

Geoelectric Field Maps: Progress on NOAA's operational near real-time Geoelectric Field Estimation Capability

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Acknowledgements

- Collaborators:
Antti Pulkkinen – NASA/CCMC
David Boteler – NRCAN
Greg Lucas - USGS
- Data providers: USGS & NRCAN
- Interpolation Algorithm: SECS from FMI
- Conductivity model upgrade:
NSF's Earthscope USArray project



Motivation & Milestones for E-field Maps

- **Goal is to provide something better than the Kp index/G-scale or local K-indices to indicate geomagnetic activity level for systems affected by geomagnetically induced currents (GIC)**
- **Geoelectric Field – identified as the key space weather parameter needed by the electrical power industry**
 - **Space Weather Workshop 2011:**
'...the best, most useful environment parameter...'
 - **Referenced by industry standards groups (NERC/FERC)**
Used to describe the benchmark geomagnetic storm event and vulnerability assessment requirements
 - **National Space Weather Action Plan (SWAP) (OSTP 2015) highlights the Geoelectric field in Goal 1.1 (Benchmarks) & Goal 5.5 (Enhance Understanding)**
- **Local-regional activity can differ from globally averaged activity levels**
- **The geoelectric field is a direct indicator of induction hazard**

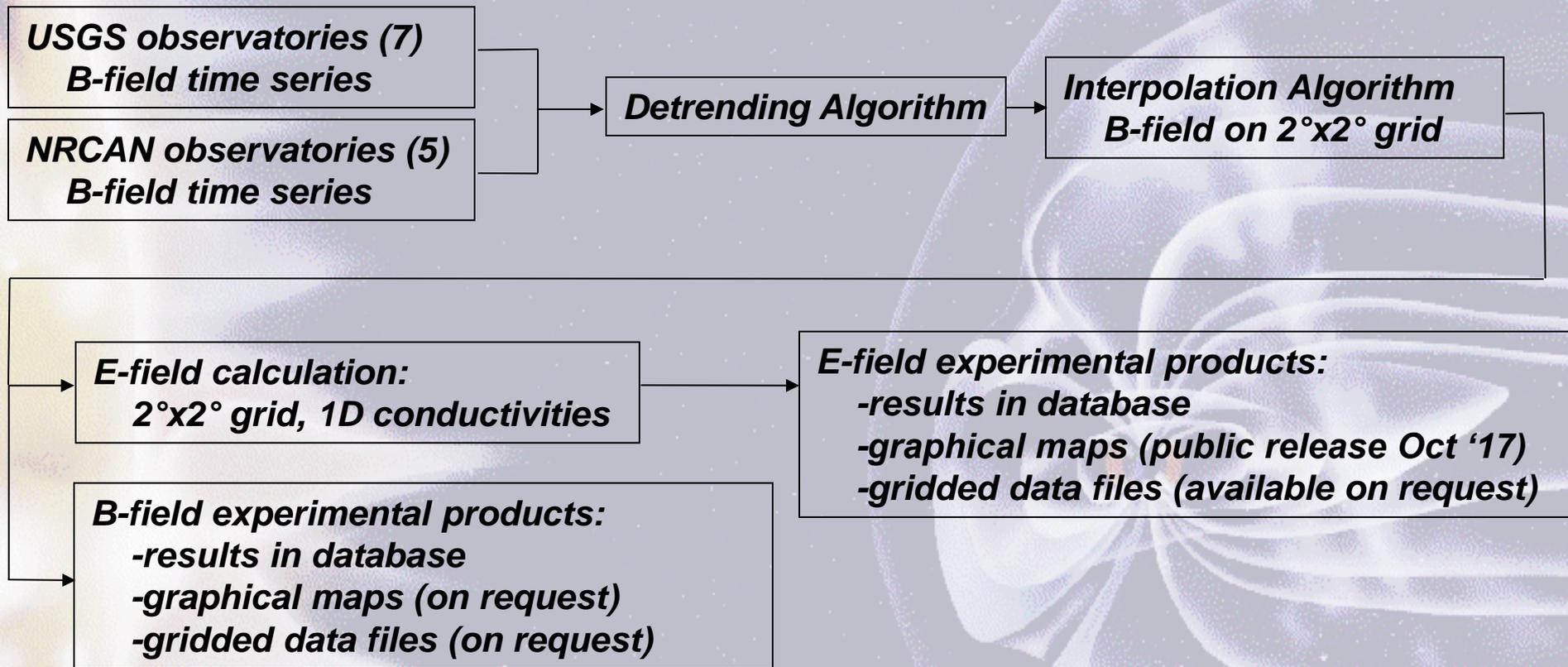


How will the information will be used?

- The geoelectric field enables calculation geomagnetically induced currents
- The GIC calculation requires realistic system modeling
 - Users are developing realistic models of their systems (a standards requirement)
- Calculated GIC can be compared to measured GIC for validation
- Assessment of GIC impacts on the system:
 - System stability when GIC is present (i.e. voltage stability)
 - Transformer behavior under GIC-caused saturation conditions
 - Impact of GIC-caused harmonics on other system components
- System planning or after-the-fact analysis:
 - Simulations can locate problem spots and focus mitigation efforts
 - Analysis can inform real-time response procedures to E-field nowcast/forecast
- The industry is developing tools to help with these assessments
- With more accurate and appropriately targeted information, the industry can make a more informed and appropriate decision in response to storm events, resulting in more efficient operations and cost savings



E-field maps – current capability



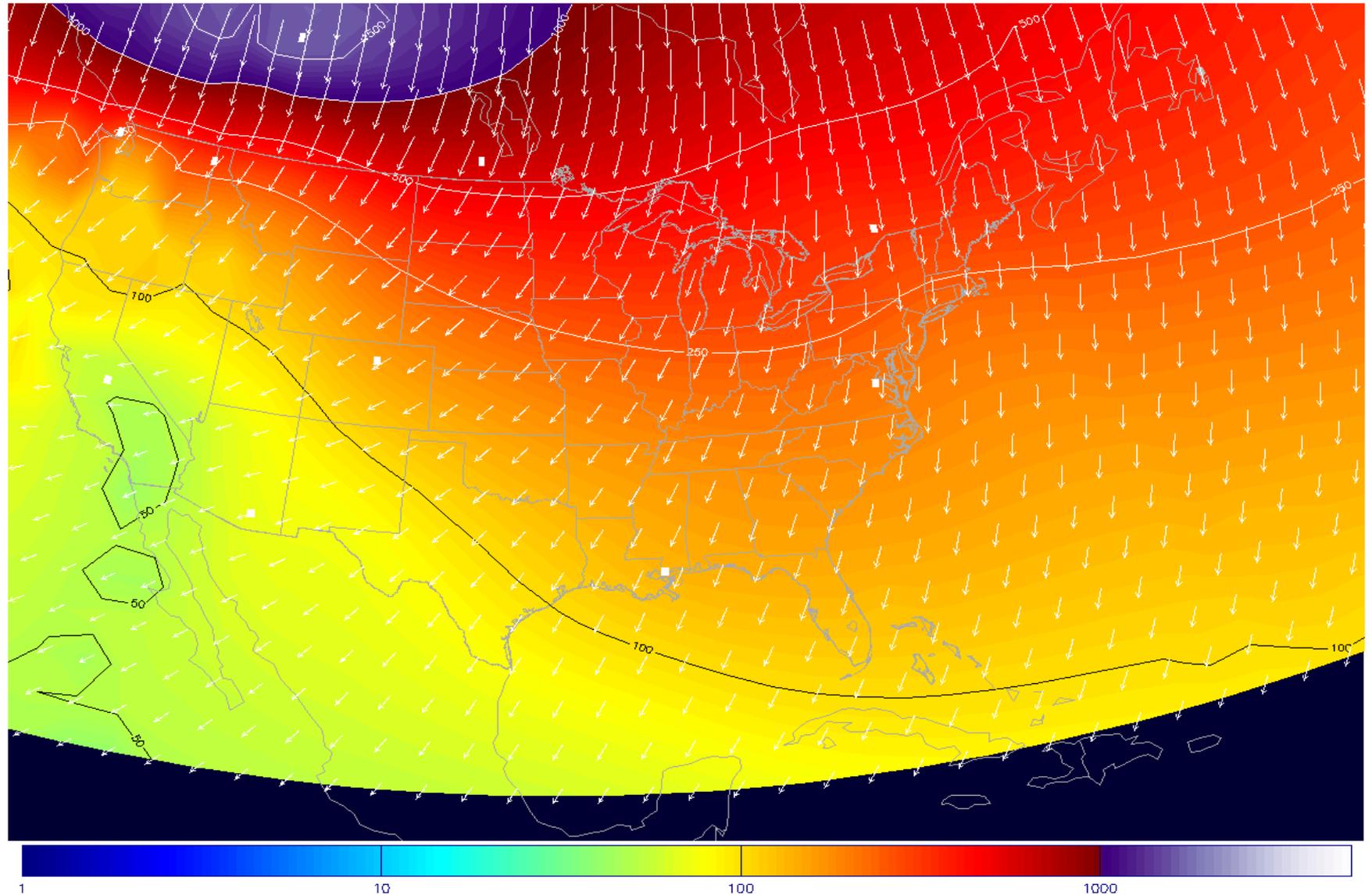
Station Latencies (typical):

BOU, BSL, FRD, FRN, NEW	~1.6 min
SJG, TUC	~2.8 min
MEA, OTT	~2-4 min
VIC, BRD, STJ	~4-8 min

B-field Interpolation Map

Geomagnetic Horizontal Perturbation Map Prototype (Version 1)

2017/09/08 13:55:00 UTC



Geomagnetic Data provided courtesy of USGS & NRCAN
This map is an experimental prototype for R&D purposes only
One-minute averaged values - 2 x 2 degree grid

Intensity Scale (nT)

