RAPID: COLLECTING PERISHABLE CRITICAL INFRASTRUCTURE OPERATIONAL DATA FOR MAY 2024 SPACE WEATHER EVENTS.

Edward Oughton (eoughton@gmu.edu)

National Academies Space Weather Roundtable

5th February 2025

NSF NSF NCAR Operated by UCAR GEORGE MASON UNIVERSITY

NSF RAPID: Collecting Perishable Critical Infrastructure Operational Data for May 2024 Space Weather Events

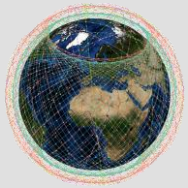
Sectors

Railroad Infrastructure Operators

Aircraft Operators

Electricity Transmission Operators

Telecoms (inc. Satellite Operators)



Oil and Gas Prospecting and Extraction

Road Infrastructure Operators

Objectives

1. Collecting and documenting operational logs from critical infrastructure operators (power and satellites)
2. Gathering contextual narratives on the effectiveness of operational decisions (power and satellites, plus forecasters & government)
3. Surveying global impacts and mitigation decisions (All sectors, plus forecasters & government)

Outputs

Research Impacts

Open Access Peer-Reviewed Papers/Data

US Leadership at International Conferences

Broader Impacts

Protecting National Security

STEM Education of Aspiring Scientists/Engineers

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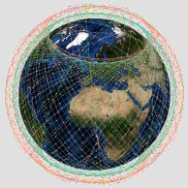

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GIC Validation Assessment in Partnership with TVA

Comparing measured and calculated GIC for the May 2024 geomagnetic storm

Lucy A. Wilkerson[1], Robert S. Weigel[1], Dean Thomas[1], Dennies Bor[1], Edward Oughton[1], Liling Huang[1]
Trevor Gaunt[2], Christopher C. Balch[3], Michael J. Wiltberger[4]
[1]George Mason University, Fairfax, VA; [2]University of Cape Town, Cape Town, ZA; [3]NOAA/SWPC, Boulder, CO; [4]NCAR/HAO, Boulder, CO

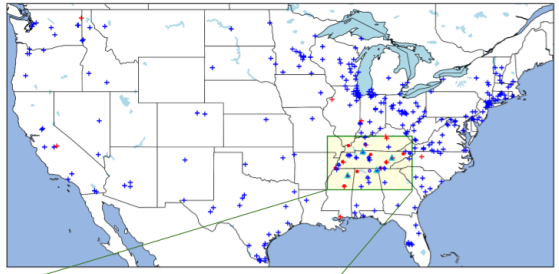
Abstract

The 10–13 May 2024 space weather events saw some of the most severe geomagnetic activity over the past 20 years, providing an event which scientists and engineers will study for decades to come. It is imperative that we use this recent event to compare the effectiveness of the various simulation models in development. Although geomagnetically induced current (GIC) estimates recorded from the storm can be accessed at any point, these measured values are sensitive to the power network configuration at the time of the event. Indeed, perishable power network data can often be lost in the weeks and months after a major Geomagnetic Disturbance (GMD), for example, pertaining to power grid configuration, motivating rapid study of recent events. This research aims to collect both GIC and magnetic field data (both measured and modeled) during the Gannon storm with the future goal of comparing methods of GIC, ΔB, and electric field estimates. Firstly, GIC estimates produced by the Tennessee Valley Authority (TVA) network simulation model for four substation locations, populated with real asset data and parameter values, were obtained, along with measured GIC and ΔB values from TVA. Next, additional measured GIC and ΔB estimates were accessed through North American Electric Reliability Corporation (NERC)'s ERO Portal. Finally, modeled ΔB data was obtained from both the Space Weather Modeling Framework (SWMF) and Multiscale Atmosphere-Geospace Environment Model (MAGE). By comparing these various sets of data, we hope to understand the predictive effectiveness of different approaches to GIC estimation.

Background

- Large geomagnetic disturbances (GMDs) result in geomagnetically induced currents (GICs) (Pulkkinen et al., 2017).
- GICs are known to negatively impact several types of critical infrastructure, such as oil pipelines, railway networks, and power grids (Boteler, Pirjola, and Nevanlinna, 1998).
- Accurate prediction of GIC impacts can help industries better prepare for such events.

Data



Type	Source	Δt	#	Symbol
GIC meas	TVA	1-s	18	○
GIC meas	NERC	1-s	396	+
GIC calc	TVA	1-m	4	△
ΔB meas	TVA	1-s	7	●
ΔB meas	NERC	1-s	15	+
ΔB calc	SWMF	1-m	19	+ △
ΔB calc	MAGE	1-m	19	+ △

References

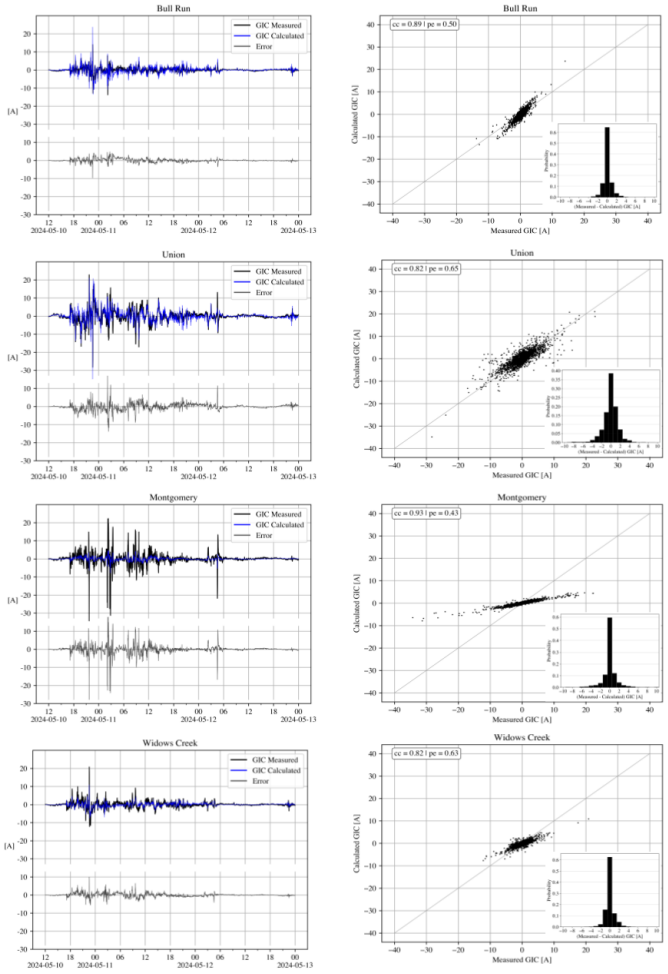
- Pulkkinen et al. (2017), *Space Weather*, 15, 7
- Boteler, Pirjola, & Nevanlinna (1998), *Advances in Space Research*, 22, 1

Acknowledgements

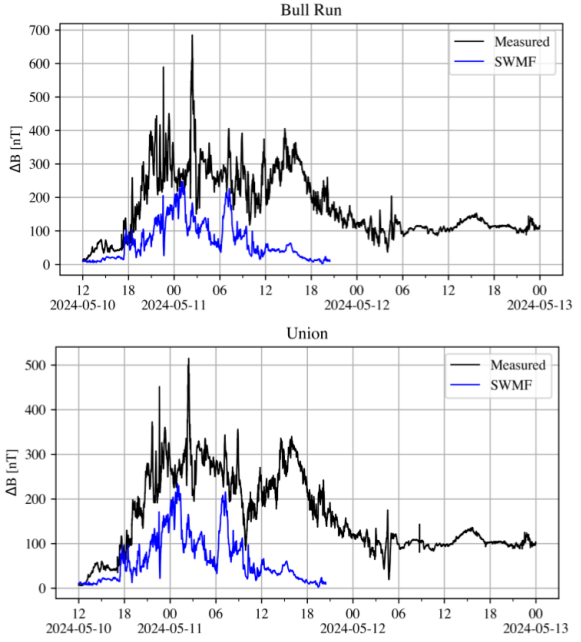
We acknowledge data from the NERC ERO Portal (and contributing data providers) and data provided directly from TVA. This work is supported by funding from NSF RAPID grant (#2434136) and the NSF National Center for Atmospheric Research (#1852977) via the Early-Career Faculty Innovator Program. We also acknowledge CCMC for execution and of the SWMF model run (id = `Dean_Thomas_070824_3`).

