Overview of GMD Research and the Texas Magnetometer Network

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Acknowledgments

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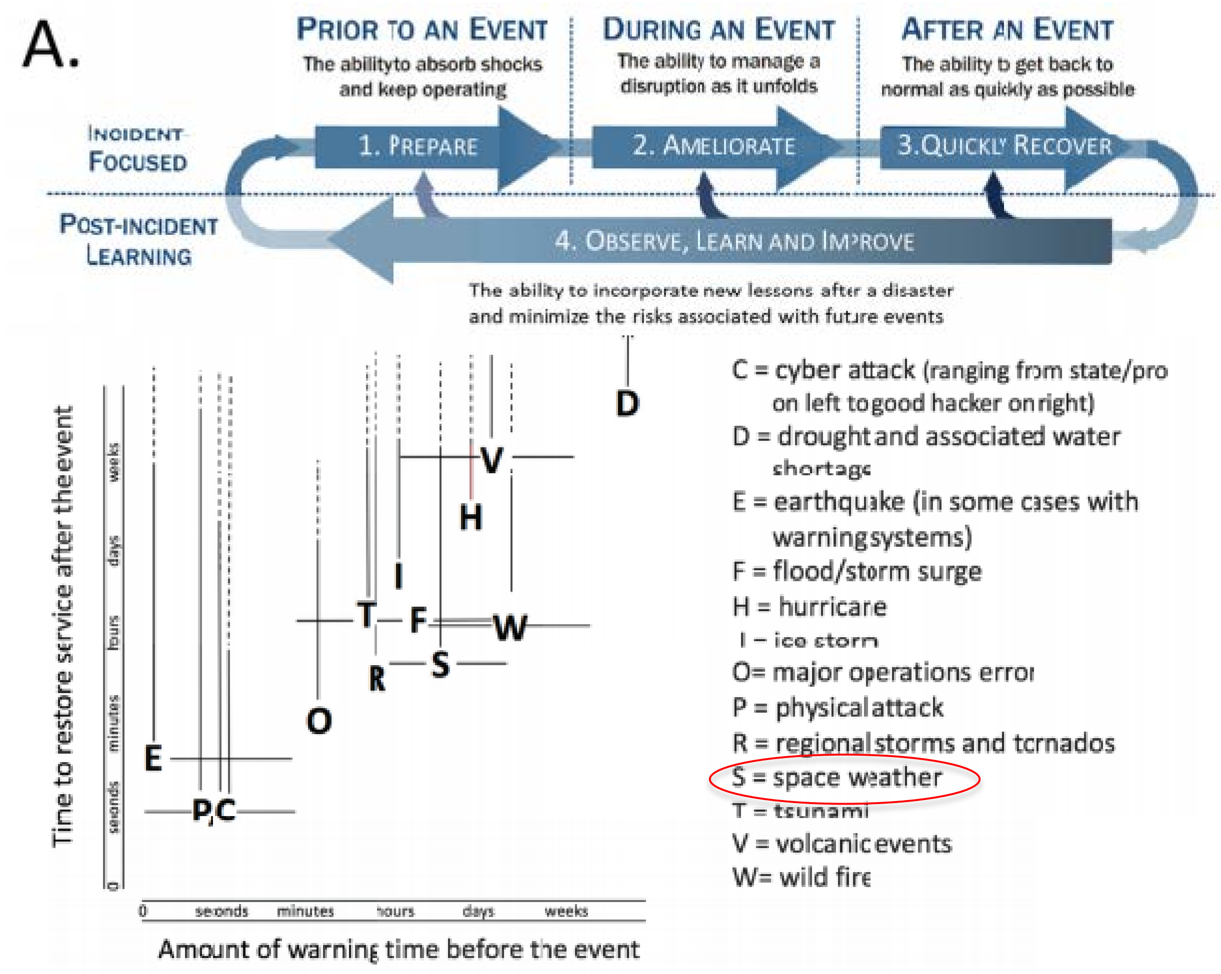
- Slides also include contributions from members of our research group, at both TAMU and UIUC and project collaborators

Overview

- Presentation briefly introduces GMDs
- State of art for modeling and assessments
- Significance of monitoring
- Magnetometer network and applications

Enhancing the Resilience of the Nation's Electricity System



Source: NAS Electric Grid Resilience Report Figures 1.2a, 3.1

An important US. National Academies report in this area, titled "Enhancing the Resilience of the Nation's Electricity System," was issued in 2017 (available for free download)

What is Space Weather?

- Like Earth, weather occurs in space by Solar Activity
  - continuous stream of plasma called the solar wind
  - periodically releases billions of tons of matter in what are called coronal mass ejections (CMEs)
    - when directed towards Earth, can cause large magnetic storms in the space environment around Earth, the magnetosphere and the upper atmosphere

CME

A CME can take around 1-3 days to reach the Earth

Source: NASA

Effects of Space Weather

Coronal mass ejections (CME’s) resulting from solar activity

High-energy charged particles interact with Earth’s magnetic field

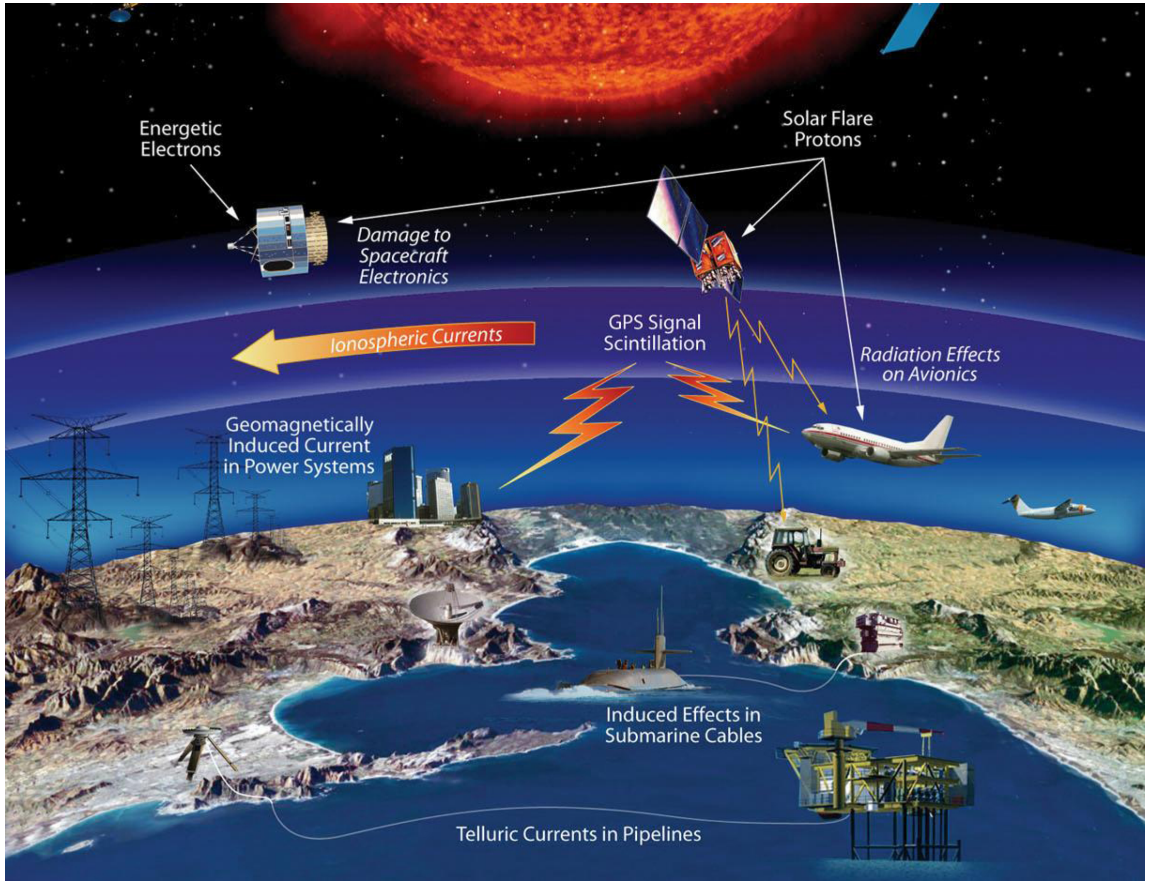
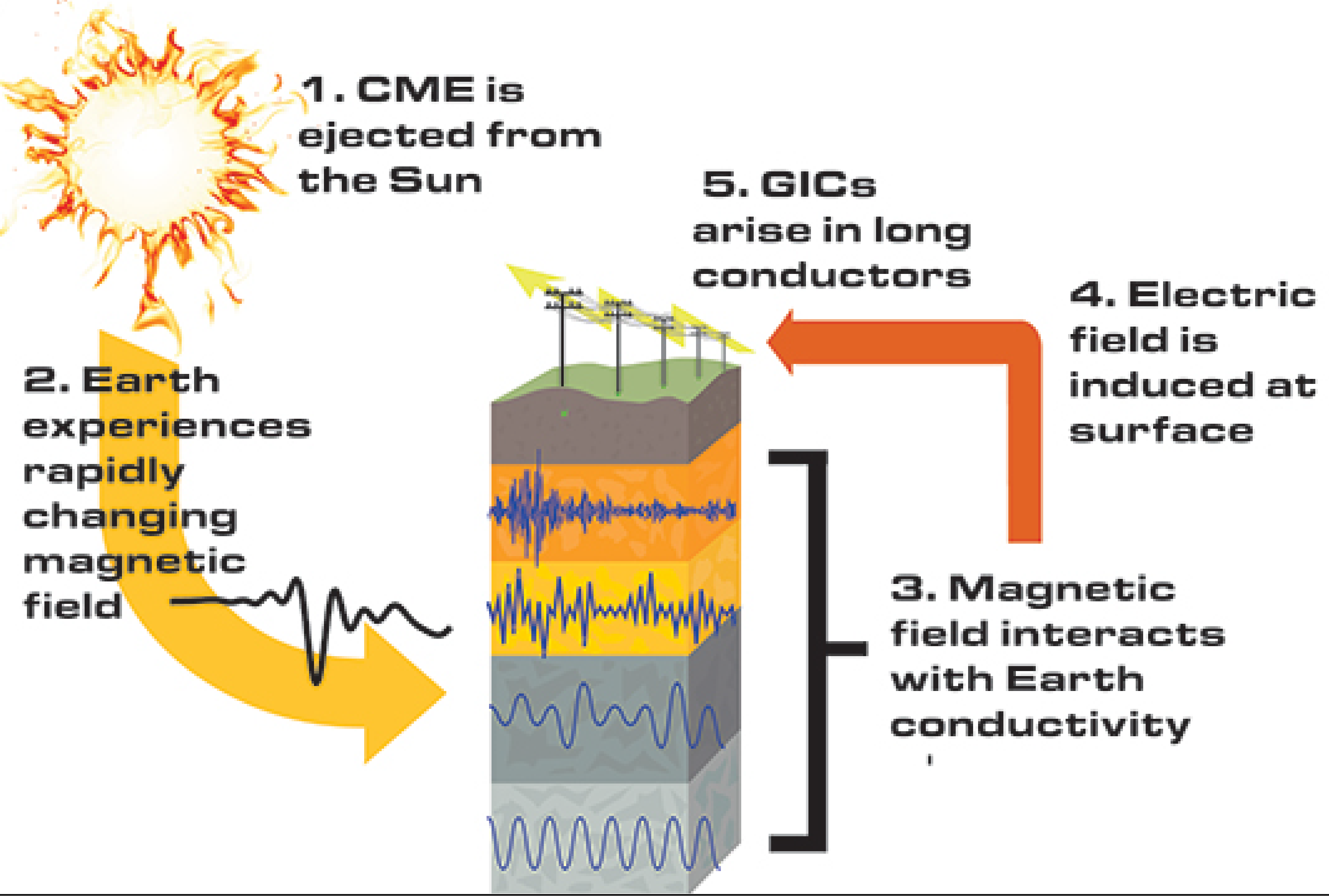


Image Source: https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html

What causes GICs?



