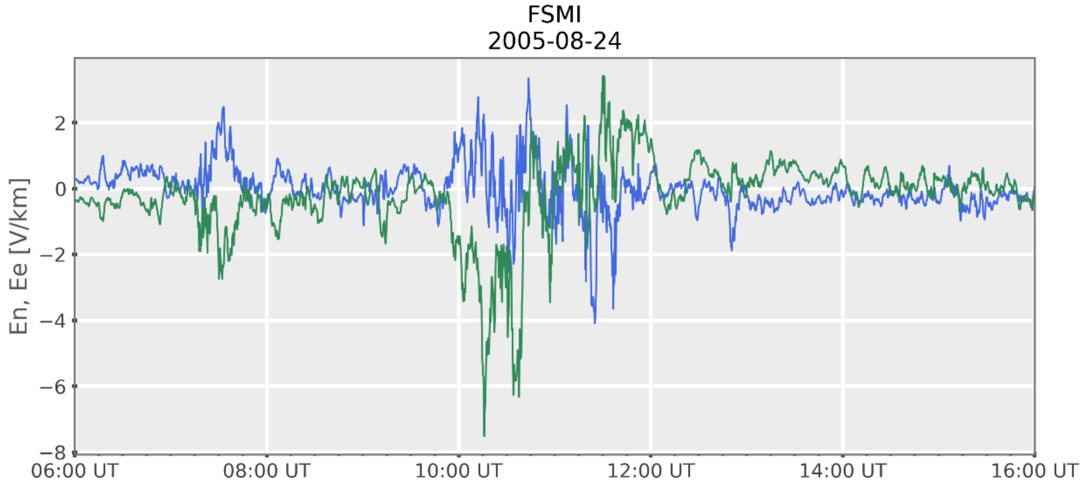
Highlights

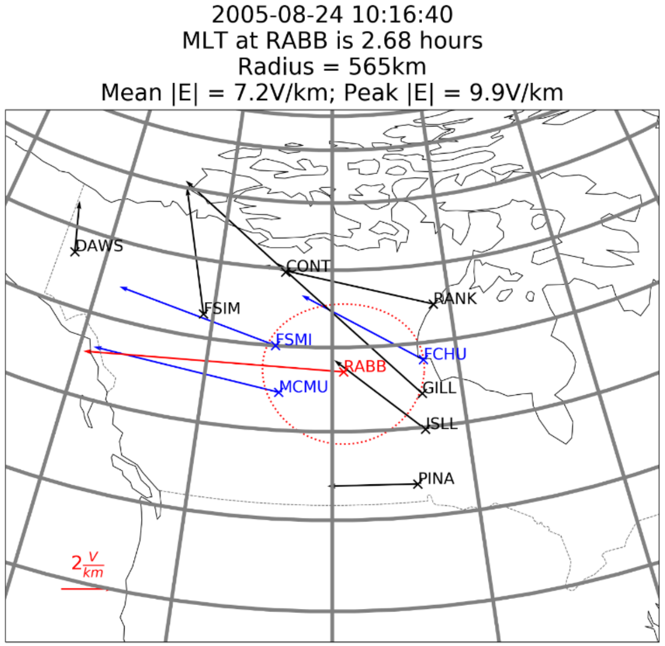
- New peer-reviewed work indicates directions for further refinements that can be considered as overall understanding of the geospace dynamics during extreme storm conditions evolves.
- Magnetic local time dependence could be considered in the future benchmark revisions
- The geomagnetic latitude scaling is associated with auroral oval and its motion during storms
- Physics-based simulations can be used to reproduce observed characteristics and characterize the extent of the auroral zone for infrequent and large storms, such as a 1-in-100-year event.

Localized Enhancements

Spatial and Temporal Extents



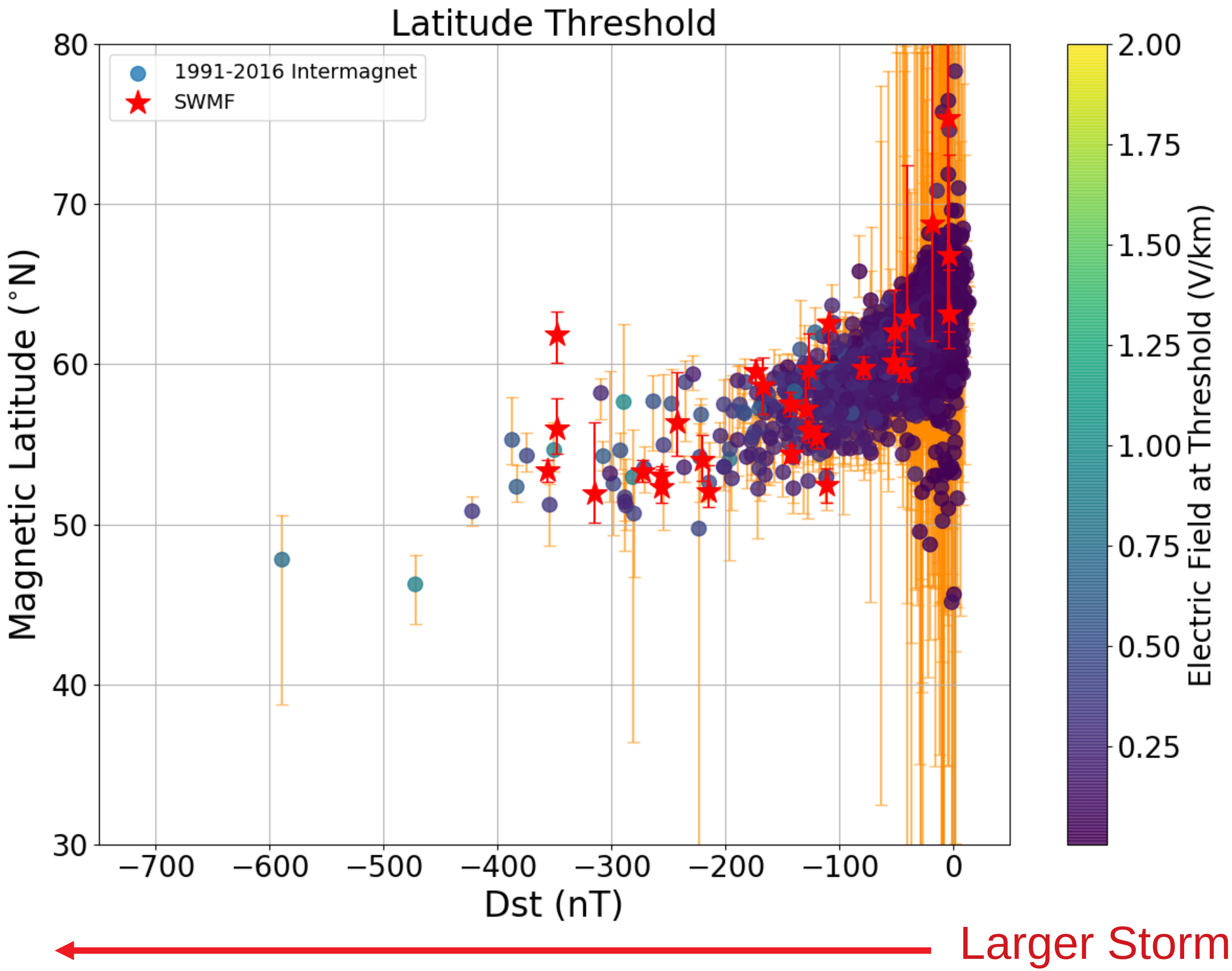




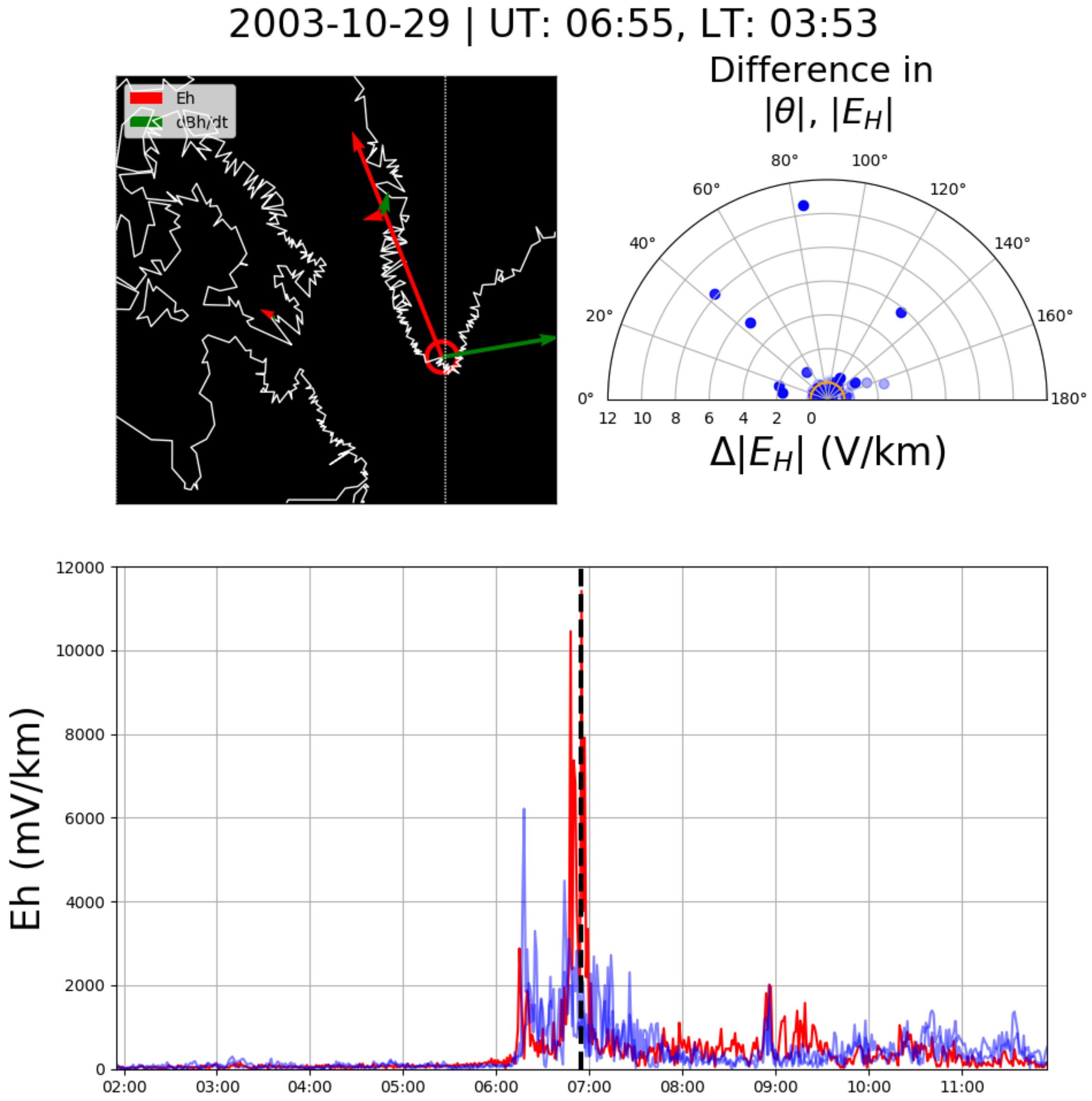
- Significant frequency content can be present at periods shorter than 1 minute
- Working on characterizing signatures of spatially localized enhancements

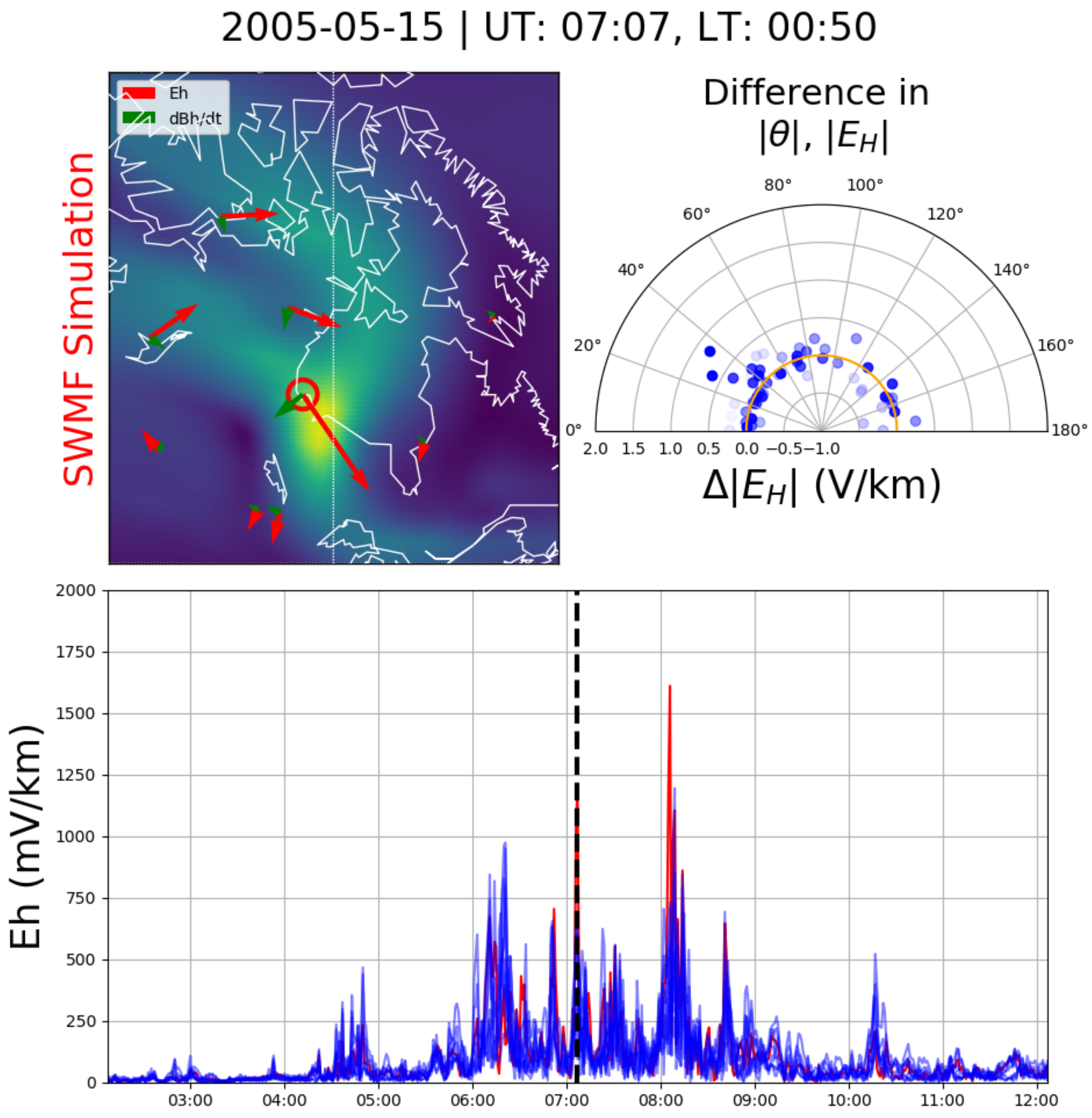
Auroral Boundary Estimation

- We can estimate the auroral boundary using historical data and MHD simulations



Localized E-Field Enhancements





Next Steps

- EPRI will continue with long-term monitoring of large power transformers in the field.
- EPRI team looking to quantify results of earth conductivity research.
- Looking to investigated in more detail different transformer designs with various tertiary winding ratings
- Schedule to complete tasks by Q4 2019 wrap-up by Q1 2020

Together…Shaping the Future of Electricity

U.S. Magnetotelluric (MT) Array Status and Integration in Powerflow Studies

Adam Schultz[1], Naoto Imamura[1], Eduardo Cotilla-Sanchez[2], Adam Mate[2], Sean Murphy[3]

[1]College of Earth, Ocean and Atmospheric Sciences, Oregon State University. [2]College of Electrical Engineering and Computer Sciences, Oregon State University. [3]PingThings, Inc.

(with contributions from Arthur Barnes, LANL)

NERC GMD Task Force, Chicago August 14, 2019

EMP/GMD

- Executive Order 13865 [Trump, March 26, 2019]

Sect'y Interior directed to:
1) Support the research, development, deployment, and operation of capabilities that enhance understanding of variations of Earth's magnetic field associated with [natural and human-made electro-magnetic pulses] EMPs, and
2) Within 4 years of the date of this order, the Secretary of the Interior shall complete a magnetotelluric survey of the contiguous United States to help critical infrastructure owners and operators conduct EMP vulnerability assessments.

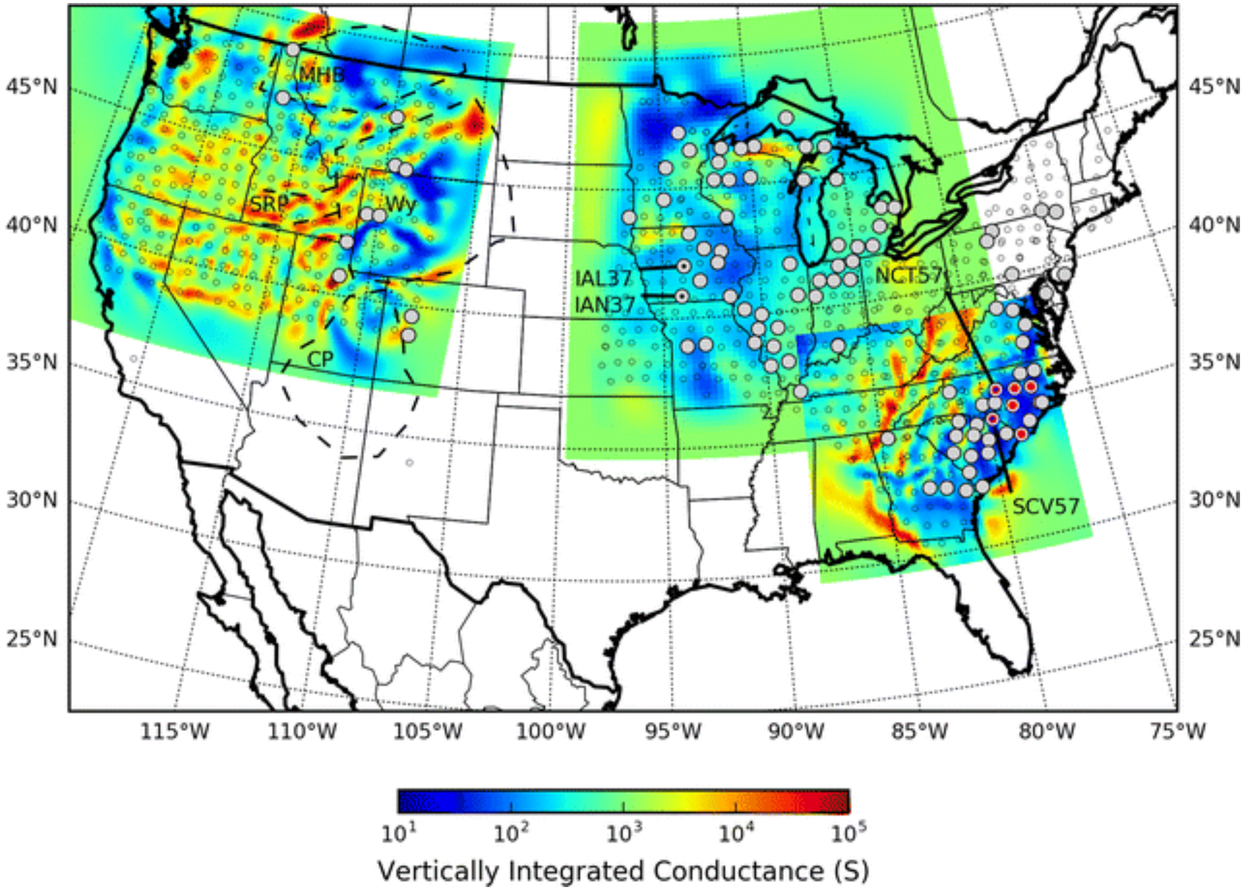
- I briefed NSC, senior Department and Agency personnel on MT Array impact on mitigating risk to power grid due to GMD/EMP at White House EEOB, April 22, 2019

- President's Budget Request FY2020
  - $1.726M for FY2020 for 1st year (presumably of four years) to complete MTArray
  - Same amount in budget passed by House Appropriations Committee
  - 2-year budget deal passed by both houses and signed by President – details to be worked out in coming months – still good possibility of Continuing Resolution until final budget negotiations complete.

3-D conductivity structure

Vertically integrated Earth conductance (from 15–150 km) calculated from the 3-D MT inverse solutions of Meqbel et al. (2014) (northwestern USA), Yang et al. (2015) (north-central USA), and Murphy and Egbert (2017) (southeastern USA).

[From: Murphy & Egbert, 2018]



Oregon State University

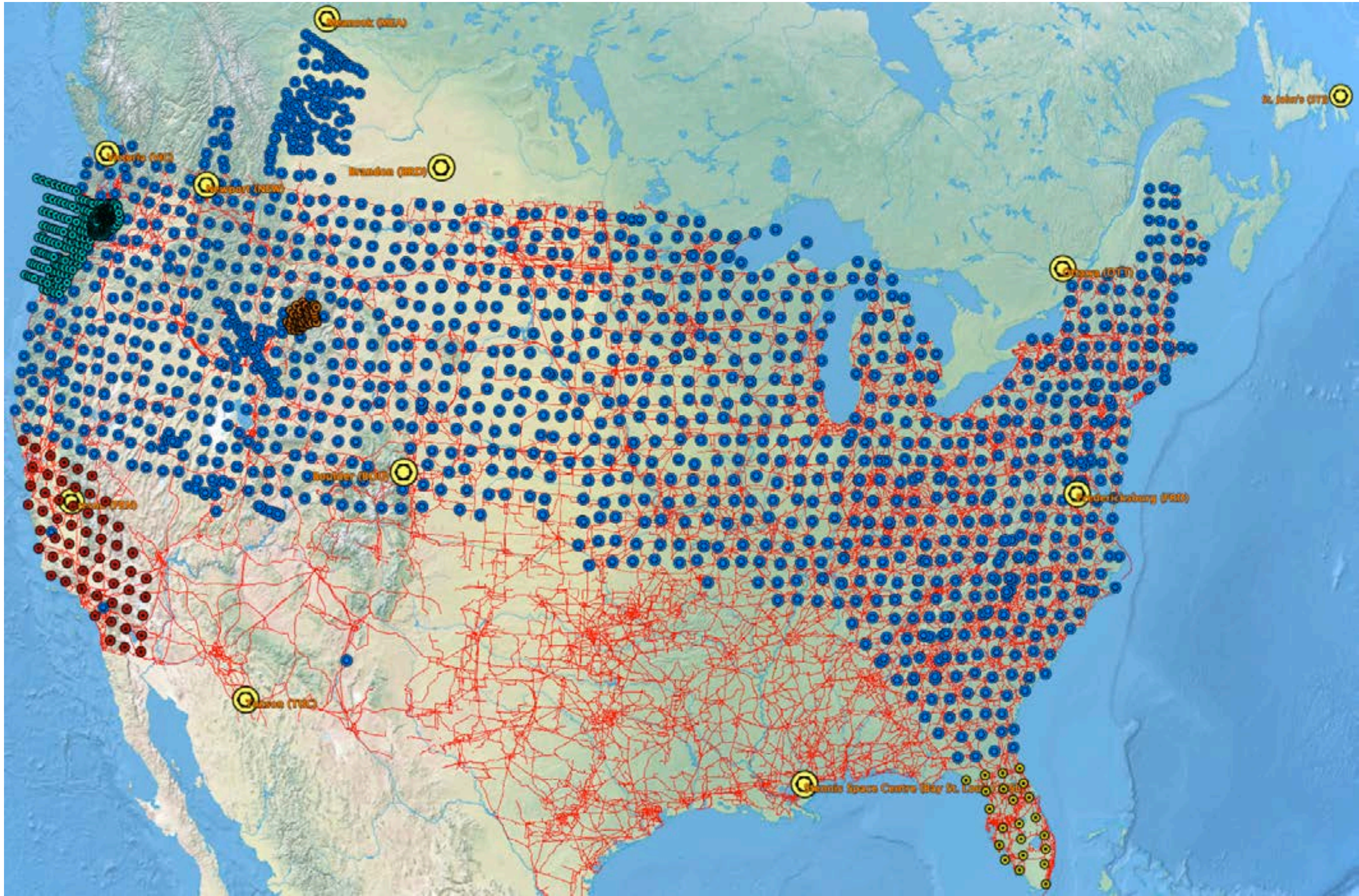
Transportable MT Array Status

College of Earth, Ocean, and Atmospheric Sciences

MT Array Operations Center

A unified public domain database of Transportable Array (70-km) station spacing long-period MT station time series, MT response functions available from IRIS.edu

blue dots	1167 OSU/NSF sites
yellow dots	47 USGS sites incl. Parts of FL; TN, AR, MO (not shown)
red dots	54 OSU/NASA sites in CA currently being installed (2019)
yellow circles:	Magnetic observatories (USGS, NRCan)
Red lines	US power transmission grid



SoCal MT Array 2019 Status and Plans for 2020

Oregon State University

College of Earth, Ocean, and Atmospheric Sciences

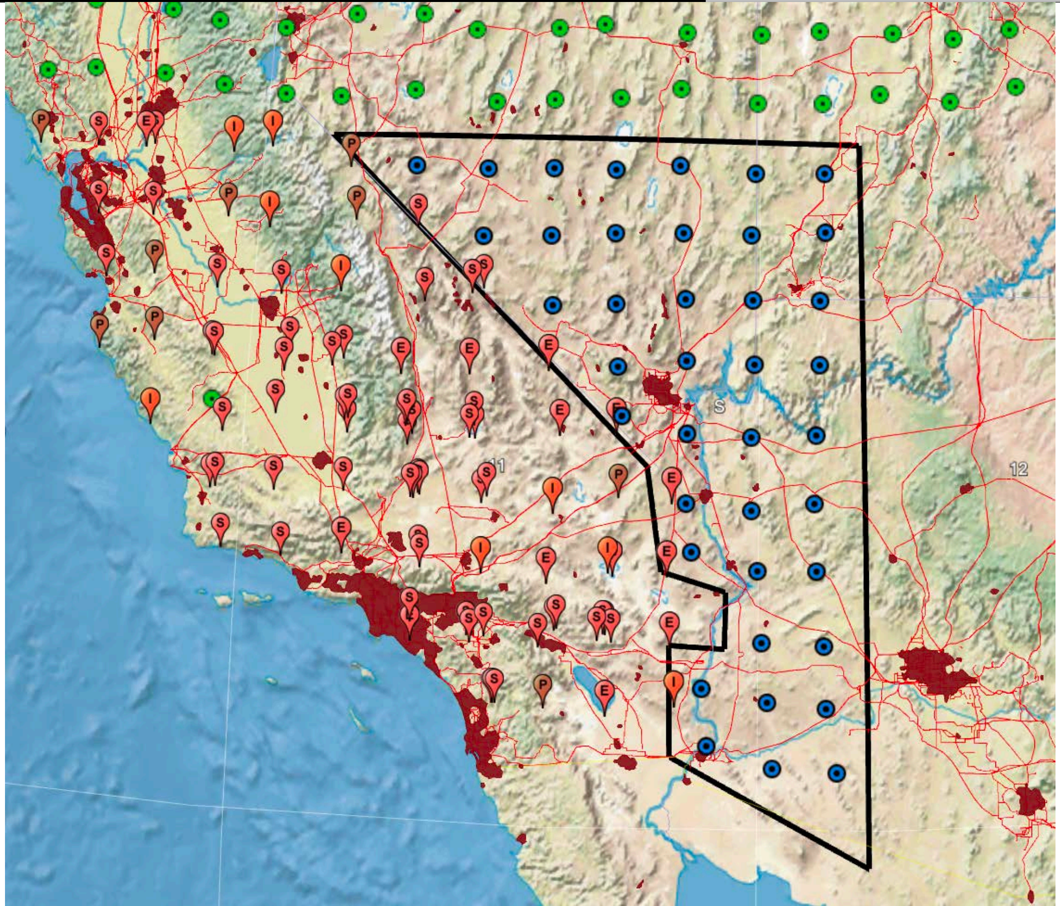
MT Array Operations Center

NASA provided bridging funding for FY2019, enabling continued operation of the MT Array following the end of the NSF EarthScope MT Program in 2018.

