NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Agenda
Geomagnetic Disturbance Workshop

August 15, 2023 | 1:00 p.m. – 5:00 p.m. Central
August 16, 2023 | 8:30 a.m. – 3:00 p.m. Central

Midwest Reliability Organization
380 St. Peter St., Suite 800
St. Paul, MN 55102

Attendees (in-person or remote): Workshop Registration

Workshop - Day 1
Join WebEx Day 1
Meeting Number 2306 716 4432
Password: GMD2023

Workshop - Day 2
Join WebEx Day 2
Meeting Number 2319 853 9307
Password: GMD2023

In-person Attendee Check-in and Lunch | 12:00 – 1:00 p.m. Central

NERC Antitrust Compliance Guidelines and Public Announcement

Agenda Items | August 15, 2023 1:00 p.m. – 5:00 p.m. Central

1. **Welcome and Workshop Overview** – NERC Staff
2. **Update from the Space Weather Advisory Group (SWAG) –** Dr. Tamara Dickinson, President, Science Matters
3. **Overview of the SWAG User Needs Survey –** Mark Olson, NERC Staff
4. **Conduct the SWAG Electricity Sector User Needs Survey (Reliability Coordinators, Transmission Operators, Generator Operators)**

SWAG members record participant responses to series of questions about their current use of space weather observations, information, and forecasts, technological systems, components or elements affected by space weather, current and future risk and resilience activities, future space weather requirements, and unused or new types of measurements or observations that would enhance space weather risk mitigation.

Break 3:00 – 3:20

5. **Conduct the SWAG Electricity Sector User Needs Survey (Planning Coordinators, Transmission Planners, Generator Owners, equipment subject matter experts).**

6. **Geomagnetically-Induced Current (GIC) Modeling in the Australian Power Grid –** Richard Marshall, Australian Government Bureau of Meteorology

7. **Day 1 Wrap-up**

August 16, 2023 8:30 a.m. – 3:00 p.m. Central

In-person Attendee Breakfast | 7:45 – 8:30 a.m.

8. **Space Weather Prediction Center Update** – Chris Balch, NOAA SWPC

9. **Electric Industry GMD Vulnerability Assessments and Mitigation Activities | Presentations and Discussion**

    a. **U.S. Department of Energy Initiatives –TVA GIC Blocker** (Joe Blankenberg, U.S. Department of Energy / Bob Arritt, EPRI)

    b. **Dominion Energy Transformer Test Results** – Dominion Energy

    c. **Midcontinent ISO GMD Vulnerability Assessments (TPL-007) Overiew** – Iknoor Singh, MISO

    d. **Preparing for TPL-007 Implementation at BC Hydro** – Sam Li, BC Hydro

    e. **U.S. Department of Energy Project for GMD Advanced Modeling** – Bob Arritt, EPRI

    f. **Calculation of Reactive Power Demand in Power Transformers** – Ramsis Girgis, Hitachi Energy

    g. **ECLIPSE (2nd Generation) Monitoring of GIC, VAR Demand, Current Harmonics, and Thermal Impact Live** – Gary Hoffman

    h. **Session wrap-up and Q&A**

Break 10:15 – 10:30

10. **NERC Section 1600 Data Collection Update (GMD Data)** – NERC Staff

    a. Data quality and reporting issues

11. **Applications for Collected GIC Data:**

    a. **Introduction** – Jenn Gannon, Computational Physics, Inc.

    b. **Solar Wind and Magnetospheric Drivers of the 12 May 2021 GIC Event** – Delores Knipp, University of Colorado Boulder [20 minutes]

    c. **Interplanetary Precursor of the GIC Event on May 12, 2021** – Cecilia MacCormack (NASA Goddard)

   d. Session wrap-up and Q&A

Lunch 11:45 a.m. – 1:00 p.m.

12. Space Weather Research and Initiatives Supporting the Electric Power Sector | Presentations and Discussion

   a. **Update of Conductivity Models with MT Data** – Jenn Gannon, Computational Physics, Inc.
   b. **Update on Continental-U.S. Electrical Conductivity and Impedance Mapping** – Adam Schultz, Oregon State University / Pacific Northwest National Lab
   c. **U.S. Geological Survey Update** – Jeff Love, USGS
   d. **Including Coast Effect in GIC Modeling** – David Boteler, NR Canada
   e. **Numerical Modeling for GMD Applications: Sun-To-Surface** – Dan Welling, University of Michigan
   f. **Los Alamos National Laboratory Power Modeling Studies Scenarios** – Steve Morley, LANL

Break 2:30 – 2:40 p.m.

13. Discuss Workshop Themes, Future Objectives, and Next Steps

14. Workshop Wrap up

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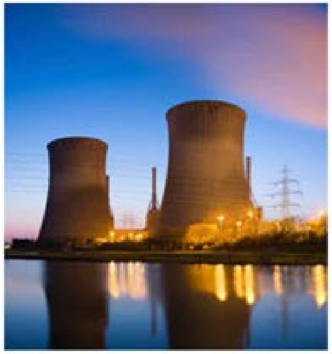
NERC-EPRI Geomagnetic Disturbance Workshop

Mark Olson, Manager, Reliability Assessments
August 15-16, 2023

RELIABILITY | RESILIENCE | SECURITY

Reducing Risk of GMD Impacts

- The ERO Enterprise reduces risks to the Bulk Power System from severe GMD events through three main efforts:
  - State of the art Reliability Standards | TPL-007-4 and EOP-010-1
  - Partnerships for leading-edge research and tool development
  - Data collection program to improve knowledge and understanding (NERC Rules of Procedure Section 1600 Data Request for GMD Data)
- **This workshop was designed with these areas in mind!**

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Workshop Info

- Workshop Objective: Promote information-sharing among industry planners and operators
- Topic areas:
  - Space Weather Information Survey
  - GMD Vulnerability Assessments and mitigation plans (TPL-007)
  - Transformer GIC impact assessments
  - Collection and use of GIC data
- Industry panelists from U.S. and Canada will share current practices and insights

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Geomagnetic Disturbance Planning Workshop

August 15, 2023 | 1:00 p.m. – 5:00 p.m. Central
August 16, 2023 | 8:30 a.m. – 3:00 p.m. Central

Midwest Reliability Organization
380 St. Peter St., Suite 800
St. Paul, MN 55102

Materials are available to workshop participants download by webex and will be made publicly available on NERC's website

Additional Workshop Content

- EPRI updates on a range of GMD programs and tools
  - Includes models and software developed with through the FERC Order No. 830 Research project that is available free of charge
- Transformer manufacturer and vendor participants discuss current activities supporting industry
- Update from U.S. NOAA Space Weather Prediction Center and other providers of space weather services
- Government agency and research organization initiatives

Housekeeping for Hybrid In-person and Webex Meeting

- Identify yourself and your organization during Q&A
- Use ‘Raise Hand’ feature in webex for questions and comments
  - Chat in webex can also be used
- Keep microphones and phones muted
  - Unmute with webex controls or by pressing *6 on your phones

Questions and Answers

For more information
Mark Olson (NERC) mark.olson@nerc.net
Bob Arritt (EPRI) barritt@epri.com

Update on the Space Weather Advisory Group (SWAG)

Geomagnetic Disturbance Planning Workshop
August 15, 2023

Dr. Tamara Dickinson
SWAG Chair
President, Science Matters Consulting, LLC.

All opinions are my own and not those of SWAG or Lockheed Martin

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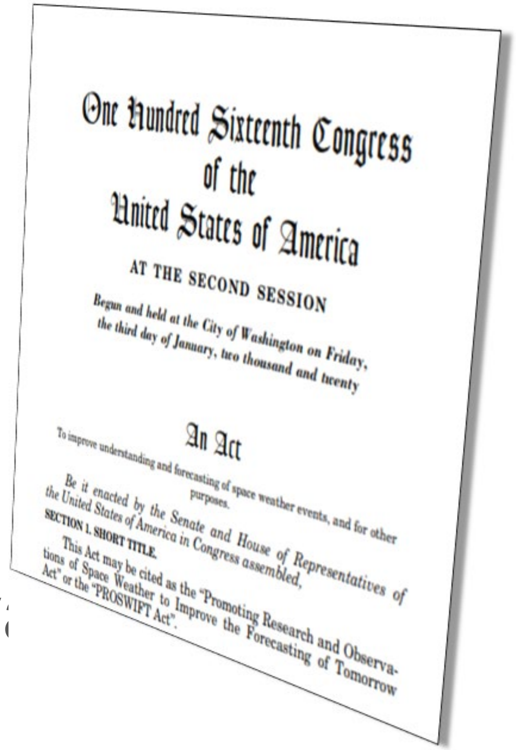
PROSWIFT Act - Overview



<u>Basic Elements</u>

- 60601 Space weather
    - Role of Federal Agencies
    - Interagency Working Group (SWORM)
    - Interagency Agreements
    - **Space Weather Advisory Group (SWAG)**
- 60602 Integrated strategy
- 60603 Sustaining and advancing critical observa
- 60604 Research activities
- 60605 Space weather data
- 60606 Knowledge transfer and information exchange (NASEM Roundtable)
- 60607 Pilot program commercial sector
- 60608 Benchmarks

PROSWIFT Act - SWAG

ESTABLISHED - **NOAA Administrator** … informs the interests and work of **SWORM**

COMPOSITION - **appointed by SWORM** , 5 *representatives* of **academic** , **commercial** space weather, **end user** communities

TERM LIMITS - 3 years terms , no more than 2 consecutive terms

CHAIR – chosen by NOAA Administrator, no more than 2 terms, regardless of whether the terms are consecutive

Committee Members

SWAG Nongovernmental End-User Representatives

Tamara Dickinson, SWAG Chair
Science Matters Consulting

Mark Olson
North American Electric Reliability Corporation

Michael Stills
United Airlines (retired)

Craig Fugate
One Concern (former FEMA Adm)

Rebecca Bishop
Aerospace Corp.

SWAG Commercial Sector Representatives

Jennifer Gannon
Computational Physics, Inc.

Conrad Lautenbacher
GeoOptics, Inc. (former NOAA Adm)

Seth Jonas
Lockheed Martin

Kent Tobiska
Space Environment Technologies

Nicole Duncan
Ball Aerospace

SWAG Academic Community Representatives

Tomas Gombosi
University of Michigan, Ann Arbor

Delores Knipp
University of Colorado, Boulder

Scott McIntosh
National Centers for Atmospheric Research

Heather Elliott
Southwest Research Institute

George Ho
Johns Hopkins University Applied Physics Laboratory

PROSWIFT Act - SWAG Duties

Advise White House SWORM Subcommittee on:

- Facilitating advances in the space weather enterprise of the US
- Improving the ability of the US to prepare for, mitigate, respond to, and recover from space weather phenomena
- Enabling the coordination and facilitation of R2O2R
- Developing and implementing the integrated strategy for coordinated observation

Conduct a comprehensive user needs survey of space weather products

PROSWIFT Act - User Survey

User Survey Requirements:

1. Assess the **adequacy of Federal Government goals** for lead time, accuracy, coverage, timeliness, data rate, and data quality for space weather observations and forecasting;
2. Identify options and methods to **advance the above goals**;
3. Identify **opportunities for collection of data** to address the needs of space weather users;
4. Identify methods to **increase coordination of space weather R2O2R**;
5. Identify opportunities for new technologies, research, and instrumentation to aid in understanding, monitoring, modeling, prediction, and warning of space weather; and
6. Identify methods and technologies to **improve preparedness** for space weather.

Sectors for User Needs Survey

- **Electric Power Grid**
- Space Situational Awareness/ Space Traffic Coordination
- GNSS
- Aviation
- Emergency Management
- Human space flight
- Research

- Satellite
- National Security
- Radio Frequency Application (comms and Radar)

SWAG Meetings

2021

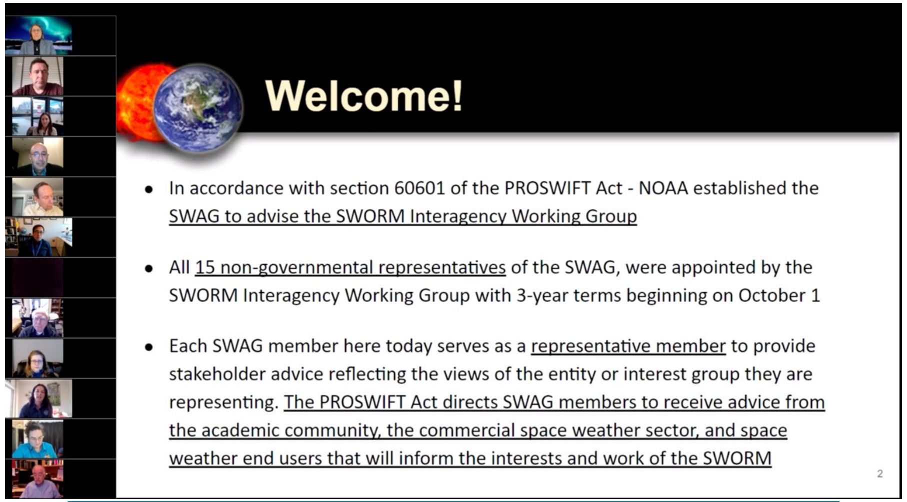
- Kickoff meeting December (virtual)

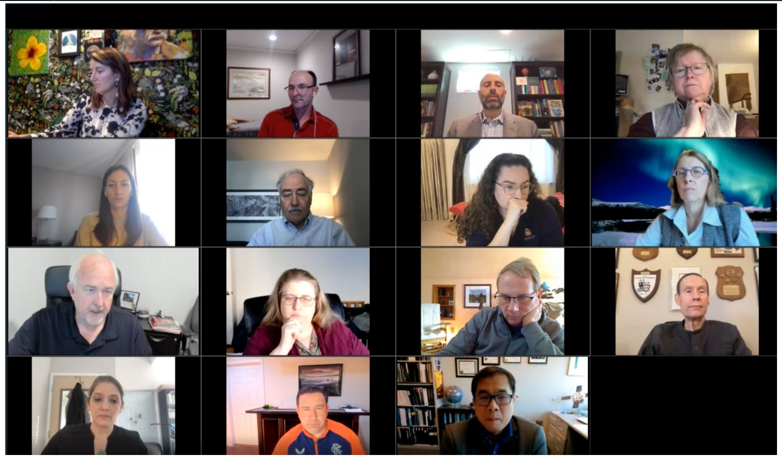
2022

- Two meetings (virtual)
- Develop the user needs survey and process

2023

- In-person meeting January
  - Gathered input for our report
- Conduct the user needs survey
- Contemplating a Fall meeting (virtual) focused on community building





For meeting information please visit: www.weather.gov/swag

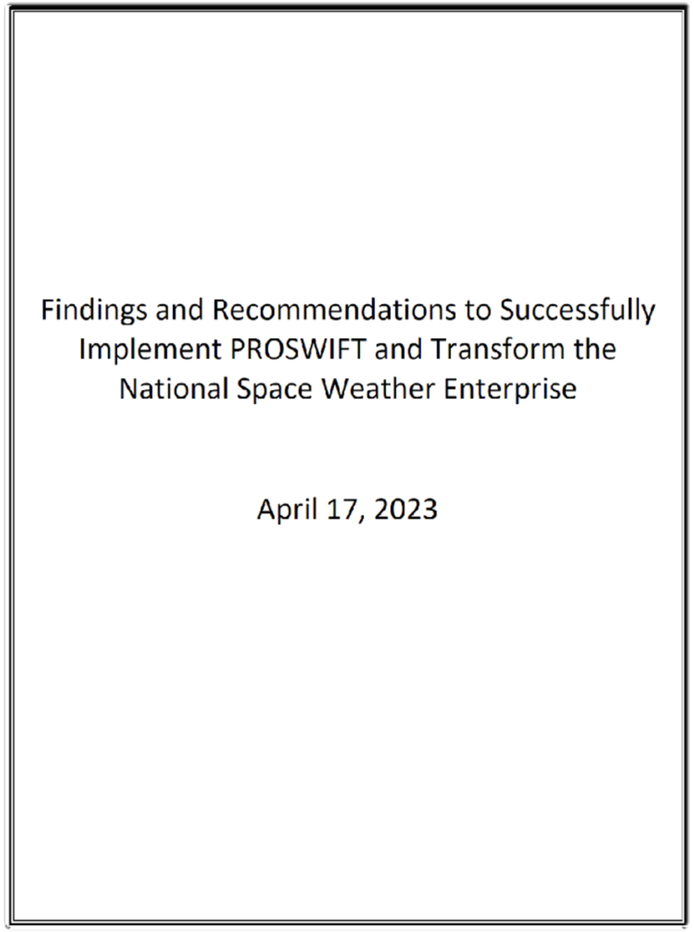
Information Gathering

- Asked by the SWORM to provide input as they update National Space Weather Strategy/Action Plan/Implementation Plan
- Input for the report
    - 2015 and 2019 Strategies/Action Plans
    - White Paper on the Implementation Status of the National Space Weather Strategy and Action Plan
    - National space weather policies and statutes
    - Decadal Survey on Solar and Space Physics 2024-2033 White Papers
    - **Broader community thru a series of speakers, panels, and inputs from the public at January 2023 hybrid, open meeting**
- Audience – SWORM, Congress, Space Weather Enterprise

SWAG Report: Finding and Recommendations

Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise

www.weather.gov/swag


Findings and Recommendations to Successfully Implement PROSWIFT and Transform the National Space Weather Enterprise

April 17, 2023

Broad Set of Space Weather Topics Covered

Overarching Recommendations
Ground-Based and Airborne Sensors and Networks
In-Space Architectures and Space-Based Observations
Data and Computing Infrastructure for Space Weather Operations
Improving Benchmarks, Metrics, and Scales for Space Weather End-Users
Space Weather Risk to Evolving Infrastructure Systems and Services
Economic Assessments on The Costs of Space Weather and the Value Of Forecasting and Mitigation
Promote Focused and Continued Engagement Across Industry and Government Space Weather Stakeholders
Additional Findings and Recommendations
Next Steps

SWORM Progress

- SWORM has made significant progress over the last nine years to build awareness and move the Nation towards resilience to space weather
- Technology, infrastructure systems, and national priorities continue to evolve–with the space domain becoming increasingly important to national and economic security

Priority Recommendations

1. Fund the Federal Space Weather Enterprise. (R.1.1.)
2. Create and fund an applied research program office for space weather within NOAA to coordinate, facilitate, promote, and transition applied research across the national space weather enterprise. (R.2.1.)
3. Ensure OSTP staffing and White House led prioritization and coordination across the national space weather enterprise. (R.3.1. and more)
4. Protect space weather sensors from spectrum interference. (R.5.1.)
5. Provide long-term support for operational ground-based and airborne sensors and networks. (R.6.2.)
6. Provide and fund critical operational space weather services beyond near-Earth.

Priority Recommendations

7. Fund NASA missions that advance fundamental science to support space weather research. (R.10.1.)
8. Coordinate benchmark development or improvement with industry. (R.14.1.)
9. Quantify the societal benefits for addressing risk from space weather by performing national-level and industry-wide economic assessments and consider space weather in the context of broader national risk (R.18.1. and R.4.1.)
10. Support coordinated applied research within the thermosphere (above 100 km altitude) which is critical for space traffic coordination. (R.24.1-3.)
11. Foster and lead a global space weather enterprise. (R. 25.1-4)

Next Steps

- SWAG looks forward to engaging SWORM agencies and other relevant stakeholders on these findings and recommendations
- SWAG looks forward to future engagement with SWORM and Congress on this report, as well as opportunities to monitor and assess SWORM's implementation progress
- SWAG will seek to provide additional input on resilience focused actions and other needs of end users in the forthcoming results of the user-needs surveys
- Look into any issues in more detail as requested by SWORM.
- Sessions at upcoming conferences and workshops.

THANKS!

dickinson.tamara@yahoo.com

www.weather.gov/SWAG

Broad Set of Space Weather Topics Covered

Overarching Recommendations
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BACKUP SLIDES

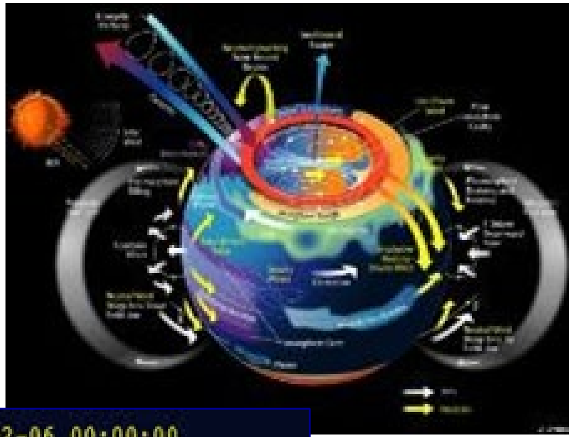
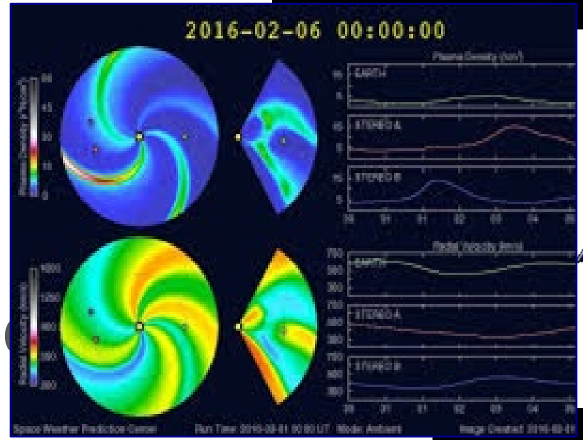
Input to Space Weather Enterprise

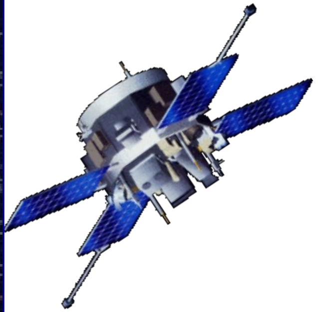
- 2015 and 2019 National Space Weather Strategies
  - Community input was via a Request for Information
  - Community didn't feel it was an all of community activity
- Congress heard you - Enter SWAG
  - Chartered to advise SWORM
  - Members from academia, end-users, and commercial space sectors
  - Representatives of our communities
    - Expected to reach into our communities to get input

PROSWIFT Act - User Survey

The comprehensive **user needs survey** of space weather products will identify:

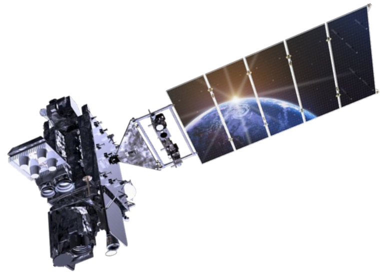
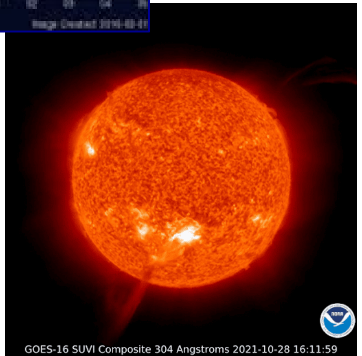
- space weather research
- observations
- forecasting
- prediction
- modeling advances required to improve space weather products.







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Next Steps		

Priority Recommendations

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2. Create and fund an applied research program office for space weather within NOAA to coordinate, facilitate, promote, and transition applied research across the national space weather enterprise. (R.2.1.)
3. Ensure OSTP staffing and White House led prioritization and coordination across the national space weather enterprise. (R.3.1. and more)
4. Protect space weather sensors from spectrum interference. (R.5.1.)
5. Provide long-term support for operational ground-based and airborne sensors and networks. (R.6.2.)
6. Provide and fund critical operational space weather services beyond near-Earth.

Priority Recommendations

7. Fund NASA missions that advance fundamental science to support space weather research. (R.10.1.)
8. Coordinate benchmark development or improvement with industry. (R.14.1.)
9. Quantify the societal benefits for addressing risk from space weather by performing national-level and industry-wide economic assessments and consider space weather in the context of broader national risk (R.18.1. and R.4.1.)
10. Support coordinated applied research within the thermosphere (above 1000 km altitude) which is critical for space traffic coordination. (R.24.1-3.)
11. Foster and lead a global space weather enterprise. (R. 25.1-4)

Overarching Recommendations

Funding the implementation of PROSWIFT

R.1.1. Fund the Federal Space Weather Enterprise.

Enabling NOAA to achieve their space weather priorities and accomplish their space weather mission

R.2.1. Create and fund an applied research program office for space weather within NOAA to coordinate, facilitate, promote, and transition applied research across the national space weather enterprise.

R.2.2. Develop internal NOAA strategies to ensure agency-wide coordinated implementation of PROSWIFT and their national space weather policy responsibilities – both overall and within each service office.

R.2.3. Expand NOAA R2O2R functionality to enable the transition to full operations.

Overarching Recommendations

Ensuring coordination of space weather across the Federal Government

R.3.1. Ensure OSTP staffing and White House led prioritization ansd coordination across the national space weather enterprise.

A national risk register

R.4.1. Consider space weather in the context of broader national risk.

Protecting space weather sensors from spectrum interference

R.5.1. Protect space weather sensors from spectrum interference.

Ground-Based and Airborne Sensors and Networks

R.6.1. Assess and publish the prioritization of ground-based and airborne sensors needed for current and future space weather products.

R.6.2. Provide long-term support for operational ground-based and airborne sensors and networks.

R.6.3. Fund the transition of NSF research sensors and networks to operations.

R.6.4. Coordinate support for ground-based and airborne sensors and networks that are essential to space-based missions.

Ground-Based and Airborne Sensors and Networks

R.7.1. Expand the use of CRADAs to improve collaboration across the academic and commercial sectors.

R.8.1. Prioritize the addition of underutilized, existing real-time magnetometer data streams over new MT survey campaigns.

In-Space Architectures and Space-Based Observations

R.9.1. Revise the National Space Weather Strategy and Action Plan to broaden service coverage of additional space environments.

R.9.2. Provide and fund critical operational space weather services beyond near-Earth.

In-Space Architectures and Space-Based Observations

R.10.1. Fund NASA missions that advance fundamental science to support space weather research.

R.10.2. Use a coordinated approach to develop and deploy missions that advance fundamental science supporting space weather.

R.10.3. Establish O2R traceability in the NASA mission formulation process.

R.10.4. Develop a prioritization of space-based sensors to enhance space weather products.

In-Space Architectures and Space-Based Observations

R.11.1. Opportunistically deploy more space weather sensors.

R.11.2. Fly space weather particle sensors on every U.S. Government procured space vehicle.

R.12.1 Sustain resilient approaches to ensure continuity of in-space, operational space weather observations.

Data and Computing Infrastructure for Space Weather Operations

R.13.1. Fund, formalize, and expand the NOAA space weather prediction testbed.

R.13.2. Improve access to space weather data.

R.13.3. Improve interagency coordination of models and data.

R.13.4. Promote and prepare for the use of AI/ML algorithms as a complement to traditional empirical and physics-based models.

R.13.5. Continue to identify and release novel and underutilized data sets that improve space weather products.

R.13.6. Promote career pathways for interdisciplinary technologists supporting the space weather enterprise.

Improving Benchmarks, Metrics, and Scales for Space Weather End-Users

R.14.1. Coordinate benchmark development or improvement with industry.

R.14.2. Promote industry participation in workshops and meetings to inform the mitigation of space weather hazards.

R.14.3. Use multiple approaches to validate benchmarks.

R.15.1. Identify and prioritize the development of key space weather metrics.

R.15.2. Update and expand NOAA space weather scales.

R.15.3. Maintain historical space weather indices.

Space Weather Risk to Evolving Infrastructure Systems and Services

R.16.1. Develop an enduring process to understand evolving infrastructure needs.

R.16.2. Leverage industry assessments and applications of magnetotelluric data and geomagnetically-induced current data to improve Earth conductivity models and geomagnetically-induced current assessment tools.

R.17.1. Promote the development of vulnerability assessments by sector owners and operators.

R.17.2. Prioritize addressing space weather risks in sectors other than electric power and aviation.

R.17.3. Address interdependencies of and cascading risks to critical infrastructure.

Economic Assessments on the Cost of Space Weather and the Value of Forecasting and Mitigation

R.18.1. Quantify the societal benefits for addressing risk from space weather by performing national-level and industry-wide economic assessments.

R.18.2. Develop and curate data necessary for effective economic assessments.

R.18.3. Broaden the scope of economic assessments.

R.18.4. Engage additional stakeholders for economic assessments.

Promote Focused and Continued Engagement Across Industry and Government Space Weather Stakeholders

R.19.1. Enhance distribution of space weather products.

R.19.2. SWORM should increase transparency by ensuring the publication of foundational documents, studies, and policies.

R.20.1. Develop standing MOUs or MOAs across and between all SWORM agencies.

R.21.1. Develop and implement broader participation in tabletop exercises.

Other Key Recommendations

Assessing and addressing national security risks from space weather

R.22.1. Develop a national security annex or policy on space weather.

Promoting public awareness and education for space weather

R.23.1. Improve public awareness, education, and engagement regarding space weather application effects.

Other Key Recommendations

Critical need for thermospheric density specification to aid operational systems

R.24.1. Support coordinated applied research for the thermosphere (above 100 km altitude) which is critical for space traffic coordination.

R.24.2. Support coordinated R2O2R workshops and testbed activities for space traffic coordination.

R.24.3. Support and encourage new processes for the incorporation of data and observations to characterize the thermosphere (above 100 km altitude) environment.

Other Key Recommendations

Enhancing global engagement

R.25.1. Foster and lead a global space weather enterprise.

R.25.2. Promote Five-Eyes space weather collaborations.

R.25.3. Formalize bi-lateral or multilateral agreements to support coordinated messaging, mutual resilience, and to further the global space weather enterprise.

R.25.4. Participate in and leverage the international standards development relevant to space environment and space weather.

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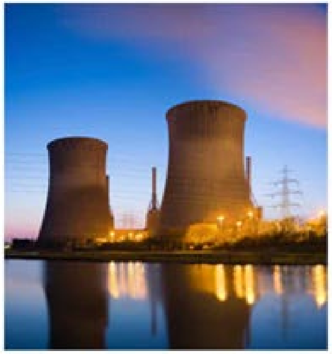
Space Weather Information User Survey

U.S. Space Weather Advisory Group (SWAG)

NERC-EPRI GMD Workshop
August 15, 2023

RELIABILITY | RESILIENCE | SECURITY

Overview

- Reliability Coordinator, Transmission Operator, Planning Coordinator, and Transmission Planner representatives are encouraged to participate in a live webex survey on August 15
  - Participants will provide feedback on their use of space weather information and how space weather information services can be improved
  - Conducted by an advisory group appointed by the U.S. National Oceanographic and Atmospheric Administration (NOAA)
  - Supports the *Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act of 2020* (PROSWIFT)
- RCs/TOPs | August 15, 1:30 – 3:00 pm central
- PCs/TPs/other NERC entities | August 15, 3:20 – 4:30 pm central
- **In-person and Remote Participants: Workshop Registration**

Survey Ground Rules

- Conducted in a workshop-discussion format.
- Participation from all webex attendees is strongly encouraged.
- **No right or wrong answers.** All experiences and opinions are valued and important. We want to hear a range of views.
- The survey is a closed discussion among participants.
- Recording will be used for note-taking purposes. Survey participants will not be identified by name or entity in reports.

Information is being collected by the U.S. Space Weather Advisory Group to identify research, observations, forecasting, prediction, and modeling advances required to improve space weather products

Survey Questions

1. How familiar are you with space weather products and services?
2. How do you consider space weather conditions in planning and operating the power system and equipment?
3. What space weather information do you use?
4. Where and how do you get the space weather information?
5. How satisfied are you with the quality and utility of current space weather observations, products, and services?
6. Based on your experience with current space weather products and services, what feedback do you have for providers to help them meet your needs?

Survey Questions (continued)

7. What do engineers and operators within the power grid sector need in future space weather information?
8. How do you use other environment or system data (e.g., GIC data, geomagnetic field variation) or information to support engineering design or operating actions?
9. How long is the information and/or data kept?
10. Can this information be shared outside of the application, company, or community?
11. How has space weather affected your systems and components?
    a. Based on how space weather has affected your systems, what are the requirements for your systems and components?

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Survey Questions (continued)

12. Are there any new technologies, research, instruments, and models that are needed to address space weather in the power sector?
13. How is space weather information used in operating procedures to reduce risk and improve resilience?
14. How is space weather information used for engineering designs that have been adopted to reduce risk and improve resilience?
15. What improvements or additional space weather products are needed to assist in increasing the resilience of the power system? Please consider both short-term (within next 1-2 years) and longer term (within 5-10 years).

Survey Questions (continued)

16. What may be limiting the power sector’s ability to take actions to reduce risk and improve resilience?
17. How could better education and training improve the sector's ability to take action?
18. Are there any other inputs that you wish to share?

Conclusion

- This concludes the Space Weather Advisory Group Survey – Power Sector.
- Feedback will be analyzed by the SWAG and included in a report along with responses from other end-user groups.
- Information is being collected to identify the space weather research, observations, forecasting, prediction, and modeling advances required to improve space weather products.
- Individual and organization names will not be included in a report without permission.

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

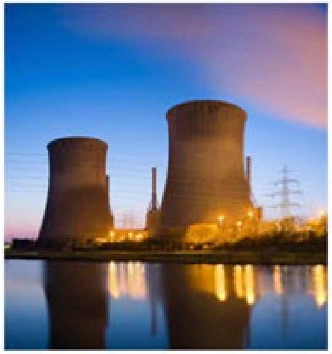
Space Weather Information User Survey

U.S. Space Weather Advisory Group (SWAG)

Mark Olson, Manager, Reliability Assessments

NERC-EPRI GMD Workshop
August 15, 2023

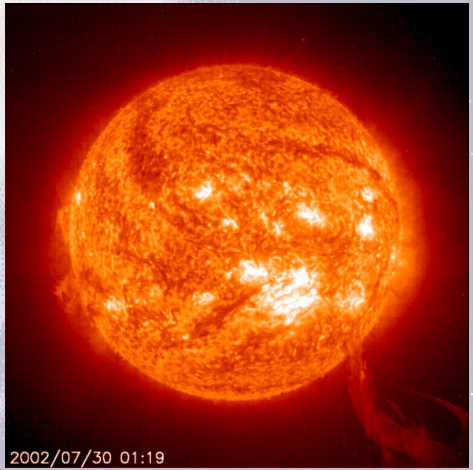
RELIABILITY | RESILIENCE | SECURITY

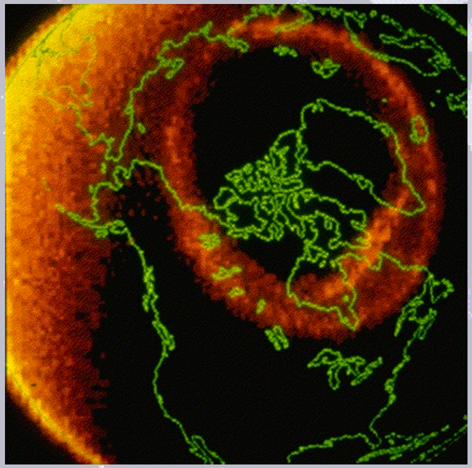



Space Weather Prediction Center Update

Outline

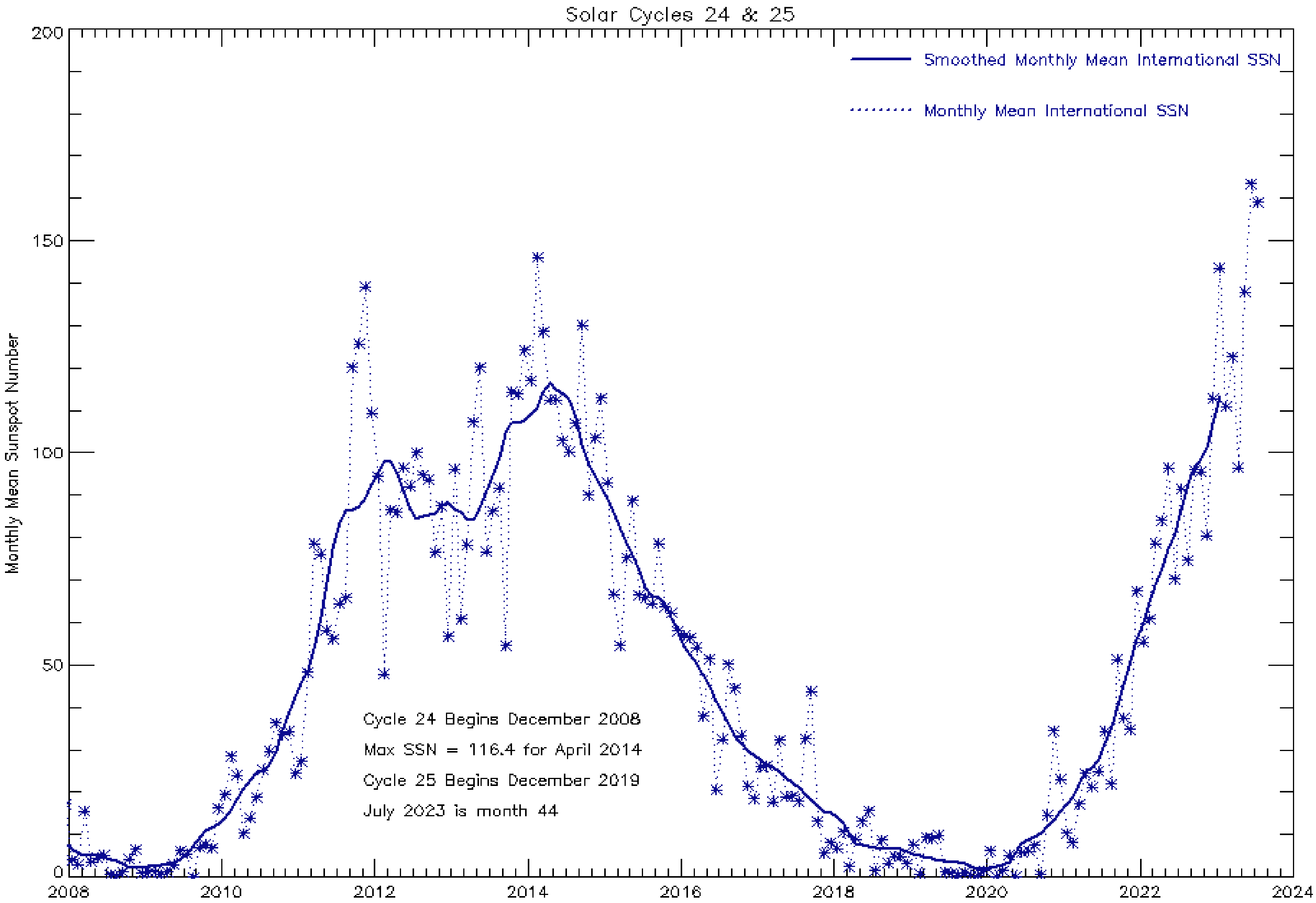
- Solar Cycle Update
- Geoelectric Field Modeling Updates
  - US-Canada 1D E-field maps
  - 3D empirical E-field maps over CONUS
  - Statistical comparison of the models
  - Recently completed E-field validation study
- Work in progress
  - E-field validation study in TVA region
  - Development of predictive geoelectric field product
- Future work
- Discussion/Conclusion



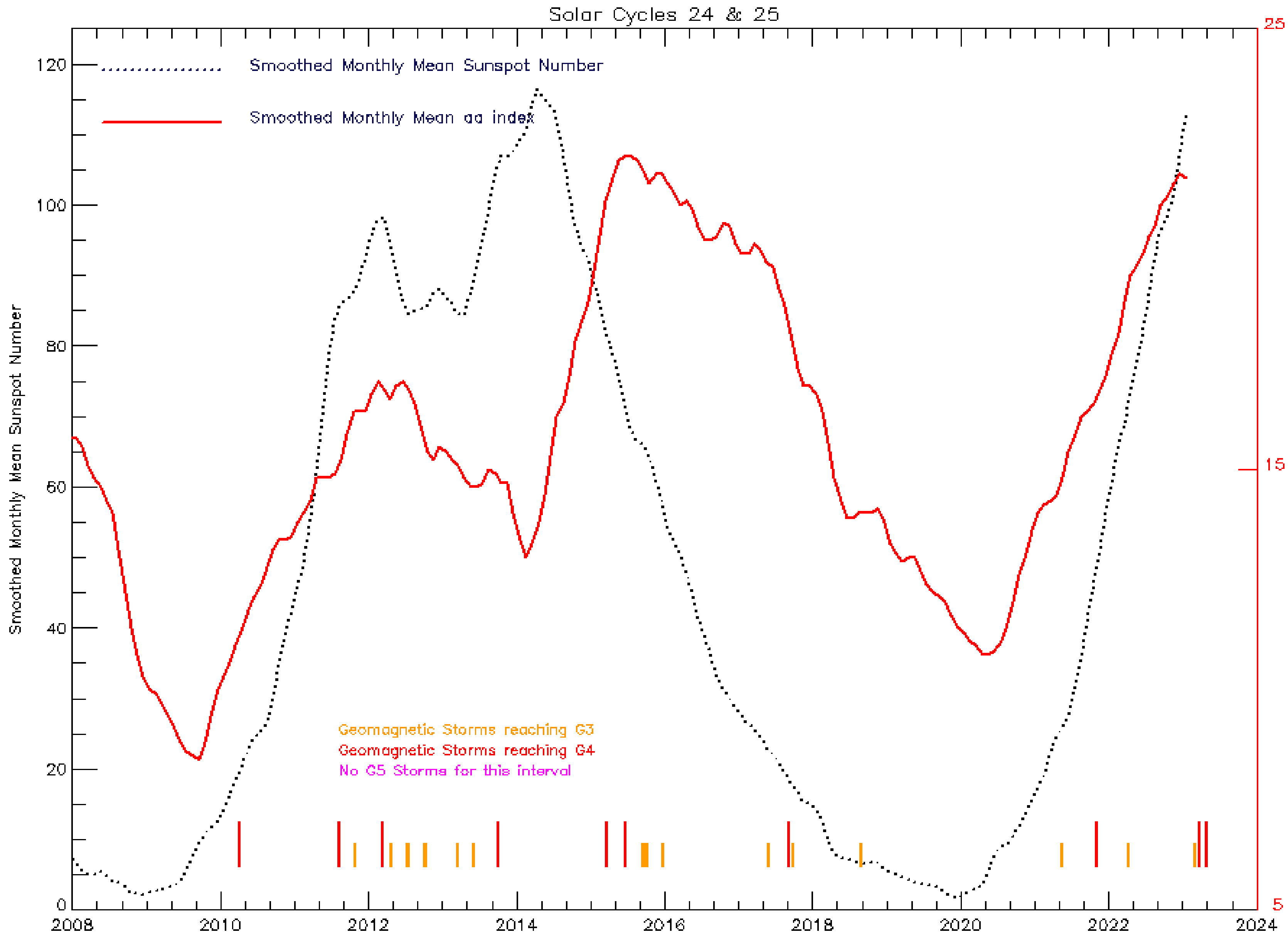


Christopher Balch
Senior Research Associate
CIRES/NOAA SWPC
NERC GMD Workshop
August 15-16, 2023
St. Paul, MN

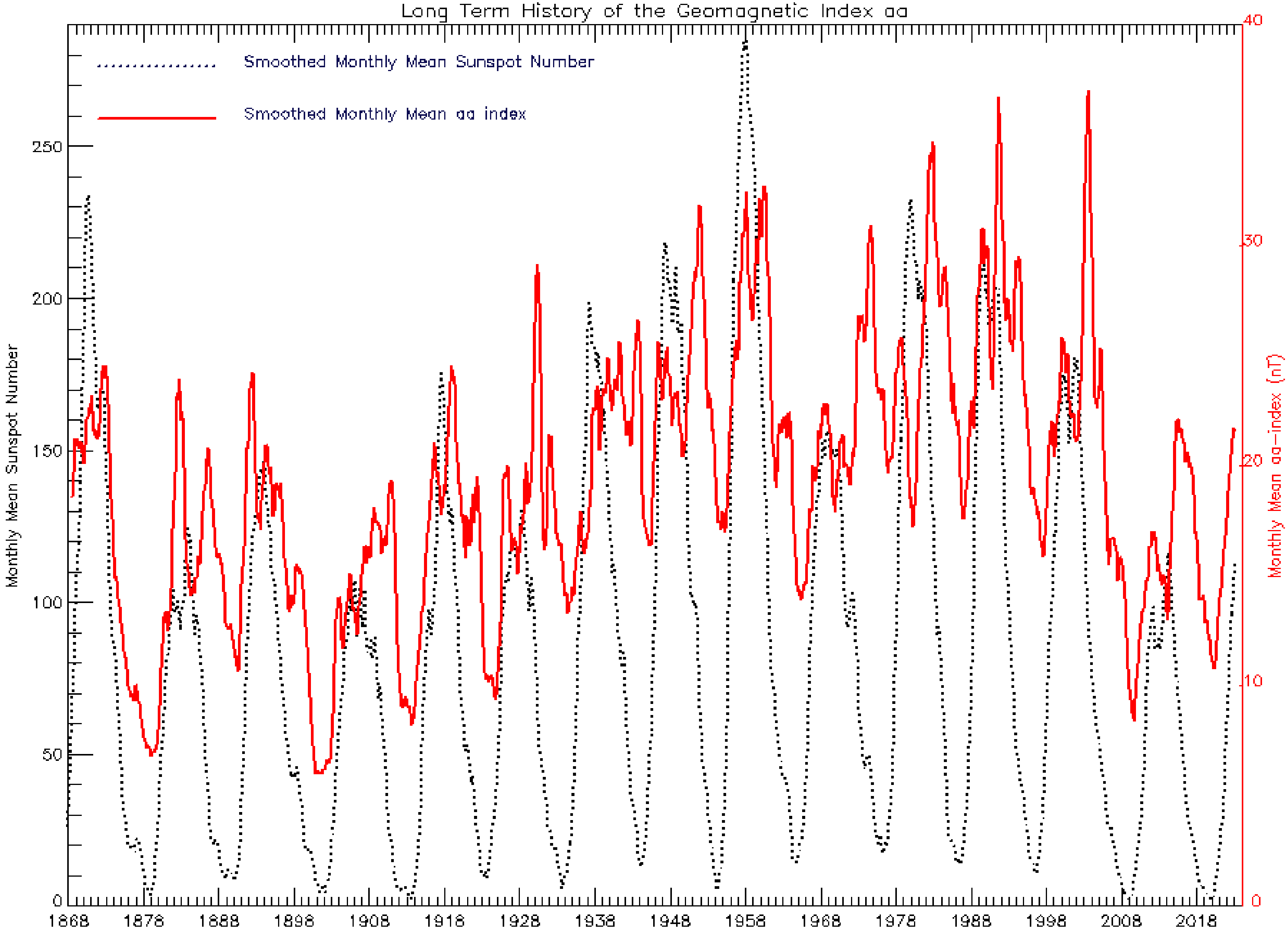
Sunspot Cycle – Heading Into Solar Maximum



Sunspot Number, aa index, Geomagnetic Storms (≥G3)

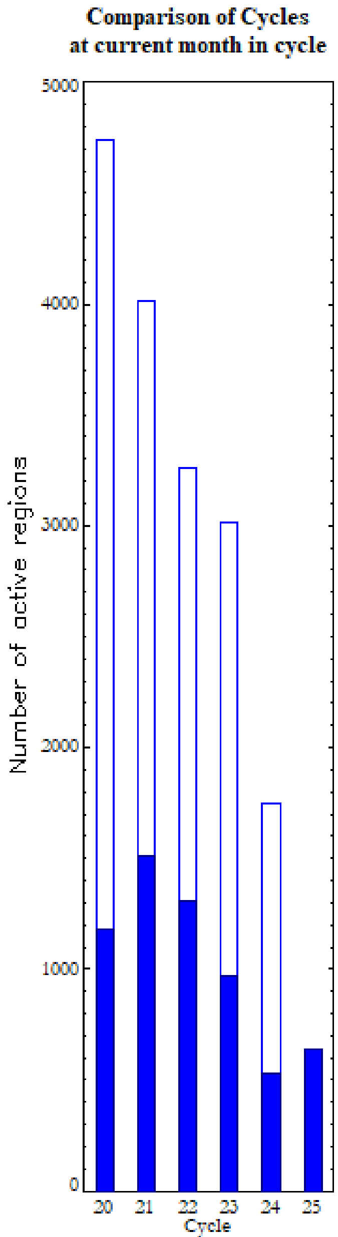


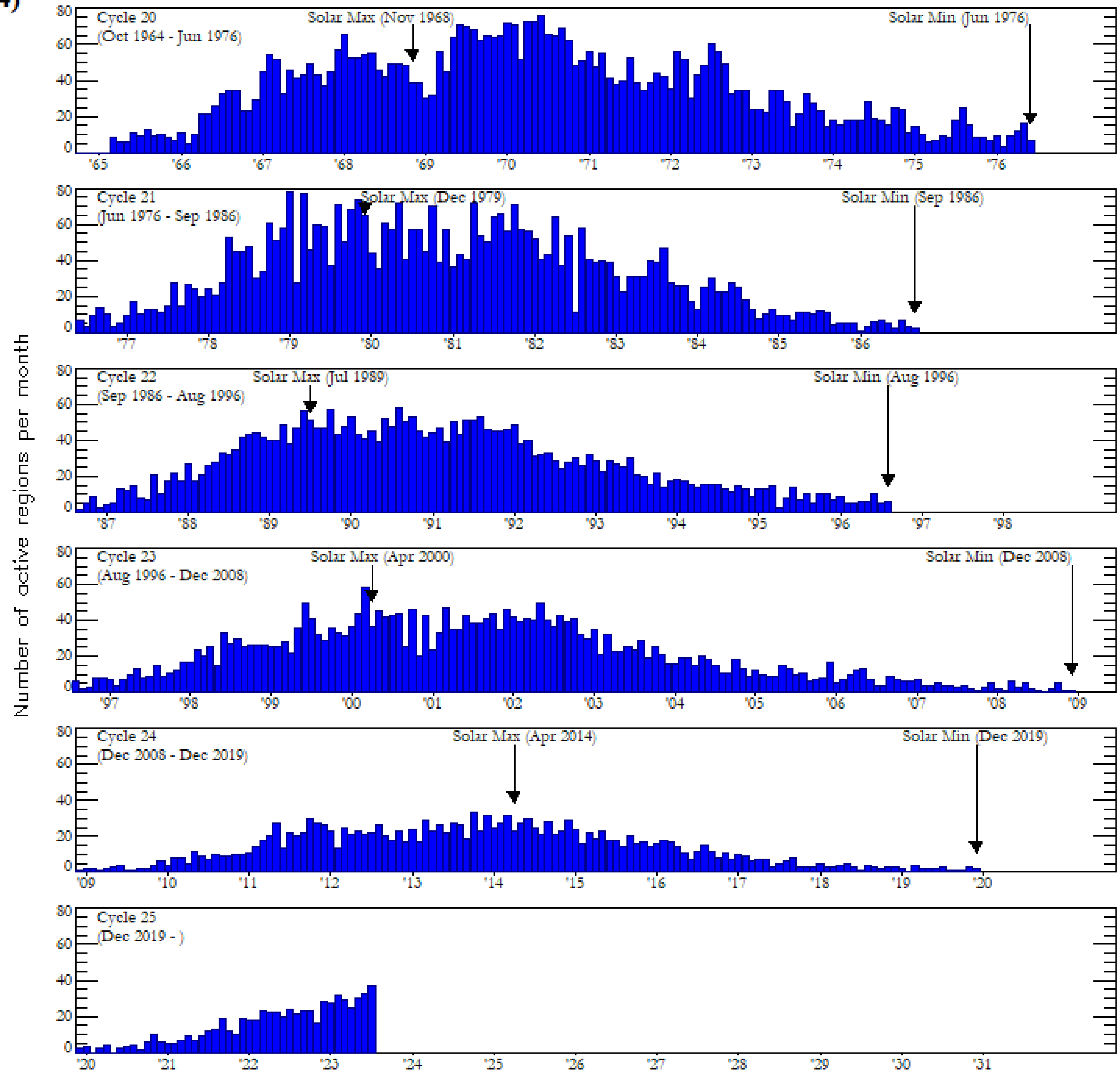
Long Term Perspective – Sunspot Number & aa-index



