Integrating space weather and ground-based magnetotelluric data with powerflow solutions for real-time assessment of risk to the power grid

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Space Weather Workshop, Boulder CO 3-April-2019

Goal – risk assessment, real-time or better mitigation

Utility control room operators need 15 min heat map forecast for actionable human intervention in control loop

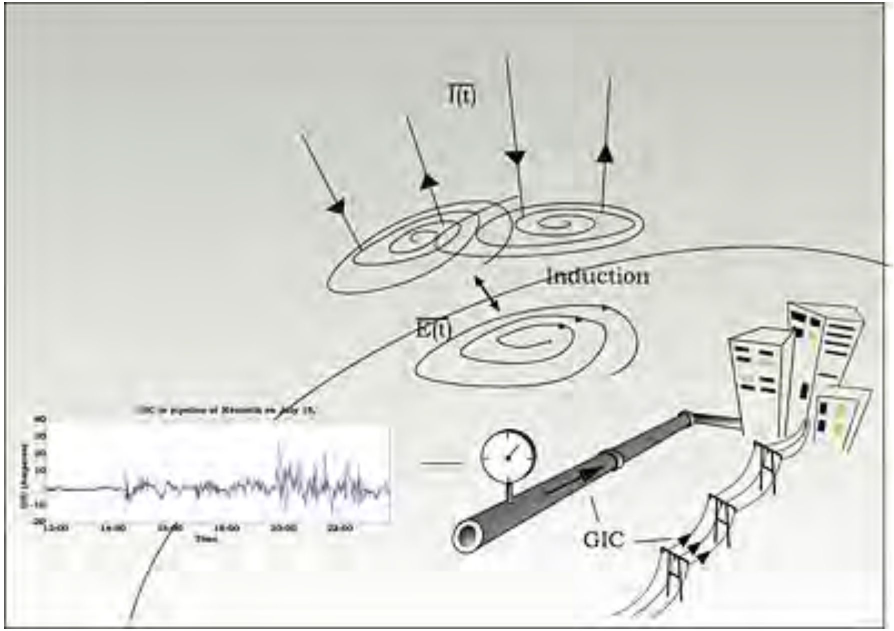


Figure source: (left) Antti Pulkkinen, NASA.
(right) A Generator Step Up (GSU) transformer failed at the Salem River Nuclear Plant during the March 1989 geomagnetic storm. The unit is depicted on the left; some of the burned 22kV primary windings are shown on the right. Though immersed in cooling oil, the windings became hot enough to melt copper, at about 2000 degrees F. John Kappenman, Metatech

Political/Regulatory

GMD/GIC Risk Assessment and Mitigation – requirements and regulatory framework

- The National Space Weather Action Plan and NSWA Strategy [NSTC, 2015; update 2019]
- Executive Order 13744 [Obama, 2016]
- Federal Energy Regulatory Commission (FERC) Orders 779 [2013], 851
- North American Electric Reliability Corporation (NERC) TPL 007-1,2/3

Risk assessments must factor in ground conductivity; mandate transmission system sensor and magnetic field data to be collected

EMP

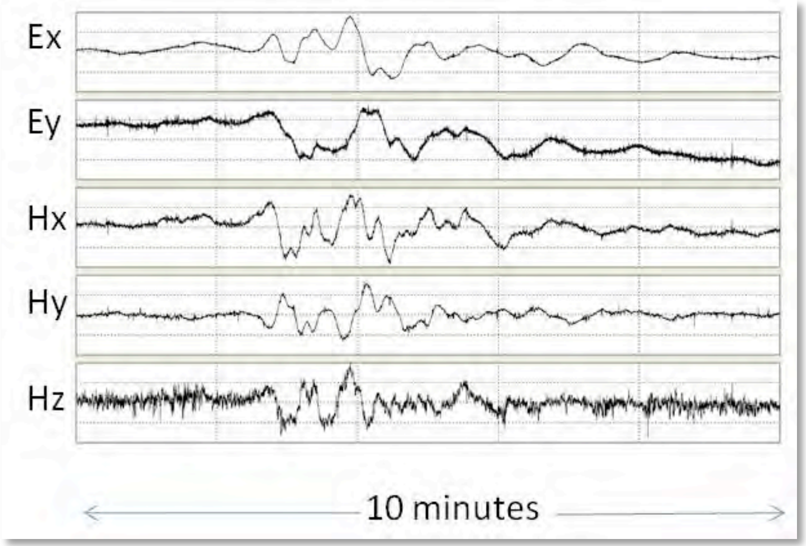
- Executive Order 13865 [Trump, March 26, 2019], President’s Budget Request FY2020

Sect’y Interior directed to:

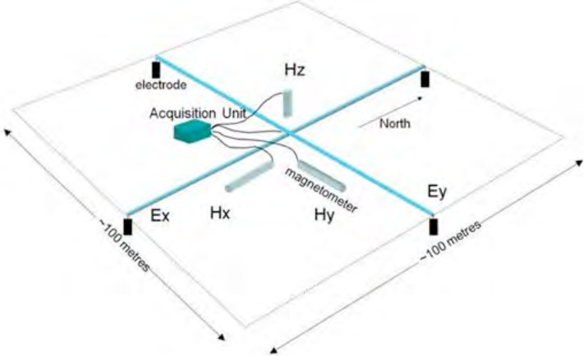
1) Support the research, development, deployment, and operation of capabilities that enhance understanding of variations of Earth's magnetic field associated with [natural and human-made electro-magnetic pulses] EMPs, and
2) Within 4 years of the date of this order, the Secretary of the Interior shall complete a magnetotelluric survey of the contiguous United States to help critical infrastructure owners and operators conduct EMP vulnerability assessments.