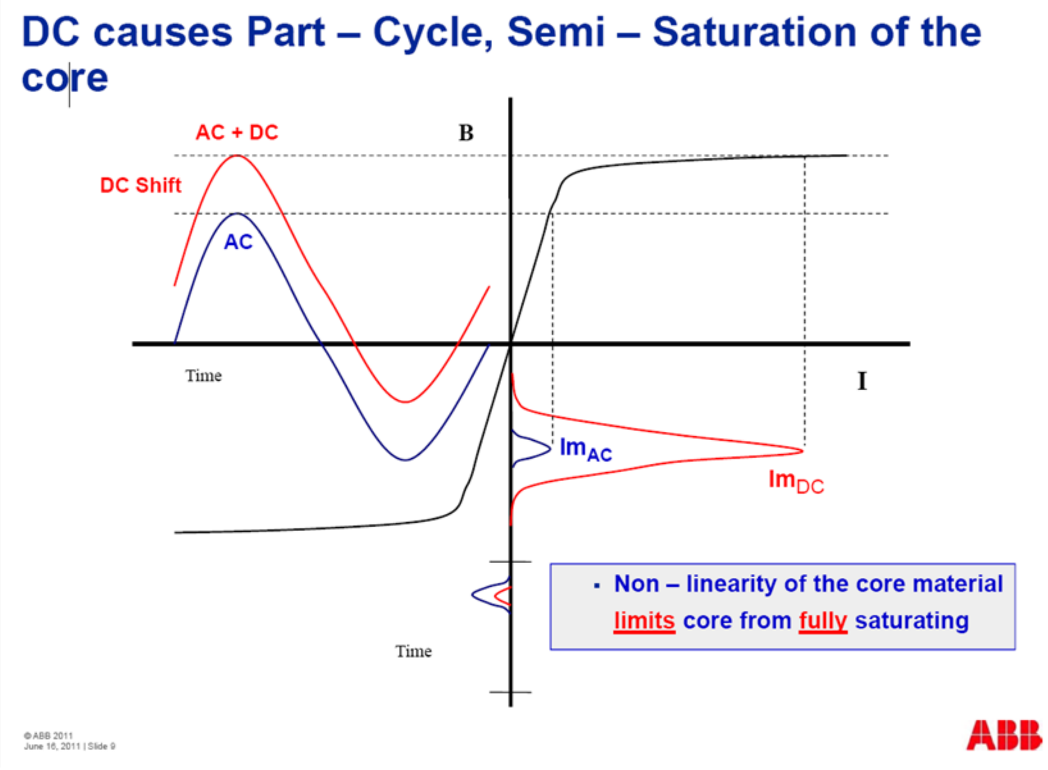
GICs (<0.1 Hz) flow through transmission lines, grounded transformers, and the Earth

Electric fields are vectors, i.e. have magnitude and direction

Image Source: Dr. Jennifer Gannon, CPI

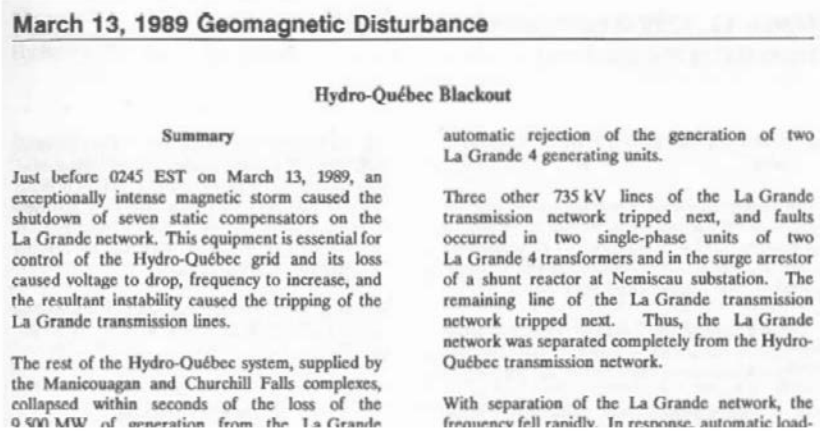
What are the impacts?

- Superimposition of dc GICs on AC power grid can push transformer flux into saturation for half-cycle
- This can cause harmonics
- In the positive sequence (e.g., PF and TS) these harmonics can be represented by <u>increased reactive power losses on the transformer</u>
- Harmonics can also cause relays to trip devices such as SVCs
- Transformer heating and damage



What are the impacts?

- Two major impacts
  - Voltage collapse due to
    - Increased transformer reactive losses
    - Tripping of reactive power support devices
  - Transformer damage (including GSUs)
- A GMD event in March 1989 caused a major blackout in Quebec
  - 7 SVCs tripped within 59 seconds, causing voltage collapse 25 seconds later.
    6 million people without power for 9 hours.
  - In US: New York Power lost 150 MW,
    New England Power Pool lost 1,410 MW, service to 96 electrical utilities in New England was interrupted. Over 200 grid issues problems erupted within minutes of the start of the storm. Luckily no blackouts.



March 13, 1989 Geomagnetic Disturbance

Hydro-Québec Blackout

Summary

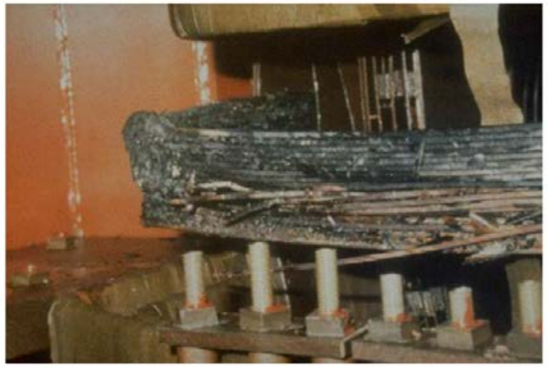
Just before 0245 EST on March 13, 1989, an exceptionally intense magnetic storm caused the shutdown of seven static compensators on the La Grande network. This equipment is essential for control of the Hydro-Québec grid and its loss caused voltage to drop, frequency to increase, and the resultant instability caused the tripping of the La Grande transmission lines.

The rest of the Hydro-Québec system, supplied by the Manicouagan and Churchill Falls complexes, collapsed within seconds of the loss of the 9 500 MW of generation from the La Grande

automatic rejection of the generation of two La Grande 4 generating units.

Three other 735 kV lines of the La Grande transmission network tripped next, and faults occurred in two single-phase units of two La Grande 4 transformers and in the surge arrestor of a shunt reactor at Nemiscau substation. The remaining line of the La Grande transmission network tripped next. Thus, the La Grande network was separated completely from the Hydro-Québec transmission network.

With separation of the La Grande network, the frequency fell rapidly. In response, automatic load-



Industry Efforts and Standards

- NERC 2012 Interim GMD Report: Four high-level recommendations
  - Improved tools for planners to develop mitigation strategies
  - Improved tools for system operators to manage GMD
  - Develop information exchange between researchers and industry
  - Review the need for enhanced NERC Reliability Standards
- FERC Order 779, 2013: NERC must develop standards requiring power system owners and operators to
  - develop and implement operational procedures to mitigate GMD (EOP-010-1)
  - conduct initial and on-going assessments of the potential impact of benchmark GMD events (TPL-007-1)
  - develop and implement a plan to prevent impacts of benchmark GMD events from causing instability, uncontrolled separation, or cascading failures

Operations: Alerts

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NOAA Space Weather Prediction Center issues Watches to power system operators etc. when K ≥ 5

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

- Watch: Driven by forecast of an impending GMD from less than a day to 72 hours (lead time depends on velocity of CME)
- Warning: Driven by upstream solar wind observations. Carry a higher degree of confidence in timing and intensity, issued minutes to a couple of hours in advance
- Alert: Driven by ground-based magnetometer observations (what is occurring now)

Source: https://www.swpc.noaa.gov/noaa-scales-explanation

Industry Efforts and Standards

- FERC Order 830, 2016: Approved TPL-007-1 with modifications
  - Benchmark Event shall not be based solely on spatially averaged data
  - Collect and publicly share GIC monitoring and magnetometer data
  - Establish deadlines for corrective action plans and mitigation
- NERC released TPL-007-2: Key requirements
  - Maintain AC system models and GIC system models
  - Develop criteria for steady state voltage performance
  - Complete a GMD Vulnerability Assessment every 5 years based on benchmark and supplemental GMD events
  - Develop a Corrective Action Plan if needed
  - Transformer thermal assessments
  - Obtain GIC monitor and GMD field data

Industry Efforts and Standards

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- NERC released TPL-007-3:
  - Canadian Variance for alternative Benchmark and Supplemental Events
- FERC Order 851, 2018: Approved TPL-007-2 with changes
  - require corrective action plans (CAP) to mitigate supplemental GMD event vulnerabilities
  - corrective action plan time-extensions to be considered on a case by case basis
- TPL-007-4 affirmed by NERC voters in November 2019

What we have done / are doing

- Validating GICs measured at actual transformers with simulated to evaluate ground conductivity models
- Real-time GIC Monitoring and Control Environment
  - Texas Magnetometer Network
  - GIC “State Estimation” (GIC Estimation)
  - Interactive GMD simulations and scenarios for visualization, control, and mitigation applications
- GMD assessments for utilities
- Algorithms for GIC impact mitigation

What we have done / are doing

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- Modeling advancements in GIC analysis, tech transfer to industry/software
  - 1D or 3D conductivity based detailed electric field modeling
  - Transient Stability
- Model validation using GIC measurements to estimate
  - Electric fields
  - Substation grounding resistances
- Developing synthetic but realistic large scale test systems, which include GMD parameters
  - https://electricgrids.engr.tamu.edu/electric-grid-test-cases/

GMD Enhanced Power Analysis Software

- By integrating GIC calculations directly within power flow and transient stability engineers can see the impact of GICs on their systems, and consider mitigation options
- GIC calculations use many of the existing model parameters such as line resistance. Some non-standard values are also needed; either provided or estimated
  - Bus or substation geo-coordinates
  - Substation grounding resistance
  - transformer grounding configuration, transformer coil resistance, whether auto-transformer, three-winding transformer, etc.

Assessments for Mitigation

- A large GMD could substantially affect power system flows and voltages
- Studies allow for testing various mitigation strategies
  - Operational (short-term) changes include re-dispatching generation to avoid long distance power transfers and reducing transformer loading values, and strategically opening devices to limit GIC flows
  - Longer-term mitigation actions include the installation of GIC blocking devices on the transformer neutrals (such as capacitors) and/or increased series capacitor compensation on long transmission lines

Overview of GMD Assessments

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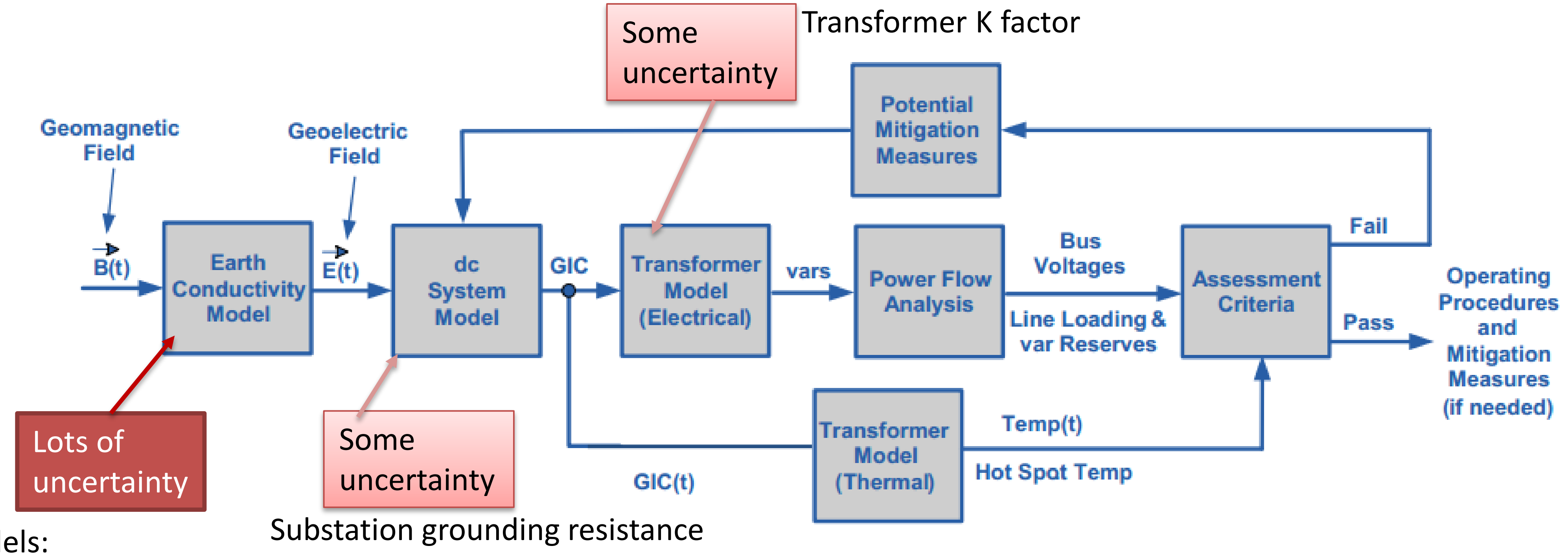