Active Regions

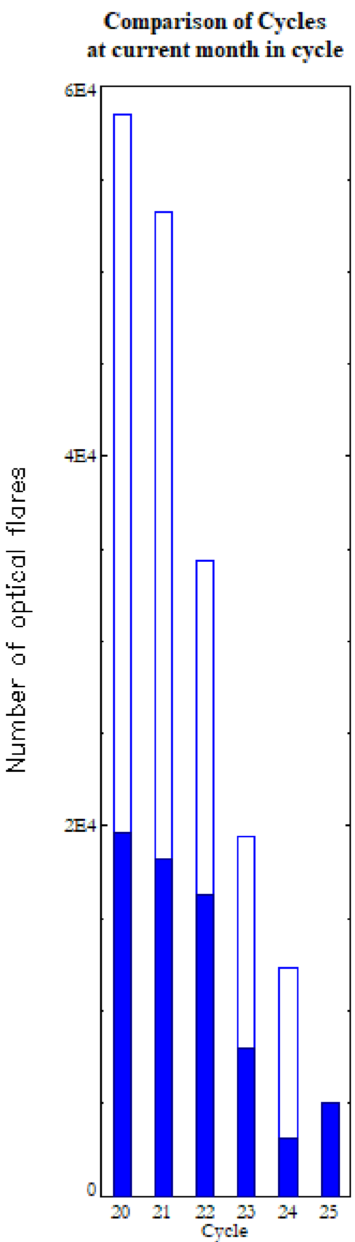
July 2023 **(Month 44)**

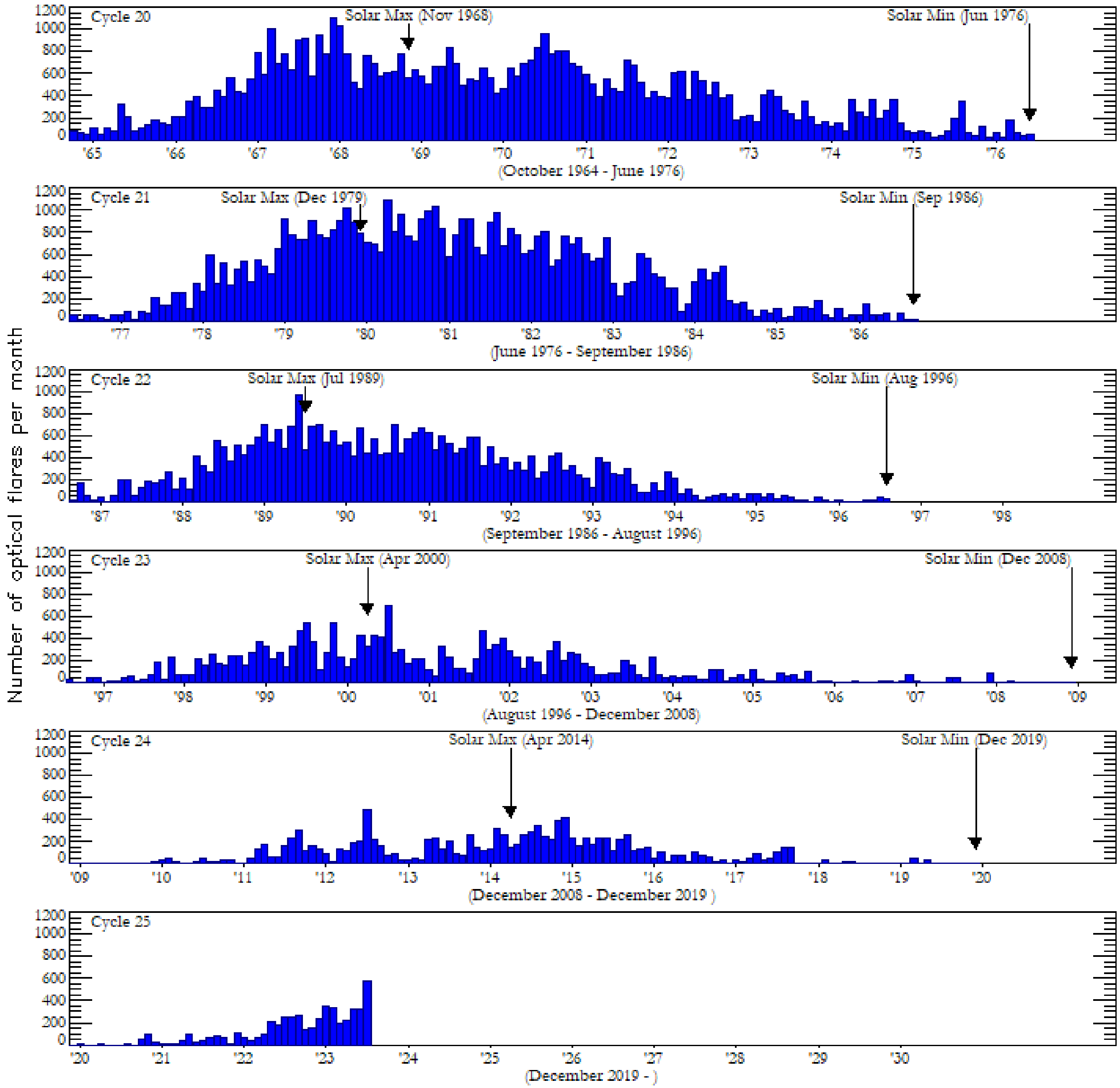




Optical Flares

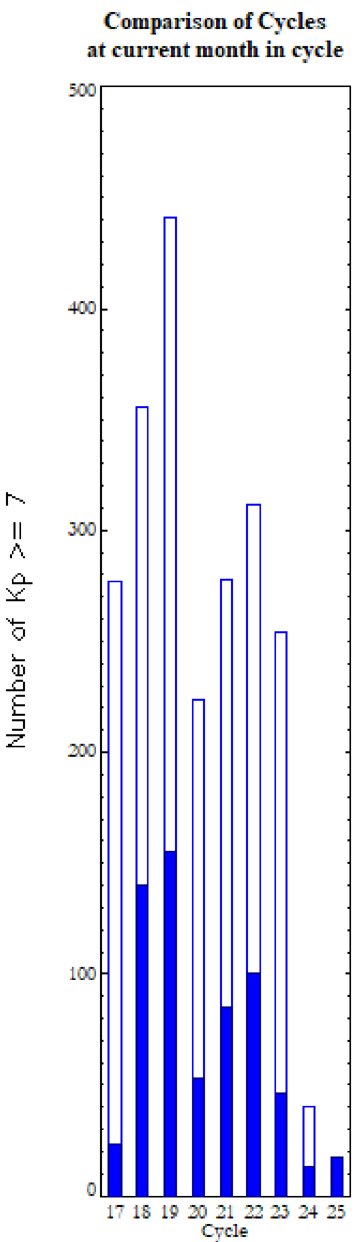
July 2023 **(Month 44)**

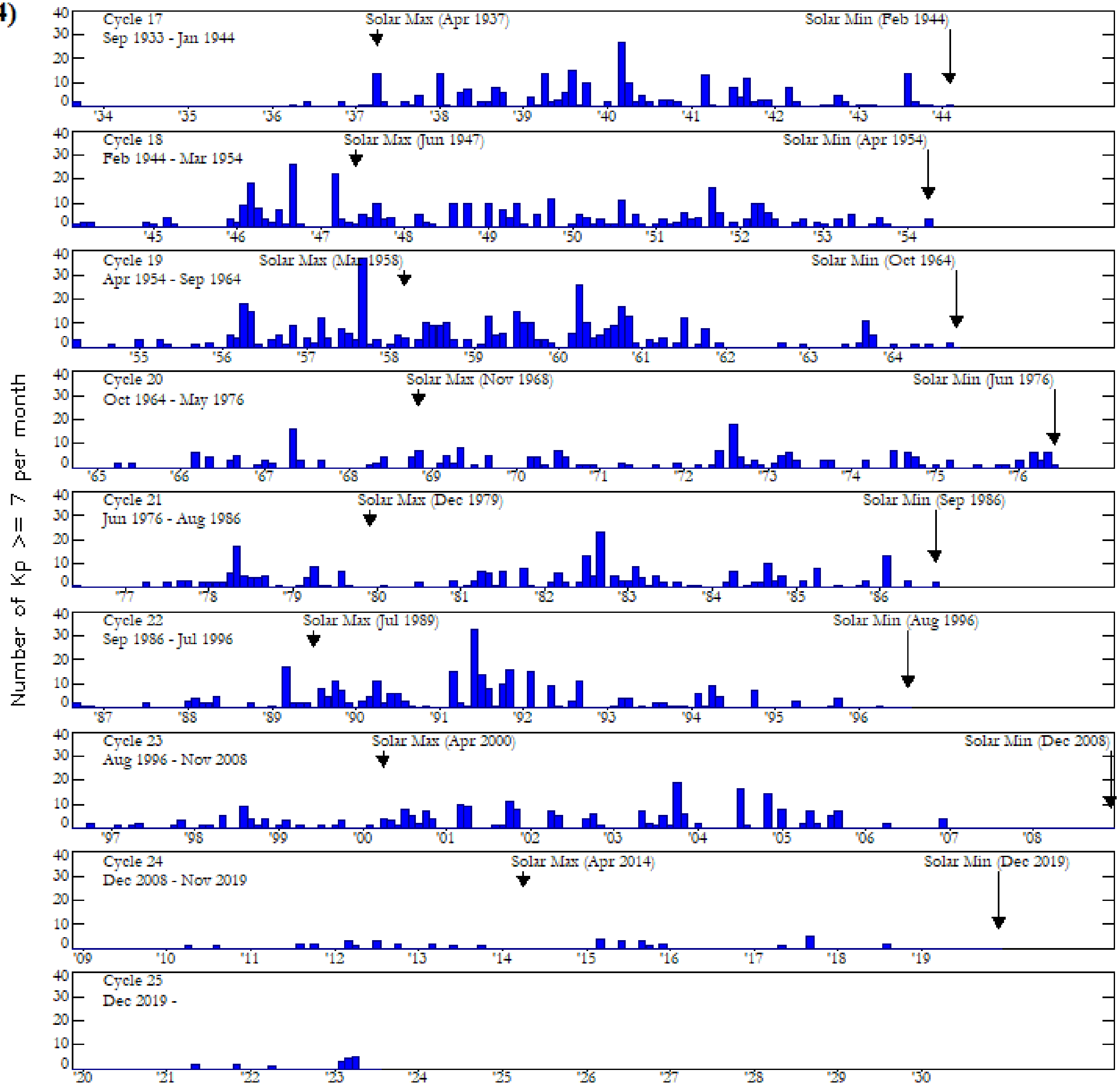




Periods with Kp >= 7

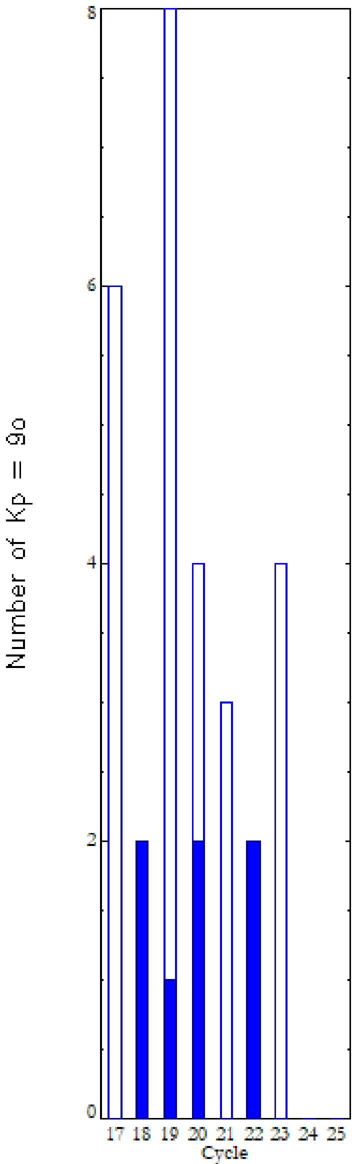
July 2023 **(Month 44)**

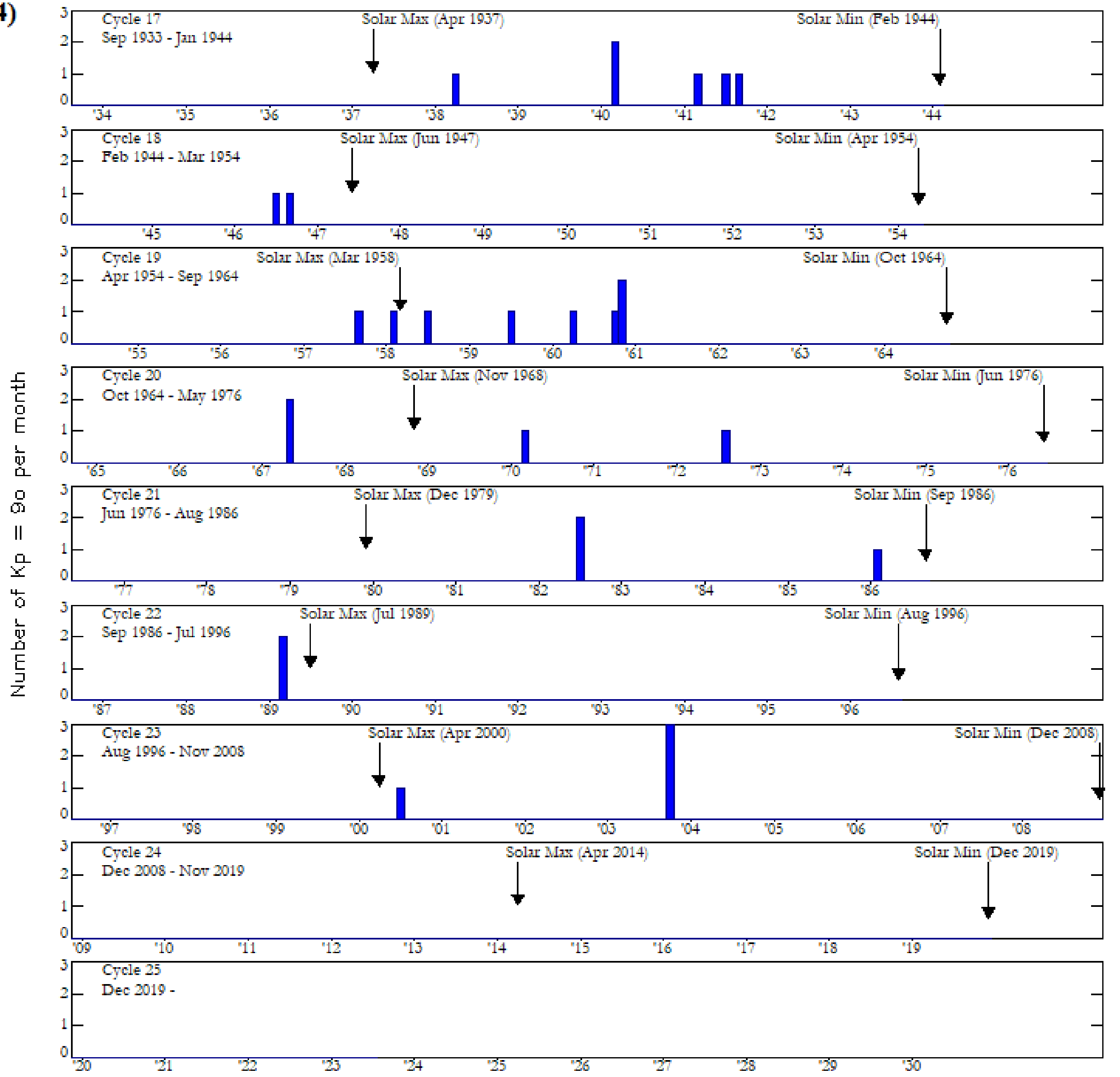




Periods with Kp = 9o

July 2023 **(Month 44)**



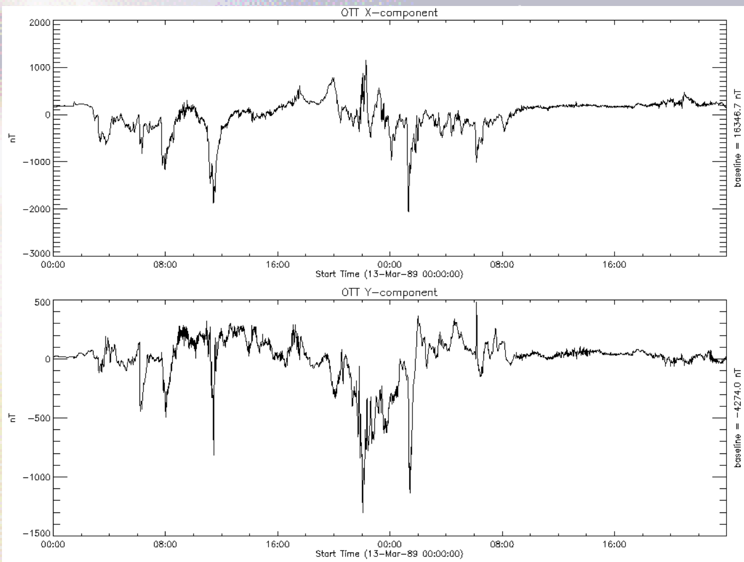


Geoelectric Field Modeling

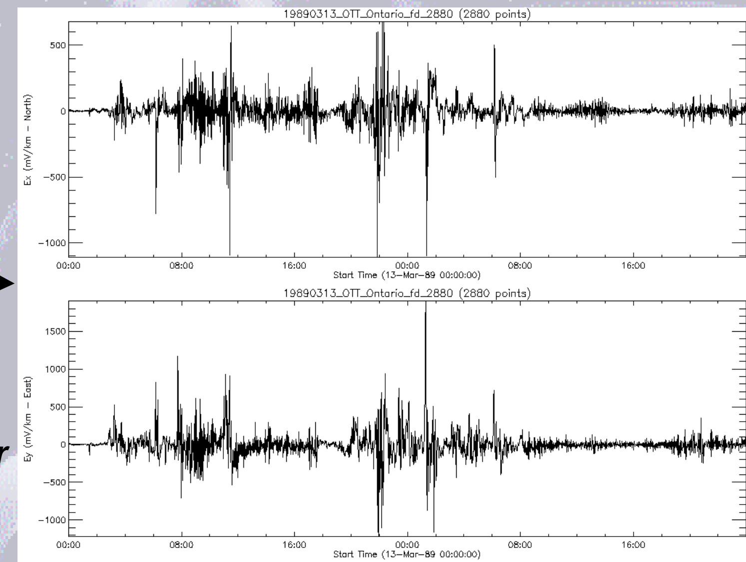
Motivation

- To provide the Electric Power Industry a better indicator than a global index to specify geomagnetic activity levels
- Geoelectric Field provides targeted, local-regional description of activity that is directly related to system impact
- Together with a system model, the geoelectric field provides an estimate of geomagnetically induced current in the system

Geoelectric Field Calculation



$$\rightarrow \begin{bmatrix} \tilde{Z}_{xx}(f_k) & \tilde{Z}_{xy}(f_k) \\ \tilde{Z}_{yx}(f_k) & \tilde{Z}_{yy}(f_k) \end{bmatrix} \rightarrow$$



Earth Conductivity:

-frequency dependent filter
-varies with location
-depends on structure below the mud

Input: Geomagnetic Field Time Series

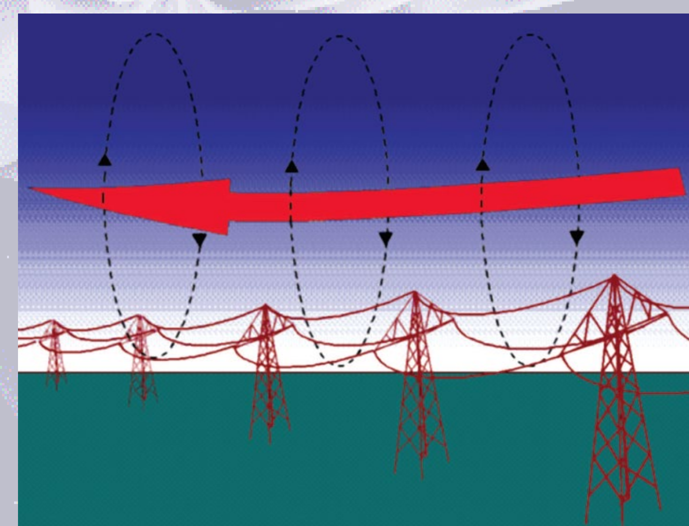
March 13-14, 1989 Geomagnetic storm observed at Ottawa (NRCAN)

Output: Geoelectric Field Time Series

Calculated Geoelectric Field with a simple conductivity model

Methods to determine the filter:

- One-dimensional multi-layer models (conductivity varies with depth) allow the filter to be calculated numerically (Trichtchenko – 2019, EPRI models - 2020)
- 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 (3D empirical model)
- MT data used with ModEM MT inversion code (Kelbert et al 2014) to generate high resolution 3D electrical conductivity model



Time varying currents in space induce currents in the Earth and in artificial conductors at the surface - Boteler (2015)

NOAA

E-field maps dataflow – Joint SWPC/NRCAN US-Canada 1D E-field Product

USGS observatories (9)
B-field time series

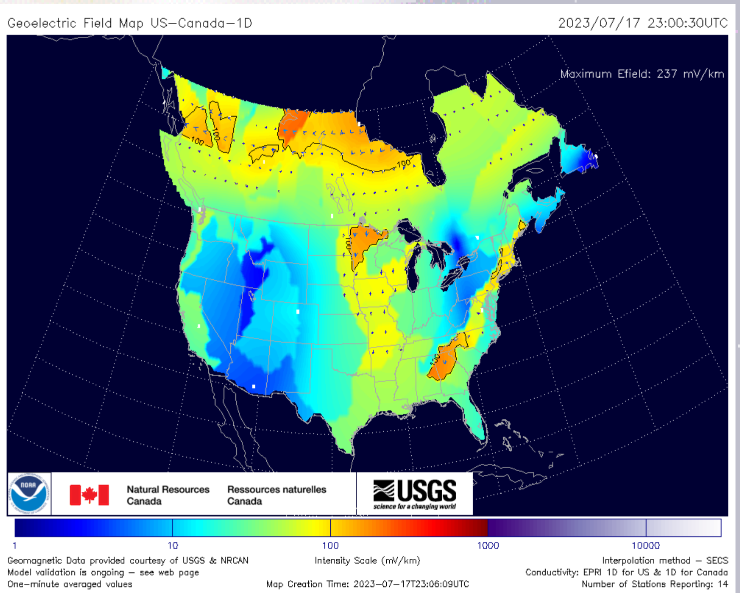
NRCAN observatories (9)
B-field time series

Detrending Algorithm

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

E-field calculation
-1D models over US & Canada
-0.5 degree spatial resolution
-6763 grid points

Near real-time E-field products
-graphical maps
-gridded data files
-daily netcdf for archive/repository
-GeoJSON format for dissemination

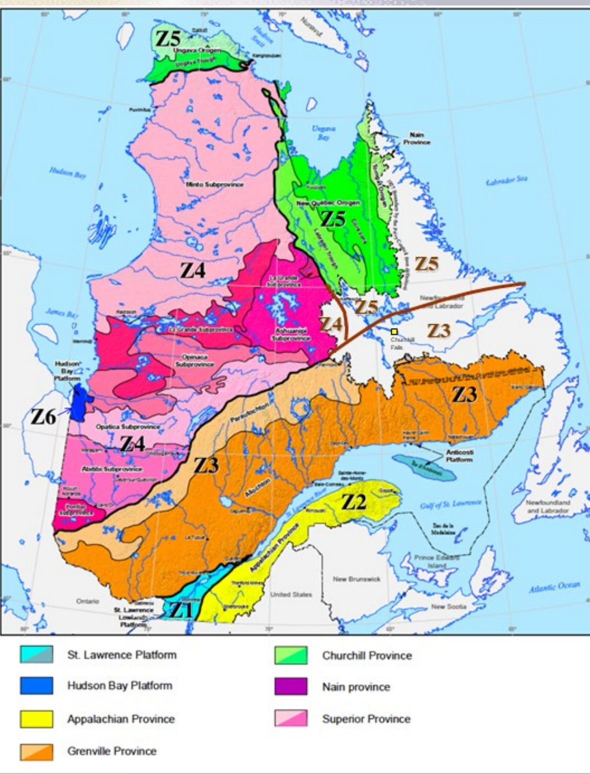


SWPC operational deployment on 6/21/2023
NRCAN to deploy on their systems later this year

URLs
https://www.swpc.noaa.gov/products/geoelectric-field-models-1-minute
https://services.swpc.noaa.gov/json/lists/rgeojson/US-Canada-1D/

1D models over Canada

- **NRCAN developed models for Canada**
- **74 physiographic regions and 1D models** (Trichtchenko et al, 2019)
- **Surface impedance calculated numerically** (Dmitriev & Berdichevsky, 1979)



Changes of resistivity with depth for 6 Zones of resistivity models for Quebec

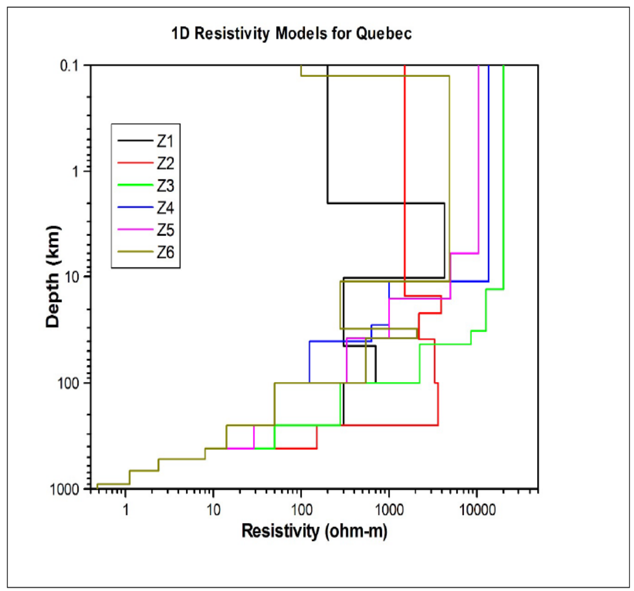


Figure 4.9.2. Variation of the resistivity for Quebec. Vertical scale is depth in kilometers, horizontal scale is resistivity in Ohm·meter

Natural Resources Canada / Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8594

One-dimensional Layered Earth Models of Canada for GIC Applications

Part 1. General Description

L. Trichtchenko, P.A. Fernberg, and D.H. Boteler

2019

Canada

← Sample of the Canadian models for Quebec Province

1D models over CONUS

- **EPRI developed models for CONUS**
- **19 physiographic regions and 1D models** (Gannon, Leonardi, Arritt, 2020)
- **Surface impedance calculated numerically** (Dmitriev & Berdichevsky, 1979)

Improving Conductivity Models for Geomagnetically Induced Current (GIC) Estimation

Guidance for Validation of GIC Models

3002017897

Technical Update, March 2020

EPRI Project Manager

R. Arritt

ELECTRIC POWER RESEARCH INSTITUTE
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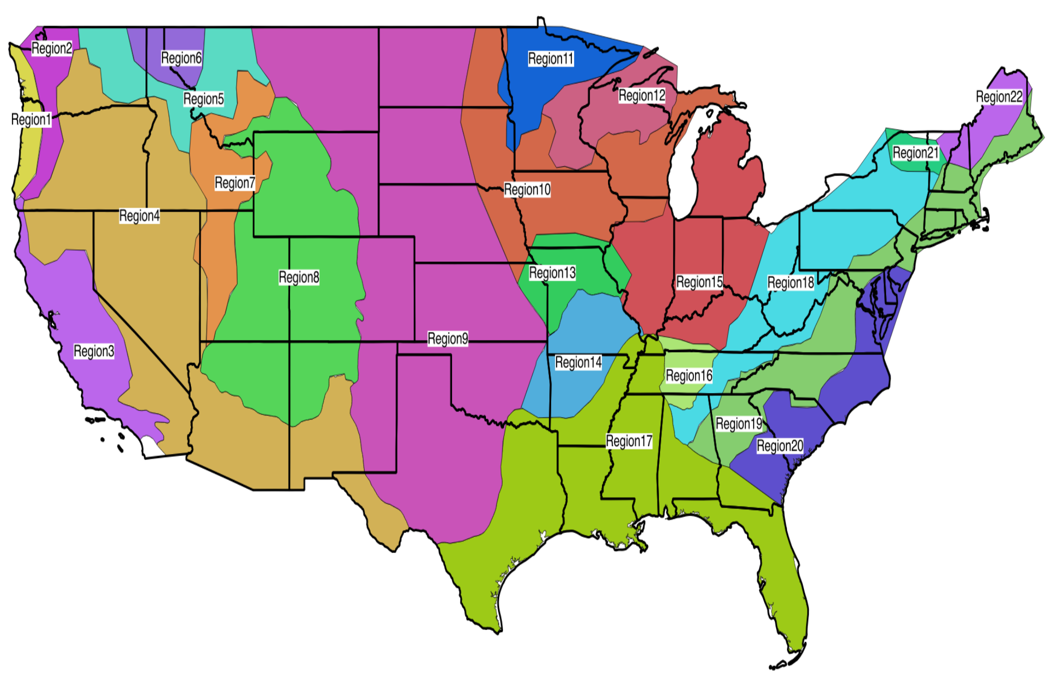

ACKNOWLEDGMENTS

The following organizations prepared this report:

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Electric Power Research Institute (EPRI)
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Principal Investigators
B. Leonardi
R. Arritt

This report describes research sponsored by EPRI.

The results presented in this report rely on the data collected at Ottawa Observatory (OTT) and by the Earthscope MT Survey.

EPRI thanks National Resources Canada for supporting its operation and INTERMAGNET for promoting high standards of magnetic observatory practice (www.intermagnet.org).

EPRI also thanks the National Geoelectromagnetic Facility and the IRIS DMC for the preparation and online availability of the EMTF resources.

This publication is a corporate document that should be cited in the literature in the following manner:

Improving Conductivity Models for Geomagnetically Induced Current (GIC) Estimation: Guidance for Validation of GIC Models. EPRI, Palo Alto, CA: 2020. 3002017897.

iii

E-field maps dataflow – 3D empirical model

USGS observatories (9)
B-field time series

NRCAN observatories (9)
B-field time series

→ ***Detrending Algorithm***

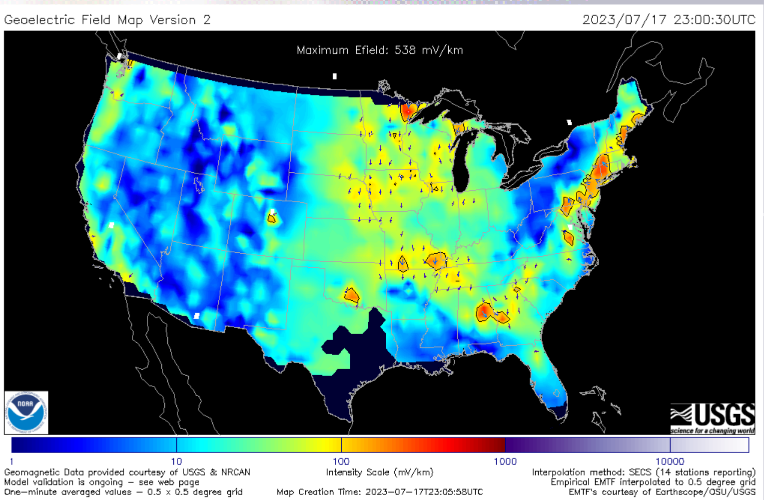
→ ***Interpolation Algorithm***
B-field on <u>0.5°x0.5° grid</u>
<u>daily netcdf for archive</u>

→ ***<u>E-field calculation</u>***

- ***NSF USArray/USGS-NASA USMTArray empirical magnetotelluric impedances covering CONUS on a quasi-regular 70 km grid***
- ***Convert to impulse responses***
- ***Convolve with B-field***
- ***Interpolate to 0.5° x 0.5° grid***

→ ***<u>Near real-time E-field products</u>***

- ***graphical maps***
- ***gridded data files***
- ***daily netcdf for archive/repository***
- ***GeoJSON format for dissemination***



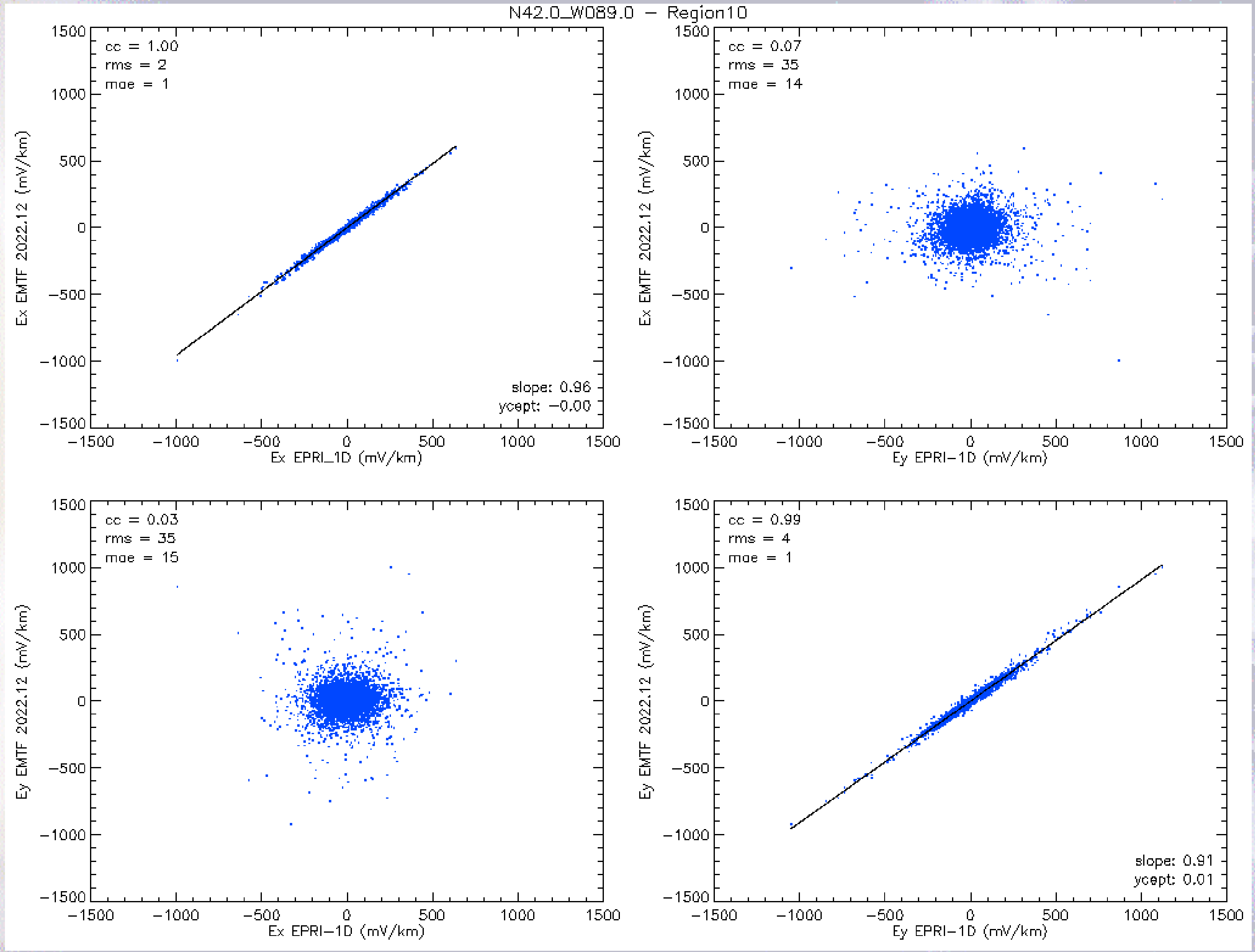
- ***Initial Operational Release September 2020***
- ***Three upgrades as new surveys have been published***
- ***Latest Upgrade June 2023***
  - ***Includes EMTF surveys as of December 2022***
  - ***1468 surveys included***
  - ***3433 grid points***

URLs
https://www.swpc.noaa.gov/products/geoelectric-field-models-1-minute
https://services.swpc.noaa.gov/json/lists/rgeojson/InterMagEarthScope/

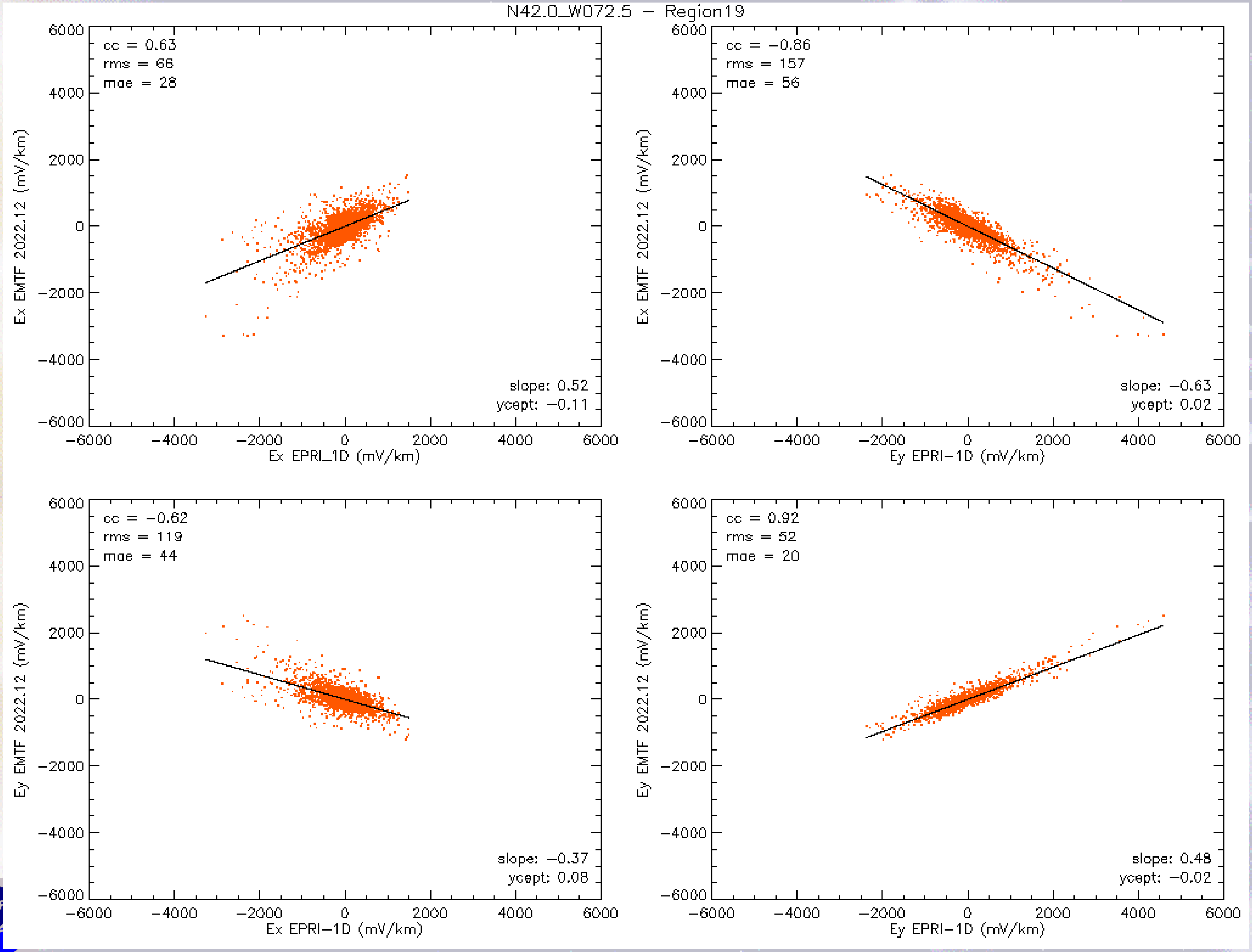
Comparison: 1D models with 3D empirical model

- Side-by-side comparison: EPRI-1D model with 3D empirical model (1/2 degree resolution for both models, EMTF 2022.12 version)
- Compare 93 days: 1-31 March 1989, 1-31 July 2000, 1-31 October 2003 (for a total 133,920 time steps)
- EPRI-1D compared with 3D empirical: 3215 grid points compared
  - 3215 Scatterplots: Ex vs Ex, Ex vs Ey, Ey vs Ex, Ey vs Ey
- Statistics at each grid point:
  Ex1Min, Ex1Max, Ey1Min, Ey1Max, Ex2Min, Ex2Max, Ey2Min, Ey2Max, Erange
  Ex1,Ex2: cc, rms, mae, b (y-cept), m (slope),
  Ey1,Ex2: cc, rms, mae, b (y-cept), m (slope),
  Ex1,Ey2: cc, rms, mae, b (y-cept), m (slope),
  Ey1,Ey2: cc, rms, mae, b (y-cept), m (slope)

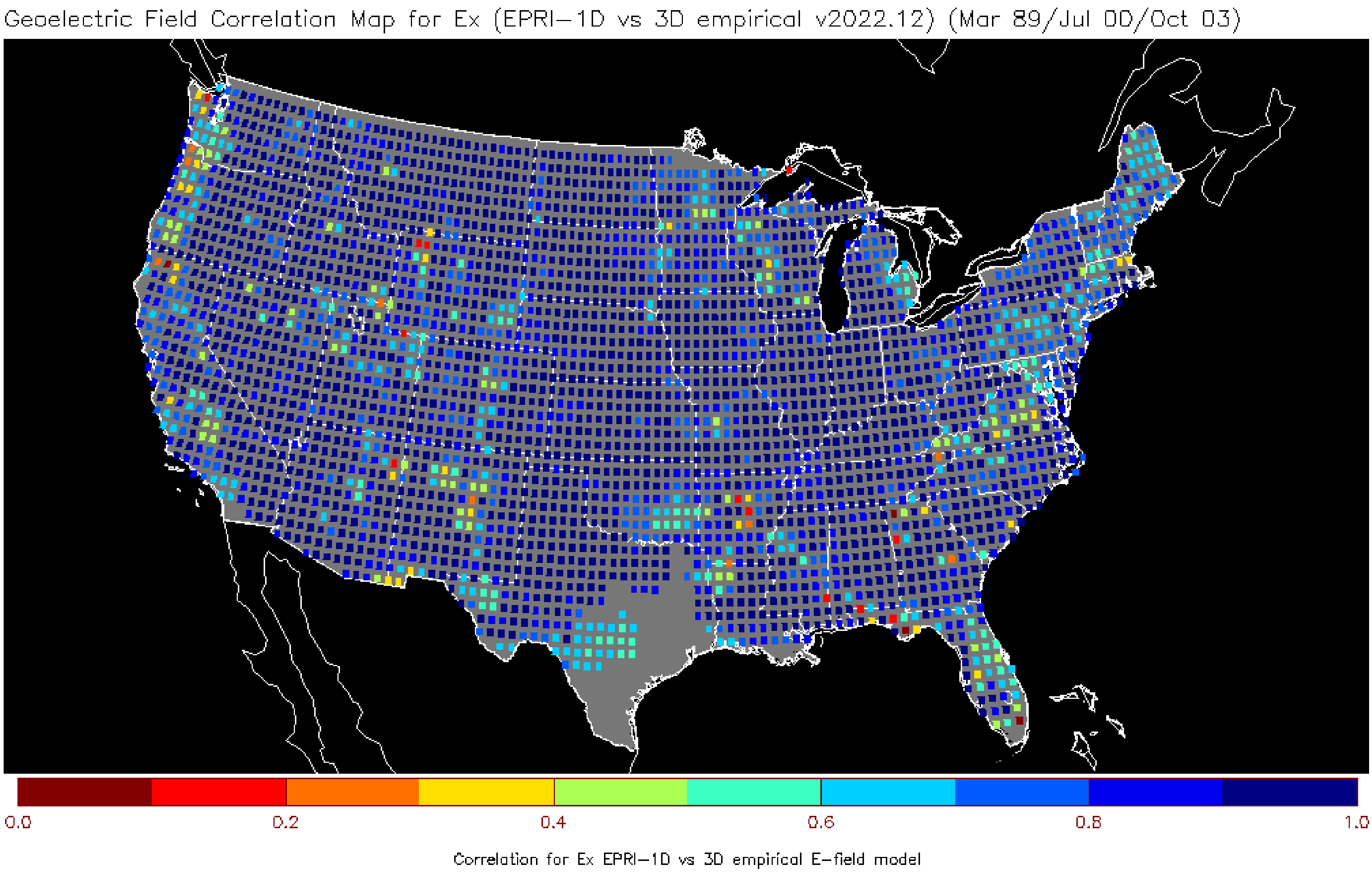
Scatterplot example



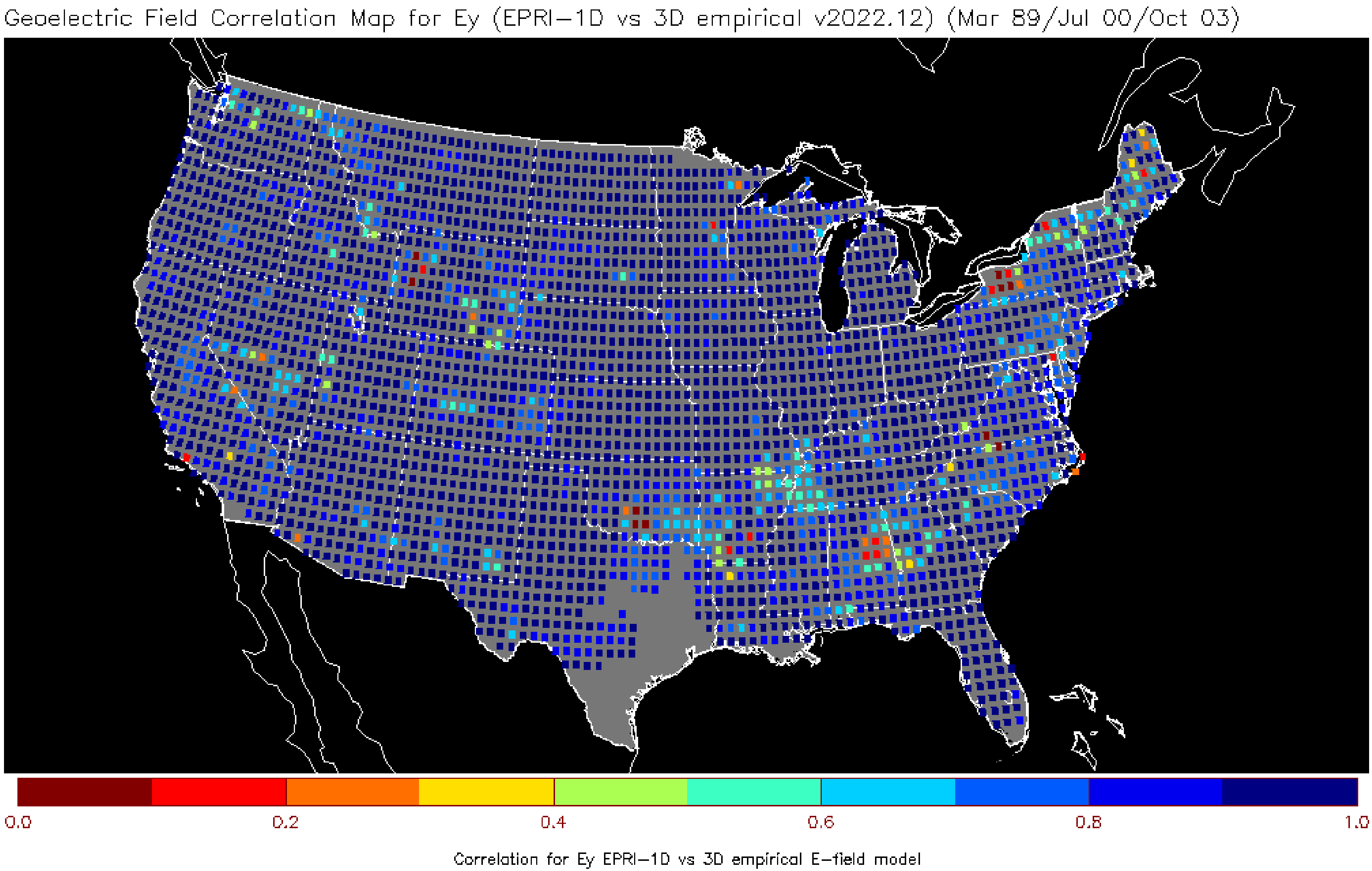
Scatterplot example



Ex correlation map: 1D vs 3D models



Ey correlation map: 1D vs 3D models



Correlation Categories

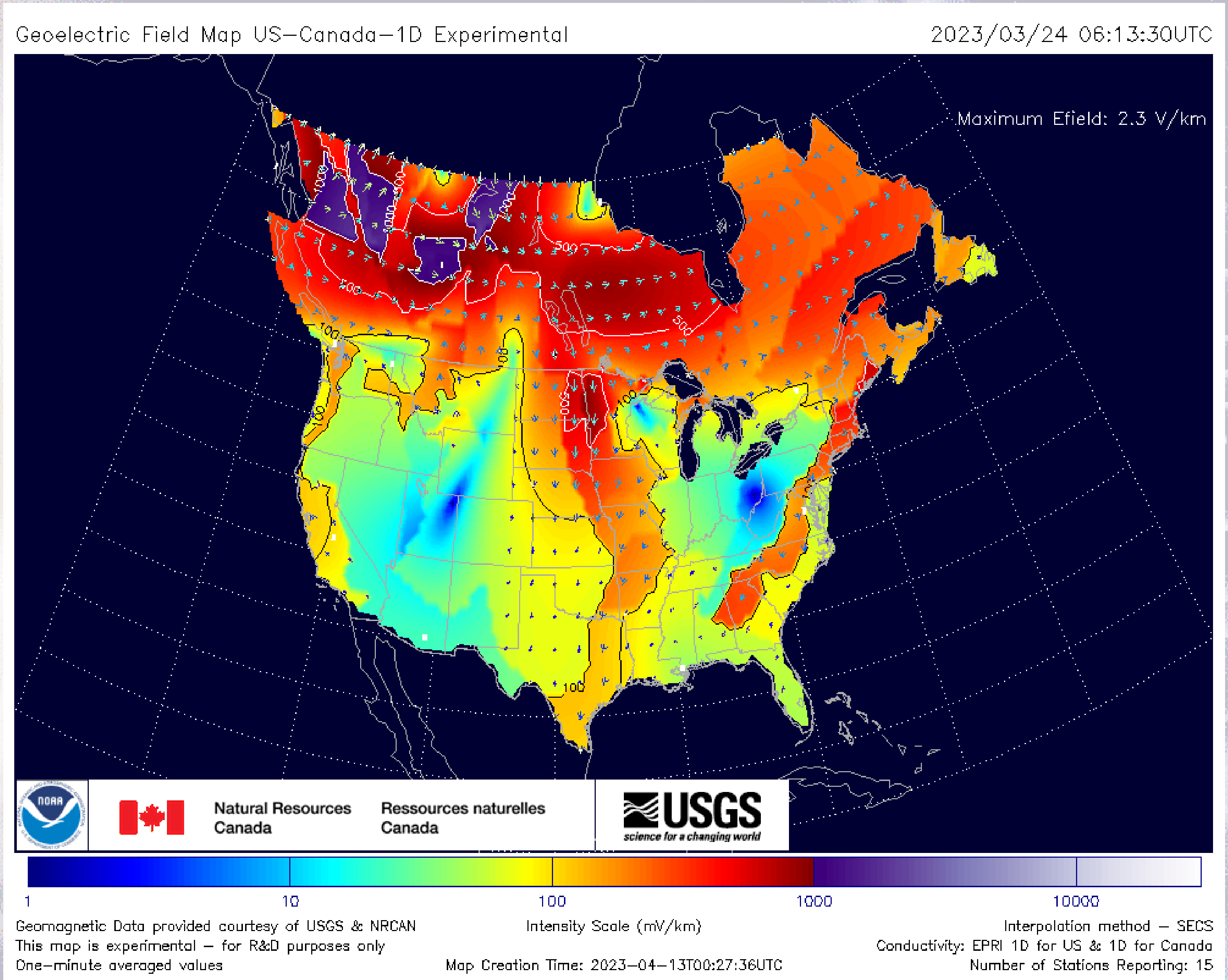
	Counts ccx1x2	Counts ccy1y2	Percent cx1x2	Percent y1y2	Cumulative % x1x2	Cumulative % y1y1
0.90 and up	1891	2268	58.82%	70.54%	58.82%	70.54%
0.80 to 0.90	619	536	19.25%	16.67%	78.07%	87.22%
0.70 to 0.80	316	202	9.83%	6.28%	87.90%	93.50%
0.60 to 0.70	164	88	5.10%	2.74%	93.00%	96.24%
0.50 to 0.60	100	41	3.11%	1.28%	96.11%	97.51%

Counts out of 3215 grid points

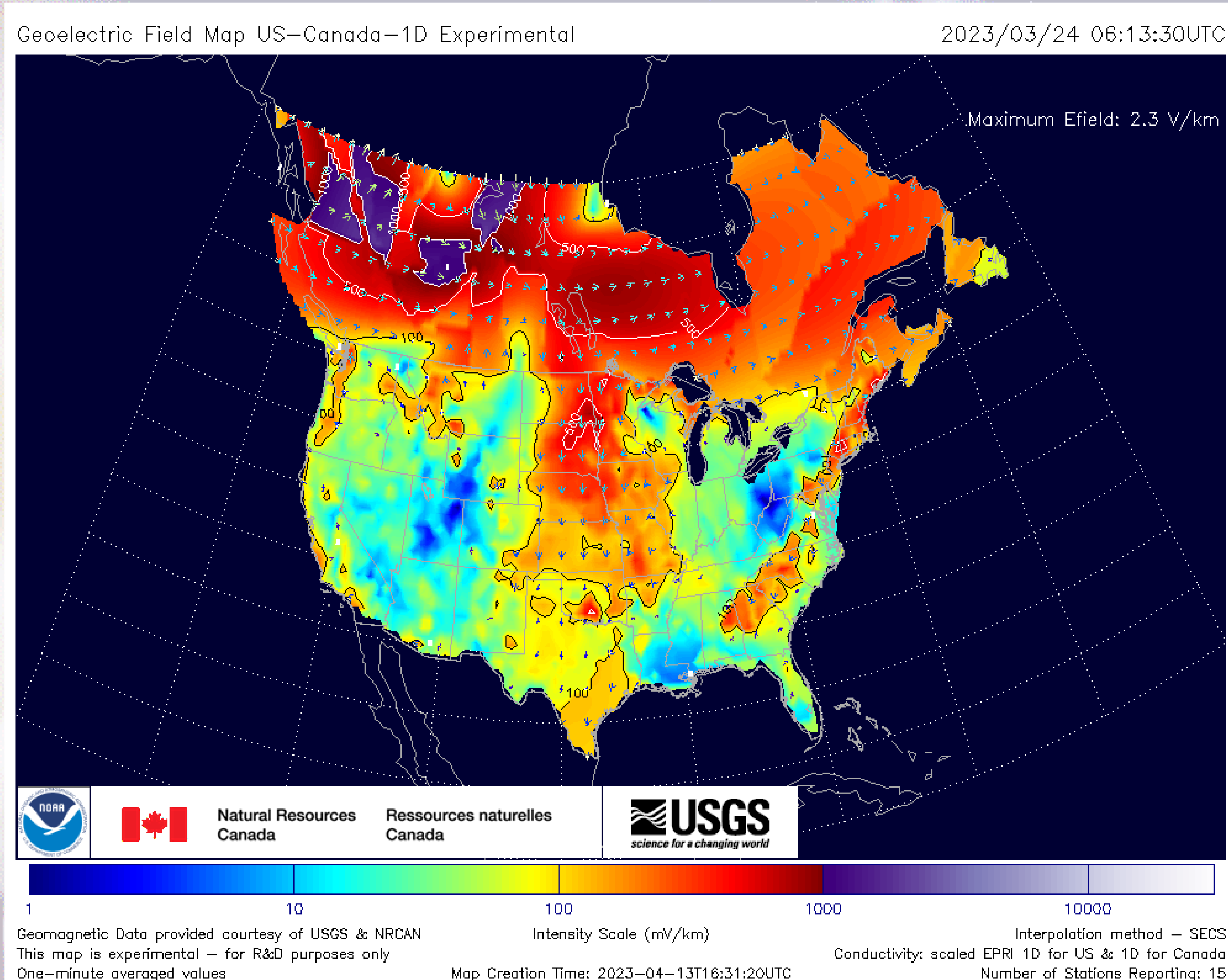
Findings

- For Ex: 87.9% of the grid points have correlation ≥ 0.70
- For Ey: 93.5% of the grid points have correlation ≥ 0.70

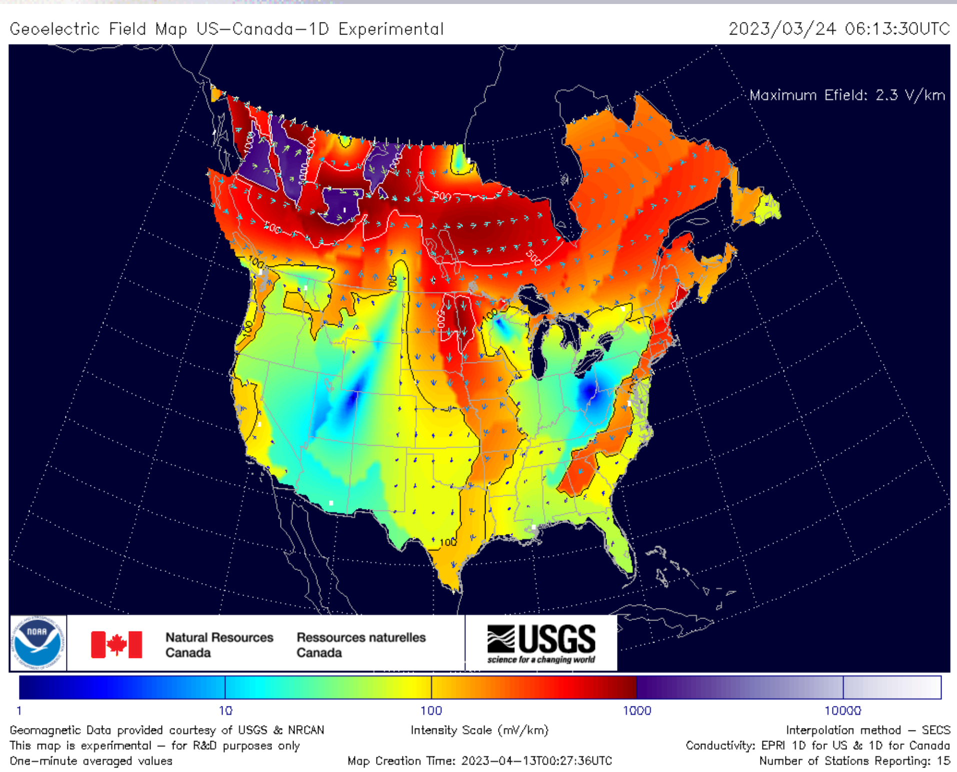
US-Canada Map during G4 storm

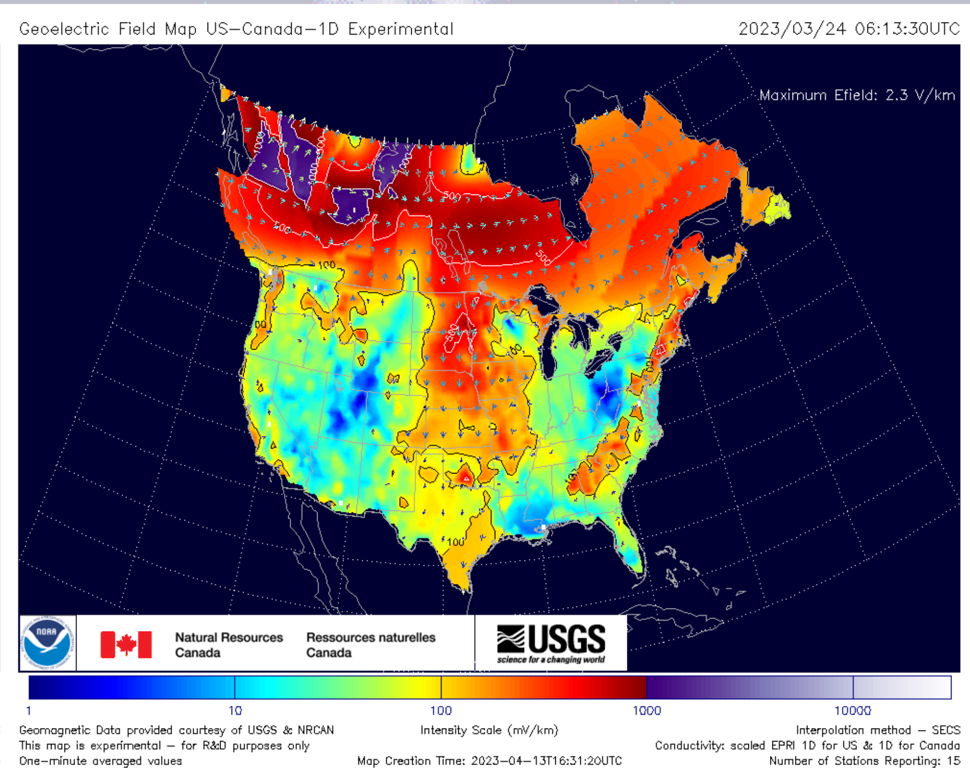


US-Canada Map with scaling factors applied



Side-by-side comparison





- Side-by-side snapshot – US-Canada E-field map
- Left – EPRI 1D models (CONUS) and NRCAN 1D models (Canada)
- Right EPRI 1D models scaled based on comparison with 3D empirical models
    - Linear scaling corrections applied for points with correlation ≥ 0.70

Validation Studies

- The validation of E-field maps for GIC applications is ongoing
- Our approach is to partner with industry to compare calculated GIC with measurements
- We select intervals of disturbed geomagnetic activity, calculate the geoelectric field, and then estimate GIC in the system using system models
- For the system model
  - Off the shelf, vendor provide tools can be used. Many of these tools are able to ingest the geojson format E-field results we provide
  - For simpler situations, we can integrate the E-field along transmission line pathways to get the induced voltage, then do a circuit analysis to determine current flows, including the current flowing at locations where a GIC measurement is being made
    (following Lentinen & Pirjola, 1985, Horton et al. 2012 methodology)
- Once a model is validated, it is then possible to study the impact of more extreme storm events (e.g. March 1989) and have some confidence about the results