The Magnetotelluric (MT) Method

By measuring the electric (E) and magnetic (H) fields at the Earth's surface, we determine the frequency dependent *impedance tensor*, which we use to image the electrical conductivity structure of the **near-surface** through the **upper mantle, and to assess the impact of geomagnetically induced currents in critical infrastructure.**



Given **H** and **Z**, **E** can be predicted; **Z** acts like linear filter on H projecting magnetic field to electric field



$$E_x(f) = Z_{xx}(f)H_x(f) + Z_{xy}(f)H_y(f) + noise$$

$$E_y(f) = Z_{yz}(f)H_x(f) + Z_{yy}(f)H_y(f) + noise$$

$$\begin{bmatrix} E_x(f) \\ E_y(f) \end{bmatrix} = \begin{bmatrix} Z_{xx}(f) & Z_{xy}(f) \\ Z_{yz}^{yx}(f) & Z_{yy}(f) \end{bmatrix} \begin{bmatrix} H_x(f) \\ H_y(f) \end{bmatrix} + noise$$

$$\mathbf{E} = \mathbf{ZH} + noise$$

Oregon State University

Status of MT Array Operations

College of Earth, Ocean, and Atmospheric Sciences

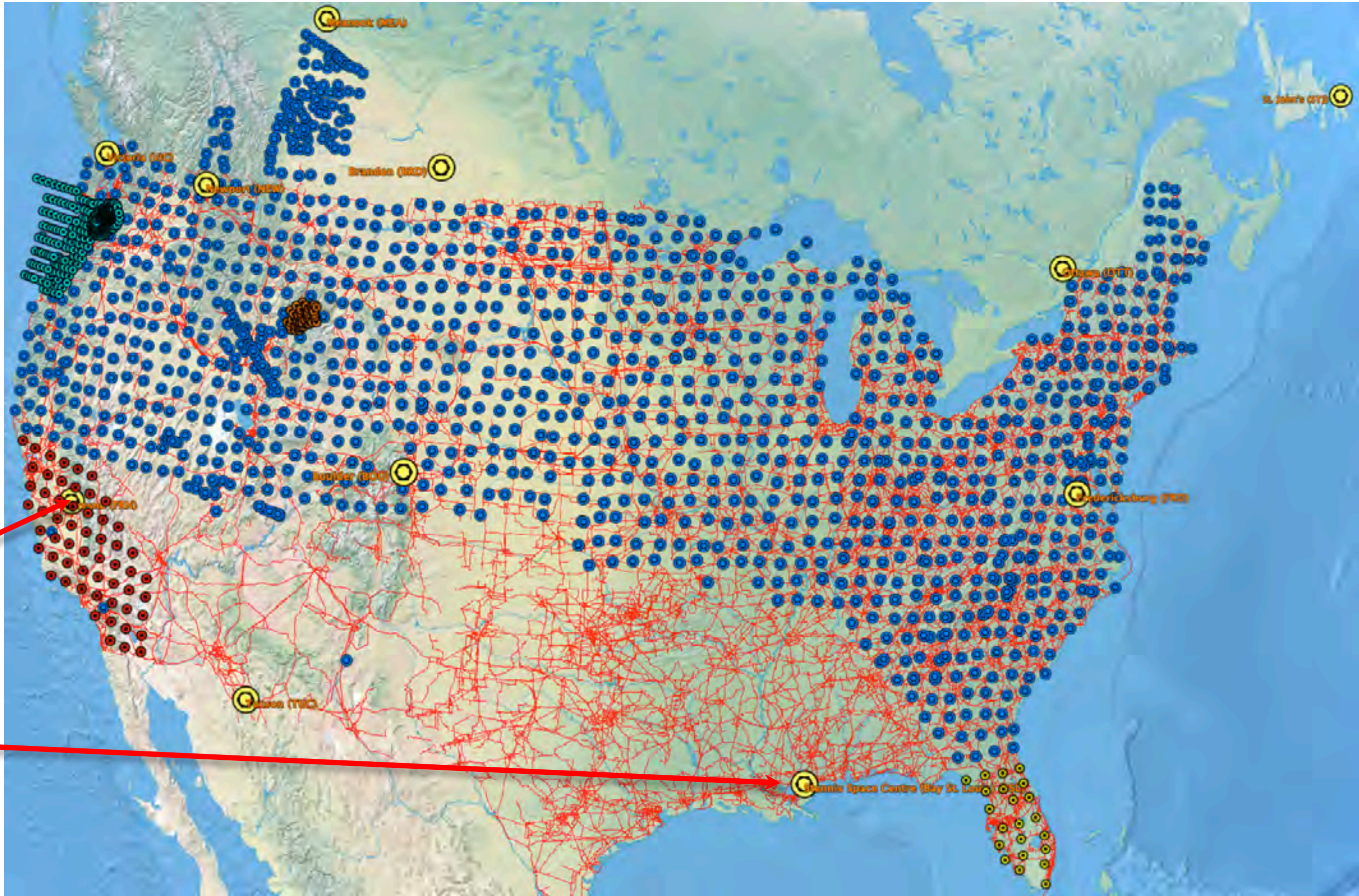
MT Array Operations Center

A unified public domain database of Transportable Array (70-km) station spacing long-period MT station time series, MT response functions available from IRIS.edu

blue dots	1167 OSU/NSF sites
yellow dots	47 USGS sites incl. Parts of FL; TN, AR, MO (not shown)
red dots	54 OSU/NASA sites in CA planned for 2019

Yellow dots:	currently operating mag observatories USGS, NRCan

Note: Fresno, Stennis/BSL, Shumagin support ends this month – particularly unfortunate timing

