Mitigating Space Weather Impacts on the Power Grid in Real-Time: Applying 3-D EarthScope Magnetotelluric Data to Forecasting Reactive Power Loss in Power Transformers

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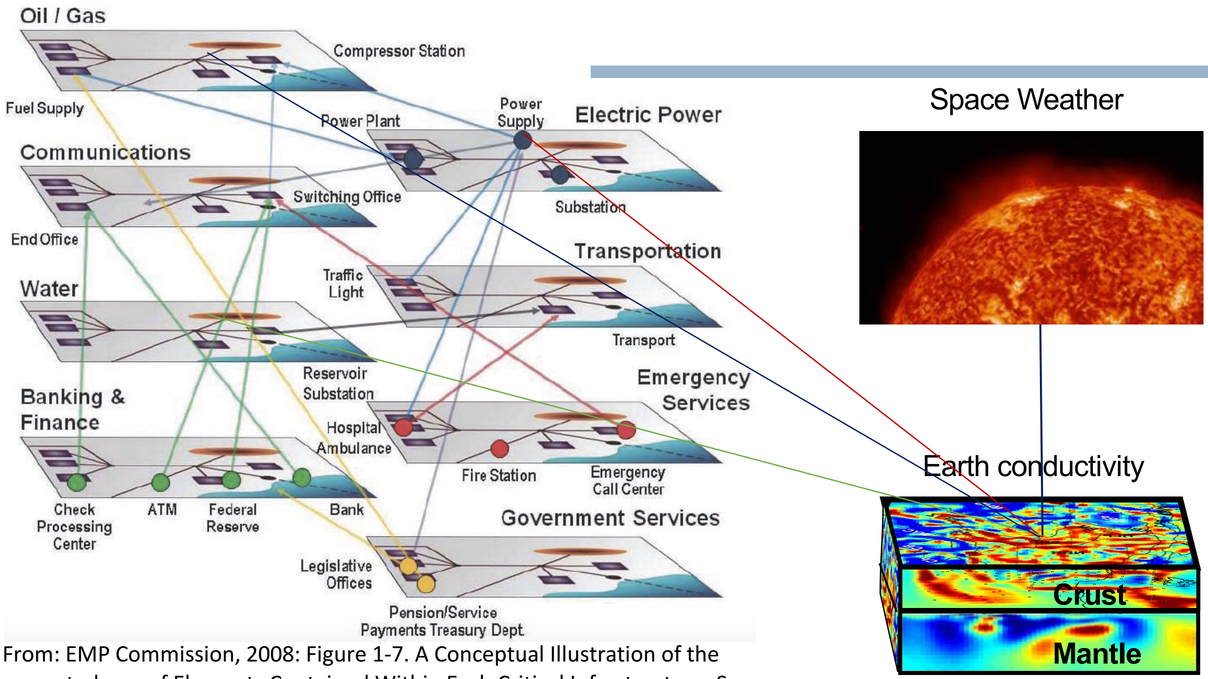
SH31D-03, 08:36 - 08:50, Morial 243-244

Interconnections: Critical infrastructure/Electromagnetic environment



(left) From: EMP Commission, 2008: Figure 1-7. A Conceptual Illustration of the Interconnectedness of Elements Contained Within Each Critical Infrastructure. Some connections are not shown (diagram provided courtesy of Sandia National Laboratory).

"In practice, understanding the interdependence may be a difficult task because subject area experts are not necessarily attuned to coupling mechanisms that span the boundary between their respective discipline and another, and because an accurate representation of the interdependence requires a familiarity with transdisciplinary phenomena." –

Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack – Critical National Infrastructures, 2008.

GICs and 3-D ground electrical structure

Accurate prediction of GIC intensity depends on the accurate prediction of the **intensity** and the **direction** of the electric field **at ground level** near power grid infrastructure

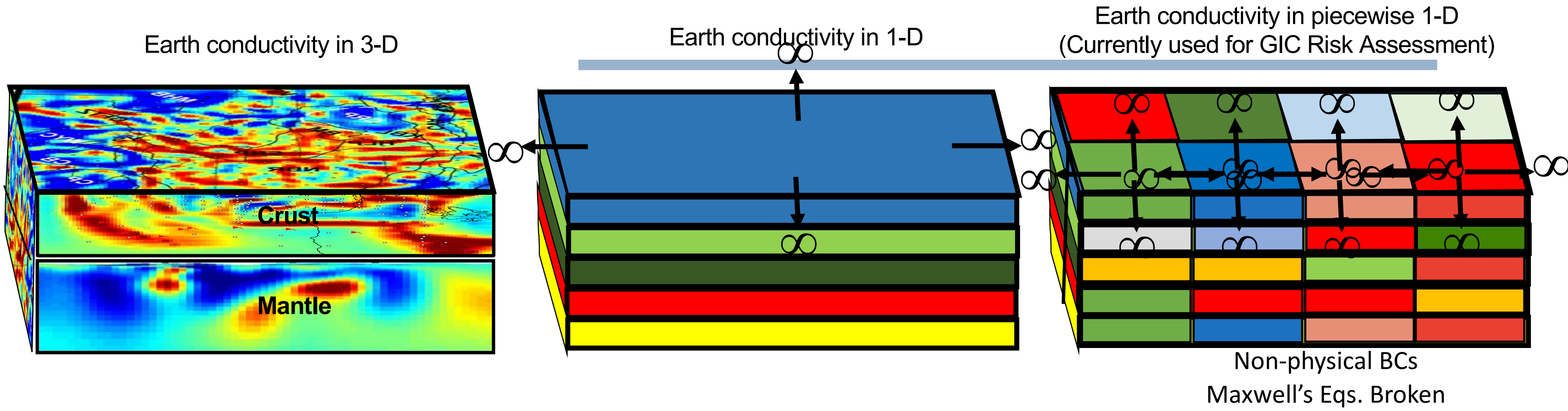
1. During a GMD, low frequency magnetic field time variations induce electric currents to flow through a wider and deeper volume of the crust and mantle than higher frequency variations; **different GMDs may produce different ground E-fields**

2. If ground conductivity is 1-D, an assumption currently used for GIC vulnerability assessments, the horizontal electric field always points 90 degrees from the horizontal magnetic field, and the intensity of the electric field does not depend on the direction of the magnetic field

3. If ground conductivity varies in 3-D, the horizontal electric field can point in varying directions relative to the magnetic field, depending on the orientation of the magnetic field, and its intensity may vary dramatically even with small changes in the direction of the magnetic field – **no 1-D model or set of adjoining 1-D models (no matter how fine-scale) within a 3-D region will produce the same ground electric fields as a 3-D model**