2024 Fall AGU, Monday 8:30 am - 12:30 pm; SH11G-2892, Hall B-C

Results

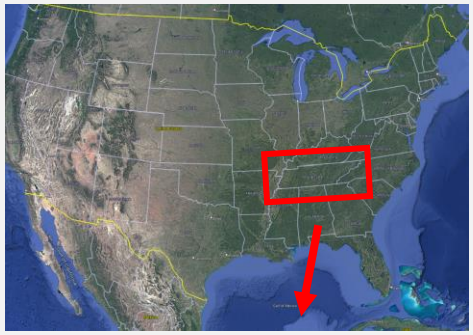


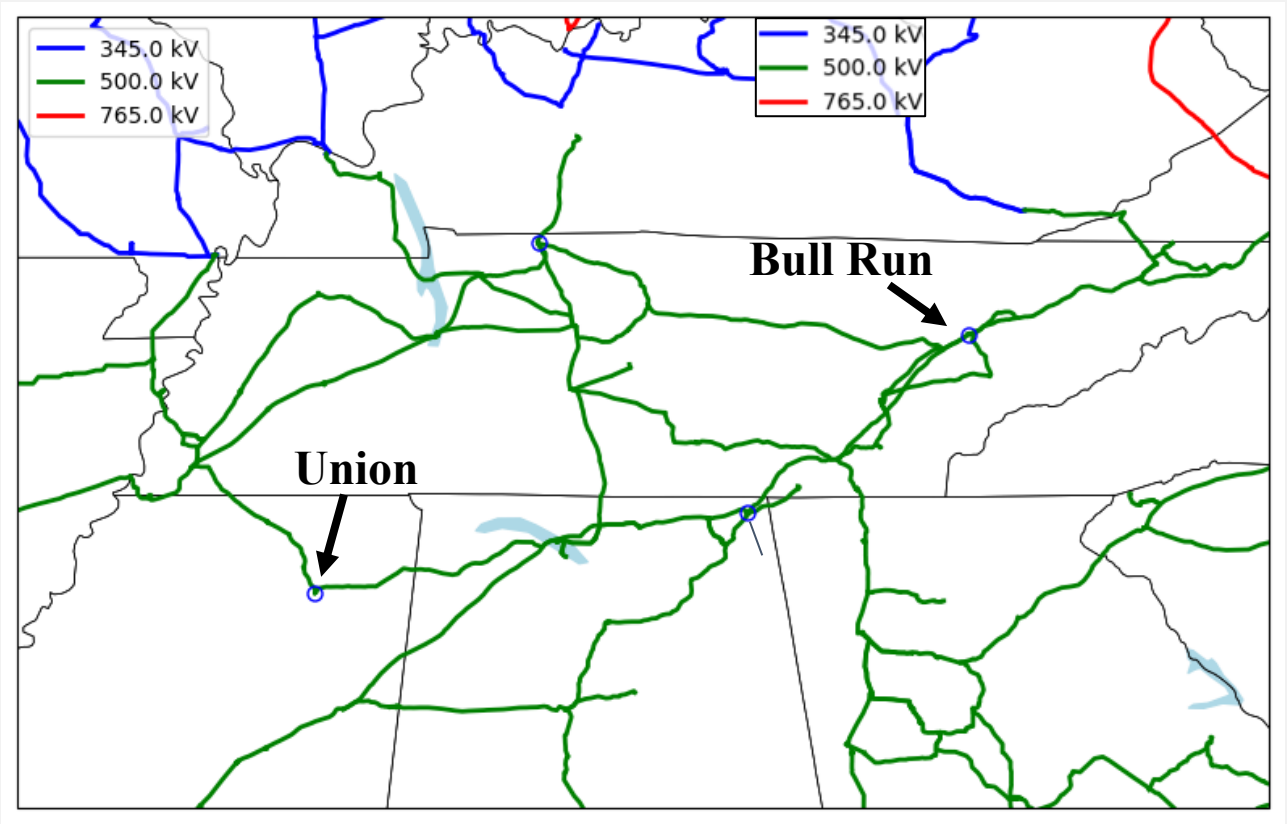
Results

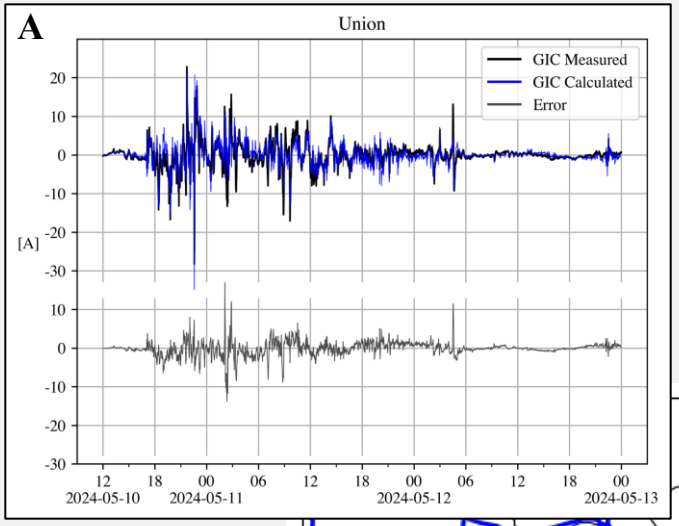


Discussion

- We have collected and pre-processed measured and modeled data from many sources during this event.
- Initial exploratory data analysis has been performed.
- Next steps:
  - Add results from OpenGGCM model
  - Compare SWMF, MAGE, OpenGGCM at sites with **ΔB**
  - Compare **E** derived from magnetometer **ΔB** data (TVA, NERC, SWMF, MAGE) + **Z** from EarthScope at all sites.
  - Use **E** with our own GMU National Grid Model to compute GIC
    - Oughton, Friday, 11:30, 202 B, GP52A-07
    - Peters, Wednesday, 8:30, eLightning Theater 6, NG31A-03
  - Compare our GIC with TVA GIC (calculated and measured)
  - Compare MAGE-derived GIC and **E** with above




345.0 kV
500.0 kV
765.0 kV
345.0 kV
500.0 kV
765.0 kV
Bull Run
Union


A
Union
GIC Measured
GIC Calculated
Error
[A]
20
10
0
-10
-20
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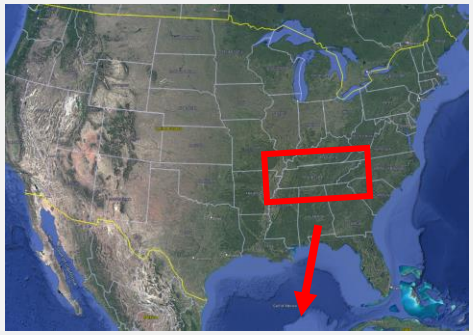
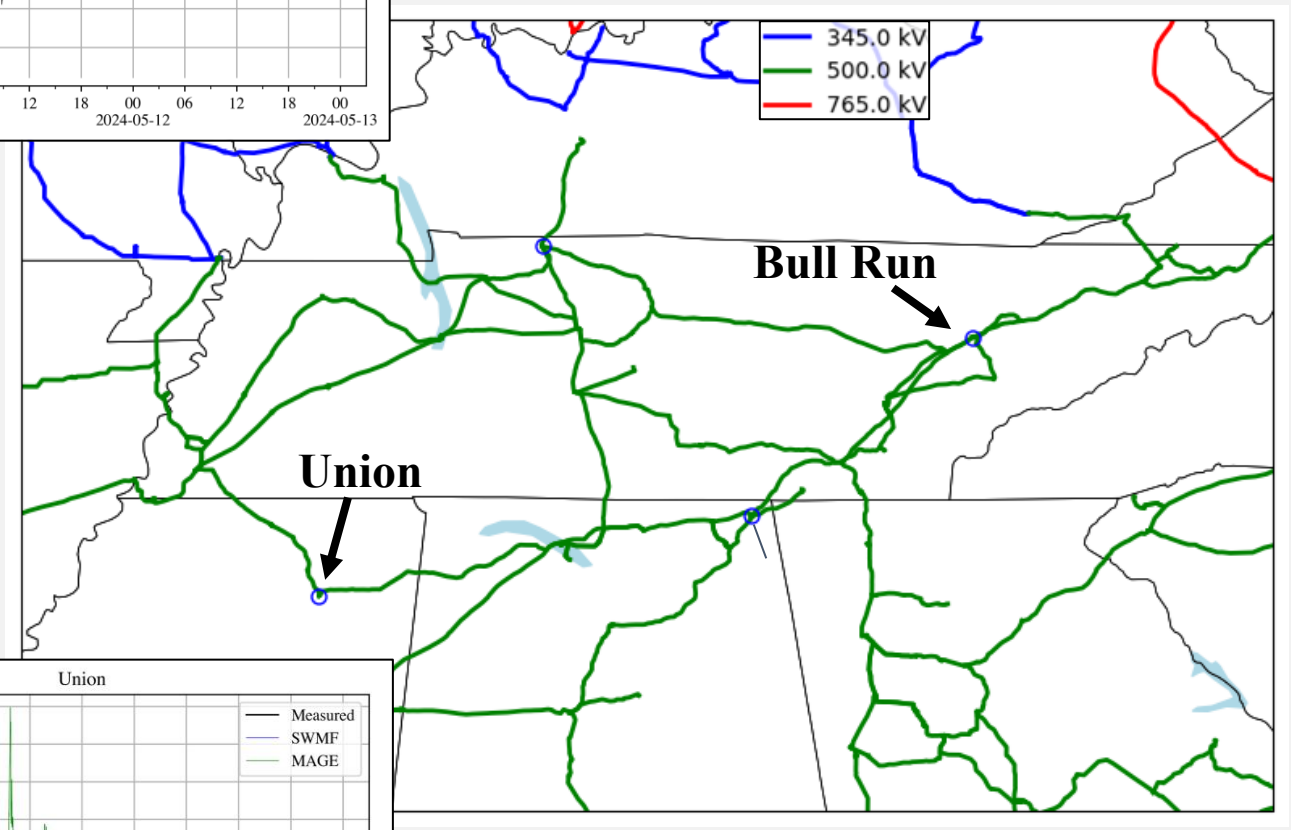
2024-05-12
2024-05-13

