Electric fields at ground level due to GMDs: Accounting for real-world 3-D ground conductivity effects

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GICs and 3-D ground 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 transmission lines and power grid infrastructure

1. Power grid electrical characteristics change dynamically as operators adapt the grid to variable loads and operating conditions

2. Digital models of the power grid, as used by the utilities, can adapt to the changing electrical characteristics of the grid

3. By inputting the electric field at ground level at every position along the path of the transmission lines, a digital prediction of GIC intensity in the grid can be produced

GICs and 3-D ground 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 transmission lines and power grid infrastructure

4. The intensity and orientation of the electric field at ground level changes with time as a result of electric currents induced to flow in the Earth’s crust and mantle by geomagnetic disturbances (GMDs). The electric field also varies with position along the ground, depending on the electrical conductivity variations below the ground

5. During the course of a GMD, low frequency magnetic field time variations induce electric currents to flow through a larger (wider area and deeper) volume of the crust and mantle than higher frequency variations

GICs and 3-D ground structure

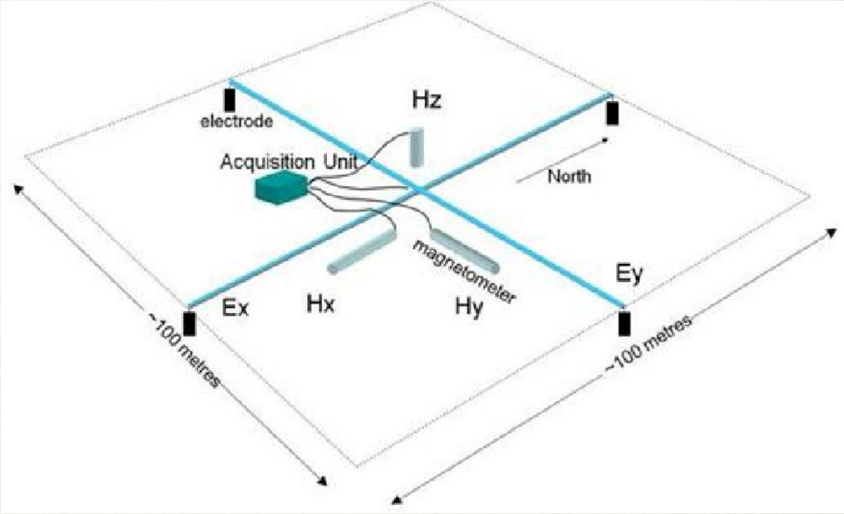
Accurate prediction of GIC intensity depends on the accurate prediction of the **intensity** and the **direction** of the electric field **at ground level** near transmission lines and power grid infrastructure

7. If ground conductivity varies only with depth (1-D), the horizontal electric field will always point in a direction 90 degrees from the horizontal magnetic field, and the intensity of the electric field will not depend on the direction of the magnetic field

8. 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

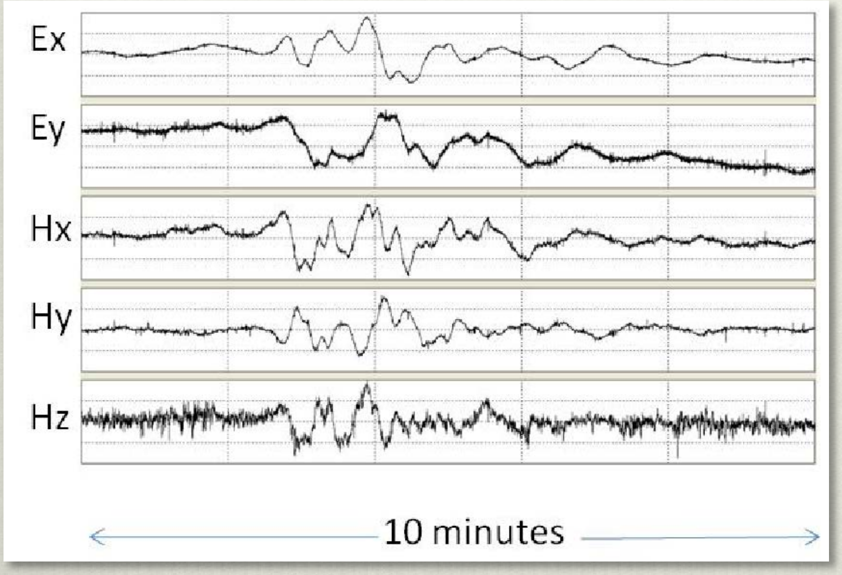
The magnetotelluric (MT) method sensor configuration

By measuring the electric and magnetic fields at the Earth's surface due to induced electric currents in the subsurface, we determine the electrical conductivity structure of the **near-surface** through the **upper mantle.** The image at left is of an installed MT data acquisition system; the figure at right shows the two horizontal electric field dipole sensors and two horizontal and one vertical magnetic field sensor.



Measurement and analysis of electric and magnetic fields at ground surface

(1) Measure raw electric and magnetic field data vs. time as recorded at ground level. E=electric H=magnetic fields. x=north, y=east, z=vertical down



(2) Calculate impedance **Z** vs. frequency, relating the electric fields to the measured magnetic fields; **Z** contains within it all the information about the 3-D electrical conductivity variations in the crust and mantle

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

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

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

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

Given H and Z, you can predict E

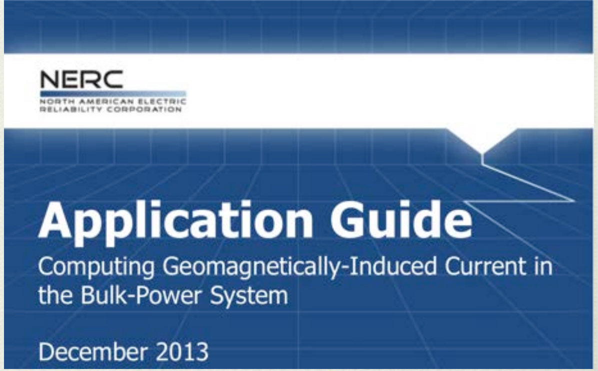


Figure 6: Location of 1-D earth resistivity models with respect to physiographic regions of the contiguous United States [6].

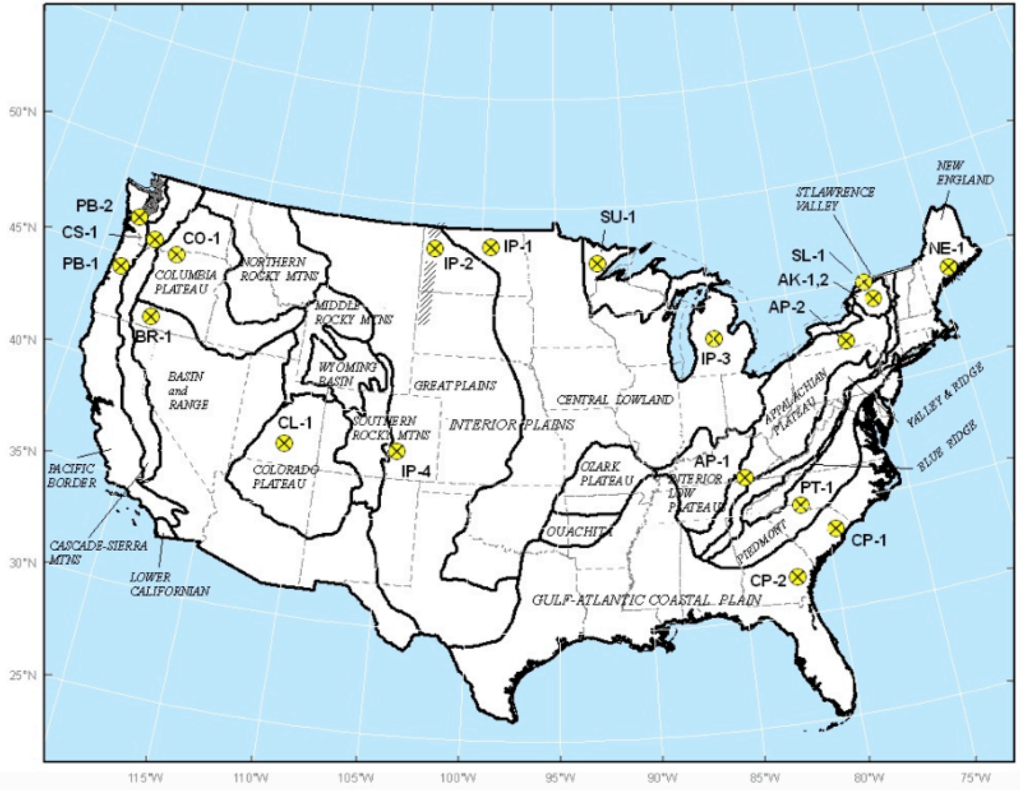
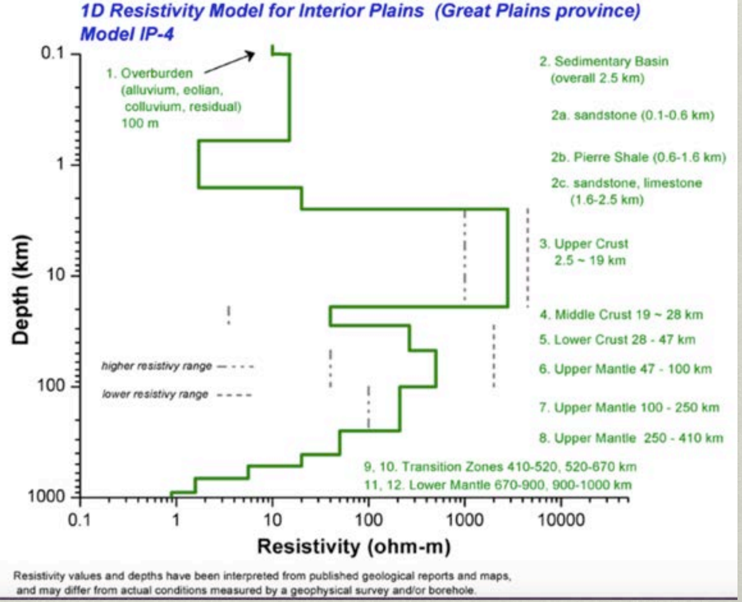