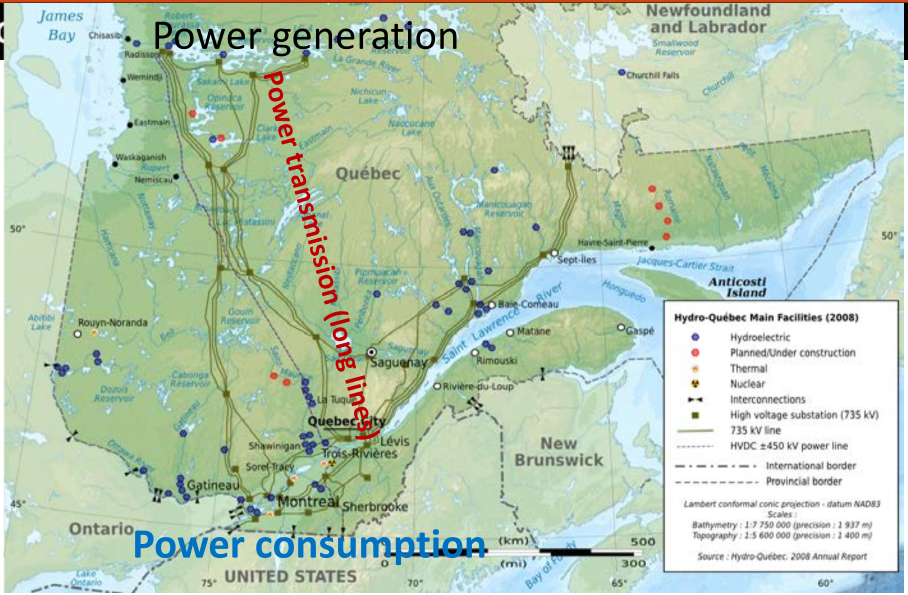
2019 NASA funding is being used to provide nearly complete MT Array coverage in Southern California (nominally 52 stations) – status indicated by letter on pin (E – extracted/completed; I – installed/operating; P – permit secured; S – candidate location being sited ahead of permitting)

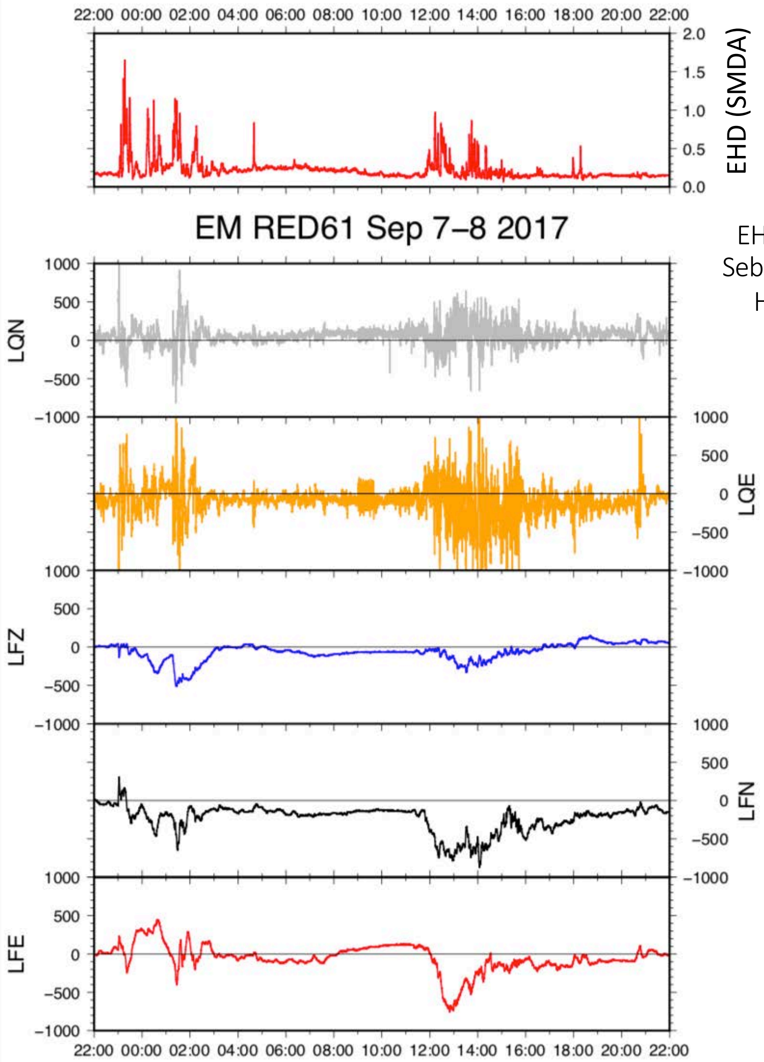
2020 NASA funding is pending to extend the MT Array into the rest of Nevada, SW Utah and western Arizona (nominally 40 stations marked as blue dots)

Previously completed EarthScope MT Array stations marked as green dots.



Rare example of simultaneous MT and transmission system sensor data during a GMD





EHD (top) credit: Sebastién Guillon, Hydro-Québec.

Coherency between ground electric fields recorded at OSU/NSF EarthScope MT stations (this example: SW Maine) and Even Harmonic Distortion in voltage measured on Hydro-Québec transmission system

Electric field (N-S at top, then E-W) components, magnetic field (vertical, N-S then E-W) components from an OSU EarthScope MT station in SW Maine during a GMD in September, 2017.

Top panel – Even Harmonic Distortion (harmonics 2,4,6,8 as percentage) in voltage, measured on Hydro-Québec power grid during the GMD.

Predicting ground electric fields

1. Our approach is to pipe the predicted magnetic fields at the locations of former MT stations through the impedance tensors we obtained for those locations, to obtain the predicted electric fields there

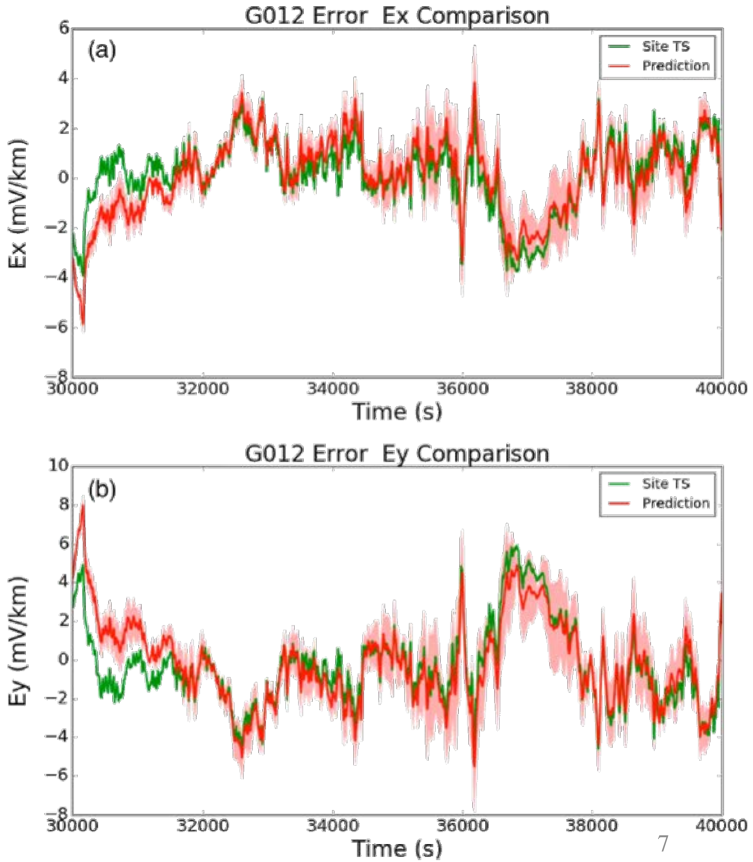
$$\begin{bmatrix}\widetilde{E_x}\\ \widetilde{E_y}\end{bmatrix} = \begin{bmatrix}Z_{xx} & Z_{xy}\\ Z_{yx} & Z_{yy}\end{bmatrix}\begin{bmatrix}\widetilde{H_x}\\ \widetilde{H_y}\end{bmatrix} + \begin{bmatrix}\widetilde{U_x}\\ \widetilde{U_y}\end{bmatrix}$$

where the tilde indicates the *predicted* field.

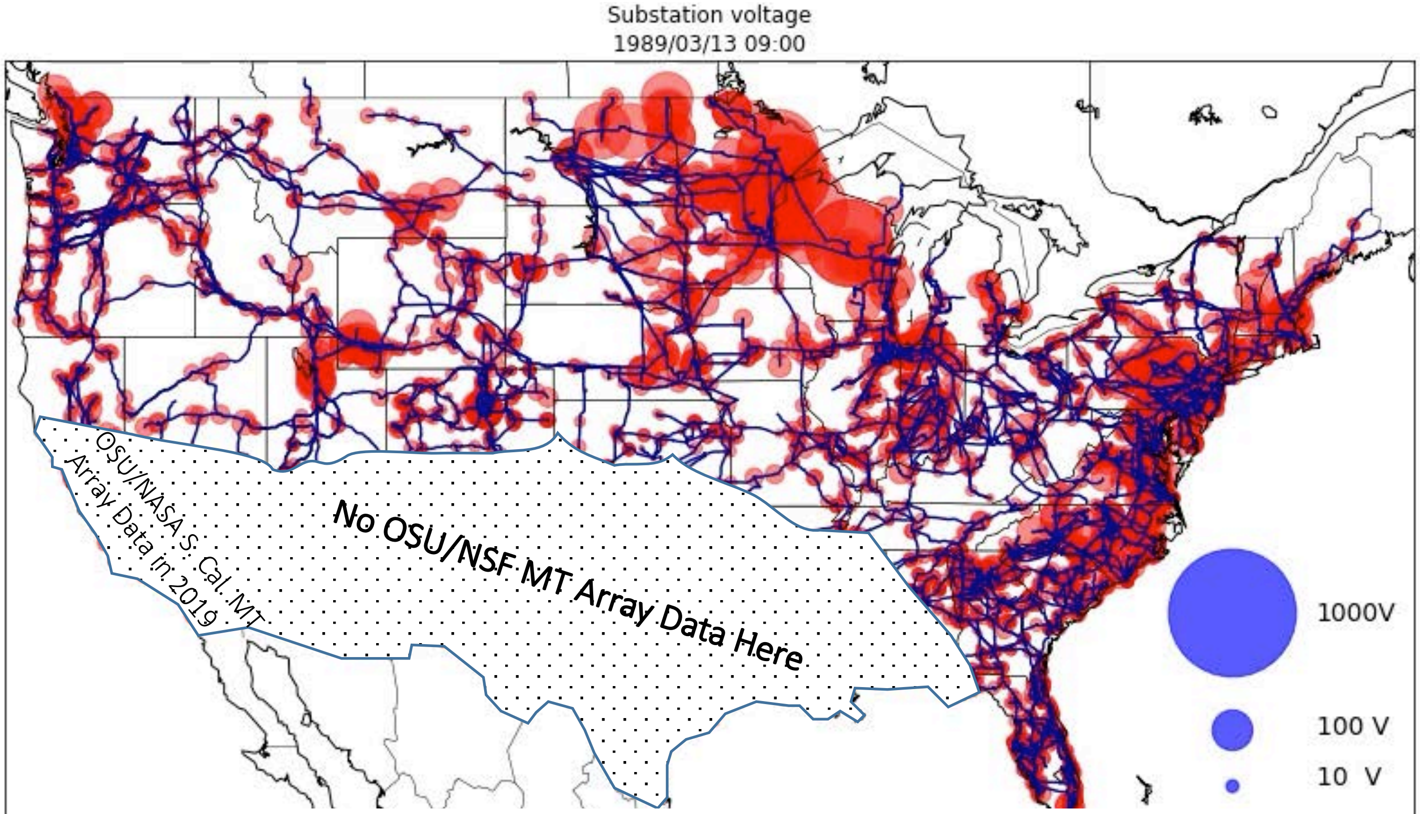
2. We use a distance weighted algorithm to project the predicted electric fields from all the neighboring MT station locations onto each point along the transmission line path.

3. Alternatively one can use 3-D models of ground conductivity derived from inversion of the impedance tensors; solve the forward problem, and derive electric fields on a grid of points. This is the USGS/NOAA approach.

4. For our approach, electric field prediction misfits at most sites are typically around 1–2 mV/km RMS at the great majority of MT sites that we have examined (for modest k_p levels, within the BPA operating area) where the distance to the nearest magnetic observatory is < 600 km.



OSU 3-D model calculated voltage at substations due to 1989 GMD, 3/13/1989 09:00-15:00UT (peak GMD)



Note – large GMD induced bus voltages in the South as well as in the North – impact of 3-D ground conductivity

Calculated 3-D ground electric fields integrated along the path of the high-voltage transmission lines. Voltage is shown relative to ground at one Ohio substation.

Note – true voltage state calculation requires integration with power flow model.

(Path integration and mapping using BEZPy by G. Lucas, USGS)

Power Flow simulations

Objective:

- integrate GIC predictions with power system simulation software
- validate developed 3-D earth conductivity structure/Impedance

Tensor modeling technique

Important terms:

- Power Flow (PF) vs Optimal Power Flow (OPF)
- AC-OPF: a non-convex problem without a guaranteed solution

Process:

determine DC GIC ➡ update RTS-GMLC ➡ run AC-OFP simulation

Geophysical Induced Bus Voltages -> AC/DC Powerflow

Julia

- Open-source, general purpose dynamic programming language
- High-performance
- Just-in-time
- Well adapted for numerical analysis

PowerModels.jl

- Julia / JuMP package
- steady-state power network optimization

PowerModelsGMD.jl

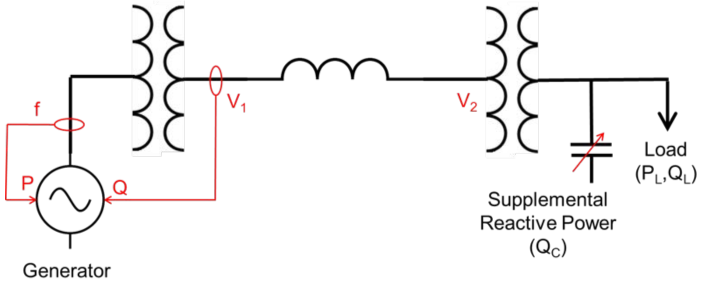
- Extensions to PowerModels.jl for quasi-dc line flows and ac power flow problems for GMD/E3 HEMP (Primary author: Arthur Barnes, LANL)
- GIC DC Solve: Solve for steady-state dc currents on lines resulting from induced dc voltages on lines.
- Coupled GIC + AC Optimal Power Flow (OPF): Solve AC-OPF problems for network subjected to GIC.
- The dc network couples to the ac network through reactive power loss in transformers
- Fast and reliable results

Reference: Carleton Coffrin, Russell Bent, Kaarthik Sundar, Yeesian Ng and Miles Lubin, PowerModels.jl: An Open-Source Framework for Exploring Power Flow Formulations, 2018 Power Systems Computation Conference (PSCC), doi: 10.23919/PSCC.2018.8442948}

https://github.com/lanl-ansi/PowerModelsGMD.jl

DC network of RTS-GMLC

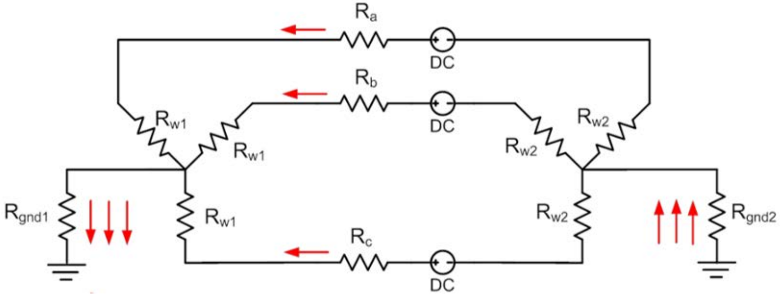
Simple AC Network



- AC power flows from left to right

S. Dahman, "Geomagnetically Induced Current (GIC) Modeling," presented at the PowerWorld Client Conference, Austin, TX, 23-Feb-2016.

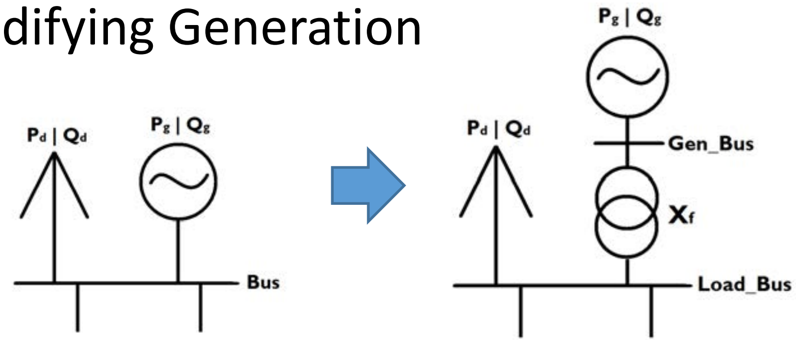
Associated DC Network

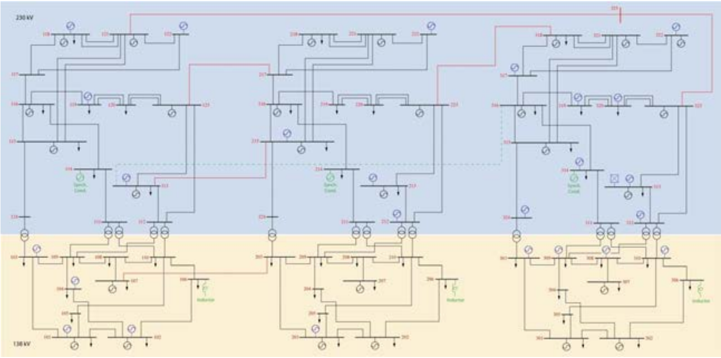


- GMD induced DC currents circulate between the transformers
- no DC current on the ungrounded Delta side of the transformer

DC network of RTS-GMLC

Modifying Generation





Modeling Transformers

- winding configuration can be guessed with good accuracy

Substation grounding resistance

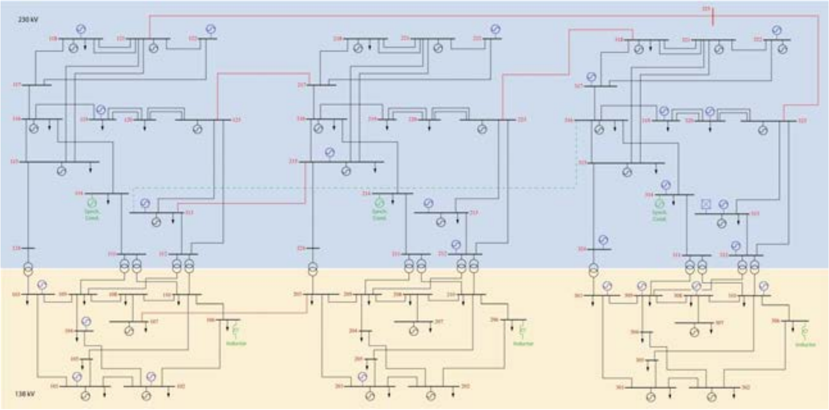
- determined with nonlinear regression

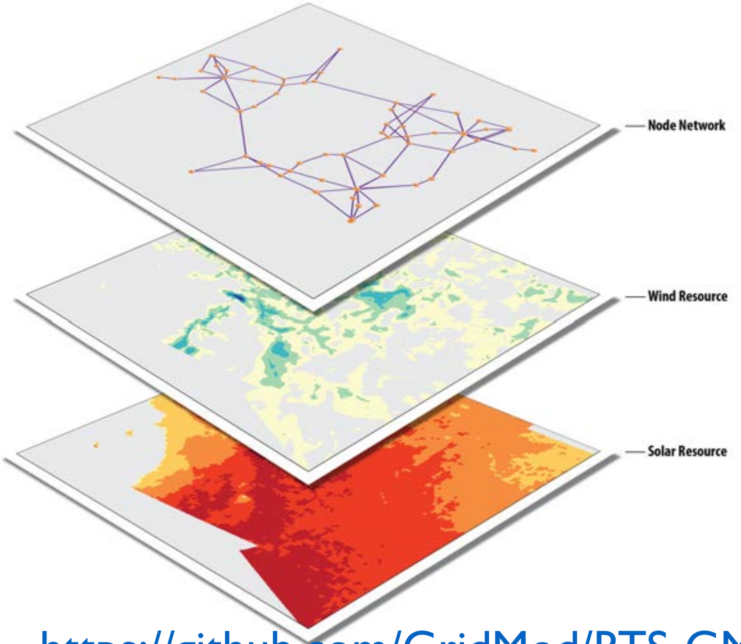
	AC	AC+DC
Bus	73	169
Branch	120	216
Generator	96	96
Transformer	15	111
Load	51	51

RTS-GMLC

Reliability Test System of the
Grid Modernization Laboratory Consortium

- developed by NREL in 2018
- modernized version of IEEE RTS-96
- customization:
  - changing geographical location
  - creation of DC equivalent network





https://github.com/GridMod/RTS-GMLC

Halloween Solar Storm

Significance:

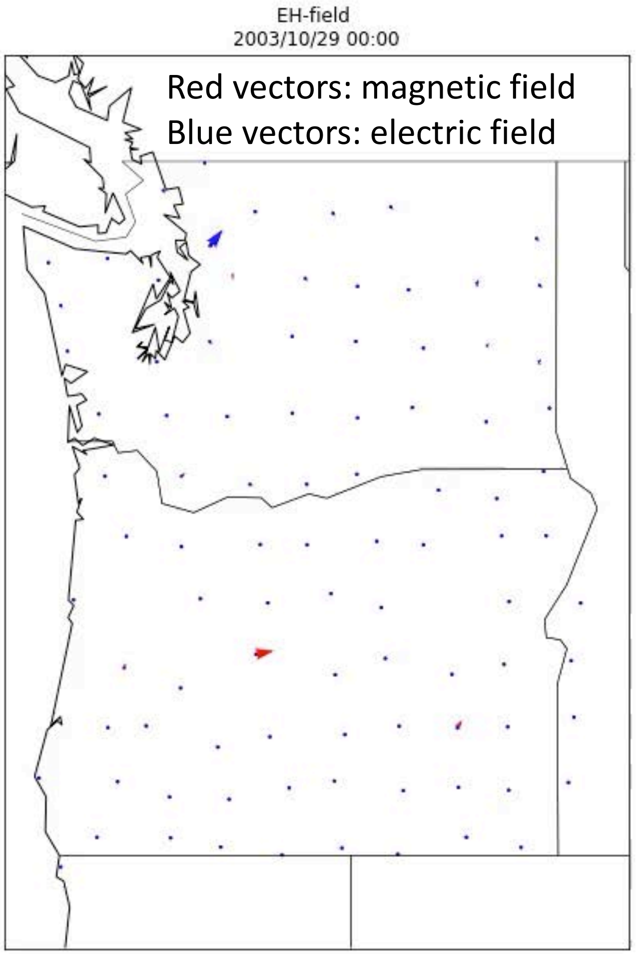
- largest ever recorded GMD event
- 10/29/2003 12:00am – 10/30/2003 11:50pm

3-D geophysical modeling technique by OSU:

- determine 3-D earth MT impedance/conductivity structure model

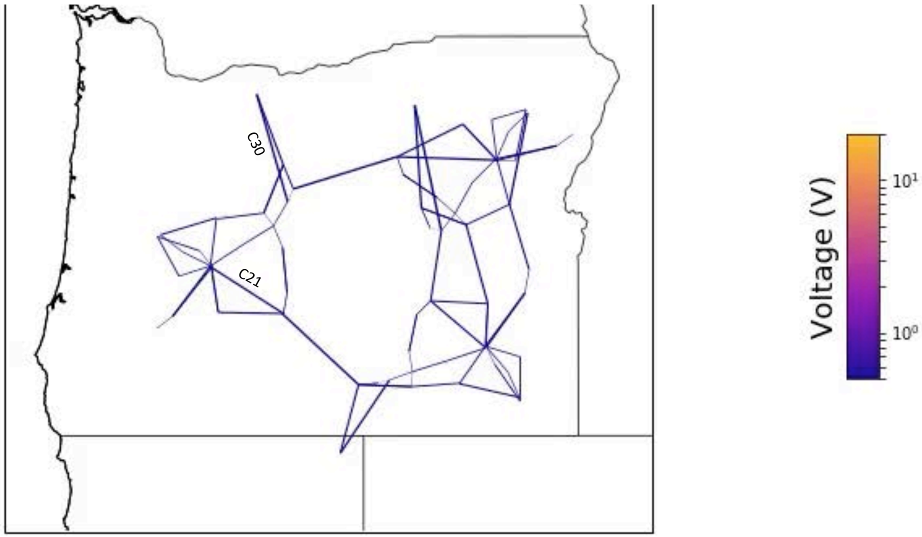
Severity of event:

- maximum induced voltage: on line C21 - 53.63V (at 10/30 7:56pm)
- longest line not necessarily going to see the largest GICs – GIC intensity depends on line orientation, B-field polarization * MT Impedance Tensor = E-field polarization

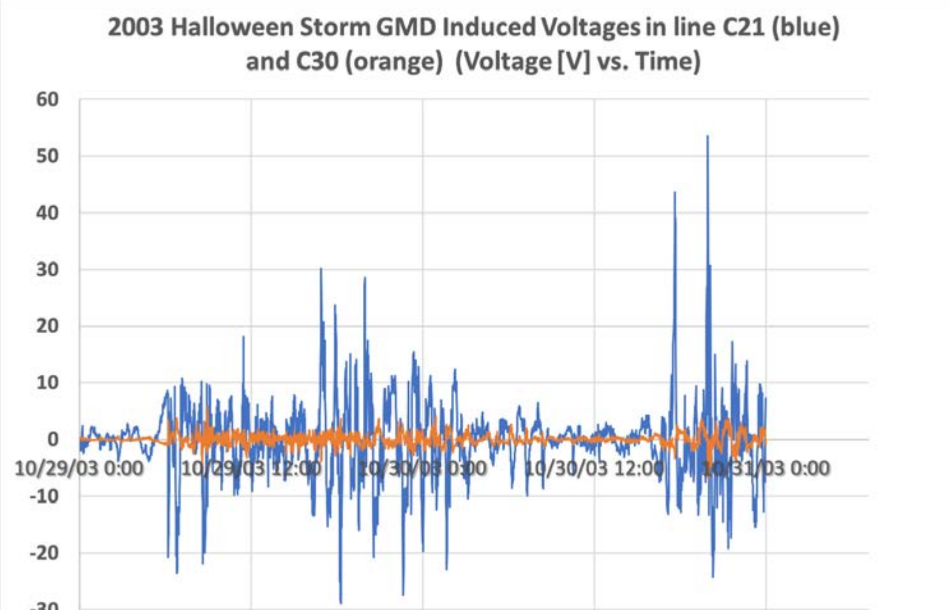


High-voltage transmission system line voltages induced by GMD using OSU/NSF EarthScope 3-D ground impedance information and magnetic field algorithm.