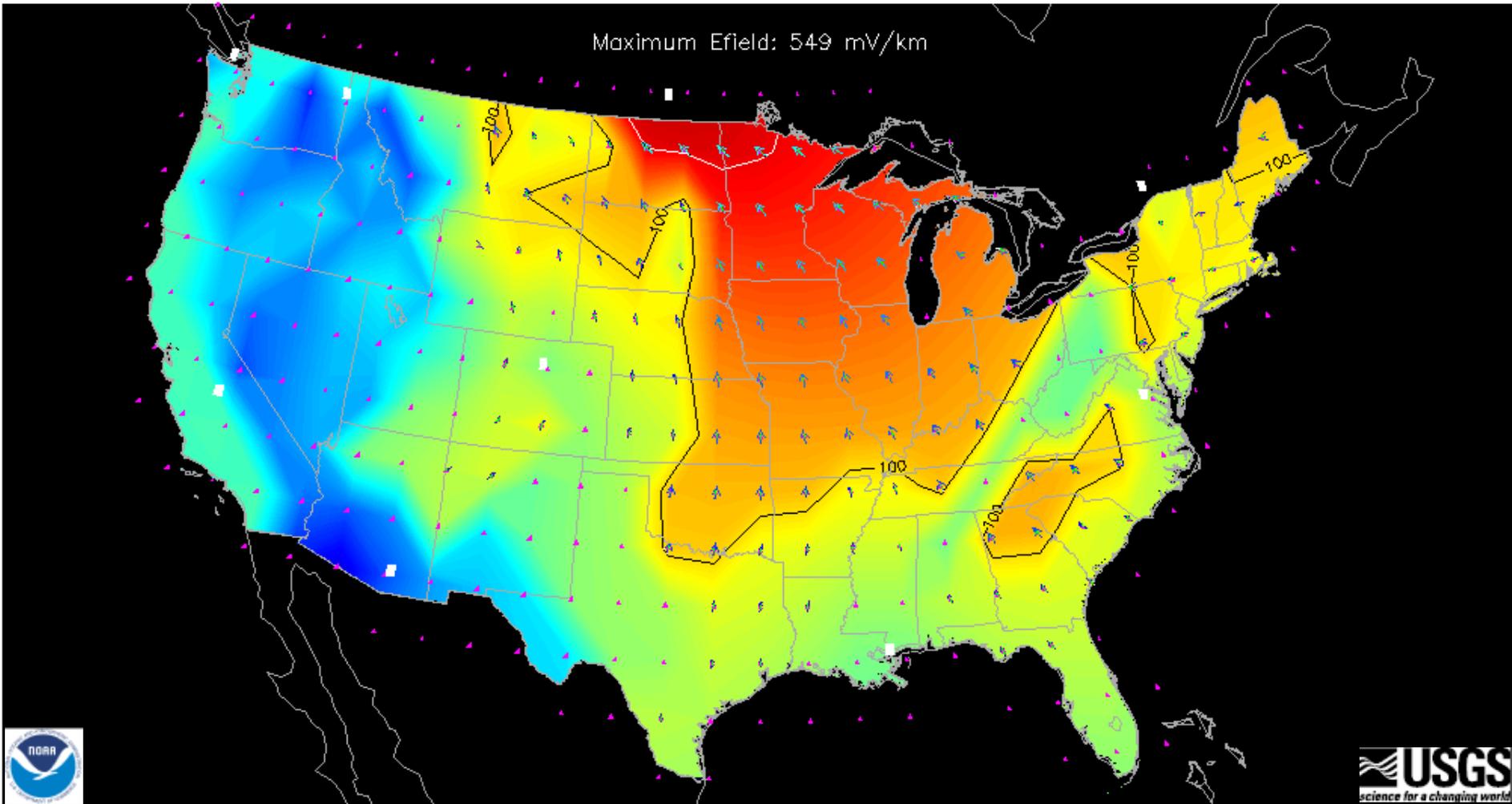
SECS Interpolation
Maximum delta H perturbation: 1652 nT
Map Creation Time: 2017/09/08 14:02:01 UTC

E-field Map – experimental prototype

Geoelectric Field Map Experimental Prototype V1

2017/09/08 13:30:30UTC

Maximum Efield: 549 mV/km



1

10

100

1000

10000

Geomagnetic Data provided courtesy of USGS & NRCAN

This map is an experimental prototype for R&D purposes only

One-minute averaged values – 2 x 2 degree grid

Intensity Scale (mV/km)

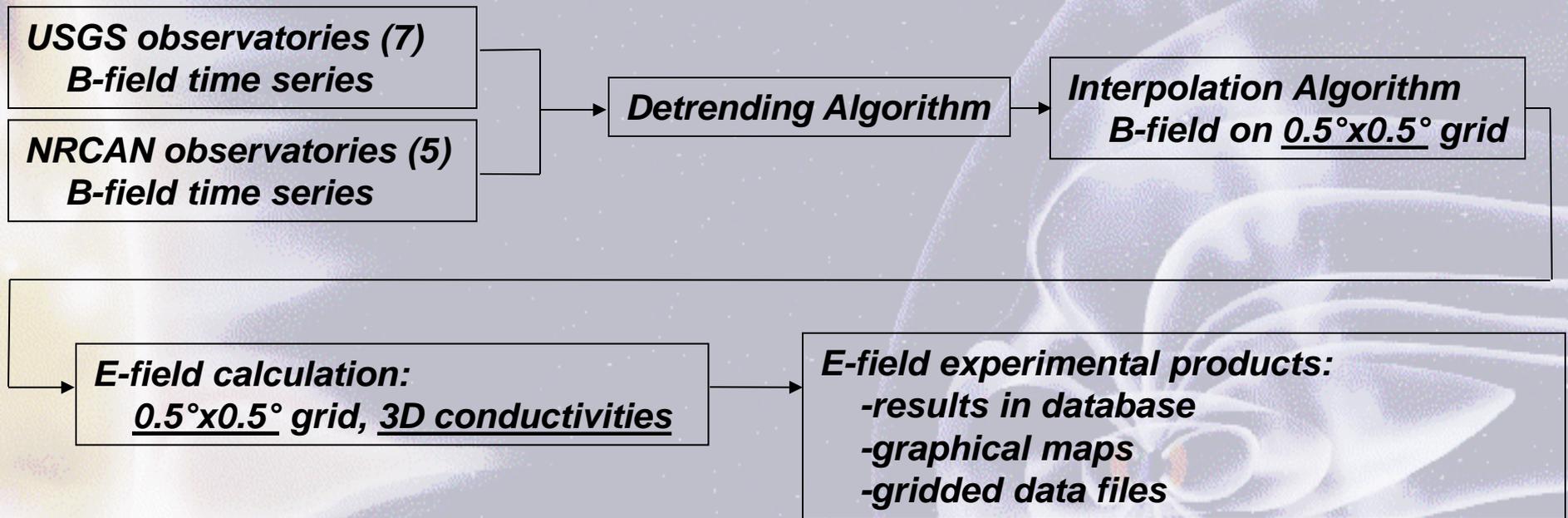
Map Creation Time: 2017-09-08T13:37:44.006UTC

Interpolation method – SECS

1D Physiographic Conductivities

Number of Stations Reporting: 10

E-field maps – near term plan



Near Term Plan for Data Dissemination: GeoJSON

- **About GeoJSON**

- Adheres to a standard (RFC 7946): <https://tools.ietf.org/html/rfc7946>
- Can be read by web and desktop GIS clients
- Can be parsed as json, or by geojson libraries in a variety of languages
- Could be returned by a geospatial data service (e.g. ESRI ArcGIS Online)
- ASCII for human readability, compresses well when served with gzip enabled

- **Sample data available from the September 2017 storm**

- **SWPC will be producing GeoJSON gridded data files soon**

Geoelectric Field Calculation

- **Input – Geomagnetic Field (B-field) time series**
- **Earth conductivity acts like a frequency dependent filter:**
 - **The effect on input amplitude and phase depends on the frequency**
 - **High frequency fields have relatively shallow penetration (top-most layers), lower frequency fields have relatively deeper penetration (lower layers with different conductivity properties)**
- **Methods to determine the filter:**
 - **One-dimensional multi-layer models (conductivity varies with depth) allow the filter to be calculated numerically (but typically with limited accuracy) (EPRI-Fernberg models - 2012)**
 - **A magnetotelluric site survey (measures B-field and E-field together) allows the filter to be constructed empirically which incorporates all the effects of the 3D Earth conductivity (not available in all locations) (Earthscape-based models)**
 - **Earthscape MT data used with ModEM MT inversion code (Kelbert et al 2014) to generate high resolution 3D electrical conductivity model. (Enables interpolation between survey sites and also filters out near surface ‘noise’)**