Figure 7: IP-4 (Great Plains) 1-D Earth conductivity model [6]



NERC GMD Standards

- Simulated GICs obtained using regional 1-D models are an improvement on those employing a global 1-D conductivity model, however there are still significant deviations from predicted and actual GICs in some locations

However from our initial reviews of the NERC Draft Standard, the concern was that the levels suggested by NERC were unusually low compared to both recorded disturbances as well as from prior studies. Therefore this white paper will provide a more rigorous review of the NERC benchmark levels. NERC had noted that model validations were not undertaken because direct measurements of geo-electric fields had not been routinely performed anyway in the US. In contrast, Metatech had performed extensive geo-electric field measurement campaigns over decades for storms in Northern Minnesota and had developed validated models for many locations across the US in the course of prior investigations of US power grid vulnerability[3]. Further, various independent observers to the NERC GMD tasks force meetings had urged NERC to collect decades of GIC observations performed by EPRI and independently by power companies as these data could be readily converted to geo-electric fields via simple techniques to provide the basis for validation studies across the US. None of these actions were taken by the NERC GMD Task Force.

It needs to be pointed out that GIC measurements are important witnesses and their evidence is not being considered by the NERC GMD Task Force in the development of these standards. GIC observations provide direct evidence of all of the uncertain and variable parameters including the deep Earth ground response to the driving geomagnetic disturbance environment. Because the GIC measurement is also obtained from the power grid itself, it incorporates all of the meso-scale coupling of the disturbance environments to the assets themselves and the overlying circuit topology that needs

Examination of NERC GMD Standards and Validation of Ground Models and Geo-Electric Fields Proposed in this NERC GMD Standard

A White Paper by:

John G. Kappenman, Storm Analysis Consultants

and

Dr. Willam A. Radasky, Metatech Corporation

July 30, 2014

NERC GMD Standards

- Kappenman and Radasky have compared NERC WG simulations vs. actual GICs measured at various sites. Tillamook Oregon is one of several instances they cite:

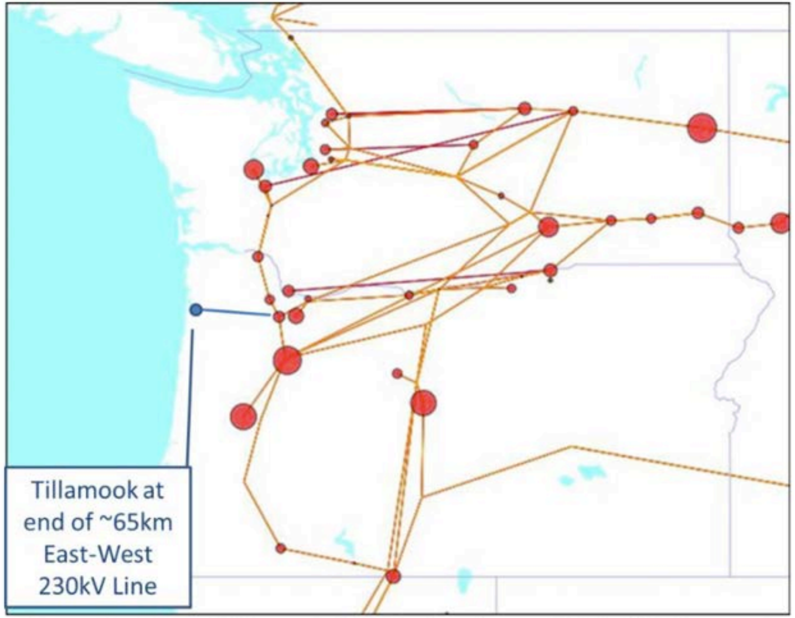


Figure 23 – Map of Tillamook 230kV substation and BPA 500kV network

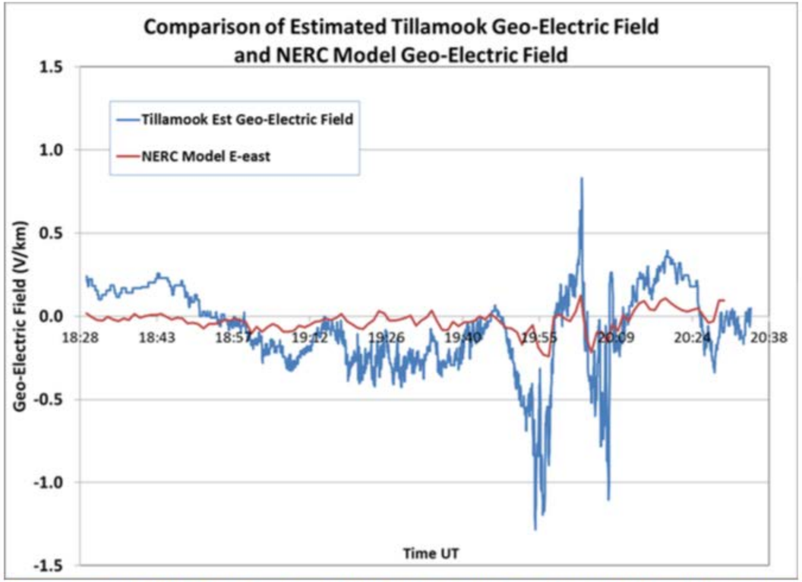


Figure 27 – Comparison of NERC Model geo-electric field with estimated geo-electric field needed to produce Tillamook GIC flows for the Oct 30, 2003 storm

NSF EarthScope MT Program

EarthScope MT Arrays

>725 US stations completed 2006-2015

95 Canadian stations completed 2006-2012

85 New US stations planned for 2016

Texas, Gulf Coast, S. Cal/Ariz/NM and the Northeast US will not be covered under current support, which ends in 2018

