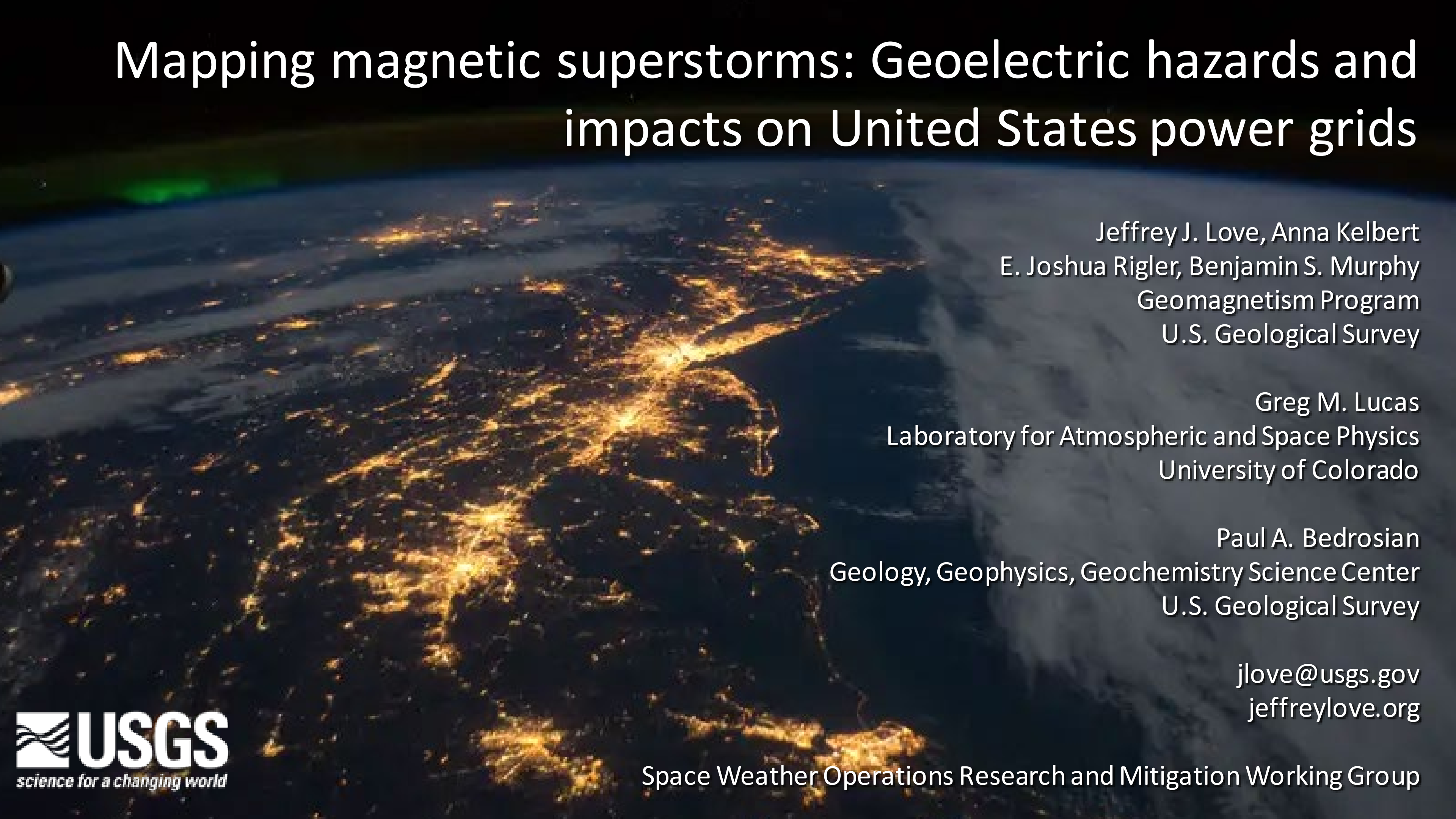

Mapping magnetic superstorms: Geoelectric hazards and impacts on United States power grids

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USGS
science for a changing world

Space Weather Operations Research and Mitigation Working Group

Some impactful magnetic storms

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One of the largest magnetic storms ever recorded. Widespread disruption of telegraph service.

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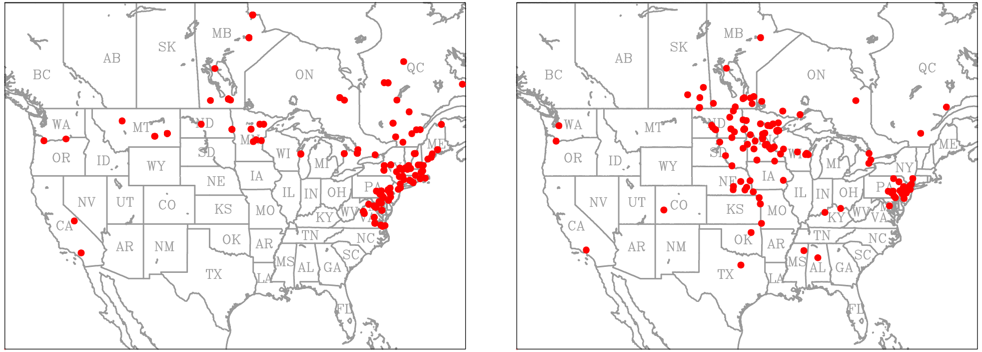
Note tomorrow’s ground-effects panel: Anna Kelbert (USGS), Jenn Gannon (CPI), Jesper Gjerloev (JHU/APL) , Arnaud Chulliat (NOAA/NCEI), Antti Pulkkinen (NASA/GSFC), and Adam Schultz (OSU).

March 1989 magnetic storm damage to a high-voltage transformer at a nuclear power center in Salem, New Jersey.

Compilation of reports of operational interference ("anomalies") experienced on North American electric-power and communication systems during several magnetic storms.