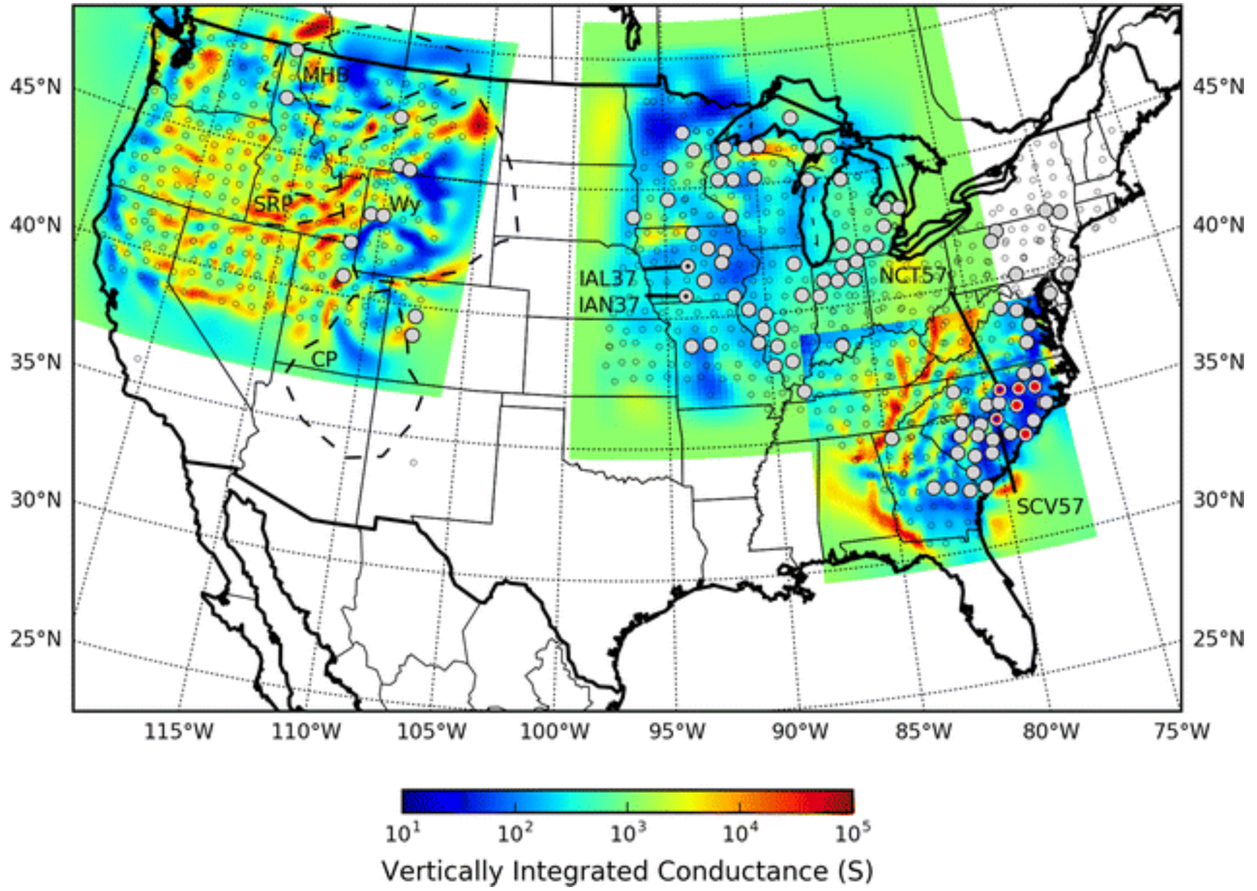


3-4 orders-of-magnitude heterogeneity at all depths

3-D conductivity structure

Vertically integrated Earth conductance (from 15–150 km) calculated from the 3-D MT inverse solutions of Meqbel et al. (2014) (northwestern USA), Yang et al. (2015) (north-central USA), and Murphy and Egbert (2017) (southeastern USA).

[From: Murphy & Egbert, 2018]



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Rare example of simultaneous MT and transmission system sensor data during a GMD

IRIS

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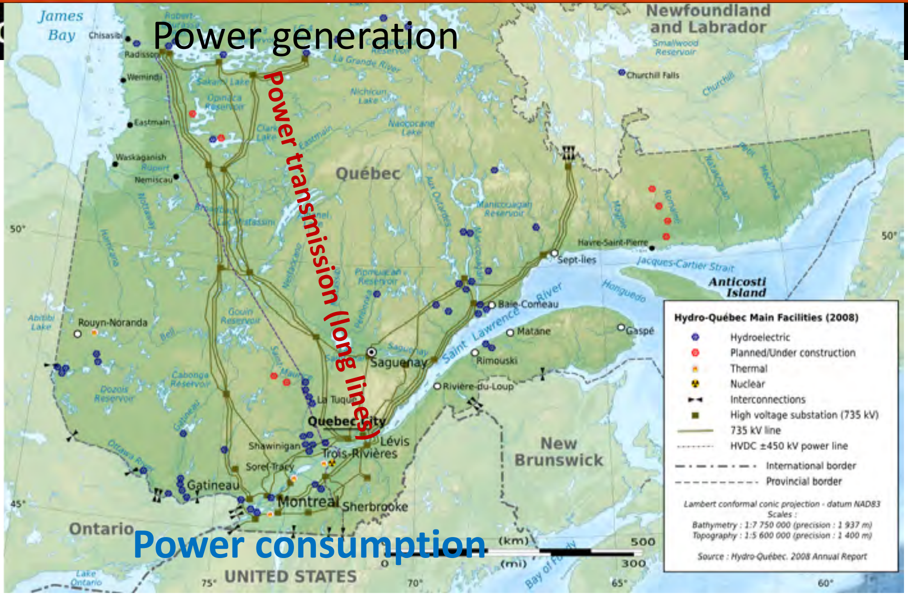
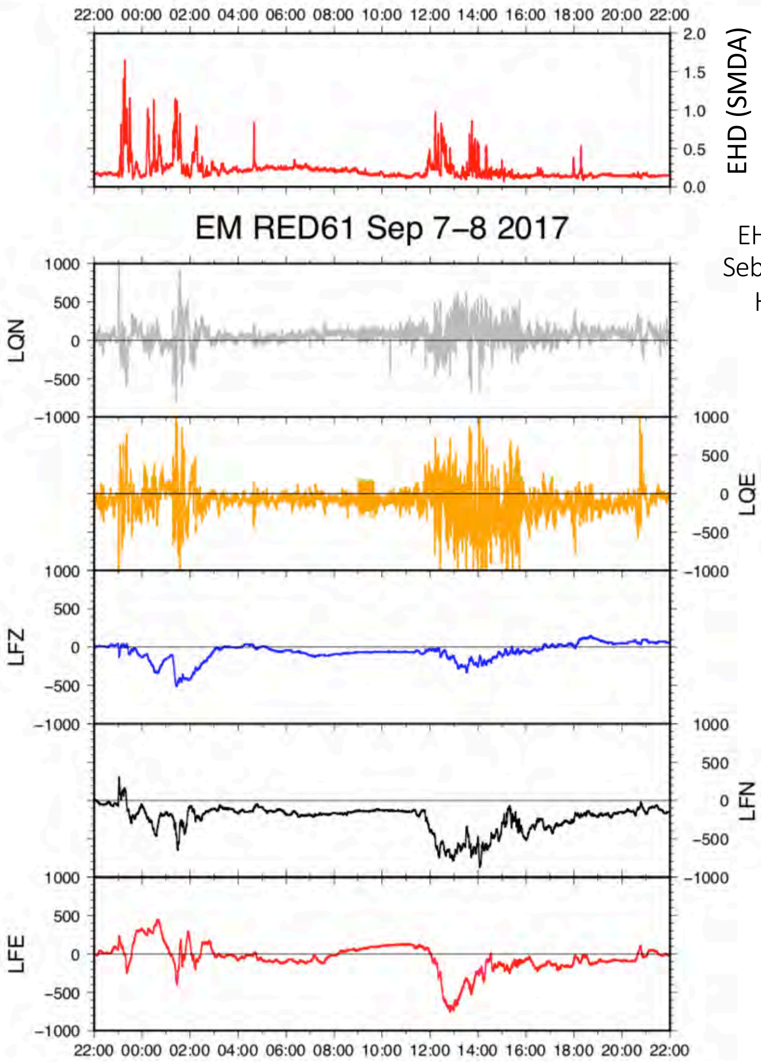