MT FlexArray

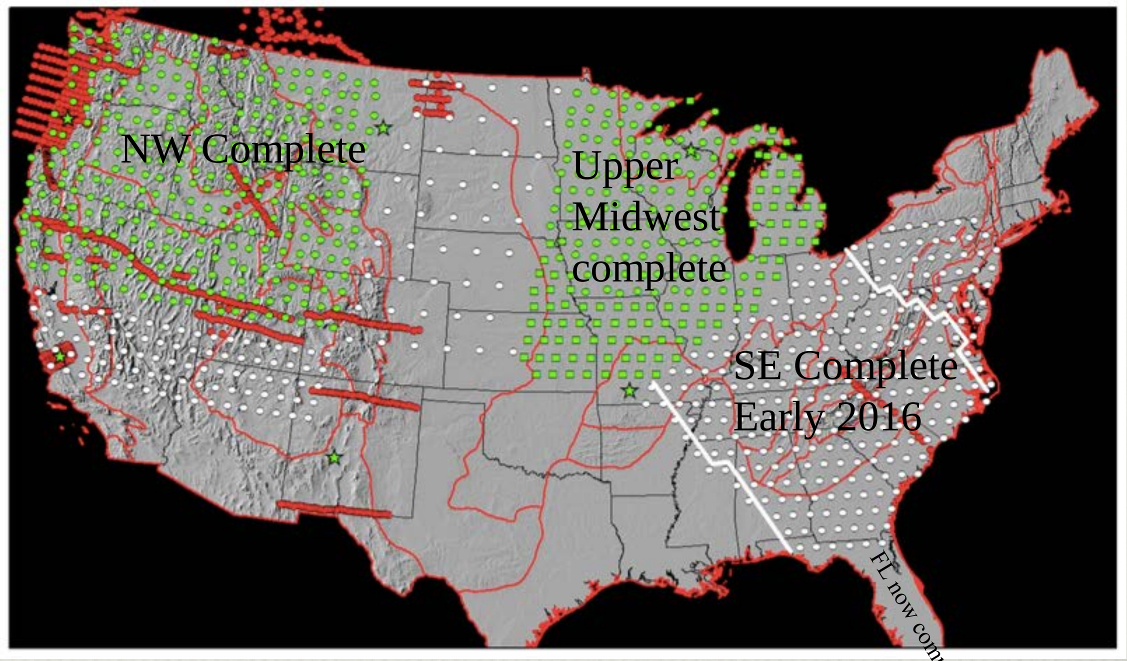
75 long-period land MT stations and 75 marine MT stations for MOCHA

150 wideband stations for iMUSH

132 long-period stations for RGR

25 synchronous long-period MT for Alaska, plus additional non-synchronous in S. Alaska

42 wideband Yellowstone array approved for 2016-2017

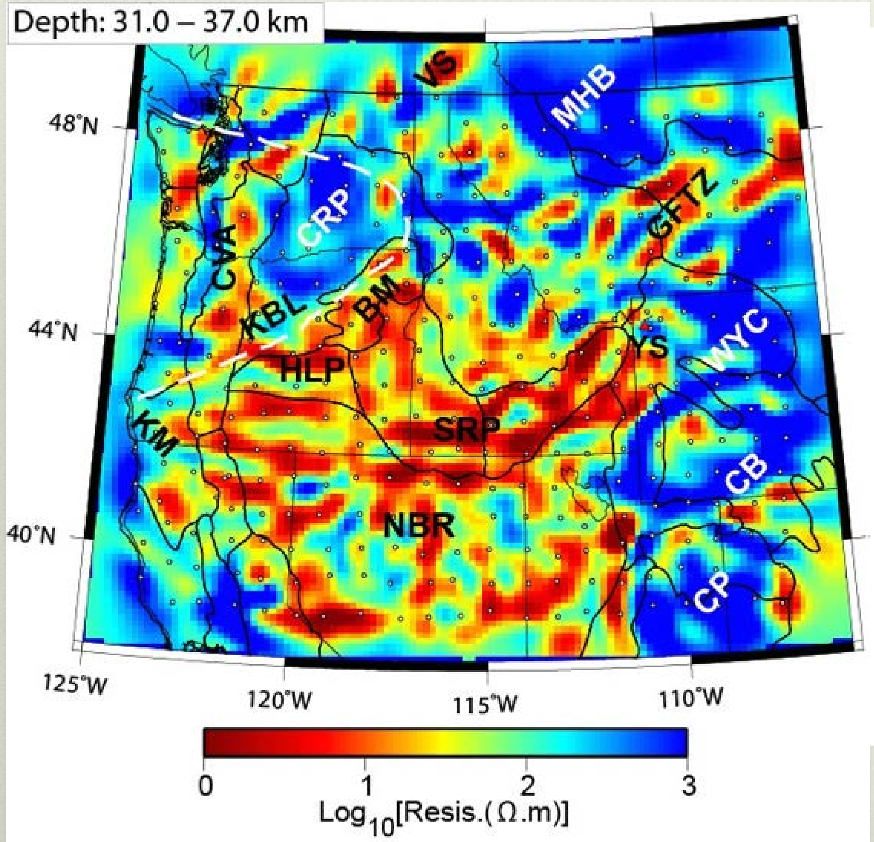


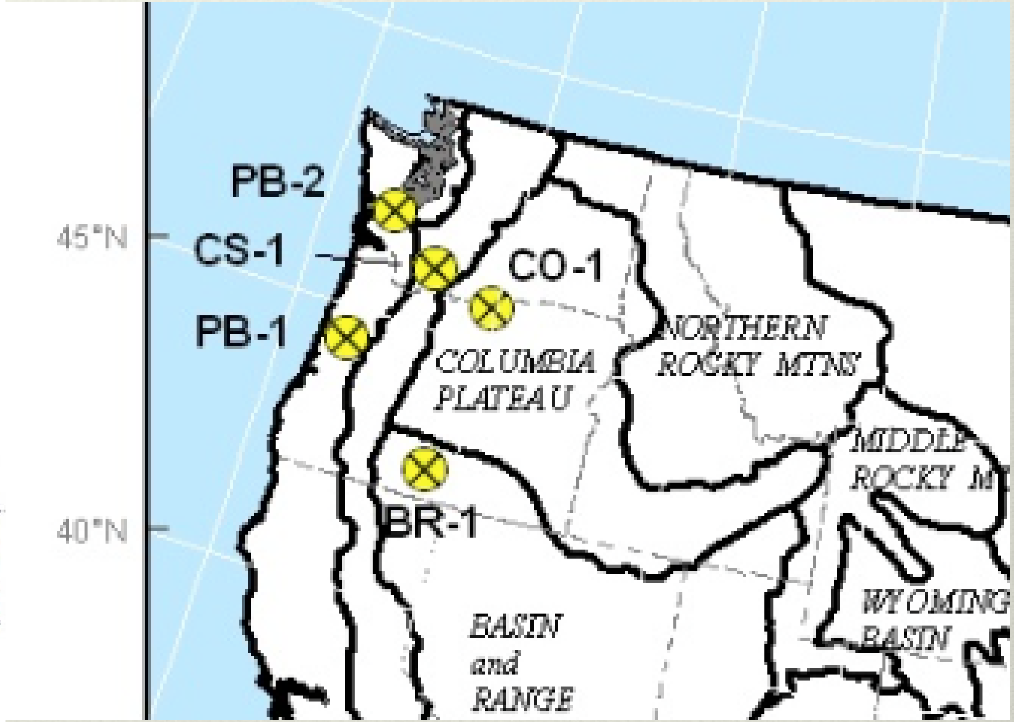
NSF's EarthScope Program ends 2018

EarthScope was motivated by fundamental geoscience questions, and not specifically installed for GICs

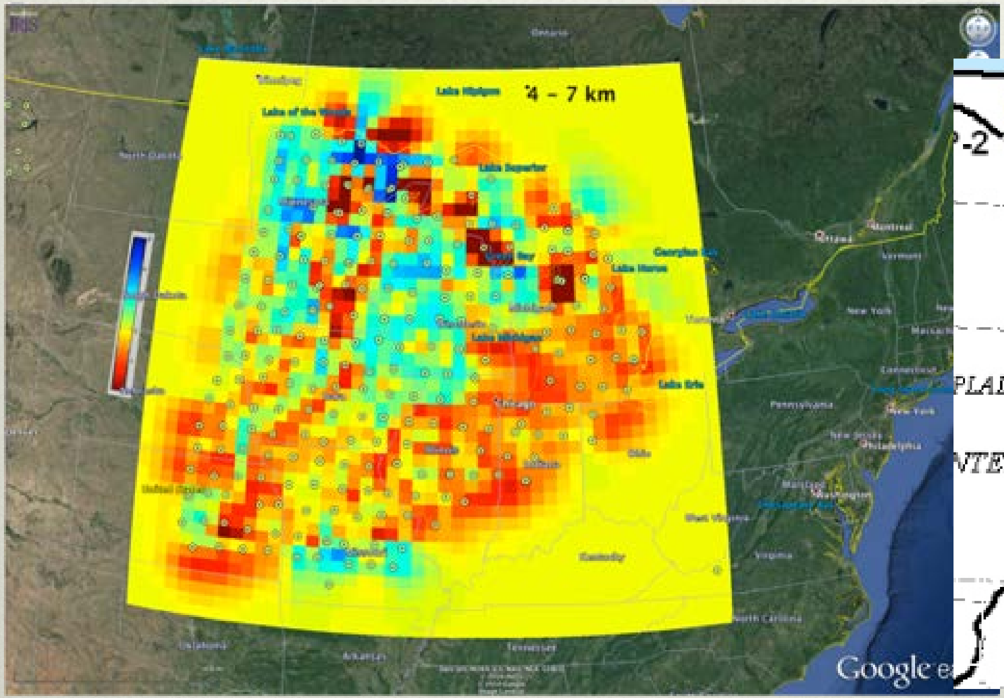
The Northeast, Texas, OK, Gulf Coast and SW not covered

