Geomagnetic Storm Risk and the Electric Grid

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Topics

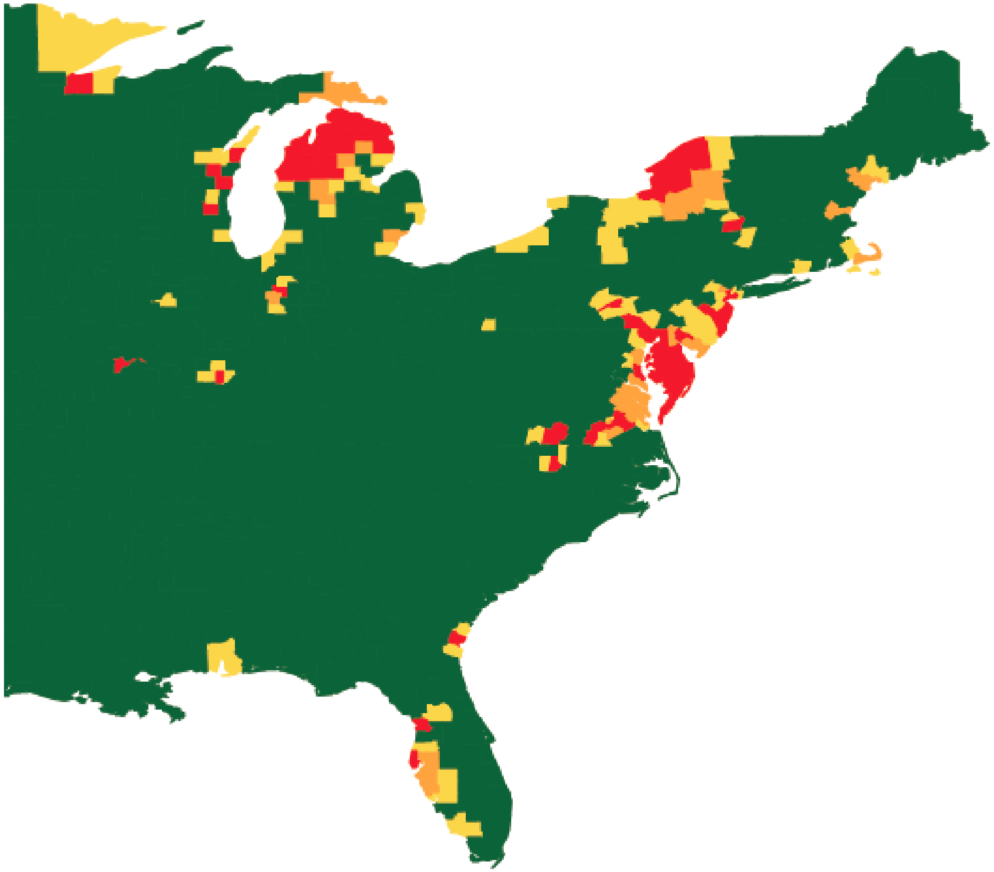
- Geophysical model
  - Magnetic latitude
  - Ground conductivity
  - Coast effect (boundary effect)
- GMD stress test scenarios
- Uses

Geomagnetic Disturbance Stress Test

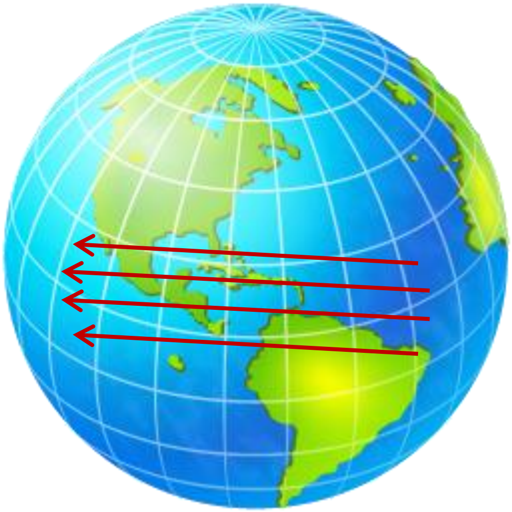
Stress-test scenarios reveal vulnerabilities and allow more efficient allocation of resources

Dominant risk factors:

- **Magnetic latitude**
- **Coastal proximity**
- **Ground conductivity**
- **Line voltage**
- **Line length**
- **Transformer core construction**



