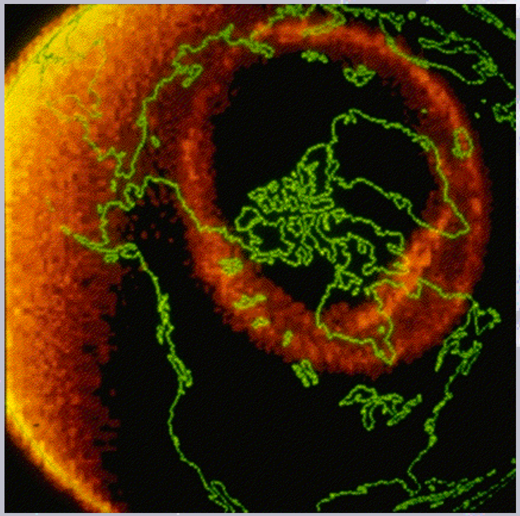
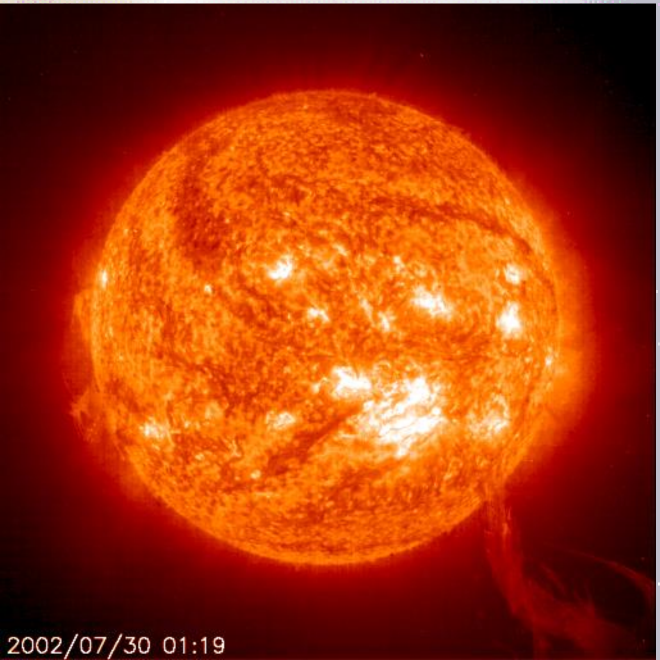
The NOAA/USGS Geoelectric Field Modeling Project: Mitigating the Impacts of Space Weather on the Nation's Electrical Power Grid

Outline

- The Sun-Earth Connection – Space Weather
- Geomagnetically Induced Currents & the Power Grid
- The NOAA/USGS Geoelectric Field Model





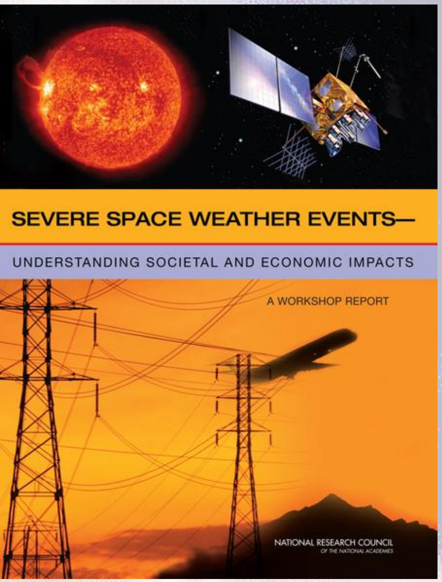
Christopher Balch
NOAA Space Weather Prediction Center

NOAA VLab forum
23 March 2021

Collaborators - Acknowledgements

- The near real-time E-field mapping project is a joint effort between
  - NOAA/SWPC
    - Geospace-geoelectric team: Balch, Singer, Camporeale, Millward, Adamson
    - SWPC development & transition team: Hill, Carpenter, Husler, Dodani, England, Gray
    - SWPC system admin & maintenance team
  - USGS Geomagnetism group (Anna Kelbert, Josh Rigler)
  - NASA/CCMC (Antti Pulkkinen)
  - University of Colorado – LASP (Greg Lucas)
- Technical advice from David Boteler – NRCan – is gratefully acknowledged
- Key data provider agencies are gratefully acknowledged:
  - U.S. observatories operated and maintained by USGS
  - Near U.S. observatories operated and maintained by NRCAN
- Magnetic field time-series interpolation algorithm developed and made available courtesy of the Finnish Meteorological Institute
  - Spherical Elementary Currents (SECS)
  - Amm & Viljanen, 1999; Pulkkien et al., 2003
- Results from NSF's Earthscope USArray project are being used as the source for improved Earth-conductivity specification

Space Weather & the Power Grid

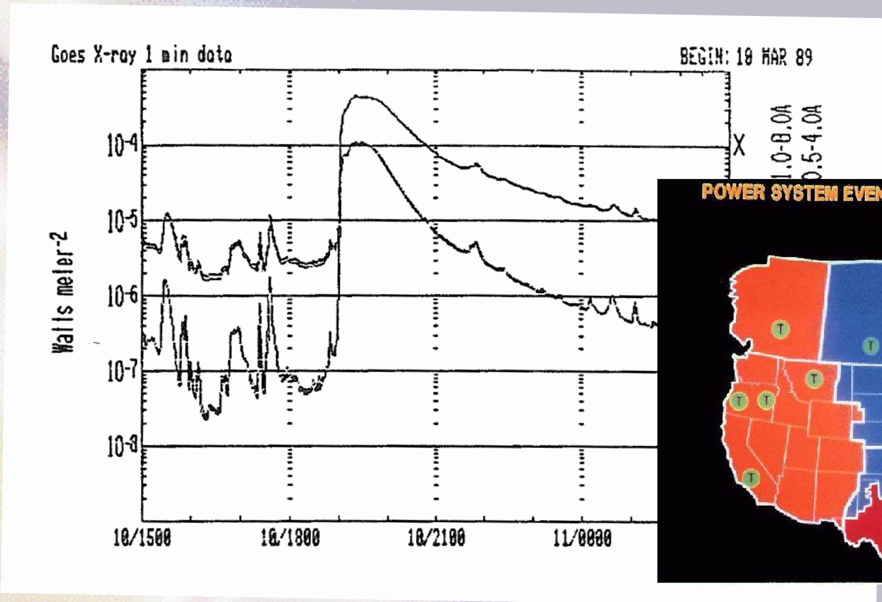


- ***A severe space weather event will impact the electrical power grid***
- ***Reliable electrical power is a prime example of 'critical infrastructure'***
- ***Known impacts from March 13, 1989***
    - *9 hour power outage in Hydro-Quebec*
    - *Transformer failure in PSE&G system*
    - *Widespread operating anomalies (211 documented)**
- ***What happens when the next severe storm hits?***

- ***Developing understanding of the physical processes is interdisciplinary***
- ***Many research, modeling, and observational projects derive inspiration from the societal impact of this issue***

**See NERC March 13, 1989 Geomagnetic Disturbance Report (1990)*

March 13, 1989 – Wake Up Call



HYDRO-QUEBEC PRESS RELEASE

Direction Relations Publiques
HYDRO-QUEBEC
MONTREAL, CANADA

MARCH 13 BLACKOUT CAUSED BY AN EXCEPTIONALLY STRONG MAGNETIC STORM

Montreal, March 15, 1989 - Hydro-Quebec confirms that the March 13 blackout was caused by the strongest magnetic storm ever recorded since the 735-kv power system was commissioned. At 2:45 AM the storm, which resulted from a solar flare, tripped five lines from James Bay and caused a generation loss of 9,450 MW. With a load of some 21,350 MW at that moment, the system was unable to withstand this sudden loss and collapsed within seconds, thereby causing the further loss of generation from Churchill Falls and Manio-Outardes.

Magnetic storms affect power system behavior, mainly in that they cause transformer saturation, which in turn reduces or distorts voltage. Hydro-Quebec's long lines and static compensators make the system particularly sensitive to such natural phenomena. For example, analyzing the events that caused the March 13 blackout, the utility's experts noted a coincidence between the exceptional intensity of the magnetic storm and the ... Chibougamau and La Verendrye

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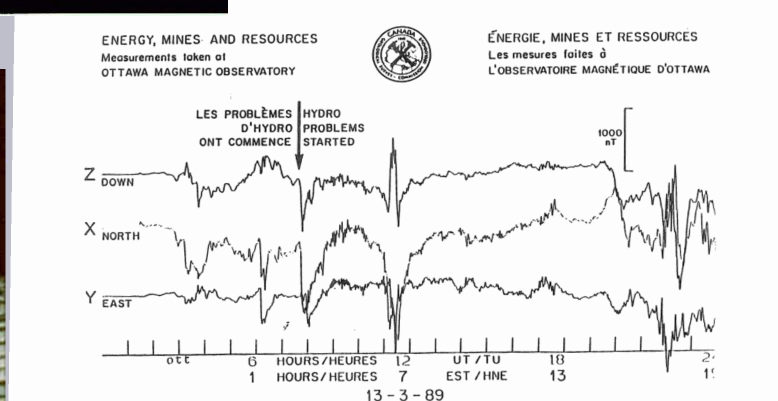
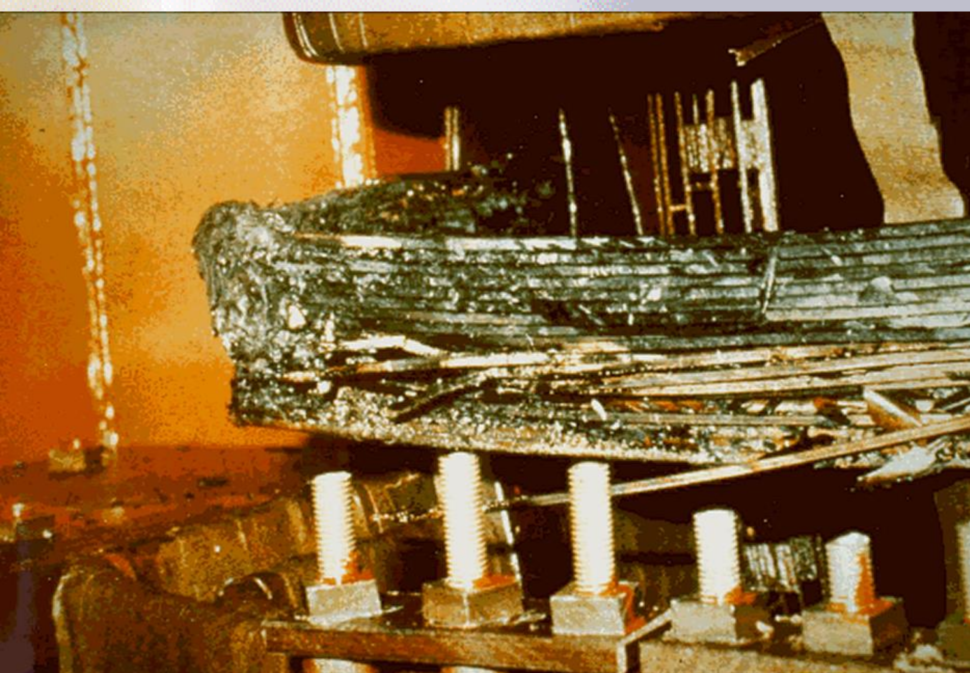




NATIONAL

THE GLOBE AND MAIL, TUESDAY, MARCH 14, 1989 A11

Quebec blackout prompts review of utility

BY ANDRE PICARD
and BENOIT AUBIN
The Globe and Mail

The Quebec government has tightened its control over Hydro-Quebec following a massive power failure yesterday, the third in less than a year, Premier Robert Bourassa revealed yesterday.

He said he has ordered the utility to produce a monthly progress report on the $2-billion upgrading of the transmission system scheduled to be completed by 1995. He also wants Hydro-Quebec to find ways to complete the improvements sooner.

Mr. Bourassa also said Hydro-Quebec is going through a difficult period that started several months ...

York states are suffering.

Yves Tanguay, a spokesman for Hydro-Quebec, said five major lines from the James Bay project exploded into flames at 2:45 a.m. yesterday because of wild power surges. The Churchill Falls and Manicouagan hydro-electric projects could not handle the extra demand, and shut down from the overload, causing power lines feeding substations around the province to "crash like a house of cards."

In addition, two transformers blew in Chibougamou, and lines outside Sherbrooke failed, cutting exports to the New England states.

By 8 a.m., power was restored to about half the households in Que...

He said the Crown corporation would spend $704-million over seven years to improve local power distribution systems and another $1.3-billion by 1994 to improve power transmission from northern dams.

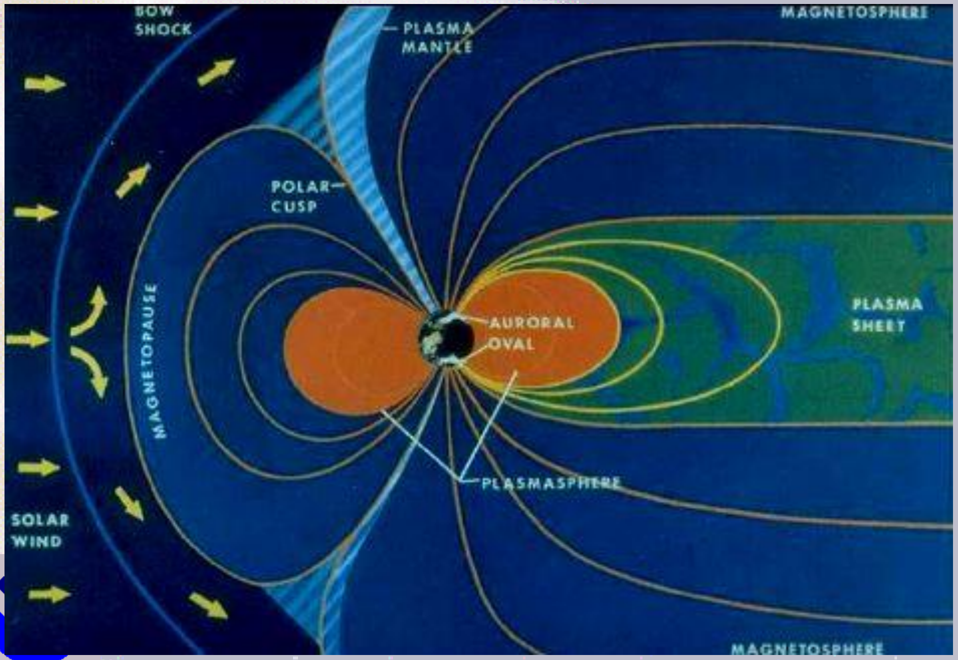
The government granted Hydro-Quebec a 4.5 per cent rate increase, less than the 5.7 per cent requested by the company.

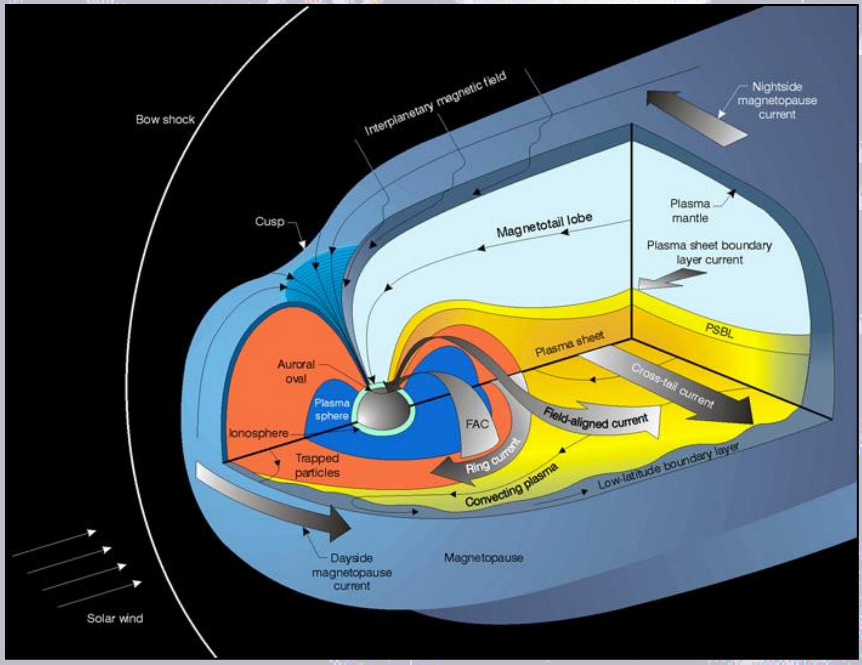
The same solar magnetic activity that is producing the brilliant aurora borealis in Northern Canada is causing perturbations in the Earth's magnetic field. This phenomenon is known to cause surges in power lines, but none so damaging as that which caused yesterday's power outage in Quebec.