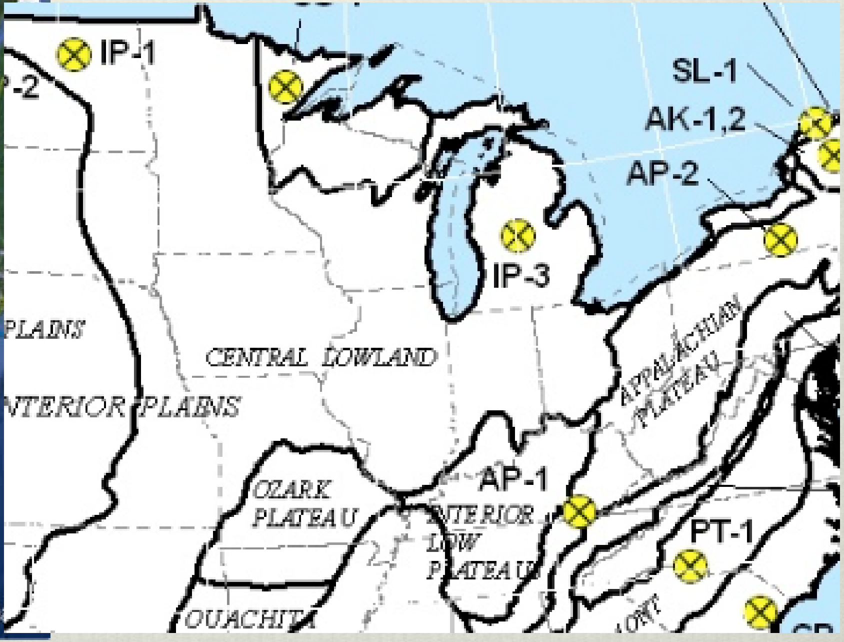
Comparison between EarthScope 3-D model of mid-to-deep crustal conductivity in NW quadrant of continental USA, with uniform regional 1-D provinces defined by USGS





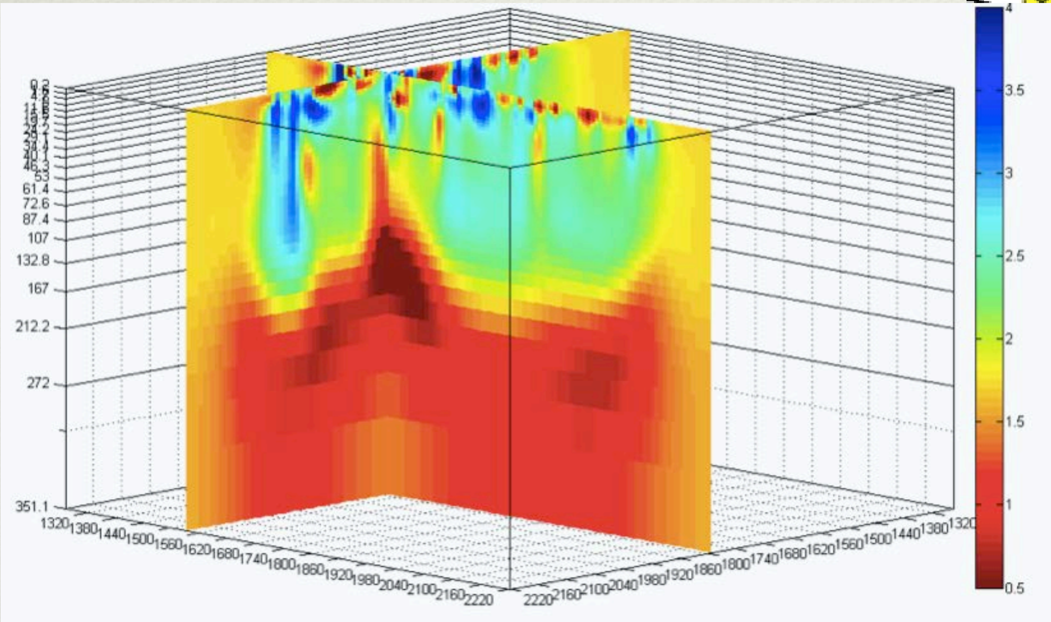
Comparison between EarthScope 3-D model of upper crustal conductivity in mid-continent region of USA with uniform regional 1-D provinces defined by USGS

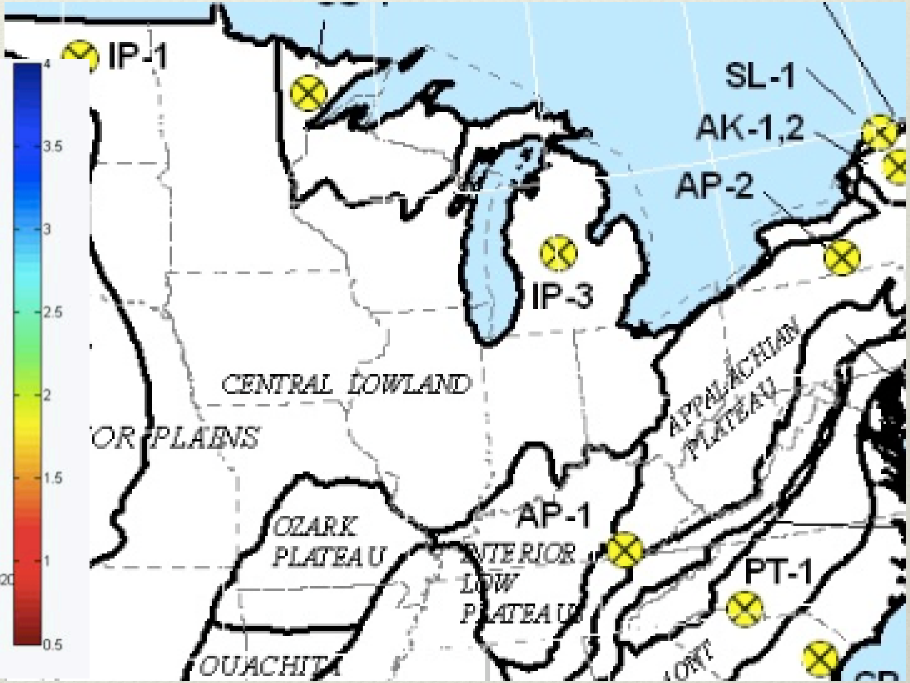




E.J. Bowles-Martinez & A. Schultz, 2014

Comparison between EarthScope 3-D model of crust & mantle conductivity in mid-continent region of USA with uniform regional 1-D provinces defined by USGS EarthScope model (15 km cell size, 51 iterations, RMS=6.78 A fossil trace of the Keewenawan Hot Spot Plume?