Interconnections: critical vulnerability

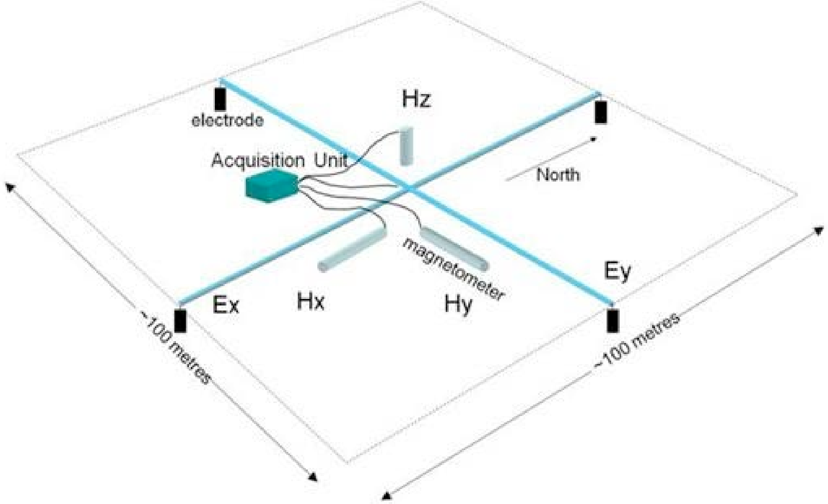
For a given inducing magnetic field, the induced electric and magnetic fields above a fully 3-D Earth behave fundamentally differently than those for a 1-D Earth



- We will consider the impact of this using real-world data, which indicates the assessed vulnerability of these systems may be significantly biased. We will also suggest means to address this.

The Magnetotelluric (MT) Method: By measuring the electric and magnetic 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.**

(left) installing an MT data acquisition system; (right) the two horizontal electric field dipole sensors and two horizontal and one vertical magnetic field sensor.



NSF EarthScope MT Project Update

EarthScope MT Transportable Array

Temporary stations every ∼70 km

Each station operates for ∼3-4 weeks

~1000 US stations completed by Oregon State Univ.

95 Canadian stations completed by Univ. Alberta

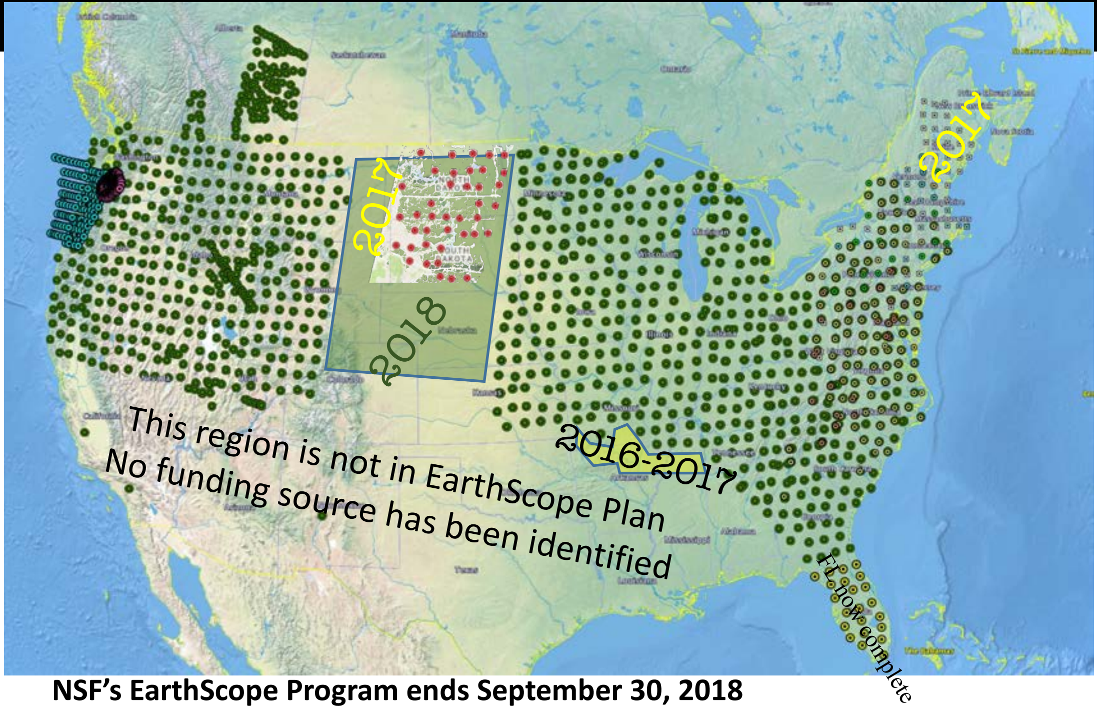
>100 US stations planned for 2018

MT FlexArray

Temporary stations every ~2 – 20 km
Each station operates days – months

424 long-period and wideband MT stations installed every ~2-20 km in PacNW, SW and Alaska

Operated for ~2-5 days (typically; sometimes longer)