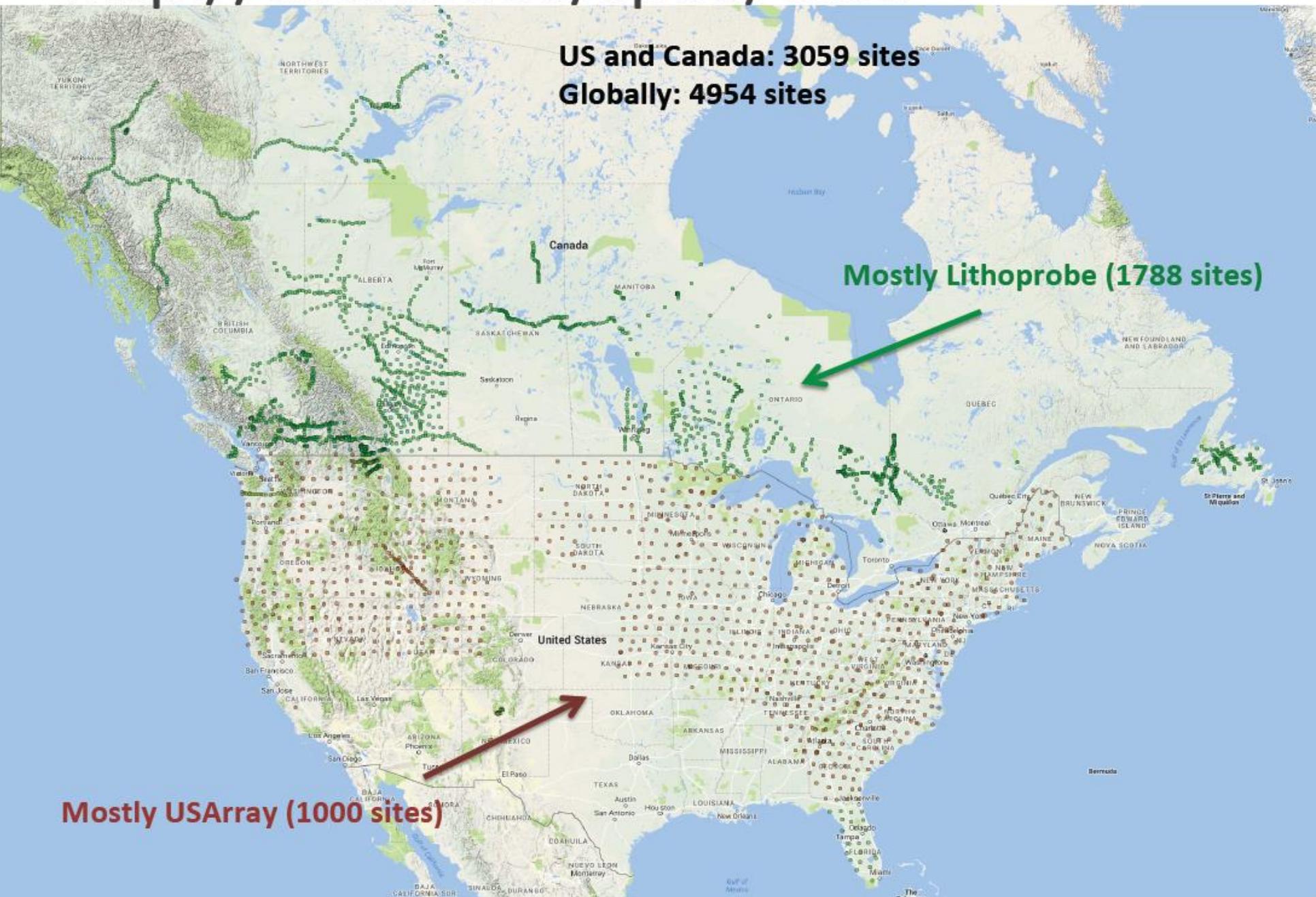


<http://ds.iris.edu/spud/emtf>

US and Canada: 3059 sites
Globally: 4954 sites

Mostly Lithoprobe (1788 sites)

Mostly USArray (1000 sites)



Geoelectric Field Calculation: Frequency Domain

- The Local Magnetotelluric (MT) transfer function relates the horizontal components of the geomagnetic field to the horizontal components of the geoelectric field in frequency domain:

$$\begin{bmatrix} \tilde{E}_x(f_k) \\ \tilde{E}_y(f_k) \end{bmatrix} = \begin{bmatrix} \tilde{Z}_{xx}(f_k) & \tilde{Z}_{xy}(f_k) \\ \tilde{Z}_{yx}(f_k) & \tilde{Z}_{yy}(f_k) \end{bmatrix} \begin{bmatrix} \tilde{B}_x(f_k) \\ \tilde{B}_y(f_k) \end{bmatrix}$$

- The components are complex-valued
- For an idealized, multi-layer one-dimensional conductivity (e.g. Fernberg models), the MT response tensor reduces to a simplified form:

$$\begin{bmatrix} \tilde{E}_x(f_k) \\ \tilde{E}_y(f_k) \end{bmatrix} = \begin{bmatrix} 0 & \tilde{Z}(f_k) \\ -\tilde{Z}(f_k) & 0 \end{bmatrix} \begin{bmatrix} \tilde{B}_x(f_k) \\ \tilde{B}_y(f_k) \end{bmatrix}$$

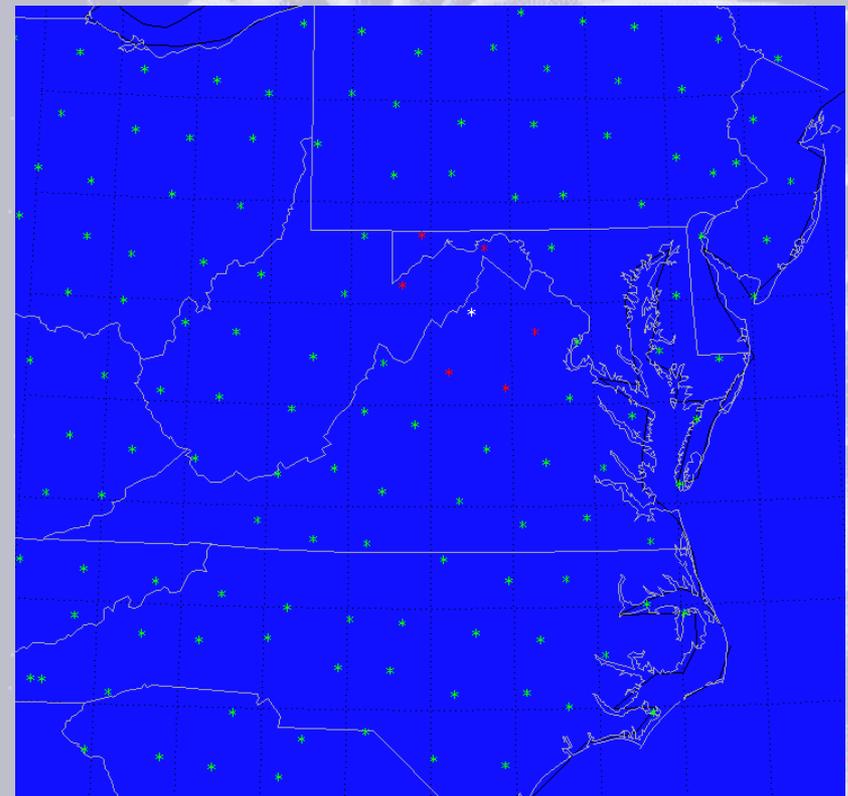
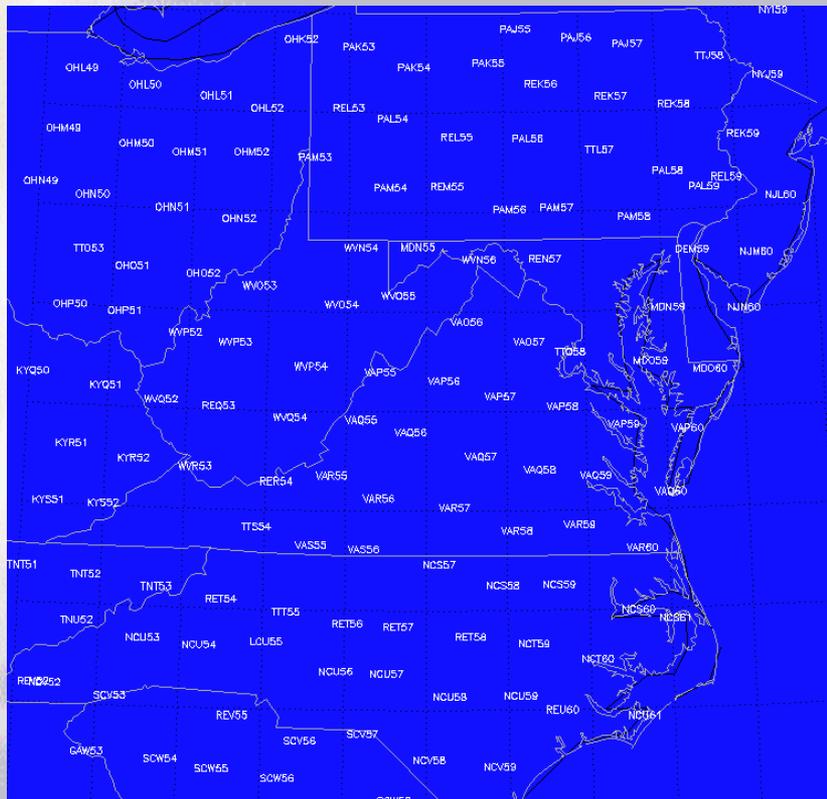
- For a uniform Earth (constant conductivity σ):

$$\tilde{Z}(f_k) = \sqrt{\frac{i\omega}{\mu\sigma}}, \text{ i.e. scales with } \omega^{1/2}$$



How should we use the MT site surveys?