SCE Validation Study

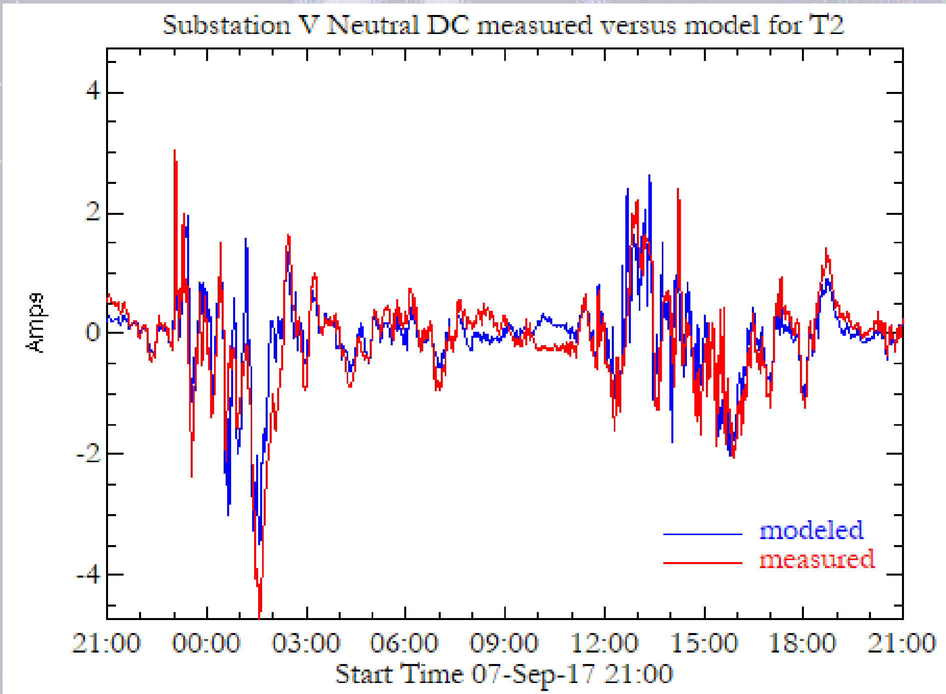
- **We compare measured and modeled GIC for two storms in substation V**
- **The Geoelectric field is integrated along lines between the next neighboring substations**
- **Using line resistances, and resistance from the substation nodes to remote earth, we calculate the voltages at the substation nodes**
- **Using the details of the circuit in substation V, we calculate the current flowing through one of the transformers where measurements were made**

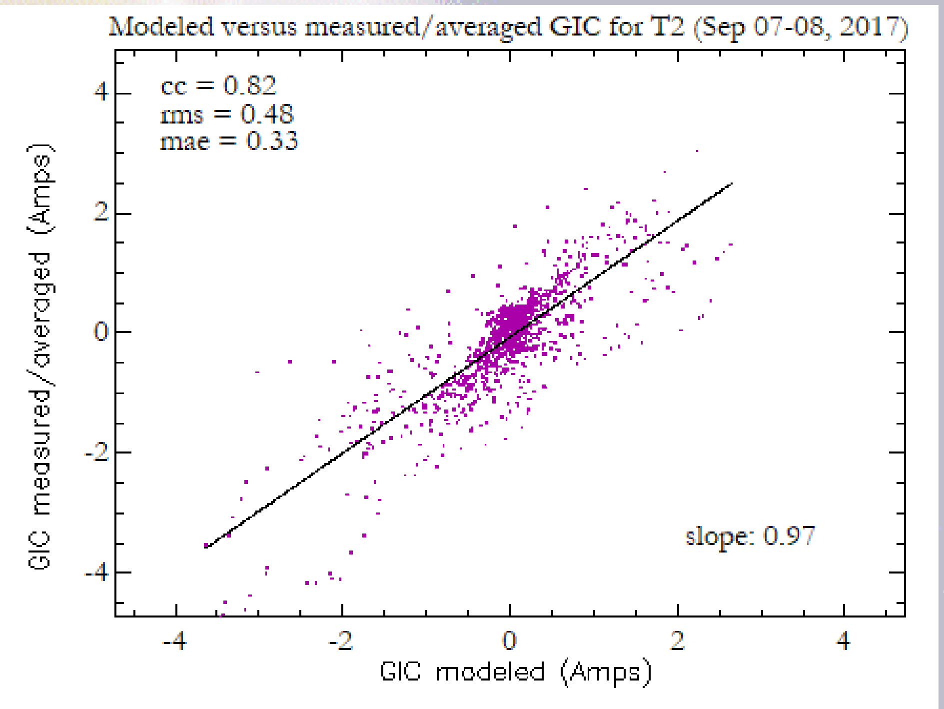
SCE Study Area
-Substations are the white squares
-500 kV lines shown in red
-230 kV lines shown in cyan
-MT survey sites shown in orange
-Black triangles are the 0.5°x0.5° grid

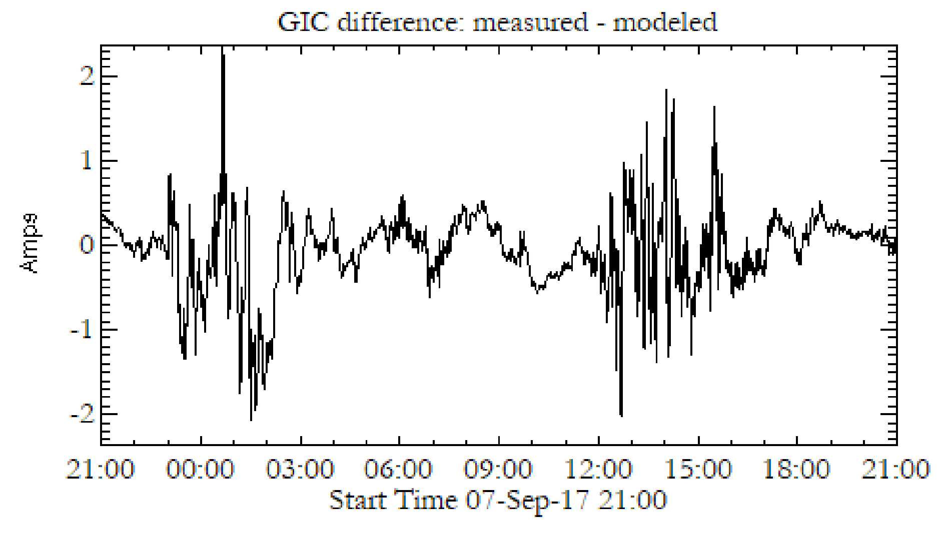
Balch et al., 2023, Proceedings IEEE Energy Conversion Congress & Exposition

SCE Validation Study – Model vs Measurement

- **Results for G4 geomagnetic storm on September 07-08, 2017**
- **Calculated GIC (blue) and measurement (red) time series show reasonable agreement**
- **Scatterplot indicates correlation at 0.82, and best fit linear regression slope of 0.97**

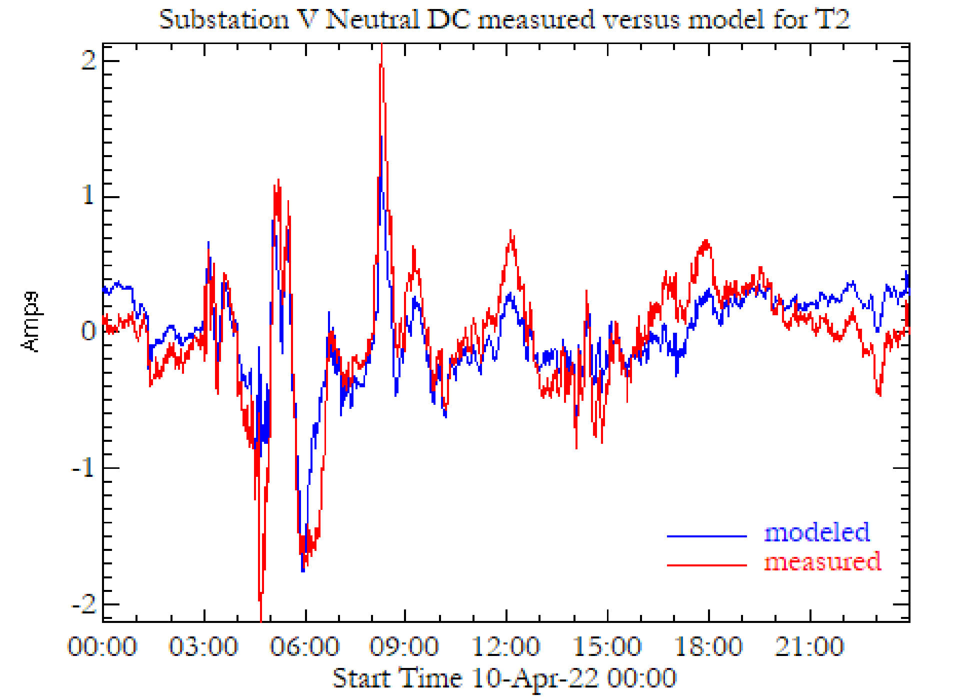


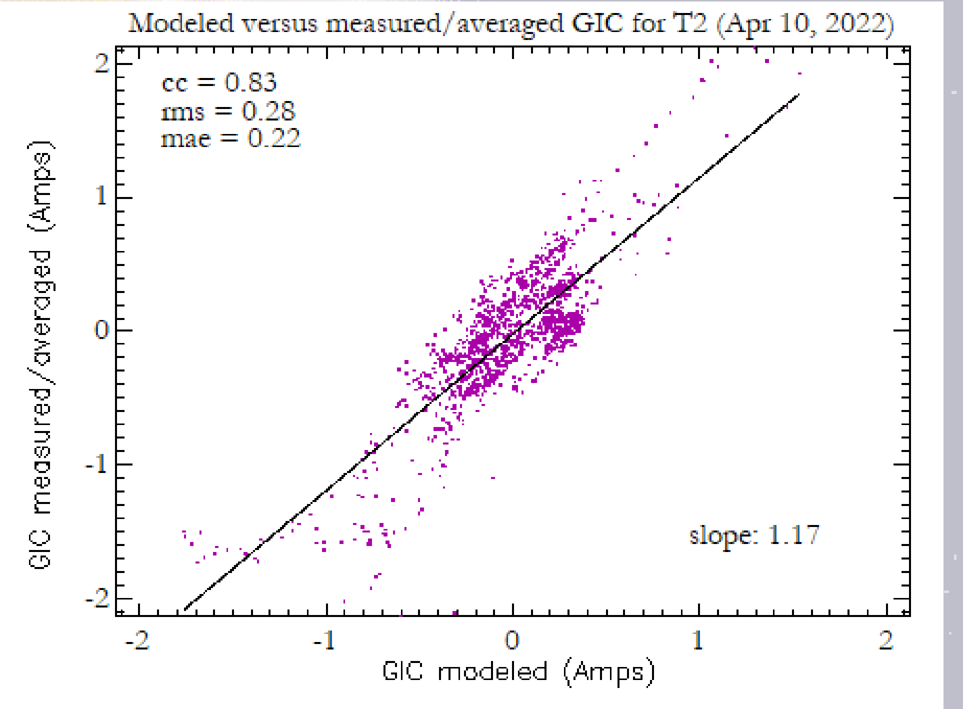


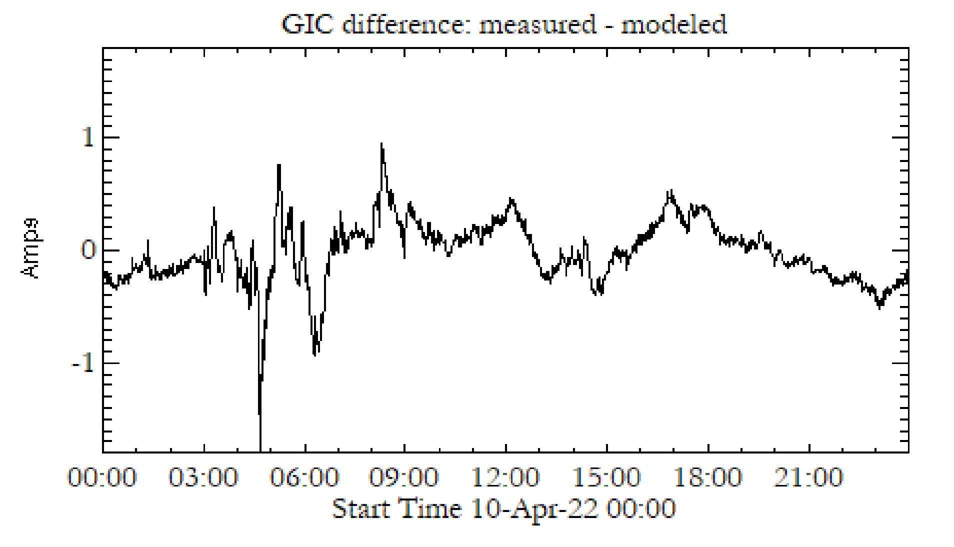


SCE Validation Study – Model vs Measurement

- **Results for G3 geomagnetic storm on April 10, 2022**
- **Calculated GIC (blue) and measurement (red) time series show reasonable agreement**
- **Scatterplot indicates correlation at 0.83, and best fit linear regression slope of 1.17**



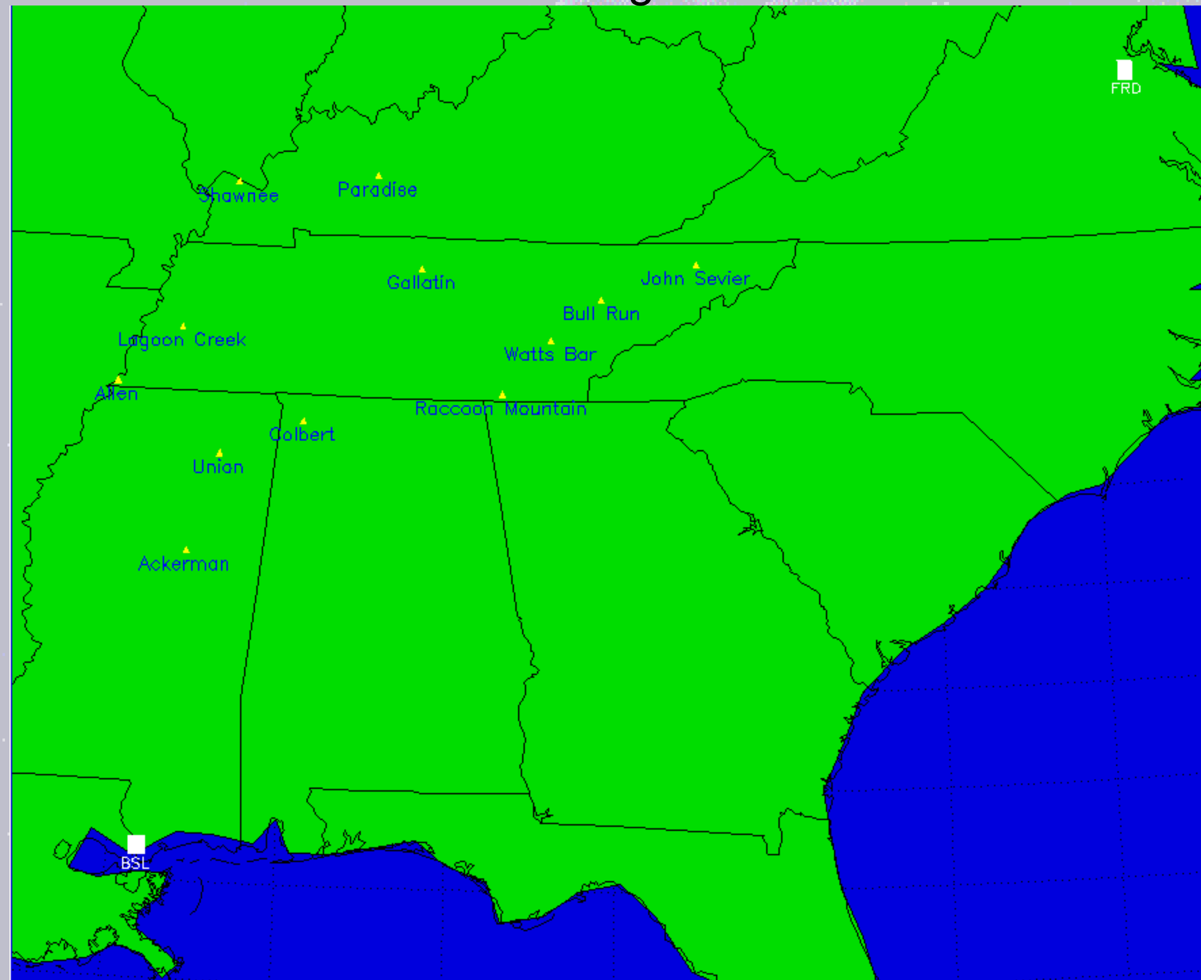




TVA Validation Study – Work in Progress

12 TVA magnetometers
2 USGS magnetometers

TVA Magnetometers (Storm Data)			
Ackerman	y	y	y
Allen	y	y	y
Bull Run		y	y
Colbert	y	y	y
Gallatin	y	y	y
John Sevier		y	y
Lagoon Creek			
Paradise	y		
Raccoon Mountain	y	y	y
Shawnee			
Union	y	y	y
Watts Bar	y	y	y



Storms

May 12, 2021
November 03-04, 2021
April 10, 2022

Data provided courtesy of TVA through the EPRI SUNBURST project

TVA Validation Study – Work in Progress

TVA GIC sensors	(Storm Data)		
Bradley	Y	Y	Y
Bull Run	Y	Y	Y
East Point			
Gleason			Y
Johnsonville			Y
Paradise			
Madison	Y		Y
Montgomery		Y	Y
Pinhook			
Raccoon Mountain			
Rutherford	Y		Y
Shelby	Y	Y	Y
Southaven	Y	Y	Y
Sullivan	Y	Y	Y
Union	Y	Y	Y
Weakley	Y	Y	Y
Widows Creek 1	Y	Y	Y
Widows Creek 2	Y	Y	Y

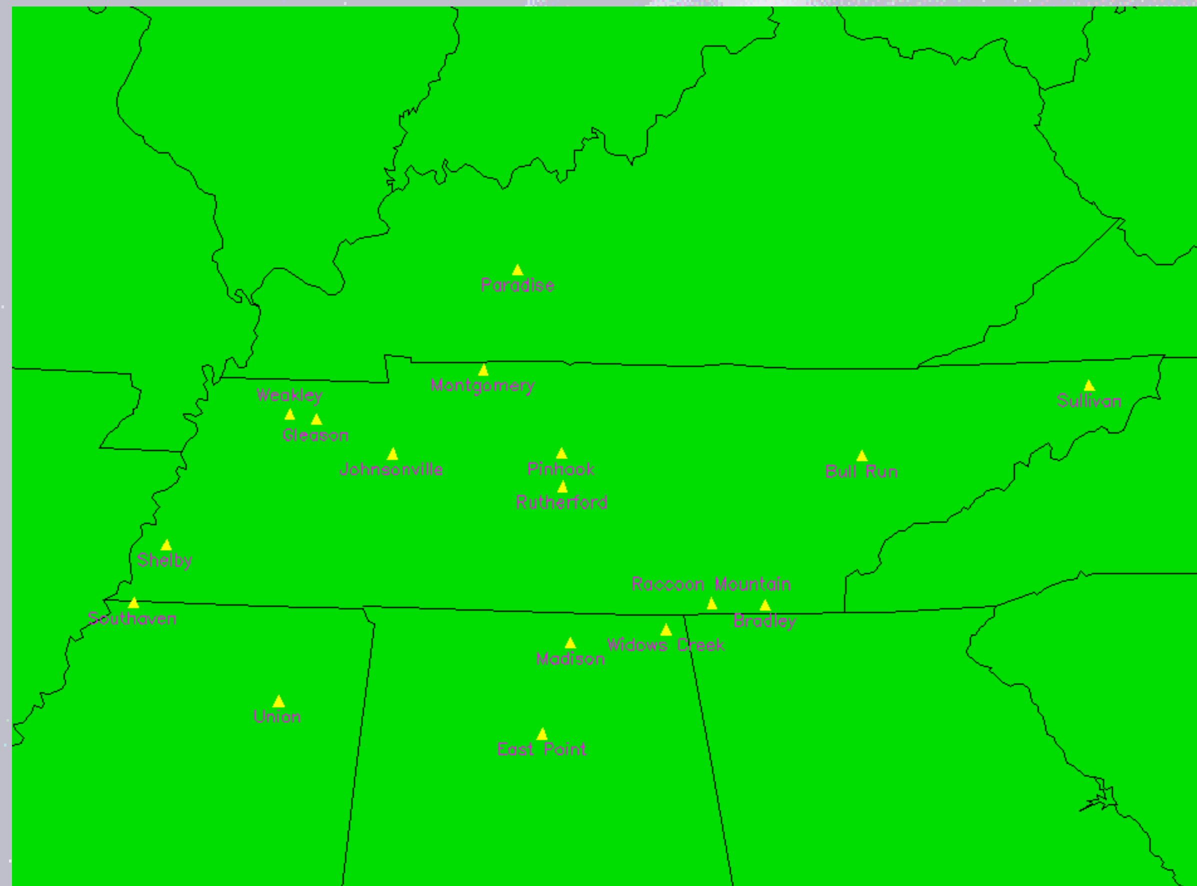
Storms

May 12, 2021

November 03-04, 2021

April 10, 2022

18 TVA GIC monitors

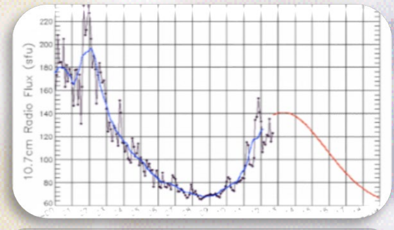


Data provided courtesy of TVA through the EPRI SUNBURST project

Predictive Geoelectric Field Product – Geospace Model

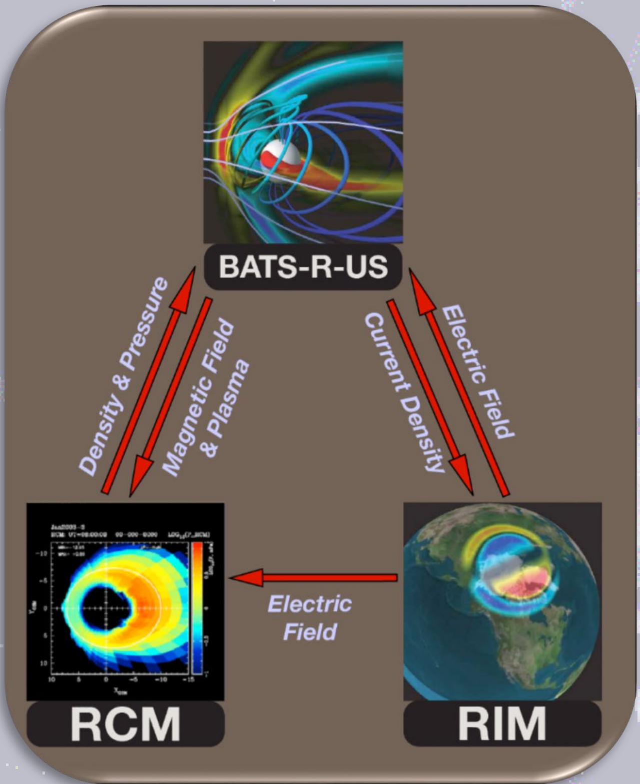
Geospace model inputs

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

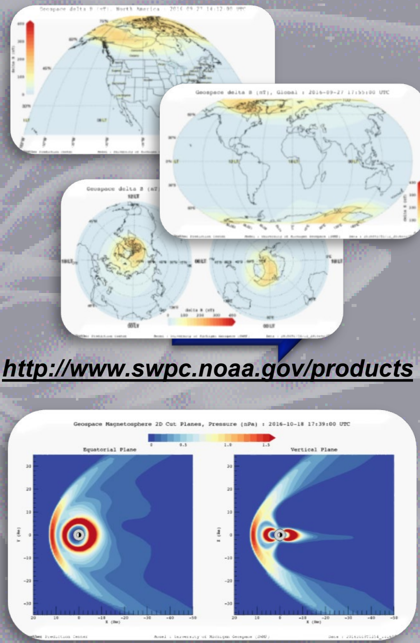


Solar F10.7 Radio Flux

Model Runs on NWS Operational Supercomputer



Operational SWMF



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

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

Predictive Geoelectric Field Product – Concept of Data Flow

B-field predictions on 2°x2° grid over CONUS
Output from Geospace Model

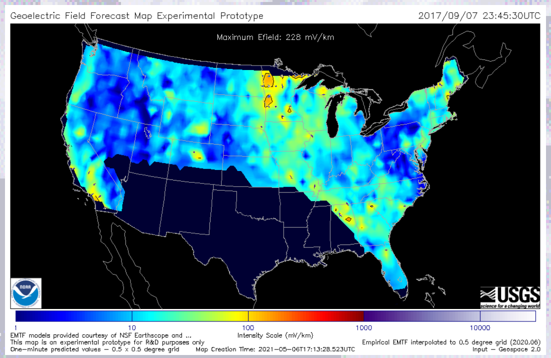
→ **Resample to 0.5°x0.5° grid**

→ **E-field calculation**

- NSF USArray/USGS-NASA-USMTArray empirical magnetotelluric impedances covering CONUS on a quasi-regular 70 km grid
- For each survey site, convolve impedance with nearest B-field predictions
- Resample/Interpolate E-field to regular 0.5°x0.5° grid

→ **Level-1 Products**

- Graphical map
- Gridded data file
- Geojson file
- Daily netcdf archive file

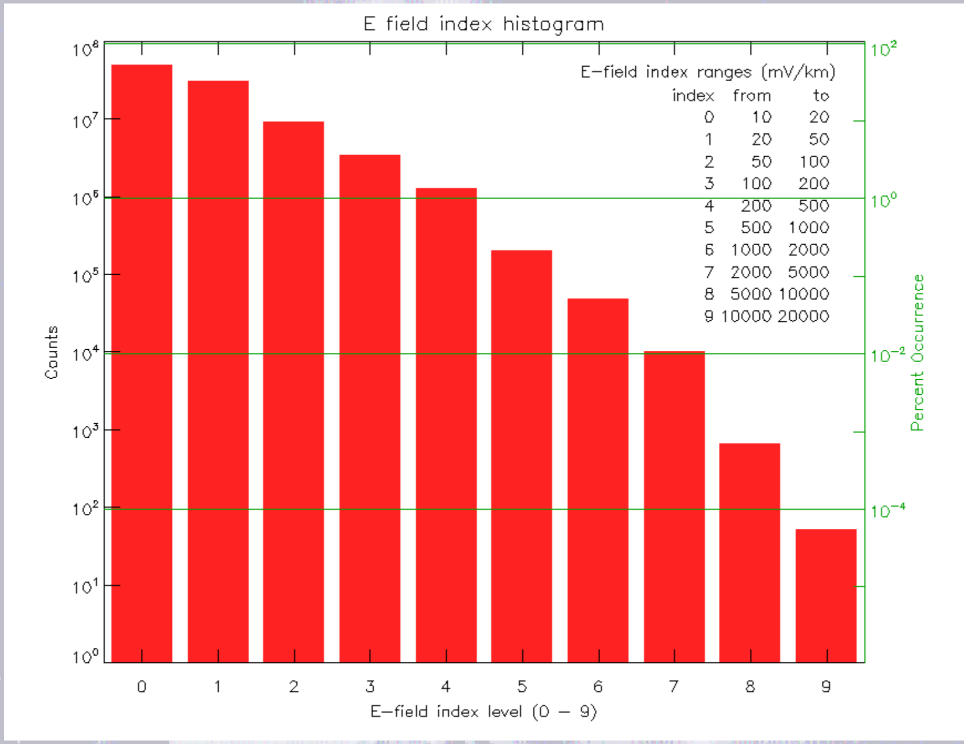


Predictive Geoelectric Field Product – Concept of an E-field index

One approach to providing forecasts and nowcasts is to construct categories (or an index) for various levels of a parameter of interest

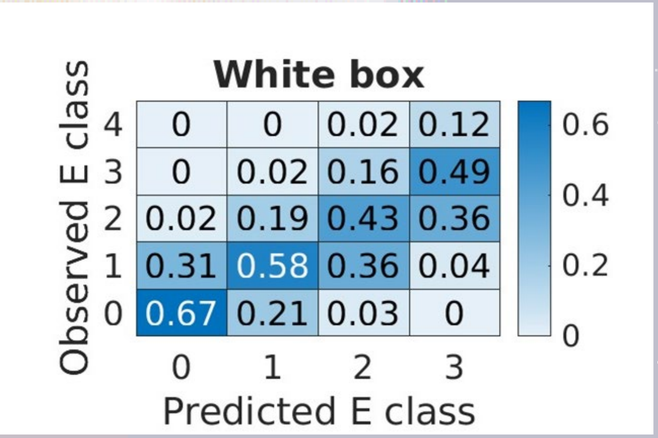
The goal is to summarize and simplify the description to enable users to quickly grasp the level of activity

The graph shows the occurrence rates of a possible E-field classification system, using the E-field magnitudes calculated for 93 days that consists of March 1989, July 2000, and October 2003 (EMTF model)



Distribution of E-field index (hypothetical) occurrences for a 93 day period using a classification system

Categorical forecast verification



Contingency table for E-field index predictions at a specific location

Given a specific prediction, this tells us the probability of what will be observed, based on previous storm events (140 storms for this sample)

This enables making a probabilistic forecast for the categories

Future Work

- Develop and test 'next generation' modeling for the surface impedance, based on an inversion of the MT surveys and construction of 3D earth models (led by USGS)
- Evaluate and assimilate more magnetometer data into the model
  - Ensure requirements for reliability, timeliness, and quality are met
- Test sensitivity of results to higher cadence (e.g. 10 second vs 1 minute)

Discussion Points

- Should the 1D vs 3D comparison analysis be applied to the 1D model output as ‘correction factors’, keeping in mind that the comparison is only possible for part of the map ?
- The validation studies are encouraging so far but need to be done in a greater variety of geological contexts to test general validity of our approach
- Would a scale or index indicating E-field magnitude be useful for the operational user community

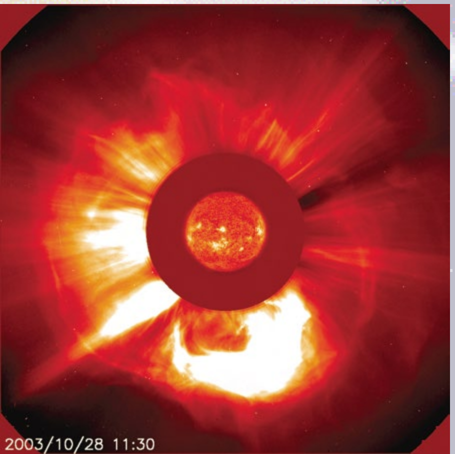
Summary

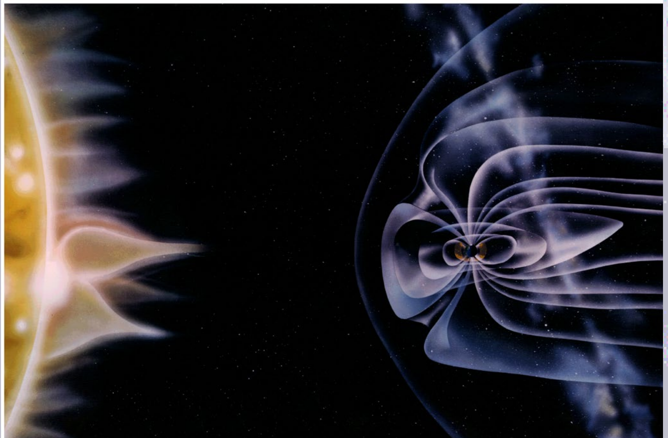
- Geoelectric modeling is a major improvement in specifying space weather for impacts on the electric power gird
- SWPC & NRCAN have developed a US-Canada E-field map product in collaboration with USGS
- The 3D empirical E-field map product was recently upgraded with new MT survey information and now covers almost all of CONUS
- We have some confidence that the E-field modeling is valid, based on a recent, published study, but the work is ongoing and more studies are needed
- SWPC is putting resources into setting up regional predictions that would indicate the probability for various levels of the local geoelectric field

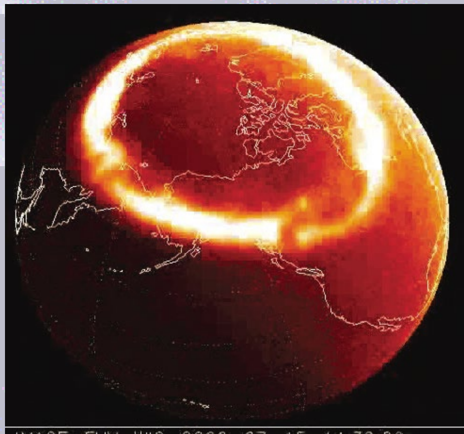
Acknowledgements

- The Geoelectric Field mapping project is a collaborative effort between NOAA/SWPC, USGS, NASA/CCMC, and NRCAN Space Weather (Balch, Camporeale, Millward, Guerra, Rasca, Singer, Kelbert, Rigler, Lucas, Pulkkinen, Boteler, et al.)
- The Geoelectric Field Mapping relies on data provider partners: USGS & NRCAN near real-time ground based magnetometer data
- NSF’s USArray program, and the follow-on NASA/USGS supported USMTArray project, along with their contractors and collaborators (OSU, IRIS) have provided of improved Earth-conductivity information in the form of MT surveys over CONUS
- New 1D models for the US-Canada 1D E-field maps were provided by NRCan for Canada (Trichtchenko, Fernberg, Boteler, 2019) & by EPRI for CONUS (developed by Gannon with EPRI support, Arritt & Leonardi, EPRI product ID 3002019425, 2020).
- We acknowledge our active validation collaborations with Southern California Edison and with the Tennessee Valley Authority which are critical to establishing the usability of the geoelectric field models
- We appreciate numerous collaborators in the power industry who are assisting with model evaluation, validation, and feedback

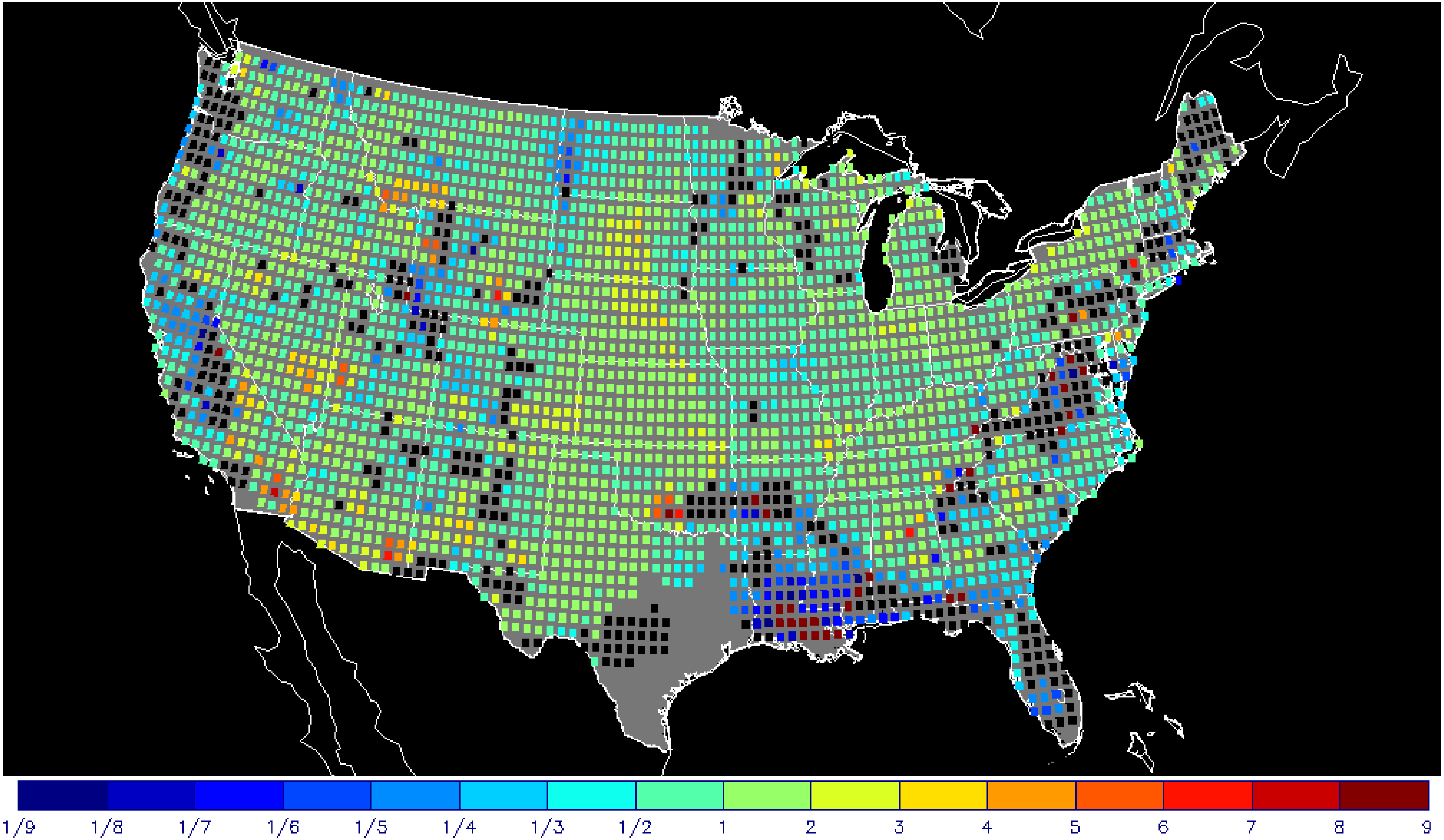
Questions?





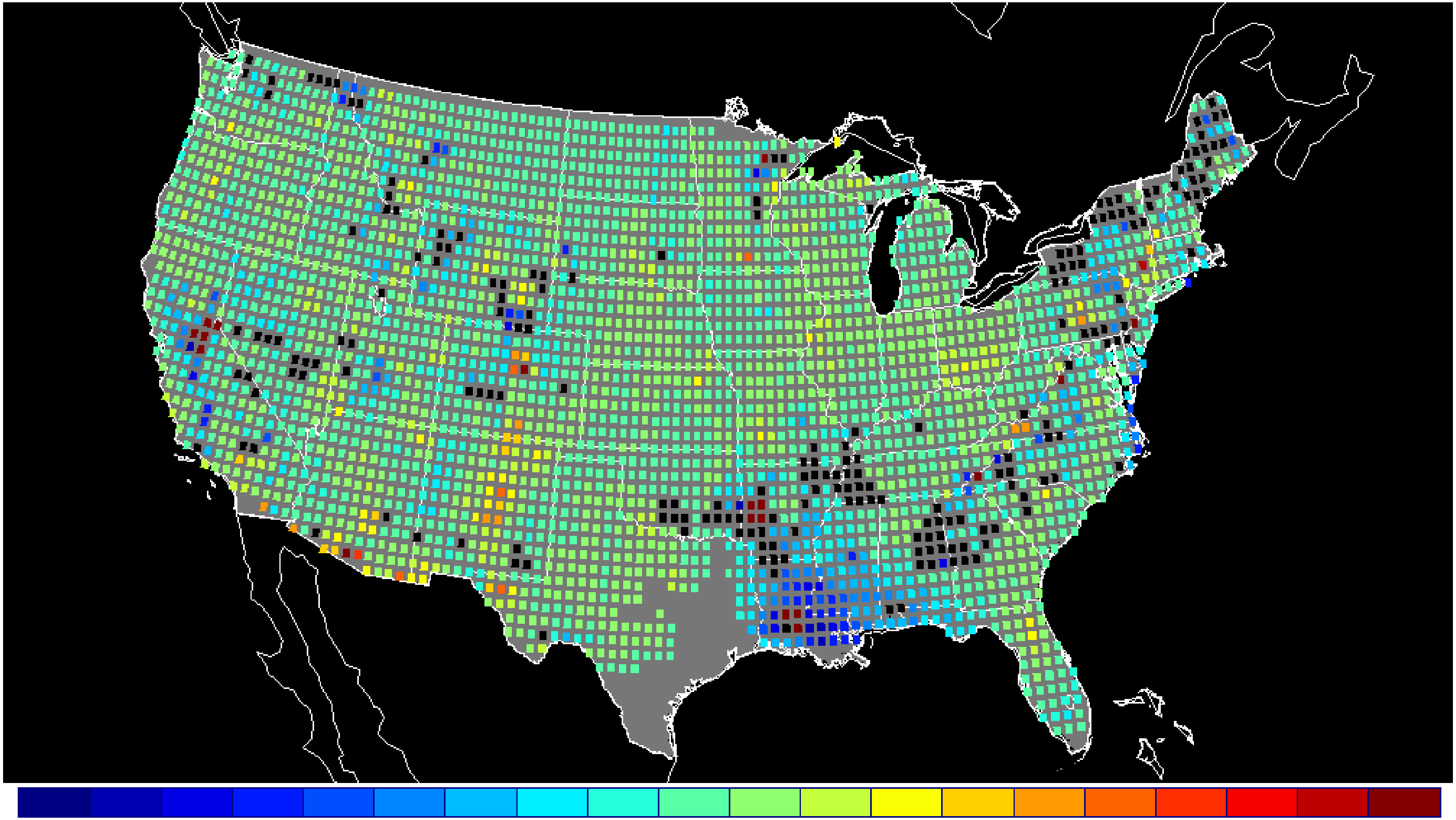


Geoelectric Field Scale Factors Map for Ex (from EPRI 1D to 3D empirical) (Mar 89/Jul 00/Oct 03)



Ex scale factor (black has correlation <= 0.70)

Geoelectric Field Scale Factor Map for Ey (from EPRI 1D to 3D empirical) (Mar 89/Jul 00/Oct 03)



MISO GMD Vulnerability Assessment (TPL-007) Overview

NERC Geomagnetic Disturbance Workshop

August 16th, 2023

Purpose & Key Takeaways

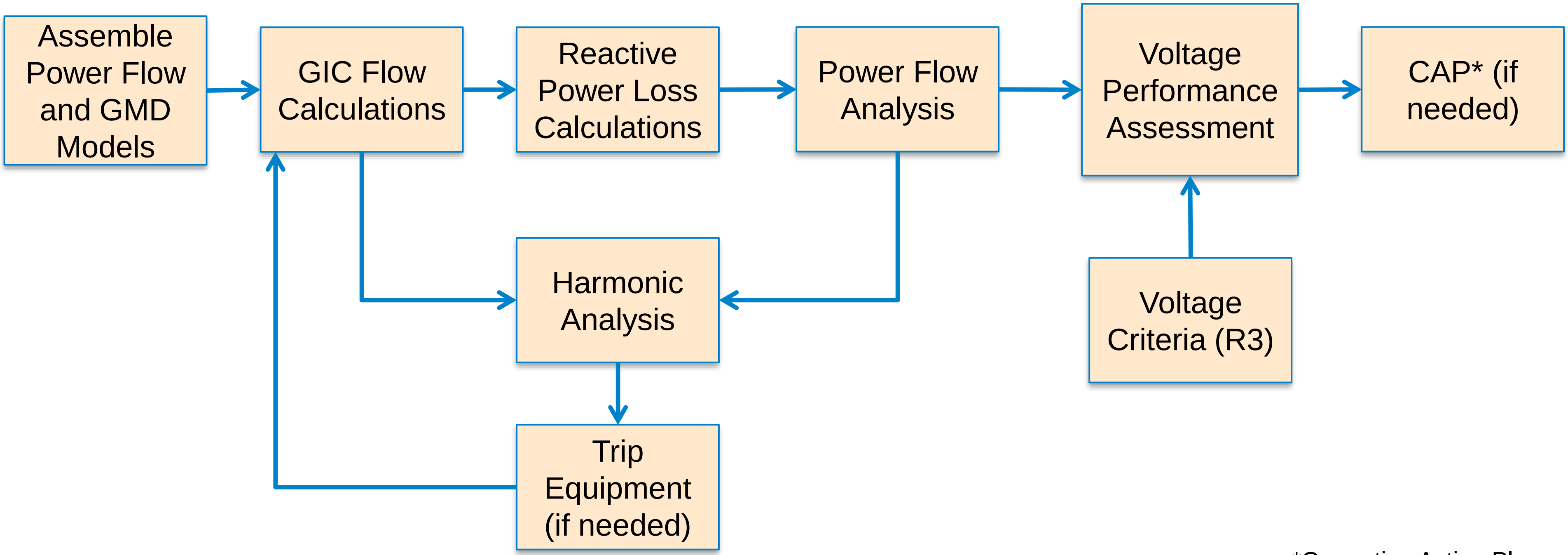
Purpose:

Overview of MISO's 2022 TPL-007-4 GMD Steady State Assessment

Key Takeaways:

- MISO performed GMD Vulnerability Assessment (R4, R8) as required by TPL-007-4 Standard
- No violations were identified in the assessment

TPL-007-4 R4, R8 Assessment – High Level Work-Flow



*Corrective Action Plan

Input for GMD Assessment

- MISO22 - 2027 Summer Peak and 2027 Summer Shoulder power flow models
- GIC Data files substation coordinates, DC resistances of lines, transformers, shunt devices etc.)
- Simulation Tools:
  - PSS-E version 34.9.1 (GIC flow calculations, voltage performance assessment)
  - EPRI GICHarm version 3.0 (harmonic calculations)

GIC Calculations (PSSE)

- *Power flow model* + *GIC model* combos assessed for benchmark and supplemental analysis
- GMD storm was simulated from 0° to 170° in 10° steps to represent various storm angles
- Output:
  - Transformer GIC flows for each of the storm angles (input for harmonic analysis)
  - Power flow solved cases to include increased MVAr losses for each of the storm angles

GIC flow to MVAr loss calculation

$$3 - phase\ MVAr\ losses = I_{eff} \times K_{factor} \times \frac{V_H}{500}$$

where,

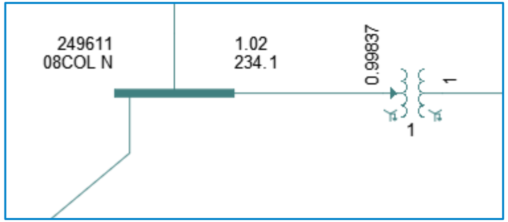
I_{eff} = Effective GIC flow in transformer in Amperes/phase

V_H = Transformer Windings highest voltage in kV

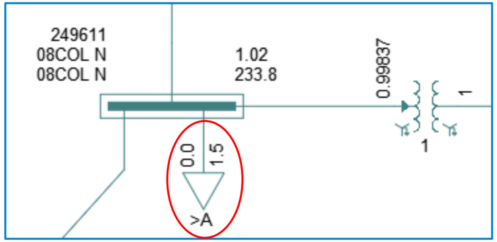
K_{factor} = MVAr/Amp scaling factor defined at 500 kV of VH

Increased reactive power losses in transformers are added to the power flow case as new reactive loads at transformer buses

BASE CASE

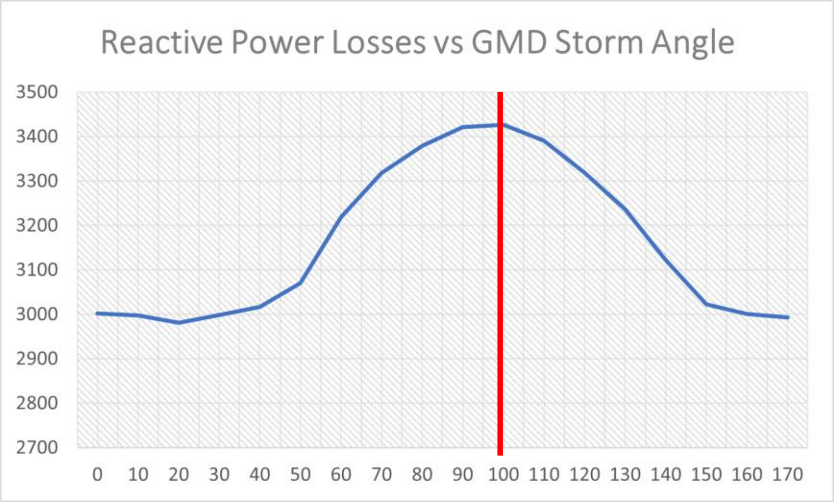


DURING GMD EVENT



Increased reactive power losses in transformers

- Maximum reactive power losses (benchmark event) = 3,426 MVAr
- Maximum reactive power losses (supplemental event) = 3,736 MVAr

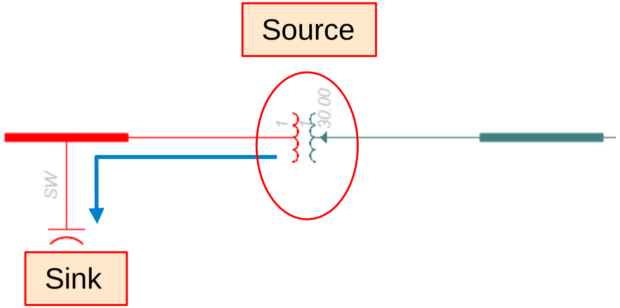


2027 SUM benchmark event

Harmonic Calculations (EPRI GICHarm)

- Input:
  - Power flow models
  - GIC models
  - Transformer GIC flows (from PSSE)
- Harmonic analysis was run up to 15th harmonic order
- Output:
  - Harmonic results for the shunt devices for each of the storm angles

Harmonic generation due to GMD



- Saturated transformers are harmonic current sources
- Cap banks provide low impedance path to harmonic current flow
- Risk of losing cap banks because of overcurrent protection (mis)operation
- Used EPRI's GICHarm tool to identify at-risk cap banks
- The tripping thresholds used were*:
  - Total RMS current (including harmonics) > 135% of nominal current, OR,
  - Total RMS voltage (including harmonics) > 110% of nominal voltage

*EPRI Assessment Guide: Geomagnetic Disturbance Harmonic Impacts and Asset Withstand Capabilities (3002017707)

GMD Assessment (R4, R8) Result Summary

- For both the benchmark and supplemental Vulnerability Assessment
  - No new voltage or thermal violations were identified for any of the models and storm angles
  - No voltage deviations violating the criteria (0.05 p.u.) were identified for any of the models and storm angles
- Only one shunt device (21.6 MVAr) was found to exceed voltage harmonic threshold and hence, was tripped in the power flow models
- GIC analysis after tripping the shunt device showed no new violations
- No Corrective Action Plan (CAP) was identified in the analysis

MISO

MISO

Contact Us

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- Ryan Hay rhay@misoenergy.org

Appendix

MISO Voltage Criteria for GMD Assessment (R4, R8)

- MISO proposes to monitor against Transmission Planners' Emergency voltage thresholds listed in TPs' Local Planning Criteria (LPC)
- If LPC absent, MISO's Default Planning Criteria's Emergency voltage thresholds to be used:

Steady State Voltage	Threshold (p.u.)
Normal Low Voltage	0.95
Normal High Voltage	1.05
Emergency Low Voltage	0.90
Emergency High Voltage	1.10

Criteria from MISO Business Practices Manual

- Emergency voltage thresholds to be applied post-GMD event, but prior to the loss of any BES elements due to harmonics
- Monitored facilities: 100 kV and above
- Facilities with violation will also be monitored for voltage deviation of more than 0.05 p.u.
- Nuclear Plants to follow voltage criteria per existing NPIRs
- MISO will share the post-event voltage results from R4, R8 assessment with the TPs if emergency thresholds are violated
- TPs don't need to provide CAPs unless there is voltage collapse, cascading or uncontrolled islanding
- MISO expects TPs to determine when voltage collapses in their system

Preparing for TPL-007 Implementation at BC Hydro

Presented at NERC GMD Workshop
St Paul, MN

Sam (Shengqiang) Li, P. Eng.
BC Hydro
Planning Coordinator Office

August 2023

BC Hydro
Power smart

Background

- BC Hydro is the main electric utility provider in the province
- BCH system has a geographically wide footprint, ranging from US boarder (N49°) to a high latitude (N59).
- Our provincial regulator is still assessing the adoption of PC function and some PC standards (e.g. TPL-007) are still held in abeyance.
- BCH is in the process of preparing for TPL-007 adoption.

Our Preparation Works:

1. Support WECC GMD case creation and GIC study
2. Participate in NWPP GIC/GMD study
3. Explore study tools (PSLF, PSS/E, PW)
4. Explore use of customized earth model
5. Explore re-defined GMD events with technical justification
5. Outreach efforts with service providers, peer utilities, and SMEs.

BC Hydro
Power smart

NRCAN 12-Zone Earth Model

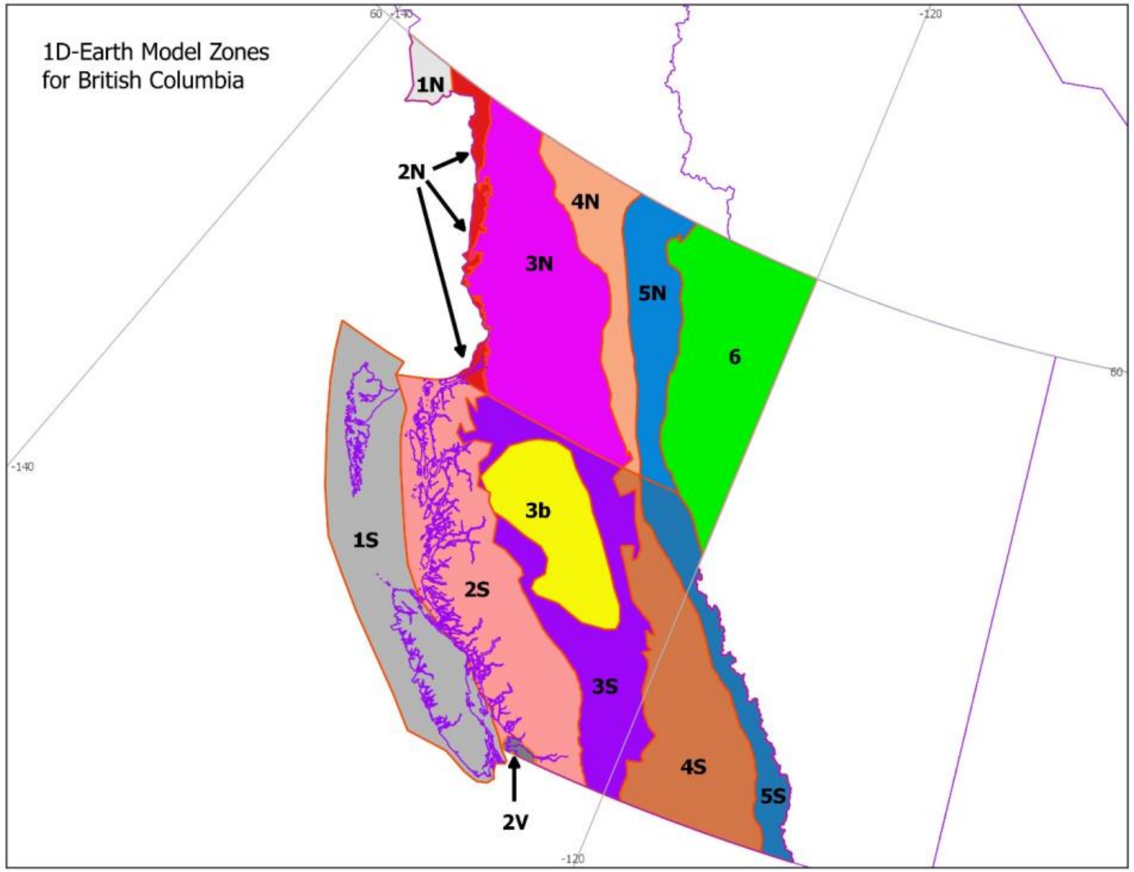
Natural Resources Canada   Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8594

One-dimensional Layered Earth Models of Canada for GIC Applications

Part 1. General Description

L. Trichtchenko, P.A. Fernberg, and D.H. Boteler



Max Effective GICs with Different Earth Model

8V/ km Benchmark Event with
Standard Earth Model (β = 0.67)

EffCur|-per phase(A)-	Storm |De	Type	|---Name-
130.97835	90	auto	[redacted] T3
129.05154	85	auto	[redacted] T2
109.01328	30	auto	[redacted] T1
76.76137	150		[redacted] T13
68.81532	50		[redacted] 4
65.23359	60	auto	[redacted] 1
64.64416	170		[redacted] T4
62.61916	160	auto	[redacted] T4
62.56128	160	auto	[redacted] 1
59.61021	170		[redacted] 1
55.84422	90	auto	[redacted] T2
55.62181	100	auto	[redacted] T4
53.24125	120	auto	[redacted] T1

8V/ km Benchmark Event with
Customized Earth Model (β differs for 12 zones)

EffCur|-per pl	Storm |De	Type	|---Name-
259.8	30	auto	[redacted] T1
134.1	90	auto	[redacted] T3
132.1	90	auto	[redacted] T2
126.0	60	auto	[redacted] 1
114.0	20		[redacted] T2
103.4	130		[redacted] T1
98.8	20		[redacted] T1
97.5	60		[redacted] T3
96.6	60		[redacted] T2
95.7	60		[redacted] T1_2
91.1	70	auto	[redacted] T11
91.0	70	auto	[redacted] T12
90.2	100	auto	[redacted] T2
89.6	100	auto	[redacted] T1

If customized earth model is used, then the redefined GMD events is likely needed.

Brainstorming for future works

Q1: What is Rationale for voltage criteria under R3?

Table 1: Bus Voltage Performance Criteria (R3)

	Acceptable Voltage (p.u.)	
	Minimum	**Maximum**
Prior to GMD Event (P0), following system posturing	0.95	1.05
GMD Event, Post-Contingency	0.8	1.10

Brainstorming for future works

Q2: What actions could TO suggest to mitigate the impact of high GICs?

How does the suggested action interact with CAP development (R7)?