Louis Champagne, president of the Union of Professional Engineers of Hydro-Quebec, said the blackout was caused by a lack of investment in equipment and employees, not natural causes.

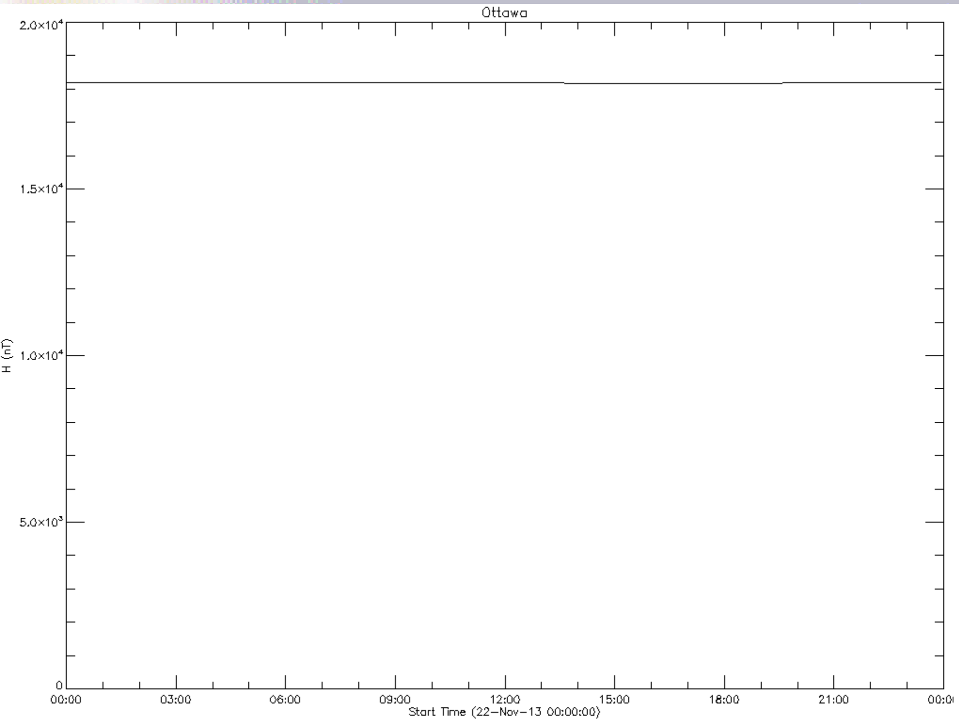
What Happened?

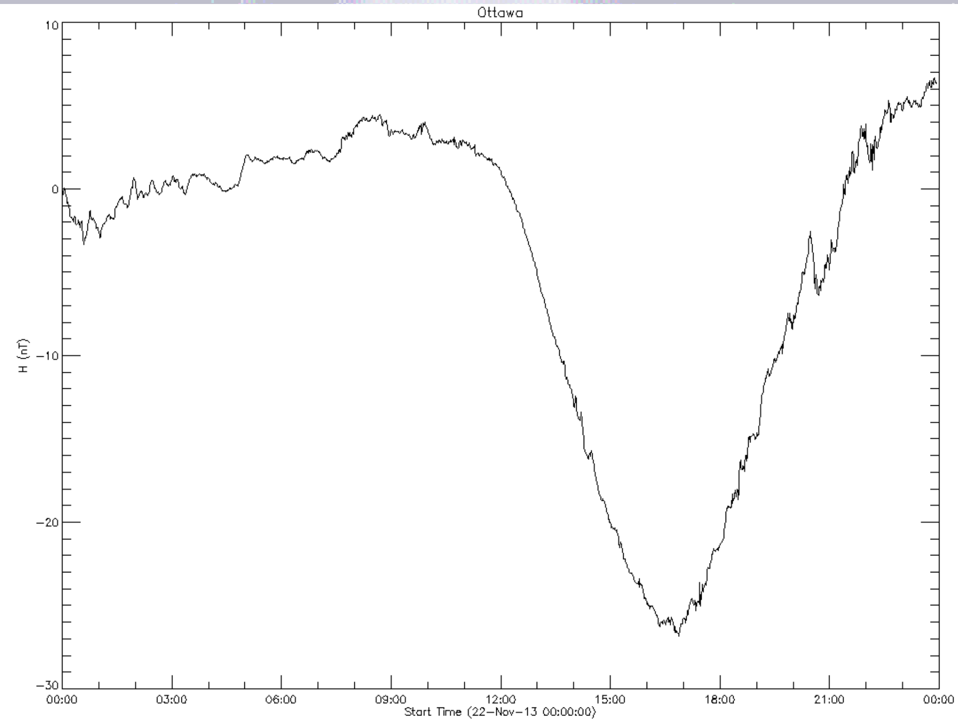
- Geomagnetic Storms
- Earth has a natural magnetic field
- Processes in space near Earth produce magnetic variations which are superposed on the background field





A Quiet Day



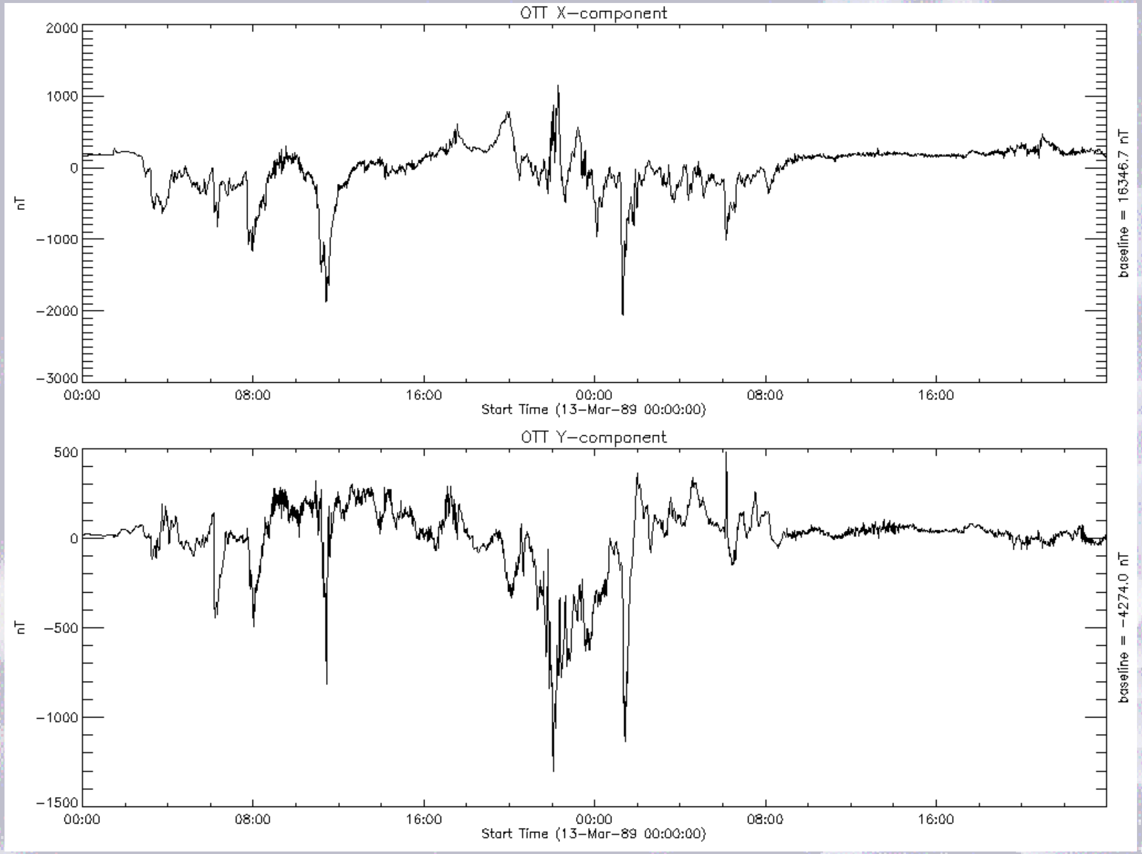


Total Horizontal Field ~18,188 nT

Quiet fluctuations about the mean ~25 nT (about 0.1%)

Even on a quiet day there are small daily fluctuations of the geomagnetic field

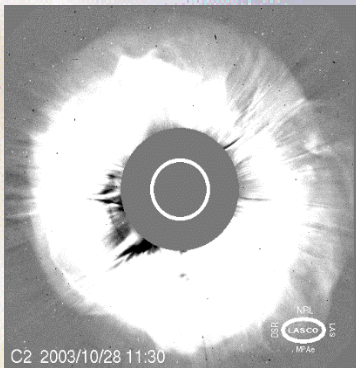
March 13, 1989



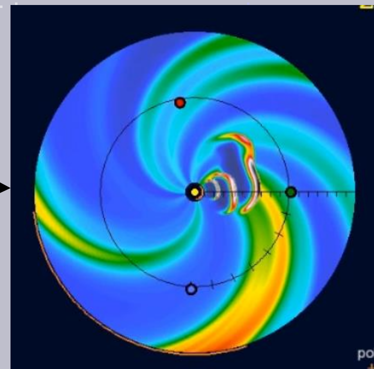
Storm fluctuations ~2000 nT (~10%)

Disturbances from the Sun travel through space and cause geomagnetic storms!

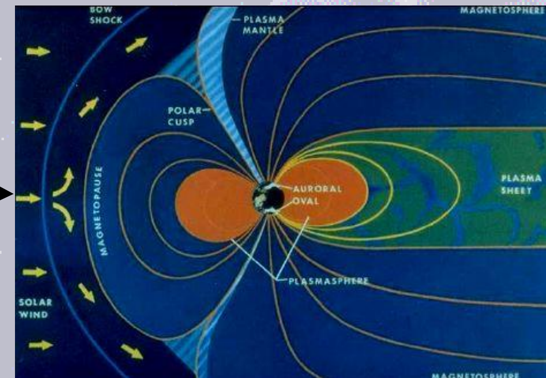
Cause & Effect - Sun to Mantle - I



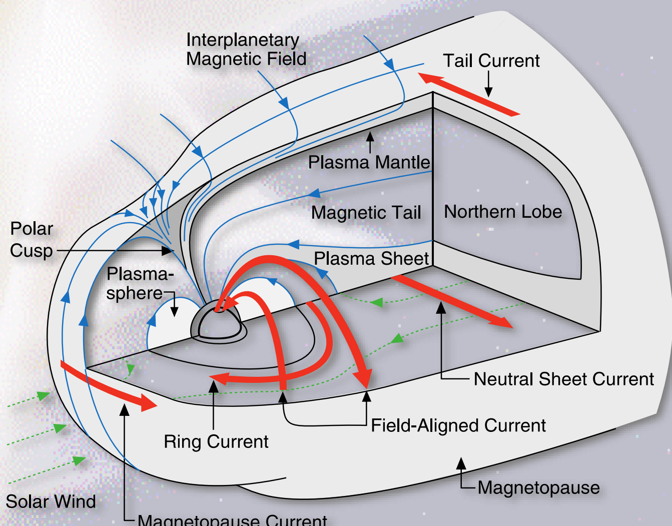
SOHO C2 data courtesy of the NASA/ESA



Output from WSA-Enlil-Cone model for series of three CME's observed in August 2011



Conceptual model for solar-wind-magnetosphere interaction



Conceptual model of the Magnetosphere. (Source - C Russell, IEEE Trans. on Plasma Science, 2000).

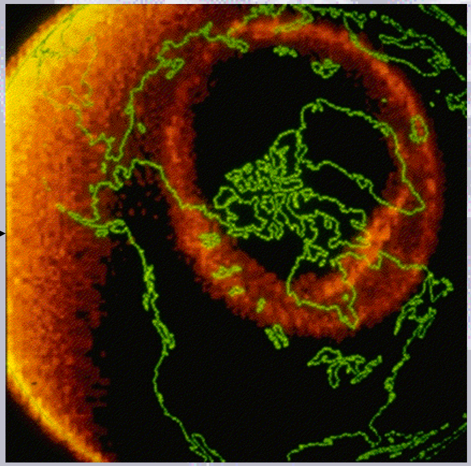
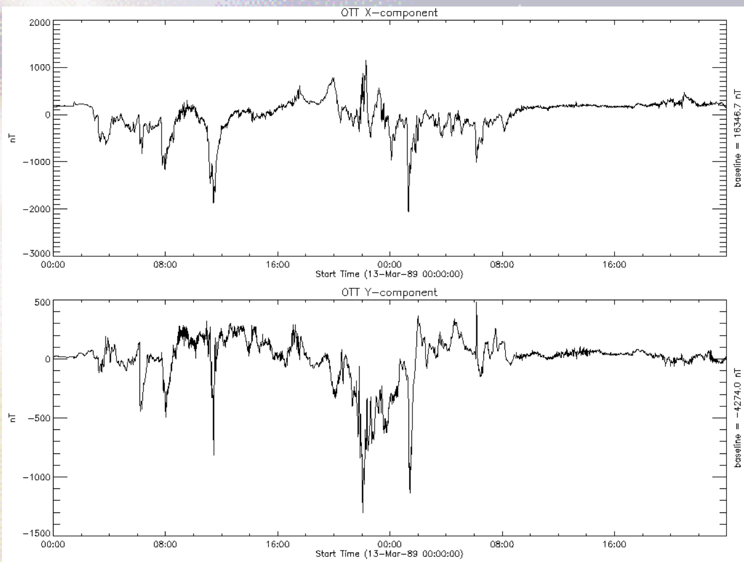


Image of the auroral oval from the Dynamics Explorer 1 Satellite (Louis Frank)

Cause & Effect - Sun to Mantle - II



Input: Geomagnetic Field Time Series

March 13-14, 1989 Geomagnetic storm observed at Ottawa (NRCAN)

$$\rightarrow \begin{bmatrix} \tilde{Z}_{xx}(f_k) & \tilde{Z}_{xy}(f_k) \\ \tilde{Z}_{yx}(f_k) & \tilde{Z}_{yy}(f_k) \end{bmatrix} \rightarrow$$

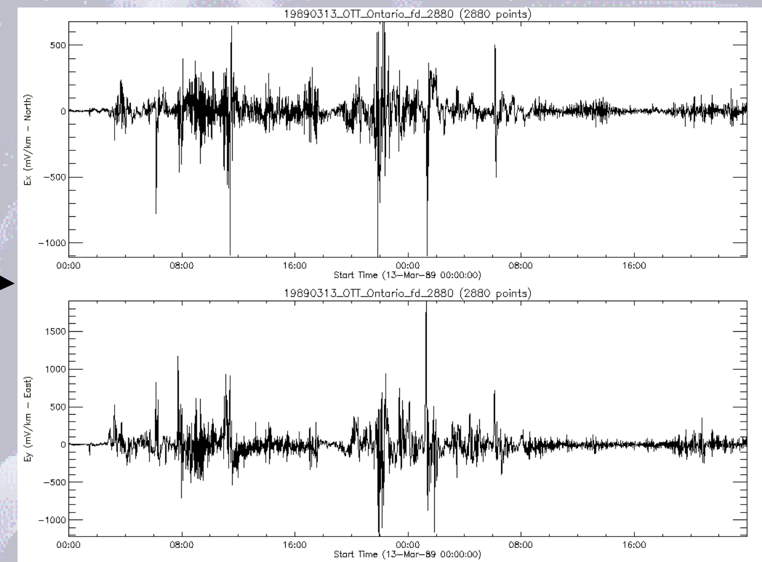
Earth Conductivity:

