NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Agenda
Geomagnetic Disturbance Workshop

October 1, 2024 | 1:00 p.m. – 5:30 p.m. Eastern
August 2, 2024 | 8:30 a.m. – 12:30 p.m. Eastern

NERC Office
1401 H Street NW Suite 410
Washington, DC 20005

Attendees (in-person): Workshop Registration

Webex Registration October 1
Webex Registration October 2

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

NERC Antitrust Compliance Guidelines and Public Announcement

Agenda Items | October 1, 2024 1:00 p.m. – 5:30 p.m. Eastern

1. **Welcome and Workshop Overview** – NERC Staff
2. **Remembering Dr. Jenn Gannon**
3. **May 2024 GMD Event Review Plan – Overview –** NERC Staff
4. **Overview of the Space Weather Event |** 2:00 – 2:20 p.m. – Shawn Dahl, NOAA SWPC
5. **Observations from review of the NERC GIC Data database |** 2:20 – 2:40 p.m.– NERC Staff

Break 3:00 – 3:20

6. **Discussion of Using the NERC Data Systems in the Event Review |** 2:40 – 3:00 p.m. – NERC Staff **and all participants**
7. **Results of GIC Model Validations from Select Areas |** 3:20 – 3:45 p.m. – EPRI
8. **Industry Analysis and Perspectives from the May GMD Event |** 3:45 – 4:45 p.m.
    a. Round Table for All Participants, with specific insights from Hydro Quebec and PJM
9. **Day 1 Wrap-up**

October 2, 2024 8:30 a.m. – 12:30 p.m. Eastern

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

10. **Analysis of Recorded Data of the Gannon GMD Event |** 8:30 – 8:50 a.m. – Ramsis Girgis, Hitachi Energy
11. **PowerWorld Presentation |** 8:50 – 9:10 a.m.– Scott Dahman
12. **U.S. Department of Energy Update |** 9:10 – 9:30 a.m. – Joseph Blankenburg
13. **Discuss of Observations of Harmonics during Gannon Storm** | 9:30 – 9:45 a.m.

Break | 9:45 – 10:10 a.m.

14. **Space Weather Prediction Center Geoelectric Field Model |** 10: 10 – 10:30 a.m.– Jordan Guerra, NOAA SWPC
15. **NASA Overview of the Gannon Storm |** 10:30 – 10:55 a.m. – Tony Iampietro, NASA Goddard Space Flight Center

Break 11:20 – 11:30

16. **Discussion of May 2024 Gannon Storm After Action Review |** Industry Perspectives
17. **Workshop Wrap up**

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NERC-EPRI Geomagnetic Disturbance Workshop

Mark Olson, Manager, Reliability Assessments
October 1-2, 2024

Reducing Risk from Geomagnetic Disturbances

- 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 is intended to support these efforts!

Workshop Info

- Workshop Objective: Identify key insights from the May 2024 GMD Event (Gannon Storm)
- Presentation topic areas:
  - Space weather event overview
  - NERC data systems observations
  - Preliminary GIC model validation results
  - Industry planner and operator analysis
  - Vendor and manufacturer analysis
  - Space weather community updates
- ***Active participation in discussion is strongly encouraged***

Materials will be made publicly available on NERC's website

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

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Remembering Dr. Jenn Gannon

Gannon Storm May 5 – 15, 2024

- Most intense space weather event on Earth in the last 20 years, since the Halloween Storms of October-November 2003
- Unlike tropical storms and hurricanes there is no policy process for naming space weather storms
- The space weather community holistically names space weather storms such as the Halloween Storm
- Community quickly coalesced around a name for the May 2024 storm – the Gannon Storm—in Jenn's honor
- She would have loved to study the impacts of this event

Dr. Jennifer Gannon
July 13, 1978 – May 2, 2024

Dr. Gannon's Contributions

NERC and the North American electric power industry are deeply indebted to Dr. Jenn Gannon for her lasting contributions to space weather readiness

- Improved earth conductivity models used in GMD vulnerability assessments
- Installed magnetometer stations and trained planners in performing GIC validation studies
- Contributed to NERC's GMD Data Collection program that shares GIC data with industry and researchers
- Worked with the space weather community to deliver products and services to support the needs of grid owners and operators

Station in the Texas Magnetometer Network | NSF project collaboration with CPI (Jenn Gannon) and Texas A&M

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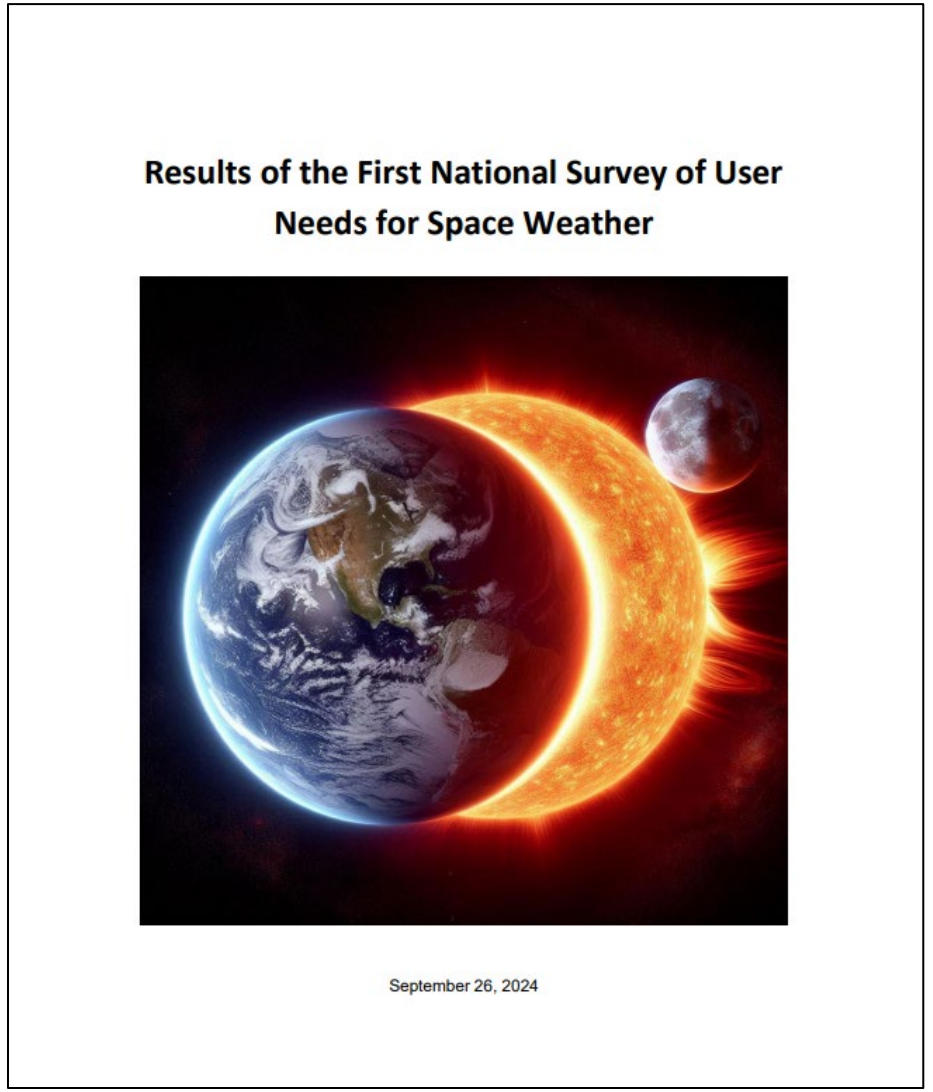
Space Weather Advisory Group User Survey

October 1, 2024

RELIABILITY | RESILIENCE | SECURITY

Published - Survey of Needs

- Required by the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act
- Survey conducted by the Space Weather Advisory Group (SWAG)
- Power sector input was provided via the NERC-EPRI August 2023 GMD Workshop
- Over 125 participants from the electric sector
- Other sectors:
  - Space traffic management
  - Emergency management
  - Aviation
  - Human space flight
  - Global Navigation Satellite Systems (GNSS)



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?

Findings and Recommendations

- **Finding 2.1.** Validation of GIC models and vulnerability assessments using GIC and magnetic field measurements are a key priority to advance mitigation of the impacts from GIC.
  - Recommendation 2.1.1. NOAA, in collaboration with USGS, should support one or more existing (non-Federal) operational magnetometer arrays and assess priorities for new installations to provide increased public access to geomagnetic field data with adequate coverage, prioritizing areas of higher hazard.
  - Recommendation 2.1.2. NOAA should collaborate with DOE and electric power industry software providers to integrate geoelectric field maps and estimates into standard electric power industry software used for GIC studies and GMD vulnerability assessments.
  - Recommendation 2.1.3. NOAA, in collaboration with USGS, should invest in infrastructure to ingest magnetic field data from privately owned sensors into operational geoelectric field models to support industry needs.

Findings and Recommendations

- **Finding 2.2.** The electric power industry finds existing space weather alerts and warnings to be useful for triggering preparatory actions prior to the onset of a GMD event.
  - Recommendation 2.2.1. DOE and industry should develop a process for direct sharing of real-time GIC data—for situational awareness—between operators through open access data models and cooperative agreements.
  - Recommendation 2.2.2. NOAA should continue to validate and evolve predictive models of the geoelectric field to improve forecasting capabilities and alert lead times.
  - Recommendation 2.2.3. NOAA should support the development of regional and local alerts through private sector partnerships.
  - Recommendation 2.2.4. NOAA, in collaboration with the electric power industry (particularly the power grid RCs), should identify and implement ways to minimize alert latencies, for example, through the use of automated tools that reduce human intervention in the communication path. Enabling industry-to-industry sharing of data is an initial first step.

Findings and Recommendations

- **Finding 2.3.** Harmonic studies are an important component of assessing GIC risk.
  - Recommendation 2.3.1. DOE should lead a collaborative effort with the electric power sector to develop capabilities, guidance, and tools for incorporating GIC-related harmonics in GMD vulnerability assessments and promote widespread adoption and use through standard system planning tools, training, and best practices.

Findings and Recommendations

- **Finding 2.4.** Effective GIC mitigation is an interdisciplinary, cross-sector, and community-wide effort requiring increased collaboration between DOE, the National Labs, and the power industry.
  - Recommendation 2.4.1. DOE, the National Labs, and power industry should collaborate to update vulnerability assessment tools and capabilities. This collaboration should consider capabilities using recent Earth conductivity data, harmonic assessment approaches, and model validation insights.
  - Recommendation 2.4.2. NOAA and USGS, in collaboration with the space weather commercial sector, should provide expanded training opportunities for the power industry on current capabilities for warnings, alerts, and geoelectric field estimates, including those from the commercial sector.
  - Recommendation 2.4.3. DHS and DOE should solicit sector representatives to participate with other infrastructure sectors and emergency managers to understand and mitigate risks from interdependencies

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May 2024 Geomagnetic Disturbance Event Review

Working Meeting

October 1, 2024

May 2024 Gannon GMD Event

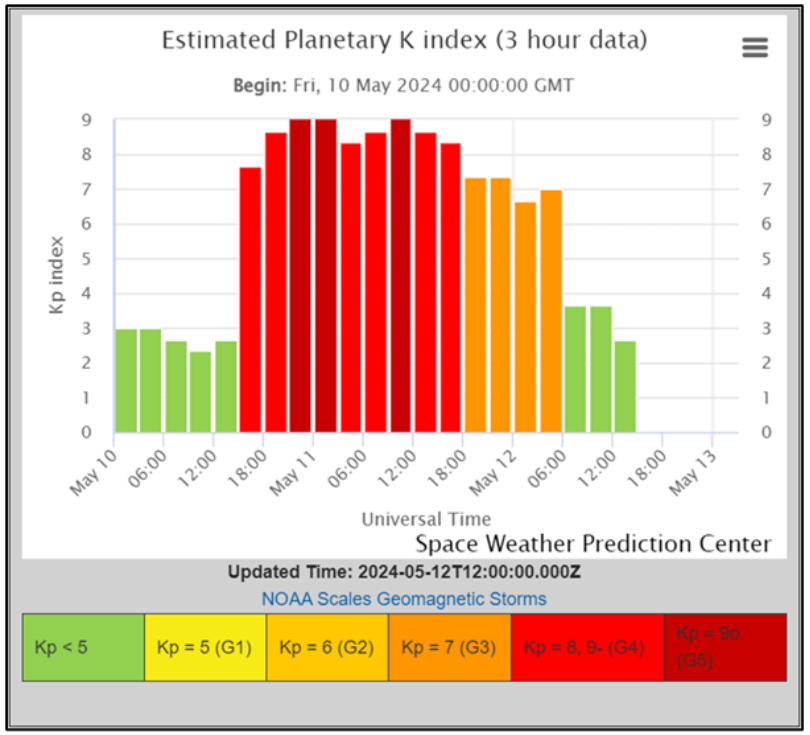
- From May 10-12 strongest geomagnetic disturbance (GMD) in over two decades
- Reliability Coordinators (RC) received early warning from the U.S. Space Weather Prediction Center (SPWC)
- The BPS remained stable while some impacts were observed
- NERC and industry are collaborating on an after-action review

Geomagnetic Storms

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)

Early Action

- SWPC initiated voice notification to RCs six hours prior to onset of GMD event using NERC hotline
- Actions taken by system operators:
  - Implementing GMD Operating Procedures and 'Conservative Operations' protocols
  - Scheduling additional generation
  - Cancellation of some transmission maintenance
  - Increased monitoring of system geomagnetically-induced currents (GICs) and system performance



The K index characterizes the magnitude of GMD events. SWPC alerts RCs prior to GMD events that are expected to be K7 and stronger

After Action Review

- Analysis of grid conditions during the event can validate and improve GMD tools and operating procedures
- NERC data collection systems and industry feedback are being analyzed for insights:
  - Impact of GIC on equipment
  - Validation of models used for GMD Vulnerability Assessments
  - Effectiveness of operating mitigations
- Results of a collaborative review with industry and researchers will be available in early 2025

NERC Data Sources include GMD Data System, Transmission Availability Data System (TADS), and Generator Availability Data System (GADS)

Working Group Participants

- BC Hydro
- AEP
- Dominion Energy
- Hydro One
- Hydro Quebec
- IESO
- Manitoba Hydro
- National Grid
- PJM
- TVA
- WECC
- NERC
- EPRI
- NOAA SWPC

Review Plan Objective

Goal: Use data and analysis from the event to ***validate*** or ***identify needs for improvements*** to GMD vulnerability assessment tools, models, and mitigation

Focus Areas

- **Impact of GIC-related harmonics on the BPS:** *How did harmonics affect BPS equipment? What levels of harmonic distortion were observed? What levels are predicted?*
- **Transformer thermal impacts:** *What effect did GIC levels have on transformer heating?*
- **GMD Benchmarks:** *How did peak geoelectric fields and magnetic field signature compare to the Benchmark GMD Event in TPL-007?*
- **GIC Model Validation:** *Did GIC models provide reasonable estimates of GIC?*
- **GMD Operations Best Practices:** *What operating actions were taken? How can operator situational awareness be better supported?*

Actions

1. Analyze NERC transmission availability database for impacts
   - Who: NERC Staff with support from registered entity data providers and working group
   - When: analysis begins after August 15 Transmission Availability Data System (TADS) reporting deadline
   - What: Anonymized summaries of impacts to transformers, lines, and other equipment will be reviewed to understand the scope of impacts to equipment from the event

Similar review of NERC generator availability database can be performed after the November reporting deadline for GADS

Status: review in progress

Actions

2. Perform GIC model validations
   - Who: EPRI and participating entities (voluntary)
   - When: ongoing through December
   - What: Use GIC measurements and geoelectric field estimates to evaluate model performance
     - Geographic areas of interest:
       - areas with complex earth structure (e.g., upper mid-west U.S., New England, Piedmont geographic region)
       - Areas where entities believe the observed GIC levels during the event were higher or lower than unexpected

Status: preliminary results for some geographic areas are available; more areas desired

Actions

3. Analyze observed transformer heating impacts
   - Who: EPRI and participating entities (voluntary)
   - When: ongoing through December
   - What: Review available information from transformers that were affected by high GIC (identified in TADS) or equipped with thermal instrumentation to inform models and vulnerability assessment
     - Identify unexpected transformer thermal issues
     - Compare thermal modeling results with observed measurements where available
     - Review available thermal measurement data and modeled estimates for the May event to examine potential transformer thermal hot-spot heating that can be produced by GIC signatures from solar storms with similar characteristics

Status: limited thermal measurements available. More discussion needed.

Actions

4. Analyze observed harmonic impacts to transmission equipment
   - Who: EPRI and working group participants
   - When: ongoing through December
   - What: Review available information from transmission equipment that was potentially affected by GIC-related harmonics (identified in TADS or GADS) to inform models and vulnerability assessment tools and procedures
     - Identify unexpected harmonic impacts (e.g., equipment tripping)
     - Obtain measured harmonic distortion where available and compare with modeled/predicted values

Status: NERC Data system review in progress

Actions

5. Industry observations and analysis
   - Covering equipment impacts, entity analysis, and operating experience/lessons

Status: Workshop discussion topic

Discussion – Gannon Storm Review Plan

Questions and Answers

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May 2024 Geomagnetic Disturbance Event Review

Working Meeting

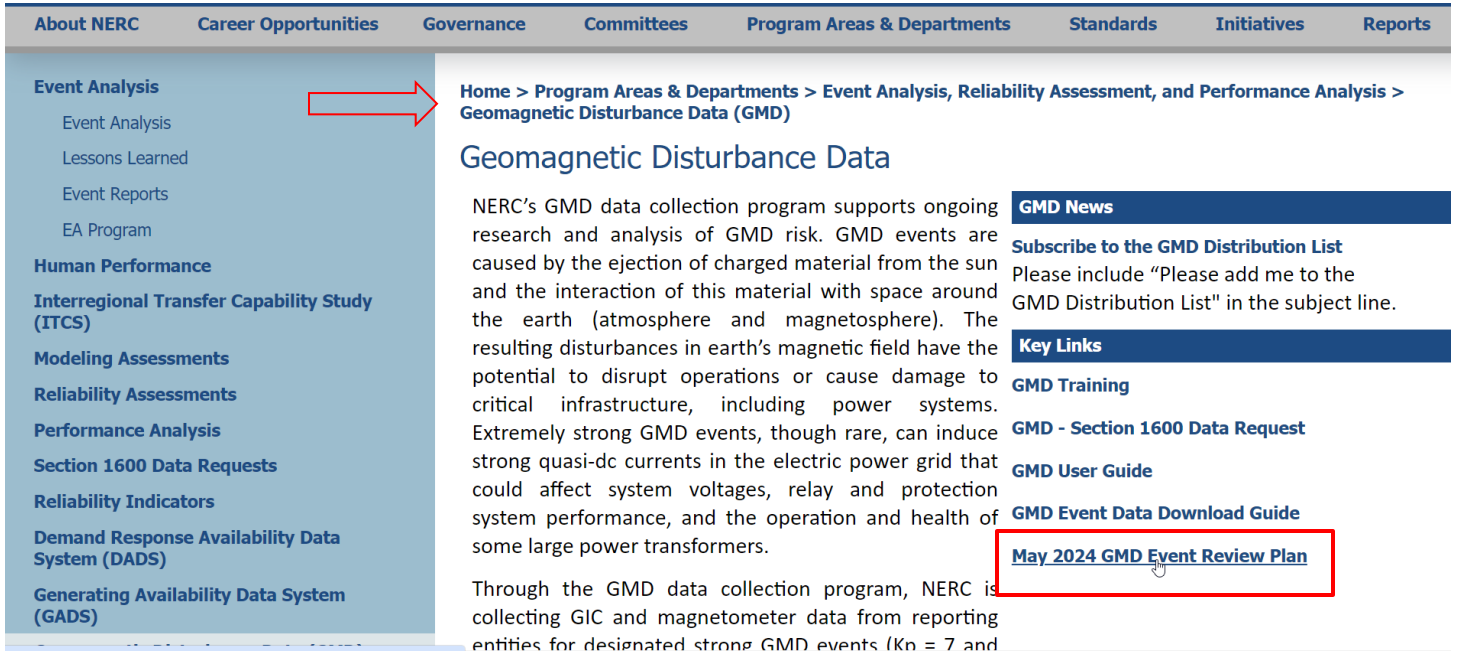
October 1, 2024

GMD Event Review Schedule

- **June – September** | Event Information Collection and Review
- **October 1 – 2** | Discussion at NERC-EPRI GMD Workshop
- **November – December** | Report preliminary results
- **January (2025)** | Report results and recommendations

Overview of 2024 GMD Event Review Plan

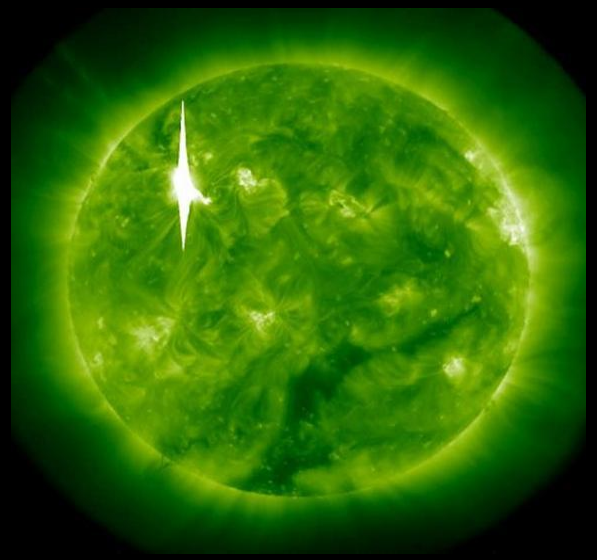
- NERC data collection systems and industry feedback will be analyzed for insights:
  - Impact of GIC on equipment
  - Validation of models used for GMD Vulnerability Assessments
  - Effectiveness of operating mitigations
- Document results in a report: stand-alone or part of annual State of Reliability Report
- Share findings with industry and researchers in early 2025

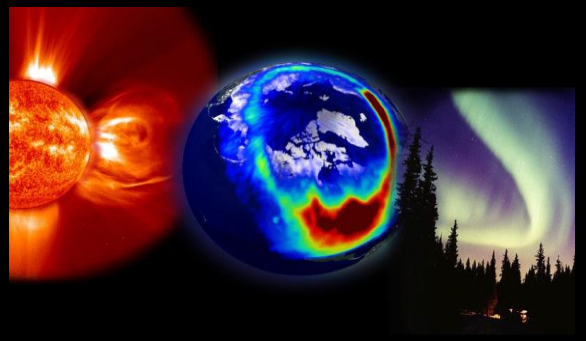


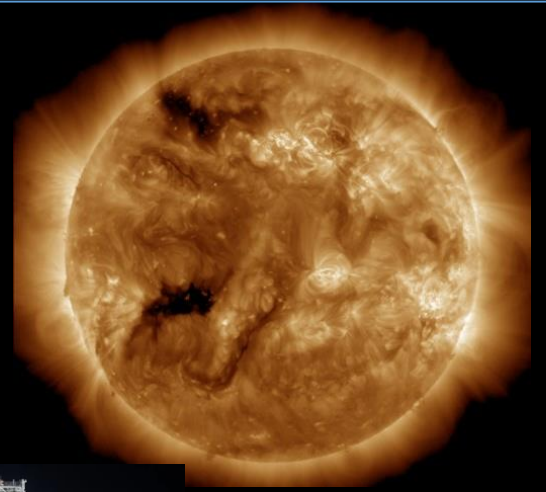
Next Steps

- [Include follow up activities from October meeting]

Essential Space Weather Information
May 10-11th Gannon Storm



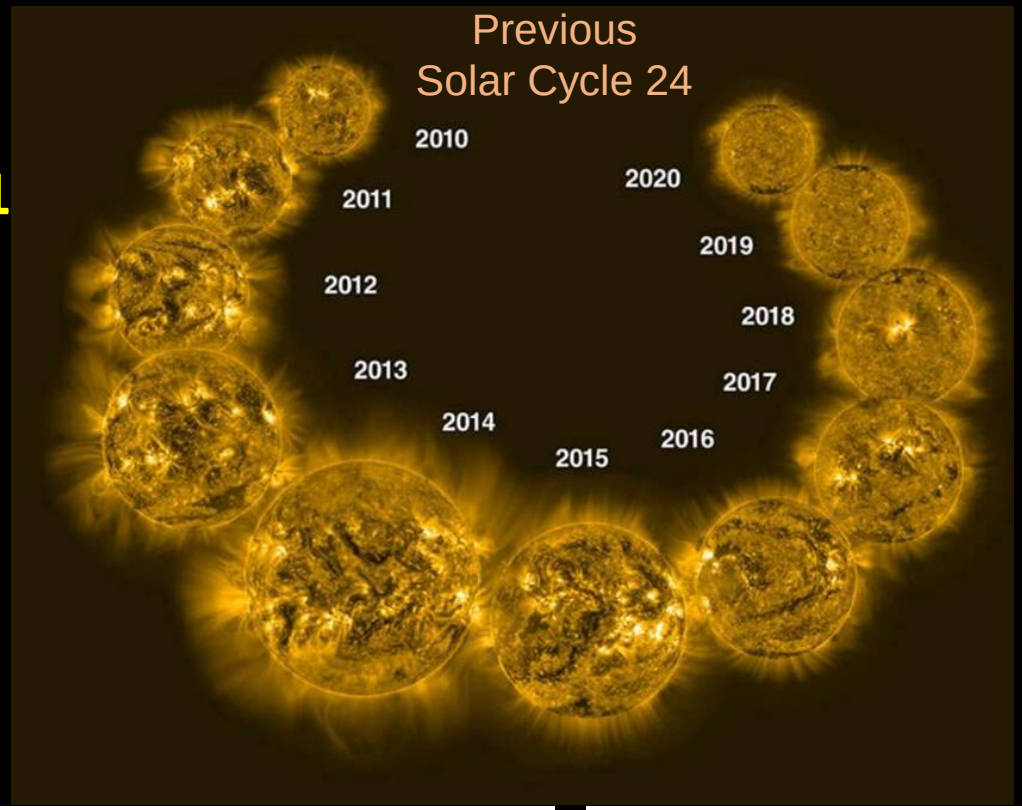




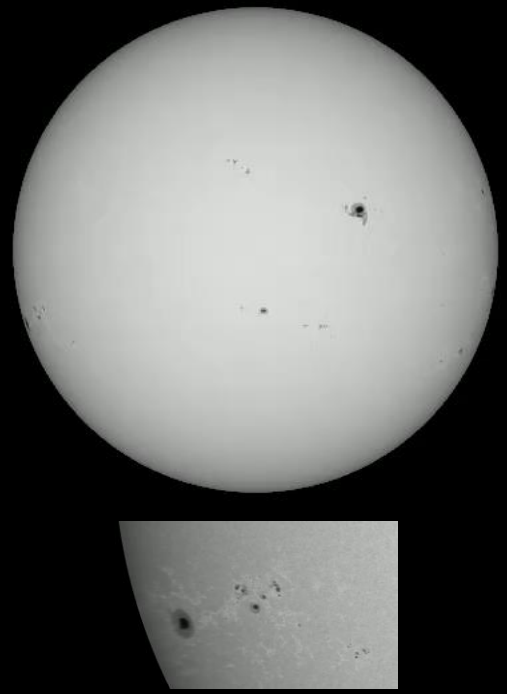
SWPC: "Safeguarding Society with Actionable Space Weather Information"

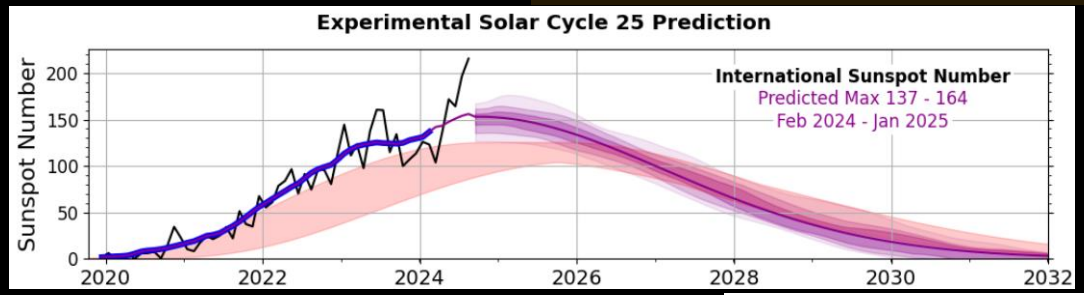
Sunspots & Solar Cycle

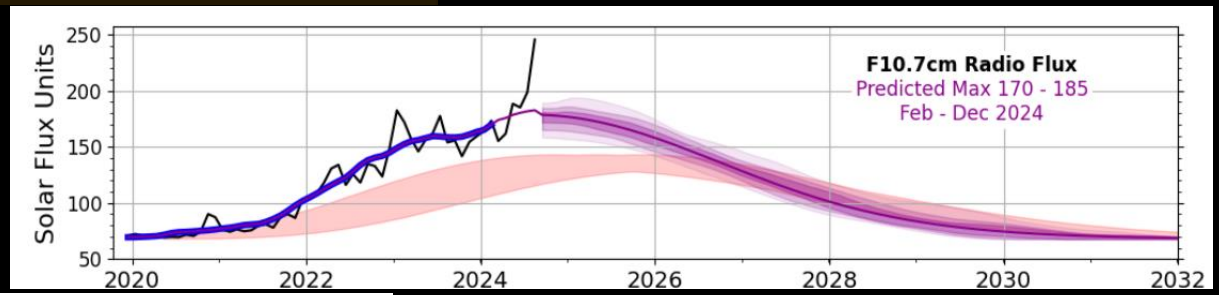
On average, every 11 years the Sun goes from quiet to active and back to more quiet. This is called the "Solar Cycle".

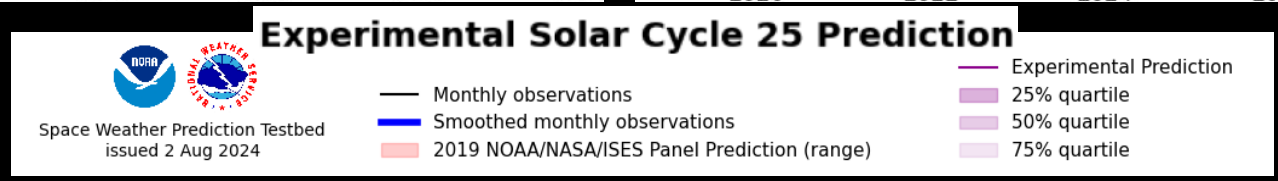


Current Solar Cycle 25
In/around maximum

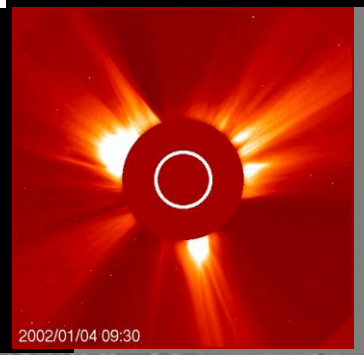




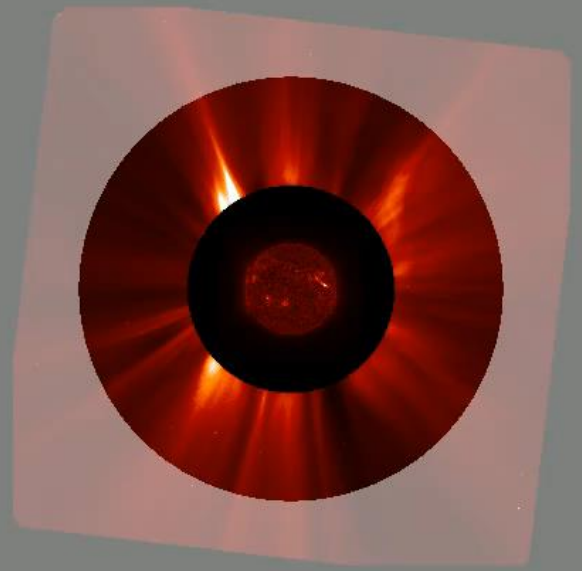




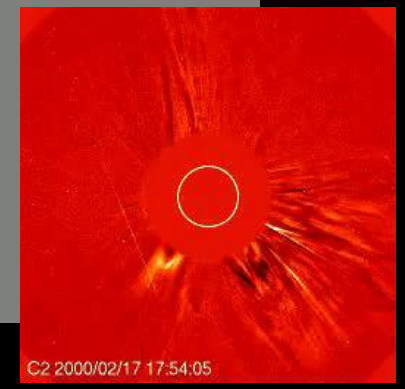
Coronal Mass Ejections (CME)



Tremendous expulsions of solar and embedded magnetic fields. Their impact to our magnetosphere can cause major changes resulting in **Geomagnetic Storms**

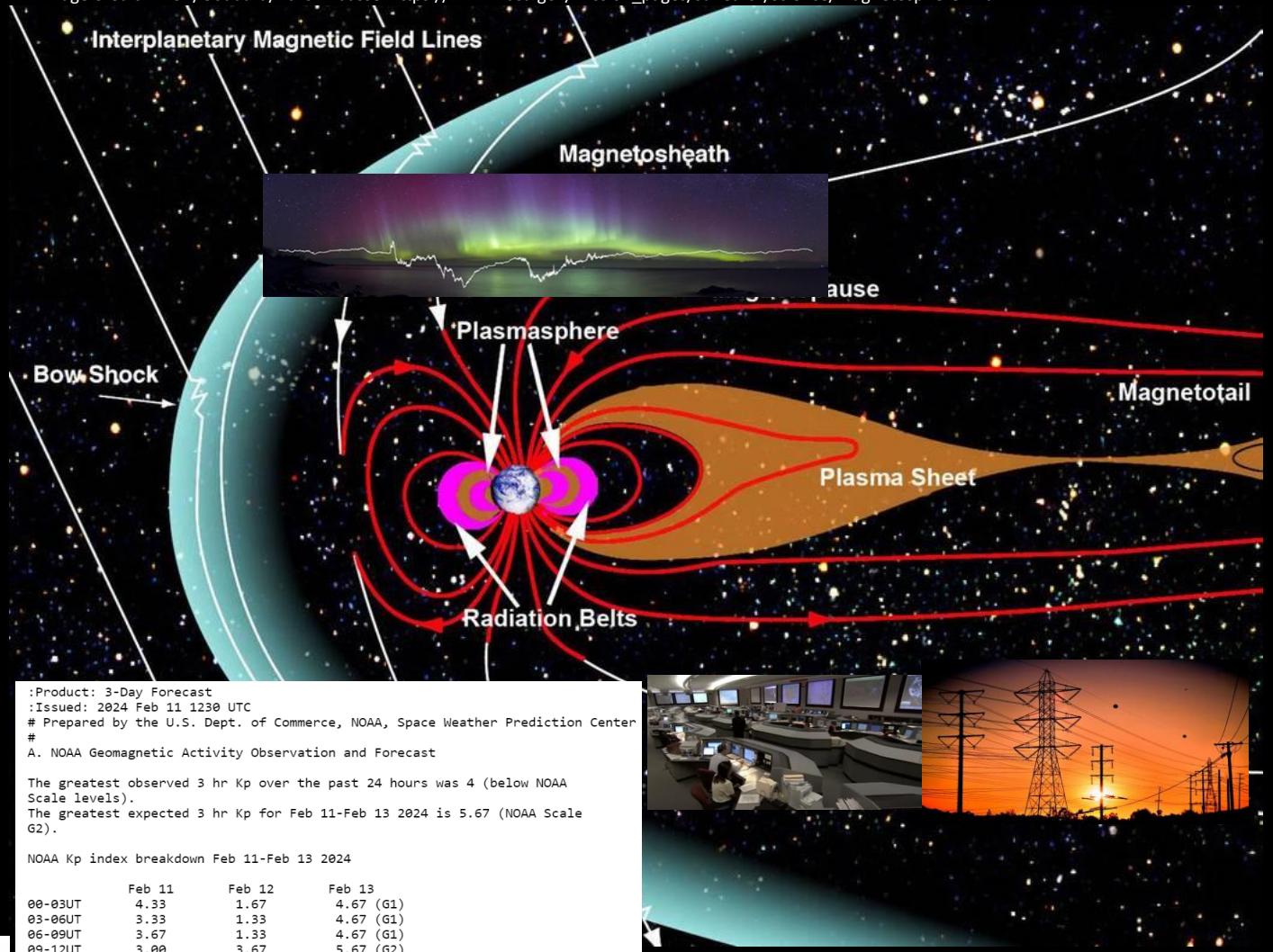


Fastest Earth-directed CMEs can get here is in 15 hours. Usually, they are slower and take 2 to 4 days.



Geomagnetic Storms

Image Credit: NASA/Goddard/Aaron Kaasse https://www.nasa.gov/mission_pages/sunearth/science/magnetosphere2.html

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:Product: 3-Day Forecast
:Issued: 2024 Feb 11 1230 UTC
# Prepared by the U.S. Dept. of Commerce, NOAA, Space Weather Prediction Center
#
A. NOAA Geomagnetic Activity Observation and Forecast

The greatest observed 3 hr Kp over the past 24 hours was 4 (below NOAA
Scale levels).
The greatest expected 3 hr Kp for Feb 11-Feb 13 2024 is 5.67 (NOAA Scale
G2).

NOAA Kp index breakdown Feb 11-Feb 13 2024

             Feb 11       Feb 12       Feb 13
00-03UT       4.33         1.67         4.67 (G1)
03-06UT       3.33         1.33         4.67 (G1)
06-09UT       3.67         1.33         4.67 (G1)
09-12UT       3.00         3.67         5.67 (G2)
12-15UT       3.33         3.00         4.67 (G1)
15-18UT       3.67         3.00         4.33
18-21UT       3.67         4.00         4.00
21-00UT       4.67 (G1)    5.00 (G1)    3.67

Rationale: Periods of G1 (Minor) geomagnetic storms are likely on 11-13
with G2 (Moderate) likely on 13 Feb due to the anticipated arrival of
multiple CMEs.
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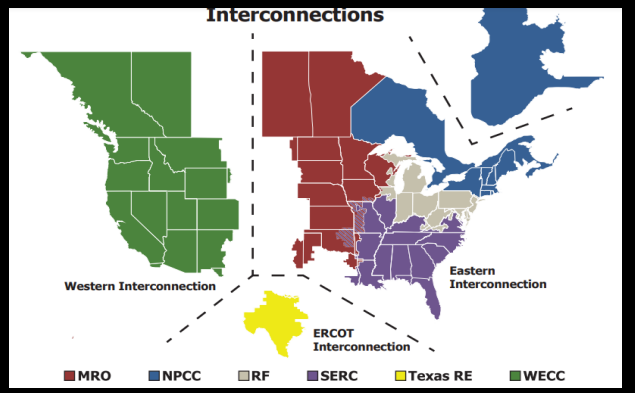
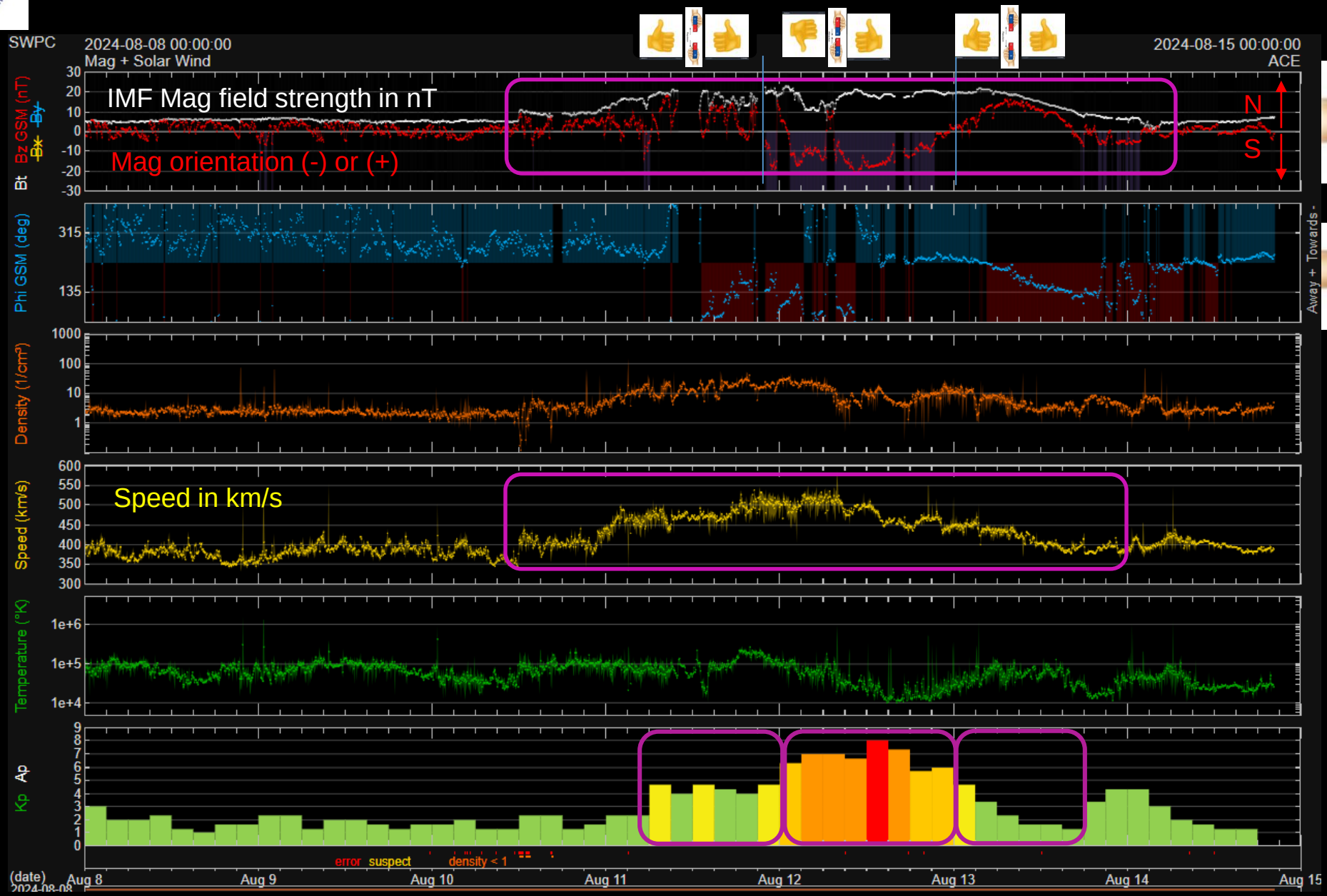
When a CME strikes and envelopes Earth's magnetic field, storms may begin. In particular, if the CME mag field connects with Earth's.

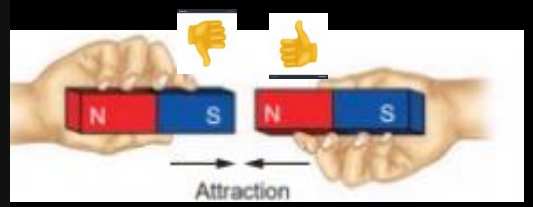
G3 and greater — **Protection of the Power Grid**

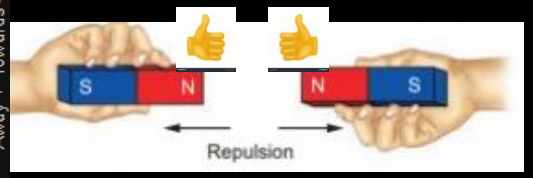


Can produce problematic geomagnetic induced currents on power that can trigger necessary protective measures, voltage alarms, harmonics, heating, etc.

Real-Time Solar Wind – Aug 8-14th w/ CME







Notice how the orientation shifts between N/S; by comparison, this CME mag strength was 4x above background as compared to early May – which was 12x above background

Kp 4 – Kp5 **(G1)** w/ N-directed IMF; but Kp6-Kp8 **(G2-G4)** when IMF shifted S-directed. Rapidly decreased when IMF rotated N-ward again.

Normal Sequence of Events

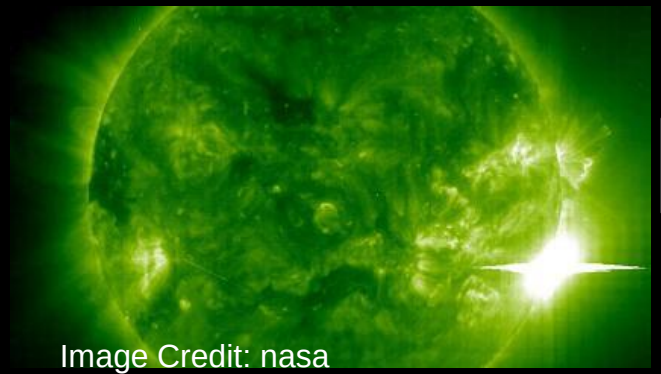
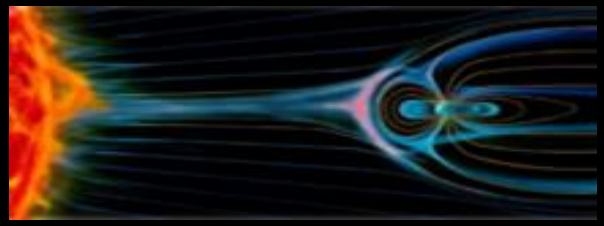


Image Credit: nasa

R2

ALERT
Sent at R2 or greater

Probabilities predicted in 3-day forecast; a flare occurs (speed of light), effect already taking place in outer atmosphere



S1

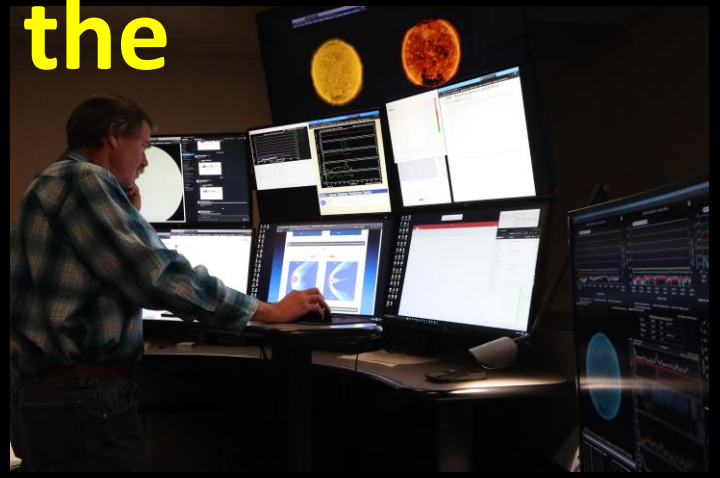
WARNING
Sent for S1 or greater
ALERT
Sent for each S1-S5 level

Probabilities predicted in 3-day forecast;
Can be nearly speed of light, but warnings possible

WATCHES
Sent for G1 - G4 or greater
WARNING
Sent for Kp4-7+ (G1 - G3+)
ALERT
Sent for each level through Kp 9z (G1-G5)

Geomagnetic Storms can be predicted out to 3 days; so watches and warnings possible. Science limits threshold capabilities however

Typical Actions related to just the Power Grid regarding Geomagnetic Storms



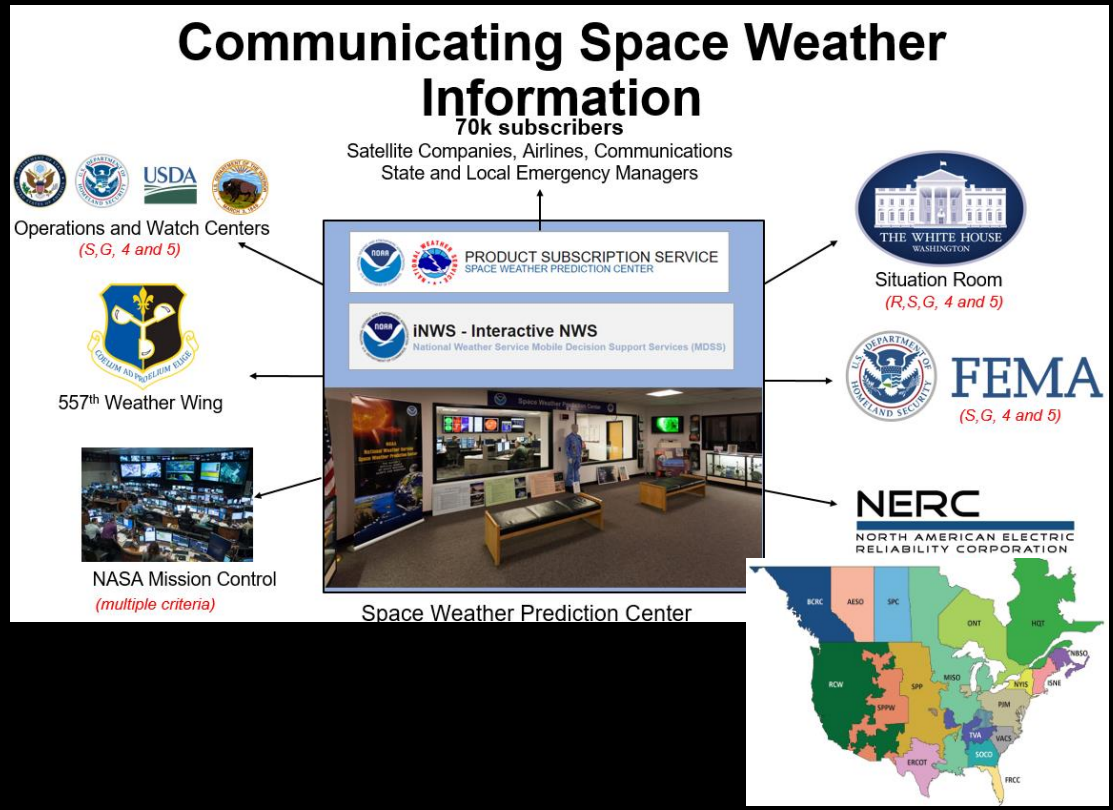
G1 Phone call to Wisconsin Electric Control Area and the New York ISO

G2 Phone call to Wisconsin Electric Control and the New York ISO (NY only for G2 Watch)

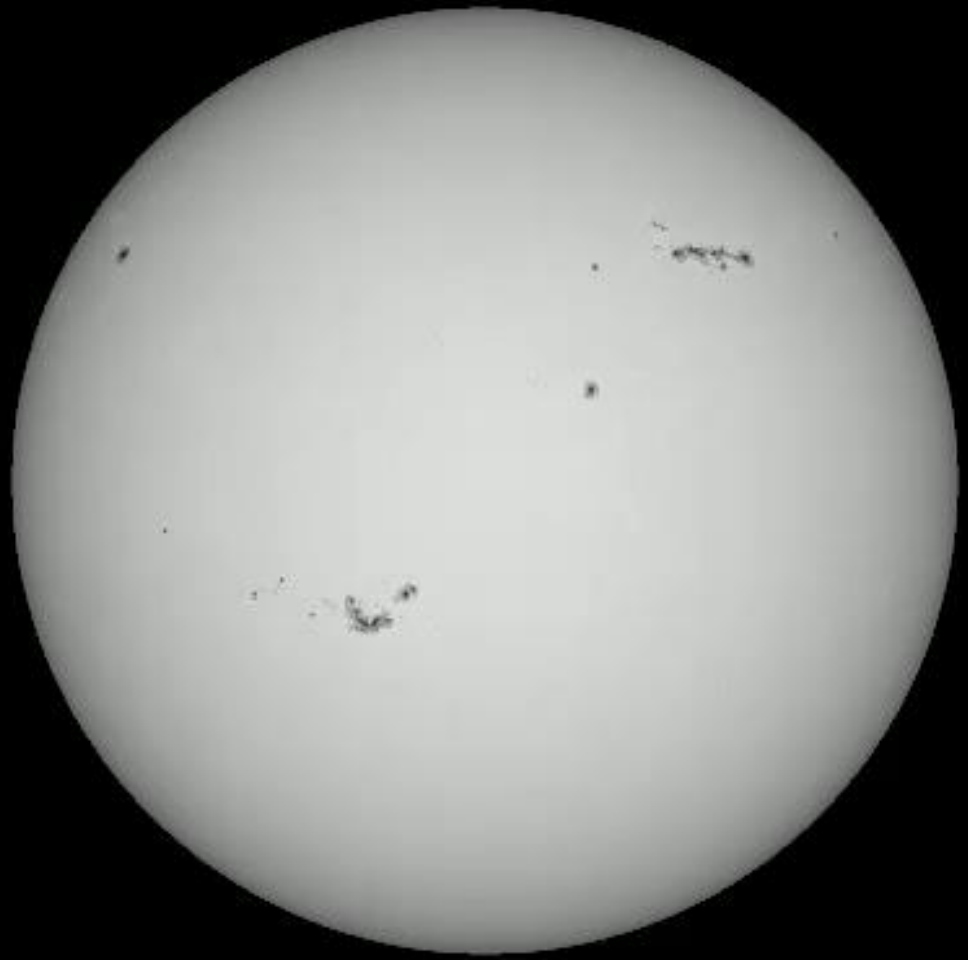
G3 NERC Hotline Call and Wisconsin Electric Control Area (G3 Watch – call NY only)

G4 NERC Hotline Call and Wisconsin Electric Control; FEMA notified; possibly the NSC/WHSR

G5 NERC Hotline Call and Wisconsin Electric Control; FEMA notified; NSC/WHSR informed

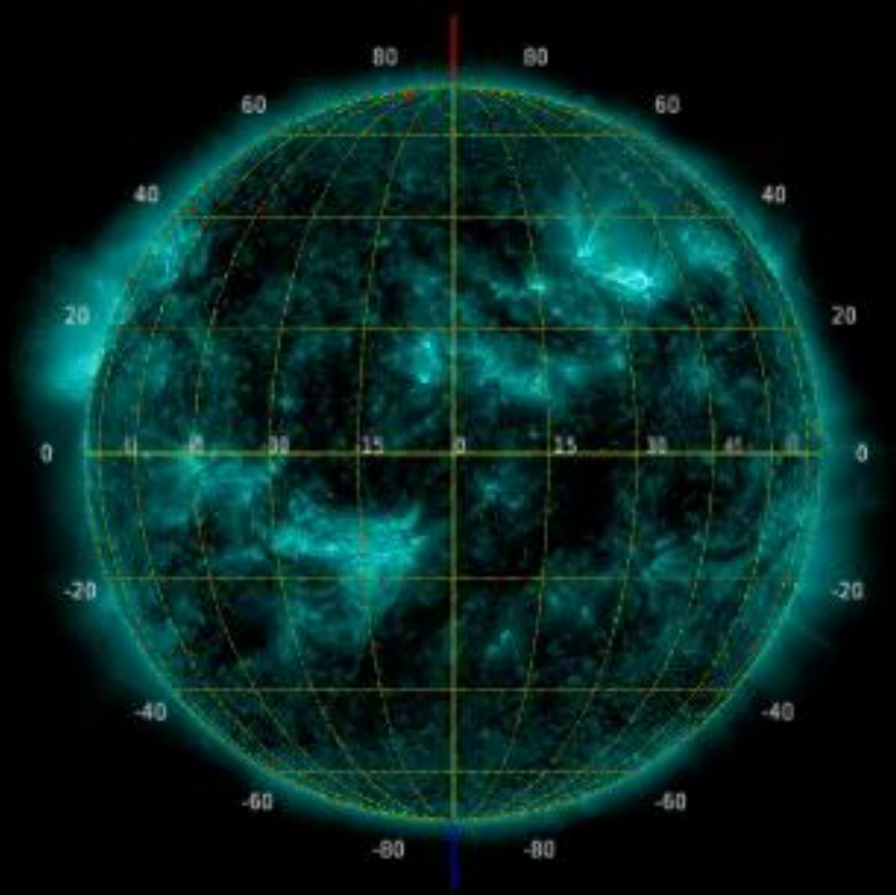


Sunspots: May 8th through May 12th



Massive sunspot groups present on the Sun. The northern cluster was responsible for numerous R2-R3 level events, but no CMEs of note. The southern region, however, became very magnetically complex and began to be of major concern for more impactful space weather events as it rotated westward.

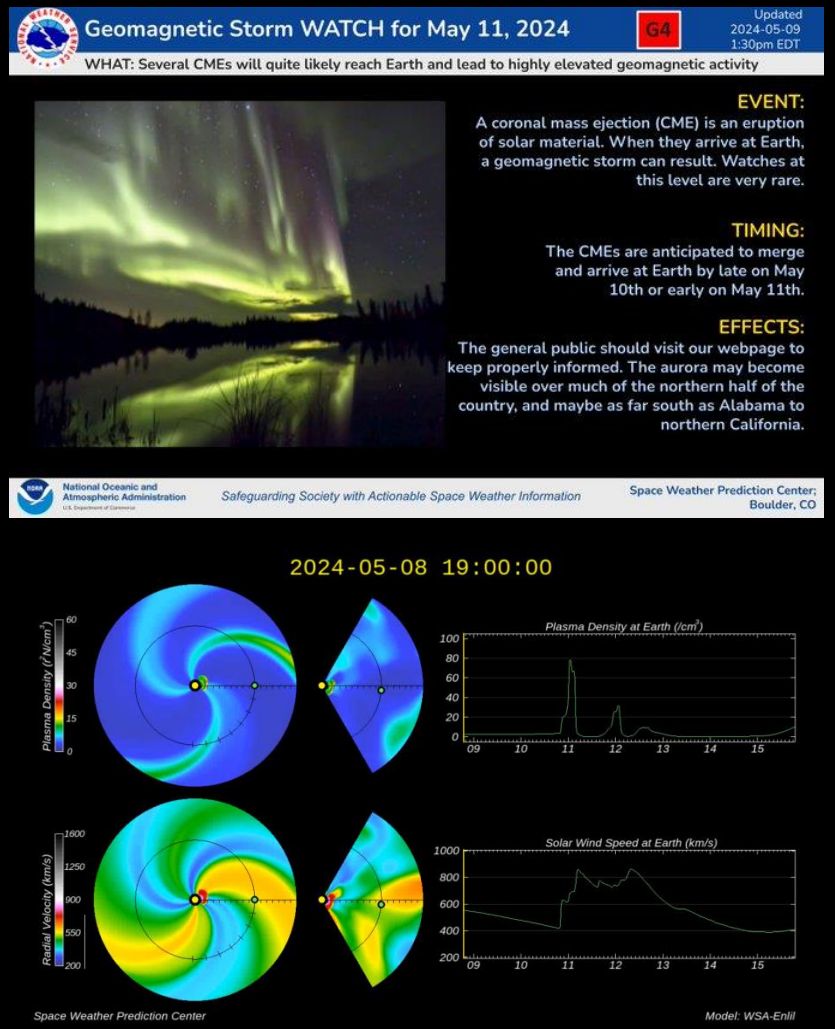
Solar Flares: May 8th through May 12th



Multiple CMEs analyzed and at least 5 were determined to have Earth-directed components. G3 Watch issued over 36 hours in advance.

Frequent solar flares occurred over these days. The northern region produced numerous flares at the R2-R3 level, but no CMEs were observed of note. The southern region eventually began flaring and provided plenty of activity, to include associated CMEs.

CMEs: to Arrive May 10-11th: G4 Storm Likely



Confidence increased and G3 was upgraded to the very rare G4 or Greater Watch 24 hours in advance.

Coronagraph imagery confirmed the explosive CMEs expelling from the Sun. Most of these CMEs were determined to have Earth-directed components, with later CMEs moving faster and model results suggested arrivals beginning 10 May and lasting into 11 May. A G3 (Strong) Watch was issued 36 hours in advance of the CME arrivals. This was eventually upgraded to a G4 Watch 24 hours prior to CME arrivals.

Unprecedented Media Engagement

Early Friday, May 10, SWPC held a telemedia conference attended by over 1300 reporters; including from the AP, NY Times, Bloomberg News, CNN, Reuters

Throughout the event, SWPC gave over 150 individual broadcast or radio interviews including National and International media outlets

SWPC Service Coordinator, Shawn Dahl, on NBC Nightly News

The huge solar storm is keeping power grid and satellite operators on edge

Advance warning successfully mitigated many impacts

"SWPC was indispensable to NERC…grid operators across North America took significant steps to prepare before the storm."

A MAJOR SATELLITE OPERATOR

Thank you for the updates and keeping us in the loop in real time. We are taking protective measures to minimize the impact on our satellite operations and overall network health.

Post-Event NERC Webinar Feedback

"Congratulations to NERC, SWPC, and EPRI for all your great work in protecting the grid – and the country! – during this event! This was no joke and y'all should be thanked and congratulated for your effective efforts! Thank you!"

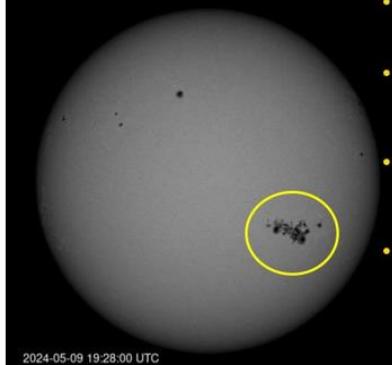
The Weather Company

"This was the first space weather event that we were able to actively take preparedness actions for, and that was definitely due to having at least a day of advanced warning (thank you!)."

First G4 or Greater Watch Since 2005

Active Space Weather Conditions Through Weekend

WHAT: Large Sunspot Groups and Flares Lead to First G4 Watch Since 2005



- On Thursday, May 9, the NOAA Space Weather Prediction Center issued a Severe (G4) **Geomagnetic Storm Watch – the first since January 2005.**
- At least **five earth-directed coronal mass ejections (CMEs)** were observed and expected to arrive as early as midday Friday, May 10, 2024, and persist through Sunday, May 12, 2024. This is an unusual event.
- Several strong flares have been observed over the past few days and were associated with a large and magnetically complex sunspot cluster (NOAA region 3664), **which is 16 times the diameter of Earth.** Additional solar activity is expected from the region.
- **Only three Severe geomagnetic storms have been observed during this solar cycle which began in December 2019.** The last G4 (Severe) was on March 23, 2024, and the last G5 (Extreme) was the Halloween Storms in October 2003. That G5 resulted in power outages in Sweden and damaged power transformers in South Africa.

National Oceanic and Atmospheric Administration — *Safeguarding Society with Actionable Space Weather Information* — Space Weather Prediction Center; Boulder, CO

Prompted immediate action to provide decision support services to technology and infrastructure operators, including electric power grid operators, satellite partners, aviation, and other sectors.

THE WHITE HOUSE WASHINGTON
Situation Room

"The Biden Administration is monitoring the situation"

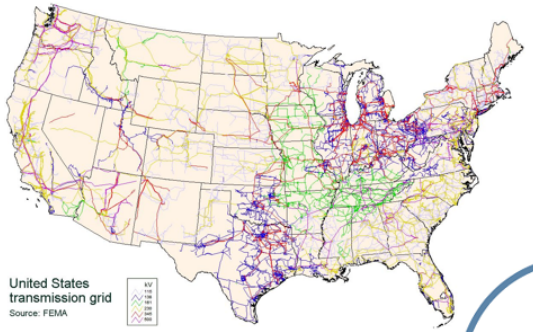
Operations and Watch Centers
(S,G, 4 and 5)

FEMA
(S,G, 4 and 5)

557th Weather Wing

NASA Mission Control

Impact-based Decision Support



- **SWPC activated the North American Electric Reliability Corporation (NERC) hotline to discuss the *G4 or Greater Watch.***
- **NERC disseminated the information, providing nearly six hours of advanced lead time for around 3,000 electric utility companies nationwide.**
- **NERC leadership acknowledged the support, saying, *"SWPC was indispensable to NERC…grid operators across North America took significant steps to prepare before the storm."***

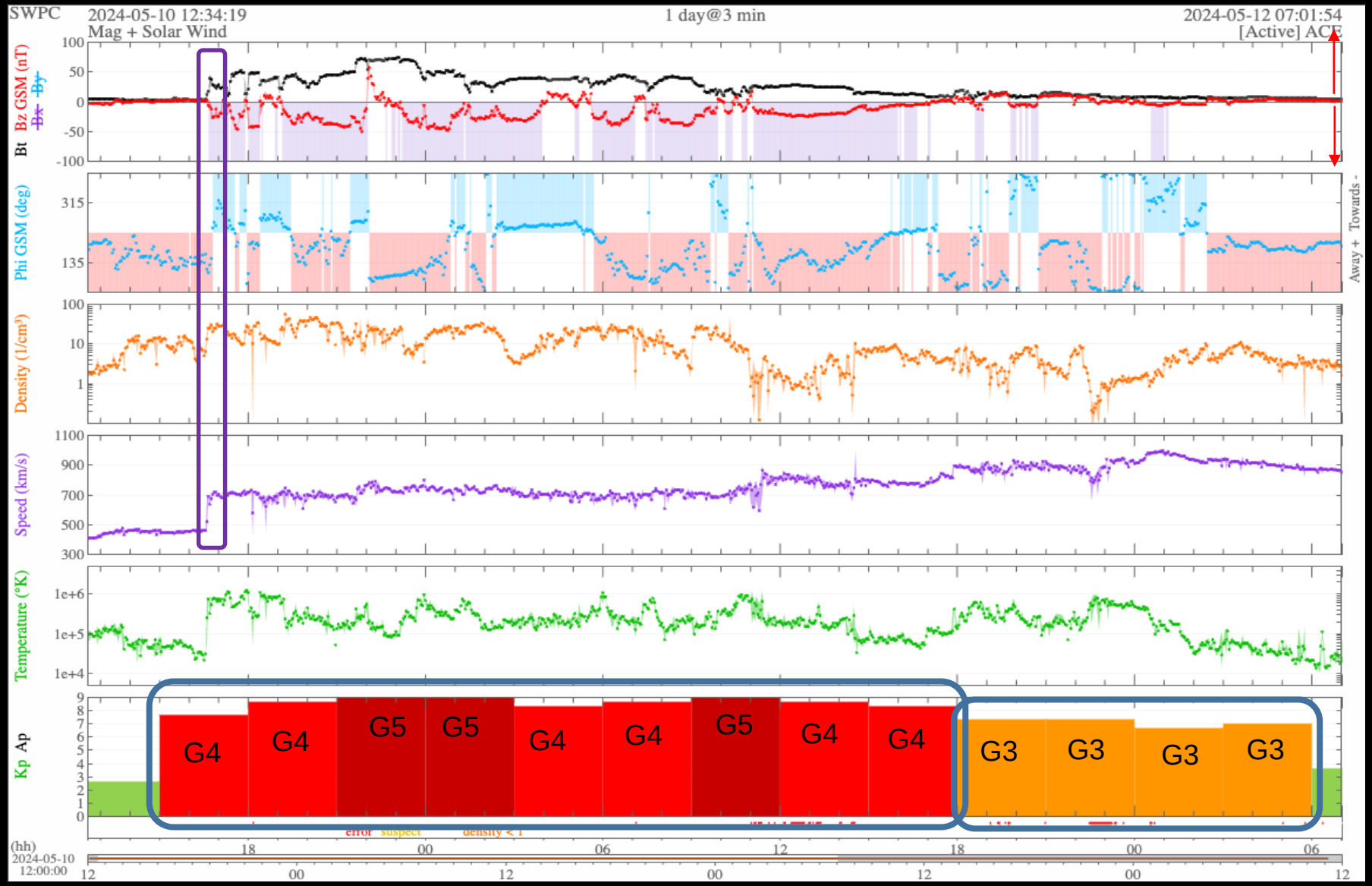
NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Impact-based Decision Support

CYBERSECURITY & INFRASTRUCTURE SECURITY AGENCY
CISA

- **Coordinated extensively with State Watch Centers, FEMA Regions I-X, and the Cybersecurity and Infrastructure Security Agency.**
- **Provided detailed briefings on expected impacts and recommended precautions.**

CME Arrivals in Solar Wind



North (+)

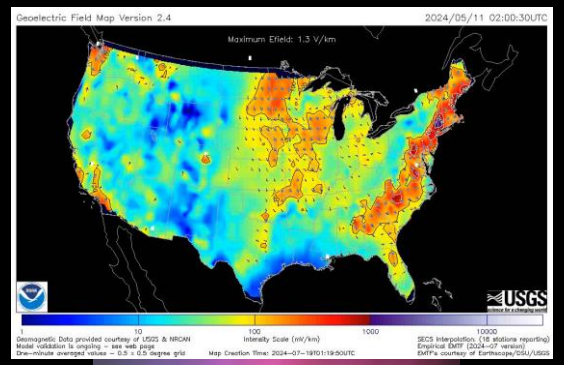
South (-)

Speed (km/s)

24 hours at G4-G5

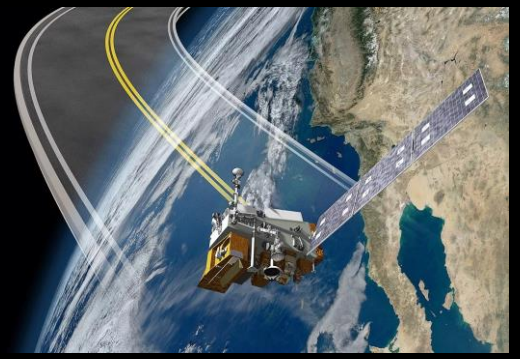
36 hours at G3+ (12 hours of G3)

G5 Geomagnetic Storm: 10-12 May 2024



Energy Sector

- US and Canada grid operators took numerous actions to mitigate impacts
- High voltage lines tripped in northern Europe
- UK transformers overheated/alarmed
- New Zealand disconnected northern islands power



Satellite Operations

- ~5000 Satellites experienced increased drag, necessitating more frequent station-keeping burns and collision avoidance maneuvers
- Degraded Starlink service
- Global communications satellite lost sync lock


Image: Ken Trombatore

Aviation

- Trans-oceanic flights rerouted due to High Frequency radio loss
- WAAS used for precision landing and performance based navigation unavailable for ~15 hrs
- NOTAM advising of comms/nav disruptions

NAWAS?