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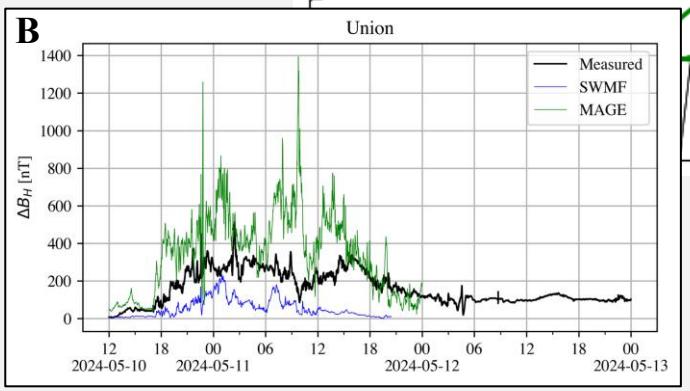
B
Union
Measured
SWMF
MAGE
ΔB_H [nT]
1400
1200
1000
800
600
400
200
0
12
18
00
06
12
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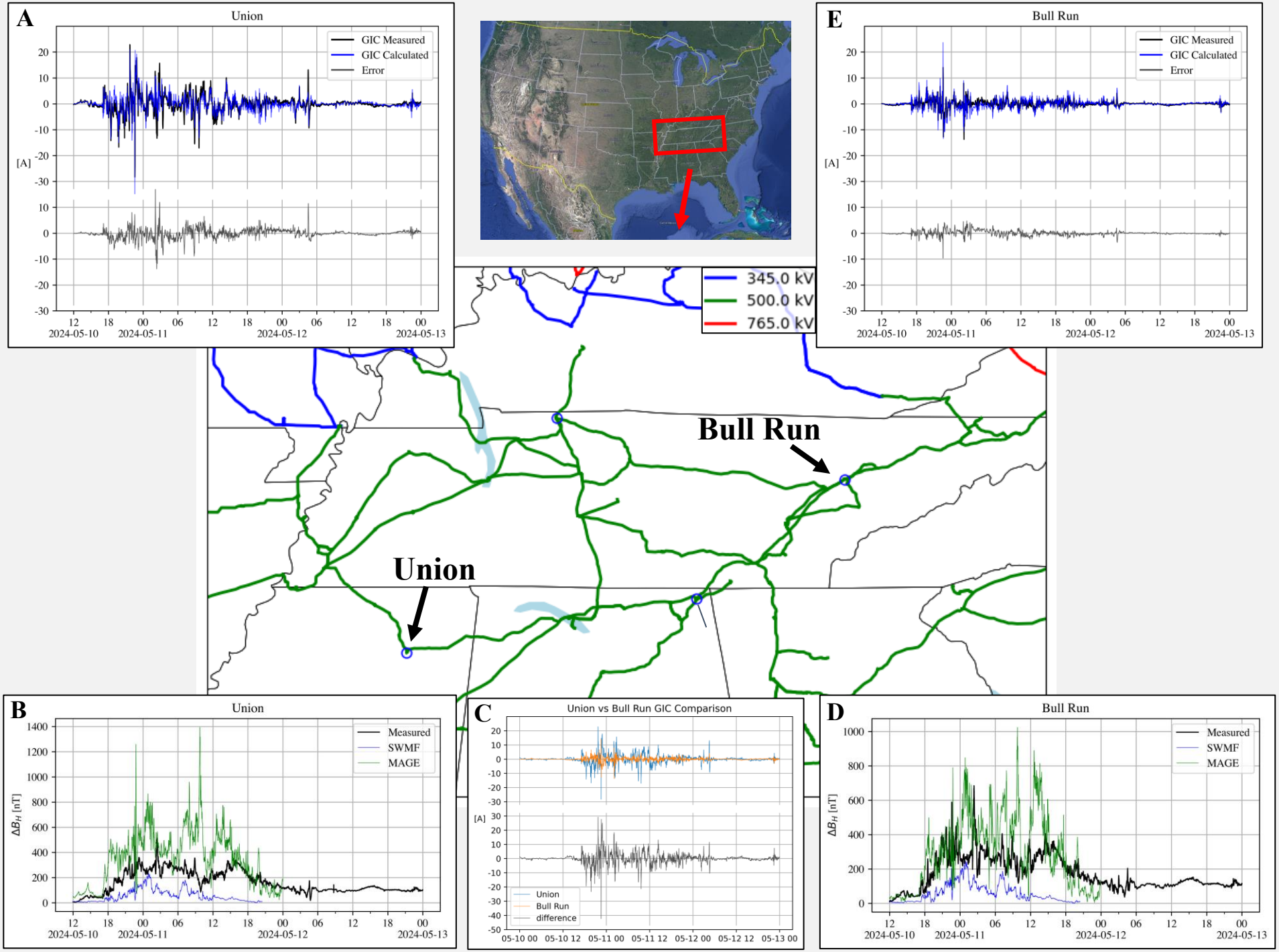
2024-05-10
2024-05-11
2024-05-12
2024-05-13


A
Union
GIC Measured
GIC Calculated
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Bull Run
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Union
B
Union
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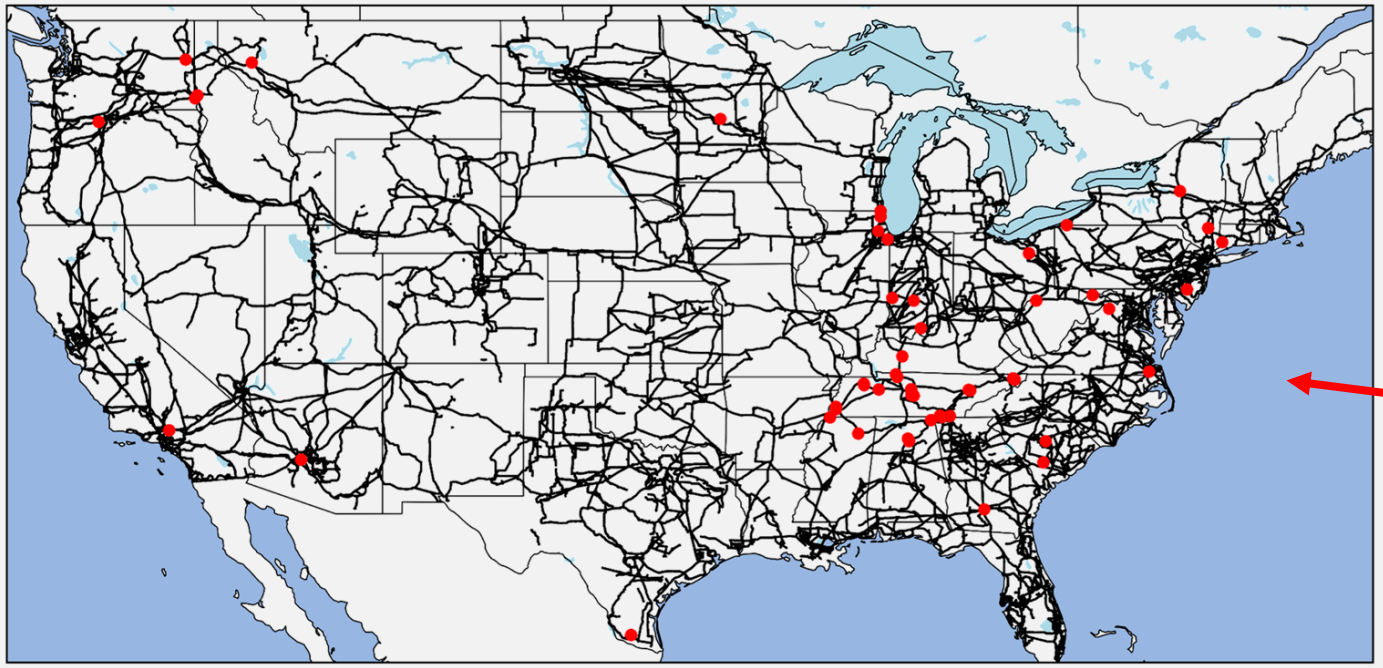
SWMF
MAGE
ΔB_H [nT]
C
Union vs Bull Run GIC Comparison
Union
Bull Run
difference
D
Bull Run
Measured
SWMF
MAGE
ΔB_H [nT]

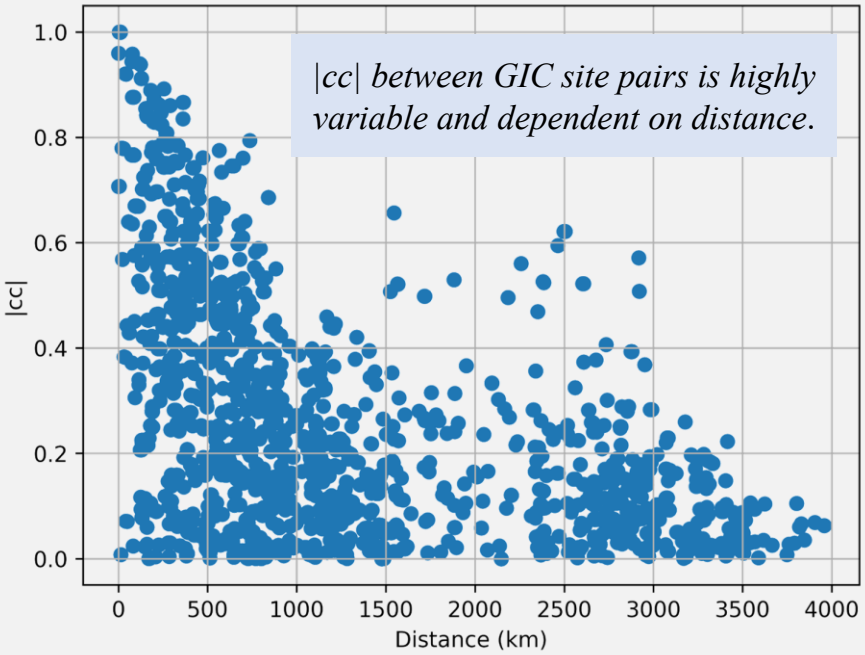
(A) CONUS Transmission Lines with GIC Monitoring Devices



NERC site had ~400 GIC monitors for May 2024 storm.

~50 appeared valid via manual inspection and are plotted here.

(B) Preliminary Analysis



Work in progress tasks:

1. Continue analysis of SWMF and MAGE ΔB data for all TVA sites.
2. Will add **Z** information and results of E/GIC computed from ΔB and **Z**.
3. Write up evaluation and circulate working paper draft by Space Weather Workshop
4. Integrate any requested revisions and submit for peer-review by the end of Spring 2025.