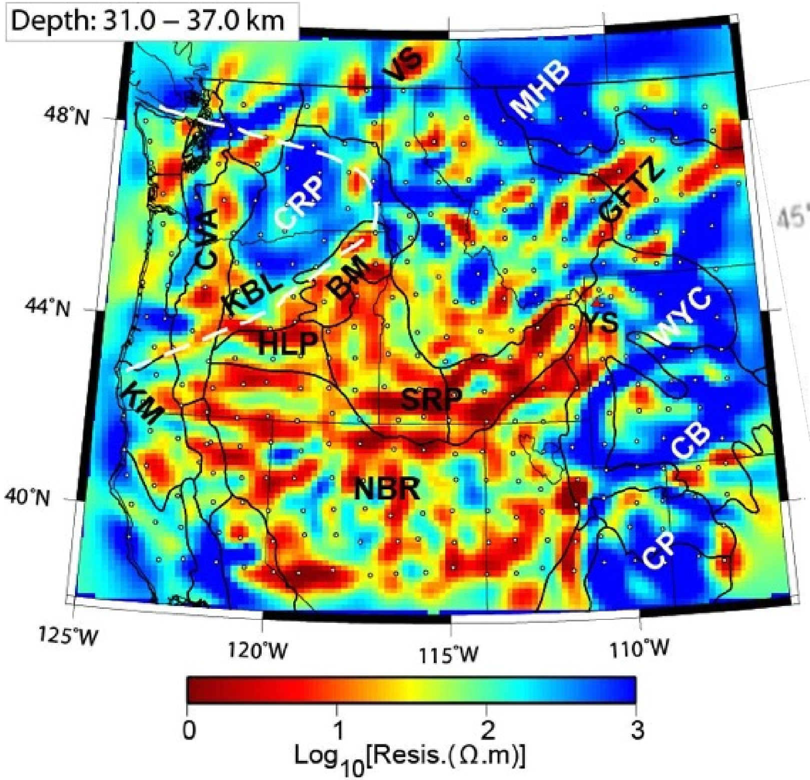


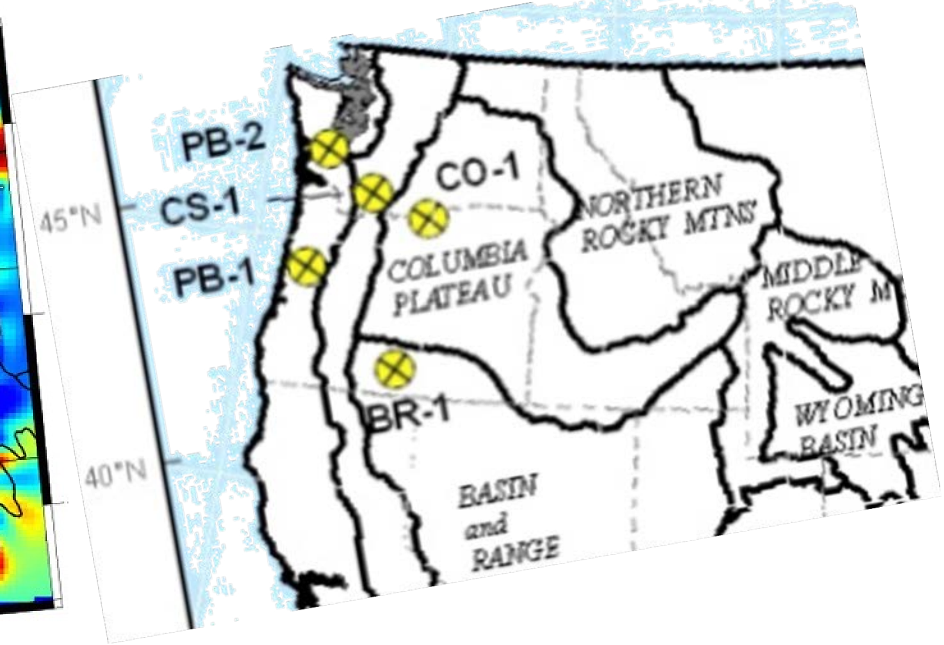
NSF's EarthScope Program ends September 30, 2018

EarthScope was motivated by fundamental geoscience questions, not GICs

Texas, Oklahoma, most of Arkansas, Gulf Coast States, S. Cal/Ariz/NM, S Colorado and SW Kansas will not be covered under current support, which ends in 2018

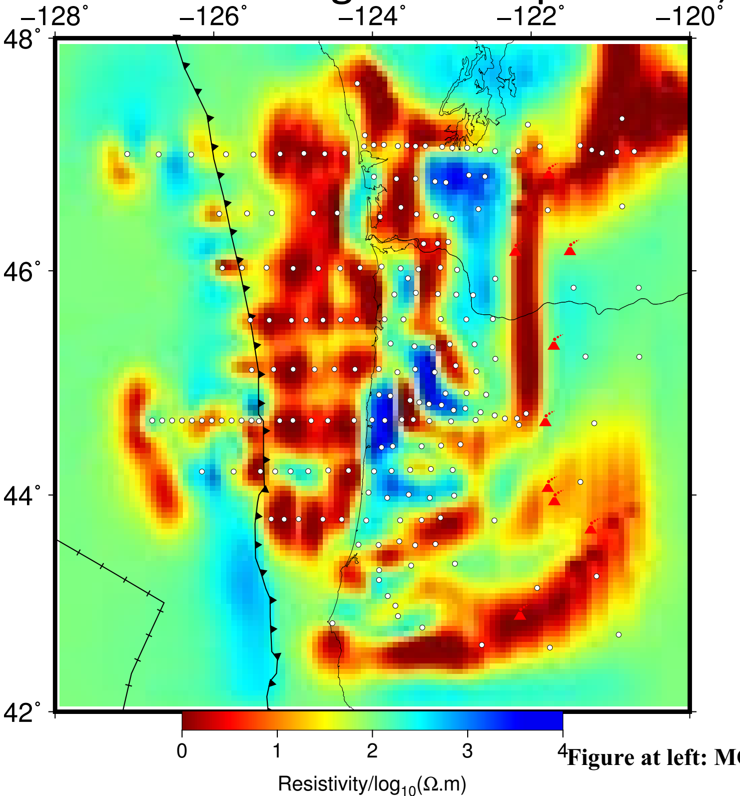
Comparison between EarthScope 3-D model of crust & mantle conductivity in NW quadrant of continental USA, with uniform regional 1-D provinces defined by EPRI (2012)

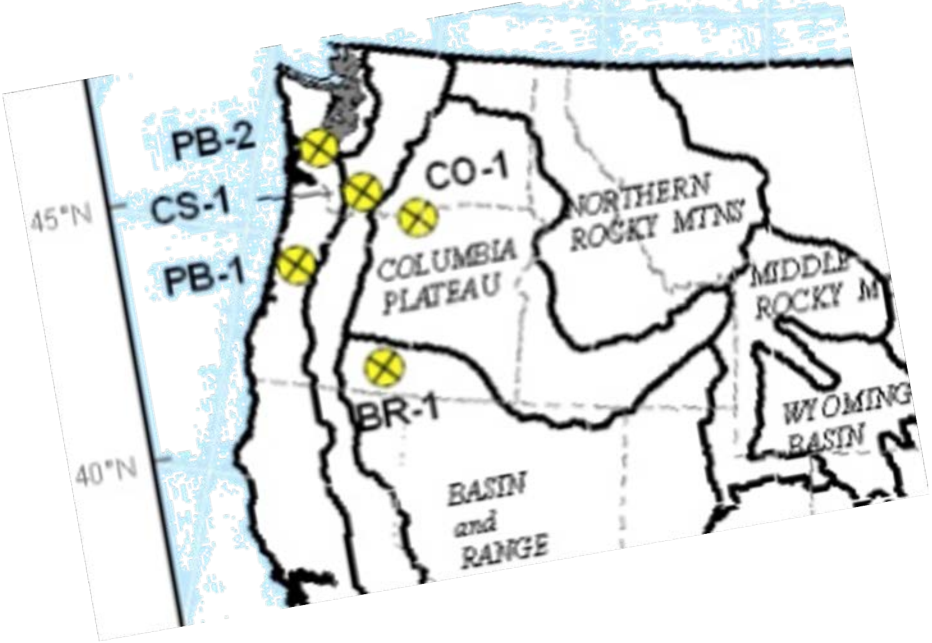




EPRI, Technical Report 1026430, R. Lordan (2012)

Even higher resolution view of Cascadia Margin conductivity structure along curved top surface of slab using EarthScope MT TA, MOCHA MT Array, EMSLAB and CAFÉ-MT data sets



