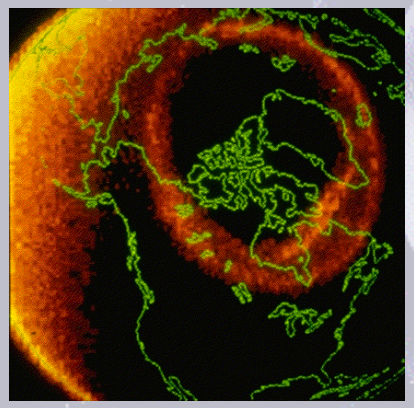
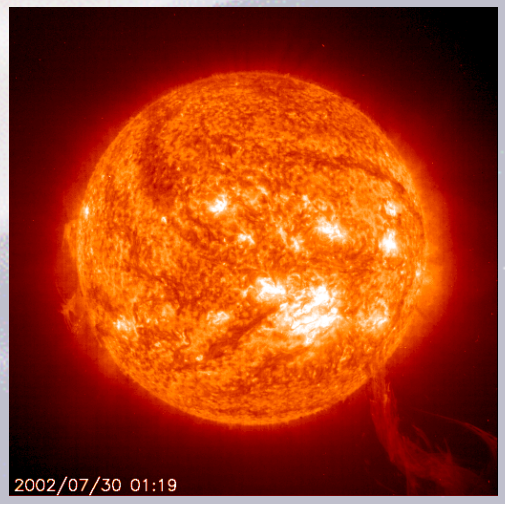
NOAA's Geoelectric Field Modeling

Outline

- Introduction
- Geoelectric Field Modeling
- Summary

NOAA/SWPC
Boulder, Colorado



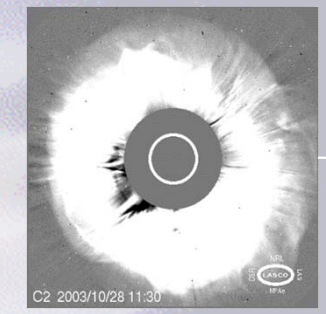


Christopher Balch – NOAA/SWPC

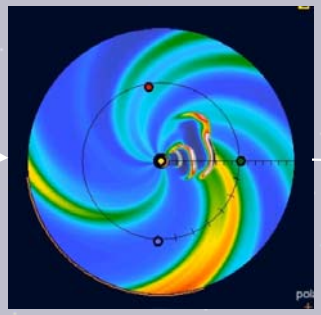
Introduction

- **NOAA Space Weather Prediction Center Mission:**
  Safeguarding Society with Actionable Space Weather Information
- **SWPC is one of NWS's national prediction centers**
- **Space Weather Forecast Office - staffed 24 hours x 7 days**
- **Synthesis of space weather data and information**
- **Nation's official source of space weather alerts, warnings, watches and forecasts**

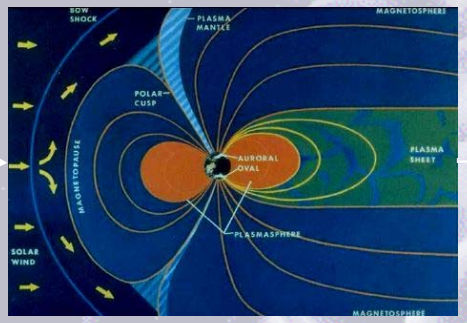
Cause & Effect - Sun to Mantle - I



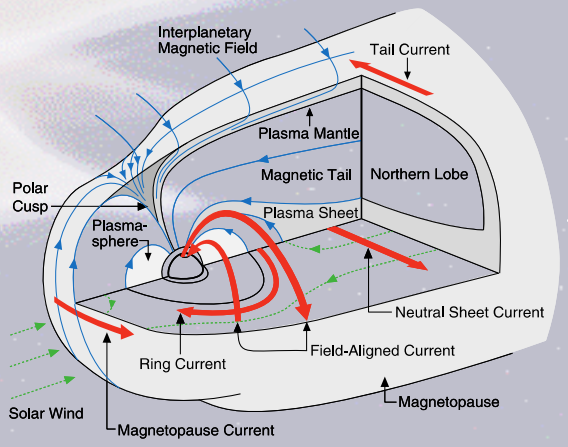
SOHO C2 data courtesy of the NASA/ESA



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).