For power transmission network we've used the RTS-GMLC (Reliability Test System Grid Modernization Lab Consortium) test case but moved to Oregon, and we are using LANL's Julia and PowerModelsGMD package, for power flow simulations on the test case, and to determine the GIC flows and possible impacts on the power waveforms in the system elements.



Animation ref: BEZPy, G. Lucas, USGS



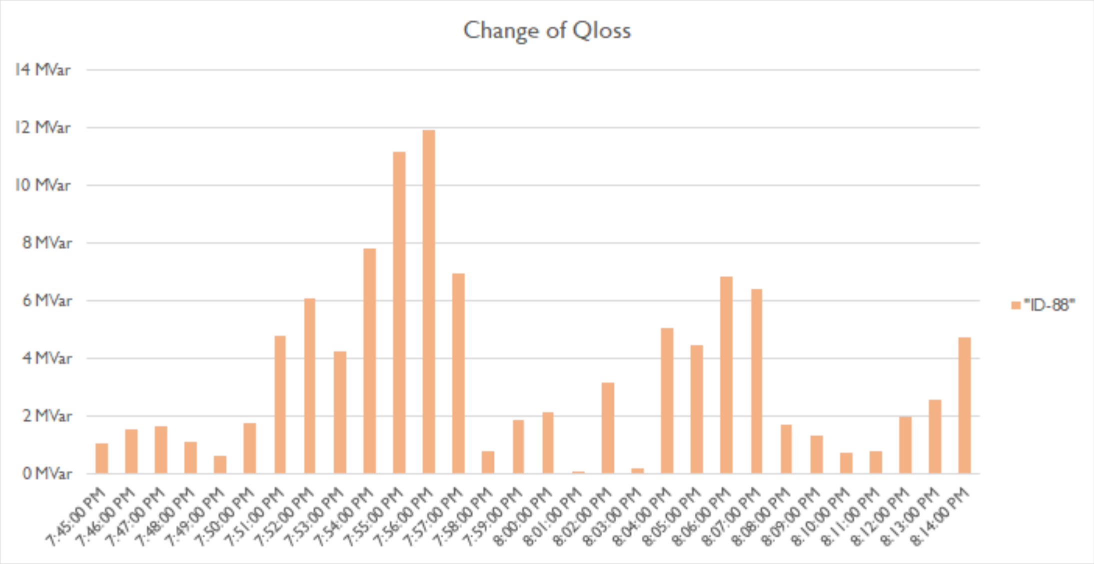
Note – the orientation of the transmission lines and 3-D ground induction effects that vary throughout the region lead to dramatic variations in transmission line induced voltages. The longest transmission line does not necessarily have the largest voltage.

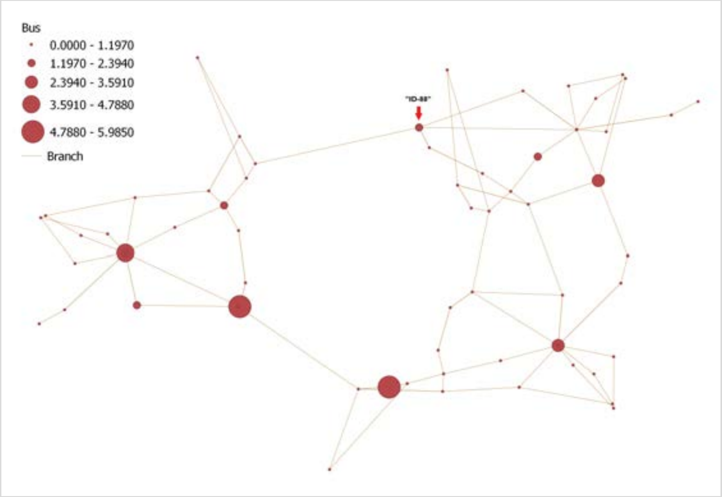
AC-OPF results

During GMD Q losses:

- Greatest loss on "branch ID-88"
- Line voltages essentially unchanged

Avg. Q_{loss}	77.66 MVar
Lowest Q_{loss}	63.05 MVar (TP-1)
Highest Q_{loss}	116.06 MVar (TP-12)





10/30 7:58 PM

AC-OPF results

Oregon State University

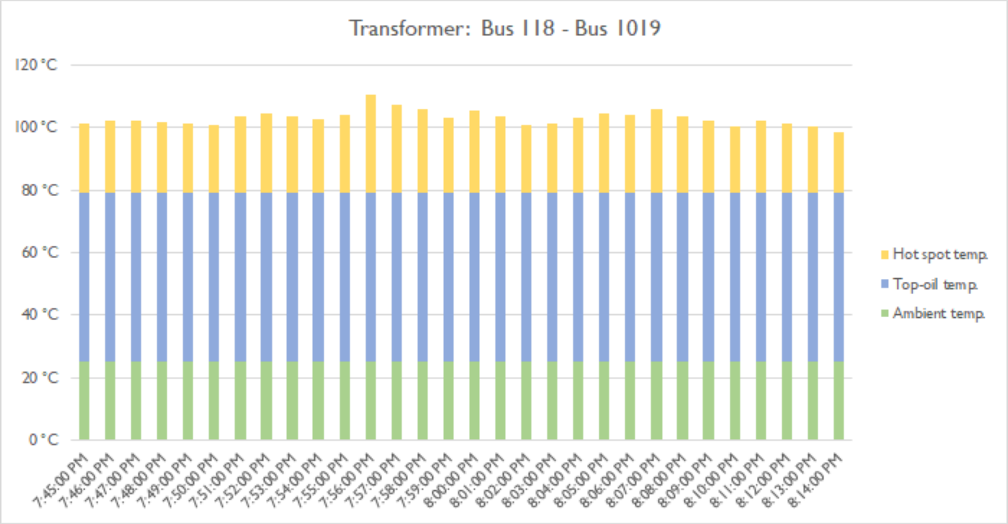
NASA NSF IRIS

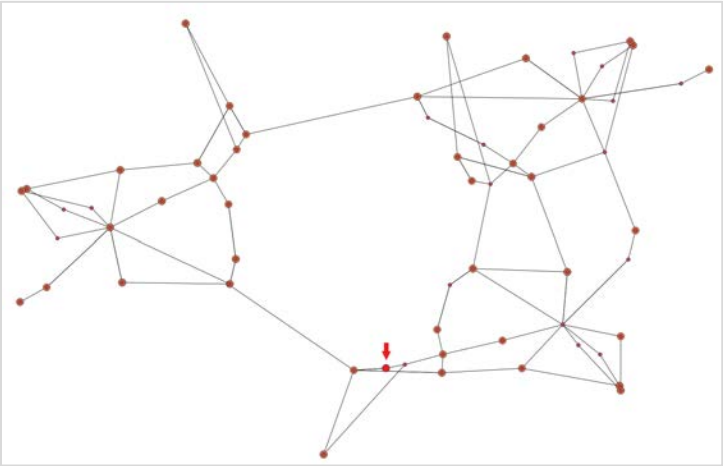
College of Earth, Ocean, and Atmospheric Sciences

National Geoelectromagnetic Facility

Transformer temperatures:

- Actual = Ambient + Top-oil + Hot spot





Oregon State University

Power Flow example – 2003 Halloween Storm

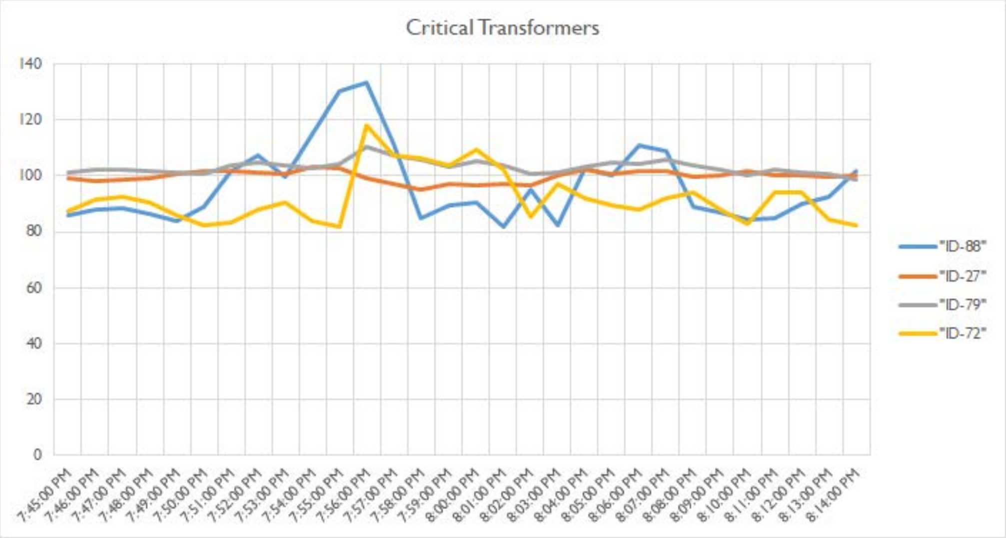
College of Earth, Ocean, and Atmospheric Sciences

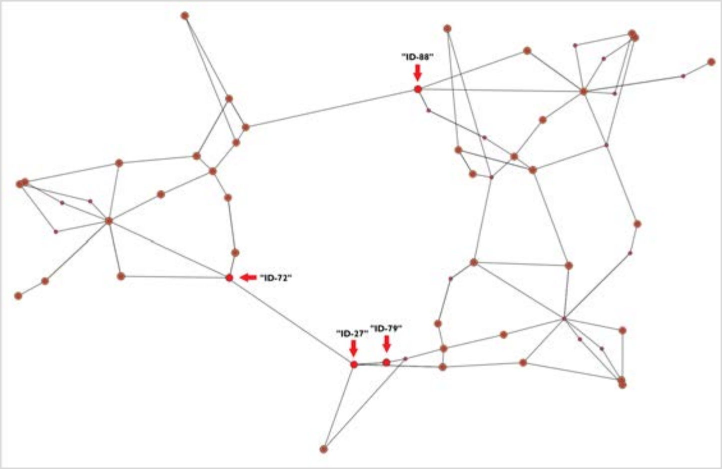
National Geoelectromagnetic Facility

AC-OPF results

Transformer temperatures during peak GMD:

- most critical transformers based on temperature

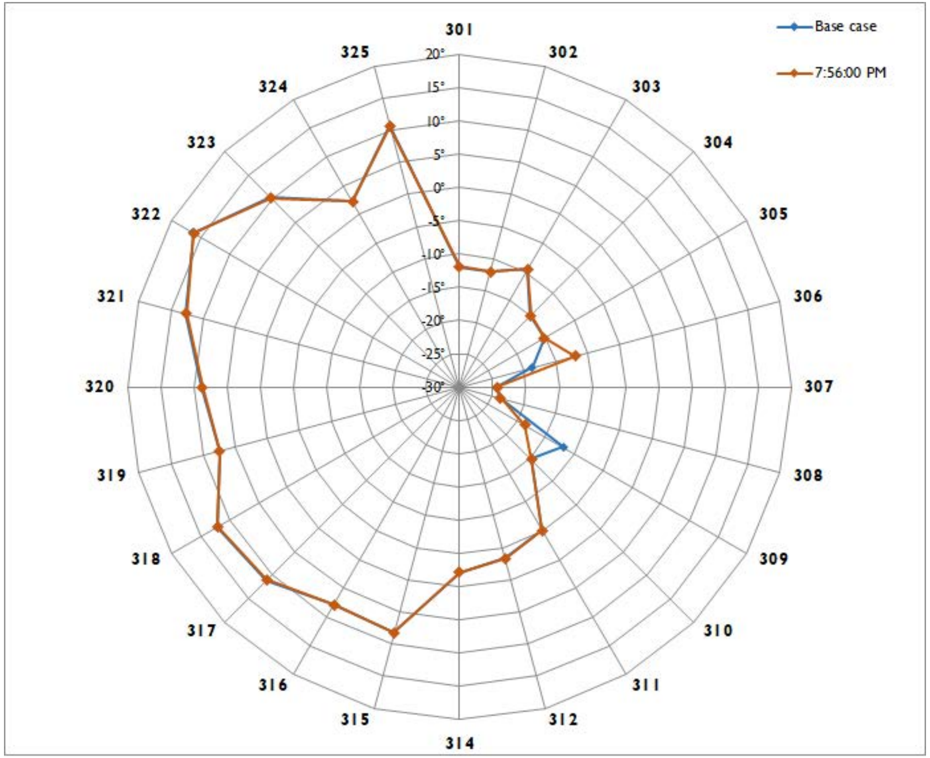




AC-OPF results

The phase angle difference between two buses – indicating relative stress across the grid illustrates how reactive power flows through the system as Qloss takes place.

Diagram displays voltage-current phase angle difference between slack bus (Bus 313) and each of the other buses in Area 3 during base case (blue) and during most severe time of GMD (red). Note the shift in Bus 306 and 309 phase angles during GMD.



AC-OPF results

Bus AC voltages:

- all bus remain inside the acceptable range

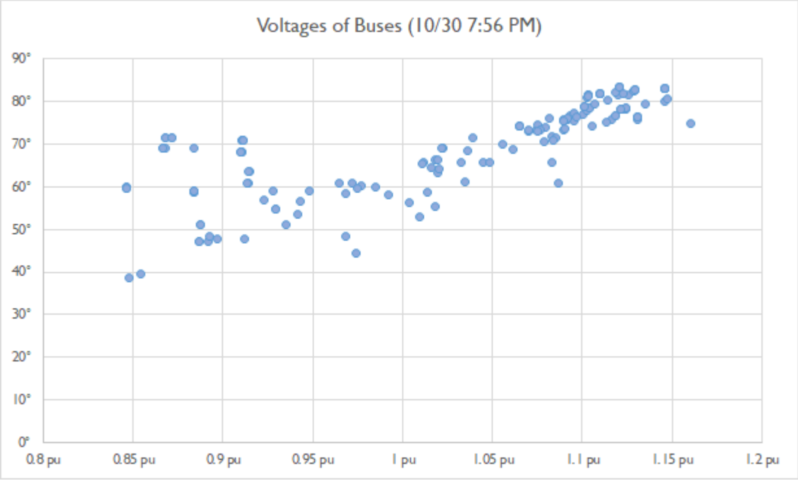
During GMD event:

- V magnitudes remain unchanged
- V angles only slightly affected

Generating units:

- P_g remain unchanged
- Q_g increases to balance Q_{loss}

Base case – [p.u.] voltages	
between 0.95 and 1.05	28
between 0.85 and 0.95 between 1.05 and 1.15	135
below 0.85 above 1.15	6



Acknowledgements

The authors acknowledge the support of

National Science Foundation (NSF) Award IIP - 1720175 “PFI:BIC - A Smart GIC-Resilient Power Grid: Cognitive Control Enabled by Data Mining at the Nexus of Space Weather, Geophysics and Power Systems Engineering”

NASA Grant Number 80NSSC19K0232/IRIS Subaward SU-19-1101-05-OSU

NSF EarthScope Program Cooperative Agreements EAR-0733069 and EAR-1261681 respectively through subcontracts 75-MT and 05-OSU-SAGE “Operation and Management of EarthScope Magnetotelluric Program” from Incorporated Research Institutions for Seismology (IRIS) to Oregon State University to acquire the MT data used in this work.

Dr. Arthur Barnes, Los Alamos National Lab for hosting Adam Mate (OSU) during efforts to integrate geophysical and power flow solutions

Questions? Adam.Schultz@oregonstate.edu

Extreme Value Analysis of GIC Based On Historic Geomagnetic Field Data

Geomagnetic Disturbance Task Force (GMDTF) Meeting
Chicago, IL
August 14, 2019

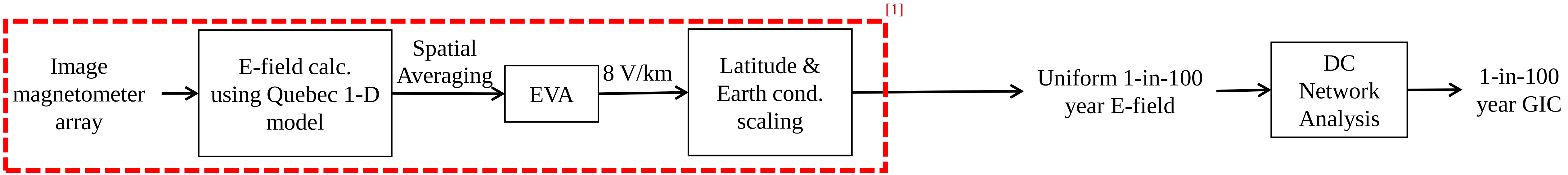
Rishi Sharma, Ph.D. Student
Advisor: Dr. James McCalley
Iowa State University

Overview

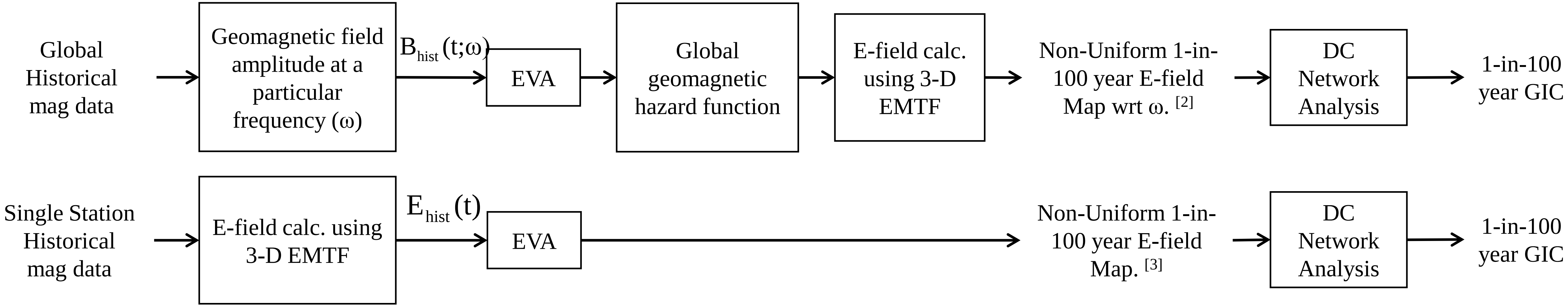
1. 100-Year GIC Computation Approaches.
2. Modified 100-Year GIC Computation Approach.
3. Geomagnetic Field Scaling & GIC Computation.
4. 100-Year GIC for Iowa & Ongoing work.

100-Year GIC Computation Approaches

Using 1-D Earth conductivity models:



Using 3-D Earth conductivity model approach as indicated in [2] & [3]:



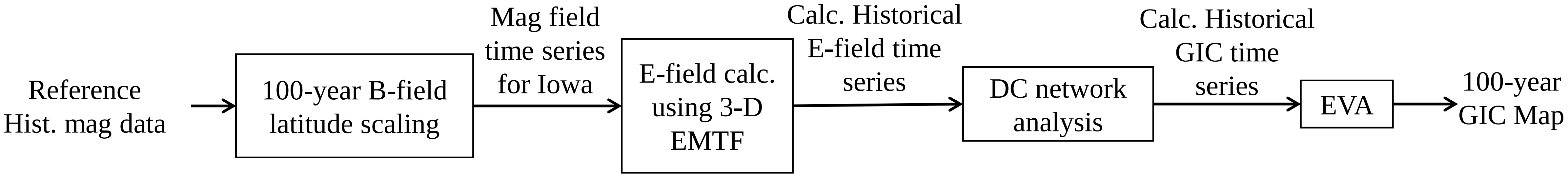
[1] NERC Standard Drafting Team, "Benchmark Geomagnetic Disturbance Event Description," 2016.
[2] J. J. Love and P. A. Bedrosian, "Extreme-Event Geoelectric Hazard Maps," *Extrem. Events Geosp.*, no. April, pp. 209–230, 2018.
[3] J. J. Love, G. M. Lucas, A. Kelbert, and P. A. Bedrosian, "Geoelectric Hazard Maps for the Pacific Northwest," *Sp. Weather*, vol. 16, no. 8, pp. 1114–1127, 2018.

Modified 100-Year GIC Computation Approach

Issues regarding the existing 3-D modeling approach:

- Peak E-fields at all sites not from same storm.
- Directionality of 100-year E-field not available.
- E-field magnitude inaccurately characterizes storm time E-field.
- High fidelity long-term geomagnetic field observations unavailable in US.

To address these shortcomings:



Case Study: Determination of 100-year GIC for Iowa

- Geomagnetic field data: Boulder Magnetic Observatory 1-min geomagnetic field data obtained from World Data Centre for Geomagnetism (Edinburgh).
- 3-D EMTF: Courtesy of the U.S. Geological Survey.
- Transmission network data: 101 Bus transmission network data MidAmerican Energy Company.

Geomagnetic Field Scaling & GIC Computation

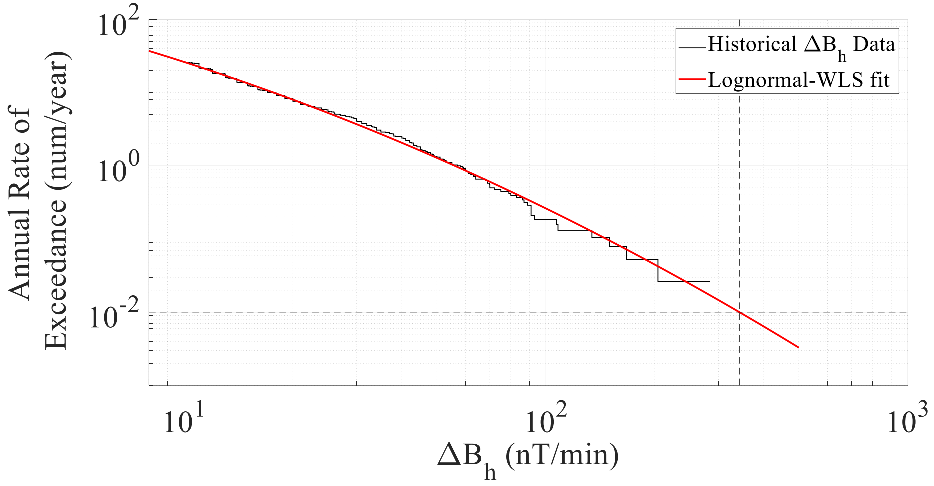


Fig 1: Lognormal WLS fit obtained to determined 100-year ΔB_h

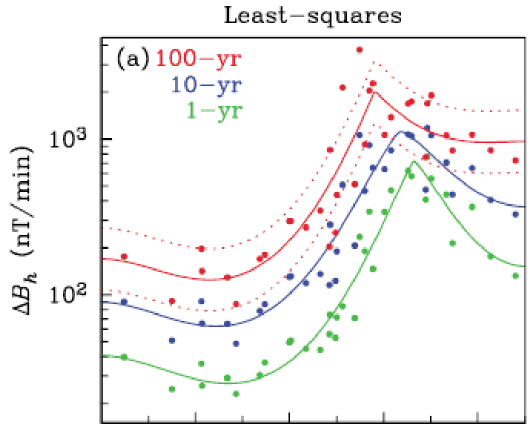
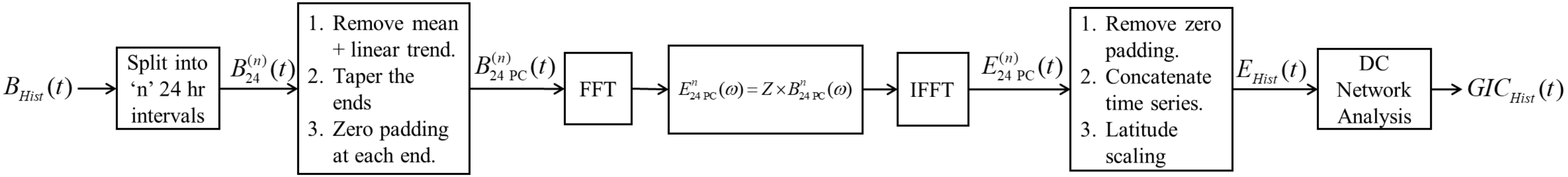


Fig 2: Magnetic latitude map obtained for ΔB_h in [1]

- Geomagnetic field latitude scaling factor:

$$\text{Latitude Scaling Factor} = \frac{\text{100-year } \Delta B_h \text{ for Iowa using fig 2 [1]}}{\text{100-year } \Delta B_h \text{ for BOU observatory data}}$$

- Algorithm for GIC time series computation is illustrated below using a 1-min sample, 24 hour time series *B(t)* and 3-D EMTF. The algorithm is based on [2].



[1] J. J. Love, P. Coïsson, and A. Pulkkinen, "Global statistical maps of extreme-event magnetic observatory 1 min first differences in horizontal intensity," *Geophys. Res. Lett.*, vol. 43, no. 9, pp. 4126–4135, 2016.
[2] EPRI "How to Calculate Electric Fields to Determine Geomagnetically-Induced Currents."

100-Year GIC for Iowa

- 100-year GIC at a particular substation in Iowa is 31.9 and 37.7 Amps for MLE and WLS estimators respectively.
- Using the 100-year GIC the voltage collapse, harmonics and temperature rise assessment can be performed.