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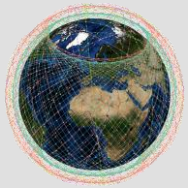

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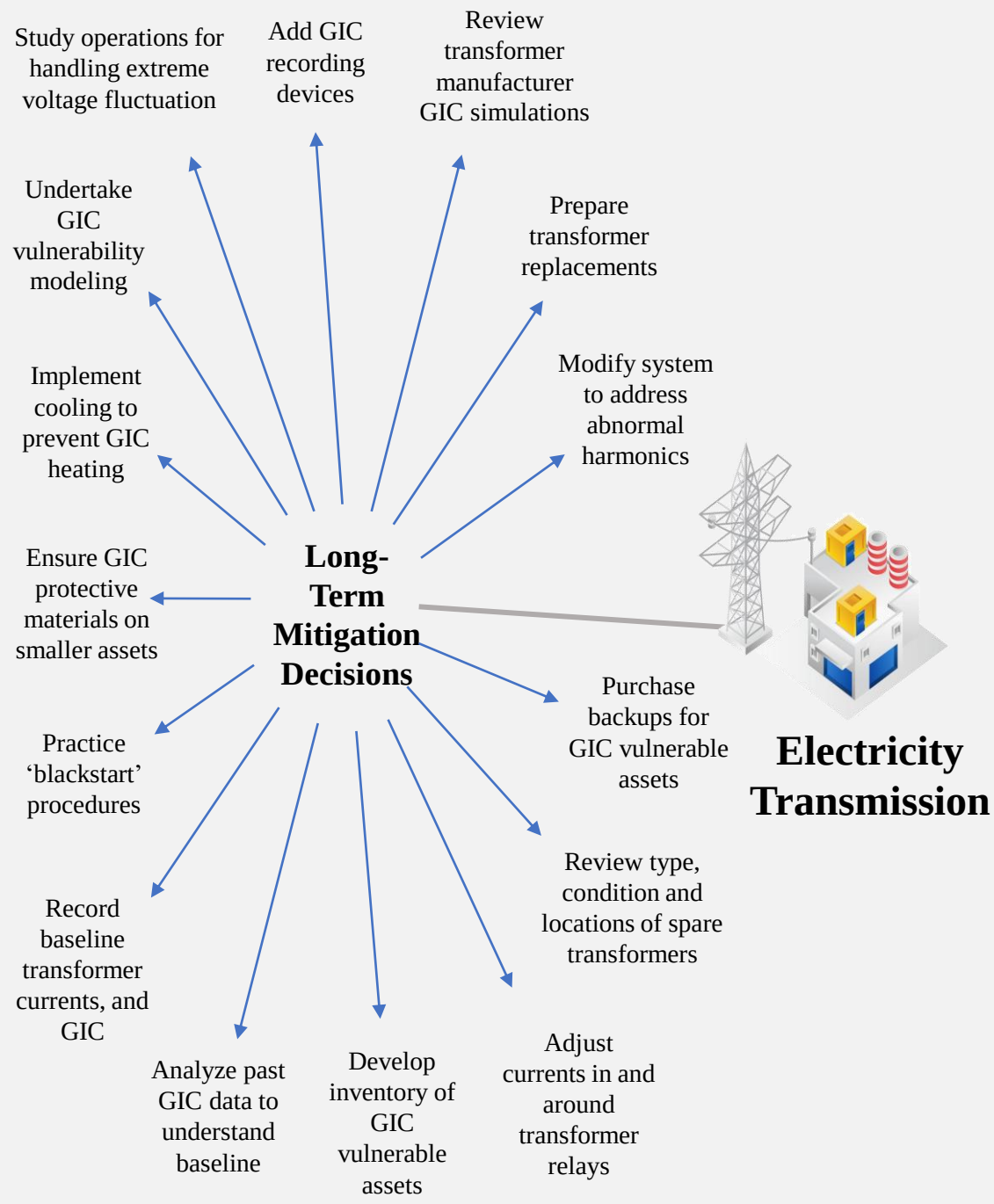
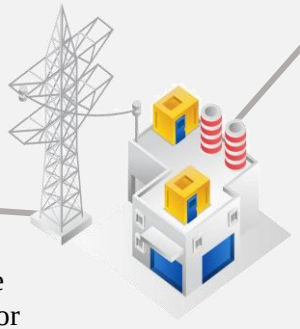
Targeted Critical Infrastructure Sector Interviews


Study operations for handling extreme voltage fluctuation
Add GIC recording devices
Review transformer manufacturer GIC simulations
Undertake GIC vulnerability modeling
Prepare transformer replacements
Implement cooling to prevent GIC heating
Modify system to address abnormal harmonics
Ensure GIC protective materials on smaller assets
Long-Term Mitigation Decisions
Purchase backups for GIC vulnerable assets
Practice 'blackstart' procedures
Review type, condition and locations of spare transformers
Record baseline transformer currents, and GIC
Analyze past GIC data to understand baseline
Develop inventory of GIC vulnerable assets
Adjust currents in and around transformer relays
Electricity Transmission



Electricity Transmission

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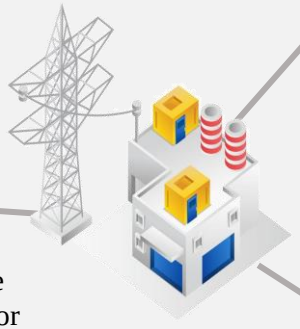
Short-Term Mitigation Decisions

- Activate GIC blocking devices
- Increase reactive power reserves
- Alert staff to prepare operational plans
- Cancel employee time off
- Implement line rearrangement
- Cease power transfers to other networks
- Bring additional assets online
- Load reduction of assets
- Bring more generation capacity online
- Take vulnerable assets offline
- Bring assets undergoing maintenance online
- Increase staff situational awareness
- Cancel network maintenance to free-up labor



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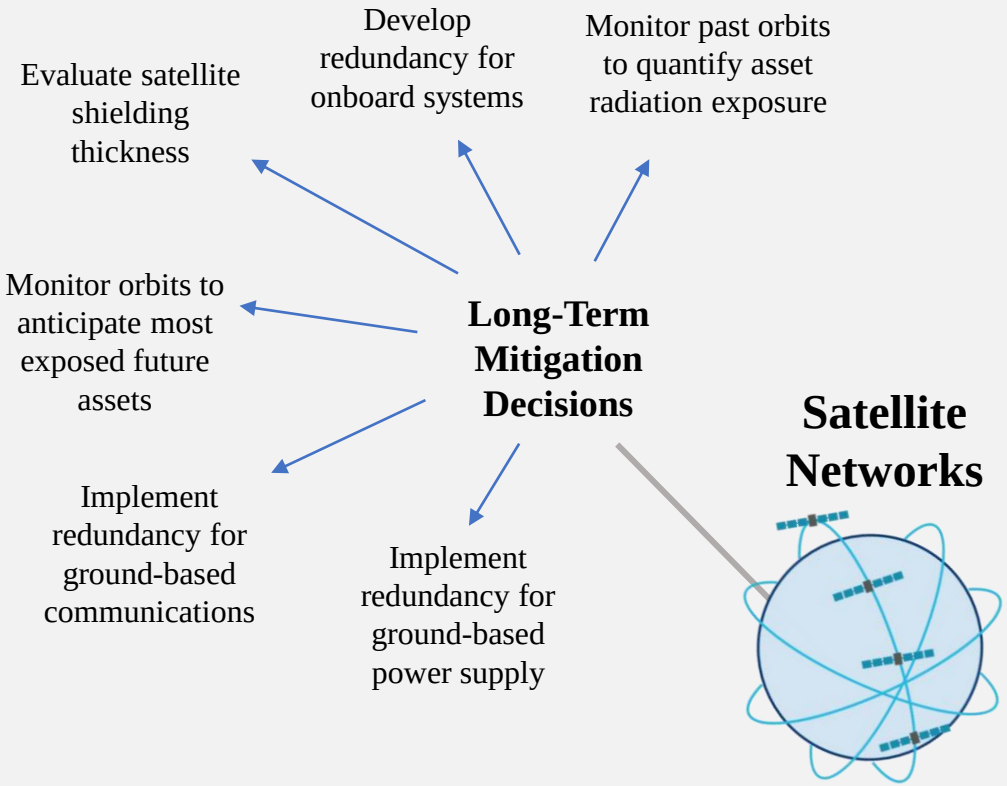
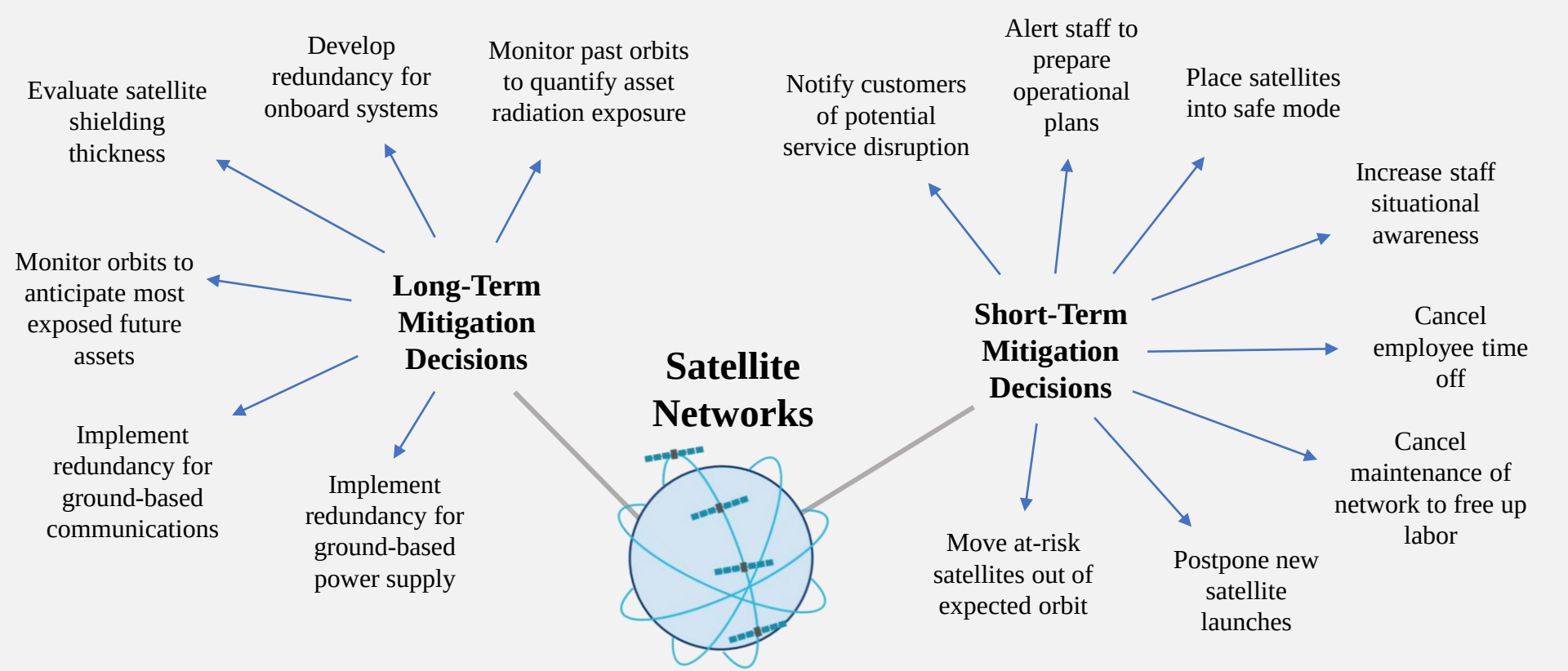
Post-Event Decisions