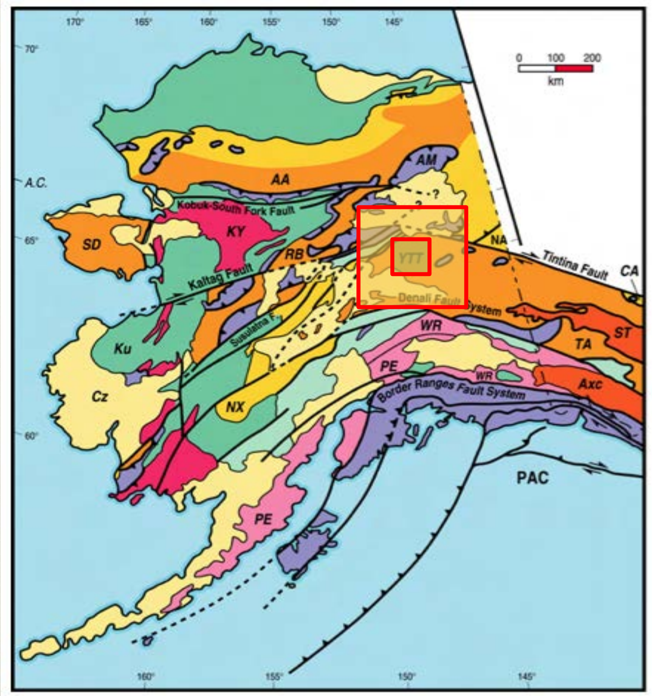


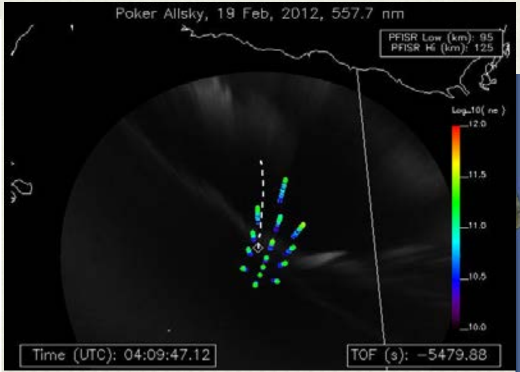


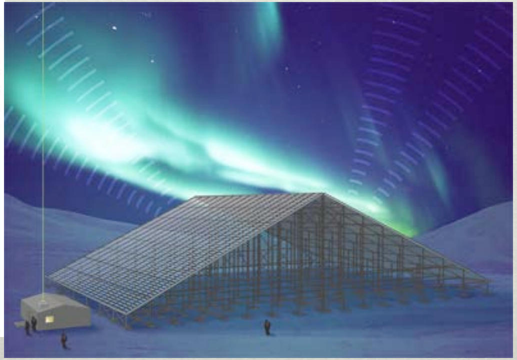
E.J. Bowles-Martinez & A. Schultz, 2014

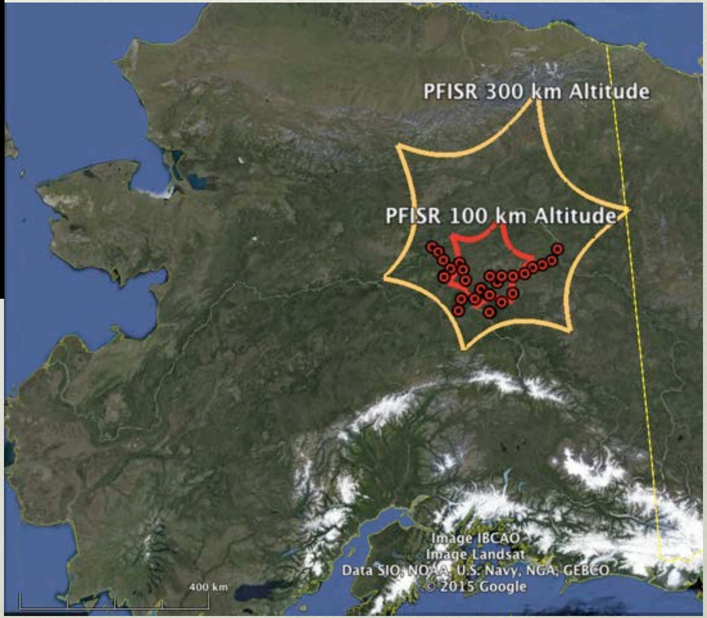
Simultaneous imaging of ionospheric currents and ground conductivity

Joint AGS/EAR synchronous ionospheric/GIC/MT imaging in 2015









The electric and magnetic fields as actually measured during one day in the interior of Alaska. The area shown is approximately 300 km wide

In the following animation, we show the electric and magnetic fields for one day, on 10/12/2015

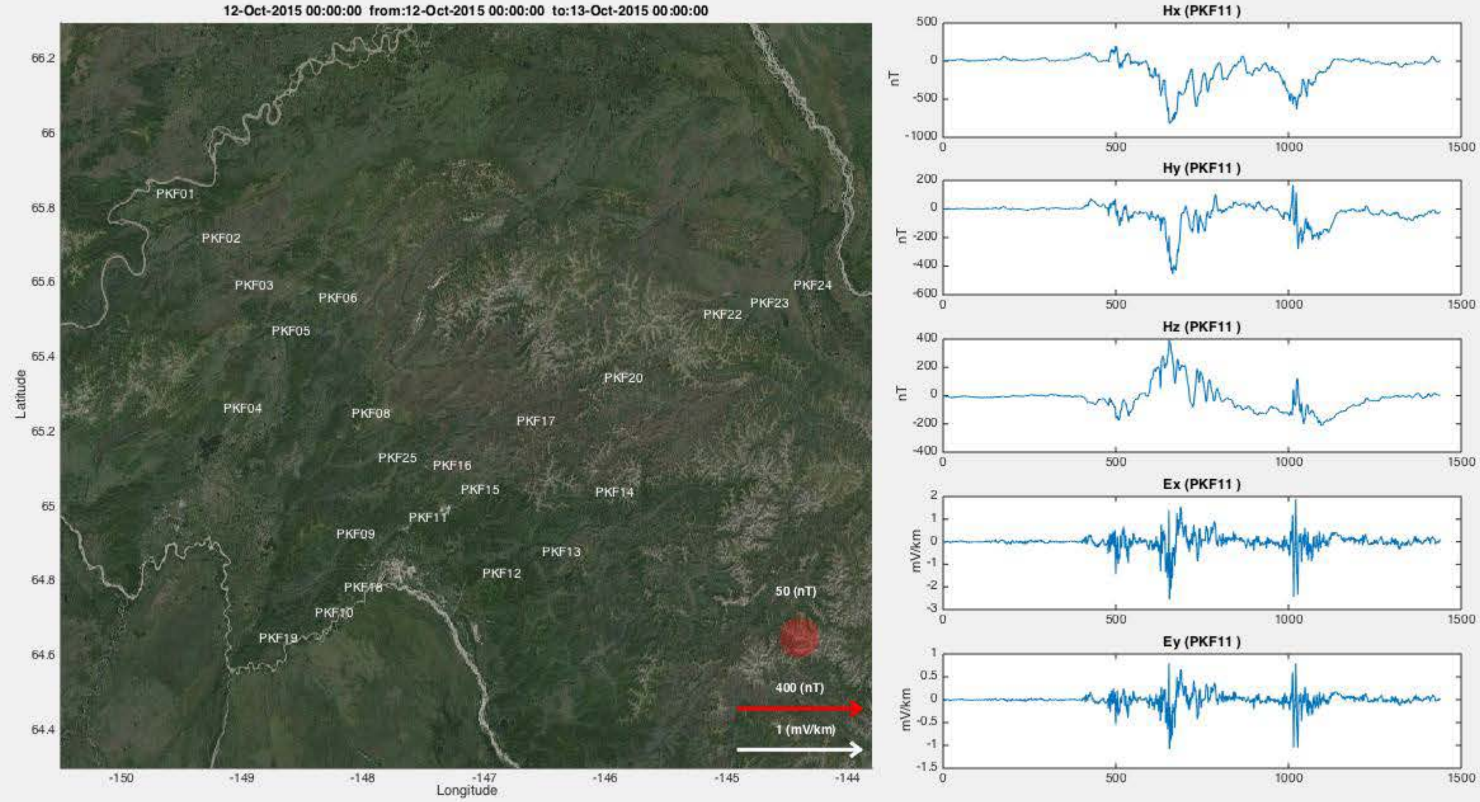
One-minute averaged values of the variations in the fields around that day's mean value are shown

- Horizontal Electric Field = white arrows
- Horizontal Magnetic Field = red arrows
- Vertical Magnetic Field = red (when pointed down)/blue (when pointed up) circles

If ground conductivity varies only with depth, the electric field would always be at a right angle to the magnetic field, and the intensity (length) of the electric field vector would NOT depend on the orientation of the magnetic field

When the animation plays, note how the electric field at each site is typically NOT at a right angle to the magnetic field, and that the electric field intensity is very sensitive to magnetic field direction. This is characteristic of strongly 3-D ground conductivity variations