R6. Each Transmission Owner and Generator Owner shall conduct a benchmark thermal impact assessment for its solely and jointly owned applicable BES power transformers where the maximum effective GIC value provided in Requirement R5, Part 5.1, is 75 A per phase or greater. The benchmark thermal impact assessment shall: *[Violation Risk Factor: Medium] [Time Horizon: Long-term Planning]*

6.1. Be based on the effective GIC flow information provided in Requirement R5;

6.2. Document assumptions used in the analysis;

6.3. Describe suggested actions and supporting analysis to mitigate the impact of GICs, if any; and

6.4. Be performed and provided to the responsible entities, as determined in Requirement R1, within 24 calendar months of receiving GIC flow information specified in Requirement R5, Part 5.1.

Brainstorming for future works

Q3: What criteria is used for determining cascading in Table 1?

Table 1: Steady State Planning GMD Event				
Steady State: a. Voltage collapse, Cascading and uncontrolled islanding shall not occur. b. Generation loss is acceptable as a consequence of the steady state planning GMD events. c. Planned System adjustments such as Transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings.				
Category	**Initial Condition**	**Event**	**Interruption of Firm Transmission Service Allowed**	**Load Loss Allowed**
Benchmark GMD Event – GMD Event with Outages	1. System as may be postured in response to space weather information[1], and then 2. GMD event[2]	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event	Yes[3]	Yes[3]
Supplemental GMD Event – GMD Event with Outages	1. System as may be postured in response to space weather information[1], and then 2. GMD event[2]	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event	Yes	Yes

Feedback

Highly appreciated if you could share your valuable thoughts and experience in the Q&A session.

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Accurate Calculation of Reactive Power Demand in Power Transformers

Presentation to NERC / EPRI GMD Planning Workshop

Dr. Ramsis Girgis

August 16th, 2023

Hitachi Energy

Calculation of VAR Demand

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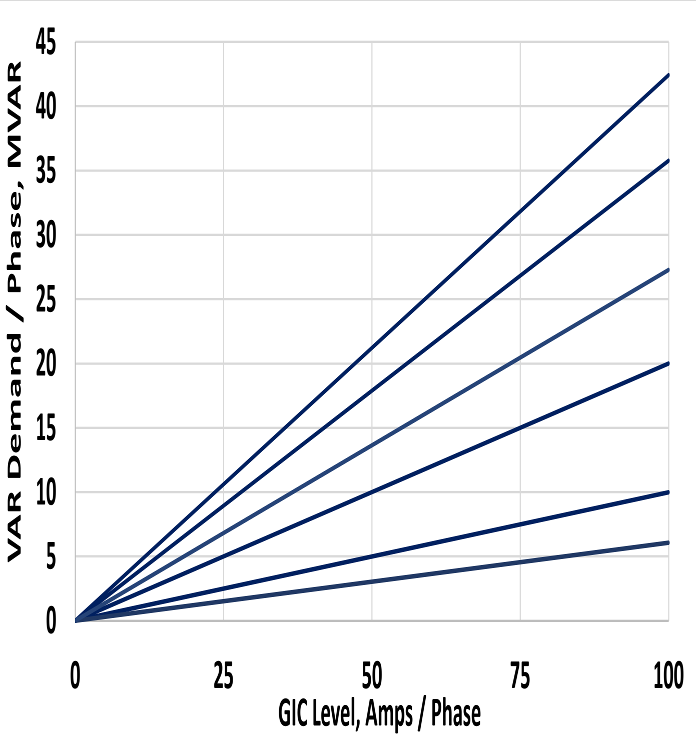
Existing Calculation

- Same method of calculation for all transformers (VAR / Phase = k x GIC x V_{Phase})
- One fixed value for the “K” Factor for all 1-phase transformers (1.18)
- Same value of the “K” Factor for 5-limb Core form and 7-limb Shell form (0.66)
- One very low value for all 3-phase Shell form with the D Core Type (0.33)
- One low value for all 3-phase Core form with the 3-limb Core Type (0.29)
- For transformers with unknown Core Types
  - One value for transformers with HV winding ≤ 400 kV (0.60)
  - Another very different value for all transformers with the HV winding of > 400 kV (1.68)

❖ Those two values do not appear to have theoretical basis



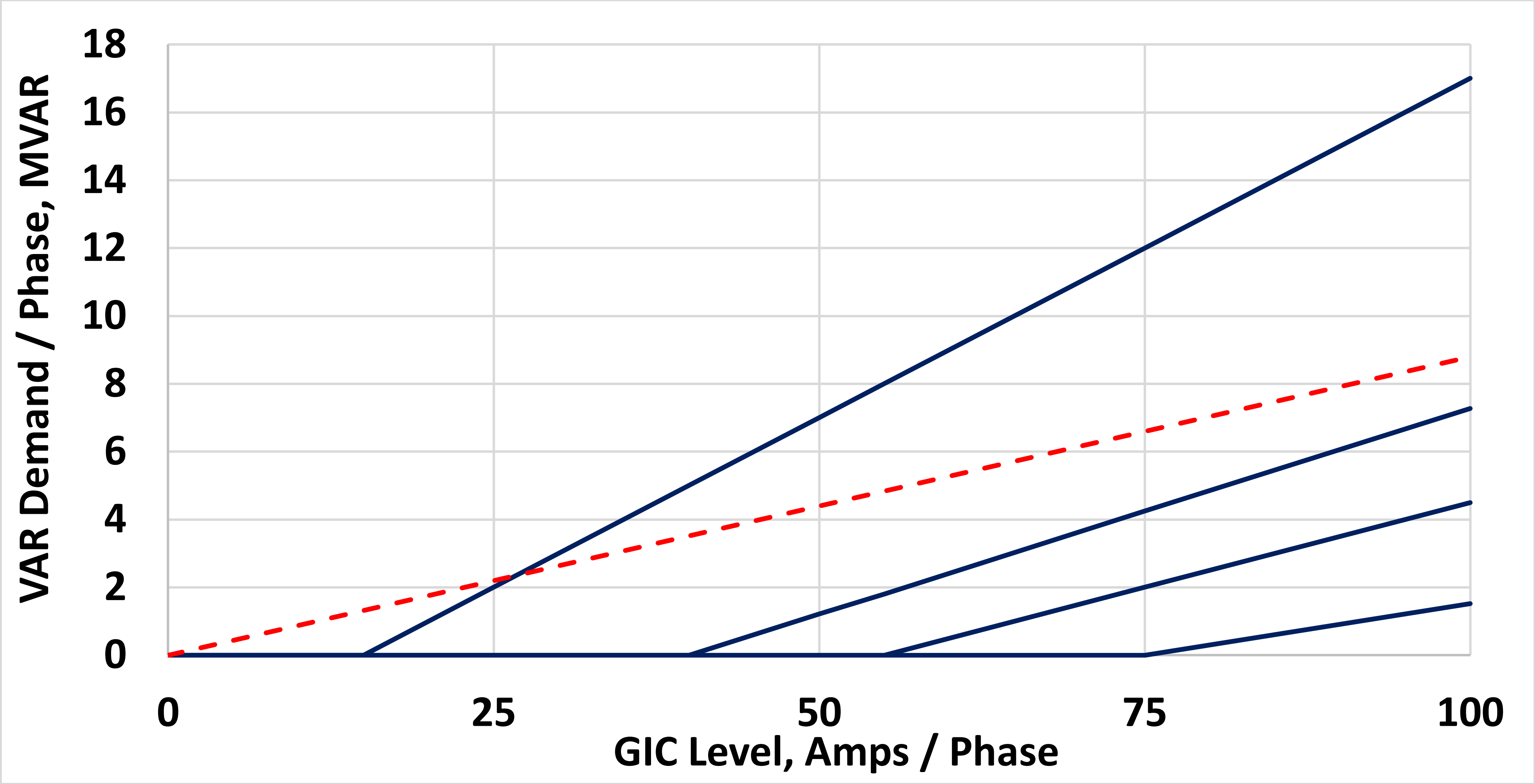
Hitachi Energy Calculation

- “K” factor is a function of Core type, transformer type, and transformer design
- Different calculation for 3-phase, core form transformers with the 3-limb core type

❖ **VAR = 0 for GIC ≤ I_{CS}** **VAR / Phase = k x (GIC – I_{CS}) x V_{phase} for GIC > I_{CS}**

Hitachi Energy

VAR Demand for 3-phase core form transformers with the 3-limb core type



Comparison of Calculated Values of VAR Demand

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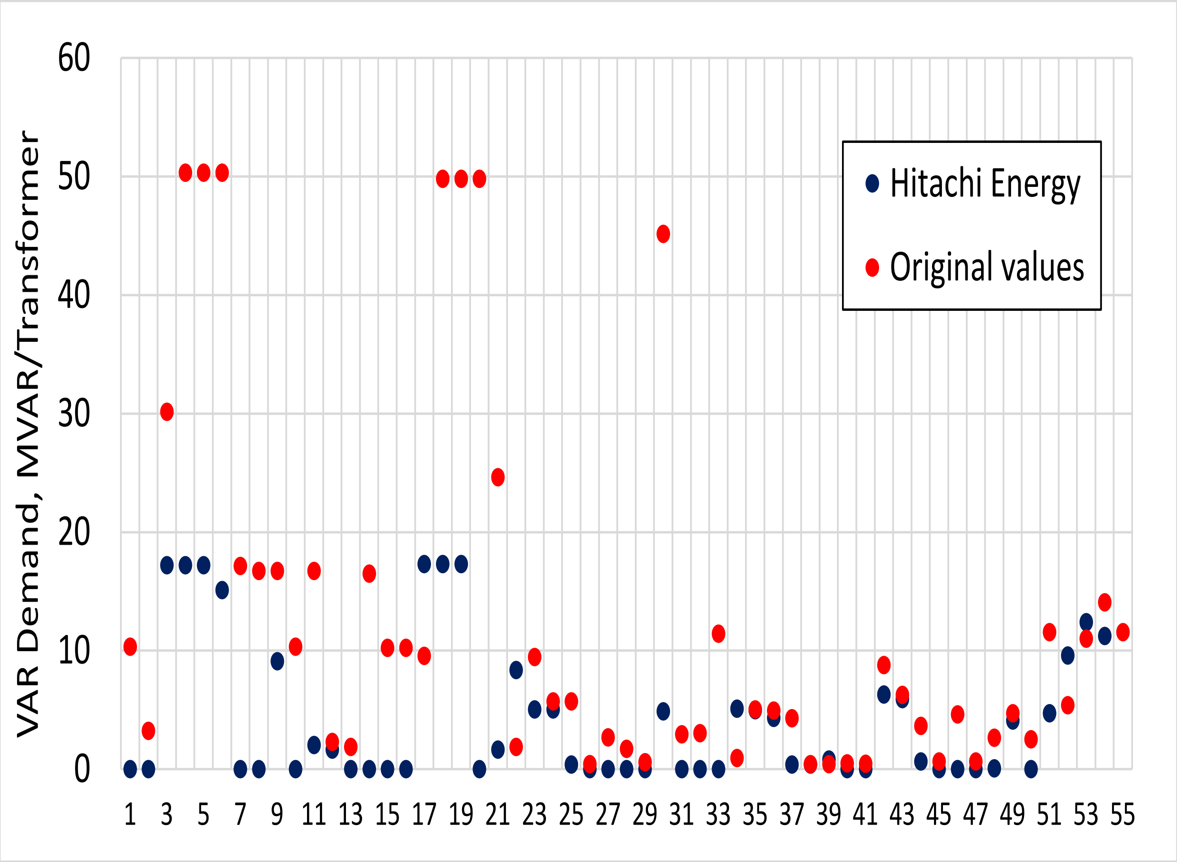
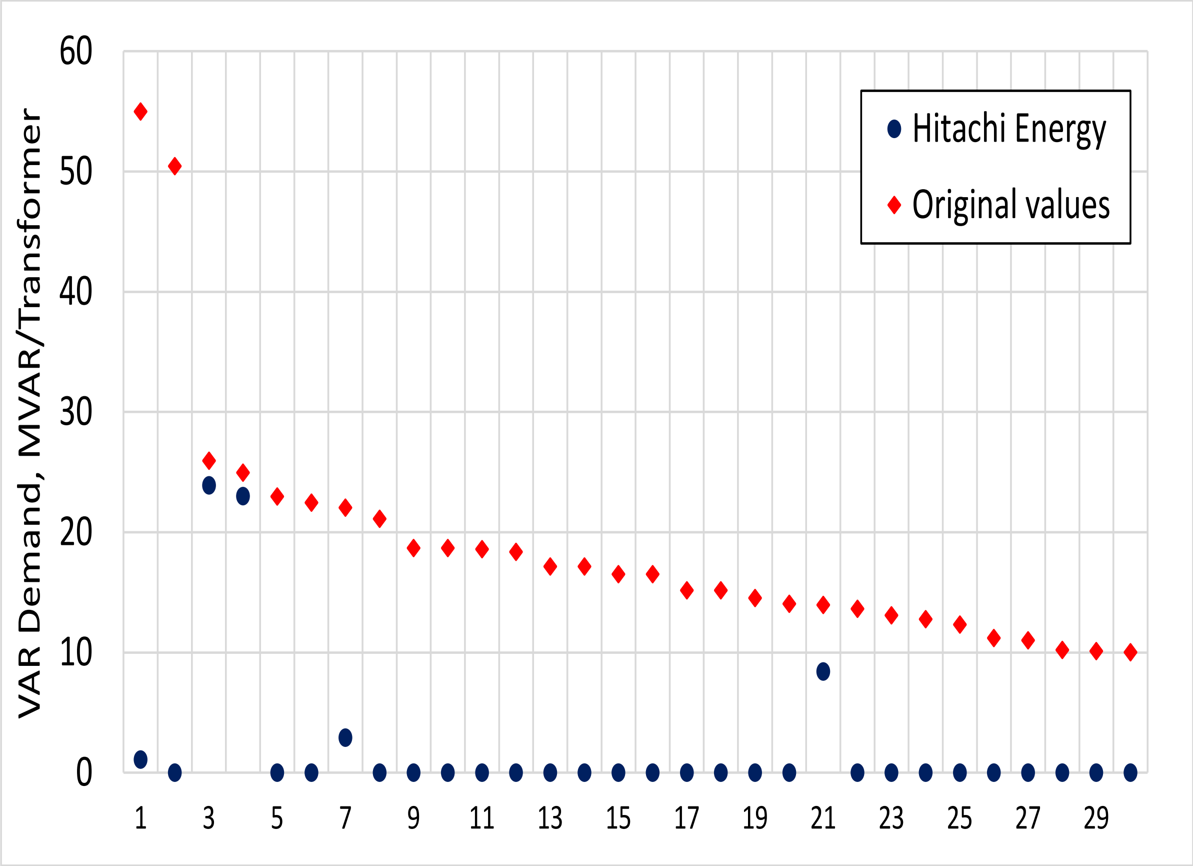
Performed for 286 individual Transformers ≥ 230 kV, GSUs, Step-downs, 3-windings, and Autos, 230 to 765 kV, 32 to 870 MVA



Service Region 1



Service Region 2

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Summary of Final results of the VAR Demand Calculation for the Fleet

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Region	Calculation		Ratio
	Original	Hitachi Energy	
1	417	159	2.6
2	486	71	6.8
3	693	226	3.1
Total	1596	456	3.5

- Total VAR Demand as calculated by Hitachi Energy is about 1/3rd of original value.
- Because of the large number of 3-phase core form transformers with the 3-limb core in Region 2, calculated VAR demand by Hitachi Energy is lower than original value by almost a factor of 7
- **Significant impact on results of System Vulnerability studies and corrective actions needed**

Hitachi Energy

Example Results of GIC System Vulnerability Assessment Study

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For the Benchmark GMD event (8 V/km), Under Peak-Load Conditions

1. Low voltage criteria violations in a # of Service Areas
2. Reactive Power Margin violations in one Service Area
3. Units in one Service Area cannot control bus voltages to their specified voltage setpoints

Recommended Operating Procedure to mitigate violations mentioned above

1. Turning on thermal units at a certain location
2. Curtailing Power exports from this Utility to another Utility
3. Curtailing Industrial loads in a specific Service Area
4. A combination of curtailing Power exports and curtailing load at a specific Service Area

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On-Line Monitoring of GIC and its Thermal impact on Power Transformers in Real Time

Presentation at NERC / EPRI GMD Planning Work Shop

August 16, 2023

Presenters:

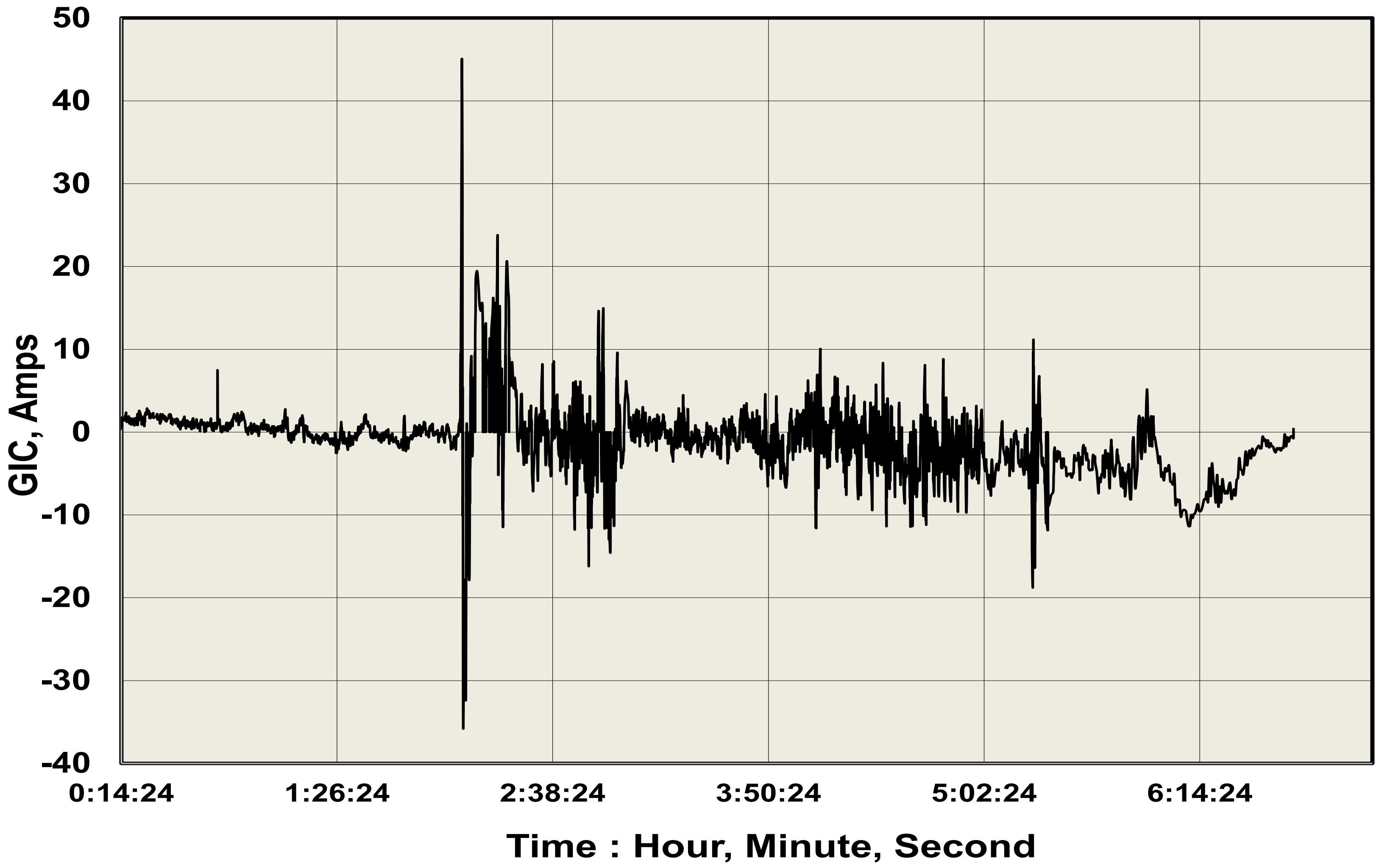
Homer Portillo, Advanced Power Technologies

Ramsis Girgis, Hitachi Energy

Advanced Power Technologies

Hitachi Energy

Typical GIC Signature



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How is GIC Measured & Transducer Characteristics

Split Core

Solid Core

- Measured with Split Core, or Solid Core, Hall Effect CT installed over the neutral conductor from neutral bushing
- Hall Effect CT has an operating temperature range of -50° C to 85°C w/o drift and uses an IP65 rated enclosure
- Measurement Range - 500 Amperes to + 500 Amperes Quasi-DC
- Has a BIL of 110 kV

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Method to detect Incipient Part-Cycle Core Saturation caused by GIC

- When GIC flows into the Neutral of a Power Transformer or a Power Transformer Bank, it causes Part-Cycle Core magnetic Saturation of the transformer / Transformers.

- As a result, the monitored Sum of the magnitudes of the even order harmonic currents is greater than the sum of the magnitudes of the odd order harmonic currents. This provides an early warning to Dispatch

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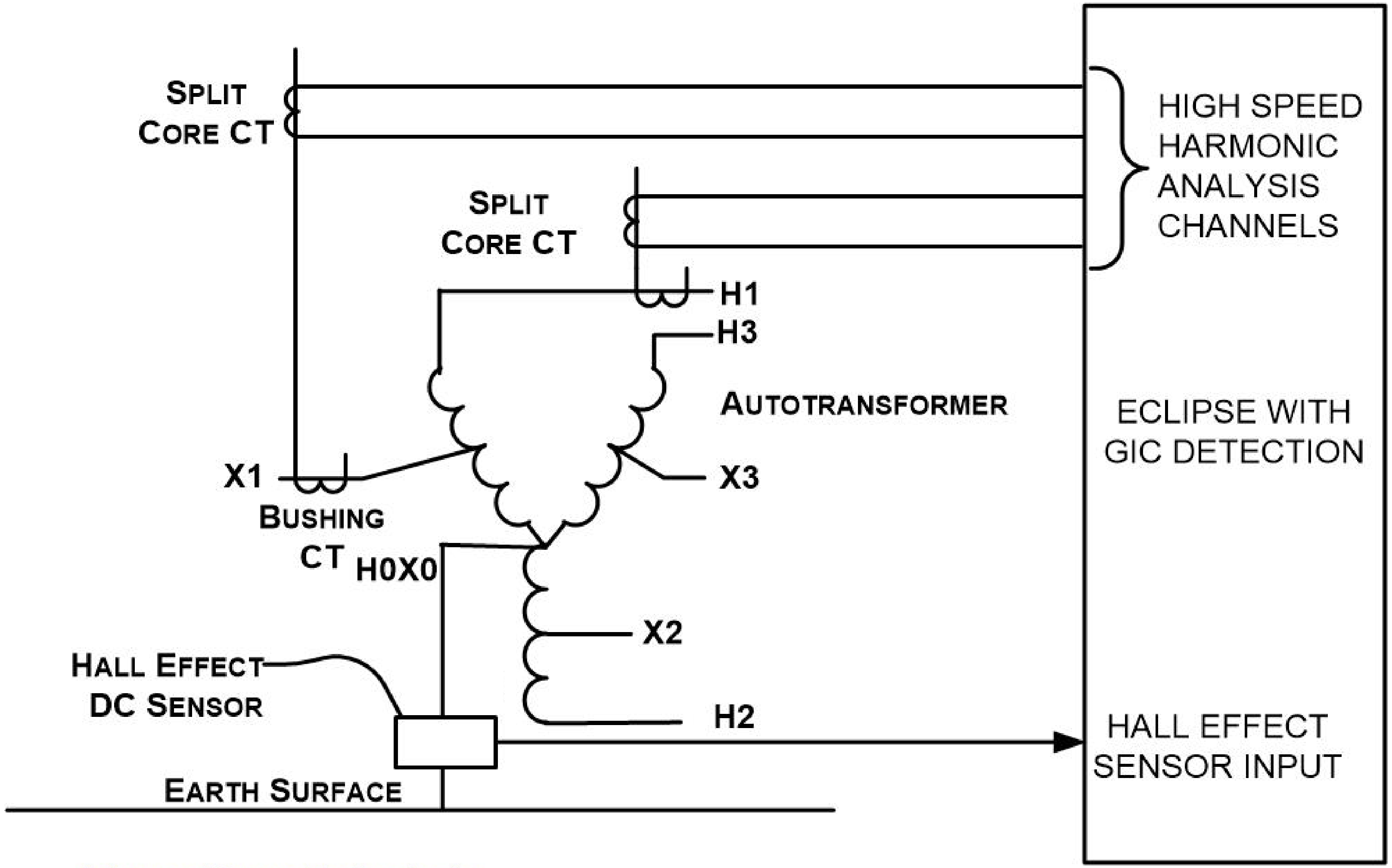
US Patent 9,018,962 Foreign Patents Pending

ECLIPSE GIC autotransformer core saturation detection connections



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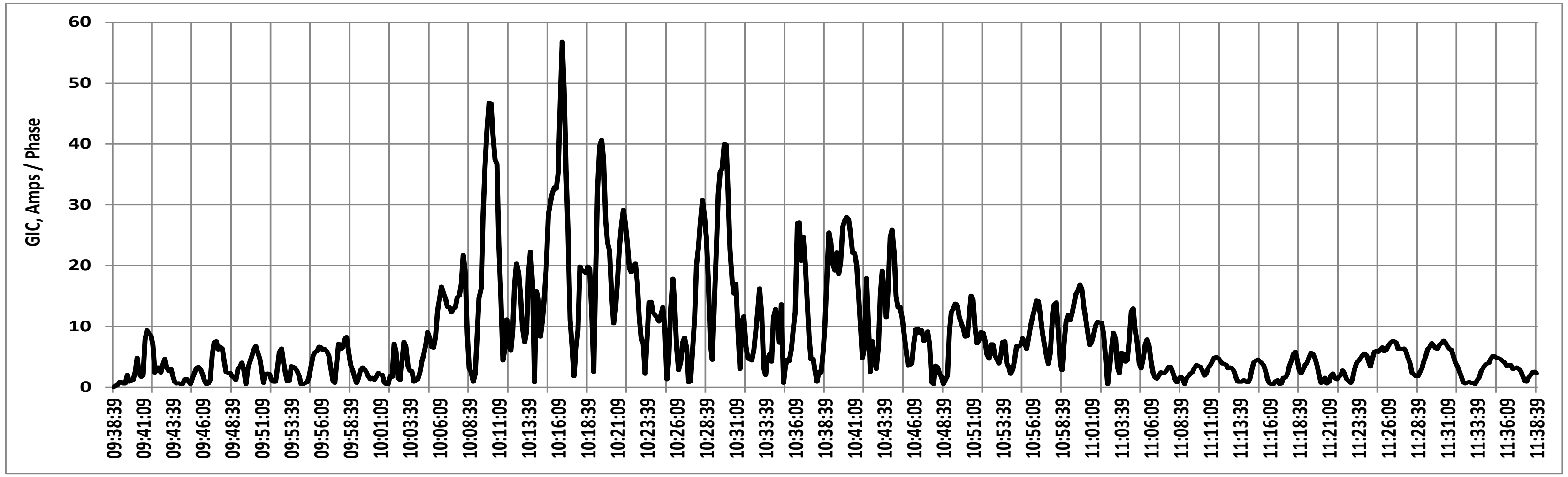
US Patent 9,018,962 Foreign Pat. Pending

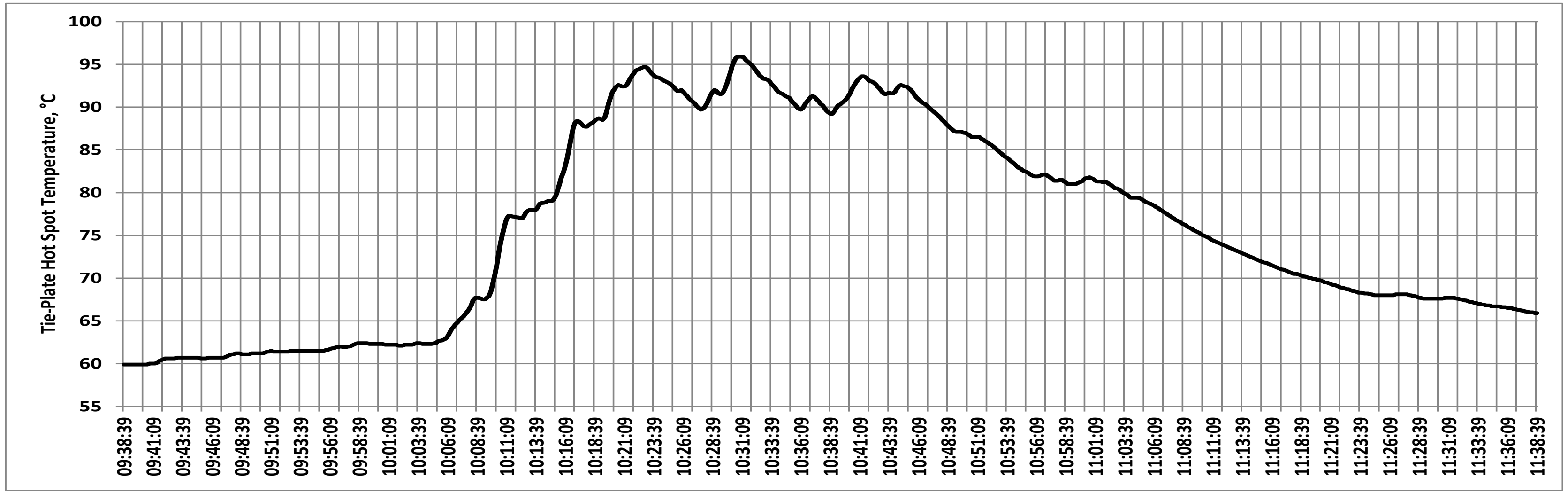
Concept of 2nd Generation ECLIPSE: Monitoring Thermal Impact of GIC on Power Transformers using GIC Thermal Models

- Properly developed Thermal Models can predict heating of the Windings and Structural Parts caused by GIC in Power Transformers
    - Tie-Plates in Core Form Transformers
    - Tank walls in Shell Form Transformers
        - To be monitored externally by TC / Fiber Optics to be connected to the GIC Monitor
- Why is this important?
    - Overheating of windings results in degradation of winding insulation
    - Overheating of structural parts results in the evolution of gas bubbles that can lead to dielectric failures
- Providing values of the hot spot temperatures online, and in real-time, provides situational awareness to owners and operators of Power Transformers highly susceptible to overheating caused by high levels of GIC

Thermal Model Calculations Using GIC Data



GIC, Amps



Hot spot temperature, °C

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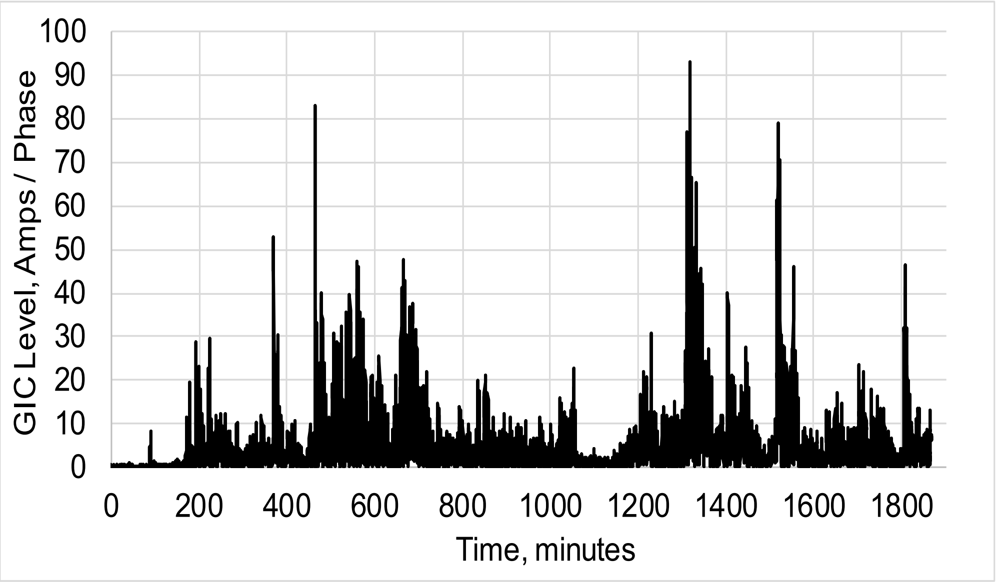
Determination of Candidate Transformers for 2nd Generation ECLIPSE

- Perform GIC Thermal Fleet Assessment using Benchmark GIC signature with corresponding GIC levels
- Identify Transformer (s) on a fleet that is / are highly susceptible to overheating of windings / Structural Parts caused by high levels of GIC
  - Some examples:
    - 4 on one fleet
    - 3 on another fleet
    - 1 on a 3rd fleet
    - Expecting > 4 on one fleet



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Thank you!

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NERC

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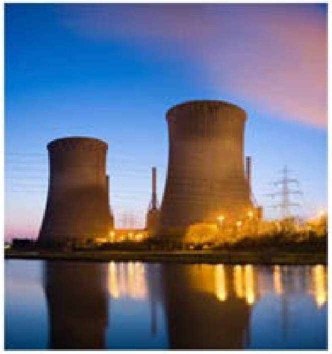
Geomagnetic Disturbance Data

Maria Kachadurian, Senior Analyst – NERC

Geomagnetic Disturbance Planning Workshop

August 15-16, 2023

RELIABILITY | RESILIENCE | SECURITY

Data Reporting Instructions

- DRI Highlights
  - The GMD Data Request was developed to meet Federal Energy Regulatory Commission (FERC) directives in Order No. 830 for collecting geomagnetically induced current (GIC) and magnetometer data from registered entities for the period beginning May 2013
  - KP 7 or greater
  - Annual reporting period: April 1 – March 31
    - Report by June 30
  - Most recent reporting deadline: June 30, 2023

Information Collected

- Device Data:
  - GIC Device Data (Spreadsheet Template)
  - Magnetometer Device Data (Spreadsheet Template)
- Event Data:
  - GIC Monitor Sample Data (CSV)
  - Magnetometer Sample Data (CSV)
- Target Sample Rate: every 10 seconds
  - Must be consistent and provide regular periodicity
- Missing data must be accounted for
- Confidential treatment of data upon request

Metadata
as of 3/31/2023

- Data collected for 17 Reportable Events
- 26 Active Magnetometers
- 478 Active GIC Monitors
- 82 NERC Registered Entities
- 3,470 GIC Reporting Batches (unique combinations of DeviceID and Event)
- 147 Magnetometer Reporting Batches (unique combinations of DeviceID and Event)

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Events and Devices

Event	GIC Monitors Reporting	Mags Reporting
2013E01	82	2
2013E02	88	2
2015E01	113	2
2015E02	119	2
2015E03	128	7
2015E04	126	2
2015E05	125	4
2015E06	128	4
2017E01	163	6
2017E02	169	6
2017E03	169	6
2018E01	228	5
2021E01	**348**	**17**
2021E02	**342**	**21**
2022E01	**385**	**20**
2023E01	**369**	**19**
2023E02	**376**	**19**

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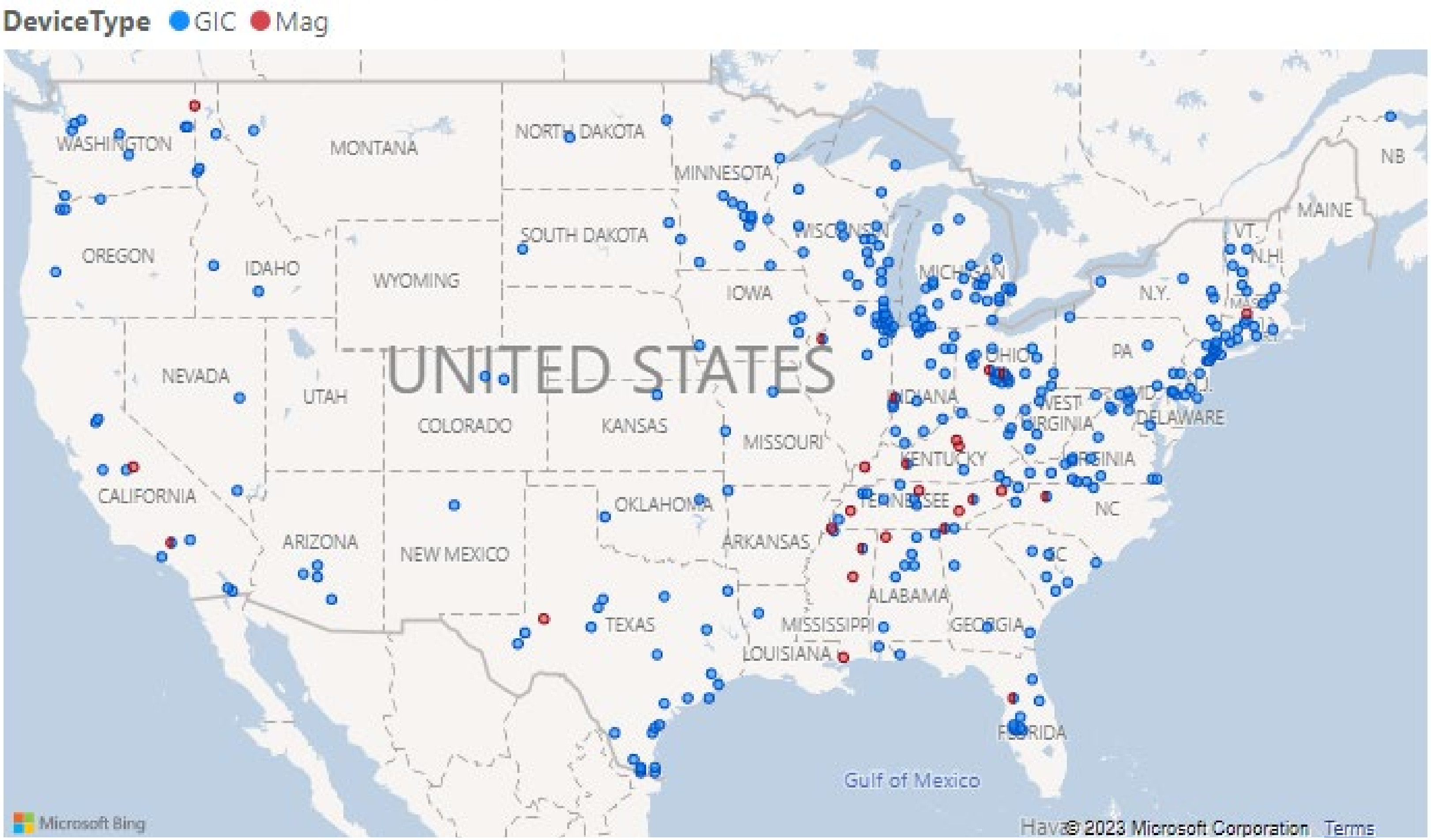
Device Locations

GIC, Magnetometer Device Location



Data Quality Analysis

Event Reporting Analysis

- Analyzed each GIC device for each event in mandatory reporting period
  - Overall average standard deviation is .82
  - Standard deviation range 0 – 237.71
  - 65 device/event combinations reported all zeros
  - 30 device/event combinations reported the same value (non-zero) for duration of event
  - 9 unique device IDs with average standard deviation of zero
    - 7 devices with all zeros
    - 2 devices with same measurement throughout event

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Event Reporting Anomalies

2022E01 Count	2022E01 Minimum	2022E01 Maximum	2022E01 Std Dev	2023E01 Count	2023E01 Minimum	2023E01 Maximum	2023E01 Std Dev	2023E02 Count	2023E02 Minimum	2023E02 Maximum	2023E02 Std Dev	Average StDev
17275	-2.4	-2.4	0	43190	-6.8	5.75	2.41709	34550	-6.52	6.3	2.3578	1.280197274
34550	0	0	0	43190	0	0	0	51825	0	0	0	0
17275	0.6	0.9	0.08635	21595	0.5	1.38	0.09278	17275	0.31	1	0.10365	0.237399667
34550	0	0	0	43190	0	0	0	34550	0	0	0	0.275692024
34550	0	0	0	43190	0	0	0	34550	0	0	0	0.429033949
17275	0	1	0.17138	21595	0	0.9	0.1542	12955	-0.5	0.1	0.07444	0.130532199
480	-0.5	0.1	0.07089	3600	-5.6	1	0.67838	2863	-6.3	13.8	1.04015	0.310912752
1018	-1.3	-1.2	0.04683	2131	-1.4	-1.3	0.04956	681	-1.4	-1.3	0.02771	0.555113314
626	0	0.1	0.02585	828	-0.1	0	0.03218	571	0	0.1	0.01376	0.154661046
49	-3	5	1.35369	60	-3	3	1.22636	48	-19	11	3.71592	1.111333669
49	-4	4	1.37982	60	-1	5	1.21421	48	-1	1	0.79783	1.20896683
17877	-4.7	7.7	0.80774	26003	-13.7	17.2	3.95555	27025	-26.1	301.6	15.343	3.955278825
547	0	0	0	686	0	0	0	550	0	0	0	0
2658	-7.7	2.7	0.86289	3585	-3.5	5.8	0.77326	2825	-7.4	6.5	0.8278	0.828679918
172741	-3.5	2.9	0.30071	215941	-5.9	3	0.30341	172741	-3.6	2.4	0.30539	0.474110525
172741	-2.7	3.4	0.34199	215941	-6.6	8.1	0.48328	172741	-4.3	4.8	0.50726	0.345231546
172741	-0.9	1.1	0.17433	215941	-1.8	1.8	0.1495	172741	-2.1	2.9	0.22216	0.253741544
172741	-1.5	2.4	0.2881									0.434184125
172741	-0.2	0.3	0.05429									0.110257536
172741	-4	2.8	0.57811	215941	-6	4.4	0.8676	172741	-3.1	4.1	0.39515	0.637705484

- All same value (non-zero)
- All zeros
- Recent events zero
- No event data

Missing Data Report Analysis

- Missing Data Quality Report required if data not available for an event, for gaps greater than 10 minutes, or other types of data issues identified
- Since mandatory reporting began:
  - 405 GIC Missing Data Reports
  - 31 Magnetometer Missing Data Reports

Missing Data Responses	GIC Monitor	Magnetometer
Device Malfunction	19%	39%
Data Recording Device Malfunction	31%	13%
Operator Error	1%	0%
Other (narrative required)	42%	29%
Data Quality (narrative required)	6%	19%

Missing Data Report Analysis, cont'd.

- Top GIC Monitor narrative responses:
  - 26% - Issue with collection of data
  - 19% - Inactive sensor/not installed yet
  - 13% - Issue with GIC Sensor
- Top Magnetometer narrative responses:
  - 62% - Issue with magnetometer/Sensor Failed
  - 10% - Measuring sources of current other than earth's magnetic field
- Additional findings:
  - Reports submitted for inactive devices
  - Reports used to backfill for events prior to device installation
  - Entities using same Missing Data Reason for each report submission

What We Have Learned

- Anomalous event data affects overall data quality
  - Repercussions on use of GMD data for research/modeling purposes
- Current Missing Data Quality Report process is ineffective
- Data quality issues could be due in part to lack of device data review prior to data reporting and/or lack of understanding of the data and reporting requirements

Action Plan

- Address Data Quality Issues
  - Improve feedback to data reporters
    - Additional Training
    - Clarification of reporting requirements in the Data Reporting Instructions
    - Modifications to the application
- Revise Application
  - Automate process for identifying data gaps
    - Improve awareness of data quality to the data reporters and research community
  - Provide additional reports to address data anomalies
  - Improve data validations

Resources

- Resources
  - NERC GMD Web page - Geomagnetic Disturbance Data (nerc.com)
    - Current list of reportable events
    - Reporting Templates
    - Training
      - Available as PDF or Streaming Webinar
    - GMD User Guide – Intended for data reporters
    - GMD Event Data Download Guide – Intended for stakeholders who leverage collected data for research, studies, etc.
    - Questions? Email gmd@nerc.net

Questions and Answers

Update on CONUS Electrical Conductivity and Impedance Mapping

Adam Schultz

Oregon State University
College of Earth, Ocean, and Atmospheric Sciences

NERC GMD Workshop, St Paul, MN 15-16 August 2023

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This was a bridging operation while we navigated the Senate and House appropriations process, assisted by a number of key supporters (David Bardin, the late Bill Harris, Maj. General Julie Bentz, the Oregon congressional delegation, the Secure the Grid Coalition and many others).

After briefing the National Security Council, our efforts were included in the Executive Order on EMP, a line item appeared in the federal budget through Dept. of Interior/US Geological Survey/Geomagnetism Program. A series of Cooperative Agreements between USGS and Oregon State University continued OSU's ability to execute the MT Array data acquisition program on behalf of USGS, with the target of completing all of CONUS by end of May 2024.

The MT Array – a brief history

Mapping the electrical impedance/structure of CONUS has been a monumental effort by OSU and its subcontractors and collaborators that, when completed, will have taken more than 18 years to achieve.

Our work at OSU was assisted mightily by external subcontractors who at various times provided field crews, day-to-day crew supervision, and carried out siting/permitting tasks.

Our subcontractors include GSY-USA, the late Phil Wannamaker (Univ. Utah), Zonge International, and for the past 11-years, Green Geophysics, Inc.

We have depended on scores of dedicated field crew members working under harsh conditions in all weather, up to and included over 115-degree temperatures, massive flooding, bushwacking and isolation.

What is exceptional about this program is that all of our data exists entirely in the public domain, and we have no proprietary hold on the data. So as Principal Investigator, other people get to publish results on our data before we get the chance to do so ourselves.

This unrestricted access includes the technical service providers such as CPI, the electric utilities, federal agencies such as NOAA/SWPC and of course USGS as well as academics. These data are meant to be used to mitigate risk to the power grid, so please use this vast collection of time series, impedance data and resulting conductivity models.

The MT Array – a brief history

At this point, I'd particularly like to recognize my closest collaborator over the last 11-years, Dr. Louise Pellerin, President of Green Geophysics and the heart of our field operations.

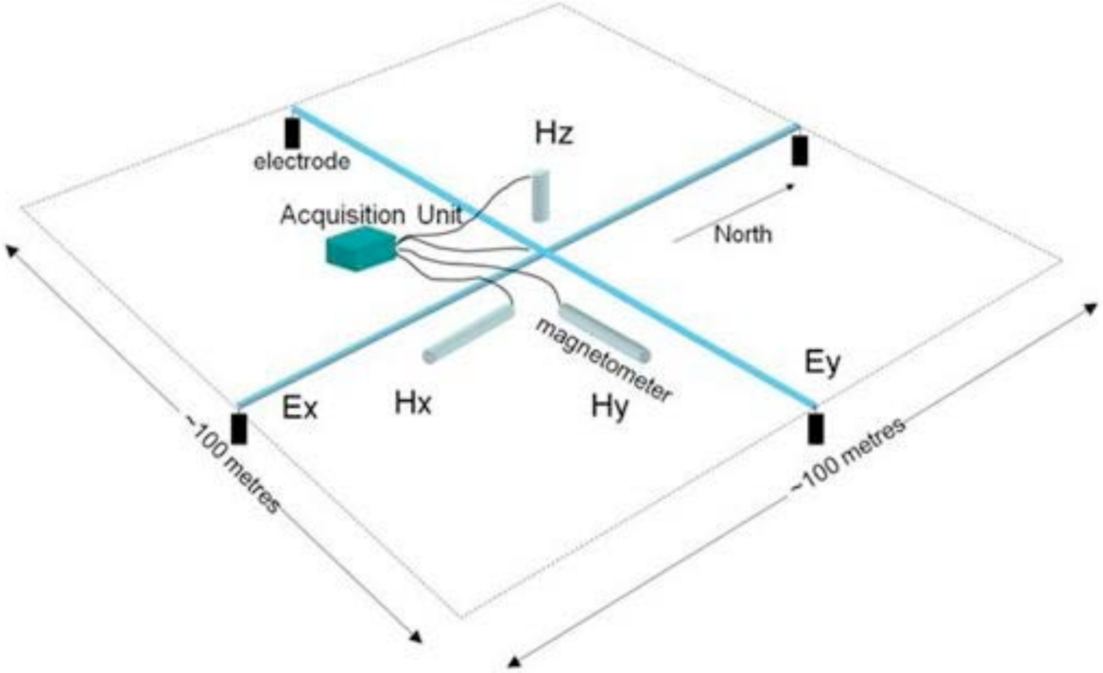
Lu was instrumental in keeping the program going; rolling with the endless punches and chaos of federal government shutdowns, continuing resolutions, unknown budgets, late payments, etc. that most companies couldn't have handled. Lu was deeply involved in all aspects of the project, understood its importance to the nation, and she was committed to seeing it through to completion despite dealing with ill health for the past several years.

When Lu got the surprise diagnosis of late-stage metastatic pancreatic cancer on January 3rd this year, her first priority was to restructure her company so that the work could continue without interruption. Most people would have thrown in the towel at that stage given the implications of the diagnosis, but not Lu. She understood the importance of this data set, and she spent the rest of January and part of February on the restructuring. Lu died on March 23rd. The completion of the MT Array would not be possible without her efforts.

Oregon State University MTArray Project to Map the Geoelectric Structure of the US in 3D - funded by NSF, NASA, USGS (2006-2024)

The Magnetotelluric (MT) Method: By measuring the electric and magnetic fields at the Earth's surface, we determine the frequency dependent *impedance tensor*, which we use to image the electrical conductivity structure of the **near-surface** through the **upper mantle.**

(left) installing an MT data acquisition system; (right) the two horizontal electric field dipole sensors and two horizontal and one vertical magnetic field sensor.



Operational cadence

After sites that meet our criteria are selected, and usually following protracted efforts at securing permits, our crews install our gear where it is left operating autonomously. For most of the past 17 years, the data were exclusively saved internally to the instruments, so sites were re-visited after ~11-days to check on data quality and make any necessary adjustments/repairs. Following one or more service calls, once data quality meets standards, the site is extracted and the gear relocated to the next available grid point.

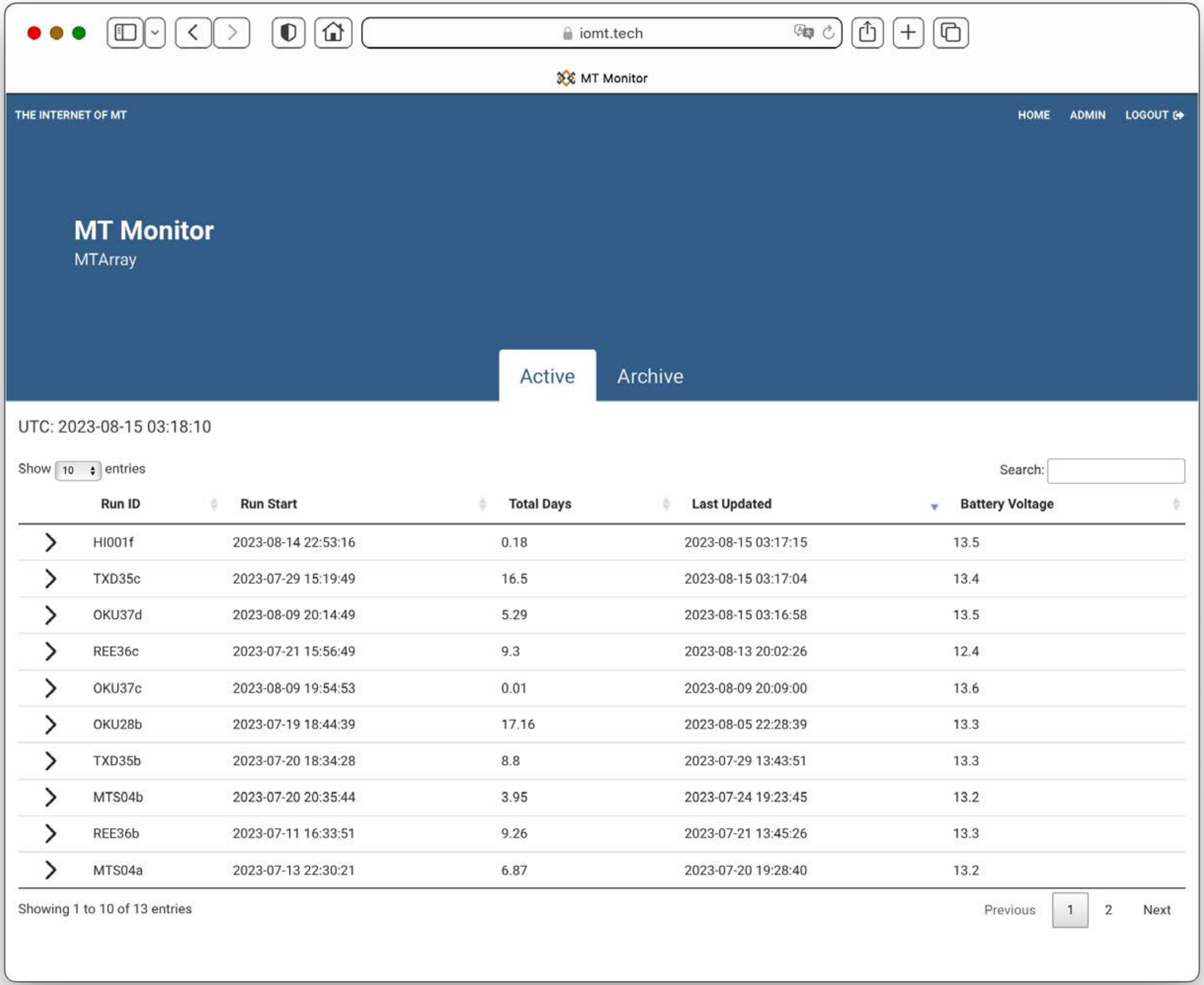
Once the data are fully extracted, under our current cooperative agreement, USGS does the final processing and archival push to the public database for MT data.

We operate anywhere between 1 and 4 2-person crews at any given time.

Last year we began to roll out real-time telemetry capability. Following iterative testing and debugging, full-scale roll-out is ongoing, and the data are transmitted in 40-s blocks. This stream is available immediately through our MT data portal: IoMT.tech IoMT is the Internet of Magnetotellurics (MT).

With real-time telemetry we know the full status of our installation at all times and we can process the data remotely. This saves a great deal of time and money.