- Revise future preparation plans
- Share data with other operators
- Assess dissolved gas levels in exposed assets
- Place an order for new EHV assets
- Undertake modeling evaluation activities
- Share experiences with other operators
- Remove assets from service for inspection
- Replace exposed EHV assets with new ones
- Investigate unusual observations / conditions


Evaluate satellite shielding thickness
Develop redundancy for onboard systems
Monitor past orbits to quantify asset radiation exposure
Monitor orbits to anticipate most exposed future assets
Long-Term Mitigation Decisions
Satellite Networks
Implement redundancy for ground-based communications
Implement redundancy for ground-based power supply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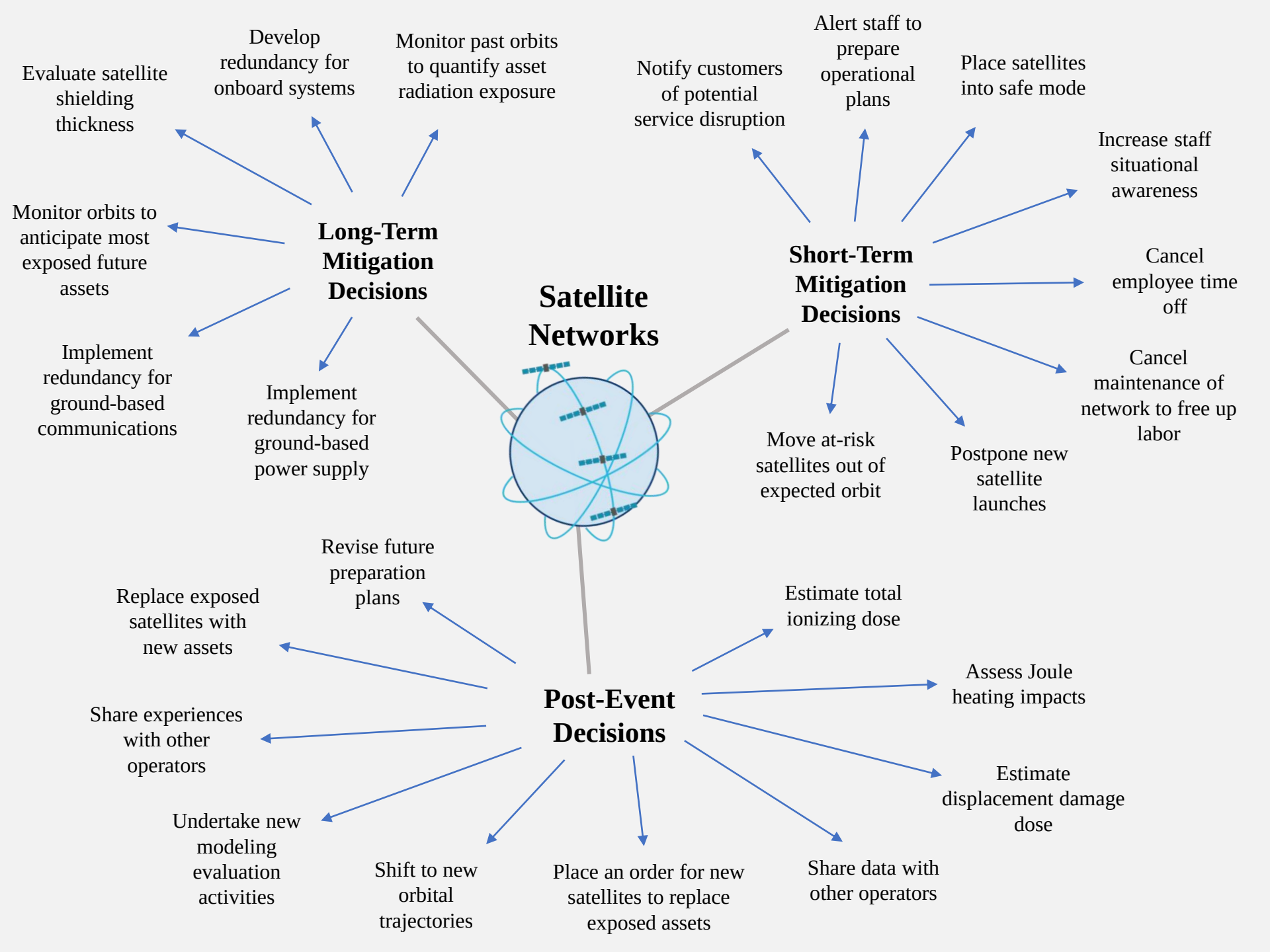
Short-Term Mitigation Decisions
Notify customers of potential service disruption
Alert staff to prepare operational plans
Place satellites into safe mode
Increase staff situational awareness
Cancel employee time off
Cancel maintenance of network to free up labor
Move at-risk satellites out of expected orbit
Postpone new satellite launches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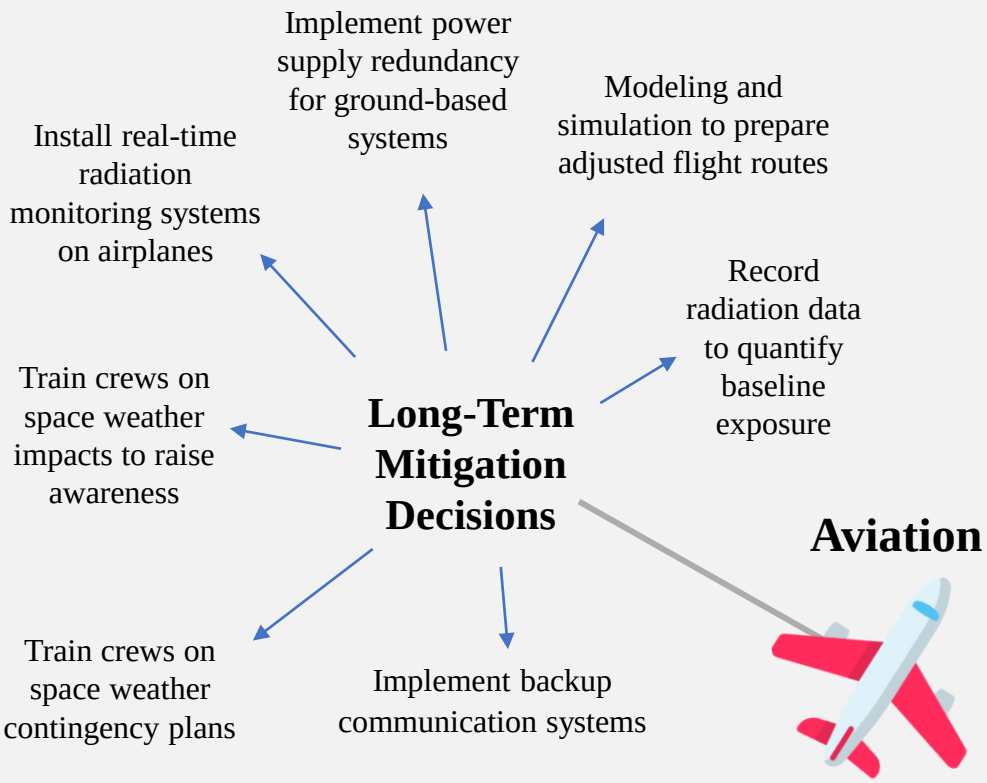
Cancel maintenance of network to free up labor
Move at-risk satellites out of expected orbit
Postpone new satellite launches
Post-Event Decisions
Revise future preparation plans
Replace exposed satellites with new assets
Share experiences with other operators
Undertake new modeling evaluation activities
Shift to new orbital trajectories
Place an order for new satellites to replace exposed assets
Share data with other operators
Estimate displacement damage dose
Assess Joule heating impacts
Estimate total ionizing dose