- Surveys are on a nominal (irregular) 70 km grid
- What E-field do we use for the power lines?
- Should the site-based transfer functions be spatially averaged to represent regional (vs local) conductivity?
- The validation efforts will help answer these questions



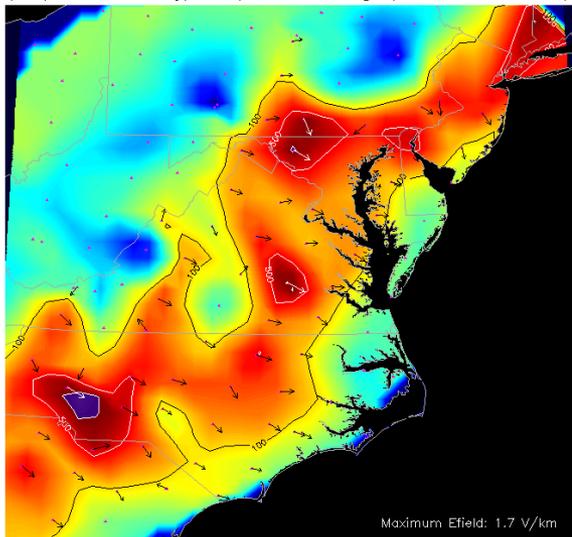
Side by side comparison

Geolectric Field Map Experimental Prototype V2 (East Atlantic Region)

2017/09/08 12:57:00UTC

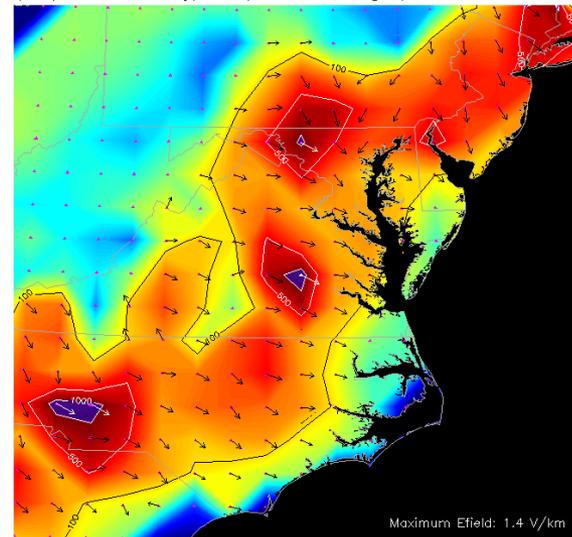
Geolectric Field Map Experimental Prototype V2 (East Atlantic Region)

2017/09/08 12:57:00UTC



Geomagnetic Data provided courtesy of USGS
 This map is an experimental prototype for R&D purposes only
 One-minute averaged values - nominal 70 km grid
 Map Creation Time: 2017-12-07T00:44:05.356UTC

Interpolation method - nearest observatory
 Earthscope Transfer functions (GE3) no smoothing
 Input Magnetometer Data is FRD



Geomagnetic Data provided courtesy of USGS
 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: 2017-12-11T23:48:23.320UTC

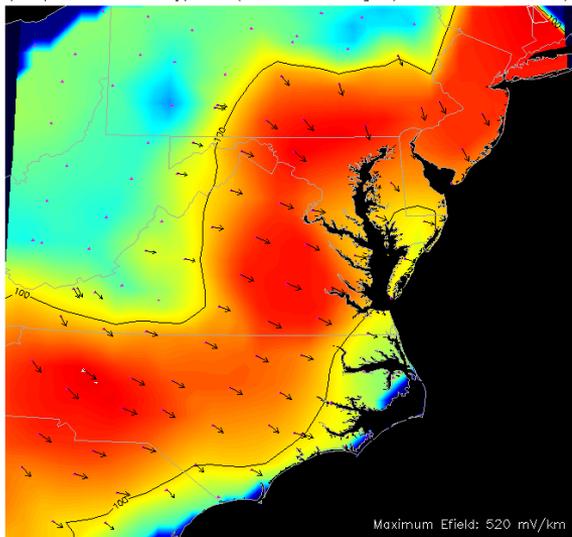
B-field Interpolation method - nearest observatory
 Earthscope Transfer functions no smoothing & interpolated
 Input Magnetometer Data is FRD

Geolectric Field Map Experimental Prototype V2 (East Atlantic Region)

2017/09/08 12:57:00UTC

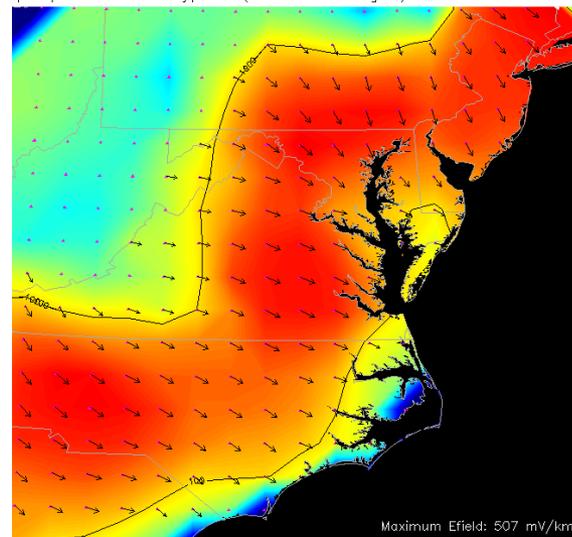
Geolectric Field Map Experimental Prototype V2 (East Atlantic Region)

2017/09/08 12:57:00UTC



Geomagnetic Data provided courtesy of USGS
 This map is an experimental prototype for R&D purposes only
 One-minute averaged values - nominal 70 km grid
 Map Creation Time: 2017-12-07T00:35:16.079UTC

Interpolation method - nearest observatory
 Earthscope Transfer functions (GE3) 100km smoothing
 Input Magnetometer Data is FRD

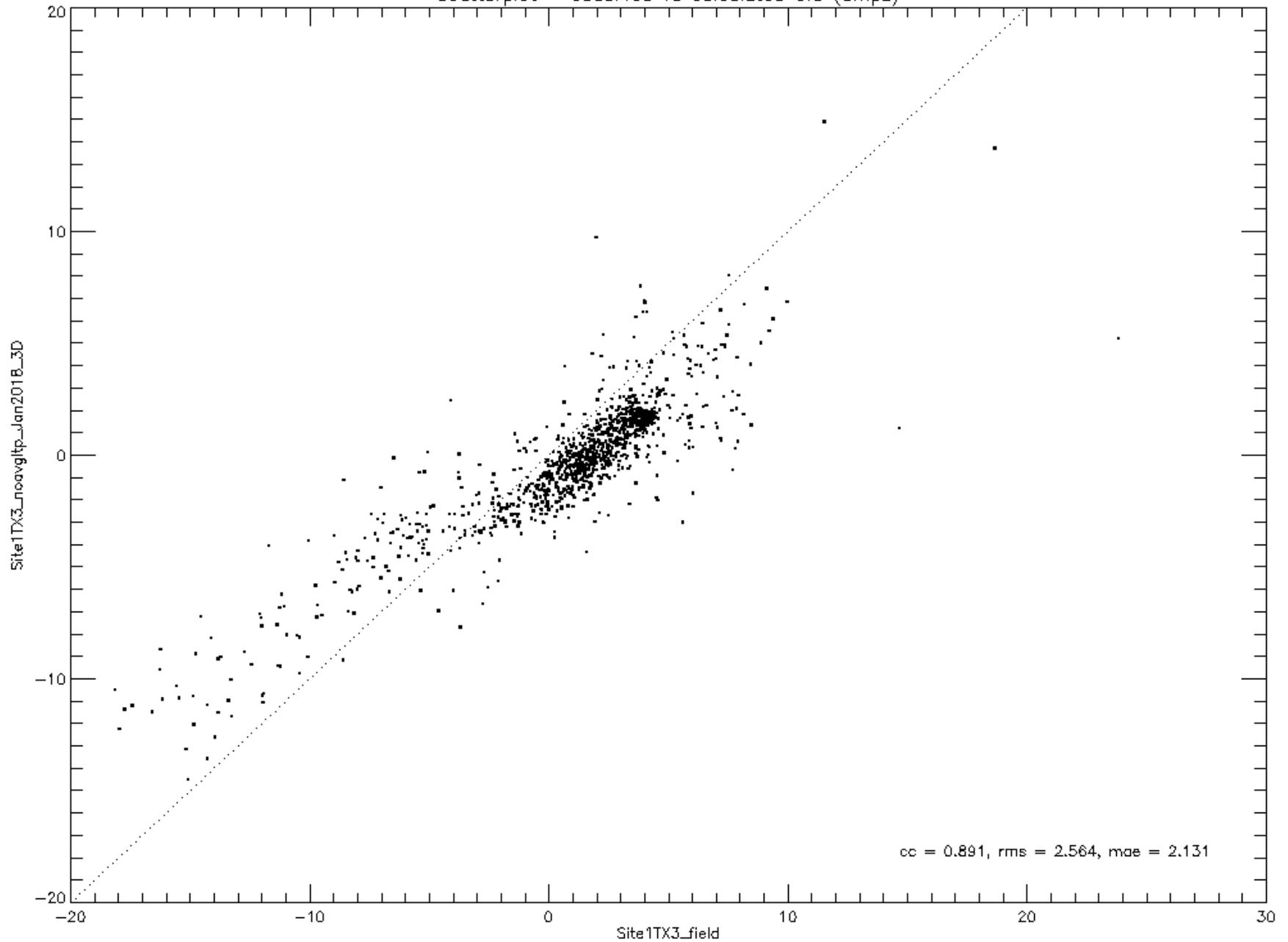


Geomagnetic Data provided courtesy of USGS
 This map is an experimental prototype for R&D purposes only
 One-minute averaged values - 0.5 x 0.5 degree grid
 Map Creation Time: 2017-12-11T20:00:08.230UTC

Interpolation method - nearest observatory
 Earthscope Transfer functions 100km smoothing & interpolated
 Input Magnetometer Data is FRD

Sample validation plot (preliminary)

Scatterplot - observed vs calculated GIC (amps)