Coherency between ground electric fields recorded at OSU/NSF EarthScope MT stations (this example: SW Maine) and Even Harmonic Distortion in voltage measured on Hydro-Québec transmission system



EHD (top) credit: Sebastién Guillon, Hydro-Québec.

Electric field (N-S at top, then E-W) components, magnetic field (vertical, N-S then E-W) components from an OSU EarthScope MT station in SW Maine during a GMD in September, 2017.

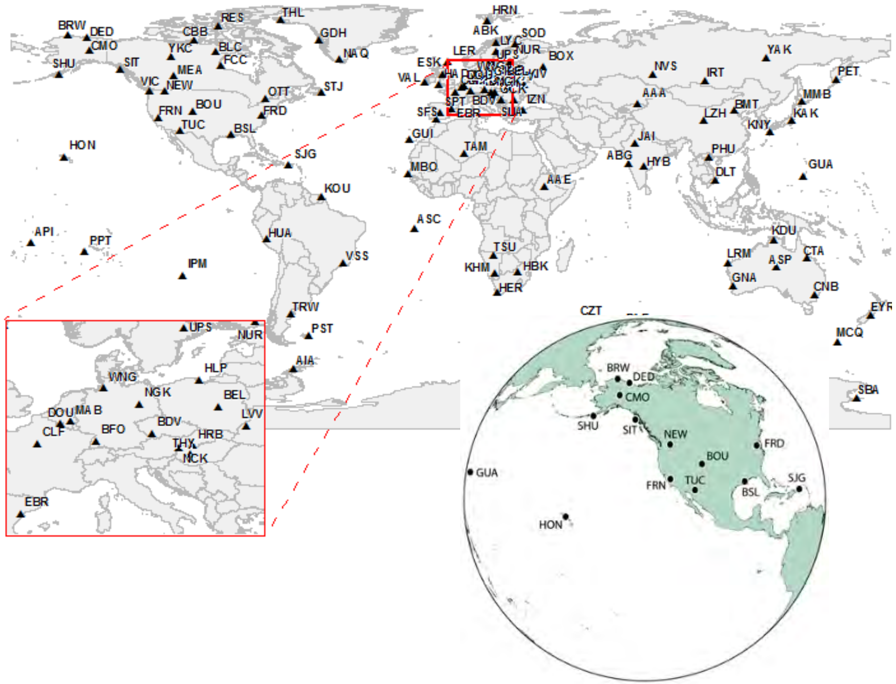
Top panel – Even Harmonic Distortion (harmonics 2,4,6,8 as percentage) in voltage, measured on Hydro-Québec power grid during the GMD.

Predicting ground magnetic fields

MT stations are generally temporary and there are few magnetic observatories or long-term variometer stations. How do we know the magnetic field today at a location distant from an observatory when no magnetometers are installed?

Real-time predictions based on real-time geomagnetic observatory data streams:

- Physics model based methods such as spherical elementary currents (Amm & Viljanen, 1999; Pulkkinen et al., 2003)
- Geometrical projection method using multi-observatory-to-MT station transfer function (Bonner & Schultz, 2017)