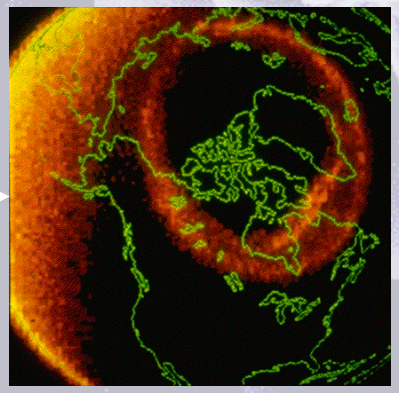
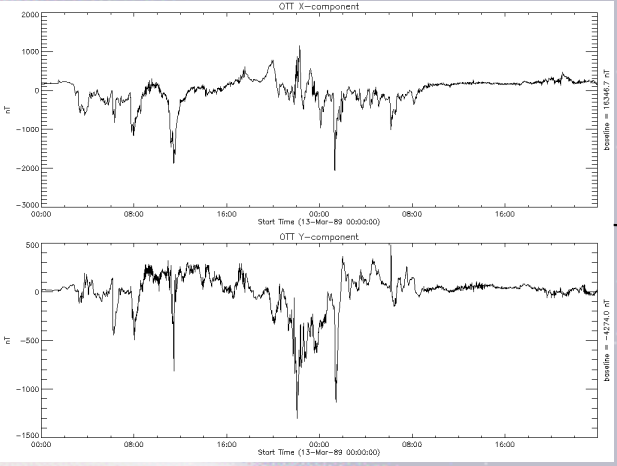


Image of the auroral oval from the Dynamics Explorer 1 Satellite (Louis Frank)

Cause & Effect - Sun to Mantle - II



Input: Geomagnetic Field Time Series

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

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

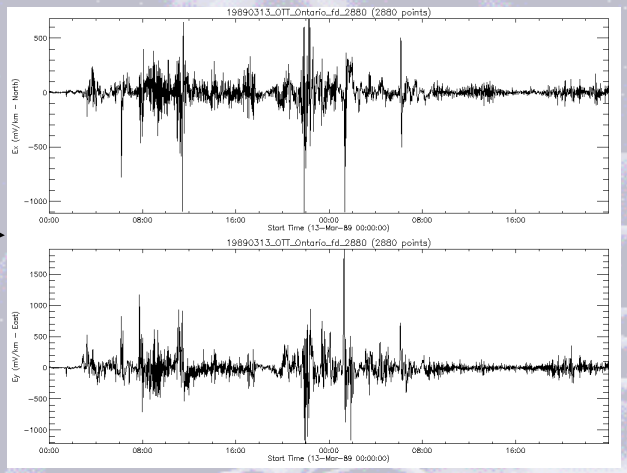
Earth Conductivity:

-frequency dependent filter

-varies with location

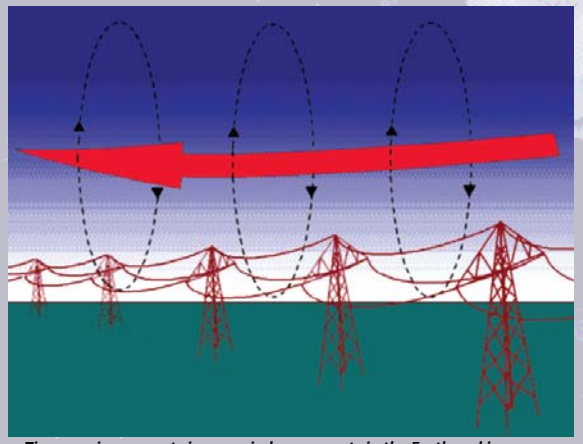
-depends on structure

<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

Geoelectric Field Modeling

Motivation

- To provide the Electric Power Industry a better indicator than a global index (e.g. Kp index/G-scale) to specify geomagnetic activity levels
- The Geoelectric Field is the key space weather parameter that is needed
- Geoelectric Field provides targeted, local-regional description of activity that is directly related to system impact
- Together with a system model, the geoelectric field provides an estimate of geomagnetically induced current in the system