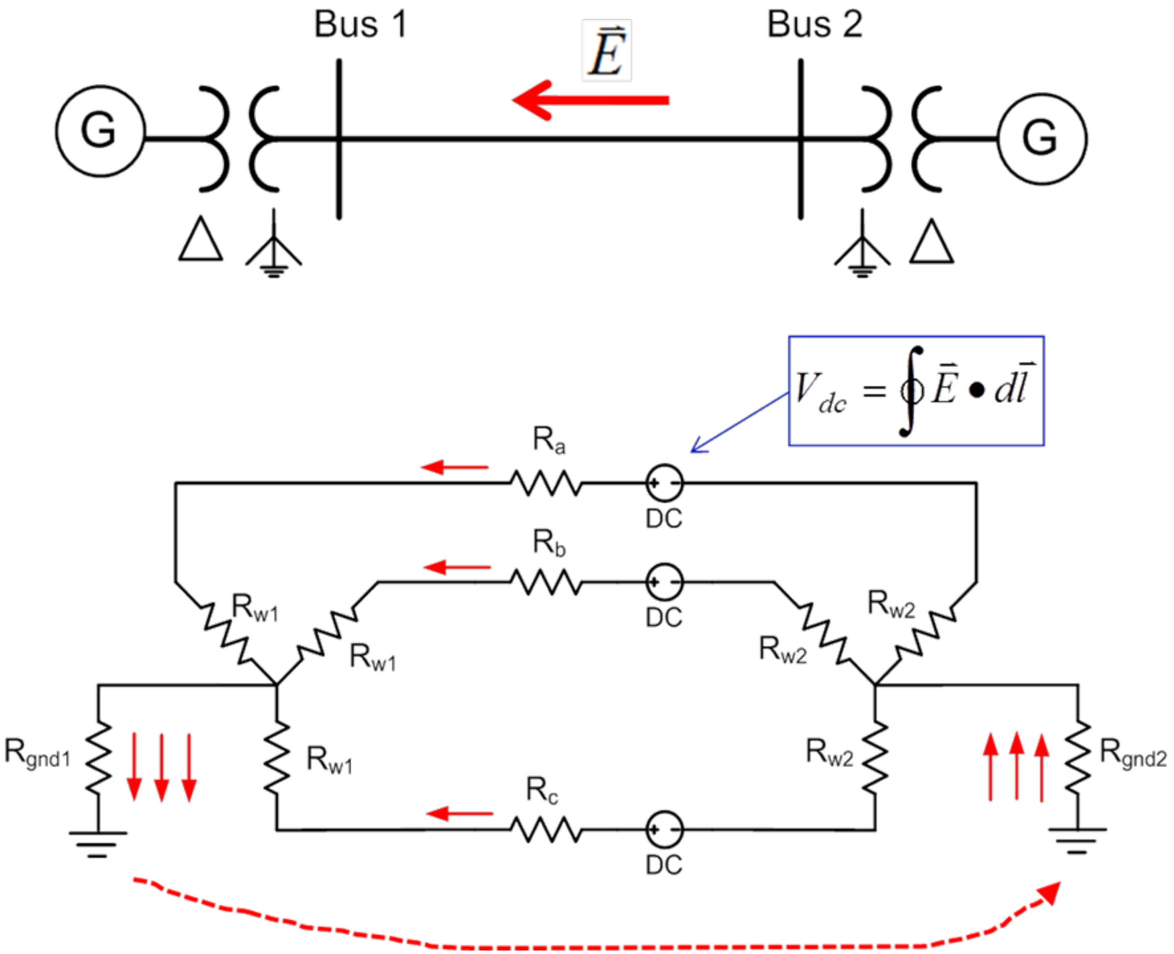
Models:
Uniform,
1D, 3D,….

Image Source: http://www.nerc.com/pa/Stand/WebinarLibrary/GMD_standards_update_june26_ec.pdf

How do we model a GMD?

- Non-uniform electric fields can be modeled by considering dc voltage sources in series with transmission lines

- The magnitude of the dc voltage is determined by integrating the electric field variation over the line length



Relating GICs to Transformer Mvar Losses

Transformer positive sequence reactive power losses vary as a function of the GICs in the coils and the ac voltage

A common approach is to use a linear model

$$Q_{loss} = KV_{pu} I_{GIC,Eff}$$

K depends on core-type, number of phases, etc.

The $I_{GIC,Eff}$ is an effective current that is a function of the GICs in both coils; whether auto or regular the equation is

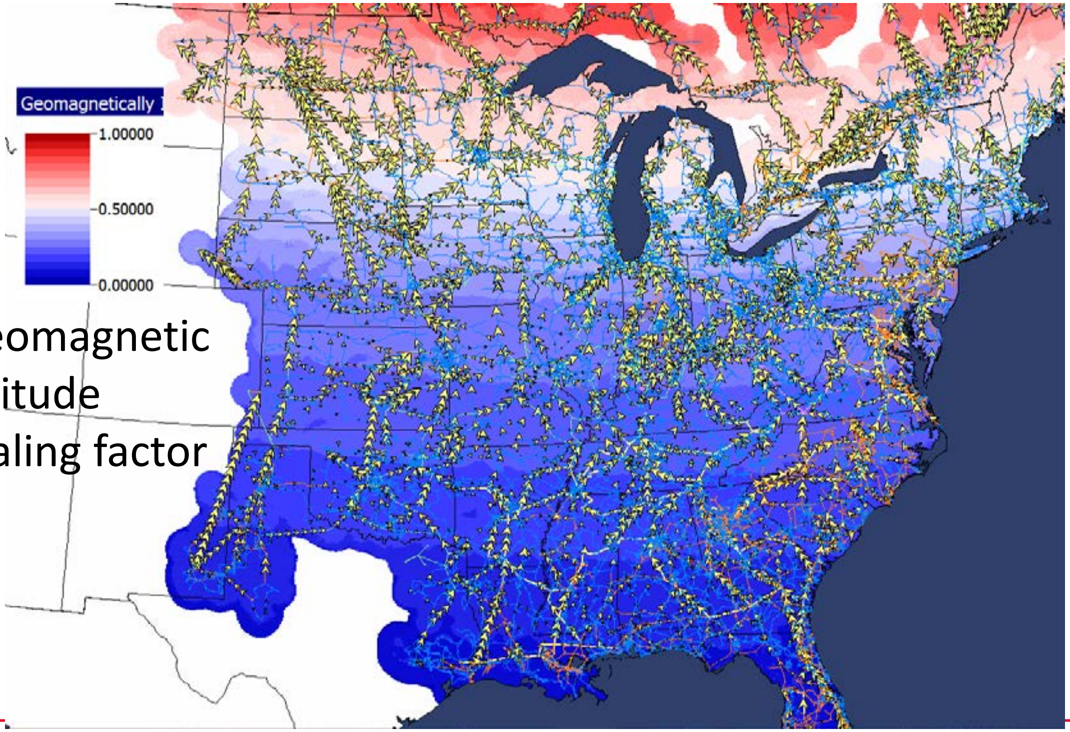
$$I_{GIC,Eff} = \left| \frac{a_t I_{GIC,H} + I_{GIC,L}}{a_t} \right| \quad \text{where } a_t \text{ is the turns ratio}$$

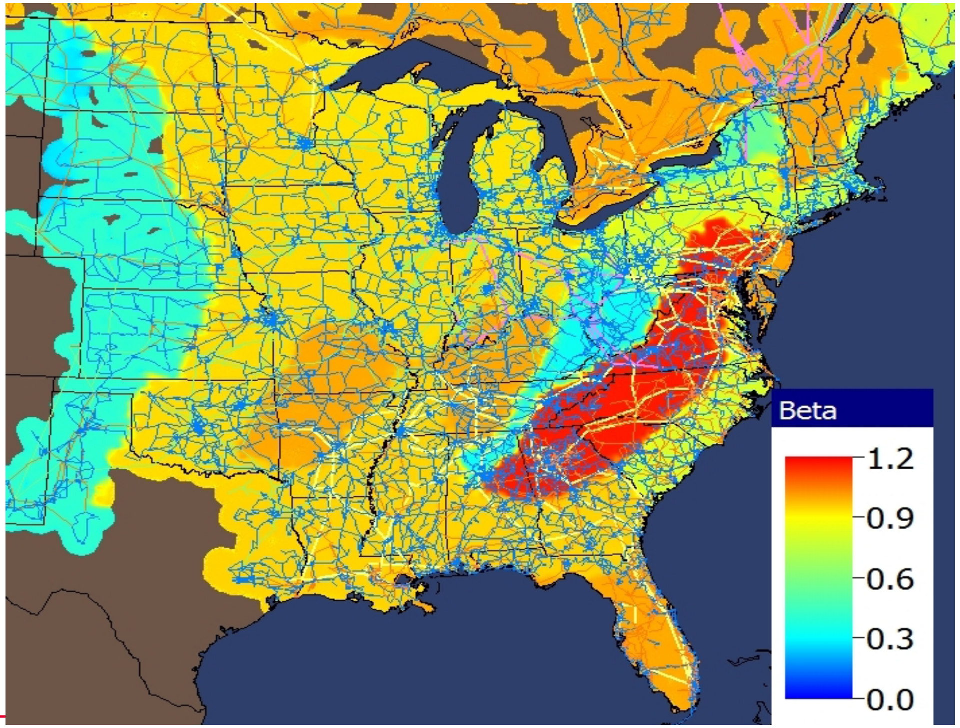
Electric Field Modeling

- Four main methods
  - Single snapshot (usually peak), E_{mag} and E_{angle}; e.g. NERC Benchmark Event
    - A special case is electric field hotspot (localized field enhancement)
  - Spatially-uniform time-varying, E_x and E_y (northward and eastward components) e.g. NERC Benchmark Time Series for Transformer Thermal Analysis
  - Enter series dc voltages directly for each line, time series
  - Spatio-temporally varying electric field, 3-dimensional data (lat,long points forming a “grid”, time and E_x, E_y)
    - E.g. B3D format, NOAA .JSON files

NERC Benchmark Event

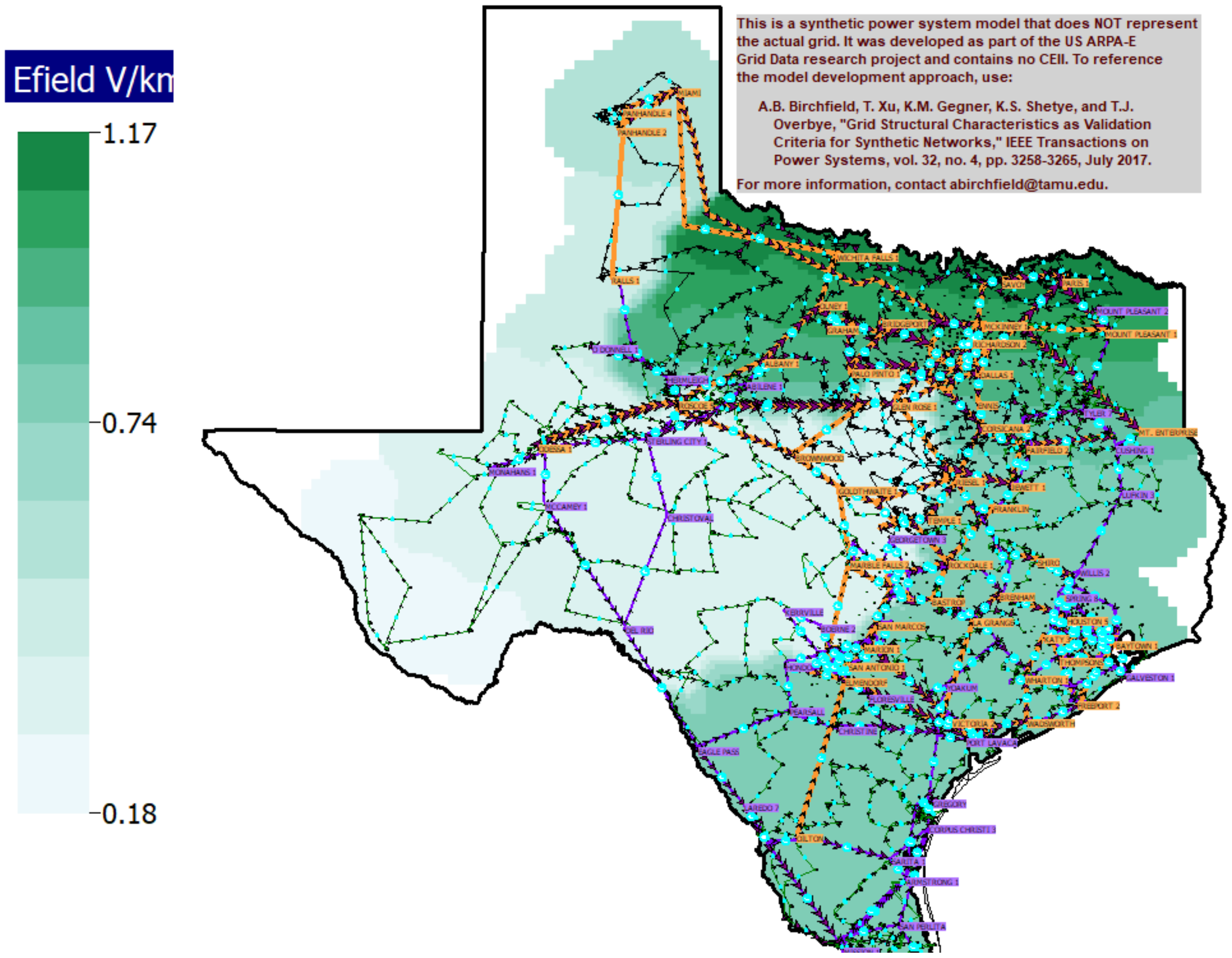
- Electric field scaled by two factors
  - $E_{\text{peak}} = 8 * \alpha * \beta$ V/km
  - "1 in a 100 year" event