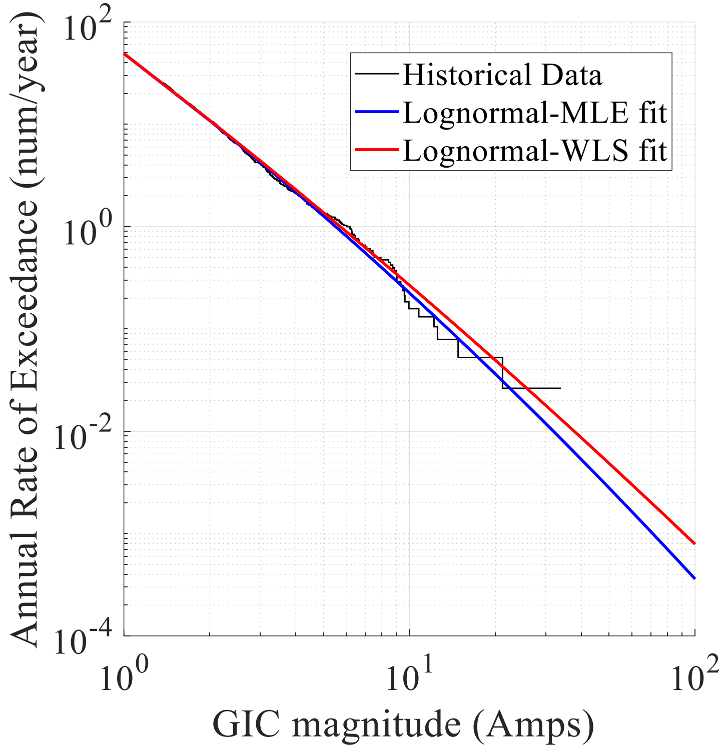


Fig 1: WLS and MLE Lognormal fits obtained to determined 100-year GIC

Ongoing Work

- Improved geomagnetic field Scaling: Currently the historic geomagnetic field time series scaling is based only on the 1-min difference. But the 100-year 10-min ramp change R and 10-min RMS of change S can also be included in scaling the B-field to further improve the scaling.
- Development of Benchmark GIC map that indicates 100-year GIC for all the transmission substations in Iowa, to identify network vulnerability.
- 100-year voltage drop and temperature rise assessment based on historic geomagnetic field data.

Questions?

Texas Magnetometer Network

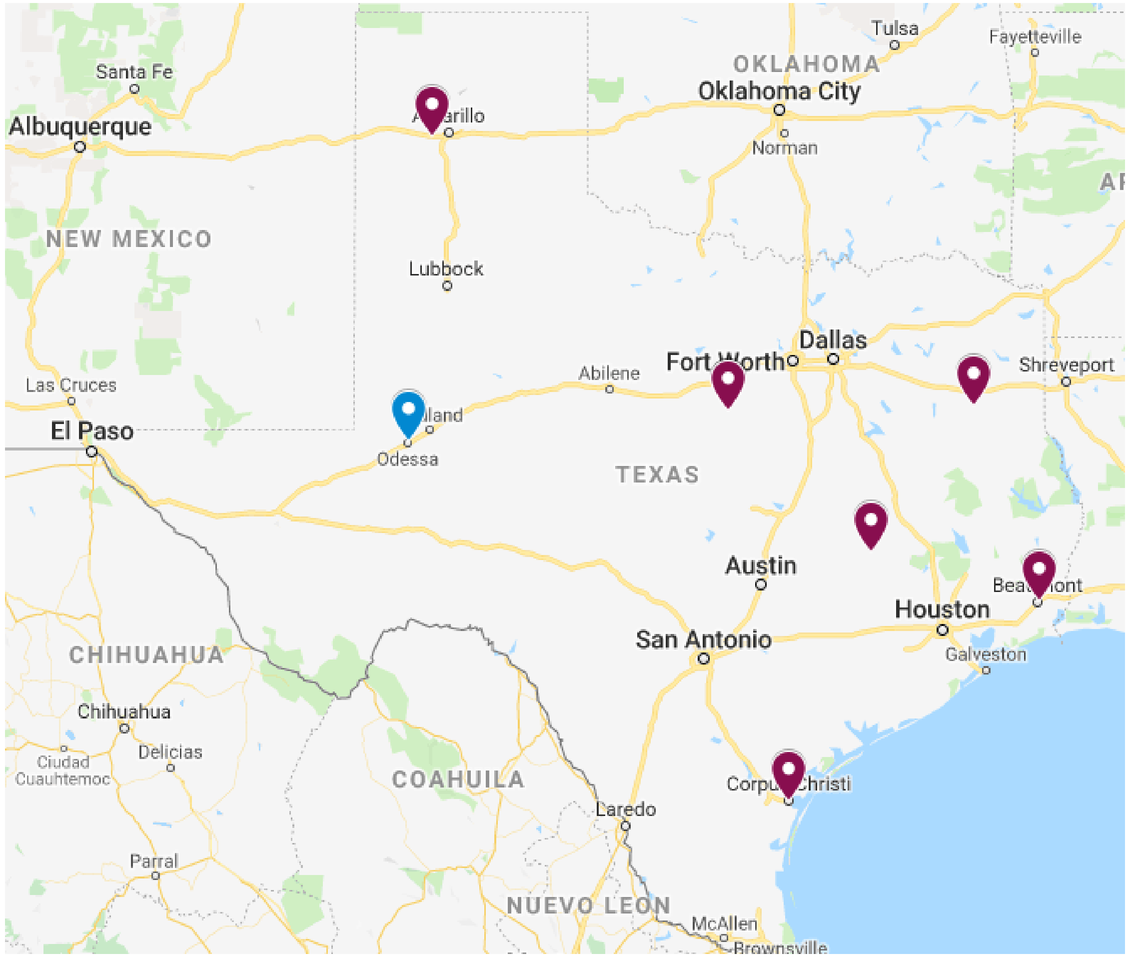
Komal Shetye
Research Engineer
Texas A&M University

NERC GMD Task Force Meeting
August 14th, 2019

shetye@tamu.edu

Texas Magnetometer Network

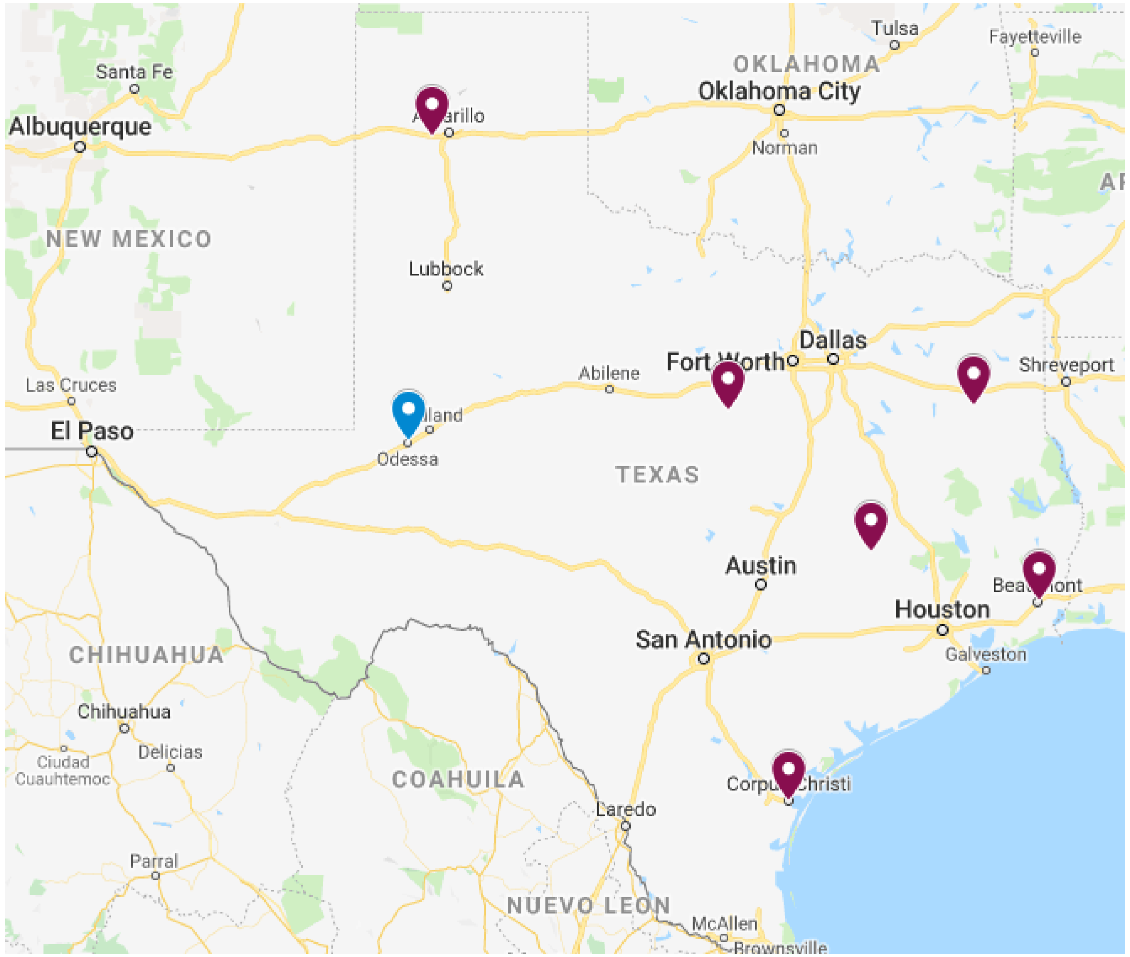
TEXAS A&M UNIVERSITY



- Six magnetometers being installed by Texas A&M and CPI (Jenn Gannon), funded by State of Texas
  - Built off of our NSF project (Hazards SEES Award #1520864) design which deployed six mags throughout US, including one in West TX
- Locations
  - Texas A&M AgriLife Research (five sites)
  - RELLIS (near TAMU College Station)

Texas Magnetometer Network

TEXAS A&M UNIVERSITY



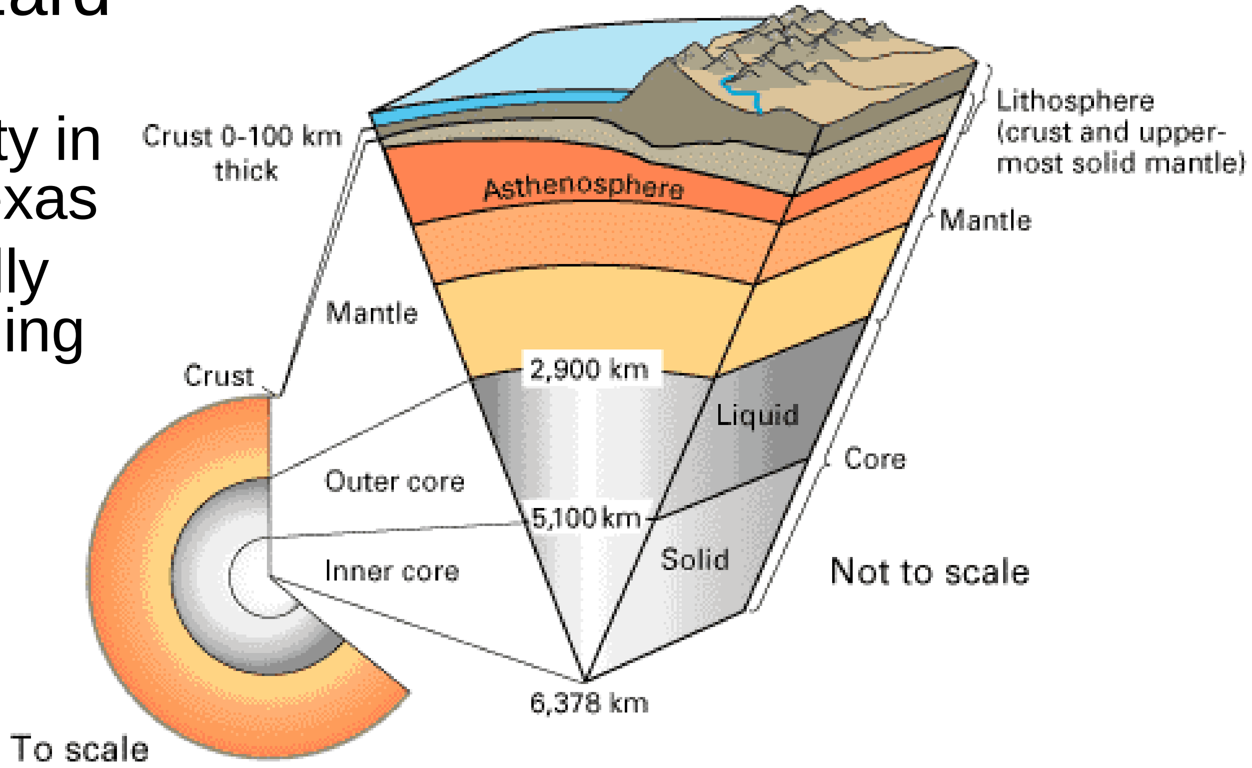
- Installation Schedule
  - In progress: Amarillo
  - Early September: College Station, Overton, Stephenville
  - TBD: Beaumont, Corpus Christi
- Consulted with utilities on locations; near GIC monitors
- Network will provide data in real-time directly to TAMU and utilities for GMD planning and operations

Motivating Factors

TEXAS A&M UNIVERSITY

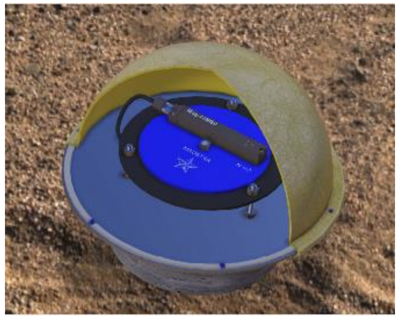
Improve understanding of Texas geophysics for GIC and EMP hazard analysis

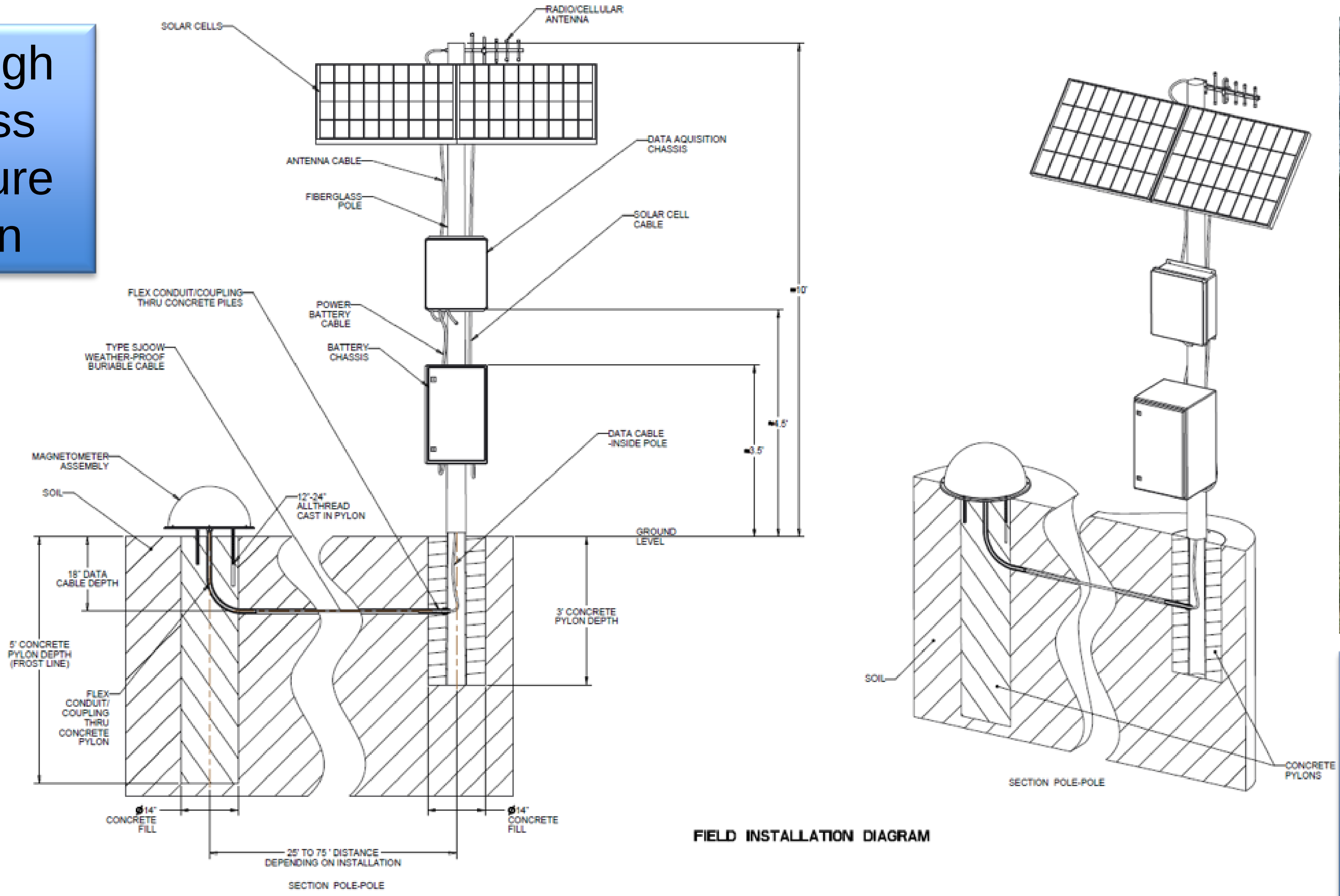
- There is a high degree of uncertainty in available conductivity models for Texas
- There are no models built specifically for Texas; this limits our understanding of how GIC and EMP hazard varies between locations
- Measurements and model improvements could realize immediate gains in GIC and EMP hazard analysis
- Multiple ways to achieve this goal



Magnetometer Setup

Connect through wireless access points for secure communication





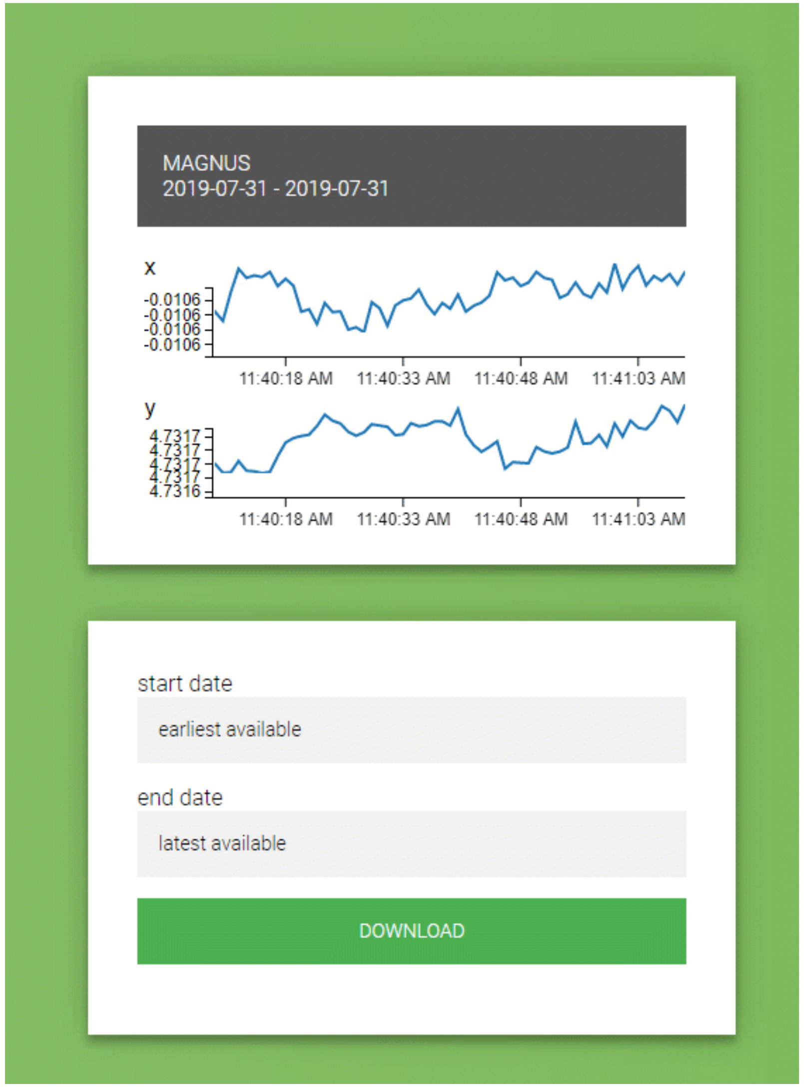
Autonomous operation (low power, solar panels)

Magnetometer Setup

Images: Jenn Gannon at Computational Physics Inc. (CPI)

Magnetometer Network Features

- Real-time data delivery (fraction of a second latency)
- Web-based data download in .csv format
- Real-time temperature correction
- Low-noise magnetic field measurements

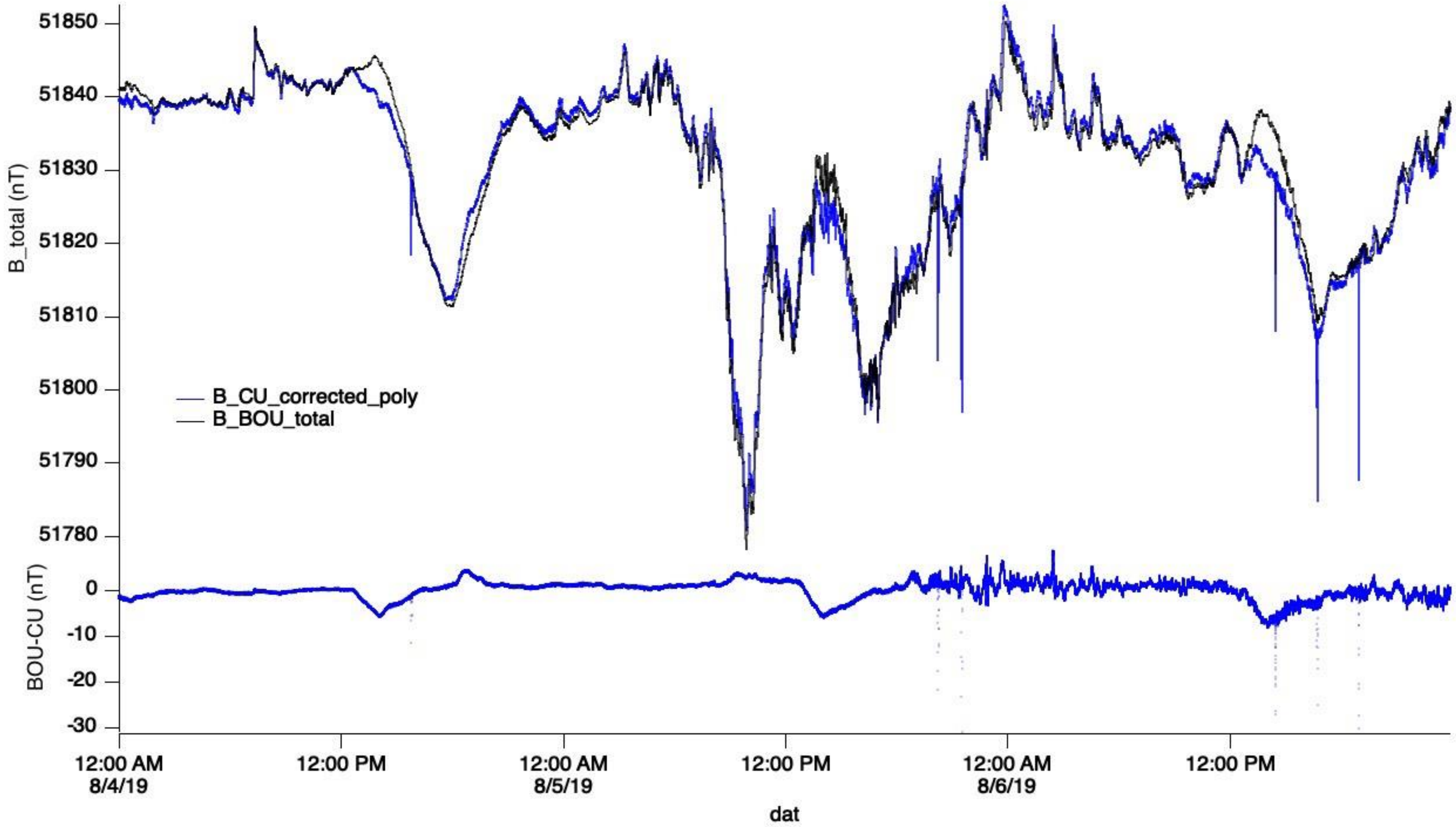


Note: Preliminary prototype of interface to access data

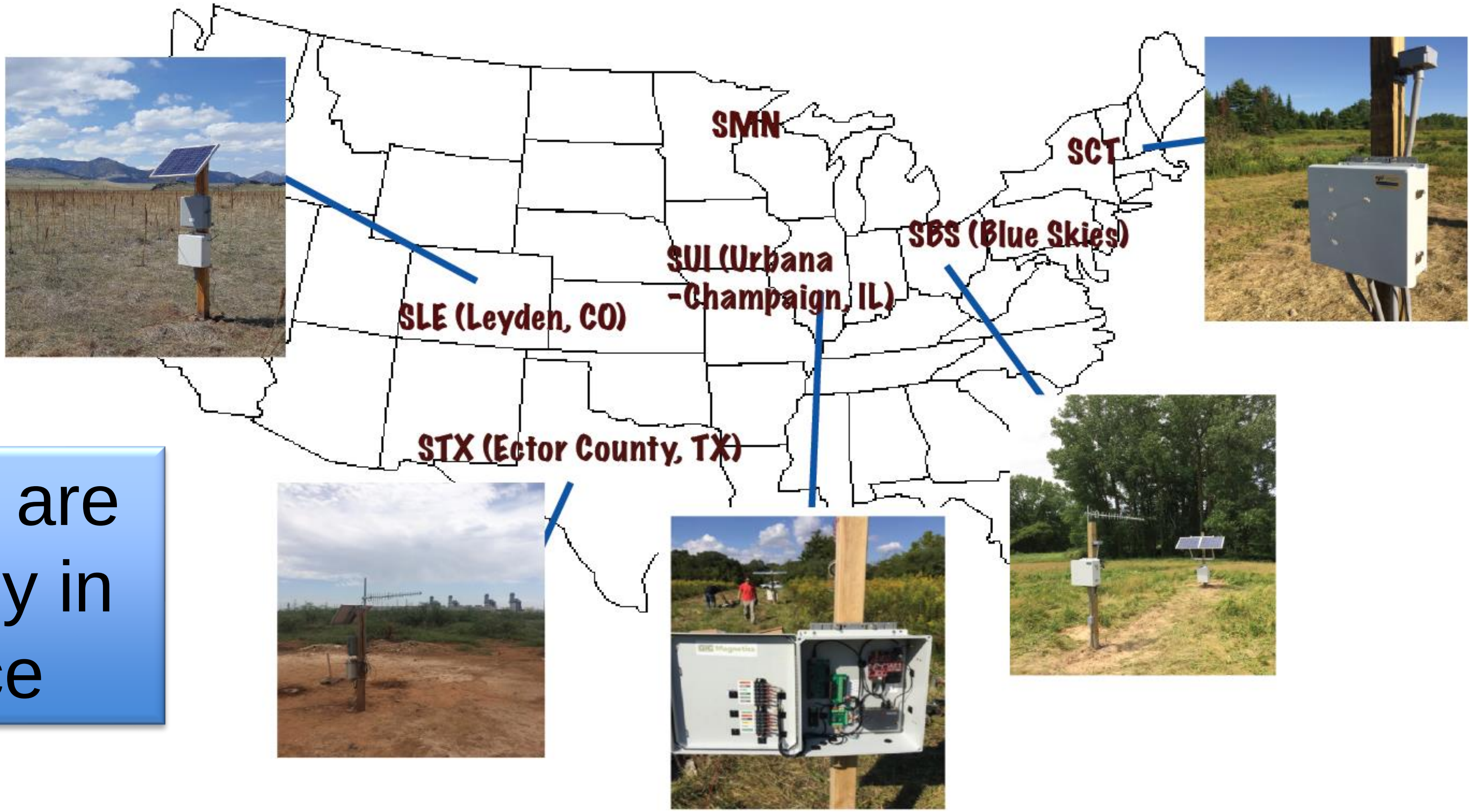
Courtesy: Jenn Gannon

Magnetometer Data Validation

- Test installation of TAMU equipment in CU Boulder
- Comparison with USGS BOU data
- Has been testing for three months, real time data transmission, 0% data loss over the wireless connection
- Data spikes from site work on the test install