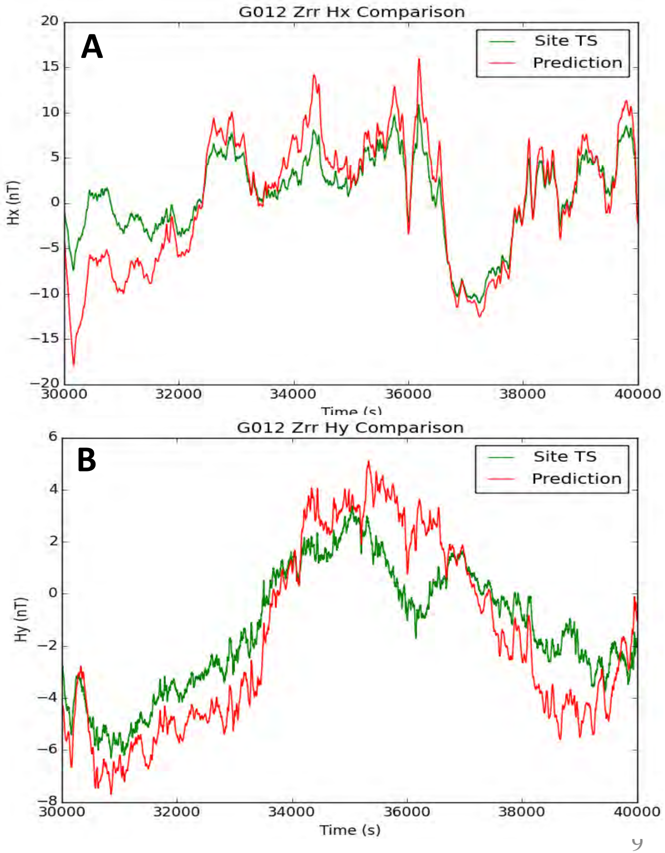


Predicting ground magnetic fields

Real-time prediction of the magnetic field near Portland, Oregon by projecting the magnetic fields at:

- Newport, WA
- Fresno, CA
- Boulder, CO
- Honolulu, HI

through the multi-station transfer function for that location



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Geomagnetic field spatial complexity

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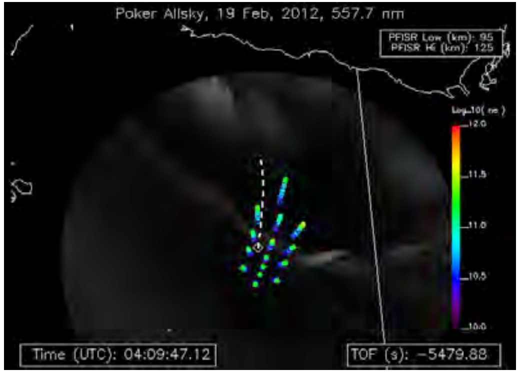
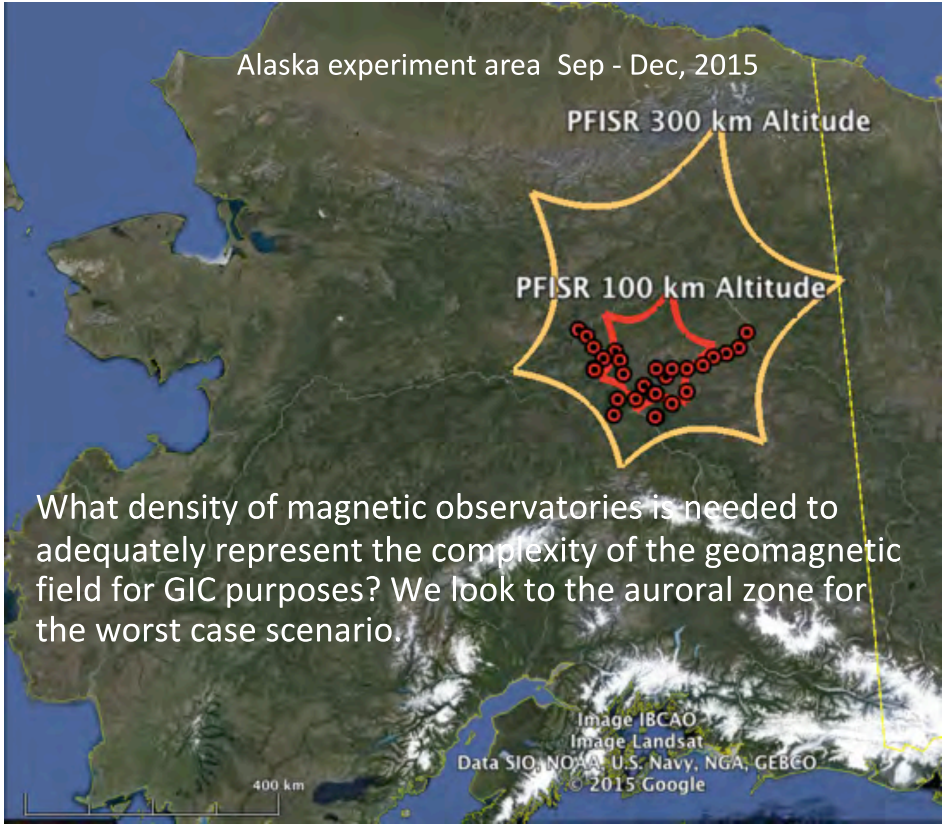