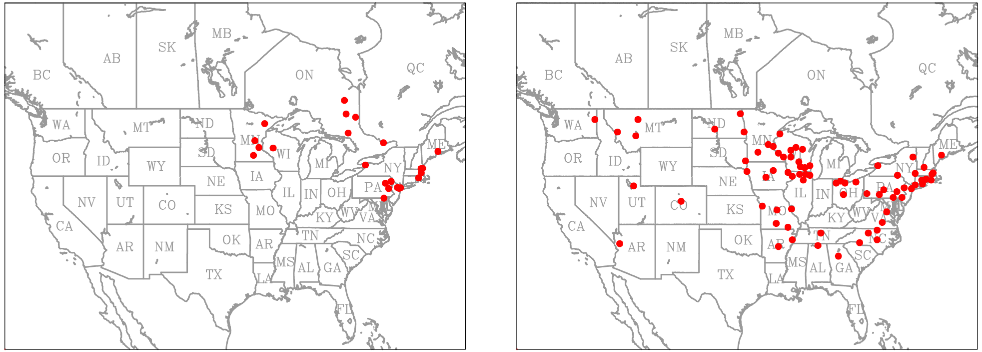
(a) March 1989 power–grid anomalies

(b) August 1972 power–grid anomalies



(c) March 1940 power–grid anomalies

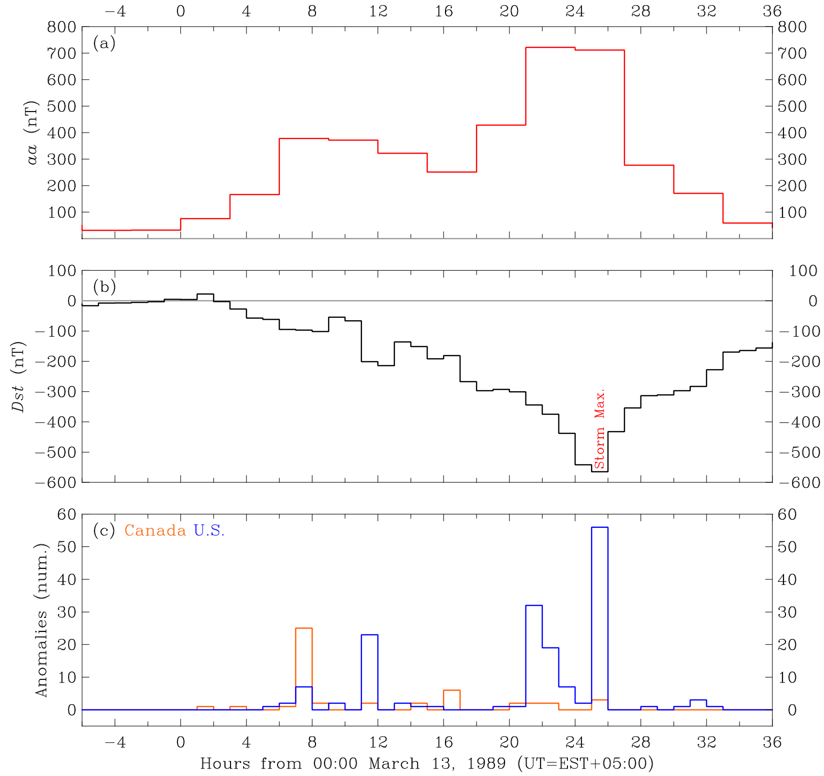
(d) March 1940 comm.–line anomalies (U.S. only)



Operational anomalies tend to be concentrated in the Mid-Atlantic, the Northeast, and in the upper Midwest United States.

Love, J. J. & Murphy, B. S., 2022. North American electricity power-grid and communication-network anomalies for several magnetic storms, U.S. Geological Survey data release, https://doi.org/10.5066/P9N4DVNT.

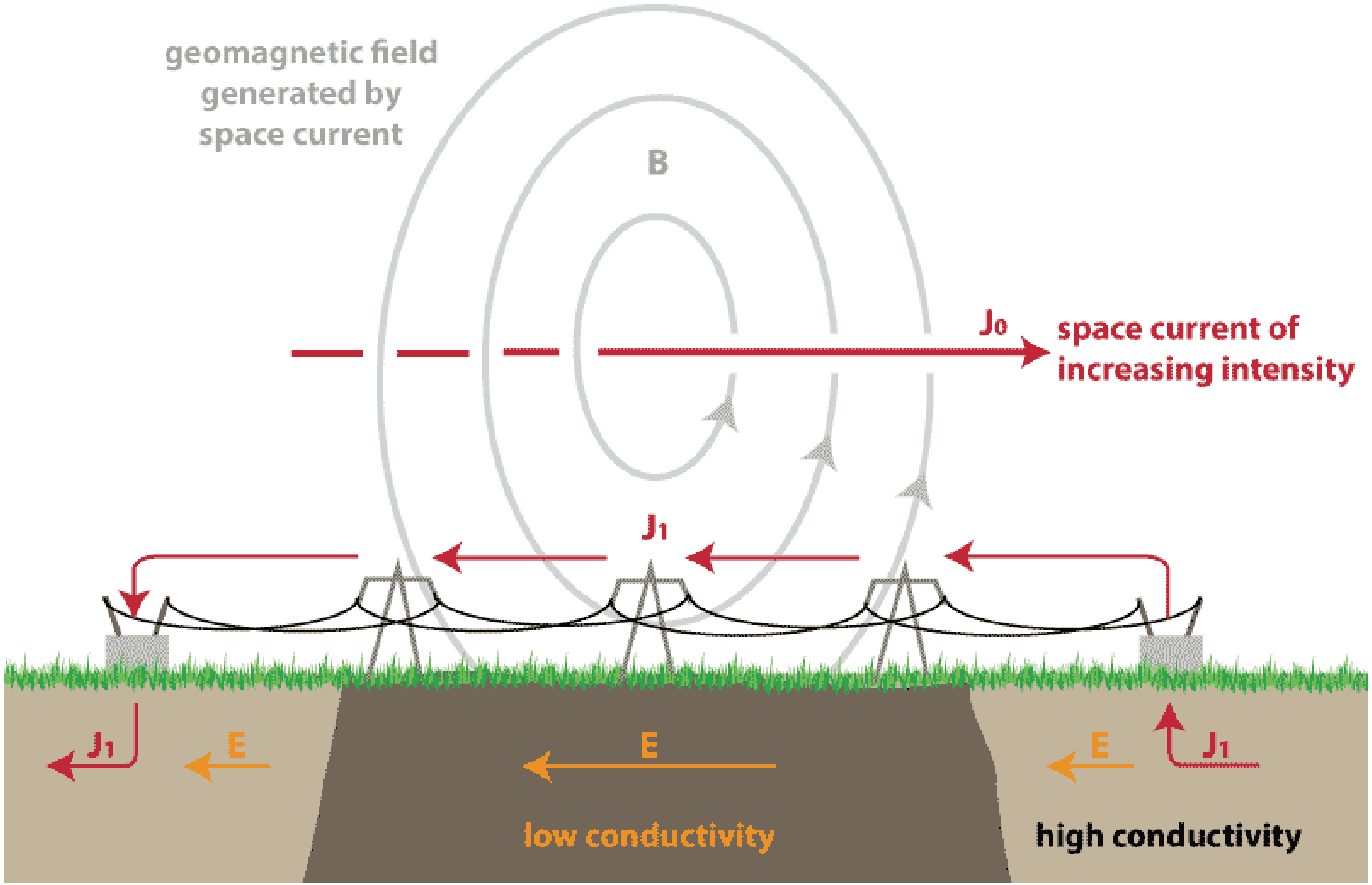
When was operational interference experienced across North America during the March 1989 storm?