Acknowledgements

- The Geoelectric Field mapping project is a collaborative effort between NOAA/SWPC, USGS, NASA/CCMC, and NRCAN Space Weather (Balch, Camporeale, Millward, Kelbert, Rigler, Lucas, Pulkkinen, Boteler, et al.)
- The Geoelectric Field Mapping relies on data provider partners: USGS & NRCAN near real-time ground based magnetometer data
- NSF's Earthscope project, OSU, USGS and IRIS are key providers of improved Earth-conductivity information.
- We appreciate numerous collaborators in the power industry who are assisting with model evaluation, validation, and feedback

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) (e.g. 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) (3D empirical model)
  - 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') (Future)

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:**

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

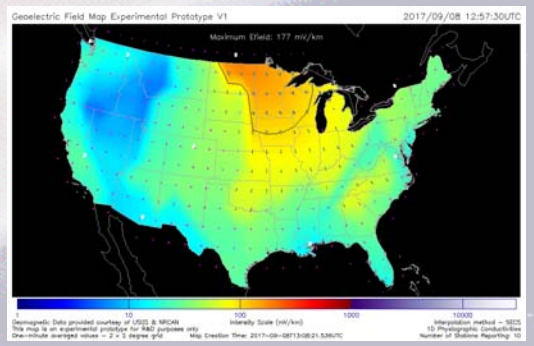
E-field maps dataflow – 1D model

USGS observatories (9)
B-field time series

NRCAN observatories (9)
B-field time series

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

→ E-field calculation: 2°x2° grid,
Fernberg 1D conductivities → E-field products:
-graphical maps
-gridded data files
-daily netcdf (for archive/repository)
-GeoJSON format for dissemination



Operational deployment
completed in September 2019

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

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

E-field maps dataflow – 3D empirical model

USGS observatories (9)
B-field time series

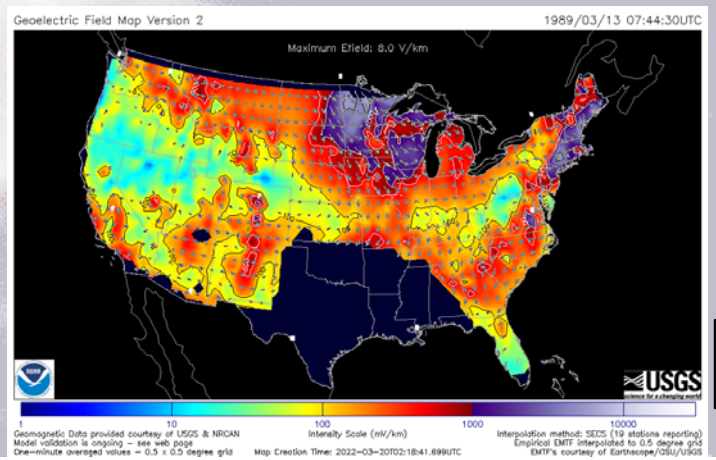
NRCAN observatories (9)
B-field time series