-frequency dependent filter

-varies with location

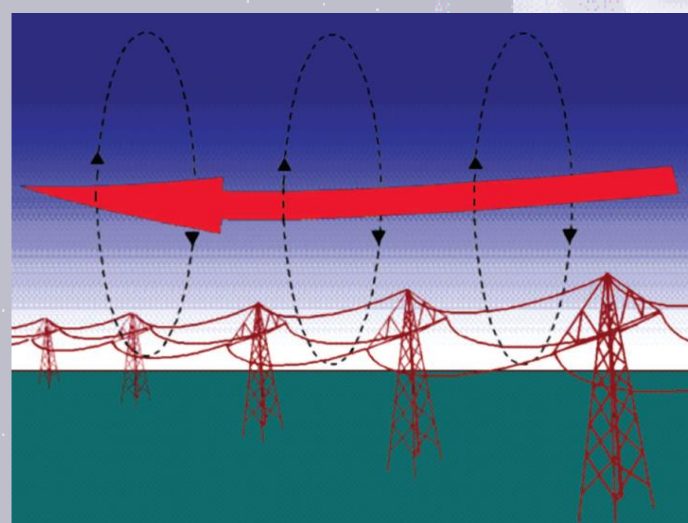
-depends on structure

<u>below the mud</u>



Output: Geoelectric Field Time Series

Calculated Geoelectric Field with a simple conductivity model



Time varying currents in space induce currents in the Earth and in artificial conductors at the surface - Boteler (2015)

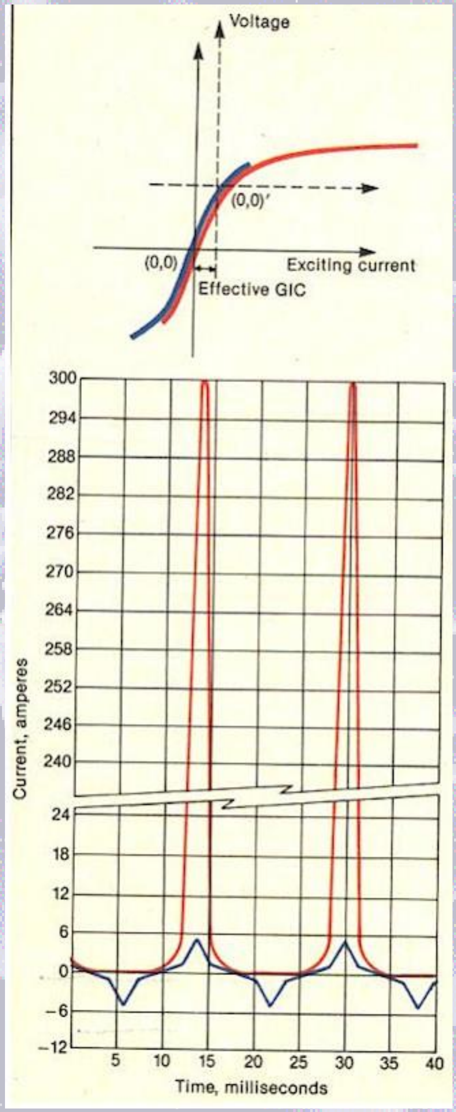
The induced electric field drives current in conductors on and below the surface of the Earth

GIC and the Power Grid

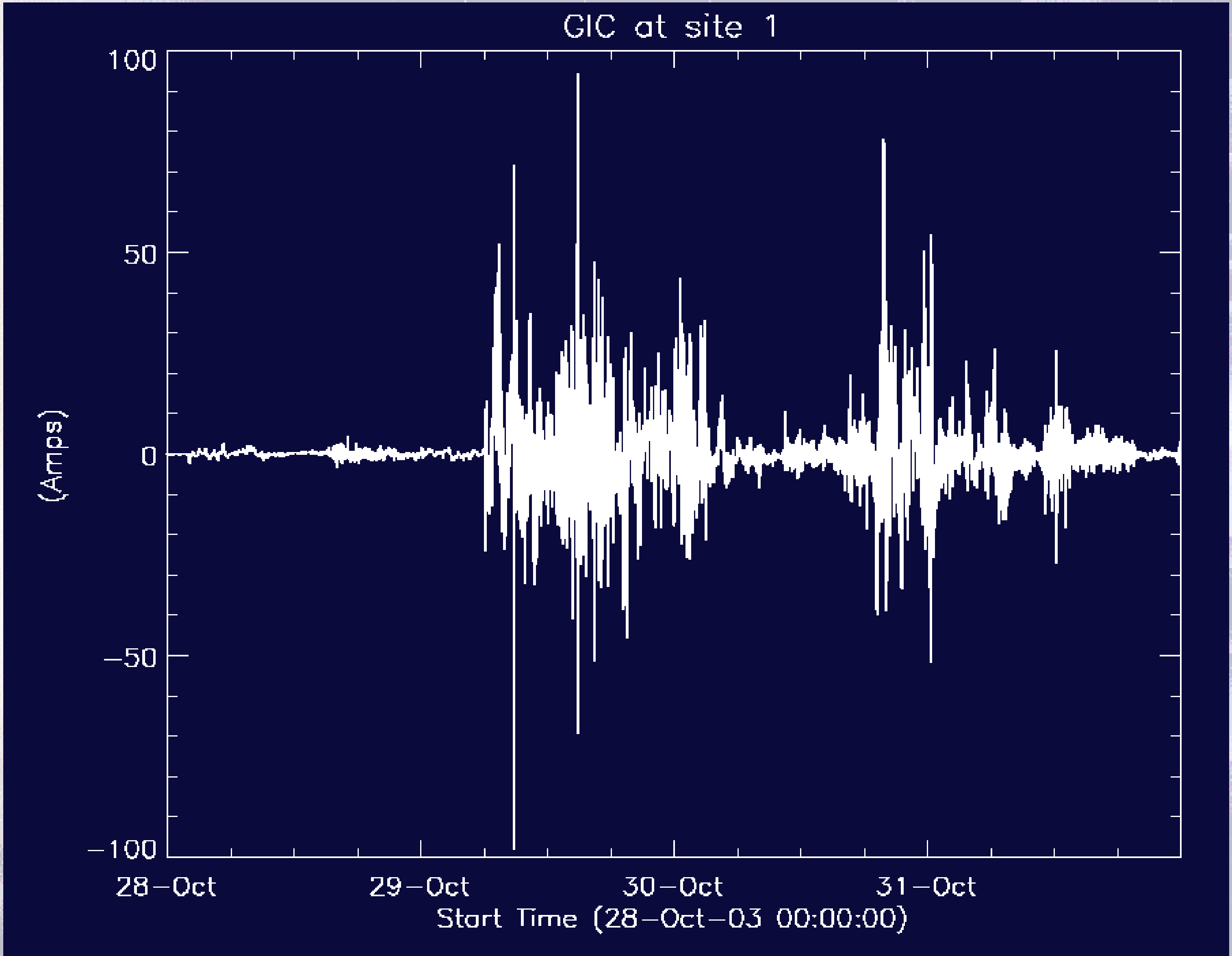
- Geomagnetically induced electric current flows along natural and artificial conductors
- Currents flow to and from ground through windings of power transformers
- ½ cycle saturation in transformers is the root of the problem
  - Transformer exciting current exceeds normal levels
  - Magnetic material saturates
  - Loss of back EMF with high voltage leads to excess currents, stray magnetic flux, abnormal heating from eddy current
  - Transformer adds a large inductive-reactive load to the system, requiring high levels of capacitive reactive loading to maintain system stability
  - Saturating transformers add significant harmonics to currents and voltages, often causing equipment to trip

Half-Cycle Saturation

- **Results from GIC test**
  (Kappenman & Albertson ,1990)
- **Blue curve – normal exciting current**
- **Red curve – exciting current with 75 Amps of DC current introduced in the neutral**
- **Blue curve peaks ~ 5 Amps**
- **Red curve peaks ~300 Amps**
- **Highly distorted waveform with even & odd harmonics**
- **High inductive reactive loss: e.g. 50 MVARs vs ~ 1 MVAR normally**

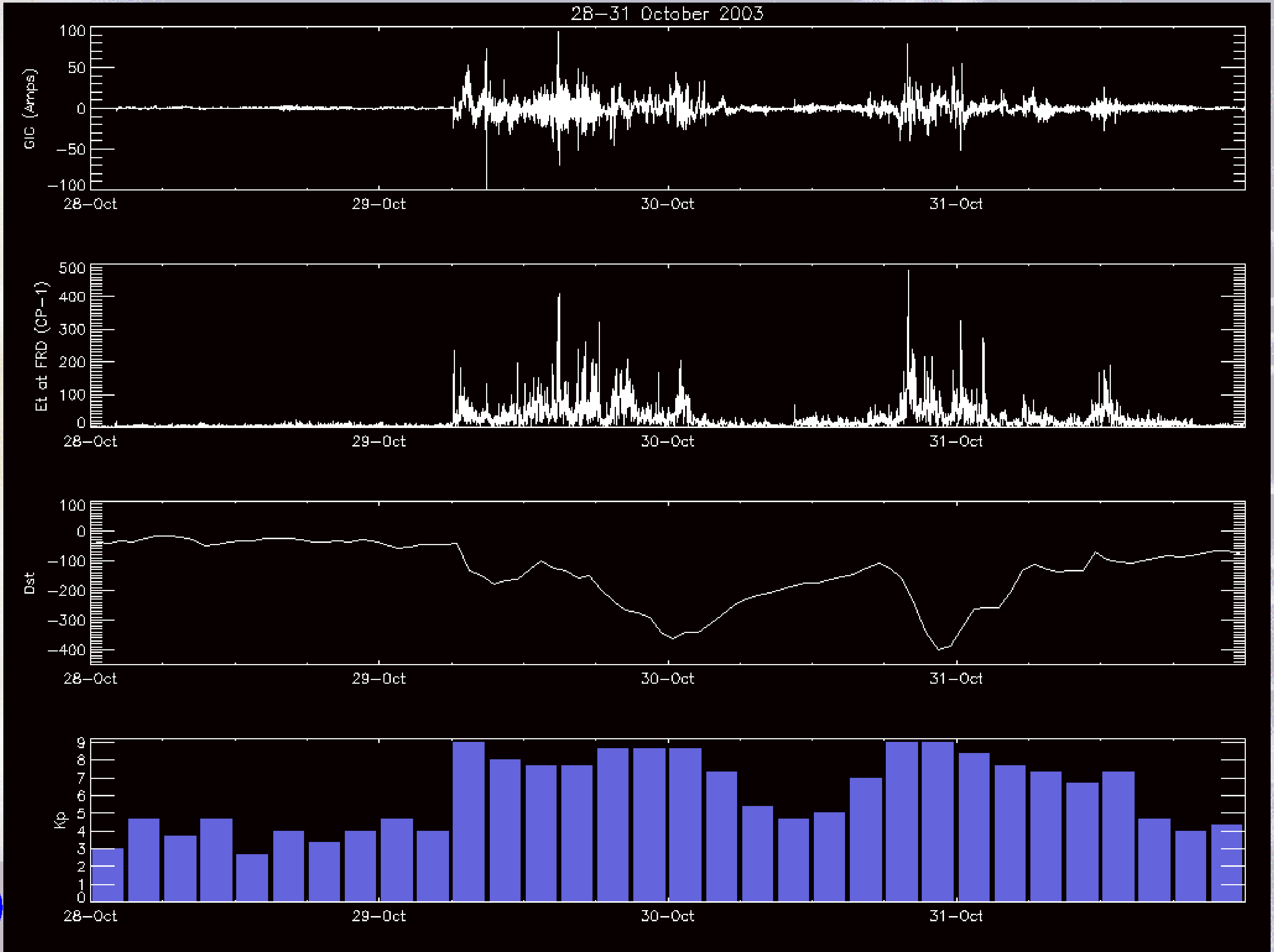


GIC measurement during a geomagnetic storm



Data courtesy of the EPRI SUNBURST project

GIC compared with other Storm Measures



Geoelectric Field Modeling

- **The Electric Power Industry requires a better indicator than the Kp index/G-scale or local K-indices to specify geomagnetic activity levels**
- **The Geoelectric Field – has been identified as the key space weather parameter that is needed (not G, Kp, Dst, dB/dt, etc):**
  - **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)**
- **Key Advantages for using the Geoelectric Field:**
  - **Local-regional activity is characterized: there can be significant differences in comparison to globally averaged quantities**
  - **The geoelectric field directly indicates the induction hazard; whereas the indices do not**

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
    - Could consider installing a less vulnerable transformer
    - Possible to modernize relays as newer devices are less susceptible
    - Possible to implement GIC ‘blockers’ – but requires full system analysis
  - Analysis can inform real-time response procedures to E-field nowcast/forecast

A Brief Overview of Calculating GIC

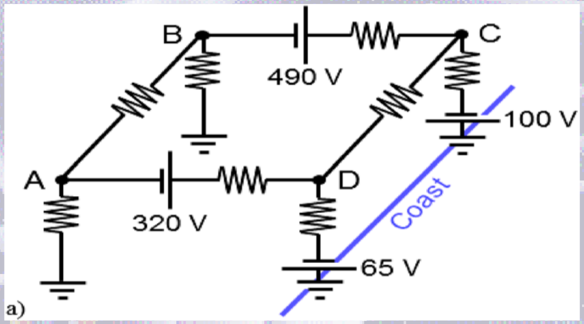
$v_{ij}^* = \int_i^j \boldsymbol{E} \cdot \boldsymbol{dl}$, *i.e. from node* i *to node* j

Combined with line resistance we find source currents between lines which can be translated into a net induced nodal current source at each node.