Project support: NSF-AGS and EAR

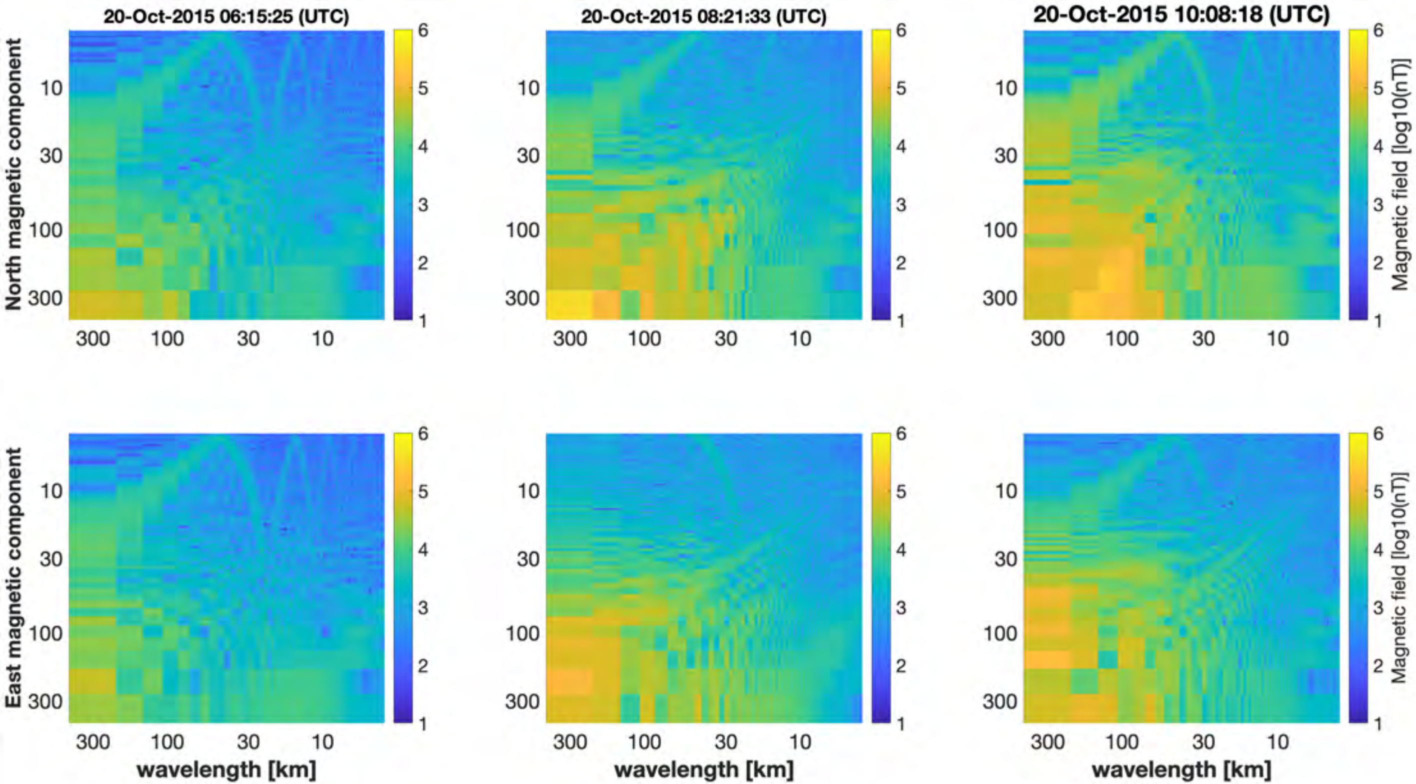
Poker Flat PFISR
(Advanced Modular Incoherent Scattering Radar)



Geomagnetic field spatial complexity – downward continuation of ionospheric B fields for $f < 0.1$ Hz

North and east magnetic field wavelength spectra above Poker Flat AK PFISR array from equivalent thin sheet (Hall) currents for 3 different snapshots. Peak k_p=2.7, AE=1000 nT

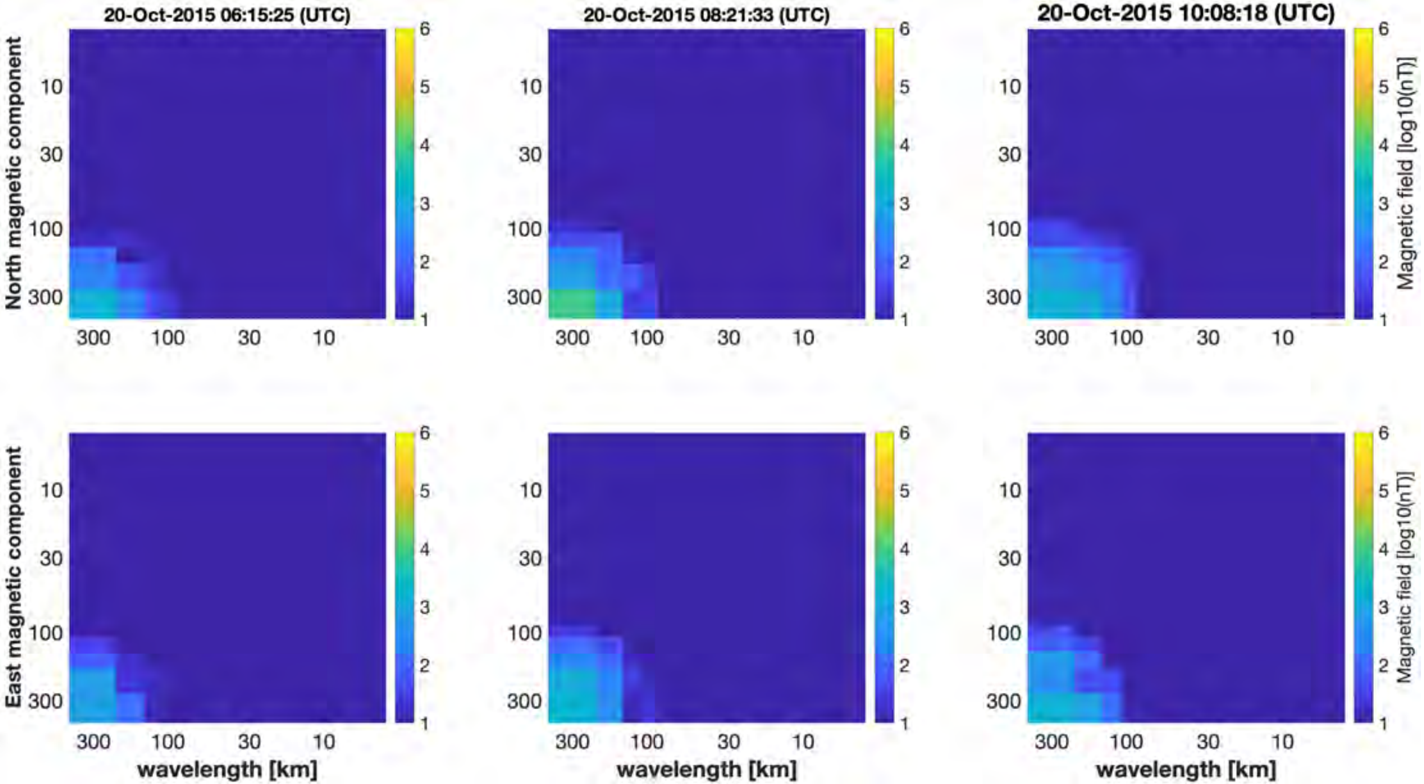
At base of ionosphere, z = 100 km



Geomagnetic field spatial complexity – downward continuation of ionospheric B fields for $f < 0.1$ Hz