During the March 1989 storm, operational anomalies tended to be realized during main-phase, and, especially during maximum -Dst.

These observations highlight the need for short-term forecasting and real-time monitoring and “nowcasting”.

Boteler, 2019, doi:10.1029/2019SW002278; Love et al. under review.



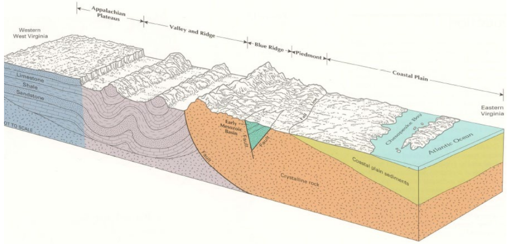
Love, J. J., Bedrosian, P. A. & Schultz, A., 2017. Down to Earth with an electric hazard from space, Space Weather, 15(5), 658-662, https://doi.org/10.1002/2017SW001622.

Input signal
time series

Convolution
through a filter

Output signal
time series

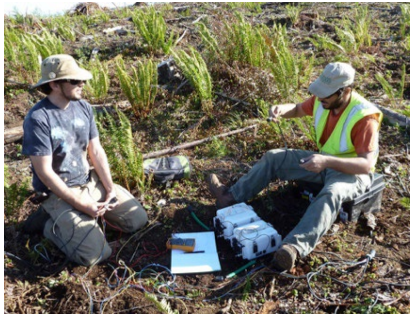
Geomagnetic
variation



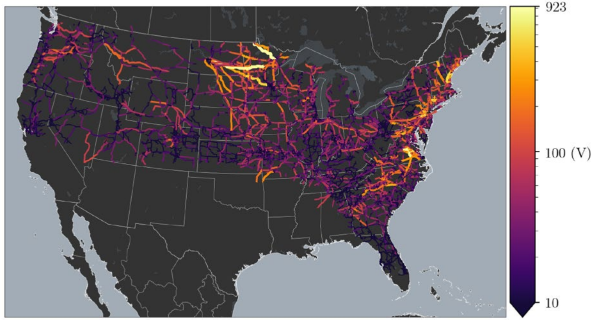
Geoelectric
field

Geomagnetic variation
recoded at observatory

Impedance measured during
magnetotelluric survey

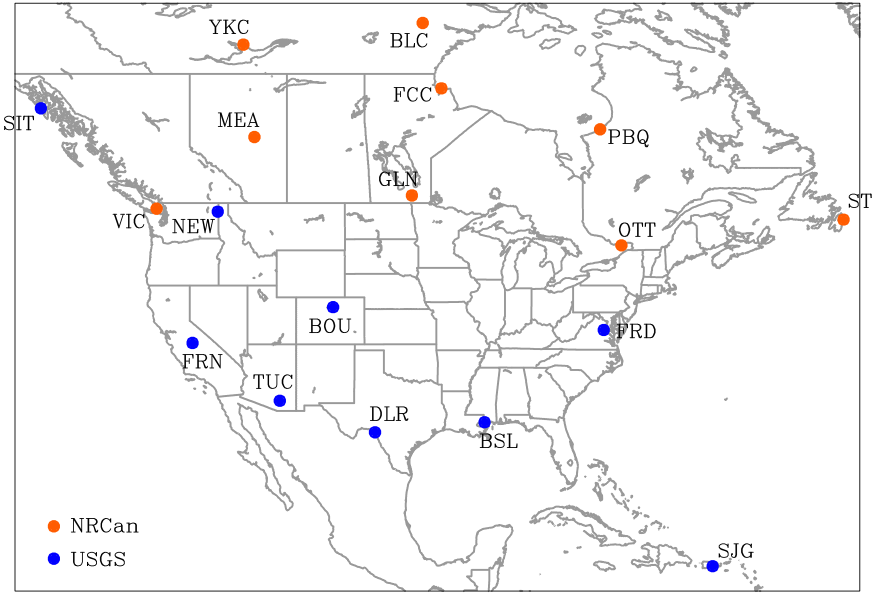


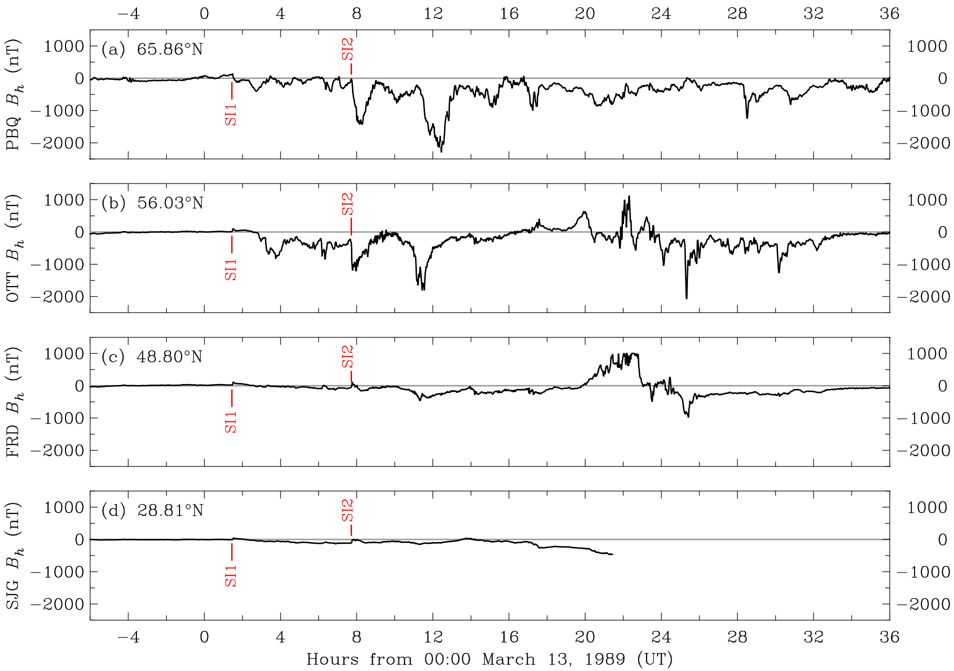
Geoelectric hazards
mapped onto power grids



Love, J. J., Rigler, E. J., Pulkkinen, A., Balch, C. C., 2014.
Magnetic storms and induction hazards, Eos, Trans. AGU, 95(48), 445-446, https://doi.org/10.1002/2014EO480001.