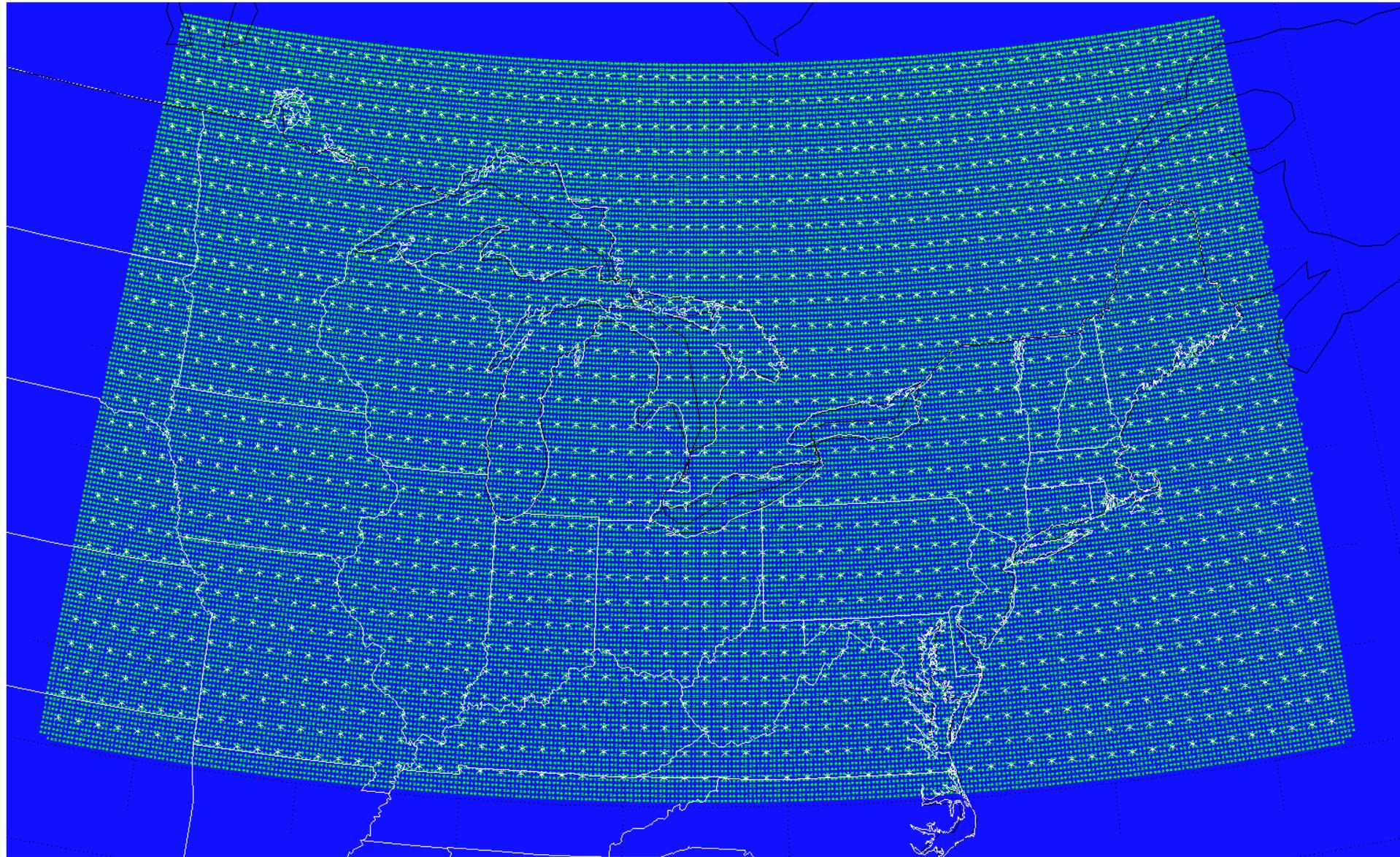


Conductivity Upgrade using inversion models

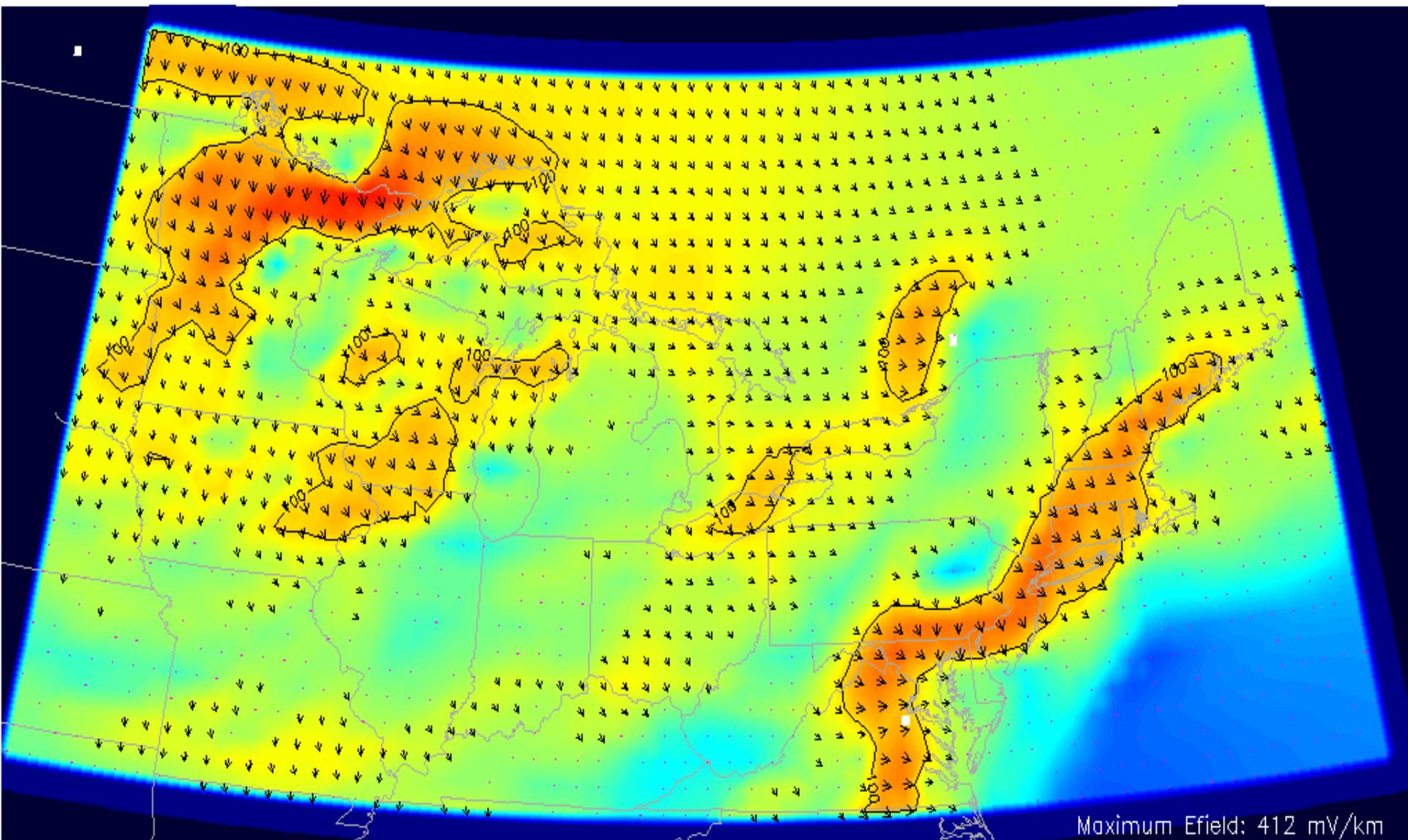
- **3D model(s) constrained by MT survey data (Kelbert et al. – in press - 2018/TBD)**
- **Enables calculation of transfer functions at 0.1 degree resolution**
- **We smooth to 0.5 degree grid with 50 km averaging radius as an initial hypothesis on the appropriate regional scaling for GIC applications**
- **We run E-field calculations using this model for the September 2017 storm**



Sample high resolution grid



**0.1 degree resolution model from MT inversion (USGS)
together with $\frac{1}{2}$ degree grid**



Maximum Efield: 412 mV/km



1 10 100 1000 10000

½ degree grid with 50 km averaging radius – sample E-field calculation

Challenges

- **Observatory delays, drop-outs, varying latency**
 - We could generate maps using a smaller number of observatories, trading accuracy for timeliness
 - Should SWPC generate 'preliminary' maps with incomplete (but more timely data), which are later updated as slower data arrives?
- **Sparseness of the observatory network is a concern**
 - Very important to add more observatories to the network
 - Interpolation model accuracy needs to be determined
- **Ongoing work on spatial averaging of the transfer functions**
- **More end-user participation in validation is needed**

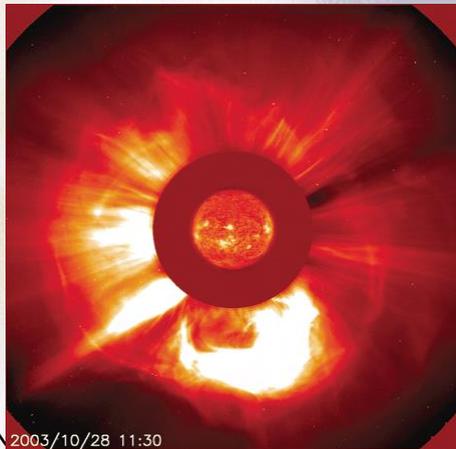


Next Steps

- **Initial upgrade to conductivity using 3D model provided by USGS**
 - This will include an upgrade from 2 degree to $\frac{1}{2}$ degree spatial resolution
- **Ongoing collaboration with industry for validation**
- **Increase cadence from one minute to one second**
- **Investigate summary measure or indicator**
- **Investigate forecast capabilities using Geospace model**



Questions?