North and east magnetic field wavelength spectra above Poker Flat AK PFISR array from equivalent thin sheet (Hall) currents for 3 different snapshots. Peak k_p=2.7, AE=1000 nT

At ground level,
z = 0 km



Predicting ground electric fields

1. Our approach is to pipe the predicted magnetic fields at the locations of former MT stations through the impedance tensors we obtained for those locations, to obtain the predicted electric fields there

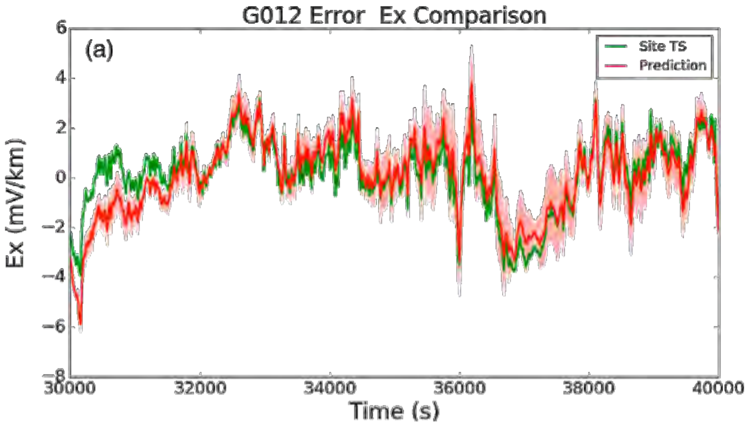
$$\begin{bmatrix}\widetilde{E_x}\\ \widetilde{E_y}\end{bmatrix} = \begin{bmatrix}Z_{xx} & Z_{xy}\\ Z_{yx} & Z_{yy}\end{bmatrix}\begin{bmatrix}\widetilde{H_x}\\ \widetilde{H_y}\end{bmatrix}+\begin{bmatrix}\widetilde{U_x}\\ \widetilde{U_y}\end{bmatrix}$$

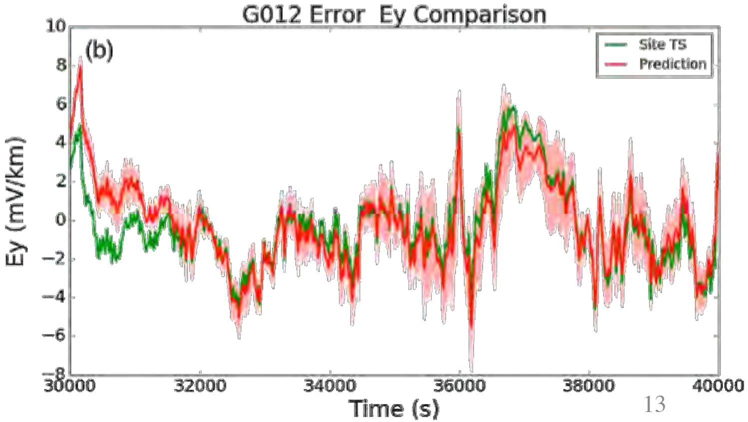
where the tilde indicates the *predicted* field.

2. We use a distance weighted algorithm to project the predicted electric fields from all the neighboring MT station locations onto each point along the transmission line path.

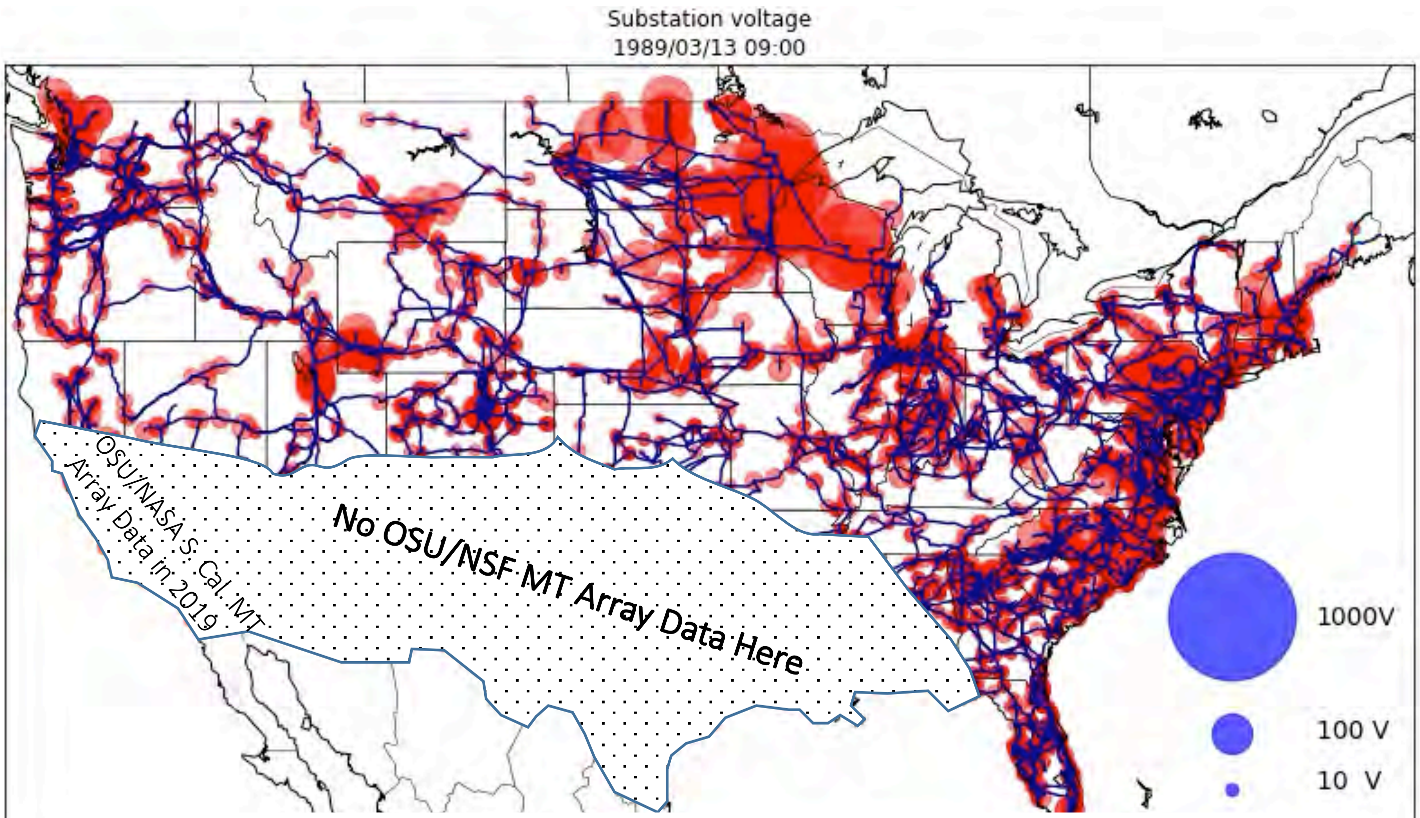
3. Alternatively one can use 3-D models of ground conductivity derived from inversion of the impedance tensors; solve the forward problem, and derive electric fields on a grid of points. This is the USGS/NOAA approach.