For example:

$J_A \stackrel{\text{def}}{=} j_{DA} - j_{AB}$

with $j_{DA} = v_{DA}^*/r_{DA}$ ***and*** $j_{AB} = v_{AB}^*/r_{AB}$



Credit – Boteler & Pirjola, 2017

$\mathbf{J} = \mathbf{Y}^N\mathbf{V} + \mathbf{I}$, ***Kirchoff law***

Induced nodal current sources $\mathbf{J}$:

Outflows: to other nodes: $\mathbf{Y}^N\mathbf{V}$**, to ground:** $\mathbf{I}$

$\mathbf{Y}^N$ **is the 'nodal admittance matrix'**

Nodal voltages relationship to $\mathbf{I}$: $\mathbf{V} = \mathbf{Z}^e\mathbf{I}$,

$\mathbf{Z}^e$ **is the 'earthing impedance matrix'**

Combining:

$$\mathbf{J} = \left(\mathbf{Y}^N\mathbf{Z}^e + \mathbf{1}\right)\mathbf{I}$$

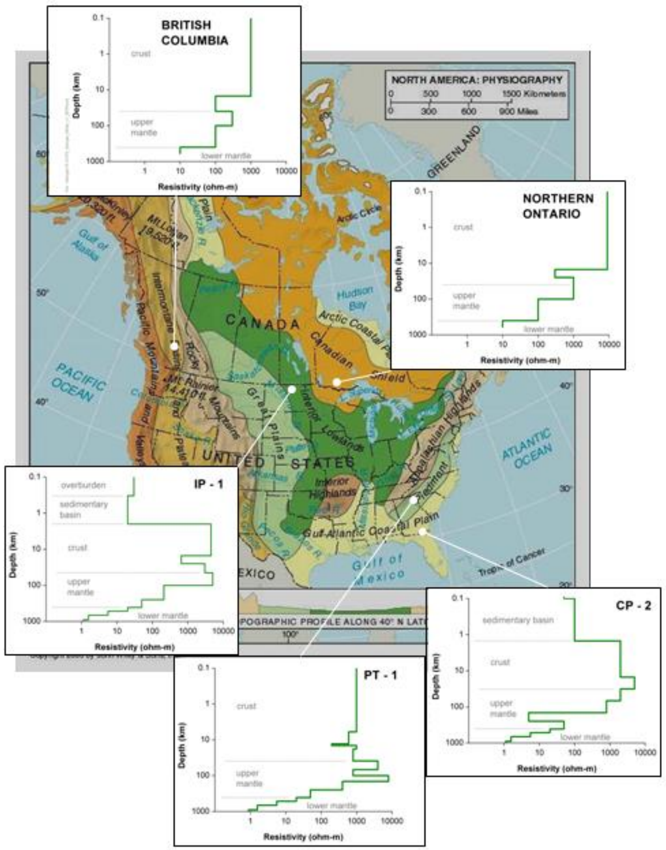
Inverting to solve for $\mathbf{I}$:

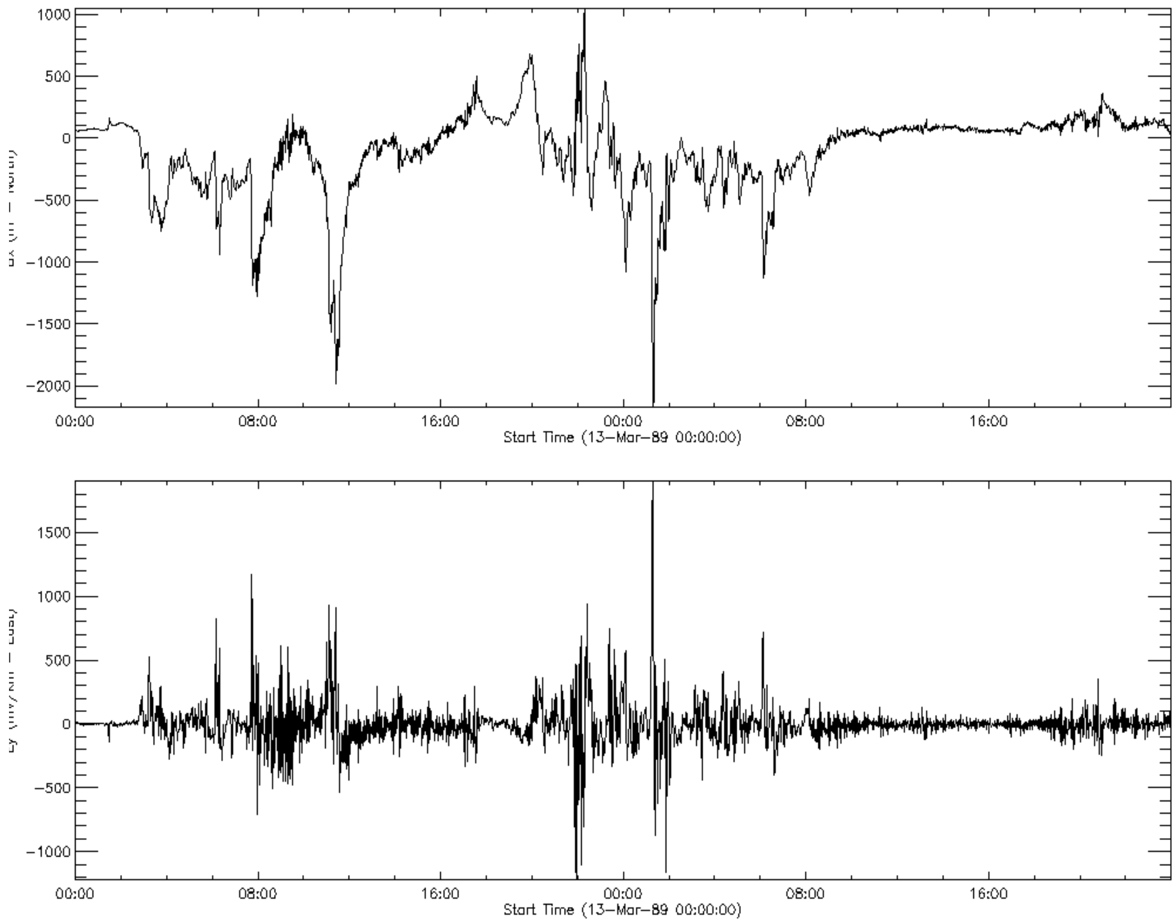
$$\mathbf{I} = \left(\mathbf{Y}^N\mathbf{Z}^e + \mathbf{1}\right)^{-1}\mathbf{J}$$

(See Lentinen & Pirjola, 1985 for original formulation)

Geoelectric Field

- **The Geoelectric Field is calculated by convolving the Geomagnetic Field variation with a frequency dependent Earth-response function**
- **The Earth response function depends on conductivity below the surface**





March 13-14, 1989 – Ottawa geomagnetic and geoelectric fields using a 1D conductivity model

Geoelectric Field Calculation

- **Input – Observed Geomagnetic Field (B-field) time series**
- **Earth conductivity acts like a frequency dependent filter:**
  - **Earth conductivity affects the input signal amplitude and phase differently, depending on the input signal 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 will have 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) (Earthscope-based models)**
  - **Earthscope 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')**

Geoelectric Field Calculation: Frequency Domain

- **The Local Magnetotelluric (MT) transfer function (aka MT response tensor) 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 (specifies how filter affects amplitude and phase of each component at each frequency)**
- **For an idealized, multi-layer one-dimensional conductivity (e.g. Fernberg models), the MT response tensor reduces to a simplified form:**

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

E-field maps data pipeline – 1D model

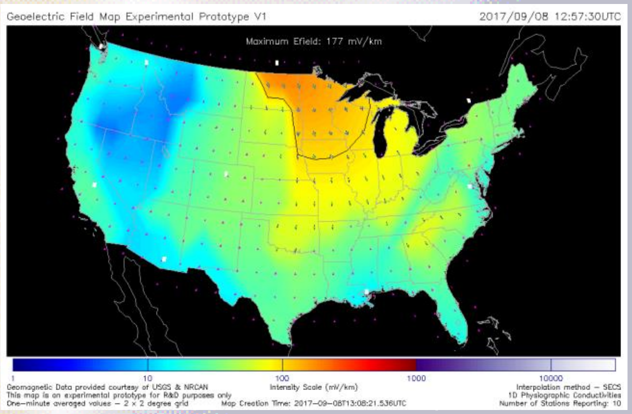
USGS observatories (8)
B-field time series

NRCAN observatories (5)
B-field time series

→ ***Detrending Algorithm*** → ***Interpolation Algorithm†***
B-field on <u>0.5°x0.5° grid</u>
(daily netcdf archive)

→ ***E-field calculation: 2°x2° grid,***
Fernberg 1D conductivities

→ ***E-field products:***
- ***-results in database***
- ***-graphical maps***
- ***-daily netcdf (for archive)***
- ***-gridded data files (available on request)***
- ***-<u>GeoJSON format for dissemination</u>***



Operational deployment completed in September 2019

† SECS - Amm & Viljanen, 1999; Pulkkinen et al., 2003

URLs
https://swpc.noaa.gov/products/geoelectric-field-1-minute
https://services.swpc.noaa.gov/json/lists/rgeojson/InterMagFB1DLP/ *(geojson files)*

E-field maps data pipeline – 3D model

USGS observatories (8)
B-field time series

NRCAN observatories (5)
B-field time series

→ ***Detrending Algorithm*** →

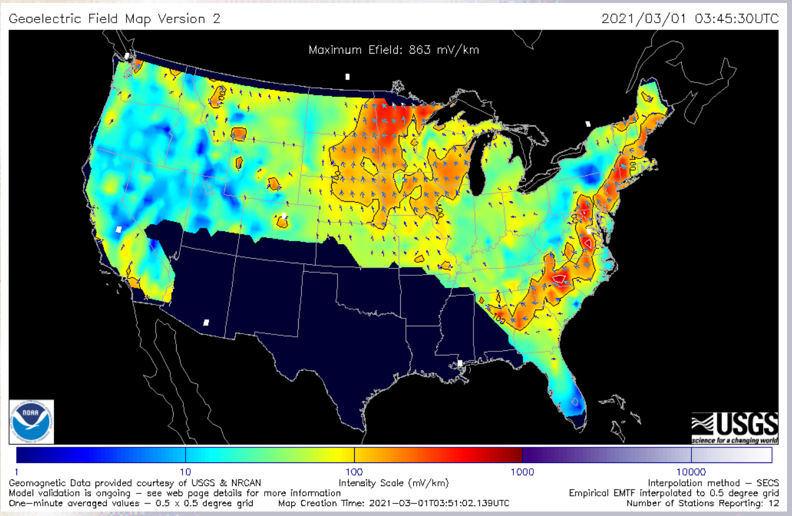
Interpolation Algorithm
B-field on <u>0.5°x0.5° grid</u>
<u>daily netcdf for archive</u>

→

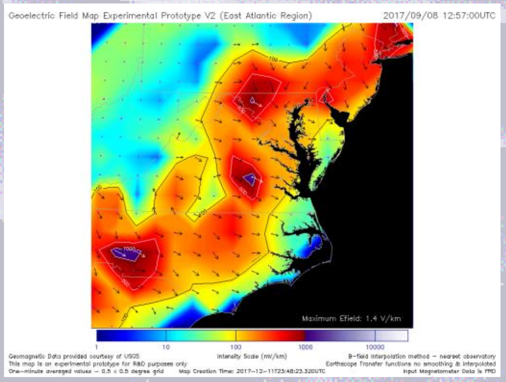
E-field calculation:
-<u>Earthscope Transfer Functions & (USGS for FL)</u>
-<u>Interpolate to 0.5°x 0.5° grid</u>
-Gaps in coverage

→

E-field products:
-results in database
-graphical maps
-gridded data files
-daily netcdf for archive/repository
-GeoJSON format for dissemination

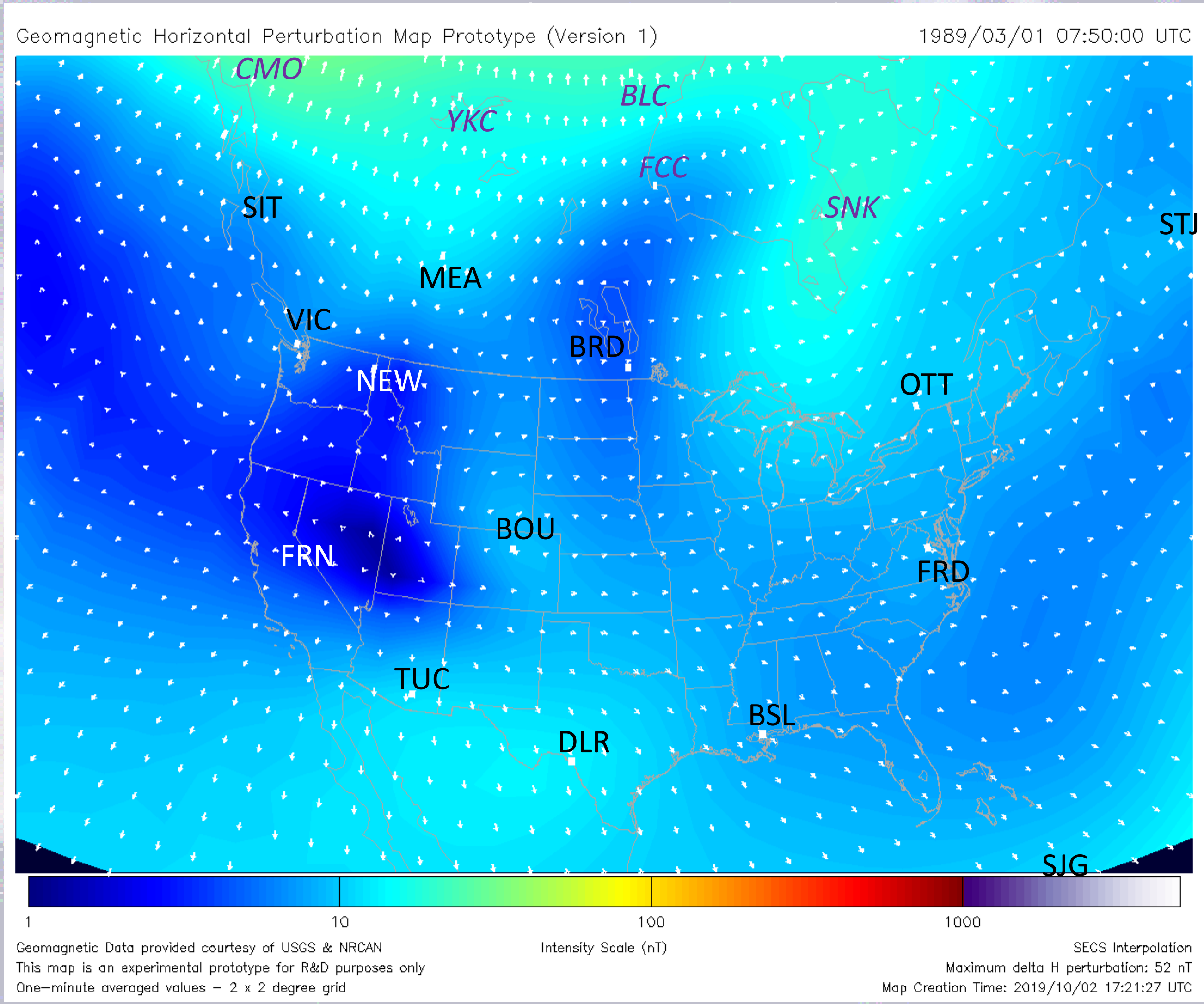


Operational in September 2020



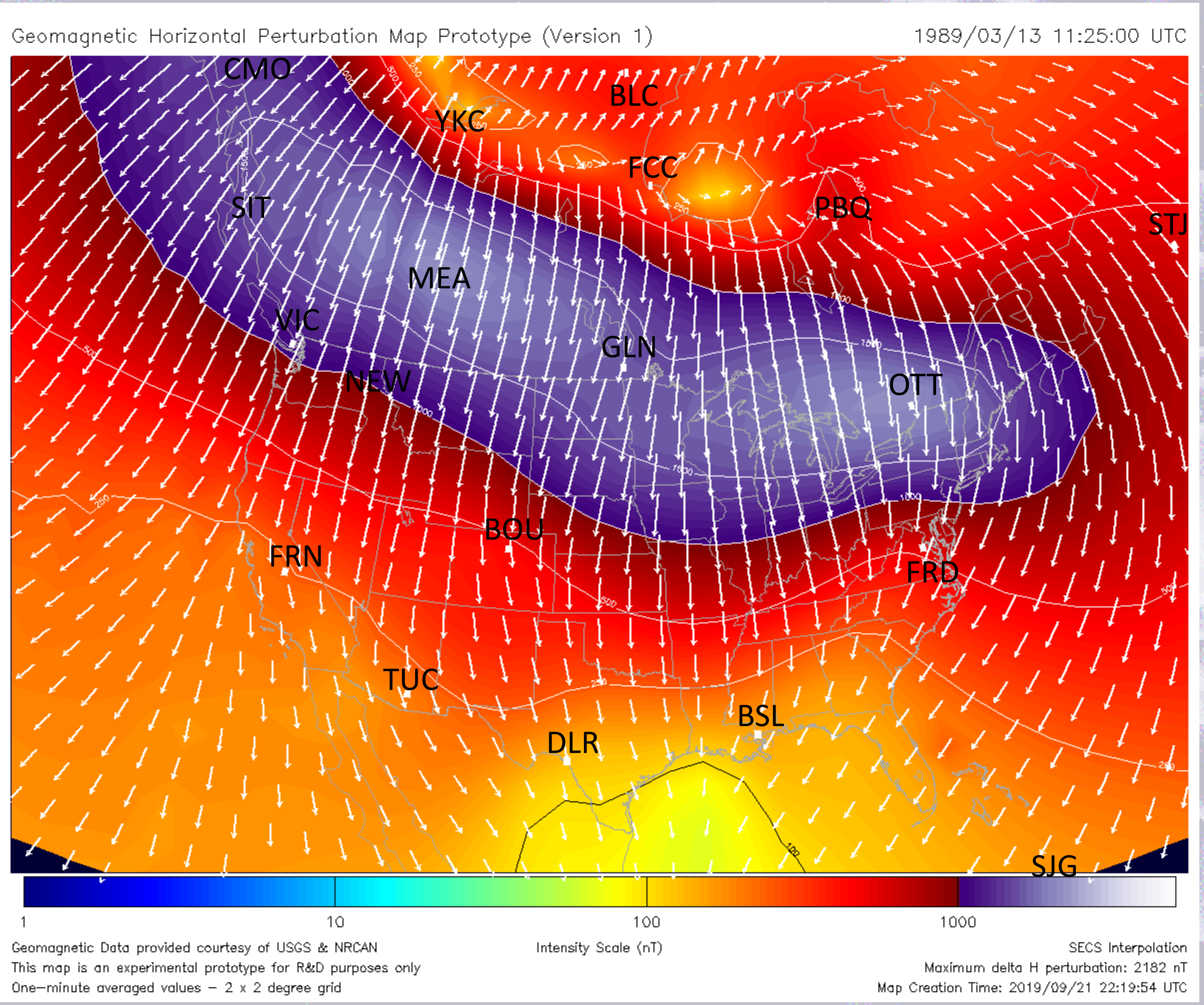
https://swpc.noaa.gov/products/geoelectric-field-1-minute-empirical-emtf-3d-model/
https://services.swpc.noaa.gov/json/lists/rgeojson/InterMagEarthScope/