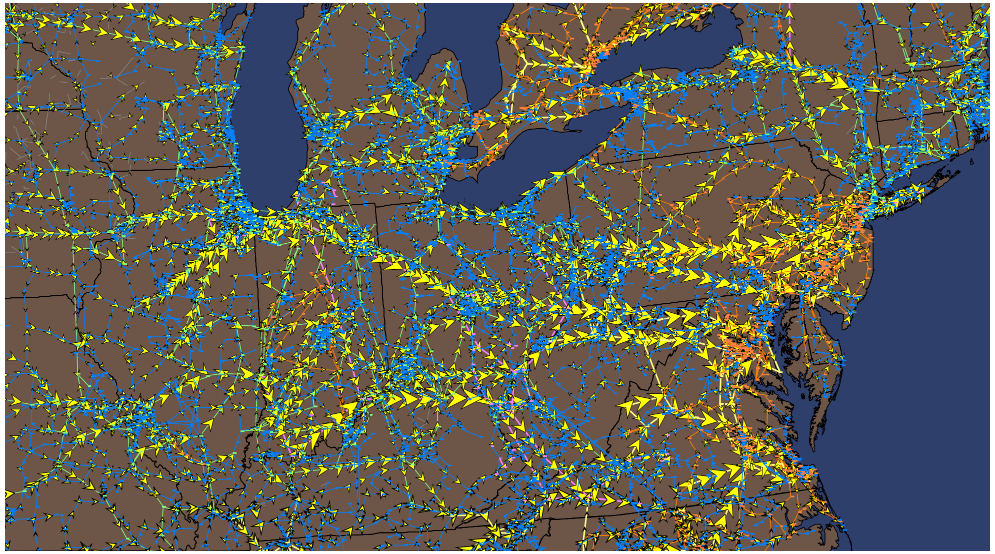
NSF Project Magnetometers (SHM)

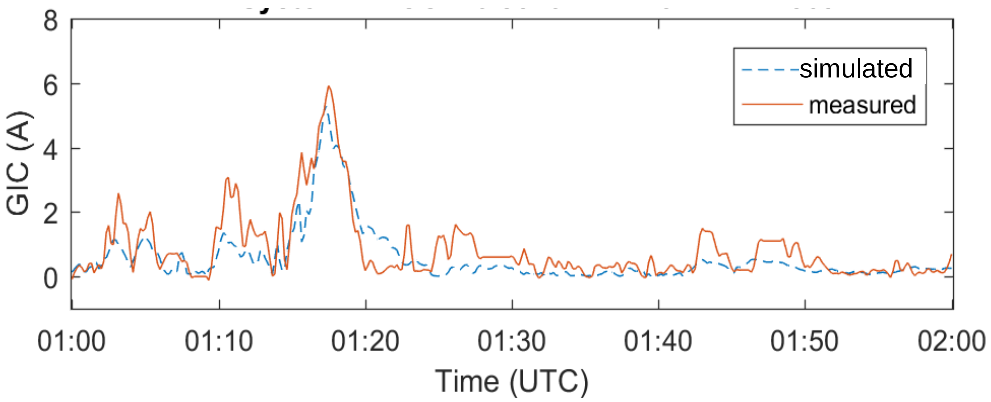


These are already in place

Moving Forward

- We plan to harness the data from the mags in Texas and the rest of the SHM network for our research and studies (12 mags in total)
- Collaboration
  - TPL-007 is requiring magnetic field (and GIC) monitoring; can work with utilities to provide magnetic field data
  - We can use GIC neutral data from utilities with this magnetic field data to develop transfer functions and validate GMD models
  - Sharing data for research





Other News – GMD Short Course

TEXAS A&M UNIVERSITY

- First offered in April 2019 at the brand new Smart Grids Control Center at RELLIS
- Next one will be held late January 2020, great weather to visit Texas!
- Details at https://epg.engr.tamu.edu/electric-grid-impacts-of-geomagnetic-disturbances/

Thank You!

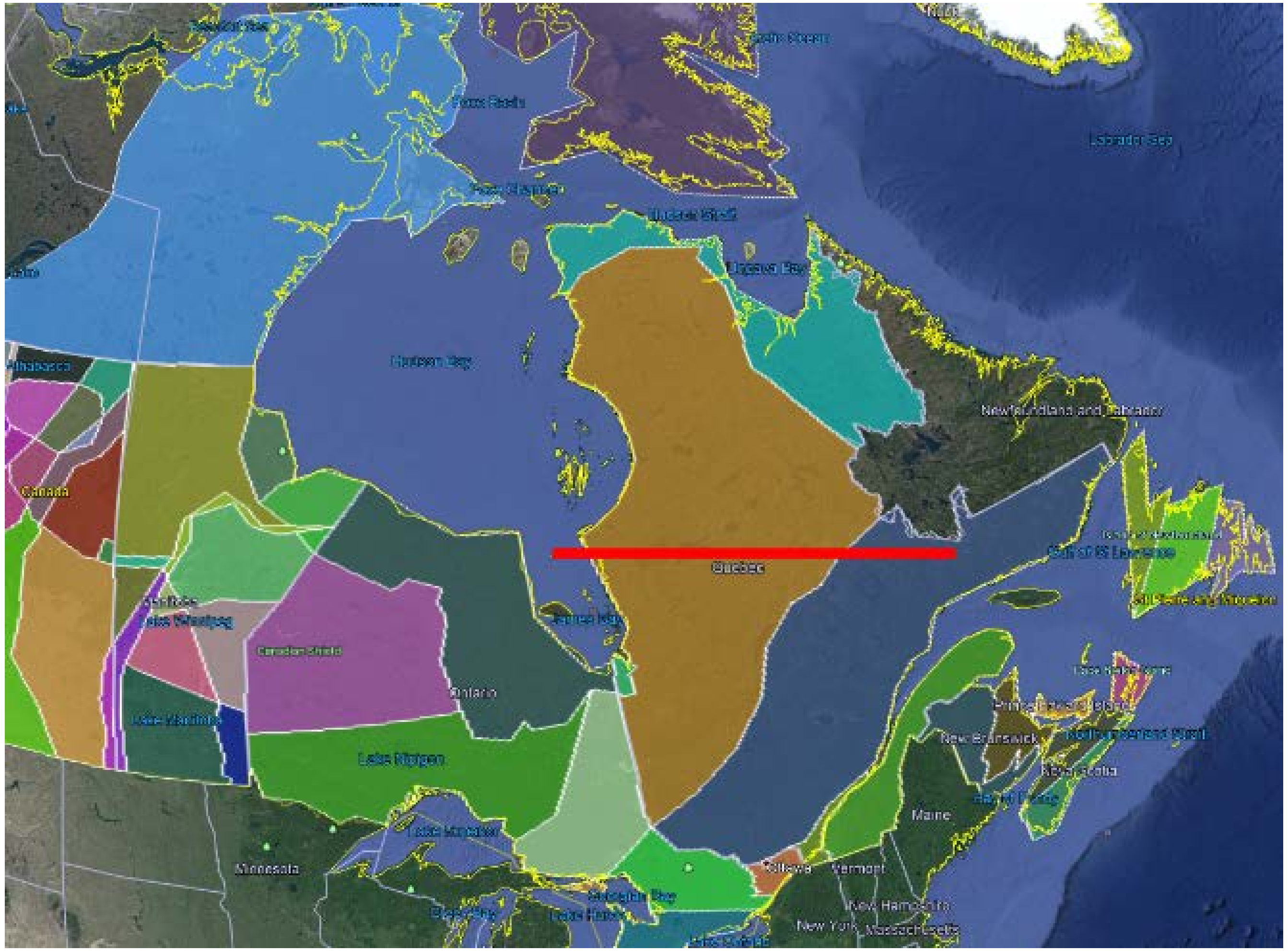
Amarillo Installation

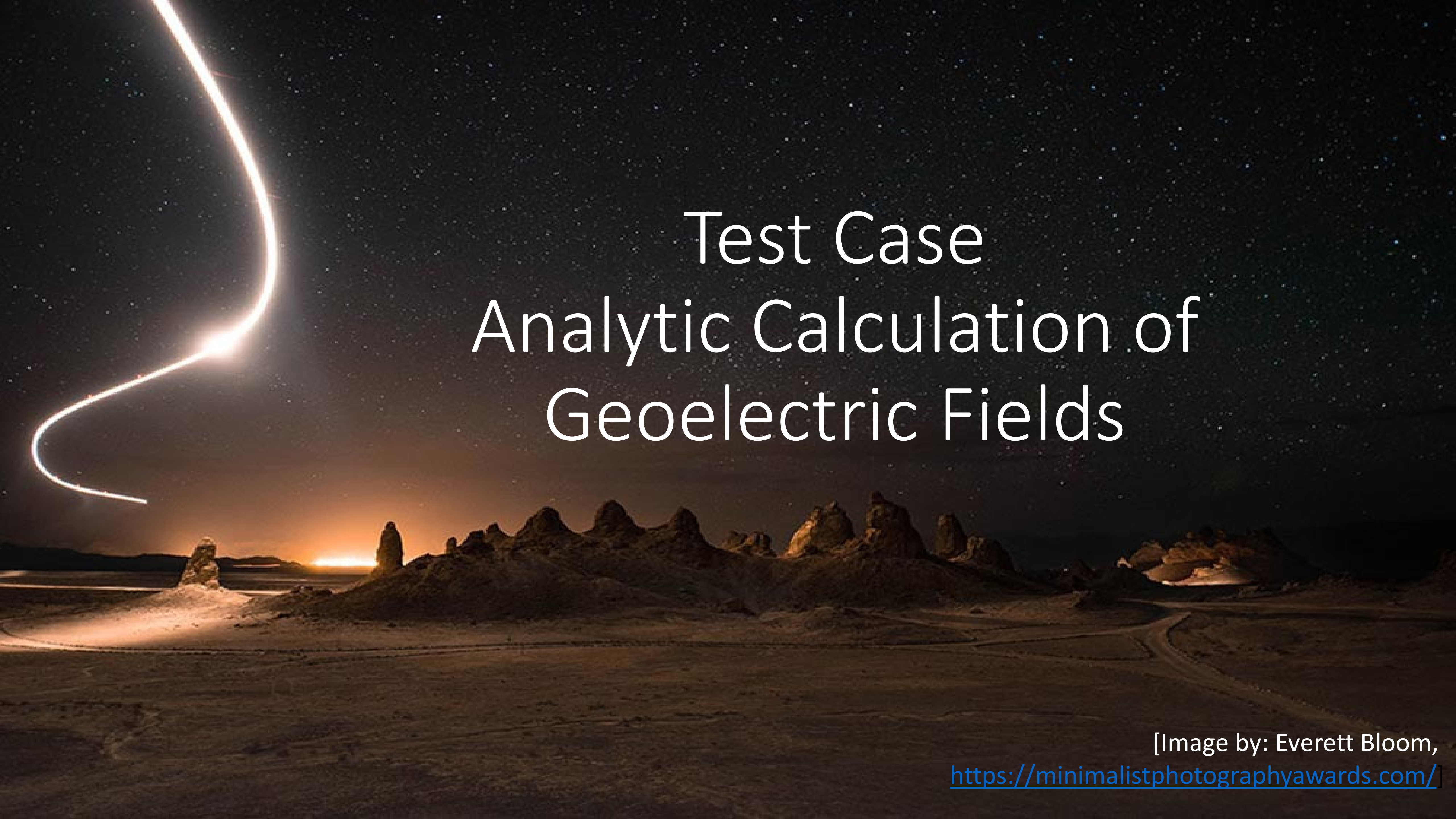
Picture from Yesterday!

shetye @tamu .edu

NRCan Update

- Analytic E Field Test Case
- Coast Effect
- GIC due to a Finite Electrojet





Test Case
Analytic Calculation of Geoelectric Fields

[Image by: Everett Bloom, https://minimalistphotographyawards.com/]

Testing E Field Calculations

- Generate a synthetic magnetic field data
- Determine Earth transfer function
  - Case 1: uniform conductivity model
  - Case 2: layered conductivity model
- Analytic calculation of electric fields
- Generate electric field data set

Synthetic Magnetic Field Data

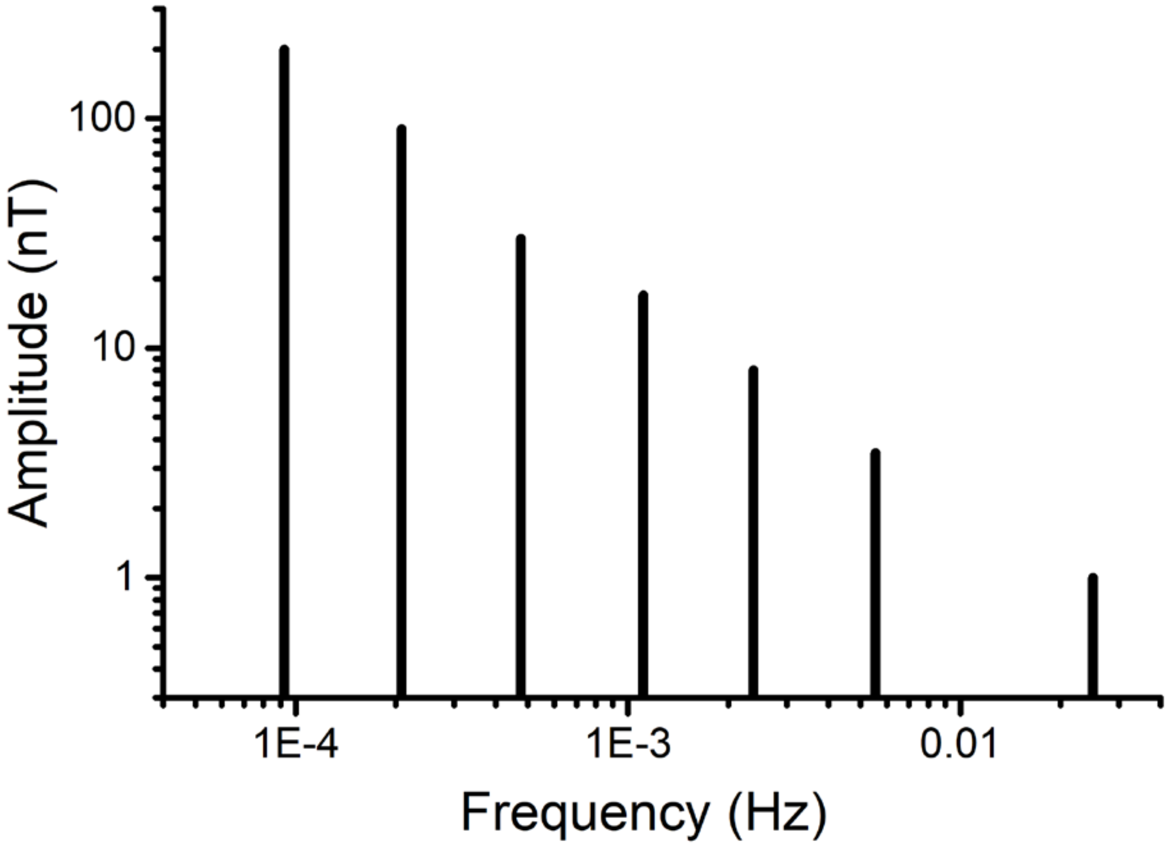


Table 1. Parameters of synthetic test magnetic field variation.

m	A_m (nT)	Φ_m (deg)	f_m (Hz)	$T_m = 1/f_m$ (min)
1	200	10	0.00009259	180
2	90	20	0.00020833	80
3	30	30	0.00047619	35
4	17	40	0.00111111	15
5	8	50	0.00238095	7
6	3,5	60	0.00555555	3
7	1	70	0.025	2/3

Earth Transfer Function

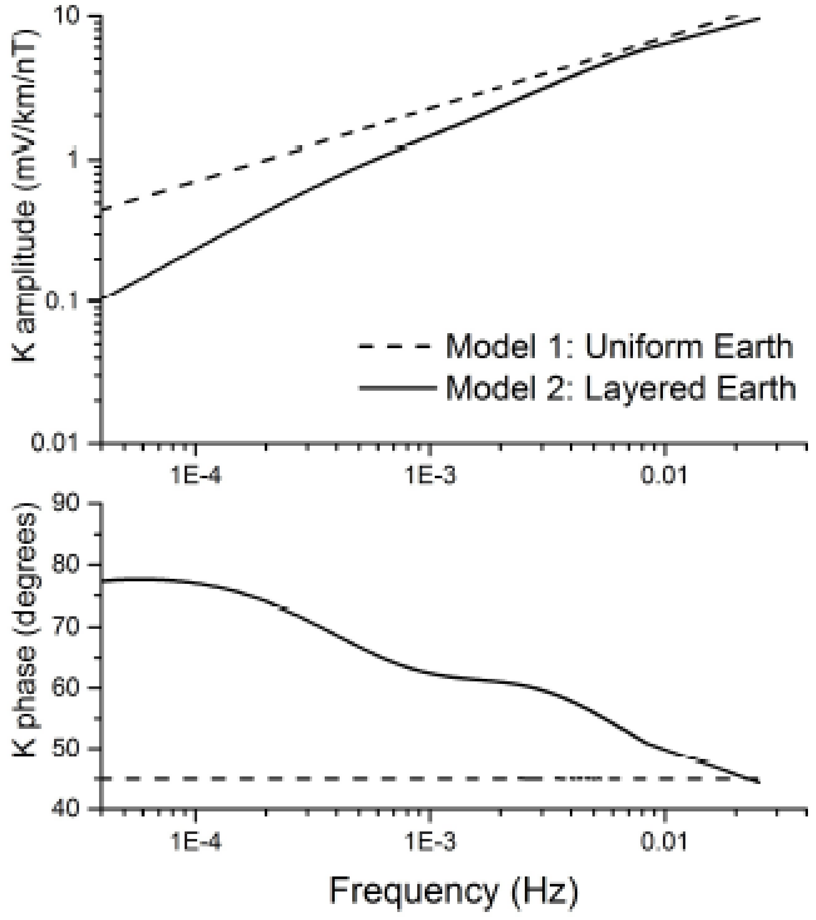


FIGURE. 2. Amplitude and phase of the transfer function *K*(*f*) for a 1000 Ωm uniform Earth (dashed lines) and for a multi-layer Earth (5-layer Québec model) (solid lines).

TABLE 2.
Transfer function *K*(*f*) for the frequencies in the synthetic test magnetic field variation for a 1000 Ωm uniform Earth.

m	f_m (Hz)	Amplitude $\lvert K_m \rvert$ (mV/km/nT)	Phase, θ_m (deg)
1	0.000093	0.6804	45.00
2	0.000208	1.0206	45.00
3	0.000476	1.5430	45.00
4	0.001111	2.3570	45.00
5	0.002381	3.4503	45.00
6	0.005556	5.2705	45.00
7	0.025	11.1803	45.00

TABLE 3.
Transfer function *K*(*f*) for the frequencies in the synthetic test magnetic field variation for a multi-layer Earth (5-layer Québec model).

m	f_m (Hz)	Amplitude, $\lvert K_m \rvert$ (mV/km/nT)	Phase, θ_m (deg)
1	0.000093	0.2188	77.15
2	0.000208	0.4480	73.76
3	0.000476	0.8681	67.17
4	0.001111	1.5392	62.08
5	0.002381	2.5935	60.58
6	0.005556	4.6625	54.97
7	0.025	9.6047	44.38

Analytic Electric Field (Uniform Model)

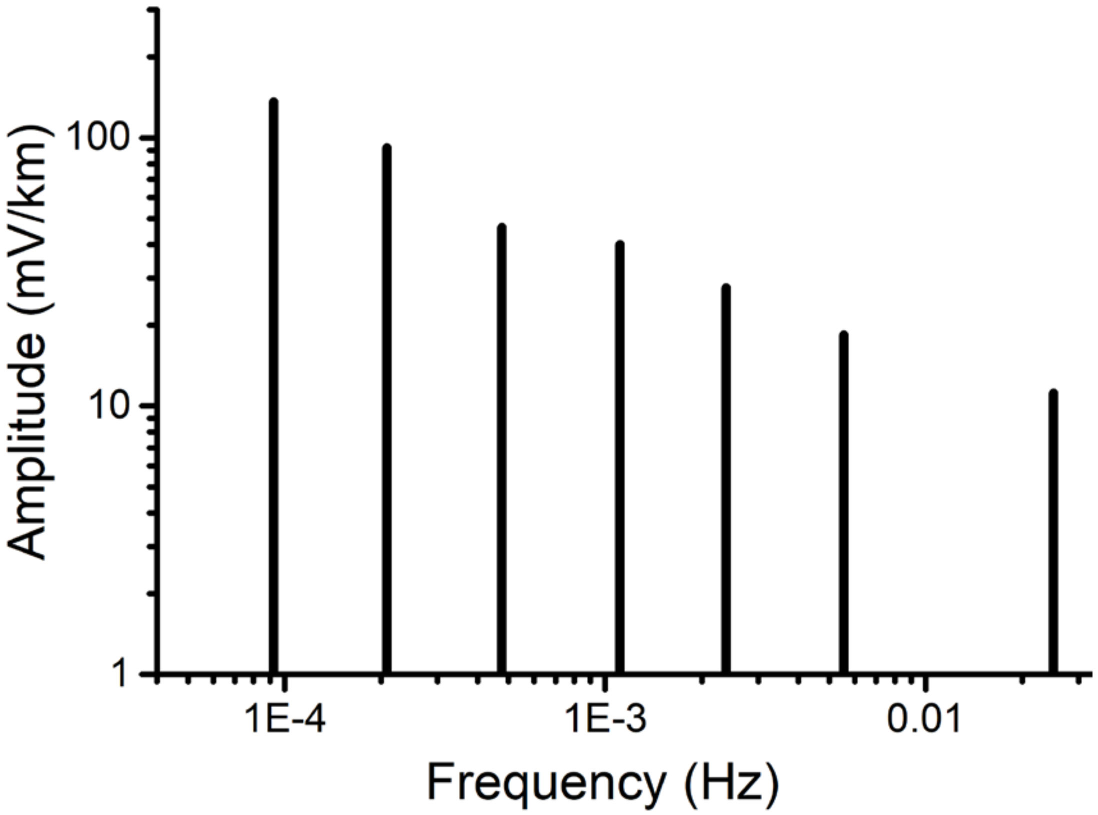


TABLE 6.
Parameters of electric field waveform for a 1000 Ωm uniform Earth.

m	f_m (Hz)	Amplitude, E_m (mV/km)	Phase, φ_m (deg)
1	0.000093	136.08276	55.00
2	0.000208	91.85587	65.00
3	0.000476	46.29100	75.00
4	0.001111	40.06938	85.00
5	0.002381	27.60262	95.00
6	0.005556	18.44662	105.00
7	0.025	11.18034	115.00

Analytic Electric Field (Layered Model)