→ Detrending Algorithm

→ Interpolation Algorithm
B-field on 0.5°x0.5° grid
daily netcdf for archive

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

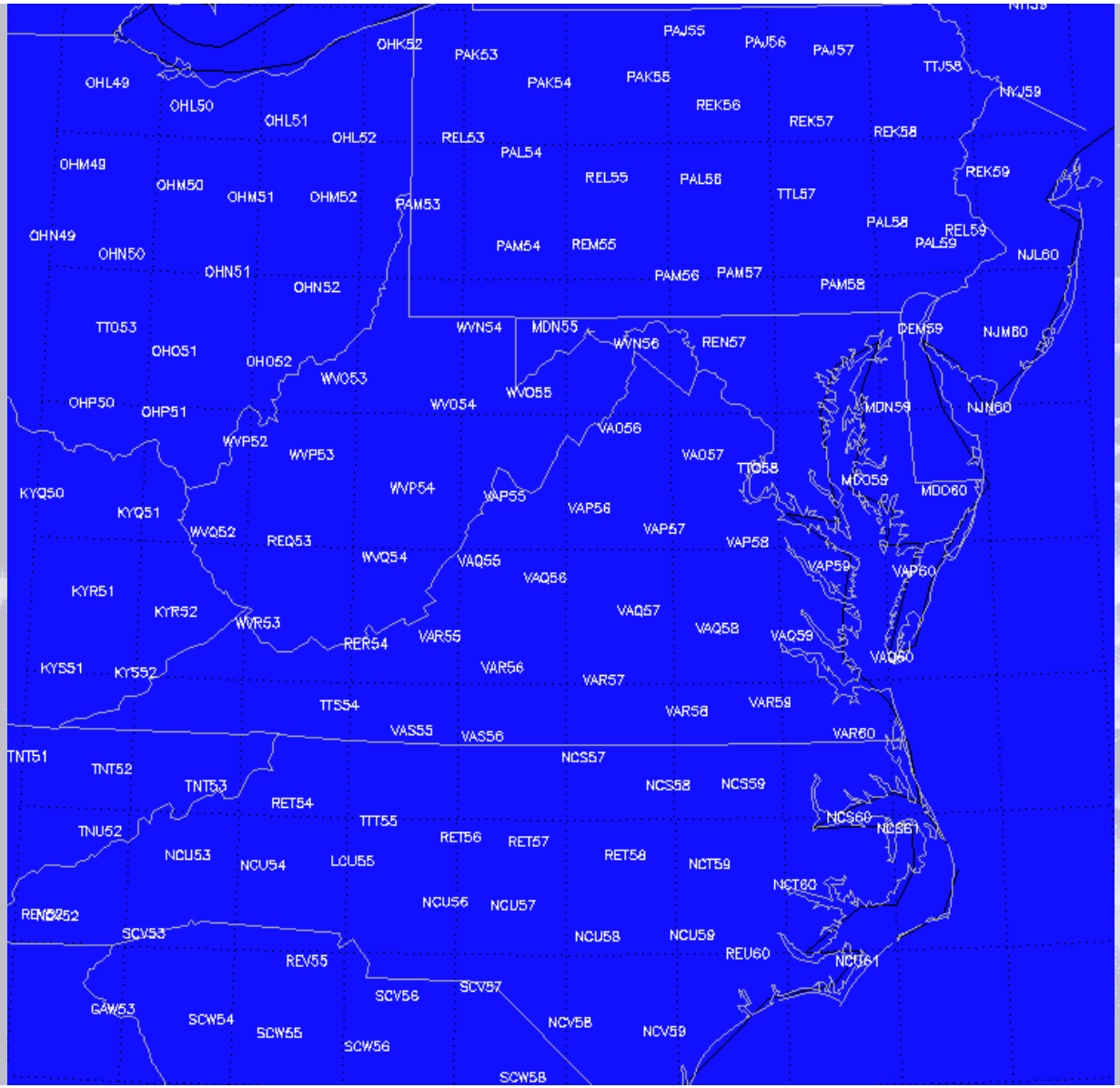
→ E-field products:
-graphical maps
-gridded data files
-daily netcdf for archive/repository
-GeoJSON format for dissemination



-Initial Operational Release September 2020
-Upgrade using new EMTF surveys March 2022
-Future upgrades planned as more surveys are completed

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

Survey Sites the mid-Atlantic Region



E-field maps dataflow – Joint SWPC/NRCAN US-Canada 1D Experimental Product

USGS observatories (9)
B-field time series

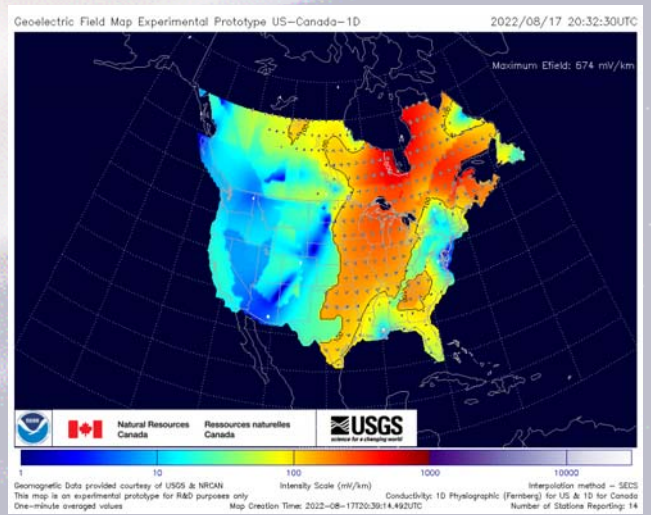
NRCAN observatories (9)
B-field time series