Image: John Deere

GPS Systems

- Loss of lock on GPS signals
- Range errors
- Both civilian and defense
- Idled Midwest planting

The New York Times May 13, 2024

Solar Storm Crashes GPS Systems Used by Some Farmers, Stalling Planting

Atomic Clock

- Surprising 0.1% variation in NIST Cesium clocks

May 10th-12th: One of the Strongest Solar Storms, but G5 not the worst and not significantly impactful

Historical Comparison of May 2024 Solar Storms

WHAT: How did the G5 Geomagnetic Storm Compare to Other Major Events?

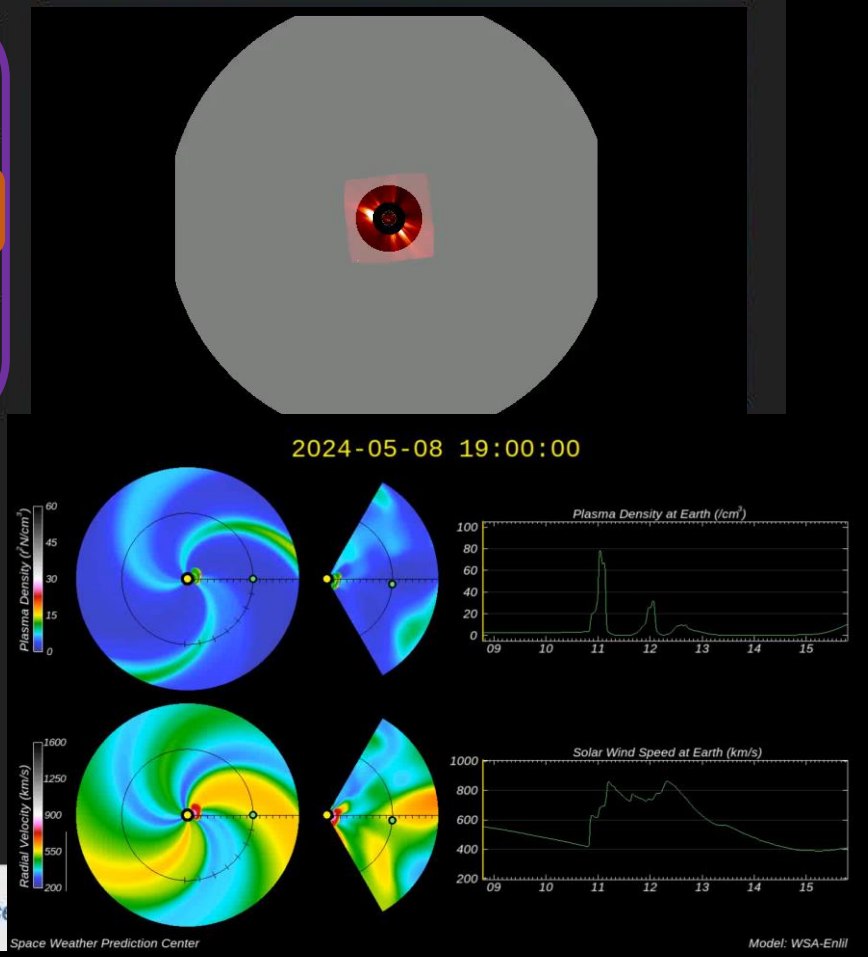
Index	MAY 2024	OCT 2003	MAR 1989	MAY 1921	SEP 1859
Disturbance Storm Index (nT)	-412	-383	-589	~ -907	~-1200
A_p-Index	271	204	246	NA	NA

Disturbance Storm Index (Dst): An index of magnetic activity derived from a network of near-equatorial geomagnetic observatories that measures the intensity in space of the ring of westward current around Earth (higher negative values generally correlate with stronger storms)

A_p-Index: The average from eight daily values gives the A_p-index of a certain day (every 3-hour K-value - or measure of geomagnetic activity - is converted into a linear scale). Days with higher geomagnetic activity have a higher daily A_p-value.

National Oceanic and Atmospheric Administration
U.S. Department of Commerce

Safeguarding Society with Actionable Spac



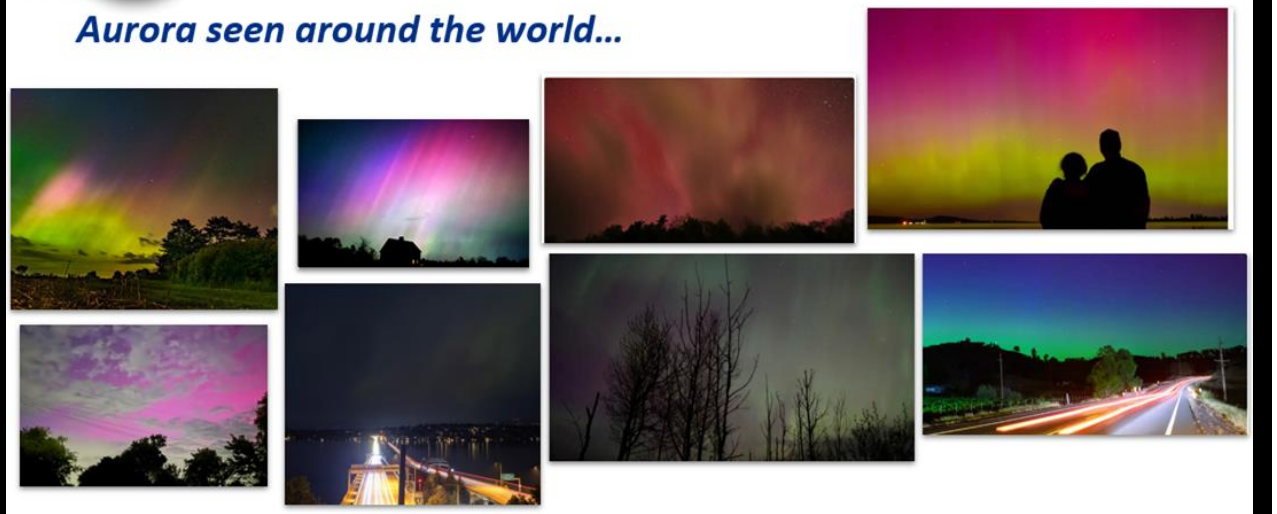
- By one measure of geomagnetic storm strength - called the *disturbance storm time index* - this event was quite similar to historic storms in 1958 and 2003.

It may compete with some of the lowest-latitude aurora sightings on record over the past *500 years*, though scientists are still assessing this ranking.

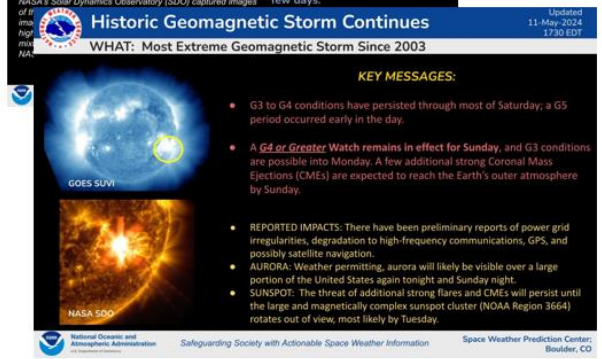
Spectacular won over Consequential

The Popular Story

Aurora seen around the world…

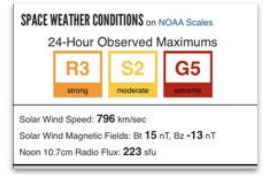


Authoritative Voice for Space Weather



NOAA SWPC SPACE WEATHER PREDICTION CENTER

spaceweather.gov



- This event underscored the interconnectedness and vulnerability of modern infrastructure to space weather.
- SWPC's proactive measures and detailed briefings enabled industries to implement necessary precautions.
- Demonstrated the importance of preparedness and the effectiveness of coordinated responses to space weather threats.

NERC Post-Event Webinar Feedback

Congratulations to NERC, SWPC, and EPRI for all your great work in protecting the grid – and the country! – during this event! This was no joke and y'all should be thanked and congratulated for your effective efforts! Thank you!

In my opinion ***this was the most prepared for and successfully mitigated extreme space weather storm in history***; thanks to all the government involvement and stress over the past 10-20 years, education and preparedness among the our technological infrastructure; and all the efforts of the Space Weather Prediction Center to inform all sectors possible before and throughout the event. If these actions were not accomlished, this storm would have been much more impactful. More work is to be done though, as this particular storm was less intense than the 1989 storm and likely 3-5x less strength of what we know is historically possible

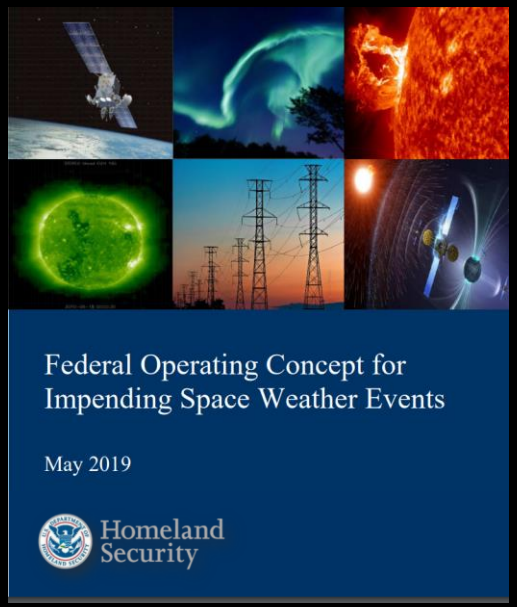
Thank You!

POC for your questions or needs

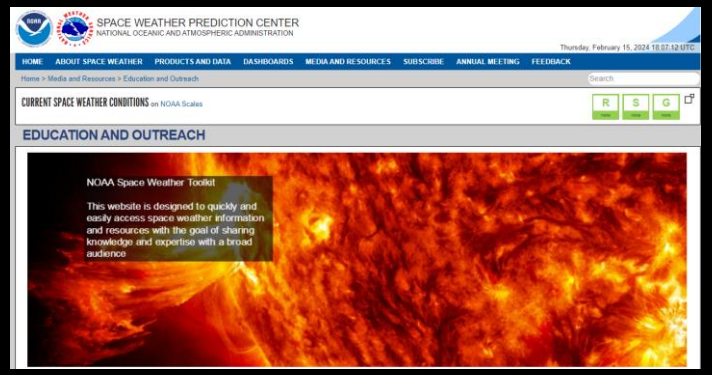
Shawn Dahl – SWPC Service Coordinator
shawn.dahl@noaa.gov

Additional Training and Resources:

https://emilms.fema.gov/is_0066/



https://www.fema.gov/sites/default/files/2020-07/fema_incident-annex_space-weather.pdf



https://www.swpc.noaa.gov/content/education-and-outreach

"Safeguarding Society with Actionable Space Weather Information"

NERC
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NERC GMD Database
Gannon Storm Review

Maria Kachadurian, Principal Analyst – NERC

Geomagnetic Disturbance Workshop
October 1–2, 2024

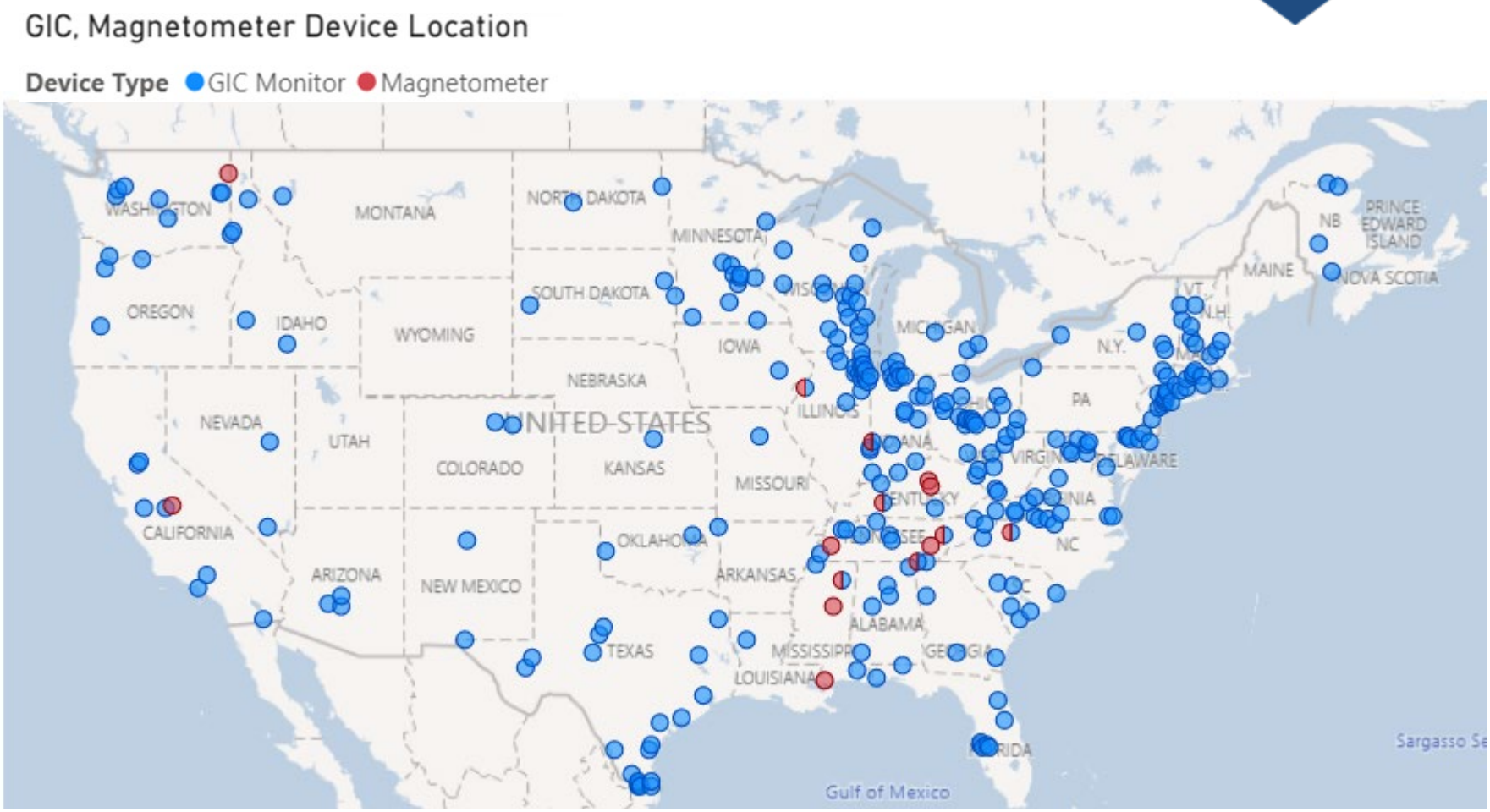
RELIABILITY | RESILIENCE | SECURITY



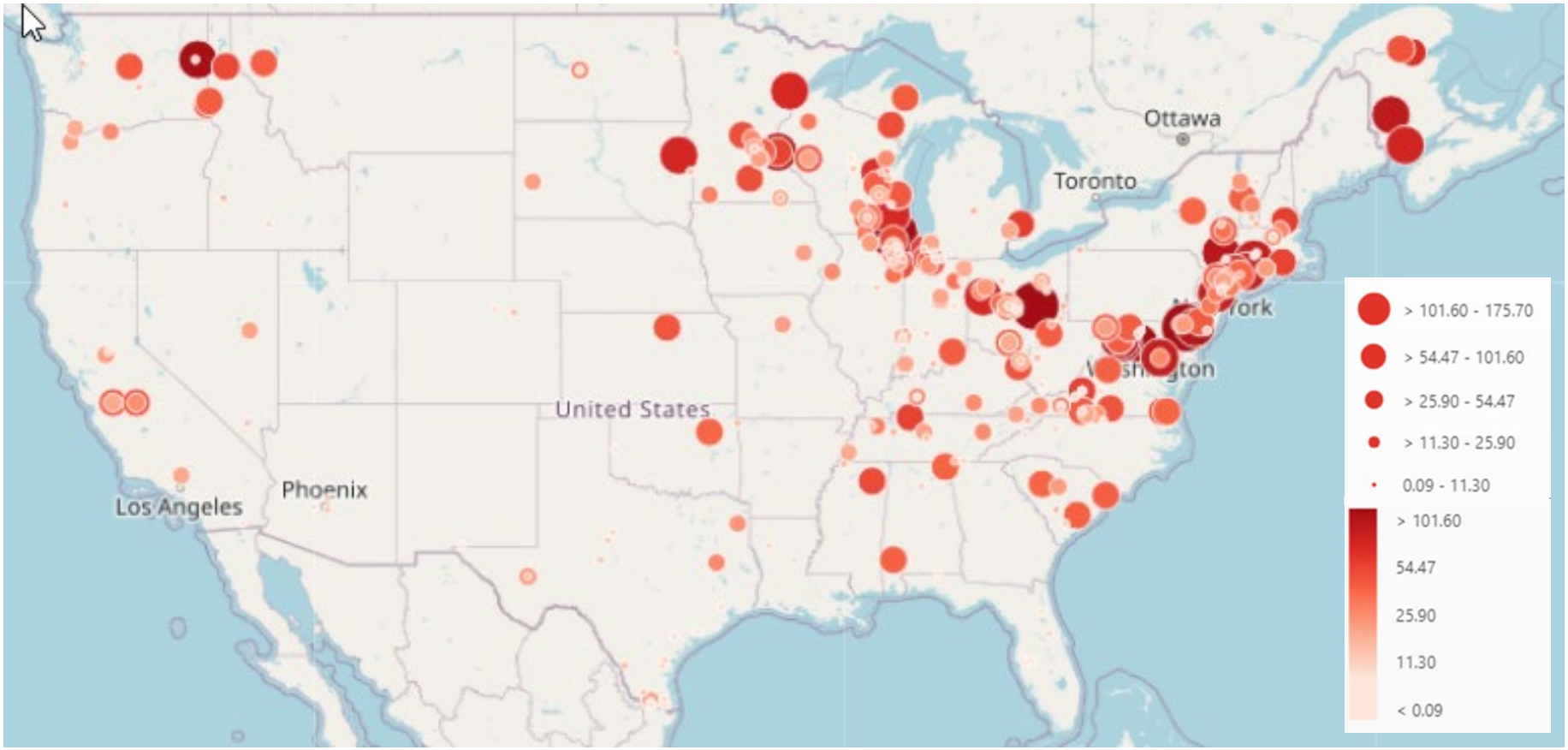

Metadata
as of 9/27/2024

- Event name: 2024E04
  - Event Start: 5/10/2024 00:00
  - Event End: 5/12/2024 23:59
- Data submissions collected:
  - GIC Monitors – 393
    - 78% submission rate
  - Magnetometers – 15
    - 58% submission rate
  - 75 NERC Registered Entities
  - Event statistics:
    - Maximum GIC reading – 175.70
    - Average reading – 1.62
    - Standard Deviation – 3.54
    - Number of GIC readings collected – 20,244,900

Reporting Device Locations
2024E04



Maximum per Device



Bubble Size Indicates Size of Maximum Reading

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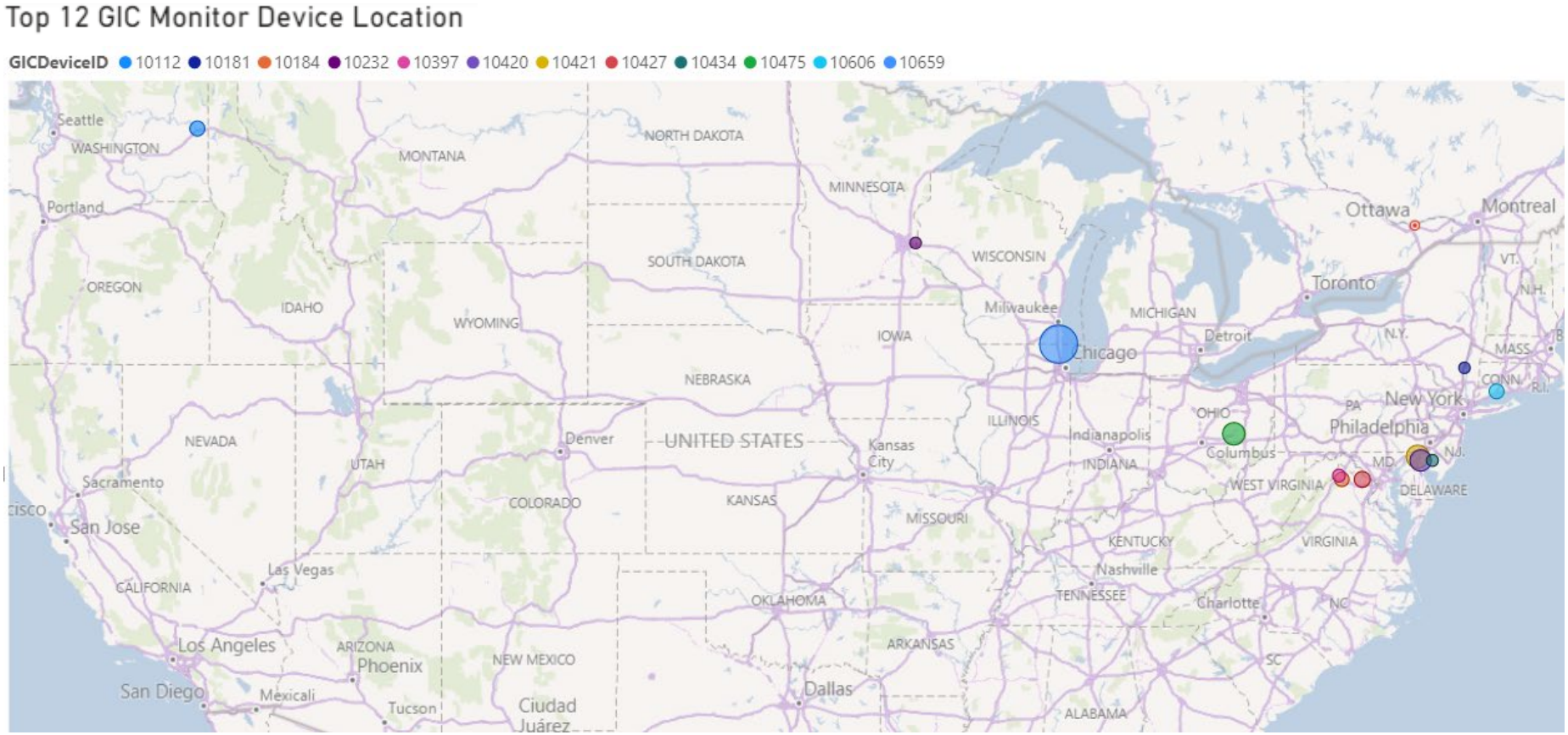
Devices with Top 12 Readings

GIC Device ID	Maximum Reading	Average Reading	Standard Deviation	Latitude	Longitude
10659	175.7	9.942203	11.67344	42.5	-87.9
10421	125.5	6.33951	7.265326	39.5	-75.5
10475	123.2	4.083634	5.612009	40.2	-81.9
10420	119.6	5.303016	6.702929	39.5	-75.5
10427	101.6	5.534237	6.026821	39	-77.5
10112	98.2	4.43712	6.567555	47.7	-117.4
10606	97.9	4.149756	6.937468	41.3	-72.9
10184*	96.4	3.394827	5.464988	39	-78.2
10397	90.7	3.576646	5.586292	39.1	-78.3
10434	88	3.829017	5.997155	39.5	-75.1
10232	86.49	3.3915	5.220794	45	-92.8
10181*	86	3.395489	5.736201	41.9	-74

*Sunburst Device

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Top 12 GIC Monitor Locations
Based on Maximum Readings



Bubble Size Indicates Size of Maximum Reading

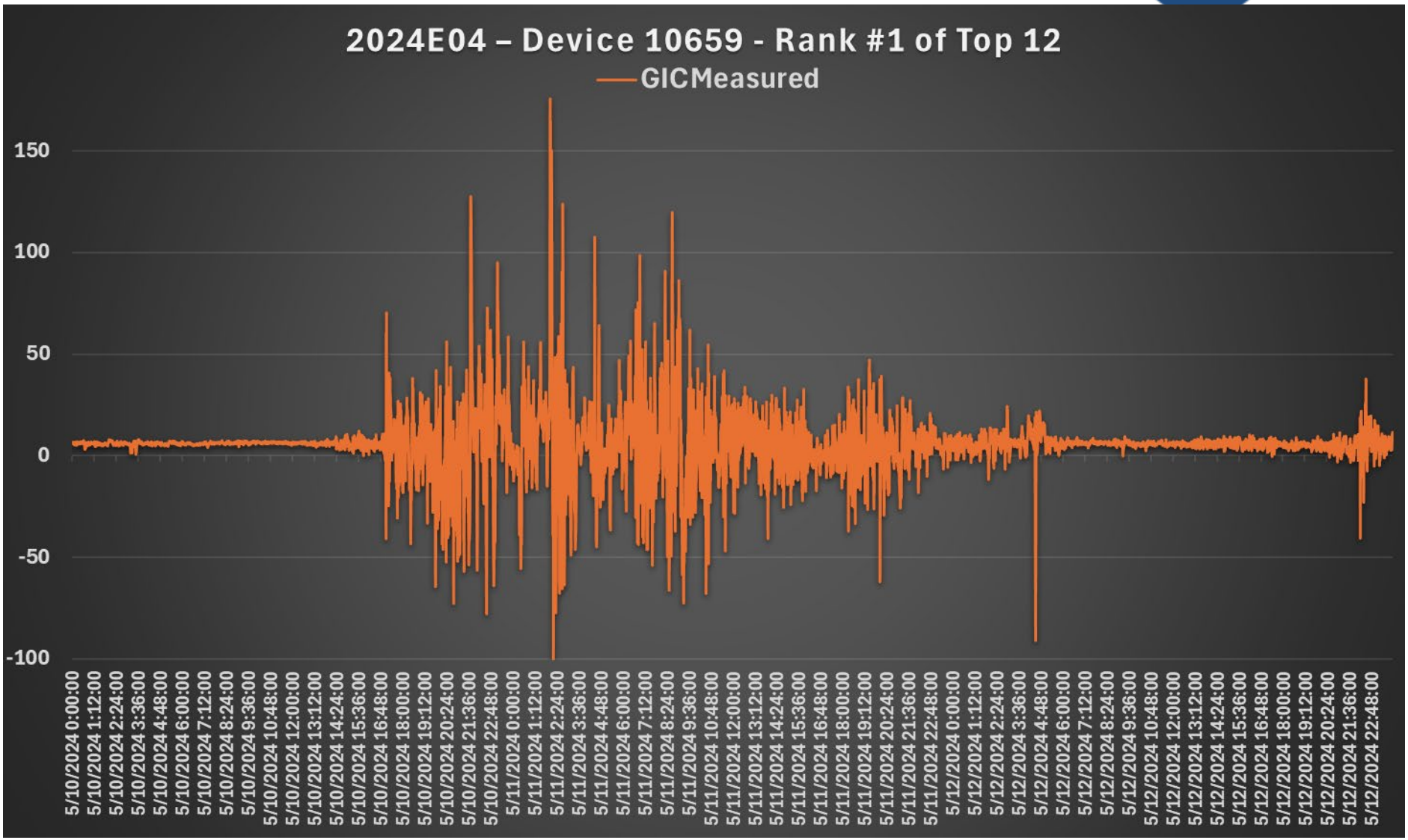
NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Time at Maximum Readings

GIC Device ID	Maximum Reading	Time at Maximum, (Chronological Order), UTC	Latitude	Longitude
10397	90.7	5/10/2024 18:37:50	39.1	-78.3
10232	86.49	5/10/2024 21:50:00	45	-92.8
10184	96.4	5/10/2024 22:37:39	39	-78.2
10659	175.7	5/11/2024 2:03:30	42.5	-87.9
10475	123.2	5/11/2024 2:06:00	40.2	-81.9
10606	97.9	5/11/2024 2:07:00	41.3	-72.9
10181	86	5/11/2024 2:07:31	41.9	-74
10420	119.6	5/11/2024 2:09:11	39.5	-75.5
10421	125.5	5/11/2024 2:09:15	39.5	-75.5
10427	101.6	5/11/2024 2:09:25	39	-77.5
10434	88	5/11/2024 2:09:50	39.5	-75.1
10112	98.2	5/11/2024 12:39:00	47.7	-117.4

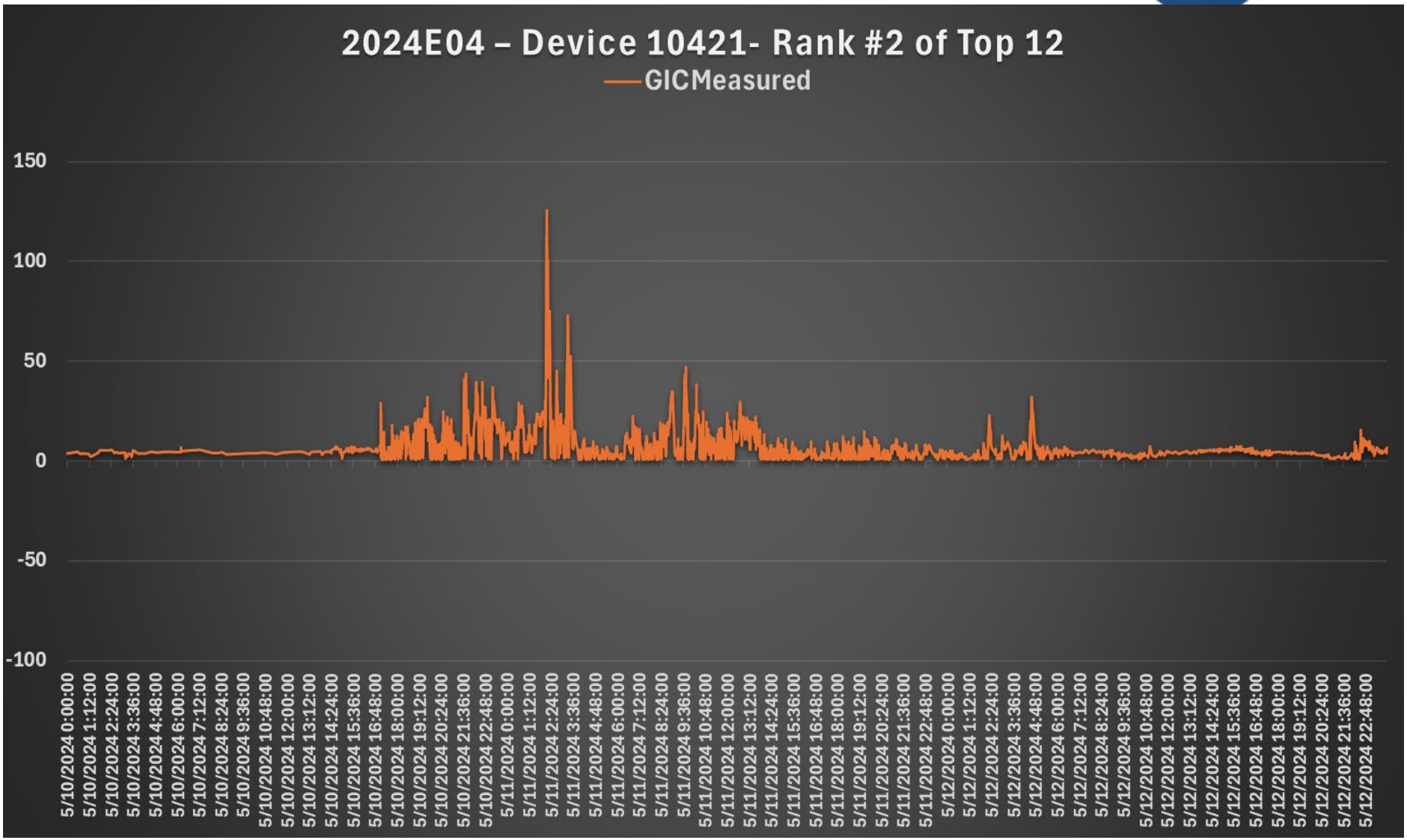
Device 10659

Location: 42.5, -87.9, Maximum: 175.7



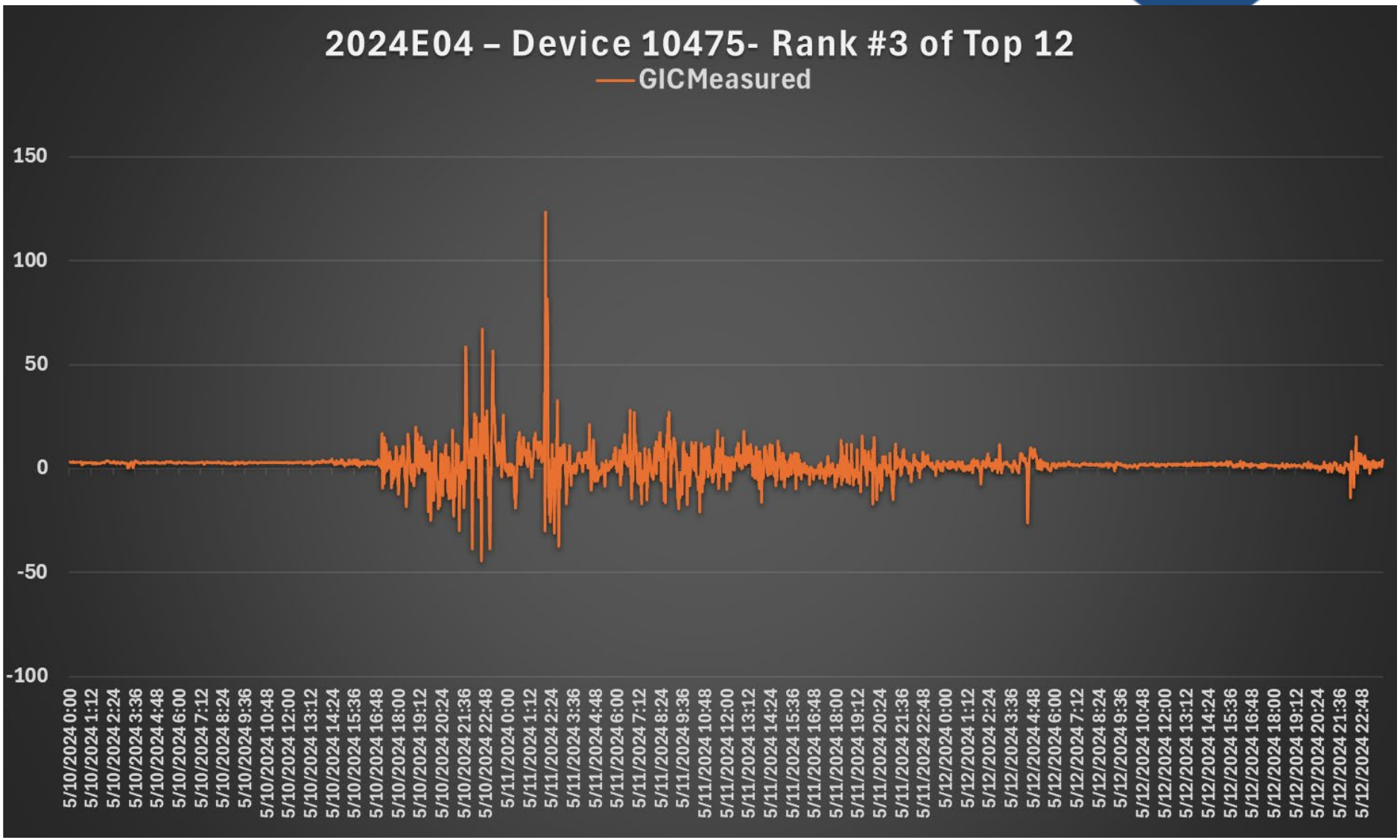
Device 10421

Location: 39.5, -75.5, Maximum: 125.5



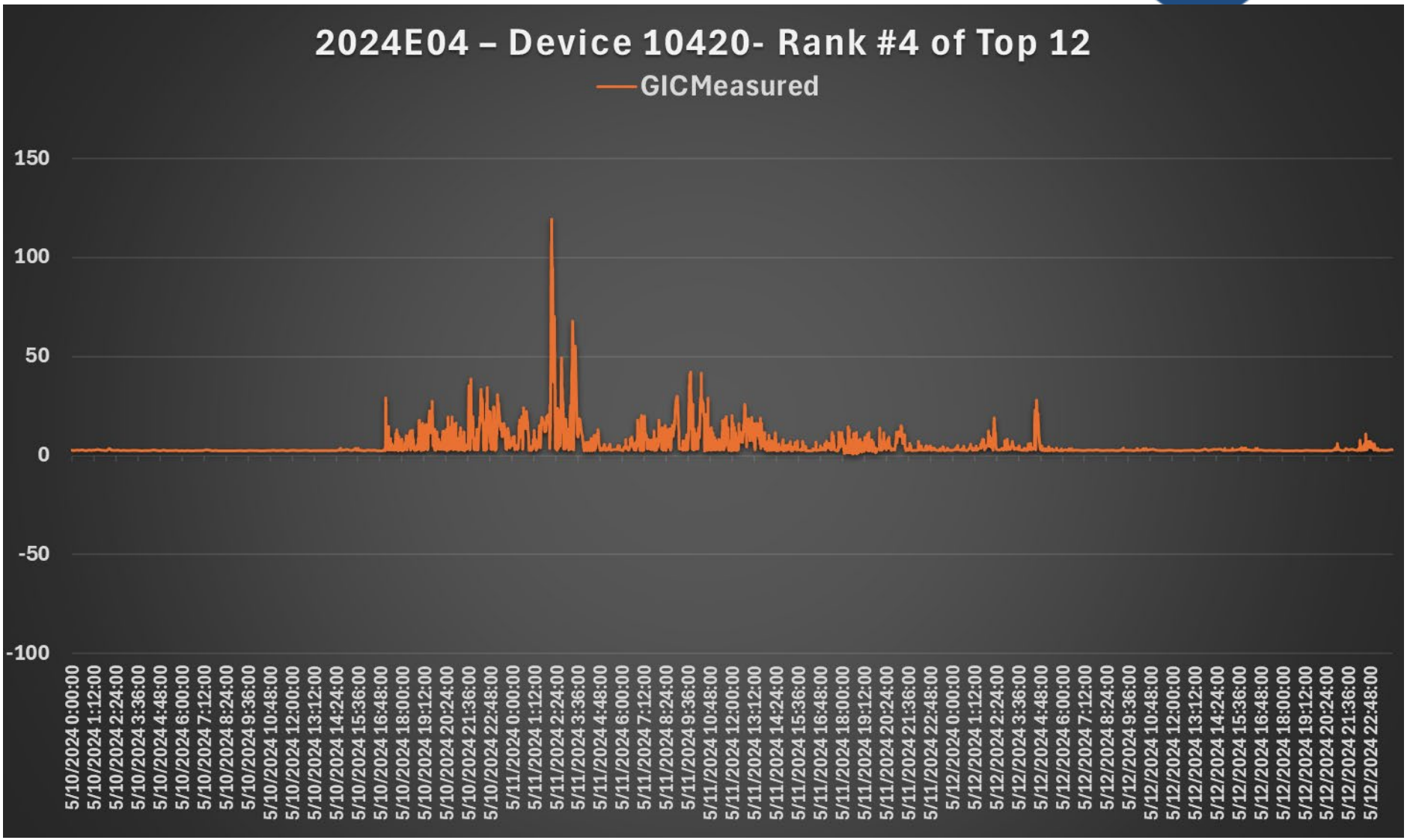
Device 10475

Location: 40.2, -81.9, Maximum: 123.2



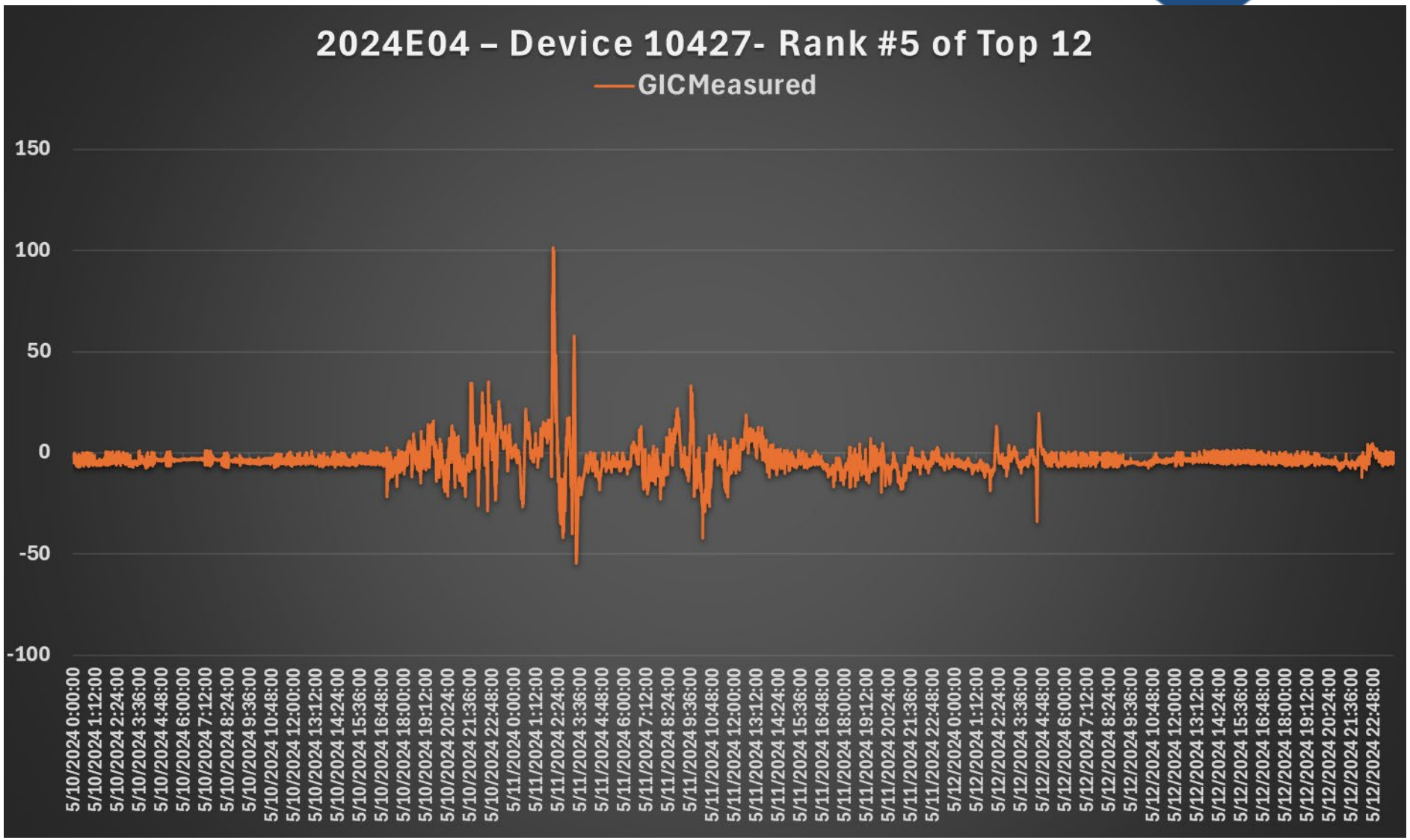
Device 10420

Location: 39.5, -75.5, Maximum: 119.6



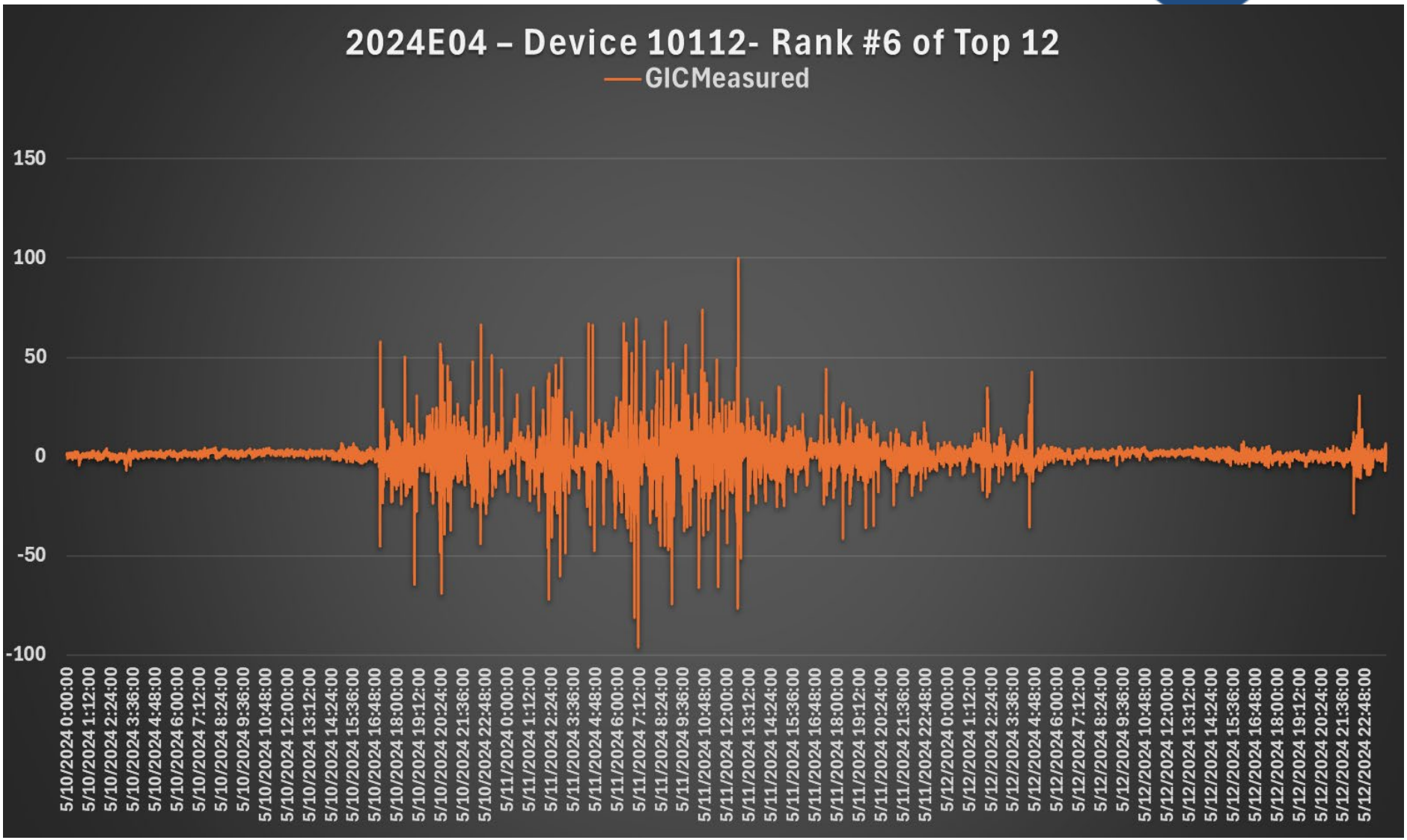
Device 10427

Location: 39, -77.5, Maximum: 101.6



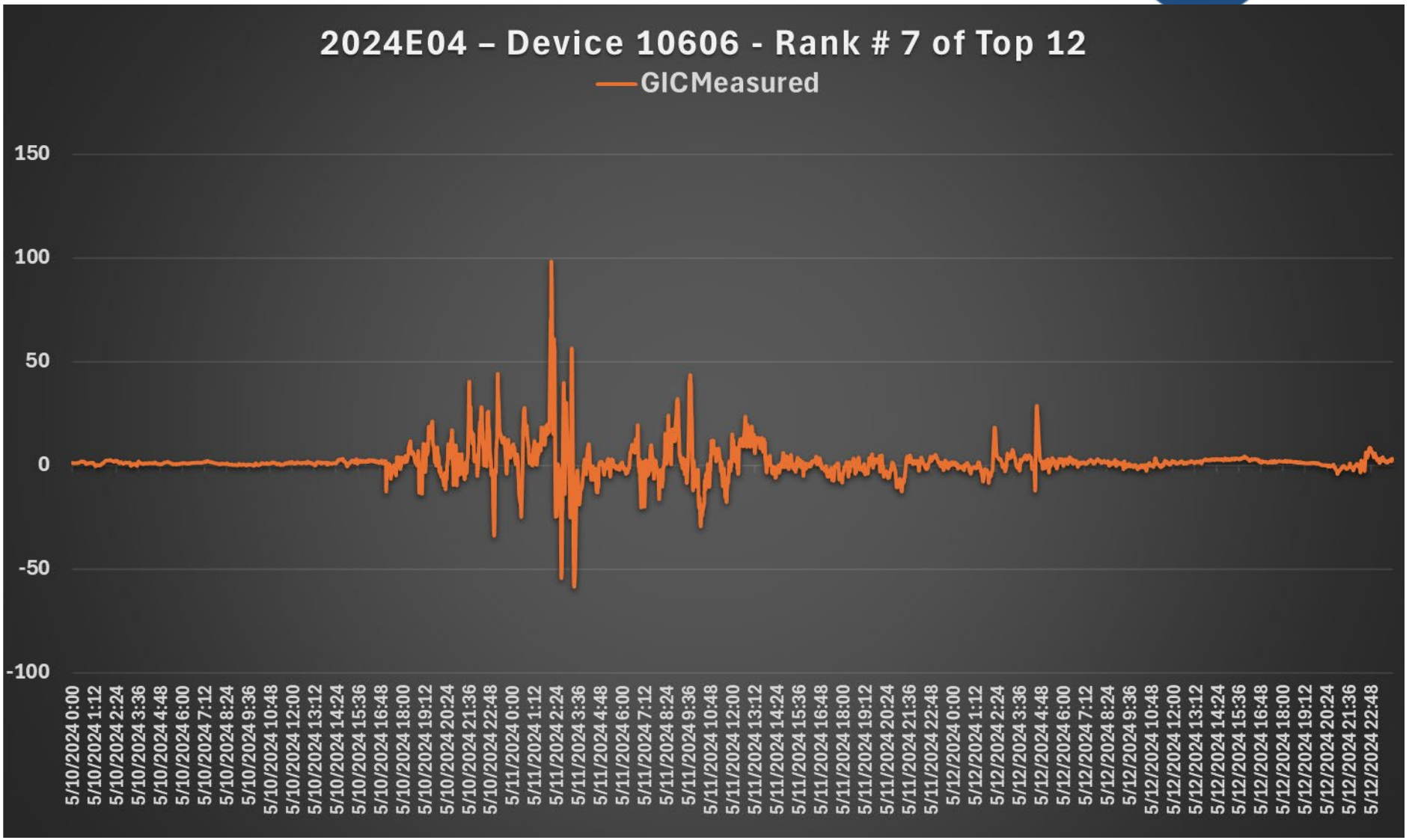
Device 10112

Location: 47.7, -117.4, Maximum: 98.2

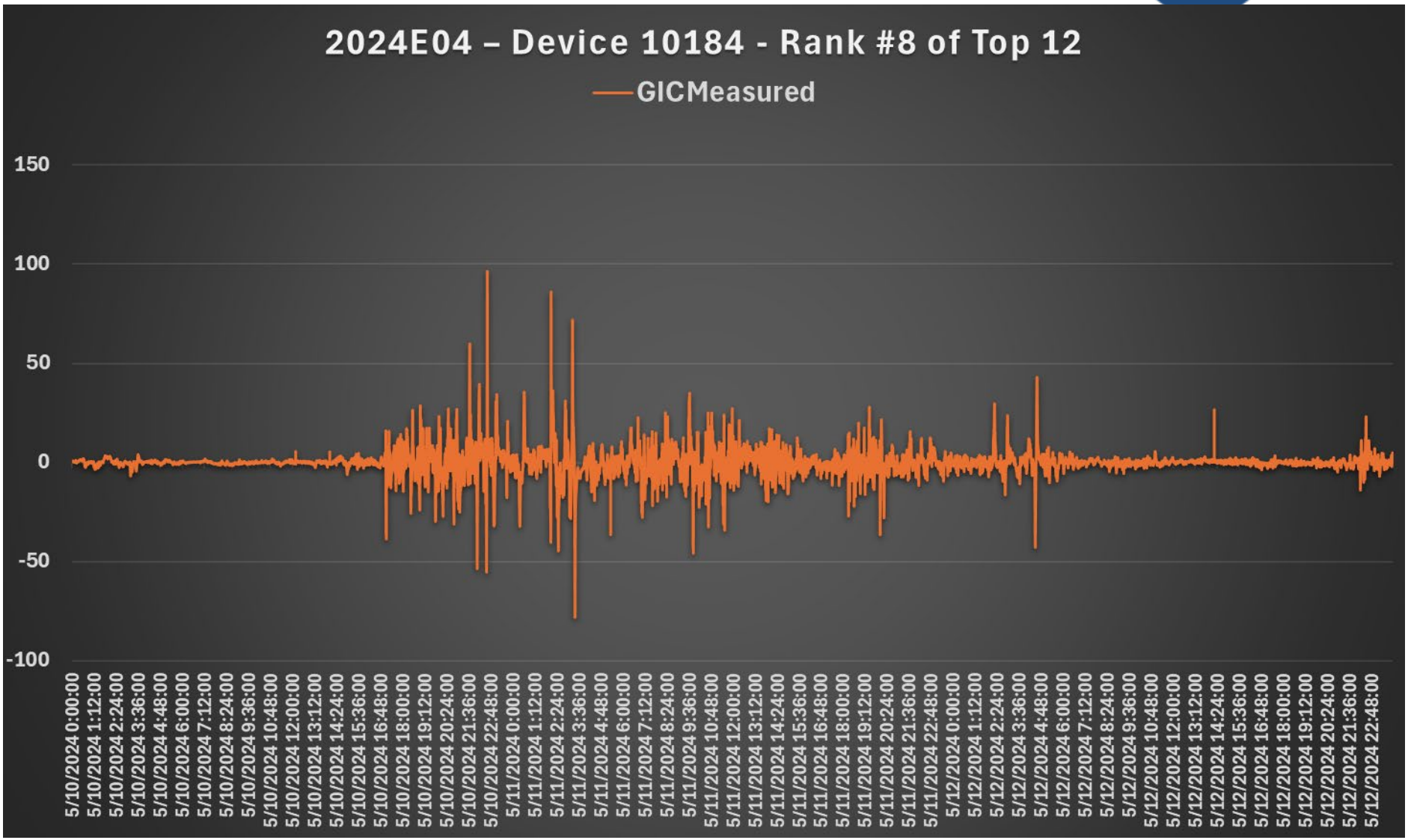


Device 10606

Location: 41.3, -72.9, Maximum: 97.9

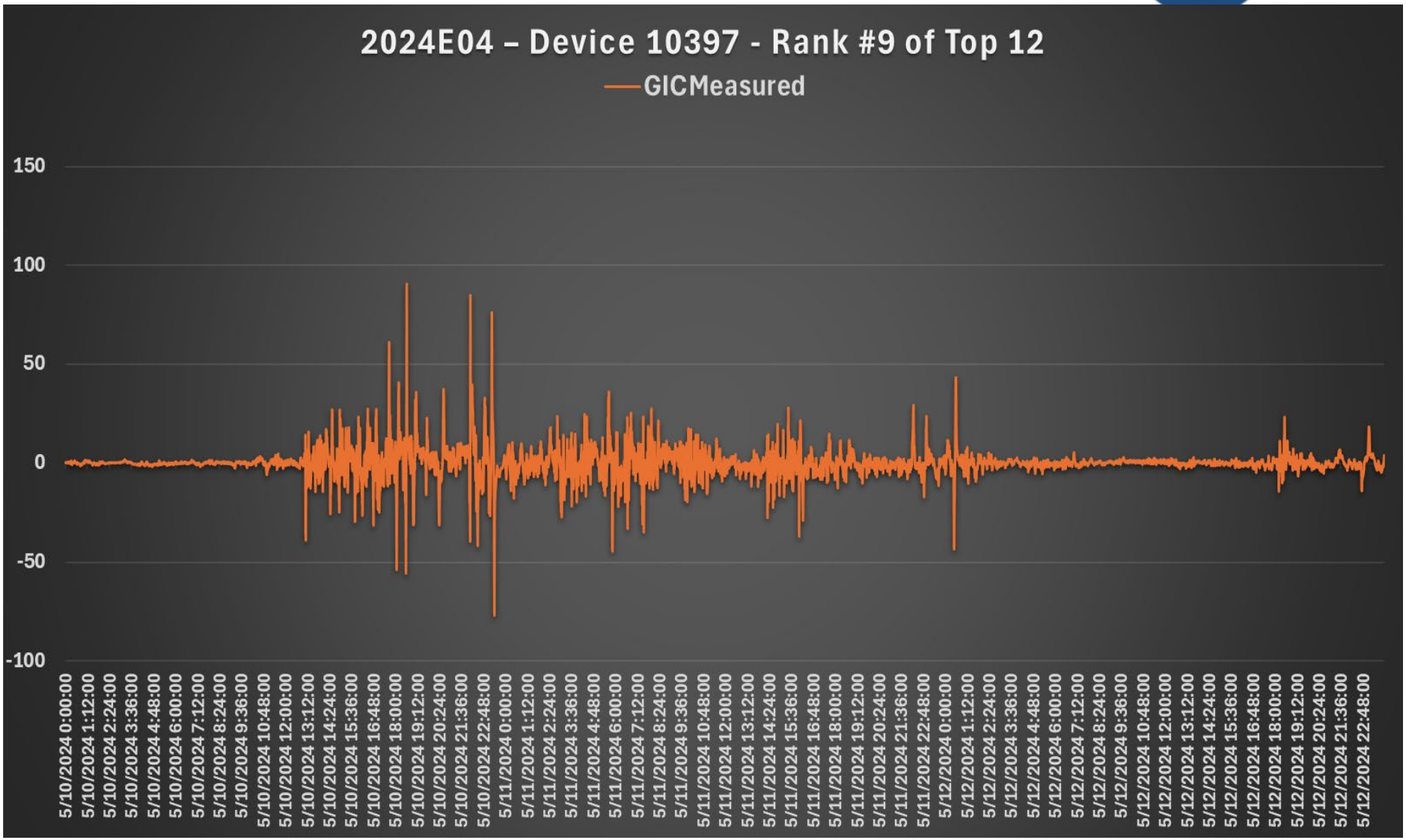


Device 10184
Location: 39, -78.2, Maximum: 96.4

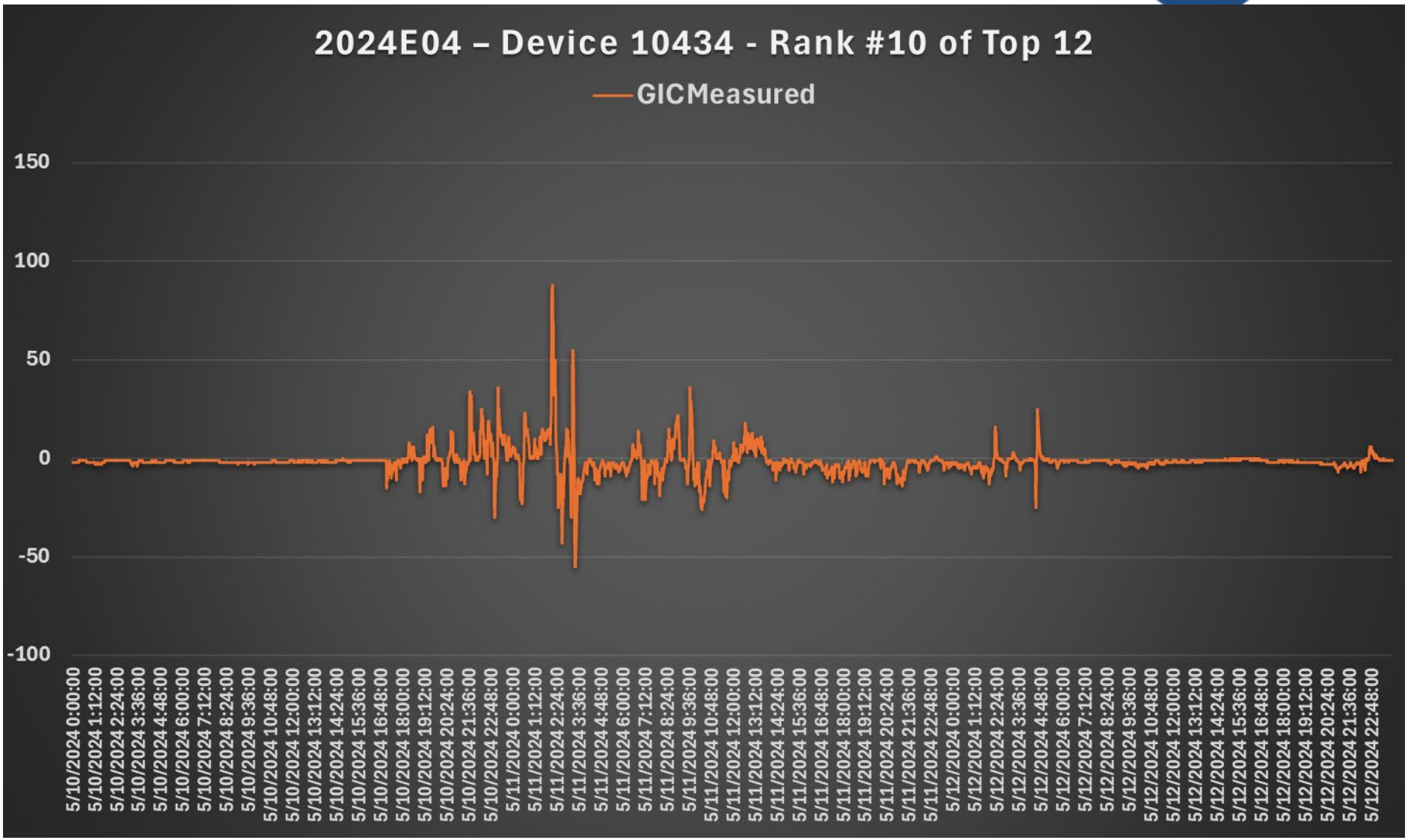


Device 10397

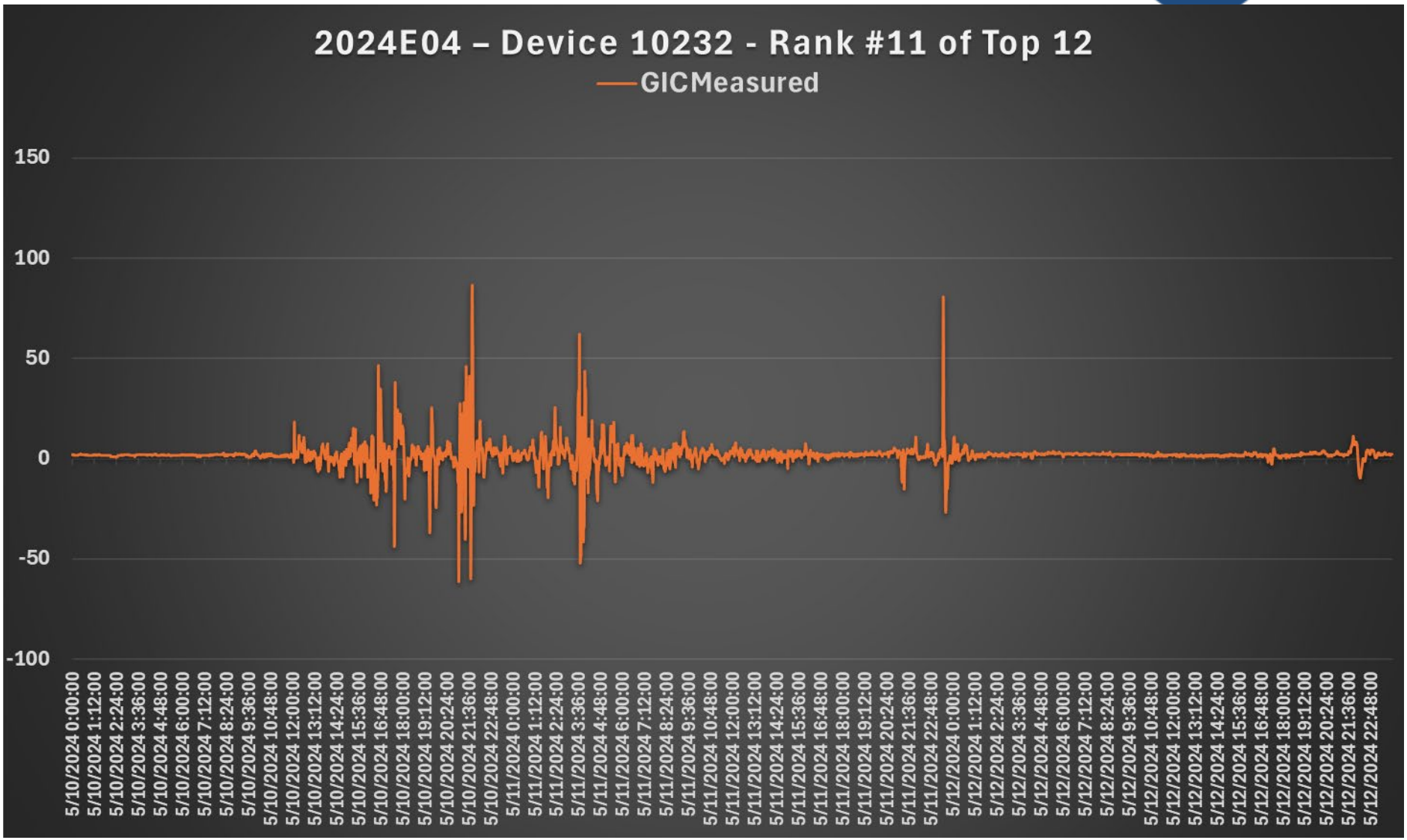
Location: 39.1, -78.3, Maximum: 90.7



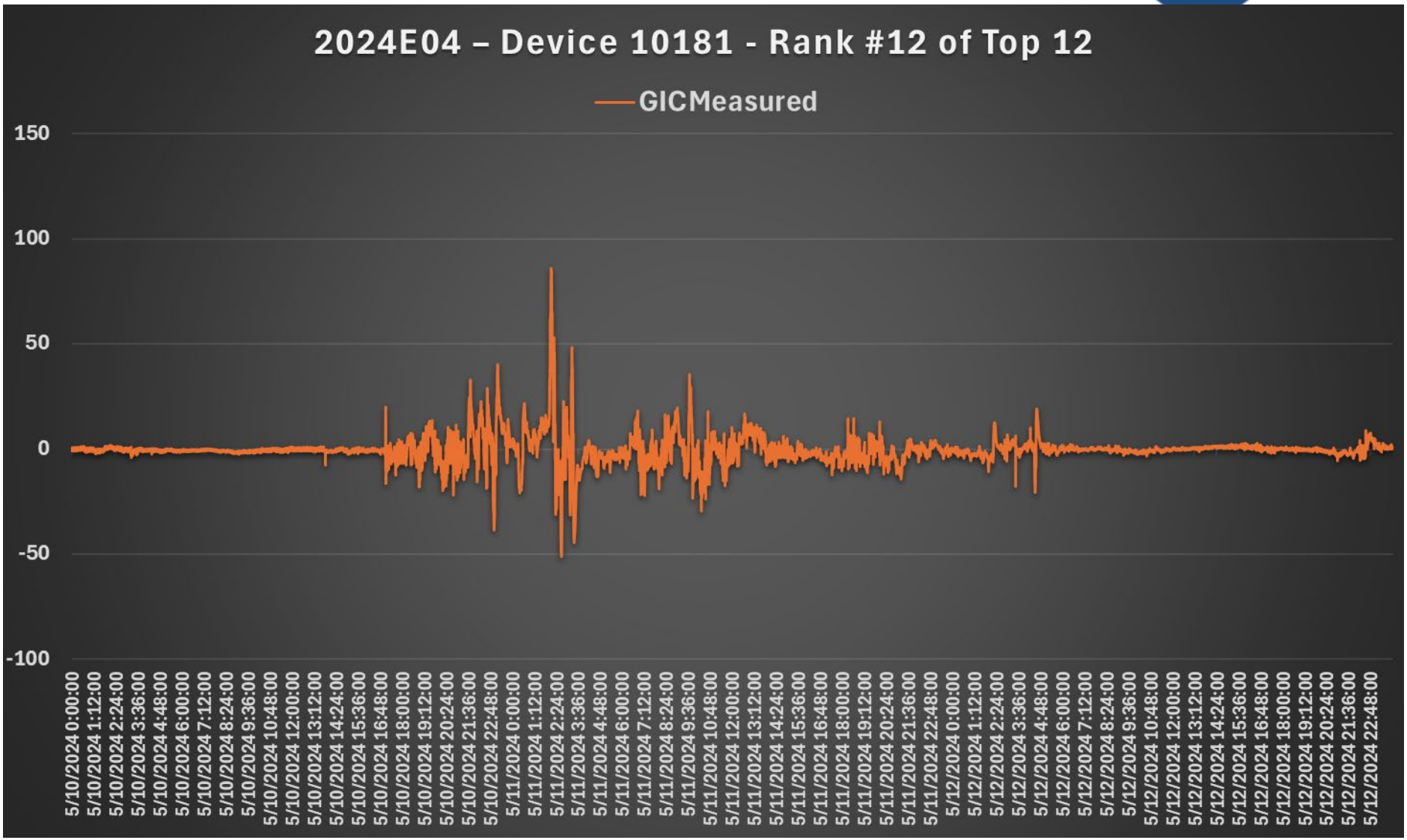
Device 10434
Location: 39.5, -75.1, Maximum: 88