Implement power supply redundancy for ground-based systems
Modeling and simulation to prepare adjusted flight routes
Install real-time radiation monitoring systems on airplanes
Record radiation data to quantify baseline exposure
Train crews on space weather impacts to raise awareness
Long-Term Mitigation Decisions
Aviation
Train crews on space weather contingency plans
Implement backup communication systems

Aviation

Long-Term Mitigation Decisions

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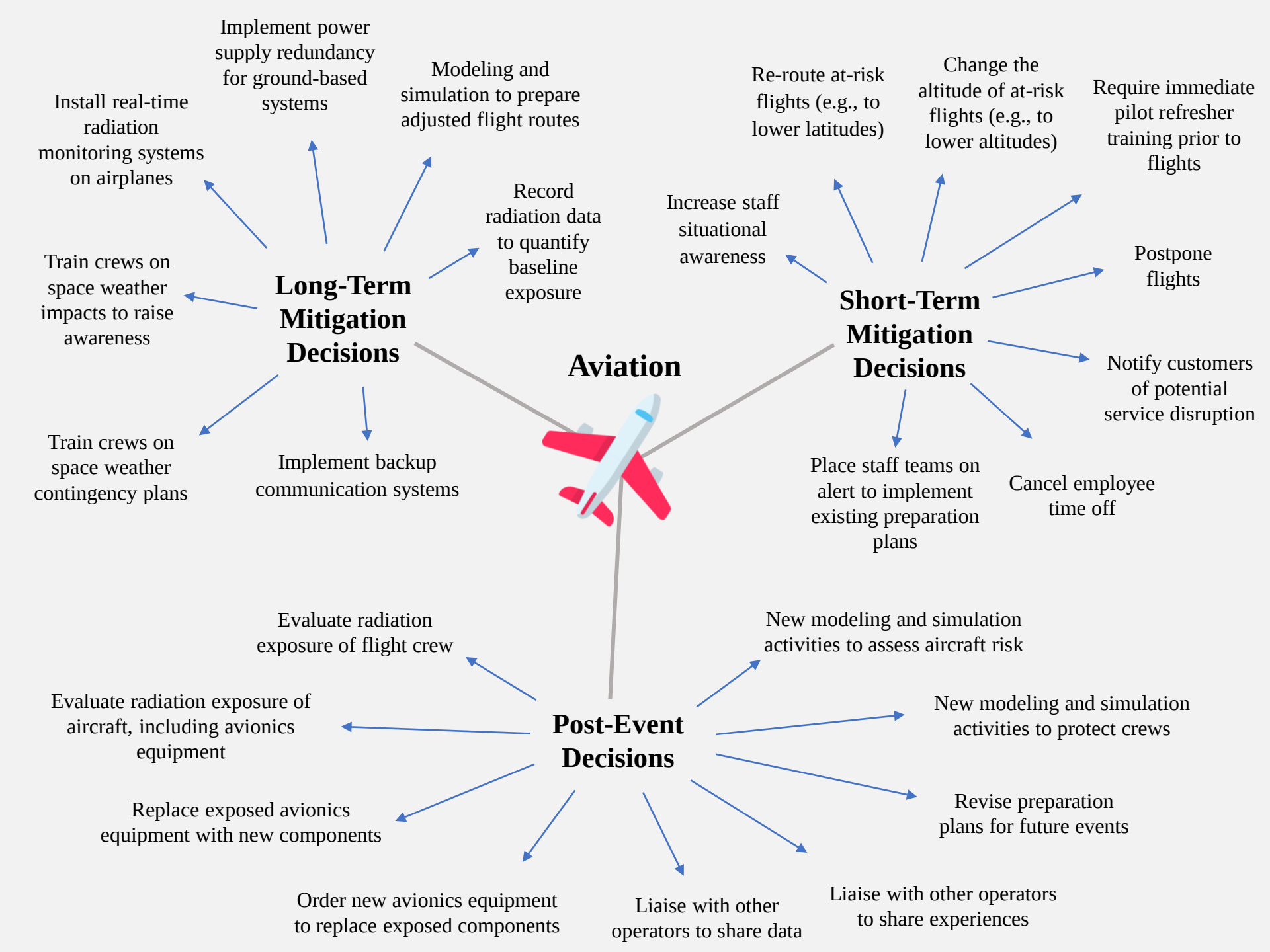
Short-Term Mitigation Decisions

- Re-route at-risk flights (e.g., to lower latitudes)
- Change the altitude of at-risk flights (e.g., to lower altitudes)
- Require immediate pilot refresher training prior to flights
- Increase staff situational awareness
- Postpone flights
- Notify customers of potential service disruption
- Place staff teams on alert to implement existing preparation plans
- Cancel employee time off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Require immediate pilot refresher training prior to flights
Increase staff situational awareness
Postpone flights
Notify customers of potential service disruption
Place staff teams on alert to implement existing preparation plans
Cancel employee time off
Post-Event Decisions
Evaluate radiation exposure of flight crew
New modeling and simulation activities to assess aircraft risk
Evaluate radiation exposure of aircraft, including avionics equipment
New modeling and simulation activities to protect crews
Replace exposed avionics equipment with new components
Revise preparation plans for future events
Order new avionics equipment to replace exposed components
Liaise with other operators to share data
Liaise with other operators to share experiences

Rail

Long-Term Mitigation Decisions

- Modeling and simulation to understand GIC rail signaling impacts
- Modeling and simulation to understand GIC electrified rail impacts
- Modeling and simulation to understand GIC transformers impacts
- Modeling and simulation to understand terrestrial radio comms. impacts
- Modeling and simulation to understand satellite comms. impacts
- System design changes to protect electric rail operation
- Develop inventory of GIC vulnerable assets
- Purchase backups for GIC vulnerable assets
- Prepare for how to replace a damaged transformer
- Review the type, condition and locations of spare transformers
- Add devices to transformers, power lines, or other assets to record baseline transformer currents and GIC
- Train staff on space weather impacts to raise awareness
- Implement backup comms. in case of disruption
- Train staff on space weather contingency plans
- Implement backup power systems in case of disruption

Short-Term Mitigation Decisions

- Require train operators to slow to a safe speed when approaching junctions
- Postpone scheduled rail services
- Cancel scheduled rail services
- Notify customers of potential service disruption
- Place staff teams on alert to implement preparation plans
- Monitor potential false signal tripping
- Cancel employee time off to maximize available labor resources
- Increase staff situational awareness
- Frequent communication with train operators to confirm near-real-time location

Post-Event Decisions

- Investigate conditions of exposed signaling systems
- Investigate conditions of exposed power systems
- Remove transformers from service for inspection
- Replace exposed assets with new components
- Place an order for new apparatus to replace exposed transformers
- Undertake new modeling and simulation activities
- Liaise with other operators to share data
- Liaise with other operators to share experiences
- Revise preparation plans for future events

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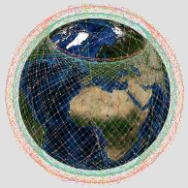

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Critical Infrastructure Sector Survey

Critical Infrastructure Operator Space Weather Mitigation Decisions over the 2024 Solar Maximum

Noah Rivera[1], Edward Oughton[1], Lucy Wilkerson[1], Bob Weigel[1], Dean Thomas[1] and Trevor C. Gaunt[1]

[1]*George Mason University, Fairfax, VA, USA*

Abstract

The Gannon geomagnetic storm of May 10th 2024 was the first time since the famous 2003 Halloween storms that the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center issued an Extreme G5 geomagnetic event warning. Although the May 2024 space weather events produced beautiful aurora in lower latitudes (even southern Florida), the reality is that these were highly challenging operational conditions for critical infrastructure operators, particularly for electricity transmission and satellite networks. As with Halloween 2003, the space weather community will study the Gannon storm for decades. Therefore, this provides strong motivation to collect perishable operational decision data from critical infrastructure operators. Indeed, scientists and engineers modeling space weather impacts urgently need this new data to advance our fundamental scientific understanding of these hazards across local, regional, national and global scales, as highlighted by the US National Space Weather Strategy and Action Plan. Firstly, this poster reports the range of mitigation options identified for power and satellite networks from a systematic literature review, broken down chronologically. Secondly, we report fast-track results from targeted surveying of 32 electricity transmission and 25 satellite operators via the ChronoStorm survey (www.chrono-storm.com), collecting information on mitigation decisions implemented over the solar maximum. Gathering this perishable data helps to provide a historical log of the steps taken to protect critical infrastructure during solar cycle 25. This enables future generations of scientists and engineers to better understand how to model space weather hazards, and further inform critical infrastructure protection decisions, ensuring national security.

Research Questions

Research Questions:

1. What are the mitigation decision options available to power and satellite network operators?
2. Which mitigation decision options are being frequently used over the 2024 solar maximum (in terms of pre-, during- and post-event chronological periods)?