2003/10/28 11:30

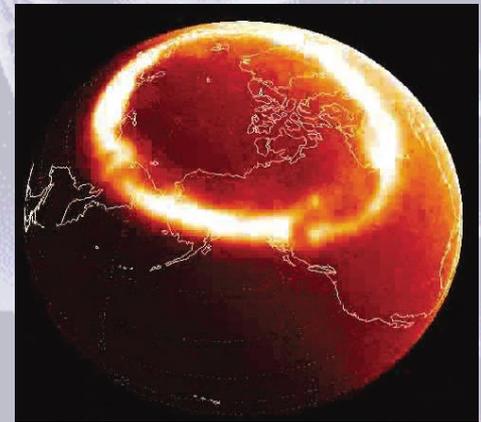
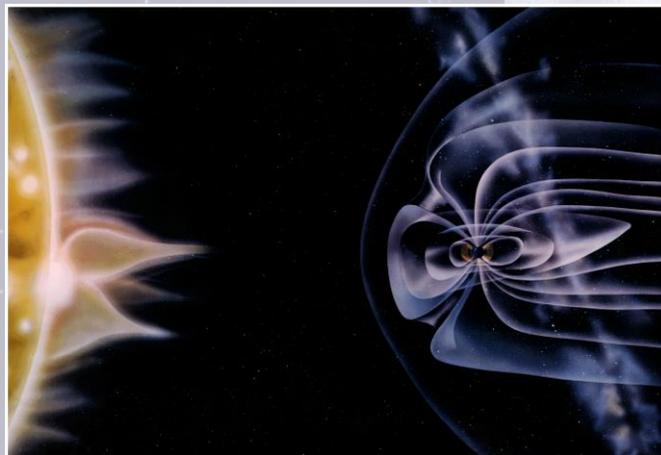
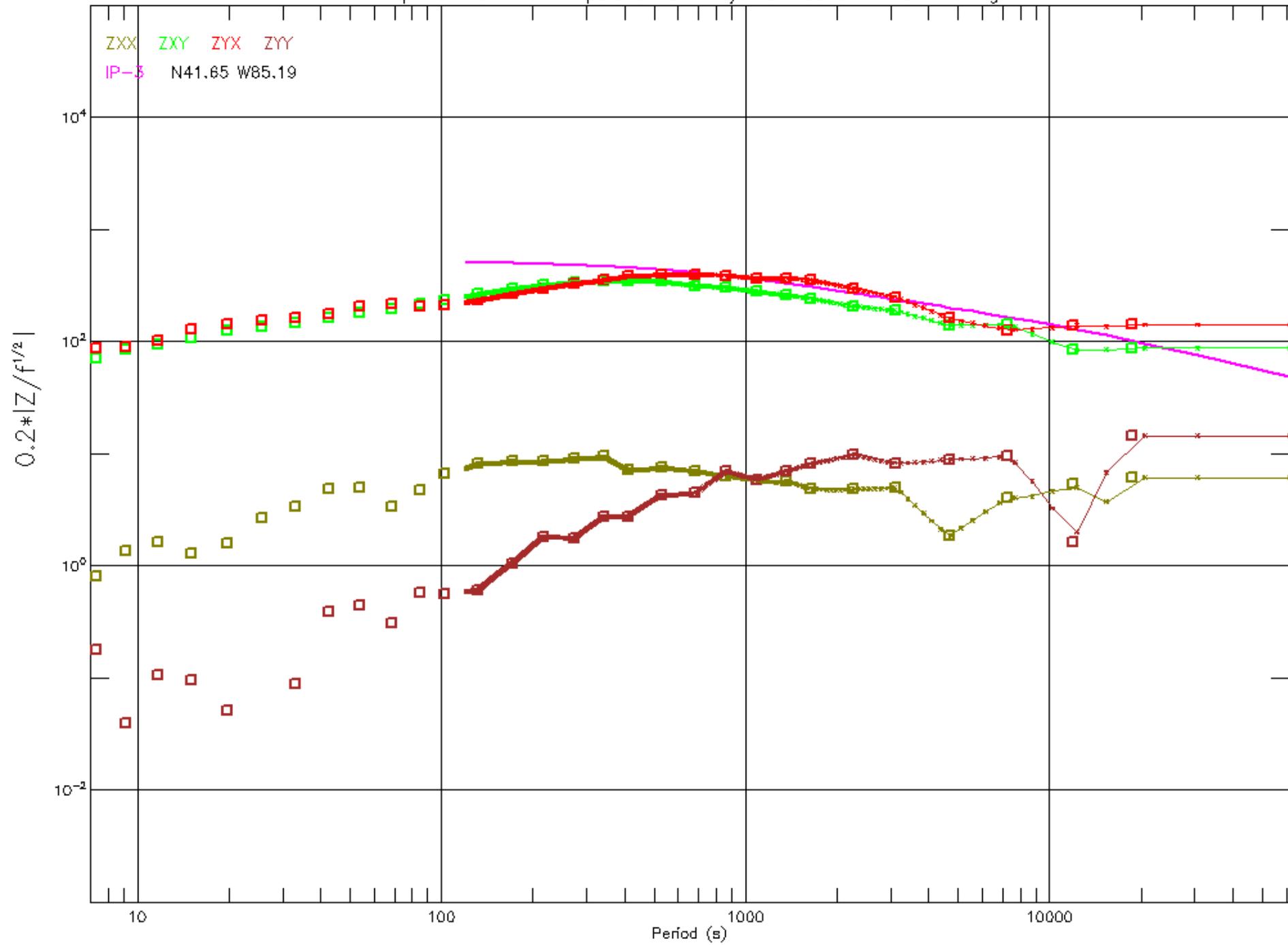
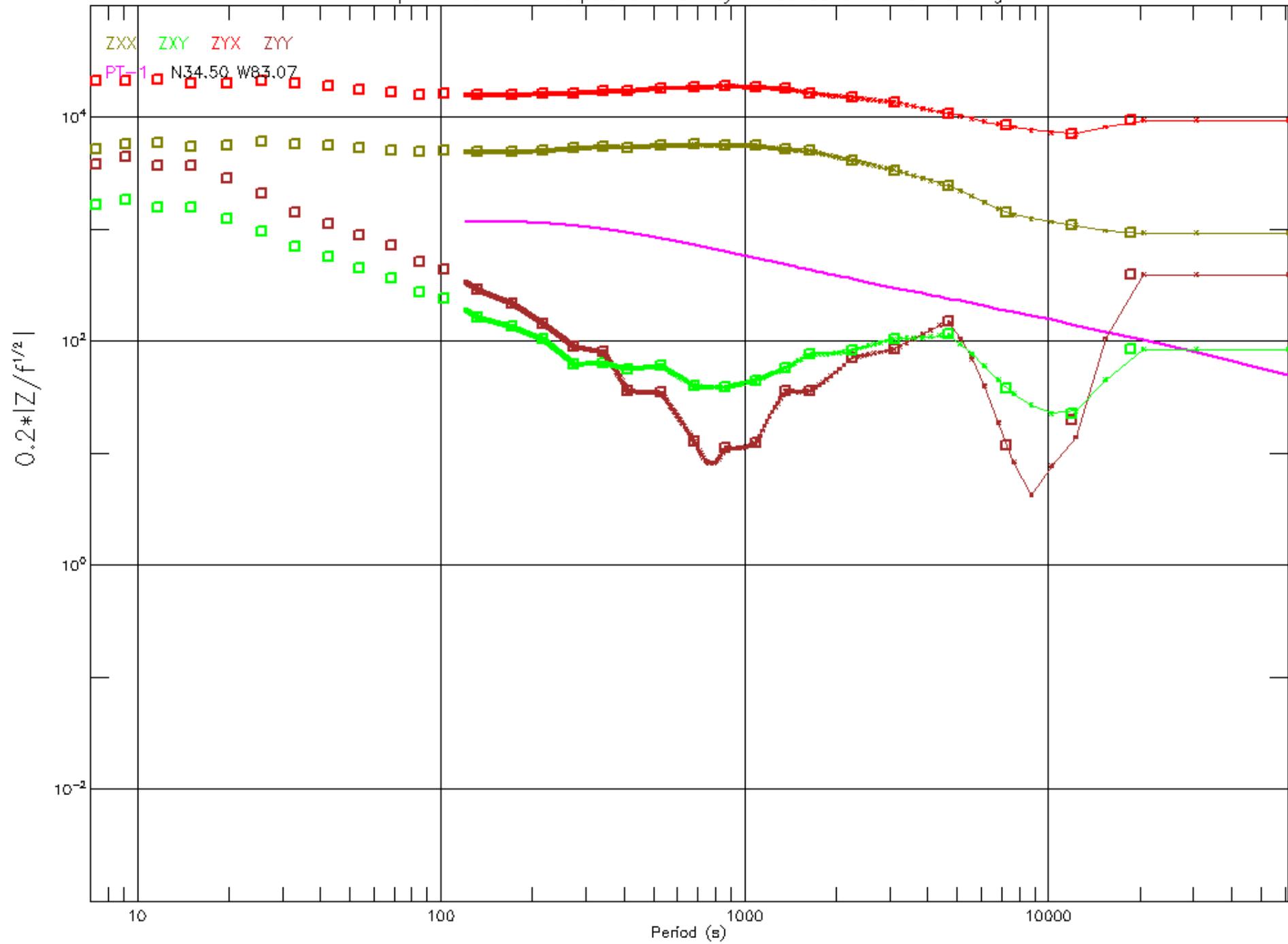