Device 10232
Location: 45, -92.8, Maximum: 86.5



Device 10181
Location: 41.9, -74, Maximum: 86



Next Steps

- Continue Data Cleanup Efforts
  - Reach out to device owners with anomalous readings
    - Attempt to obtain correct GIC monitor data
    - Advise to recalibrate GIC monitor
  - Monitor data completion rate for all events
    - Send reminders as reporting deadline approaches
- Application Changes – 2025
  - Provide additional reports to address data anomalies
  - Implement additional data validations
  - Automate process for identifying data gaps
  - Improve awareness of data quality to the data reporters and research community

Questions and Answers

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

NERC Data Systems
May 2024 Review

Maria Kachadurian, Principal Analyst – NERC

Geomagnetic Disturbance Workshop
October 1–2, 2024

RELIABILITY | RESILIENCE | SECURITY




Section 1600 Data Requests

- Section 1600 of the North American Electric Reliability Corporation (“NERC") Rules of Procedure, authorizes NERC to request data (“Data Request") that is necessary to meet its obligations under section 215 of the Federal Power Act.
- Each Section 1600 data request specifies
  - Data to be collected
  - Registered entity function(s) to which it applies
  - Criteria for reporting requirements
- Current Section 1600 Data Requests in Effect
  - Generating Availability Data System (GADS)
  - Geomagnetic Disturbance Data System (GMD)
  - Misoperation Information Data Analysis System (MIDAS)
  - Transmission Availability Data System (TADS)

GADS/TADS/MIDAS Findings

GADS
As of 9/27/2024

- Reporting is mandatory for:
  - Conventional generating units 20 MW+
  - Wind plants with total installed capacity 75 MW+
  - Solar plants with total installed capacity 100 MW+
- Reporting Deadline, Q1 – Q3 2024: November 15
- Potential GMD-related outages during May 10–12 timeframe:
  - Number of outages due to Transmission System Problems (other than catastrophe) : 4
    - One outage specified KP 9+ GMD as outage cause
  - Regions affected: Northeast Power Coordinating Council (NPCC)
  - Unit types affected: Fossil-Steam (2), Combined Cycle Block, Pumped Storage/Hydro

TADS
As of 9/27/2024

- TAD collects transmission outage data for:
  - Bulk Electric System AC Circuits (Overhead and Underground)
  - Transmission Transformers (No Generator Step-up Units)
  - Bulk Electric System AC/DC Back-to-Back Converters
  - Bulk Electric System DC Circuits
- Reporting Deadline, Q2 2024: August 15, 2024
  - Potential GMD-related outages during May 10–12 timeframe: 12 outages
    - 10 outages – AC circuit equipment
      - Causes: Unknown, Failed AC Circuit Equipment, Power System Condition, Failed Protection System Equipment, Other
    - 2 outages – Transformers
      - Cause: Failed AC Substation Equipment
    - Regions affected: NPCC, RF, MRO, WECC, TRE

MIDAS
As of 9/27/2024

- Protection System Operations and Misoperations are reported by Transmission Owners, Generator Owners, and Distribution Providers on a quarterly basis
- Reporting Deadline, Q2 2024: August 29, 2024
  - Potential GMD-related Misoperations during May 10–12 timeframe: 2 Misoperations
    - Misoperation category: Unnecessary Trip – Other than Fault
    - Equipment Type: Generator, Shunt Capacitor
    - Cause Name: Unknown/Unexplainable, Relay failures/malfunctions
    - Region affected: NPCC, SERC

Next Steps

- NERC will continue to monitor databases for new data submissions related to GMD event
  - November 15, 2024 - run preliminary analysis on GADS data
- NERC Performance Analysis team will continue to validate and gain more information regarding current identified outages
- Industry questions/observations can be submitted to NERC via GMD@nerc.net

Questions and Answers

Results of GIC Model Validations from Select Areas

Geomagnetic Disturbance Workshop

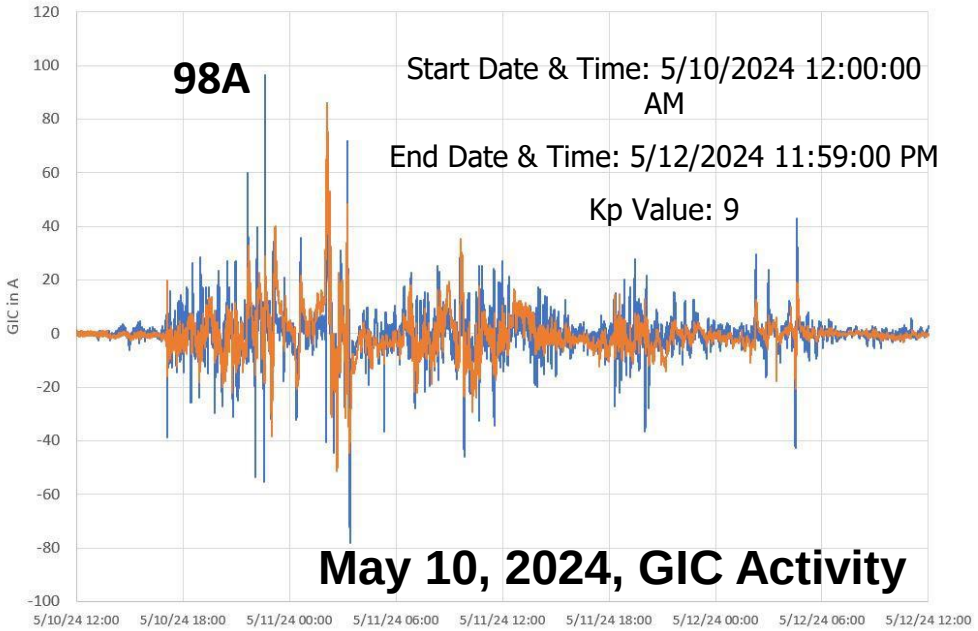
October 1st, 2024

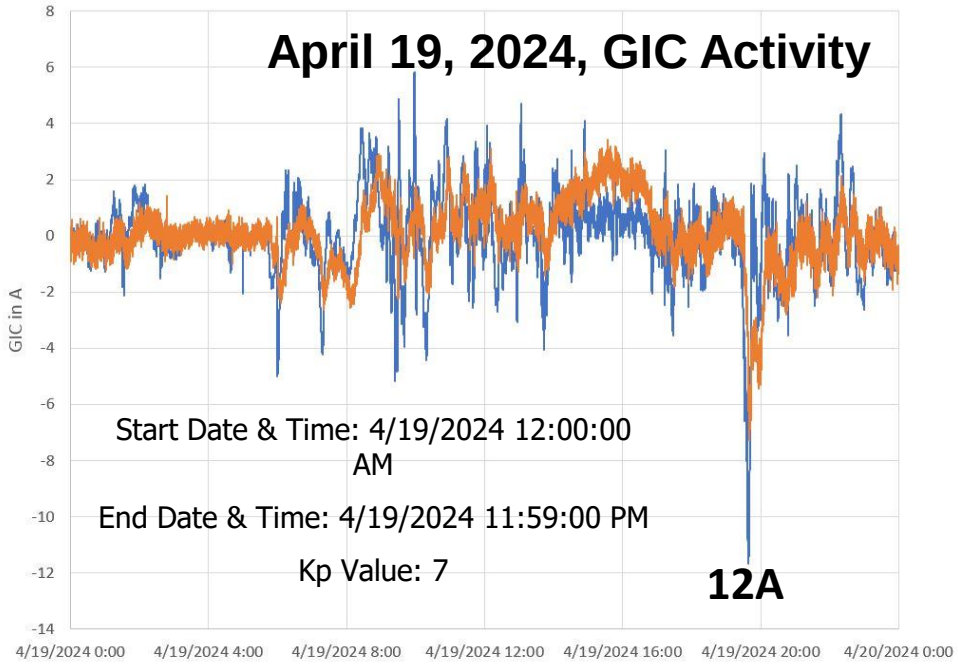
Agenda

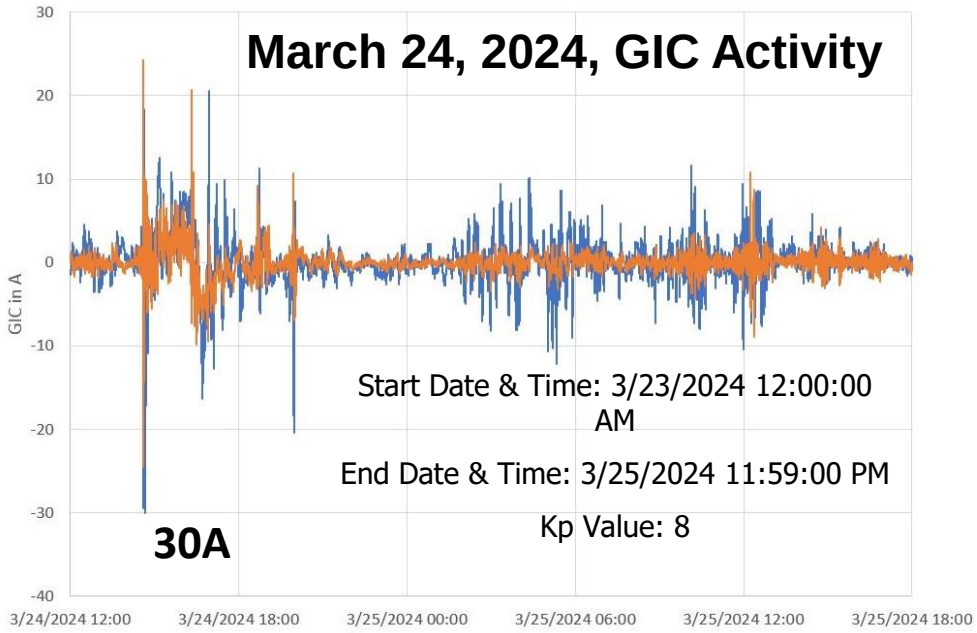
- Observations
  - GIC Measurements
  - E-Field Calculations
  - Magnetometers Measurements
  - Preliminary GIC Validation Model Results
- Next Steps

GIC Responses to Varying Storm Levels

- The largest GIC measurement reported on the EPRI network was recorded on the RF GIC monitors that measured a peak of 60A GIC per phase (180A GIC Neutral).

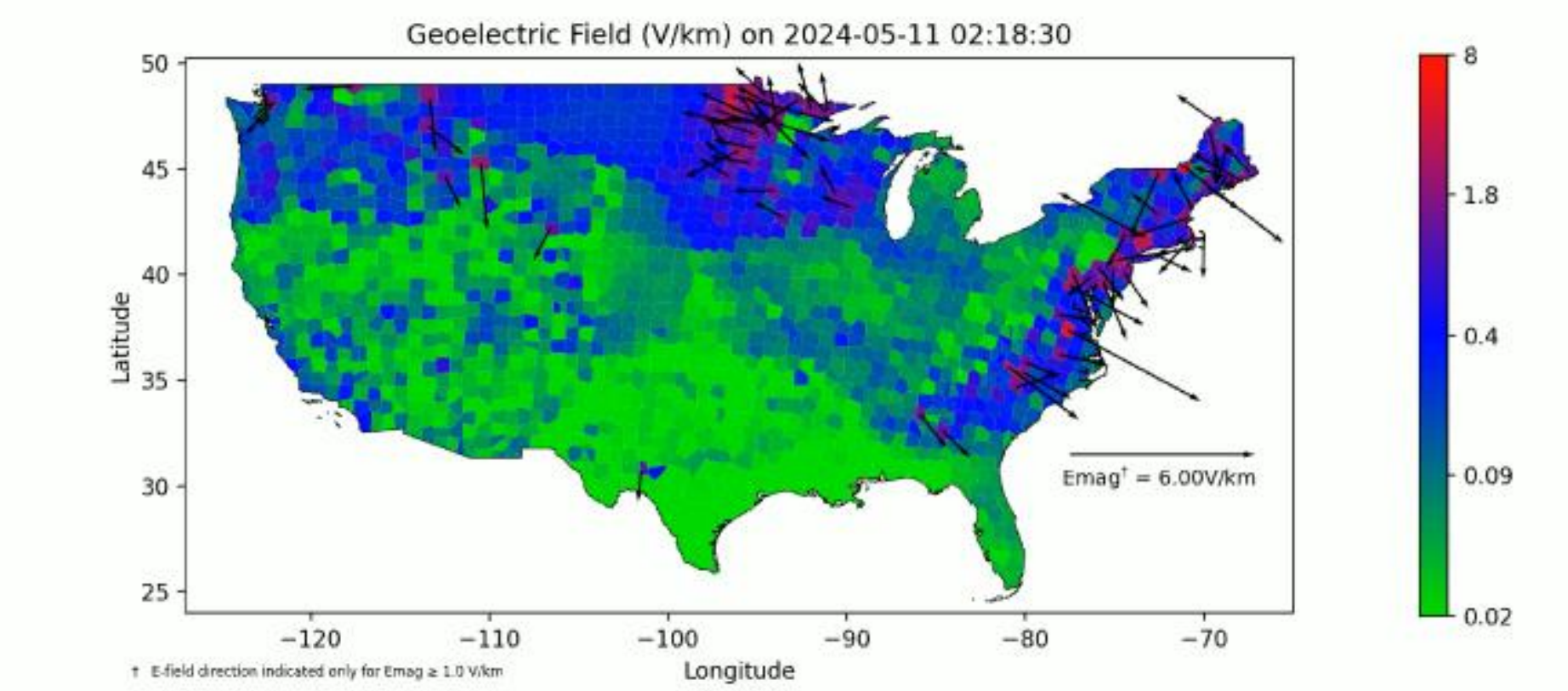




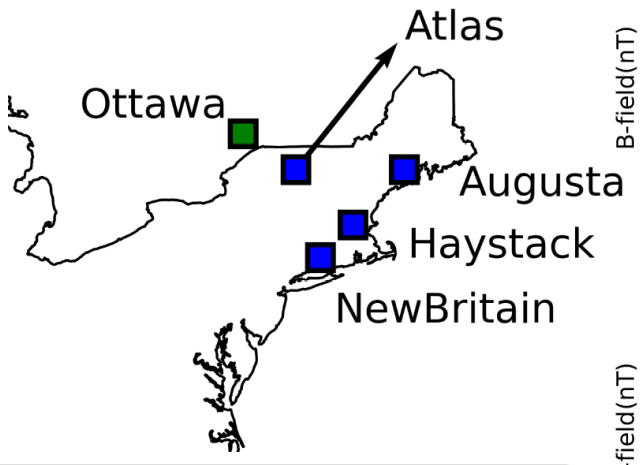


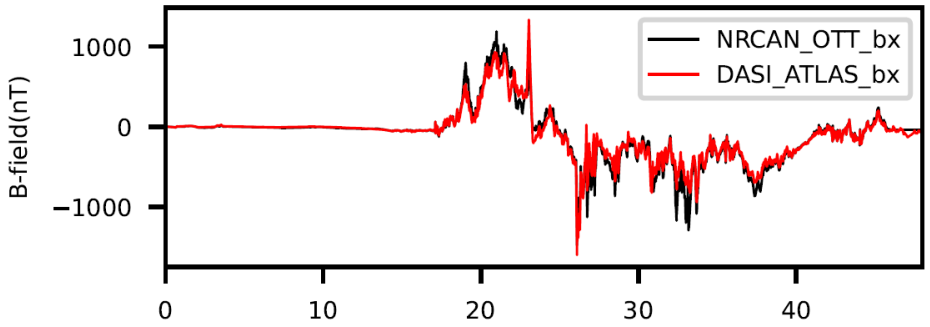
Gannon Storm

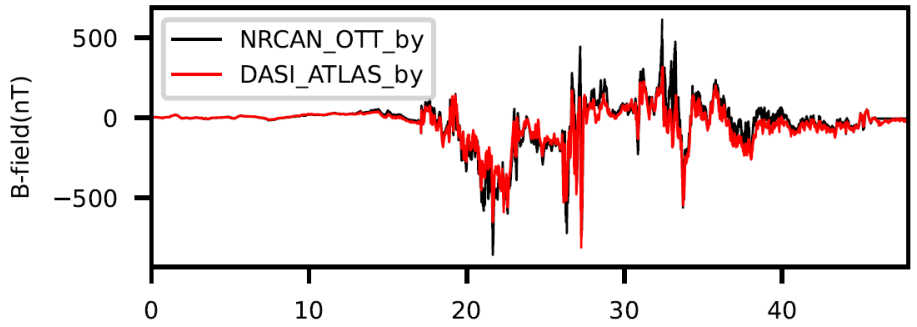
- High Geoelectric-Field Activity Appalachian and Minnesota Region

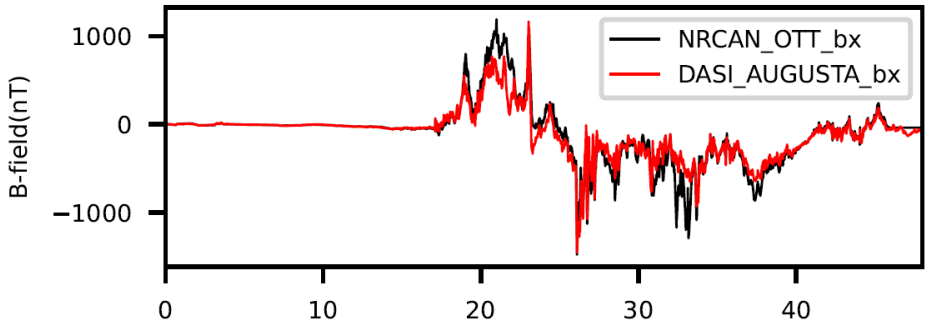


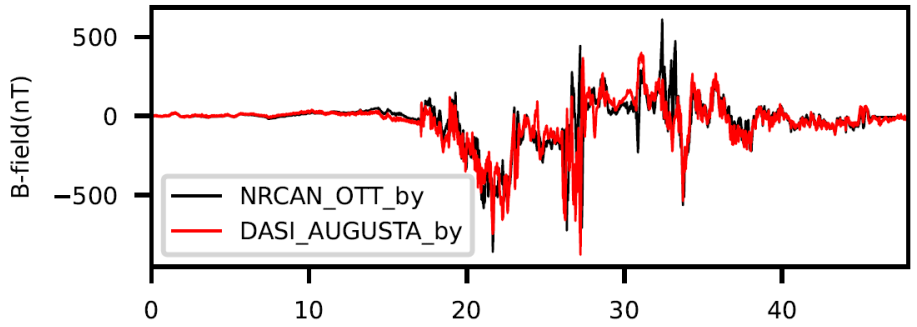
Slight variations in Differences in Magnetometer Responses.

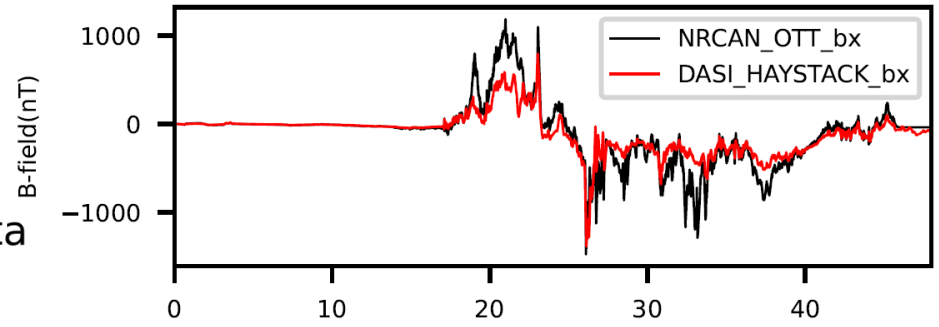


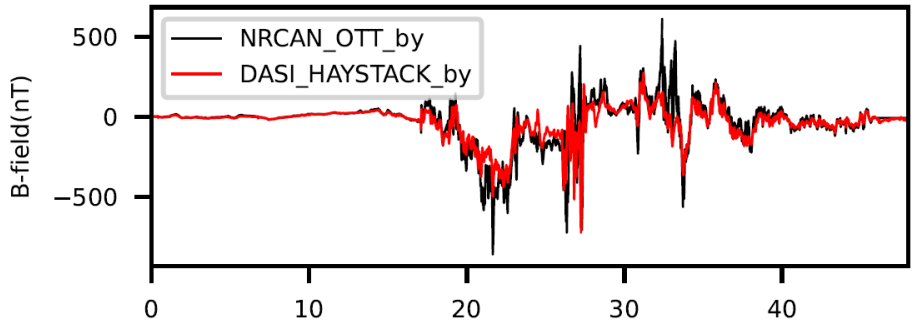


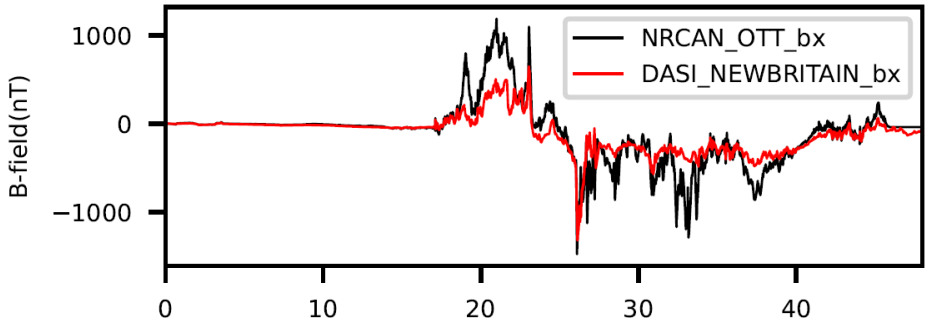


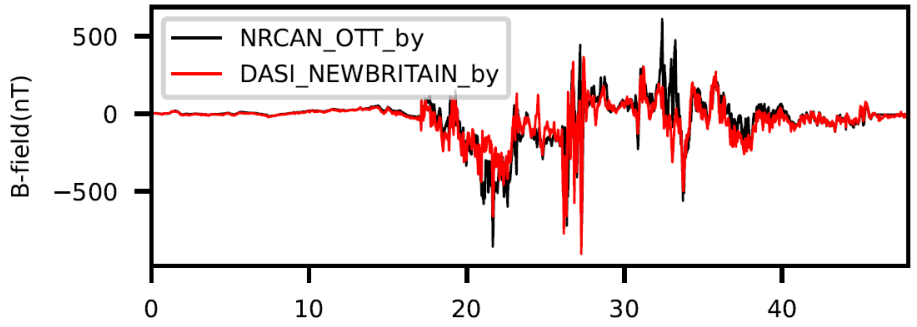


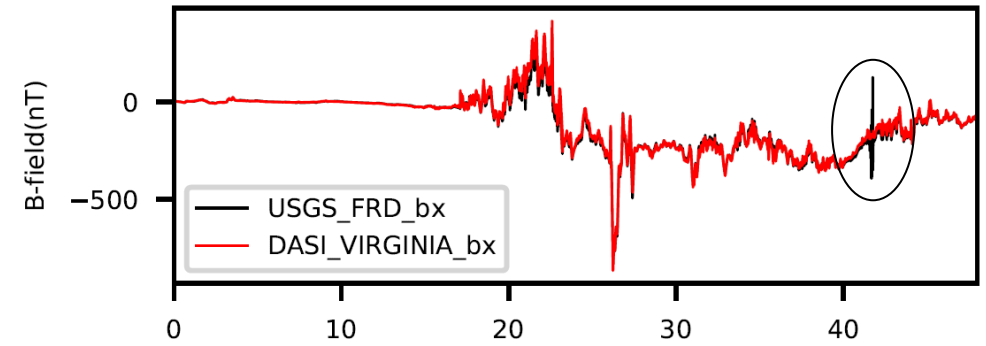


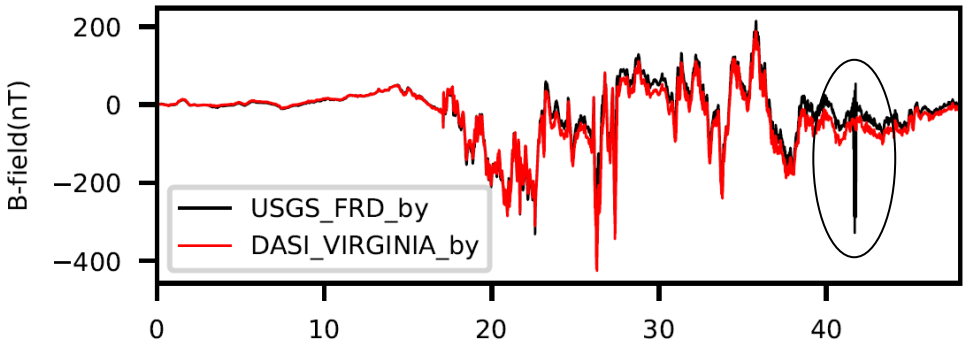


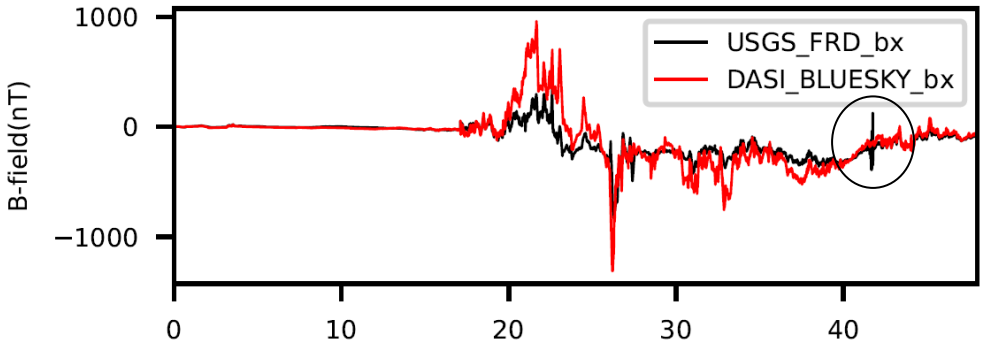


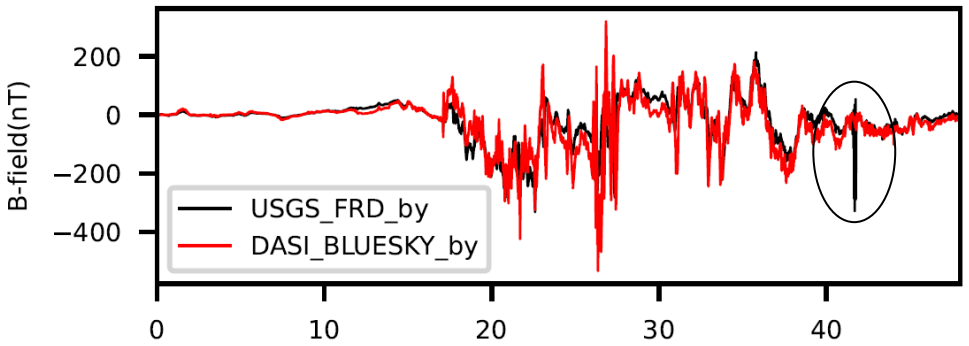


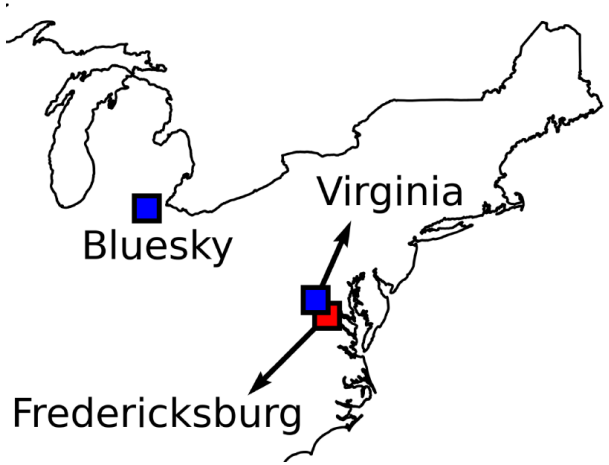










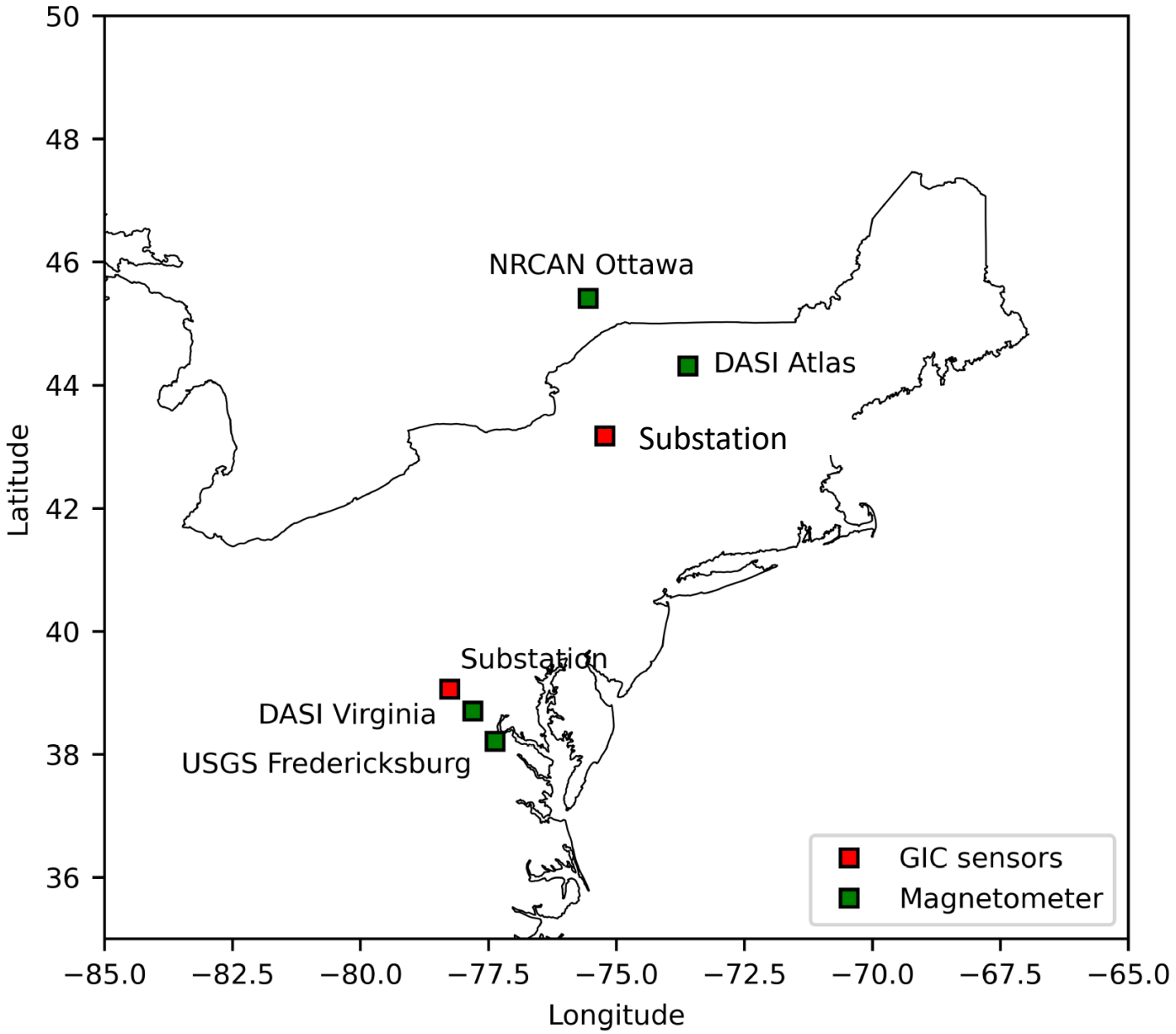


USGS Observatories

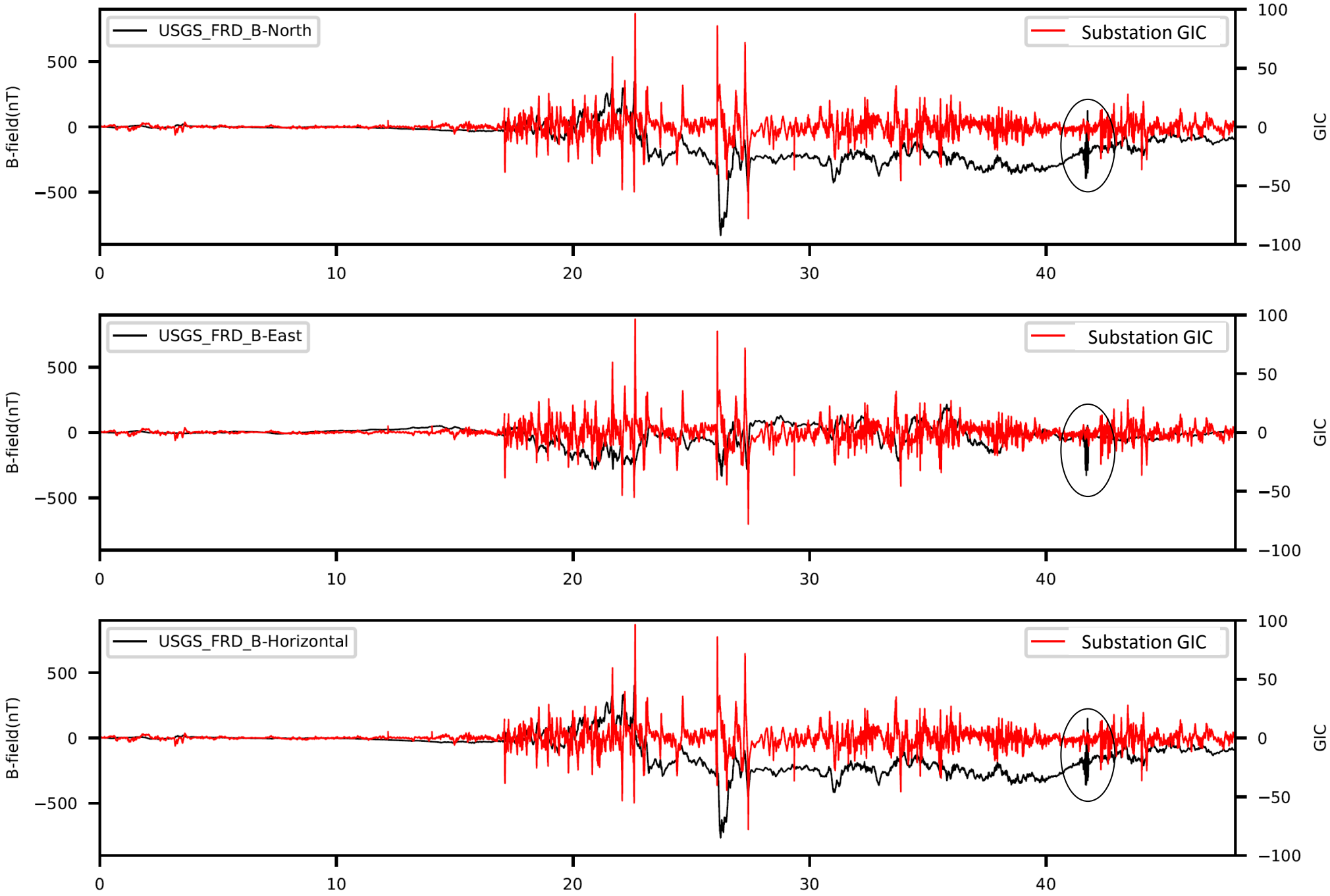
DASI CPI MagStar Network

Slight variations in Differences in Magnetometer Responses, greater further away.

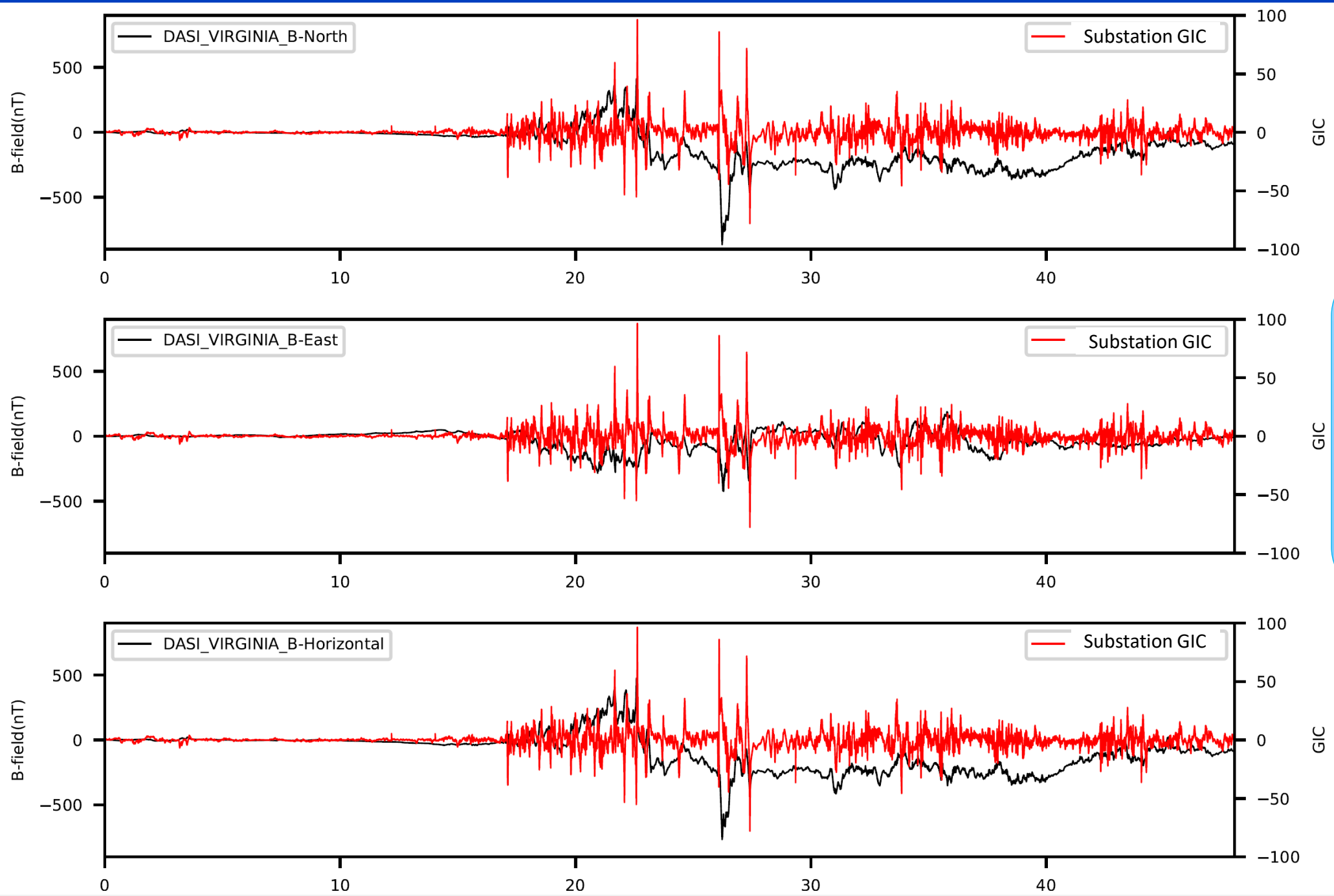
Magnetometer and GIC sensor locations.



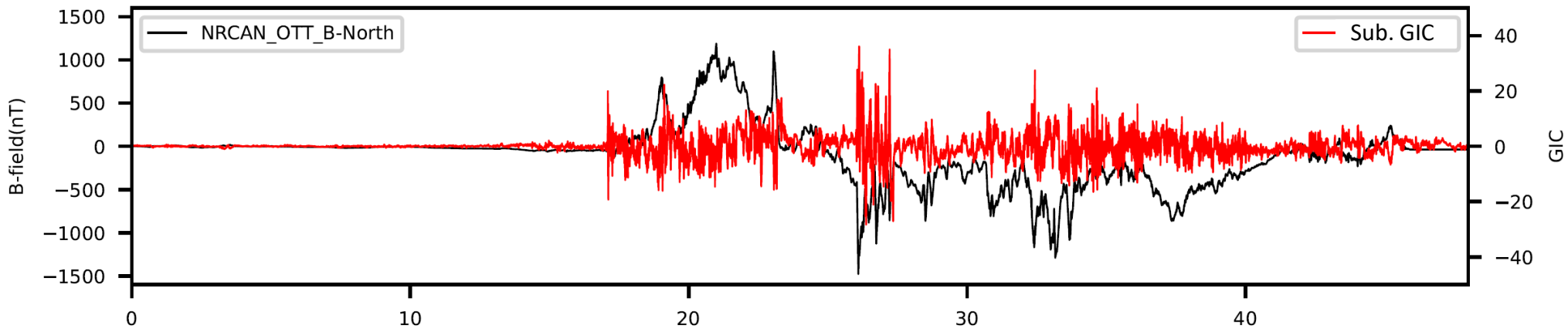
Comparisons to measured GICs in proximity to magnetometers.

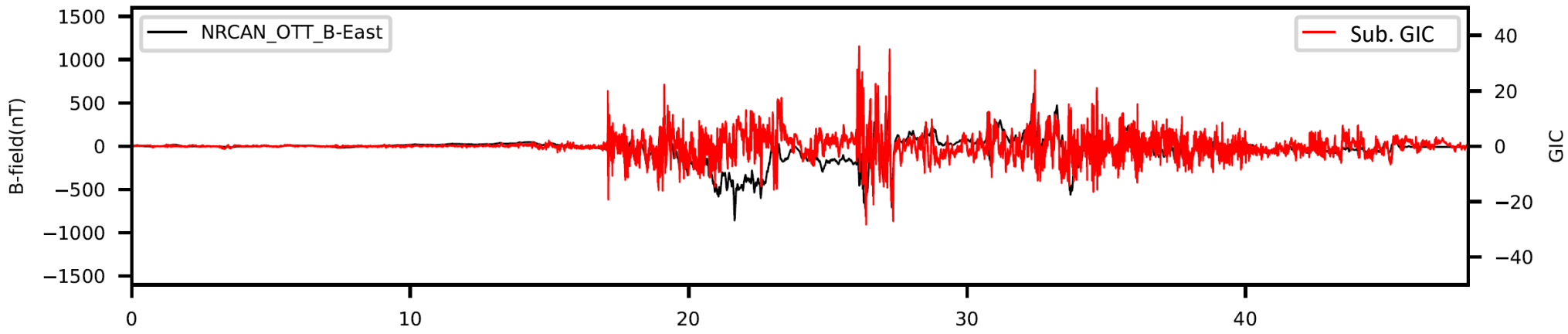


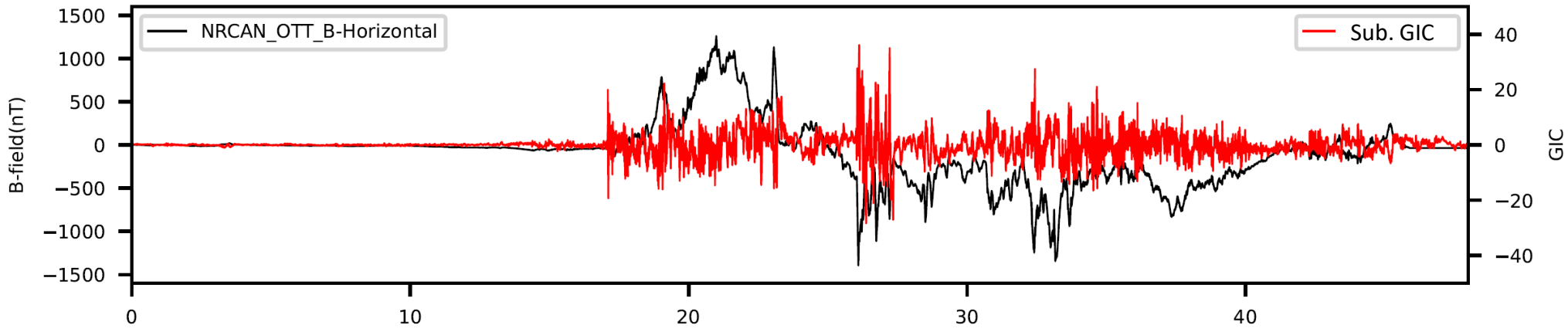
Mid-Atlantic GIC Comparison to USGS FRD Mag.



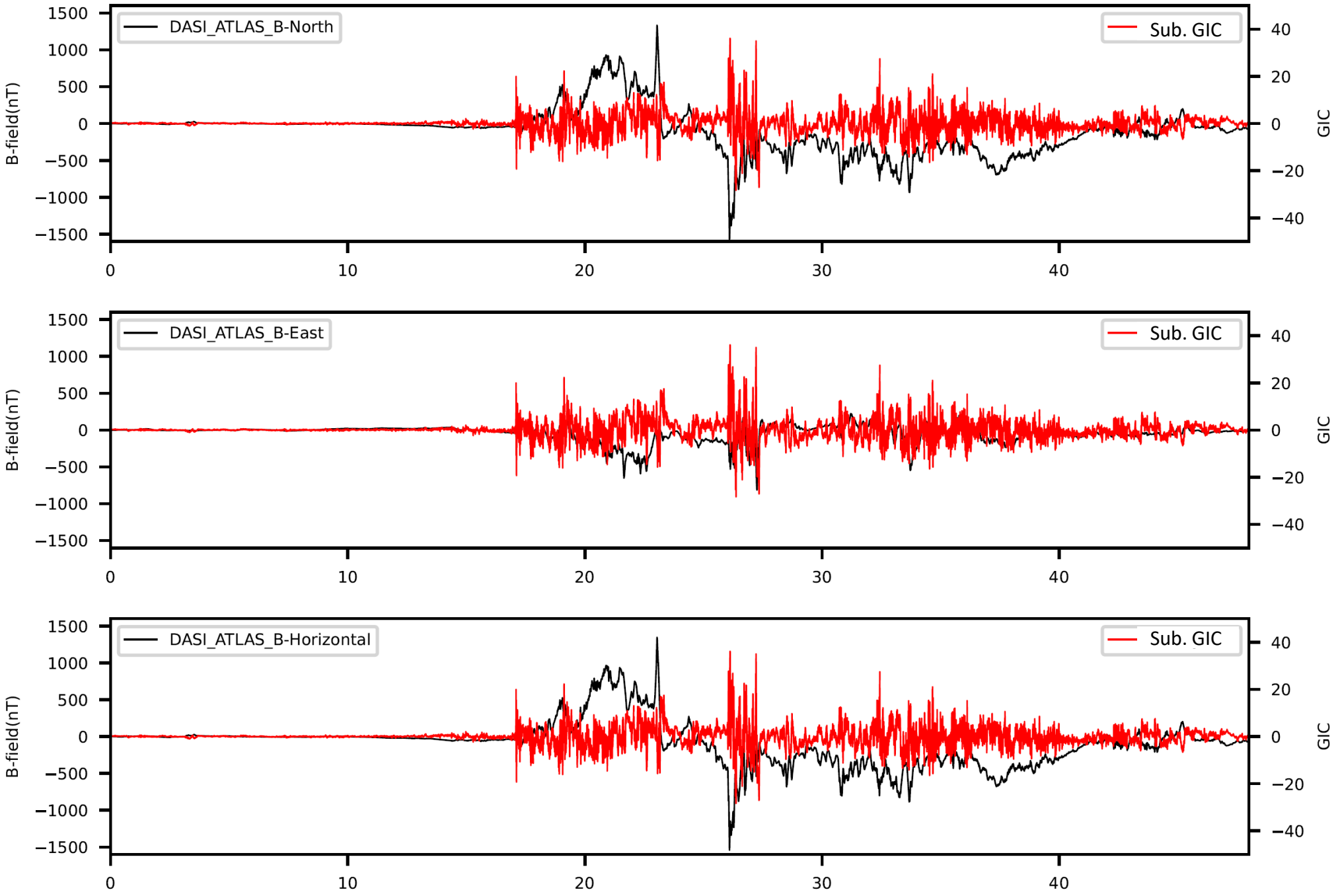
Mid-Atlantic GIC Comparison to DASI Virginia.







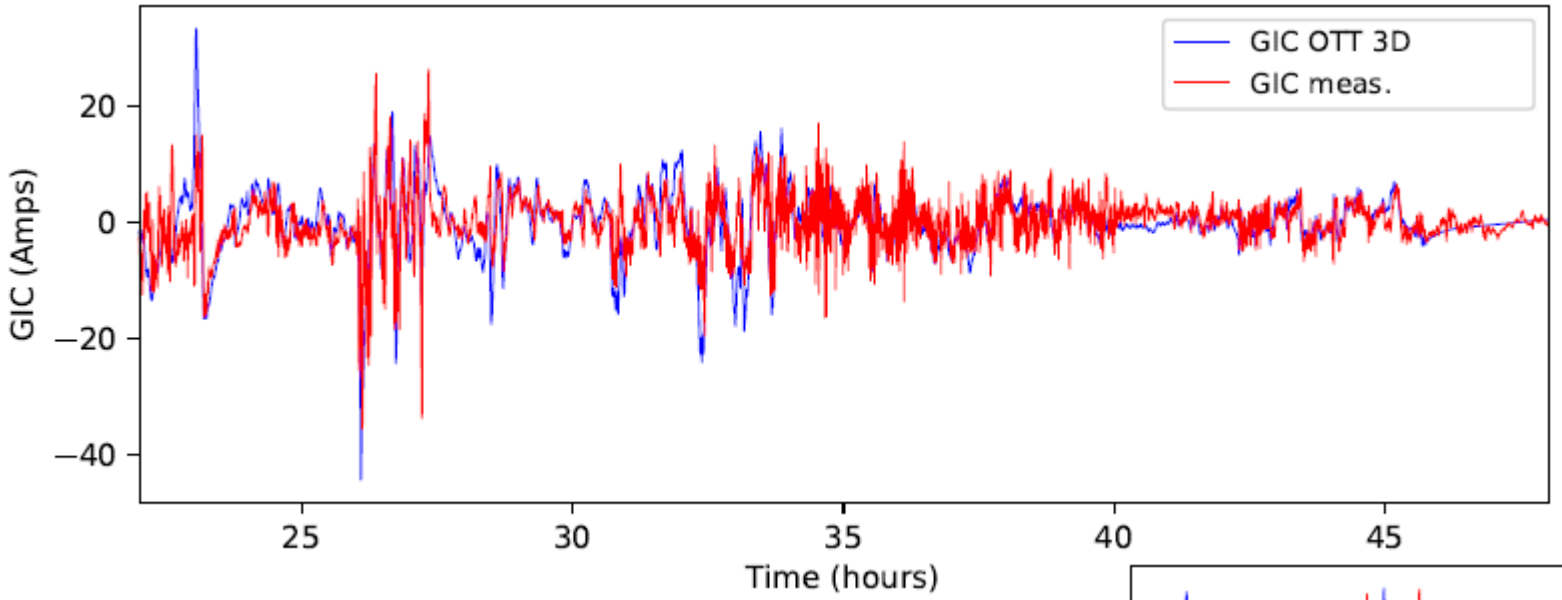
Northeast GIC Comparison to NRCAN OTT.



Northeast GIC Comparison to DASI ATLAS.

May 10th-11th GMD Event –Model Validation

- Validated GIC model in updated Earth Model in Appalachian Region



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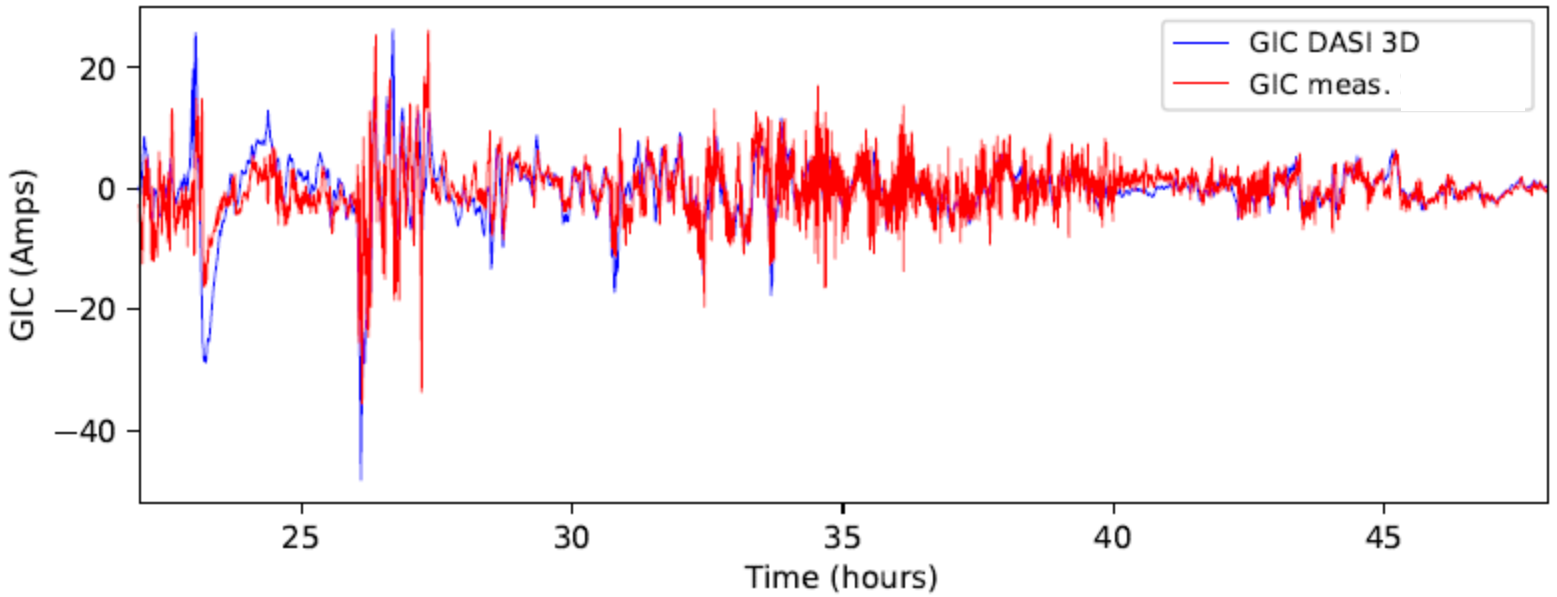

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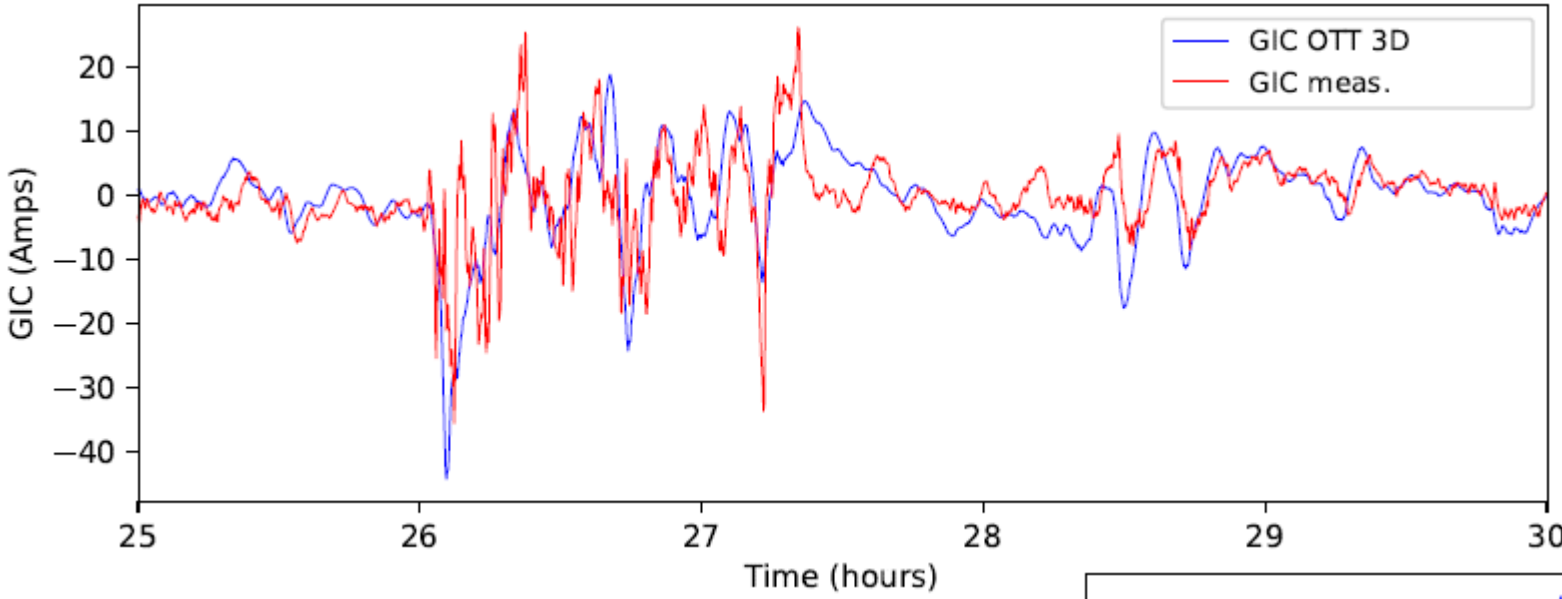

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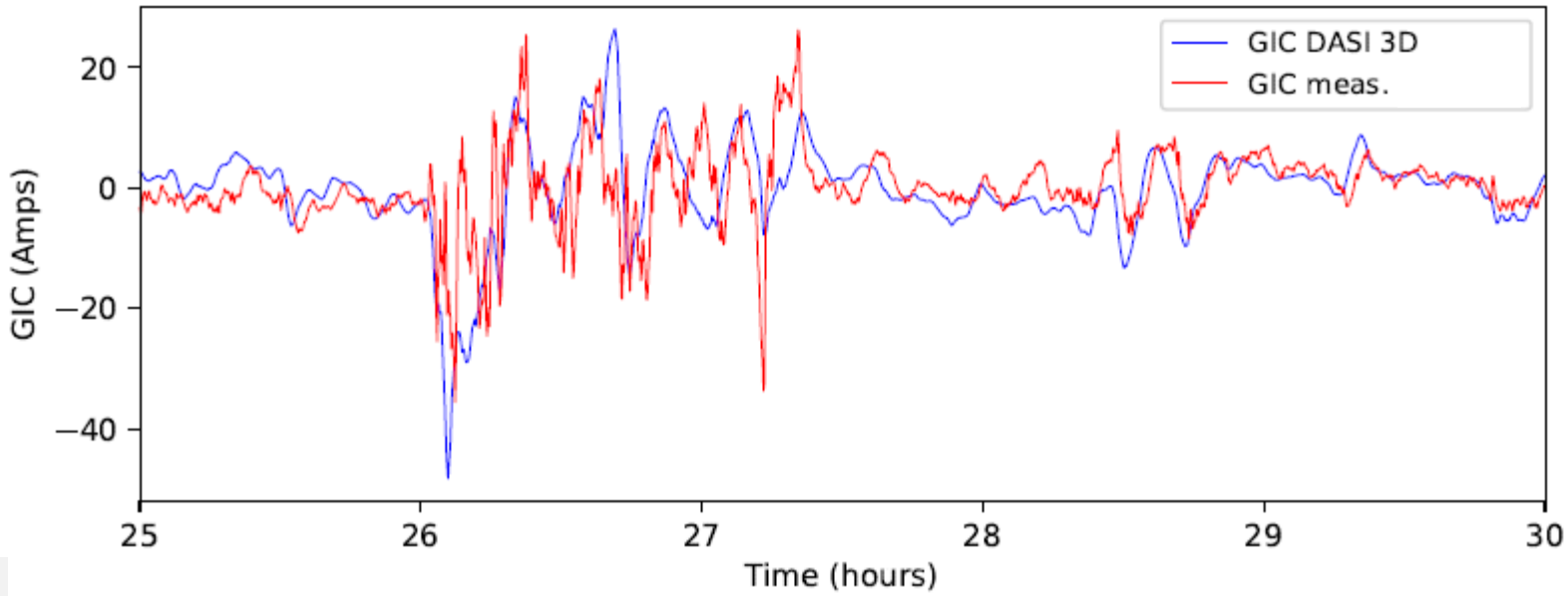

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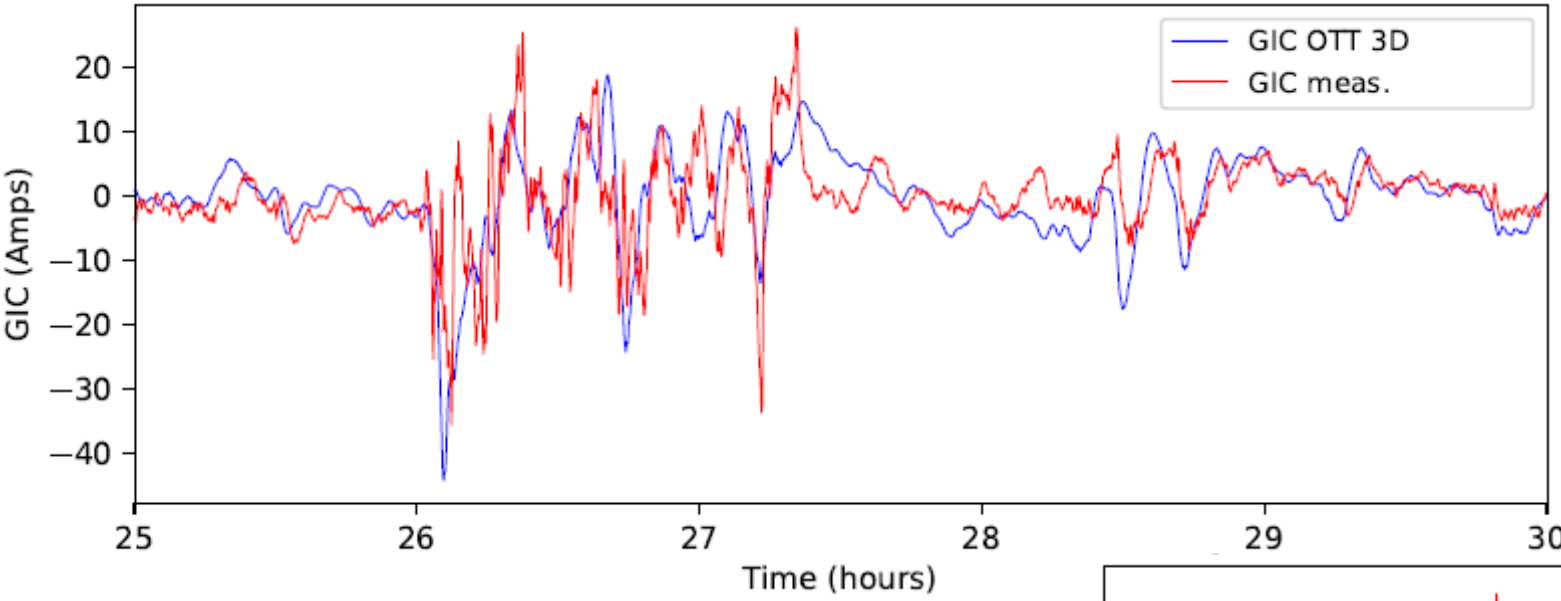

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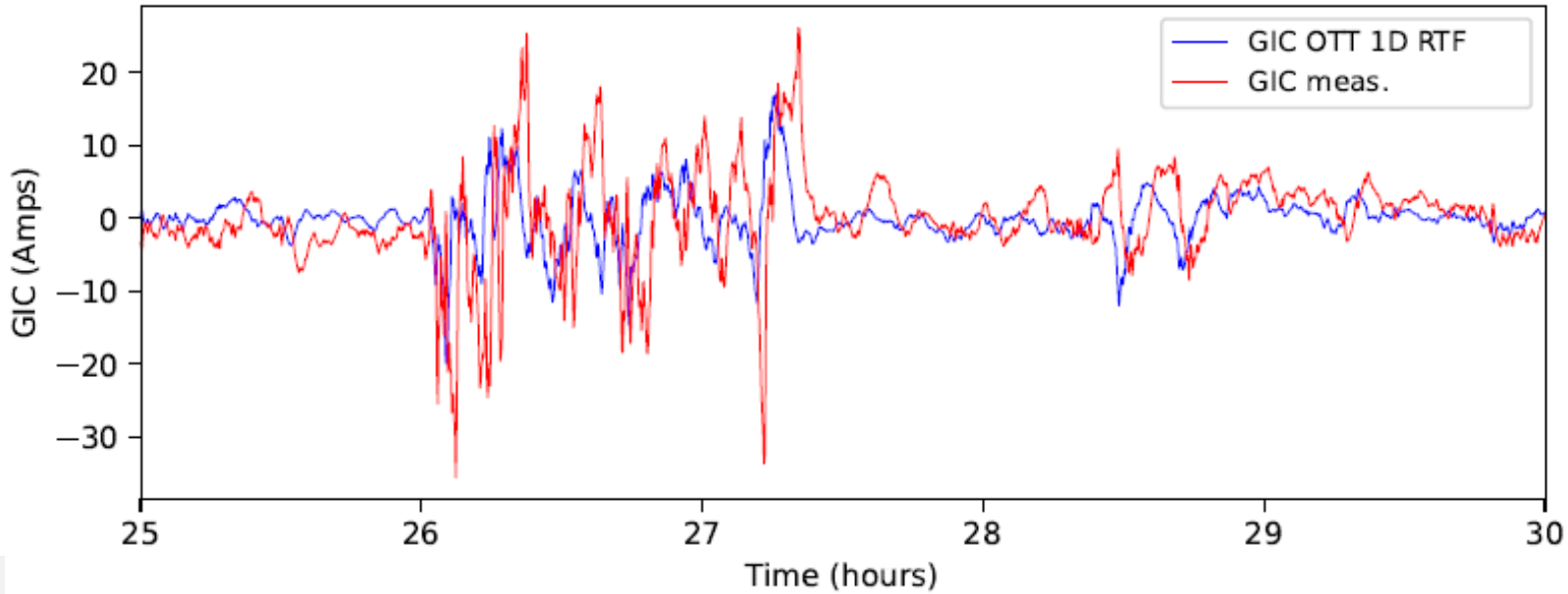
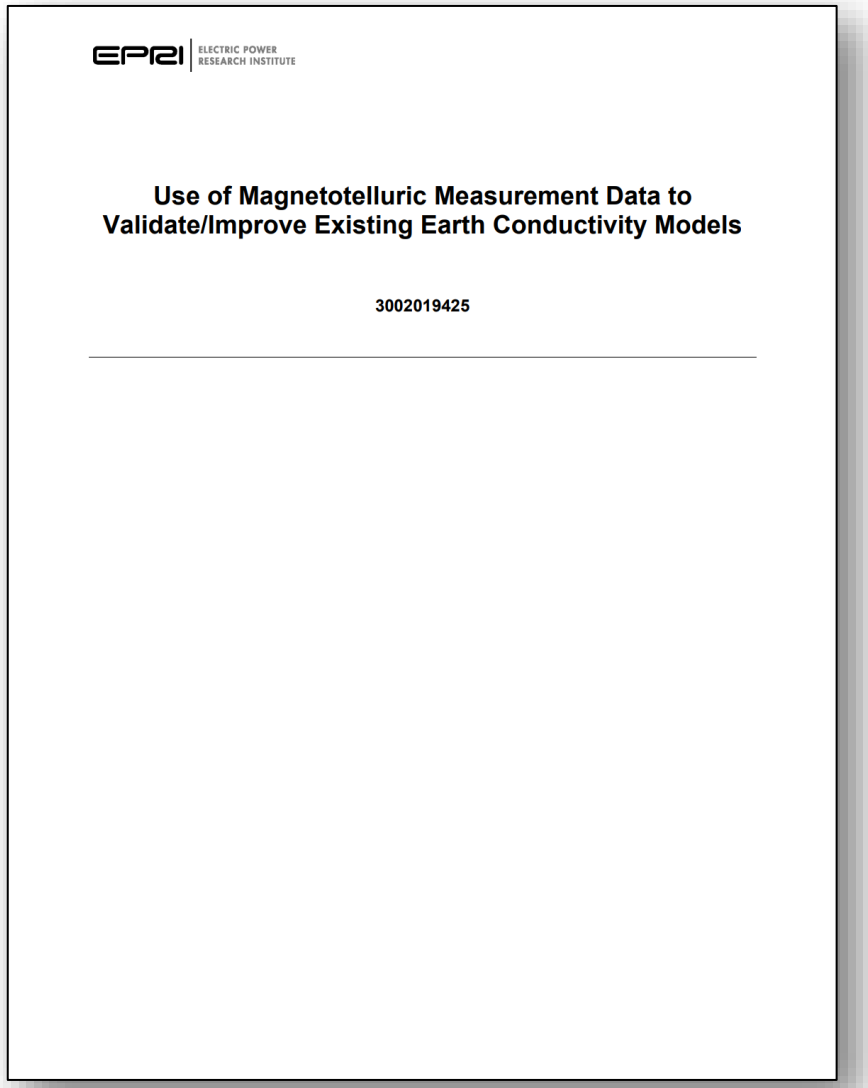


GIC Model Validation

- Perform GIC validation with multiple storms
  - Varying magnitudes and frequencies
- Use different magnetometers even if in proximity to each other.
- Use engineering judgment for peaks and general phase structure for best GIC validation.