IoMT.tech



iomt.tech

MT Monitor

THE INTERNET OF MT

HOME ADMIN LOGOUT

MT Monitor

MTArray

Active | Archive

UTC: 2023-08-15 03:18:10

Show 10 entries

Search:

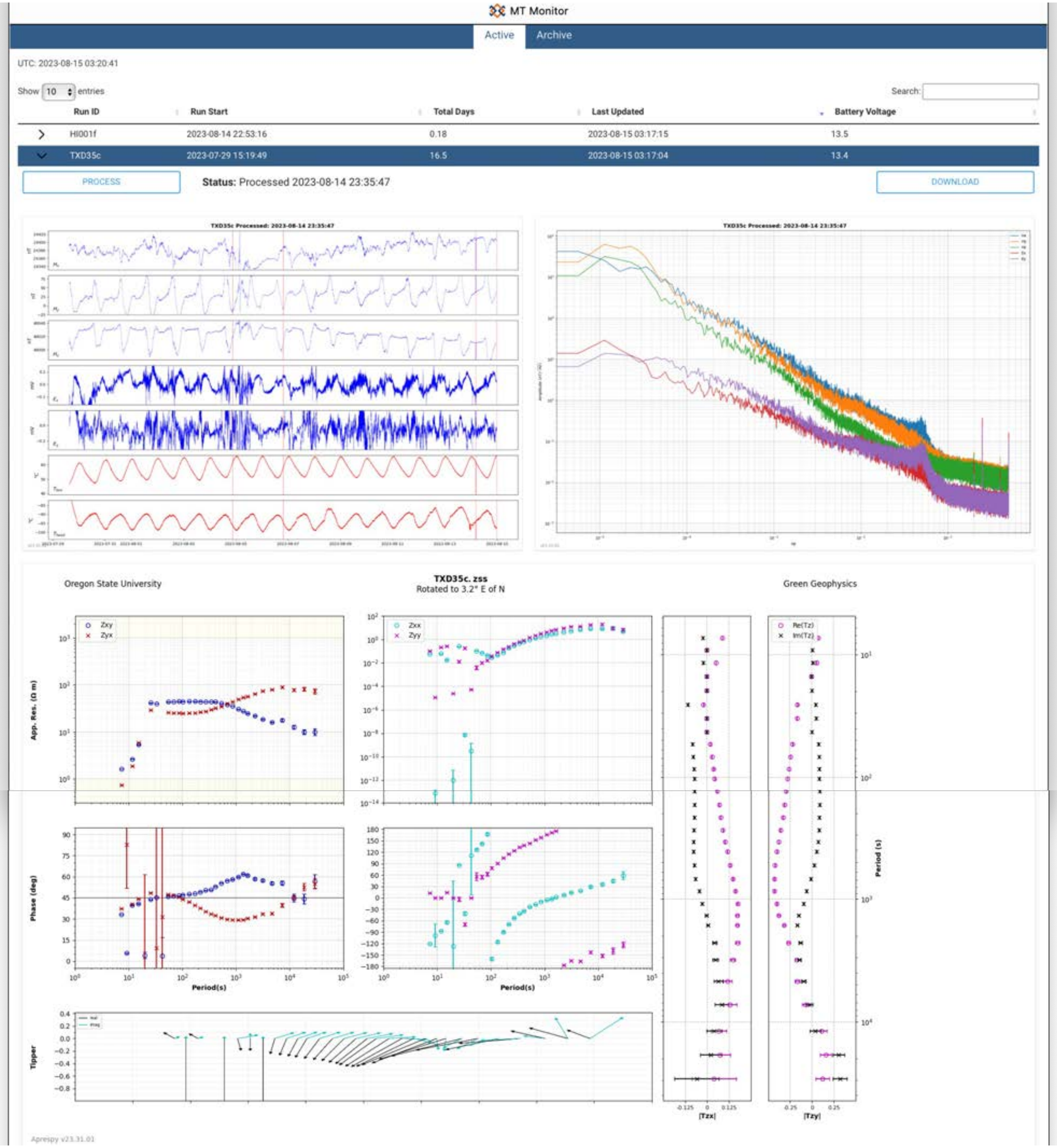
	Run ID	Run Start	Total Days	Last Updated	Battery Voltage
>	HI001f	2023-08-14 22:53:16	0.18	2023-08-15 03:17:15	13.5
>	TXD35c	2023-07-29 15:19:49	16.5	2023-08-15 03:17:04	13.4
>	OKU37d	2023-08-09 20:14:49	5.29	2023-08-15 03:16:58	13.5
>	REE36c	2023-07-21 15:56:49	9.3	2023-08-13 20:02:26	12.4
>	OKU37c	2023-08-09 19:54:53	0.01	2023-08-09 20:09:00	13.6
>	OKU28b	2023-07-19 18:44:39	17.16	2023-08-05 22:28:39	13.3
>	TXD35b	2023-07-20 18:34:28	8.8	2023-07-29 13:43:51	13.3
>	MTS04b	2023-07-20 20:35:44	3.95	2023-07-24 19:23:45	13.2
>	REE36b	2023-07-11 16:33:51	9.26	2023-07-21 13:45:26	13.3
>	MTS04a	2023-07-13 22:30:21	6.87	2023-07-20 19:28:40	13.2

Showing 1 to 10 of 13 entries

Previous 1 2 Next

Time series

Power spectra for all channels



Impedance tensor vs. period (s) scaled into apparent resistivity and phase

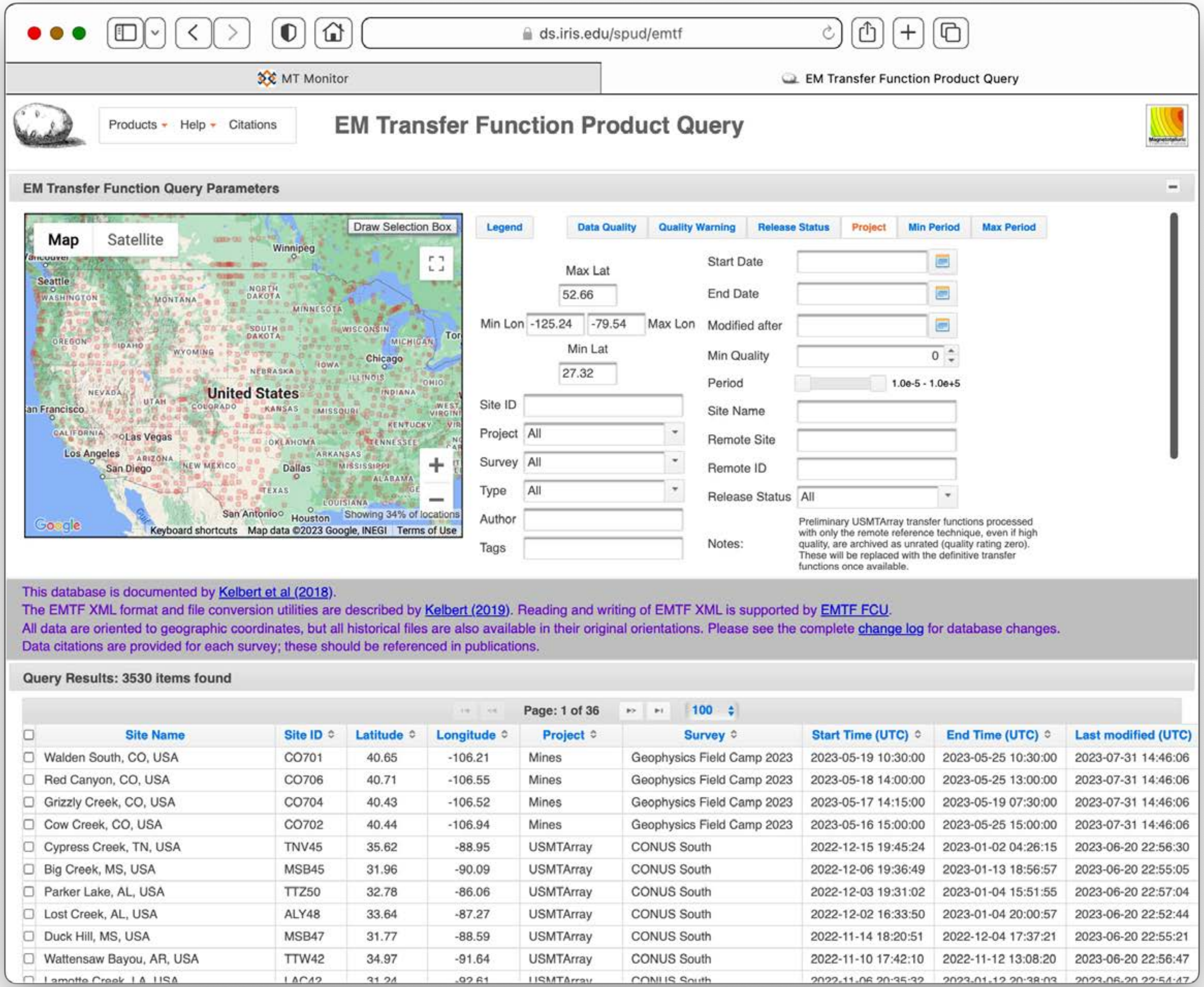
Real, Imag induction vector magnitudes

Induction vectors

Archive – how to obtain impedance and other derived MT data

The national archives for long-period MT impedance and related data is at: ds.iris.edu/spud/emtf

Data search can be through the map, or by geographic bounding box, by station name or other designated search fields



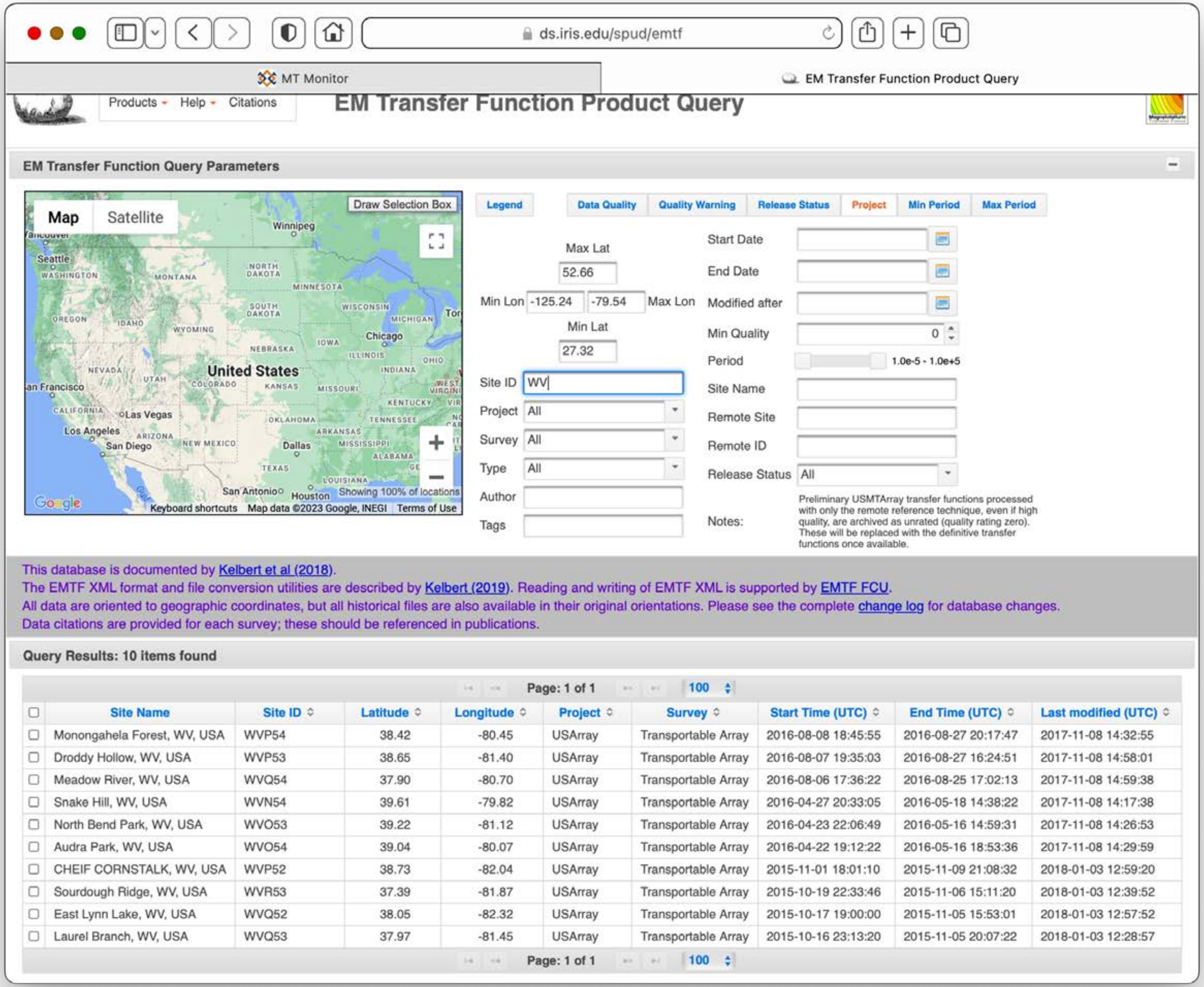
Archive – how to obtain impedance and other derived MT data

Example: we'll search for all stations that had been installed in West Virginia.

Our station naming convention is to use the 2-letter code for the state as the first two characters of the station name (unless the station is a relocation of a previously attempted station at the same grid point).

So we enter "WV" in the Side ID field and search – notice the stations that come up are all in WV.

Let's select Audra Park, WV…

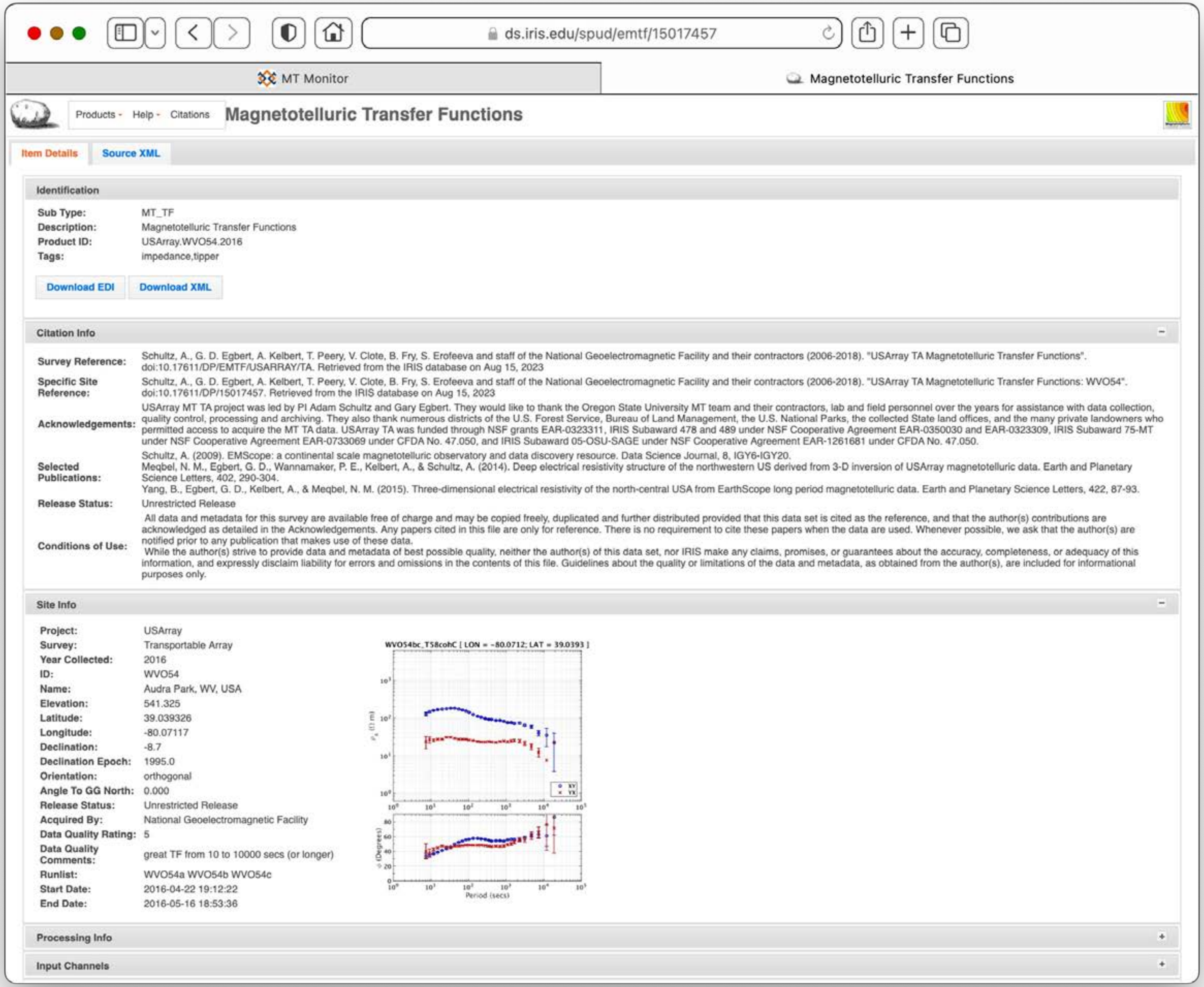


Site Name	Site ID	Latitude	Longitude	Project	Survey	Start Time (UTC)	End Time (UTC)	Last modified (UTC)
Monongahela Forest, WV, USA	WVP54	38.42	-80.45	USArray	Transportable Array	2016-08-08 18:45:55	2016-08-27 20:17:47	2017-11-08 14:32:55
Droddy Hollow, WV, USA	WVP53	38.65	-81.40	USArray	Transportable Array	2016-08-07 19:35:03	2016-08-27 16:24:51	2017-11-08 14:58:01
Meadow River, WV, USA	WVQ54	37.90	-80.70	USArray	Transportable Array	2016-08-06 17:36:22	2016-08-25 17:02:13	2017-11-08 14:59:38
Snake Hill, WV, USA	WVN54	39.61	-79.82	USArray	Transportable Array	2016-04-27 20:33:05	2016-05-18 14:38:22	2017-11-08 14:17:38
North Bend Park, WV, USA	WVO53	39.22	-81.12	USArray	Transportable Array	2016-04-23 22:06:49	2016-05-16 14:59:31	2017-11-08 14:26:53
Audra Park, WV, USA	WVO54	39.04	-80.07	USArray	Transportable Array	2016-04-22 19:12:22	2016-05-16 18:53:36	2017-11-08 14:29:59
CHEIF CORNSTALK, WV, USA	WVP52	38.73	-82.04	USArray	Transportable Array	2015-11-01 18:01:10	2015-11-09 21:08:32	2018-01-03 12:59:20
Sourdough Ridge, WV, USA	WVR53	37.39	-81.87	USArray	Transportable Array	2015-10-19 22:33:46	2015-11-06 15:11:20	2018-01-03 12:39:52
East Lynn Lake, WV, USA	WVQ52	38.05	-82.32	USArray	Transportable Array	2015-10-17 19:00:00	2015-11-05 15:53:01	2018-01-03 12:57:52
Laurel Branch, WV, USA	WVQ53	37.97	-81.45	USArray	Transportable Array	2015-10-16 23:13:20	2015-11-05 20:07:22	2018-01-03 12:28:57

Archive – how to obtain impedance and other derived MT data

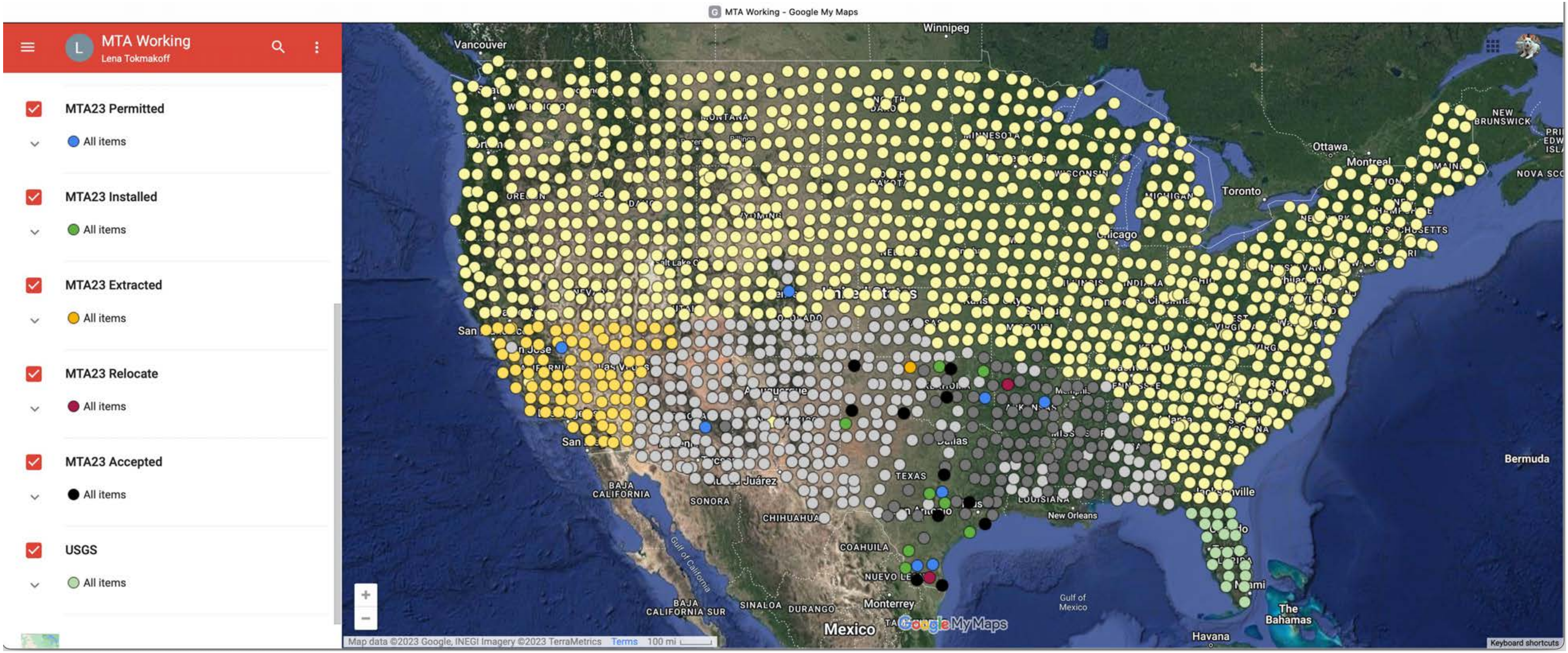
The MT impedance and related data for Audra Park, WV appear in the plot, and can be downloaded in either EDI or XML formats.

(Electric and magnetic time series data are also available through IRIS data services)



The MT Array – completion status as of August 14, 2023

A ~1900 station array of temporary ground-level electric and magnetic field monitoring stations covering the conterminous USA operated by Oregon State University since 2006 – for completion mid-2024



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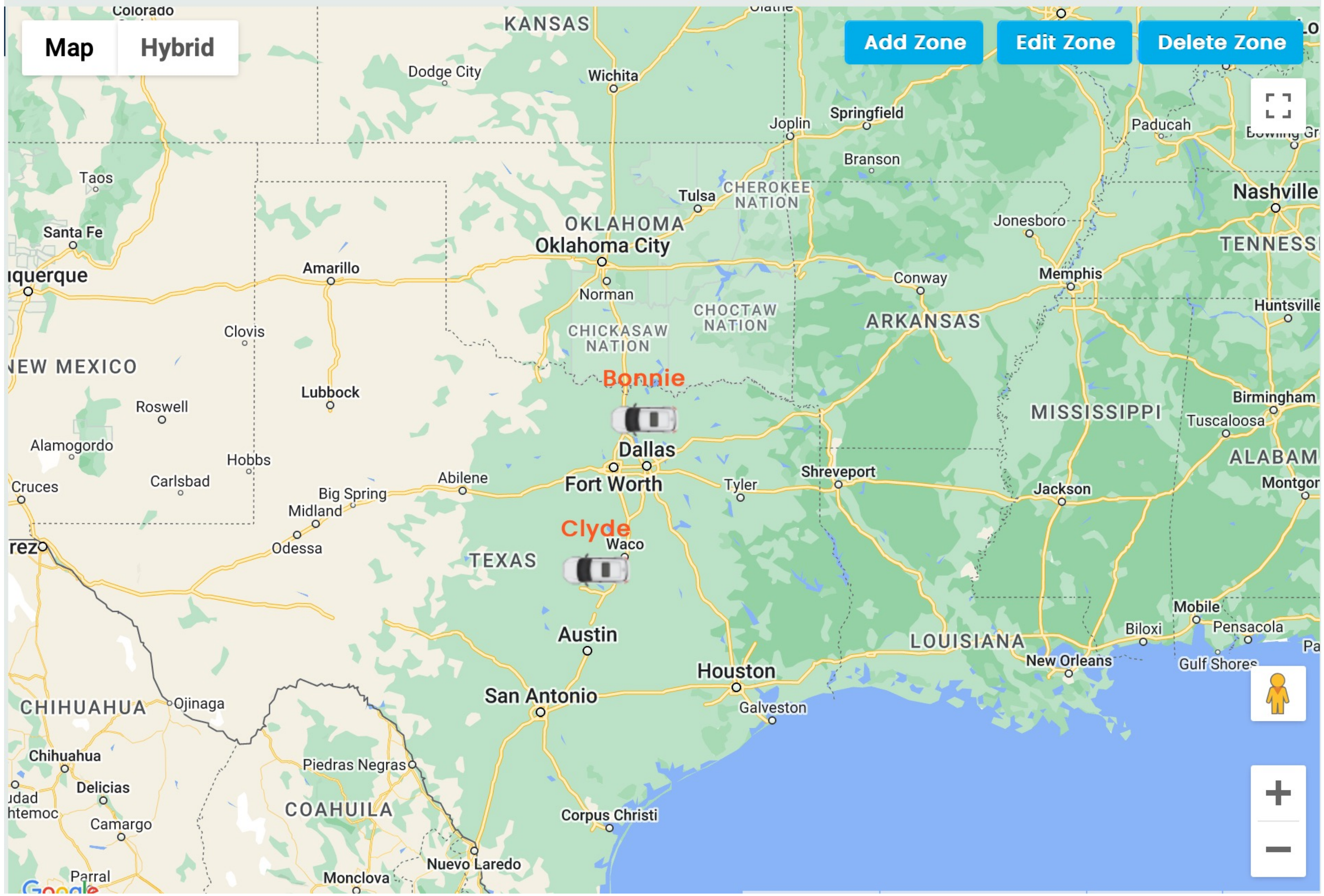
At the moment we've got two survey trucks in the field (crew names "Bonnie" and "Clyde"), both in Texas.



Toward ubiquitous knowledge of the geo-EM environment

The Internet of MT (IoMT)

Goal – decrease cost of long-period MT system acquisition and operation by an order-of-magnitude to make mass deployment of hundreds-to-thousands of permanently installed electric and magnetic sensors for continuous monitoring feasible – synchronized and streaming to cloud data services

- High fidelity view of time- and space- variations in magnetic field and induced electric fields at ground level. Electric fields are low-cost add-ons that validate estimates of electric field azimuthal orientation as well as intensity
- Provide both (3D) impedance (EMTF) data and continuous time series

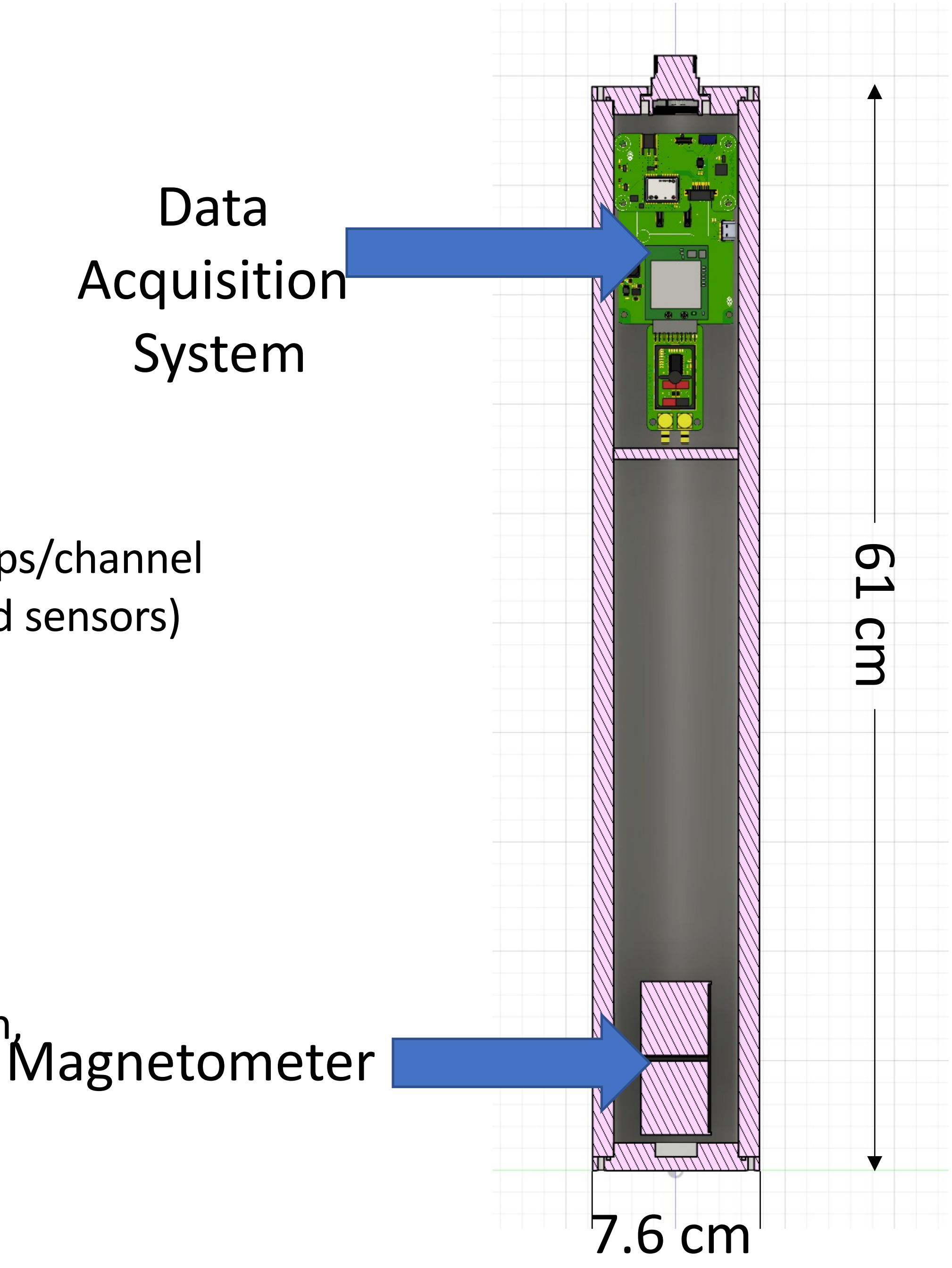
IoMT Dart (2023)

- Internet of MT Data Acquisition with Rapid Telemetry
  - First in a family of devices
  - Low cost
  - Integrated magnetometer
  - GNSS timing and positioning
  - WIFI communication and control
  - LTE based telemetry
  - Fast installation – auger small diam hole 60 cm down into ground, insert DART and quick orientation and level

Developed by collaboration between Enthalpion Energy LLC and Chaytus Research and Engineering, LLC

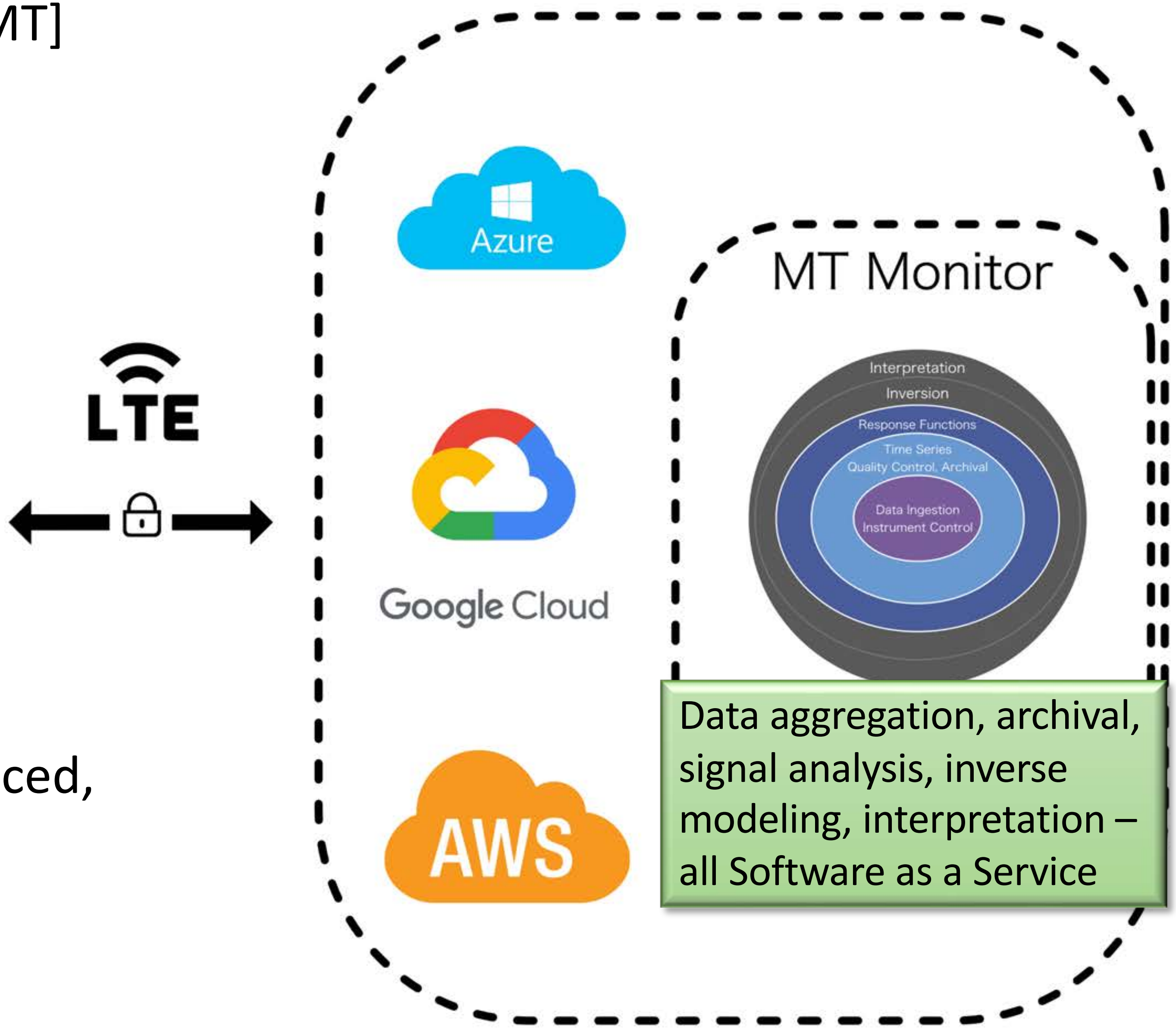
Dart v2.0 Specs

- Low power:
  - < 1 W without telemetry
  - < 2 W with telemetry
- Up to 9 independent 32-bit ADCs
- 1 Hz base sampling rate (long-period), and up to 38,400 sps/channel (wideband – accepts external induction coil magnetic field sensors)
- GNSS for timing and positioning
- FPGA for high-speed throughput
- WiFi
- Carrier hopping LTE
- Polymer housing – two form factors – cylindrical as shown, also compact Pelican™-style case



IoMT [the internet of MT]

Ultra low-cost cloud synced,
Integrated MT system



The authors acknowledge the support of

DART system development by Chaytus Research and Engineering LLC (Brady Fry) and Enthalpion Energy LLC (Adam Schultz)

Other project support from
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US Geological Survey-Oregon State University Cooperative Agreements G20AC00094, G22AC00255

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.

Questions? Adam.Schultz@oregonstate.edu

Update on CONUS Electrical Conductivity and Impedance Mapping

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Our subcontractors include GSY-USA, the late Phil Wannamaker (Univ. Utah), Zonge International, and for the past 11-years, Green Geophysics, Inc.

We have depended on scores of dedicated field crew members working under harsh conditions in all weather, up to and included over 115-degree temperatures, massive flooding, bushwacking and isolation.

What is exceptional about this program is that all of our data exists entirely in the public domain, and we have no proprietary hold on the data. So as Principal Investigator, other people get to publish results on our data before we get the chance to do so ourselves.

This unrestricted access includes the technical service providers such as CPI, the electric utilities, federal agencies such as NOAA/SWPC and of course USGS as well as academics. These data are meant to be used to mitigate risk to the power grid, so please use this vast collection of time series, impedance data and resulting conductivity models.

The MT Array – a brief history

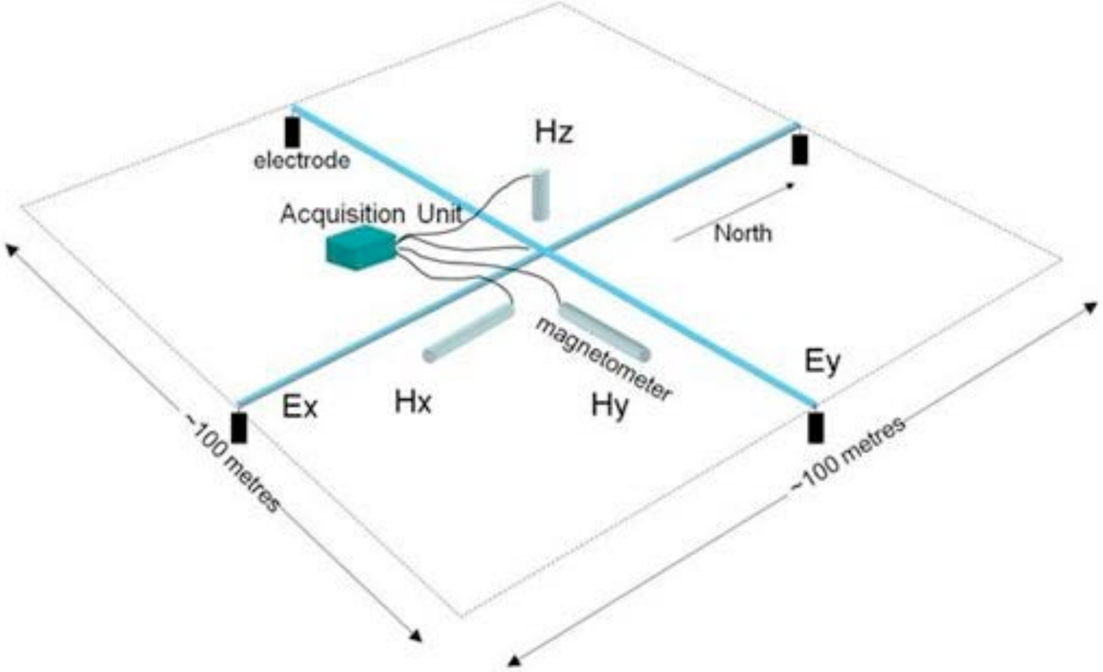
At this point, I'd particularly like to recognize my closest collaborator over the last 11-years, Dr. Louise Pellerin, President of Green Geophysics and the heart of our field operations.

Lu was instrumental in keeping the program going; rolling with the endless punches and chaos of federal government shutdowns, continuing resolutions, unknown budgets, late payments, etc. that most companies couldn't have handled. Lu was deeply involved in all aspects of the project, understood its importance to the nation, and she was committed to seeing it through to completion despite dealing with ill health for the past several years.

When Lu got the surprise diagnosis of late-stage metastatic pancreatic cancer on January 3rd this year, her first priority was to restructure her company so that the work could continue without interruption. Most people would have thrown in the towel at that stage given the implications of the diagnosis, but not Lu. She understood the importance of this data set, and she spent the rest of January and part of February on the restructuring. Lu died on March 23rd. The completion of the MT Array would not be possible without her efforts.

Oregon State University MTArray Project to Map the Geoelectric Structure of the US in 3D - funded by NSF, NASA, USGS (2006-2024)

The Magnetotelluric (MT) Method: By measuring the electric and magnetic fields at the Earth's surface, we determine the frequency dependent *impedance tensor*, which we use to image the electrical conductivity structure of the **near-surface** through the **upper mantle.**
(left) installing an MT data acquisition system; (right) the two horizontal electric field dipole sensors and two horizontal and one vertical magnetic field sensor.



Operational cadence

After sites that meet our criteria are selected, and usually following protracted efforts at securing permits, our crews install our gear where it is left operating autonomously. For most of the past 17 years, the data were exclusively saved internally to the instruments, so sites were re-visited after ~11-days to check on data quality and make any necessary adjustments/repairs. Following one or more service calls, once data quality meets standards, the site is extracted and the gear relocated to the next available grid point.

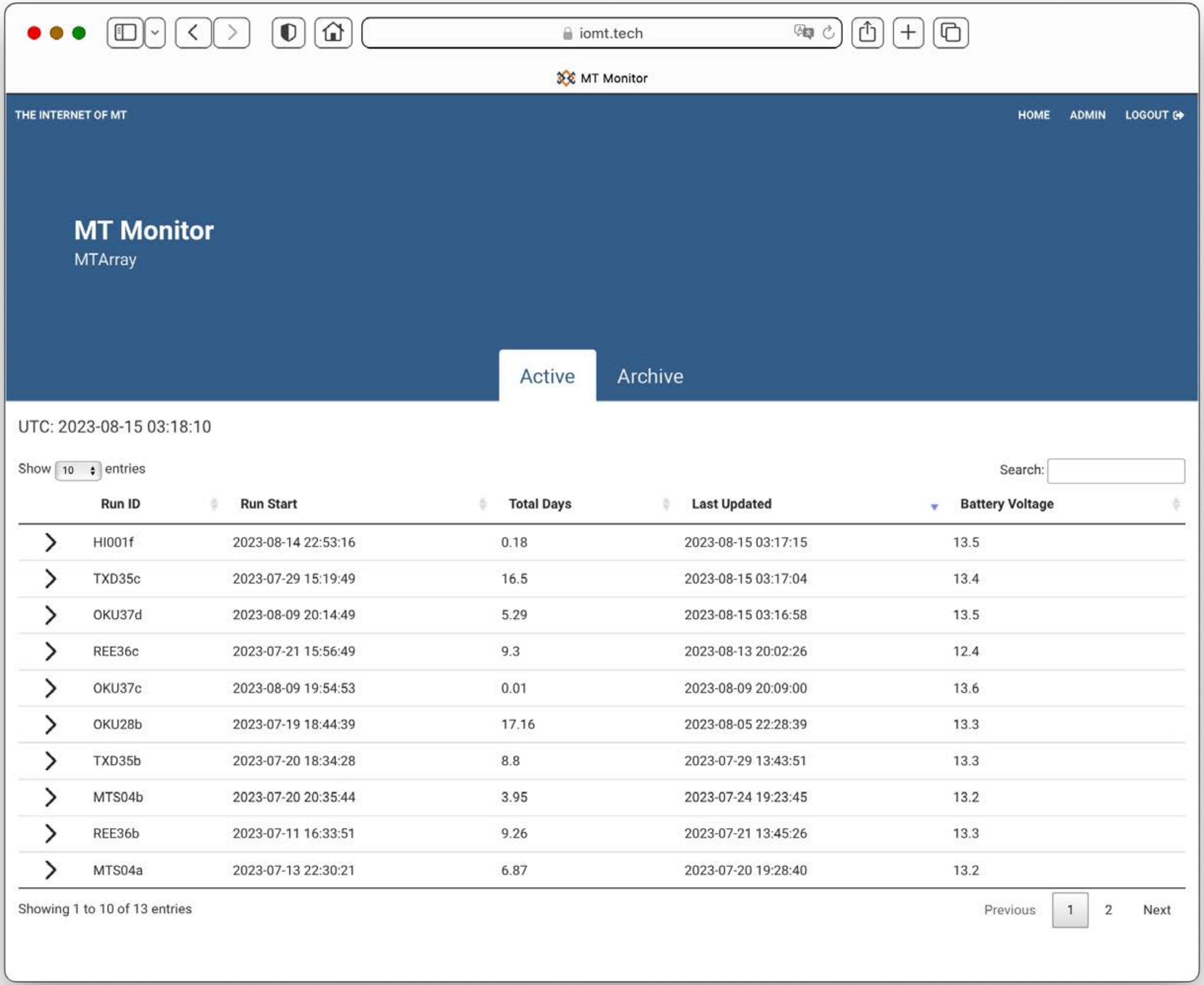
Once the data are fully extracted, under our current cooperative agreement, USGS does the final processing and archival push to the public database for MT data.

We operate anywhere between 1 and 4 2-person crews at any given time.

Last year we began to roll out real-time telemetry capability. Following iterative testing and debugging, full-scale roll-out is ongoing, and the data are transmitted in 40-s blocks. This stream is available immediately through our MT data portal: IoMT.tech IoMT is the Internet of Magnetotellurics (MT).

With real-time telemetry we know the full status of our installation at all times and we can process the data remotely. This saves a great deal of time and money.

IoMT.tech

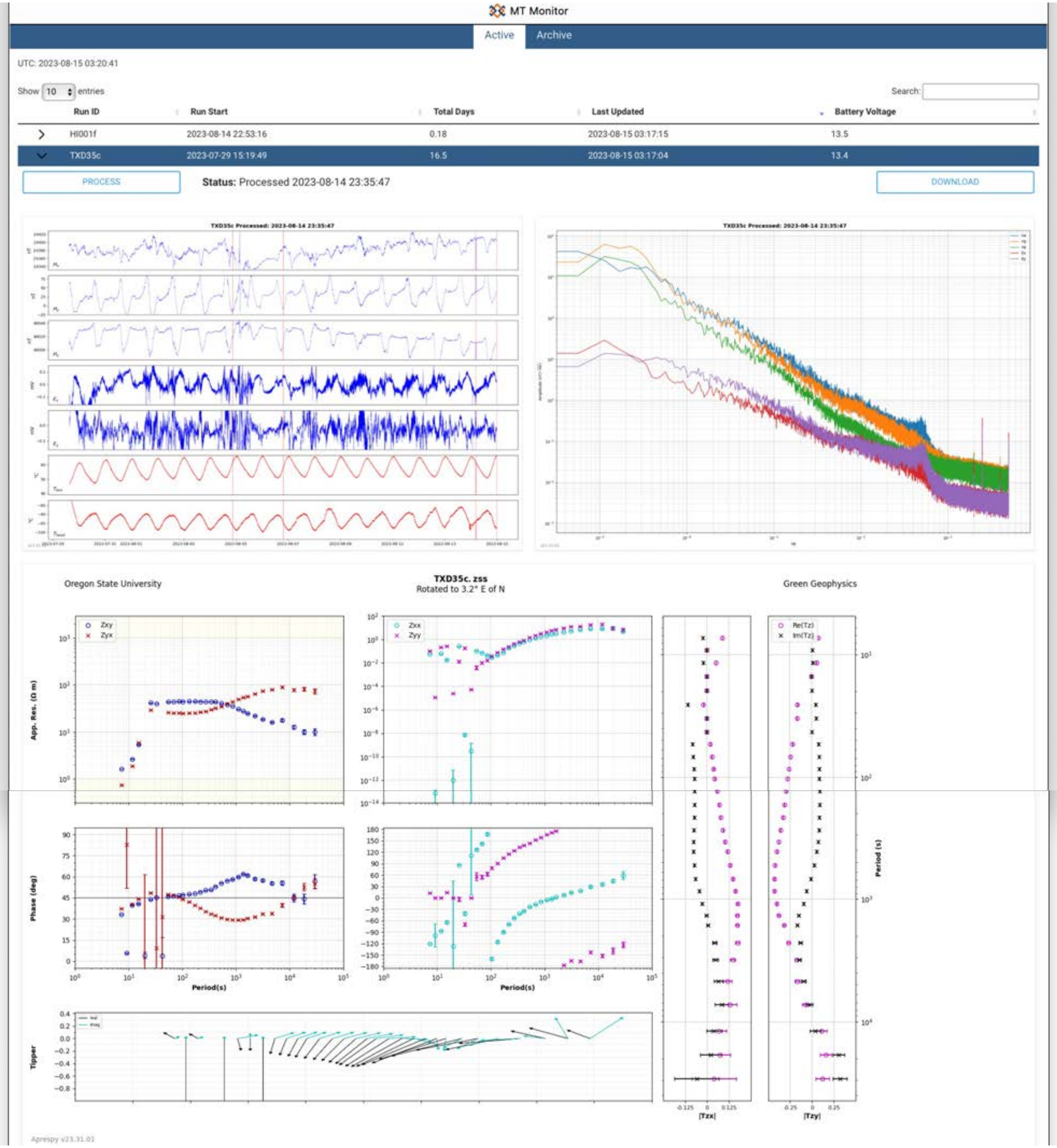


	Run ID	Run Start	Total Days	Last Updated	Battery Voltage
>	HI001f	2023-08-14 22:53:16	0.18	2023-08-15 03:17:15	13.5
>	TXD35c	2023-07-29 15:19:49	16.5	2023-08-15 03:17:04	13.4
>	OKU37d	2023-08-09 20:14:49	5.29	2023-08-15 03:16:58	13.5
>	REE36c	2023-07-21 15:56:49	9.3	2023-08-13 20:02:26	12.4
>	OKU37c	2023-08-09 19:54:53	0.01	2023-08-09 20:09:00	13.6
>	OKU28b	2023-07-19 18:44:39	17.16	2023-08-05 22:28:39	13.3
>	TXD35b	2023-07-20 18:34:28	8.8	2023-07-29 13:43:51	13.3
>	MTS04b	2023-07-20 20:35:44	3.95	2023-07-24 19:23:45	13.2
>	REE36b	2023-07-11 16:33:51	9.26	2023-07-21 13:45:26	13.3
>	MTS04a	2023-07-13 22:30:21	6.87	2023-07-20 19:28:40	13.2

Time series

Impedance tensor vs. period (s) scaled into apparent resistivity and phase

Induction vectors



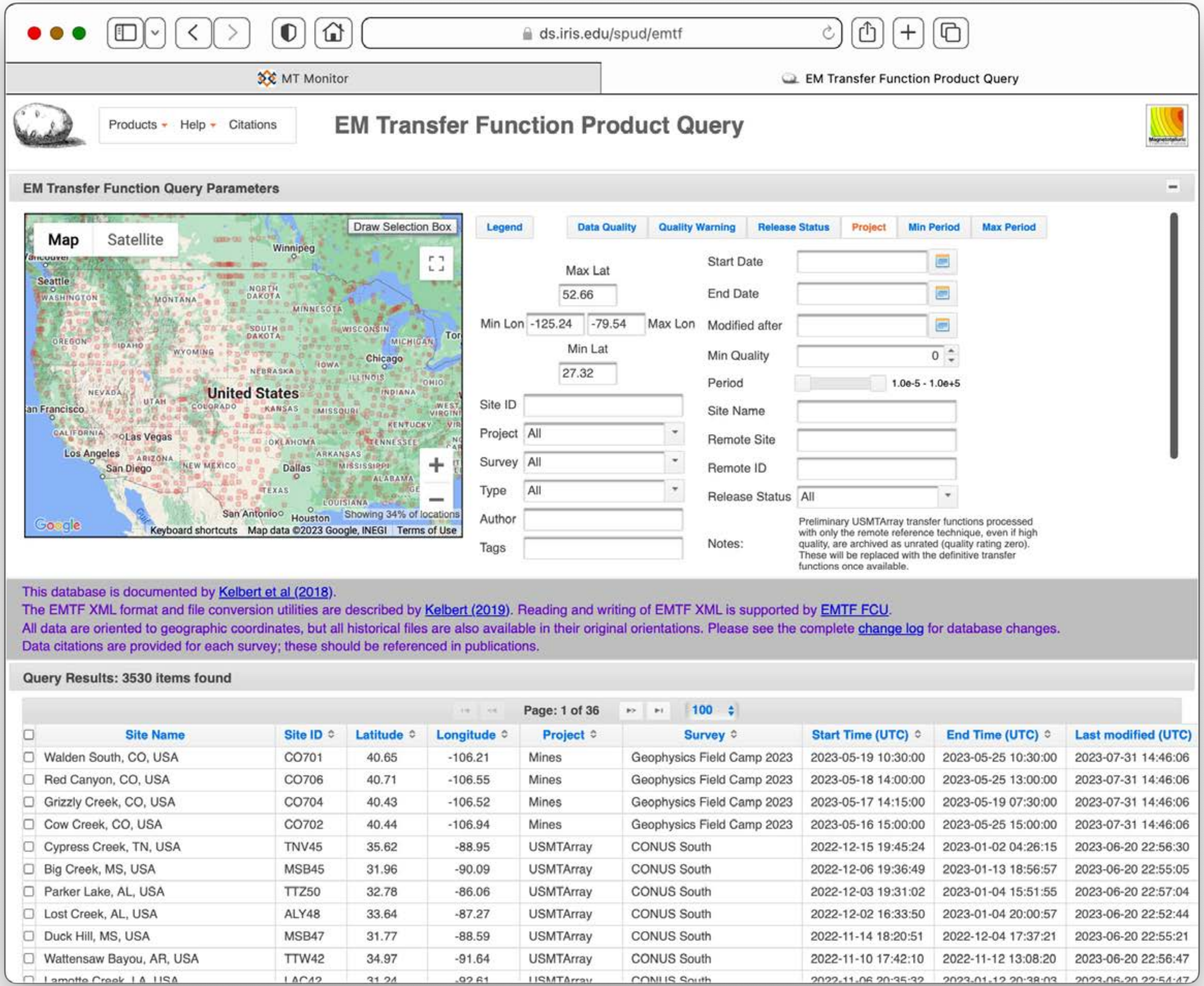
Power spectra for all channels

Real, Imag induction vector magnitudes

Archive – how to obtain impedance and other derived MT data

The national archives for long-period MT impedance and related data is at: ds.iris.edu/spud/emtf

Data search can be through the map, or by geographic bounding box, by station name or other designated search fields



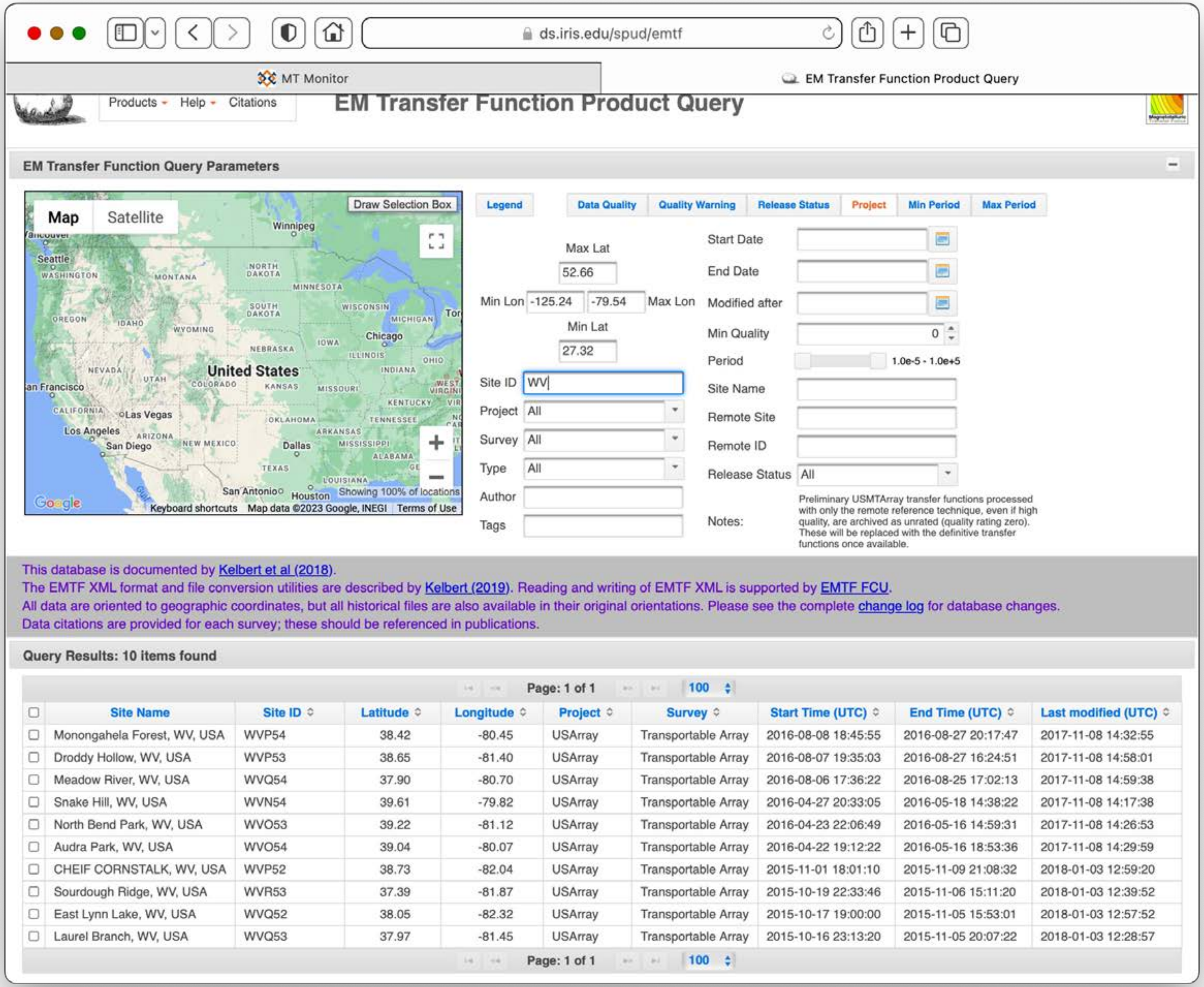
Archive – how to obtain impedance and other derived MT data

Example: we'll search for all stations that had been installed in West Virginia.

Our station naming convention is to use the 2-letter code for the state as the first two characters of the station name (unless the station is a relocation of a previously attempted station at the same grid point).

So we enter "WV" in the Side ID field and search – notice the stations that come up are all in WV.