Sample B-field interpolation map – Quiet Time

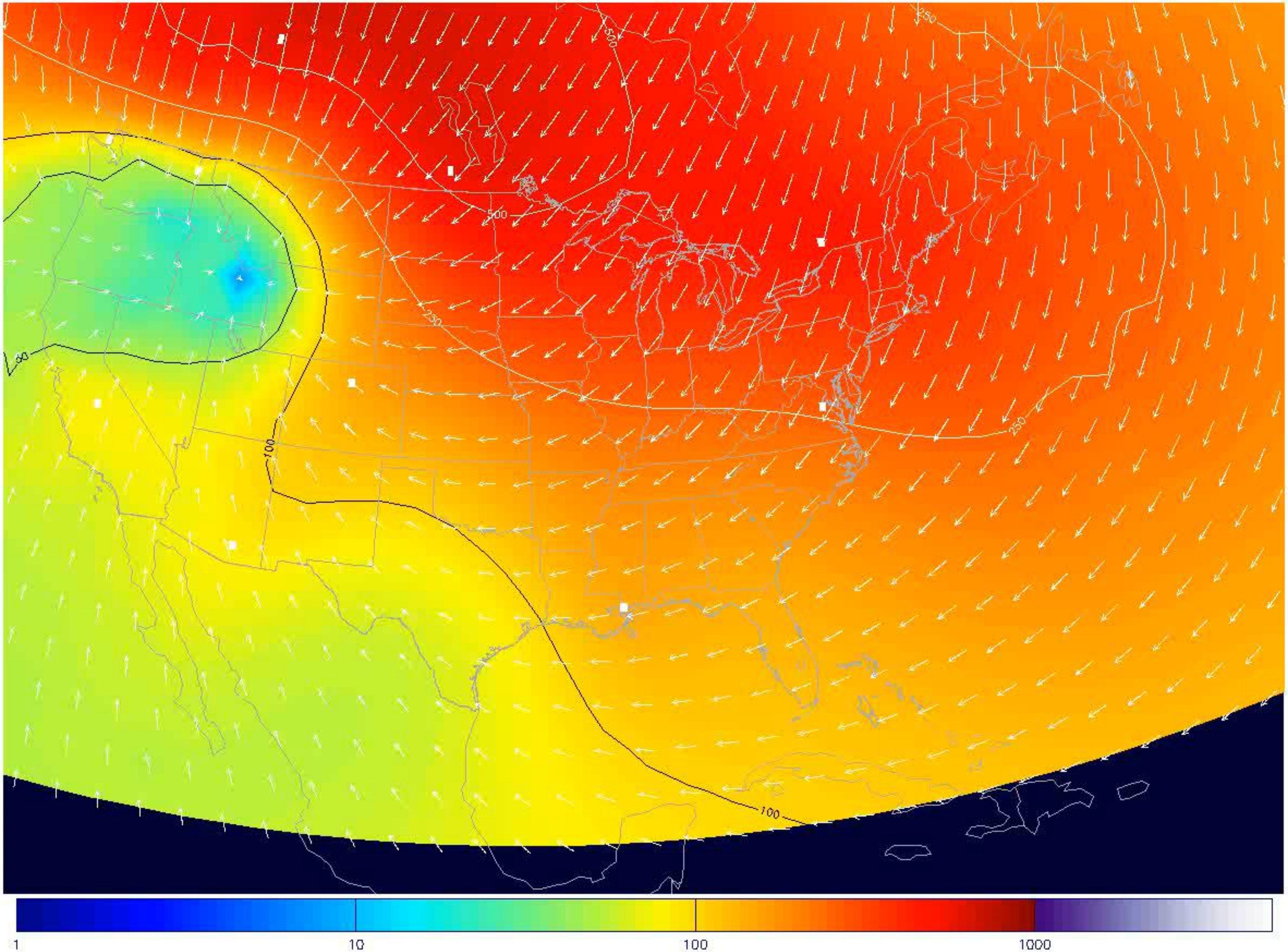


The high latitude stations: CMO, YKC, BLC, FCC, SNK are planned to be added to the network in FY 2021

B-field interpolation map – March 13, 1989



Geomagnetic Horizontal Perturbation Map Prototype (Version 1) 2017/09/08 13:00:00 UTC



Intensity Scale (nT)

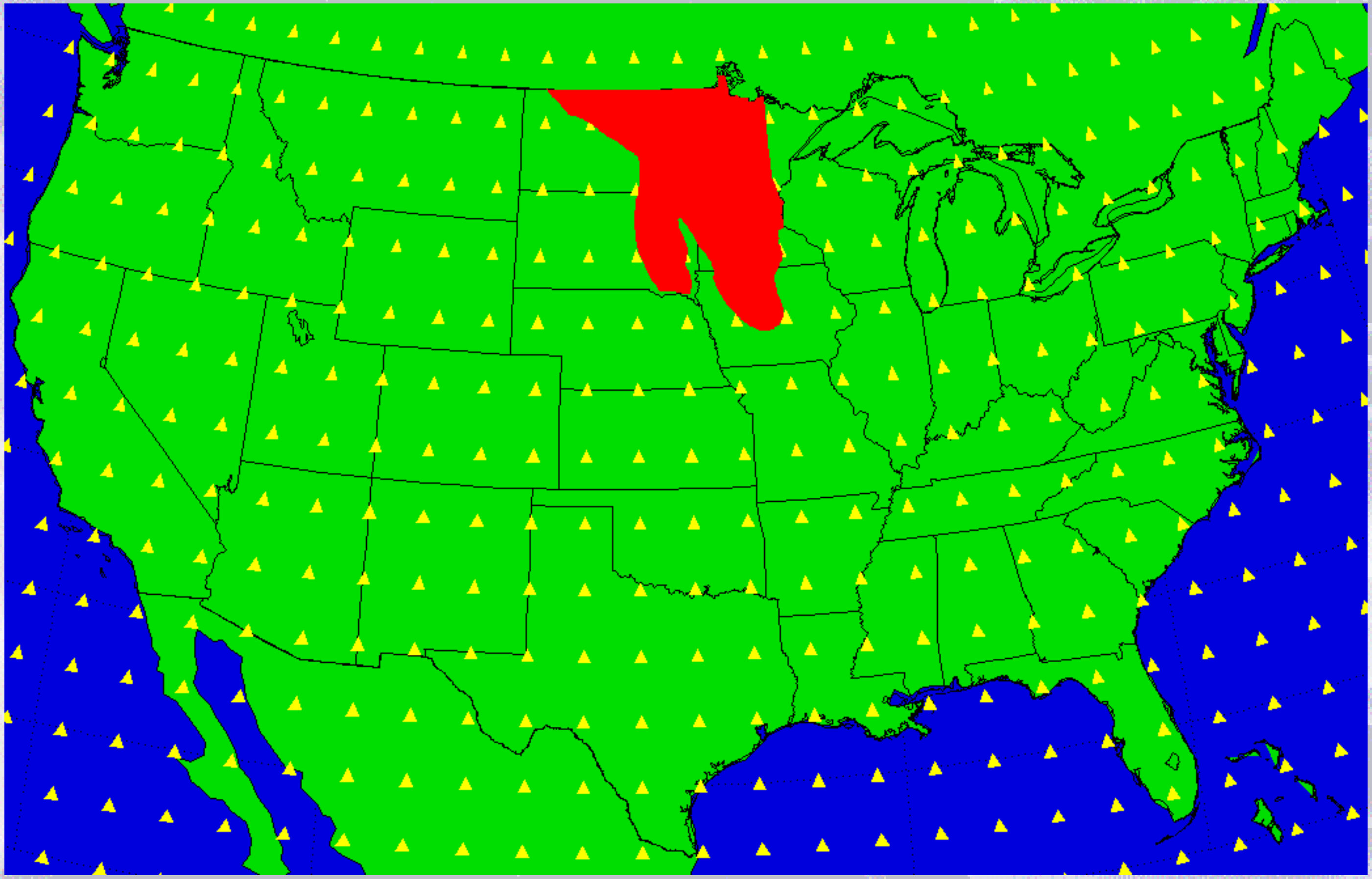
Geomagnetic Data provided courtesy of USGS & NRCAN
This map is an experimental prototype for R&D purposes only
One-minute averaged values – 2 x 2 degree grid

SECS Interpolation
Maximum delta H perturbation: 633 nT
Map Creation Time: 2017/09/08 13:07:12 UTC

E-field map generation – 1D model

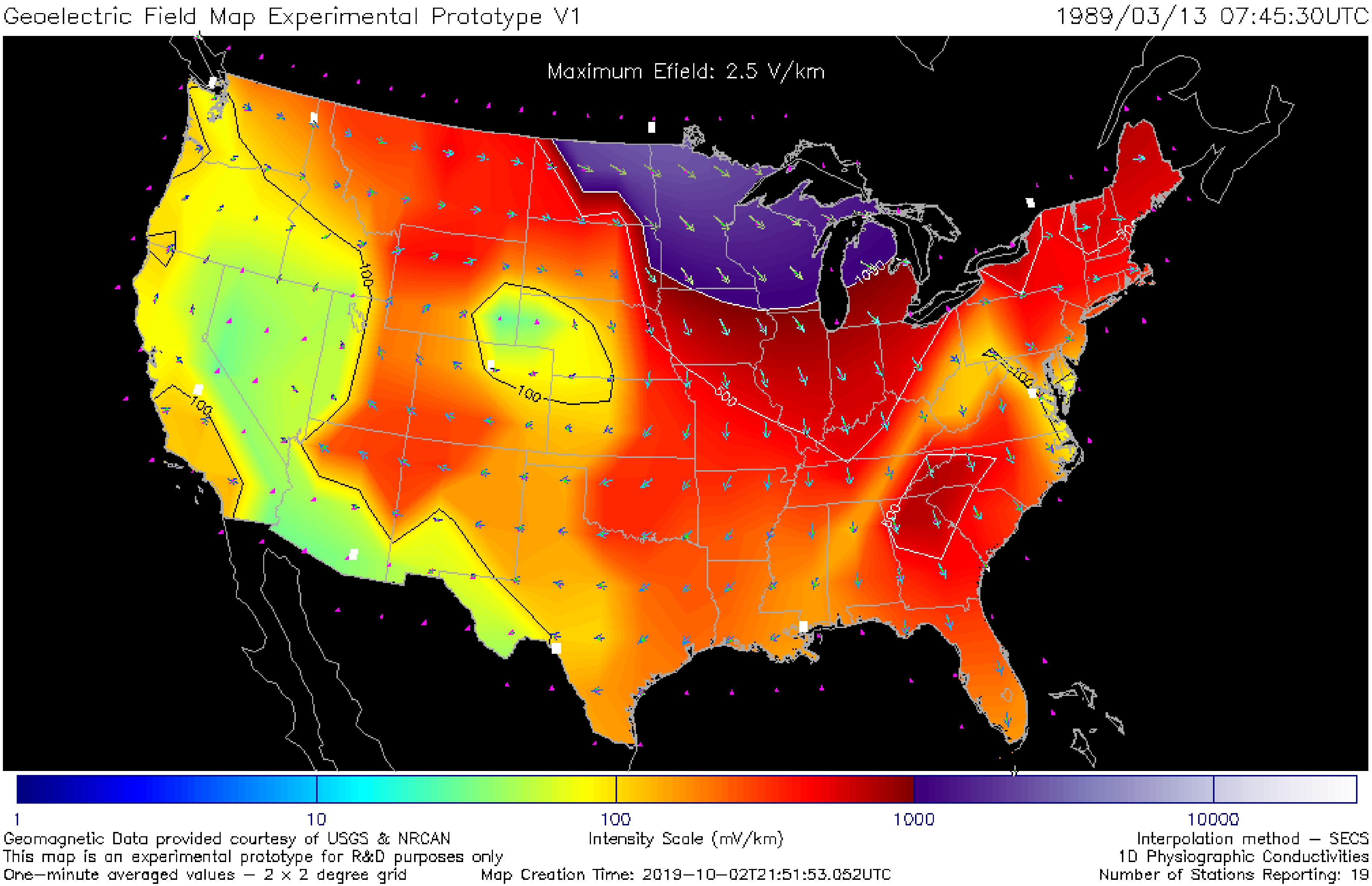
- Defined a set of geographic gridpoints
  - Two degree resolution over CONUS
- For each gridpoint:
  - Use interpolated B-field time series as input
  - Determined the conductivity model for the grid point
  - The initial release uses 1D conductivity models (Fernberg 2012)
  - The maps have been running at SWPC experimentally in October 2017 and operationally since September 2019
- E-field for each grid point is calculated in near real-time (283 grid points for each time step)

Physiographic Region 1D model



- *2 degree x 2 degree grid*
- *Region 12b, interior plains, central lowland, western lake*
- *All grid points in the region are assigned conductivity model IP-1*