Magnetic observatories spanning the study region, in operation in 1989 and providing 1-minute resolution data.



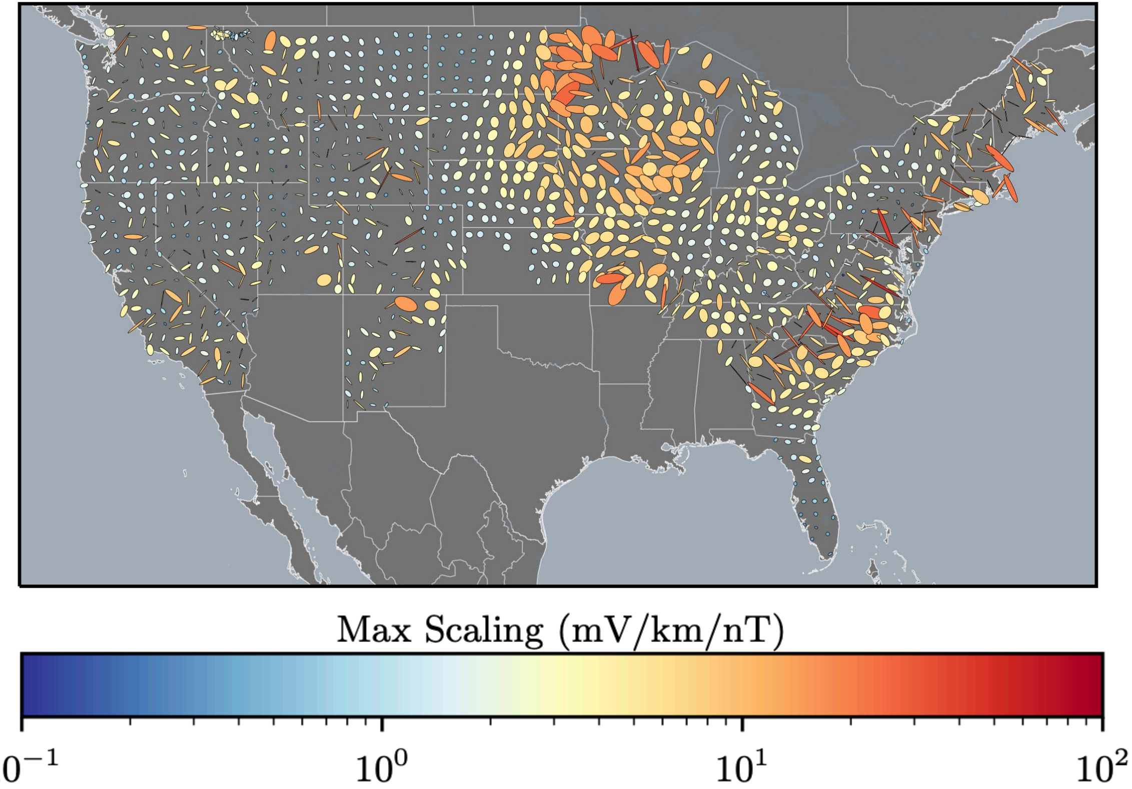


Natural Resources Canada

Storm-time geomagnetic disturbance displays important geographical-temporal dependence. Additional geomagnetic monitoring is needed, especially for event-by-event mapping of voltages on individual grid lines.

Love & Finn, 2011, https://doi.org/10.1029/2011SW000684; Newitt & Coles, 2007, https://link.springer.com/referencework/10.1007/978-1-4020-4423-6.

Geography of impedance amplitude and polarization at 120 seconds.



Schultz et al., 2006-2018, https://doi.org/10.17611/DP/EMTF/USARRAY/TA.

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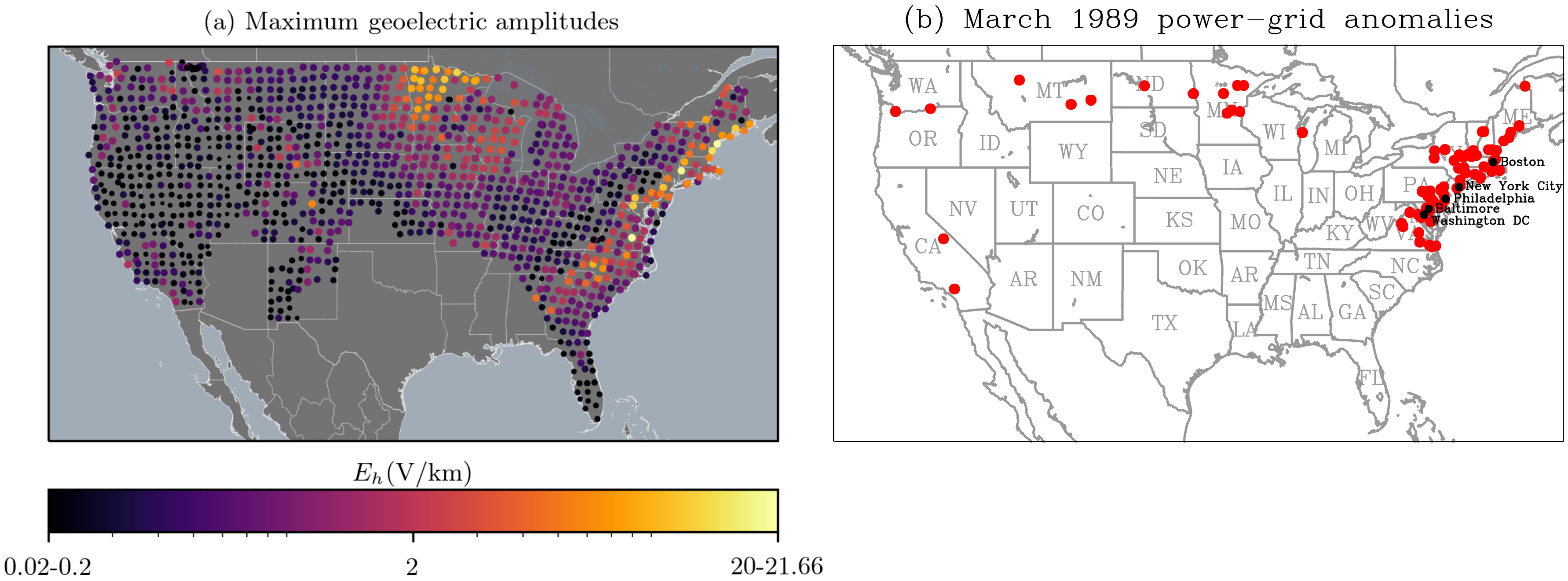
Surface electromagnetic impedance can differ significantly from one location to another, depending on subsurface minerology and fluid content.