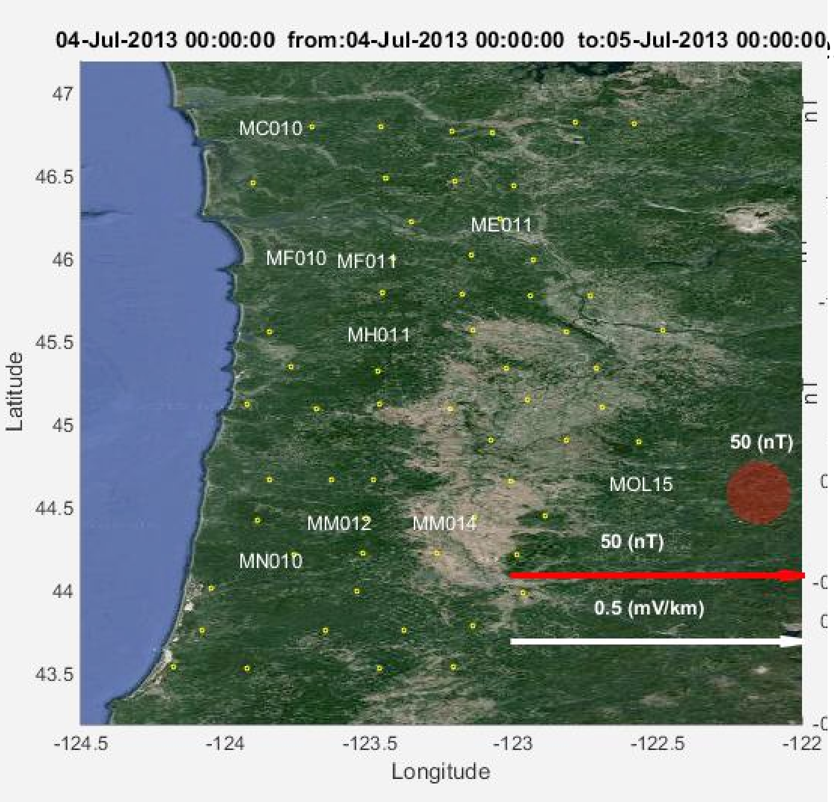


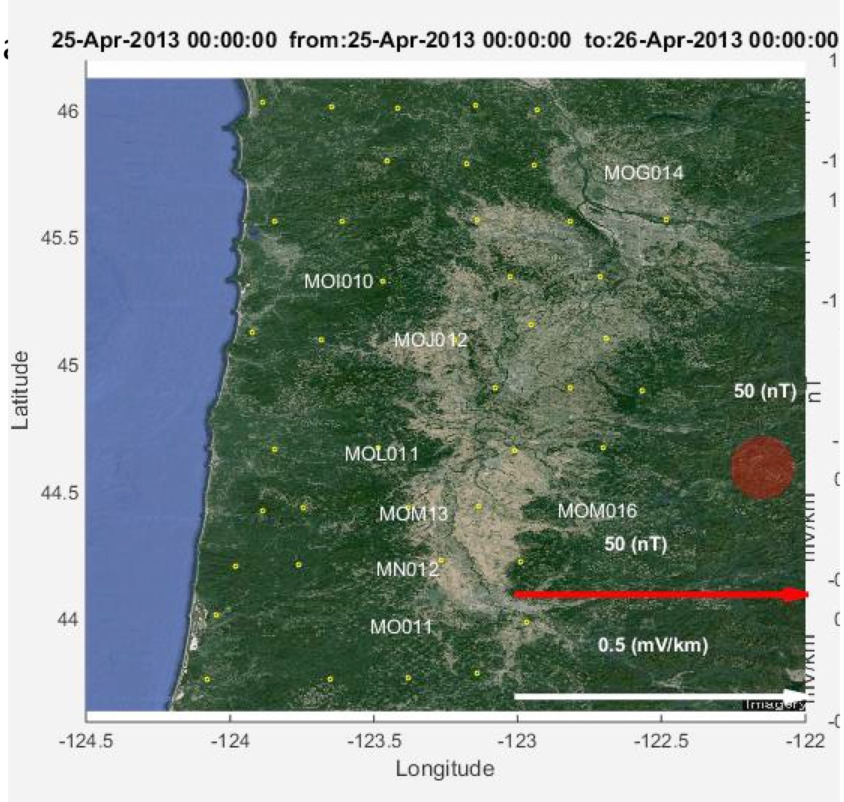
EPRI, Technical Report 1026430, R. Lordan (2012)

Figure at left: MOCHA Project Team, 2017

Impacts of 3-D Ground Structure

Illustrating 3-D ground conductivity effects: The electric and magnetic fields as actually measured during two different one day periods in western Oregon.





How good an electric field prediction can make?

(a) and (b) show the N-S (x) and E-W (y) recorded and predicted electric fields based on projecting the magnetic fields at a site near Portland, Oregon from magnetic field data recorded at Newport, WA; Boulder, CO; Fresno, CA; Honolulu, HI, and then projecting them through the local impedance tensors previously obtained for that former MT station location.

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 within this BPA operating area.

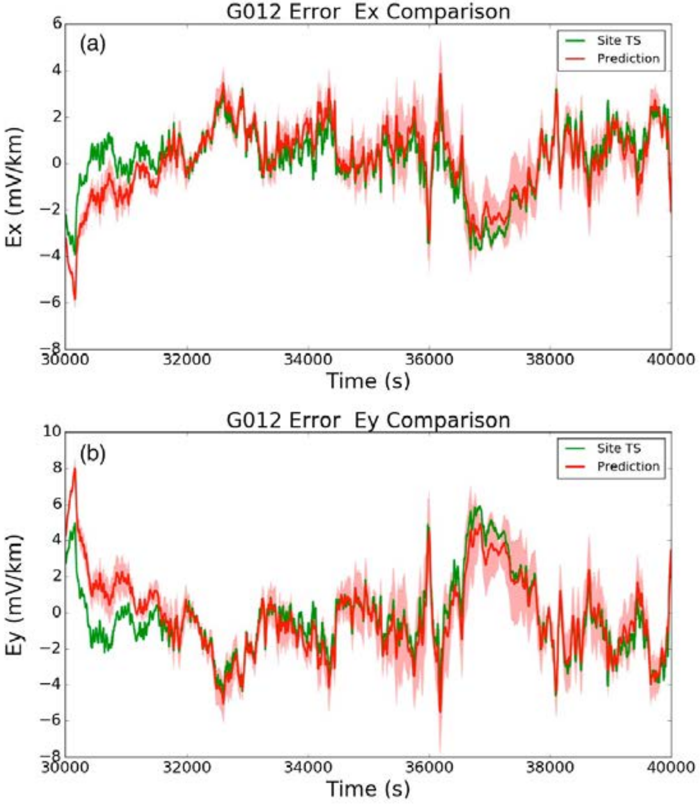
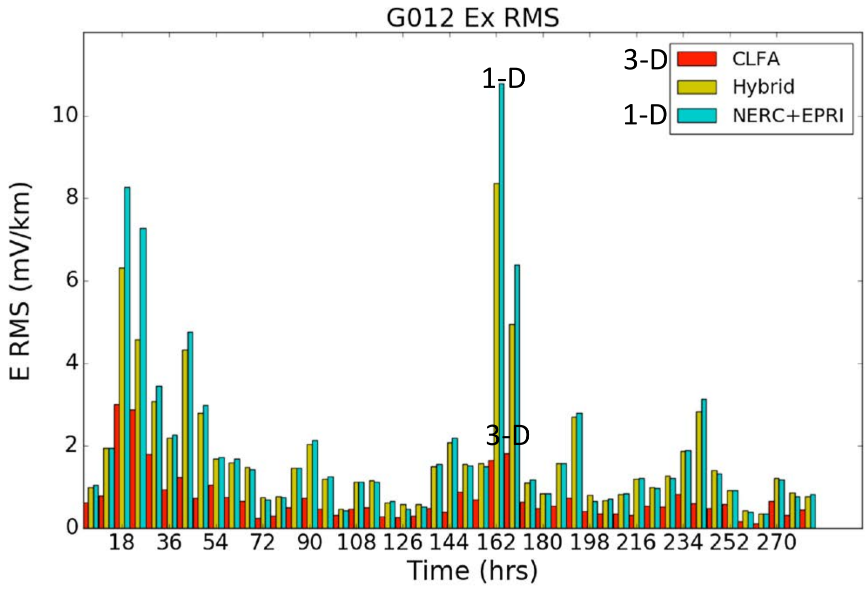
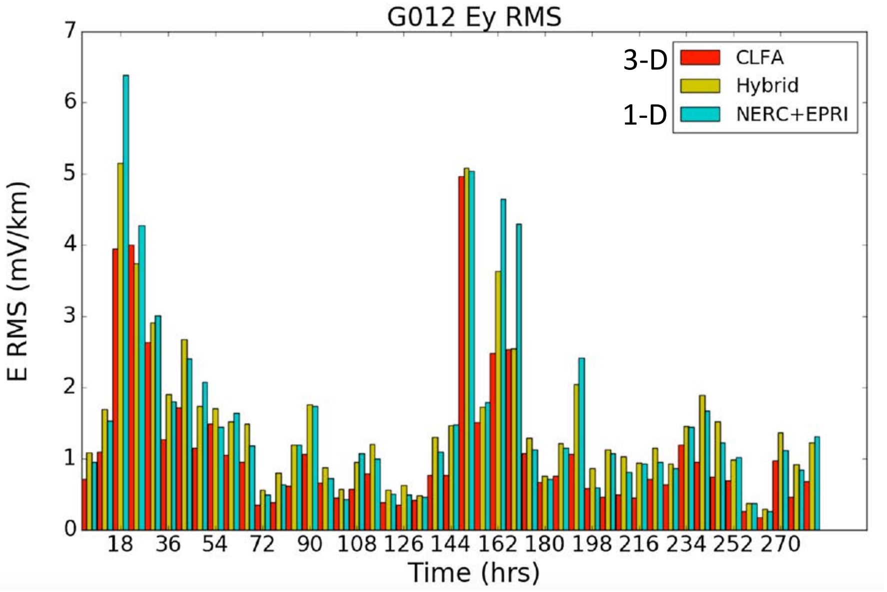