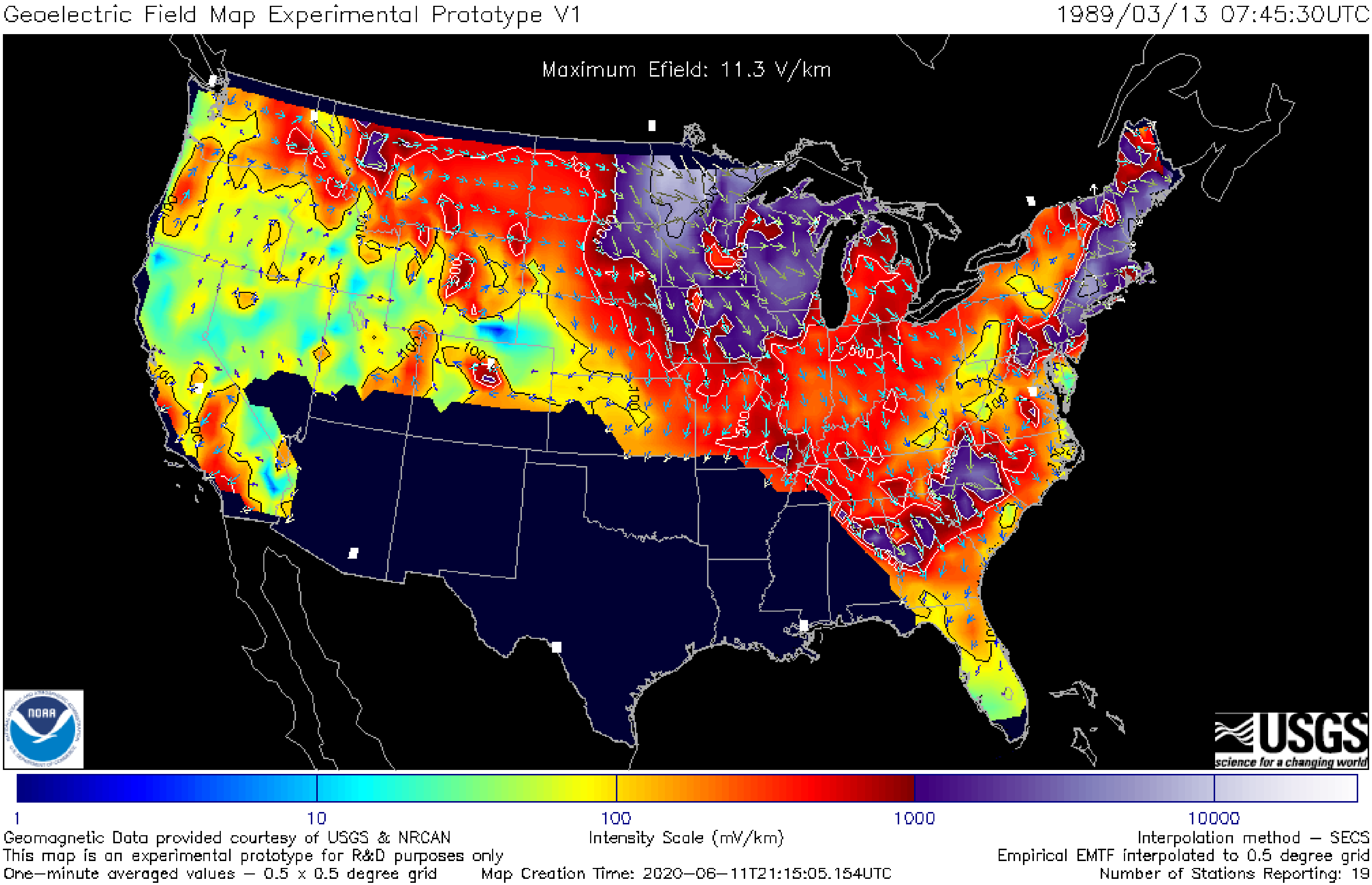
2 x 2 degree Fernberg 1D Map



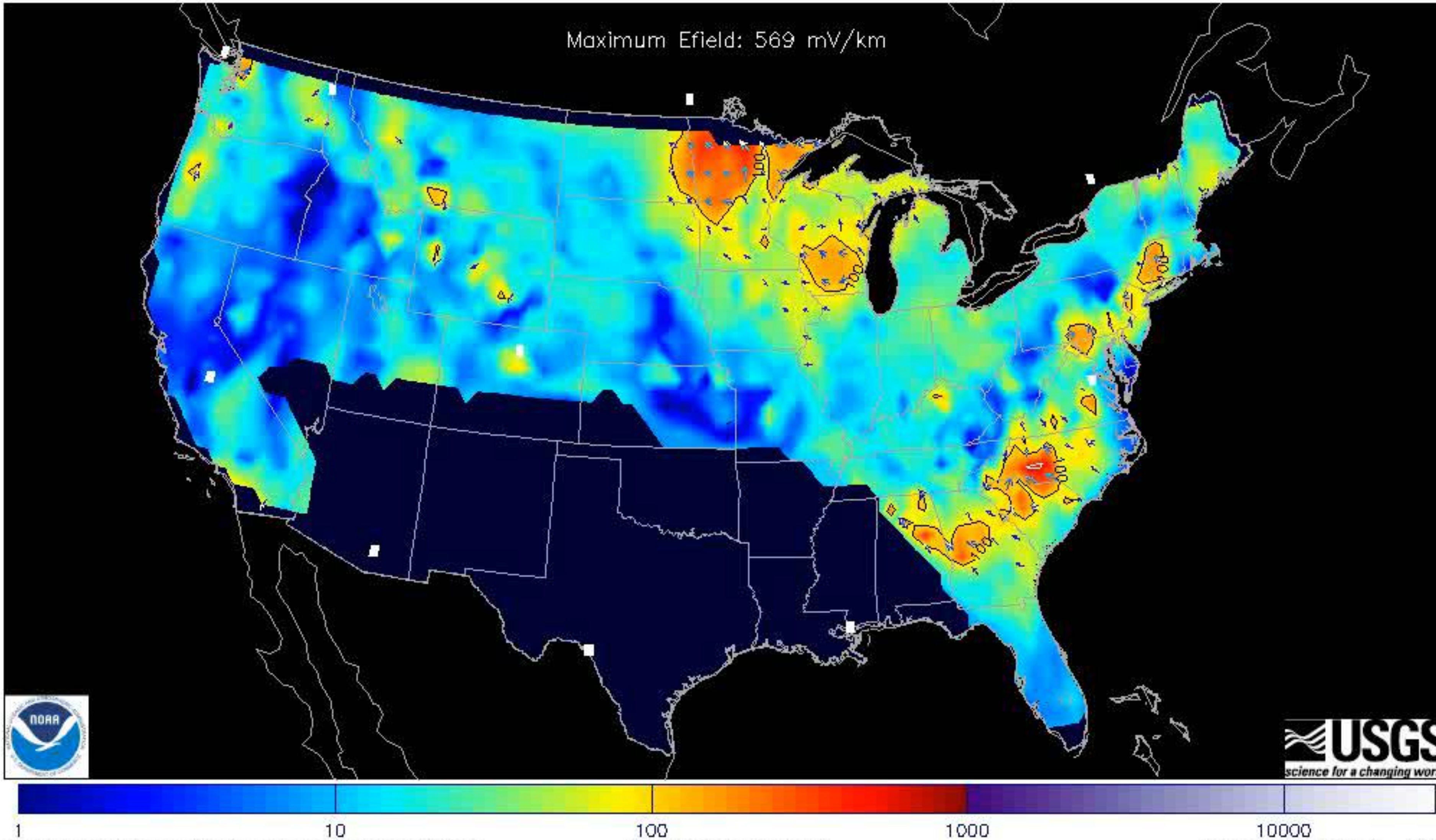
E-field map generation – 3D model

- Produce interpolated B-field time series over CONUS using a 0.5 degree resolution grid in longitude and latitude.
- For each magnetotelluric survey site over CONUS
  - Find the nearest interpolated B-field time series and use as input
  - Calculate the E-field time series at each survey location using the published transfer function (1084 surveys available as of June 2020)
  - Resample the E-field map (irregular grid) to a regularly spaced ½ degree resolution grid, omitting all points that are more than 100 km from an MT survey site (2800 grid pts)
- The 3D maps have been running experimentally at SWPC since June 2020 and operationally since September 2020

0.5 x 0.5 degree Empirical 3D Map



Geoelectric Field Map Experimental Prototype V1 1989/03/13 07:30:30UTC

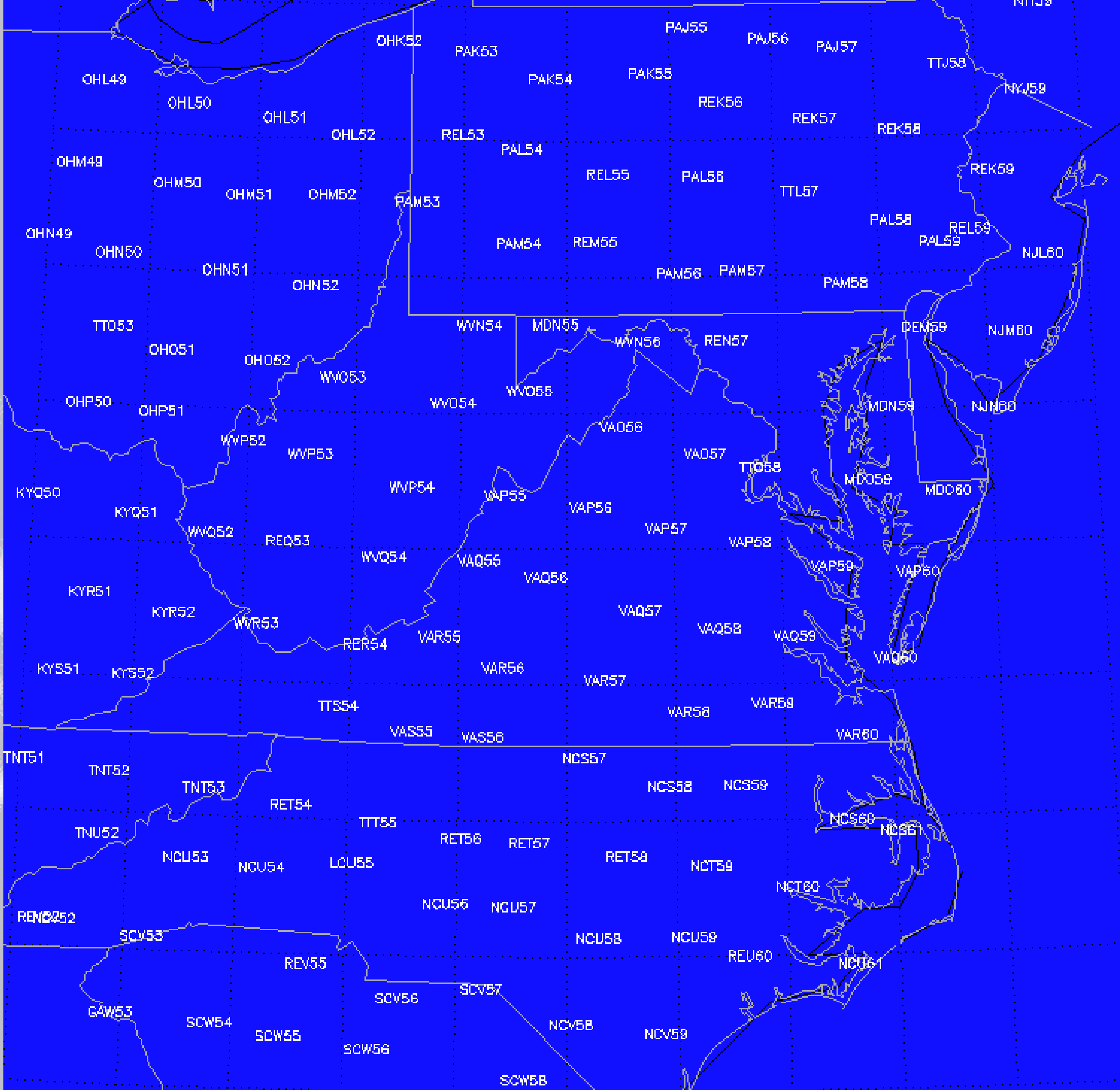


Geomagnetic Data provided courtesy of USGS & NRCAN
Intensity Scale (mV/km)
Interpolation method – SECS
This map is an experimental prototype for R&D purposes only
Empirical EMTF interpolated to 0.5 degree grid
One–minute averaged values – 0.5 x 0.5 degree grid
Map Creation Time: 2020–06–11T21:13:48.869UTC
Number of Stations Reporting: 19

MT Survey locations – 3/21/2021

Graphic from IRIS website:
ds.iris.edu/spud/emtf

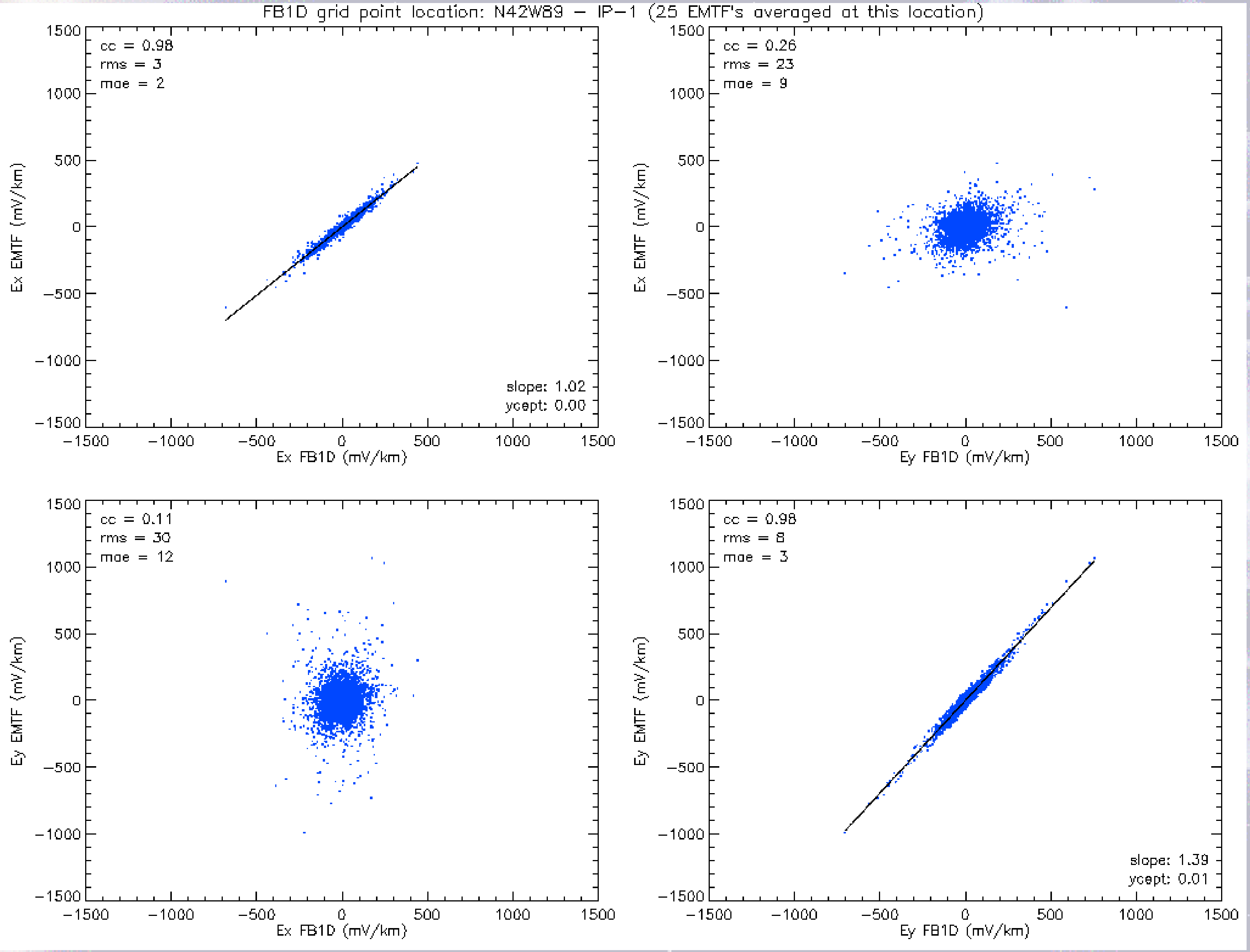
Survey Sites the mid-Atlantic Region



Model Comparisons with Historical Data

- **Goal: Compare the two different conductivity models by running side-by-side calculations using historical data – to help characterize the ‘error bars’ in the 1D maps**
- **We choose full months with Kp = 9o (G5) occurrence: March 1989, July 2000, October 2003 (93 days)**
- **Historical data from 10 USGS stations and 8 Canadian stations (9 for March 1989)**
- **The data are detrended & interpolated to a 0.5 x 0.5 degree grid**
- **The Fernberg 1D maps are calculated for each time step on the same 2 x 2 degree grid as the operational version**
- **The empirical 3D maps are calculated on a 0.5 x 0.5 degree grid as described on the previous slide**
- **To compare models, for each point in the 1D map, we average together all the 3D empirical map grid points that are within one degree (158/209 available locations)**

Scatterplots



North-Central Illinois

Correlation Table

For correlations between the Ex components we get the following distribution:

Category	# of points	% of total
Correlation over 0.90	84	53.2%
Correlation from 0.80-0.90	45	28.5%
Correlation from 0.70-0.80	15	9.5%
Correlation from 0.60-0.70	10	6.3%
Correlation from 0.50-0.69	1	0.6%
Correlation less than 0.50	3	1.9%