EPRI ELECTRIC POWER RESEARCH INSTITUTE

Use of Magnetotelluric Measurement Data to Validate/Improve Existing Earth Conductivity Models

3002019425

Use of Magnetotelluric Measurement Data to Validate/Improve Existing Earth Conductivity Models. EPRI, Palo Alto, CA: 2020. 3002019425.

GMD Workshop

- October 30-31, 2024, at Texas A&M
  - https://epg.engr.tamu.edu/electric-grid-impacts-of-geomagnetic-disturbances/
- EPRI GMD Tool Workshop this year on December 11, 2024

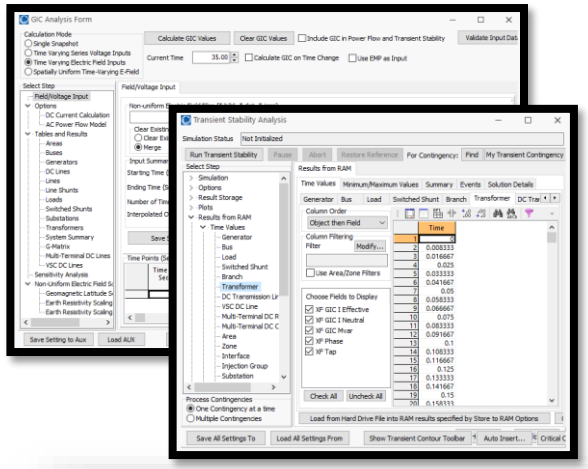
DOE/PNNL Integration Tool Overview

- Tool integrates functionalities of B2eCalc, PowerWorld, PSSE, ETTM and GICHarm.
- Tool manual indicates installation instructions, module functions and input data file description.

B2ECalc: E-field computation

E-field (.b3d)*

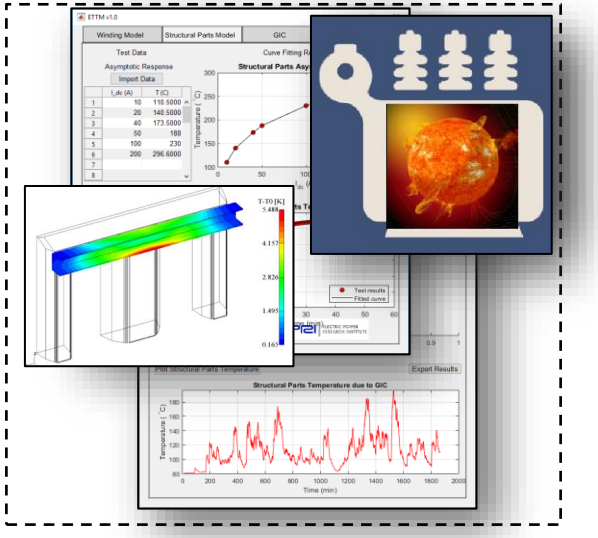
GIC calculations



GIC (.txt)*

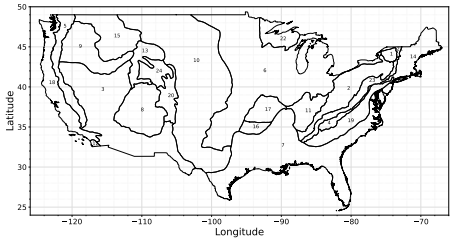
GIC (.xlsx)*

ETTM: Transformer Thermal Analysis

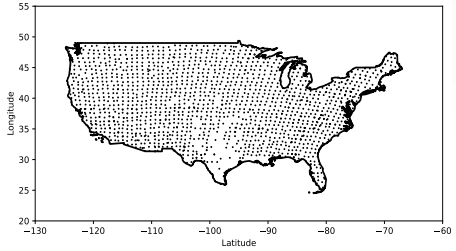


GICHarm: Harmonic Analysis

1D Regional Response



EMTF locations

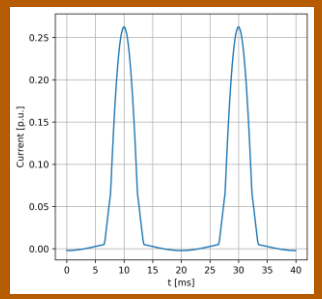


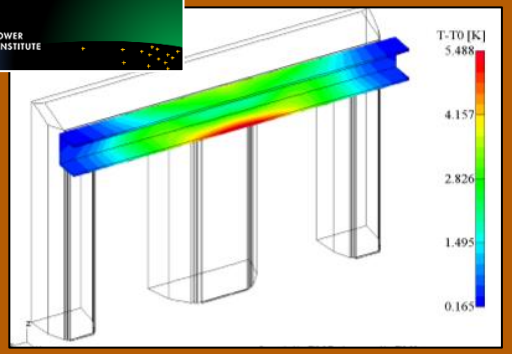
PowerWorld CORPORATION

PSS®E

Answering the Key GMD Research Needs

Planning Analysis



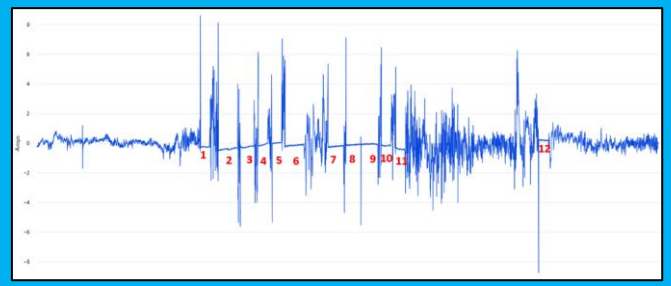


Predicting GIC/harmonic/ thermal responses

Monitoring

Obtaining GIC monitor data from planning area

Mitigation/Operation



Operational and Hardware Mitigation Measures

Research/Compliance Needs for the 1-in-100-year GMD Event

PJM's Operating Experience
May 2024 GMD Event

Dr. Emanuel Bernabeu
Sr. Director, Applied Innovation & Analytics
PJM Interconnection

NERC GMD Workshop
October 1, 2024

Agenda

01 Introduction

02 Situational Awareness

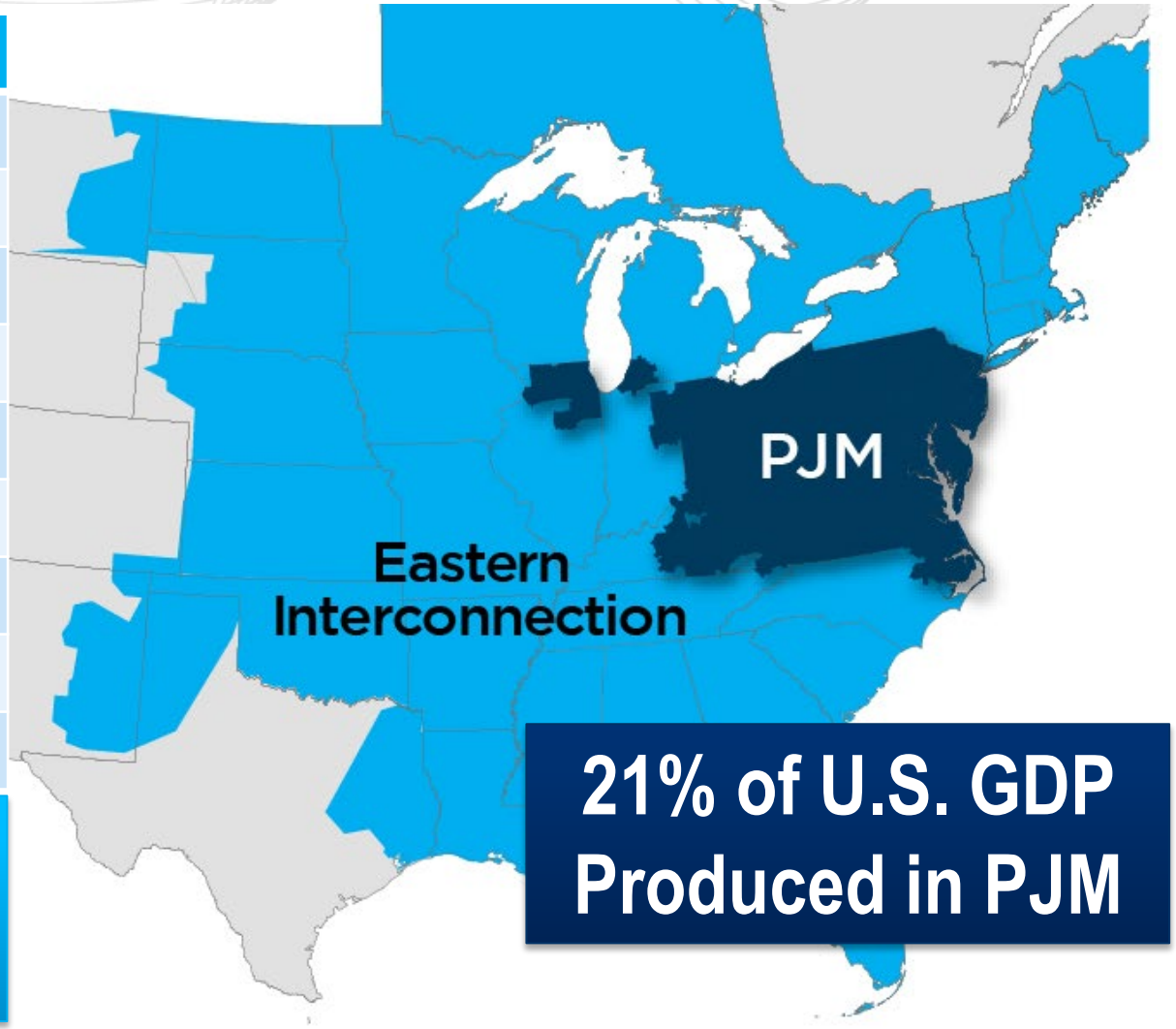
03 Operating Procedures

04 Final Remarks

PJM as Part of the Eastern Interconnection

Key Statistics	
Member companies	1,090
Millions of people served	65+
Peak load in megawatts	165,563
Megawatts of generating capacity	180,785
Miles of transmission lines	88,185
Terawatt hours of annual energy	770
Generation sources	1,439
Square miles of territory	368,906
States served	13 + DC

- 26% of generation in Eastern Interconnection
- 25% of load in Eastern Interconnection
- 20% of transmission assets in Eastern Interconnection



As of 2/2024

PJM's Core Function

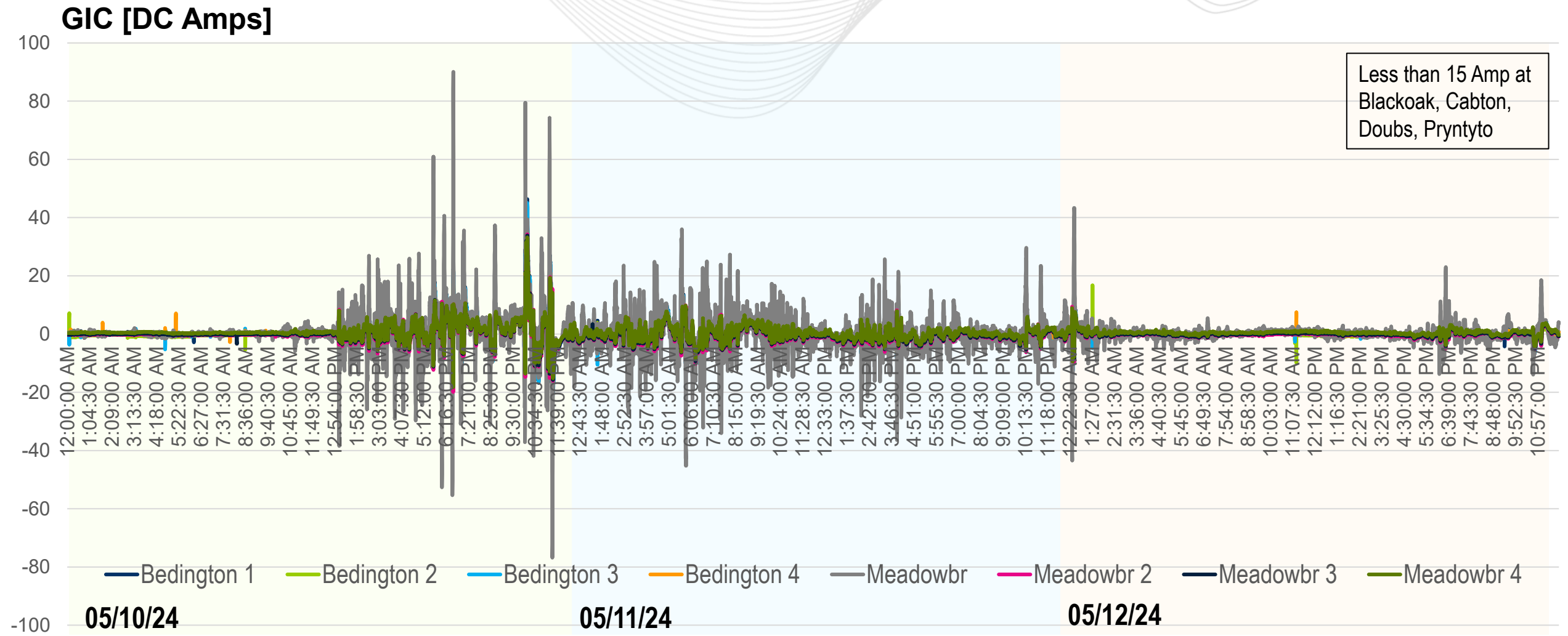
Markets | Planning | Operations

GMD Risk Assessment

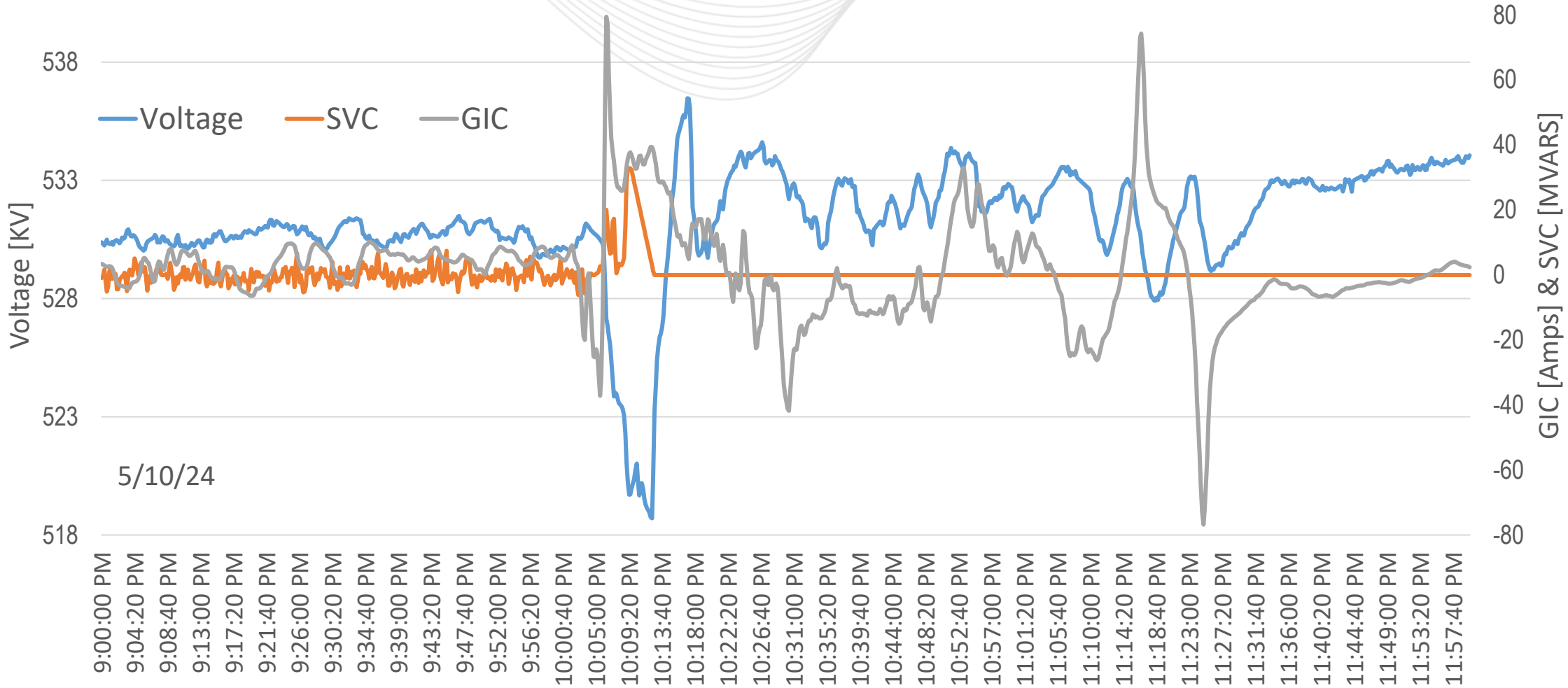
Transformer Failure

Voltage Stability

GIC > 15 Amps

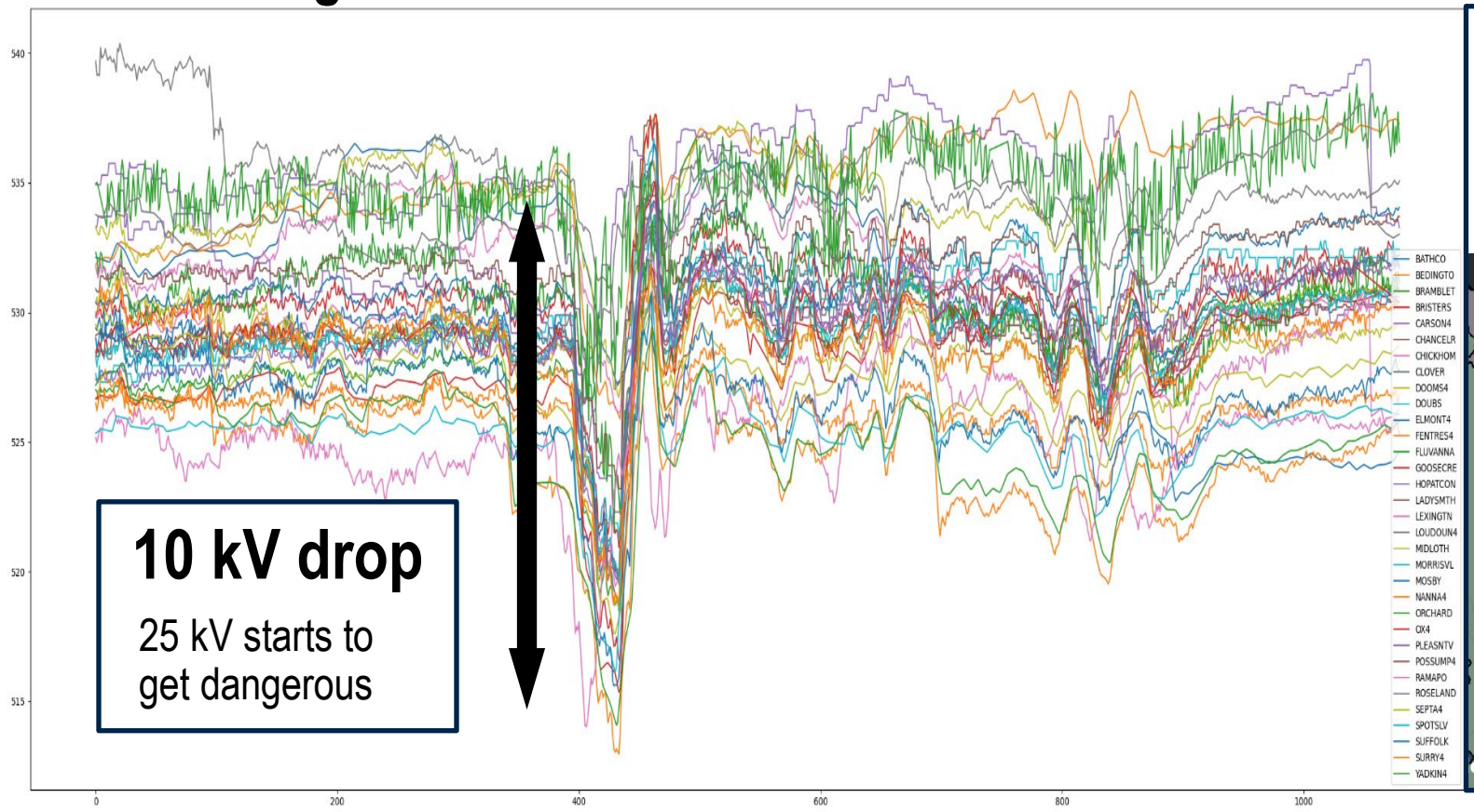


SVC Trip

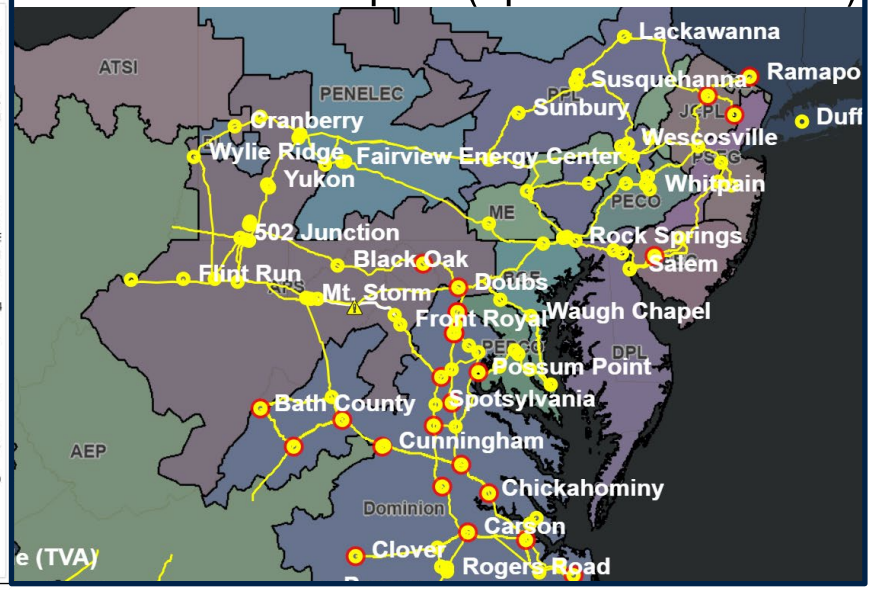


Voltage Stability

500 kV Voltage



765 kV negligible impact
500 kV – 10 kV voltage drop
345 kV negligible impact
230 kV smaller impact (~pattern as 500 kV)



Final Remarks

Operating Procedures

NOAA and Field Monitoring to Enhance Situational Awareness.

Keeping the Lights On

NERC Standards & Model Validation

Periodic Studies and Continued Validation using GMD Events.

Hardening the System

Equipment Specifications Requirements for GMD

AURORAL ZONE

Hydro-Québec

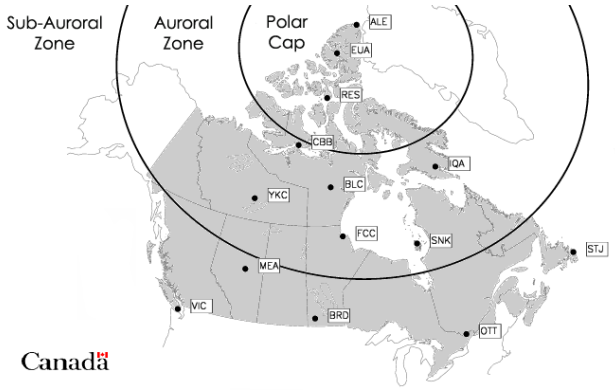
Hydro Generation in North

Load in South (600 miles)

- Montreal-Quebec

Wide-Area

Auroral Zone



Hydro-Québec Control Center

From 2005 to 2016:
Real time alert on a single/double EHD Measure (Even Harmonic Distortion)

Before 2005 (March 1989):
The Voltage Asymmetry was used instead of EHD.

GIC causes partial saturation of transformer cores and inductors. This results in an asymmetrical deformation of the voltage wave, which can be measured using peak voltages or harmonic content

$$\text{EHD}\ (2,4,6,8) = \frac{\sqrt{V_2{}^2 + V_4{}^2 + V_6{}^2 + V_8{}^2}}{\sqrt{V_1{}^2 + V_2{}^2 + \cdots + V_8{}^2}}$$

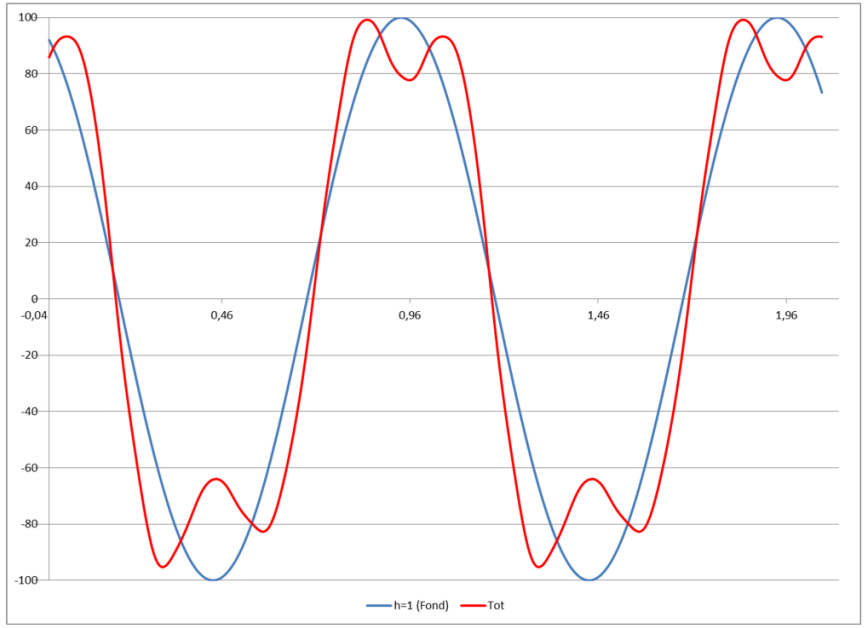
where V_i is the Voltage Amplitude or Harmornic #i $(i\ x\ 60\ Hz)$

Voltage Asymmetry : $(V^+ - V^-) / (V^+ + V^-)$

Saguenay (1989)
– Asym = 2%

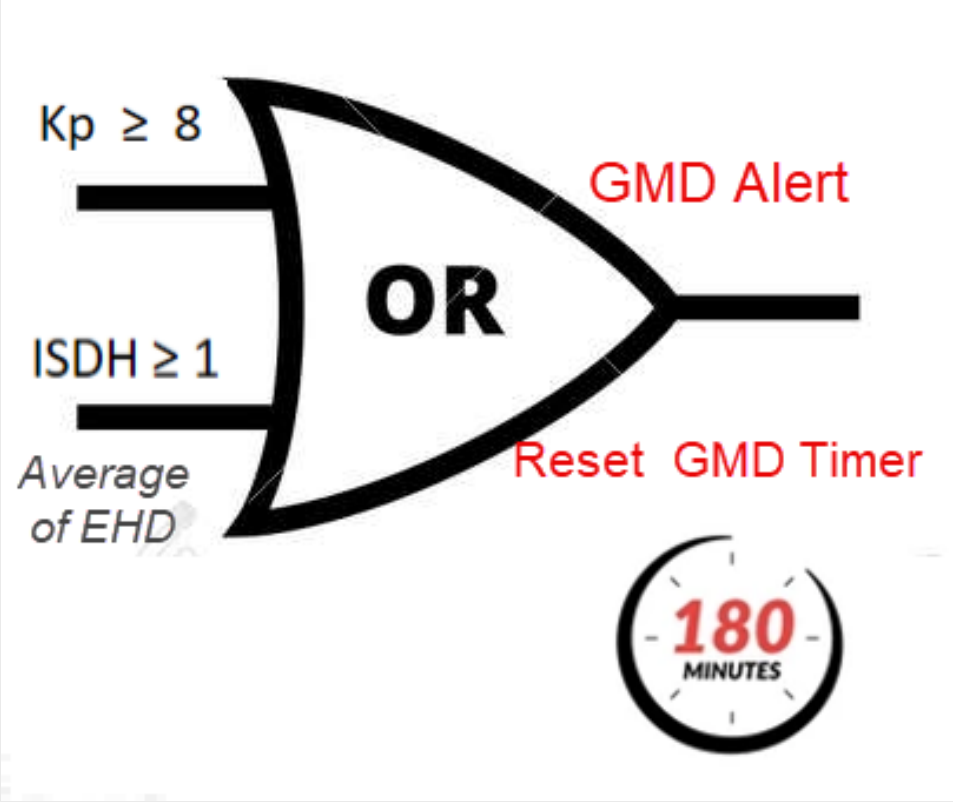
Academic Example

Asymmetry 2 % :
(99-95)/(99+95)=2 %



Hydro-Québec Control Center monitor

Real-time Conditions for GMD Alert:



Now (since 2017)

ISDH - Harmonic Distorsion Severity Average

→ Threshold = 1.0 for at least 1 minute ←

is used (with Kp index) to activate GMD Alert

$$= \frac{4}{N} \times \sum_{i=1}^{N} \frac{\textbf{EHD Measure } i}{\text{Threshold of EHD Measure } i}$$

$$where \quad \rightarrow \quad N = \text{Number of valid EHD Measure}$$

There are 10 EHD measures distributed across the BULK electricity network

→ Threshold of Measure i =

2.2 % *for all 9 Hydro Québec EHD measures*

5.0 % *for the EHD measure on the 765 kV line to USA*

2024 May 10th GMD

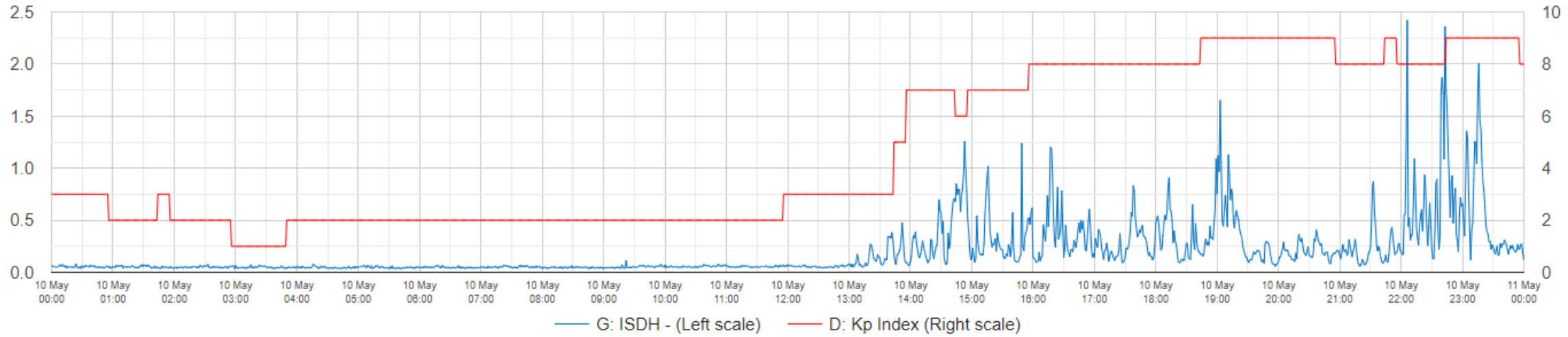
Hydro-Québec Control Center

- Voltage variations (15 kV drop) are observed (but still in normal operating range)
- ISDH (Average of EHD), Kp reached 7, 8 and 9 during afternoon

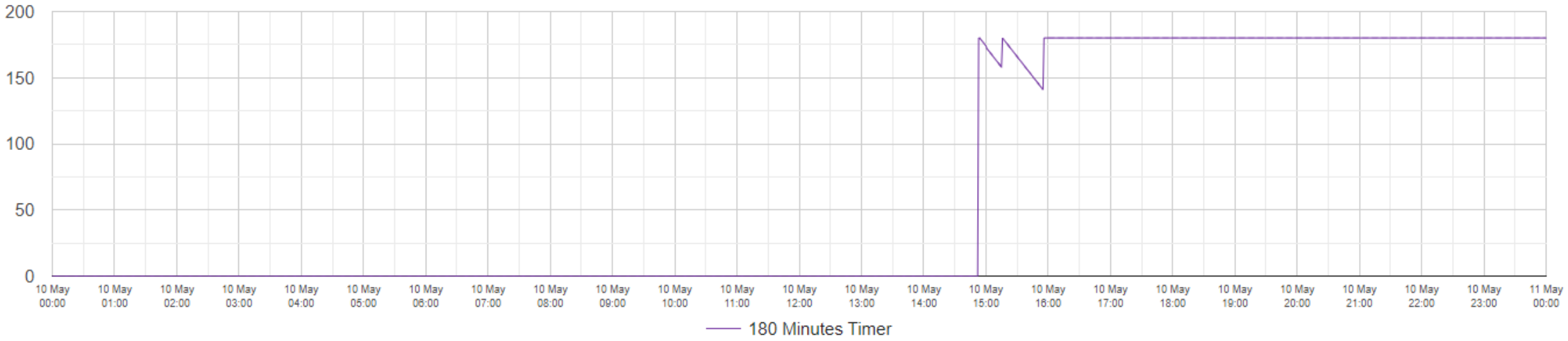
  - Activation of « Conservative Mode » and limit planned outages
  - Try to bring back SVCs (Static VAR Compensator) and Series Compensation
  - AC/DC Back-to-Back Converters to neighboring system volontary decreased of 50%
  - Raise and maintain high electrical voltage of the main electric network

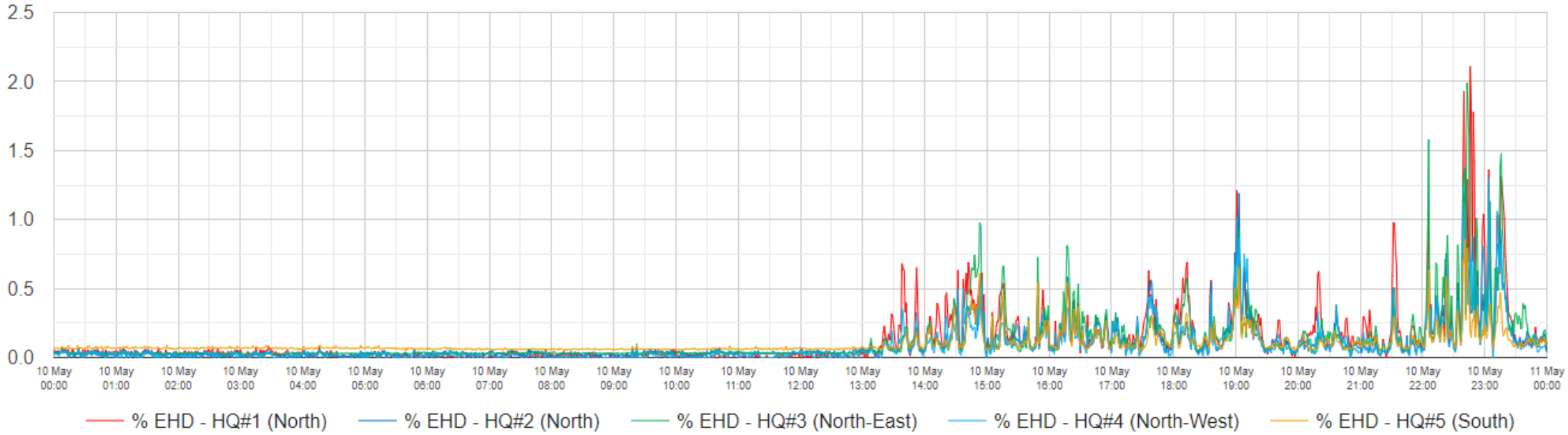
May 10th – EHD, Kp

May 10th - ISDH (Harmonic Distorsion Severity Index where threshold = 1.00) and Kp Index (threshold=8)

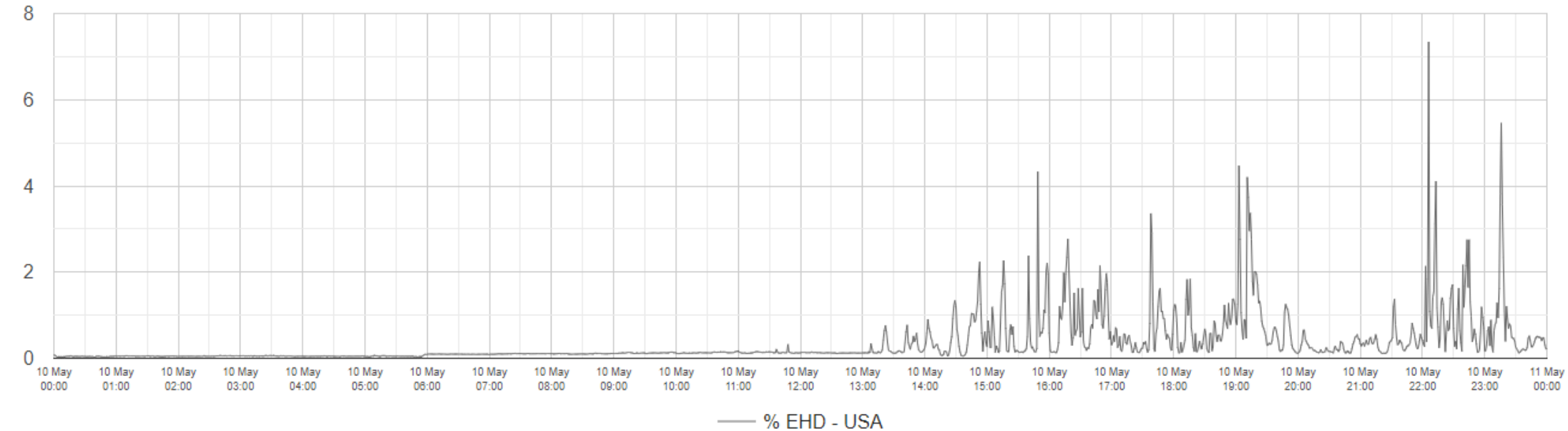


Geomagnetic Storm ConditionTimer (180 min)



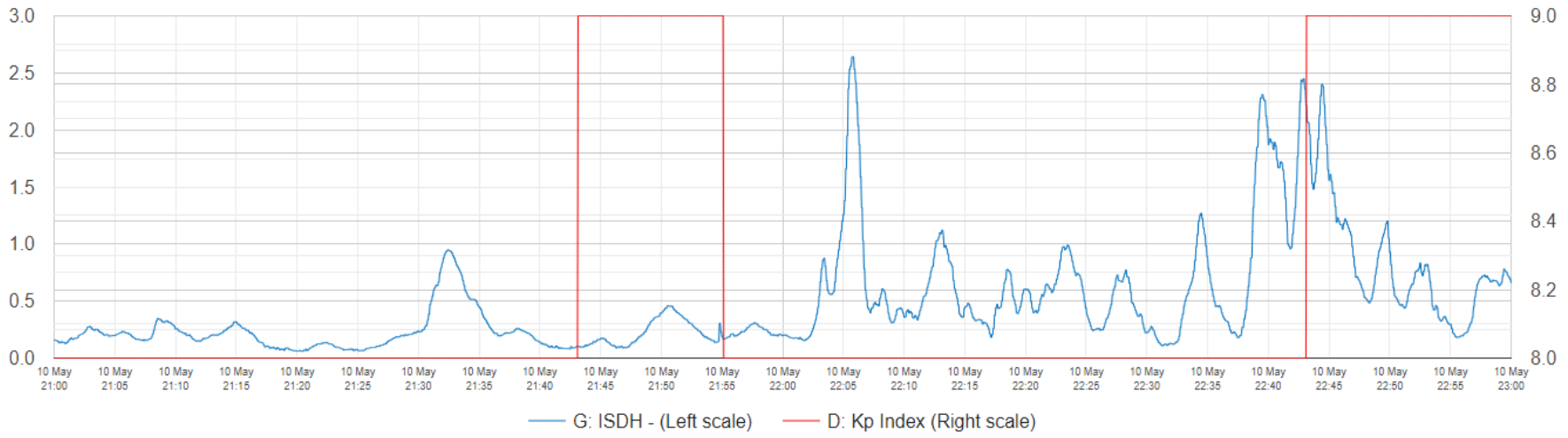


% EHD - Even Harmonic Distorsion 2,4,6,8 - Line to USA

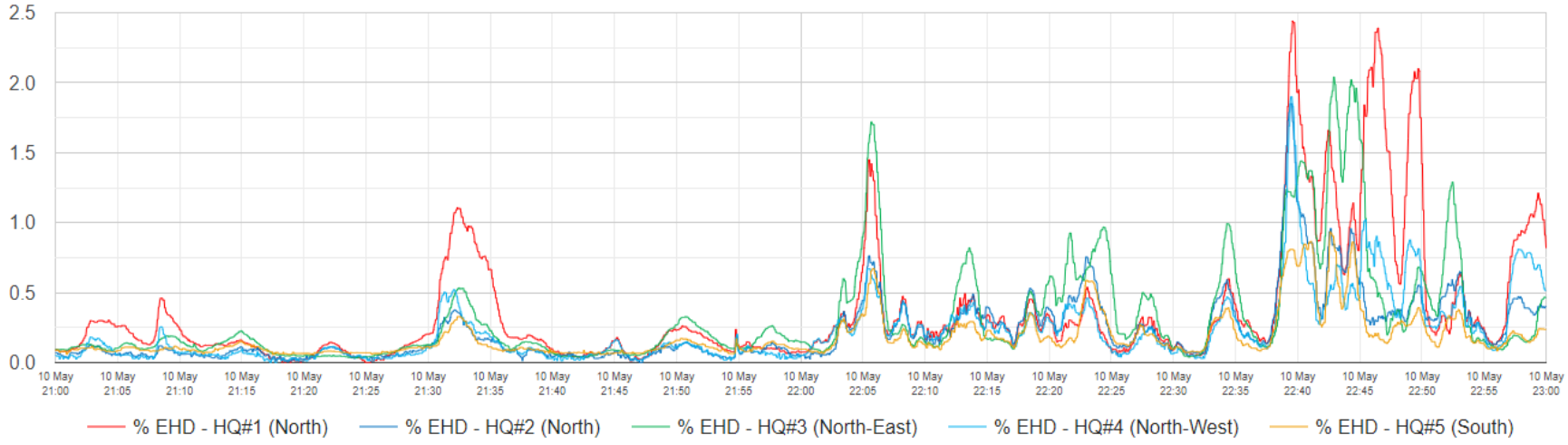


May 10th – 09:00 PM to 11:00 PM EST |EHD, Kp

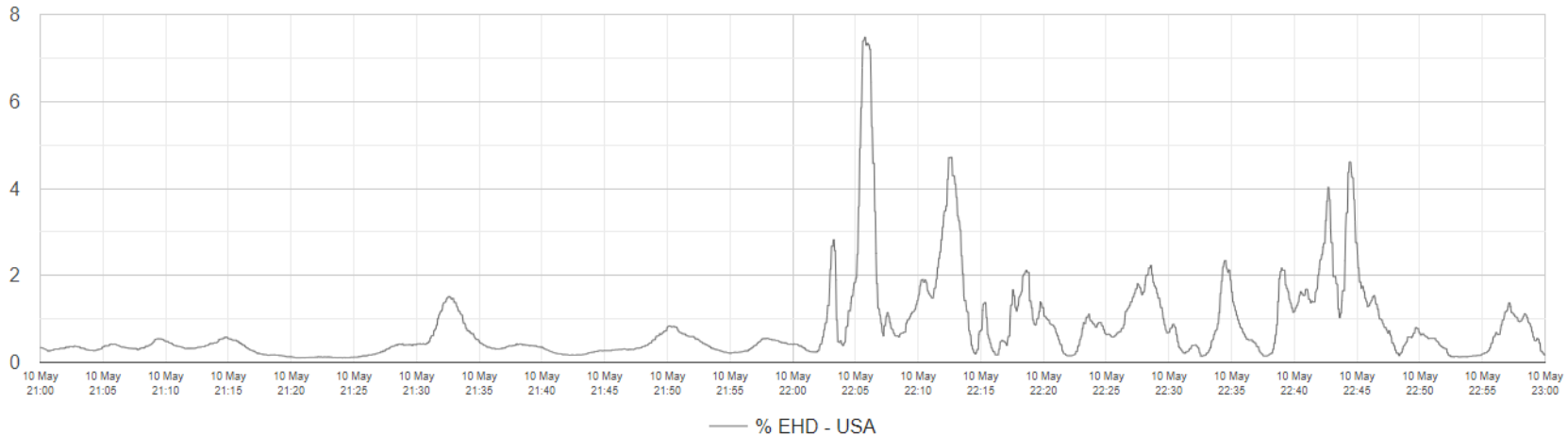
May 10th [10:00PM to 00:00AM] - ISDH (Harmonic Distorsion Severity Index) where threshold = 1.00 and Kp Index (threshold=8)



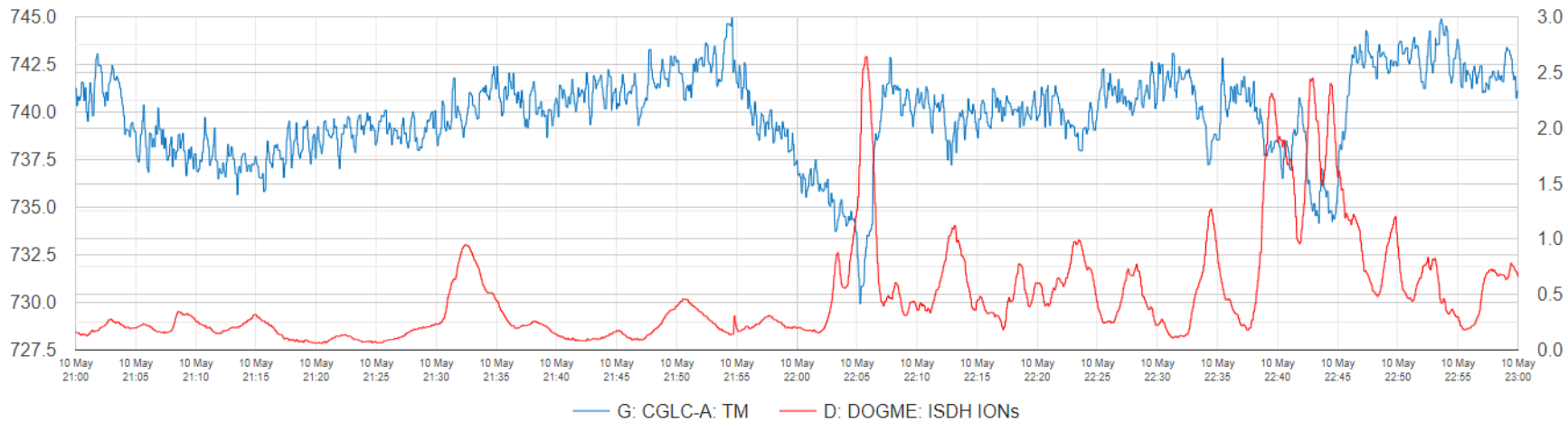
% EHD - Even Harmonic Distorsion 2,4,6,8 - Hydro-Québec



% EHD - Even Harmonic Distorsion 2,4,6,8 - Line to USA



Average voltage of the Montreal Loop VS ISDH



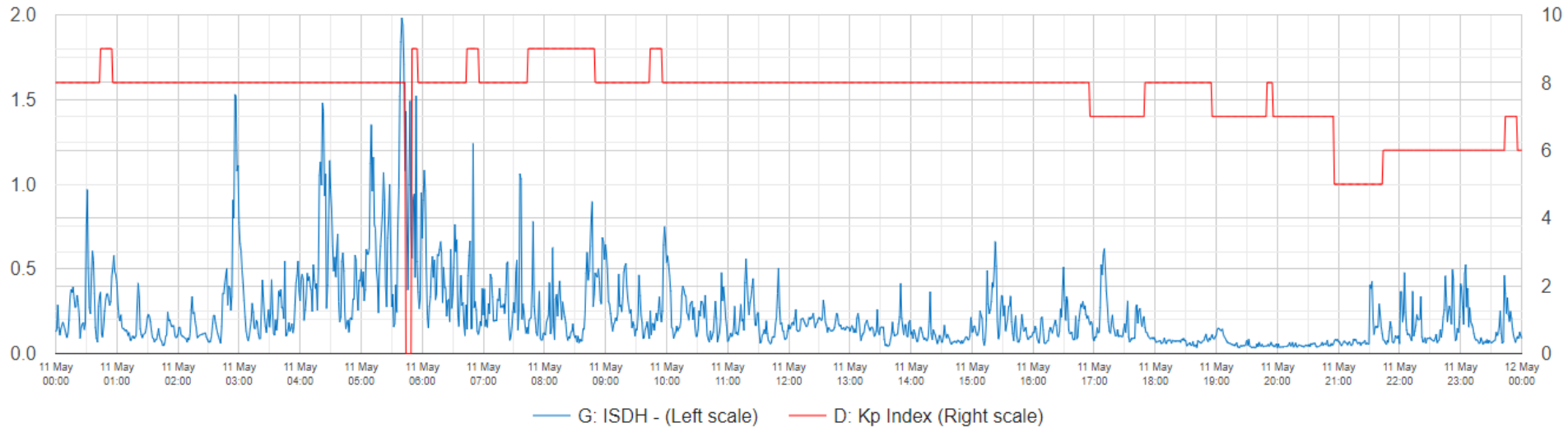
2024 May 11th GMD

Hydro-Québec Control Center

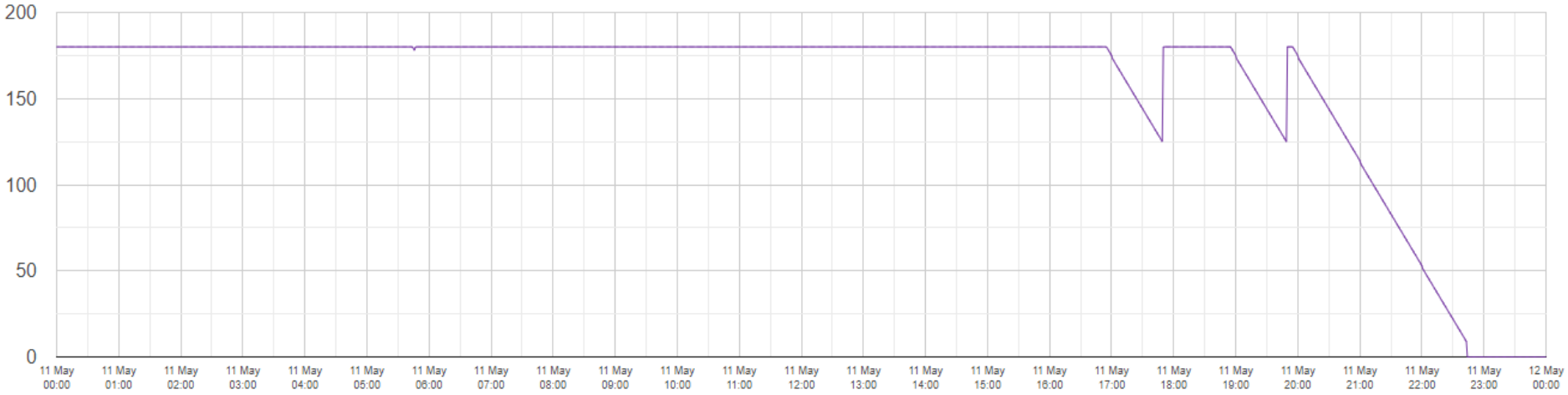
- ISDH (Average of EHD) during night and morning, Kp = 8 and 9
- Maintain « Conservative Mode » untill 10:45 PM EST (End of 180 minutes timer Kp = 5-6)

May 11th – EHD, Kp

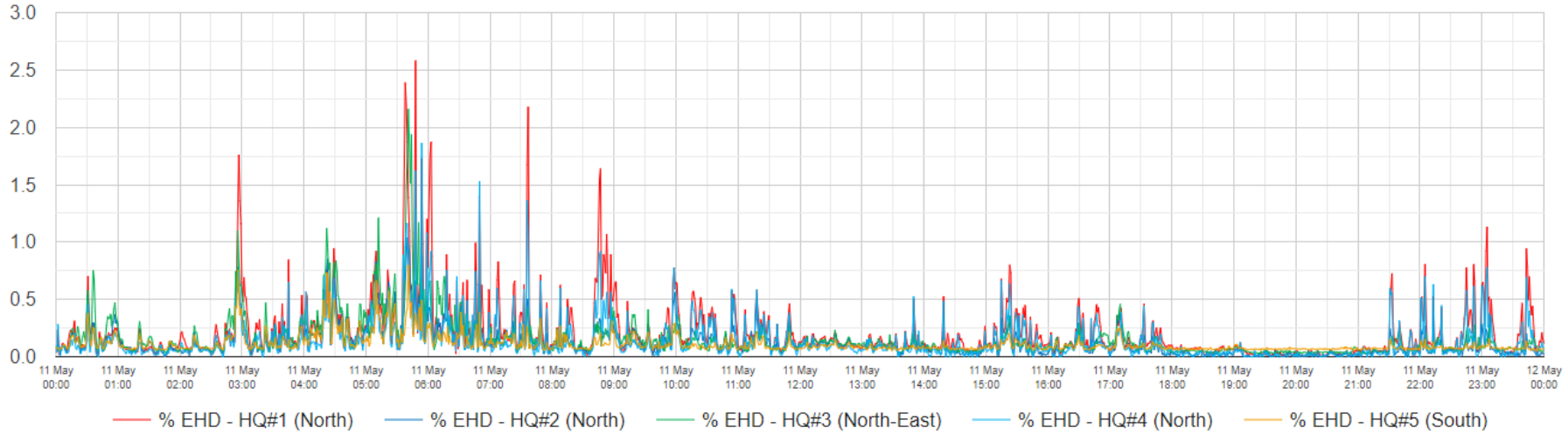
May 11th - ISDH (Harmonic Distorsion Severity Index where threshold = 1.00) and Kp Index (threshold=8)



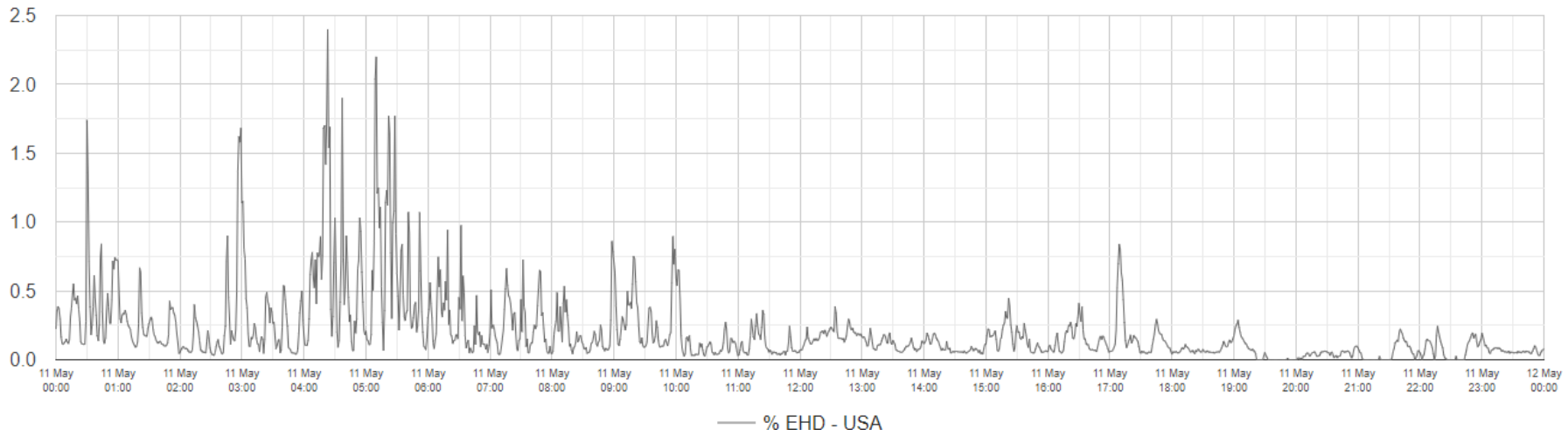
Geomagnetic Storm ConditionTimer (180 min)



% EHD - Even Harmonic Distorsion 2,4,6,8 - Hydro-Québec



% EHD - Even Harmonic Distorsion 2,4,6,8 - Line to USA



2024 May 12th GMD

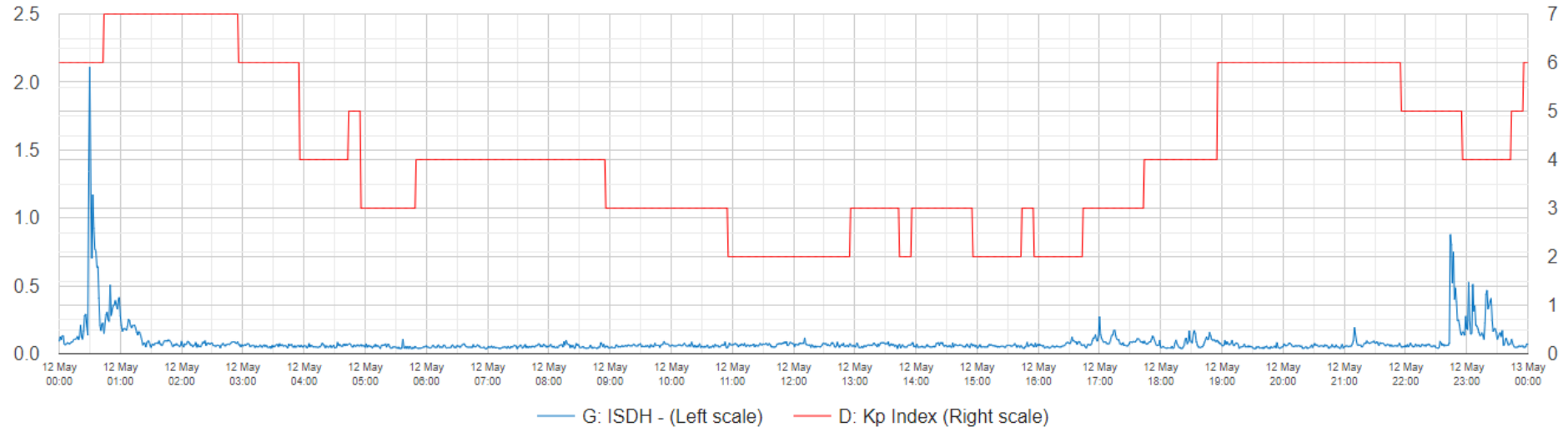
Hydro-Québec Control Center

- ISDH (Average of EHD) reached threshold à 1:00 AM, Short but strong GMD North of Québec
  - Reactivation of « Conservative mode »
  - Reduction of some GMD restrictions during the day but maintain of « Conservative Mode »

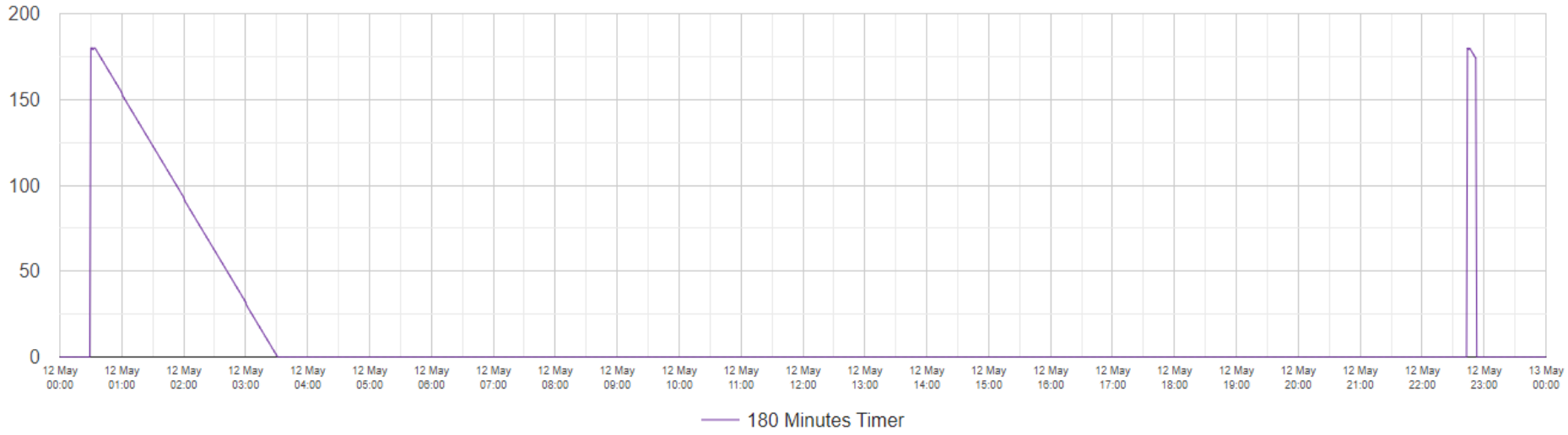
*** At Hydro-Québec, no device trips relatively to this GMD Event ***