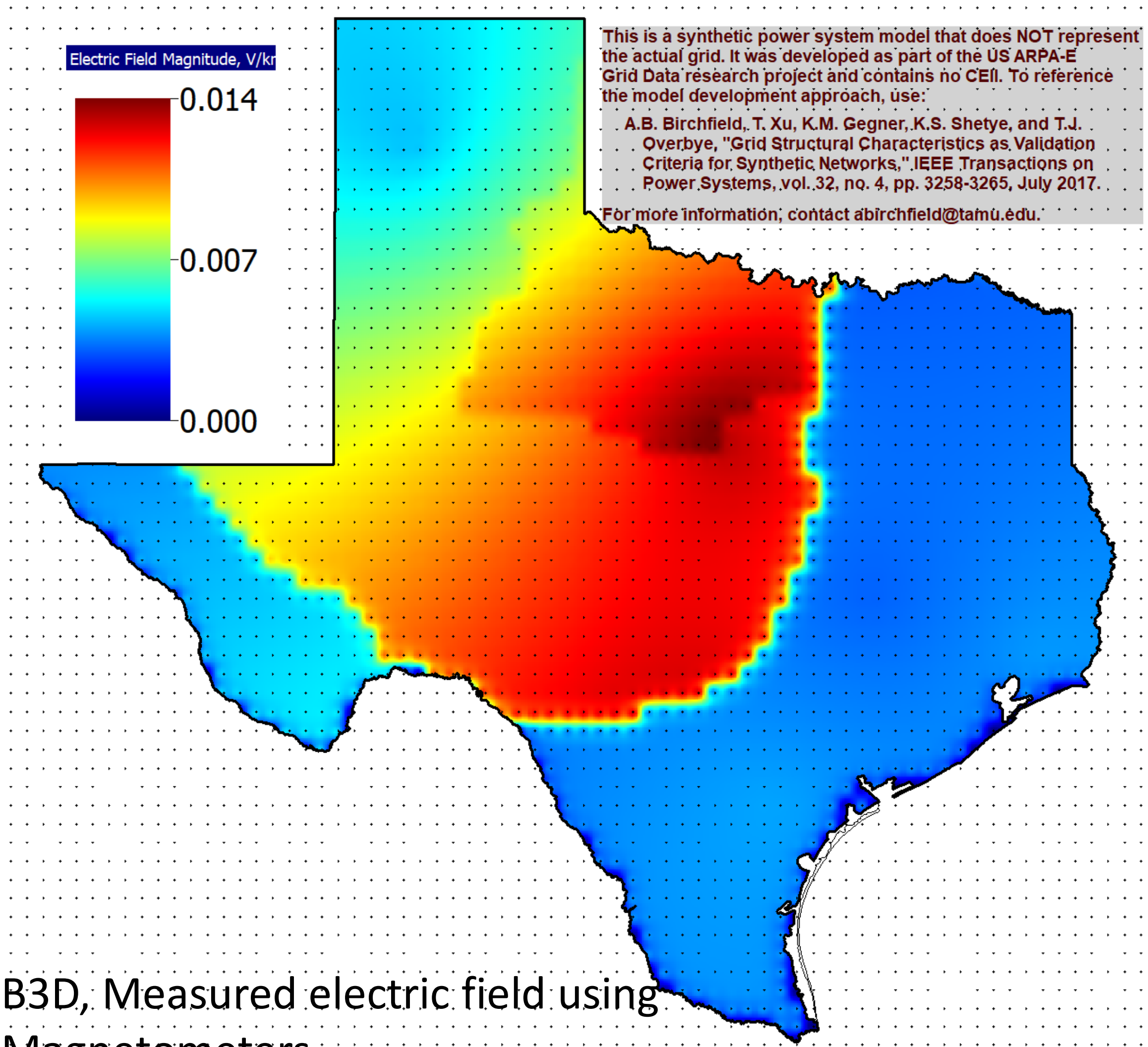


The beta scalars depend on the assumed 1-D models

Visualizing the Electric Field



Single Snapshot, NERC Benchmark Event



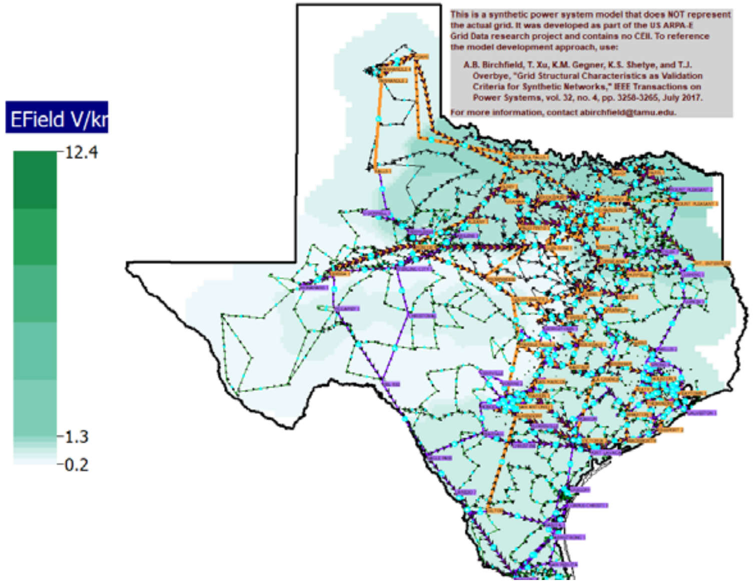
B3D, Measured electric field using Magnetometers

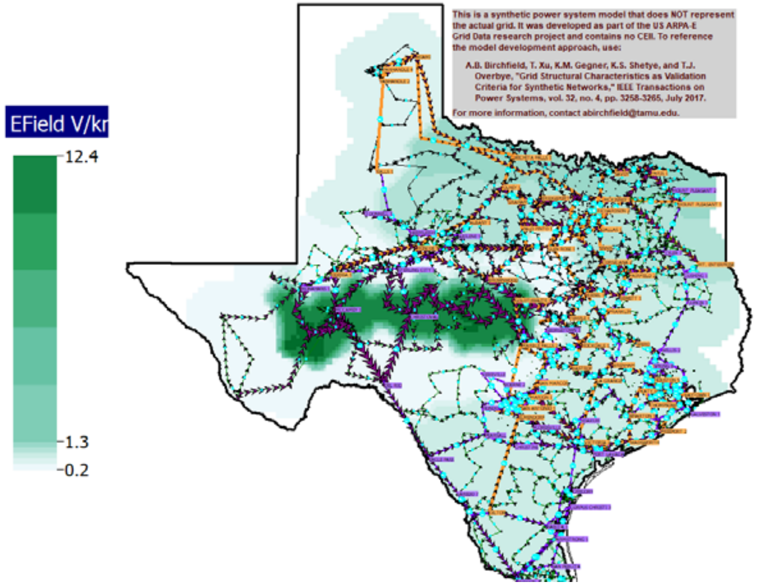
Electric Field Hotspot

- Assess impacts of localized intensifications
  - Defined by size/area (a box, e.g. 100 km tall 500 km wide), magnitude, and duration
  - E.g. NERC Supplemental GMD Event $E_{\text{peak}} = 12 * \alpha * \beta_s$ V/km

Benchmark E field applied everywhere, supplemental inside the box in the West

Hotspot with α,β Scaling





Hotspot without α,β Scaling

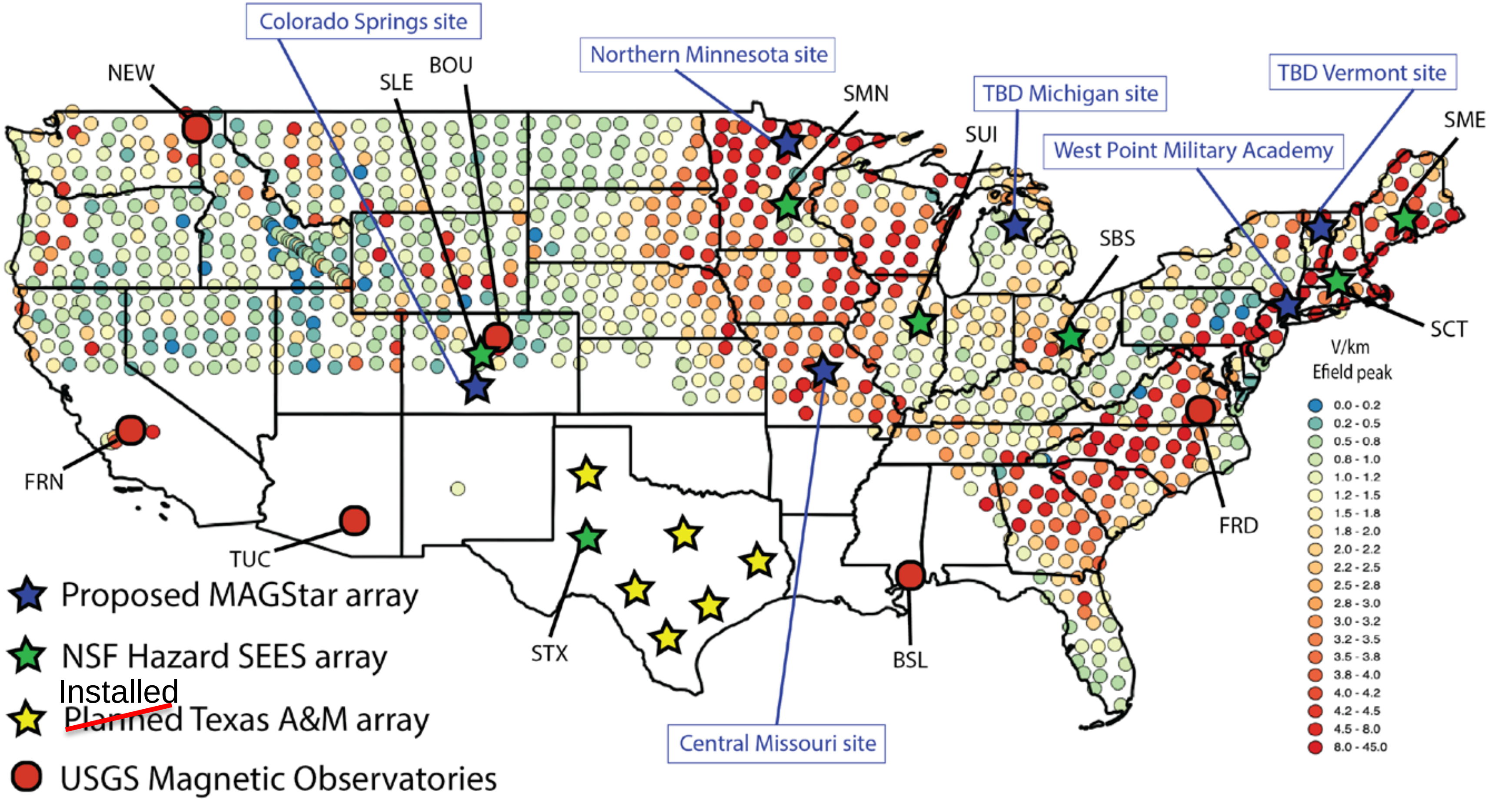
In some regions, beta factors can significantly reduce the impact of the hotspot

Texas Magnetometer Network

- 6 magnetometers installed by Texas A&M and Computational Physics Inc. (CPI)
  - **<u>Completed</u>** Dec 2019
  - Building on the results of our NSF project design
- Locations
  - 5 Texas A&M AgriLife Research sites (Amarillo, Beaumont, Beeville, Overton, Stephenville)
  - 1 local on RELLIS Campus (Bryan, TX)
- 1 mag installed under prior NSF project at Odessa

Motivating Factors

- Improve understanding of Texas geophysics for GIC hazard analysis
- There is a high degree of uncertainty in available conductivity models for Texas
- There are no models built specifically for Texas; this limits our understanding of how GIC hazard varies between locations



Dots: Temporary B and E measurements from where Z transfer functions were derived

Magnetometer Setup

Connect through wireless access points for secure communication

Beaumont

Beeville

Autonomous operation (low power, solar panels)

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

Measuring magnetic field

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- Site placement is important!