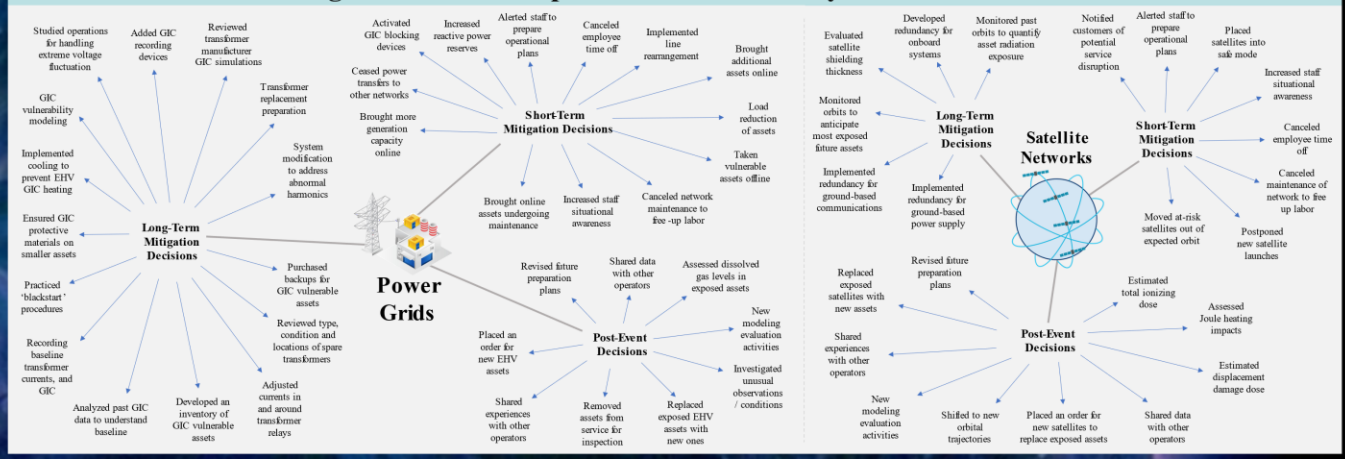
Method

1. Undertaking a systematic literature review of possible mitigation decision options available to critical infrastructure operators, for example, across power, satellite, aviation, rail and other activities dependent on Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS).
2. Building a website capable of capturing these responses and undertaking targeted sampling of operators.
3. Analyzing the obtained results and synthesizing preliminary findings (the survey period is set to continue running until Spring 2025).

Importantly, a targeted sampling approach (McGrew et al., 2014) is adopted given (i) there are not a vast number of operators, so the response rate matters, and (ii) targeted operators have first-hand experience from recent events (e.g., May/October 2024).

The systematic literature review is reported in the full-length paper, which includes the following key documents, NERC (2011), U.S. DoE (2019), U.S. DoE (2018), Airbus Defence & Space (2015), and The Aerospace Corporation (2017).

Possible Mitigation Decision Options Identified via Systematic Literature Review



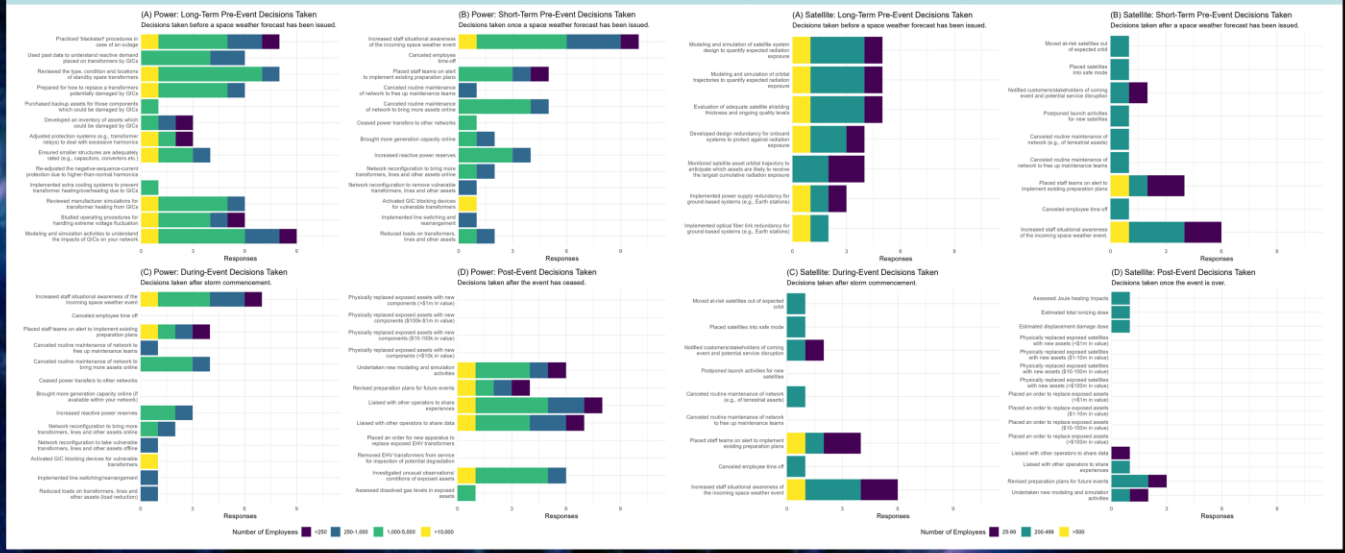
Initial Findings From Fast-Track Results

- Almost all operators are implementing long-term advanced mitigation options, with a large number of decision responses identified in both the power and satellite surveys.
- However, the majority of power mitigation measures are taken in advance (especially as part of long-term planning), with substantially fewer being taken during an event.
- Surprisingly, respondents report no damaged/replaced power or satellite assets over the solar maximum in 2024. However, numerous power operators experienced unusual observations/conditions in exposed assets requiring further investigation.

Take the ChronoStorm Survey

Are you a critical infrastructure operator and willing to participate in this research? Visit the ChronoStorm website (www.Chrono-Storm.com) or follow the QR code to take the survey now!

Fast-Track ChronoStorm Survey Results for Mitigation Decision Options in Current Use



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North American Electric Reliability Corporation (NERC), 2011. *Industry Advisory Preparing for Geo-Magnetic Disturbances.*
The Aerospace Corporation, 2017. *Metrics For Addressing Satellite Operator Needs.*
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Acknowledgements

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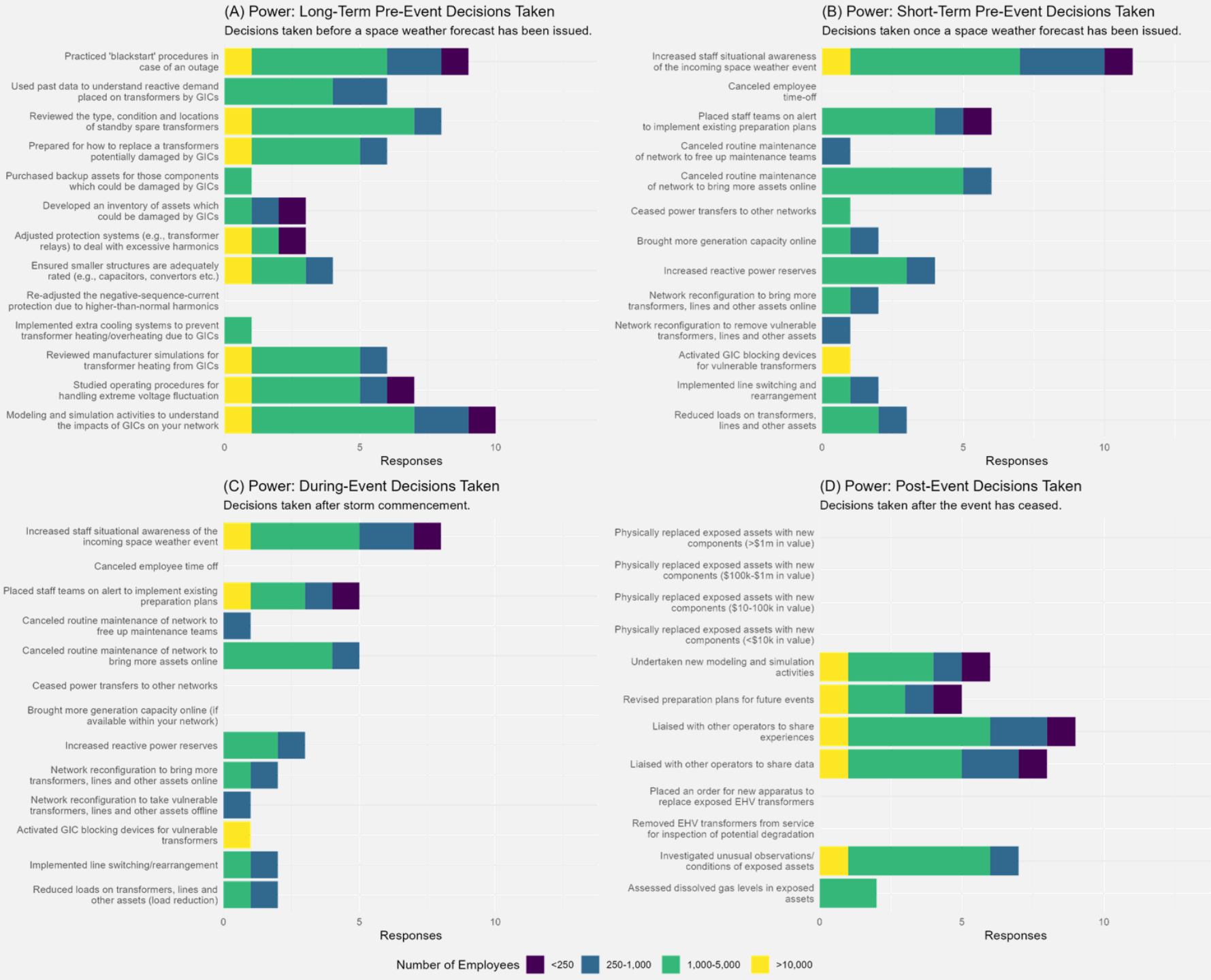
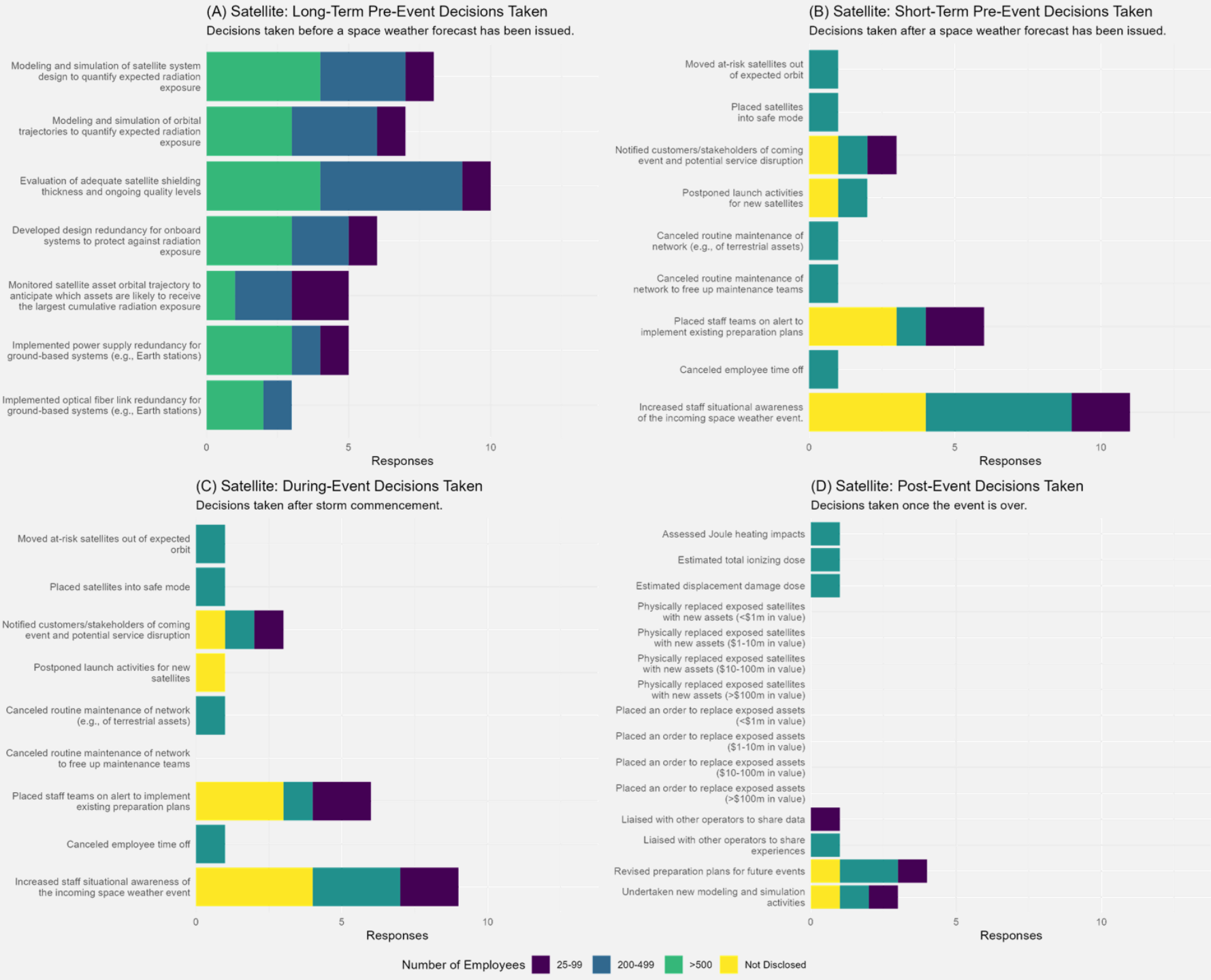