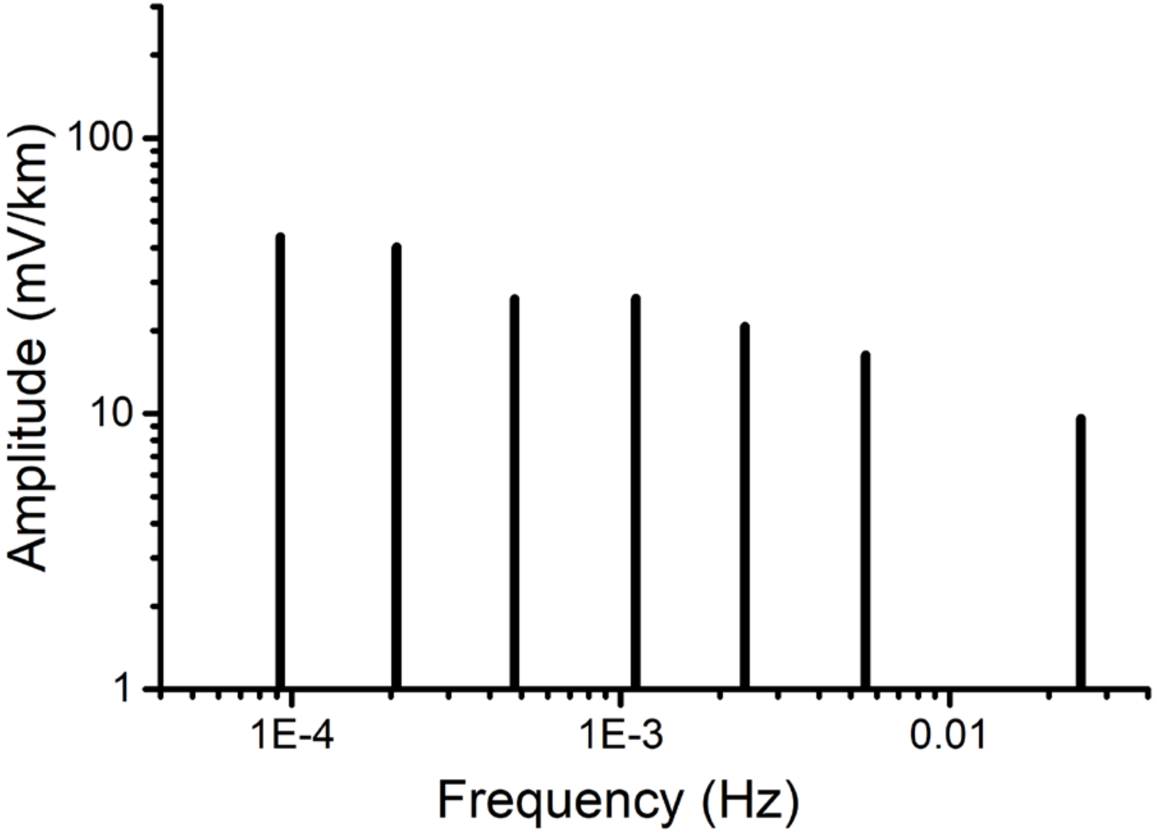
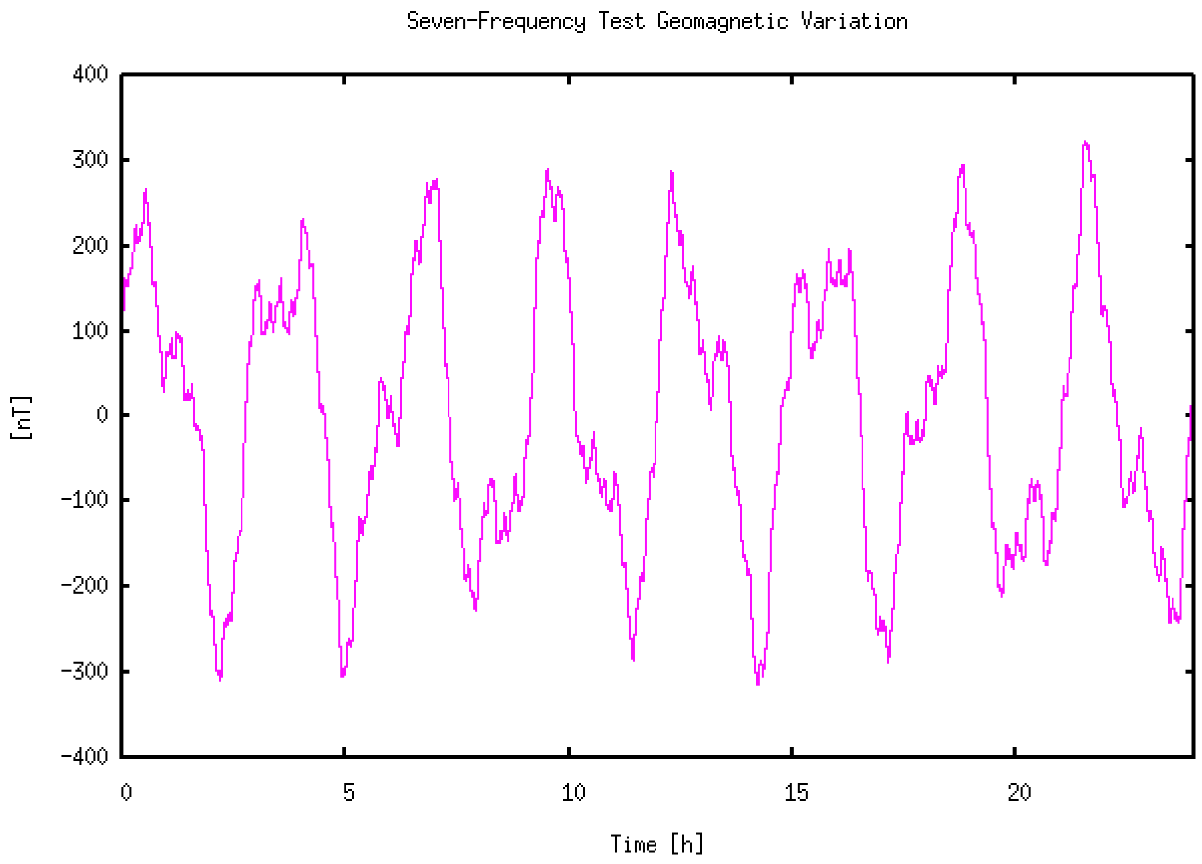
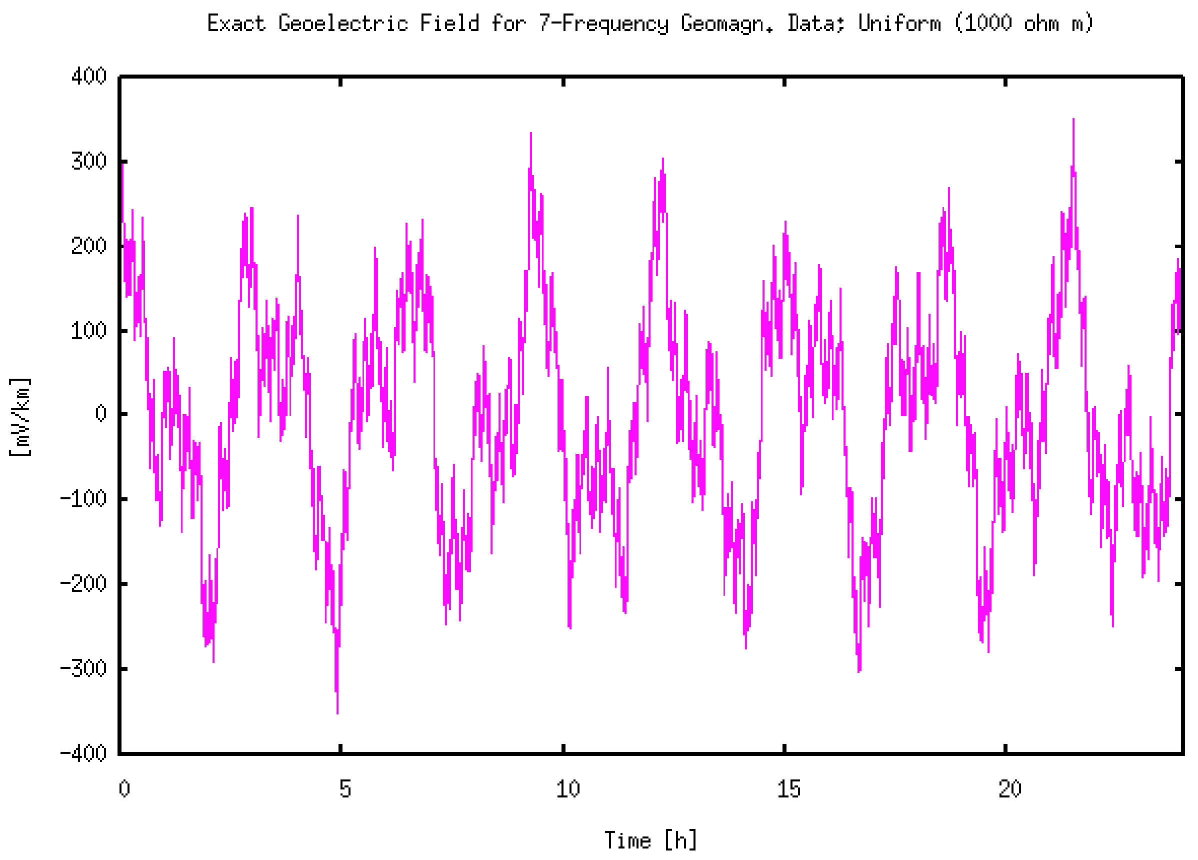


TABLE 7.
Parameters of electric field waveform for a multi-layer Earth (5-layer Québec model).

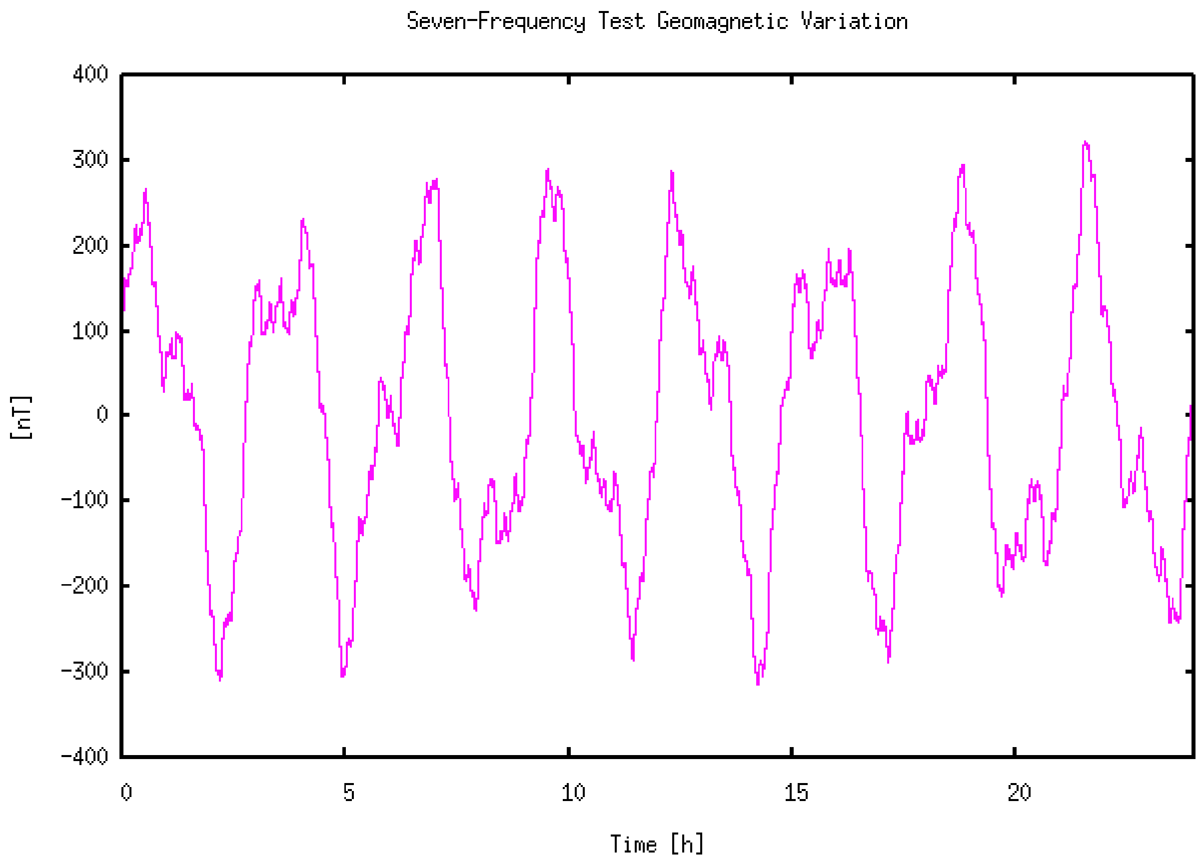
m	f_m (Hz)	Amplitude, E_m (mV/km)	Phase, φ_m (deg)
1	0.000093	43.76735	87.15
2	0.000208	40.32326	93.76
3	0.000476	26.04161	97.17
4	0.001111	26.16634	102.08
5	0.002381	20.74819	110.58
6	0.005556	16.31864	114.97
7	0.025	9.60469	114.38

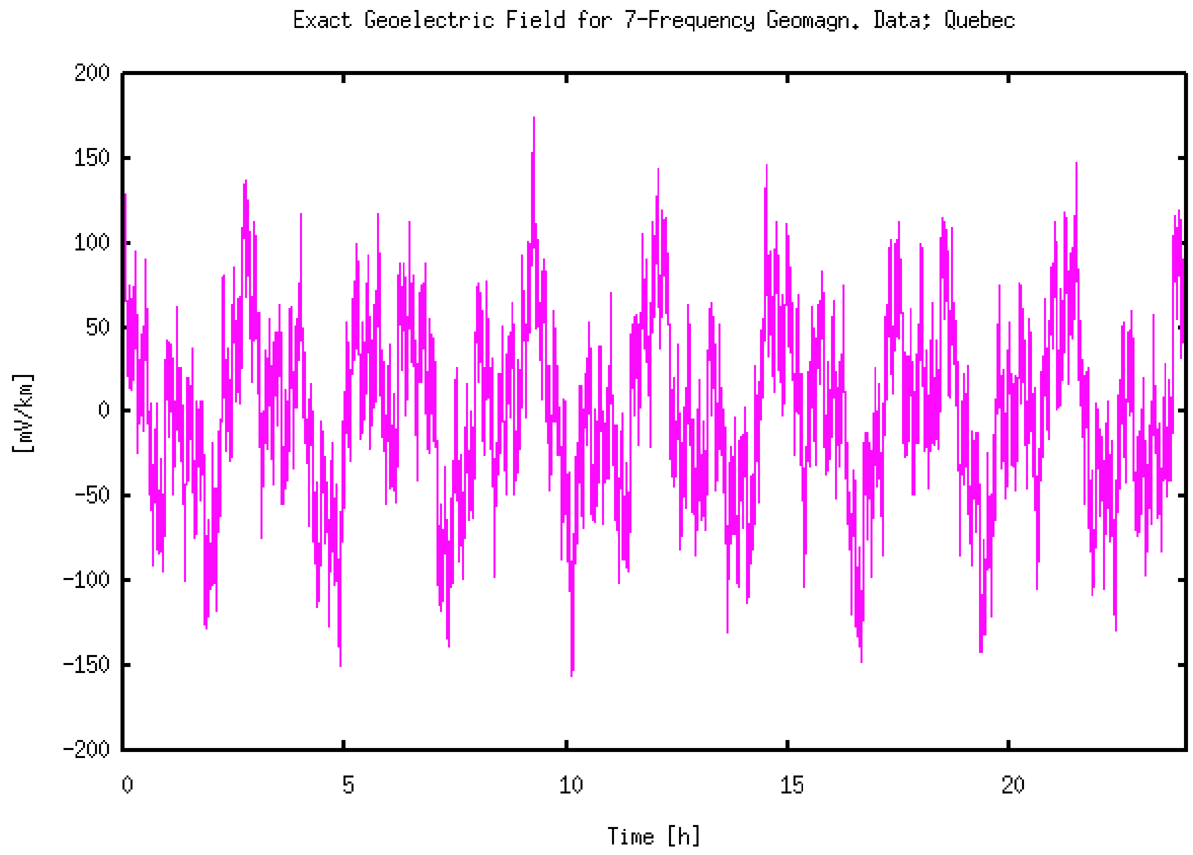
Test Datasets (Uniform Model)





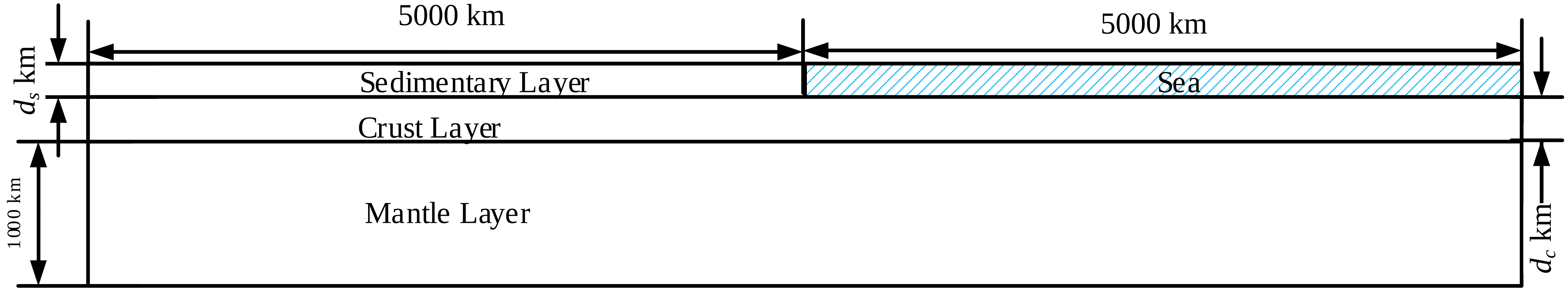
Test Datasets (Layered Model)