Figure 8. High-pass filtered electric field time series for data recorded at MT site G012 (green curves) and for data predicted for that location ±95% confidence interval (red curves) by projecting the vector magnetic field variation data recorded at the four magnetic observatories through a multiple station transfer function, resulting in a predicted magnetic field that is then projected through the local impedance tensor to yield the prediction of the local electric field at that site. Two sets of orthogonal electric field components are shown in the (a) north-south (*x*) and (b) east-west (*y*) directions.

Real-time E-field prediction by CLFA





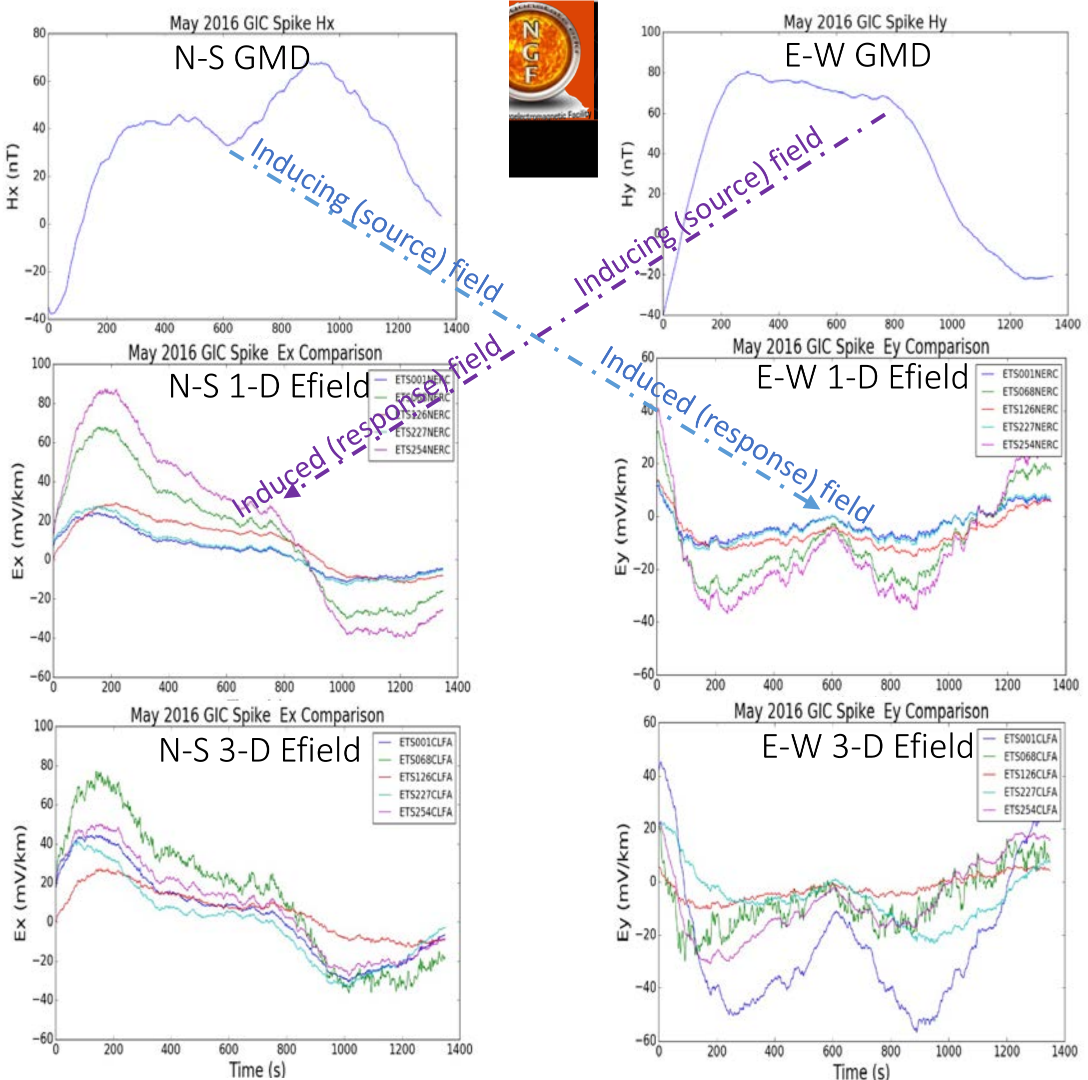
$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(site_i - pred_i)^2}$$

RMS misfit between the (top) north-south (E_x) and (bottom) east-west (E_y) electric field components actually measured at MT station location G012 and those predicted by the NERC (cyan), hybrid (yellow), and the CLFA (red) methods, calculated within 6 h bins for a 10^6 s time series section.