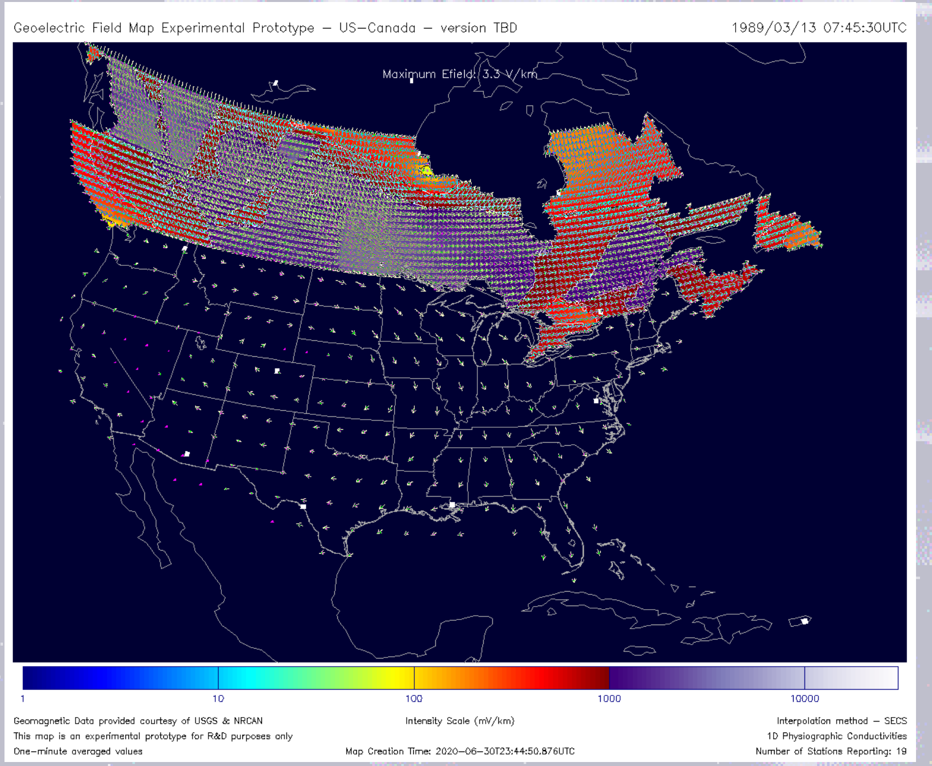
Likewise, for the Ex components, we get the following distribution

Category	# of points	% of total
Correlation over 0.90	79	50.0%
Correlation from 0.80-0.90	46	29.1%
Correlation from 0.70-0.80	14	8.9%
Correlation from 0.60-0.70	7	4.4%
Correlation from 0.50-0.69	5	3.2%
Correlation less than 0.50	7	4.4%

We note that a majority of the points have sufficiently high correlations that one could simply use the line-fit correction to get a reasonable conversion between the two models at those locations.

E-field maps – in development
Joint US-Canada E-field map

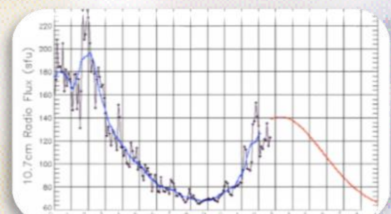
- **Partnership with NRCAN to develop US-Canada E-field map**
- **Northern boundary will extend up to 60 degrees latitude**
- **NRCAN space weather specifies conductivities for Canada**
- **Four high latitude magnetometers to be added: YKC, BLC, FCC, SNK**



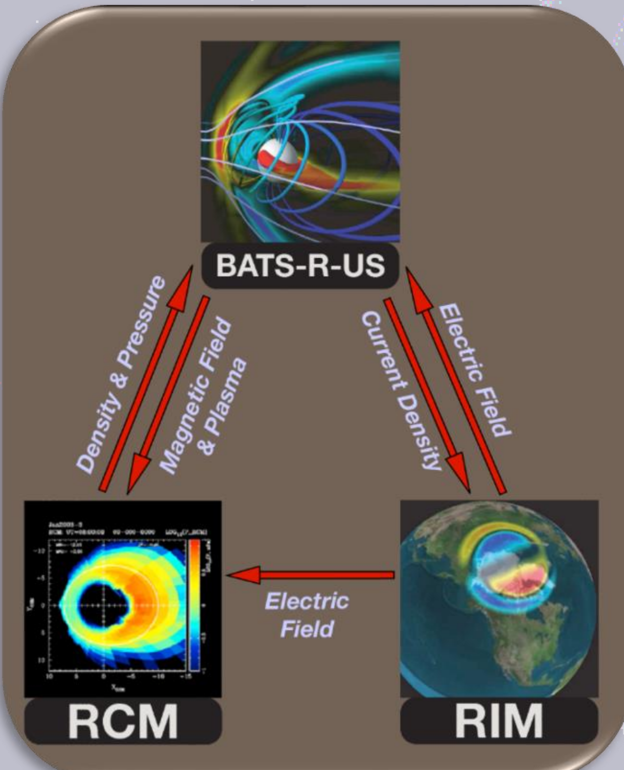
Forecasting: Operational Geospace Model

Implementation at NWS

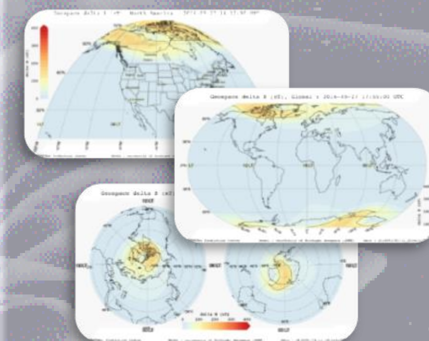
DSCOVR
Solar Wind Data:
V, n, T, B



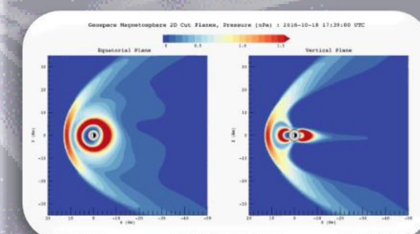
Solar F10.7 Radio Flux



Operational SWMF



http://www.swpc.noaa.gov/products

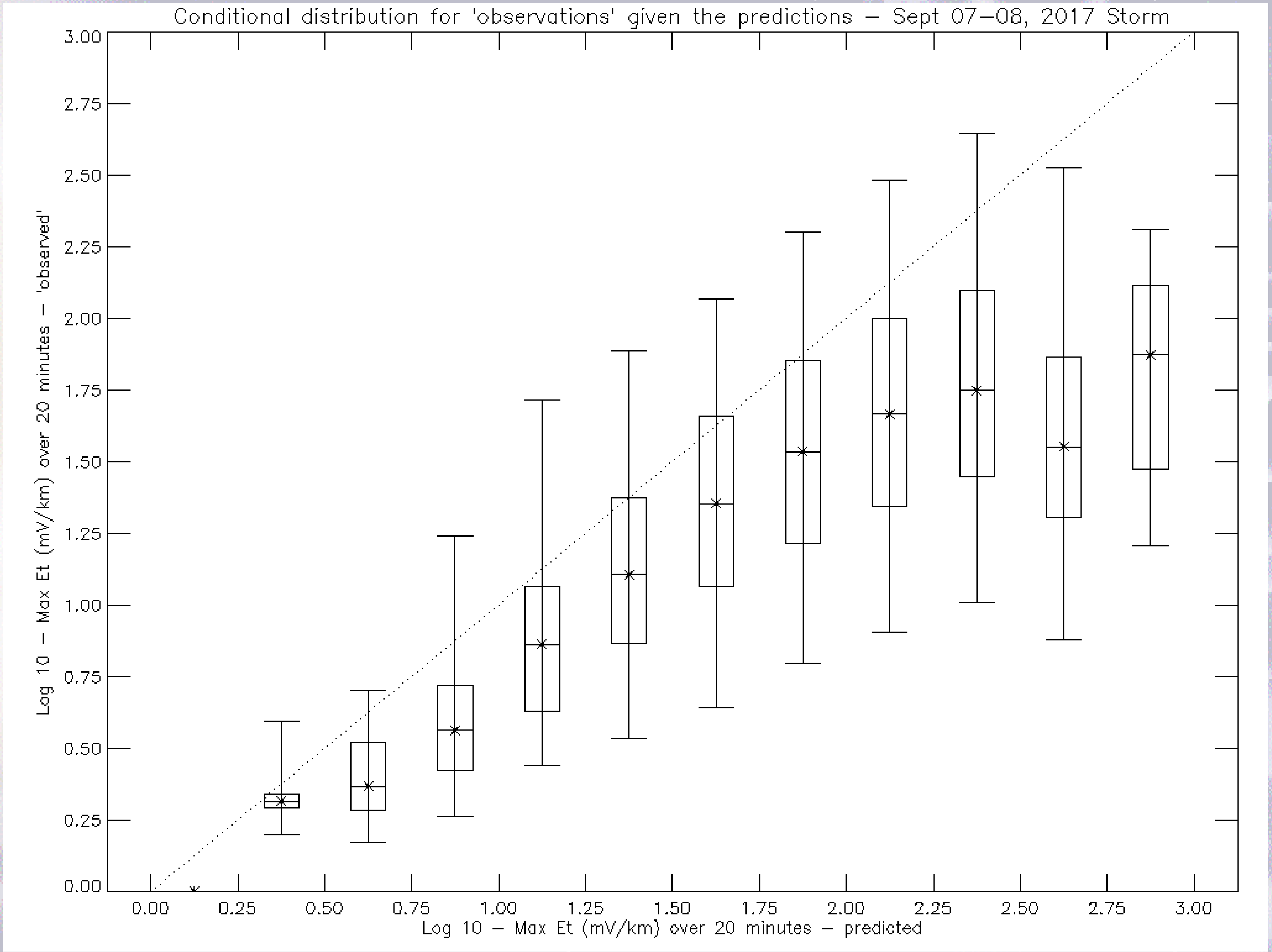


Predicts Geomagnetic Variations on a 2°x2° grid over lower 48 states

SWPC is looking at using the model output for the E-field predictions

E-Fields: nowcast vs forecast

07-08 September 2017 storm



E-Fields: nowcast vs forecast

07-08 September 2017 storm

- Define an ‘event’ as |E| exceeding 100 mV/km over a 20 minute interval (for the September 07-08, 2017 storm)
- We compare predictions from Geospace with ‘observations’ from the ground-based mag calculation
- The 2x2 contingency table is shown below.
- There are more false alarms than hits, and there are a lot of misses
- The hit rate = 0.55 (hits over total events) is higher than the false alarm rate =0.14 (false alarms over total non-events) so at least the True Skill Statistic = 0.41 is positive
- Given that the forecast=yes, the probability of an event is ~27%
- Given that the forecast=no, the probability of an event is ~5%
- These results are limited to just one storm only – so further analysis is required to gain more confidence in this assessment
- There is likely sensitivity to choice of threshold

Fcst\Obs	Yes	No
Yes	748	2062
No	601	12720

Future Plans

- Geospace-Geoelectric coupling end-to-end demonstrations and comparisons with nowcast maps – milestone for FY 2021
- Joint US-Canada E-field maps (1D)
  - Experimental for FY 2021
  - Demonstration for operational use in FY 2022 (proposed)
- Ongoing validation studies with industry, comparing modeled and measured GIC
- Ongoing need to improve the number of input magnetic observatories – (interpolation model inaccurate when you are too far from an observatory)
- Look to USGS & other subject matter experts to improve the modeling effort in the future
  - For example, may need to go to higher spatial and time resolution for better results

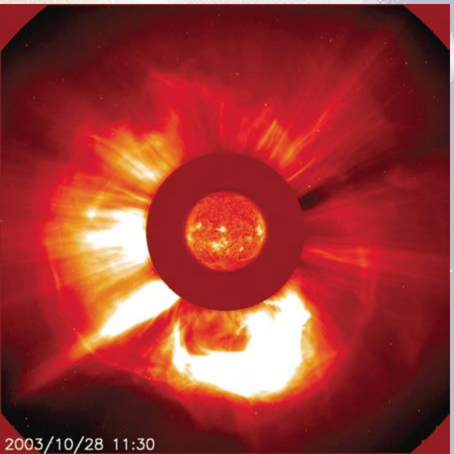
Summary

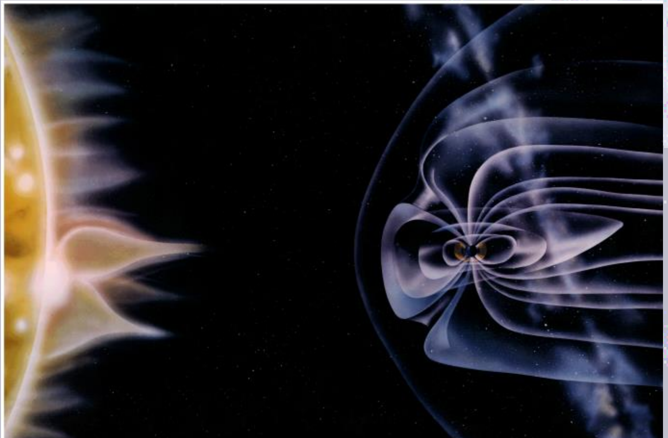
- Geoelectric modeling is a major improvement in specifying space weather for impacts on the electric power gird
- The geoelectric field accounts for variation of the induction effect by region and is directly related to the current induced in these systems
- Accomplishments to date include:
  - 1D model operational in 2019
  - 3D empirical model operational in 2020

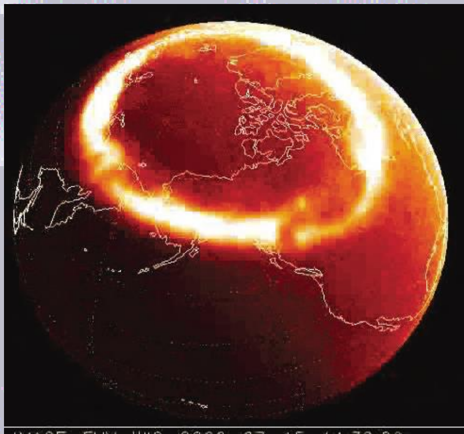
Summary

- Work in progress – key elements:
  – Testing coupled geospace-geoelectric results to find a way to forecast power grid impacts
  – Developing joint US-Canada E-field map product
  – Validation Studies with end users
  – Developing better magnetometer network (to improve spatial coverage of the input data)
- Future tasks
  – Consider more advanced models developed by USGS and other Earth-model experts
  – Consider regions where higher spatial resolution is needed
  – Increase cadence (e.g. 10 second sample period)

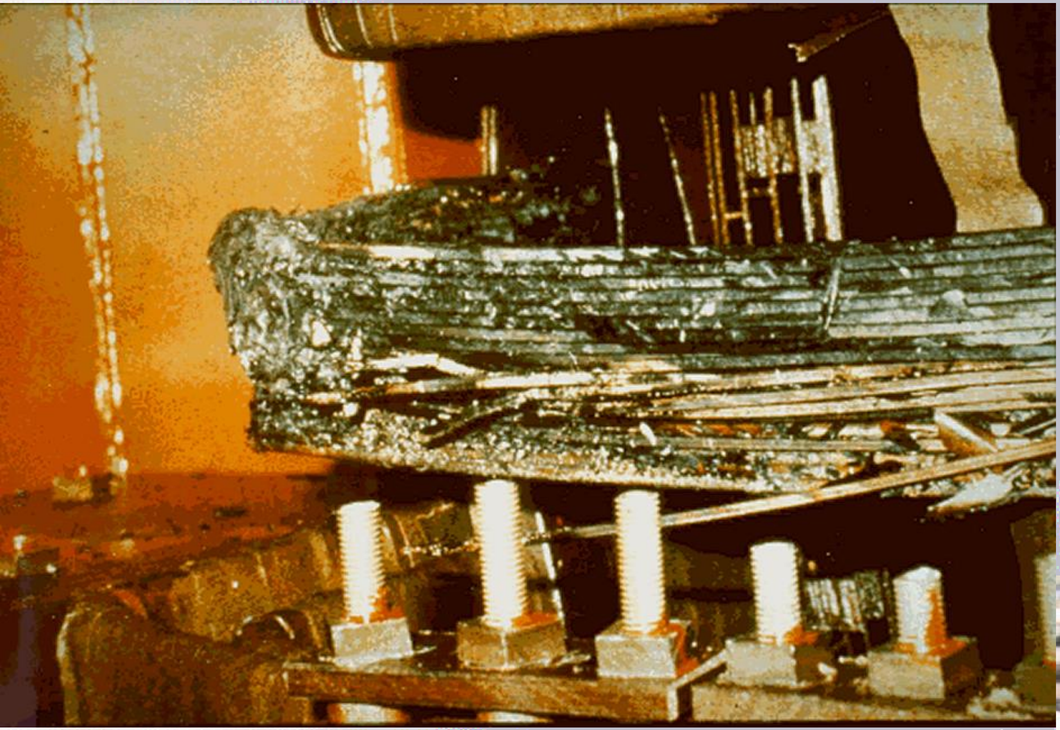
Questions?