The lithosphere is relatively resistive (high impedance) in the upper Midwest and in the Eastern United States. Also polarized in the East.

The lithosphere is relatively conductive (low impedance) in Michigan, Illinois, the Appalachian basin, and much of the West.

Comparison of March 1989 geoelectric amplitudes with power-grid operational interference



(a) Maximum geoelectric amplitudes

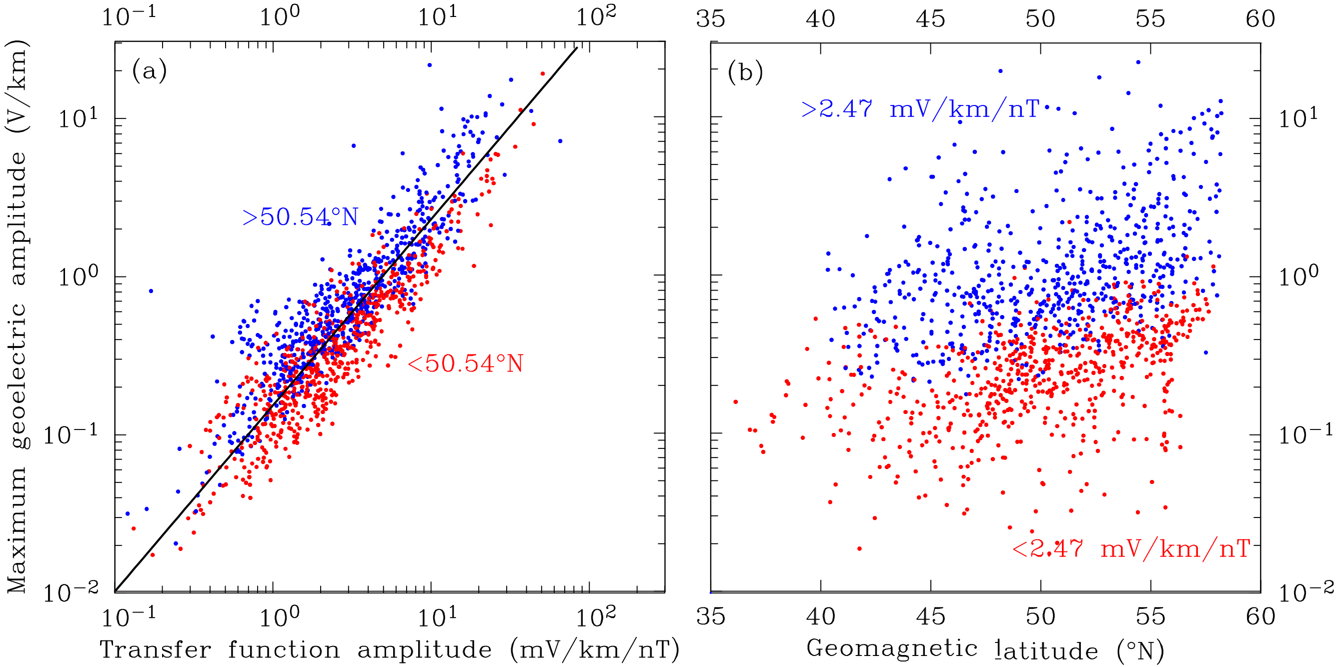
(b) March 1989 power−grid anomalies

Our geoelectric amplitude map shows significant geographic differences peak amplitude for the March 1989 storm. Our map also shows correlation with a (qualitative and anecdotal) anomalies list reported by the North American Electric Reliability Corporation for the March 1989 storm.

Though 1989 operational interference to the U.S. grid did not result in blackouts, it did result in transformer damage and significant operational "stress".

The geoelectric hazard analysis combined with the March 1989 anomalies record provides us with understanding of where more serious problems would likely be manifest during an even more intense storm – the Mid-Atlantic and Northeast United States.

How are geoelectric hazards organized in geography during March 1989?



Geoelectric hazards are affected by both geomagnetic activity and surface impedance.

Over-all hazard amplitude is controlled by storm intensity.

Regional differences in amplitude are primarily controlled by differences in impedance.

Love et al. under review.

100-year 1-minute duration voltages on the national power grid.

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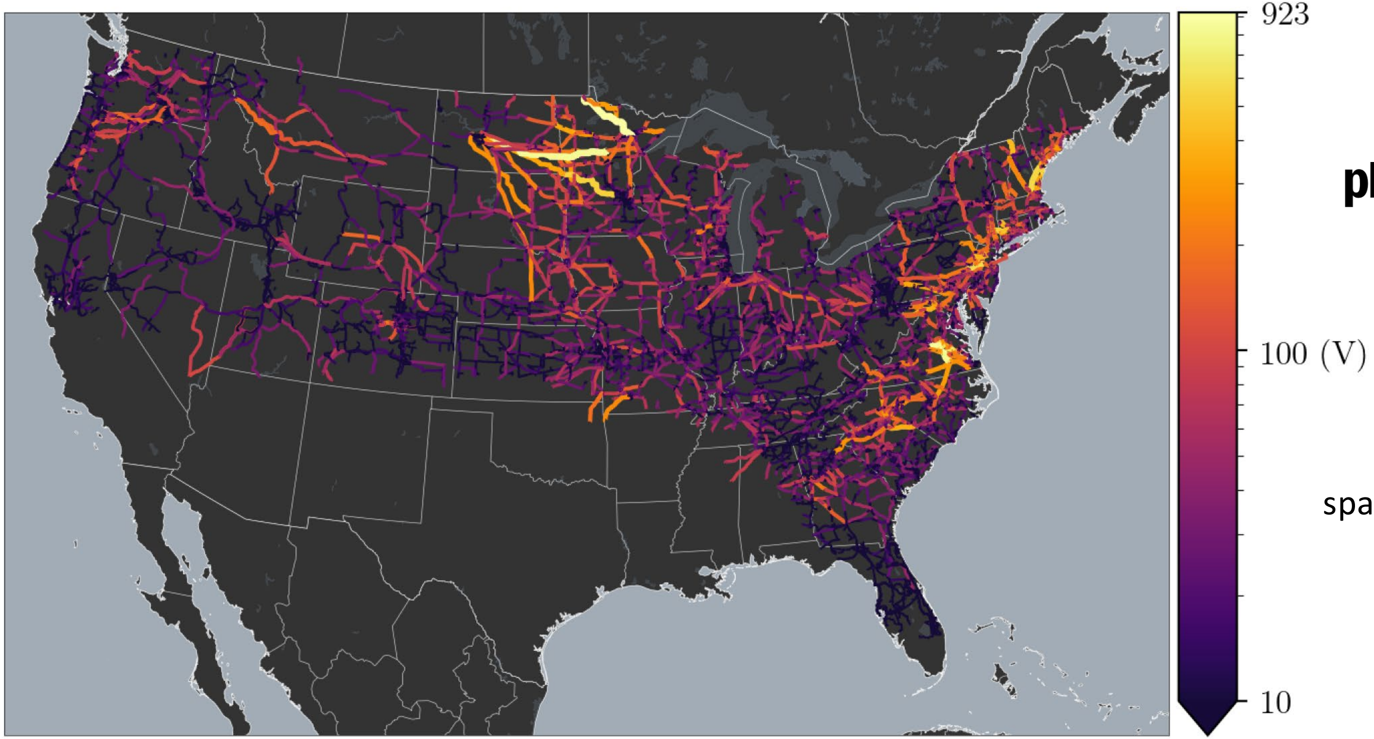
LASP
Laboratory for Atmospheric and Space Physics
University of Colorado Boulder