Let's select Audra Park, WV…

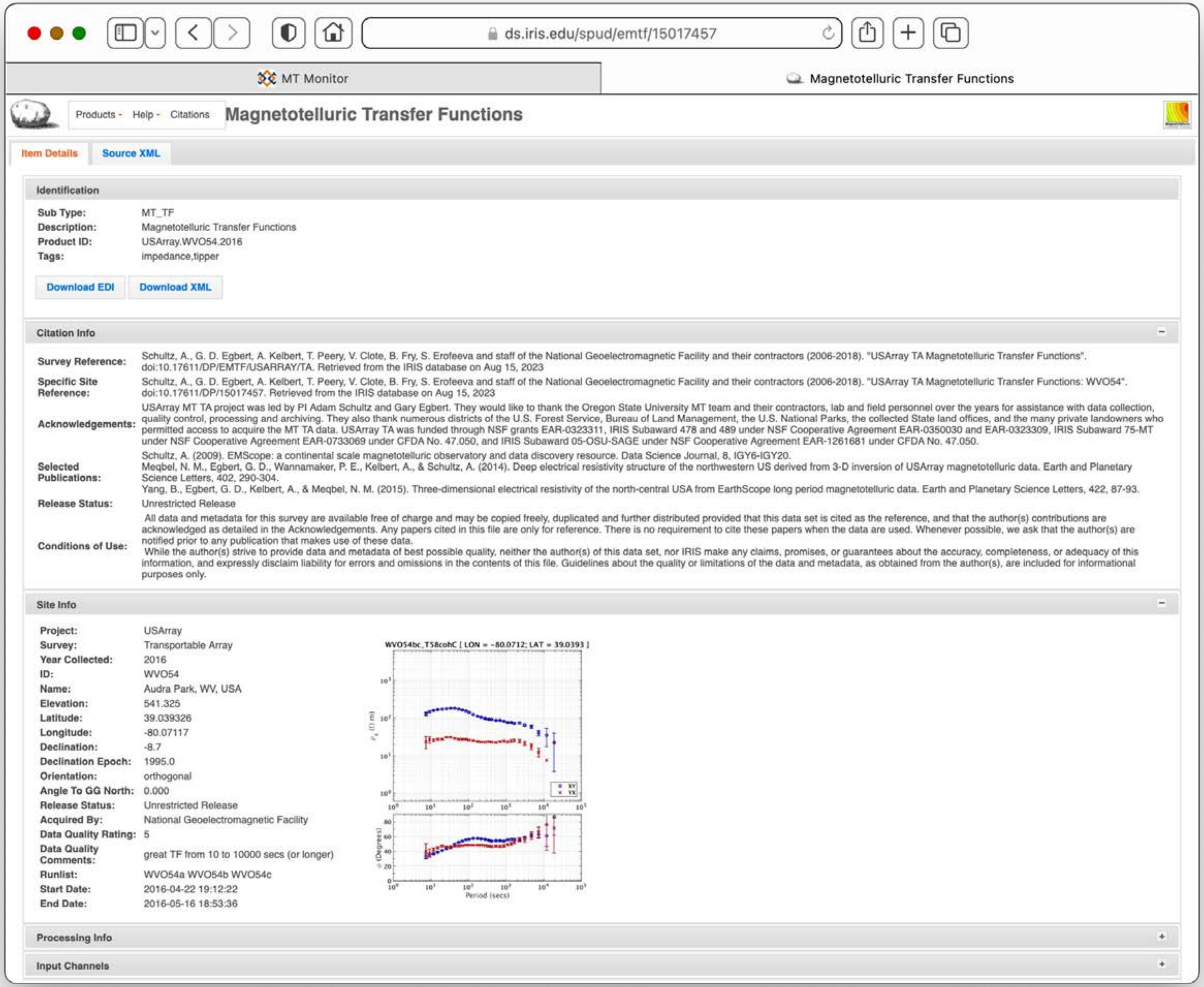


Site Name	Site ID	Latitude	Longitude	Project	Survey	Start Time (UTC)	End Time (UTC)	Last modified (UTC)
Monongahela Forest, WV, USA	WVP54	38.42	-80.45	USArray	Transportable Array	2016-08-08 18:45:55	2016-08-27 20:17:47	2017-11-08 14:32:55
Droddy Hollow, WV, USA	WVP53	38.65	-81.40	USArray	Transportable Array	2016-08-07 19:35:03	2016-08-27 16:24:51	2017-11-08 14:58:01
Meadow River, WV, USA	WVQ54	37.90	-80.70	USArray	Transportable Array	2016-08-06 17:36:22	2016-08-25 17:02:13	2017-11-08 14:59:38
Snake Hill, WV, USA	WVN54	39.61	-79.82	USArray	Transportable Array	2016-04-27 20:33:05	2016-05-18 14:38:22	2017-11-08 14:17:38
North Bend Park, WV, USA	WVO53	39.22	-81.12	USArray	Transportable Array	2016-04-23 22:06:49	2016-05-16 14:59:31	2017-11-08 14:26:53
Audra Park, WV, USA	WVO54	39.04	-80.07	USArray	Transportable Array	2016-04-22 19:12:22	2016-05-16 18:53:36	2017-11-08 14:29:59
CHEIF CORNSTALK, WV, USA	WVP52	38.73	-82.04	USArray	Transportable Array	2015-11-01 18:01:10	2015-11-09 21:08:32	2018-01-03 12:59:20
Sourdough Ridge, WV, USA	WVR53	37.39	-81.87	USArray	Transportable Array	2015-10-19 22:33:46	2015-11-06 15:11:20	2018-01-03 12:39:52
East Lynn Lake, WV, USA	WVQ52	38.05	-82.32	USArray	Transportable Array	2015-10-17 19:00:00	2015-11-05 15:53:01	2018-01-03 12:57:52
Laurel Branch, WV, USA	WVQ53	37.97	-81.45	USArray	Transportable Array	2015-10-16 23:13:20	2015-11-05 20:07:22	2018-01-03 12:28:57

Archive – how to obtain impedance and other derived MT data

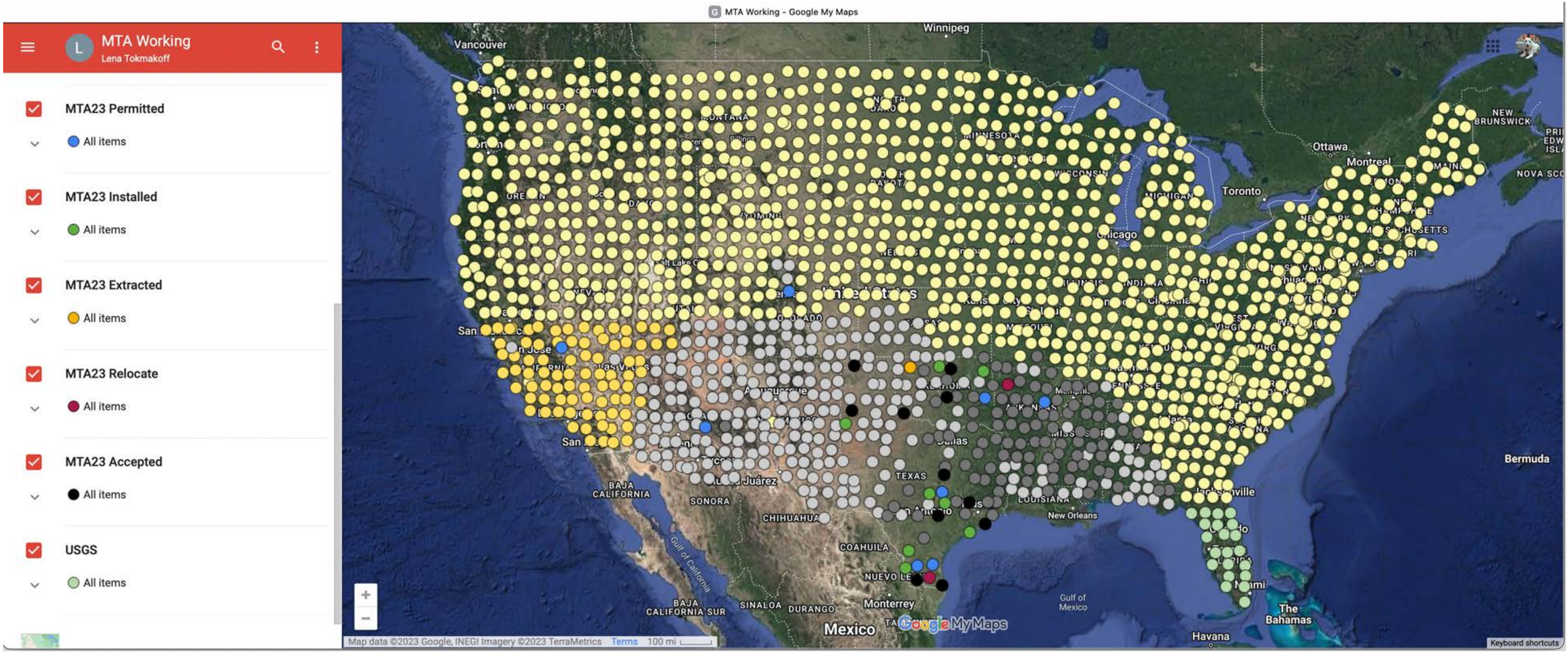
The MT impedance and related data for Audra Park, WV appear in the plot, and can be downloaded in either EDI or XML formats.

(Electric and magnetic time series data are also available through IRIS data services)



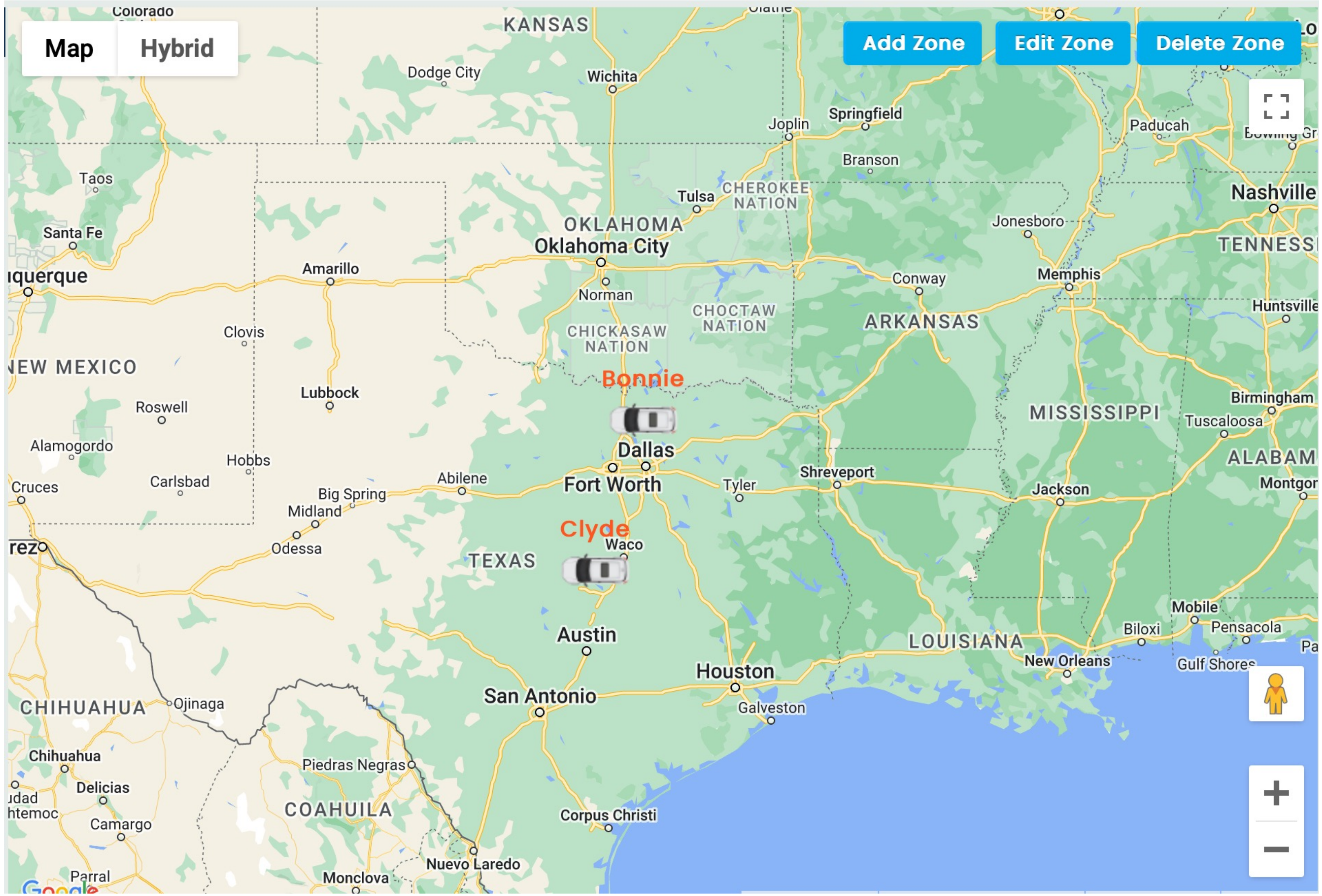
The MT Array – completion status as of August 14, 2023

A ~1900 station array of temporary ground-level electric and magnetic field monitoring stations covering the conterminous USA operated by Oregon State University since 2006 – for completion mid-2024



The MT Array – completion status as of August 14, 2023

At the moment we've got two survey trucks in the field (crew names "Bonnie" and "Clyde"), both in Texas.



Toward ubiquitous knowledge of the geo-EM environment

The Internet of MT (IoMT)

Goal – decrease cost of long-period MT system acquisition and operation by an order-of-magnitude to make mass deployment of hundreds-to-thousands of permanently installed electric and magnetic sensors for continuous monitoring feasible – synchronized and streaming to cloud data services

- High fidelity view of time- and space- variations in magnetic field and induced electric fields at ground level. Electric fields are low-cost add-ons that validate estimates of electric field azimuthal orientation as well as intensity
- Provide both (3D) impedance (EMTF) data and continuous time series

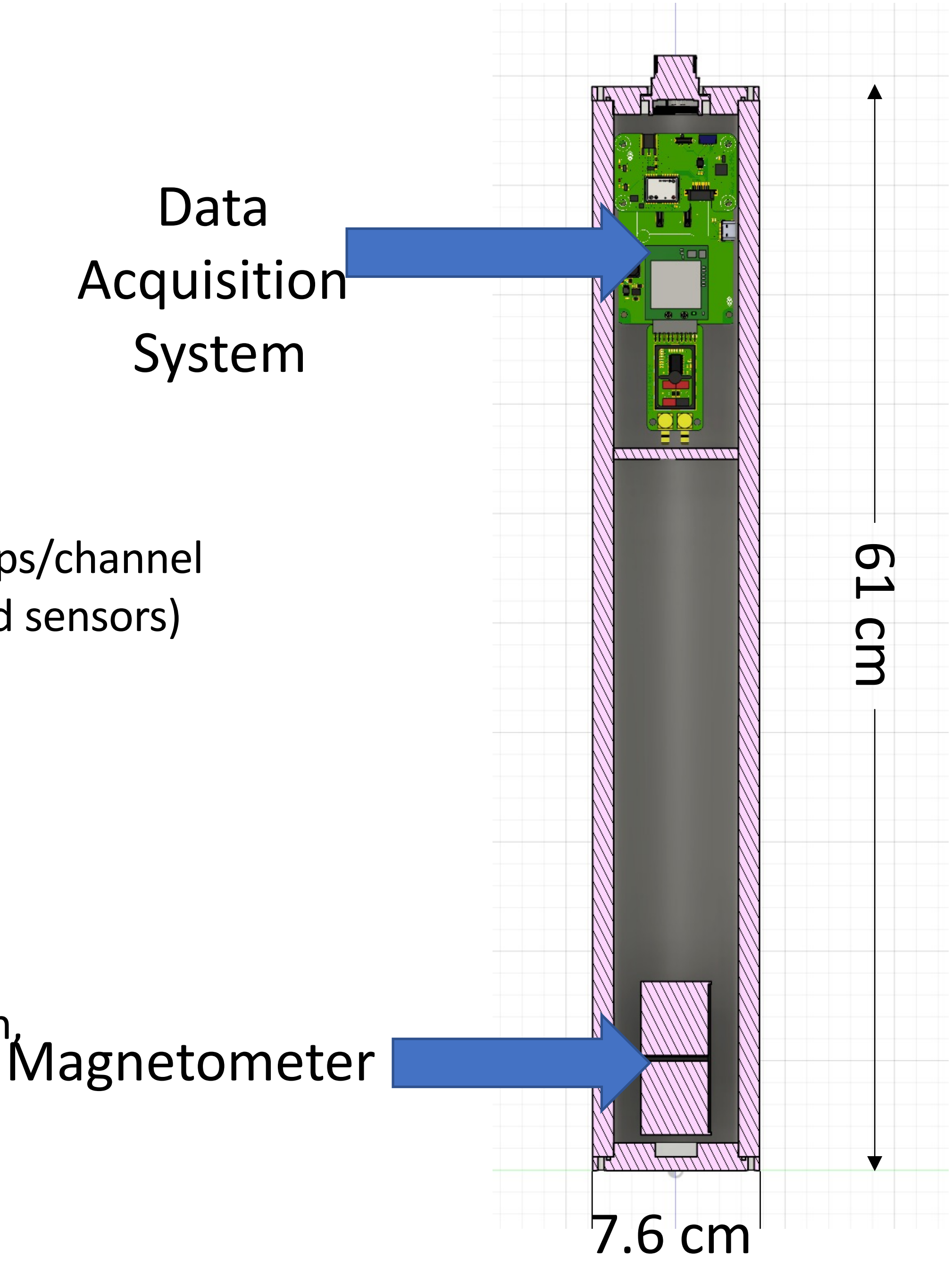
IoMT Dart (2023)

- Internet of MT Data Acquisition with Rapid Telemetry
  - First in a family of devices
  - Low cost
  - Integrated magnetometer
  - GNSS timing and positioning
  - WIFI communication and control
  - LTE based telemetry
  - Fast installation – auger small diam hole 60 cm down into ground, insert DART and quick orientation and level

Developed by collaboration between Enthalpion Energy LLC and Chaytus Research and Engineering, LLC

Dart v2.0 Specs

- Low power:
  - < 1 W without telemetry
  - < 2 W with telemetry
- Up to 9 independent 32-bit ADCs
- 1 Hz base sampling rate (long-period), and up to 38,400 sps/channel (wideband – accepts external induction coil magnetic field sensors)
- GNSS for timing and positioning
- FPGA for high-speed throughput
- WiFi
- Carrier hopping LTE
- Polymer housing – two form factors – cylindrical as shown, also compact Pelican™-style case



IoMT [the internet of MT]

Ultra low-cost cloud synced,
Integrated MT system

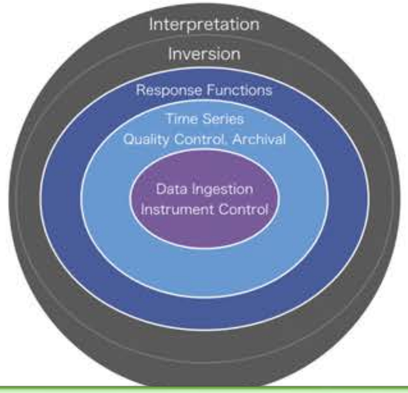
LTE

Azure

Google Cloud

AWS

MT Monitor



Data aggregation, archival, signal analysis, inverse modeling, interpretation – all Software as a Service

The authors acknowledge the support of

DART system development by Chaytus Research and Engineering LLC (Brady Fry) and Enthalpion Energy LLC (Adam Schultz)

Other project support from
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”

US Geological Survey-Oregon State University Cooperative Agreements G20AC00094, G22AC00255

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.

Questions? Adam.Schultz@oregonstate.edu

Incorporating the Coast Effect into GIC Modelling

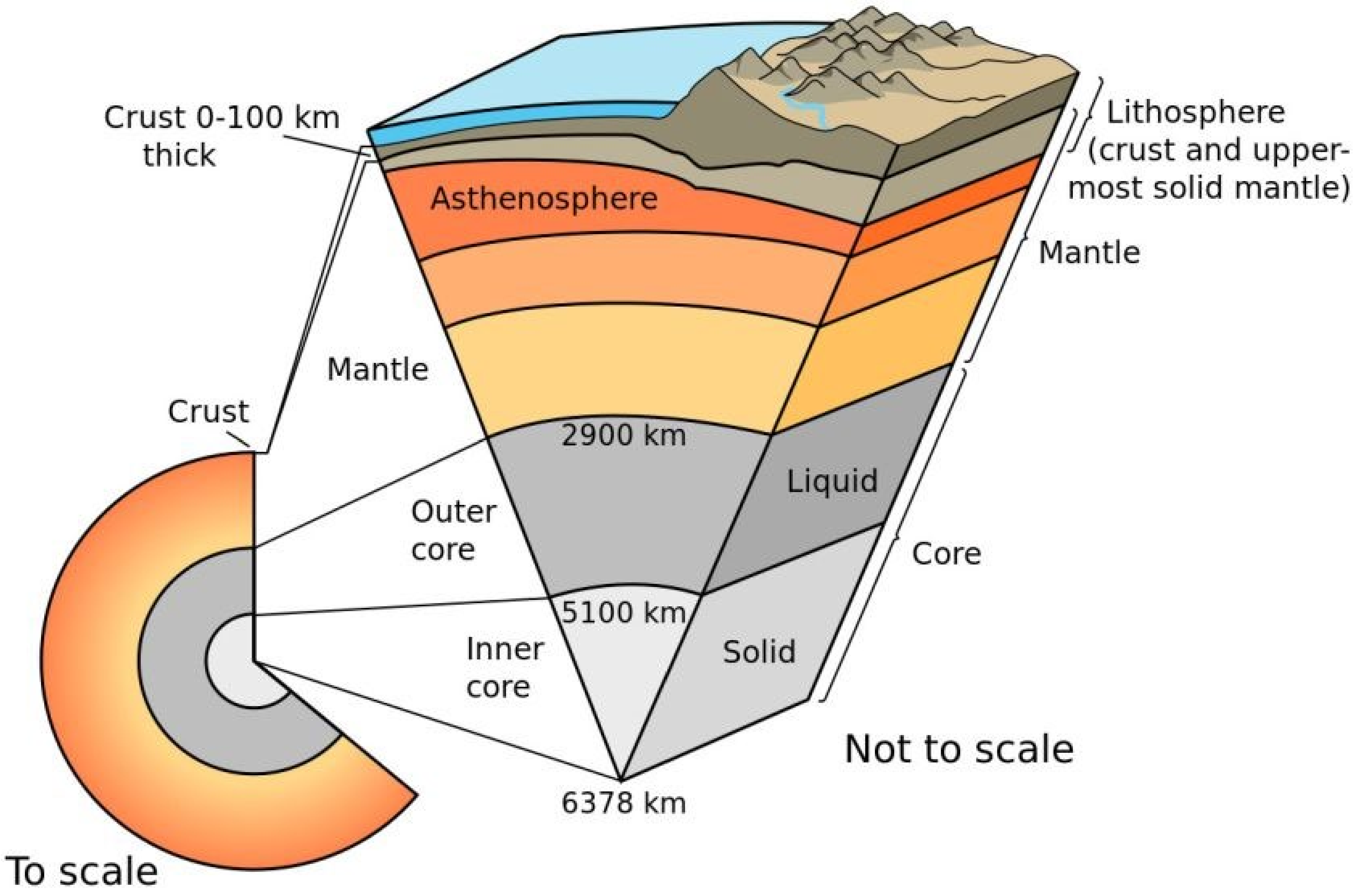
D. H. Boteler
Geomagnetic Laboratory
Natural Resources Canada

NERC GMDTF Meeting, St Paul, 15-16 August 2023

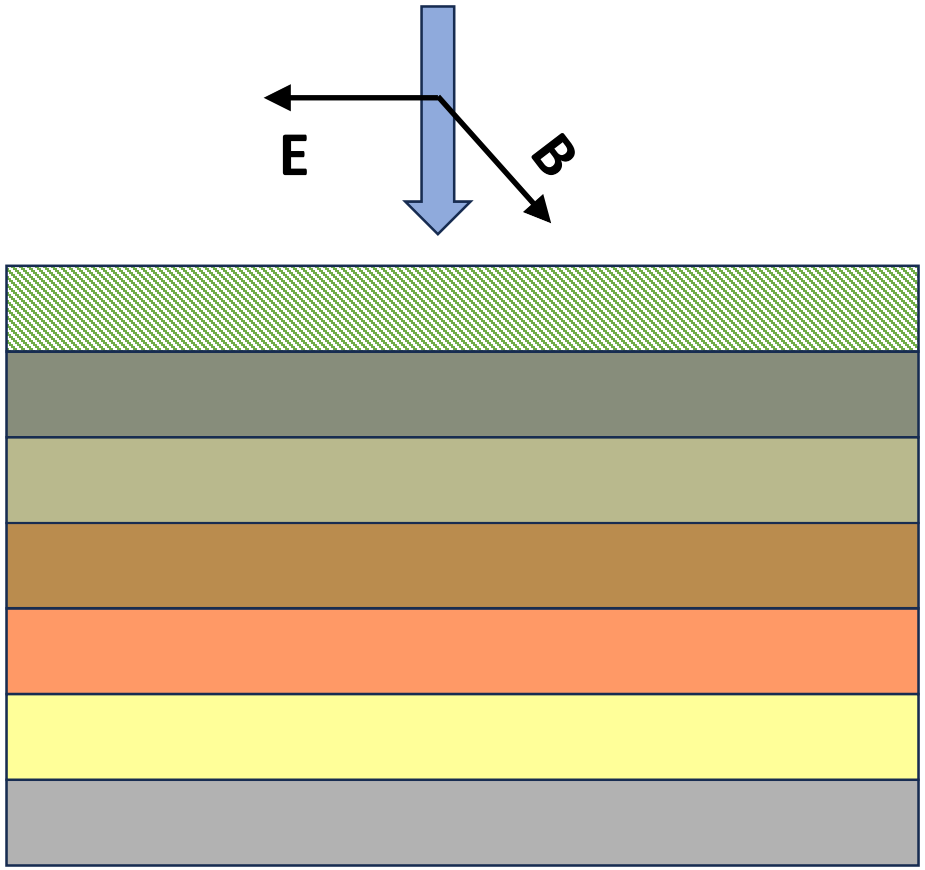
OUTLINE

- Geomagnetic Induction Refresher
- Physics of the Coast Effect
- Modeling Techniques
- Generalised Thin Sheet Model
- Transmission Line Model
- Adding the Coast Effect to GIC Modeling
- Proposal for Testing the Method

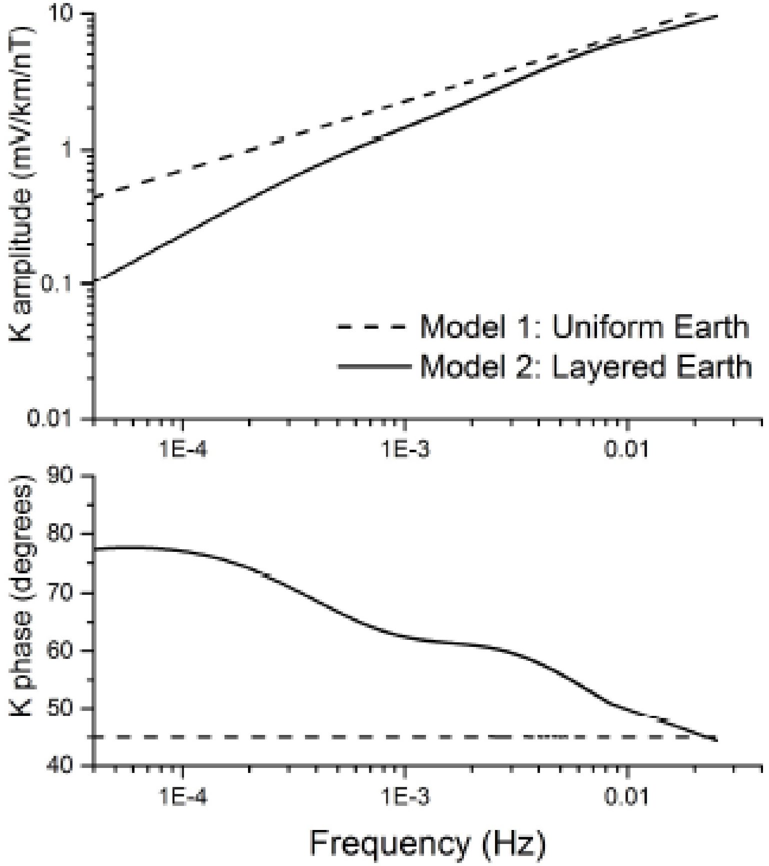
Geomagnetic Induction Refresher (1)

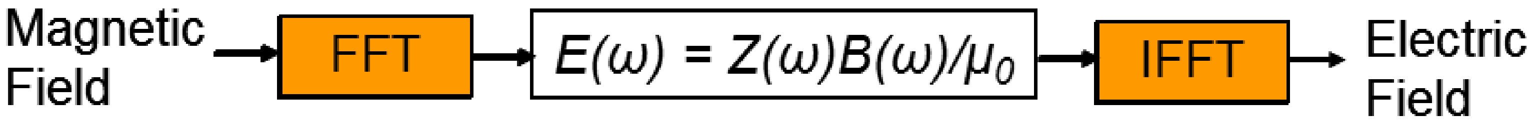


Geomagnetic Induction Refresher (2)

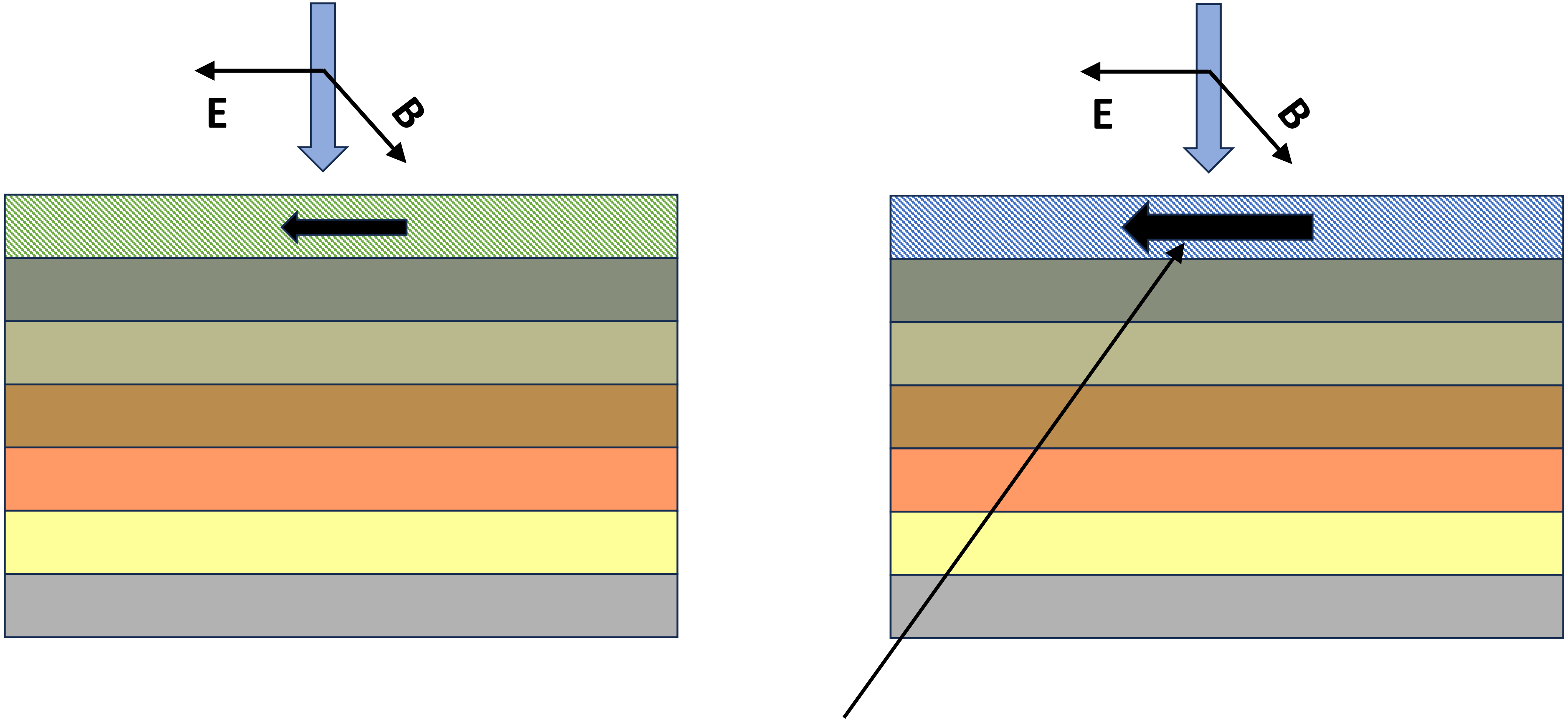


Earth Transfer Function





Physics of the Coast Effect (1)

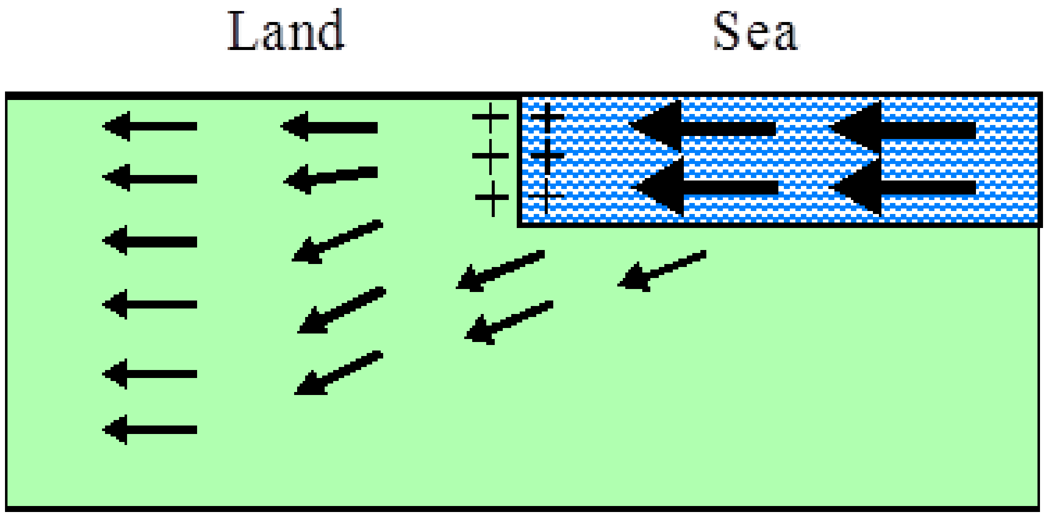


Larger induced currents in the sea

Physics of the Coast Effect (2)

Basic Mechanism

- Induced current is larger in the sea than in the land
- For electric field perpendicular to the coast this causes charge accumulation at the coast
- This increases the electric field on the land side and decreases the electric field on the sea side
- Result is current continuity across the coast



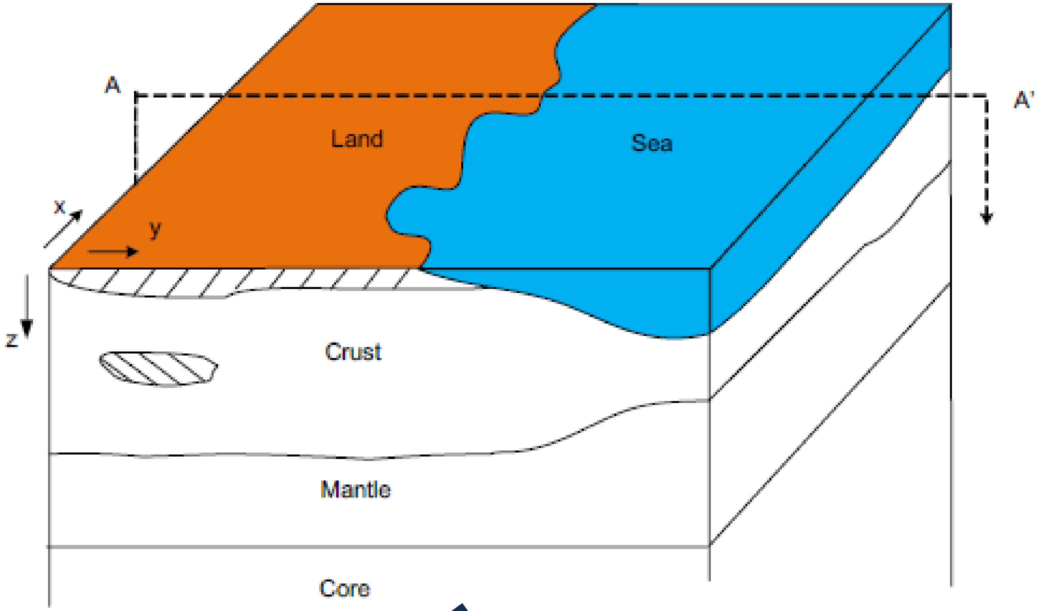
$$J_1 = J_2$$

$$\sigma_1 E_1 = \sigma_2 E_2$$

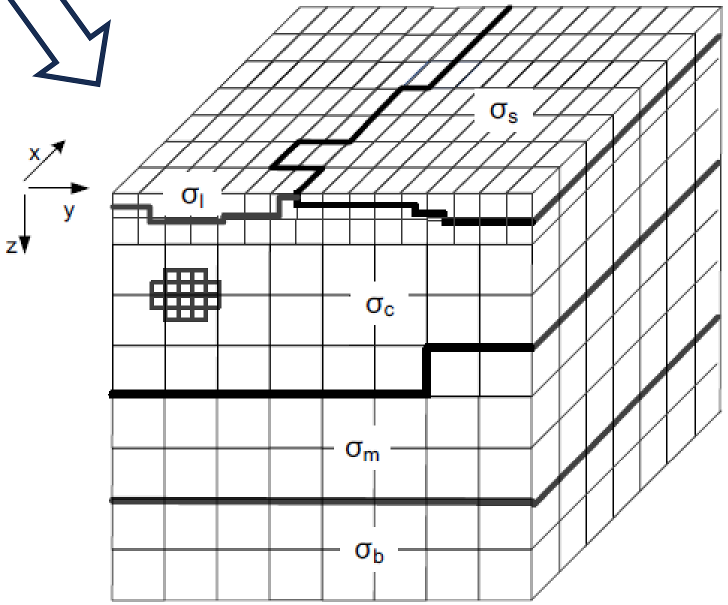
$$\frac{E_1}{E_2} = \frac{\sigma_2}{\sigma_1}$$

Modeling Techniques

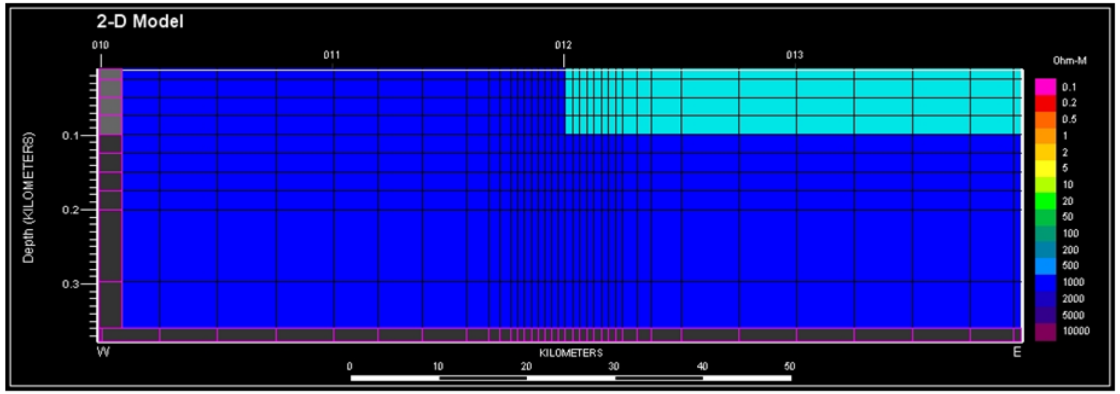
- Finite difference models
- Finite element models
- Thin-sheet models



3-D Model

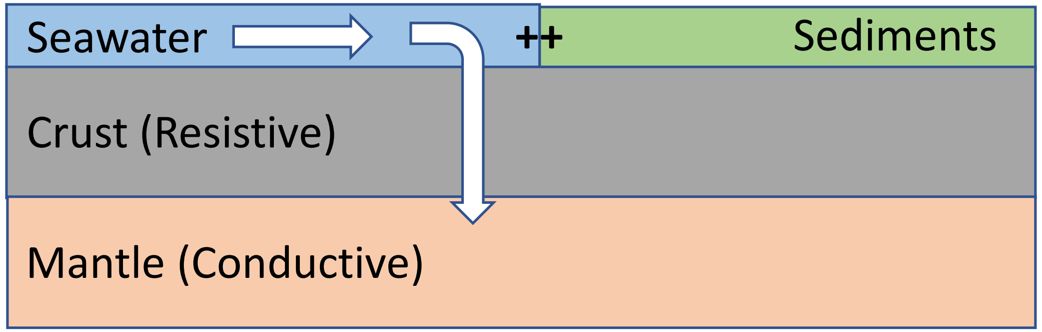


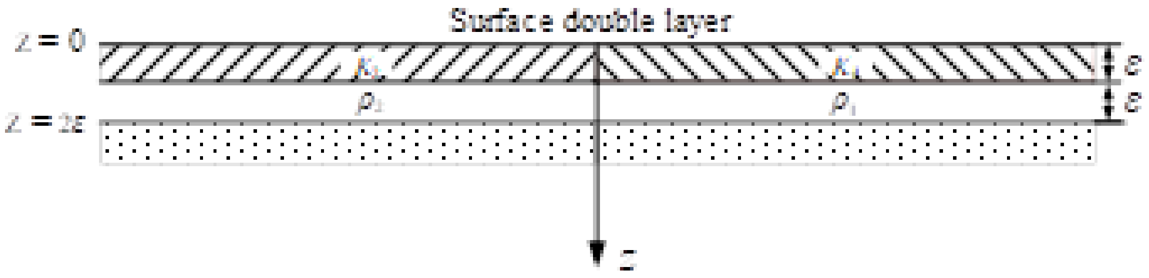
2-D Model



Generalised Thin Sheet Model

Ranganayaki and Madden (1980)





integrated conductivity, $\tau = \sigma_s d_s$,

integrated resistivity, $\lambda = d_c/\sigma_c$

$$E(x) = E_1 + C_1 e^{x/D_1} \qquad x < 0$$

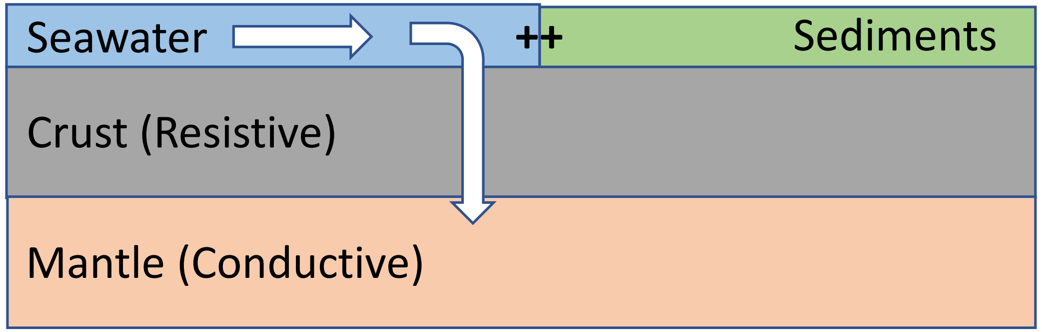
$$E(x) = E_2 + C_2 e^{-x/D_2} \qquad x > 0$$

$$C_1 = \frac{\tau_2 E_2 - \tau_1 E_1}{\sqrt{\tau_1 \lambda_1}\left(\tau_1/\sqrt{\tau_1 \lambda_1} + \tau_2/\sqrt{\tau_2 \lambda_2}\right)}$$

$$C_2 = -\frac{\tau_2 E_2 - \tau_1 E_1}{\sqrt{\tau_2 \lambda_2}\left(\tau_1/\sqrt{\tau_1 \lambda_1} + \tau_2/\sqrt{\tau_2 \lambda_2}\right)}$$

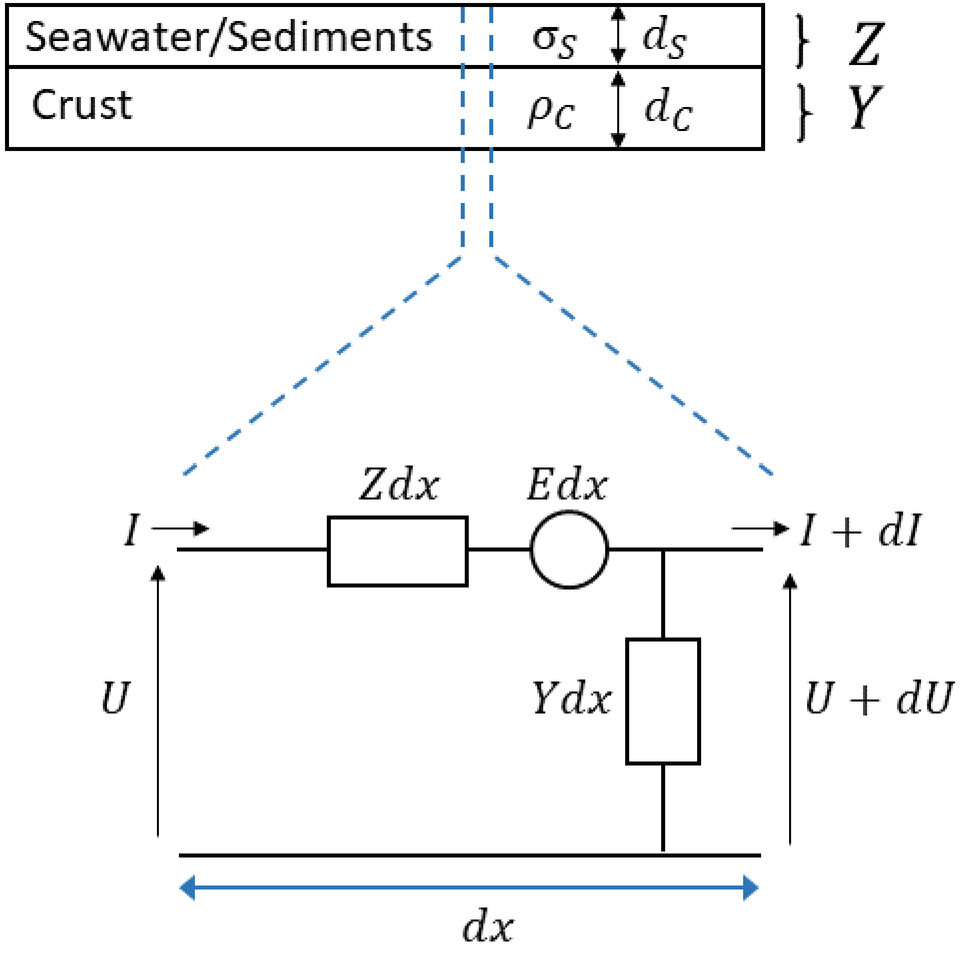
Transmission Line Model

Wang et al (2023)

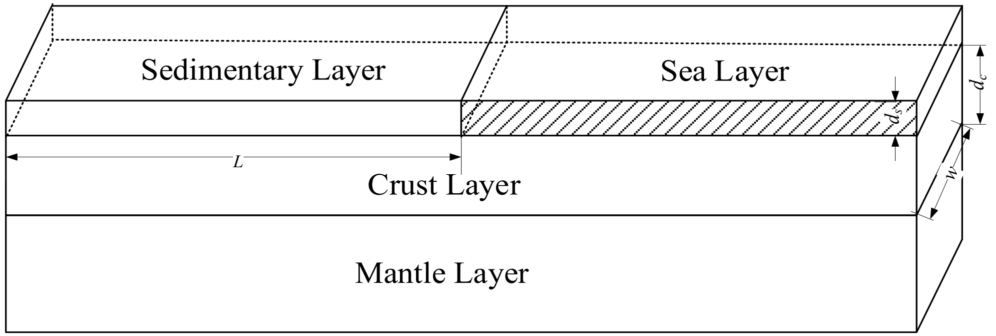


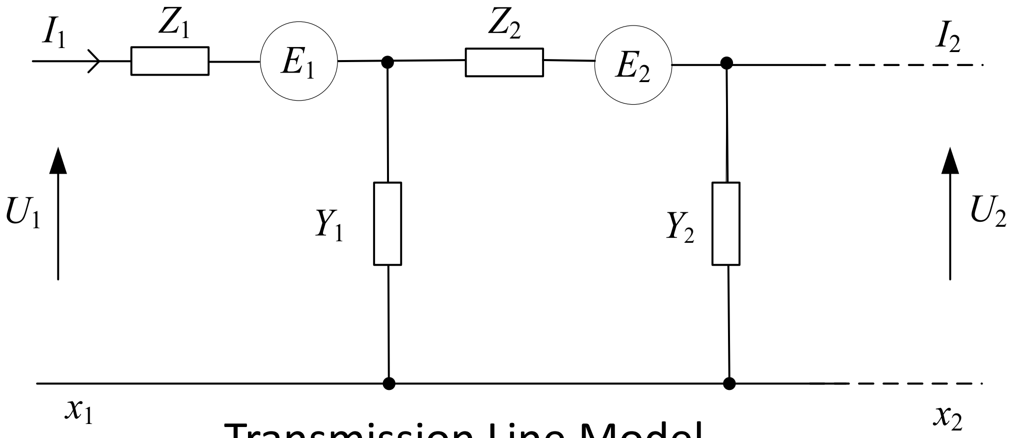
$$E(x) = E_1 - \gamma_1 V_j e^{\gamma_1 x} \qquad x < 0$$