→ Detrending Algorithm

→ Interpolation Algorithm
B-field on 0.5°x0.5° grid
daily netcdf for archive

→ E-field calculation:
-1D models over US & Canada
-0.5 degree spatial resolution
-3568 grid points

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



Release as public experimental product will be soon
SWPC plans for operational deployment by 6/30/2023

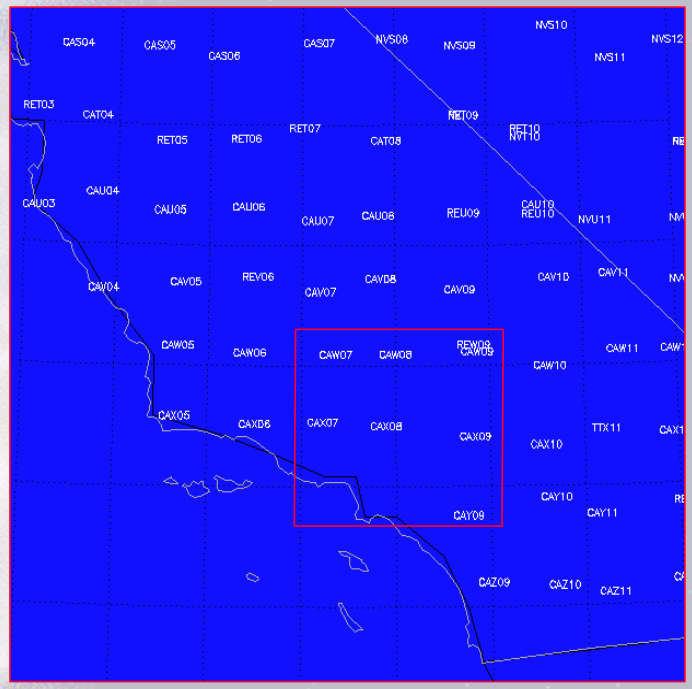
1D models over CONUS will be ‘fine-tuned’ to be as consistent with the 3D models as possible

Quality flags will be implemented to indicate areas where correlation with 3D models is poor