  ⇒ No metal, current-carrying wires, fences, buildings, roads, i.e. as magnetically quiet as possible

  ⇒ Off substation grounding mat

  ⇒ Ideally within 200 miles of substation

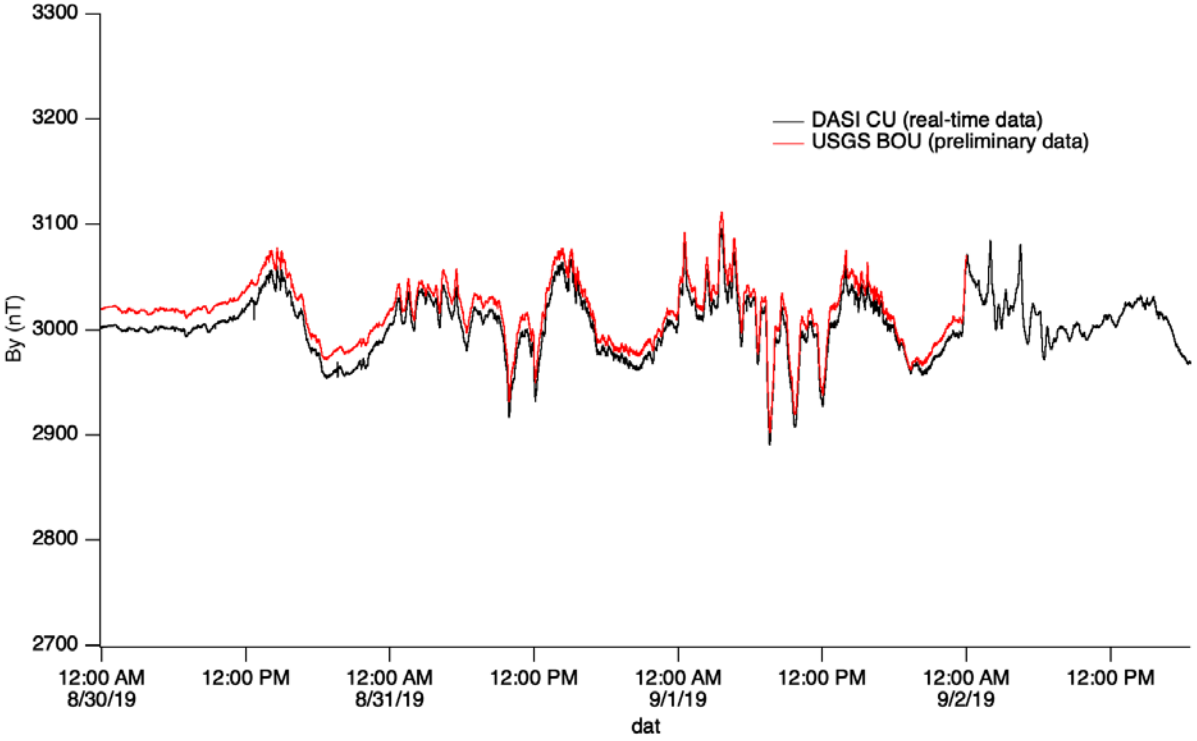
- Measure 1-second cadence

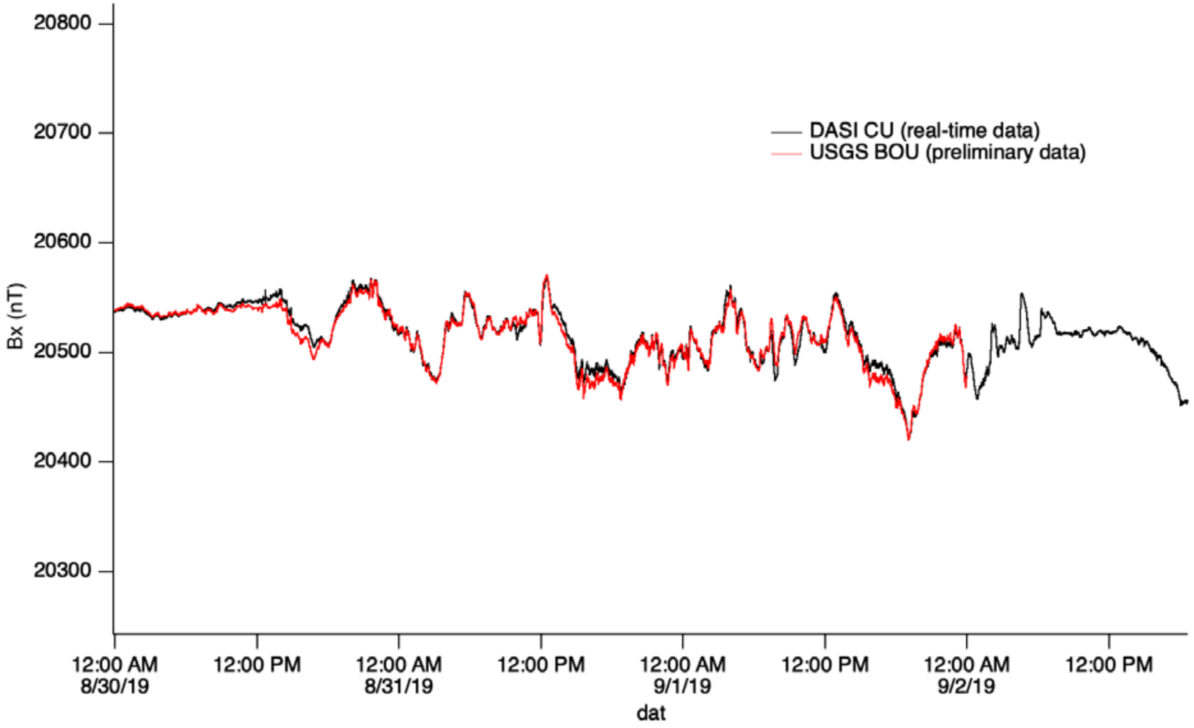
  ⇒ Fluxgate mags

  ⇒ Actually measure higher, and average to 1 second

- Align with geographic north!
- Store all of the information! (Needed to calculate E)

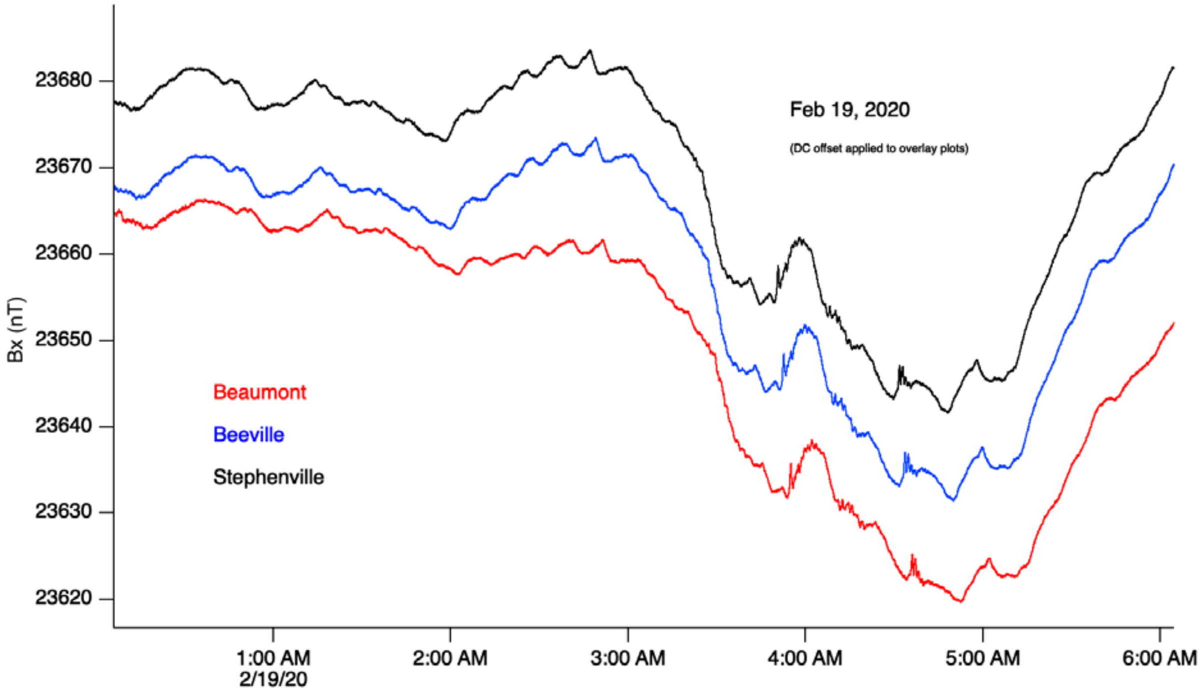
Magnetometer Data Validation





- Plots: Jenn Gannon
- Test installation of TAMU equipment in CU Boulder
- Comparison with USGS BOU (i.e. observatory quality) B data
- Has been testing for seven months, real time data transmission, 0% data loss over wireless connection

Texas Magnetometer Network



Magnetic field data data from February, G1 (minor) event

- Consulted with utilities on locations; near GIC monitors
- Network will provide data in real-time directly to TAMU
  - TAMU can provide it to utilities and other entities under partnerships
- Ongoing work
  - – Electric field calculations
  - – Data access and analytics platform/dashboard
  - – Real-time GIC visualization

Online Dashboard Prototype (Demo)

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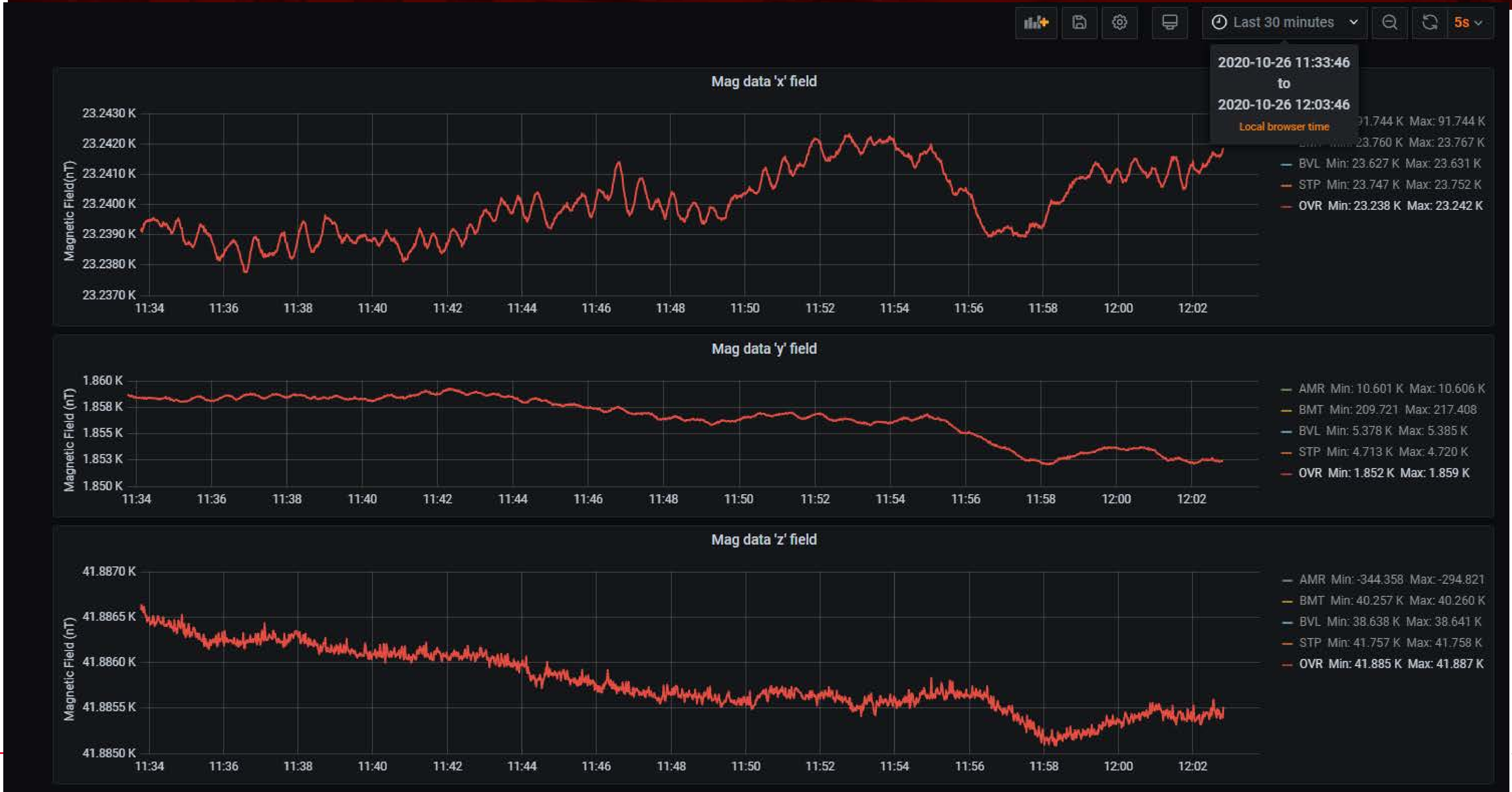