May 12th – EHD, Kp

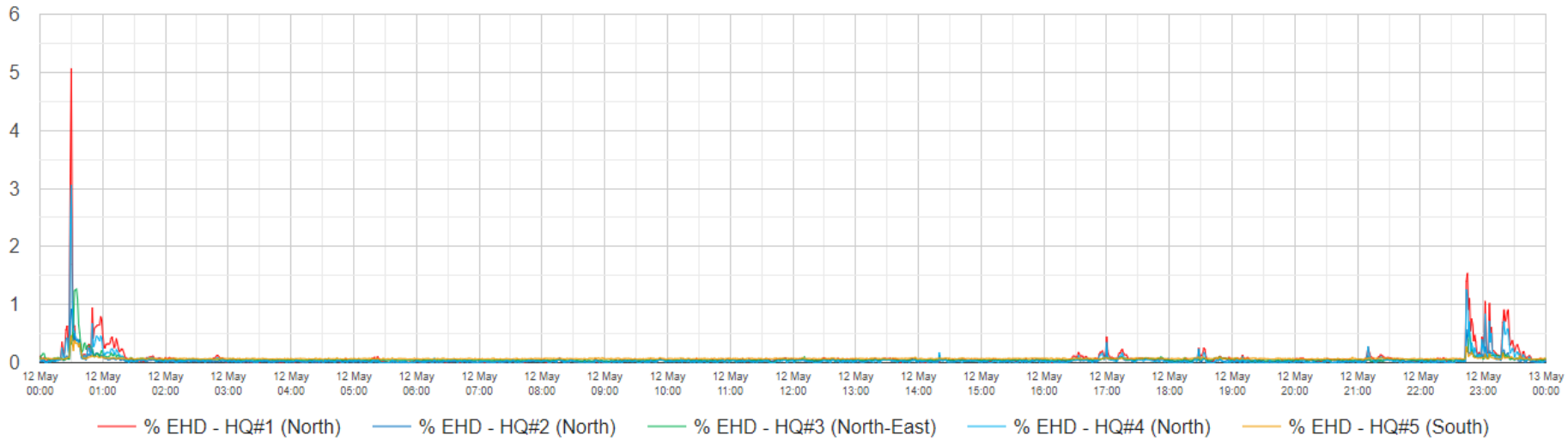
May 12th - ISDH (Harmonic Distorsion Severity Index where threshold = 1.00) and Kp Index (threshold=8)



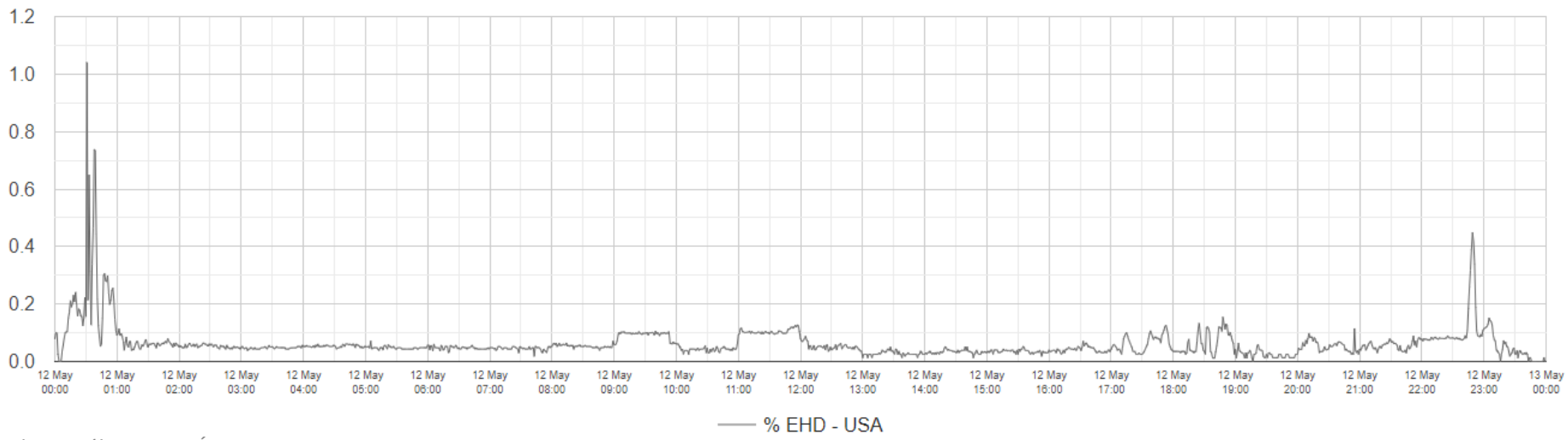
Geomagnetic Storm ConditionTimer (180 min)



% EHD - Even Harmonic Distorsion 2,4,6,8 - Hydro-Québec

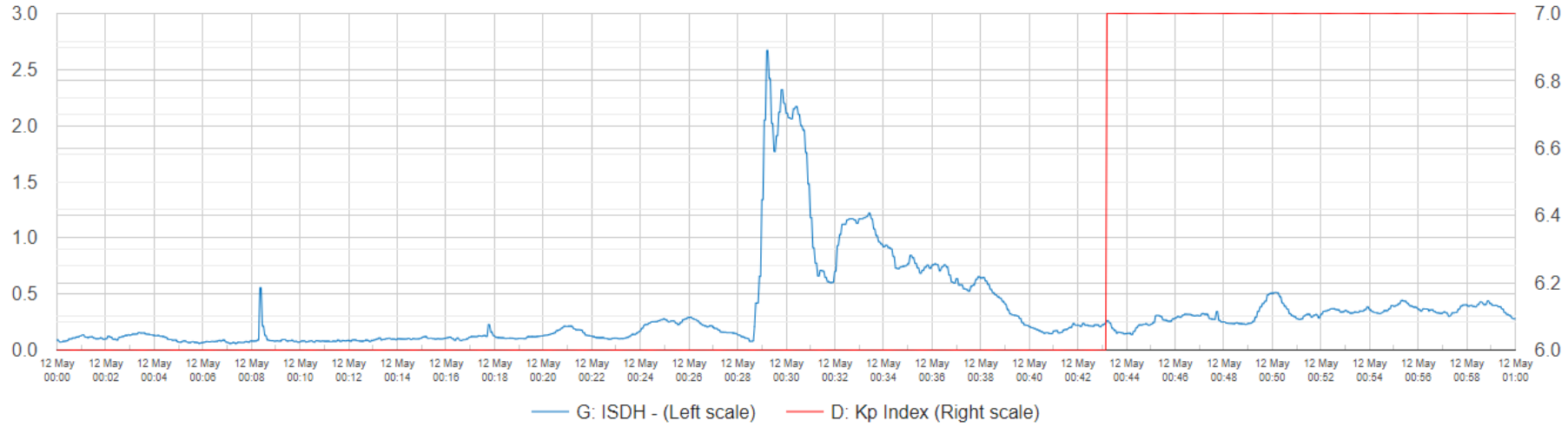


% EHD - Even Harmonic Distorsion 2,4,6,8 - Line to USA

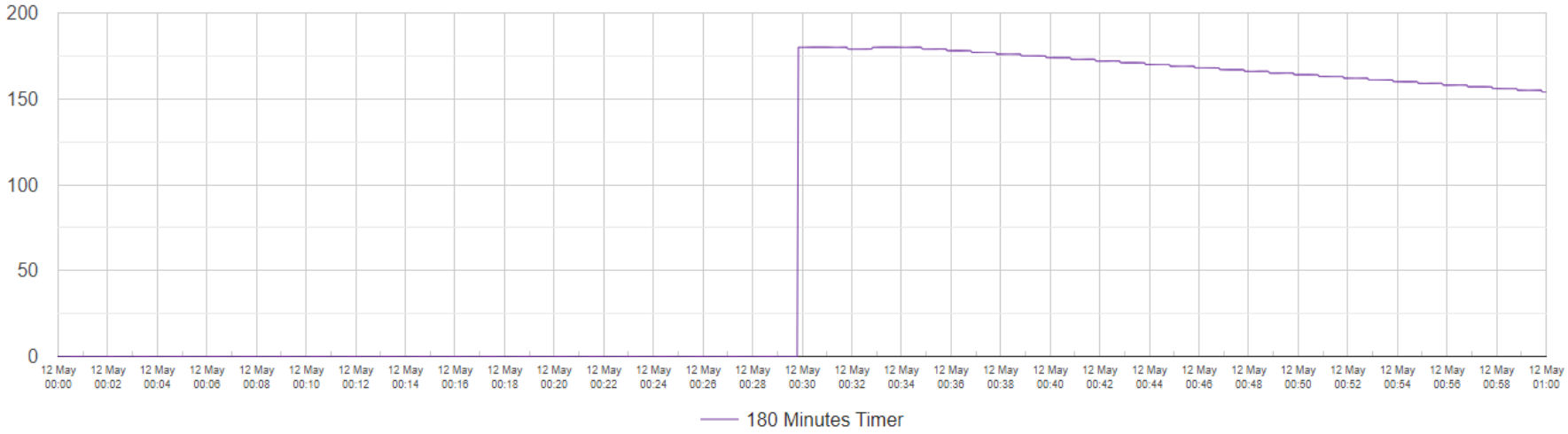


May 12th – 00:00 AM to 01:00 AM EST EHD, Kp

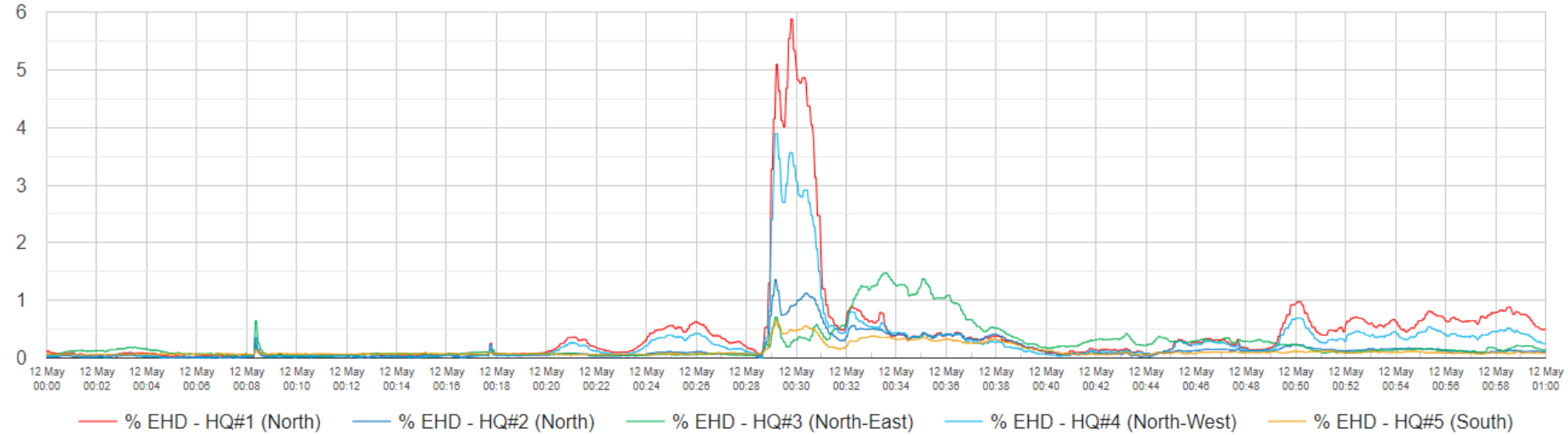
May 12th [00:00AM to 01:00AM] - ISDH (Harmonic Distorsion Severity Index) where threshold = 1.00 and Kp Index (threshold=8)



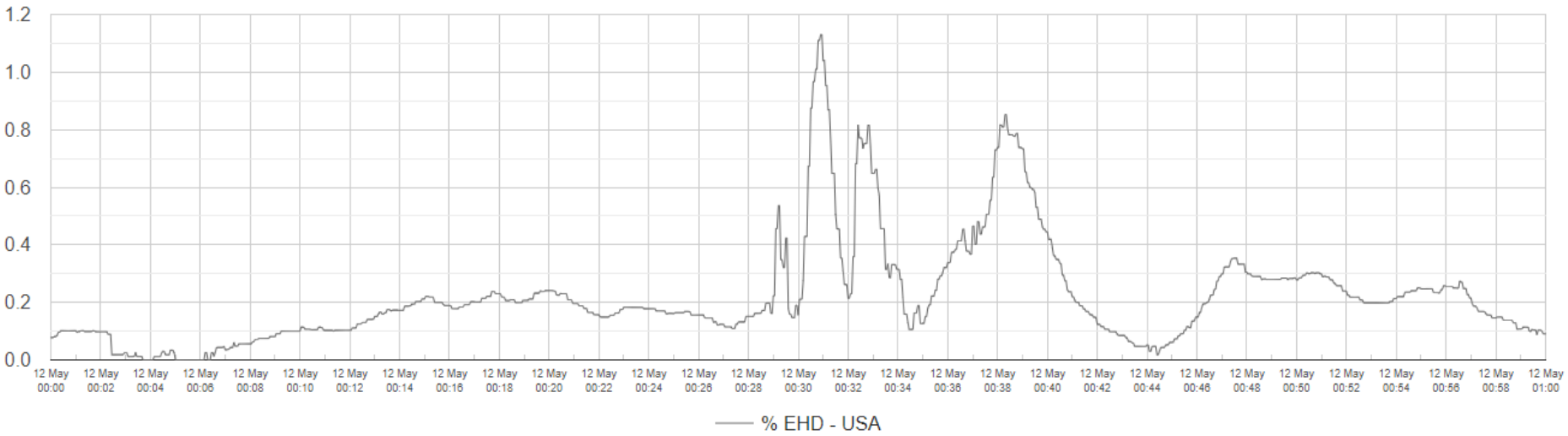
Geomagnetic Storm ConditionTimer (180 min)



% EHD - Even Harmonic Distorsion 2,4,6,8 - Hydro-Québec

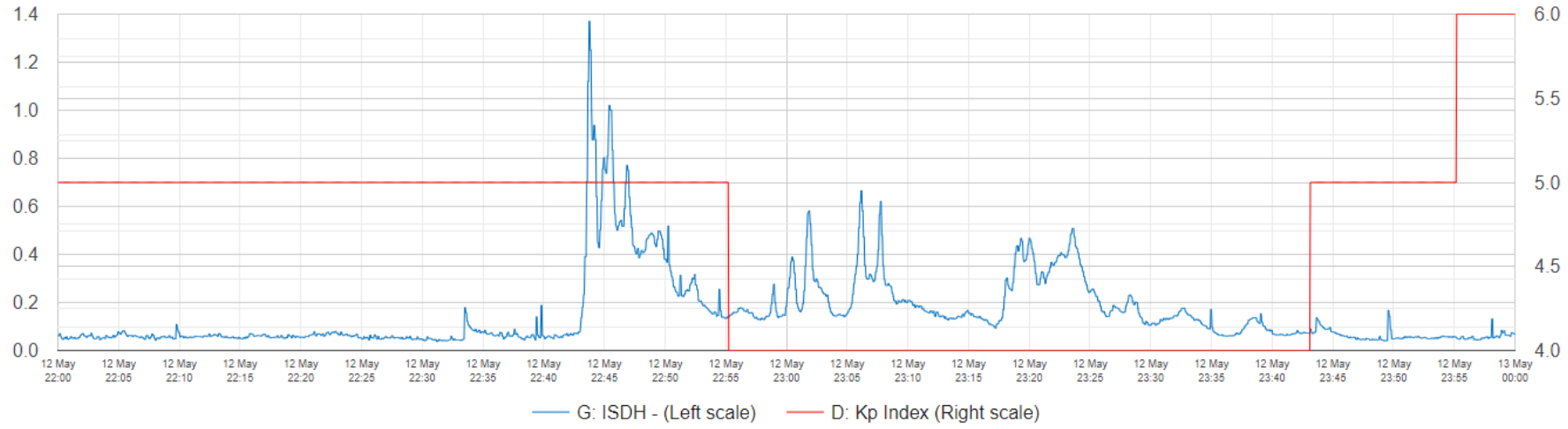


% EHD - Even Harmonic Distorsion 2,4,6,8 - Line to USA

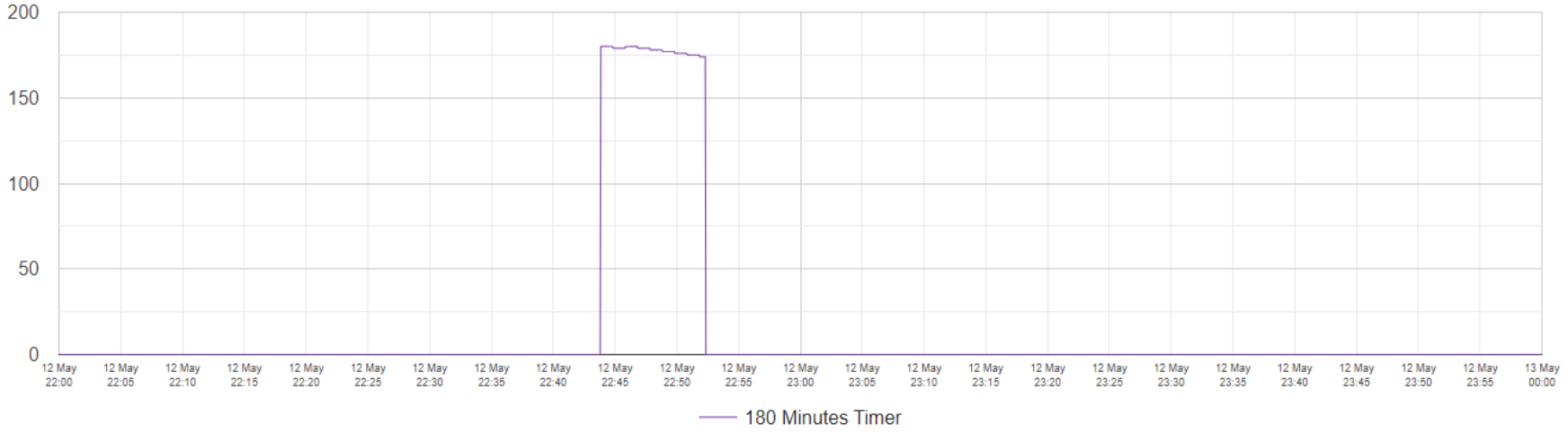


May 12th – 10:00 PM to 00:00 AM EST EHD, Kp

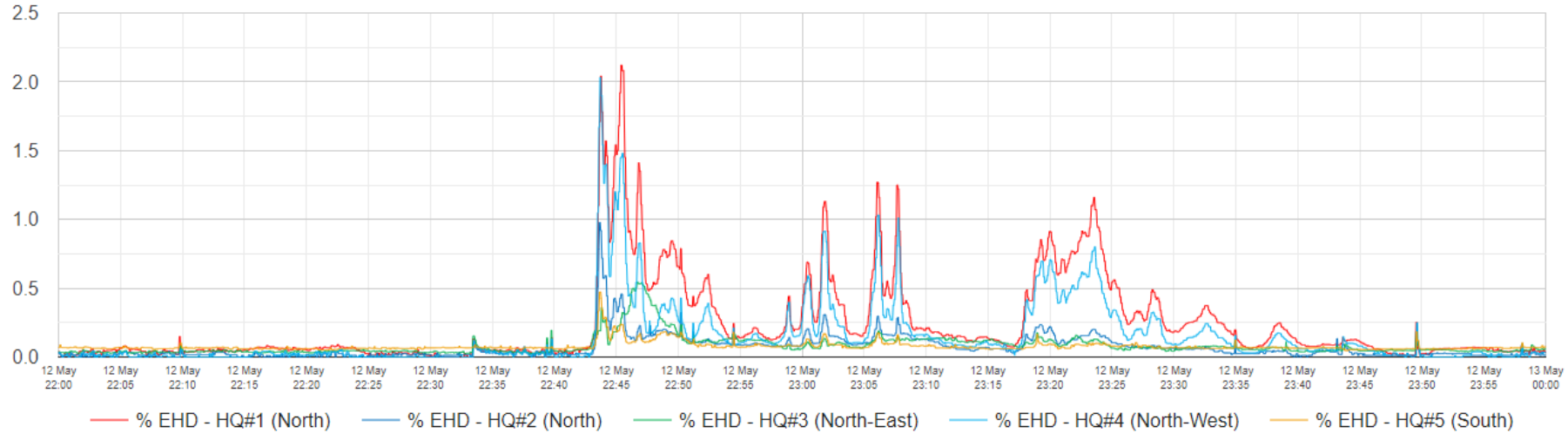
May 12th [10pm to midnight] - ISDH (Harmonic Distorsion Severity Index) where threshold = 1.00 and Kp Index (threshold=8)



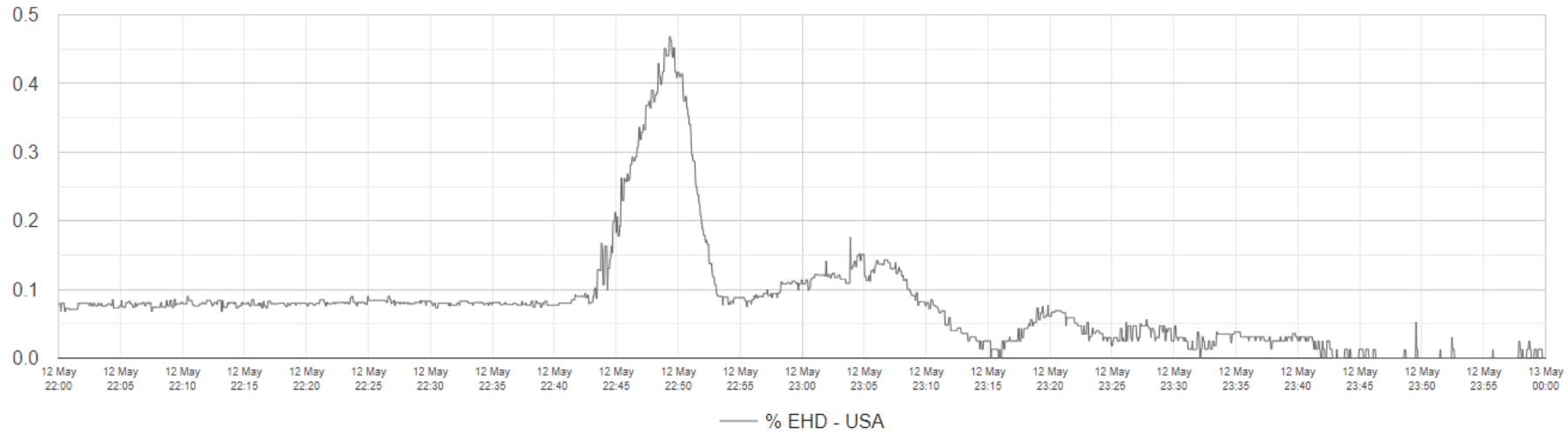
Geomagnetic Storm ConditionTimer (180 min)



% EHD - Even Harmonic Distorsion 2,4,6,8 - Hydro-Québec



% EHD - Even Harmonic Distorsion 2,4,6,8 - Line to USA

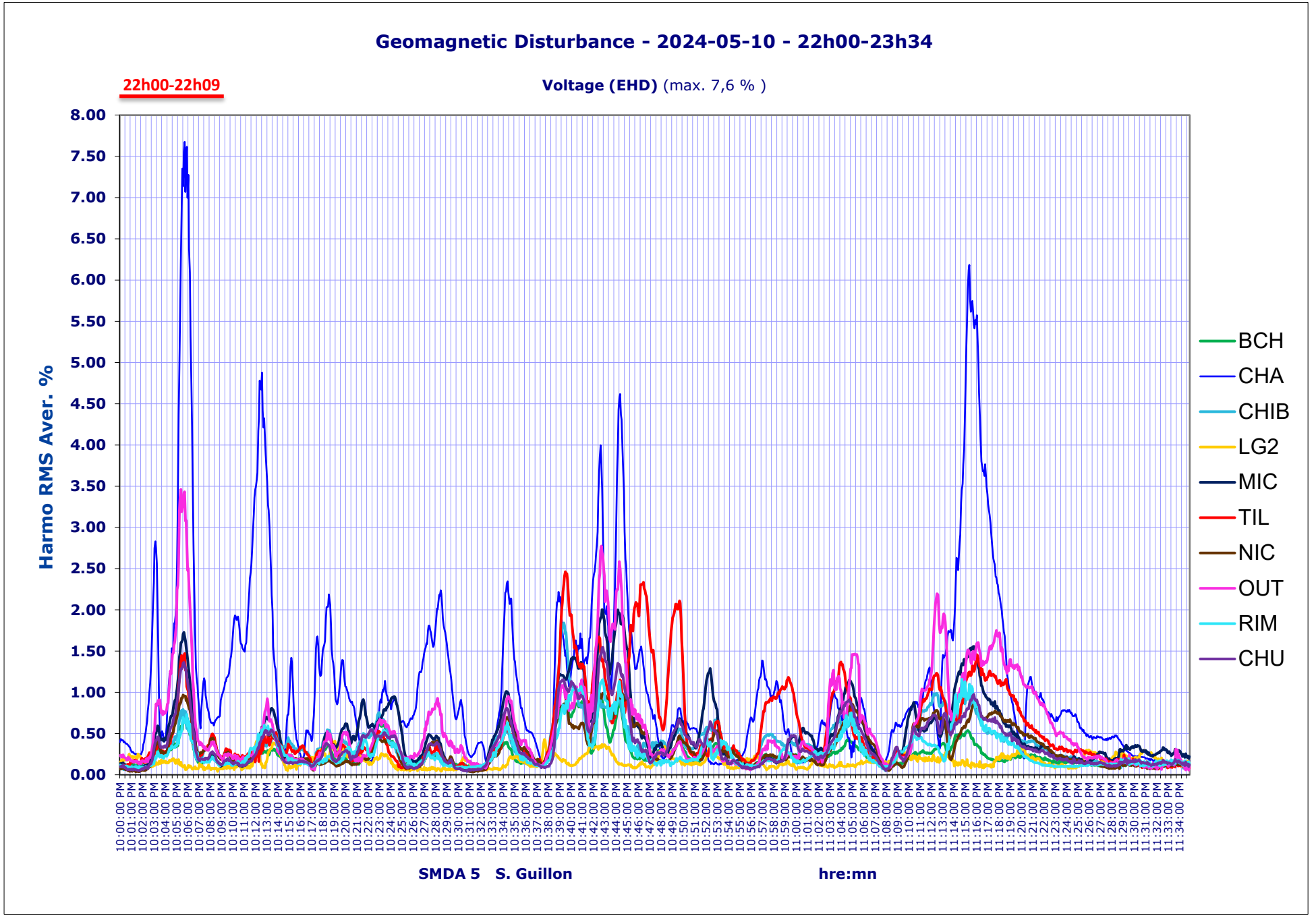


Comparaison March 1989 (blackout) vs May 2024 GMD Event

	March 1989	May 2024	May 2024
Substation	**Voltage Asymmetry**	**Date-Hours (EST)**	**Voltage EHD**
North Hydro-Québec			**6,0 %** (max)
North-West	8%	24/05/12 00:29 AM EST	3,9 %
North-East	**10 %** (max)	24/05/11 05:40 AM EST	2,2 %
Hydro-Québec		24/05/12 00h29 AM EST	**6,0 %** (max)
Center	1 %	24/05/10 10:39 PM EST	1,8 %
South	2,5%	24/05/10 10:42 PM EST	0,9 %
AC line to **USA**	≤ 5 %	24/05/10 10:05 PM EST	**7,6 %**


Thank You !!
Any Questions ?

MAY 2024 – HYDRO-QUÉBEC



Voltage Distortion (USA)

CHATEAUGUAY (see USA)

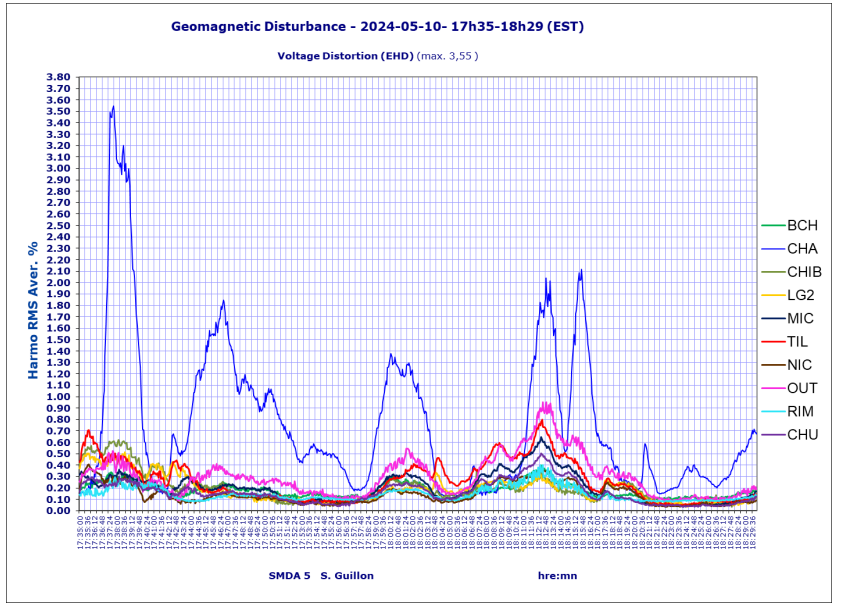
- HVDC
- Measurement on US side (in Qc)
- USA Higher than HQ
- Highest Value (7,6 %)

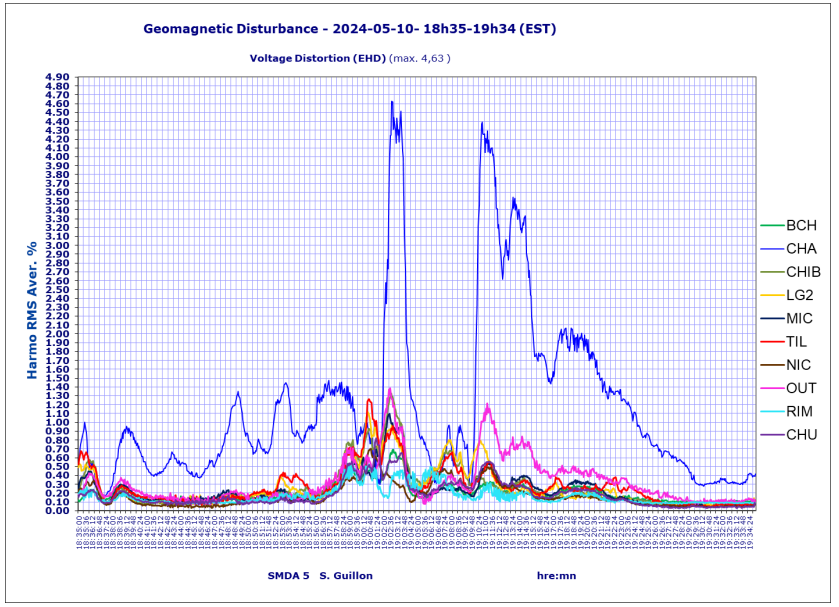
Hydro-Quebec

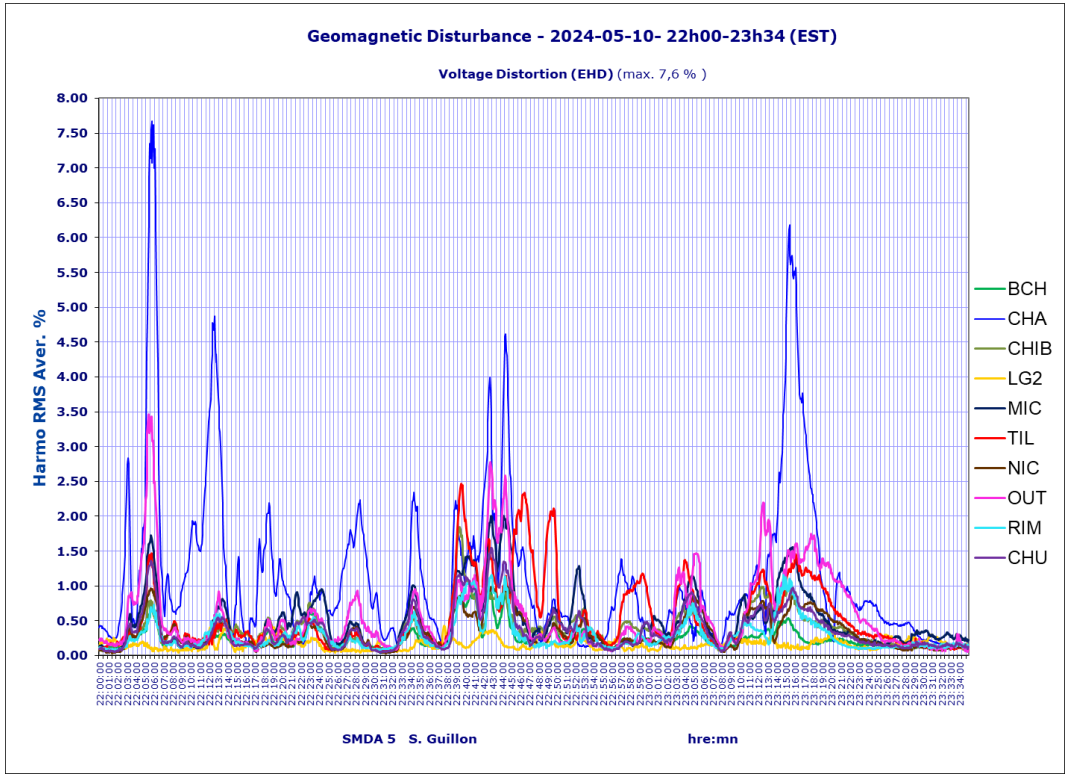
- North – Low values
- Center – Low values
- South – Higher values (OUT)

South and USA

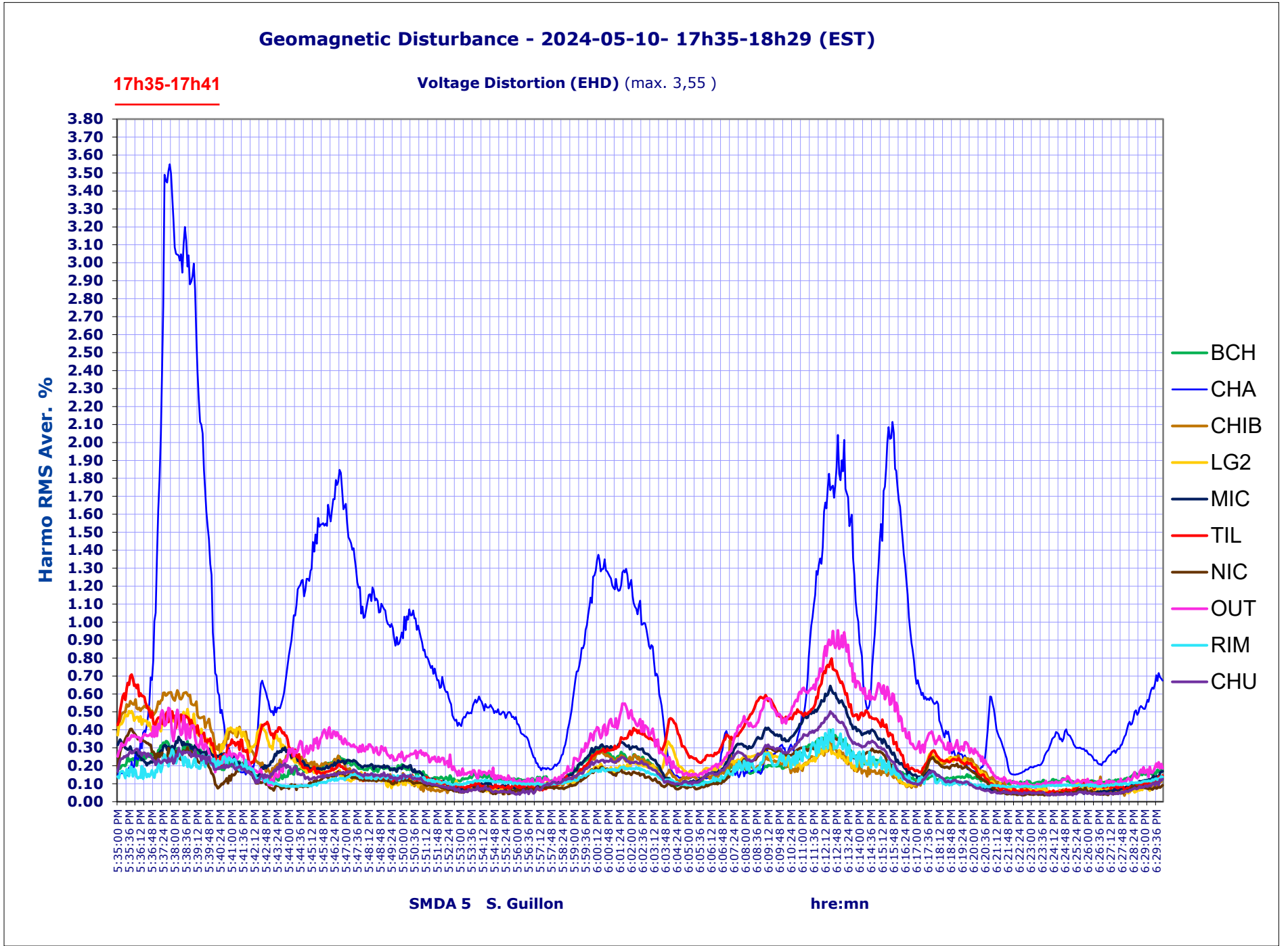
- HQ (South) similar to USA
- HQ ≤ USA (that's unusual)



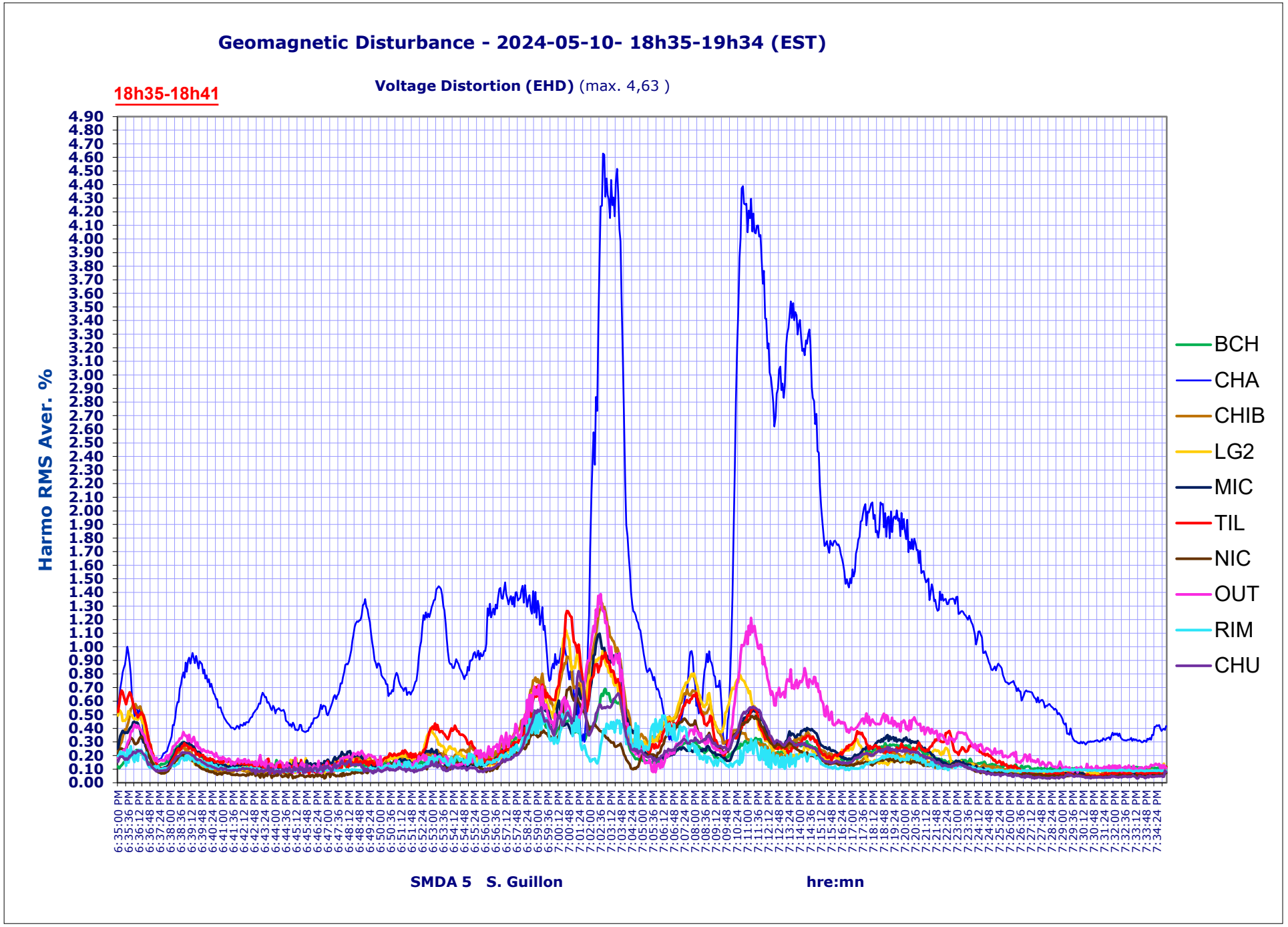




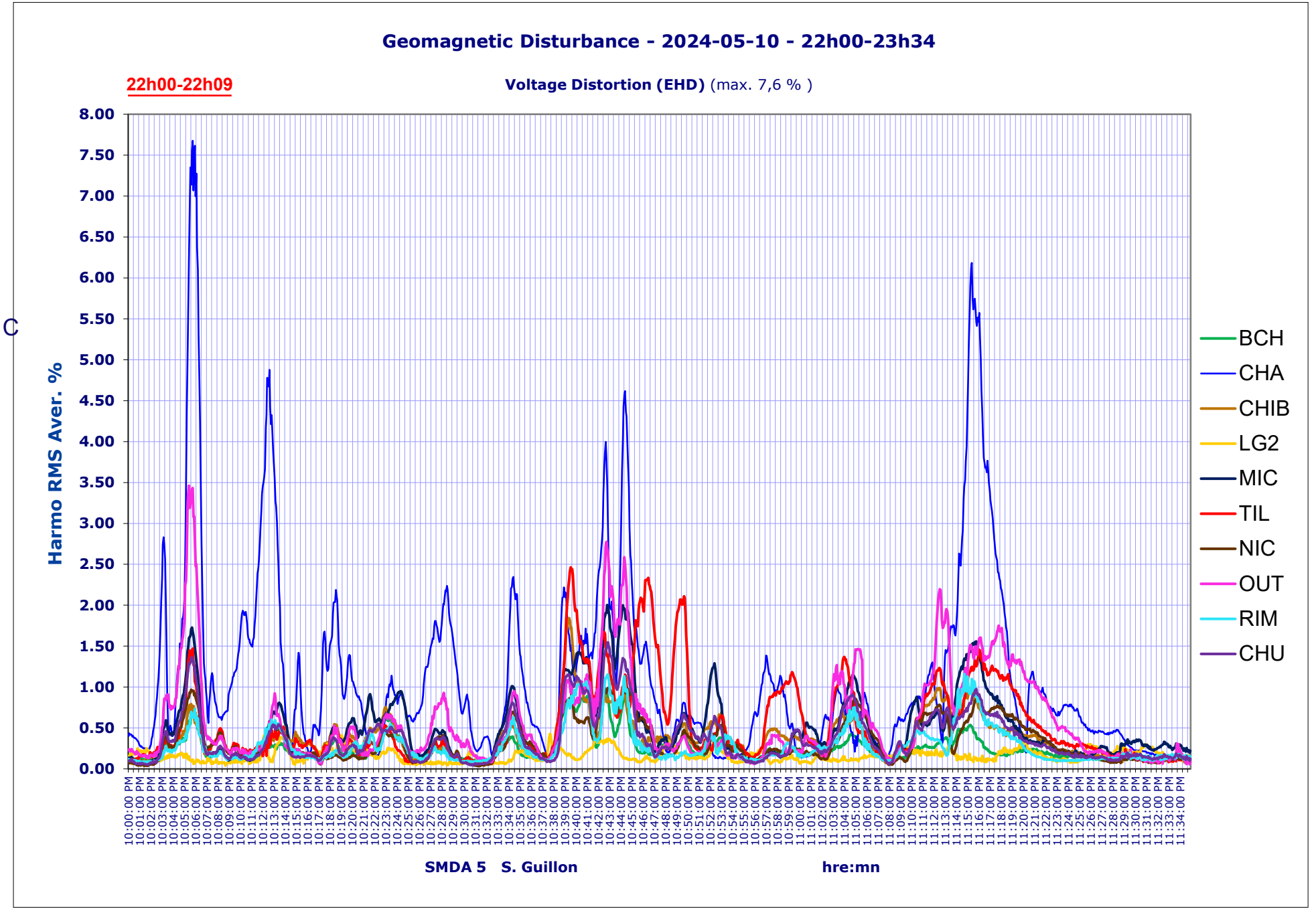
MAY 2024 – HYDRO-QUÉBEC



MAY 2024 – HYDRO-QUÉBEC



MAY 2024 – HYDRO-QUÉBEC



Voltage Distortion

Higher USA value

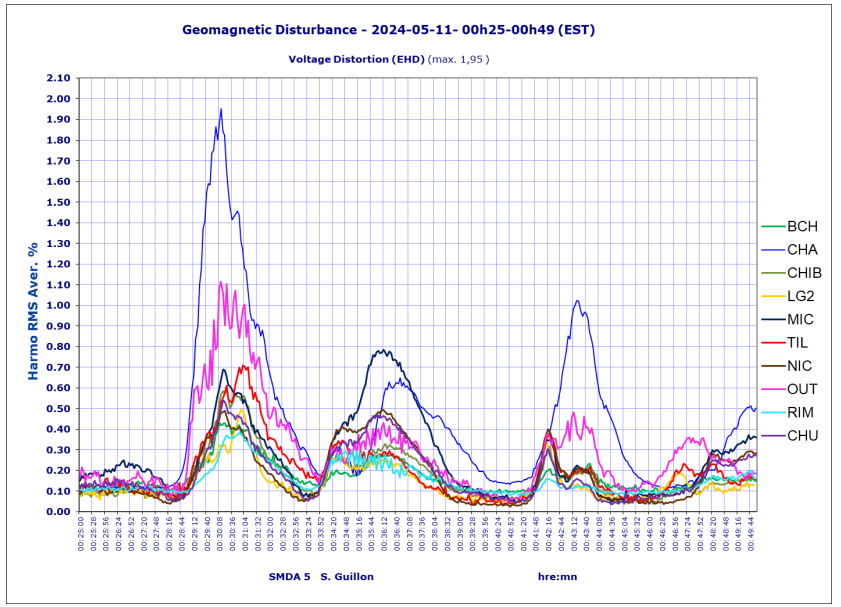
- HQ (South) similar to USA
- USA Higher than HQ
- Highest Value (7,6 %)

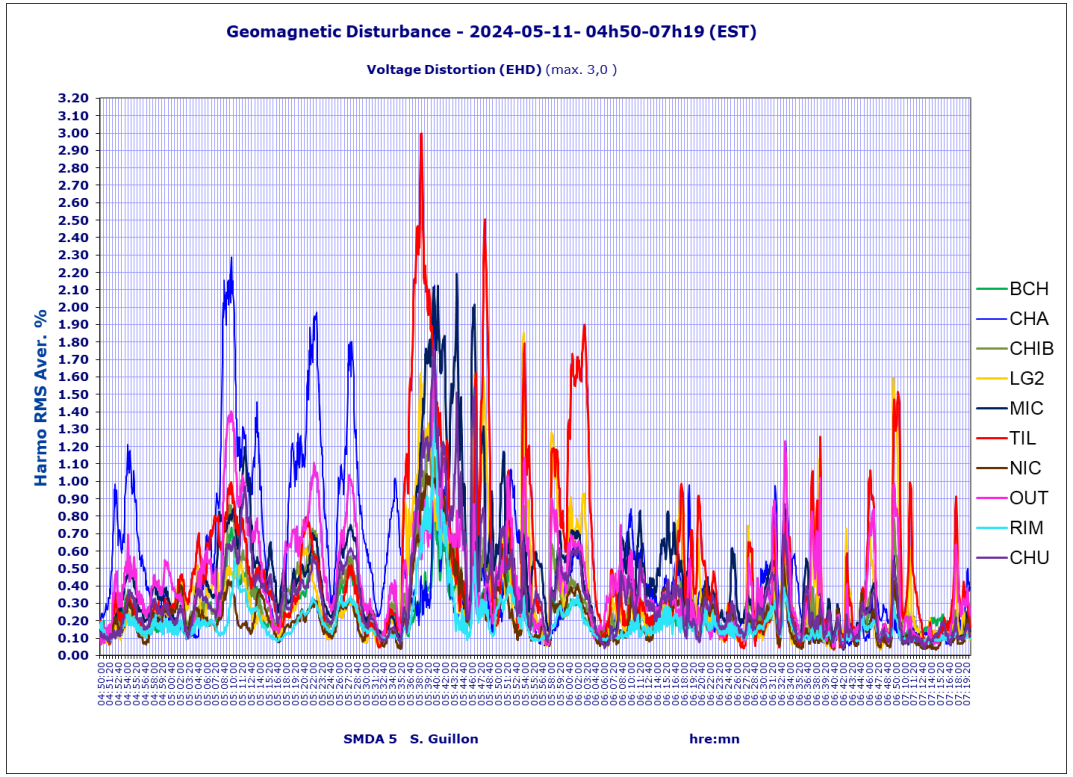
Transition to normal

- 00h25-05h34 : similar to May 10th
- 05h35-07h19 : HQ ≠ USA (distinct)

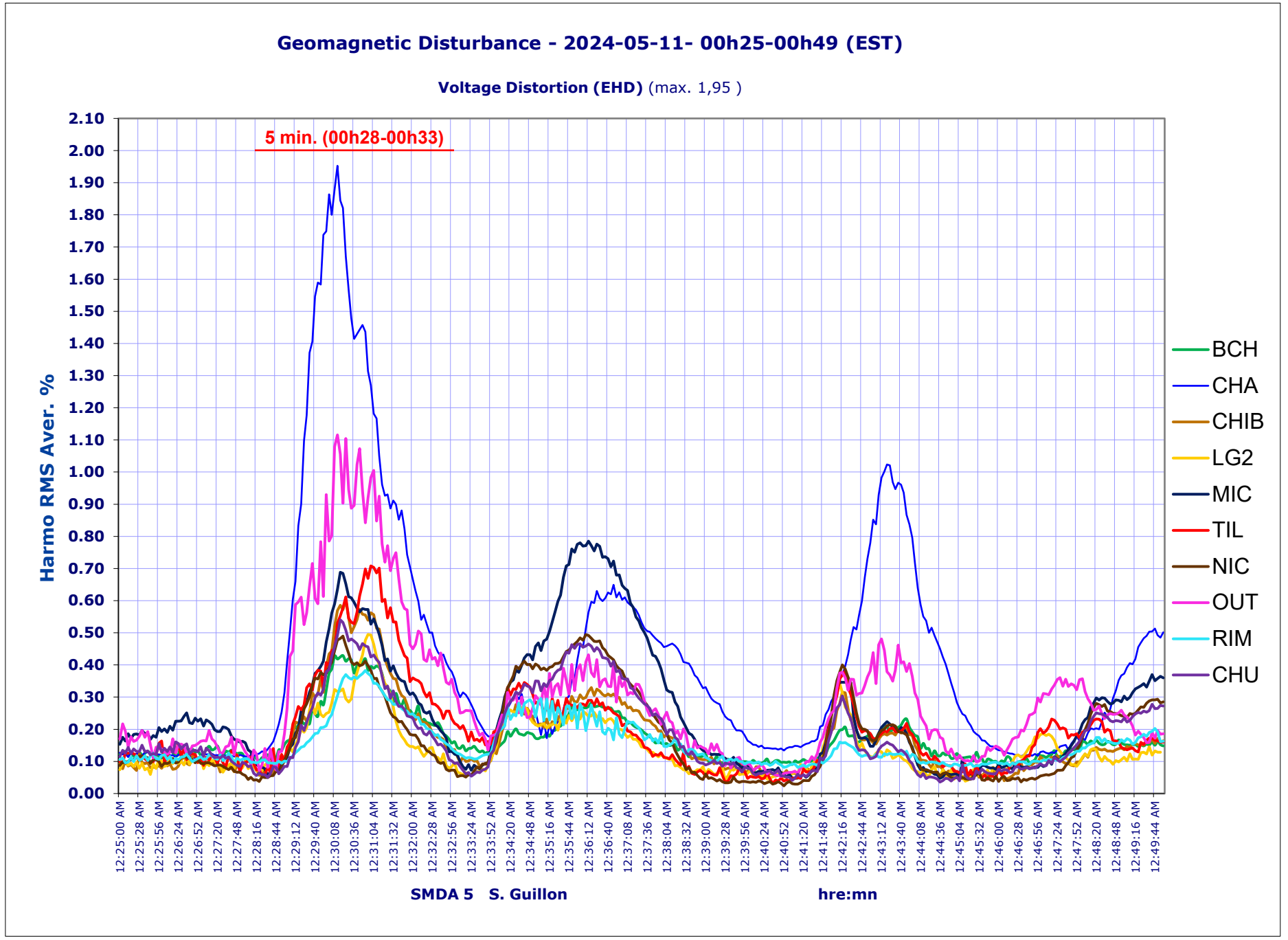
Higher HQ (North) Values

- North – Higher values (TIL, LG2)
- Center – Lower values
- HQ ≠ USA (distinct)

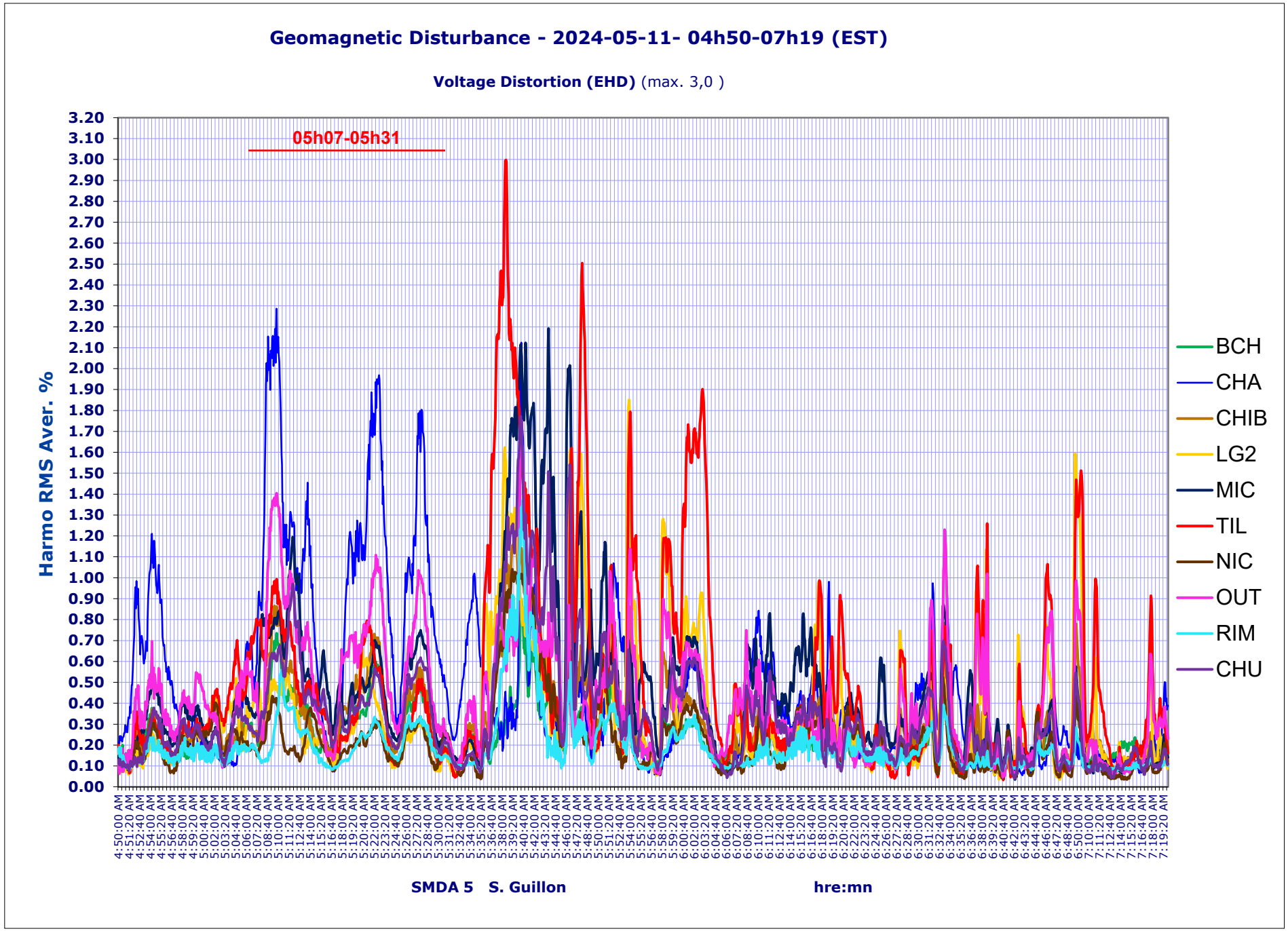




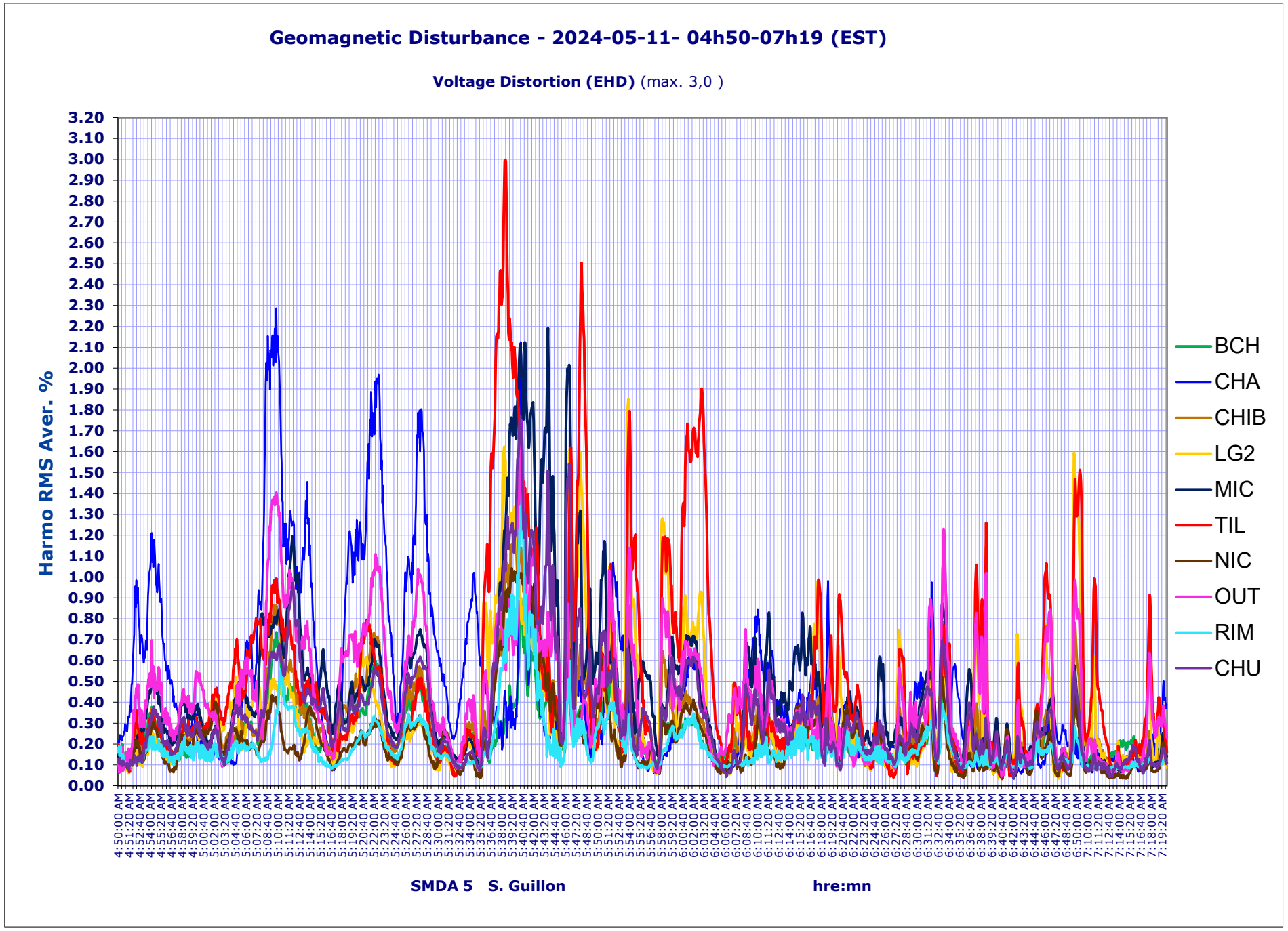
MAY 2024 – HYDRO-QUÉBEC



MAY 2024 – HYDRO-QUÉBEC



MAY 2024 – HYDRO-QUÉBEC



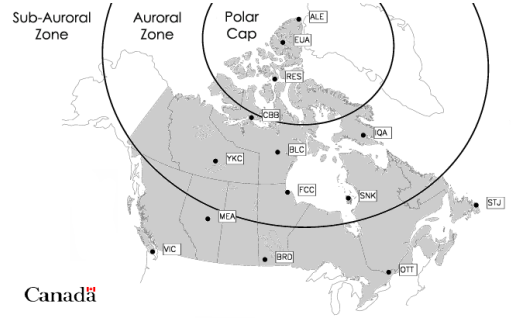
Voltage Distortion (HQ)

Hydro-Québec

- 2024-05-12 - Highest Values

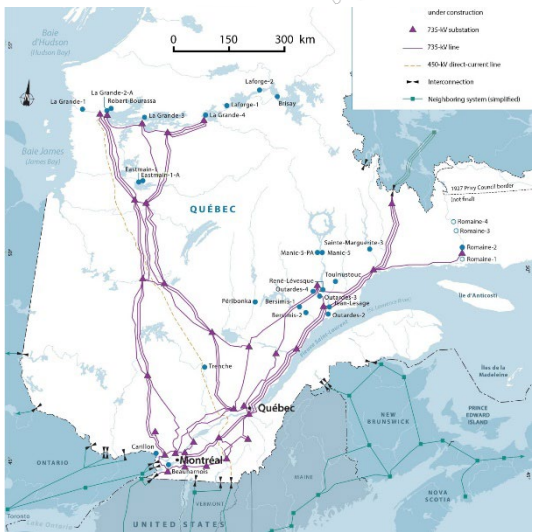
North – High and short duration (≤ 5 min)

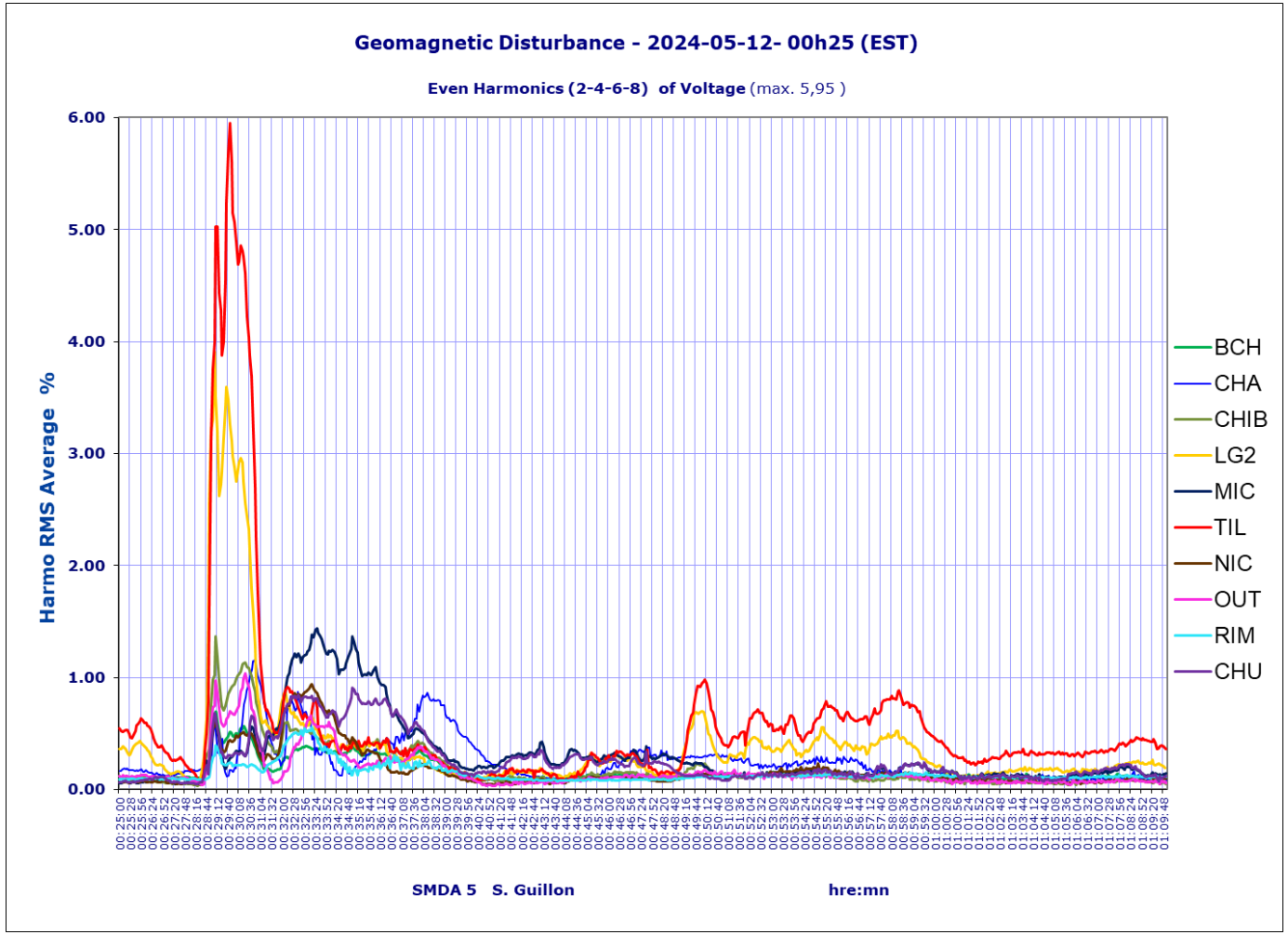
- Auroral zone
- Tilly (Close to LG4)
- LG2