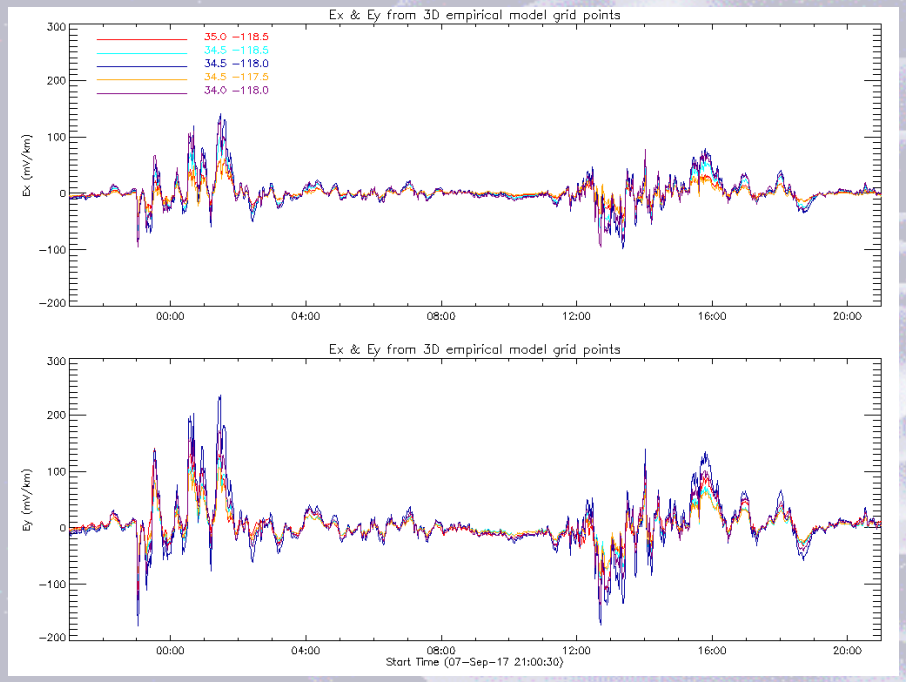
Validation Studies

- The validation of E-field maps for GIC applications is ongoing
- Our approach is to partner with industry to compare calculated GIC with measurements
- We select intervals of disturbed geomagnetic activity, calculate the geoelectric field, and then estimate GIC in the system using system models
- For the system model
  - Off-the-shelf, vendor provided tools can be used. Many of these tools are able to ingest geojson format E-field results
  - For simpler situations, we can do a circuit analysis to calculate GIC (following Lentinen & Pirjola, 1985, see also Horton et al. 2012)
- Active collaborations with SCE & TVA
- A valid model can then be used to study the impact of more extreme storm events (e.g. March 1989)

Validation Study



Study area in the context of regional MT surveys used in the Geoelectric field model



Calculated Geoelectric Fields during the September 07-08, 2017 storm

Induced voltage for line LV

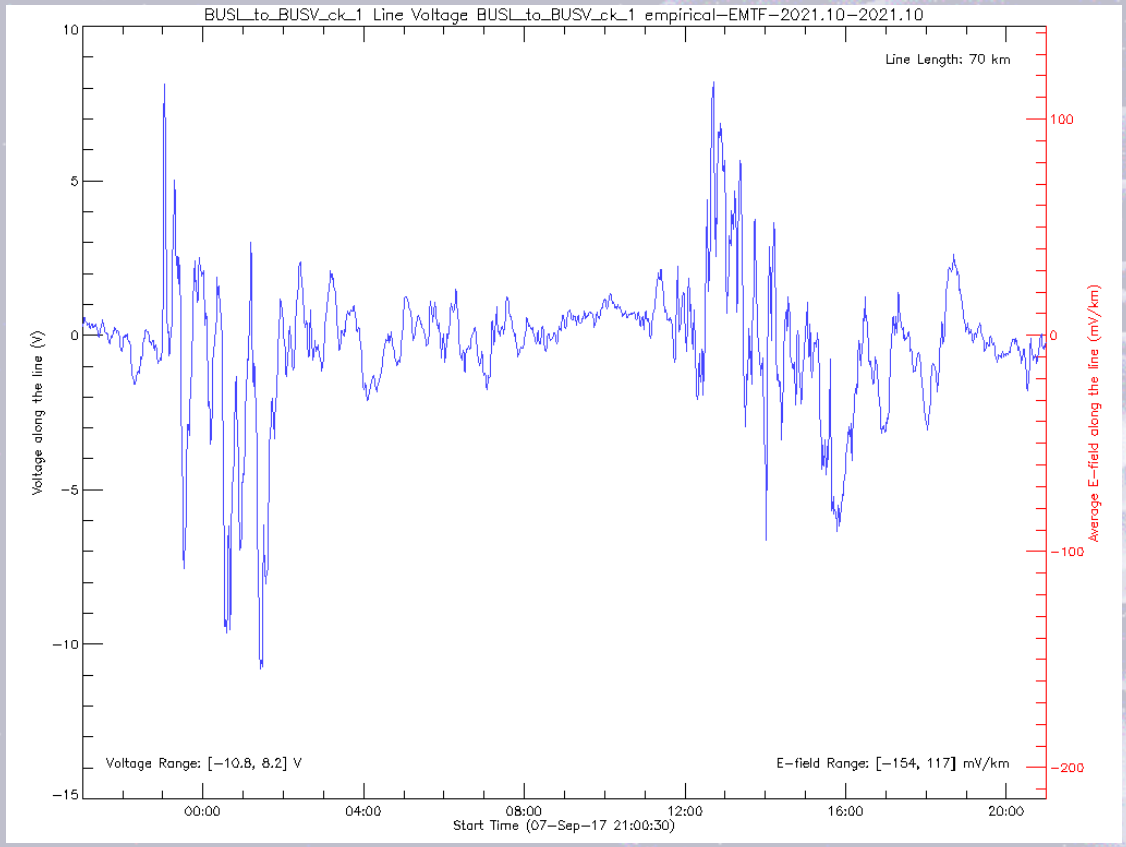
This integration uses the E-field values interpolated from the model grid points to the segments along the line