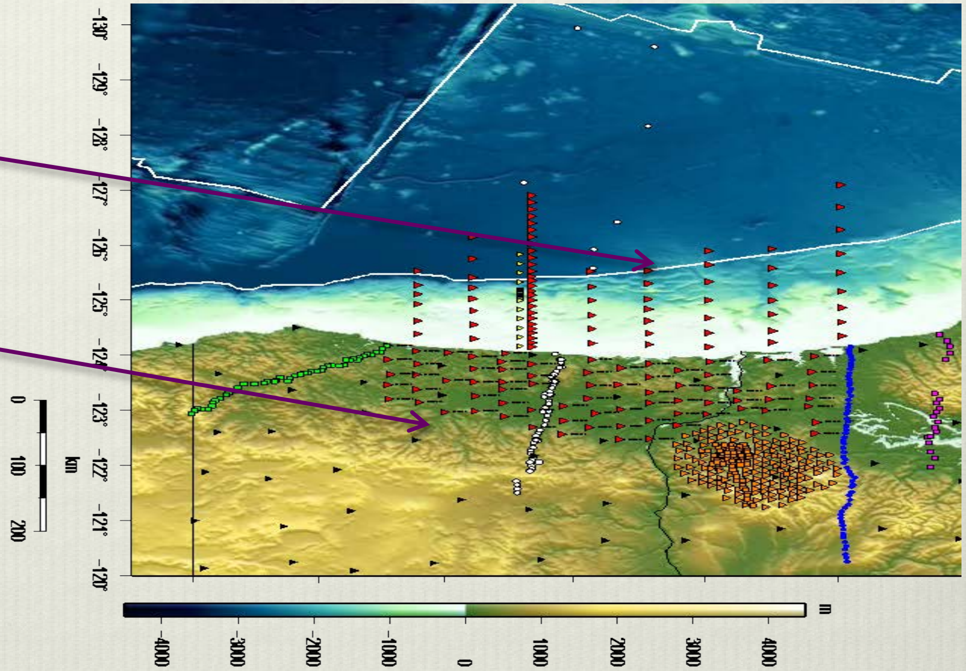
The electric and magnetic fields as actually measured during one day in the interior of Alaska. The area shown is approximately 300 km wide



Let’s return to ground-truthing GIC predictions against actual GICs as monitored -> Tillamook Oregon/Bonneville Power Administration

GeoPRISMS iMUSH Array (orange dots)

EarthScope *MOCHA* “*Magnetotelluric Observations of Cascadia using a Huge Array*” onshore-offshore MT project (red dots)



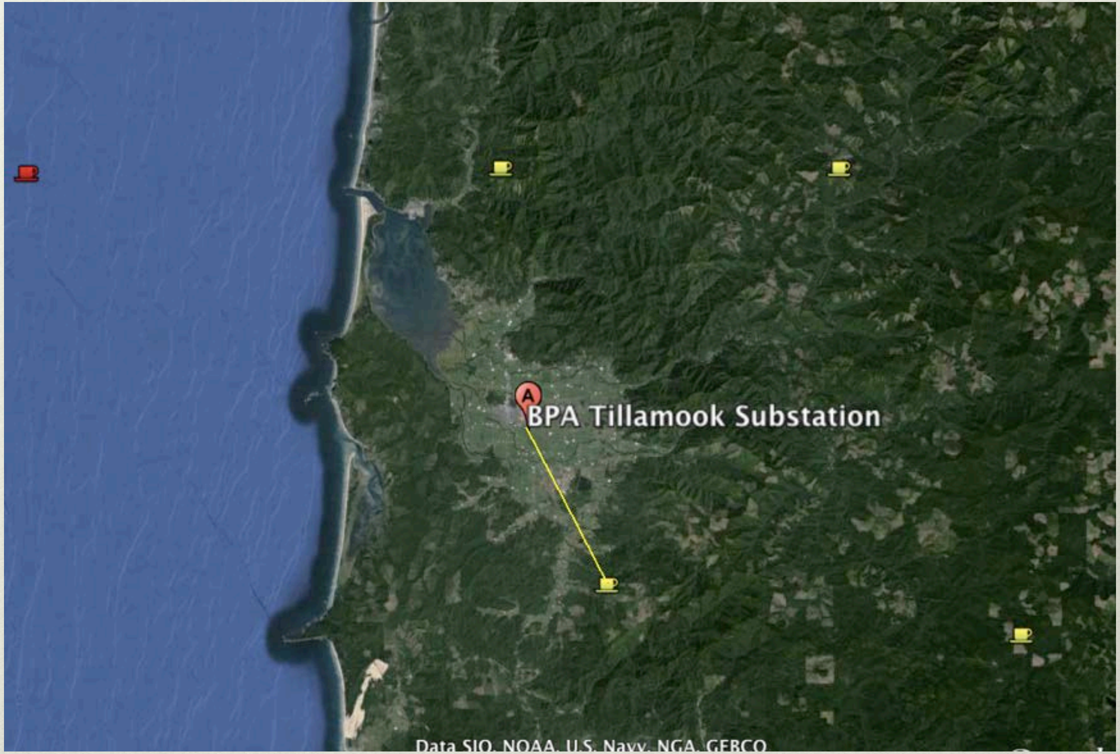
Let's return to ground-truthing GIC predictions against actual GICs as monitored -> Tillamook Oregon/Bonneville Power Administration

So the MOCHA array region, i.e. the area of the BPA transmission lines and substation is highly 3-D both on and off-shore

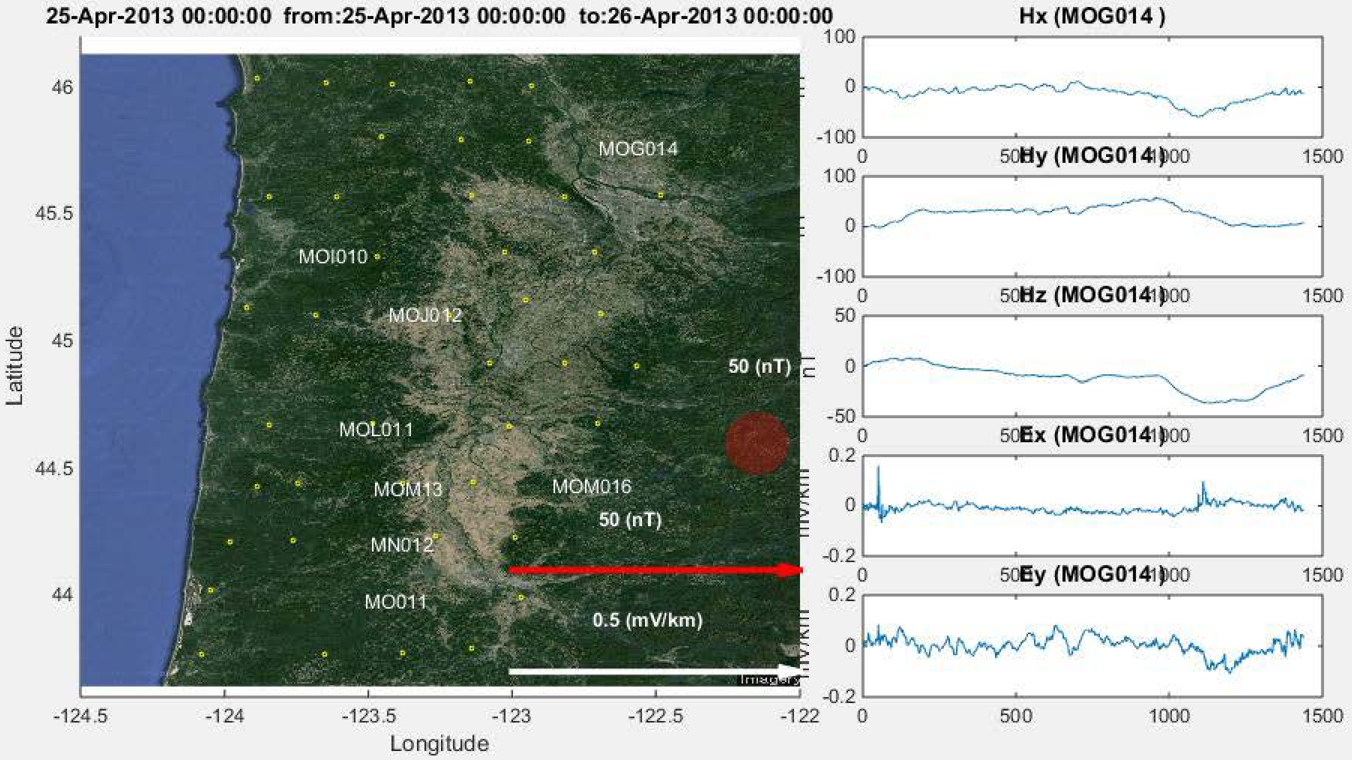
This data set is uniquely positioned to model the coast effect