IEEE SPECTRUM

ENERGYWIRE

physicsworld

NATIONAL GEOGRAPHIC

SCIENTIFIC AMERICAN.

Bloomberg NEWS

spaceweather.com

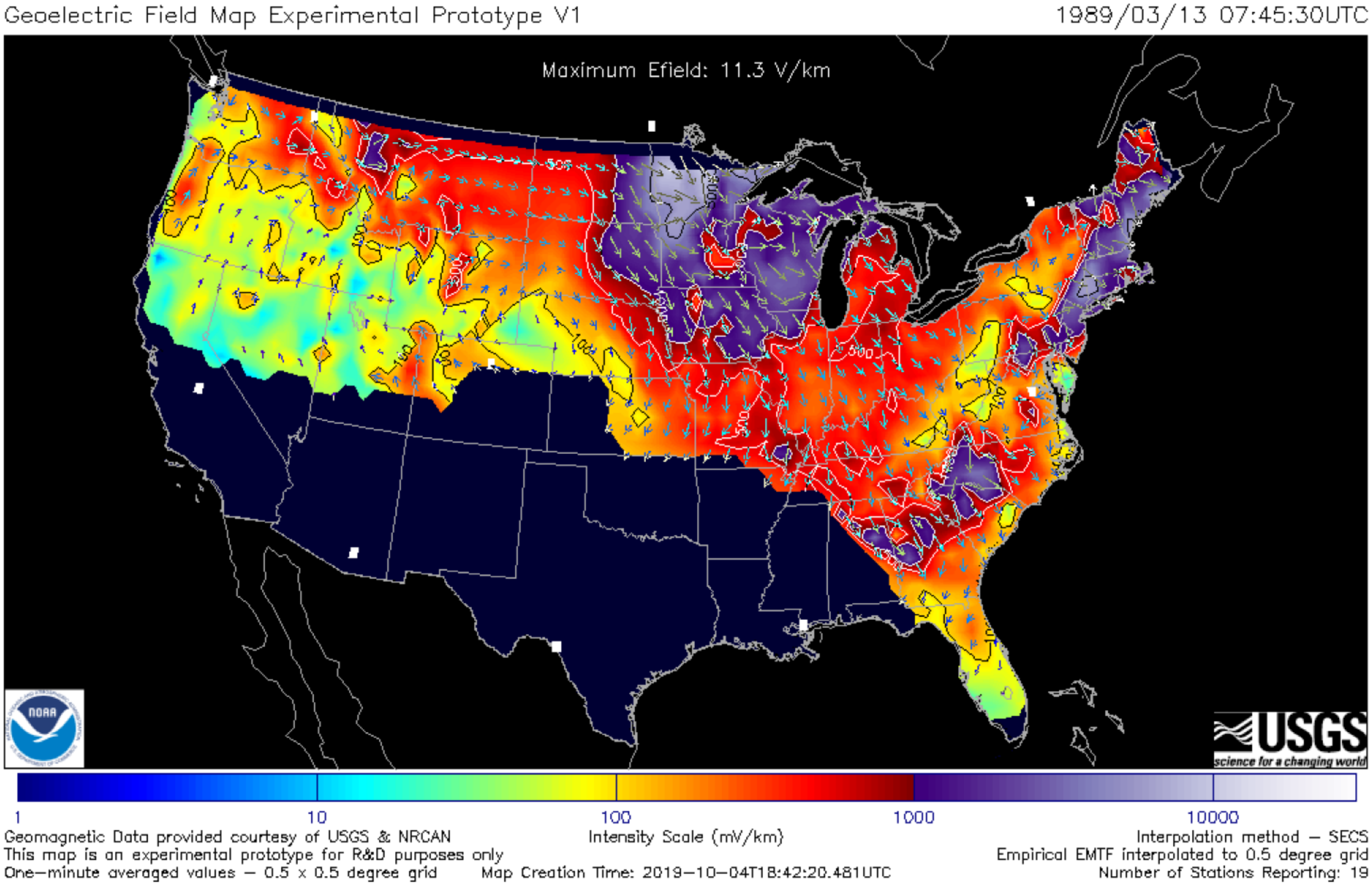
Lucas, et al. 2020, https://doi.org/10.1002/2019SW002329.

We estimate geoelectric field amplitudes for many storms and extrapolate a projection onto the power grid to obtain 100-year extreme-event voltages.

Some of these quasi-direct voltages would drive quasi-direct currents of hundreds or a thousand amps.

This is plenty sufficient to damage transformers (North American Electric Reliability Corporation, Transformer Thermal Impact Assessment, 2017).

Real-time geoelectric hazard mapping project.