4. For our approach, electric field prediction misfits at most sites are typically around 1–2 mV/km RMS at the great majority of MT sites that we have examined (for modest k_p levels, within the BPA operating area) where the distance to the nearest magnetic observatory is < 600 km.





OSU 3-D model calculated voltage at substations due to 1989 GMD, 3/13/1989 09:00-15:00UT (peak GMD)



Note – large GMD induced bus voltages in the South as well as in the North – impact of 3-D ground conductivity

Calculated 3-D ground electric fields integrated along the path of the high-voltage transmission lines. Voltage is shown relative to ground at one Ohio substation.

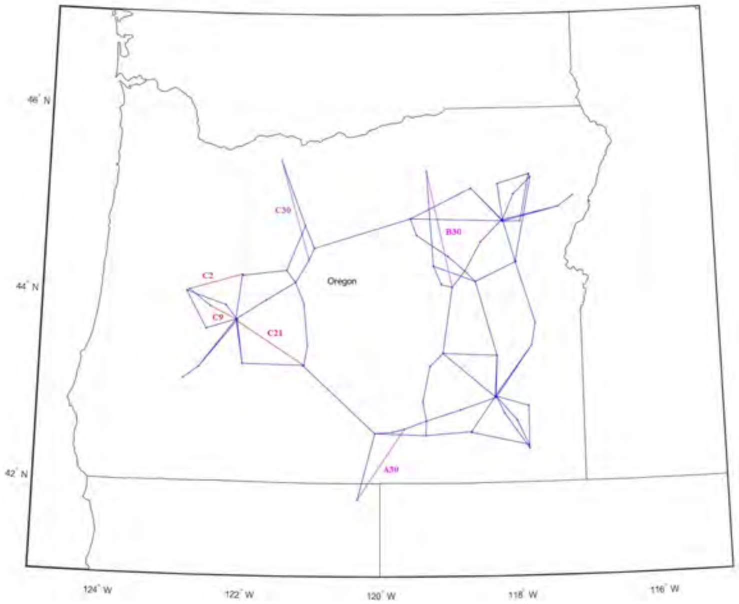
Note – true voltage state calculation requires integration with power flow model.

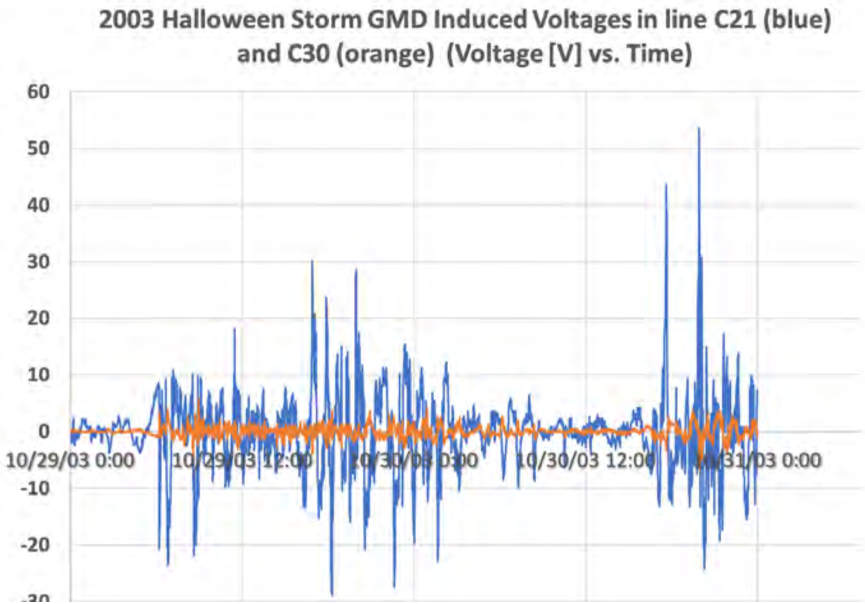
(Path integration and mapping using BEZPy by G. Lucas, USGS)

Power Flow example – 2003 Halloween Storm

High-voltage transmission system line voltages induced by GMD using OSU/NSF EarthScope 3-D ground impedance information and magnetic field algorithm.

For power transmission network we've used the RTS-GMLC (Reliability Test System Grid Modernization Lab Consortium) test case but moved to Oregon, and currently we are using LANL's Julia and PowerModelsGMD package, for power flow simulations on the test case, and to determine the GIC flows and possible impacts on the power waveforms in the system elements.





Note – the orientation of the transmission lines and 3-D ground induction effects that vary throughout the region lead to dramatic variations in transmission line induced voltages. The longest transmission line does not necessarily have the largest voltage.

Acknowledgements

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