Time Series for v_{LV}

Induced Current on LV:
$j_{LV}=v_{LV}/R_{LV}$

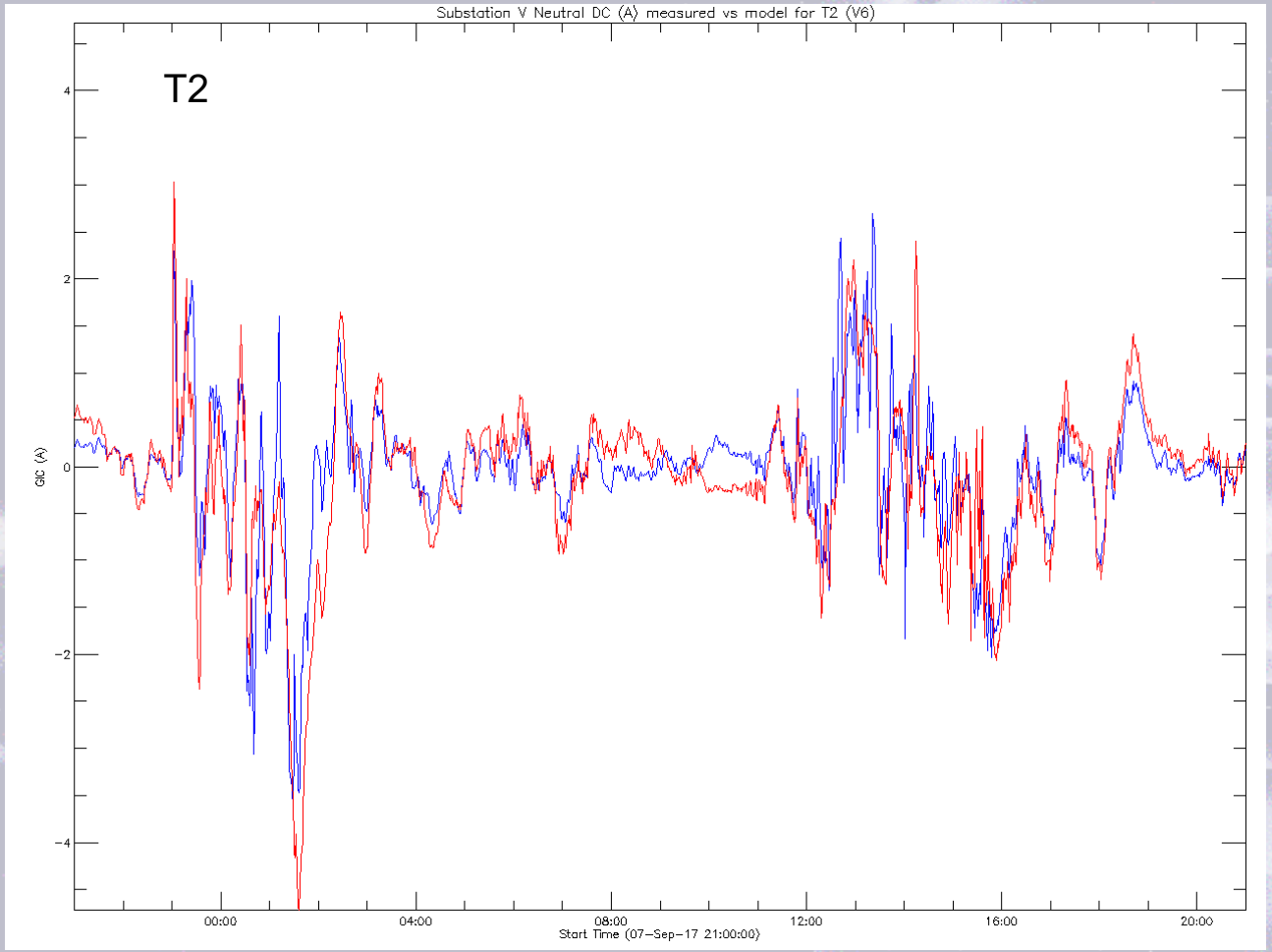
R_{LV} = 0.488067 Ω/phase

This integration is calculated for all 6 lines flowing into the substation where GIC is measured