Geoelectric Field Map Experimental Prototype V1

1989/03/13 07:45:30UTC

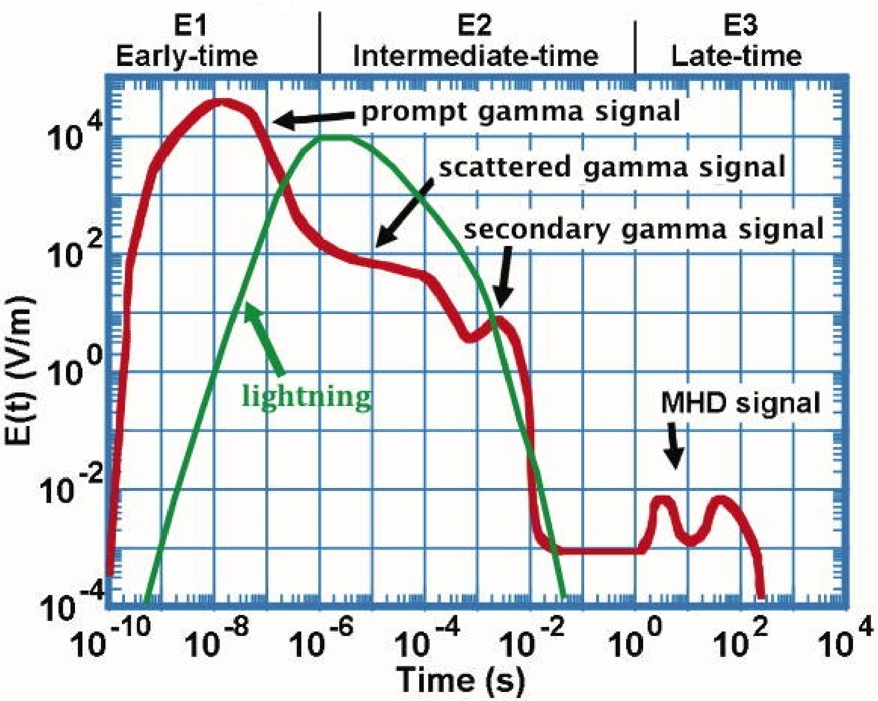
Maximum Efield: 11.3 V/km

Geomagnetic Data provided courtesy of USGS & NRCAN
This map is an experimental prototype for R&D purposes only
One-minute averaged values – 0.5 x 0.5 degree grid

Map Creation Time: 2019-10-04T18:42:20.481UTC

Interpolation method – SECS
Empirical EMTF interpolated to 0.5 degree grid
Number of Stations Reporting: 19

Lessons learned from magnetic storm hazard analysis can guide analysis of hazards associated with late-phase E3 nuclear electromagnetic pulse (EMP).



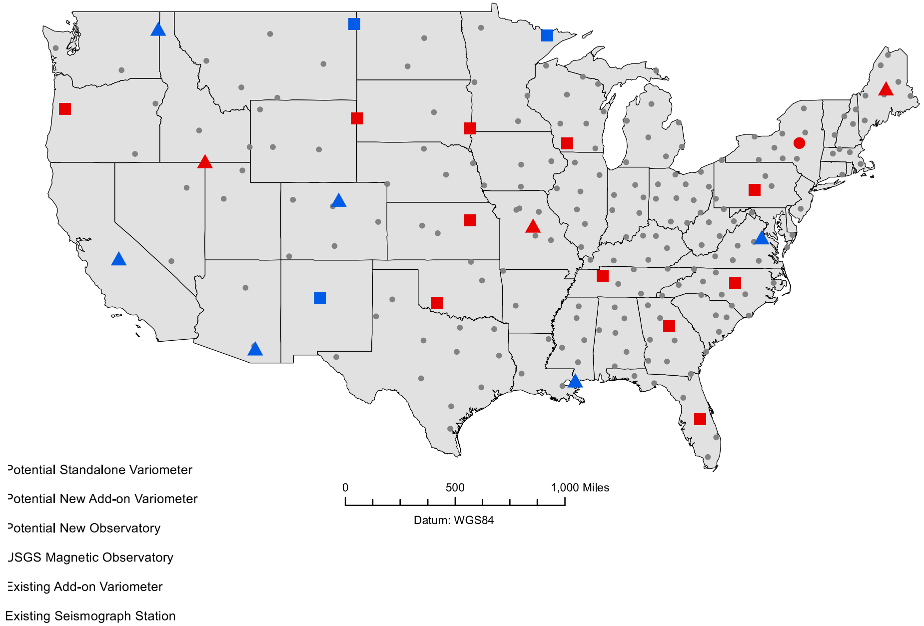
Department of Energy, 2021; Gombosi et al. 2017, https://doi.org/10.1007/s11214-017-0357-5; International Electrotechnical Commission, 1996. 1000-2-9.

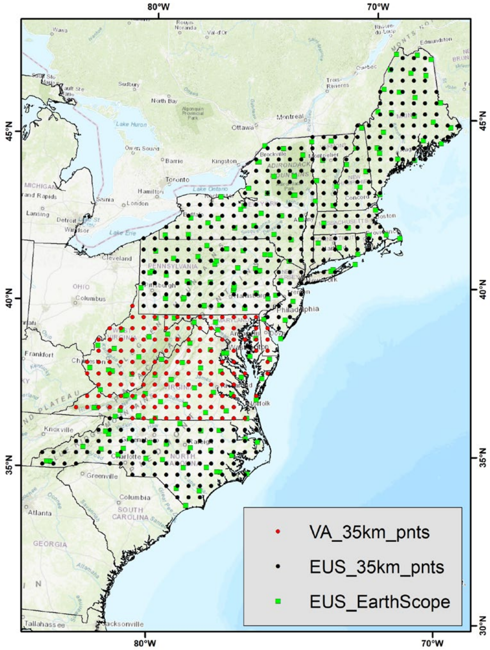
To resolve E3 EMP Earth-surface impedance, dense wideband magnetotelluric surveying is needed (covering at least 0.1 s to 1000 seconds).

Until done, E3 EMP scenario analyses of grid voltages have significant errors -- order of 100% (Love et al. 2021, https://doi.org/10.1029/2021EA001792).

A couple of USGS aspirations:

1. denser geomagnetic monitoring
2. dense wideband magnetotelluric surveying of the Mid-Atlantic and Northeast U.S.





Denser geomagnetic monitoring and would significantly improve the accuracy of maps of magnetic-storm geoelectric field hazards (Murphy et al., 2021. http://doi.org/10.1029/2020SW002693).

Dense wideband surveying would enable realistic mapping of E3 EMP hazards across the geologically complex Mid-Atlantic and Northeast United States-- the most densely populated part of the United States (Love et al. 2021, https://doi.org/10.1029/2021EA001792).