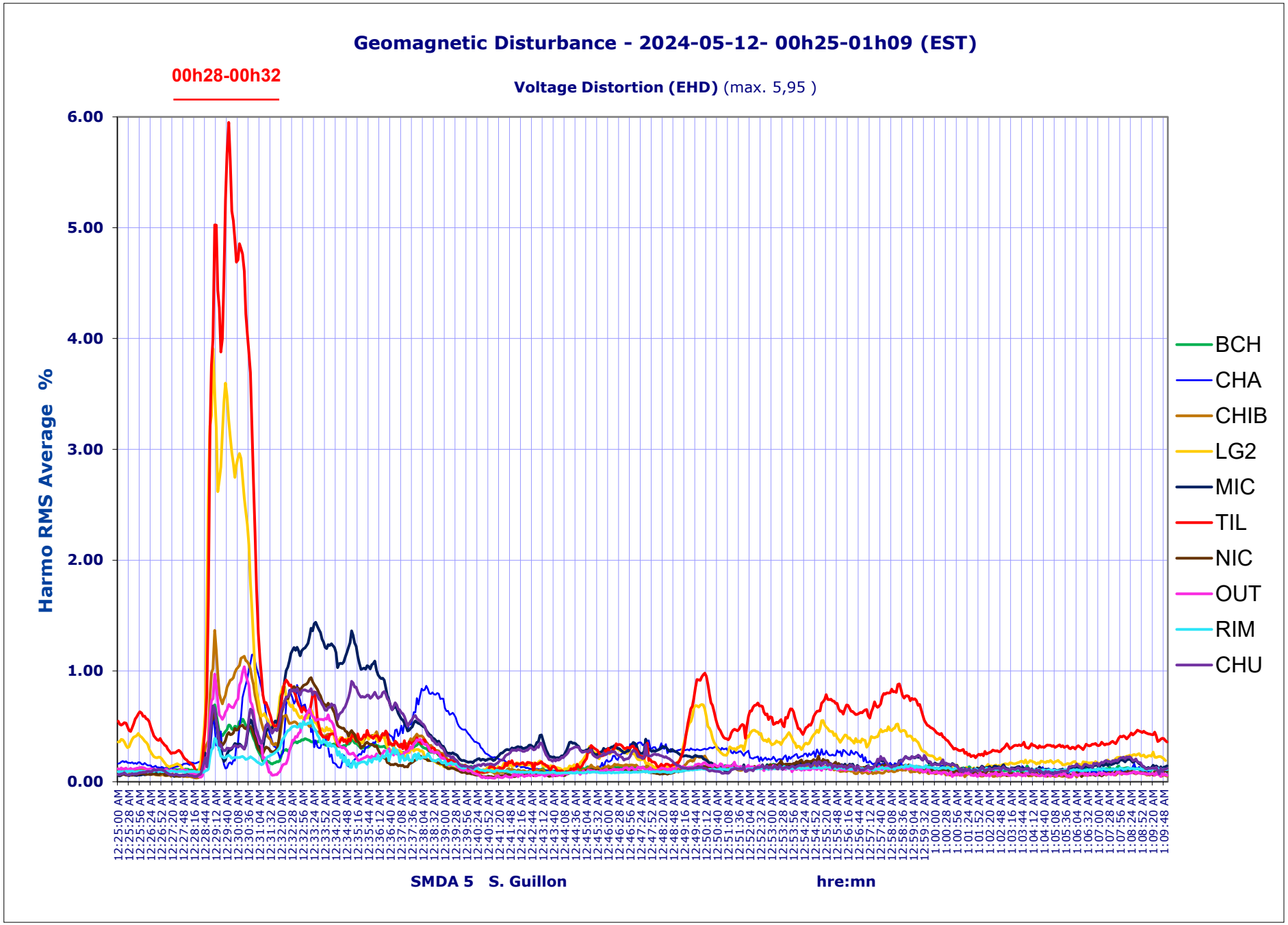
South and USA

- Average - Low values
- HQ ≠ USA (CHA)

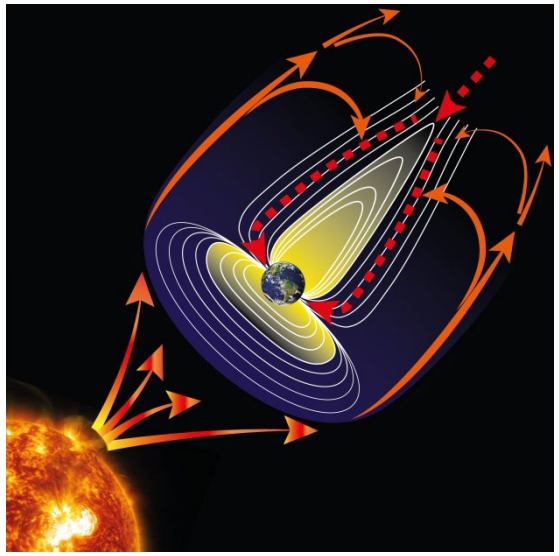




MAY 2024 – HYDRO-QUÉBEC



DC Current (GIC) : Harmonic Distortion + Reactive Power



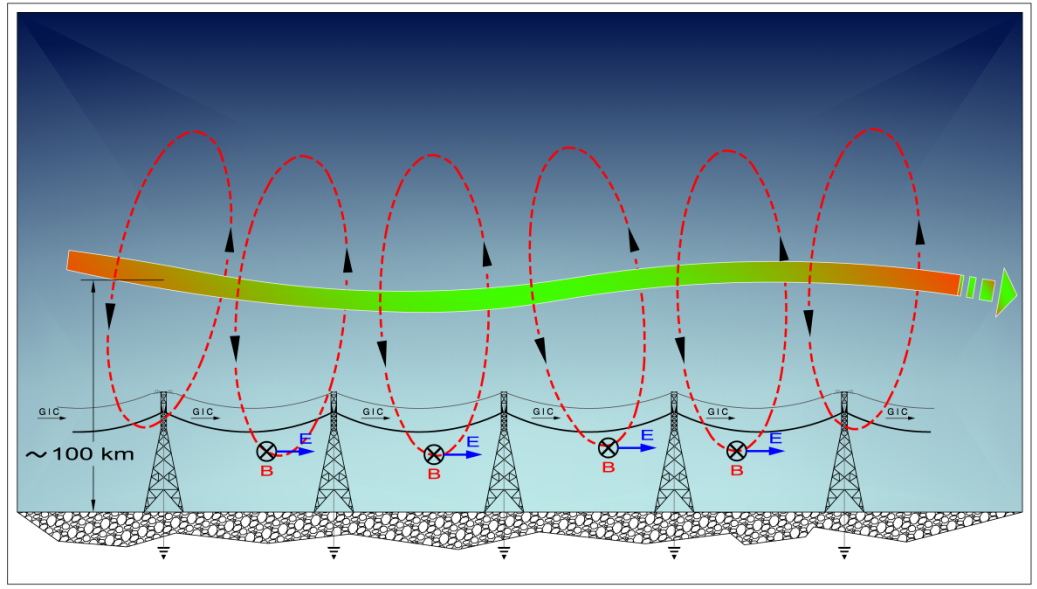
CME from the Sun

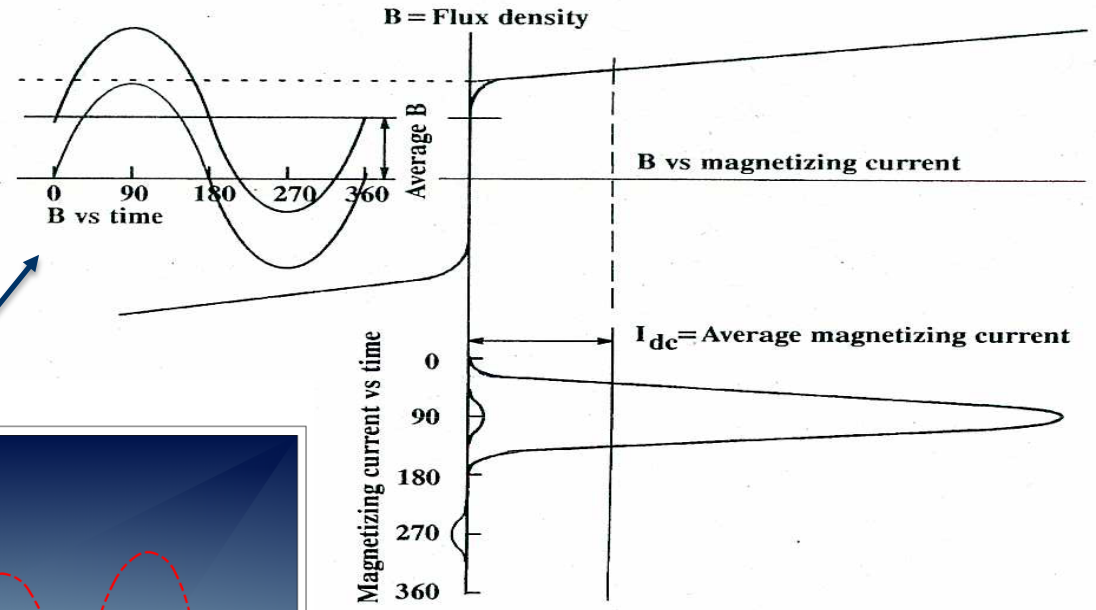
(CME : Coronal Mass Ejection)

↓

Earth's substorm

↓





Electrojet Current producing magnetic (B) and electric (E) fields

→ **DC Current (GIC)**

DC Current (GIC) in Transformer produces **Harmonics** and **Reactive power** consumption

HITACHI
Inspire the Next

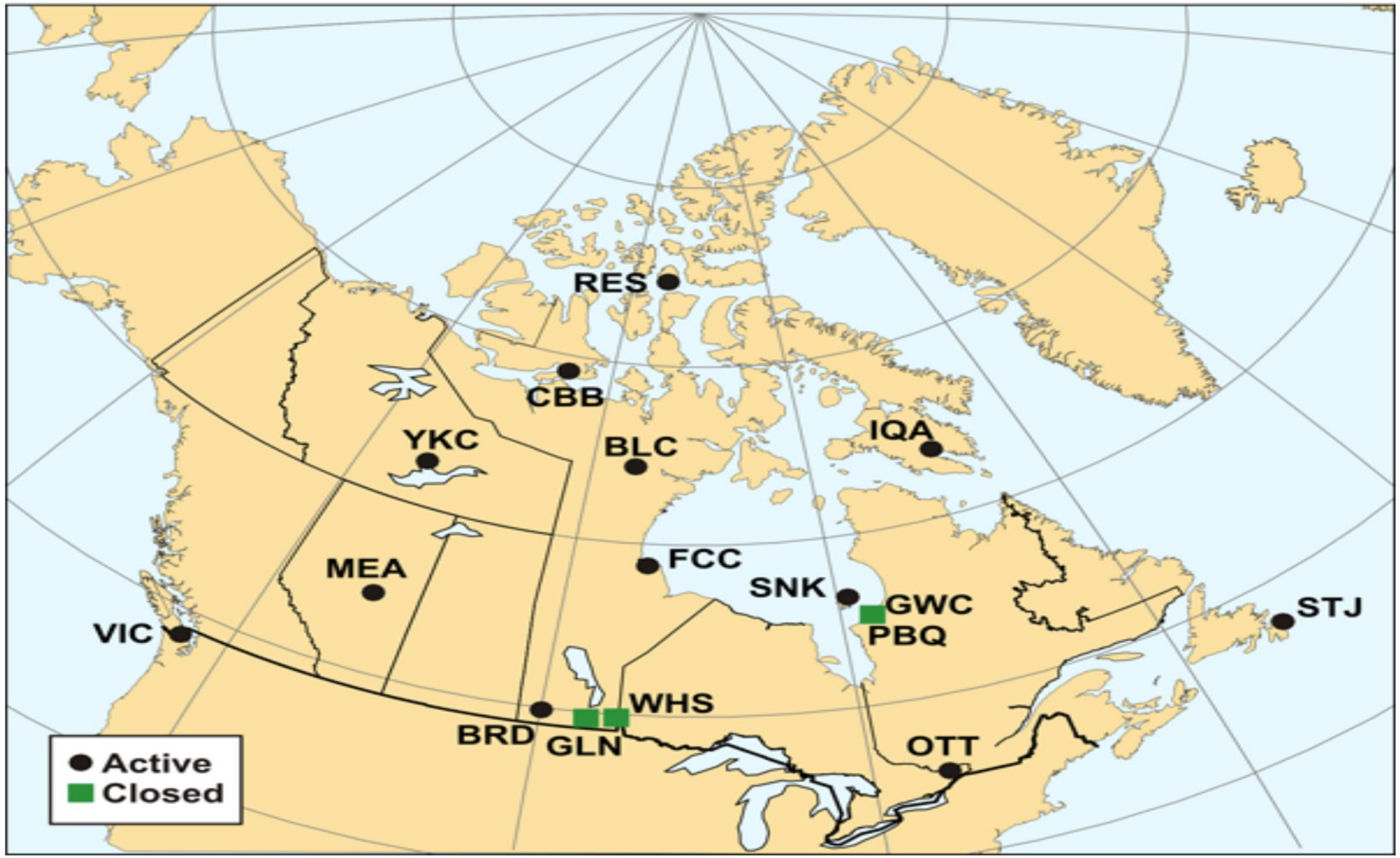
Analysis of Recorded Data of the May 2024 Gannon GMD Event

Presentation By Ramsis Girgis At NERC's Industry GIC Workshop

October 2, 2024

Hitachi Energy

Locations of Geomagnetic Observatories in Canada



Recorded Geoelectric Field levels (GMD Event – May 10 / 11, 2024)

HITACHI
Inspire the Next

Location	Latitude, °	V / km		
		E_X	E_Y	E
Ottawa**	45.4	1.5	0.5	1.6**
Victoria	48.5	0.4	0.9	0.9
Brandon	49.9	1.1	1.1	1.6
Meanook	54.6	0.7	1.7	1.8
Yellowknife	62.5	0.5	1.3	1.4
Resolute Bay	74.7	0.4	0.6	0.7

***** E at the Ottawa Observatory was 2.1 V / km early on Mach 14, 1989***
Geo-magnetic field was 1530 nT vs. 2492 in 1989

May 2024 event ~ 65 % of 1989 GMD event

Recorded Geoelectric Field levels

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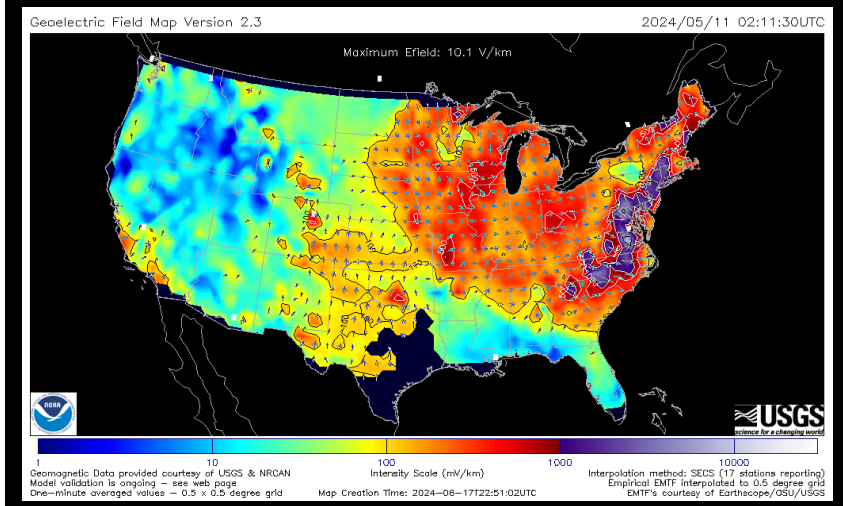
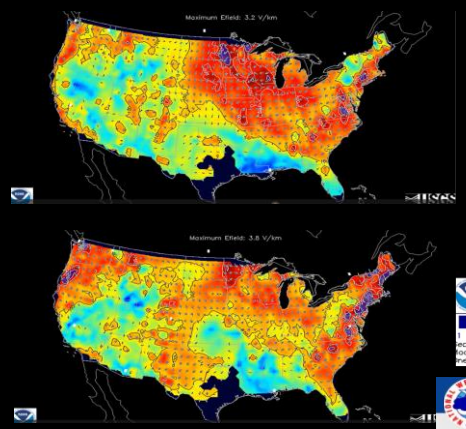
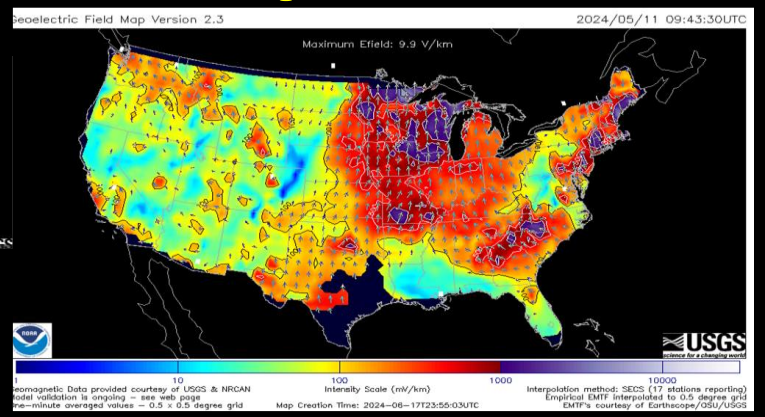
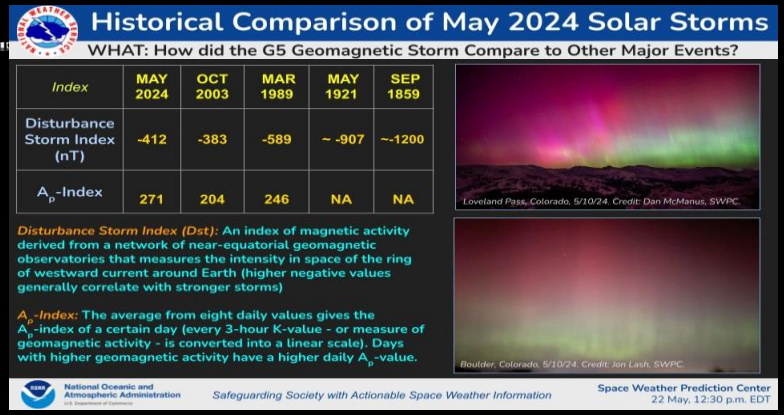
Geoelectric Field Model Output









This **storm peaked with 10.1 V/km**, and had frequent occurrences of greater than 1 V/km. Comparison with other G5 storms:

July 2000: 11.0 V/km
October 2003 Halloween Storms: 7.7 V/km
March 1989 Hydro-Quebec Storm: 14.7 V/km
September 1859 Carrington Event: Unknown – but probably stronger

May 2024 event = 10.1 / 14.7 = 68 % of 1989 GMD event

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Recorded Geoelectric Field levels (GMD Event – May 10 / 11, 2024), Contd.

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Location	Latitude, °	V / km		
		E_X	E_Y	E
Ottawa	45.4	1.5	0.5	1.6
Victoria	48.5	0.4	0.9	0.9
Brandon	49.9	1.1	1.1	1.6
Meanook	54.6	0.7	1.7	1.8
Yellowknife	62.5	0.5	1.3	1.4
Resolute Bay	74.7	0.4	0.6	0.7
Flaherty Island	56.5	2.0	3.3	3.9

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Recorded GIC Signatures in New Zealand vs. USA – May 2024 GMD Event

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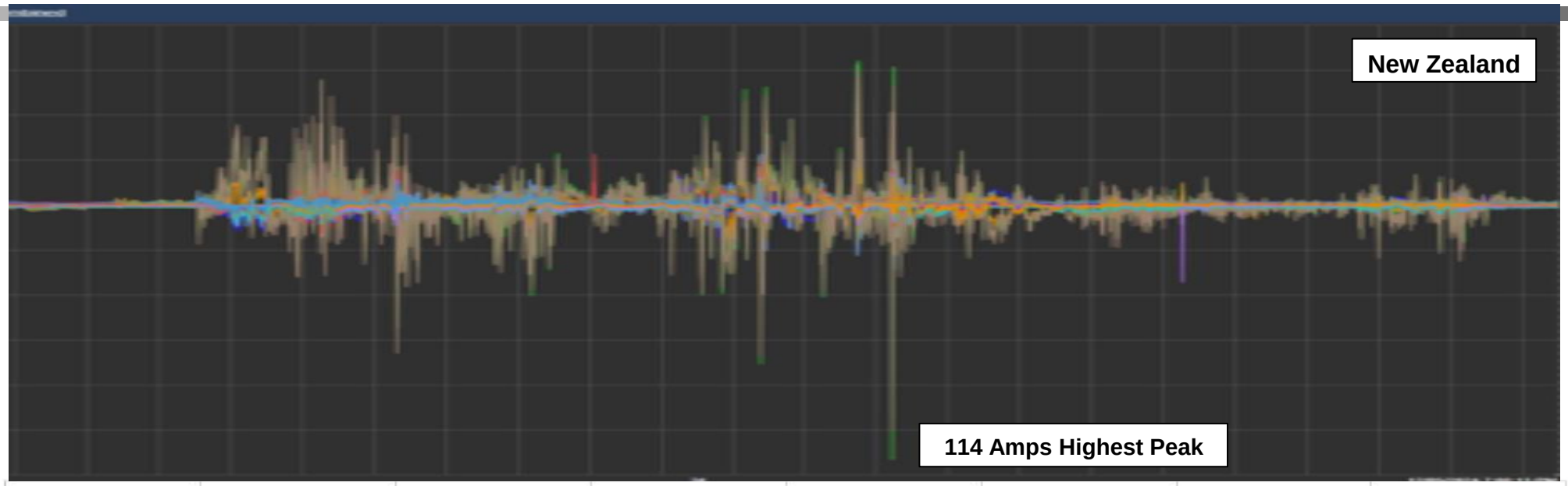

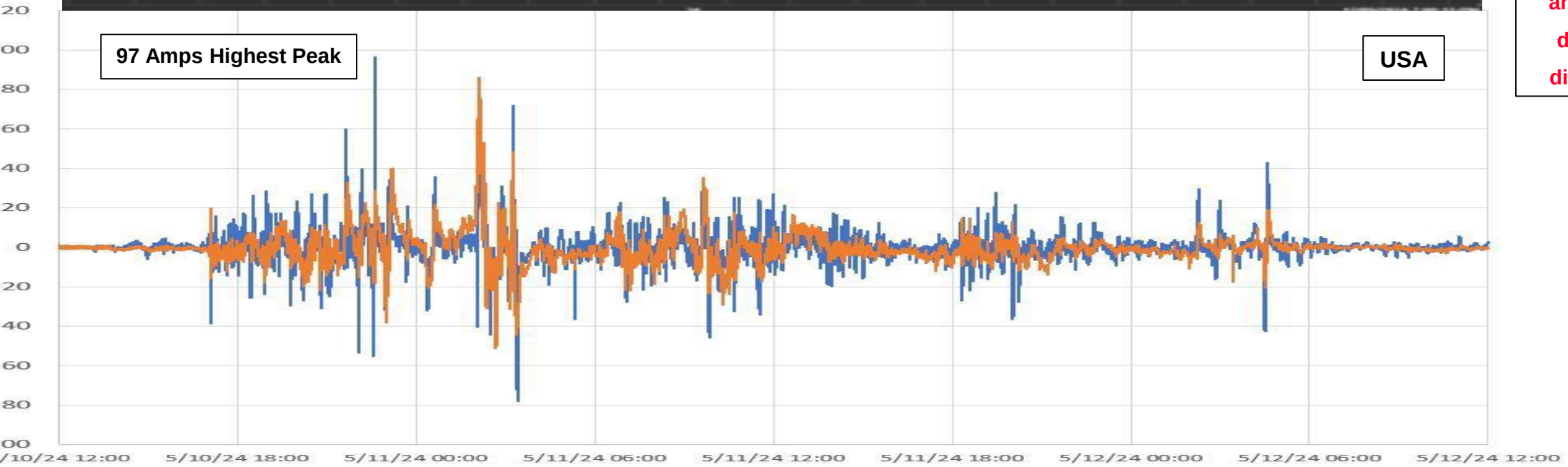

Signatures are different, and peaks occur at different times, in different Locations

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Recorded GIC Signatures in 2 different regions in New Zealand

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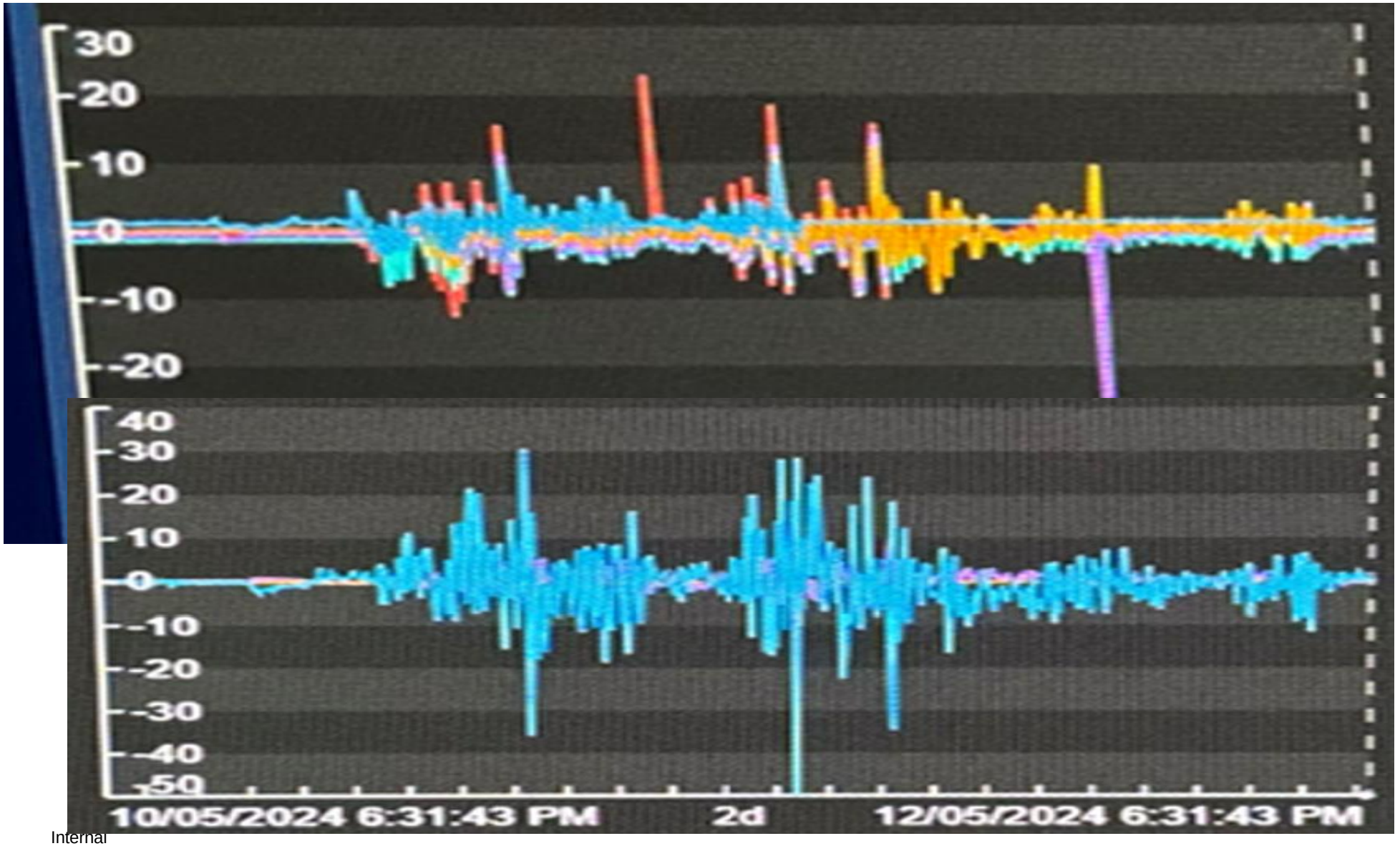

Signatures are different, and peaks occur at different times, in different Locations

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NERC GIC Signature vs. Measured at GS in NE USA on May 10 / 11, 2024 (143 Amps / Phase)

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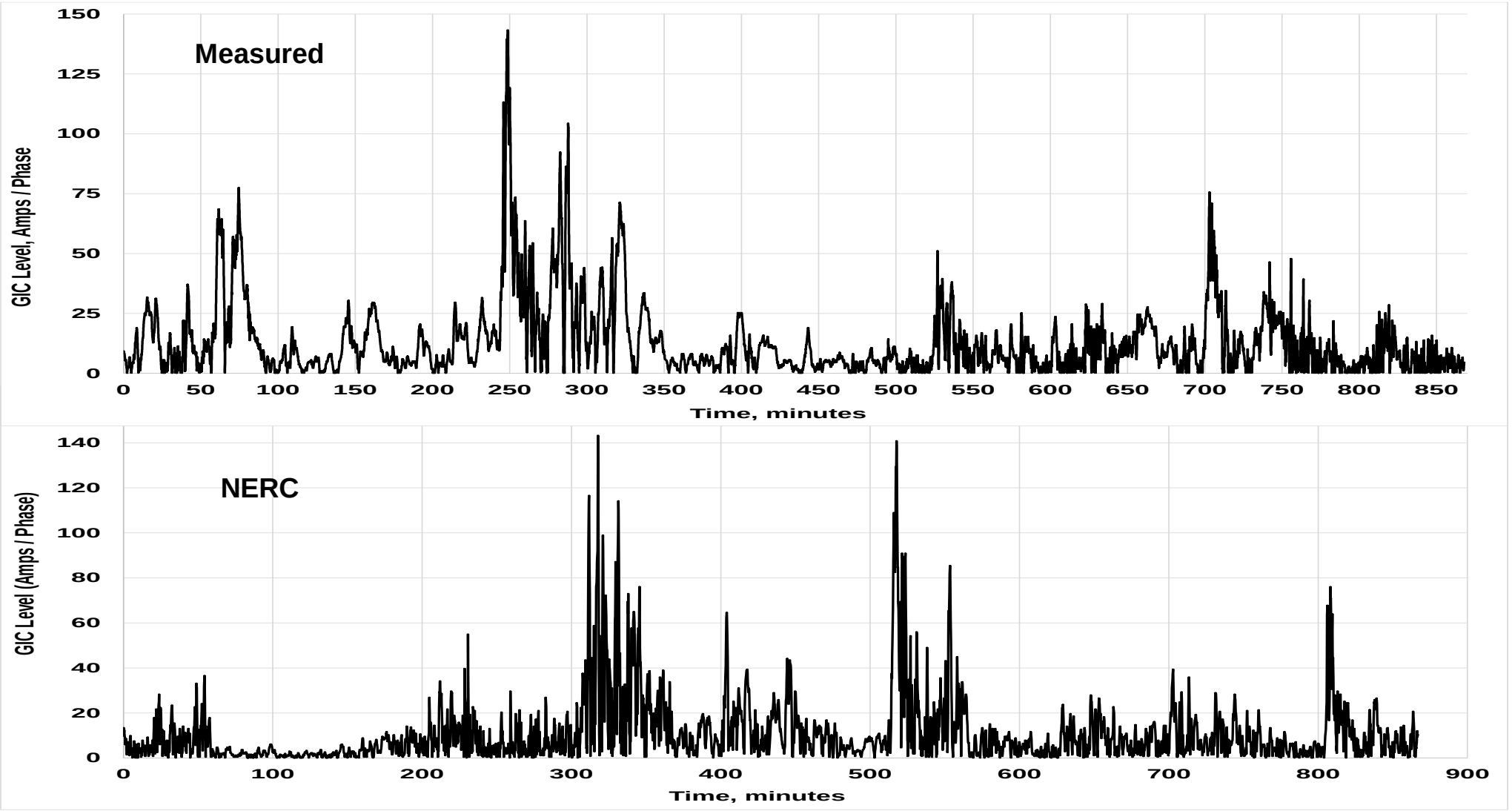

Signatures are different for different GMD storms

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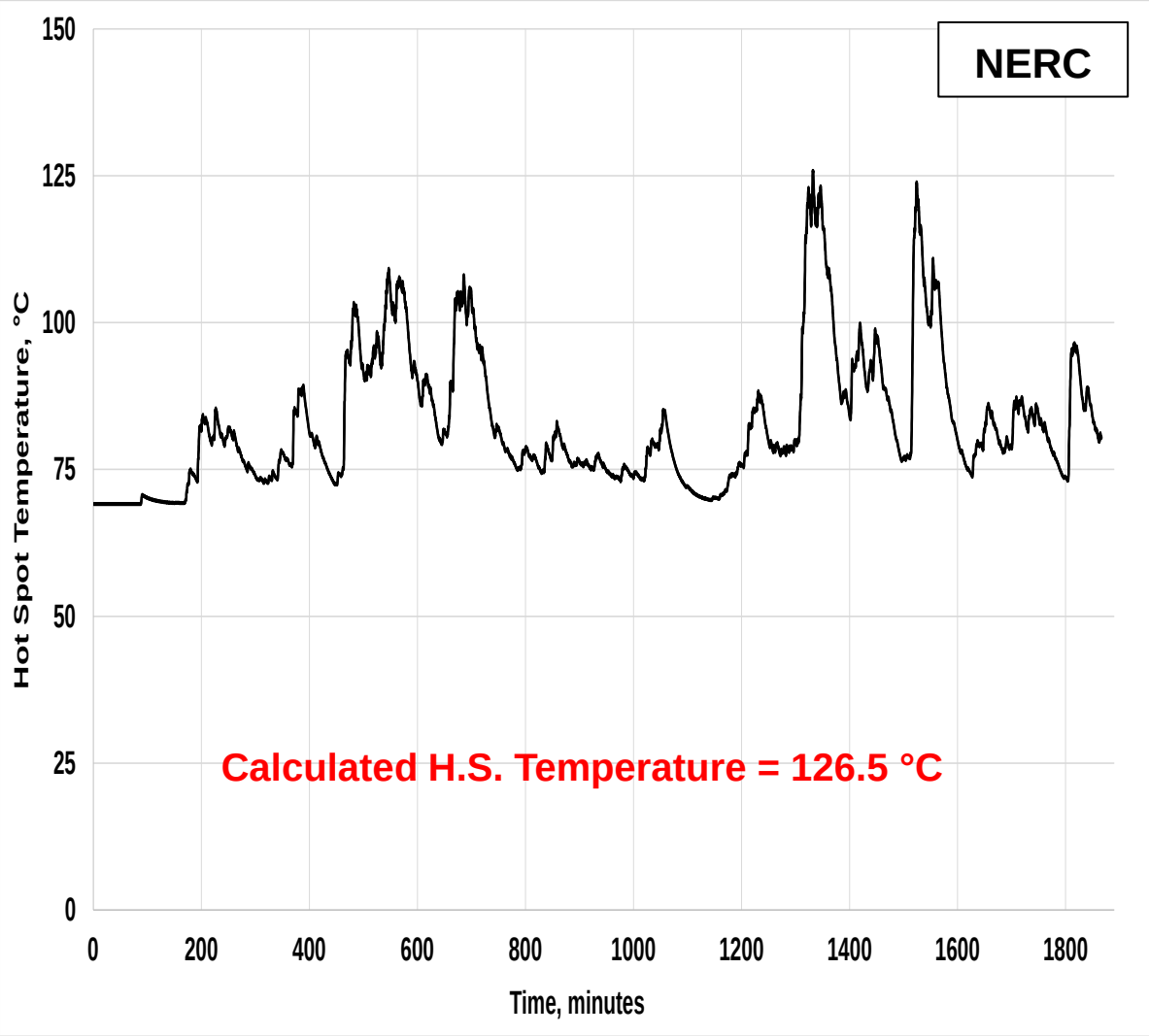
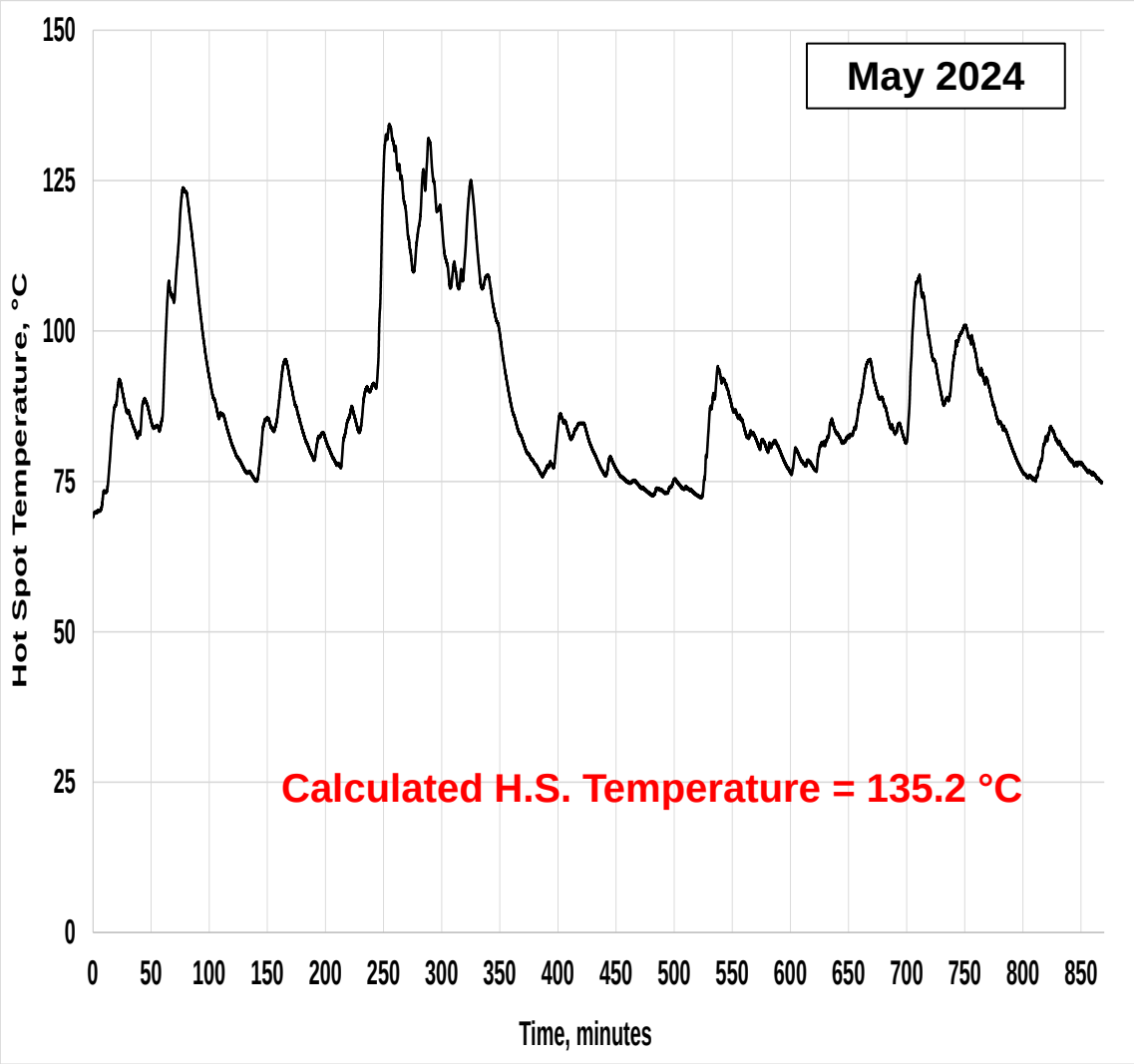
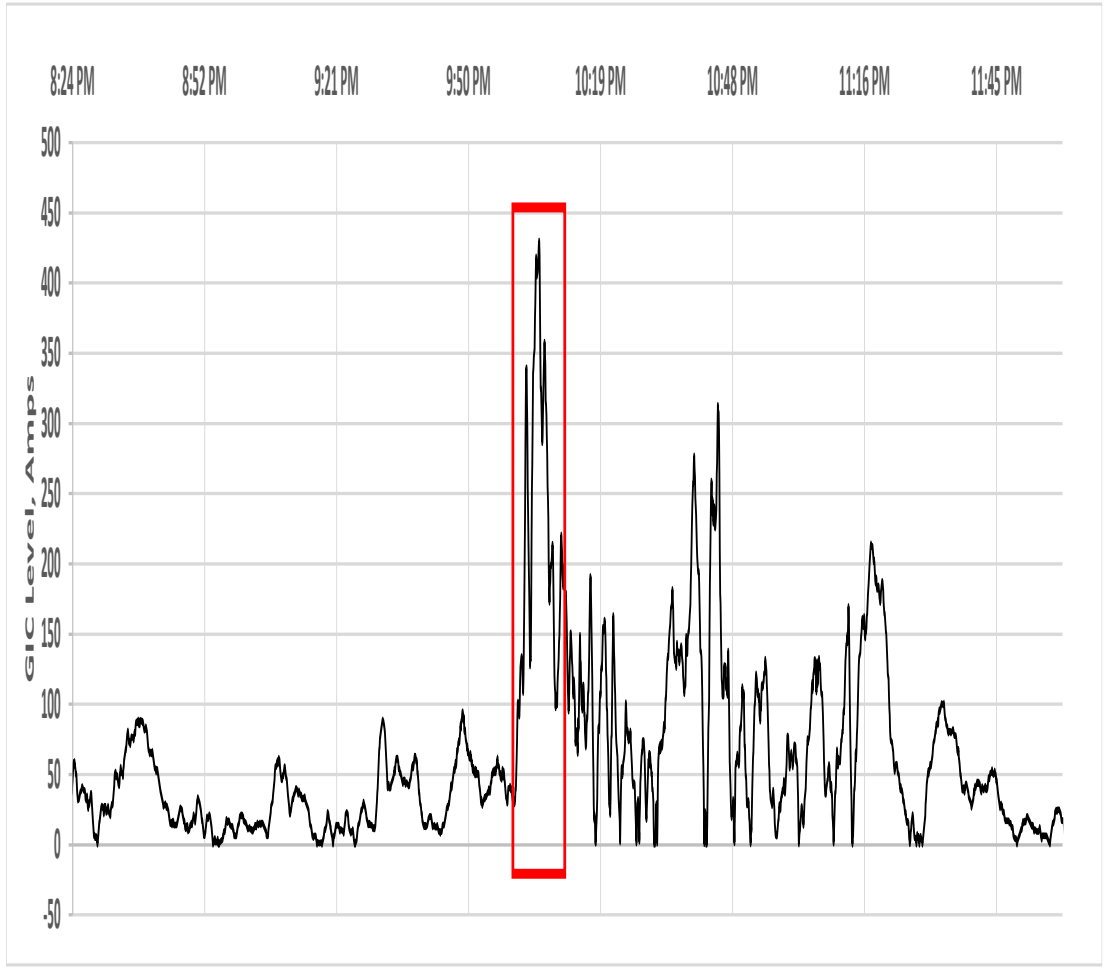
Calculated Structural Parts Hot spot temperatures – NERC vs. May 2024

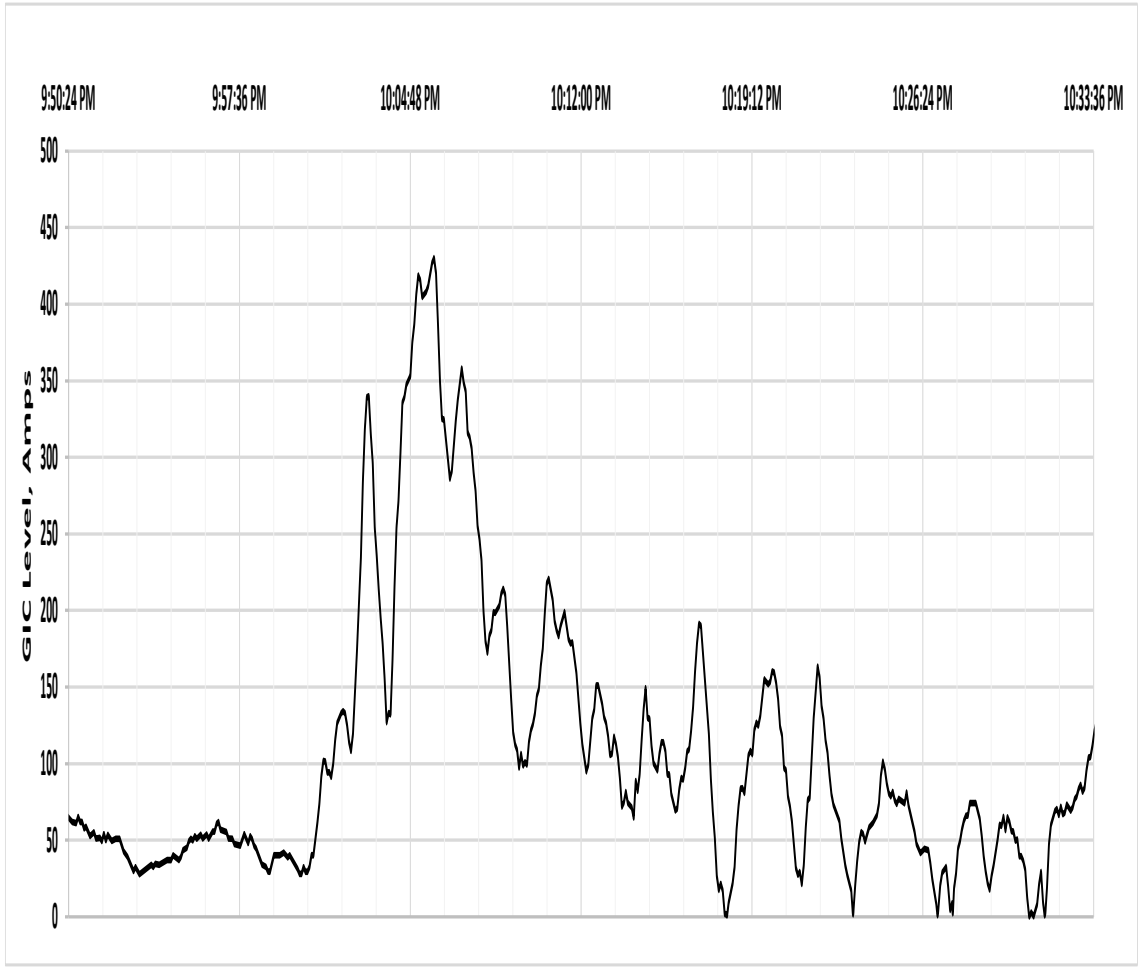




Survey of Time duration of Highest GIC pulses

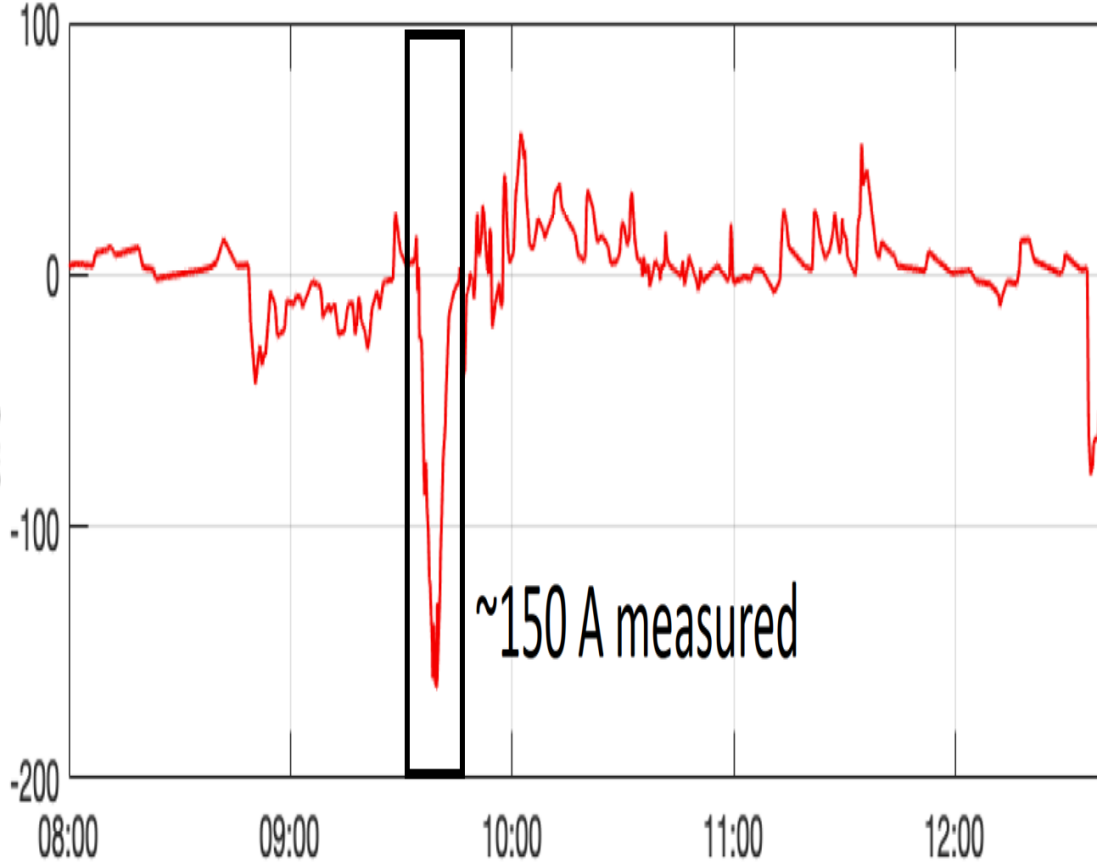
May 10 / 11, 2024 GMD Storm – Northeast USA

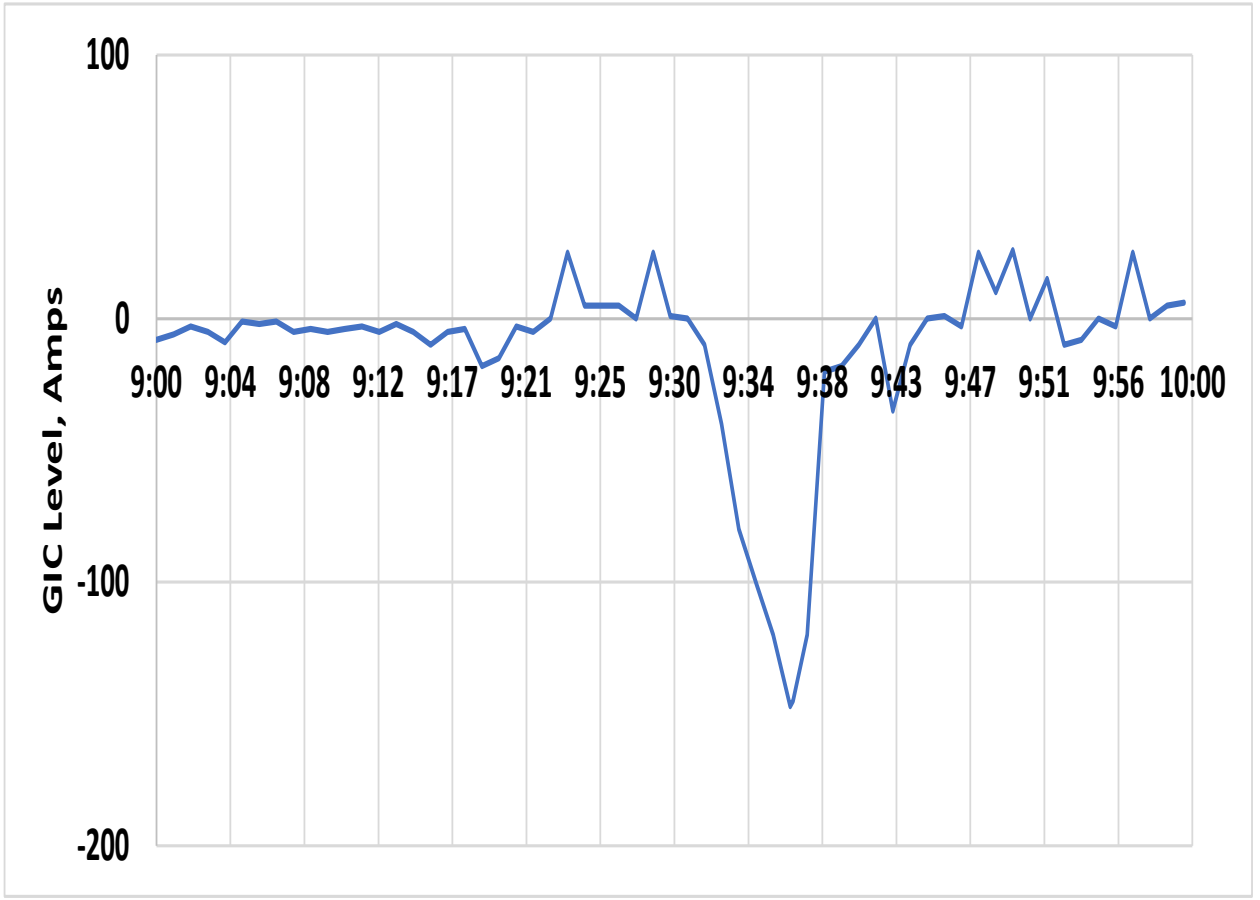




Duration of Highest GIC Pulse ~ 4 minutes

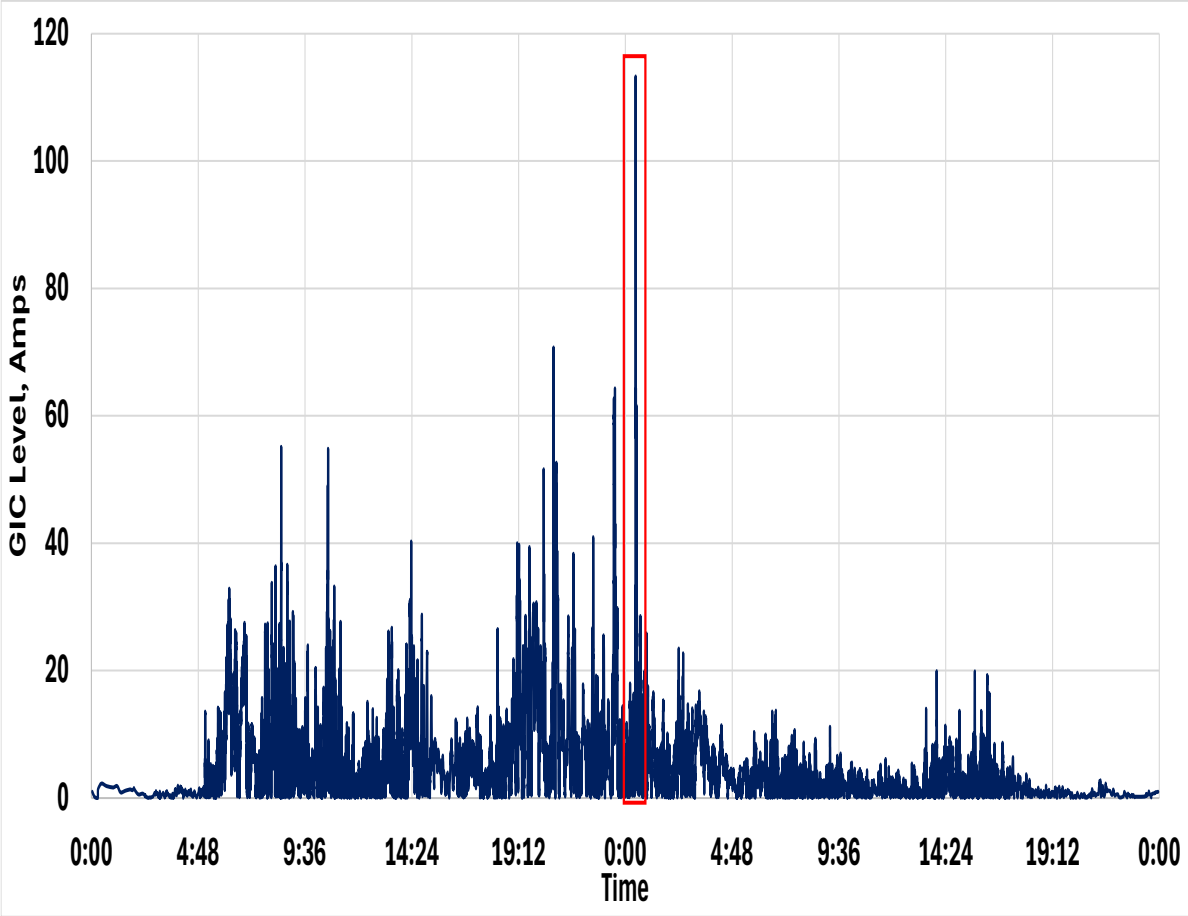
May 10 / 11, 2024 GMD Storm – Alberta, Canada

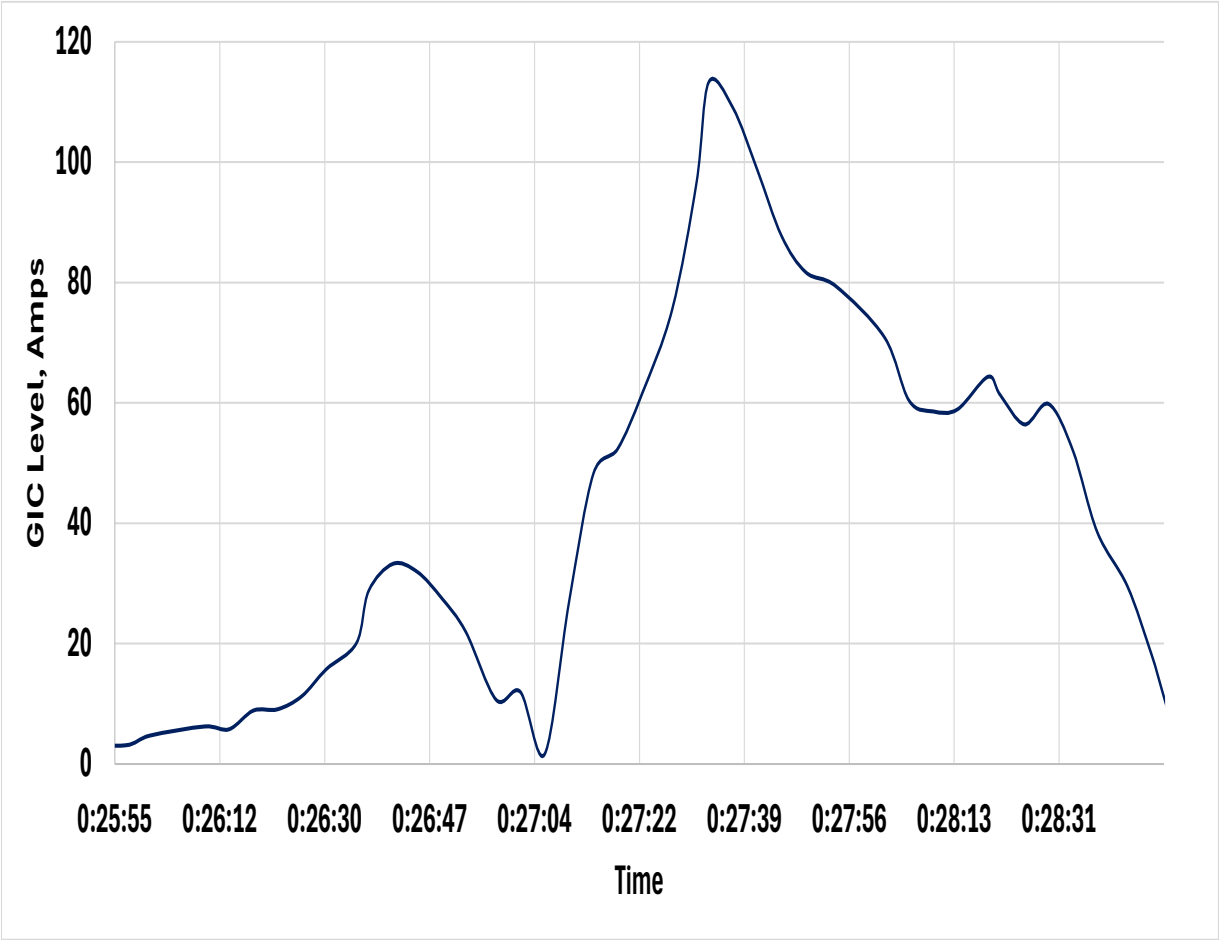




Duration of Highest GIC Pulse = 6 minutes

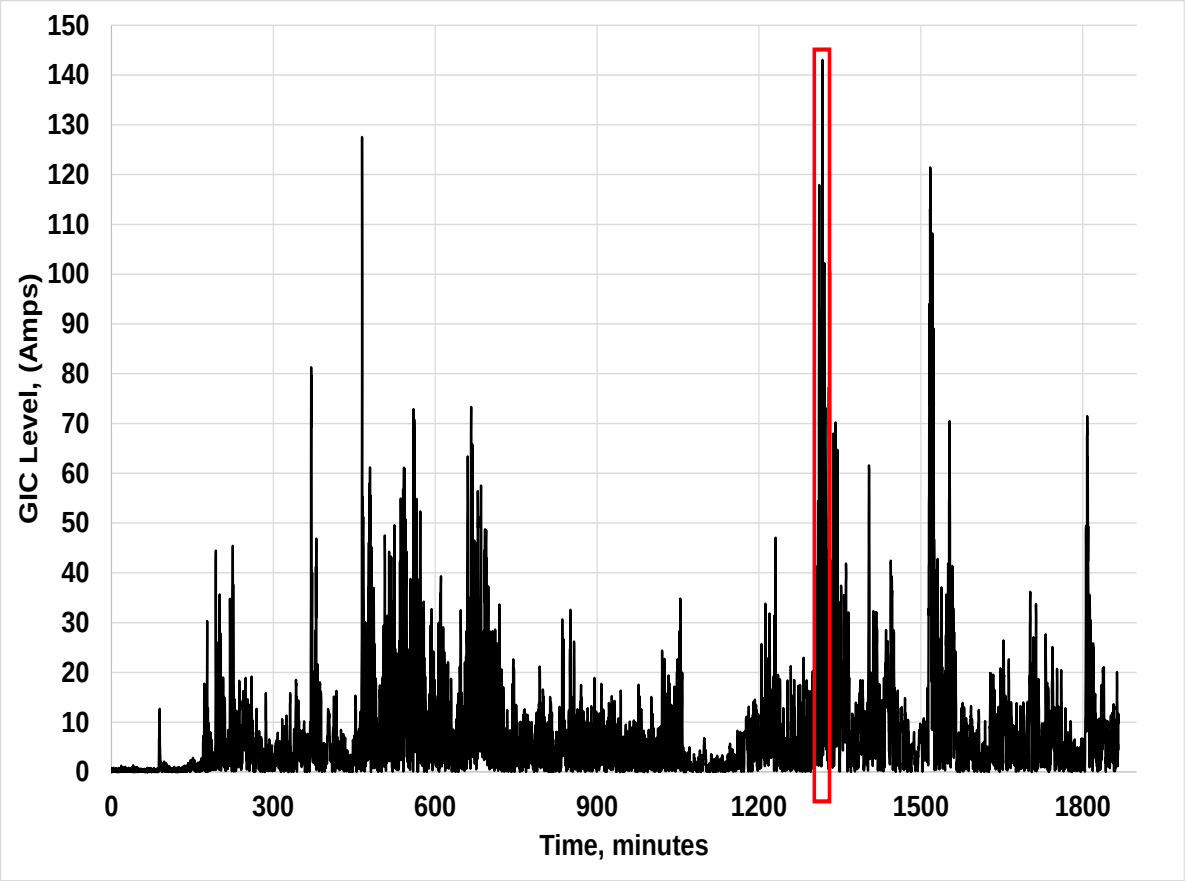
May 11 / 12, 2024 GMD Storm – New Zealand





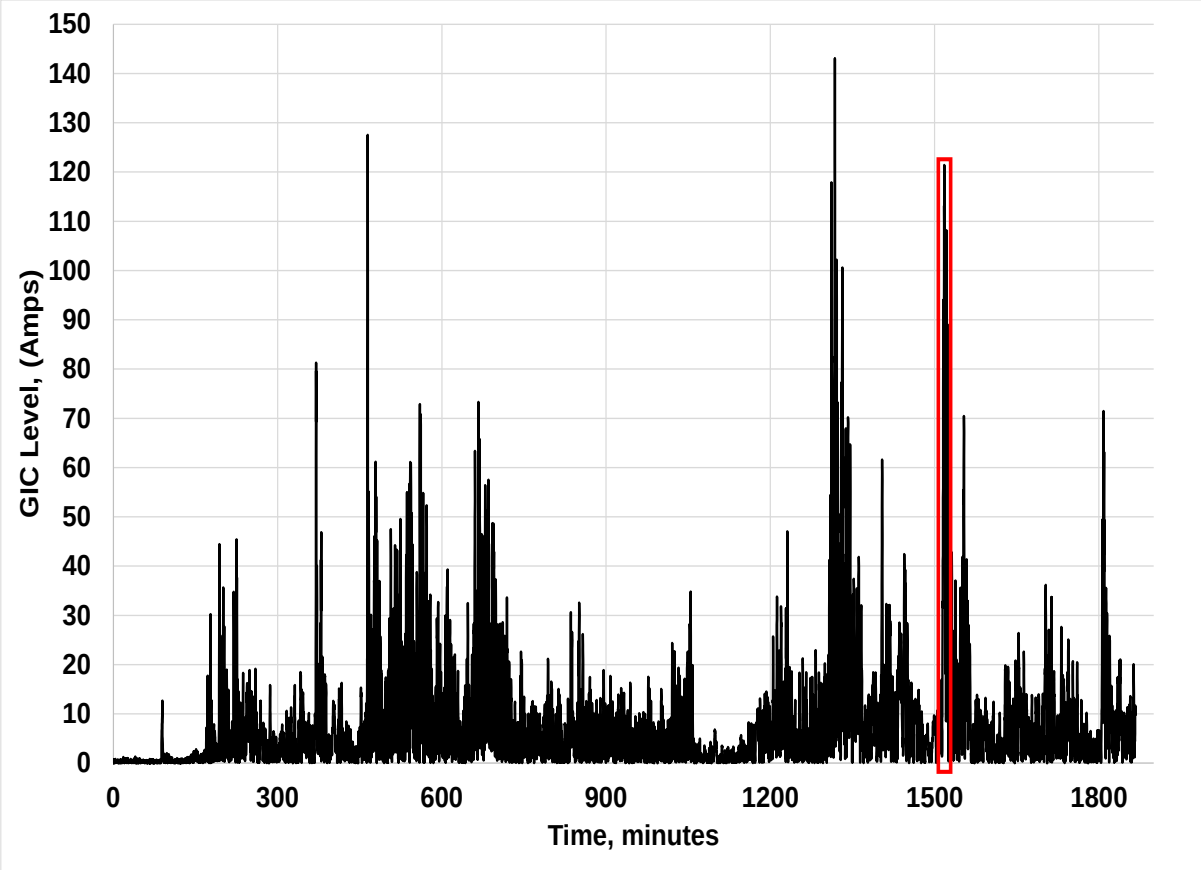
Duration of Highest GIC Pulse = 1.5 minutes

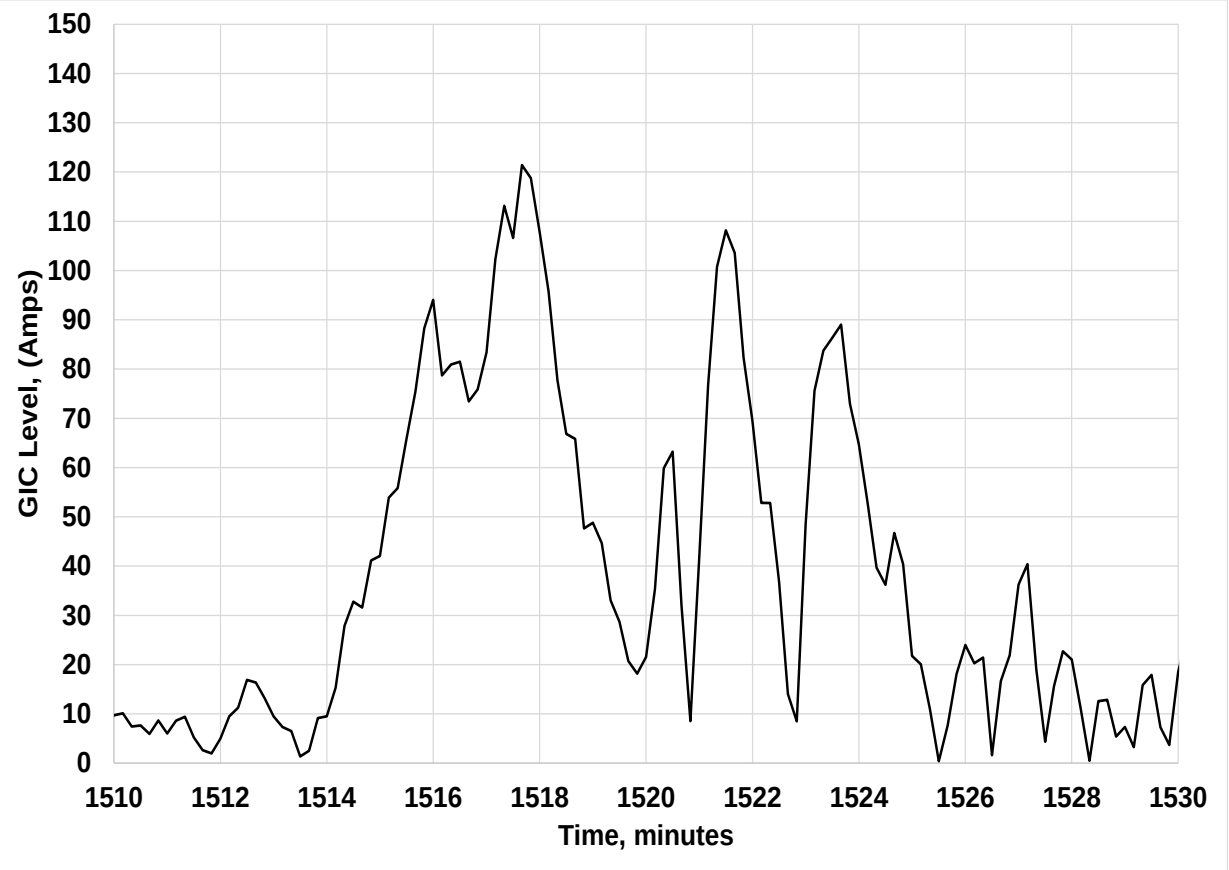
March 13, 1989 GMD Storm (NERC Signature)



Durations of Highest GIC Pulse = 2.5, 2.8, and 1.7 minutes

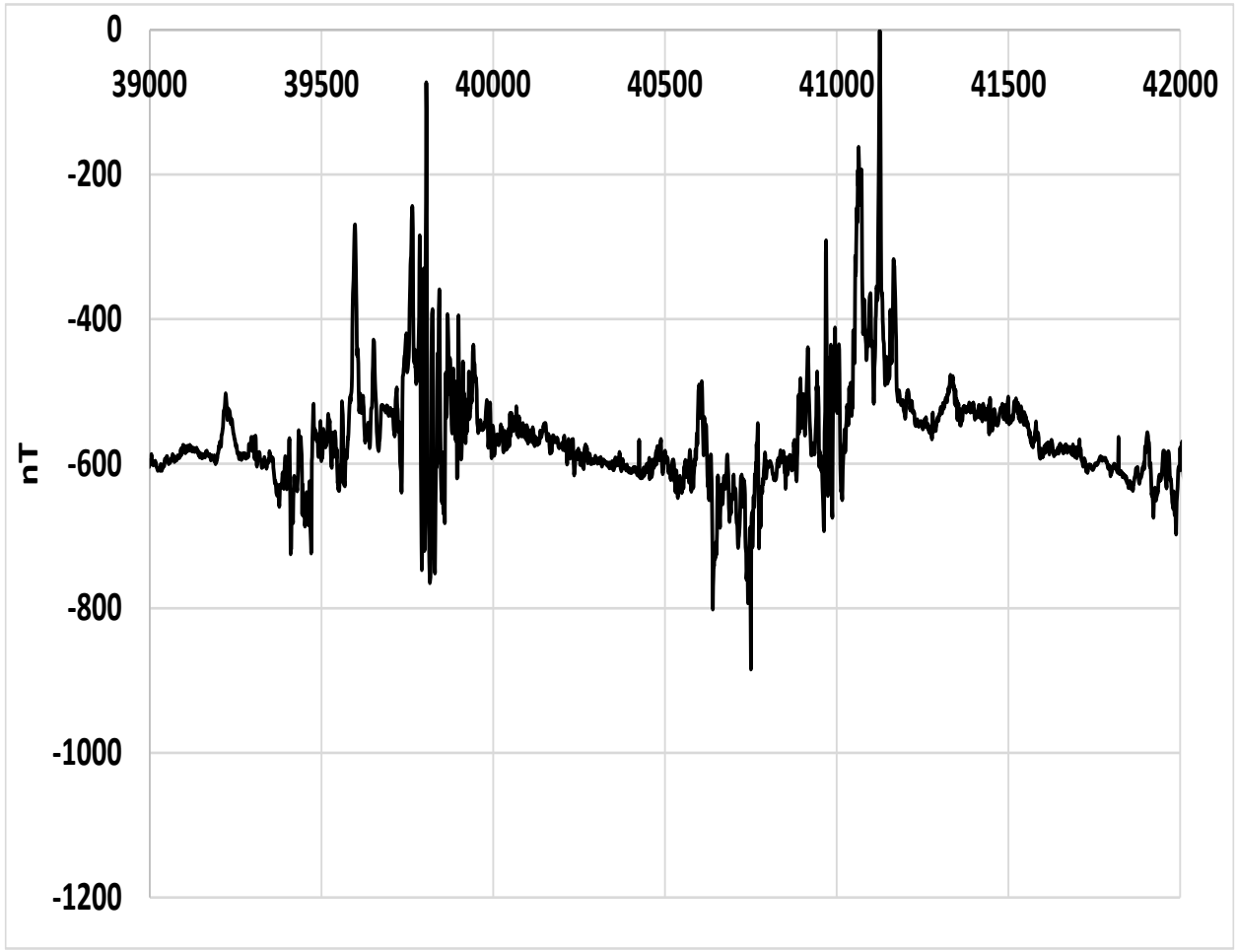
March 13, 1989 GMD Storm – NERC Signature, Cont.