GMD and resulting 1-D and 3-D ground electric fields for May 7-8 2016 GIC for 5 sites across the western intertie

North-South (left) and East-West (right) components of the GMD recorded at Newport, WA USGS magnetic observatory (top), induced 1-D (middle) and induced 3-D (bottom) ground electric fields shown for 22 ½ minute time (1350 s) period

At different time periods during the GMD, field intensification/attenuation of 3-D vs 1-D can be hundreds of percent, manifesting differently in the N-S and E-W directions, depending on polarization of the inducing GMD

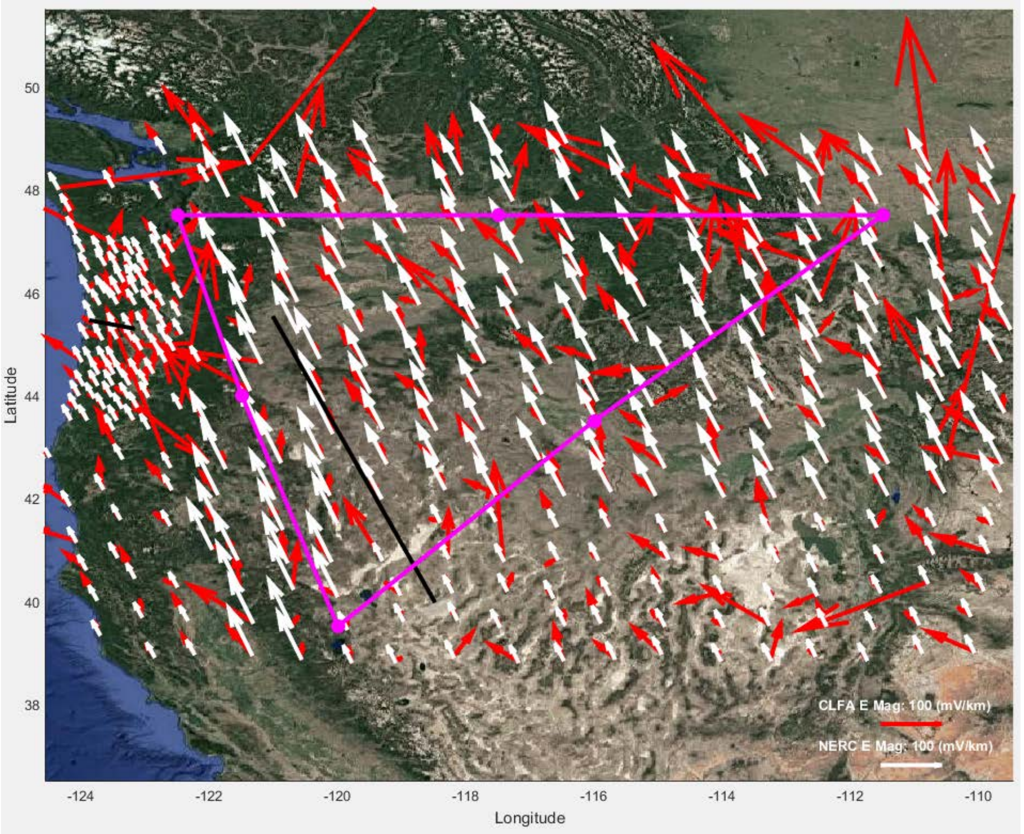


A GIC in the western grid, May 2016.

Ground electric fields strongly impacted by real-world 3-D ground conductivity structure illustrating inaccuracy of 1-D methods.

MT site locations, with vectors representing the predicted electric fields for those sites at the maximum point of a peak GIC event determined over a 180-s long time window in May, 2016.

3-D ground conductivity generated vectors are shown in red and NERC+EPRI 1-D method generated vectors are shown in white, with both having a unit length of 100 mV/km.



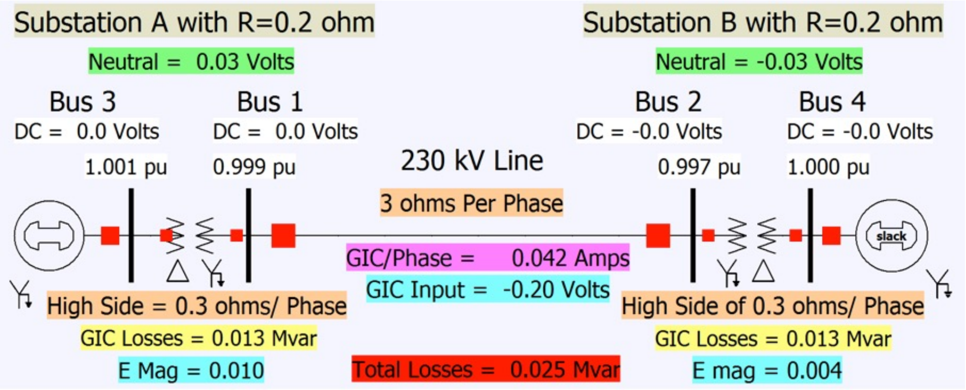
3-D Ground Electric Fields Input to Power Flow Models

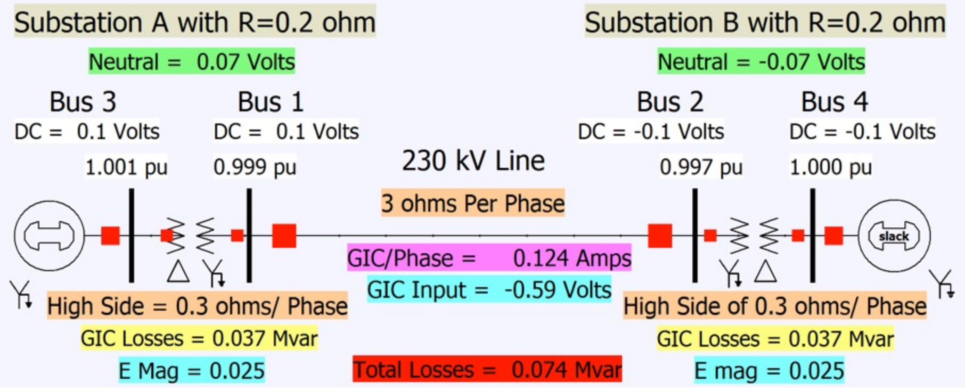
Real-time ground electric field predictions projected onto the path of high voltage electric power lines and integrated along the line path provide time-varying voltages that are…

input to an equivalent circuit that represents the power grid producing…

real-time predictions of reactive power loss at each transformer.

The effects of 3-D ground conductivity on GIC intensity can be determined





Conclusions drawn from GIC power flow simulations for 1-D and 3-D test cases for BPA Tillamook – Carlton line eastern and western substations

The different parts of the line experience different electric fields for the 3-D real-world case, but the same electric field for the 1-D case.

- At the start of a peak GMD event (**time=0 s**) the calculated electric field intensity at the two substations:

	Western Substation	Eastern Substation
3-D real-world ground conductivity	**0.004 V/km**	**0.030 V/km**
1-D Fernberg ground conductivity	**0.014 V/km**	**0.014 V/km**

Conclusions drawn from GIC power flow simulations for 1-D and 3-D test cases for BPA Tillamook – Carlton line eastern and western substations

The different parts of the line experience different electric fields for the 3-D real-world case, but the same electric field for the 1-D case. Why the apparent discrepancy of a larger peak electric field resulting in a smaller net reactive power loss?