Our 3-D model based on the 70 km EarthScope grid already shows strong deviations from the regional 1-D model, and also shows coast effects

There are three ways forward as we ground-truth GIC predictions against measured GICs



The electric and magnetic fields as actually measured during three different one day periods in western Oregon. The BPA line to Tillamook runs E-W and roughly mid-way up (in latitude) in the area shown. MT measurement stations are spaced approximately 20 km apart, and are as close as 10 km to the Tillamook substation



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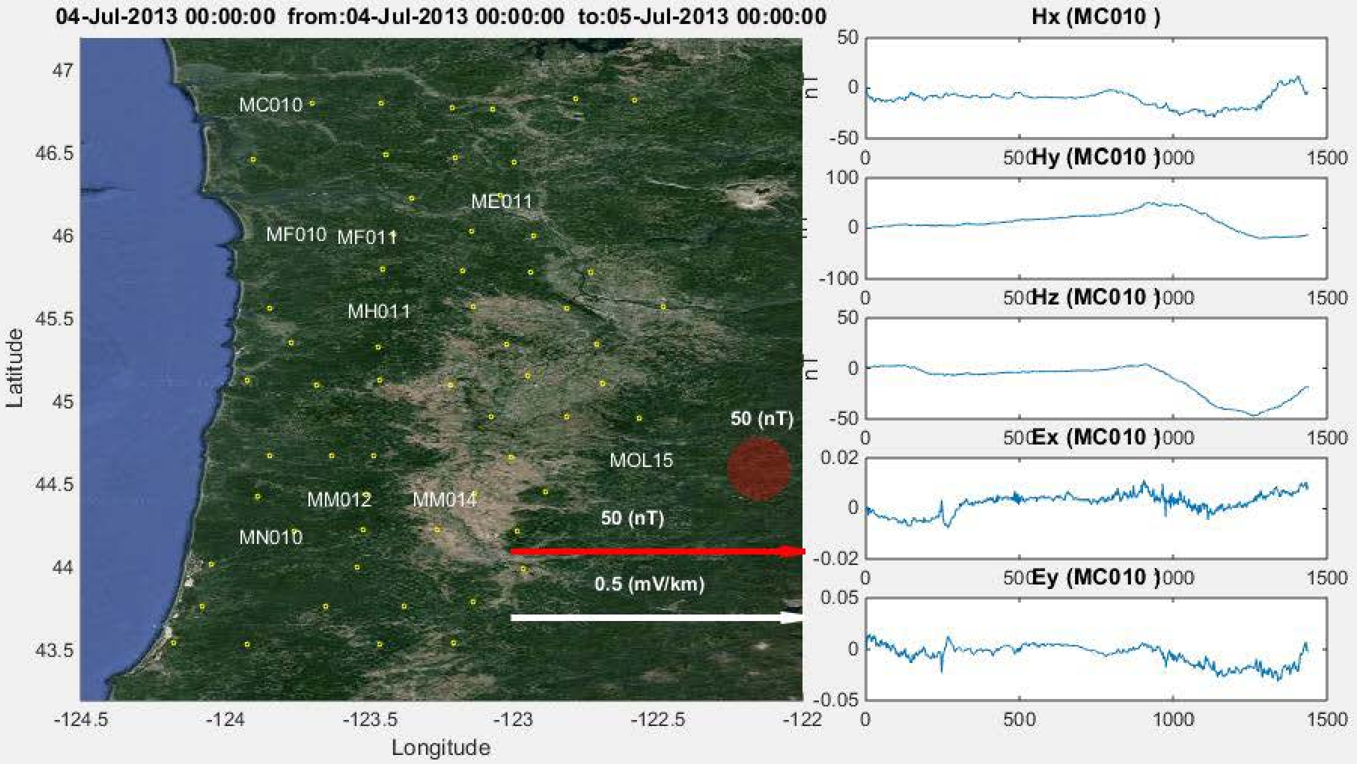

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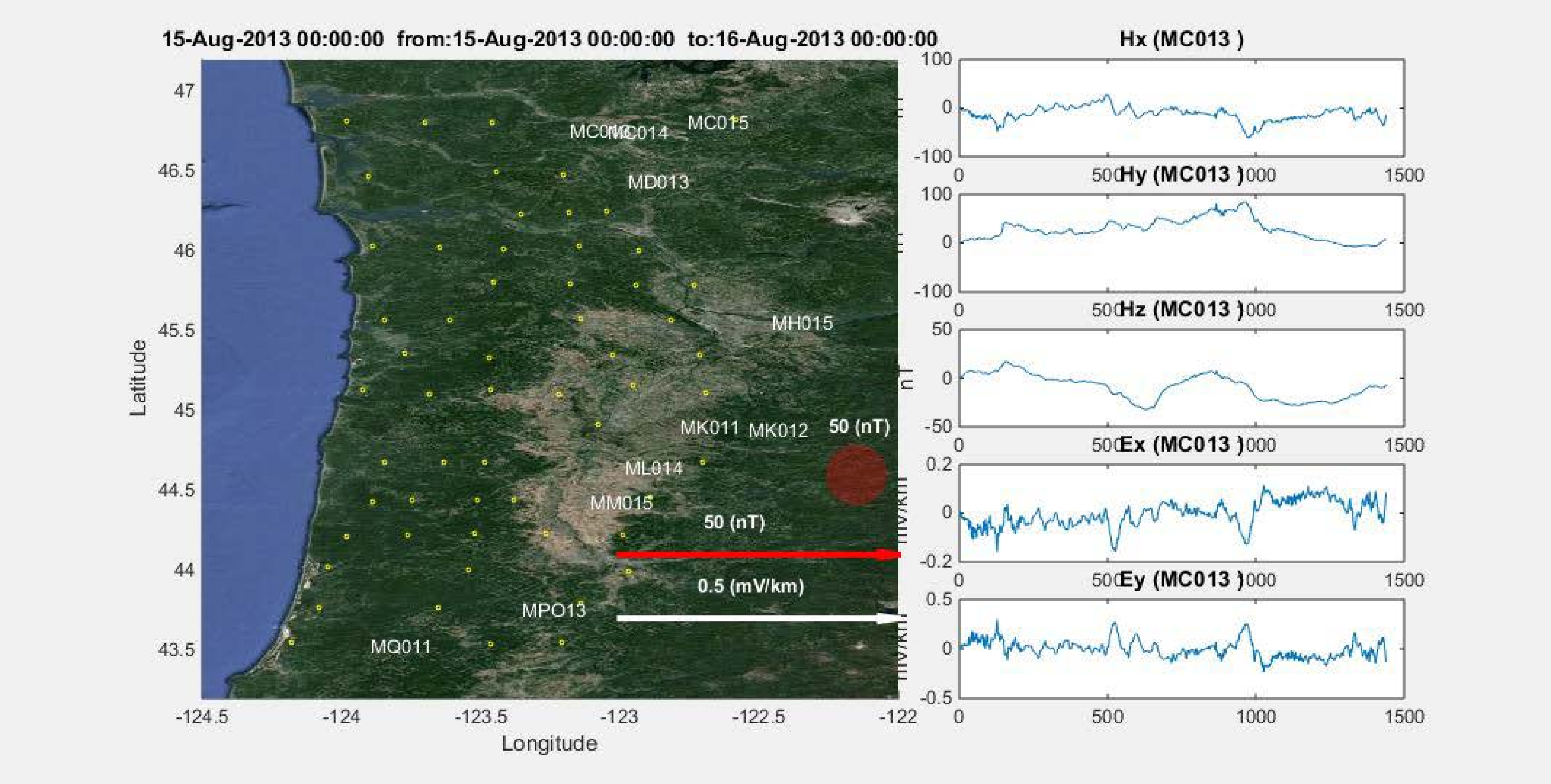
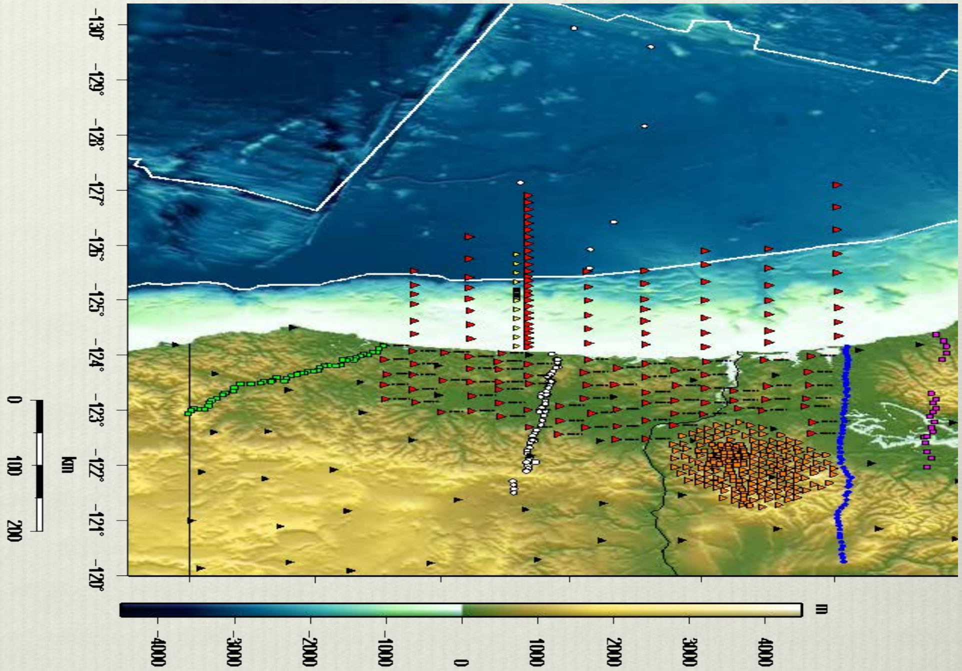