$$E(x) = E_2 - \gamma_2 V_j e^{\gamma_2 x} \qquad x > 0$$



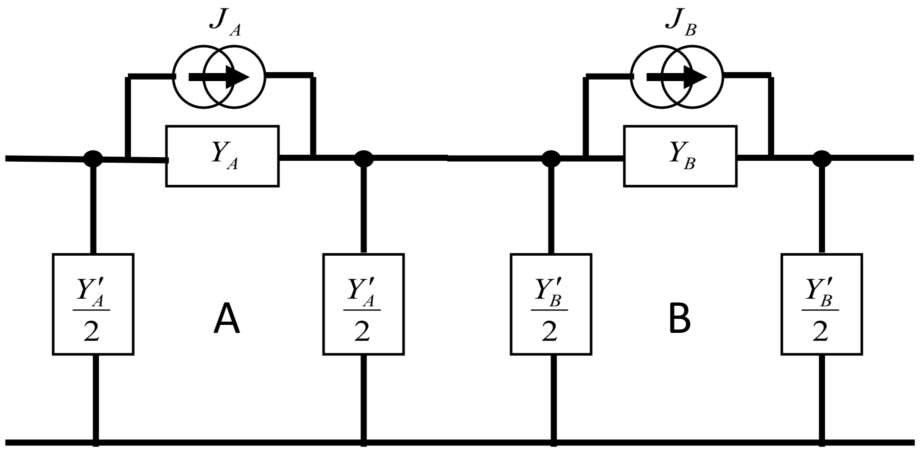
Transmission Line Model

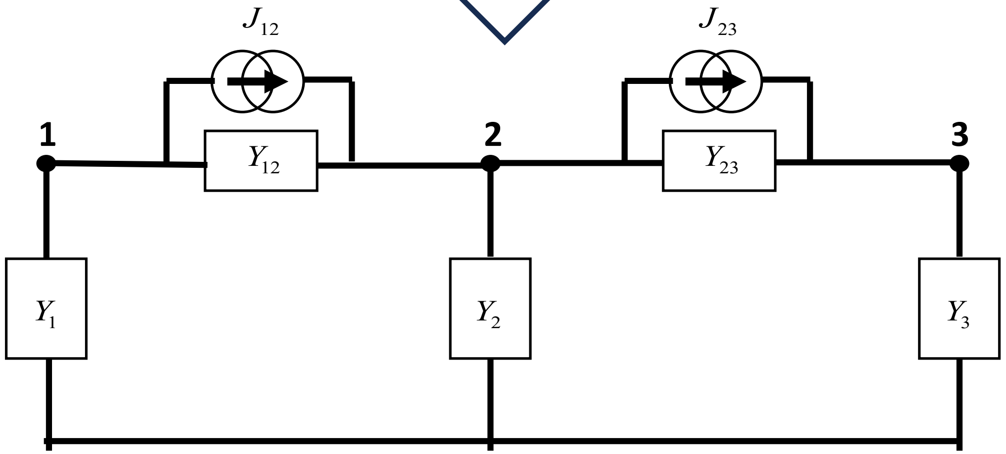




Transmission Line Model

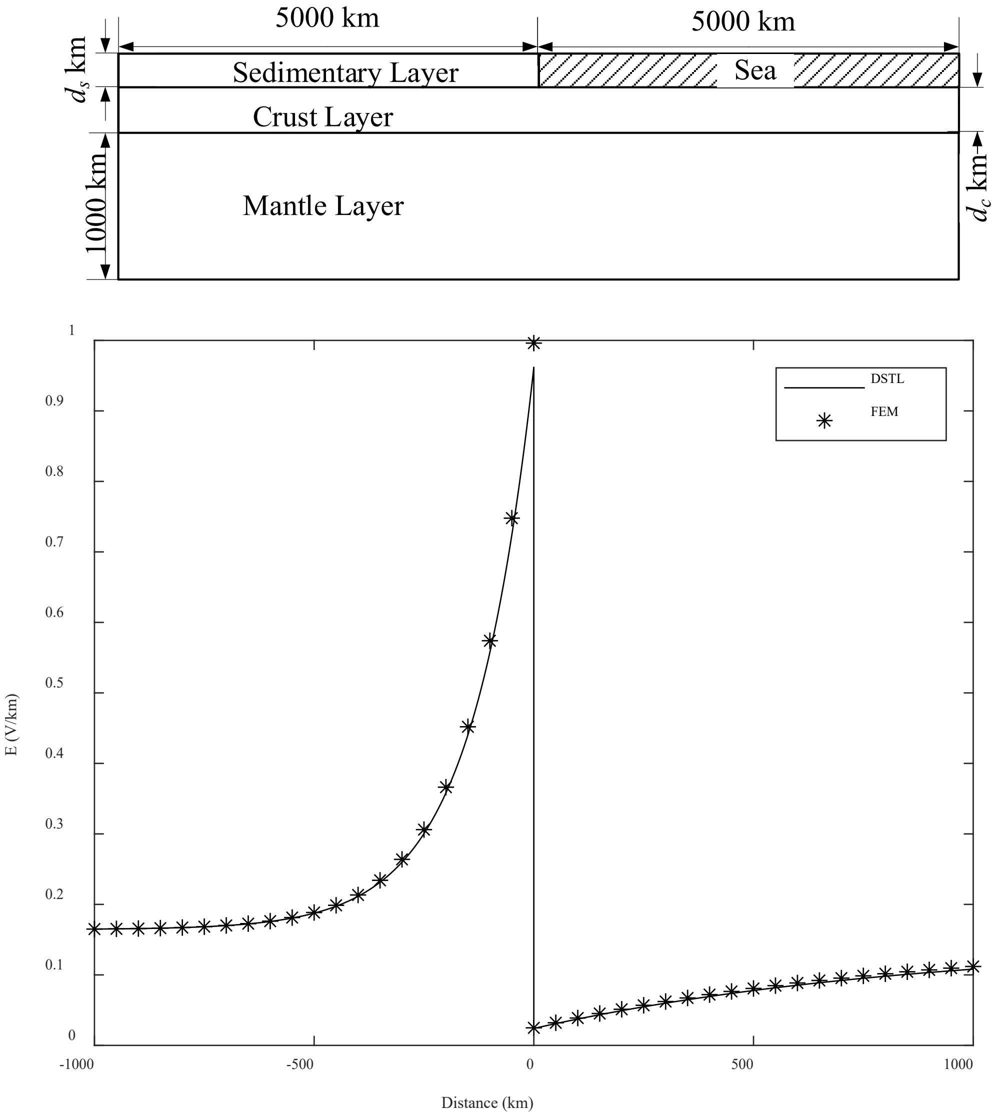
Equivalent-pi circuits

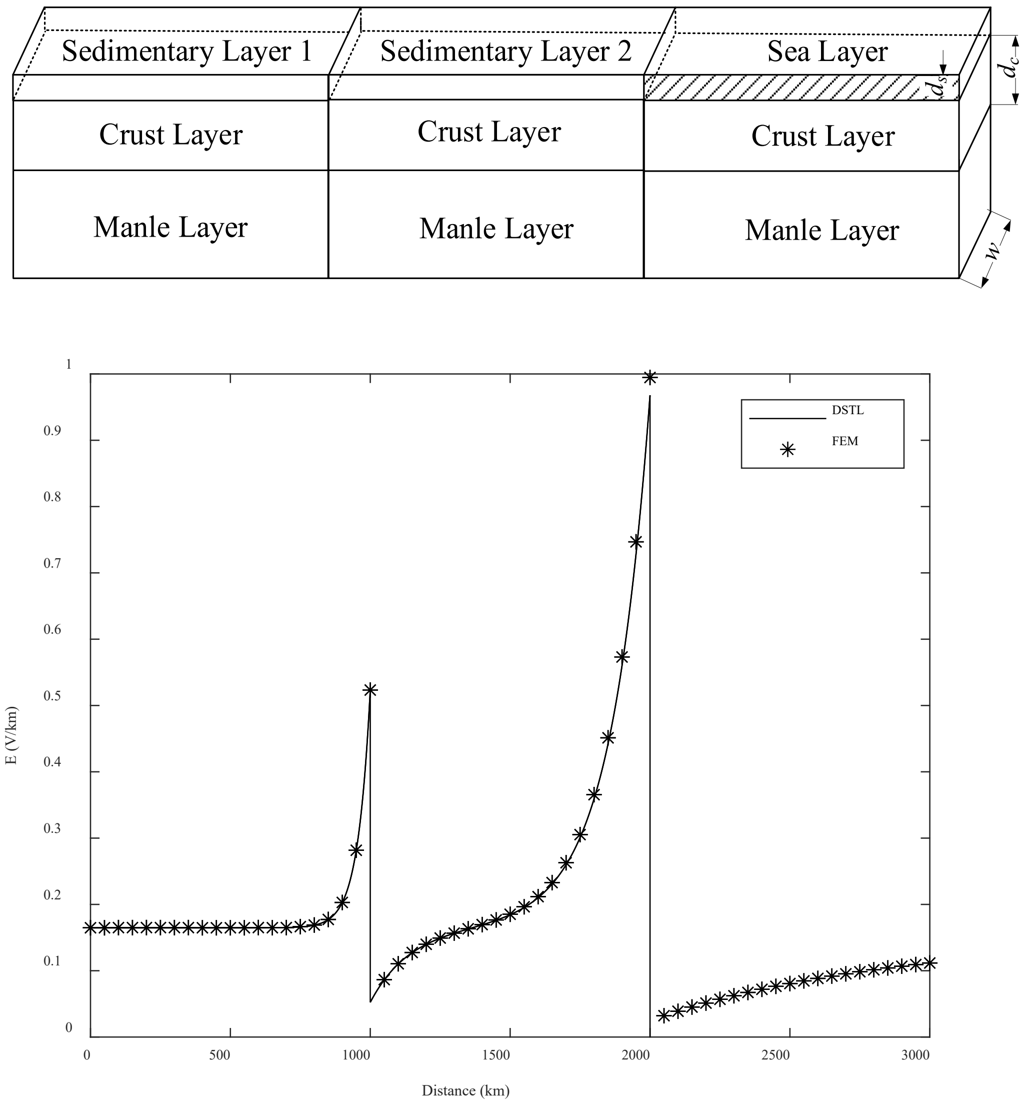




Nodal Admittance Network

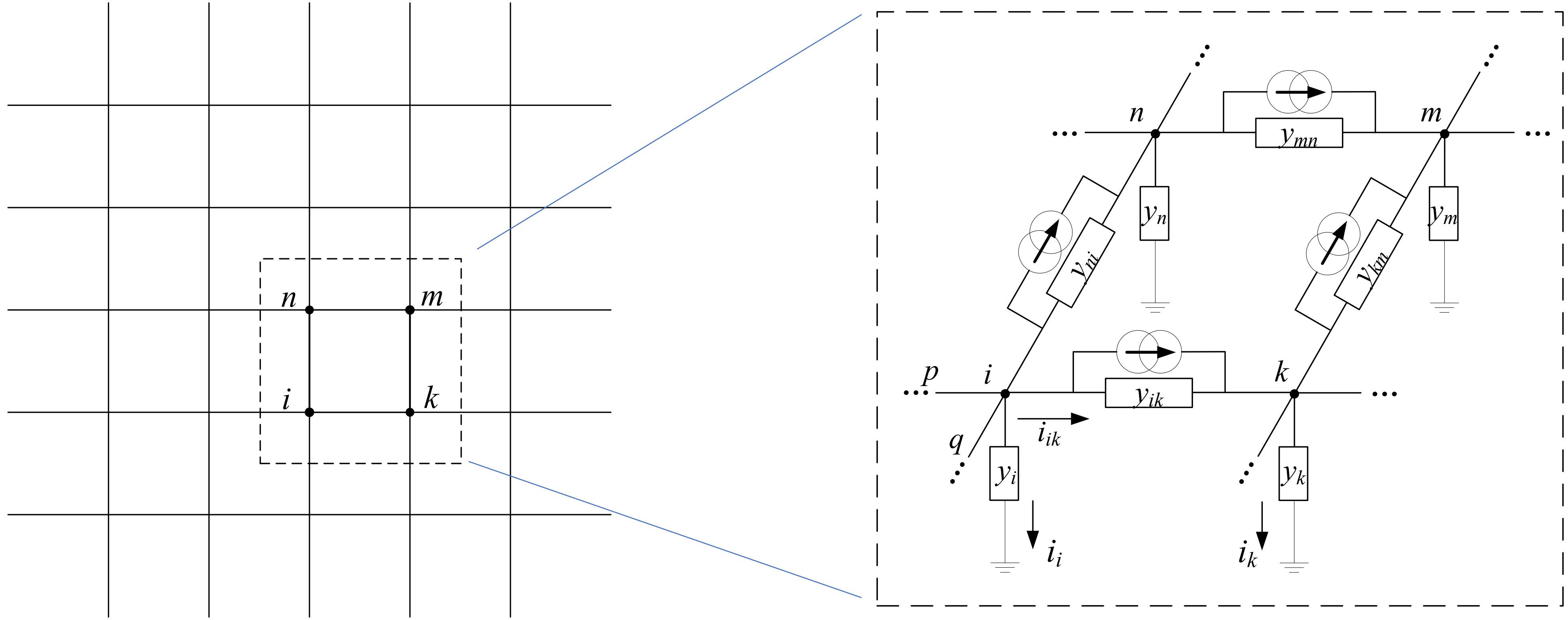
Comparison with FEM results





Extension to 2½-D Model

Transmission Sheet Model



Adding the Coast Effect to GIC Modeling

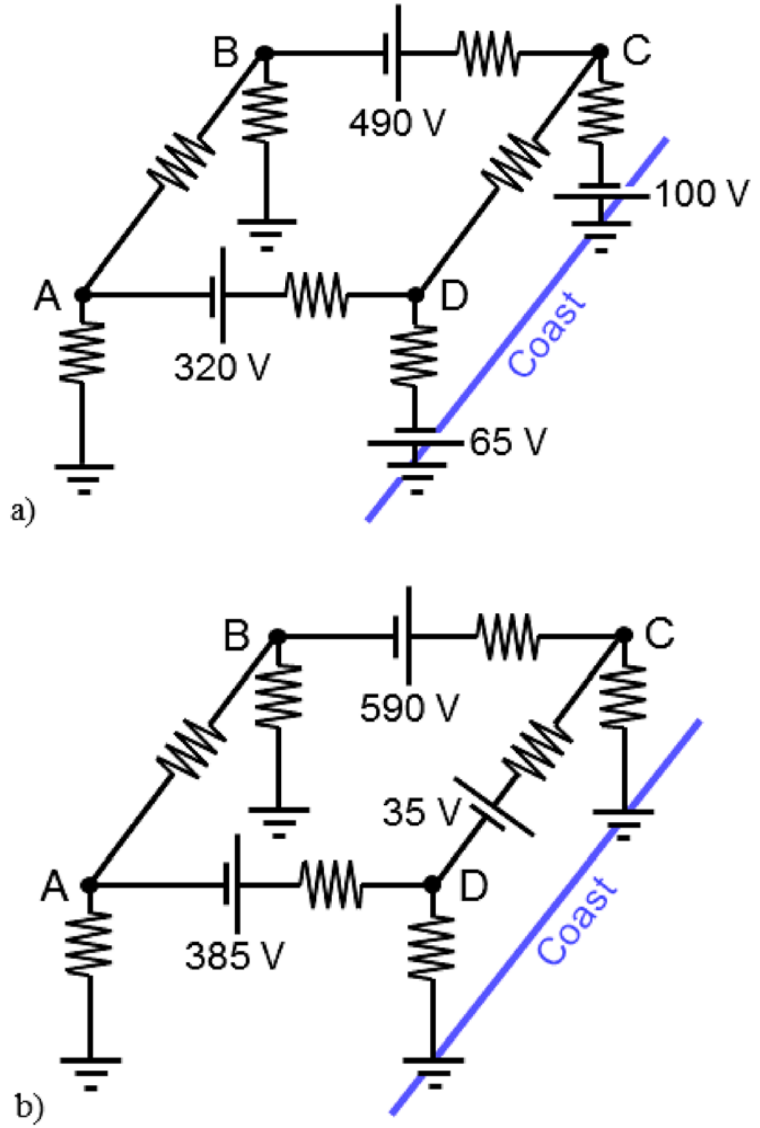
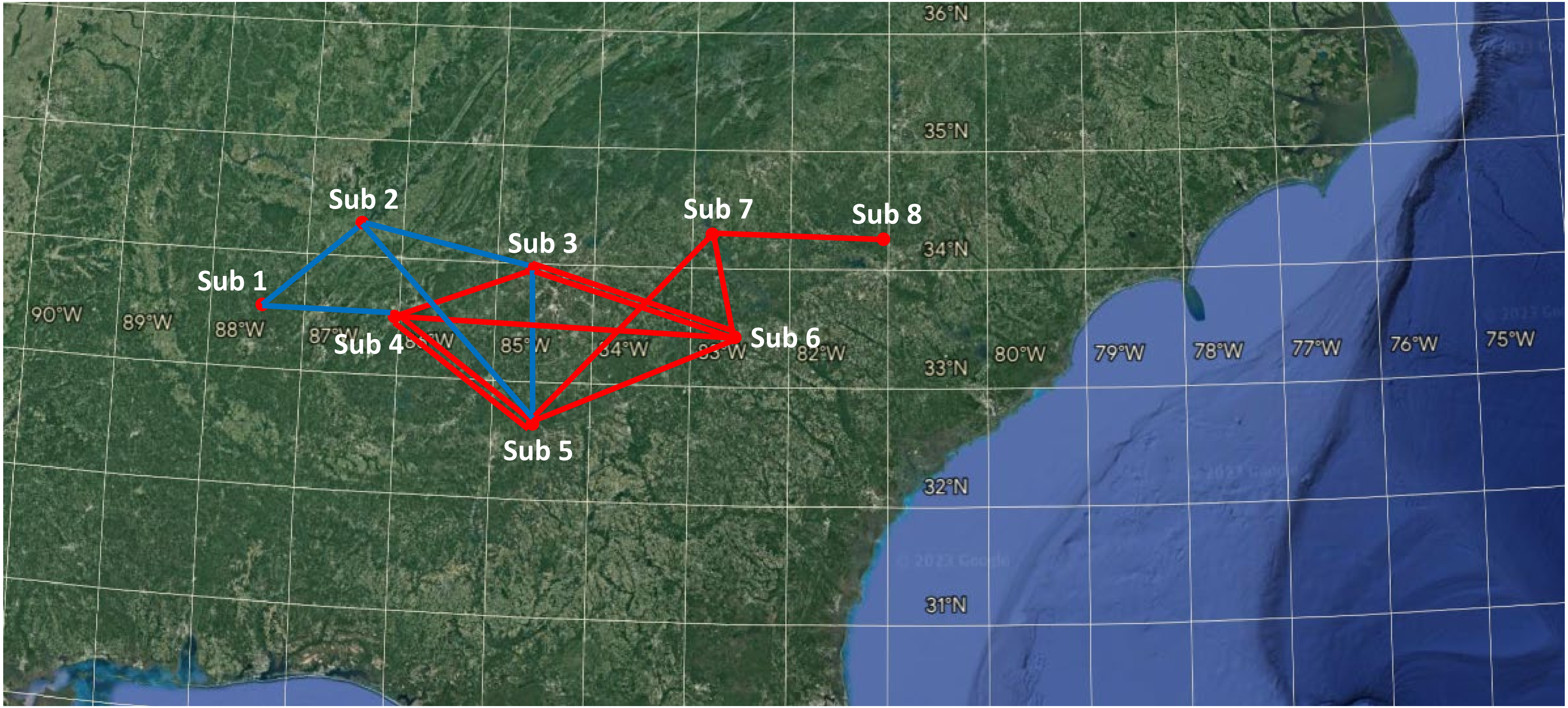


Table 1. Model Results of GIC Produced by an Electric Field Due To an Ionospheric Line Current in a Square Network Next to the Coast, Showing That Representing the Coast Effect by Voltage Sources at the Ground Points (Figure 3a) or Including it in the Voltage Sources in the Lines (Figure 3b) Gives the Same Results

Location	GIC (Using Figure 3a)	GIC (Using Figure 3b)
A to ground	−67.0	−67.0
B to ground	−95.5	−95.5
C to ground	101.3	101.3
D to ground	61.2	61.2
A to B	2.8	2.8
A to D	64.2	64.2
B to C	98.3	98.3
C to D	−3.0	−3.0

Boteler and Pirjola (2017)

Proposal for testing the Method

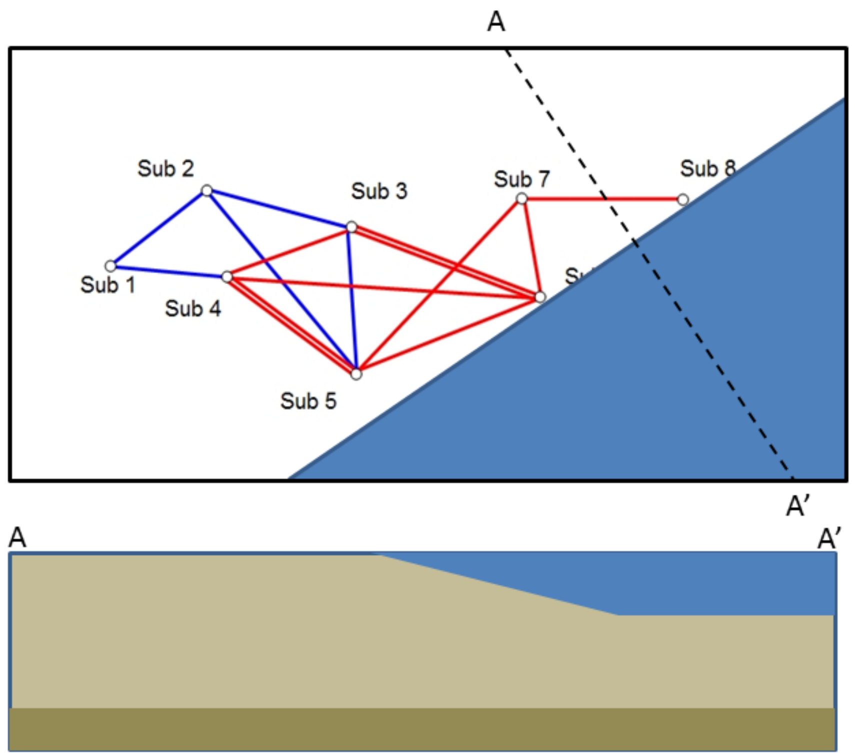


Proposal for testing the Method

Use the benchmark model from Horton et al (2012) but move it eastward so that substations 6 and 8 are near the coast.

A paper on this work will achieve 3 objectives:

- Show how to use the transmission line equations for the coast effect for modelling GIC
- Provide results for this test case that other people can use to test their software
- Show, by comparison with Horton et al (2012) results, the effect of the coast on GIC.



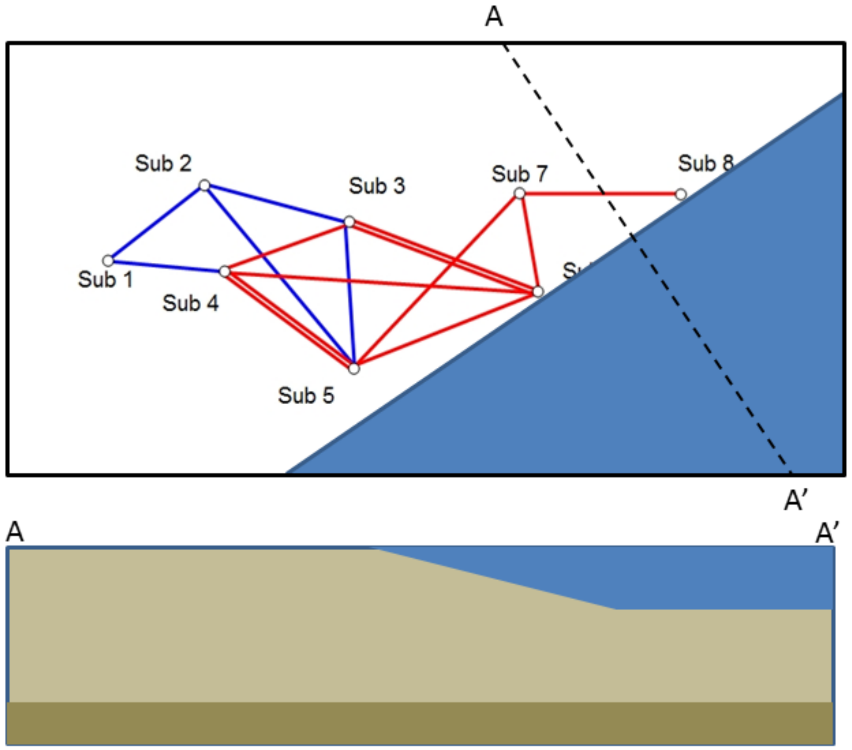
Proposal for testing the Method

Like the development of the Horton et al (2012) benchmark model, do the work as a collaboration between modelers using different software.

- Identifying where differences came from helped refine the modeling method.

Much of the preceding work was done for the IEEE Task Force on the Coast Effect.

- Finish this as a paper from the Task Force



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- Horton, R., Boteler, D.H., Overbye, T.J., Pirjola, R.J. and Dugan, R., "A test case for the calculation of geomagnetically induced currents", IEEE Trans. Power Delivery, vol 27, no 4, 2368-2373, Oct. 2012.
- Ranganayaki, R.P. and T. R. Madden, T.R. "Generalized thin sheet analysis in magnetotellurics: an extension of Price's analysis," Geophys. J. R. astr. Soc. vol. 60, 445-457, 1980.
- Wang, X., D.H. Boteler and R. Pirjola, "Distributed-Source Transmission Line Theory for Modeling the Coast Effect on Geoelectric Fields", IEEE Trans. Power Delivery, 2023. https://doi.org/10.1109/TPWRD.2023.3279462

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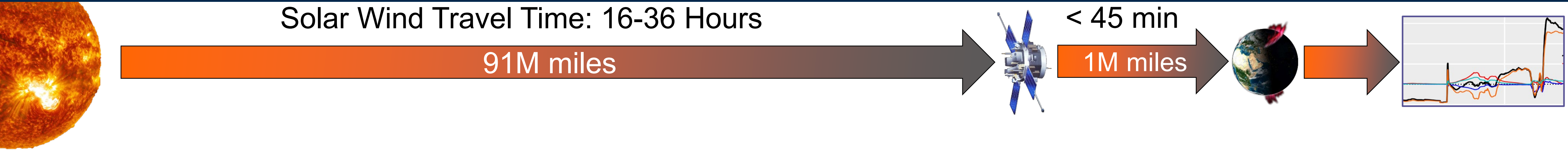
CLIMATE AND SPACE SCIENCES AND ENGINEERING
UNIVERSITY OF MICHIGAN

Sun-To-Surface Numerical Modeling for GMD Applications

NERC/EPRI Geomagnetic Disturbance Planning Workshop Meeting, August 15—16, 2023

D. Welling and the CSEM Team
University of Michigan Climate & Space

Our GMD Research and Goals

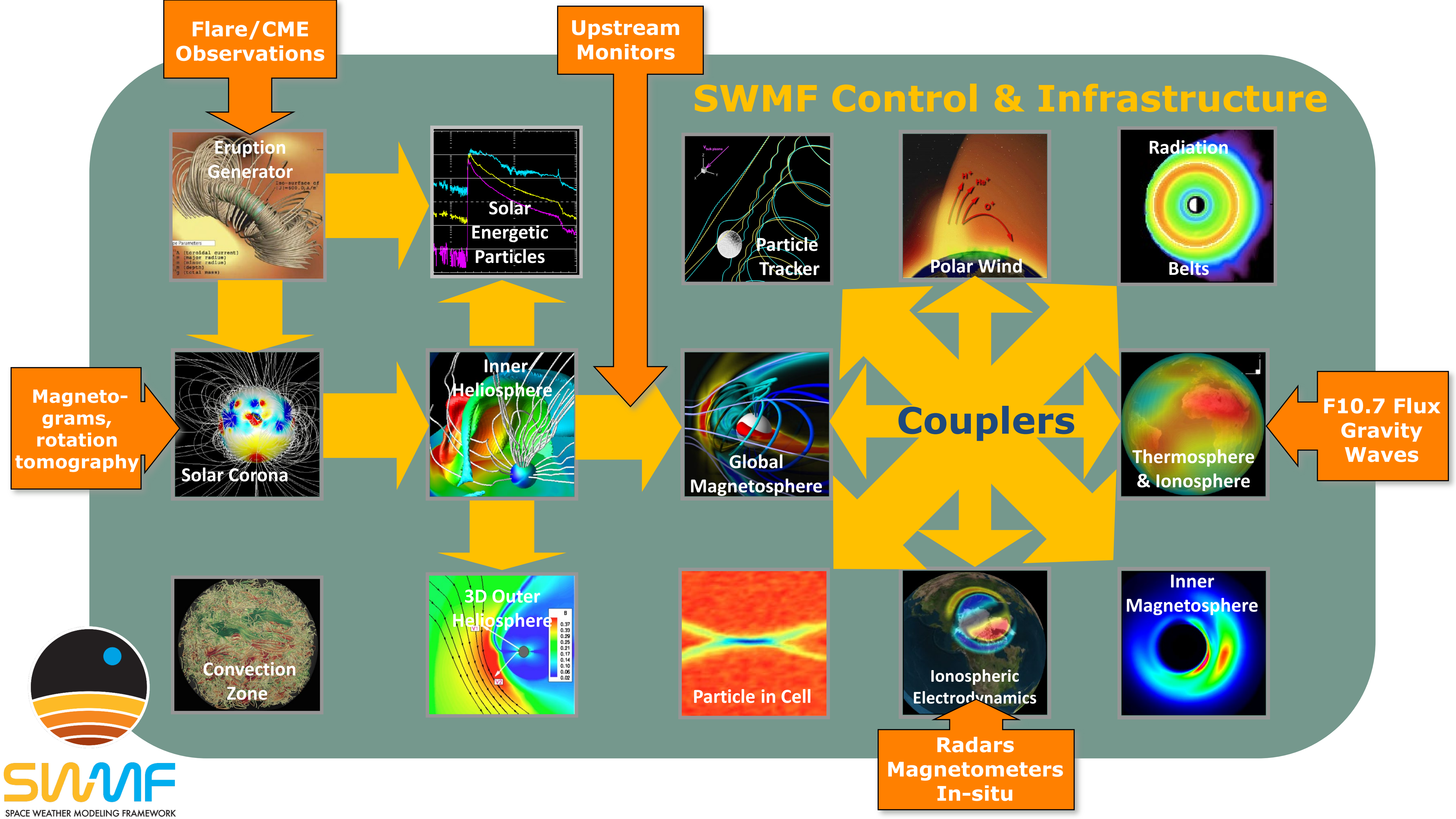


What we do at the Center for Space Environment Modeling:

- Develop models of the Sun-to-Earth system
- Exercise our models for GMD forecasting & analysis
- Support *Transition-to-Operations* using our models

Our GMD-related goals moving forward:

- Combine our solar and magnetosphere expertise to produce true long-lead-time (>24 hrs) forecasts of quiet and active GMD conditions
- Work with partners to integrate geoelectric field calculations into our framework
- Build industry partnerships to evaluate our ability to provide value to power grid operators


Flare/CME Observations
Upstream Monitors
SWMF Control & Infrastructure
Eruption Generator
Solar Energetic Particles
Particle Tracker
Polar Wind
Radiation Belts
Magneto-grams, rotation tomography
Solar Corona
Inner Heliosphere
Global Magnetosphere
Couplers
Thermosphere & Ionosphere
F10.7 Flux Gravity Waves
Convection Zone
3D Outer Heliosphere
Particle in Cell
Ionospheric Electrodynamics
Inner Magnetosphere
Radars Magnetometers In-situ
SWMF
SPACE WEATHER MODELING FRAMEWORK

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  (SW & IMF) an
- Overview of va
  Welling et al., 2
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- In operations a
  since 2016
- Can forecast in
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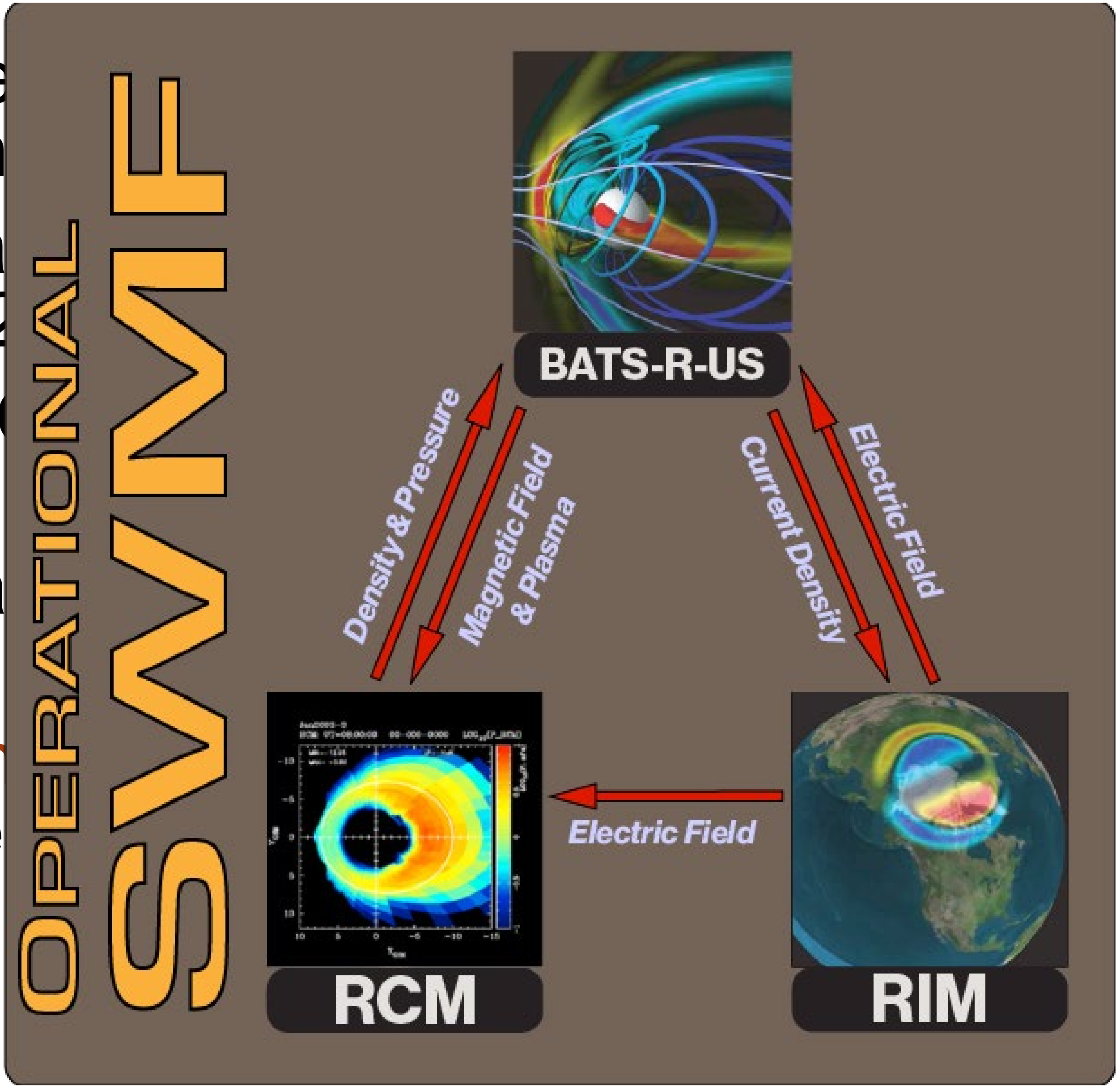
  and more.



User Need: Understanding Extremes

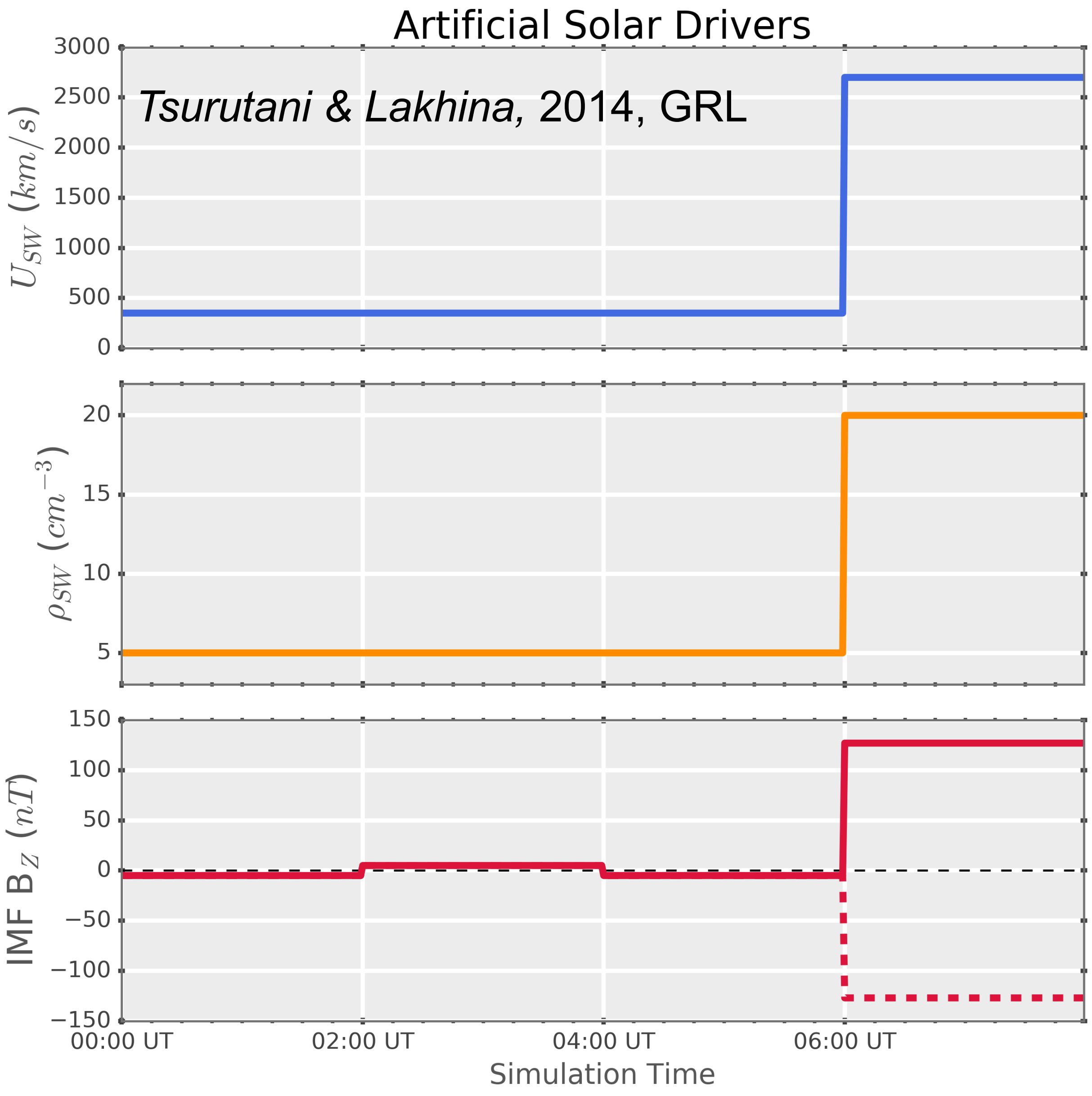
- Understanding worst-case-scenarios is a critical space weather benchmark.
- For GIC, industry needs:
  - Magnitudes of GMD
  - Direction of resultant geoelectric field
  - Must vulnerable regions.
- Constructing realistic "worst case" scenarios is challenging.

Welling et al., 2021, Space Weather

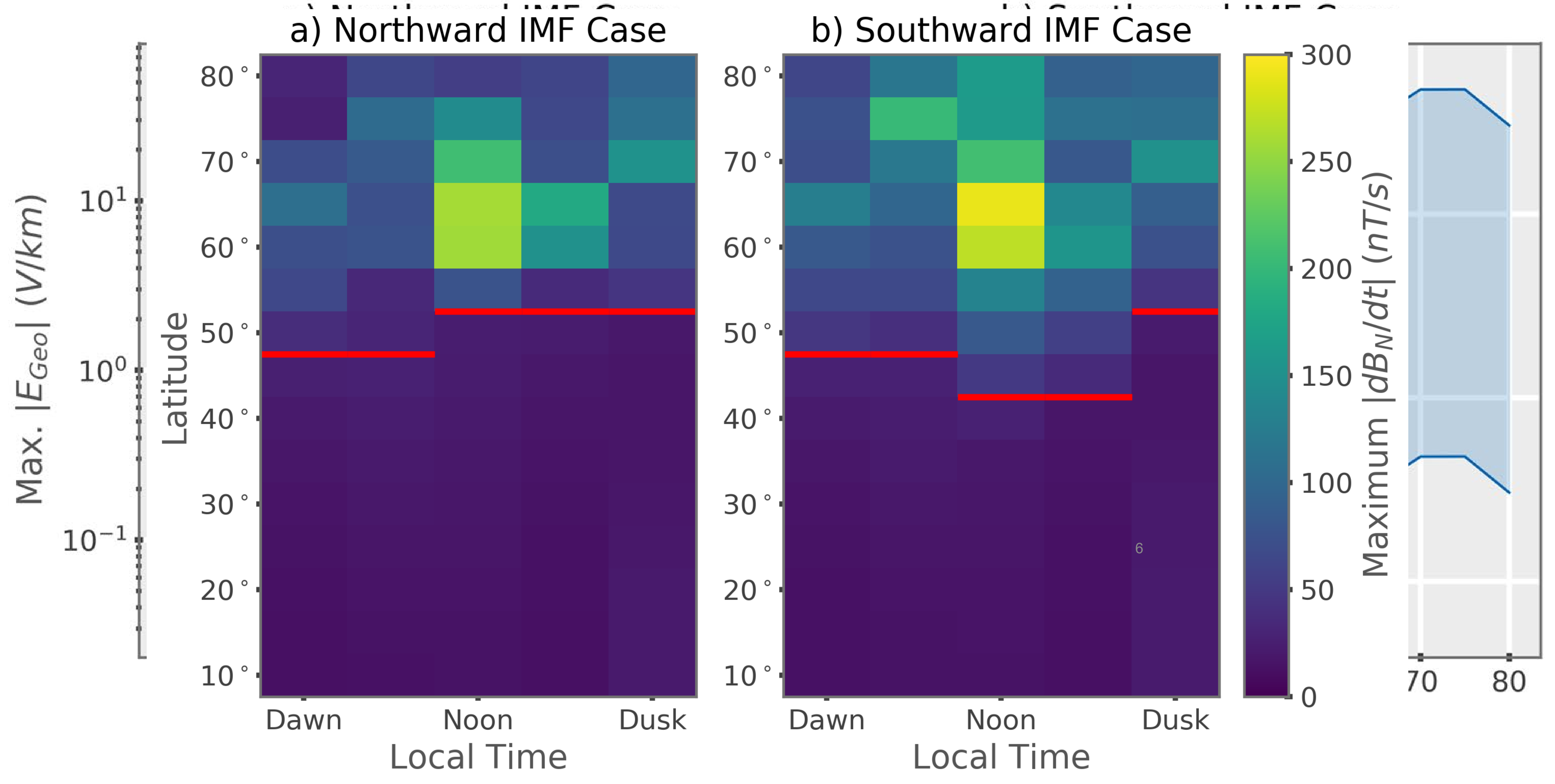
Ngwira et al., 2013 (Carrington-like storm)

Ngwira et al., 2014 (July 2012 near-miss)

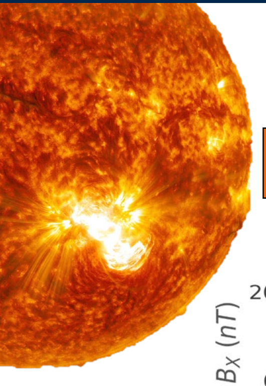
Blake et al., 2021 (Carrington-like storm)



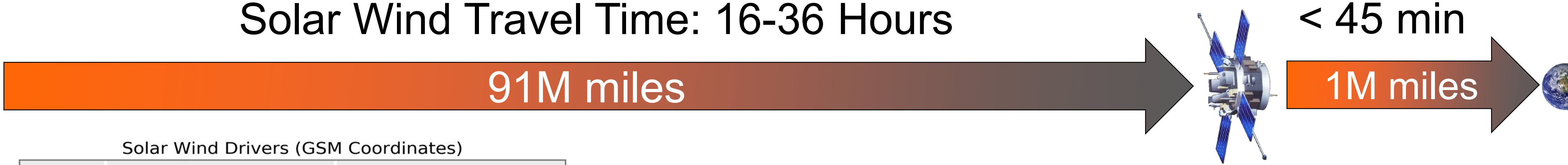
Meeting User Needs: Extreme Event Analysis

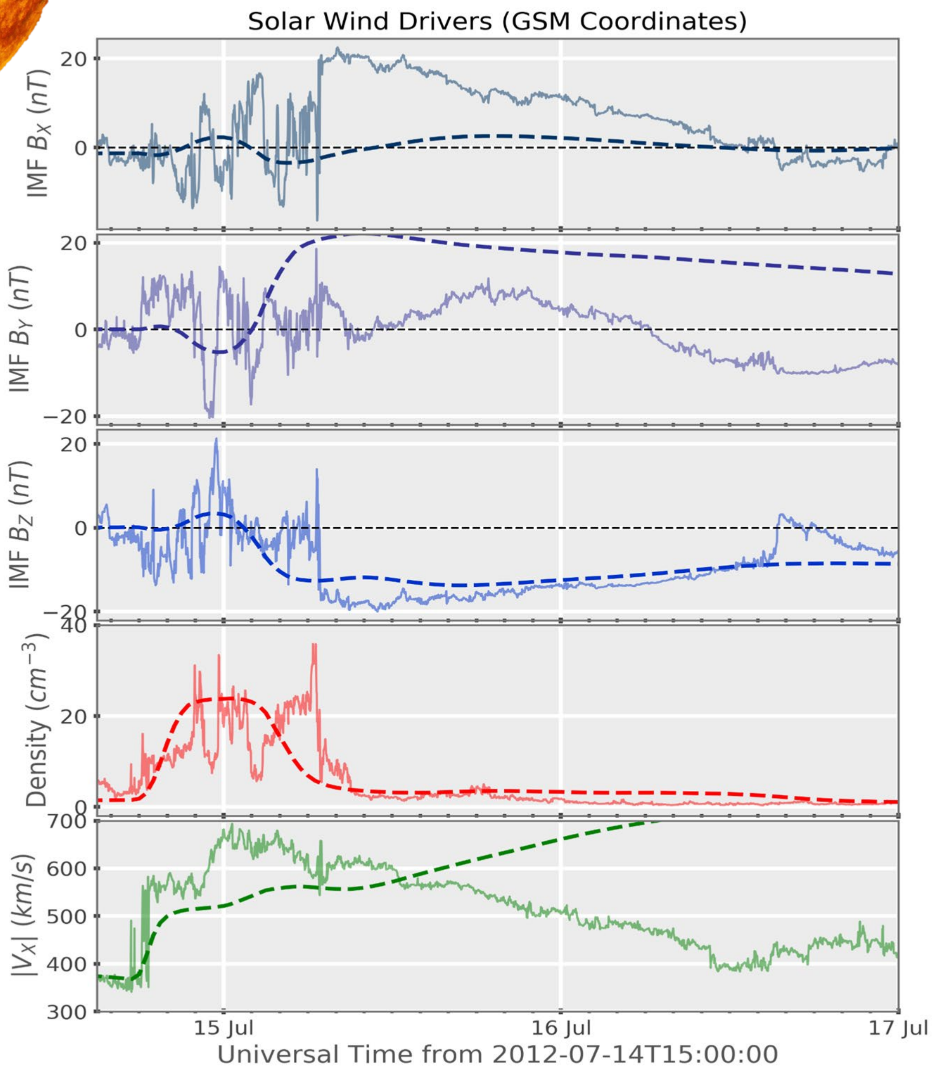


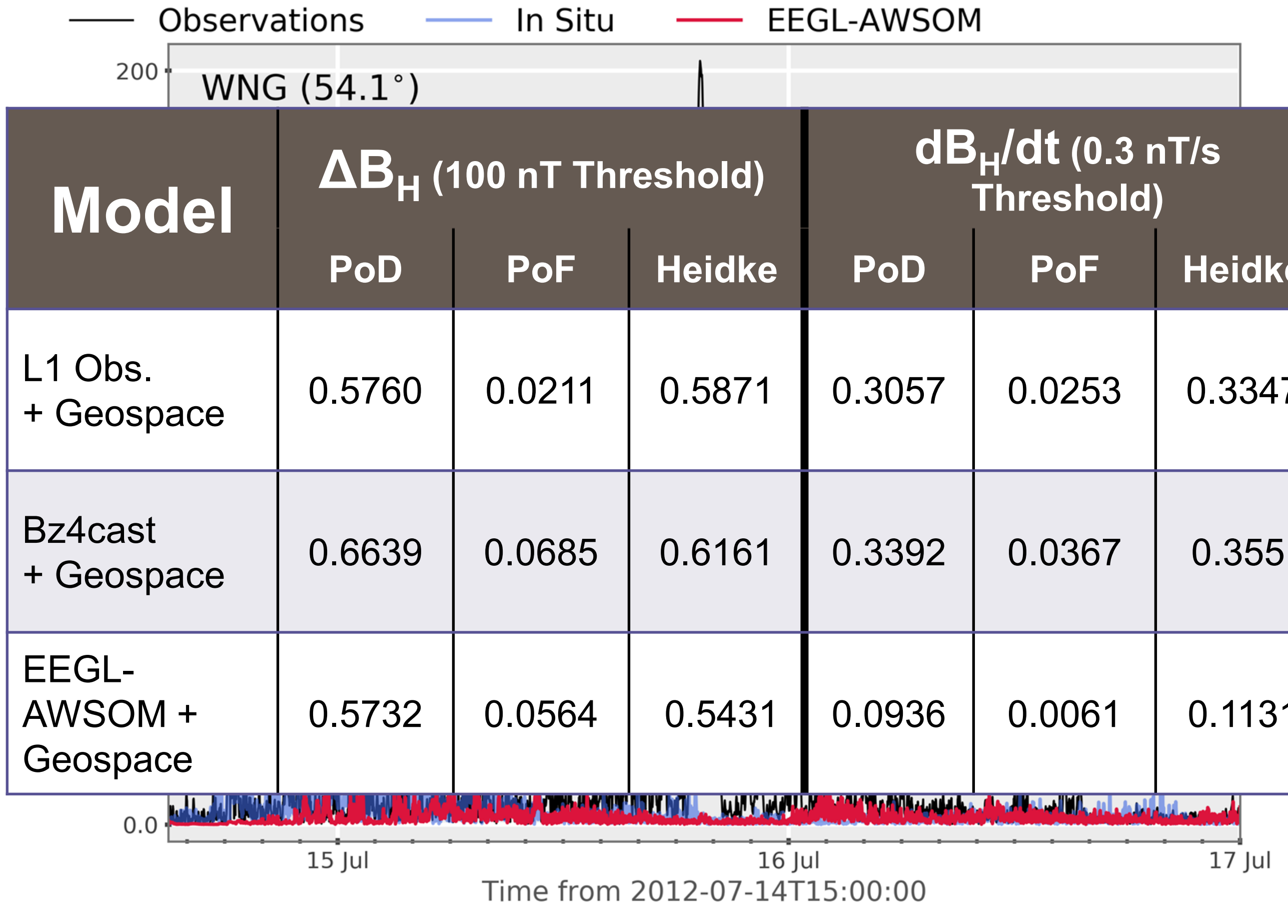
Crossing the L1 Disconnect in Forecasts



Solar Wind Travel Time: 16-36 Hours

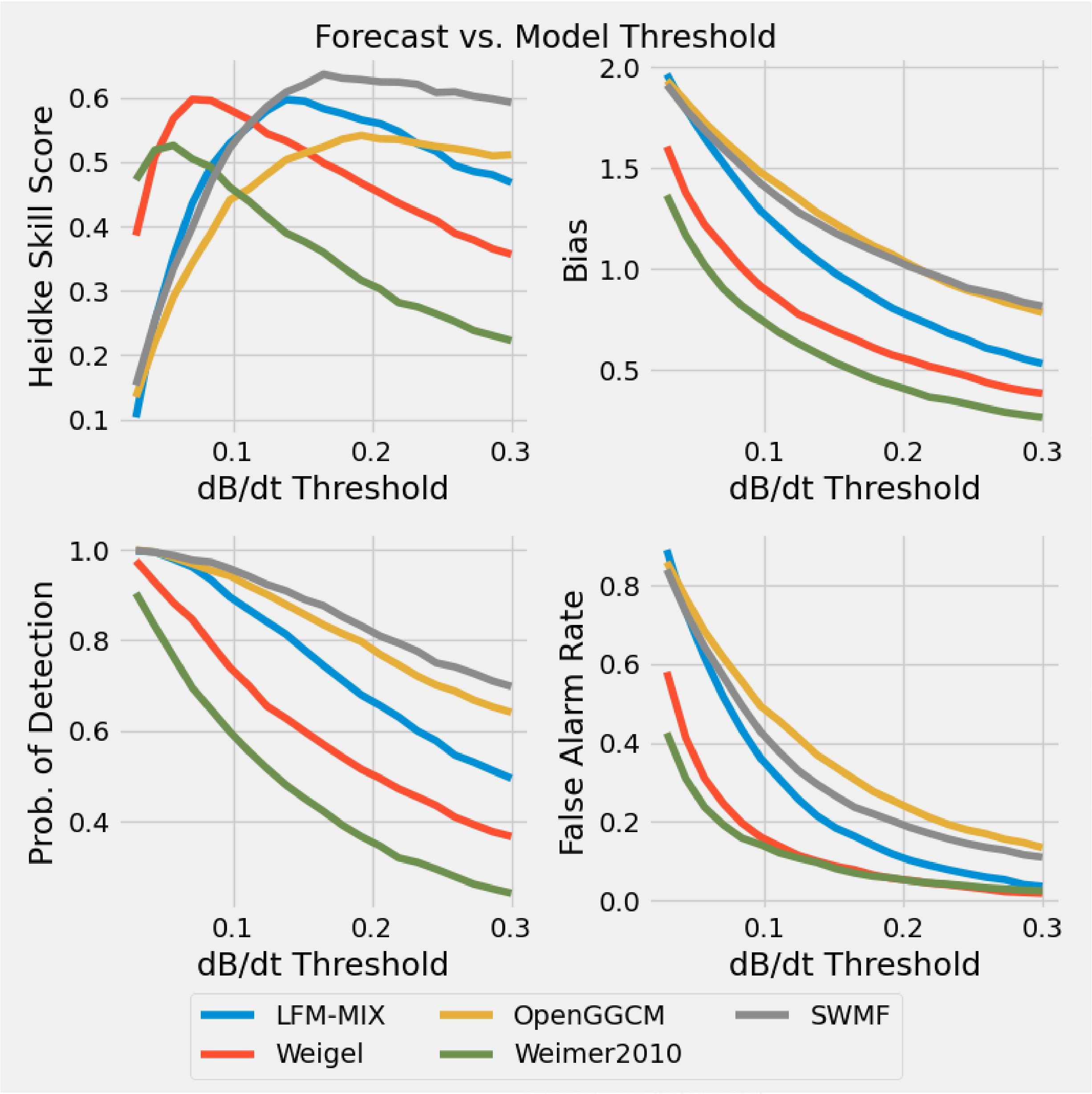






Model	**ΔB_H (100 nT Threshold)**			**dB_H/dt (0.3 nT/s Threshold)**		
	PoD	**PoF**	**Heidke**	**PoD**	**PoF**	**Heidke**
L1 Obs. + Geospace	0.5760	0.0211	0.5871	0.3057	0.0253	0.3347
Bz4cast + Geospace	0.6639	0.0685	0.6161	0.3392	0.0367	0.3551
EEGL-AWSOM + Geospace	0.5732	0.0564	0.5431	0.0936	0.0061	0.1131

Multi-Model Ensembles

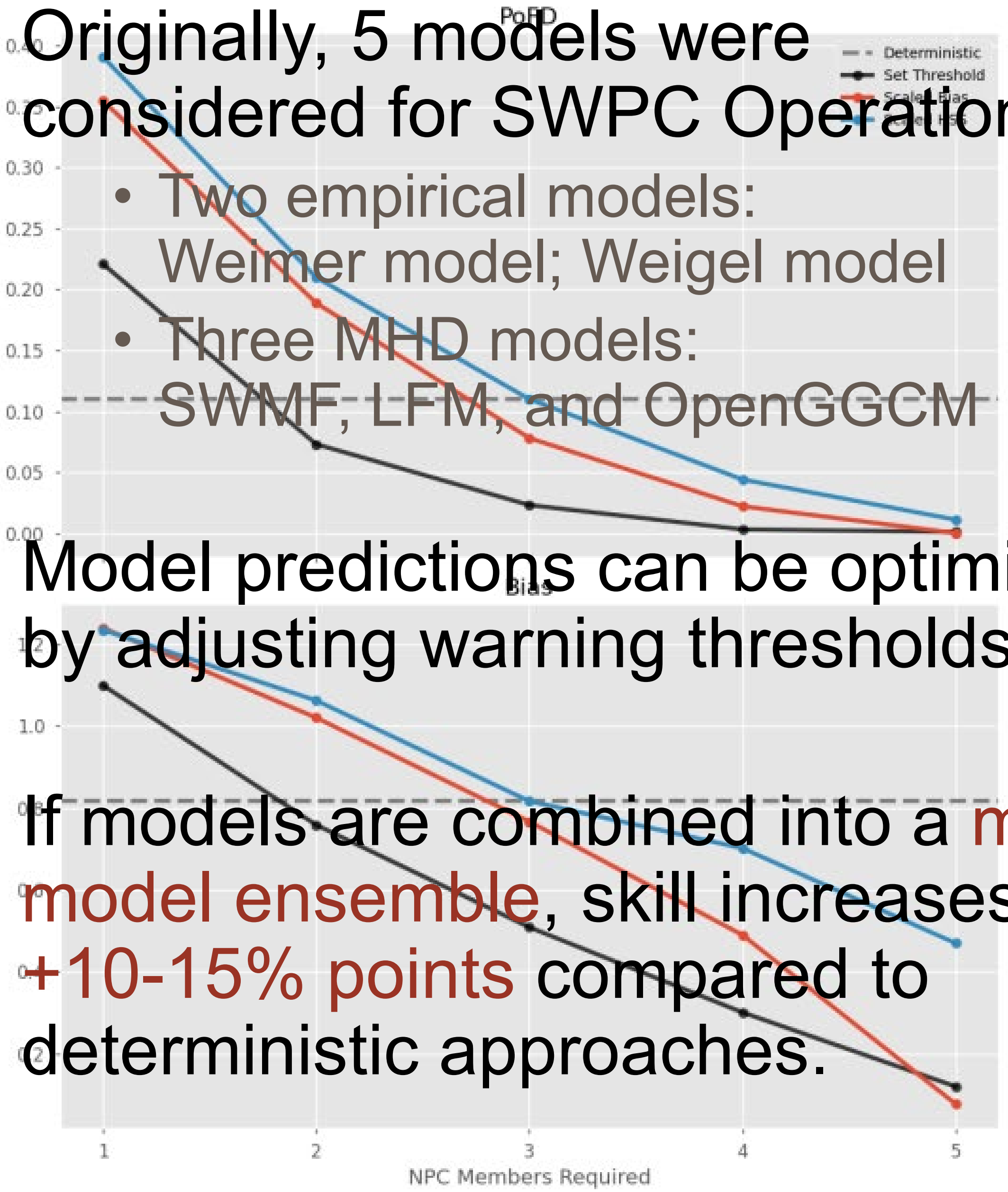


Originally, 5 models were considered for SWPC Operations:

- Two empirical models: Weimer model; Weigel model
- Three MHD models: SWMF, LFM, and OpenGGCM

Model predictions can be optimized by adjusting warning thresholds.

If models are combined into a multi-model ensemble, skill increases by +10-15% points compared to deterministic approaches.



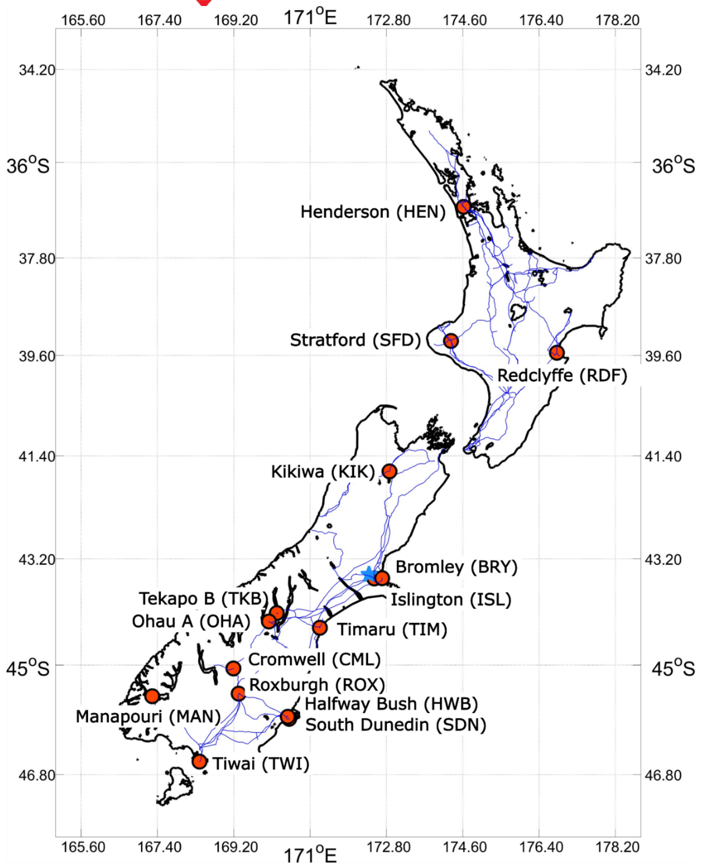
Solar Tsunamis Project

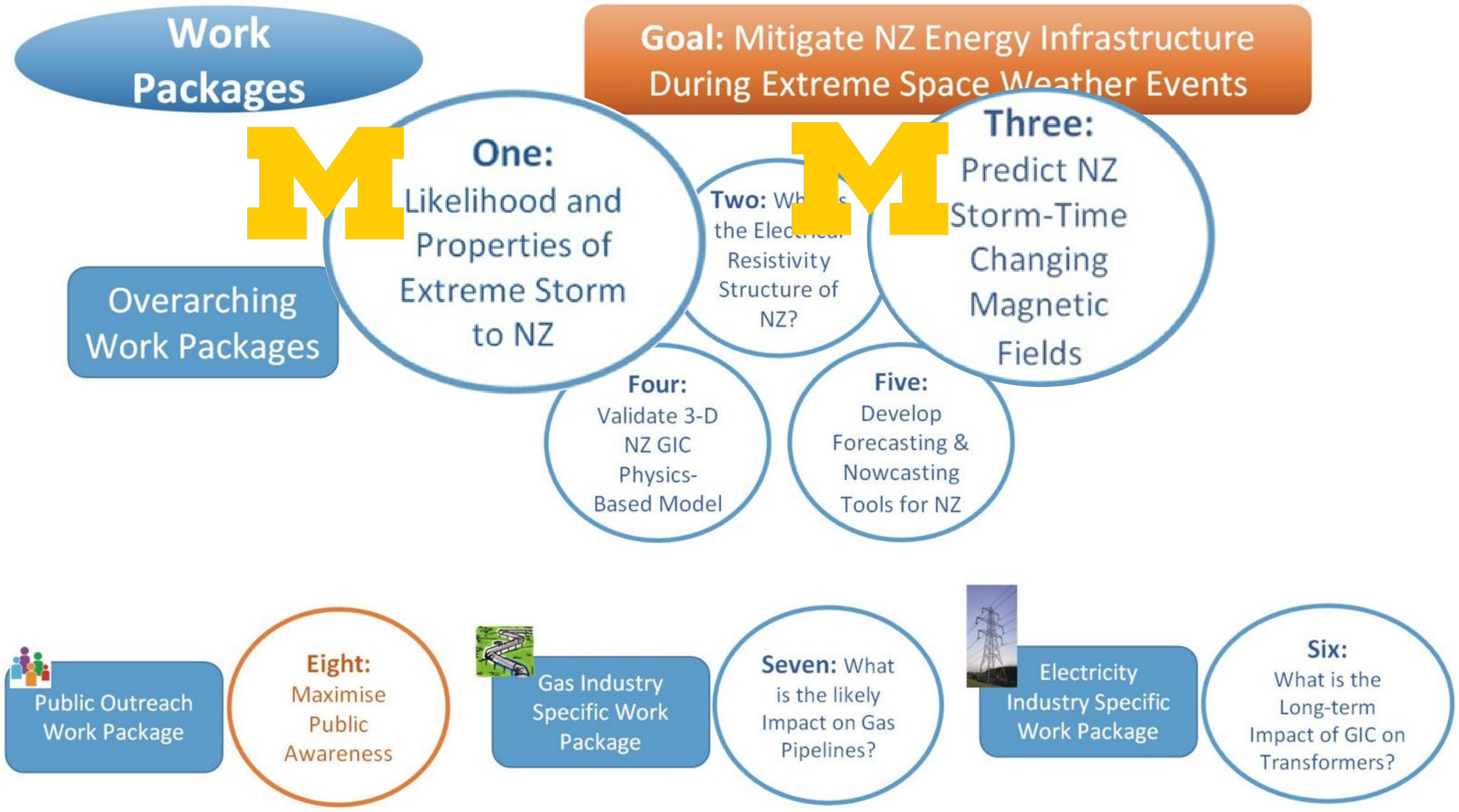
SOLAR TSUNAMIS
PARAWHENUA KŌMARU

UNIVERSITY of OTAGO
SAPERE AUDE

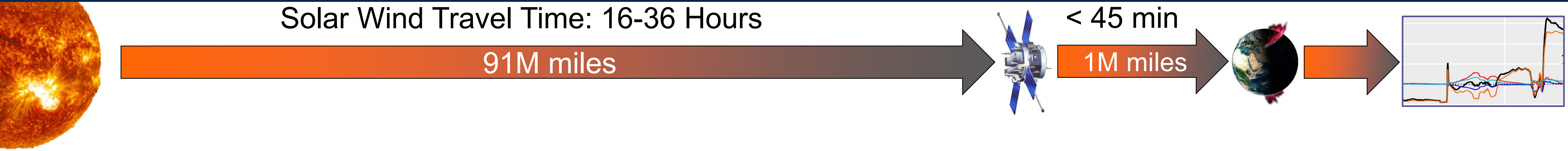
MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HIKINA WHAKATUTUKI

TRANSPOWER





Our GMD Research and Goals



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Connecting Space Weather and Power Flow Modeling to Assess Hazards

Steven K. Morley[1], Adam Mate[1], Arthur Barnes[1], David Osthus[1], Daniel T. Welling[2], Jesse Woodroffe[1], Michael K. Rivera[1]
1-Los Alamos Nat'l Laboratory
2-University of Michigan

Contact: *smorley@lanl.gov*

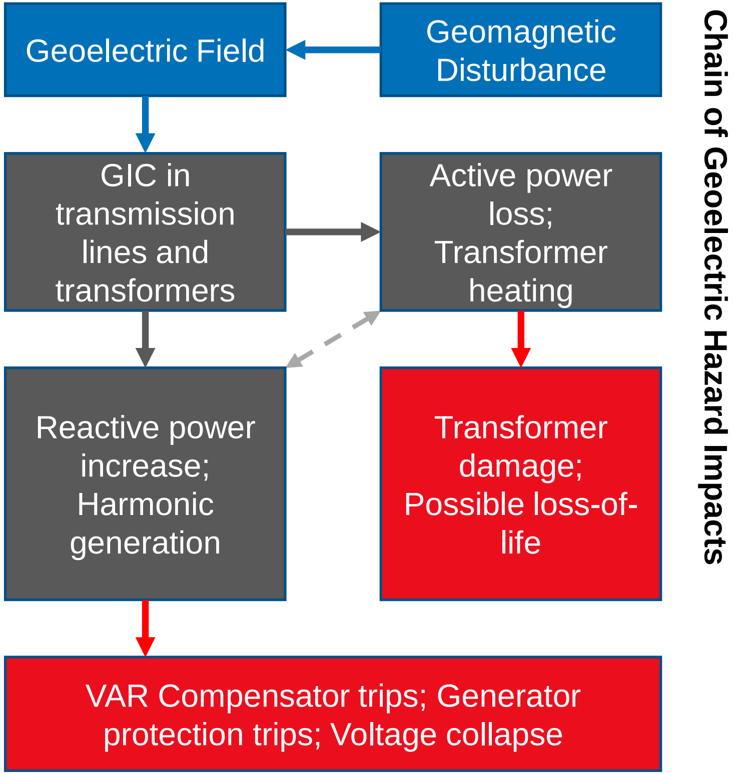
LA-UR-23-29337

Defining a Geoelectric Hazard Benchmark

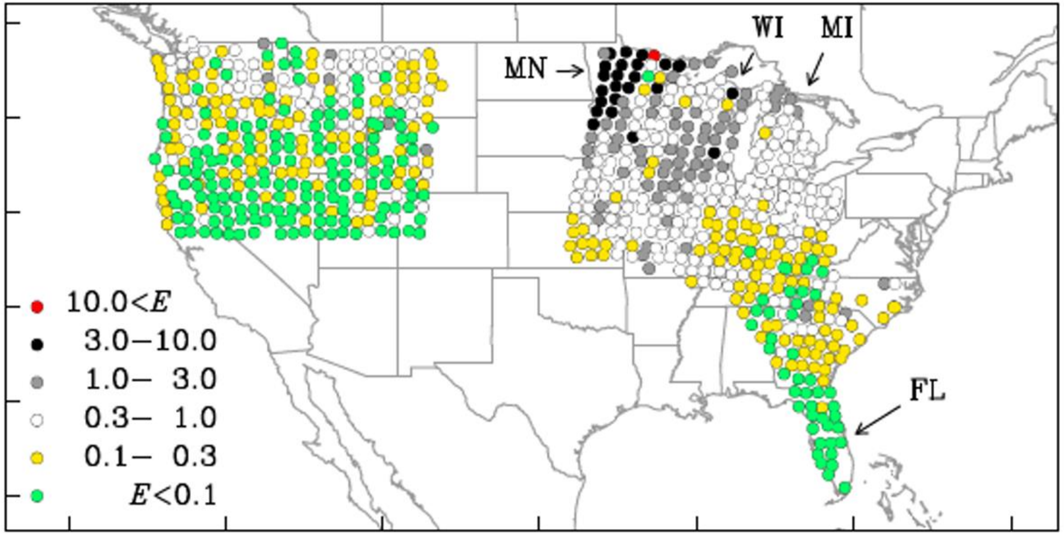
What is a benchmark for?