Transformer Damage



22-500 kV GSU transformer at PSEG's Salem Nuclear Plant in New Jersey was damaged by the March 13, 1989 geomagnetic storm

ESKOM's Station 4 Transformer 6 damage was consistent with severe geomagnetic storm of October-November 2003

Sample Gridded Data Product

20170908T133030-10-Efield-2...adir_1m\2017\09\08) - GVIM1

File Edit Tools Syntax Buffers Window Help

```
# product_filename          20170908T133030-10-Efield-2x2.dat
# time_tag                  2017-09-08T13:30:30.000
# product_generation_time   2017-09-08T13:37:44.006
# product_version           InterMagFB1DLP
# cadence                   60
# n_stations                10
# n_station_models          283
# n_gridpts                 283
# n_missing                 0
# last_insert_time          2017-09-08T13:37:31.170
# resolution                2x2
# grid_type                 Geoelectric_Lower_48
# maximum_efield            687.36
# lon,lat,Ex,Ey,quality_flag,distance_nearest_station
-81.00,24.00,22.58,-26.85,5,1107.47
-99.00,26.00,45.30,-2.42,5,1037.79
-97.00,26.00,42.30,-6.72,5,869.30
-83.00,26.00,27.58,-25.89,5,810.08
-81.00,26.00,26.65,-29.99,5,974.26
-79.00,26.00,23.71,-33.10,5,1148.38
-103.00,28.00,10.58,3.62,5,876.32
-101.00,28.00,50.70,7.95,5,1044.41
-99.00,28.00,50.72,4.45,5,946.45
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-95.00,28.00,43.41,-5.66,5,583.26
-93.00,28.00,35.08,-11.15,5,418.82
-91.00,28.00,25.58,-14.94,5,293.30
-89.00,28.00,22.38,-16.04,5,268.46
-85.00,28.00,32.03,-24.40,5,520.04
```

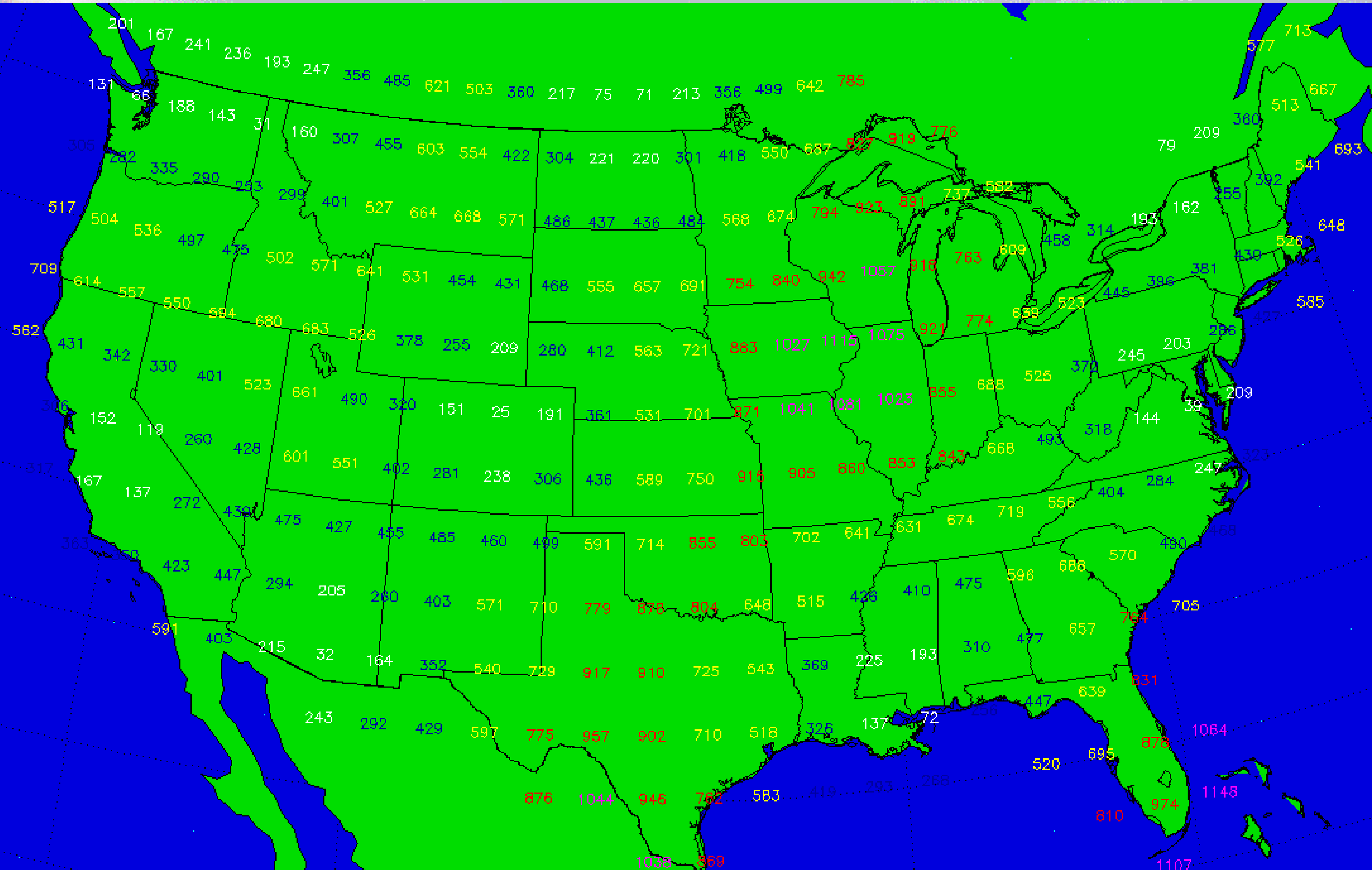
Data Dissemination via GeoJSON

- **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**

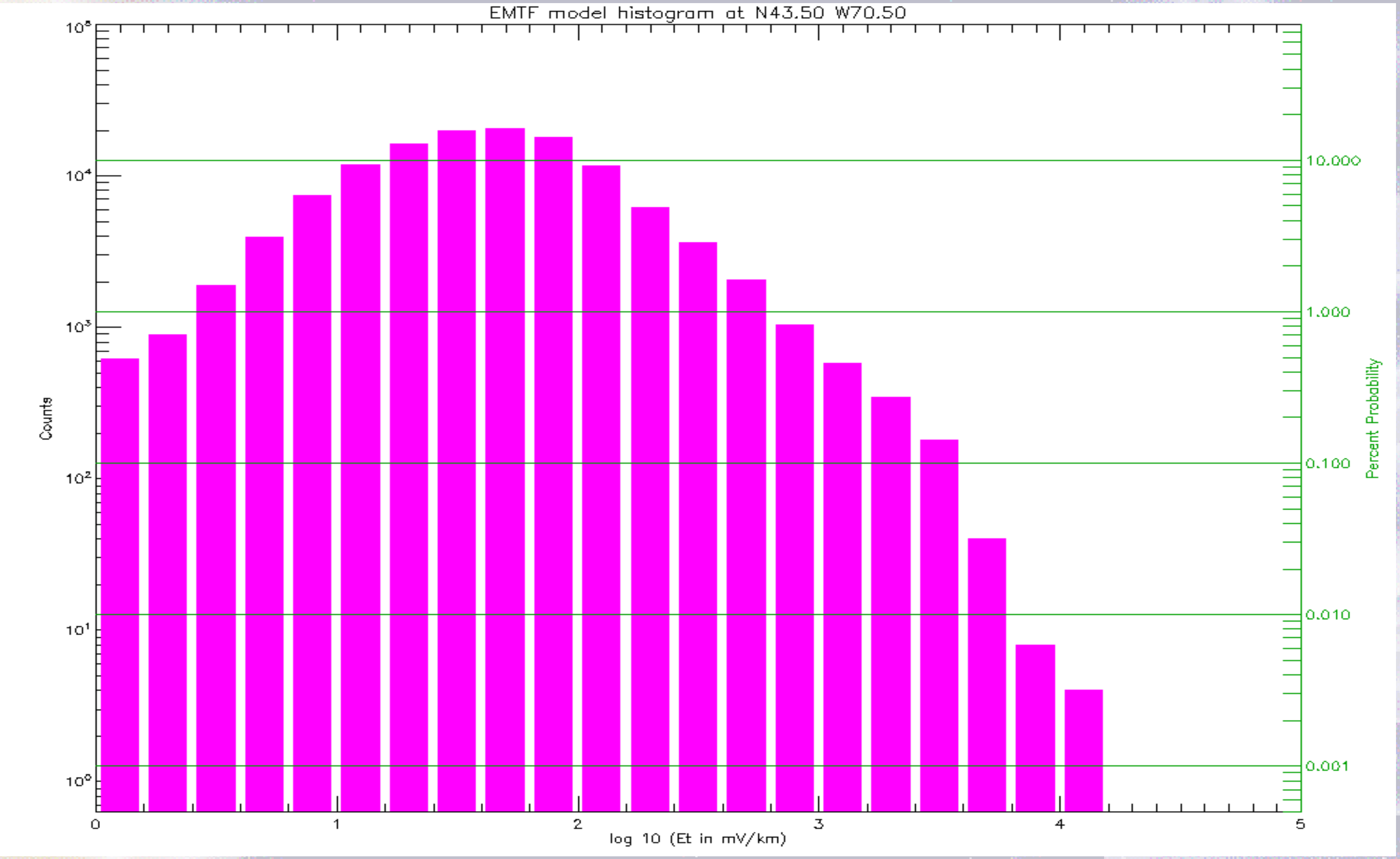
- Each "feature" has properties (data) and geometry (coordinates)
- Can contain points, lines, multi-point lines, and polygons
- Human and machine readable ASCII - compresses well with gzip
- < 5 Kilobytes compressed for each minute


```
{
  "type":"FeatureCollection",
  "features":[
    {
      "type":"Feature",
      "properties":{
        "Ex":-0.48,
"distance_nearest_station":1107.47,
        "Ey":-0.68,
        "quality_flag":5
      },
      "geometry":{
        "type":"Point",
        "coordinates":[
          -81.0,
          24.0
        ]
      },
    ...
```

Station Distances (km)



Histograms for 3D empirical model

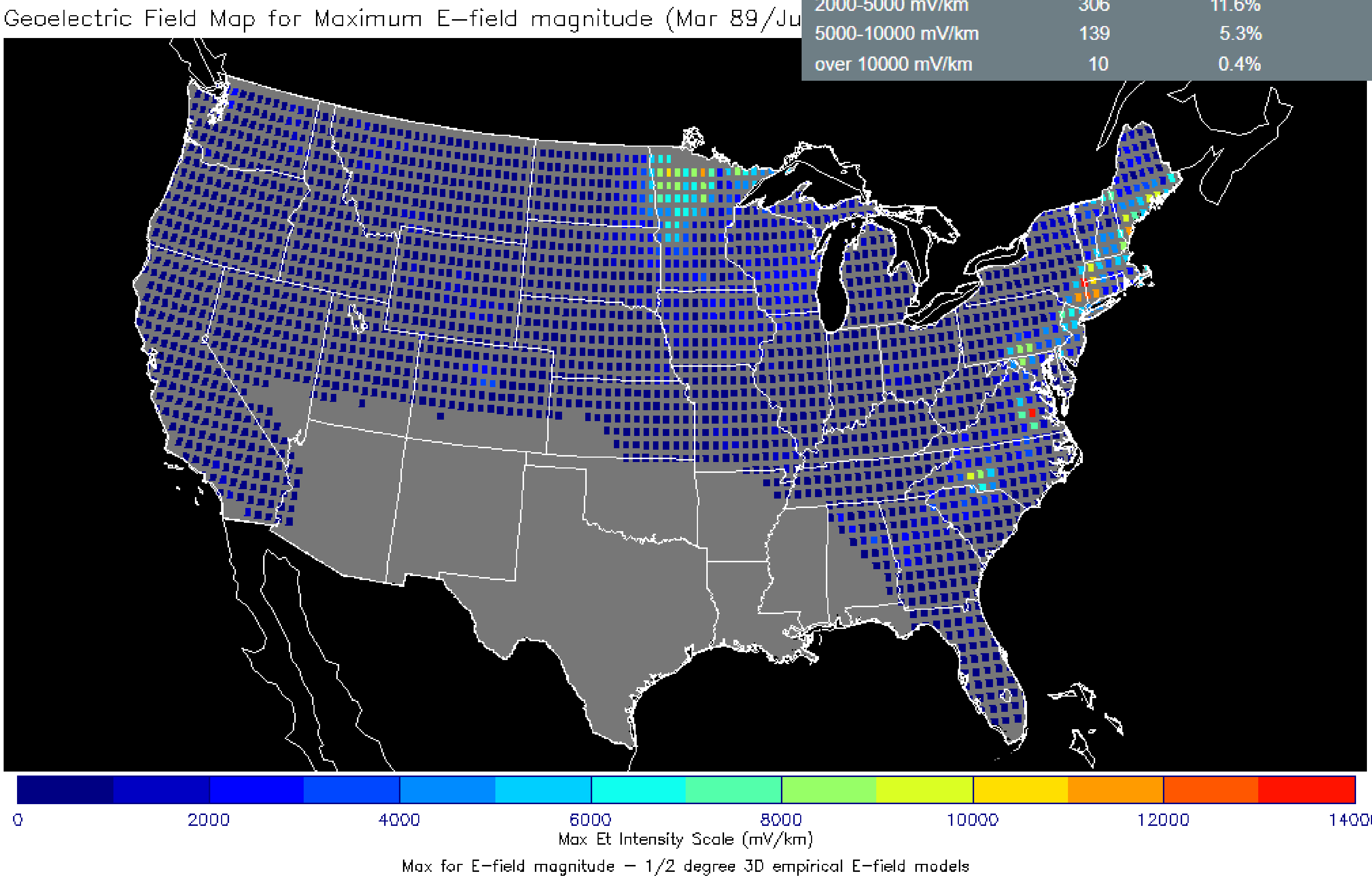


- Histograms for each 0.5 x 0.5 degree 3D empirical grid point
- 2633 grid points (this sample is for Eastern Maine)
- Shown is distribution of log 10 E-field magnitude in mV/km
- Sample period: March 1989, July 2000, October 2003

Peak Value Map for Et (3D empirical)

The distribution of grid points for given peak E-field ranges from this model (for the G5 months) is as follows:

Peak E-field magnitude	# pts	% of total
Less than 1000 mV/km	1828	69.4%
1000-2000 mV/km	348	13.2%
2000-5000 mV/km	306	11.6%
5000-10000 mV/km	139	5.3%
over 10000 mV/km	10	0.4%



Interplanetary Space: Simulation