Magnetometer Network Features

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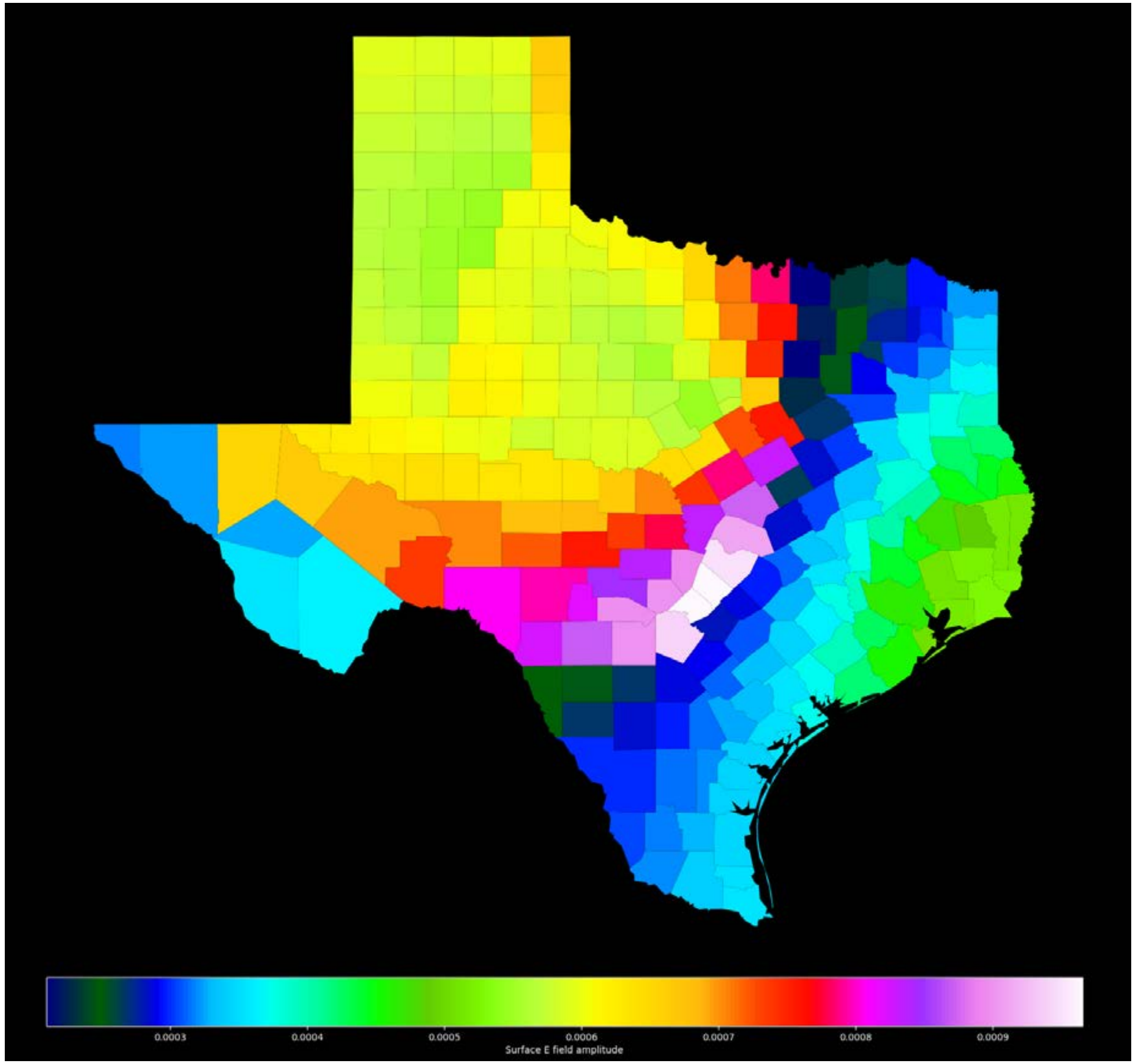
- Real-time data delivery (fraction of a second latency)
  - 1-sec resolution
- Web-based data download in .csv format
- Real-time temperature correction
- Low-noise magnetic field measurements

Electric Field Estimate



- **Real-time** electric field data, calculated from all the mags
  - Provided by CPI
  - 1 min resolution
  - Grid format (.B3D binary format)
  - Using NERC TPL-007 conductivity model
  - Values scaled in the figure here to highlight variation (non-event day)

Electric Field File Formats

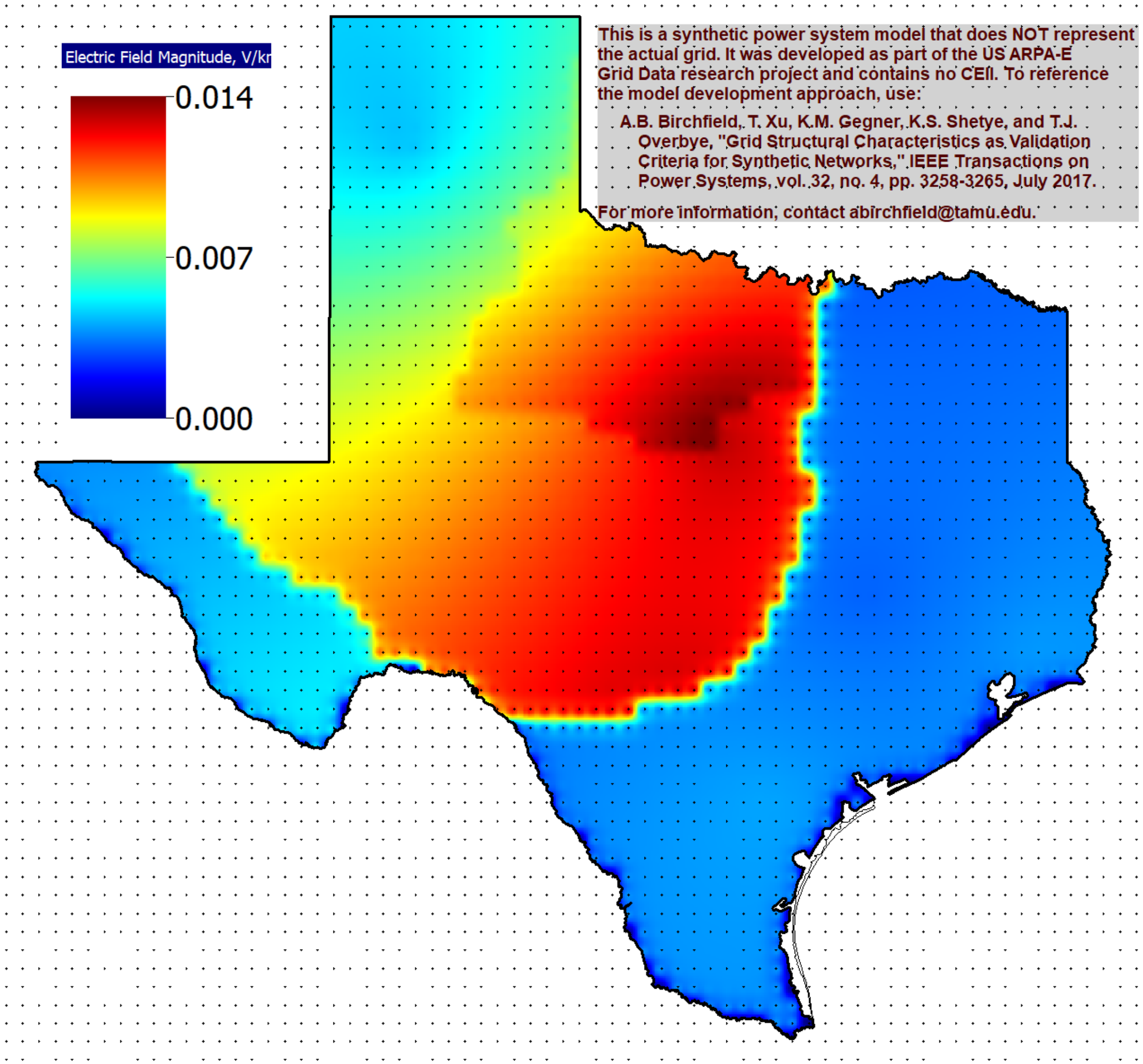
B3D – binary file, used in PowerWorld Simulator

format available at https://electricgrids.engr.tamu.edu/b3d-file-format/

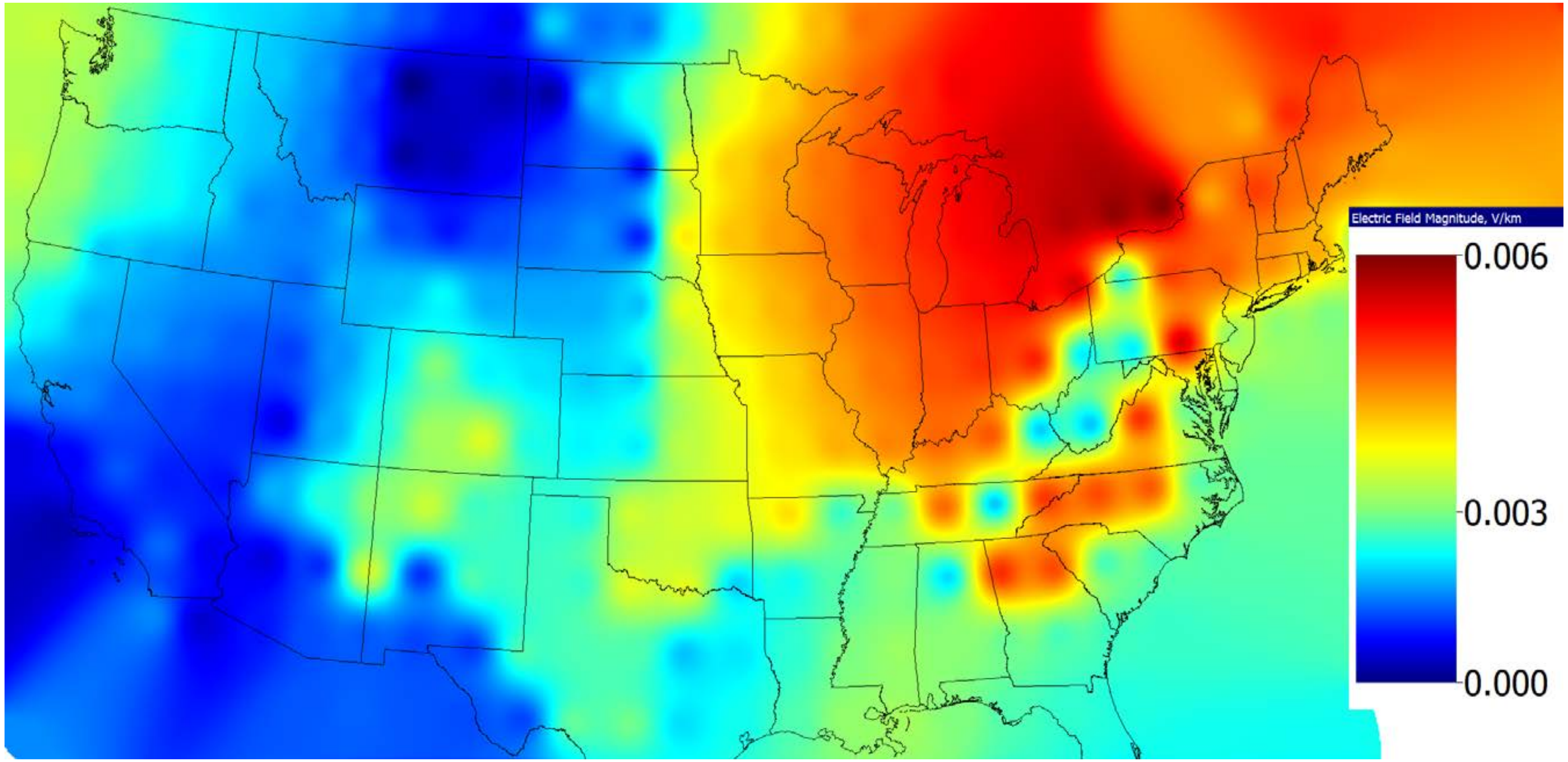
JSON – from NOAA, data available at https://services.swpc.noaa.gov/json/lists/rgeojson/