- Enhance awareness of threats among critical infrastructure owners and operators
- Provide input for engineering standards
- Provide input for vulnerability & risk assessments
- Help guide development of mitigation procedures
- Establish thresholds for action

Current landscape includes SWORM benchmarks and TPL-007 benchmark event.



SWORM Space Weather Benchmarks



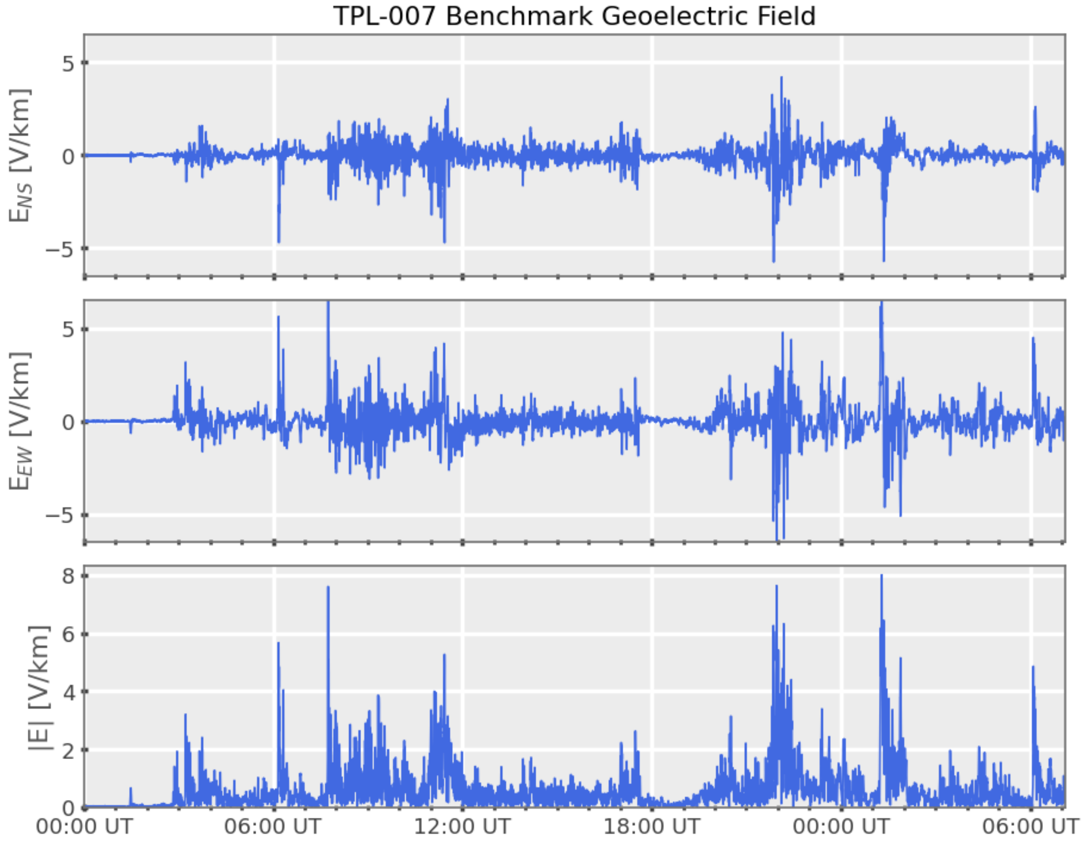
Source: Love et al., "Geoelectric Hazard Maps for the Continental United States," *Geophysical Research Letters* 43 (18, 2016), 9415–9424, doi:10.1002/2016GL070469
Note: No estimates are available outside of survey sites shown.

Figure 1. Once-per-century geo-electric exceedance amplitudes[10] (E in V/km), for north-south geomagnetic variation at 240 seconds (and over 600 seconds)

- *Phase 1*: 1-in-100-year exceedance amplitudes given for much of CONUS
  - Assumed sinusoidal driver function
- *Next Step*: Identified gaps
  - No time series information in benchmark, required for power system modeling
  - Disturbance duration was not estimated

- Space Weather Phase 1 Benchmarks, SWORM Subcommittee, June 2018
- Next Step Space Weather Benchmarks, IDA Group Report NS GR-10982, December 2019

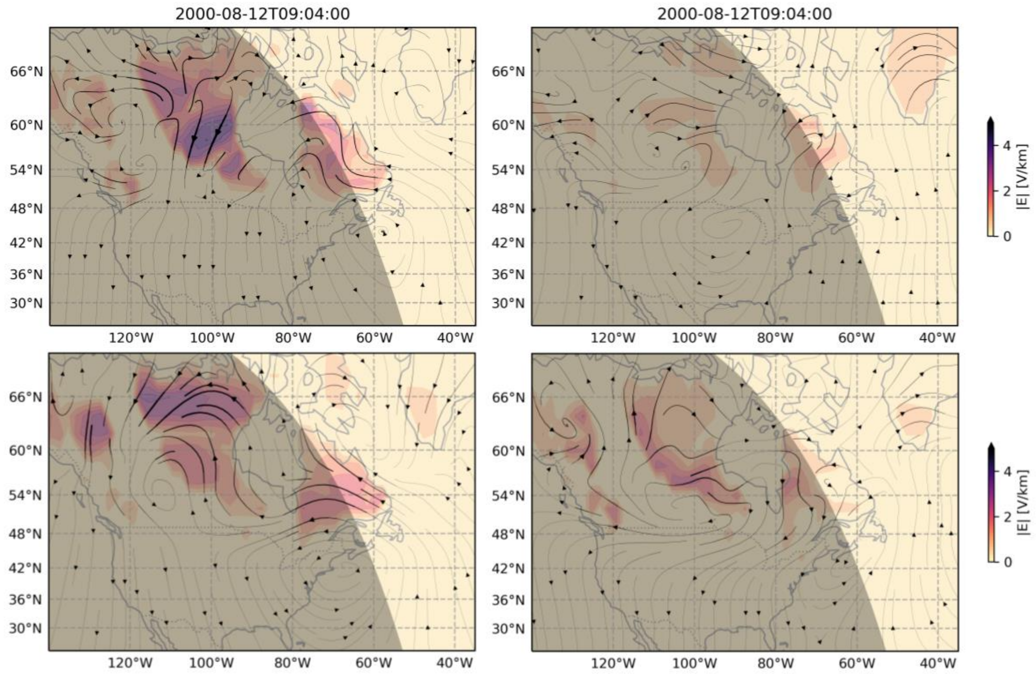
TPL-007: Industry Benchmark Event



- Time series allows power systems modeling
- Scaled so that peak |E| is 8 V/km, assuming simplified Quebec conductivity model
  - Latitude-scaling gives peak |E| at 60° and lower
  - Region-based scaling for conductivity differences
- Assumed uniform in space
- *Only a single realization*
  - ***How representative is the time series?***

Probabilistic Modeling and Analysis at LANL

Improved benchmarking via statistical and ensemble numerical models



Four snapshots taken from the same time in an 8-member ensemble using the SWPC v2 configuration

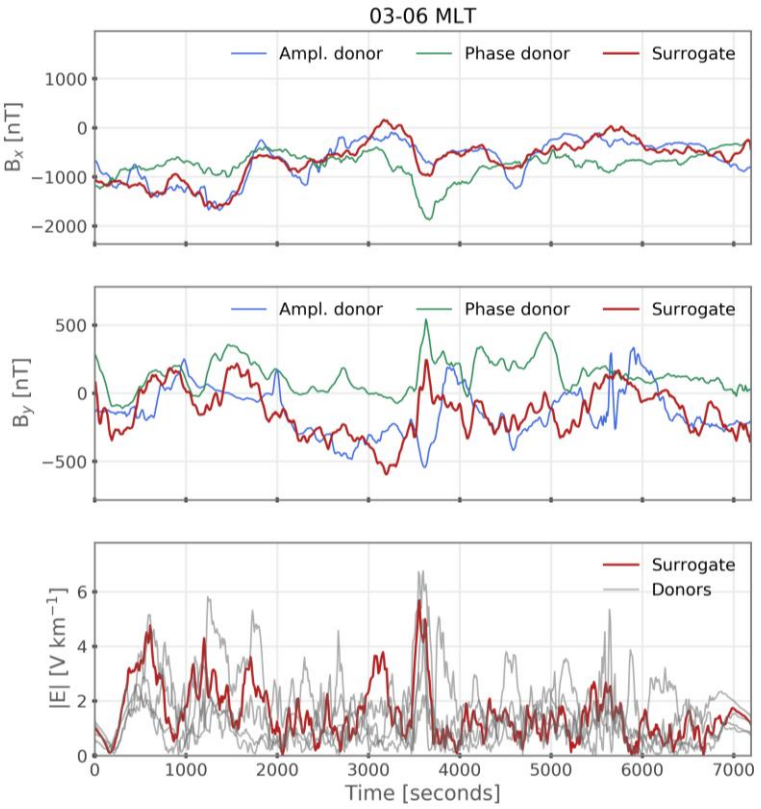
- A 1-in-X-year GMD can manifest in different ways, and the impacts may differ.
- Probabilistic analysis using multiple realizations of magnetic perturbations captures uncertainty in the benchmark
  - This requires some type of modeling approach
- Our team is working towards improved ensemble modeling, as well as fast, realistic, statistical models.

Statistical Benchmark Generation:
Spectral surrogate modeling

Generating Benchmark Time Series Using Spectral Surrogates

- TPL-007 benchmark provides only one realization of a time series with a defined peak magnitude.

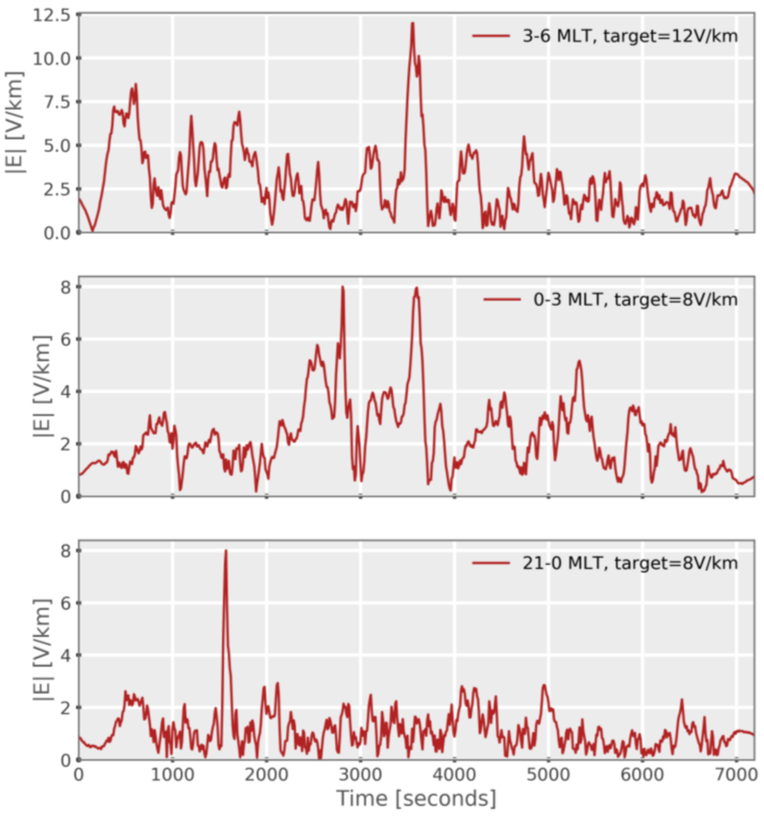
- Method:
  - Fourier transform components of magnetic perturbation signal
  - Each transformed event provides amplitude spectra and Fourier phases
  - By combining randomly drawn donor phases and donor amplitude spectra we can generate unseen, but realistic, time series



Generation of unseen time series of geomagnetic disturbance and geoelectric field using spectral surrogates. EPRI report 3002017900, 2020.

Generating Benchmark Time Series Using Spectral Surrogates

- Adding a simple optimization step to scale the amplitude spectrum can generate time series with a known peak
- This, or similar, provides multiple realizations of a geoelectric benchmark time series with the same peak value
- This allows generation of multiple realistic benchmark time series that meet the intent of TPL-007
    - Approaches for capturing 2D structure are under investigation

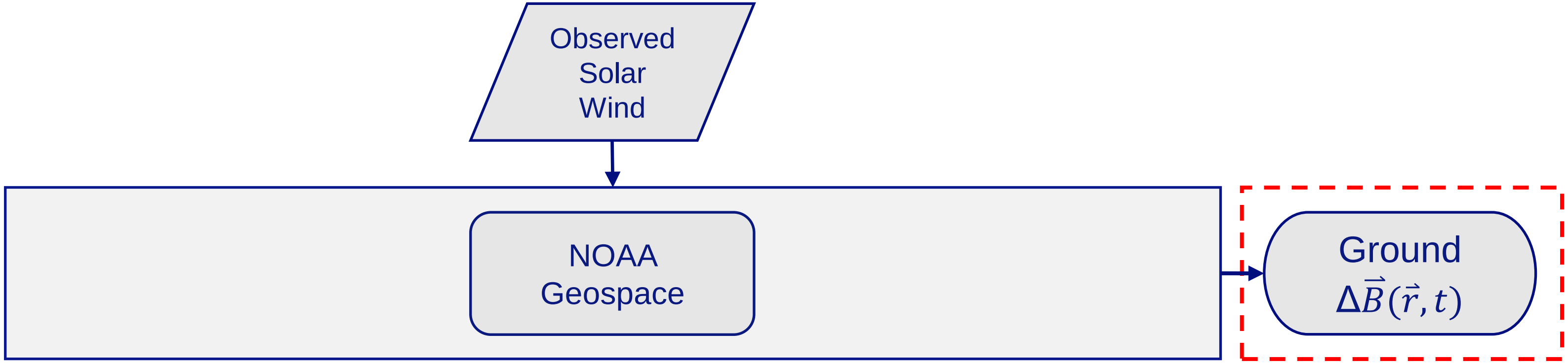


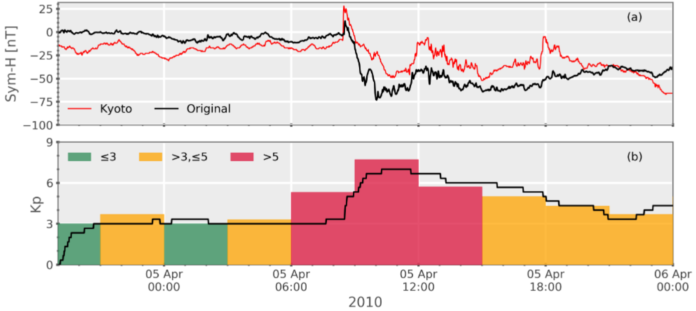
Generation of unseen time series of geomagnetic disturbance and geoelectric field using spectral surrogates. EPRI report 3002017900, 2020.

Physics-based modeling

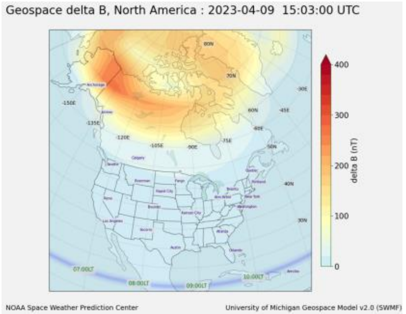
Current Electric Hazard Forecasting

Deterministic, short lead time GMD forecasts at SWPC



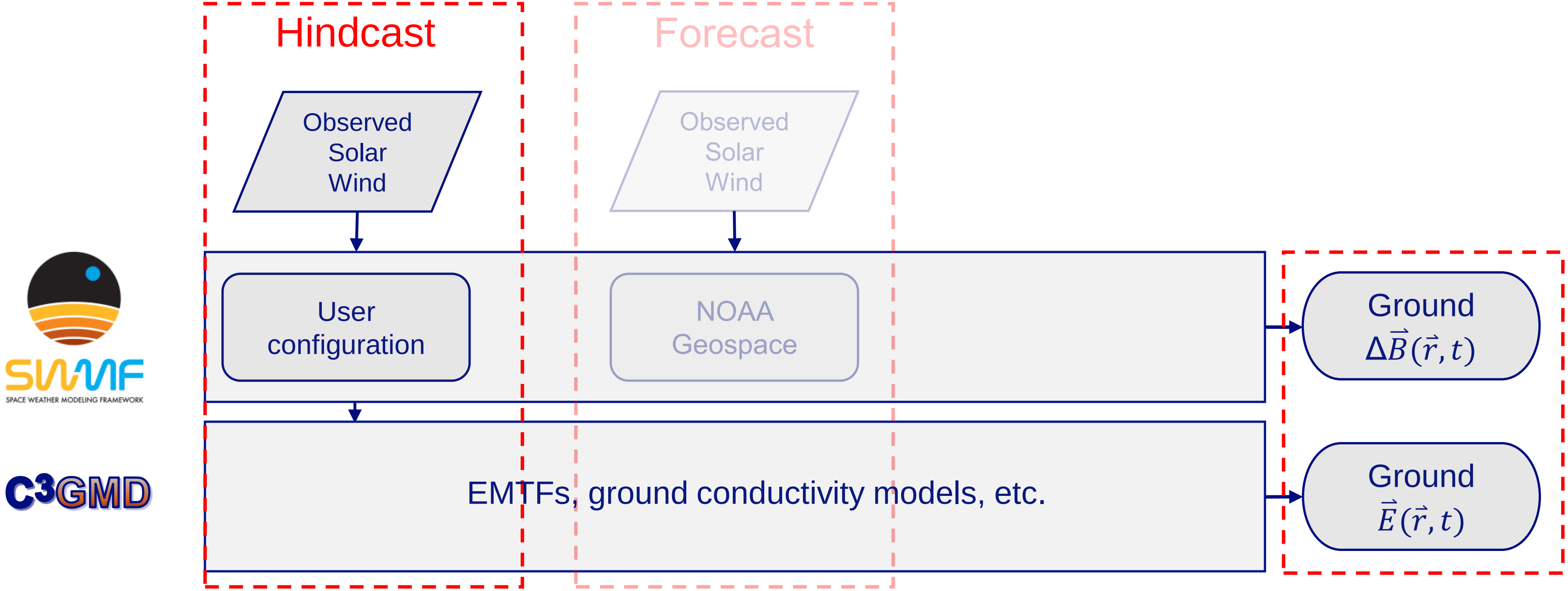


- Geomagnetic indices, e.g., Kp and Dst
- Global geomagnetic perturbation, ΔB(t)



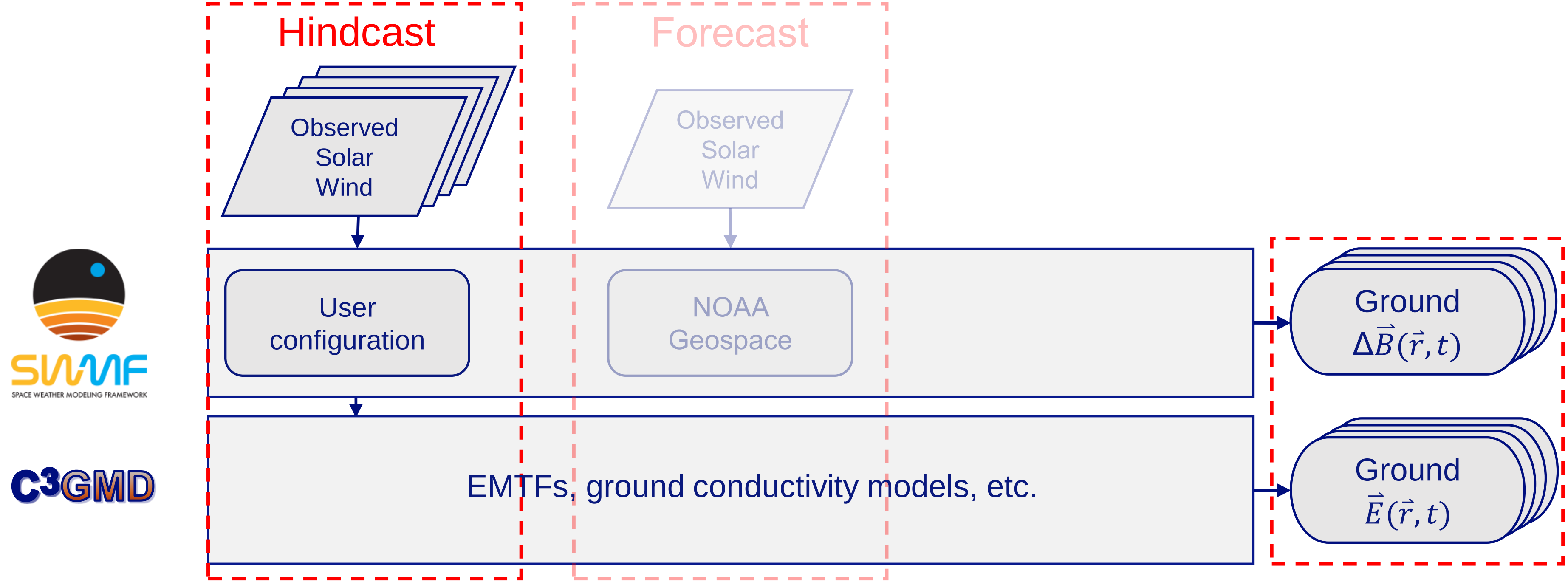
Current Electric Hazard Hindcast

Predict geoelectric field from SWMF simulation



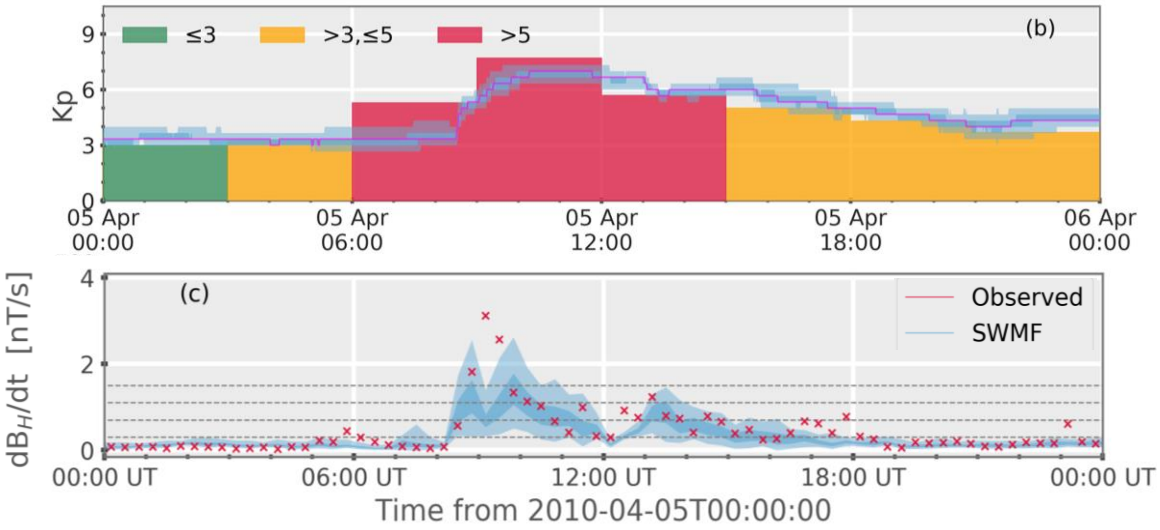
Current Electric Hazard Hindcast

Ensemble Modeling Example: Multiple Realizations of Solar Wind Driver



Ensemble Modeling enables Uncertainty Quantification

40 member ensemble; SWPC v1

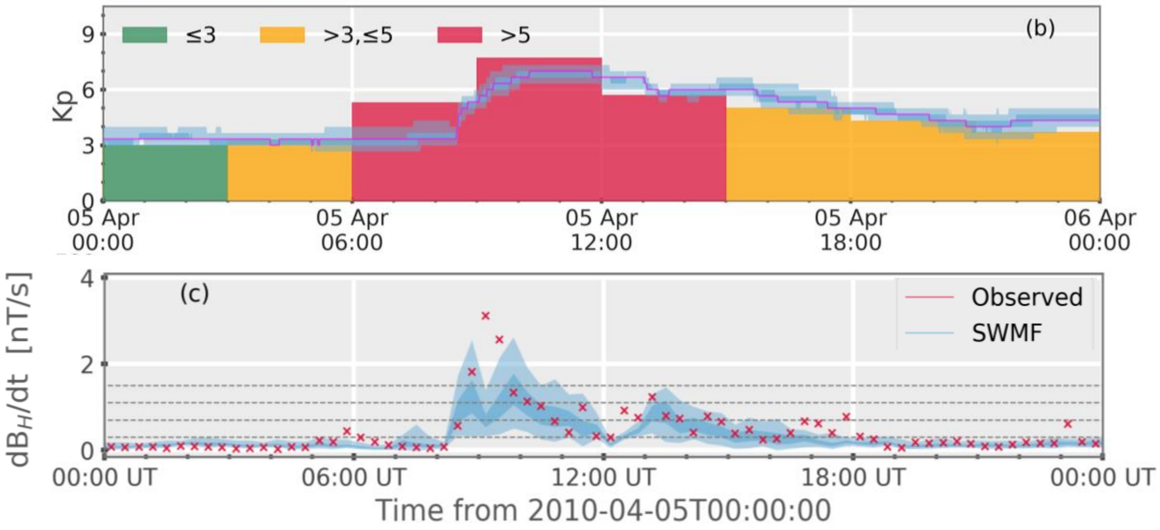


From: Morley et al., 2018

- Ensemble members can be combined to give a probability distribution of forecast value
- Provides uncertainties in outputs due to uncertainty in solar wind driving (major source of uncertainty)
- Confidence band can be used to give probabilistic event forecasts, e.g., 63% chance of a G3 storm.

Probabilistic Modeling Improves Predictive Skill

40 member ensemble; SWPC v1



From: Morley et al., 2018

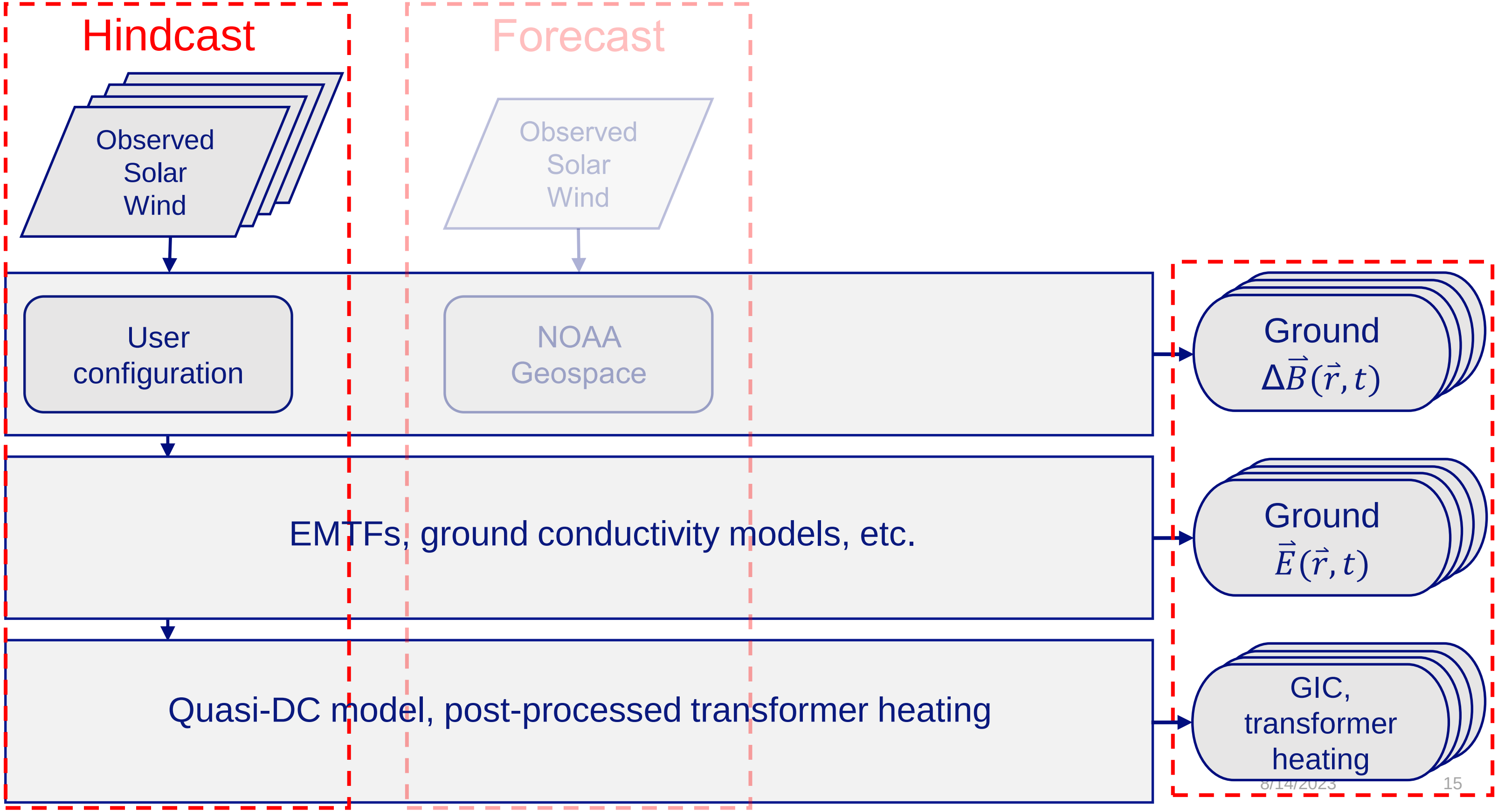
- Ensemble approach allows probabilistic prediction across full suite of model outputs
- Horizontal dB/dt shown here for model validation purposes, $\vec{E}(\vec{r},t)$ is trivially derived from model output
- Probabilistic prediction improves model skill and provides uncertainty

Current Electric Hazard Hindcast

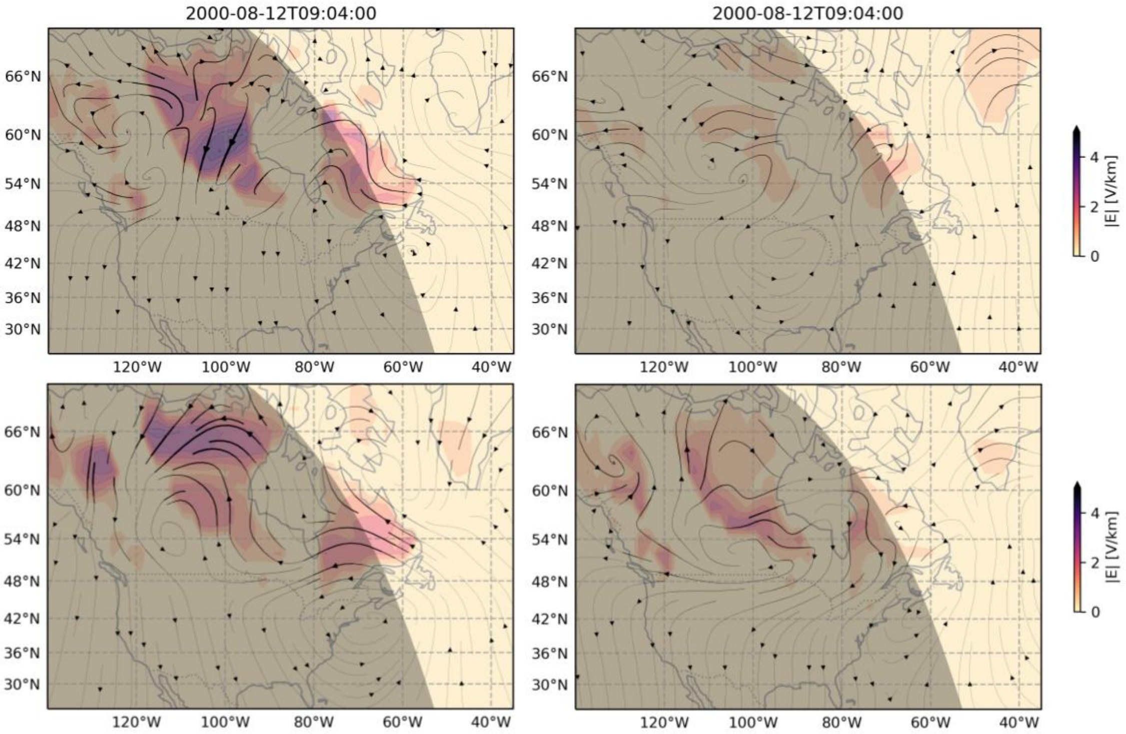
Ensemble Modeling Example: Transformer Hotspot Heating

SWMF
SPACE WEATHER MODELING FRAMEWORK

C3GMD



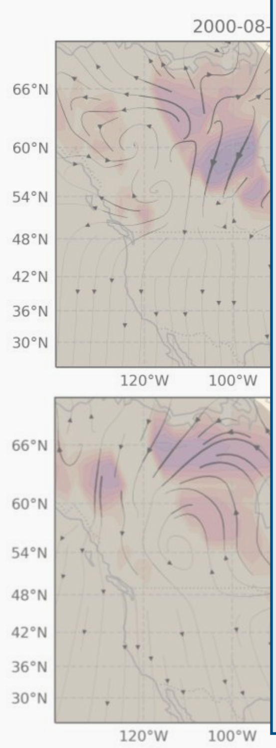
Multiple Realizations of a Moderate Geomagnetic Storm

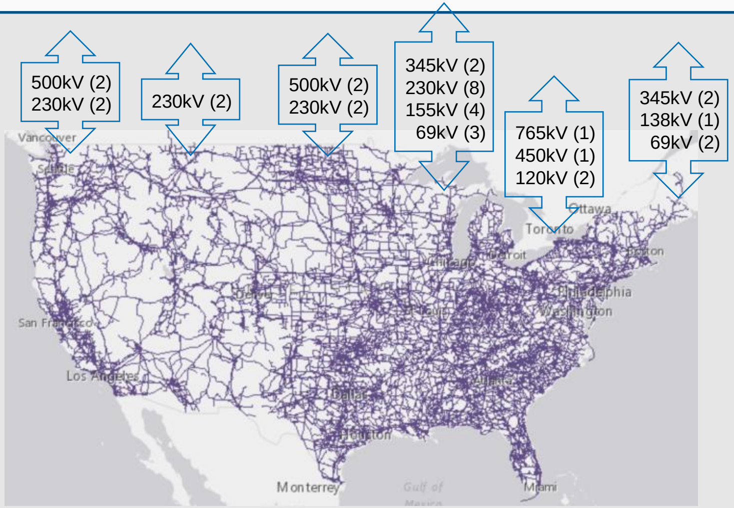


Four snapshots taken from the same time in an 8-member ensemble using the SWPC v2 configuration

- Each ensemble member provides a different realization of magnetic perturbations (including time history) and hence geoelectric field
- Large scale behavior of simulations is similar across ensemble members
- At any given time, local strength and direction of $\vec{E}(\vec{r},t)$ can differ between realizations
- As $\vec{E}(\vec{r},t)$ is required for power flow models, the power grid hazard is different for each ensemble member

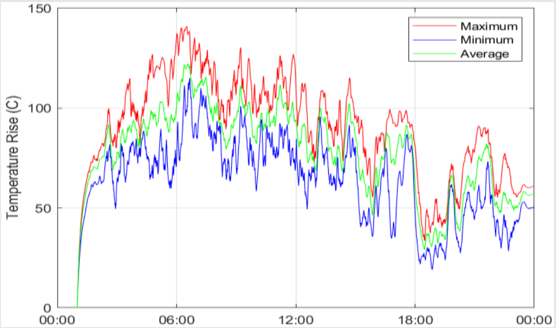
Multiple Realizations of a Moderate Geomagnetic Storm





~96k node model of North American high voltage network. Solve for GIC, then calculate transformer hotspot heating

Heating at one Canadian transformer varied by ~50ºC across a small ensemble



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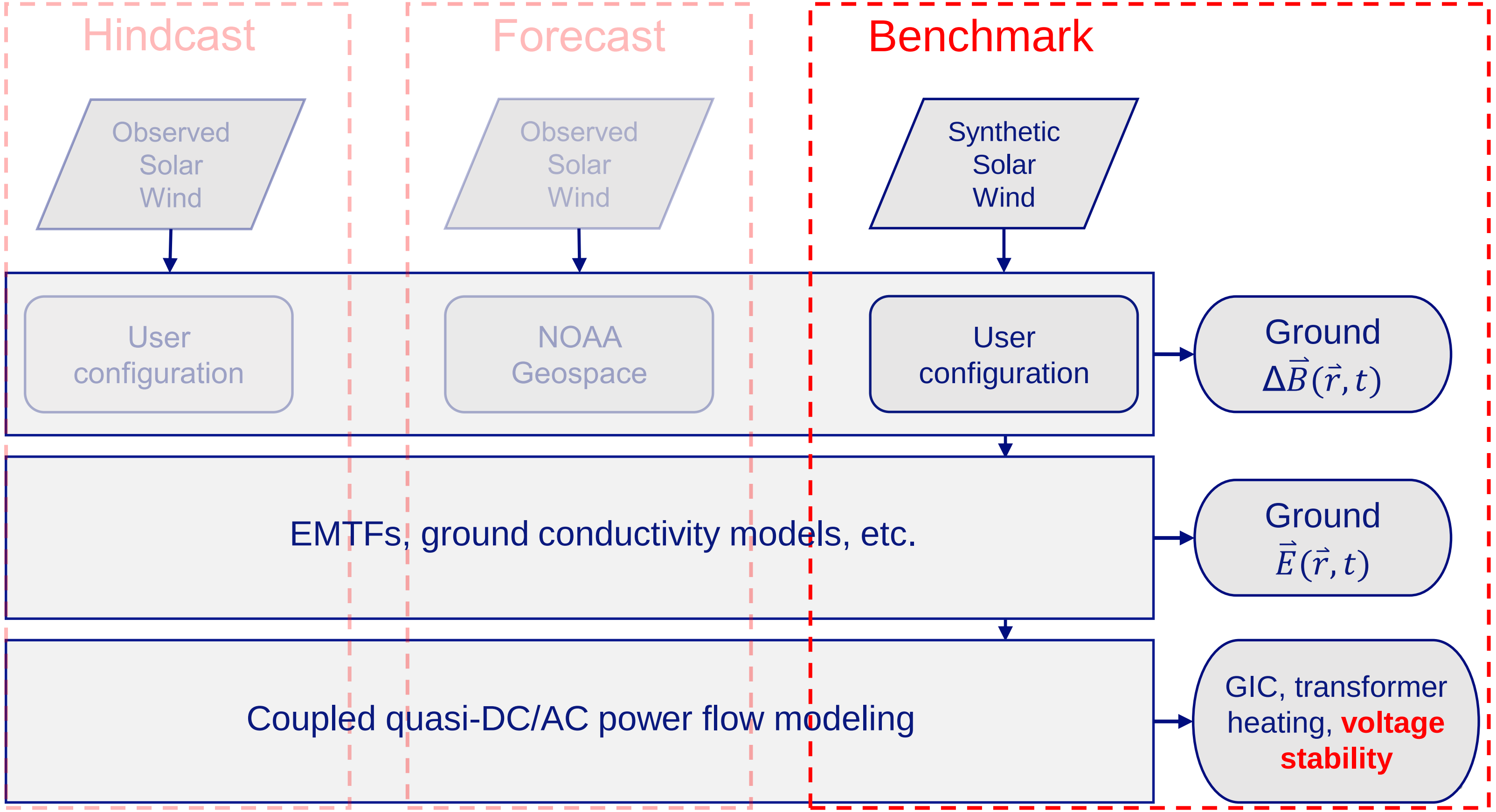
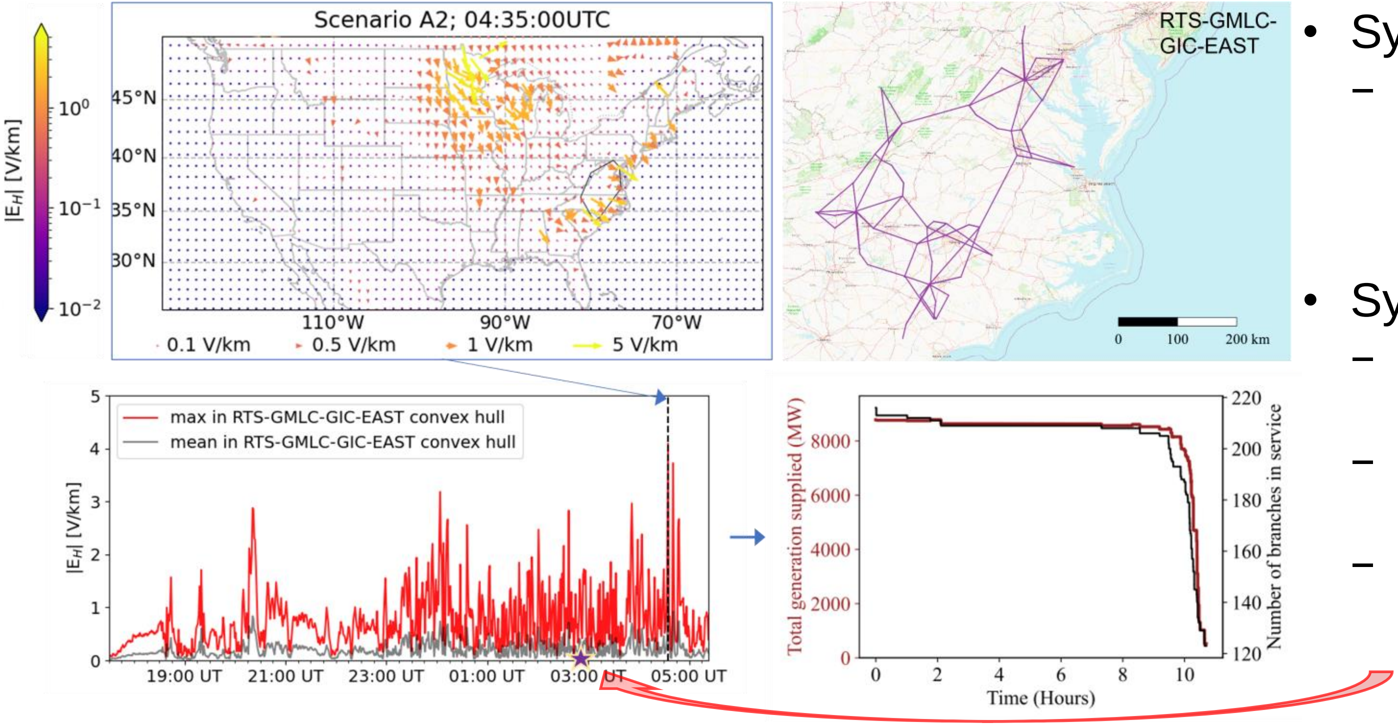
Four snapshots taken from the same time in an 8-member ensemble using the SWPC v2 configuration

End-to-End Electric Hazard Benchmarking

Work is ongoing to include ensemble modeling



Space-To-Earth Modeling of Cascading Grid Failure



- Synthetic event
  - “Scaled A2” from Blake et al. 2021, estimated return period of 281 [62, 776] years based on Dst index.
- Synthetic power grid
  - Located in Virginia/Carolinas
  - Some lines removed from service to stress grid
  - Collapse happens away from peak geoelectric field!

Mate et al., Relaxation Based Modeling of GMD Induced Cascading Failures in PowerModelsGMD.jl, 2021 North American Power Symposium (NAPS), https://doi.org/10.48550/arXiv.2108.06585.

Hazard Analysis with Uncertainties

Multiple scenarios and modeled uncertainty of event likelihood

- Scenario Definition
  - GMD scenarios specified by physics-based modeling (Blake et al., 2021)
  - Bayesian likelihood modeling gives credible intervals
  - Likelihood model includes |E| and Dst to account for
    - chance of observed |E|
    - expansion of auroral oval to lower latitude
- TPL-007 benchmark |E| is exceeded for a smaller Dst storm than the 1989 event
  - Scenario A1 is ~1-in-30 year by Dst alone
  - It is ~1-in-295 years accounting for |E|

Scenario	Sim. Dst [nT]	Est. return period [1/year]	Max |E| (3d) over PNW [V/km]	Max |E| (3d) over NE [V/km]	Max |E| (3d) over globe [V/km]
2004-11-08 (A)	-263	3.7 - 8.0	0.57	1.41	5.84
2005-05-15	-284	2.8 - 5.6	0.87	1.09	8.37
2003-11-20 (B)	-383	7.9 - 24.1	0.42	1.62	6.95
A1	-485	78 – 785	**2.02**	**4.11**	14.99
B1	-497	27.9 – 163	0.92	1.77	8.79
March 1989	**-589**	**N/A**	**N/A**	**N/A**	**N/A**
B2	-681	110 – 1586	**2.15**	2.77	11.87
A2	-757	416 – 12974	**2.82**	**5.52**	15.67
B4	-1053	498 – 23107	**3.55**	**5.02**	36.31
B5	-1059	716 - 39950	**2.73**	**6.28**	18.64

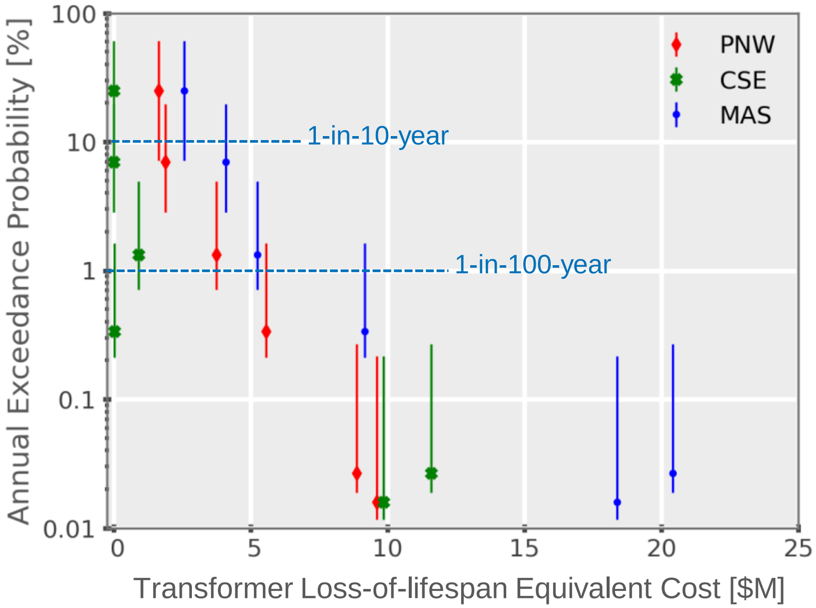
Hazard Assessment with Uncertainties

Assessment

- Impacts were investigated for selected reduced-area, regional networks
  - PNW: Pacific North-West
  - CSE: Coastal South-East
  - MAS: Mid-Atlantic States

- Impacts vary significantly by region
  - Rarer GMD generally drives stronger impact
  - “Loss-of-lifespan” estimates diminished lifespan from heating, does not necessarily imply transformer failure
  - Simulations likely underestimate localized enhancements
  - Time-of-day of event is critical

- Need to combine ensemble modeling with hazard assessment



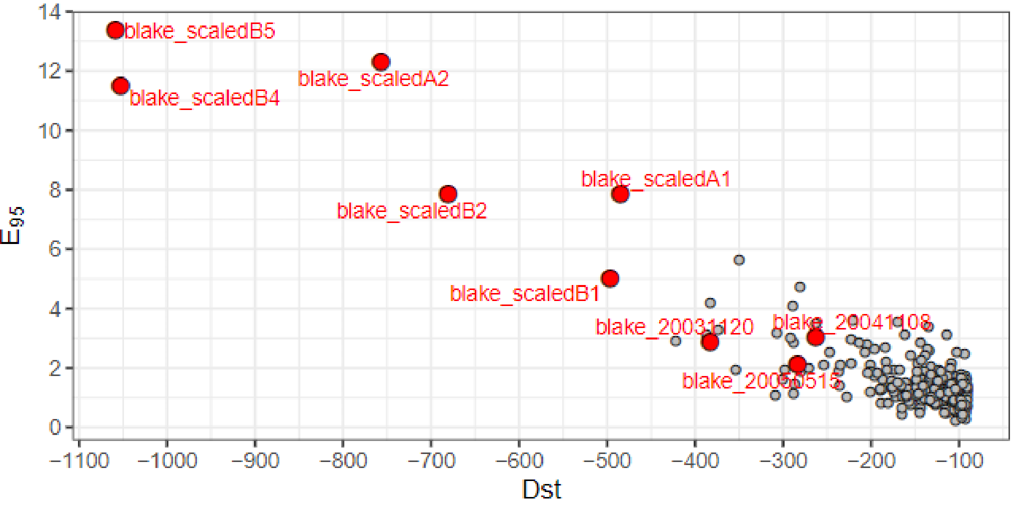
Space-to-Grid Hazard Modeling

- Demonstrated capability for ensemble-based, probabilistic prediction
  - Probabilistic prediction shown to improve model skill, while also providing uncertainty
  - Multiple realizations are required for full UQ and hazard assessment, not just “error bars”
  - SWMF/NOAA Geospace has been used to generate $\vec{E}(\vec{r}, t)$ and to simulate power grid impacts through PowerModelsGMD.jl

- Capabilities can be leveraged for:
  - Better prediction and event definition (higher skill, UQ)
  - Better event analysis
  - Better benchmarking and hazard assessment

Additional Information

Modeling the likelihood



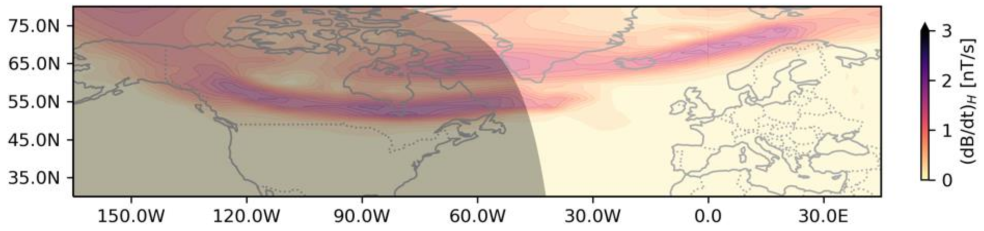
Uncertainty is obtained by 3750 draws from posterior distributions of Bayesian model of joint PDF

E.g., simulation of 2003-11-20 event is estimated as a ~13 year return period, credible interval is between 7 and 30-year return period

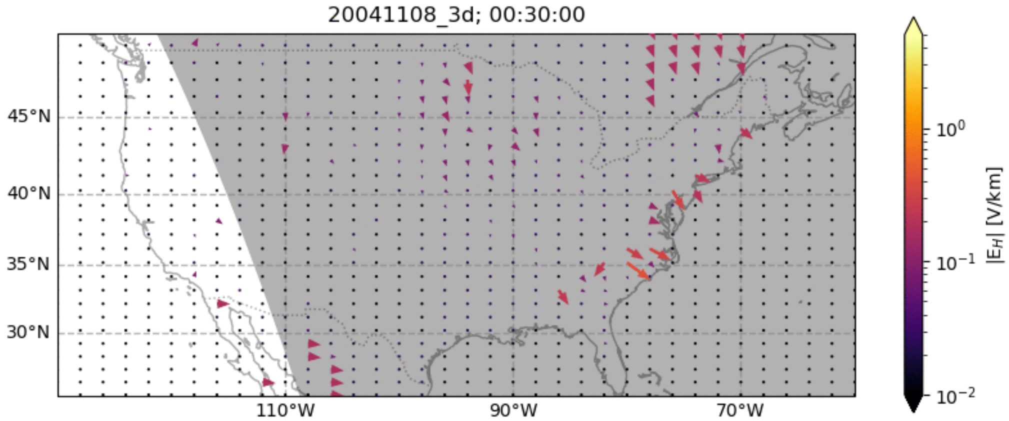
- Build Bayesian likelihood model using Dst and 95th percentile of latitudinal profile of estimated geoelectric field
  - Geoelectric field estimated using reference transform and SuperMAG data holdings
  - p(Dst) modeled as truncated t distribution
  - p(E_{95}|Dst) modeled with gamma distribution
  - Likelihood given by double integral over joint probability distribution

Deterministic, can yield short-lead time predictions

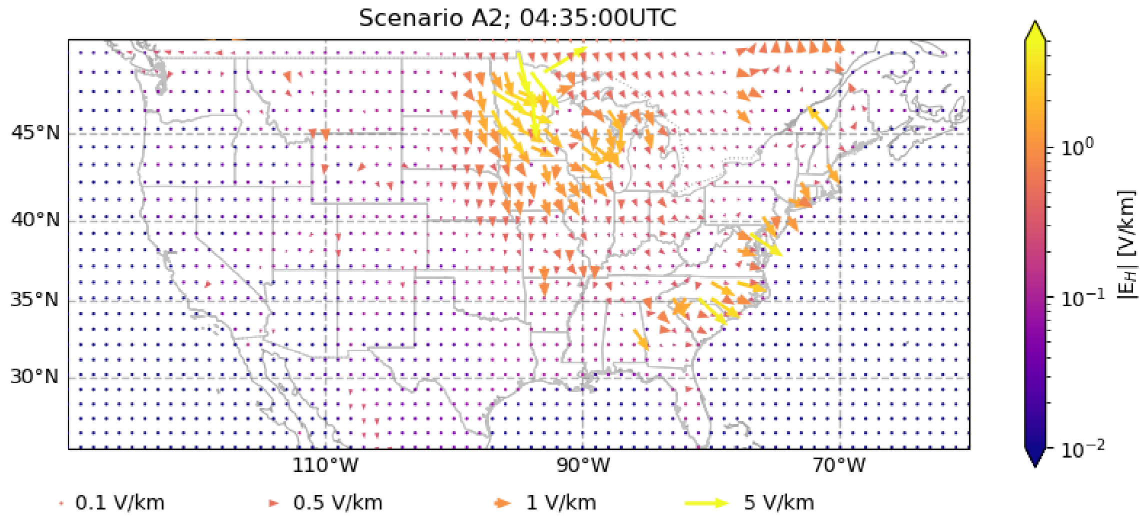
- As before, magnetic perturbations are predicted globally. These are used with C3GMD to calculate geoelectric field.
  - Top figure shows dB/dt at one time during an adaptive mesh simulation of an idealized CME with SWMF



- Global geoelectric field, $\vec{E}$
  - C3GMD is hierarchical in fidelity, uses best available per location:
    - 3D EMTF (cf. IRIS)
    - Regional 1D EMTF (EPRI)
    - Regional 1D conductivity (Fernberg)
    - Global conductivity model (locally 1D)
  - ***$\vec{E}$ is input to power systems modeling***



Simulation-derived Hazard Analysis:
High-resolution spatiotemporal geoelectric field



Geoelectric field over North America from a high resolution SWMF simulation of a 1-in-300-year geomagnetic storm. C3GMD was used to calculate the electric field from the magnetic perturbation.

- Synthetic scenarios can include larger-than-observed events
  - Events defined by inputs, so return period of |E| must be estimated from simulation results
- Provides single realization
  - Modifying inputs for ensemble modeling may change estimated event likelihood
- Model $\vec{E}(\vec{r}, t)$ + downstream impacts: transformer heating and lifespan decrease, cascading failure and outage impacts