Let's return to ground-truthing GIC predictions against actual GICs as monitored -> Tillamook Oregon/Bonneville Power Administration

1. Derive high-resolution 3-D conductivity model that encorporates the MOCHA array and iMUSH arrays into the previously analyzed 70-km grid EarthScope MT array. Use this to predict surface electric fields from any hypothesized storm/substorm/geomagnetic continuum

   Use ModEM, a modular frequency-domain forward and inverse modeling code to generate the 3-D conductivity model

   Requires integration of ModEM-derived Earth's surface E-fields into GIC codes



Let's return to ground-truthing GIC predictions against actual GICs as monitored -> Tillamook Oregon/Bonneville Power Administration

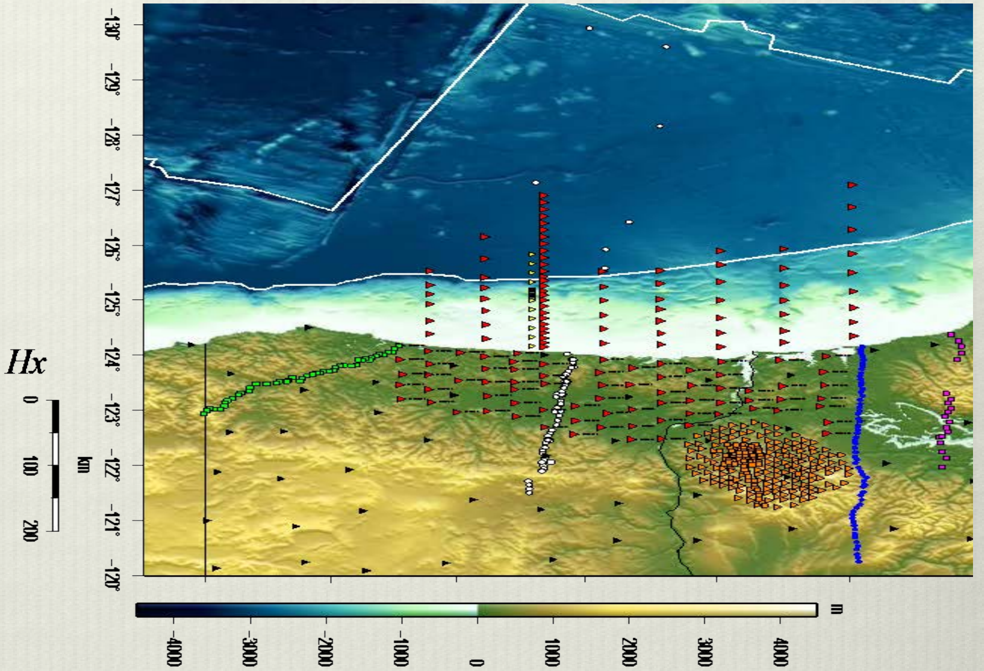
3. Exploit impedance tensor **Z** as filter to transform **H** field measurements into **E** fields

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yz} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} + \mathbf{U}$$

Determine **H** at each MT survey grid location by calculating a transfer function between a nearby magnetic observatory, and the H fields at each MT site.

$$[H_{xobs} \;\; H_{yobs} \;\; H_{yobs}] = \begin{bmatrix} G_{xobs,x} & G_{xobs,y} & G_{xobs,z} \\ G_{yobs,x} & G_{yobs,y} & G_{yobs,z} \\ G_{zobs,x} & G_{zobs,y} & G_{zobs,z} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix}$$

This can be used to project future magnetic observatory data to each point on the grid



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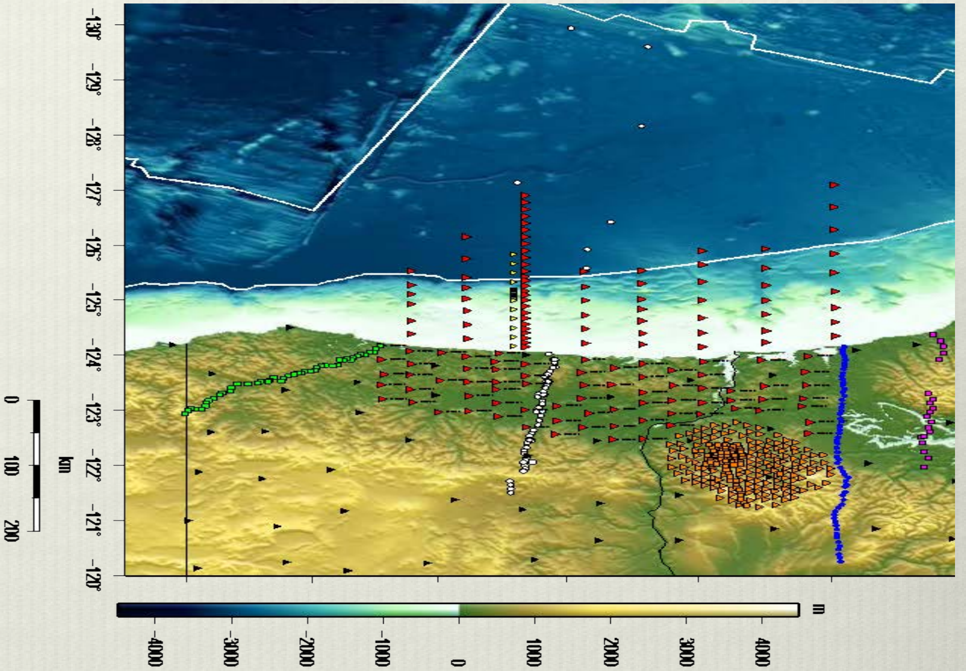
Given magnetic observatory data, compute **E** fields for any azimuth and frequency at every point in the array where impedance tensors have been obtained

Interpolate E-fields in direction of each nearest point along the transmission line, along the azimuth of the transmission lines. Integrate E-fields along the transmission lines. No 3-D conductivity model is required



Use of EarthScope and other 3-D MT data in Calculations of GIC by the electric utility industry

- The strong impact of 3-D ground conductivity structure is evident in the nearly half of the continental US that has thus far been instrumented through the NSF EarthScope MT Project. As a general rule, the electric fields at these many stations bears no resemblance to those that would arise if the 1-D ground conductivity models in the proposed standards were used
- Previous limitations to GIC prediction software that did not allow for non-uniform ground electric fields to be used as input appear to have been resolved, so there is no technical barrier to adoption of electric fields that result from real-world 3-D ground conductivity structure
- I recommend adoption of the proposed standard at this time. In a number of scenarios the use of an equivalent 1-D ground conductivity model can be an acceptable approximation, and can improve the ability to predict GICs from GMDs. It has not been shown however that this holds in all cases, and examples have been offered of inaccuracies that can result. More generally, prudence dictates using 3-D ground conductivity information
- I recommend swift adoption of an amendment to the proposed standard to require use of 3-D ground conductivity information, where it is available, and to compel completion of the national 3-D EarthScope MT grid, through utility industry support, which can be accomplished rapidly (within 4-years) and at low cost (approximately $1M per year)