Useful for GMD event recreation, post event analyses, model validation

B3D visualization



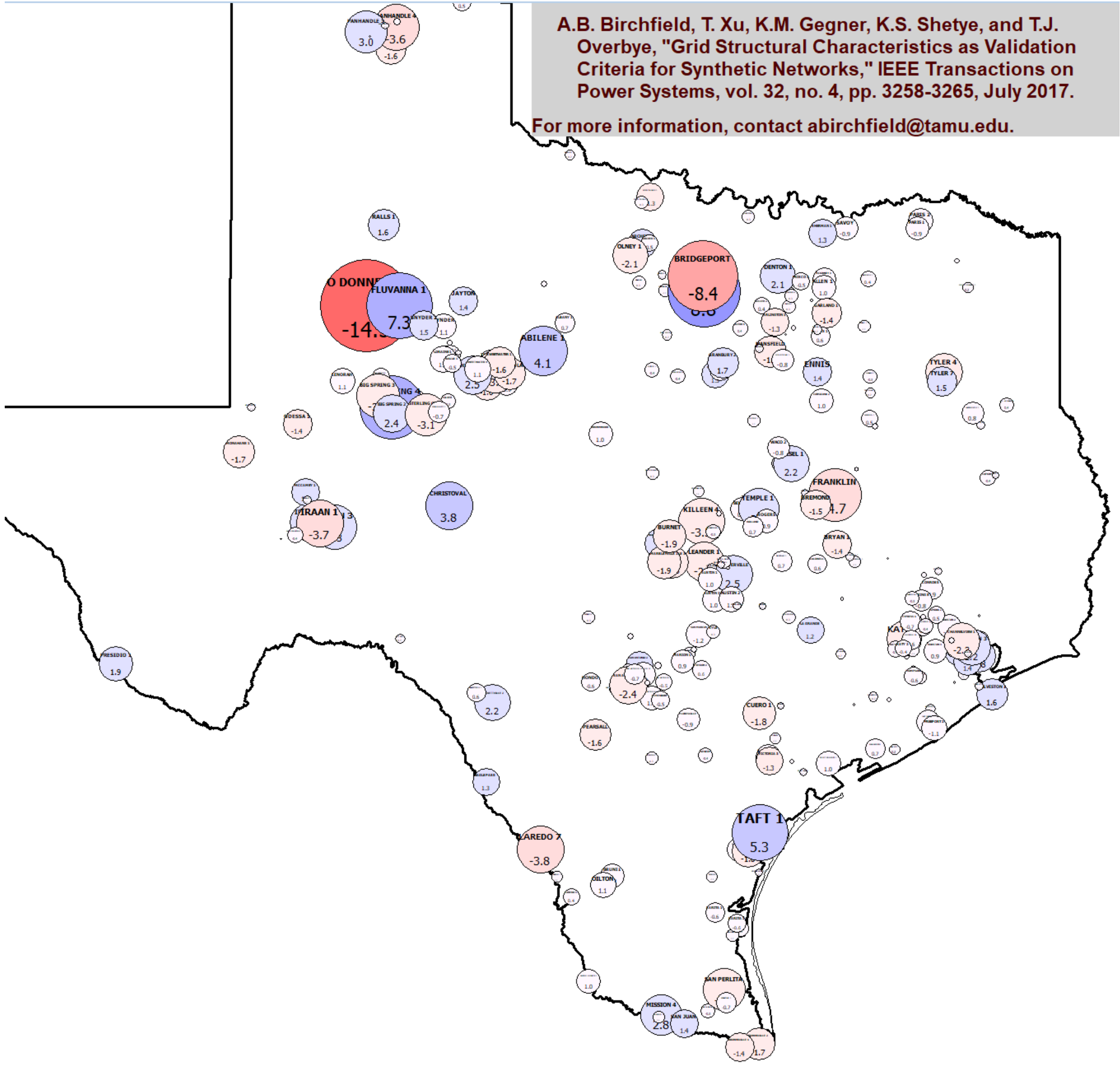
NOAA JSON file (1D conductivity)



System Operations and Mitigation

- Situational Awareness Important
  - GIC monitors, magnetometers in addition to voltages, flows
  - Presently, few of the former deployed
- GIC Estimation can be done
  - Estimating the E field and dc GICs
  - Accounting for GIC reactive losses in power system state estimator

Real-time GIC Visualization (Demo)

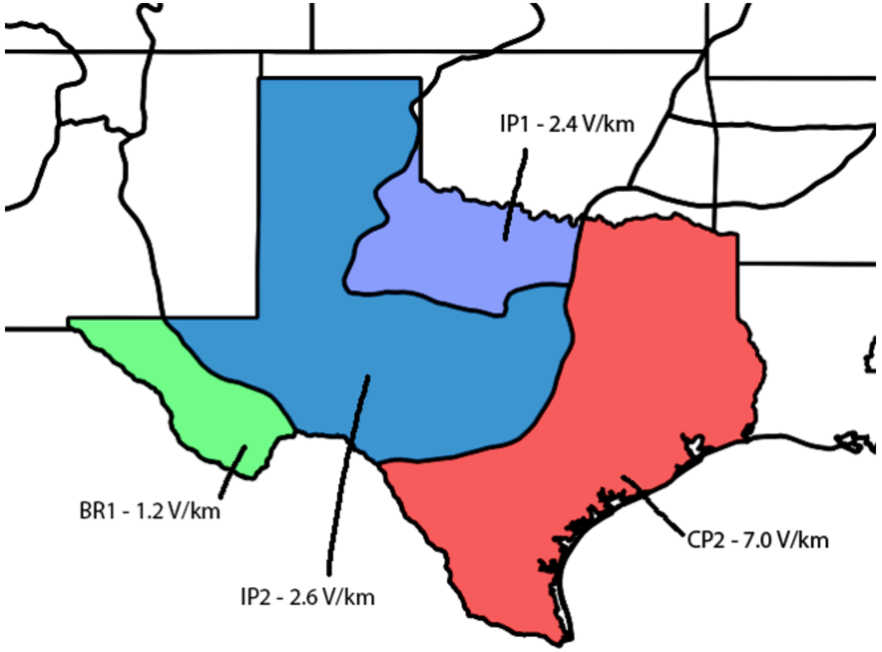


- Leverages mag. network's real-time E field estimates
  - Goal is to provide situational awareness for GMD operations
  - Real-time E data is read every minute into the PowerWorld Dynamic Studio (DS) server for GIC analysis and visualization
    - Currently a GIC simulation
    - Can extend to GIC estimation where some GIC neutral measurements are available, and remaining transformer GICs are estimated along with E field estimation improvement

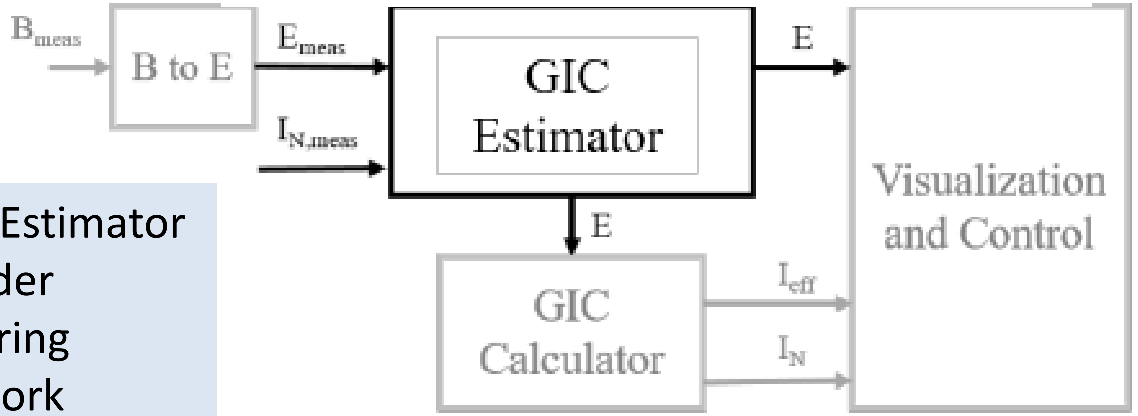
GIC Estimation

- Linearity of GICs enables an iterative-free solution, like LSE
  - States: E_x and E_y in predetermined zones
  - Measurements:
    - Transformers neutral currents, also E estimates from B measurements
    - Added noise to simulated values for this example