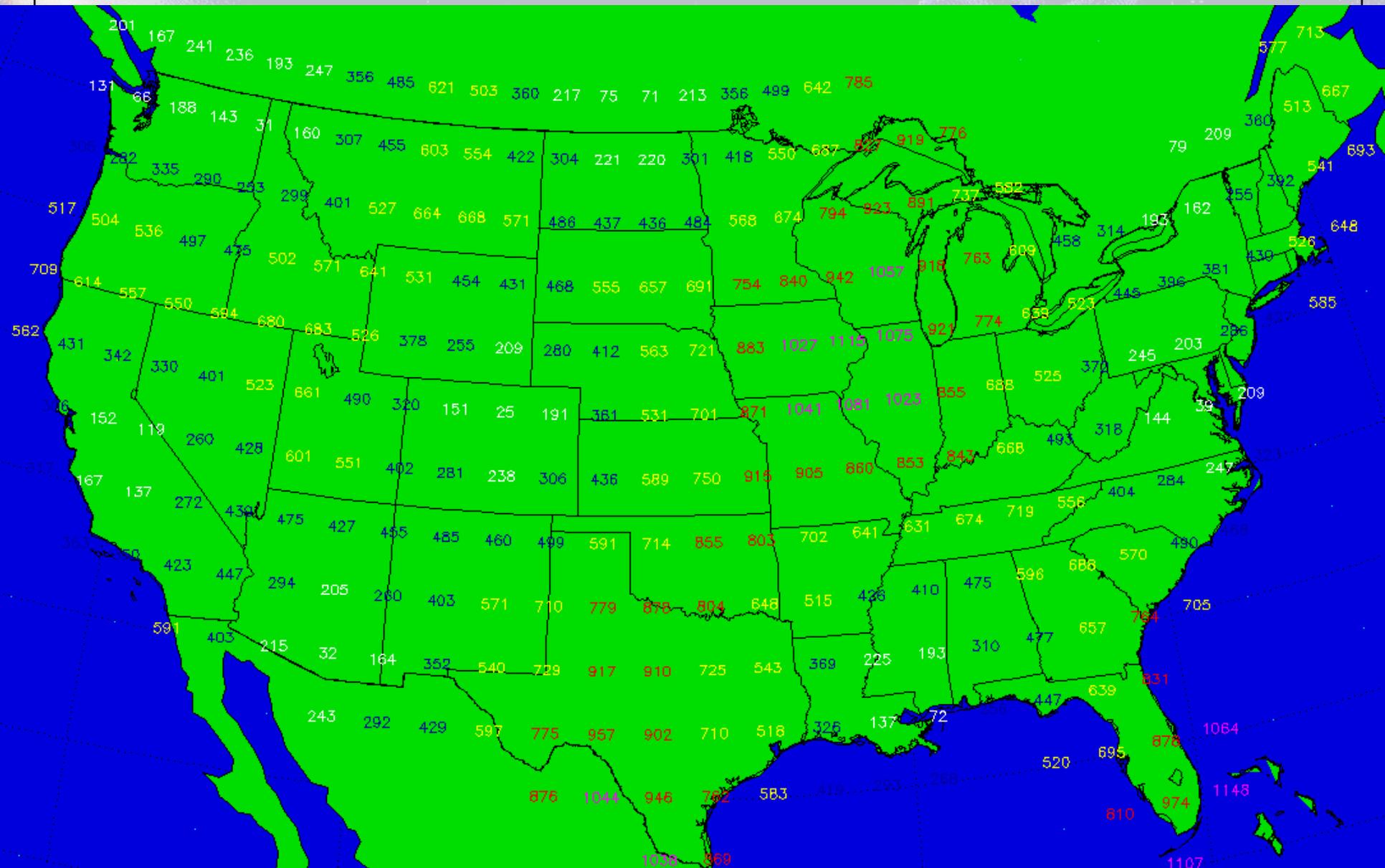
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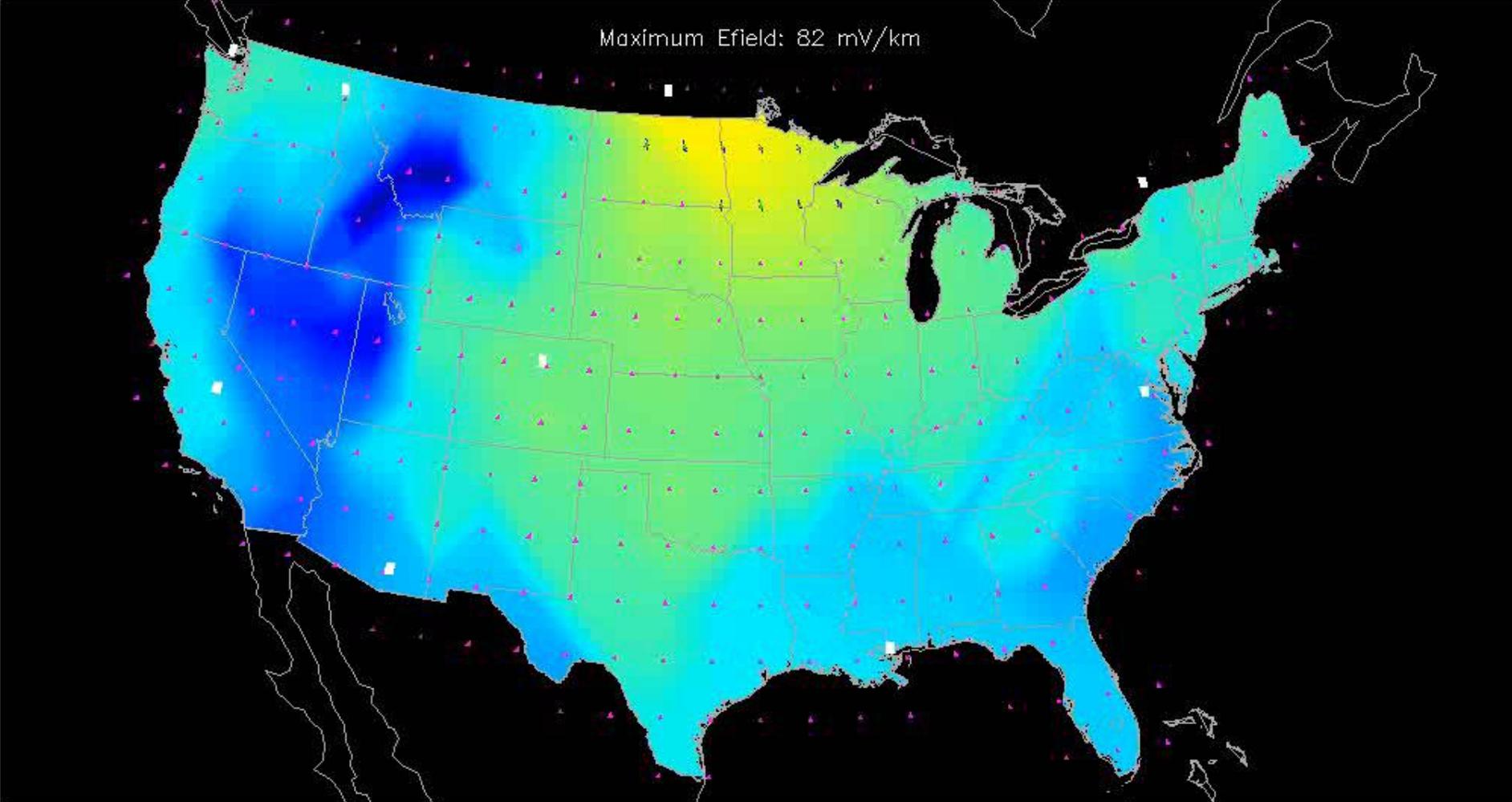






Station Distances (km)



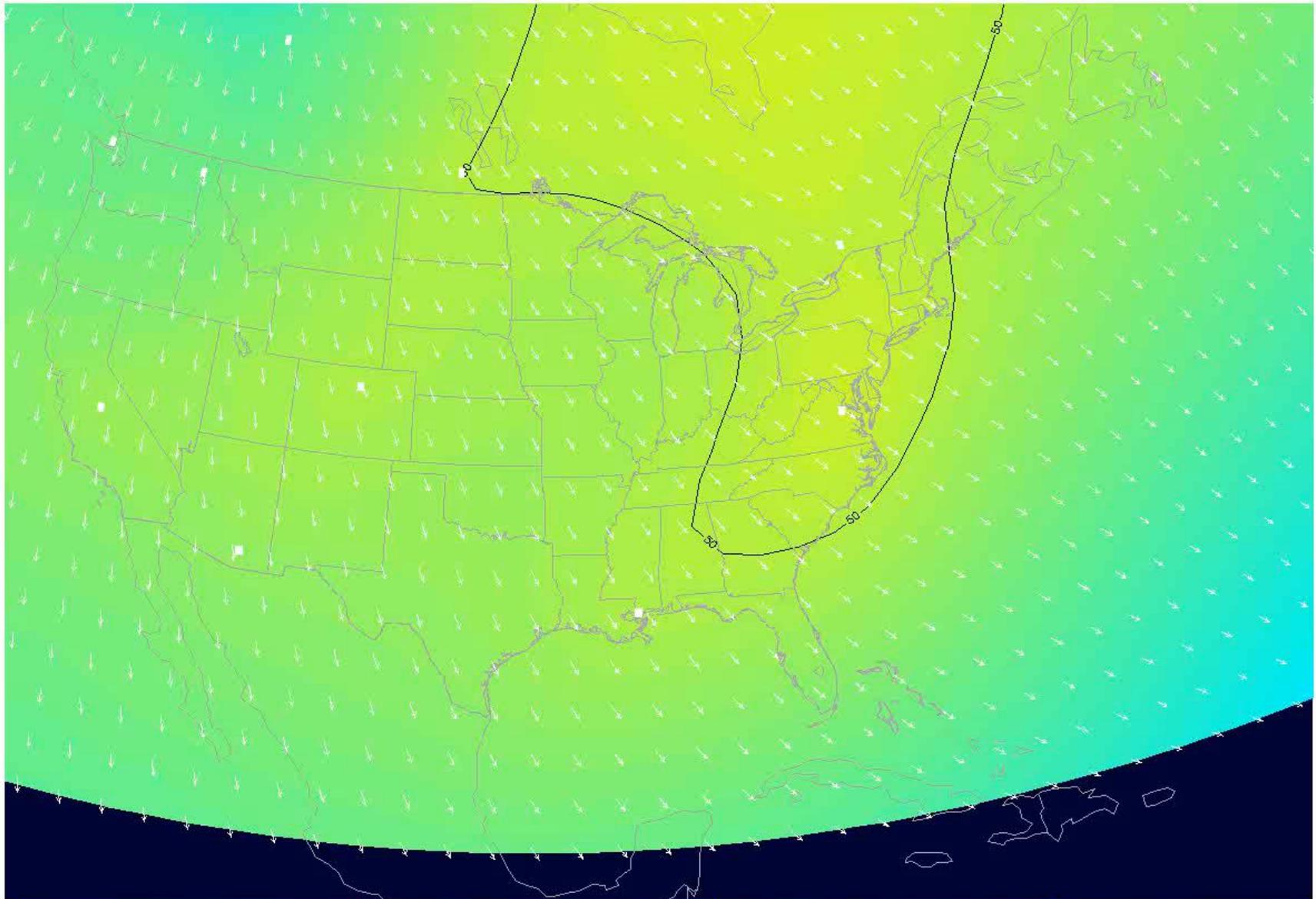


Geomagnetic Data provided courtesy of USGS & NRCAN
 This map is an experimental prototype for R&D purposes only
 One-minute averaged values - 2 x 2 degree grid