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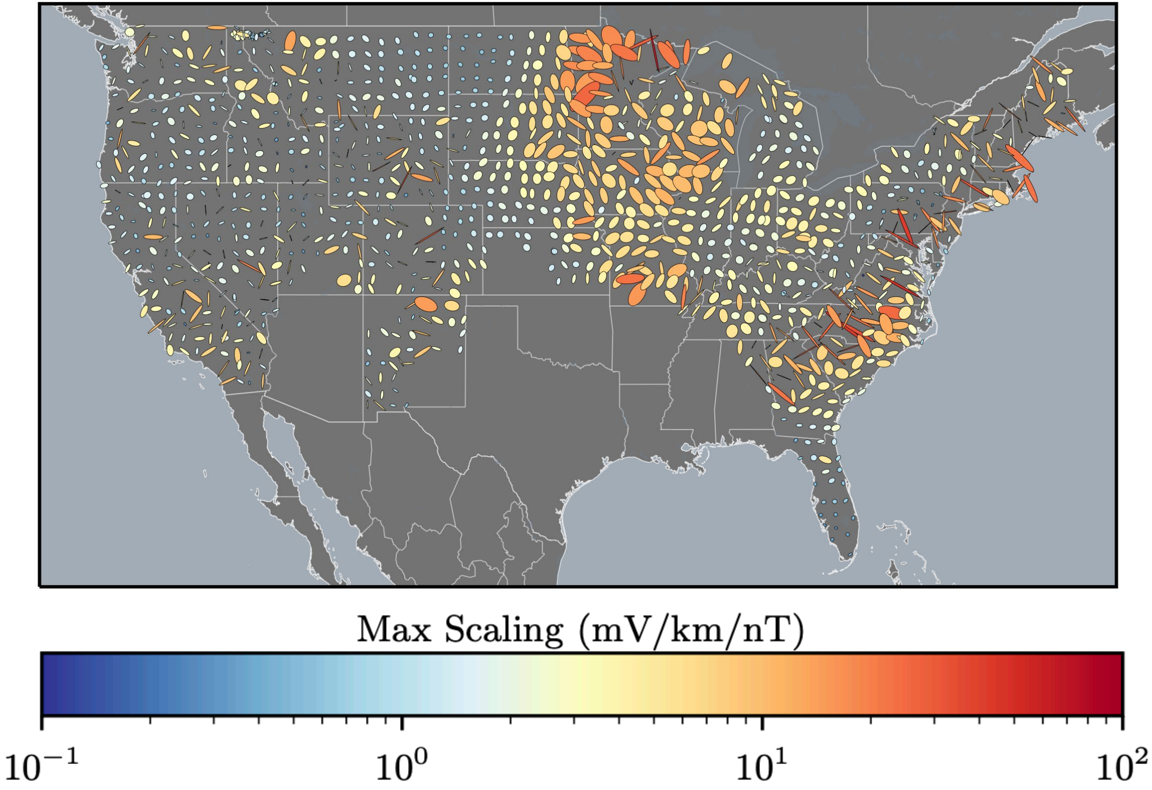
- Proper analysis of storm or EMP induced geoelectric fields coupled with power-grid systems remains to be done.

Geography of impedance amplitude and polarization at 120 seconds.



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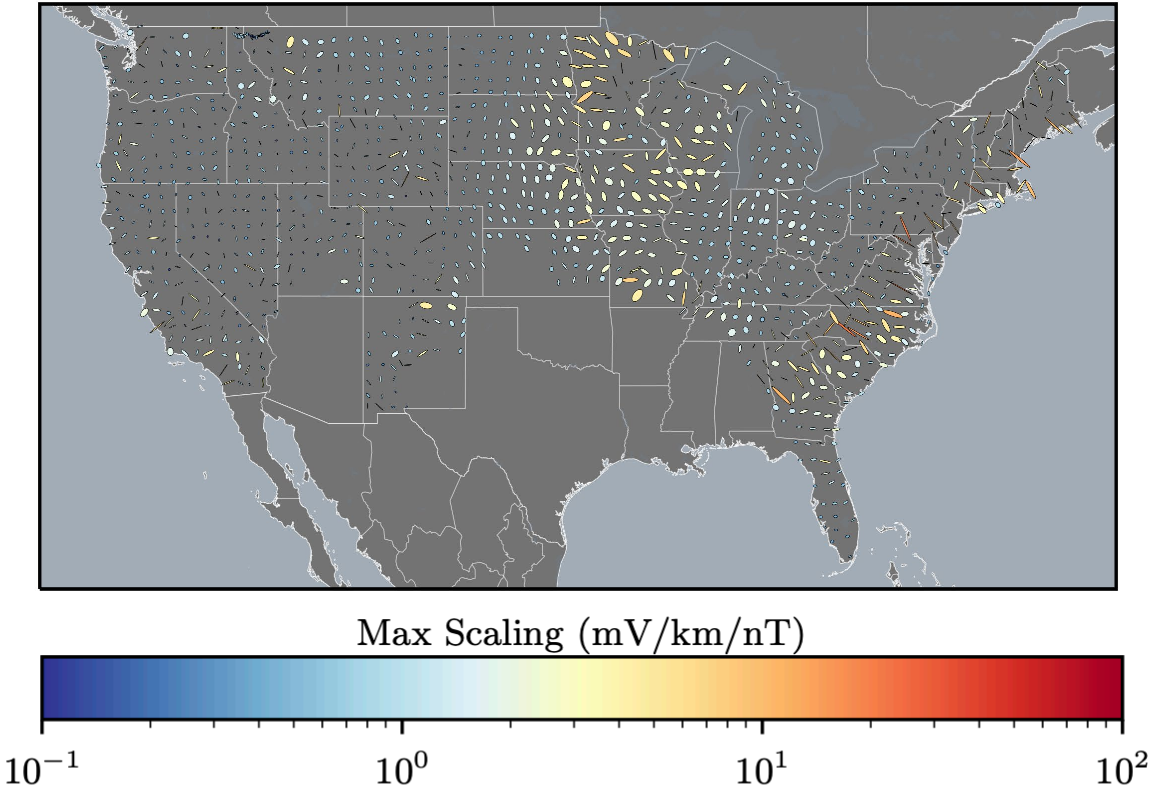
Geography of impedance amplitude and polarization at 120 seconds.



Schultz et al., 2006-2018,
https://doi.org/10.17611/DP/EMTF/USARRAY/TA.

Kelbert, et al, 2011,
https://doi.org/10.17611/DP/EMTF.1.

Surface electromagnetic can differ significantly from one location to another, depending on subsurface minerology and fluid content.

The lithosphere is relatively resistive (high impedance) in the upper Midwest and in the Eastern United States.

The lithosphere is relatively conductive (low impedance) in Michigan, Illinois, the Appalachian basin, and much of the West.