(A) Power: Long-Term Pre-Event Decisions Taken
Decisions taken before a space weather forecast has been issued.
Practiced 'blackstart' procedures in case of an outage
Used past data to understand reactive demand placed on transformers by GICs
Reviewed the type, condition and locations of standby spare transformers
Prepared for how to replace a transformers potentially damaged by GICs
Purchased backup assets for those components which could be damaged by GICs
Developed an inventory of assets which could be damaged by GICs
Adjusted protection systems (e.g., transformer relays) to deal with excessive harmonics
Ensured smaller structures are adequately rated (e.g., capacitors, convertors etc.)
Re-adjusted the negative-sequence-current protection due to higher-than-normal harmonics
Implemented extra cooling systems to prevent transformer heating/overheating due to GICs
Reviewed manufacturer simulations for transformer heating from GICs
Studied operating procedures for handling extreme voltage fluctuation
Modeling and simulation activities to understand the impacts of GICs on your network
0
5
10
Responses
(B) Power: Short-Term Pre-Event Decisions Taken
Decisions taken once a space weather forecast has been issued.
Increased staff situational awareness of the incoming space weather event
Canceled employee time-off
Placed staff teams on alert to implement existing preparation plans
Canceled routine maintenance of network to free up maintenance teams
Canceled routine maintenance of network to bring more assets online
Ceased power transfers to other networks
Brought more generation capacity online
Increased reactive power reserves
Network reconfiguration to bring more transformers, lines and other assets online
Network reconfiguration to remove vulnerable transformers, lines and other assets
Activated GIC blocking devices for vulnerable transformers
Implemented line switching and rearrangement
Reduced loads on transformers, lines and other assets
0
5
10
Responses
(C) Power: During-Event Decisions Taken
Decisions taken after storm commencement.
Increased staff situational awareness of the incoming space weather event
Canceled employee time off
Placed staff teams on alert to implement existing preparation plans
Canceled routine maintenance of network to free up maintenance teams
Canceled routine maintenance of network to bring more assets online
Ceased power transfers to other networks
Brought more generation capacity online (if available within your network)
Increased reactive power reserves
Network reconfiguration to bring more transformers, lines and other assets online
Network reconfiguration to take vulnerable transformers, lines and other assets offline
Activated GIC blocking devices for vulnerable transformers
Implemented line switching/rearrangement
Reduced loads on transformers, lines and other assets (load reduction)
0
5
10
Responses
(D) Power: Post-Event Decisions Taken
Decisions taken after the event has ceased.
Physically replaced exposed assets with new components (>$1m in value)
Physically replaced exposed assets with new components ($100k-$1m in value)
Physically replaced exposed assets with new components ($10-100k in value)
Physically replaced exposed assets with new components (<$10k in value)
Undertaken new modeling and simulation activities
Revised preparation plans for future events
Liaised with other operators to share experiences
Liaised with other operators to share data
Placed an order for new apparatus to replace exposed EHV transformers
Removed EHV transformers from service for inspection of potential degradation
Investigated unusual observations/ conditions of exposed assets
Assessed dissolved gas levels in exposed assets
0
5
10
Responses
Number of Employees
<250
250-1,000
1,000-5,000
>10,000


(A) Satellite: Long-Term Pre-Event Decisions Taken
Decisions taken before a space weather forecast has been issued.
Modeling and simulation of satellite system design to quantify expected radiation exposure
Modeling and simulation of orbital trajectories to quantify expected radiation exposure
Evaluation of adequate satellite shielding thickness and ongoing quality levels
Developed design redundancy for onboard systems to protect against radiation exposure
Monitored satellite asset orbital trajectory to anticipate which assets are likely to receive the largest cumulative radiation exposure
Implemented power supply redundancy for ground-based systems (e.g., Earth stations)
Implemented optical fiber link redundancy for ground-based systems (e.g., Earth stations)
0
5
10
Responses
(B) Satellite: Short-Term Pre-Event Decisions Taken
Decisions taken after a space weather forecast has been issued.
Moved at-risk satellites out of expected orbit
Placed satellites into safe mode
Notified customers/stakeholders of coming event and potential service disruption
Postponed launch activities for new satellites
Canceled routine maintenance of network (e.g., of terrestrial assets)
Canceled routine maintenance of network to free up maintenance teams
Placed staff teams on alert to implement existing preparation plans
Canceled employee time off
Increased staff situational awareness of the incoming space weather event.
0
5
10
Responses
(C) Satellite: During-Event Decisions Taken
Decisions taken after storm commencement.
Moved at-risk satellites out of expected orbit
Placed satellites into safe mode
Notified customers/stakeholders of coming event and potential service disruption
Postponed launch activities for new satellites
Canceled routine maintenance of network (e.g., of terrestrial assets)
Canceled routine maintenance of network to free up maintenance teams
Placed staff teams on alert to implement existing preparation plans
Canceled employee time off
Increased staff situational awareness of the incoming space weather event
0
5
10
Responses
(D) Satellite: Post-Event Decisions Taken
Decisions taken once the event is over.
Assessed Joule heating impacts
Estimated total ionizing dose
Estimated displacement damage dose
Physically replaced exposed satellites with new assets (<$1m in value)
Physically replaced exposed satellites with new assets ($1-10m in value)
Physically replaced exposed satellites with new assets ($10-100m in value)
Physically replaced exposed satellites with new assets (>$100m in value)
Placed an order to replace exposed assets (<$1m in value)
Placed an order to replace exposed assets ($1-10m in value)
Placed an order to replace exposed assets ($10-100m in value)
Placed an order to replace exposed assets (>$100m in value)
Liaised with other operators to share data
Liaised with other operators to share experiences
Revised preparation plans for future events
Undertaken new modeling and simulation activities
0
5
10
Responses
Number of Employees
25-99
200-499
>500
Not Disclosed

Next Steps

1. Finish GIC evaluation/validation paper.
2. Complete remaining interviews and survey.
3. Write up strategic mitigation decisions paper.

We intend to have working papers ready for

Space Weather Workshop (mid-March 2025)

RAPID: COLLECTING PERISHABLE CRITICAL INFRASTRUCTURE OPERATIONAL DATA FOR MAY 2024 SPACE WEATHER EVENTS.

Edward Oughton (eoughton@gmu.edu)

National Academies Space Weather Roundtable

5th February 2025

NSF NSF NCAR Operated by UCAR GEORGE MASON UNIVERSITY