Intensity Scale (mV/km)

Map Creation Time: 2017-09-08T13:08:24.243UTC

Interpolation method - SECS
 1D Physiographic Conductivities
 Number of Stations Reporting: 10



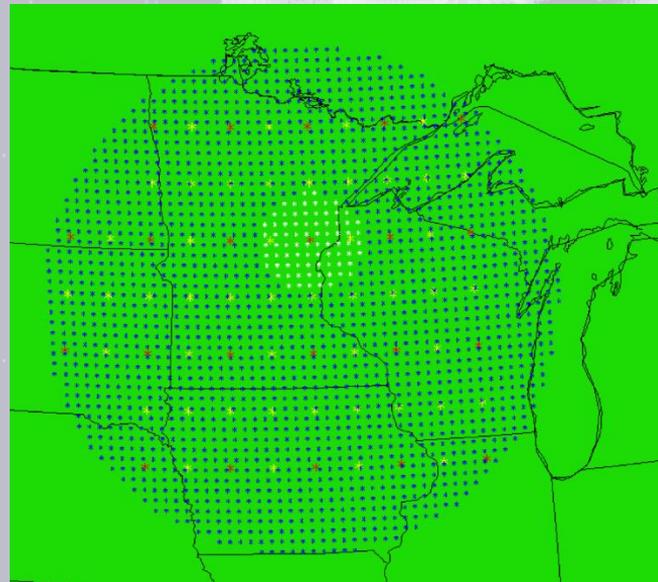
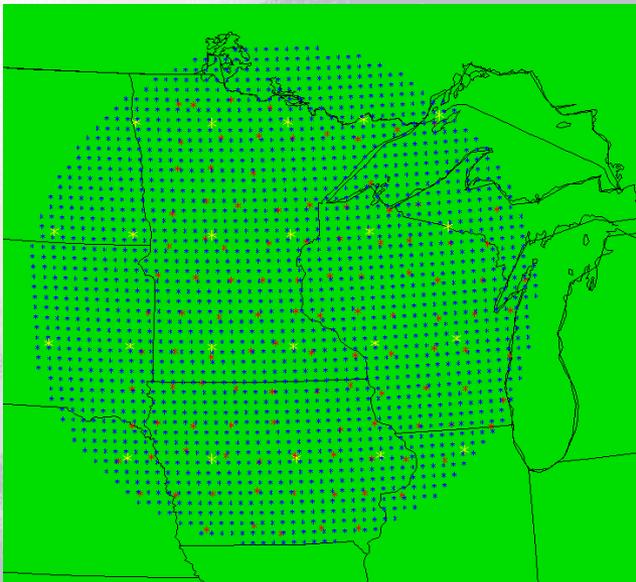
Geomagnetic Data provided courtesy of USGS & NRCAN
This map is an experimental prototype for R&D purposes only
One-minute averaged values - 2 x 2 degree grid

Intensity Scale (nT)

SECS Interpolation
Maximum delta H perturbation: 58 nT
Map Creation Time: 2017/09/08 11:06:24 UTC

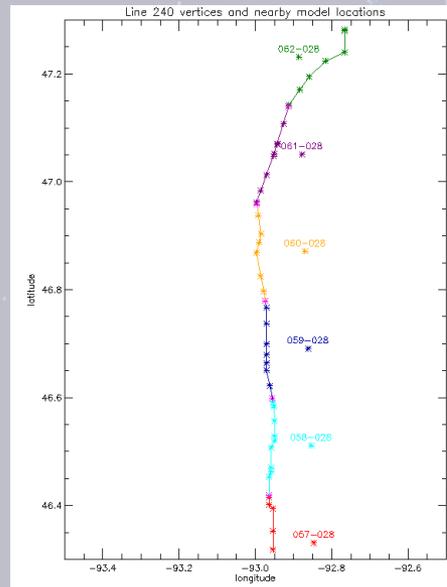
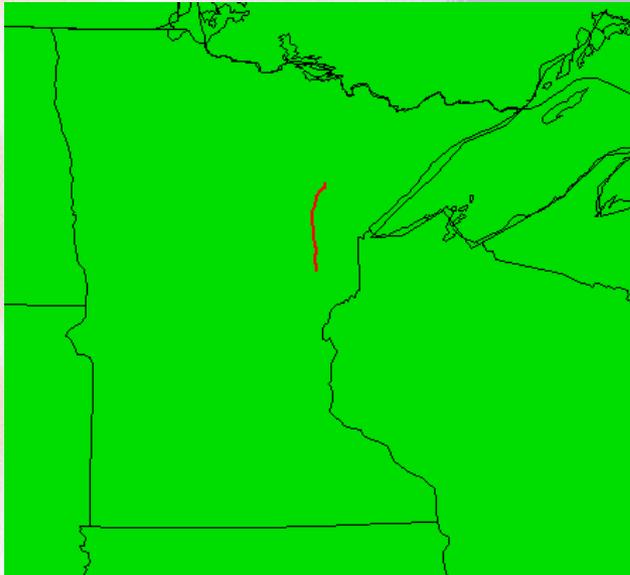
Addressing the Spatial Resolution Question

- A high-resolution 3D electrical conductivity model was obtained from a subset of the EarthScope magnetotelluric (MT) data using ModEM MT inversion code (Kelbert et al, 2014)
- Higher resolution may be achieved with a model than could be obtained by using measured impedances alone
- Modeled 3D impedances were generated for each cell of the high resolution conductivity model (20 km). Here, we focus on an area of 500 km radius around Minneapolis. For lower resolution variants, modeled impedances are averaged over a wider area, as shown



Spatial Resolution Tests

- We expect some of the 3D variability to be averaged out because the calculation of GIC integrates over the length of a power line
- We carry out E-field calculations integrated over an actual transmission line for different spatial resolution conductivity models, using the 20 km x 20 km model as the basis
- We derive two spatially averaged conductivity models:
 - 1 degree x 1 degree with 100 km averaging
 - 1/2 degree x 1/2 degree with 50 km averaging

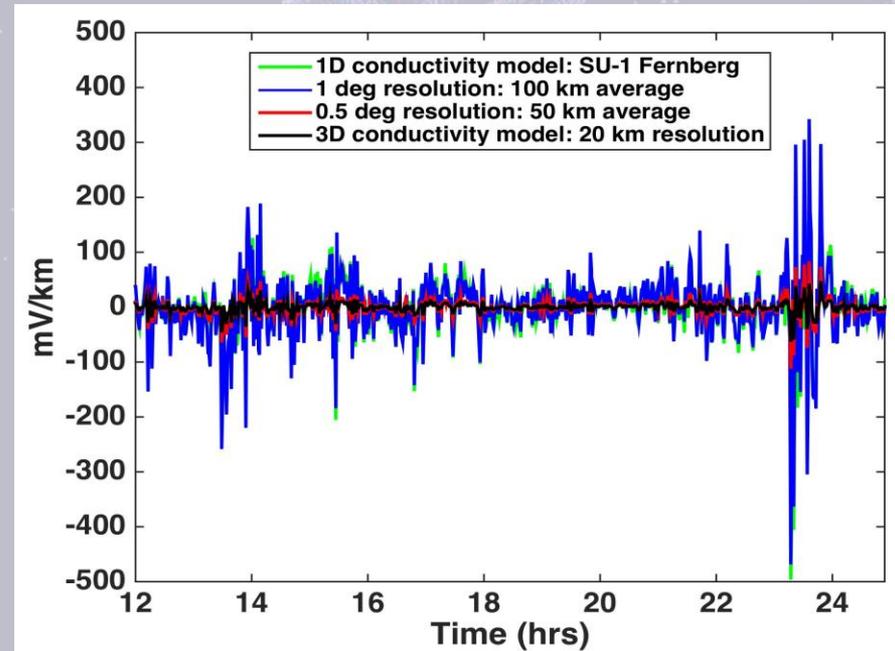


Line-averaged E-field calculation:

$$\bar{\mathbf{E}}(t) = \frac{\oint \mathbf{E}(t) \cdot d\mathbf{l}}{\oint dl} = \frac{\oint E_x(t) dx + E_y(t) dy}{L}$$

Preliminary Results

- The line-averaged E-field calculated using low resolution 3D model is fairly close to that derived using the Fernberg 1D model
- The line-averaged E-field changes significantly, though, when we use the higher resolution model ($\frac{1}{2}$ degree, 50 km)
- This case study suggests that the 3D maps will likely have to be done at $\frac{1}{2}$ degree resolution – but more case studies are in progress to check



Model	Peak-to Peak maxima (mV/km)	
1D low resolution	-500	300
3D 1 degree resolution over 100 km	-480	350
3D $\frac{1}{2}$ degree resolution over 50 km	-115	85
20 km resolution - no averaging	-60	50

Implications

- The increase of resolution from $2^\circ \times 2^\circ$ to $1/2^\circ \times 1/2^\circ$ increases the number of grid points by a factor 16
- Current maps have 283 points so it appears that the 3D maps will have something like 4528 points
- Current cadence is one-minute, but development is far along to use one-second data (one-second data is flowing into SWPC today already) to generate 10 second cadence E-field results
- Model calculations at 10 second cadence implies about 27,168 points per minute
- Important to use a standardized, agreed upon protocol for disseminating the data – are there existing protocols or standards that would be appropriate for us to develop to ?