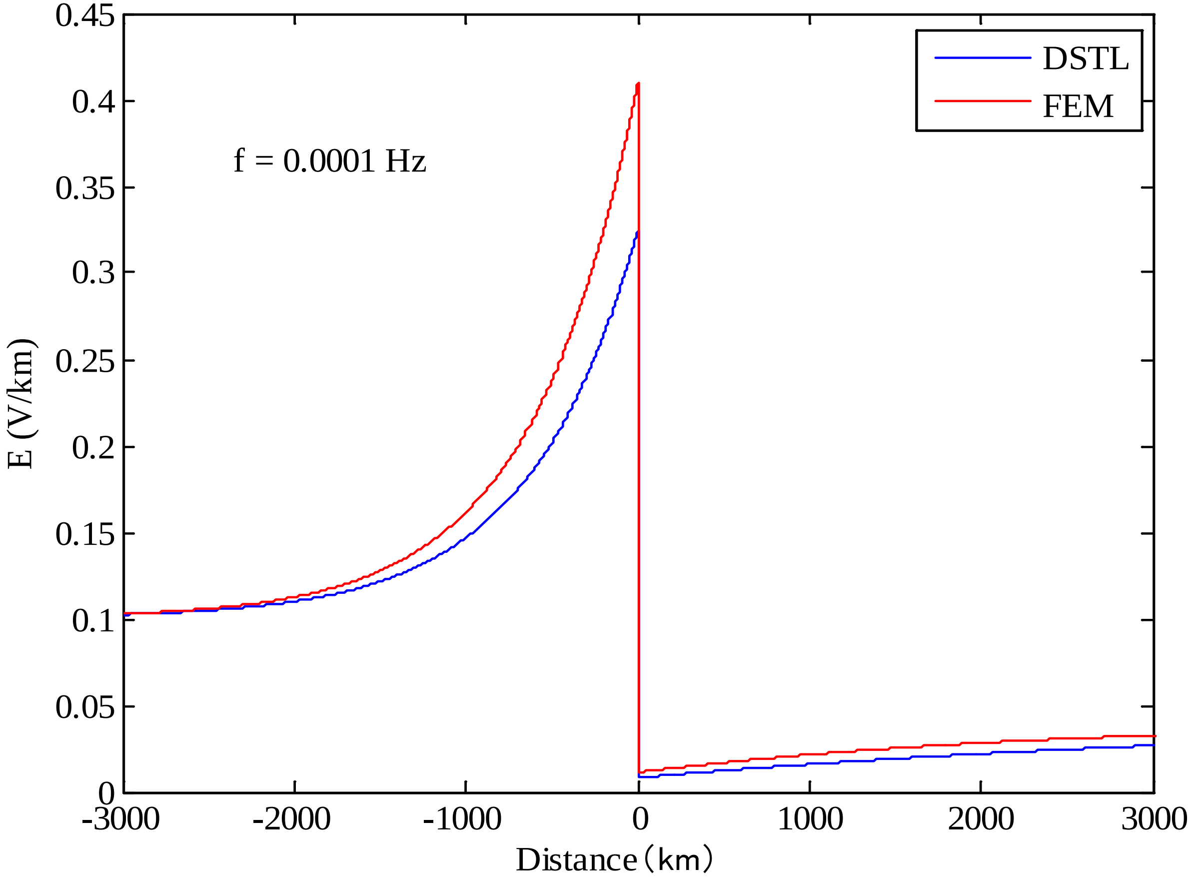


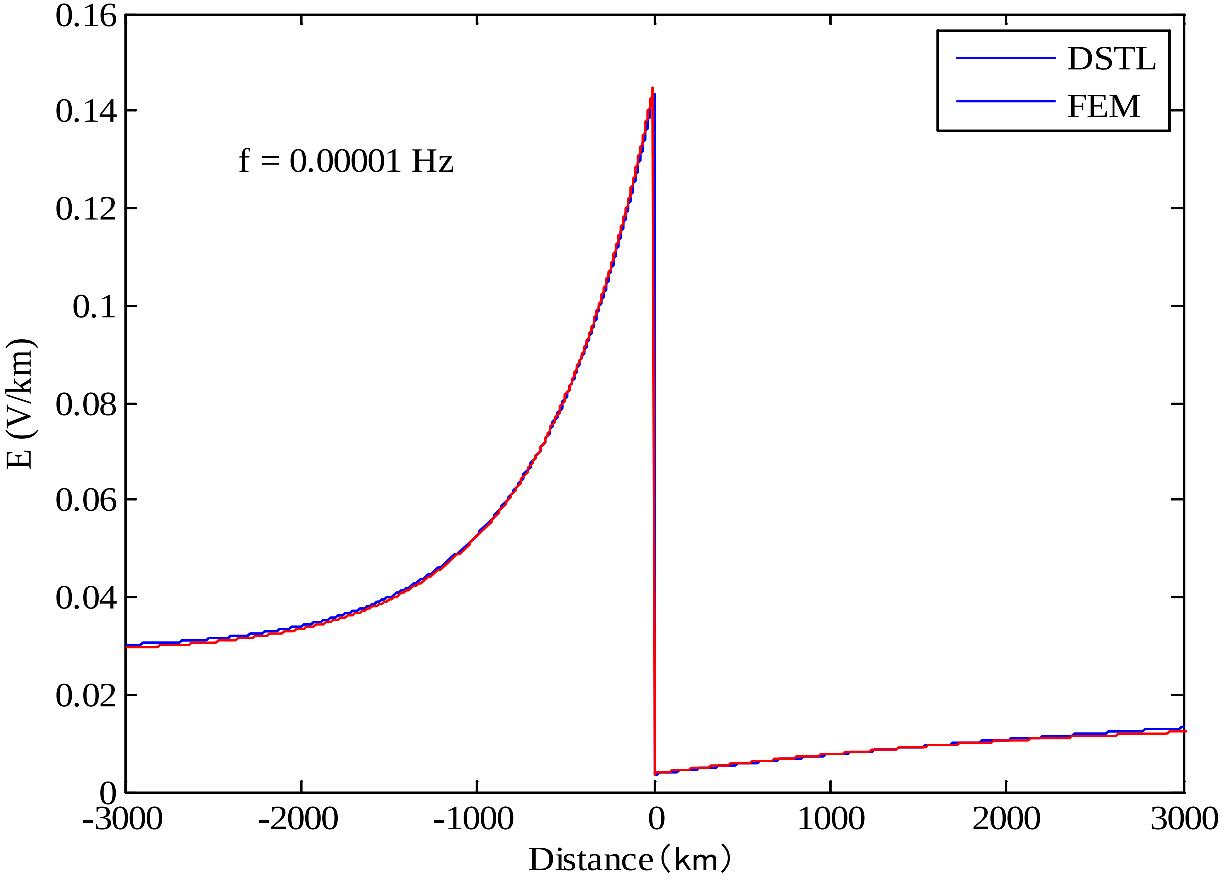
Coast Effect

Generalised Thin Sheet Model

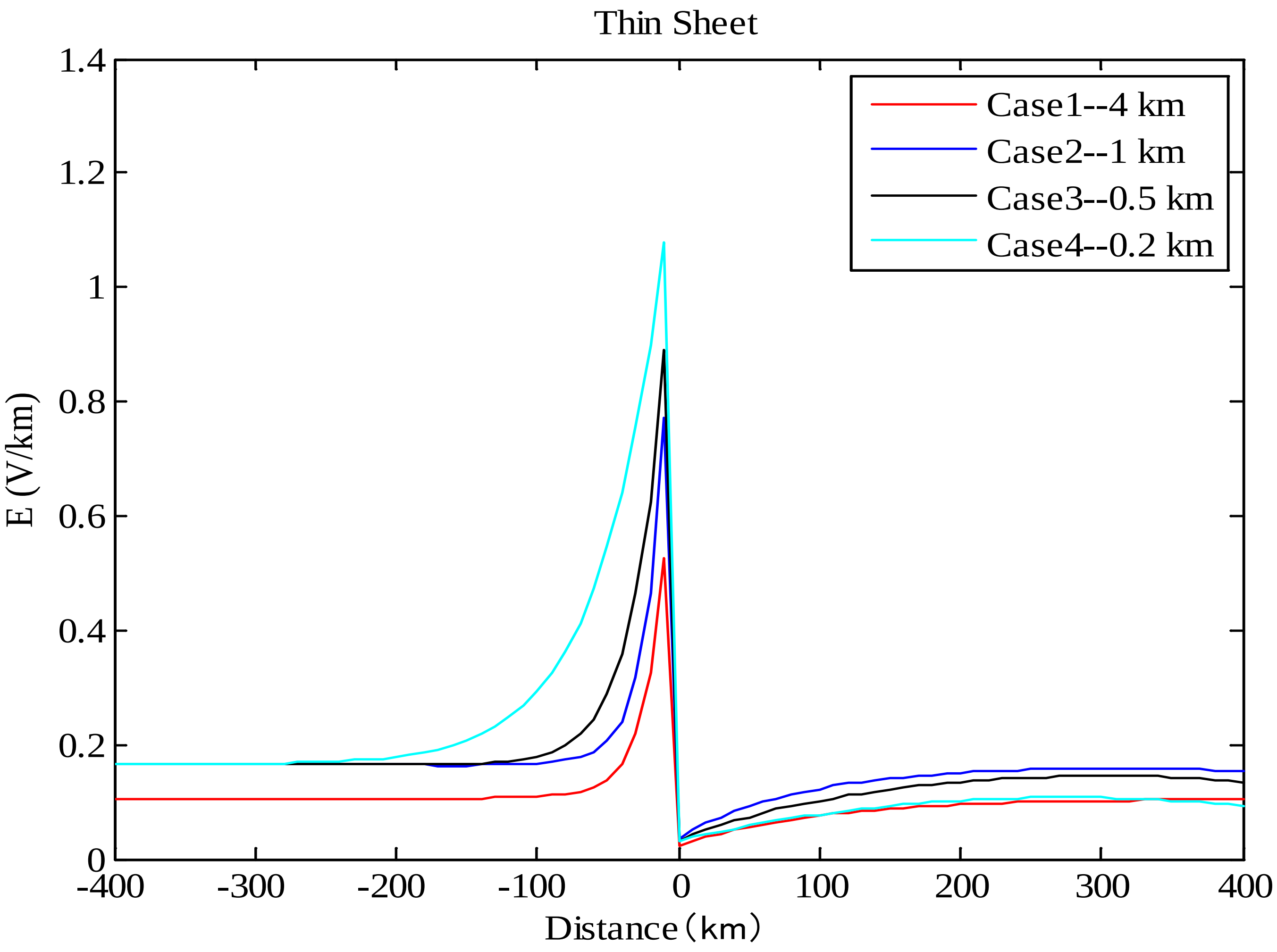


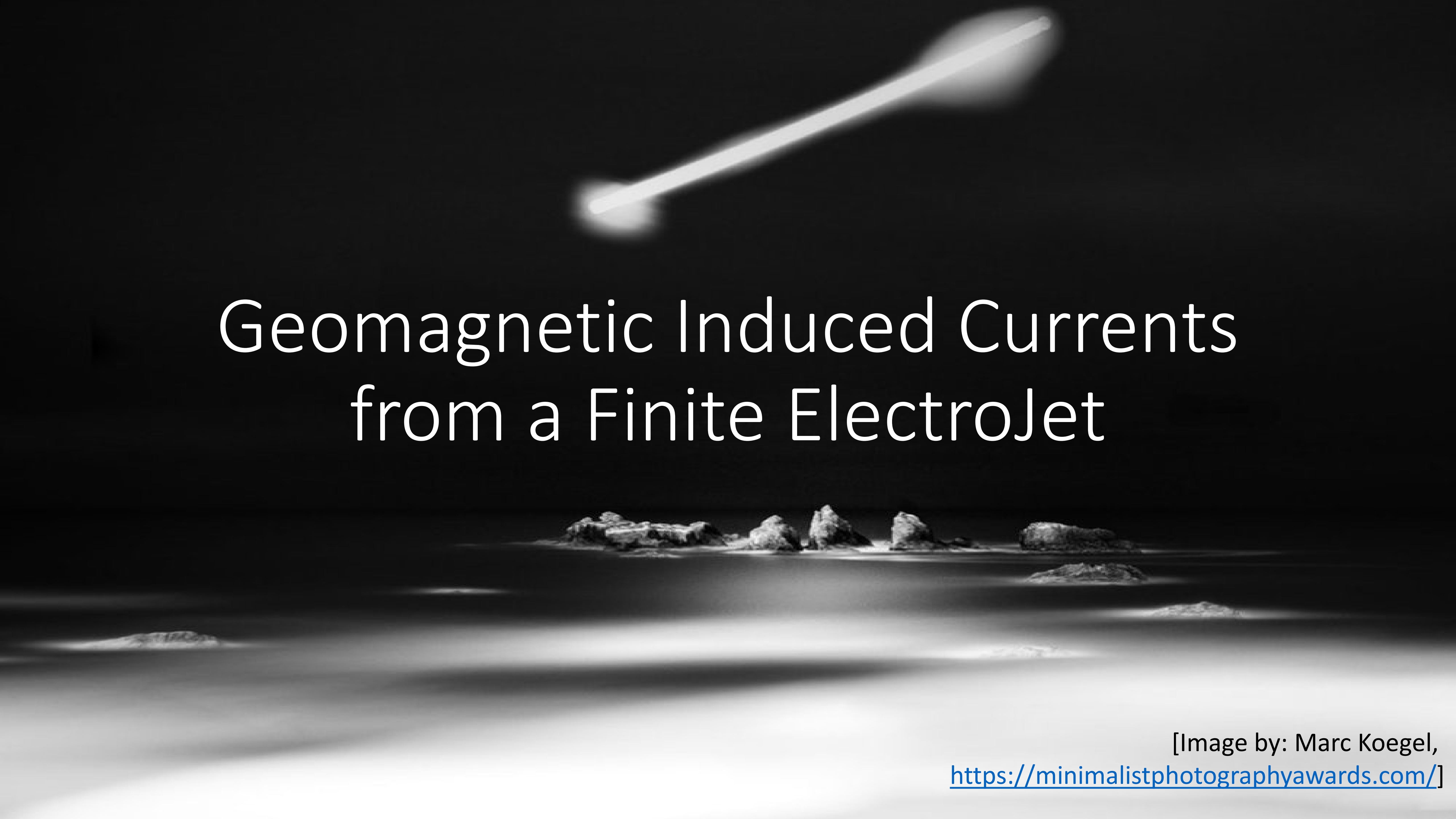
Comparison with FEM Results





Adjustment Distance

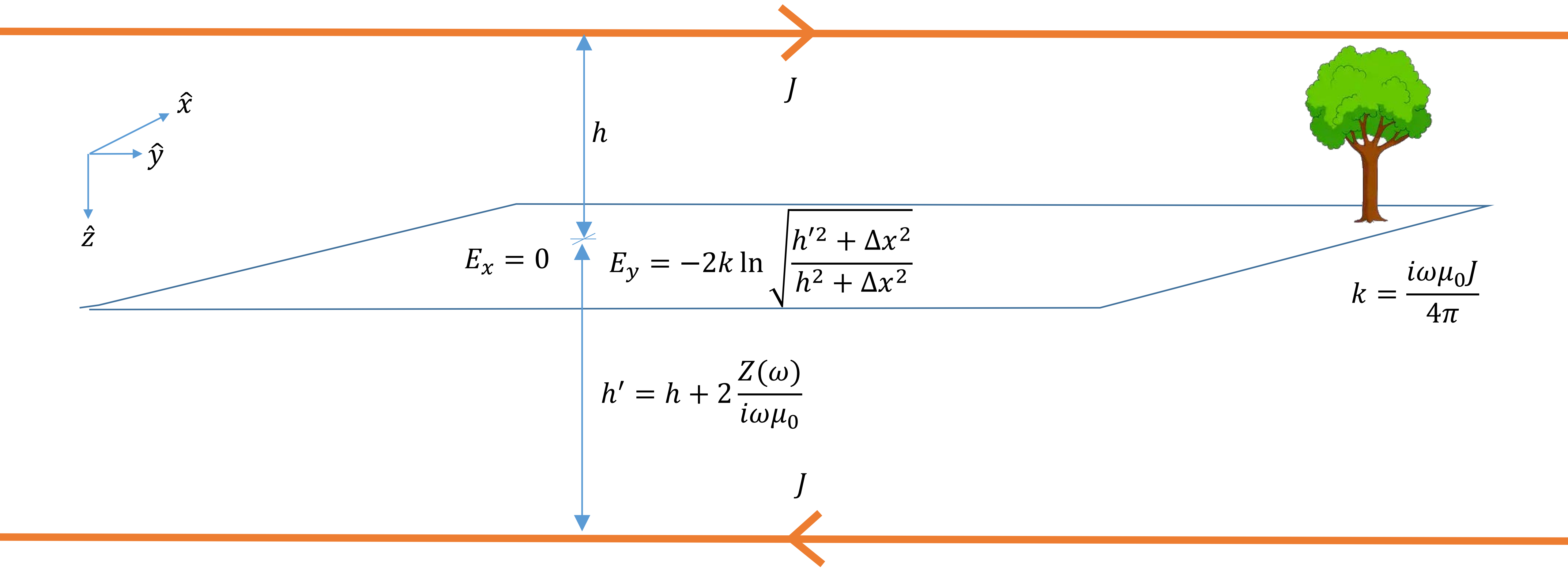




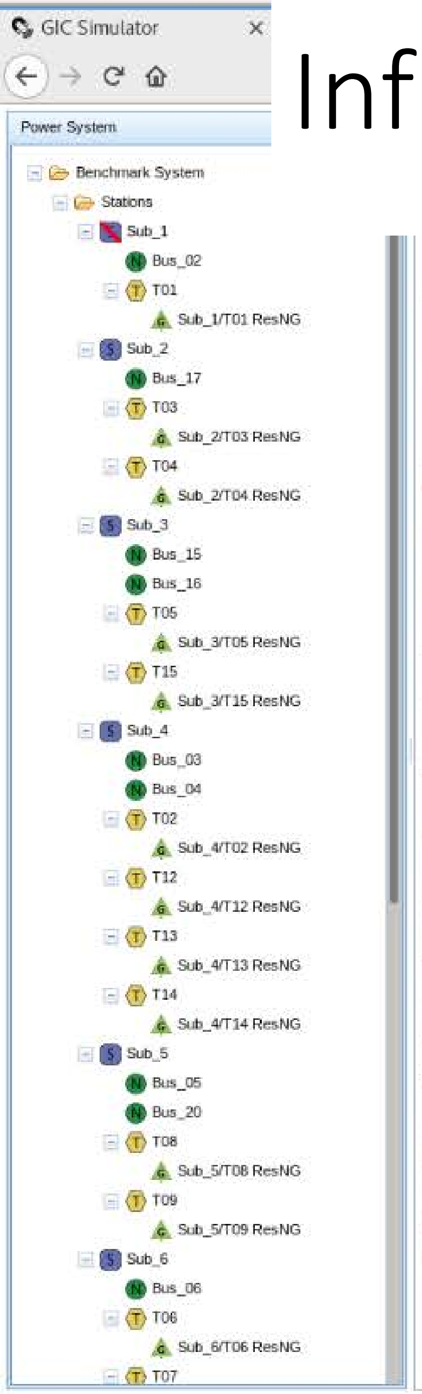
Geomagnetic Induced Currents from a Finite ElectroJet

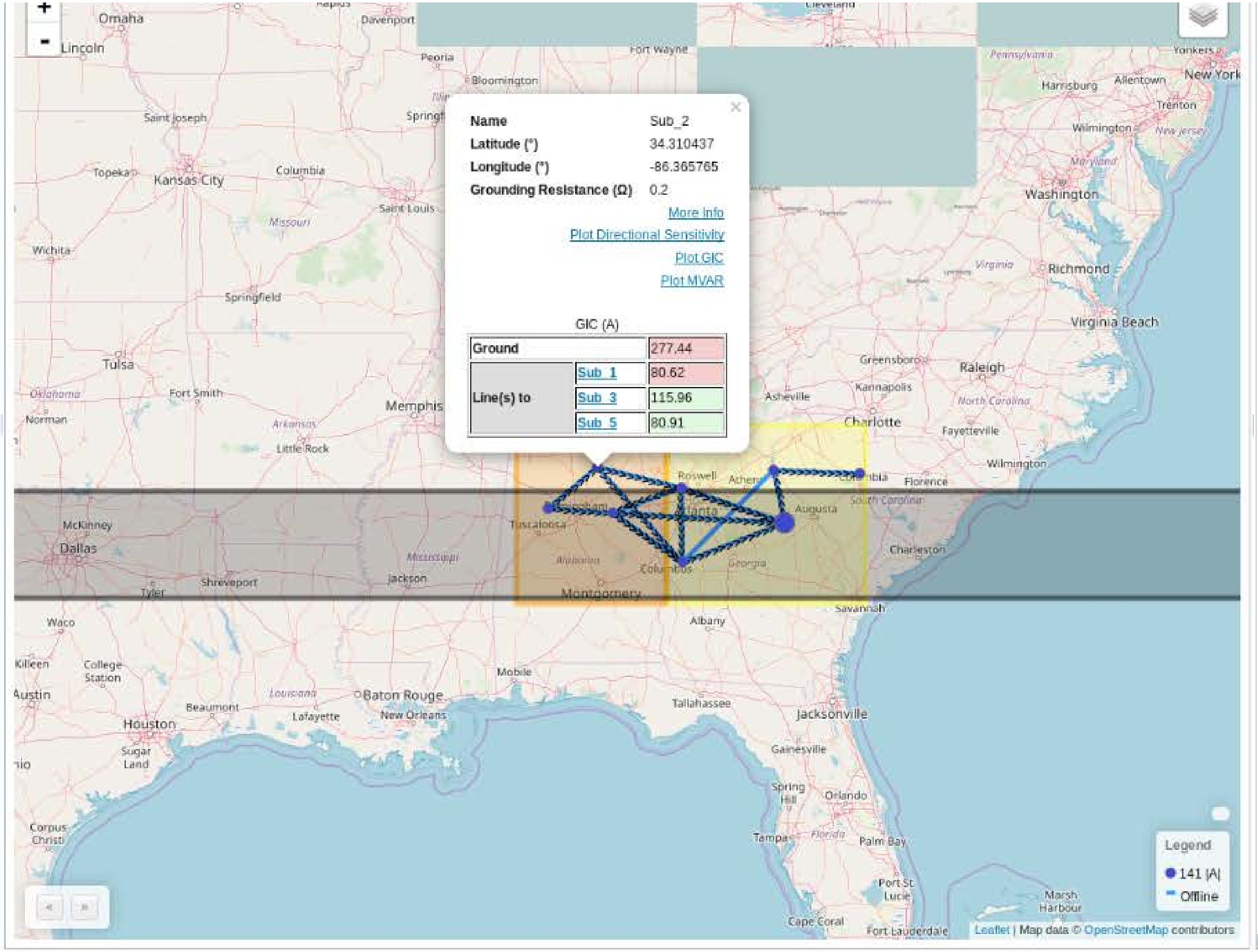
[Image by: Marc Koegel, https://minimalistphotographyawards.com/]

Infinite Electrojet Equations



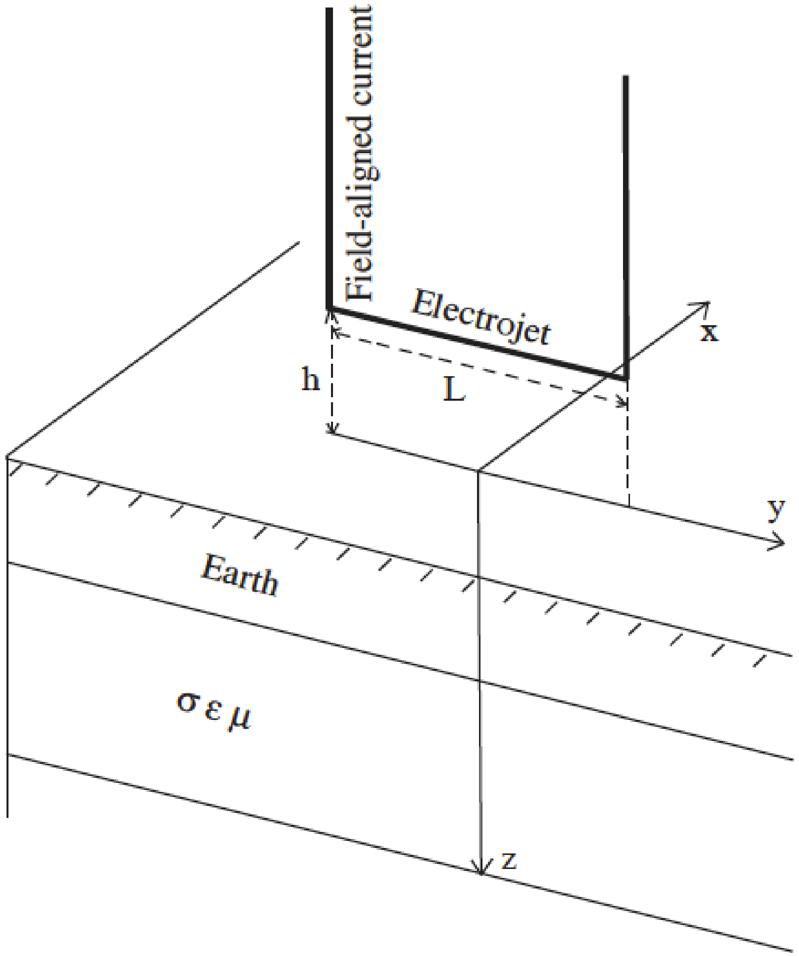
Infinite electrojet GICs in the benchmark system





Name	GIC into ground (A/Φ)	GIC into ground (A)	MVAR (VAR/Φ)	MVAR (VAR)
Sub_1	0.00, phase:0°	0.00, phase:0°	0.00, phase:0°	0.00, phase
Sub_2	277.44, phase:75°	832.32, phase:75°	138.72, phase:75°	416.16, phase:75°
Sub_3	175.42, phase:76°	526.26, phase:76°	150.44, phase:75°	451.32, phase:75°
Sub_4	192.58, phase:76°	577.73, phase:76°	702.82, phase:76°	2108.45, phase:76°
Sub_5	96.82, phase:75°	290.46, phase:75°	0.25, phase:-12°	0.74, phase:-12°
Sub_6	563.98, phase:-104°	1691.94, phase:-104°	281.99, phase:-104°	845.97, phase:-104°
Sub_7	0.00, phase:0°	0.00, phase:0°	0.00, phase:0°	0.00, phase
Sub_8	178.33, phase:-106°	535.00, phase:-106°	89.17, phase:-106°	267.50, phase:-106°

Electrojet Equivalence (Fukushima's Theorem)



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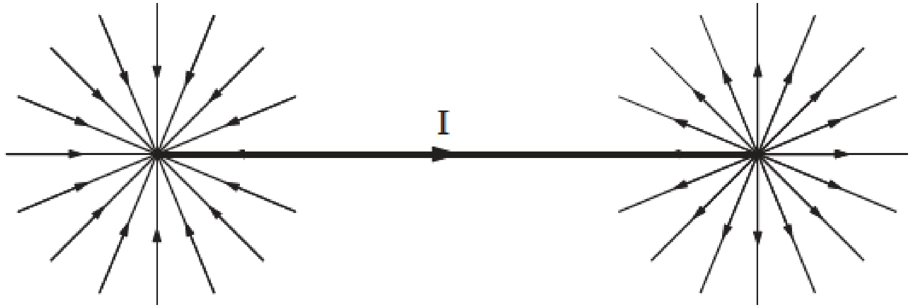


Finite Electrojet Equations

$$E_{x\downarrow} = k \frac{\Delta x}{\sqrt{(\Delta x)^2 + (\Delta y_0)^2 + h^2} + h}$$

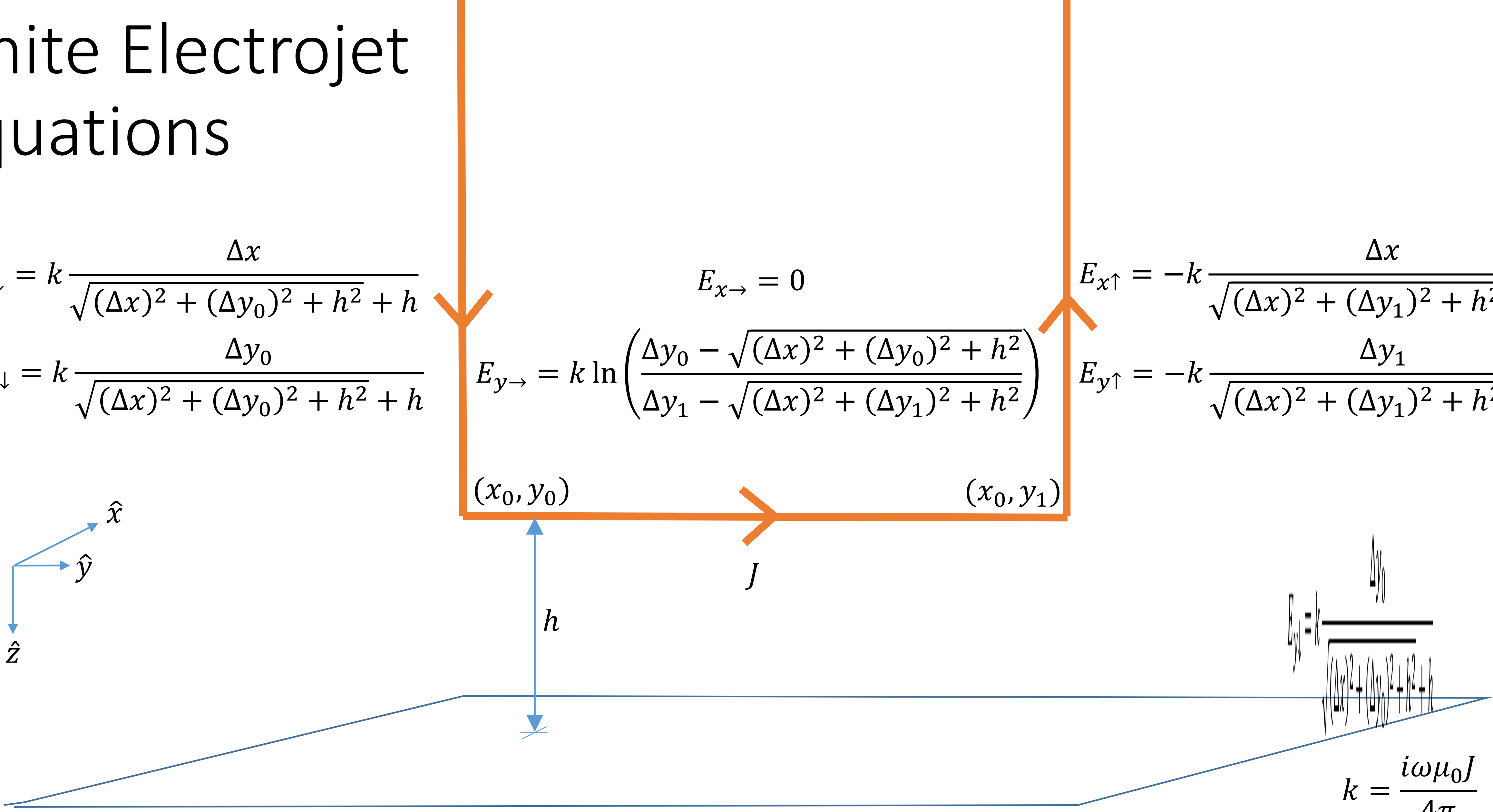
$$E_{y\downarrow} = k \frac{\Delta y_0}{\sqrt{(\Delta x)^2 + (\Delta y_0)^2 + h^2} + h}$$

$$E_{x\rightarrow} = 0$$

$$E_{y\rightarrow} = k \ln\left(\frac{\Delta y_0 - \sqrt{(\Delta x)^2 + (\Delta y_0)^2 + h^2}}{\Delta y_1 - \sqrt{(\Delta x)^2 + (\Delta y_1)^2 + h^2}}\right)$$

$$E_{x\uparrow} = -k \frac{\Delta x}{\sqrt{(\Delta x)^2 + (\Delta y_1)^2 + h^2} + h}$$

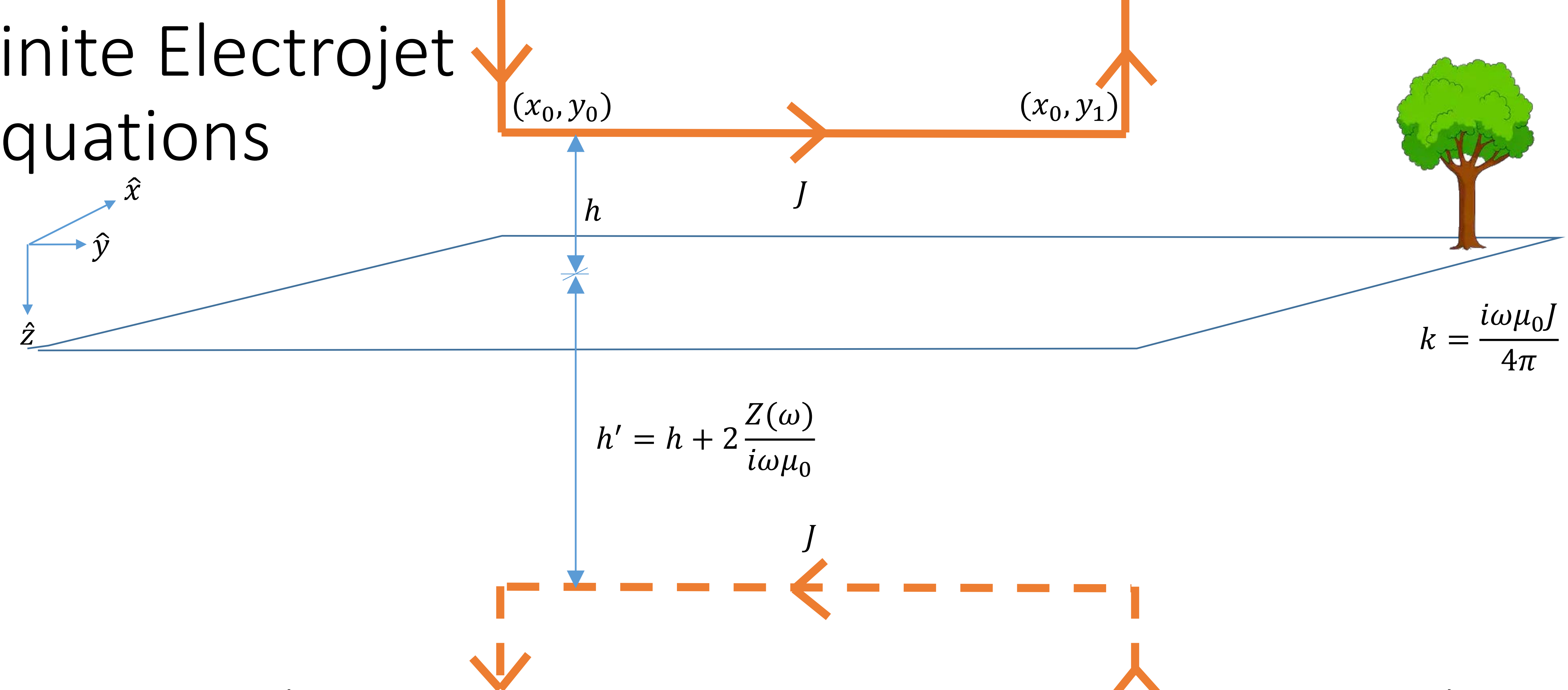
$$E_{y\uparrow} = -k \frac{\Delta y_1}{\sqrt{(\Delta x)^2 + (\Delta y_1)^2 + h^2} + h}$$



$$E_{y\downarrow} = k \frac{\Delta y_0}{\sqrt{(\Delta x)^2 + (\Delta y_0)^2 + h^2} + h}$$

$$k = \frac{i\omega\mu_0 J}{4\pi}$$

Finite Electrojet Equations



$$k = \frac{i\omega\mu_0 J}{4\pi}$$

$$h' = h + 2\frac{Z(\omega)}{i\omega\mu_0}$$

$$E_{x\uparrow} = -k\frac{\Delta x}{\sqrt{(\Delta x)^2 + (\Delta y_1)^2 + h'^2} + h'}$$

$$E_{y\uparrow} = -k\frac{\Delta y_1}{\sqrt{(\Delta x)^2 + (\Delta y_1)^2 + h'^2} + h'}$$

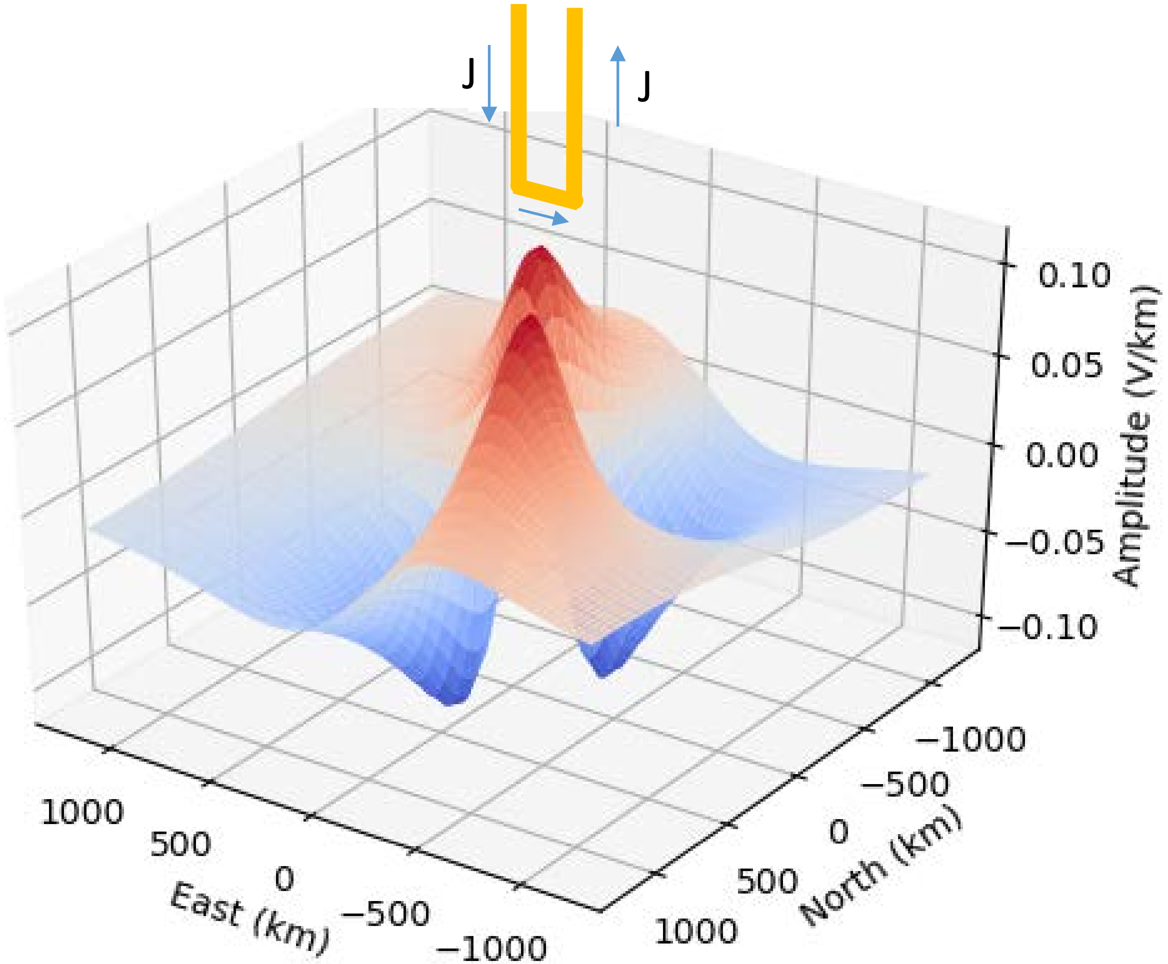
$$E_{x\rightarrow} = 0$$

$$E_{y\rightarrow} = -k\ln\left(\frac{\Delta y_0 - \sqrt{(\Delta x)^2 + (\Delta y_0)^2 + h'^2}}{\Delta y_1 - \sqrt{(\Delta x)^2 + (\Delta y_1)^2 + h'^2}}\right)$$