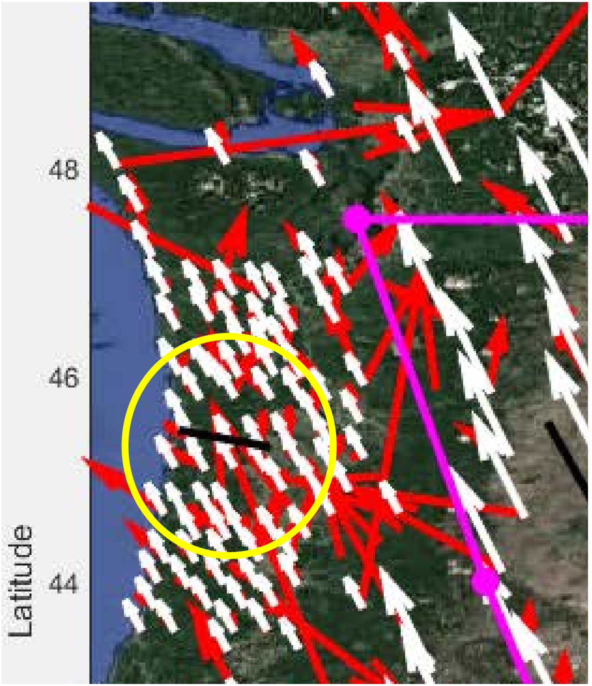
- At the start of a peak GMD event (**time=0 s**) the calculated electric field intensity at the two substations :

	Western Substation	Eastern Substation
3-D real-world ground conductivity	**0.004 V/km**	**0.030 V/km (214% of 1-D)** 0.025 MVAR (62.5% of 1-D)
1-D Fernberg ground conductivity	**0.014 V/km**	**0.014 V/km** 0.040 MVAR

A GIC in the western grid, May 2016.

Why the apparent discrepancy of a **larger** peak electric field resulting in a smaller net reactive power loss?

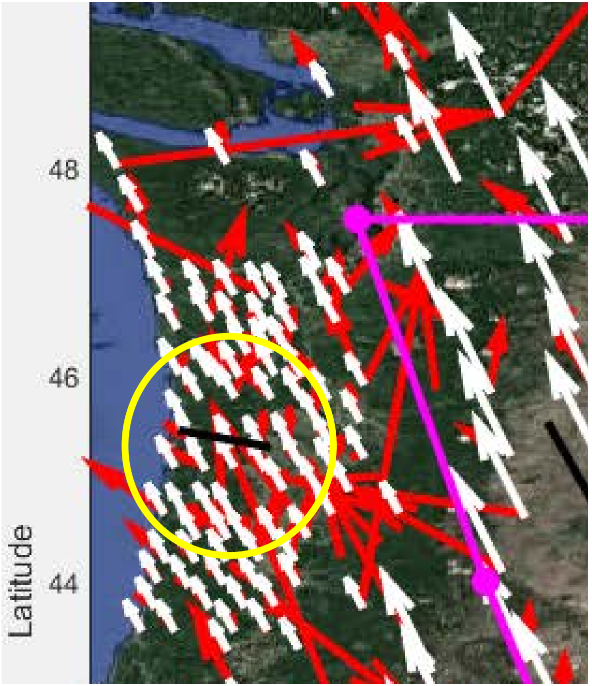
The yellow circle in the figure at right highlights the BPA Tillamook-Carlton transmission line segment. Note the east-west orientation of this line.



A GIC in the western grid, May 2016.

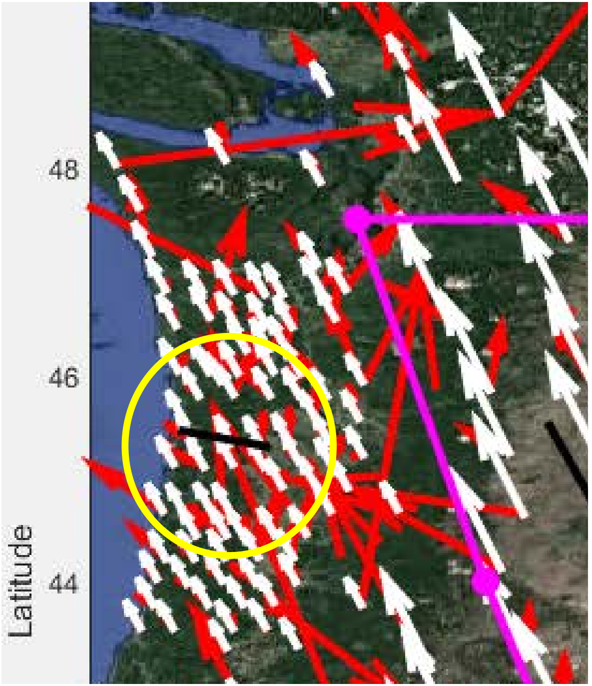
Vector orientation is a large factor in GIC strength; it can cause electric fields of greater intensity but oriented more orthogonal to the transmission lines to have lower GIC impacts than less intense fields oriented parallel to those lines.

The vector orientation changes with time during the life of the GMD. This also has an effect…



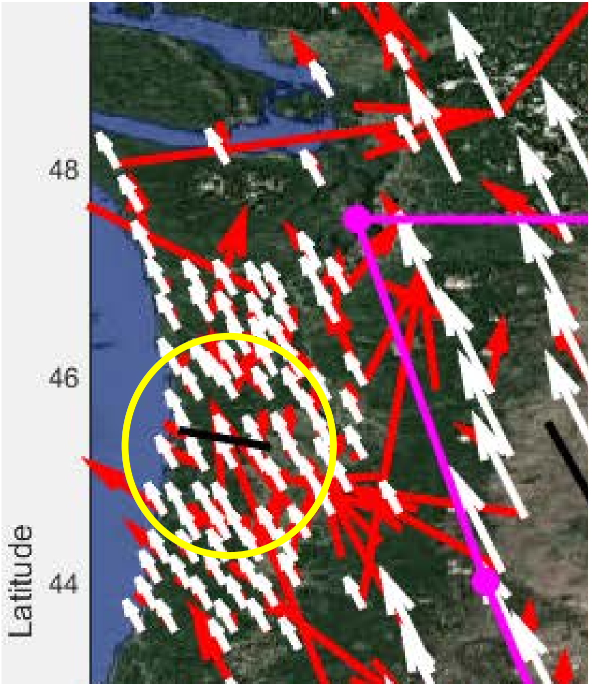
A GIC in the western grid, May 2016.

- At the start of this GMD event, the NERC+EPRI 1-D approach produces roughly 300% greater estimates of GIC current, voltage, and losses than the 3-D technique
- ~600 s later during the same GMD event the orientation of the ground magnetic field has rotated and the 3-D method produces far larger GIC predictions than the NERC+EPRI 1-D technique; GIC losses of 0.034 MVAR vs. 0.006 MVAR are found for the two methods respectively (roughly a 570% difference)
- This is because at this time period, during the same GMD event, the induced electric fields run more closely parallel to the transmission line



A GIC in the western grid, May 2016.