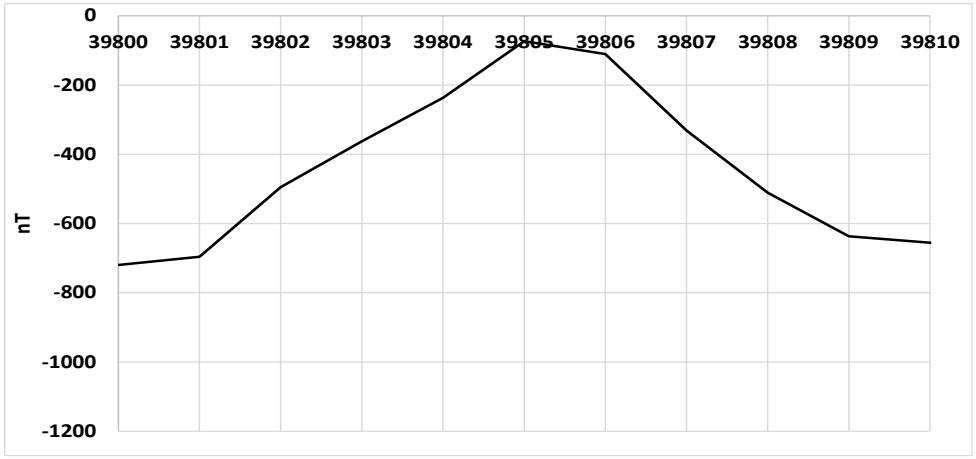


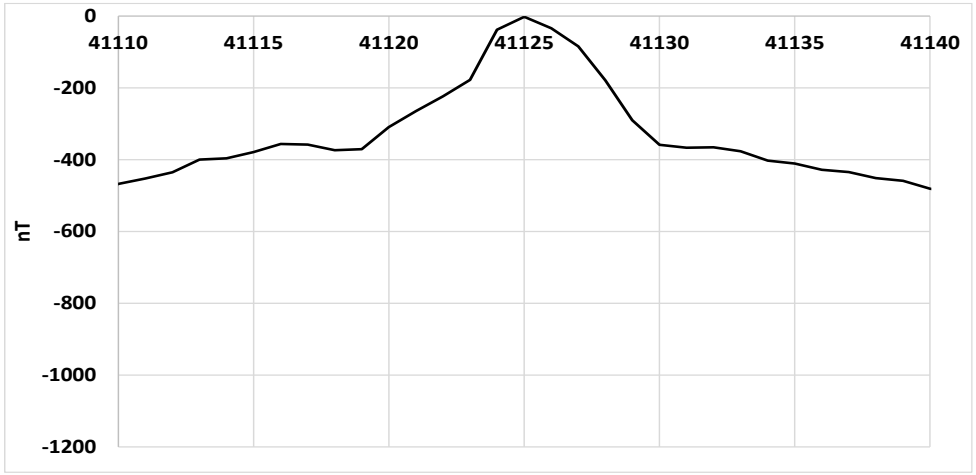


Duration of Highest GIC Pulses = 2 and 6 minutes

October 31, 2003 GMD (Halloween Storm)







Duration of Highest GIC Pulses = 8 and 10 minutes

Possible durations of high peak GIC pulses vs. NERC's Reference GIC Signature

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- NERC Signature: 1.7, 2.5, 2.8, and 6 minutes
- May 10, 2024 (Gannon storm): 1.5, 4, and 6 minutes
- Oct 31, 2003 (Halloween storm): 8 and 10 minutes

Time durations of highest GIC pulses are well represented in NERC's Reference GIC Signature

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Conclusions

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- The strength of the May 2024 Gannon GMD storm is about 2/3 of the 1989 Storm
- GIC signatures of different GMD storms are different but have the same nature
- Time durations of highest GIC pulses in NERC's Reference GIC Signature well represent those of other GIC Signature
- For the same GMD storm, transformers on the system can experience highest GIC peaks at different times. This translates into lower total VAR Demand and harmonics on the system
  - Hence lower negative impact on the system

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Power Flow Analysis of May 2024 GMD Event (Gannon Storm)

NERC Geomagnetic Disturbance Workshop

October 1-2, 2024

PowerWorld Corporation

2001 South First Street
Champaign, Illinois 61820
+1 (217) 384.6330

Scott R. Dahman, P.E.
scott@powerworld.com
http://www.powerworld.com

Acknowledgement

- Input for this analysis is a surface electric field time series provided by the NOAA Space Weather Prediction Center
  - 3D Empirical Magnetotelluric Transfer Function (EMTF)
  - Special thanks to Christopher Balch and Jordan Guerra
- A selection of historic GMD Events in PowerWorld Simulator format (*.b3d), based on NOAA SWPC EMTF models, may be downloaded from https://www.powerworld.com/knowledge-base/historic-gmd

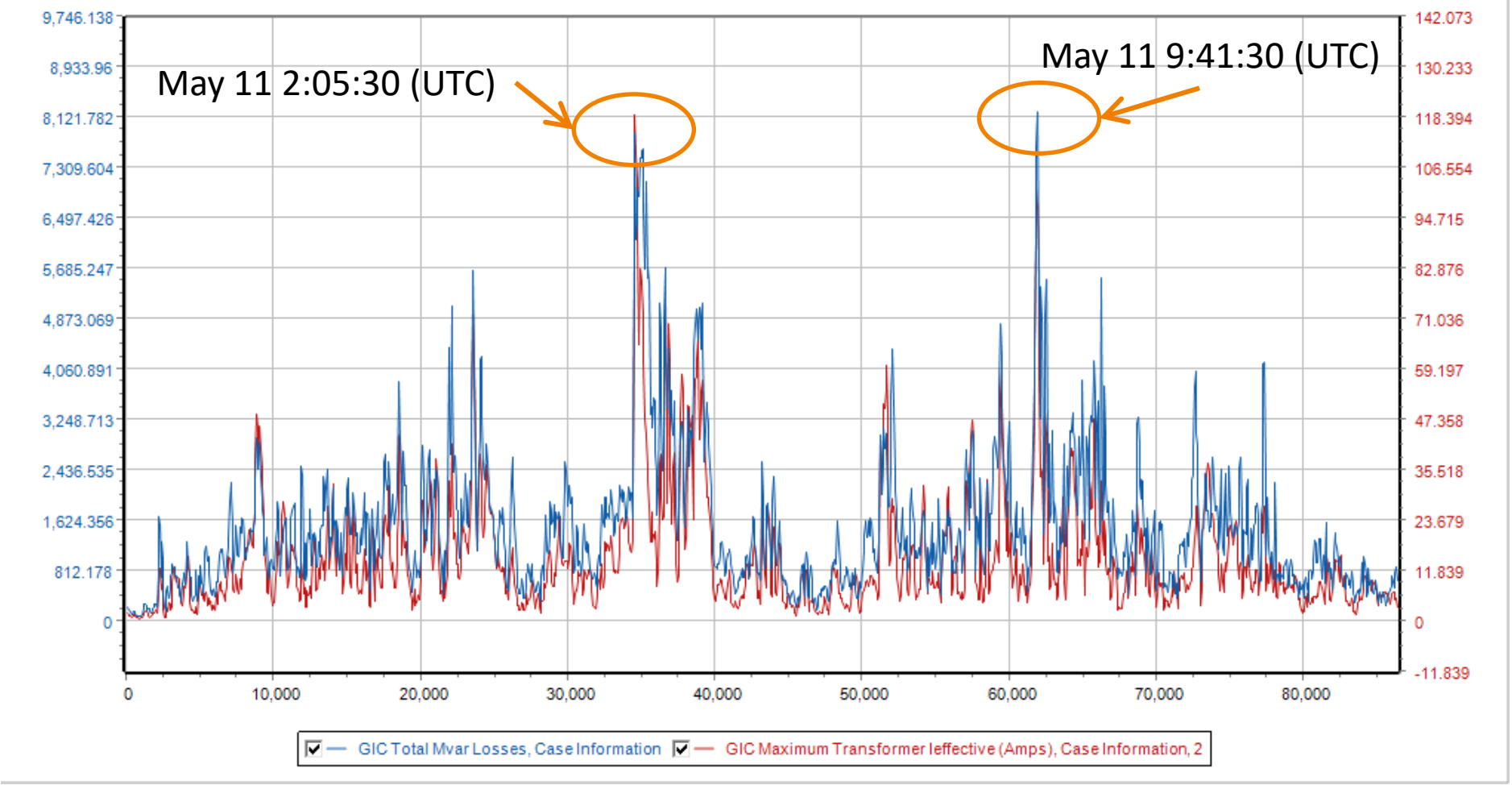
NOAA SWPC Geoelectric Field Models

- https://www.swpc.noaa.gov/products/geoelectric-field-models-1-minute
- Near real-time data for approximately the last 12 hours
- GeoJSON format
  - Text file for encoding geographic data structures, https://geojson.org/
  - Supported by PowerWorld Simulator
- US-Canada 1D Model and 3D EMTF CONUS Model

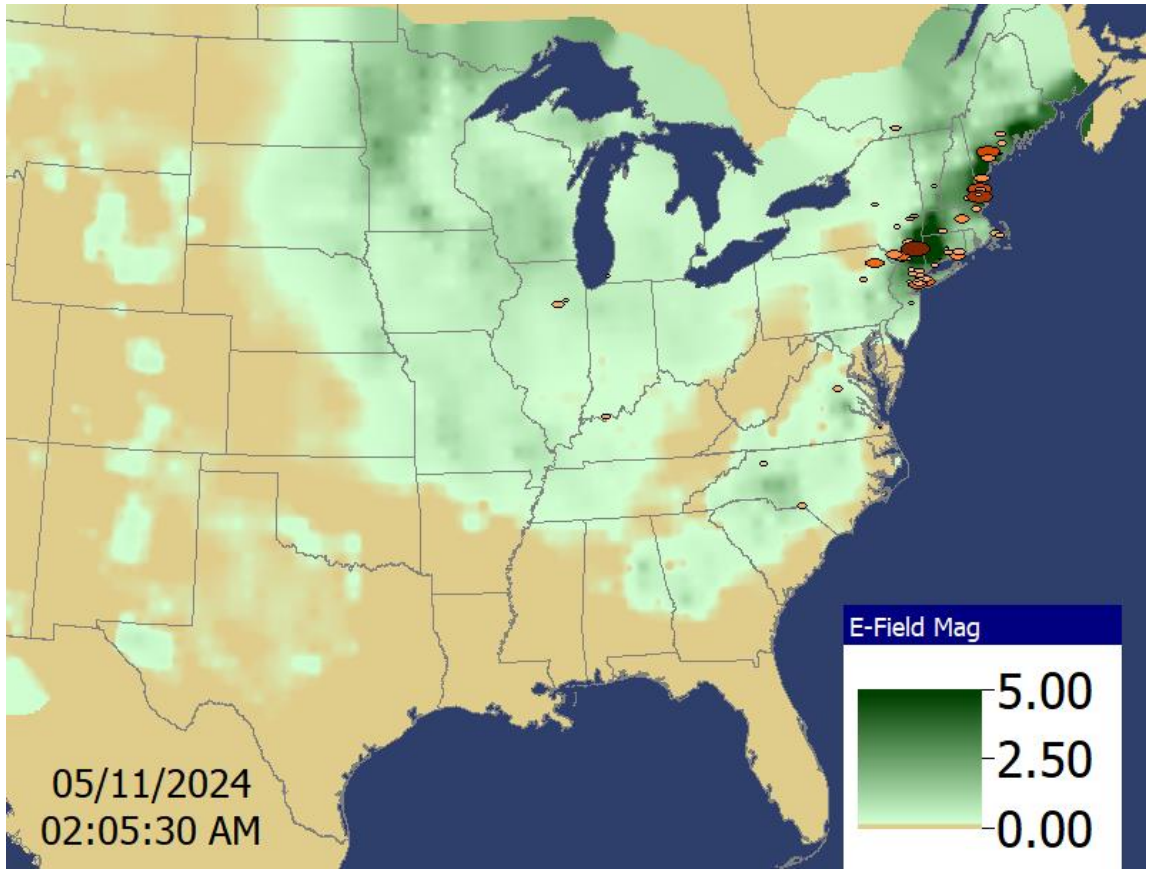
Study Process

- PowerWorld Simulator event analysis capability
  - Import E-field time series (GeoJSON or b3d formats)
  - Generate time series of GIC power system quantities (transformer currents and reactive power losses)
  - Simulate system response in power flow or transient stability time-scale
- Sample analysis of Gannon Storm

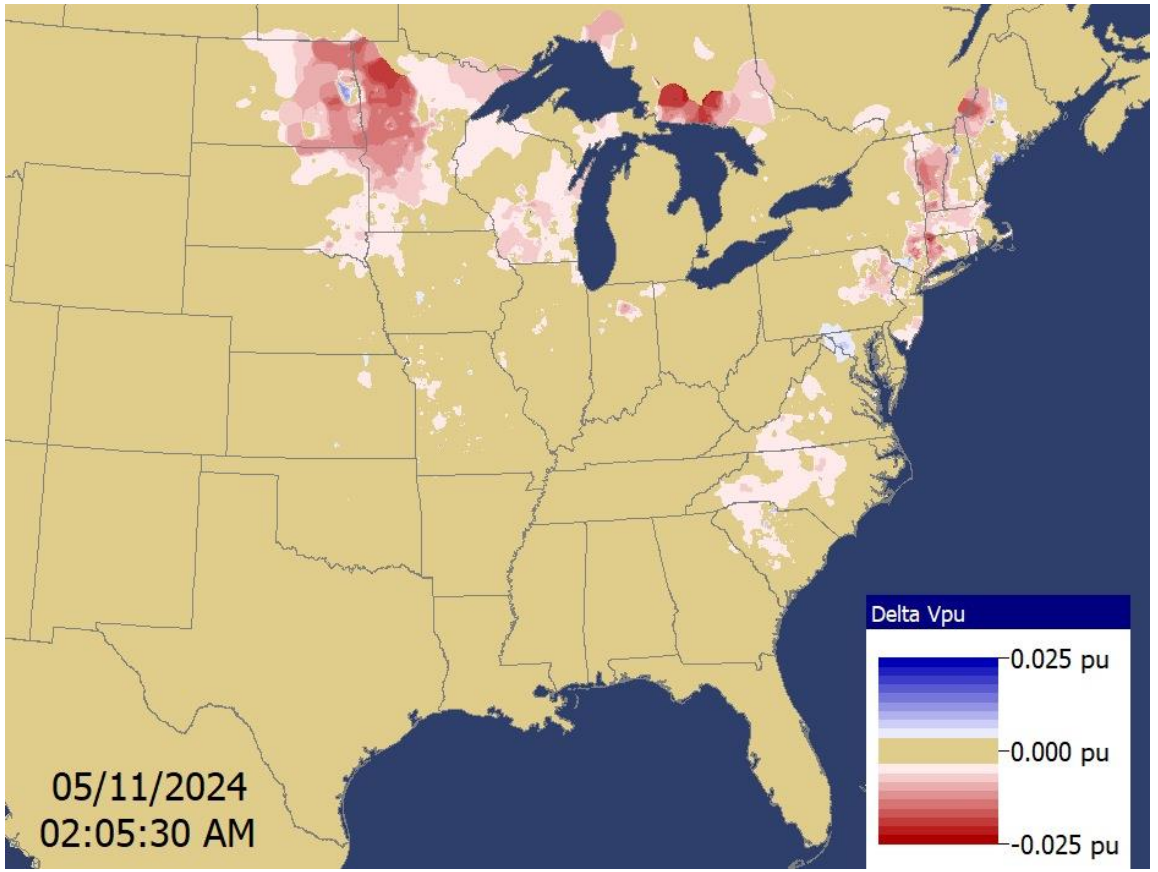
EI: System GIC Mvar Losses and Highest Transformer Effective GIC



11 May 2:05:30

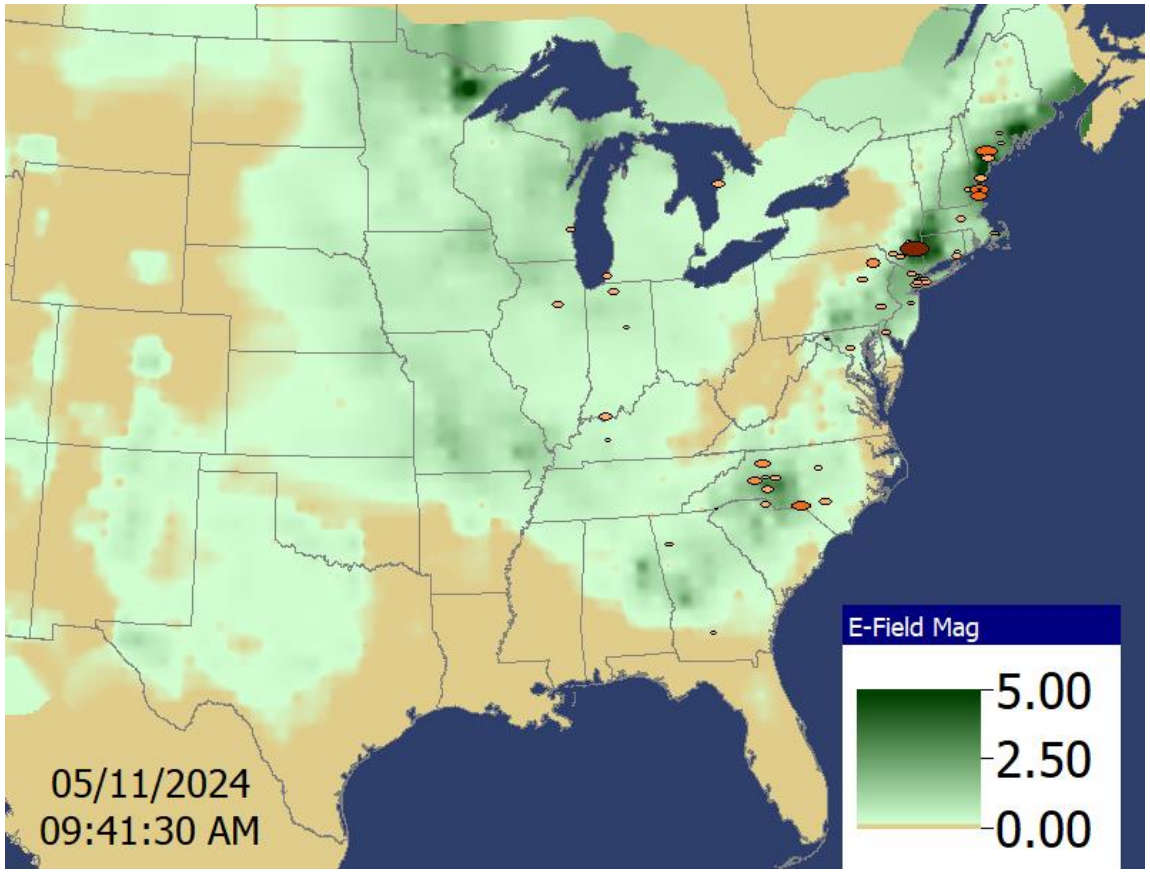


Electric Field Magnitude

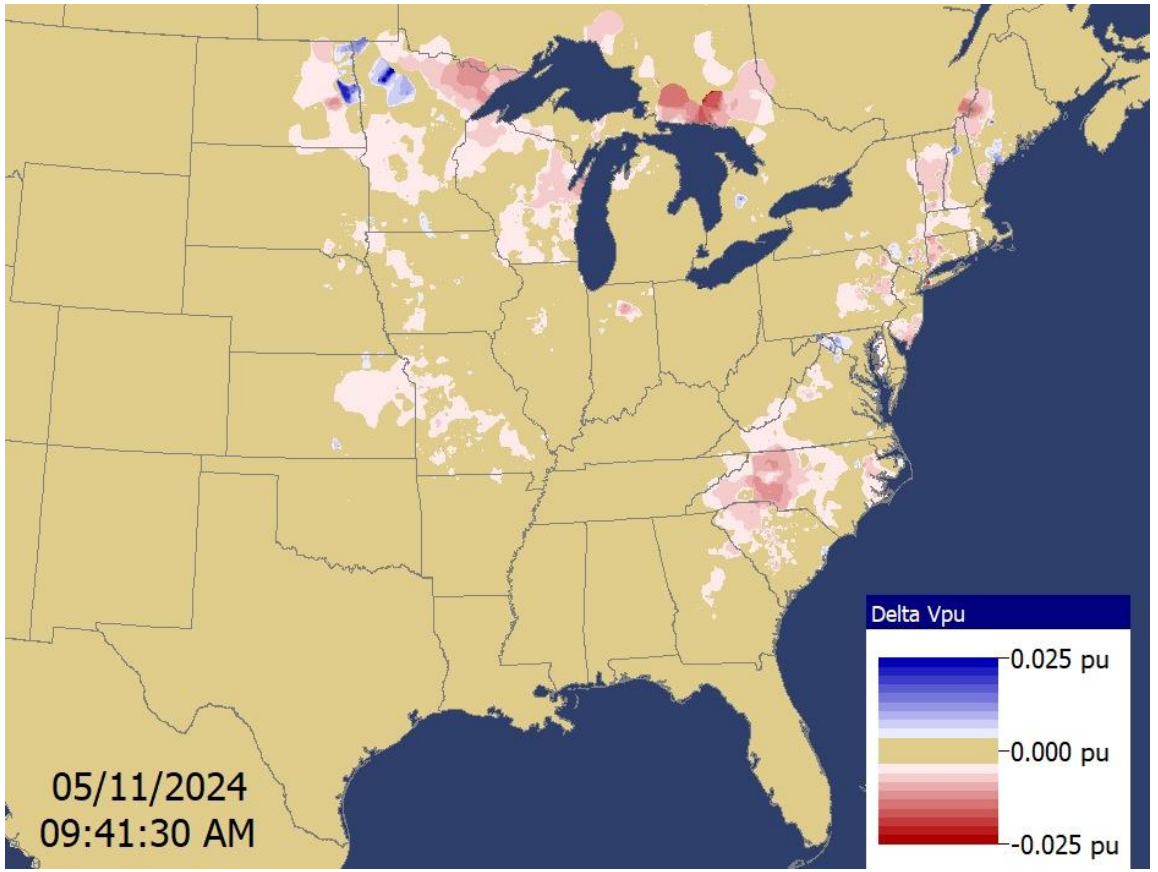


Power Flow Bus Voltage Change

11 May 9:41:30

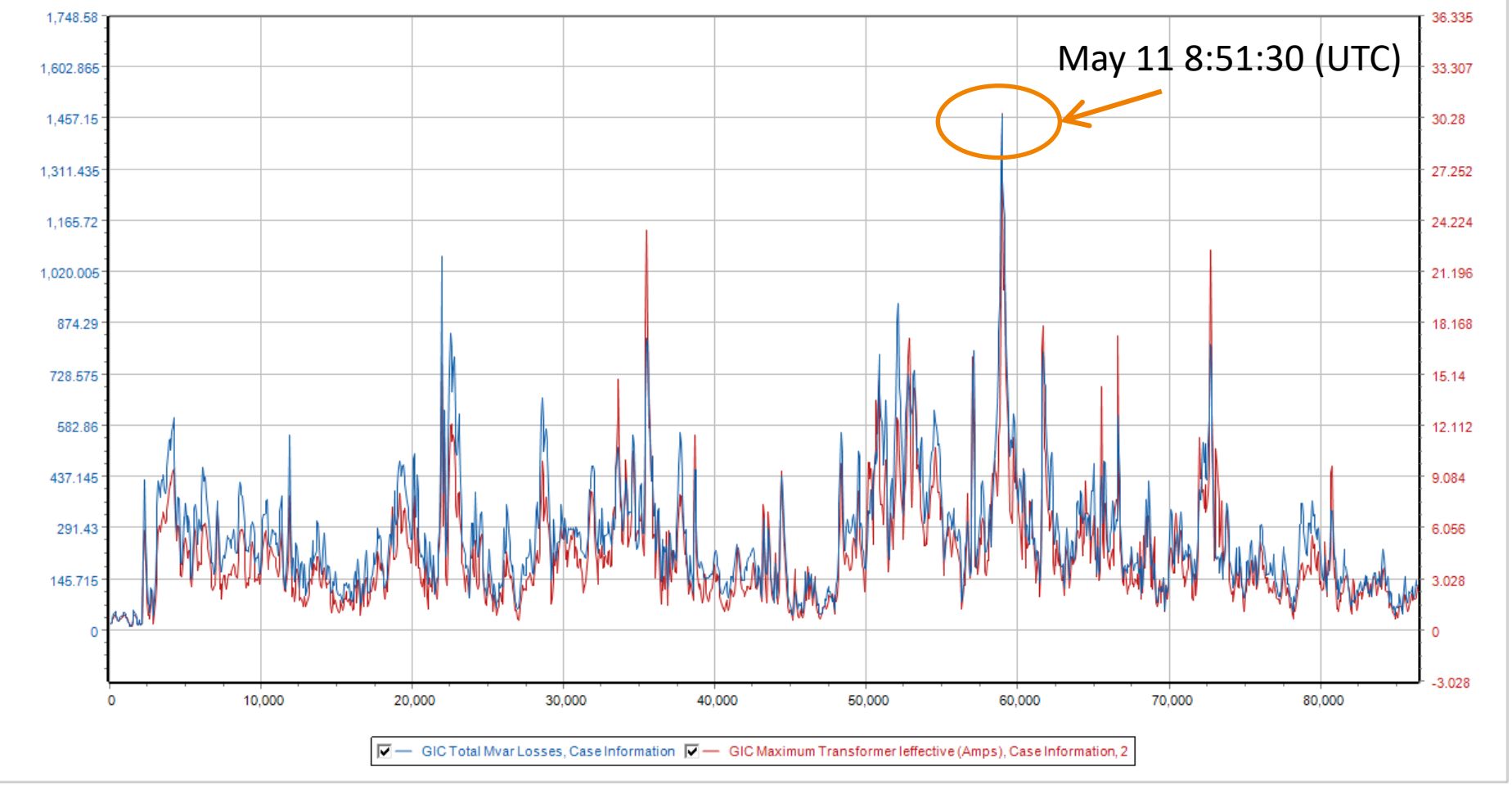


Electric Field Magnitude

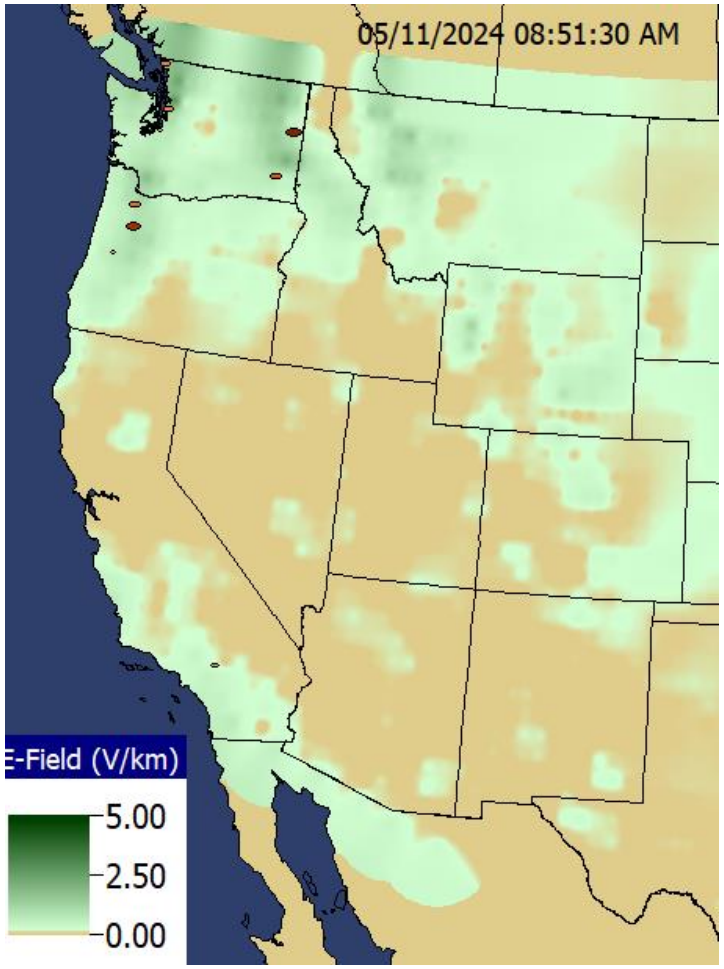


Power Flow Bus Voltage Change

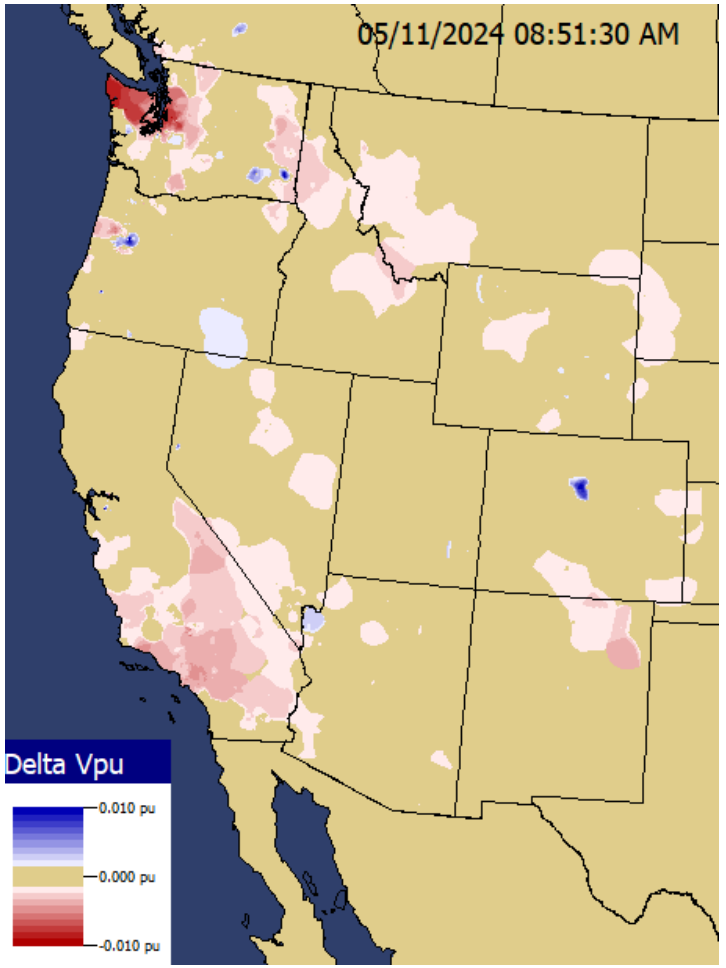
WECC: System GIC Mvar Losses and Highest Transformer Effective GIC



11 May 8:51:30



Electric Field Magnitude



Power Flow Bus Voltage Change

Video Animations

- Surface Electric Field (CONUS): https://youtu.be/2c7_tMARH4o
- Eastern Light Load Simulation: https://youtu.be/kfM6zN0DuT4
- Western Light Load Simulation: https://youtu.be/RMhfYkrpIBc
- Summary https://www.powerworld.com/knowledge-base/may-2024-gmd-event

Study Limitations

- System Topology (e.g. open/closed lines) and Parameters (e.g. dc resistance – grounding, coil, lines)
- Accuracy and precision of EMTF modeling (0.5 degree grid, CONUS only)
- Characteristics of voltage support devices
  - How much reactive power margin is available?
  - What are the time scales of the response of various devices?
- Harmonics impacts
  - Integrate EPRI GICHarm, or
  - Incorporate actual events (e.g. device trips) into modeling
- Impact of Transmission Line Routing (may soon be an option in PowerWorld Simulator)

Geoelectric Fields during the May 2024 Super Storm

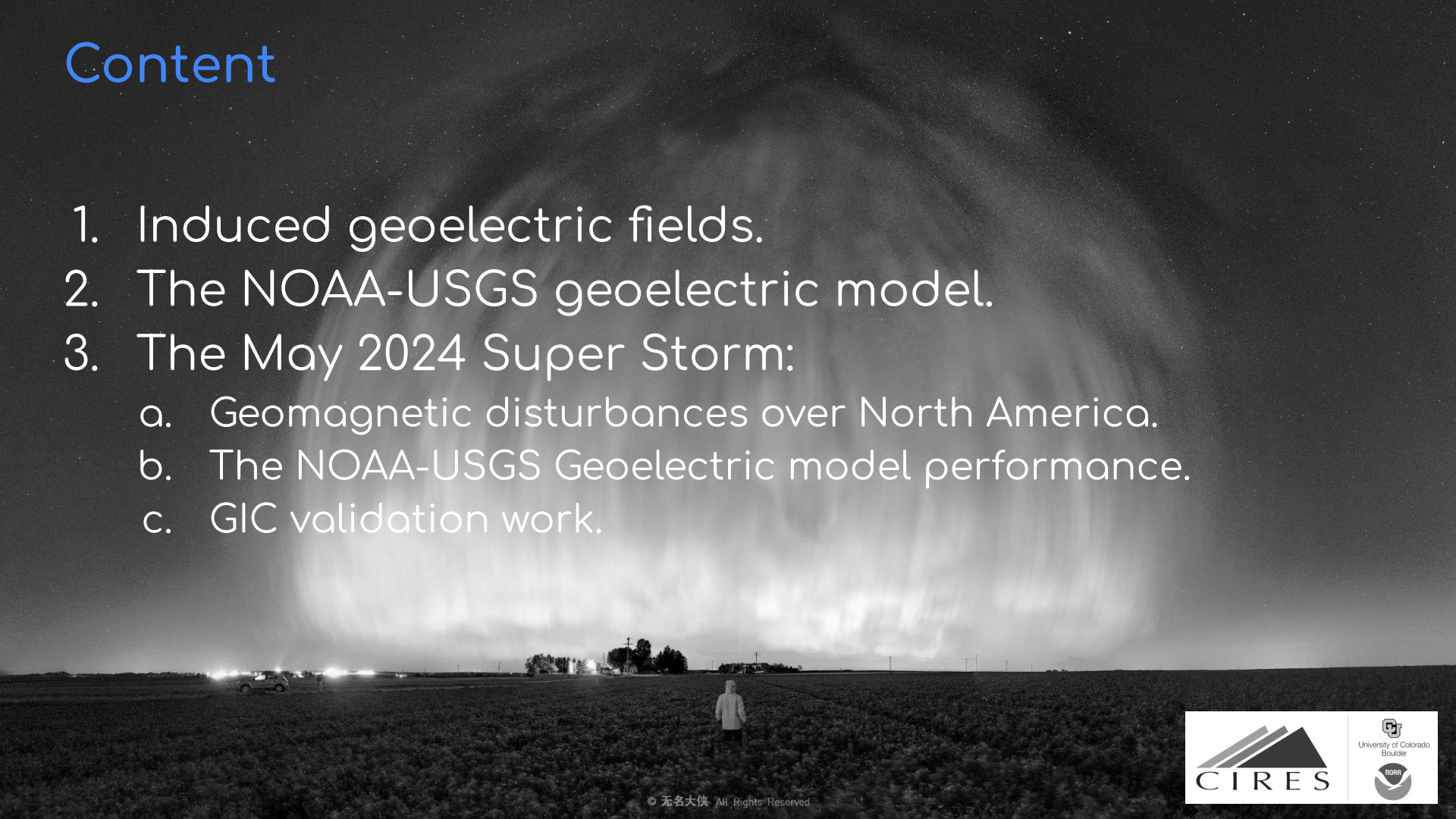
J. Guerra and C. Balch
CU/CIRES, NOAA/SWPC

Image: Aurora Dome Sky, APOD May 20, 2024.

GMD Workshop
Oct. 1-2, 2024

Content

1. Induced geoelectric fields.
2. The NOAA-USGS geoelectric model.
3. The May 2024 Super Storm:
    a. Geomagnetic disturbances over North America.
    b. The NOAA-USGS Geoelectric model performance.
    c. GIC validation work.



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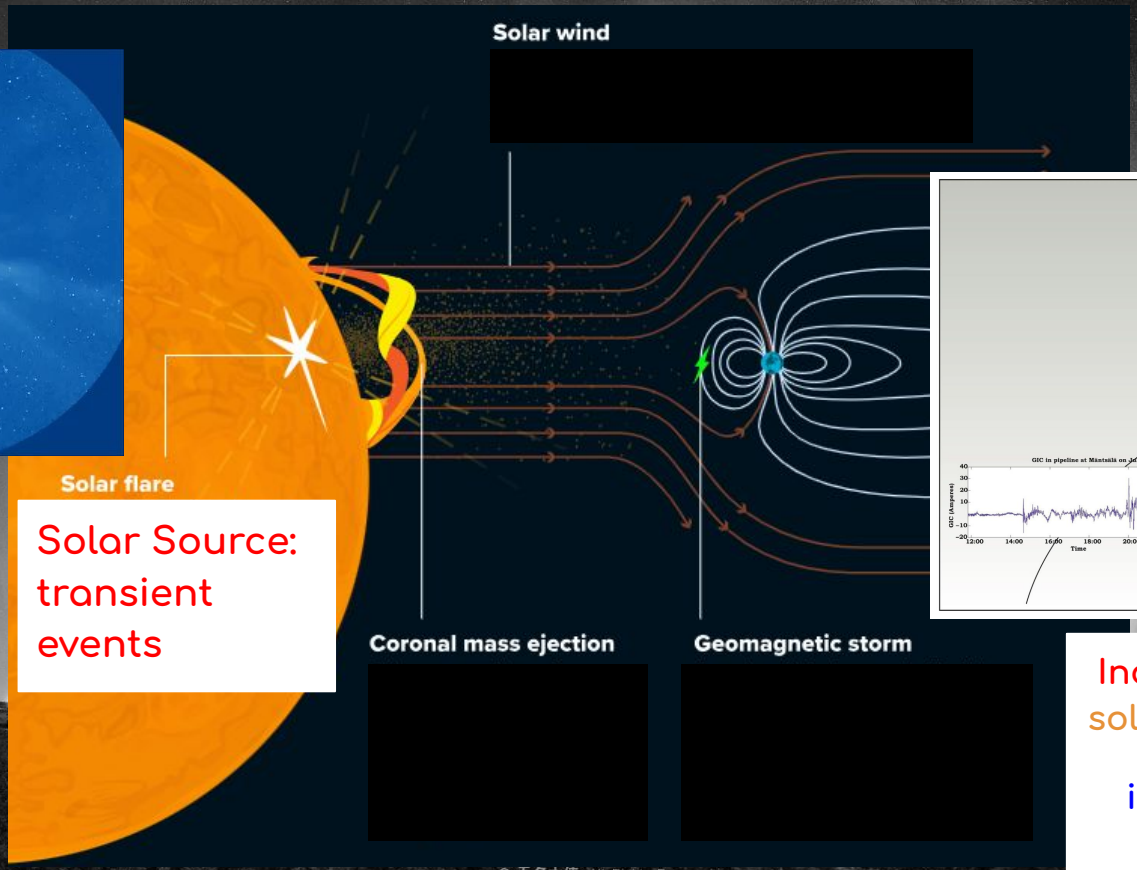
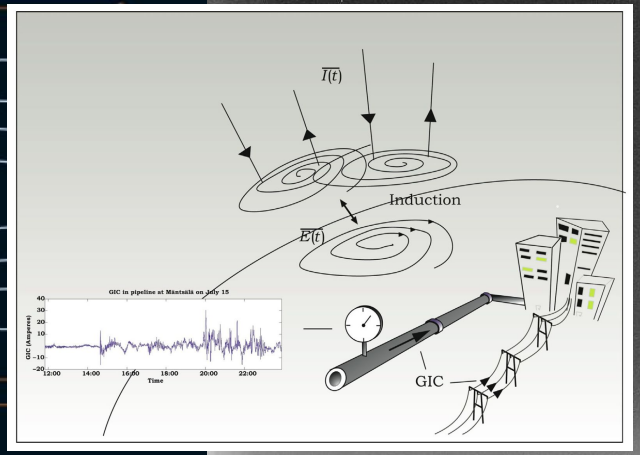
Induced Geoelectric Fields during Geomagnetic Storms



Solar Source: transient events

Ionospheric currents



Induced ground B-field + solid earth conductivity =

induced ground E-field

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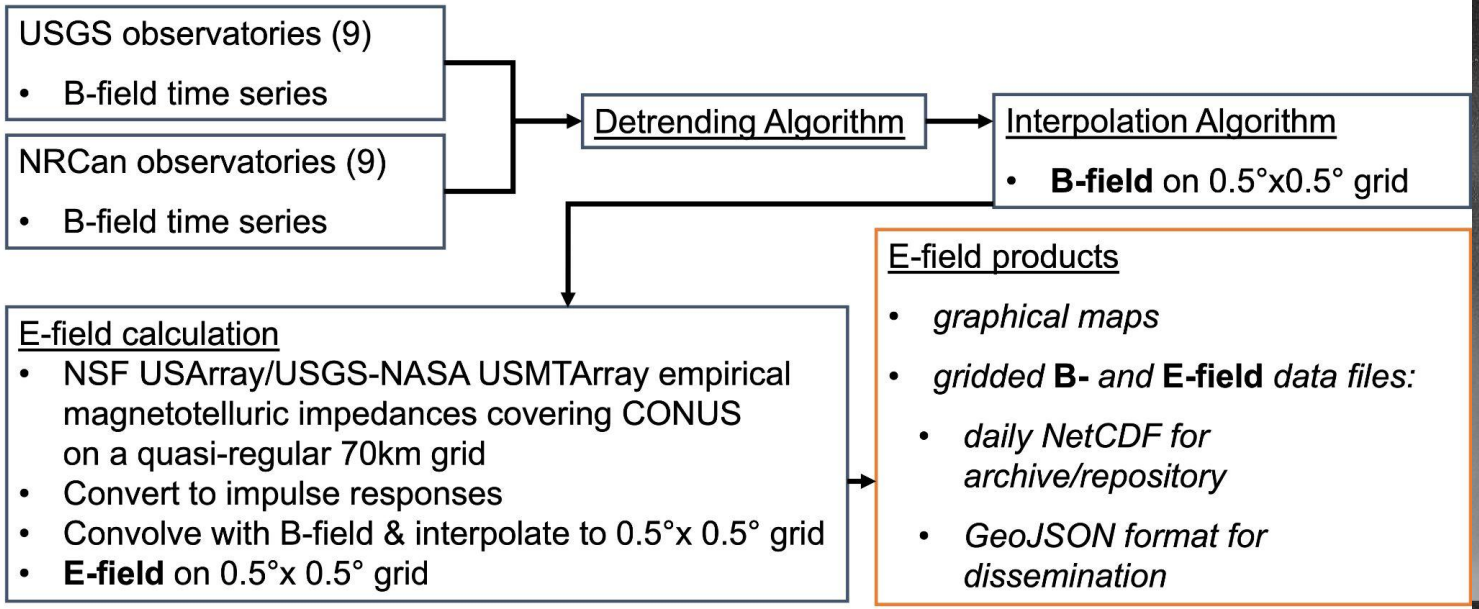
University of Colorado Boulder
NOAA

The NOAA-USGS Geoelectric Model at Glance

NOAA-USGS 3D empirical E-field model

- Operational algorithm

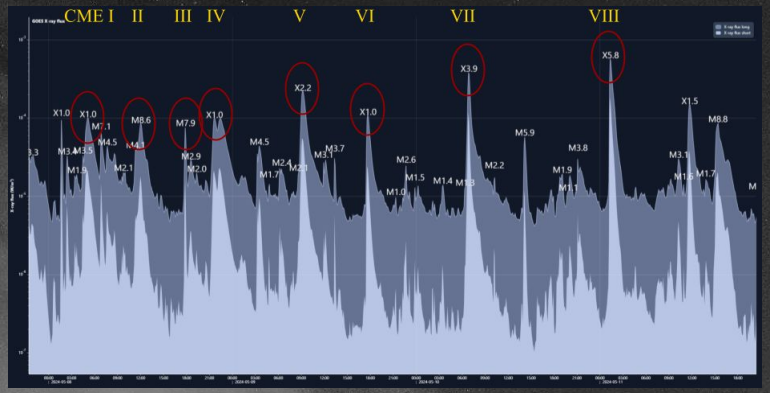


URL: https://www.swpc.noaa.gov/products/geoelectric-field-models-1-minute

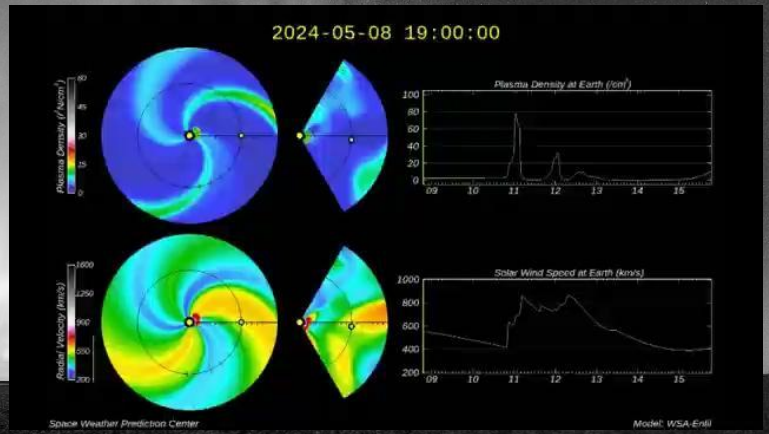
The May 2024 Super Storm

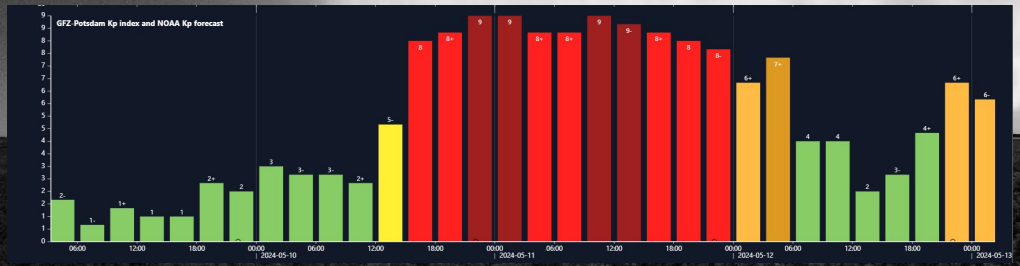
- 8 X-class flares between May 8 - 12,
- 6 associated CMEs between May 11 (15:17) and May 12 (05:08):
  - Estimated speeds = 500 - 1500 km/s
- Extreme geomagnetic activity level (Kp > 8) between May 10 18:00 and May 12 00:00.

X-ray flux: X-class flares and associated CMEs



WSA-Enlil CME propagation





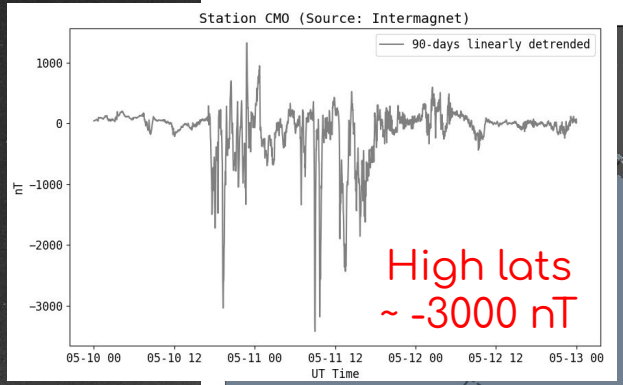
NOAA Planetary Kp Index

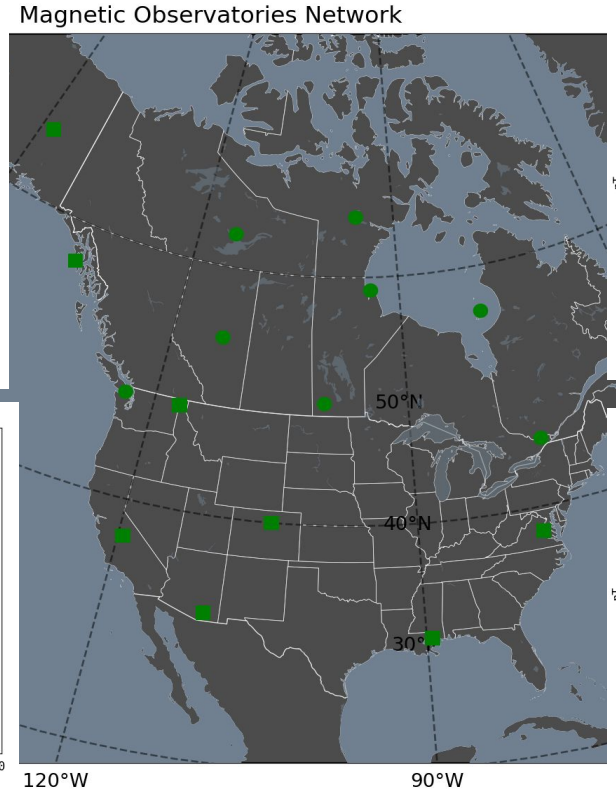
Source/credits: SWPC/SWFO, B. Muhlestein

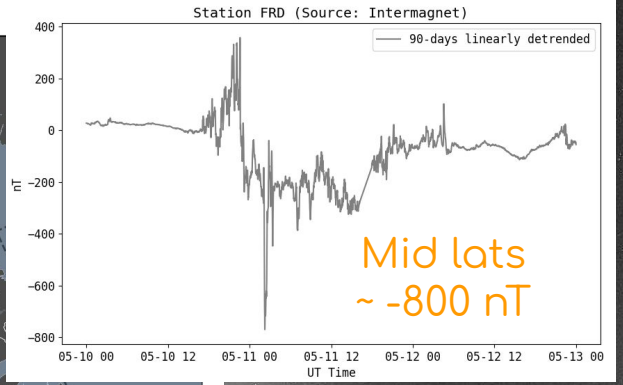
The Geoelectric Model during the May Storm

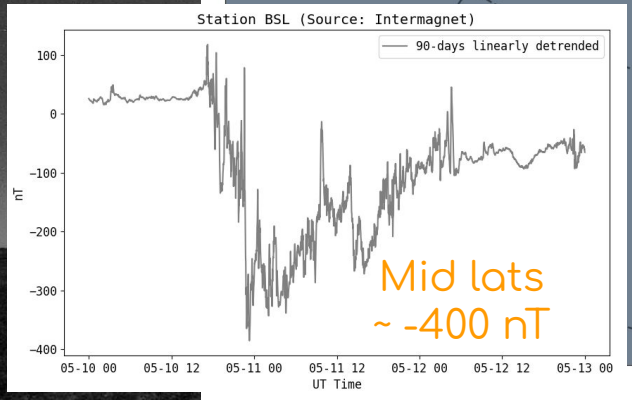
- Geomagnetic disturbances: 18 stations included.

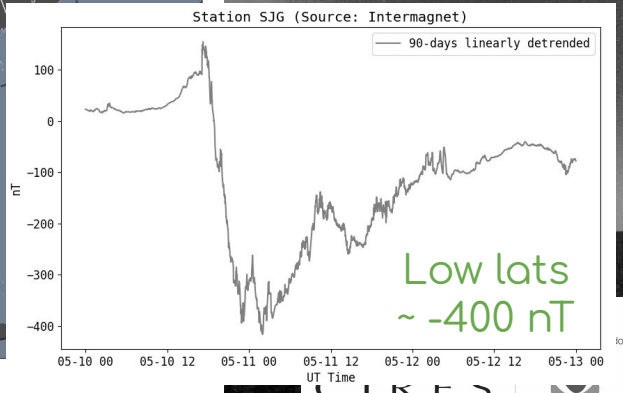
North components examples.





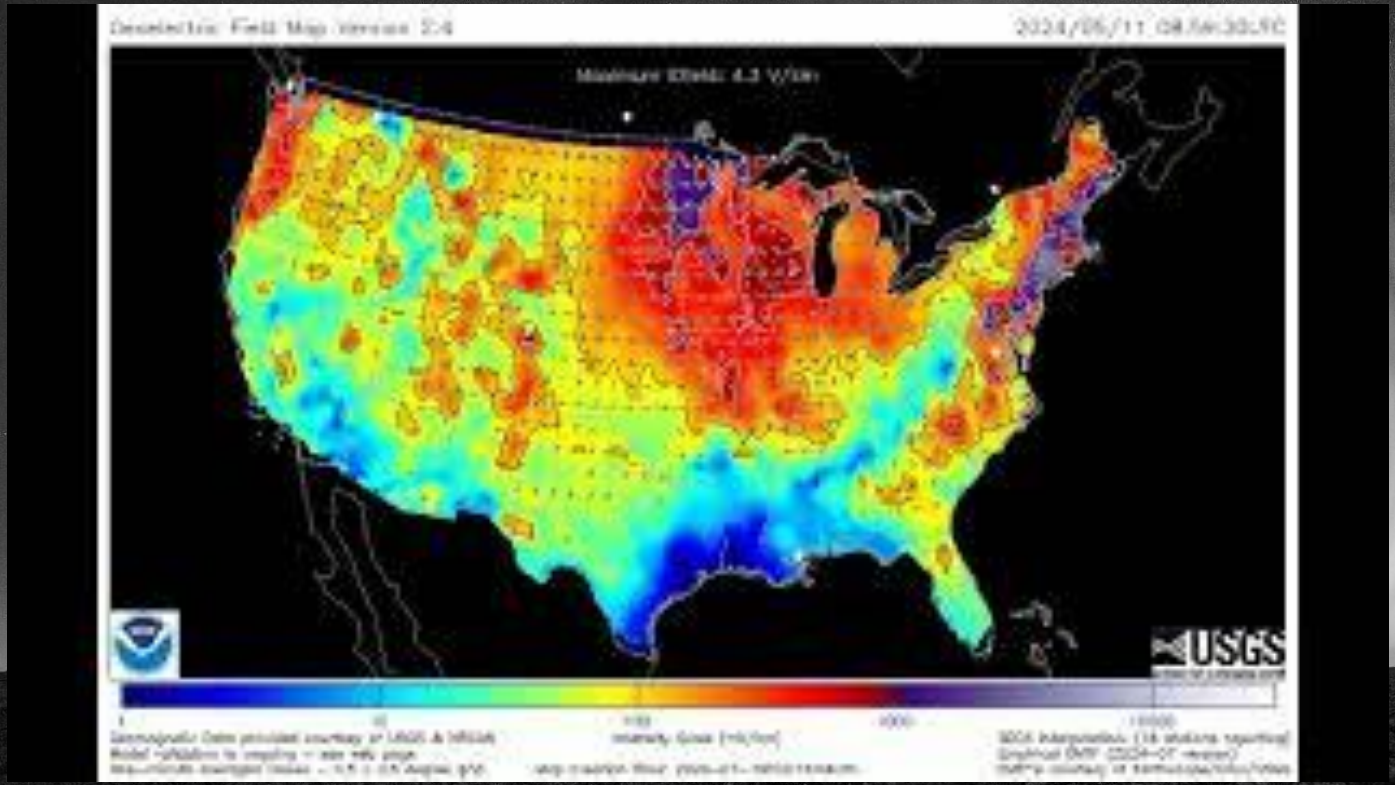






The Geoelectric Model during the May Storm

- May 10 00:00 - May 13 00:00



- Values > 500 mV/km appeared around May 10 at 17:00 UT.
- Similar values remind until May 12 at 07:00 UT

https://youtu.be/7ns9XfrxHEc?si=c-nEA_wzd6_lvcyZ

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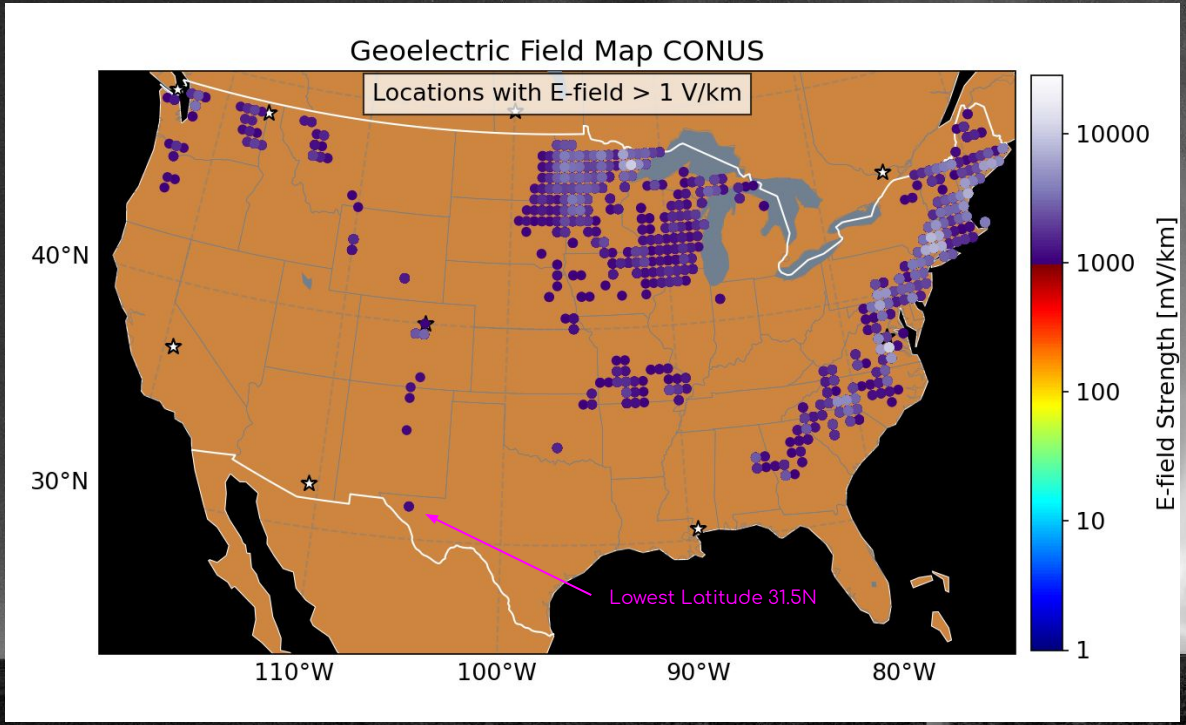
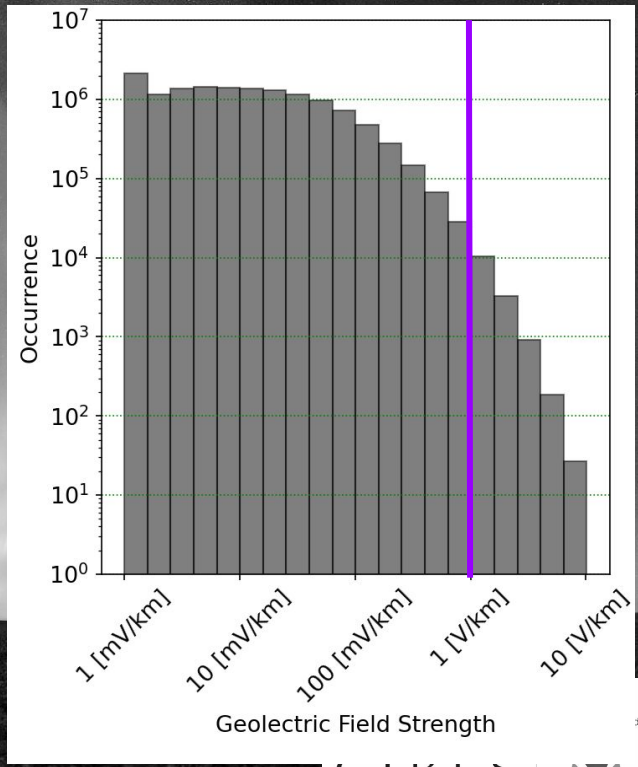
The Geoelectric Model during the May Storm

Max E-field strength for |E|> 1 V/km.



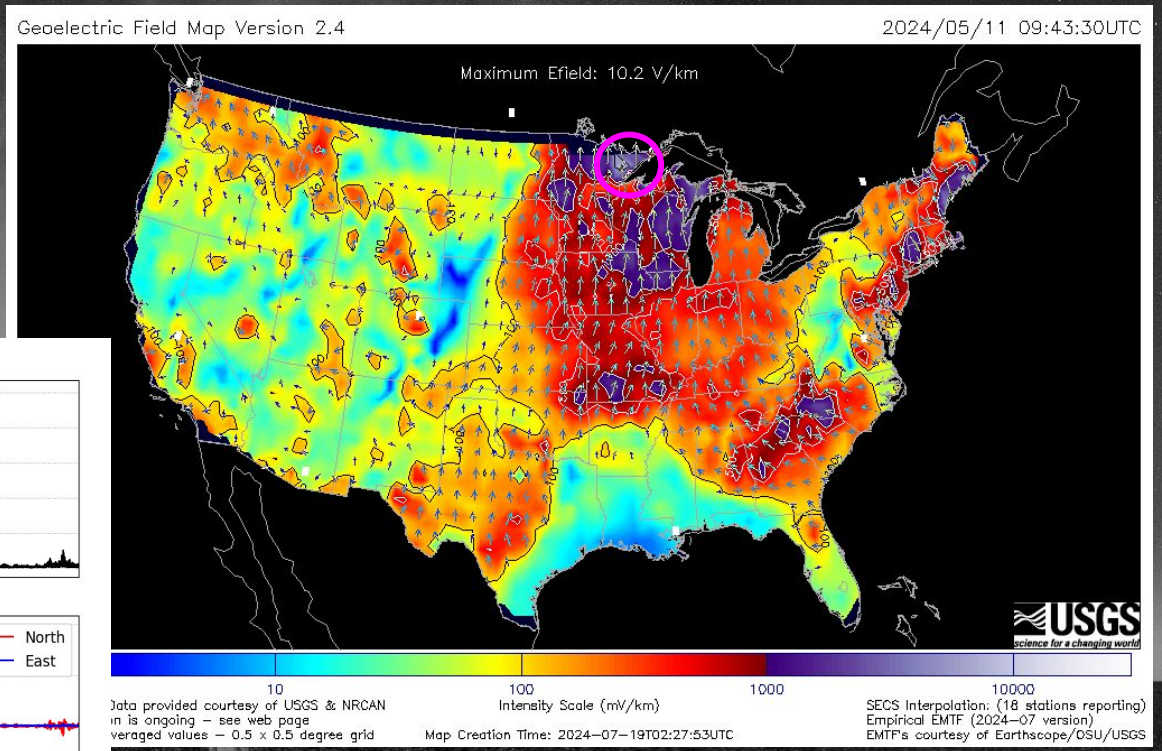
~15K instances with > 1 V/km

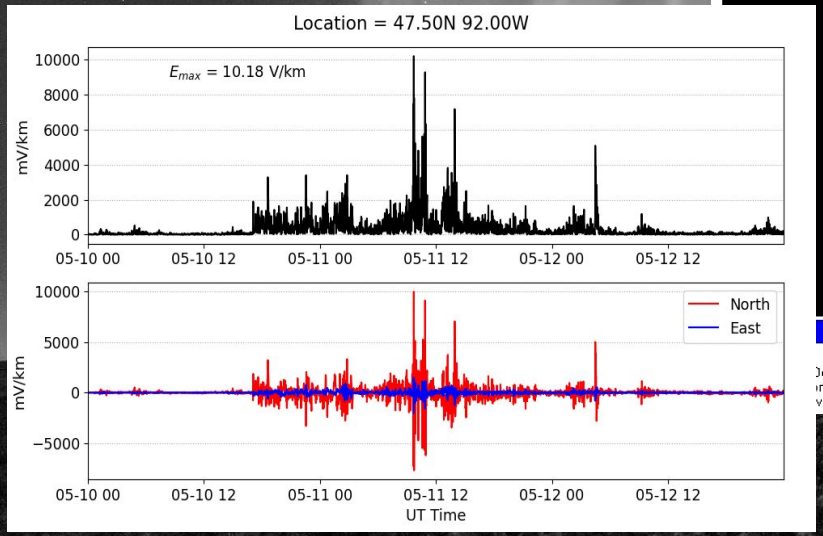


Each location had |E|> 1 V/km, at least once.