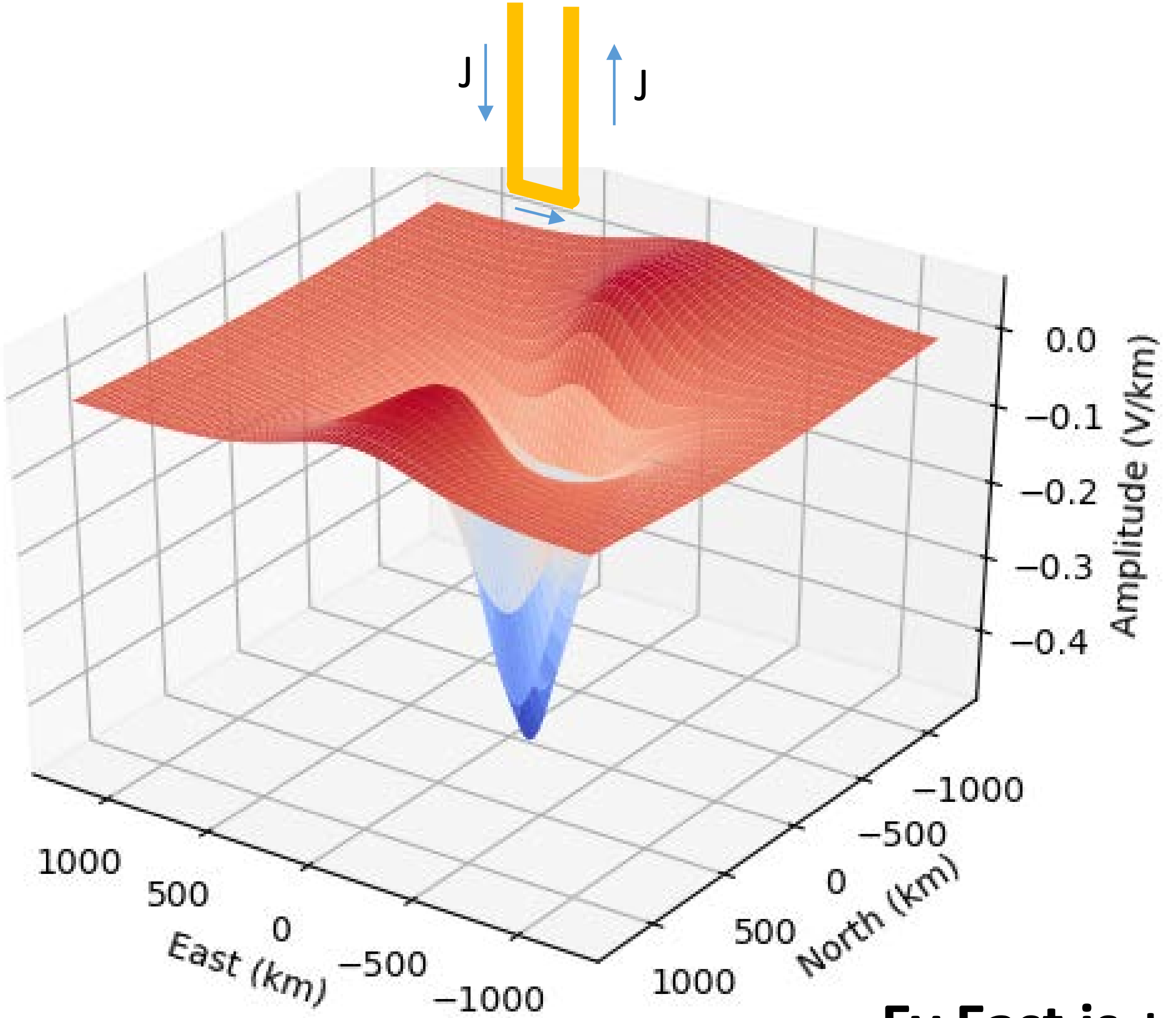
$$E_{x\downarrow} = k\frac{\Delta x}{\sqrt{(\Delta x)^2 + (\Delta y_0)^2 + h'^2} + h'}$$

$$E_{y\downarrow} = k\frac{\Delta y_0}{\sqrt{(\Delta x)^2 + (\Delta y_0)^2 + h'^2} + h'}$$

- **Calculation made by simulator**
- Electrojet height = 100 km
- Electrojet intensity = 1 MA
- Period = 5 min
- Electrojet centre (origin): longitude = 0, latitude = 0 degrees,
- Electrojet length = 500 km (y0=-250km, y1=250km)
- conductivity model = "Quebec"

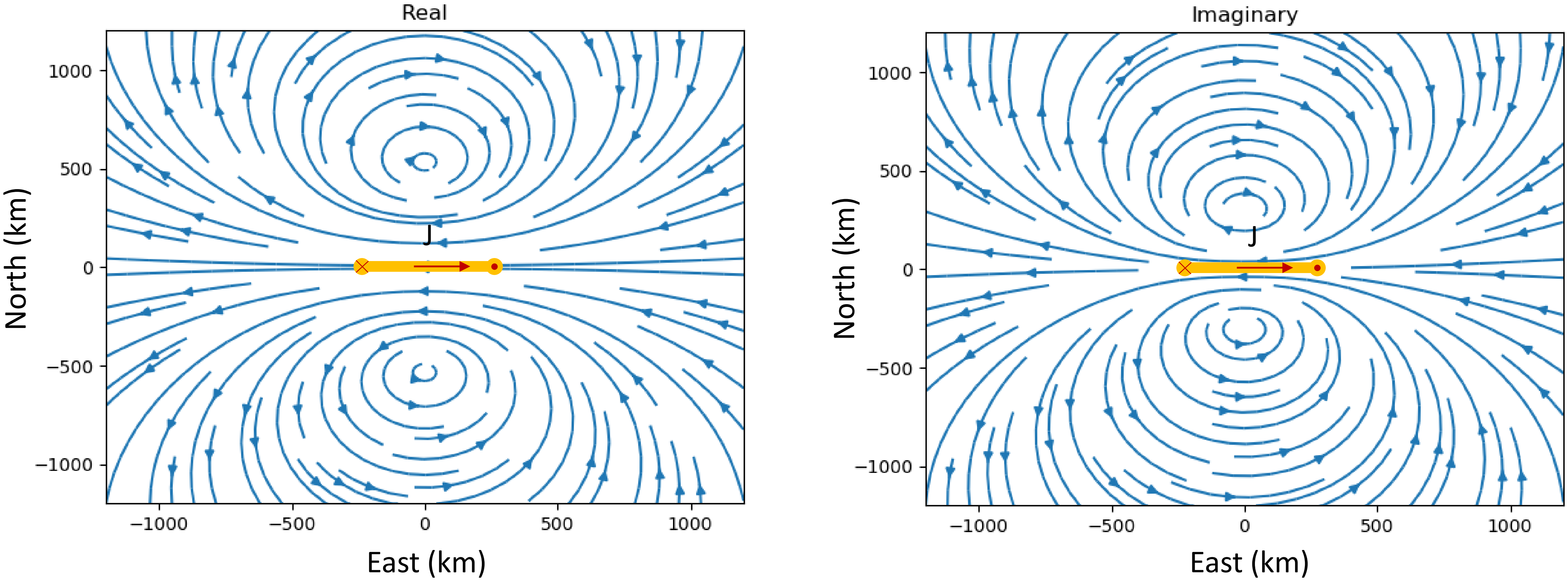


Ex North is +



Ey East is +

- **Calculation made from Risto's data**
- Electrojet height = 100 km
- Electrojet intensity = 1 MA
- Period = 5 min
- Electrojet centre (origin): longitude = 0, latitude = 0 degrees,
- Electrojet length = 500 km (y0=-250km, y1=250km)
- conductivity model = "Quebec"



- **Calculation made from Risto's data**
- Electrojet height = 100 km
- Electrojet intensity = 1 MA
- Period = 5 min
- Electrojet centre (origin): longitude = 0, latitude = 0 degrees,
- Electrojet length = 500 km (y0=-250km, y1=250km)
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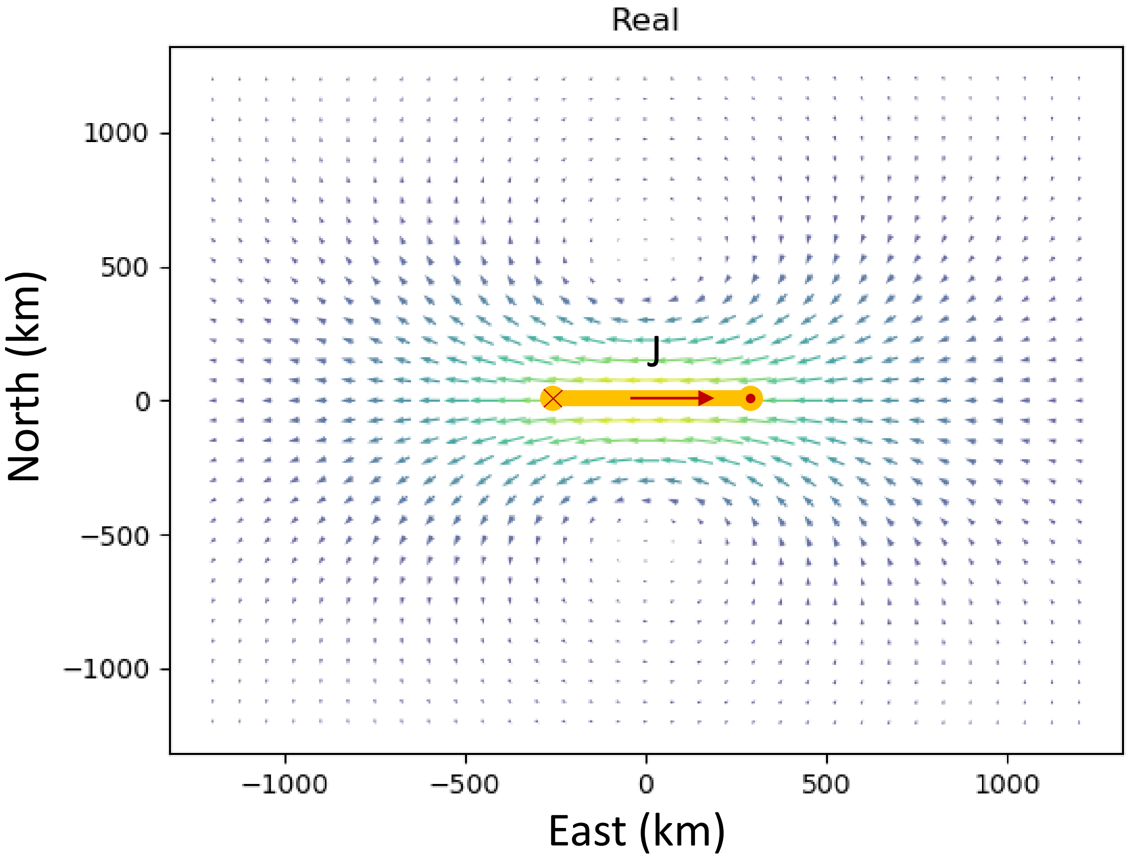
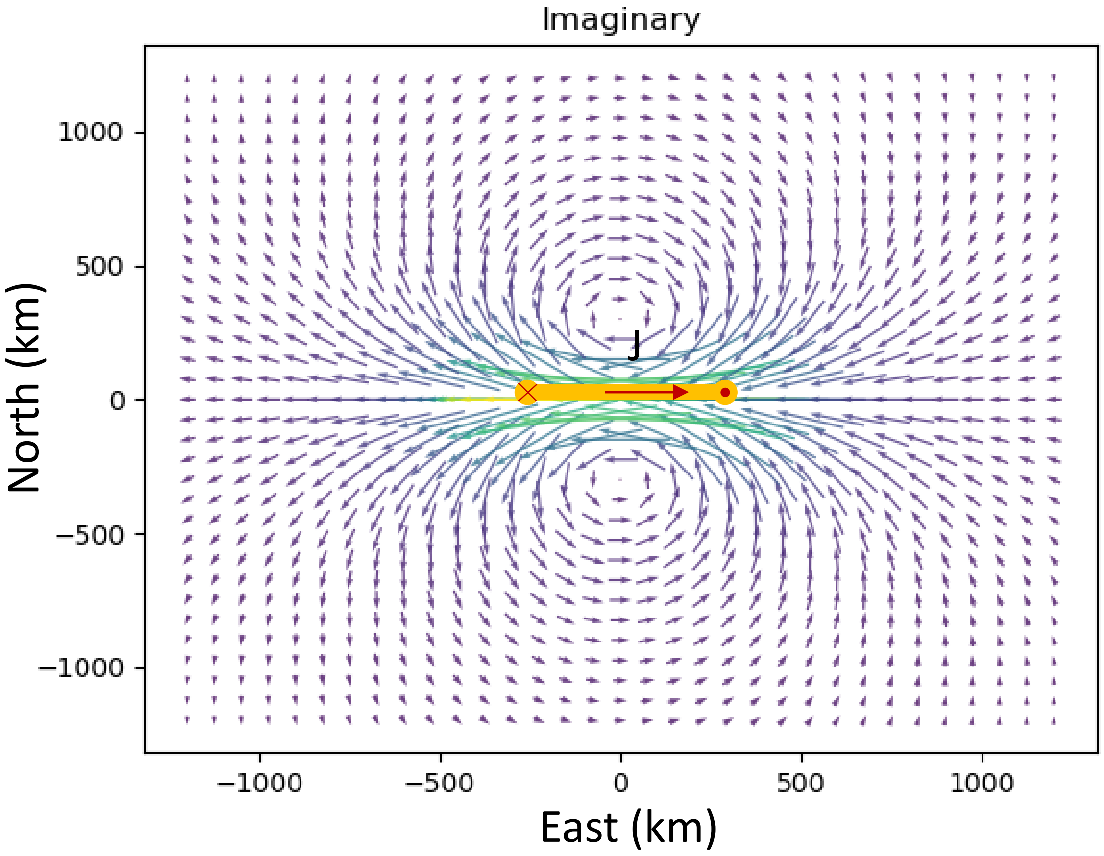


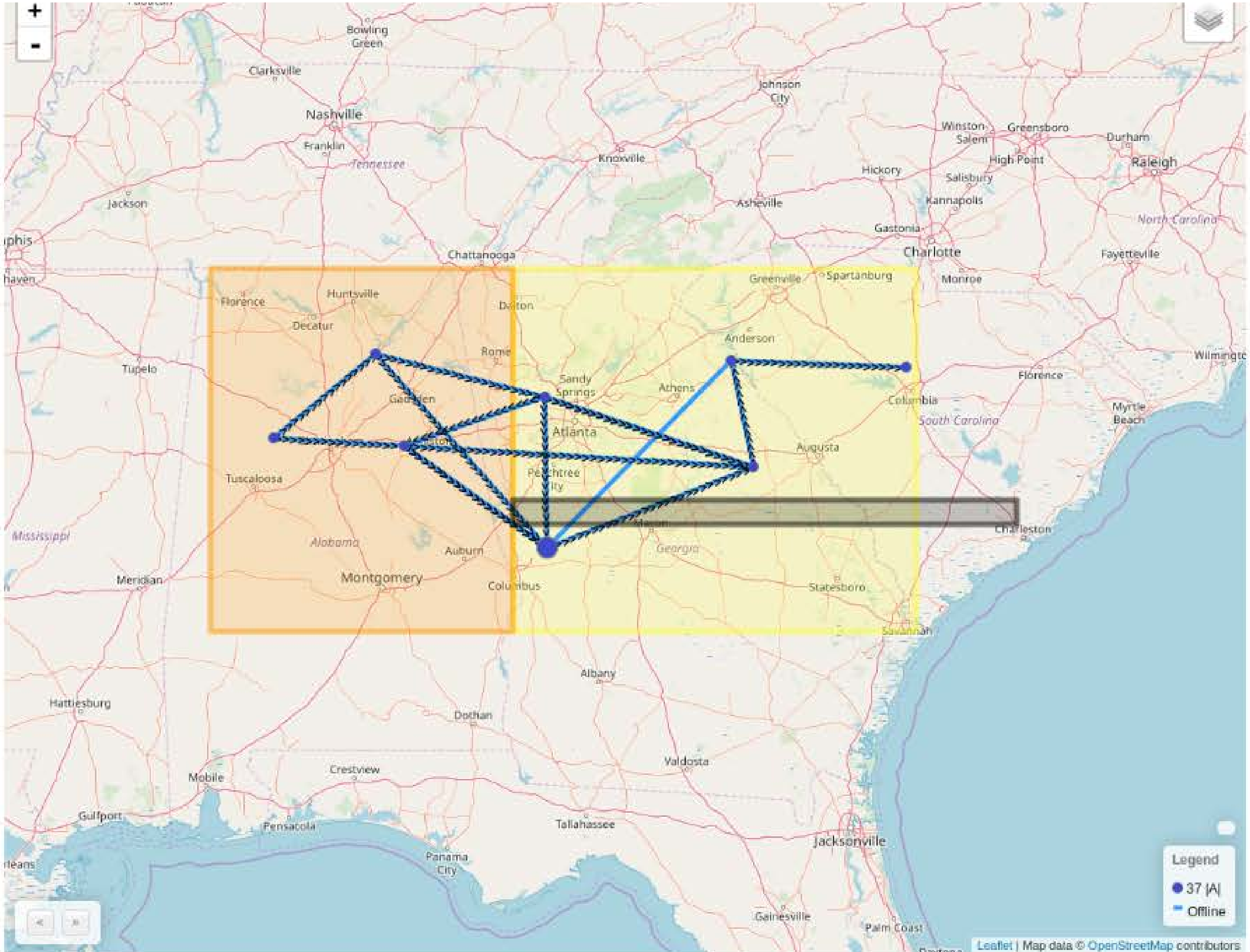


Finite electrojet GICs in the benchmark system

GIC Simulator | HTML

Power System

- Benchmark System
  - Stations
    - Sub_1
      - Bus_02
      - T01
        - Sub_1/T01 ResNG
    - Sub_2
      - Bus_17
      - T03
        - Sub_2/T03 ResNG
      - T04
        - Sub_2/T04 ResNG
    - Sub_3
      - Bus_15
      - Bus_16
      - T05
        - Sub_3/T05 ResNG
      - T15
        - Sub_3/T15 ResNG
    - Sub_4
      - Bus_03
      - Bus_04
      - T02
        - Sub_4/T02 ResNG
      - T12
        - Sub_4/T12 ResNG
      - T13
        - Sub_4/T13 ResNG
      - T14
        - Sub_4/T14 ResNG
    - Sub_5
      - Bus_05
      - Bus_20
      - T08
        - Sub_5/T08 ResNG
      - T09
        - Sub_5/T09 ResNG
    - Sub_6
      - Bus_06
      - T06
        - Sub_6/T06 ResNG



Name	GIC magnitude (A/Φ)	GIC phase (A)	MVAR (VAR/Φ)	MVAR (VAR)
Sub_1	0.00, phase:0°	0.00, phase:0°	0.00, phase:90°	0.00, phase:90
Sub_2	61.10, phase:-113°	183.29, phase:-113°	30.55, phase:-113°	91.64, phase:-11
Sub_3	73.88, phase:-113°	221.65, phase:-113°	27.78, phase:-113°	83.35, phase:-11
Sub_4	10.54, phase:-113°	31.61, phase:-113°	43.91, phase:-113°	131.73, phase:-11
Sub_5	147.42, phase:67°	442.26, phase:67°	72.35, phase:67°	217.05, phase:67
Sub_6	30.26, phase:67°	90.78, phase:67°	15.13, phase:67°	45.39, phase:67
Sub_7	0.00, phase:0°	0.00, phase:0°	0.00, phase:0°	0.00, phas
Sub_8	32.16, phase:-113°	96.49, phase:-113°	16.08, phase:-113°	48.25, phase:-11

U.S. Geological Survey Research Update

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Geologic Hazards Science Center

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Geology, Geophysics, Geochemistry Science Center

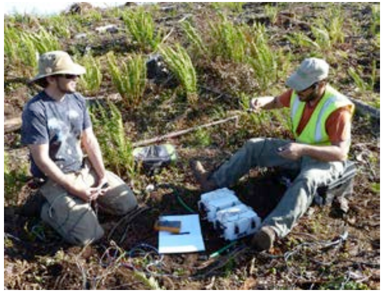
Input signal time series → Convolution through a filter → Output signal time series

Geomagnetic variation →

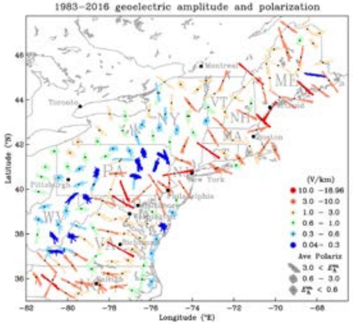
→ Geoelectric field

Geomagnetic variation recoded at observatory

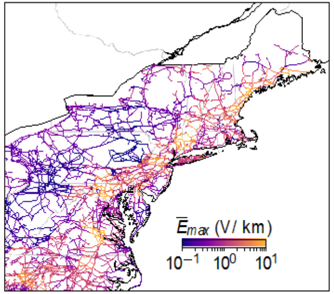
Impedance measured during magnetotelluric survey



Statistical geoelectric hazard maps

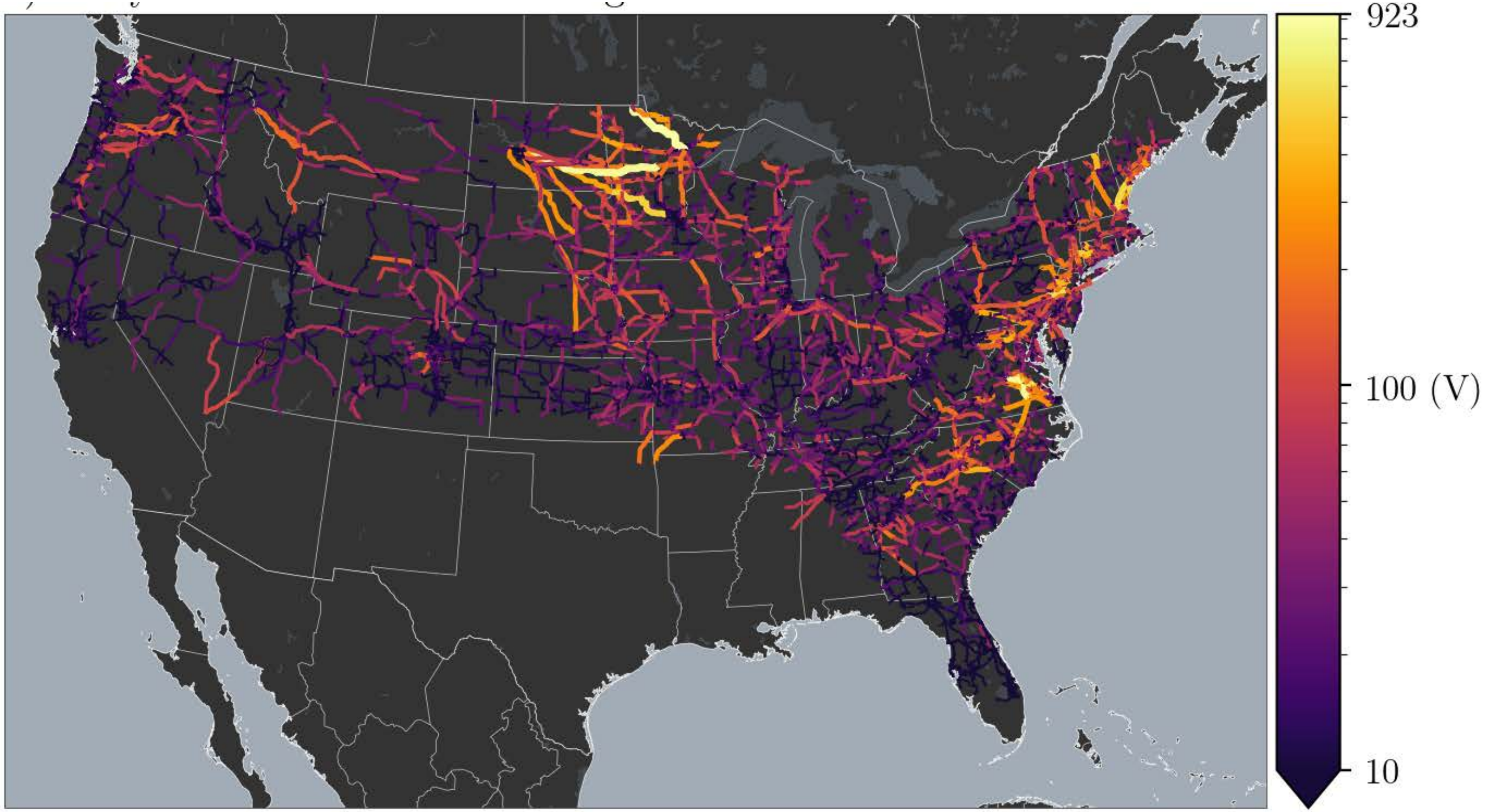


Geoelectric hazards mapped onto power grids



Love, J. J., Rigler, E. J., Pulkkinen, A., Balch, C. C., 2014.
Magnetic storms and induction hazards, Eos, Trans. AGU, 95(48), 445-446, doi10.1002/2014EO480001.

100-year voltages on the U.S. power grid



Lucas, G., Love, J. J., Kelbert, A., Bedrosian, P. A. & Rigler, E. J., 2019. 100-year Geoelectric Hazard Analysis for the United States High-Voltage Power Grid, Space Weather, submitted.