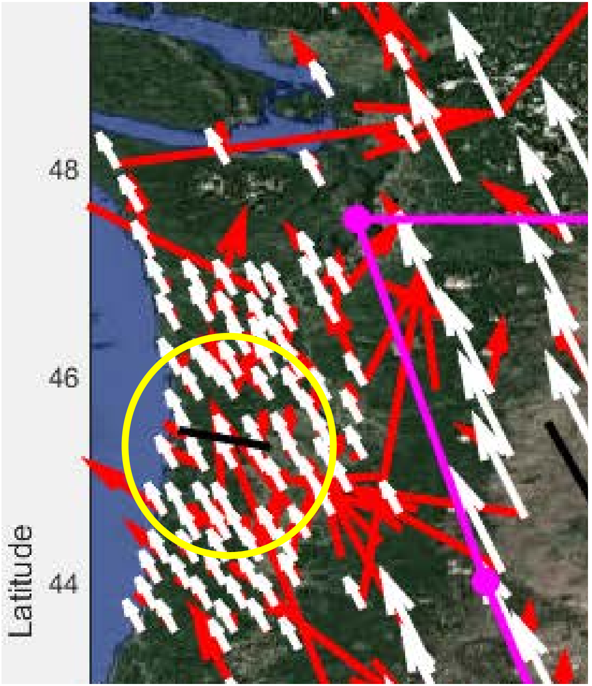
- Any risk assessment of transformer vulnerability based on the NERC+EPRI 1-D method would initially over-estimate GIC risk, but ten minutes later during the event would grossly under-estimate the severity of the impact of the GIC



A GIC in the western grid, May 2016.

For all of the transmission line and GMD test cases we have examined to-date including the Tillamook-Carlton BPA line (E-W orientation), the Pacific DC intertie line (NW-SE), and the idealized WECC circuit (closed triangular loop), we find that neglecting 3-D ground conductivity effects can lead to many hundreds of percent under- as well as over-estimation of GIC intensity and reactive power loss at individual transformers, depending on the orientation of the transmission line segments, and the orientation and intensity of the GMD

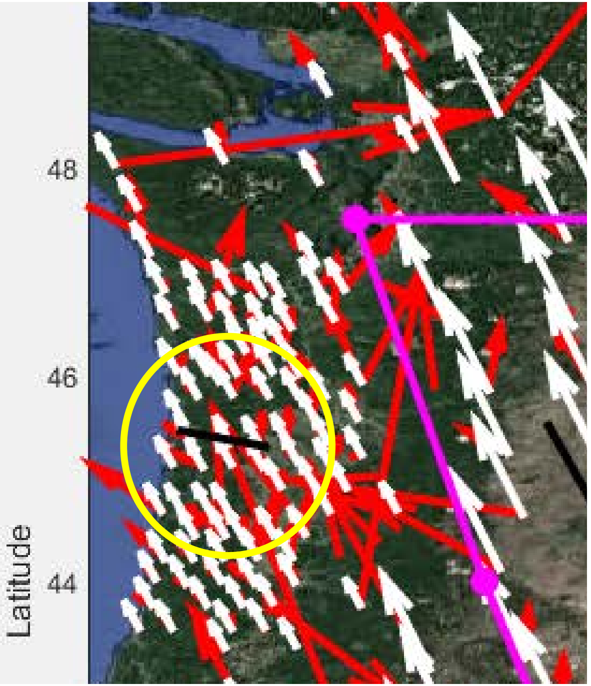
These effects **cannot** be reproduced by replacing real-world 3-D ground conductivity with a larger set of smaller area 1-D conductivity models



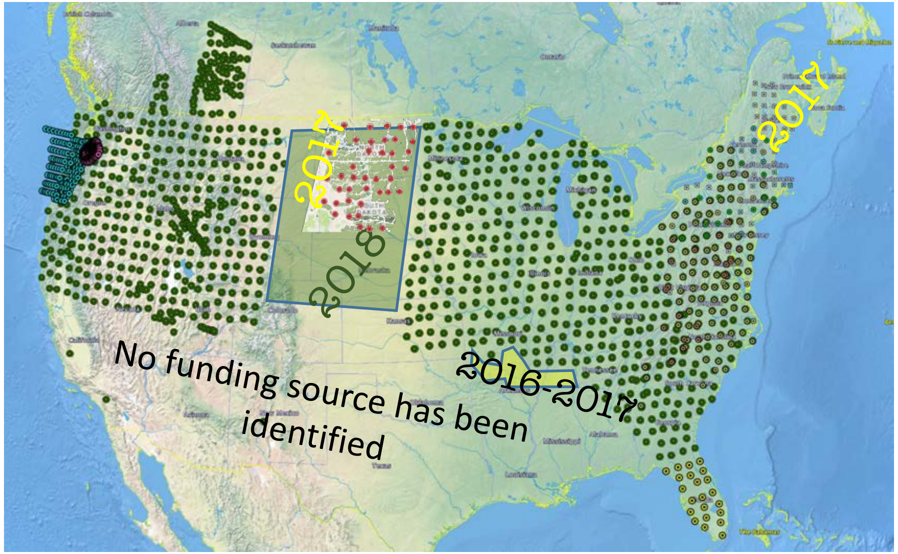
A GIC in the western grid, May 2016.

3-D ground conductivity effects are ubiquitous across the continent, at all scales, and neglecting them can either lead to erroneously high risk assessments, or under-assessments, potentially increasing costs and risks to the utilities and their customers

The 3-D algorithm is easily implemented, computationally undemanding, capable of real-time alert generation and integration with synchrophasor and neutral ground current monitoring sensors



- We have partnered with PingThings, Inc., American Transmission Company, Central Maine Power, Dominion Power and the USGS to design a Smart Service System to improve mitigation of damage from GICs at a grid test bed site
- Machine learning algorithms will be used to fuse our 3-D geophysics approach with interrogation of PMUs to determine changes in synchrophasor data associated with GICs; neutral ground currents, satellite data, etc., coupled to improved grid simulators to determine reactive power loss and related parameters
- This NSF funded project has started; we are also collaborating with NOAA in their efforts to launch a real-time national-scale ground electric field prediction data product



The MT station grid will not be complete across the southern US or in Canada using EarthScope funds; we are in discussion with relevant federal agencies to address the need to complete the MT array throughout the territory of the US.

The author acknowledges the support of

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NSF GEOPRISMS and EarthScope Programs joint Award EAR-1053632 "Collaborative Research: Onshore-offshore MT investigation of Cascadia Margin 3D Structure, Segmentation and Fluid Distribution"

NSF EarthScope Program Cooperative Agreements EAR-0733069 and EAR-1261681 respectively through subcontracts 75-MT and 05-OSU-SAGE "Operation and Management of EarthScope Magnetotelluric Program" from Incorporated Research Institutions for Seismology (IRIS) to Oregon State University to acquire the MT data used in this work.