The Geoelectric Model during the May Storm

- Maximum value = 10.18 V/km
- Location = 47.5N 92.0W (Northern Minnesota)
- Time = 2024/05/11 09:43 UT

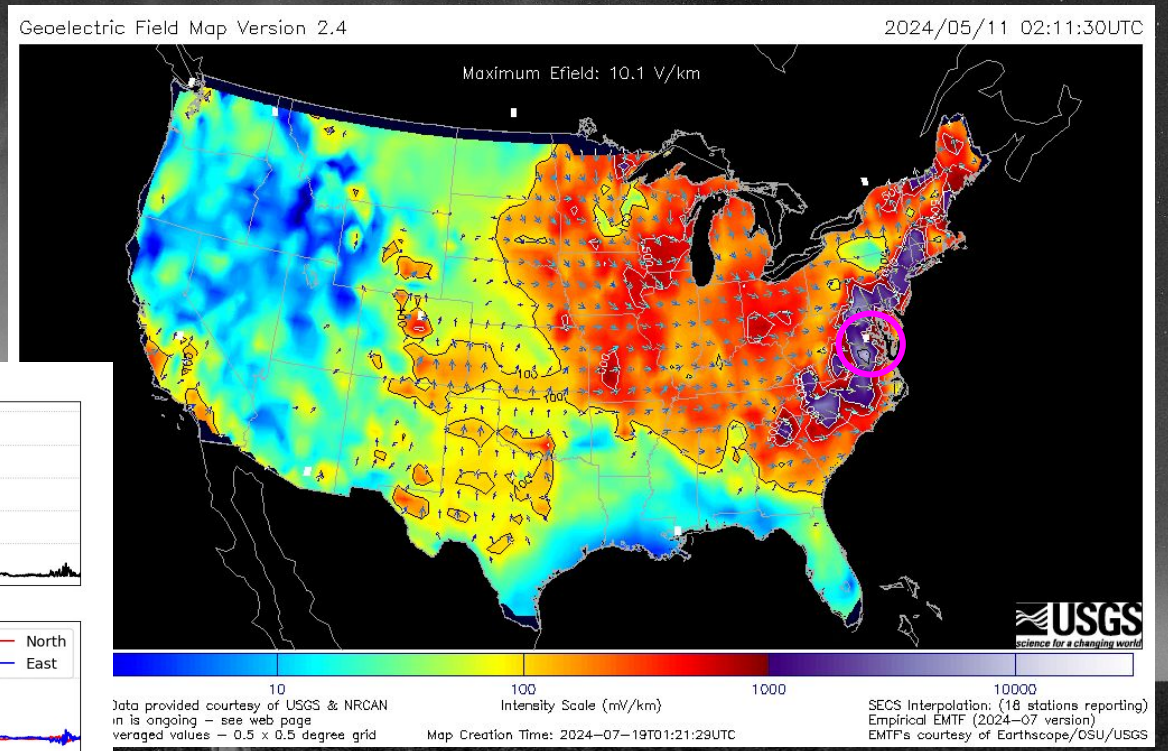


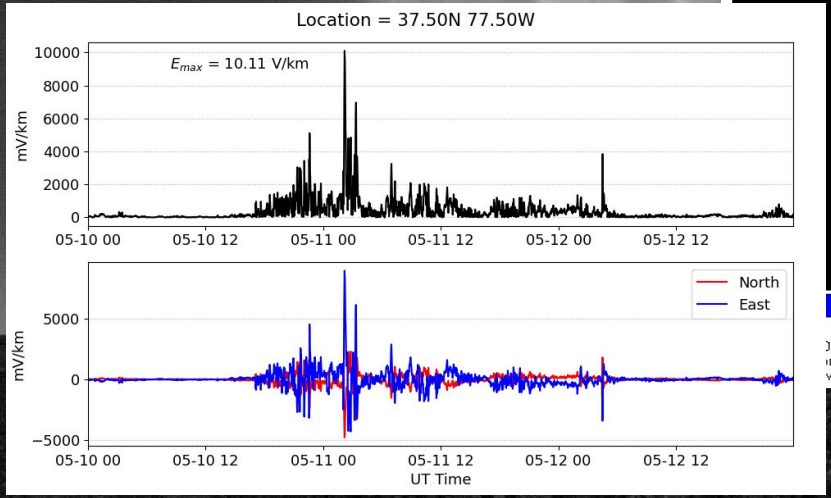


CIRES
University of Colorado Boulder
NOAA

The Geoelectric Model during the May Storm

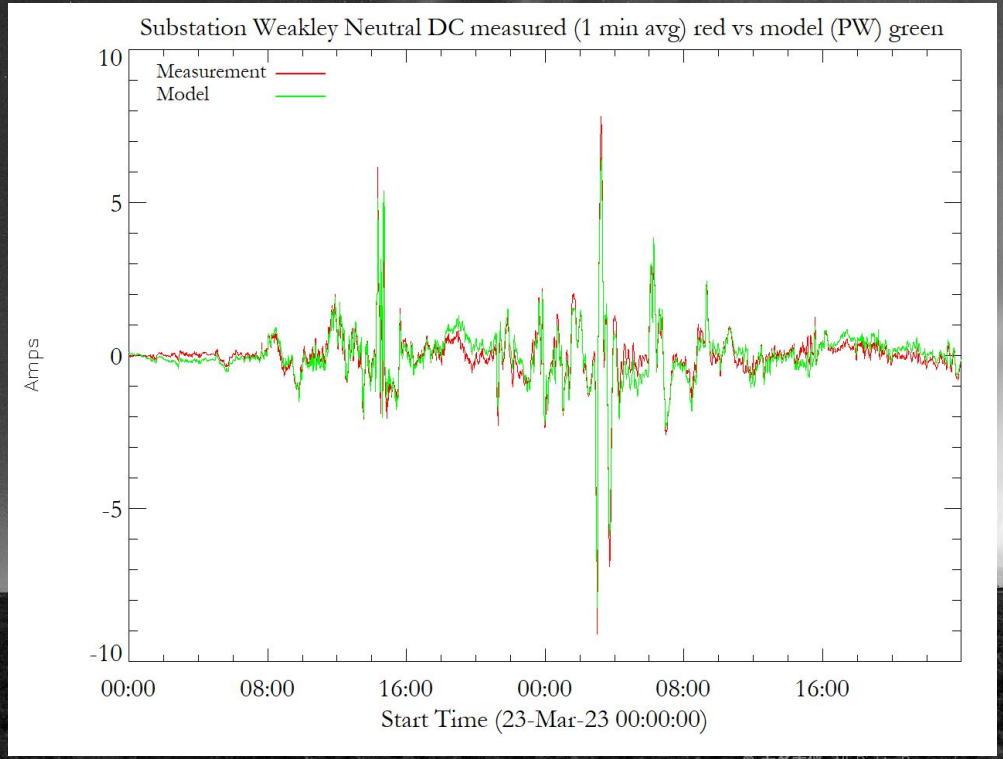
- Maximum value = 10.11 V/km
- Location = 37.5N 77.5W (Richmond Virginia)
- Time = 2024/05/11 02:11 UT





The Geoelectric Model during the May Storm

- Comparison to GIC measurements: currently working with TVA.
  - Example: TVA substation Weakley for March 2023 Storm (max Kp = 8)



Correlation Coeff. = 0.95
Linear-fit slope = 0.97

Summary

- NOAA-USGS Geoelectric model provided near real-time nowcasting of geoelectric fields during the May storm.
- Largest geoelectric fields in the order of 10 V/km in well-known highly-conductive areas (Minnesota, Virginia).
- Geoelectric fields ~ 1 V/km determined as south as western Texas.
- GIC validation work currently underway.

Questions?

For later: jordan.guerra@noaa.gov or christopher.balch@noaa.gov

A Perspective of the Real Time Analysis of the May 2024 Storm from The Moon to Mars Space Weather Analysis Office (M2M SWAO)

PRESENTED BY TONY IAMPIETRO

AS PART OF THE M2M SWAO TEAM

NASA GODDARD SPACE FLIGHT CENTER (GSFC)

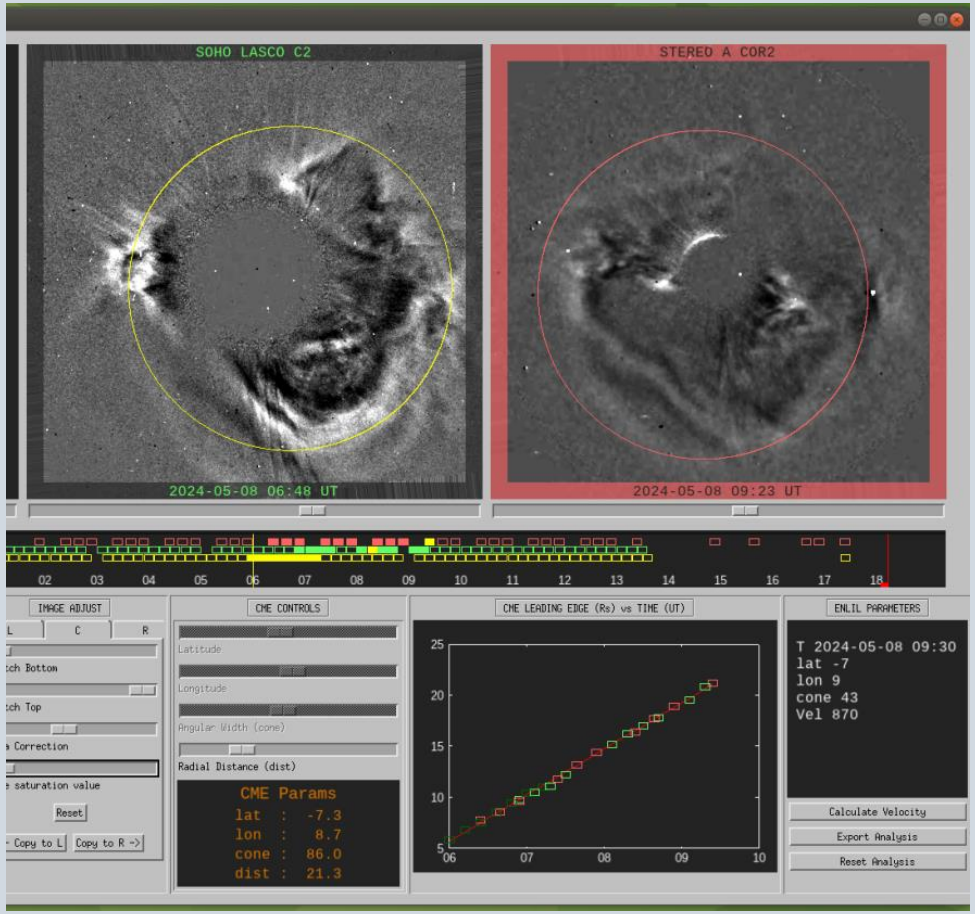
The Human-In-The-Loop of M2M SWAO

Mission Statement: The Moon to Mars Space Weather Analysis Office within the Heliophysics Science Division at NASA Goddard Space Flight Center (GSFC) carries out human-in-the-loop real-time analysis of space weather for NASA missions and conducts activities to support research to operation to research (R2O2R) to enhance space weather knowledge and predictive capabilities for the benefit of the nation.

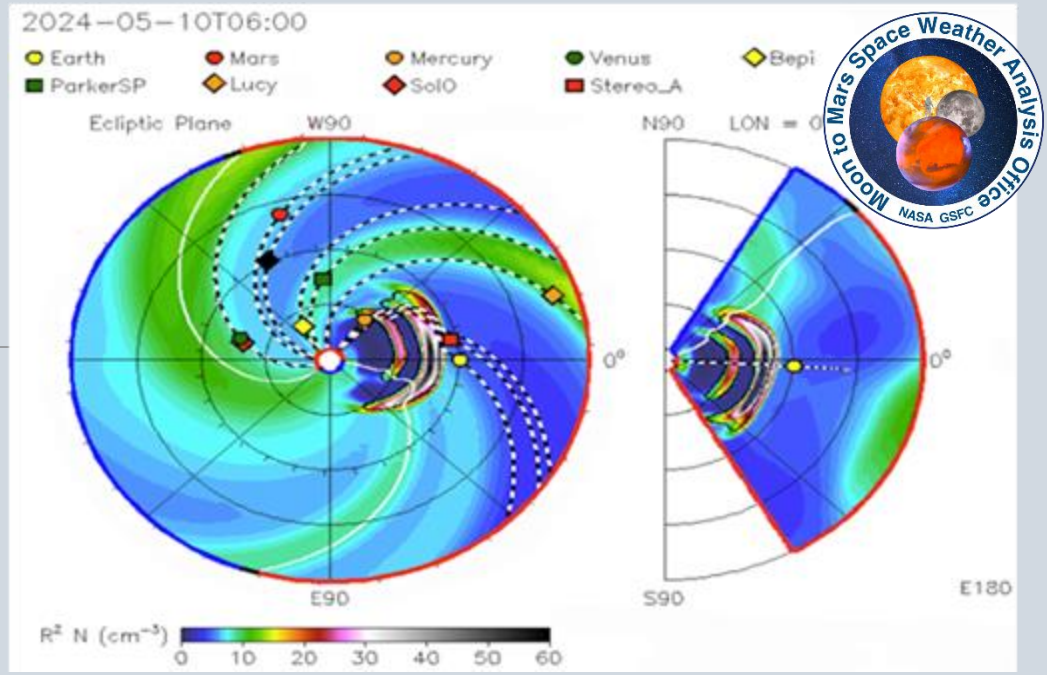
- As part of Integrated Solar Energetic Proton Alert/Warning System (ISEP):
  - Space Radiation Analysis Group (SRAG) [Model Validation, SEP Support and Scoreboards]
  - Community Coordinated Modeling Center (CCMC) [Model Val./DONKI/Scoreboards]
- As part of Mars Space Weather Collaboration:
  - Mars Atmosphere and Volatile Evolution Mission (MAVEN)
  - SRAG+CCMC
- Regular communication with SWPC, MOSWOC, Australian BOM and more via Slack Group, and LASSOS team within GSFC
- Communication with SOHO/STEREO/MAVEN/Solar Orbiter

An M2M day before the storms!

- **The typical day at M2M prior to the May storms:**
- Primary/Secondary from 8 am – 4 pm ET
- On call primary from 4 pm – 10 pm ET
- Duties include:
  - Measuring and analyzing CMEs (360° around the sun!)
  - Cataloguing other Space Wx (flares, SEPs, RBEs, etc.)
  - Daily tag-up to community at 10 am ET
    ★ You're invited! ★
  - Regular continuous communication to SRAG
  - Detailed sign-off for next day's shift
- Weekend:
  - Similar structure, no secondary, no SRAG tag-up (but still regular communication)
- When not pri/sec: "project day", anomaly support, weekly report



The May Storm (Gannon SuperStorm 2024)



- Naming the event after the late Dr. Jennifer Gannon in memorium
- M2M continued analysis of space weather on all sides of the sun, even as Earth was pummeled by this storm
- 9 X-class flares and an M-class background
- 14 Earth directed CMEs / 6 Mars directed
- Impacts modeled to Lucy, STEREO A, PSP, missions near Earth, Mars, OSIRIS-APEX, Solar Orbiter through the week
- Most grand aurora show in decades!
  - As seen in Maryland… (next)

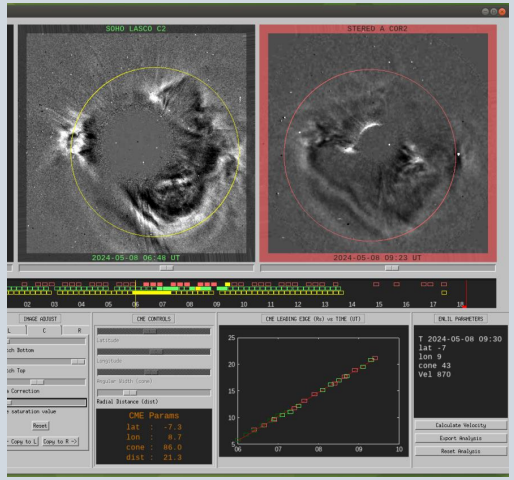
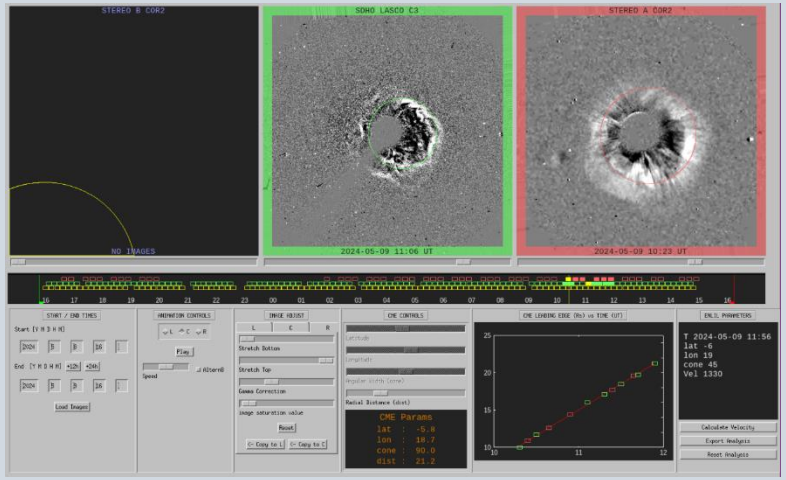
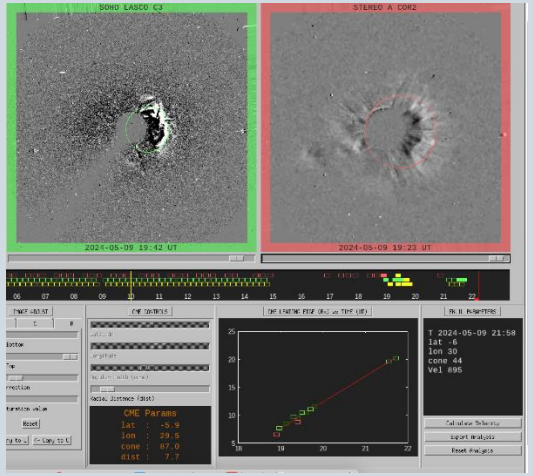
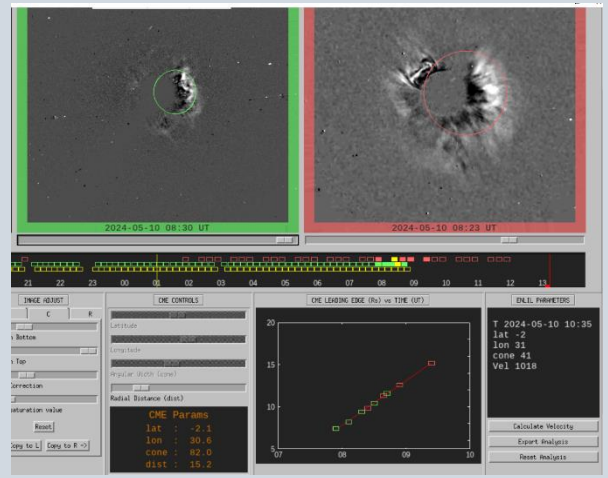
Photo: NASA Aurorasaurus ambassador Gunjan Sinha, shows the sky on May 11, looking ***south*** from near Saskatoon in Saskatchewan, Canada.

My photo! From the Washington D.C. Area

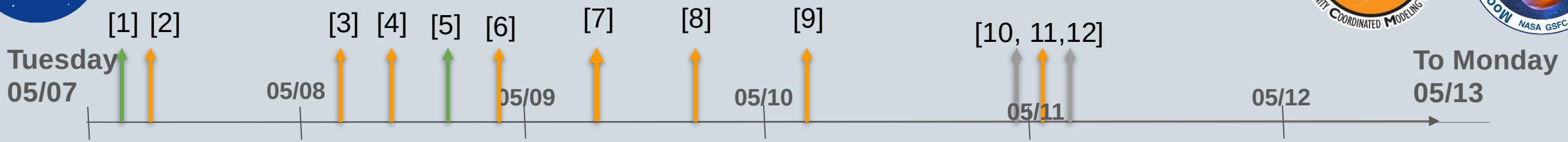
My photo! From the Washington D.C. Area

The show begins May 8th

- AR 13664 wakes up with first X-class flare and first large CME
- Numerous CMEs follow in quick succession over following days
- No one CME was “spectacular” on their own, speeds 700-1300 km/s
  - Not that they wouldn’t be impactful!
- Quickly realized we were dealing with an unusual event and had to adapt fast

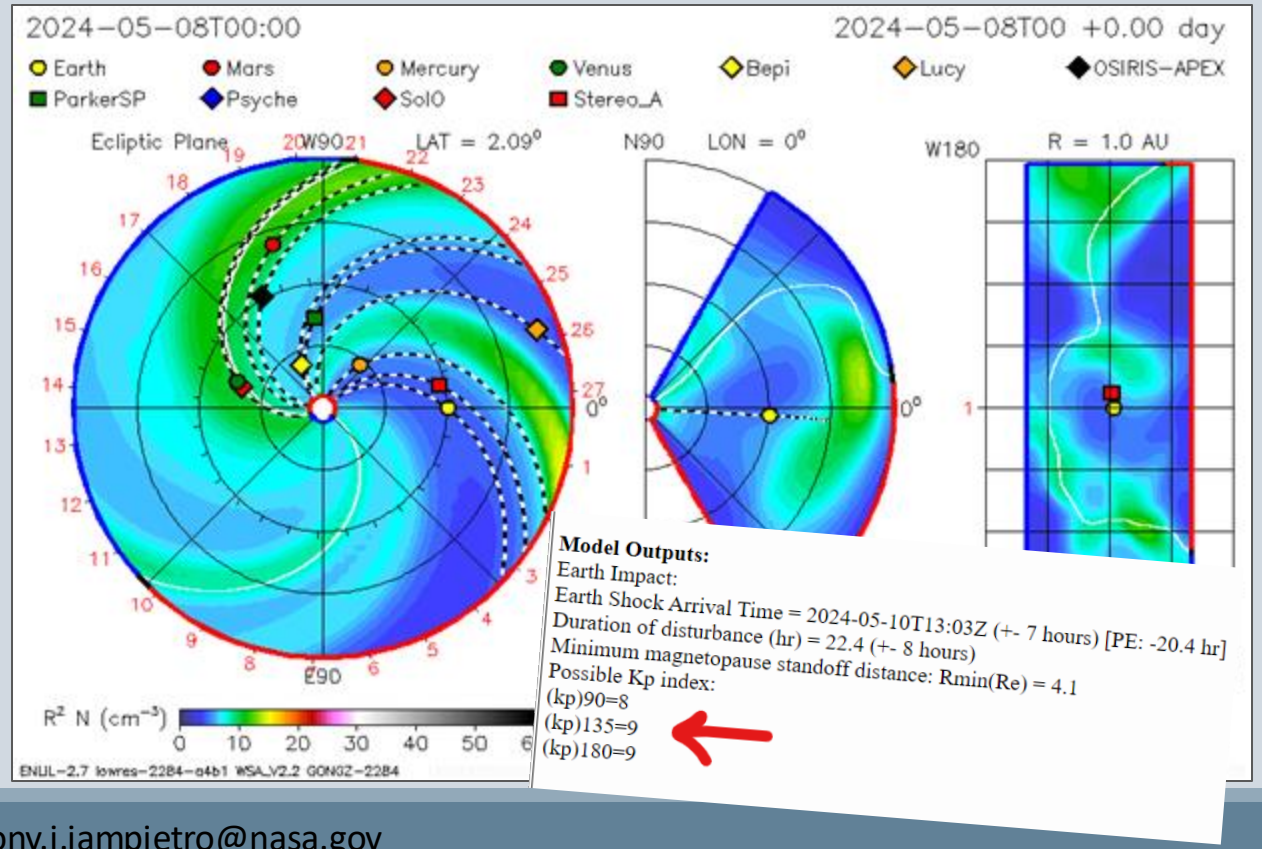
A parade of CMEs



- Table (to right) showcases # of times each CME was included in a simulation
- Total # of simulations during this time period:
  - 2AU: 27
  - 5.5AU: 7
- **Human-in-the-loop** analysis was essential for interpreting model outputs and troubleshooting.

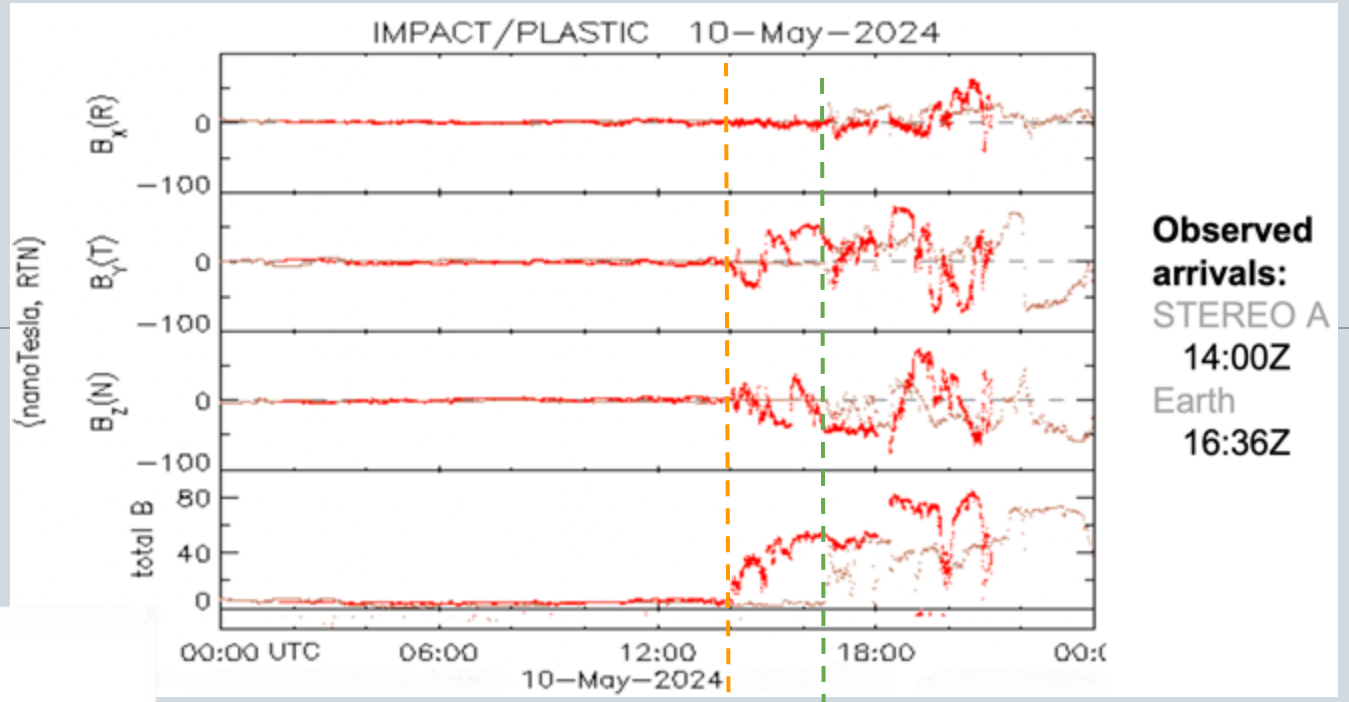
CME	2AU	5.5AU
[1]	2	0
[2]	2	0
[3]	4	1
[4]	4	1
[5]	2	2
[6]	3	3
[7]	3	3
[8]	3	0
[9]	3	0
[10]	1	0
[11]	3	0
[12]	1	0

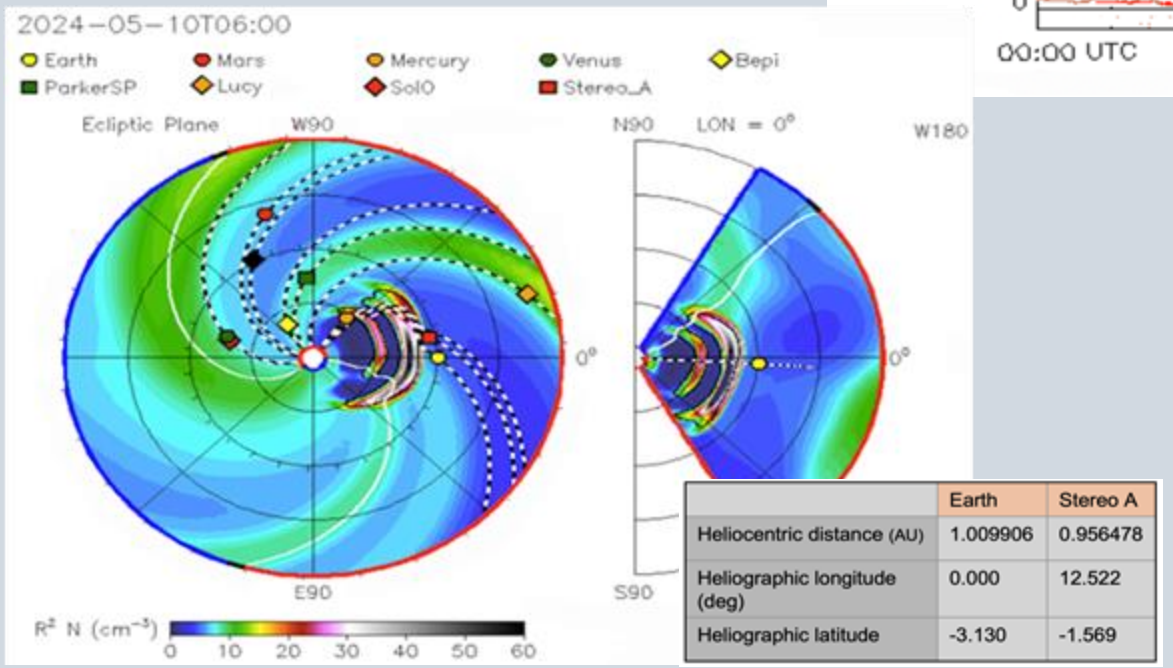
5 CME Simulation (CMEs 3,4,5,6,7)



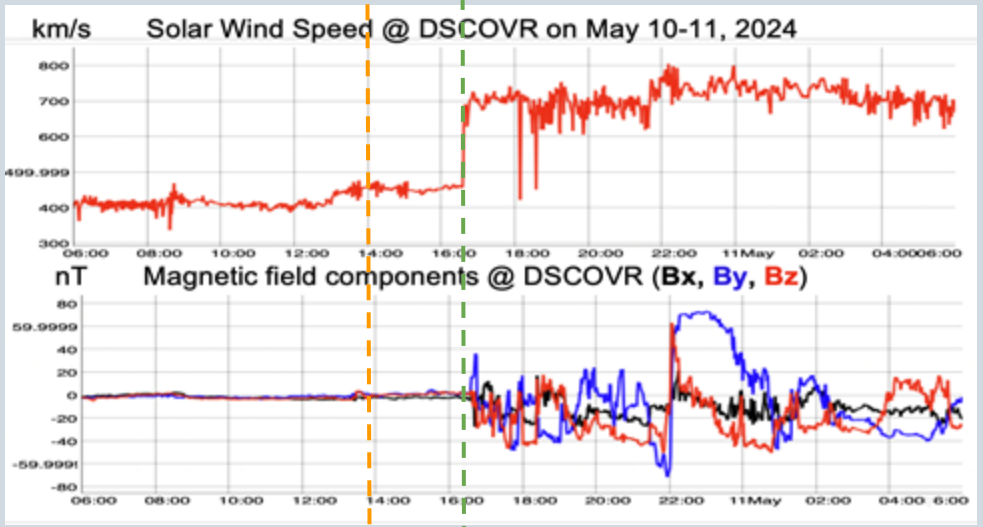
Arrival!

- STA critical for real time!
- All hands team meeting called to arrange schedule changes (outlined next slide)





	Earth	Stereo A
Heliocentric distance (AU)	1.009906	0.956478
Heliographic longitude (deg)	0.000	12.522
Heliographic latitude	-3.130	-1.569



Event Type	Start Time (UT)	DST Min	Kp Index	Directly Linked Event(s)
Geomagnetic Storm	2024-05-10 15:00		NOAA Kp: 7.67 (2024-05-10T18:00Z) NOAA Kp: 8.67 (2024-05-10T21:00Z) NOAA Kp: 9.0 (2024-05-11T00:00Z) NOAA Kp: 9.0 (2024-05-11T03:00Z) NOAA Kp: 8.33 (2024-05-11T06:00Z) NOAA Kp: 8.67 (2024-05-11T09:00Z) NOAA Kp: 9.0 (2024-05-11T12:00Z) NOAA Kp: 8.67 (2024-05-11T15:00Z) NOAA Kp: 8.33 (2024-05-11T18:00Z) NOAA Kp: 7.33 (2024-05-11T21:00Z) NOAA Kp: 7.33 (2024-05-12T00:00Z) NOAA Kp: 6.67 (2024-05-12T03:00Z) NOAA Kp: 7.0 (2024-05-12T06:00Z)	2024-05-08T05:36:00-CME-001 2024-05-08T12:24:00-CME-001 2024-05-08T19:12:00-CME-001 2024-05-08T22:24:00-CME-001 2024-05-09T09:24:00-CME-001 2024-05-10T16:36:00-IPS-001

Search Space Weather Activity Archive

Space Weather Activity Type : Geomagnetic Storm

Select Catalog (info) : M2M_CATALOG

Optional start date in format (e.g. 2013-01-31) : 2024-05-07

Optional end date in format (e.g. 2013-06-30) : 2024-05-26

search

Event Type	Start Time (UT)	DST Min	Kp Index	Directly Linked Event(s)
Geomagnetic Storm	2024-05-10 15:00		NOAA Kp: 7.67 (2024-05-10T18:00Z) NOAA Kp: 8.67 (2024-05-10T21:00Z) NOAA Kp: 9.0 (2024-05-11T00:00Z) NOAA Kp: 9.0 (2024-05-11T03:00Z) NOAA Kp: 8.33 (2024-05-11T06:00Z) NOAA Kp: 8.67 (2024-05-11T09:00Z) NOAA Kp: 9.0 (2024-05-11T12:00Z) NOAA Kp: 8.67 (2024-05-11T15:00Z) NOAA Kp: 8.33 (2024-05-11T18:00Z) NOAA Kp: 7.33 (2024-05-11T21:00Z) NOAA Kp: 7.33 (2024-05-12T00:00Z) NOAA Kp: 6.67 (2024-05-12T03:00Z) NOAA Kp: 7.0 (2024-05-12T06:00Z)	2024-05-08T05:36:00-CME-001 2024-05-08T12:24:00-CME-001 2024-05-08T19:12:00-CME-001 2024-05-08T22:24:00-CME-001 2024-05-09T09:24:00-CME-001 2024-05-10T16:36:00-IPS-001
Geomagnetic Storm	2024-05-12 21:00		NOAA Kp: 6.33 (2024-05-13T00:00Z) NOAA Kp: 5.67 (2024-05-13T03:00Z) NOAA Kp: 6.0 (2024-05-13T06:00Z)	2024-05-12T08:55:00-IPS-001
Geomagnetic Storm	2024-05-16 06:00		NOAA Kp: 6.0 (2024-05-16T09:00Z)	2024-05-16T04:35:00-IPS-001
Geomagnetic Storm	2024-05-17 18:00		NOAA Kp: 6.0 (2024-05-17T21:00Z)	2024-05-14T10:36:00-CME-001 2024-05-17T12:40:00-IPS-001

Weekend Shift

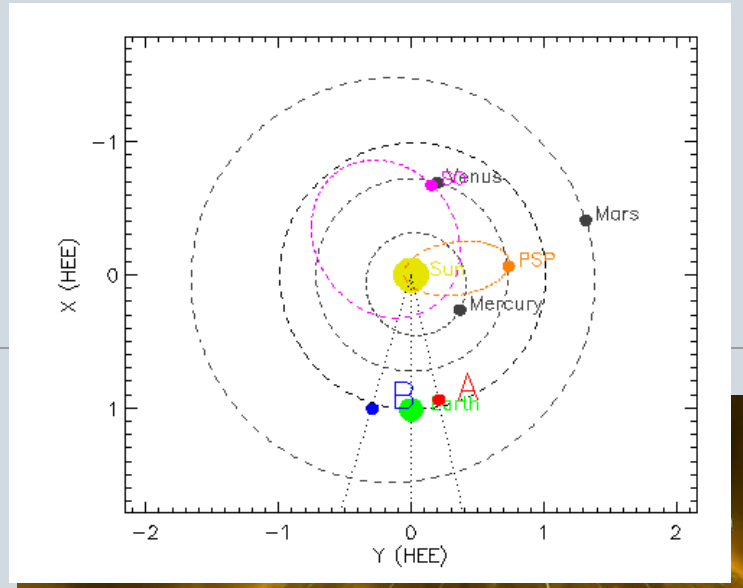
HQ called us to provide a briefing on the storm and impacts to NASA robotic missions

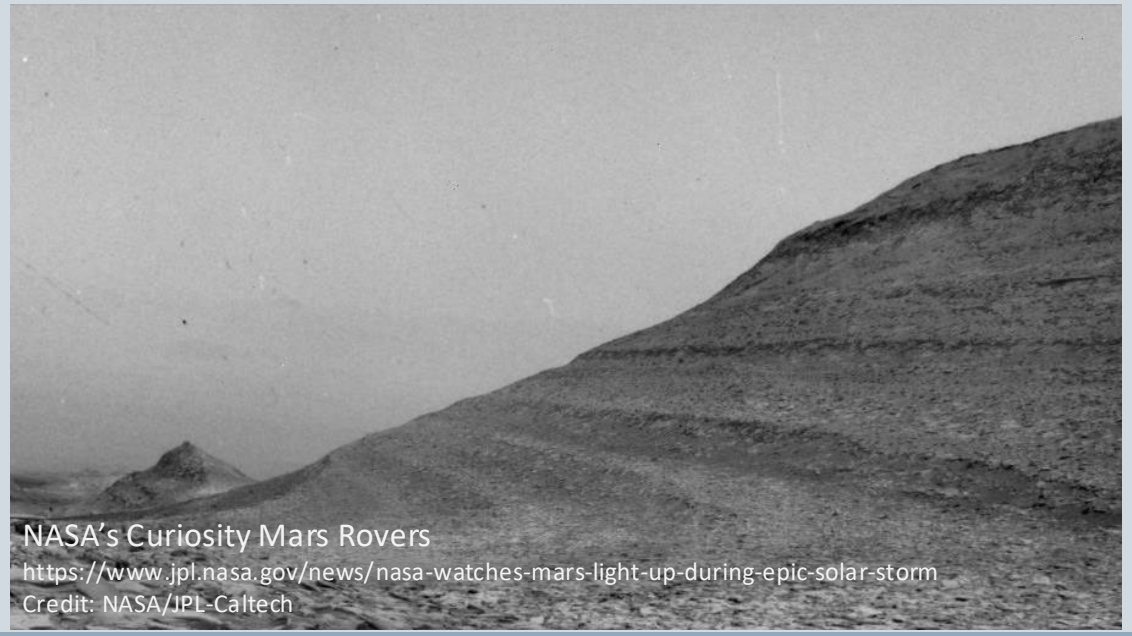
- **SWAO Team changes:**
  - Saturday/Sunday: 8 am - 4 pm onsite 1+1 analyst
  - On-call software support
  - Remote Evening Analyst (regular on-call)
- 10 am tag-up (team+GSFC leadership + HQ + SRAG + Comms)
- Evening summary of activities (GSFC leadership+HQ)
- **SRAG**
  - Open phone line with SRAG leadership
  - Teams/tag-ups
- **SWPC**
  - Emails & Teams connected by Slack
- **Comms**
  - Regular communication to support any press/social media activity

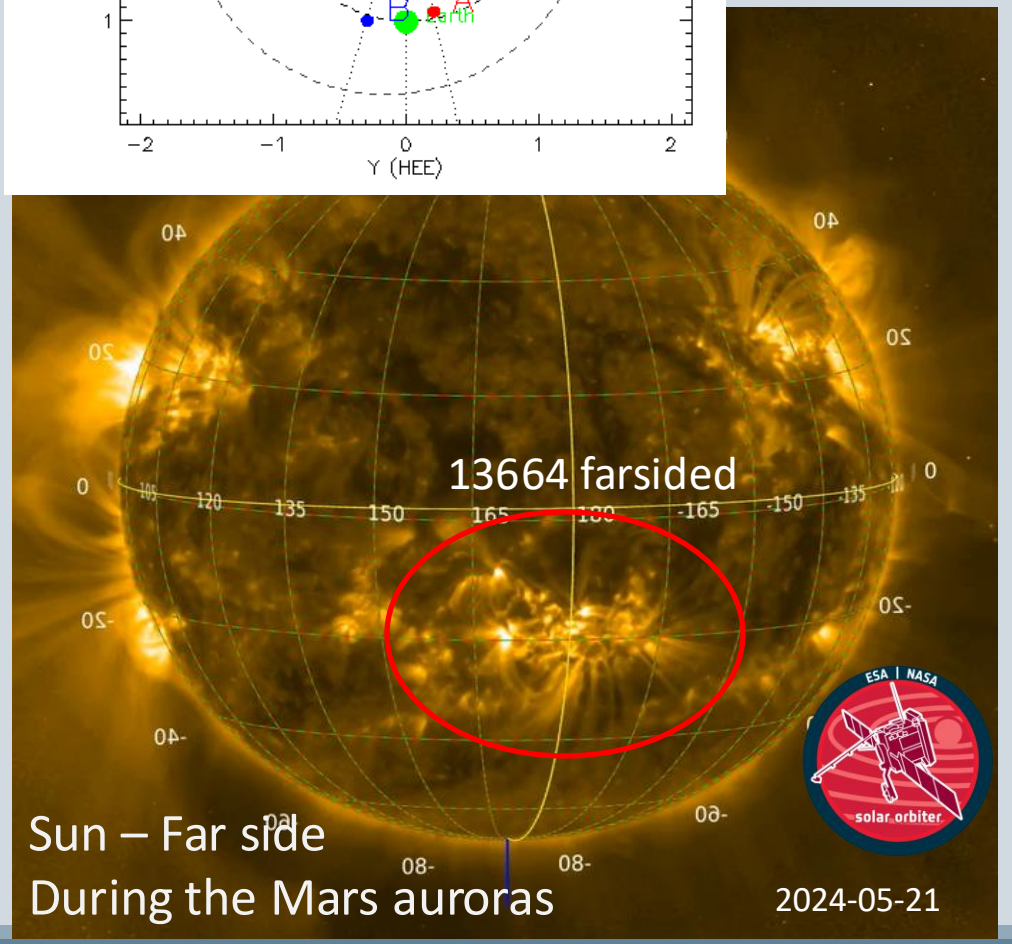
@NASASun | https://x.com/NASASun/status/1789721208776167518

AR 13664 beyond Earth

- M2M SWAO's work continued as the Earth impacts waned, as more missions & Mars were located far-sided to us
- AR 13664 continued its onslaught for days past the limb
- **We act like humans are on Mars, for preparation!**

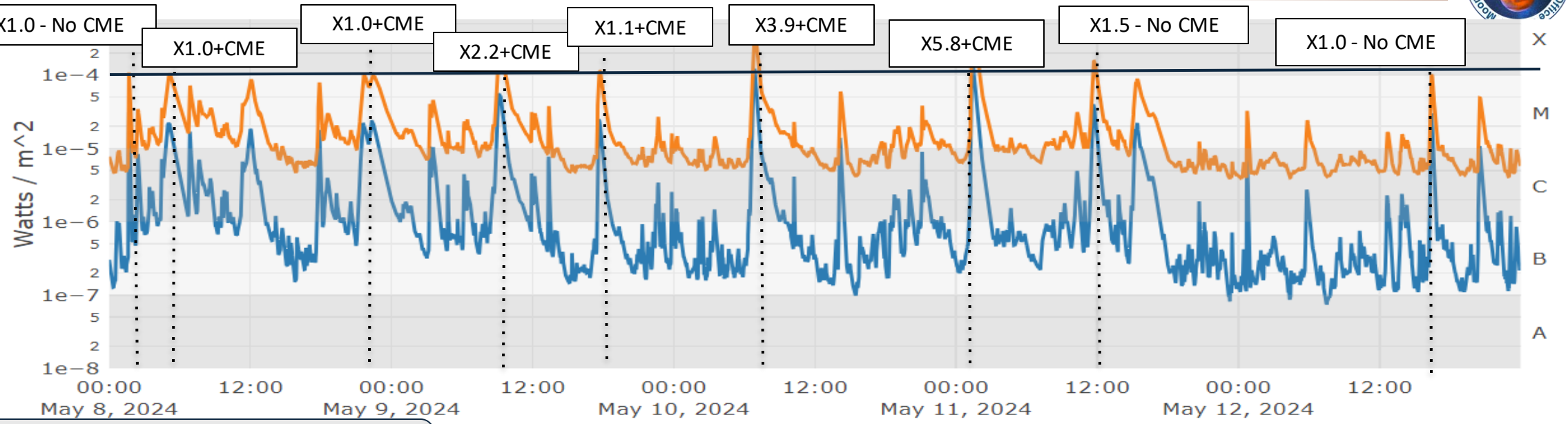



NASA's Curiosity Mars Rovers
https://www.jpl.nasa.gov/news/nasa-watches-mars-light-up-during-epic-solar-storm
Credit: NASA/JPL-Caltech



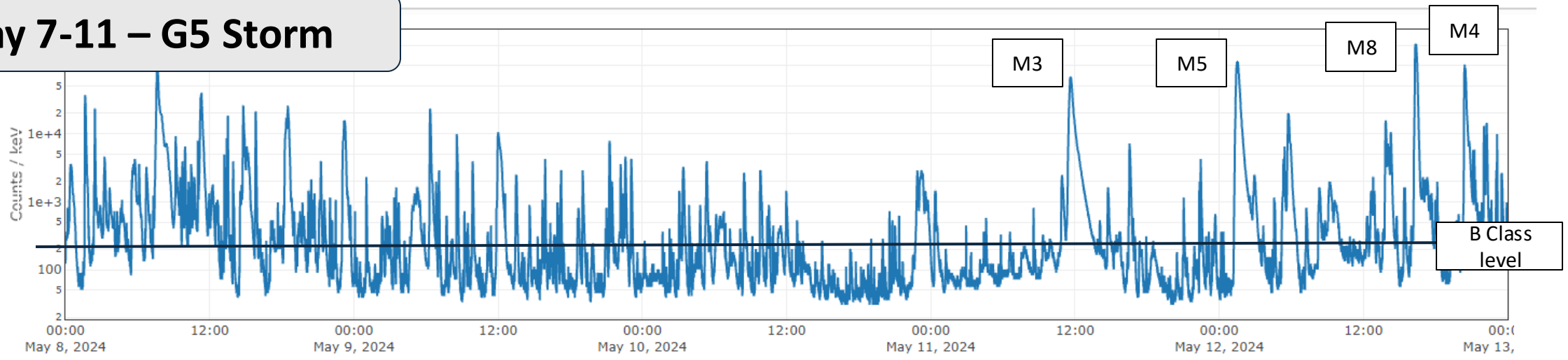
May 2024 storm – 360° Real Time Space Weather Analysis

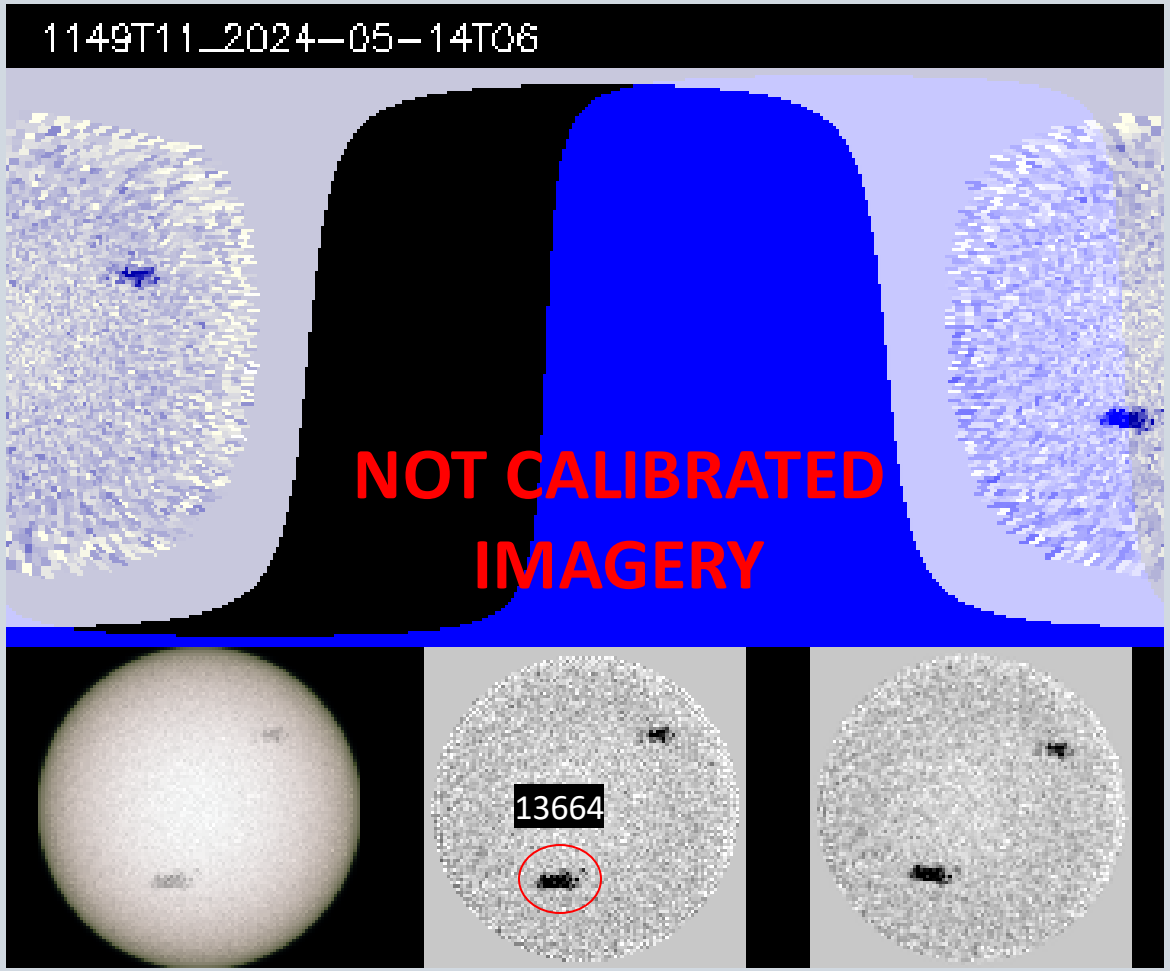
GOES Primary X-Ray Flux (Earth)



2024 May 7-11 – G5 Storm

Solar Orbiter STIX light curve plot (backside)





Credit: NASA/Caltech-JPL/ASU/SSI/Lemmon". "Mastcam-Z team"

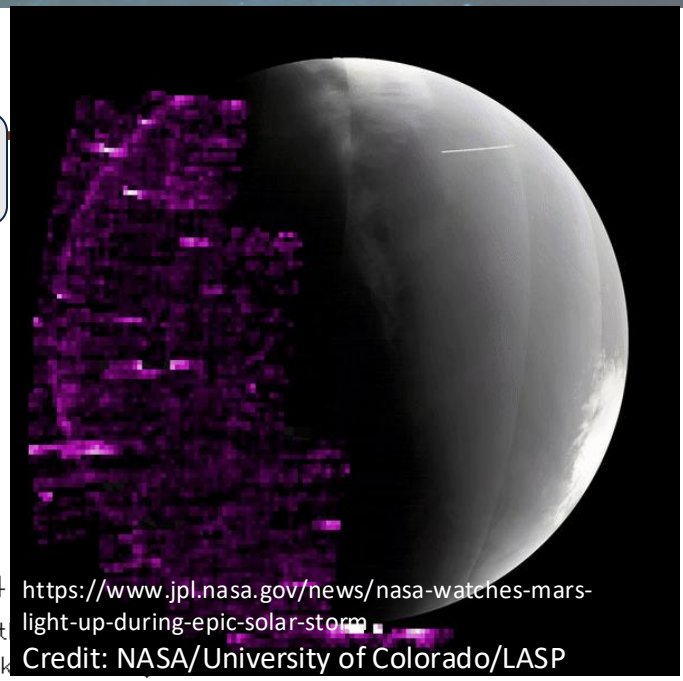
Facing Mars

PERSEVERANCE ROVER
Image courtesy of Mastcam-Z team from for informational, operational, or planning purposes

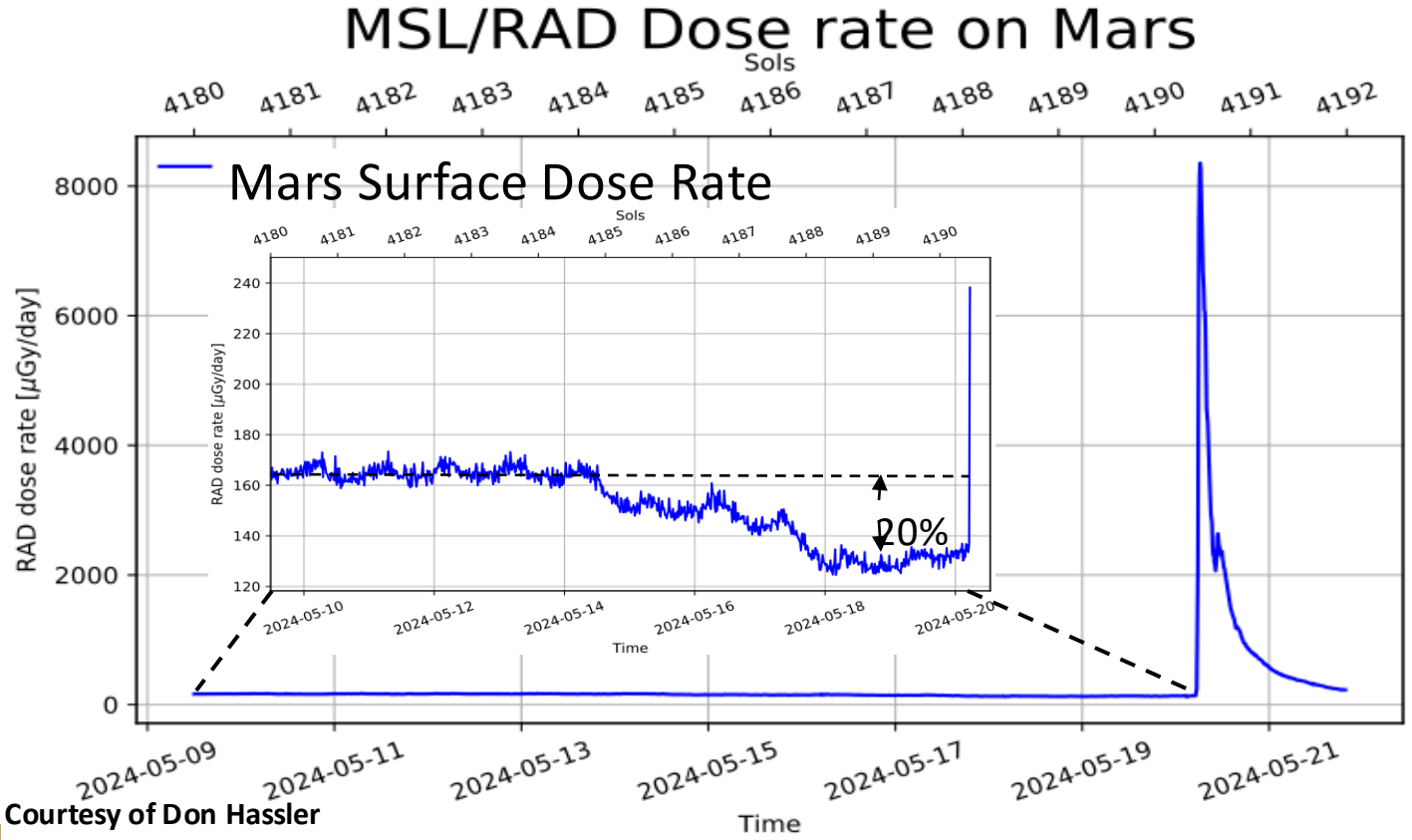
iSWA Mars Space Weather Dashboard Demo - May 11th - Link

May 2024 storm – Real Time Space Weather Analysis

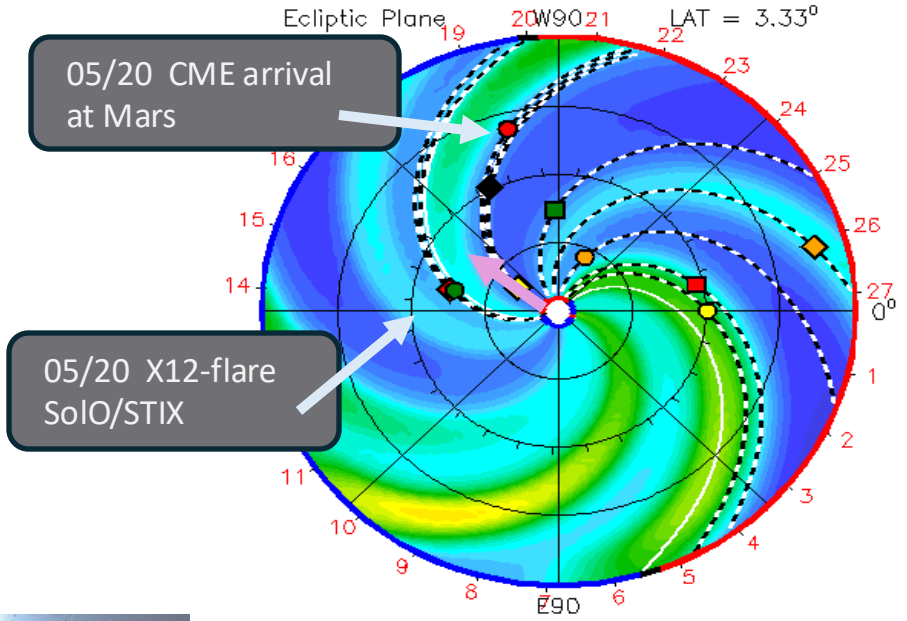
2024 May 20 – Mars Aurora



- ~8x higher dose rate than any previous event observed
- equivalent to ~30 chest x-rays for a hypothetical astronaut on the Mars surface



Courtesy of Don Hassler



Lessons learned in M2M SWAO

Storm-time readiness!

Regular shift schedule needed an overhaul for better support of our mission

- On call primary -> **evening primary**
- Primary 8 am sign on -> **7 am sign on**
- No weekend SRAG summary -> **now written**
- In practice for ~2 months now, we've all felt the positive changes!

Stressed importance of real-time data availability

- SOHO outage the prior weekend—we caught up the morning of May 7th!
- Real-time assistance from CCMC and M2M Software Support critical for success

Massive thank you to missions around the heliosphere for extended real time/near real time data sources! SOHO, STEREO A, Solar Orbiter, MAVEN, Perseverance

ARTEMIS

ARTEMIS I

Launched on November 16, 2022, for a 25.5-day uncrewed mission around the moon and back to Earth. This was the first mission towards returning astronauts to the moon and eventually sending astronauts to Mars.

During the ARTEMIS I mission, M2M:

- Provided 24/7 support for SRAG with 3 daily tag-ups
- Validated SEP Models in real-time using the SEP Scoreboards created by CCMC
- Populated CCMC's DONKI database and CME Scoreboard

ARTEMIS II

Launching no earlier than September 2025, ARTEMIS II will be the first crewed mission of the ARTEMIS series. The four astronauts selected as the ARTEMIS II Crew will have a 10-day mission, orbiting the moon before returning home.

M2M is currently working in collaboration with the Community Coordinated Modeling Center (CCMC), Space Radiation Analysis Group (SRAG), and NOAA's Space Weather Prediction Center (SWPC) to prepare in supporting the ARTEMIS II mission.

	AR 2975 (Mar 28 – Apr 2, 2022)	AR 3229 (Feb 16 – Feb 25, 2023)	AR 3234 (Feb 20 – Mar 6, 2023)	AR 3664 (May 7 - May 15, 2024)
Total # Flares	12	5	17	85
X-class Flares	1 (X1.3)	1 (X2.2)	1 (X2.0)	12 (X8.7, X3.9, X5.8)
# 'bundles' of SEP events	2 (GOES >100MeV 1pfu)	2	1	3
CMEs w. Earth impact	4	3	1	14
Total # CMEs as far as we can tell	4 (4 w. flares)	6	10 (7 w. flares)	16 May 7th-15th 24 May 7th-26th
Kp increase? (max Kp) (duration of storm)	No	Yes (max 7.0) (18 hrs)	No	Yes (max 9.0) (39 hrs)

The M2M SWAO Team!

Teresa Nieves-Chinchilla, PhD
Director
Researcher

Michelangelo Romano
Deputy
Software Support

Anna Chulaki
Analyst
Project Manager

Carina Alden
Analyst
Outreach Coordinator

Mary Pasanen, PhD
Scientific Software Developer

Mary Spencer
Analyst
Training Coordinator

Chris Stubenrauch
Analyst
Anomaly Support

Mattie Anastopulos
Analyst
Anomaly & JWST Support Lead

Hannah Hermann
Analyst
Validation Support

Tony Iampietro
Analyst
Validation Support

Melissa Kane
Analyst
Data Coordinator

Elizabeth Juelfs
Research Analyst
R2O2R

Thank you!

Any questions?

Feel free to email/contact!!

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

NERC-EPRI Geomagnetic Disturbance Workshop

Meeting Themes and Wrap-up

Mark Olson, Manager, Reliability Assessments

October 1-2, 2024

Reducing Risk from Geomagnetic Disturbances

- 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 is intended to support these efforts!

Workshop Info

- Workshop Objective: Identify key insights from the May 2024 GMD Event (Gannon Storm)
- Presentation topic areas:
  - Space weather event overview
  - NERC data systems observations
  - Preliminary GIC model validation results
  - Industry planner and operator analysis
  - Vendor and manufacturer analysis
  - Space weather community updates
- ***Active participation in discussion is strongly encouraged***

Materials will be made publicly available on NERC's website

Review Plan Objective

Goal: Use data and analysis from the event to ***validate*** or ***identify needs for improvements*** to GMD vulnerability assessment tools, models, and mitigation

Focus Areas

- **Impact of GIC-related harmonics on the BPS:** *How did harmonics affect BPS equipment? What levels of harmonic distortion were observed? What levels are predicted?*
- **System Voltage – observations, risks, insights from the storm**
- **Transformer thermal impacts:** *What effect did GIC levels have on transformer heating?*
- **GMD Benchmarks:** *How did peak geoelectric fields and magnetic field signature compare to the Benchmark GMD Event in TPL-007?*
- **GIC Model Validation:** *Did GIC models provide reasonable estimates of GIC?*
- **GMD Operations Best Practices:** *What operating actions were taken? How can operator situational awareness be better supported?*

Actions

1. Analyze NERC transmission availability database for impacts
   - Who: NERC Staff with support from registered entity data providers and working group
   - When: analysis begins after August 15 Transmission Availability Data System (TADS) reporting deadline
   - What: Anonymized summaries of impacts to transformers, lines, and other equipment will be reviewed to understand the scope of impacts to equipment from the event

Similar review of NERC generator availability database can be performed after the November reporting deadline for GADS

Status: review in progress

Actions

2. Perform GIC model validations
   - Who: EPRI and participating entities (voluntary)
   - When: ongoing through December
   - What: Use GIC measurements and geoelectric field estimates to evaluate model performance
     - Geographic areas of interest:
       - areas with complex earth structure (e.g., upper mid-west U.S., New England, Piedmont geographic region)
       - Areas where entities believe the observed GIC levels during the event were higher or lower than unexpected
   - TVA validations (w/SWPC); EPRI validation in mid-atlantic
   - What do SWPC, NRCAN, and other geoelectric field models tell us (Model comparison, risk maps, benchmark
   - Also:
     - Include some system information in after action reporting to help understand significance of GIC data
       - Voltage class where measured
       - Time-series across wide areas/interconnection
       - Duration above threshold
   - Denser mag network could improve geoelectric field models…and therefore help with validation

Actions

2.A Examine system voltage impacts

- Who: EPRI and participating entities (voluntary)
- When: ongoing through December
- What: Describe observed affects on system voltages and align with system GIC measurements (time-series)

- Powerflow analysis of the Gannon Storm can tell a story of where voltage stress occurred, with limitations (planning model, earth model coverage, assumptions in equipment modeling details)
- PJM system voltage plots show
- How might more severe events be dealt with?

Actions

3. Analyze observed transformer heating impacts
   - Who: EPRI and participating entities (voluntary)
   - When: ongoing through December
   - What: Review available information from transformers that were affected by high GIC (identified in TADS) or equipped with thermal instrumentation to inform models and vulnerability assessment
     - Identify unexpected transformer thermal issues
     - Compare thermal modeling results with observed measurements where available
     - Review available thermal measurement data and modeled estimates for the May event to examine potential transformer thermal hot-spot heating that can be produced by GIC signatures from solar storms with similar characteristics

- *Gannon storm signature has commonalities to the NERC Benchmark (peak-durations). The benchmark is useful in assessing thermal risk.*
  - *Spacing of peak-duration sequence affects heating…what is realistic/expected?*

Actions

4. Analyze observed harmonic impacts to transmission equipment
   - Who: EPRI and working group participants
   - When: ongoing through December
   - What: Review available information from transmission equipment that was potentially affected by GIC-related harmonics (identified in TADS or GADS) to inform models and vulnerability assessment tools and procedures
     - Identify unexpected harmonic impacts (e.g., equipment tripping) – can inform planners on what to look for.
     - Obtain measured harmonic distortion where available and compare with modeled/predicted values
   - Share lessons on protection and control settings to prevent harmonic operations; and equipment design considerations
   - Proper prioritization of system reliability v. equipment protection
   - *How is vulnerability changing as the system changes (DER, IBR)*

Actions

5. Industry observations and analysis
   - Covering equipment impacts, entity analysis, and operating experience/lessons

- Operating actions that focus on maximizing dynamic VAR support are most effective for reducing system risk
- DOE is interested in supporting real-time GIC data sharing. Looking to engage industry.
- Some installed GIC Blocking devices are activating early in the event (before some alerts/warnings), providing an indication for operators. Real-time information sharing would be beneficial.