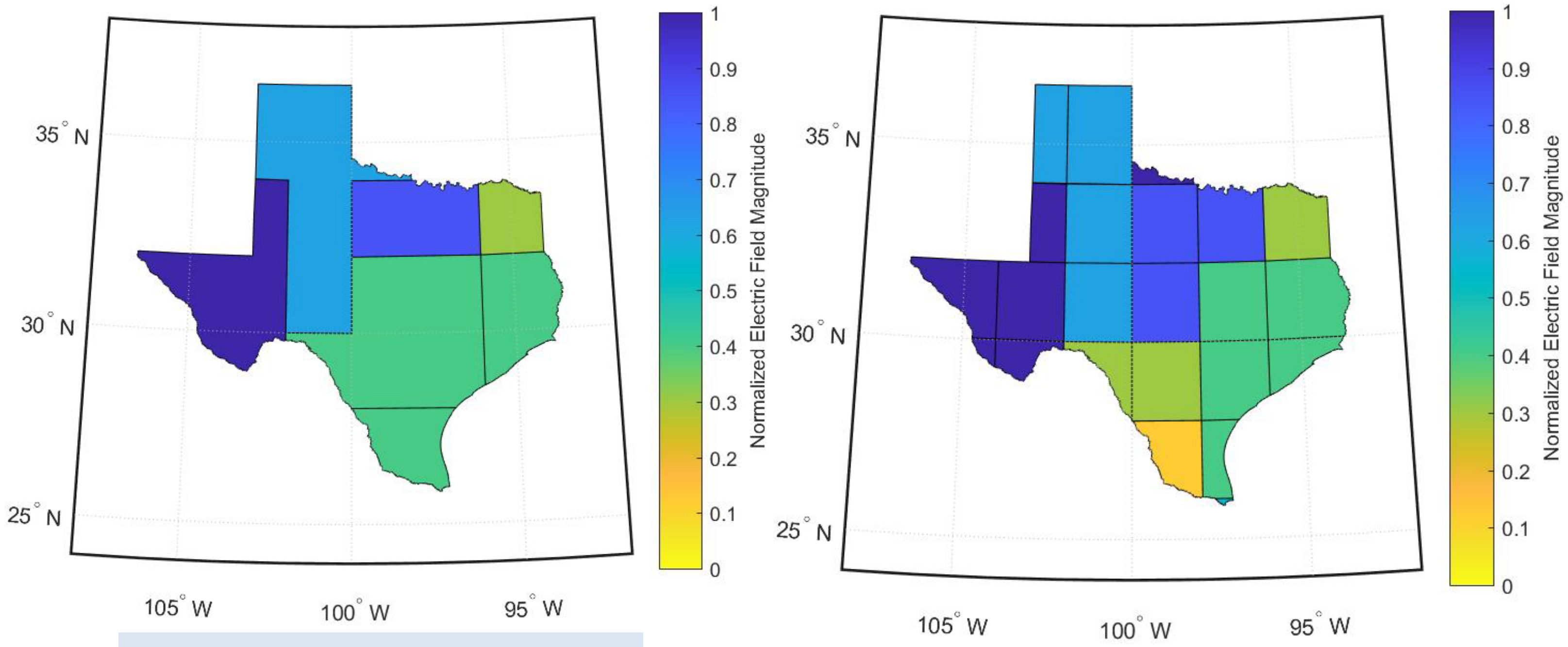
Regional resistivity zones of Texas



Role of Estimator in broader Monitoring framework



GIC Estimation Example

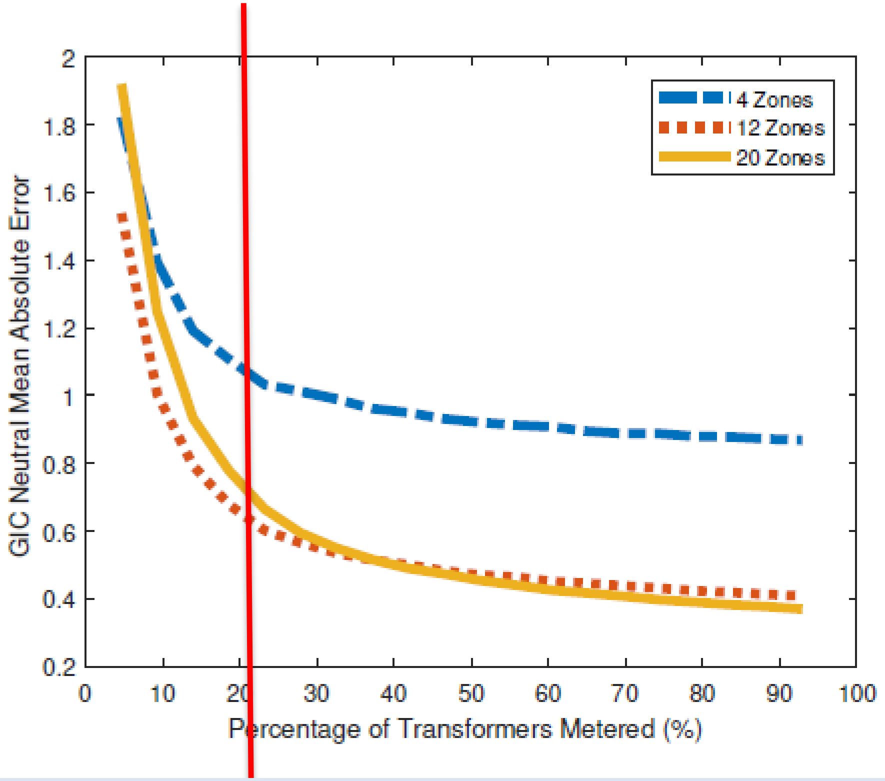


E field input zones "pseudomeasurements" estimated from B

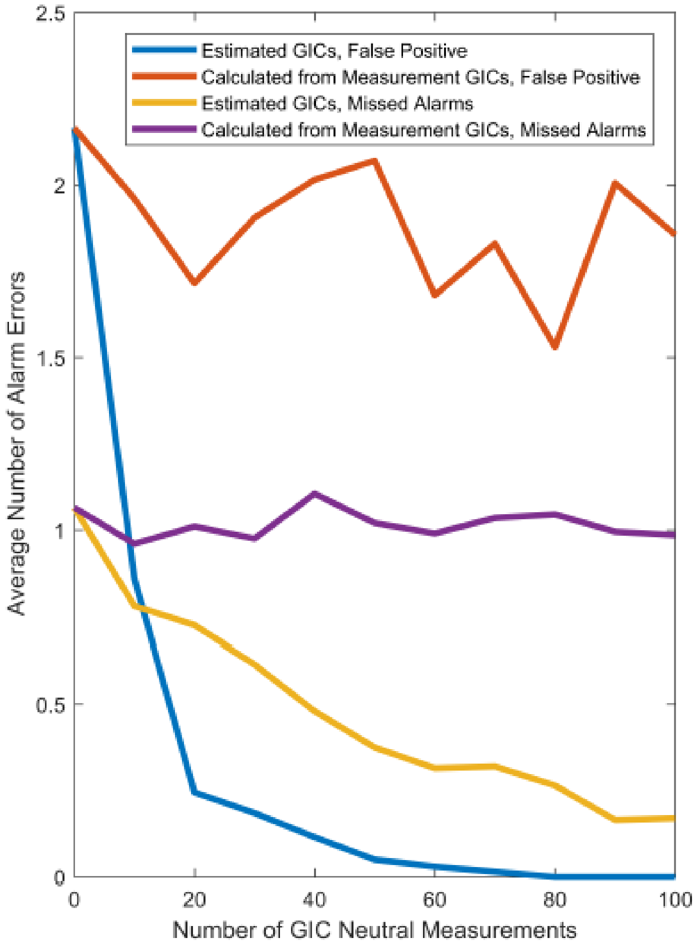
Output zones

Results for the Texas 2000 bus synthetic grid, nominal voltages from 13.2 to 500 kV, and around 850 transformers half of which are auto

GIC Estimation Example



Metering around 20% of transformers provides good observability (for this system)

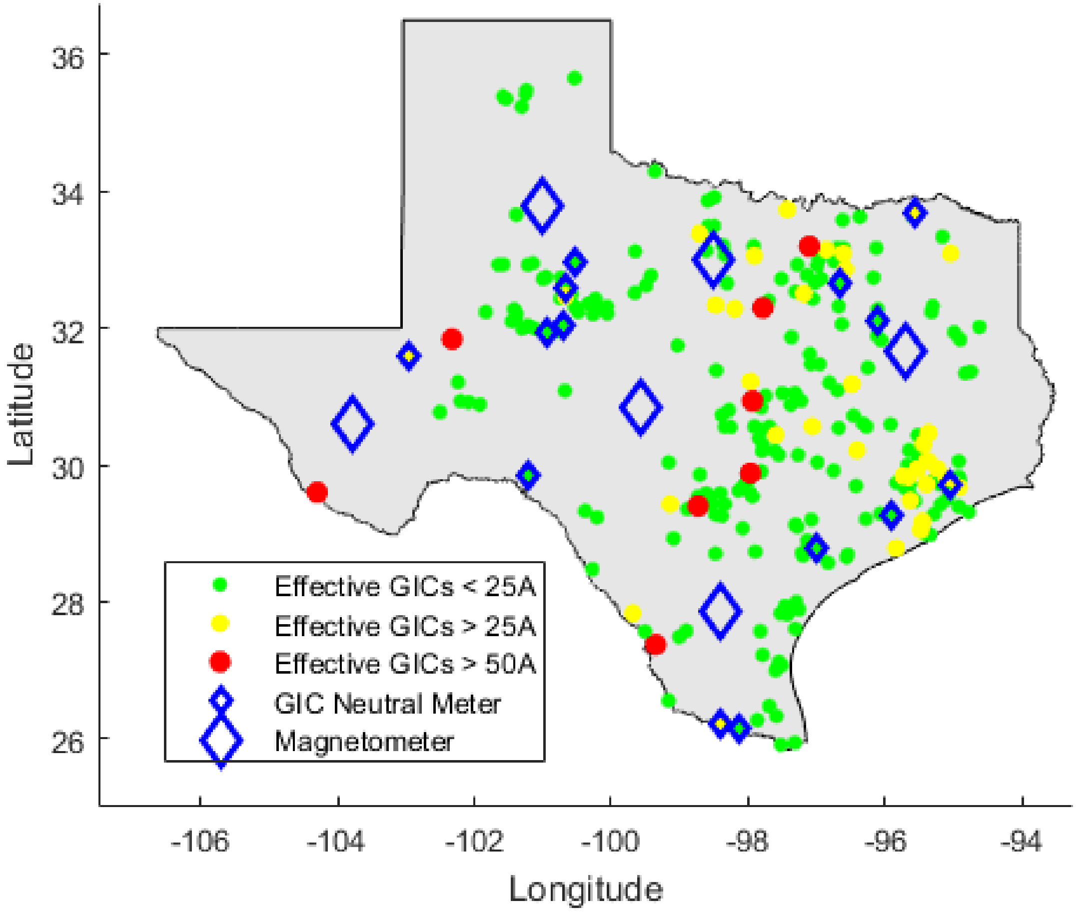


Average number of false or missed alarms (>50 A) from measurements versus estimates, per simulation from 200 Monte Carlo simulations.

Results for the Texas 2000 bus synthetic grid, nominal voltages from 13.2 to 500 kV, and around 850 transformers half of which are auto

GIC Estimation Example

- With sufficient metering (about 15 GIC neutral meters) and estimation abilities, the potential for an alarm error drops to less than once per estimation run, and decreases with more measurements.
- On average, using GIC estimation does not create alarm errors that do not already exist as a result of just the electric field inputs.
- GIC estimation is a value-added process that is low risk in addition to low effort.



Related Papers

- K. S. Shetye, C. Klauber, Z. Mao, J. Gannon, and T. J. Overbye, “Real-Time Monitoring Applications for the Power Grid under Geomagnetic Disturbances,” accepted for presentation *at the 2020 IEEE Electric Power and Energy Conference (EPEC),* 2020.
- C. Klauber, K. S. Shetye, K. Davis, and T. J. Overbye, “A GIC State Estimator for System Monitoring under Geomagnetic Disturbance.” *IEEE Transactions on Power Systems,* 2020.
- K. S. Shetye, T. J. Overbye, “An Overview of Modeling Geomagnetic Disturbances in Power Systems”, chapter in *Geomagnetically Induced Currents from the Sun to the Power Grid*, American Geophysical Union (AGU) Books, Wiley & Sons, vol. 246, pp. 175-193, 2019.
- K. S. Shetye, A. B. Birchfield, R. H. Lee, T. J. Overbye, and J. L. Gannon, “Impact of 1D vs 3D Earth Conductivity Based Electric Fields on Geomagnetically Induced Currents, *2018 IEEE PES Innovative Smart Grid Technologies Europe*, pp. 1-6, Oct 2018.
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- Y. Zhang, K. Shetye, A. Birchfield, T. J. Overbye, "Grid Impact Evaluation of Localized Geomagnetic Field Enhancements Using Sensitivity Analysis," *North American Power Symposium,* Oct 2019.
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- A. B. Birchfield, K. Gegner, T. Xu, K.S. Shetye, T. J. Overbye, "Statistical Considerations in the Creation of Realistic Synthetic Power Grids for Geomagnetic Disturbance Studies," *IEEE Transactions on Power Systems*, vol. 32, no. 2, pp. 1502-1510, Mar. 2017.
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GMD Short Course

- First offered in April 2019 at the brand new Smart Grids Control Center at RELLIS
- Next one TBD, likely Spring 2021
- Details at https://epg.engr.tamu.edu/electric-grid-impacts-of-geomagnetic-disturbances/

Last GMD course full! (24 participants, mostly industry, national labs, etc.)

Thank You!

Questions?

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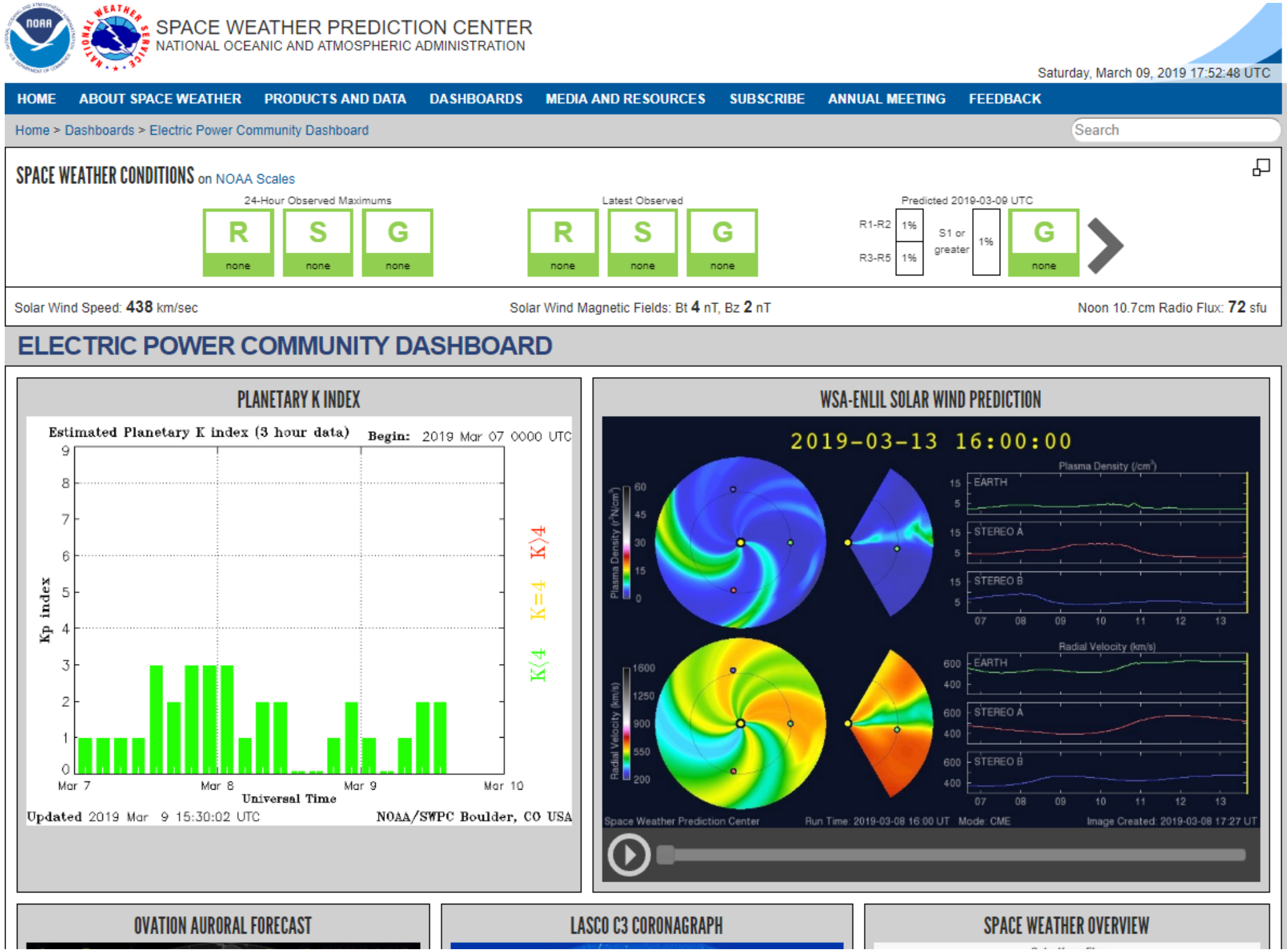
BACKUP SLIDES

RELLIS Control Room Lab

- Power Grid Operations Research and Education
- Give users (students and industry participants) the experience of operating the grid in advanced scenarios such as GMDs
  - Testbed equipped with EMS, DMS, and other industry grade tools
  - Hands on experience; and R&D of monitoring, visualization and control applications

Space Weather Prediction Center has an Electric Power Dashboard



www.swpc.noaa.gov/communities/electric-power-community-dashboard