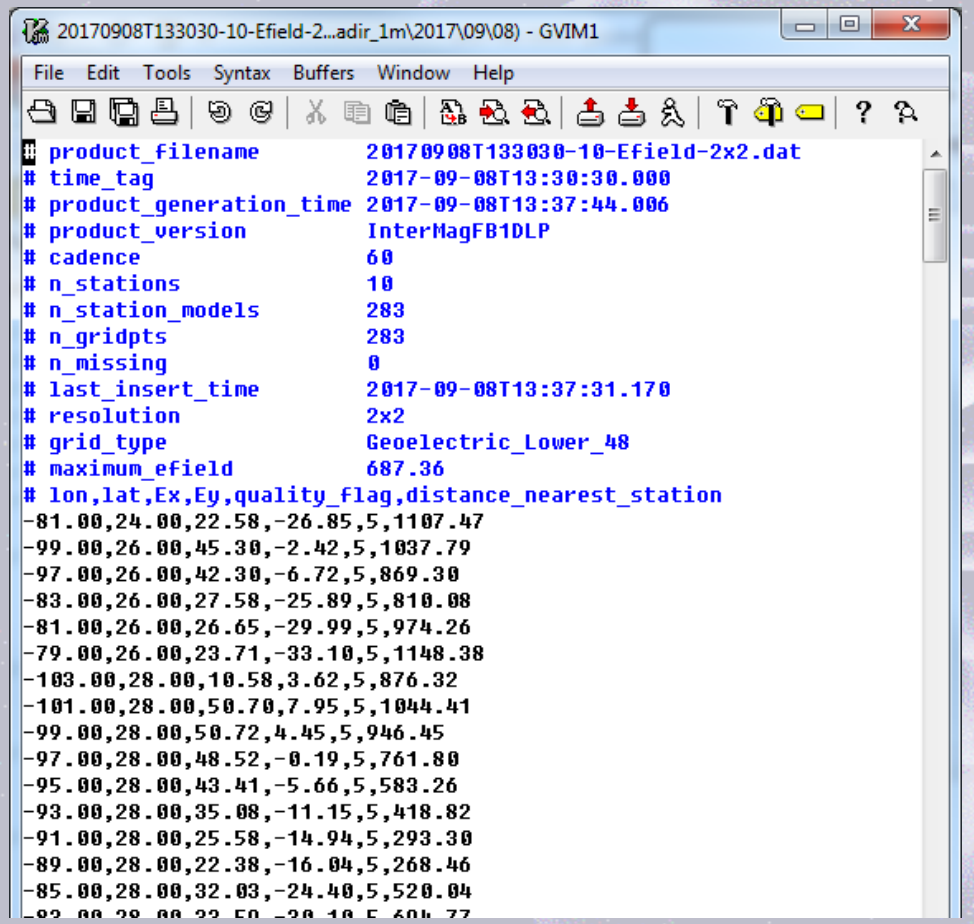
GIC Model vs Observation – transformer T2 in substation V

Model – blue
Observation - red



Geoelectric Field Gridded Data Product

Sample gridded data output
One ascii file per minute



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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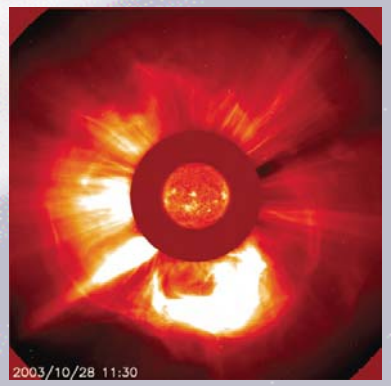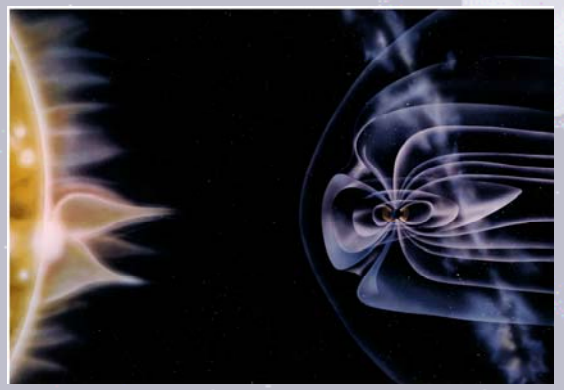
Questions?