Two Components: Global and Regional

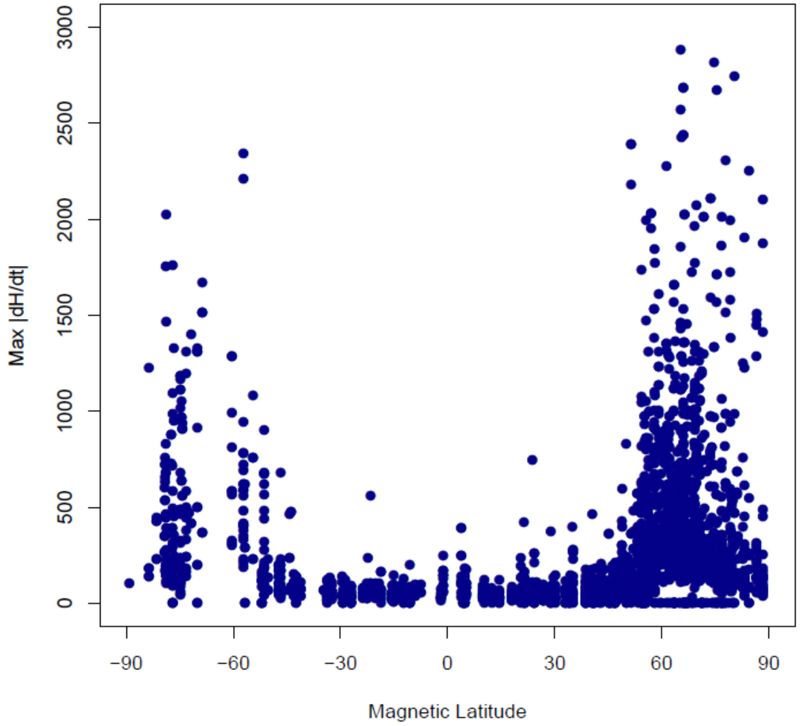


Global storm, coherent current

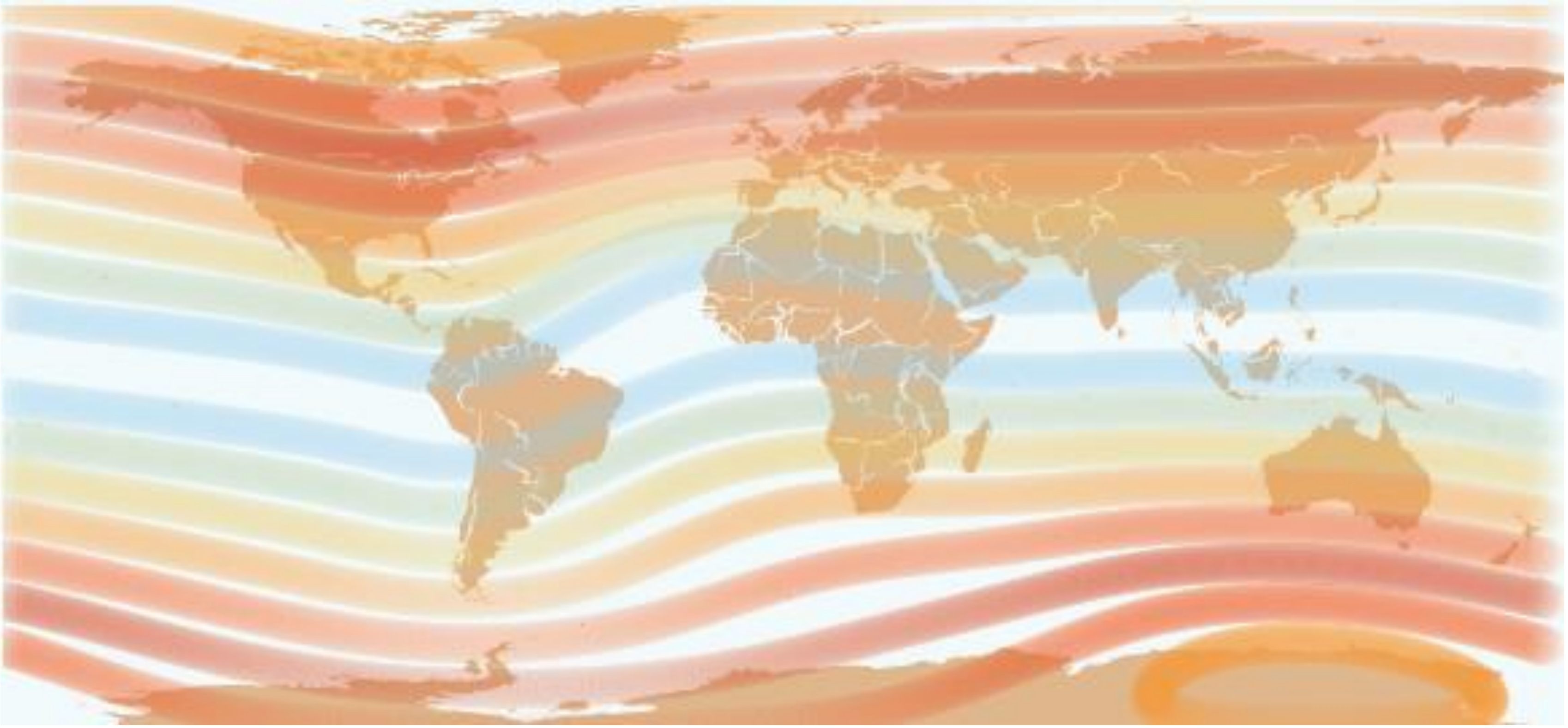
Small scale currents that cause GIC

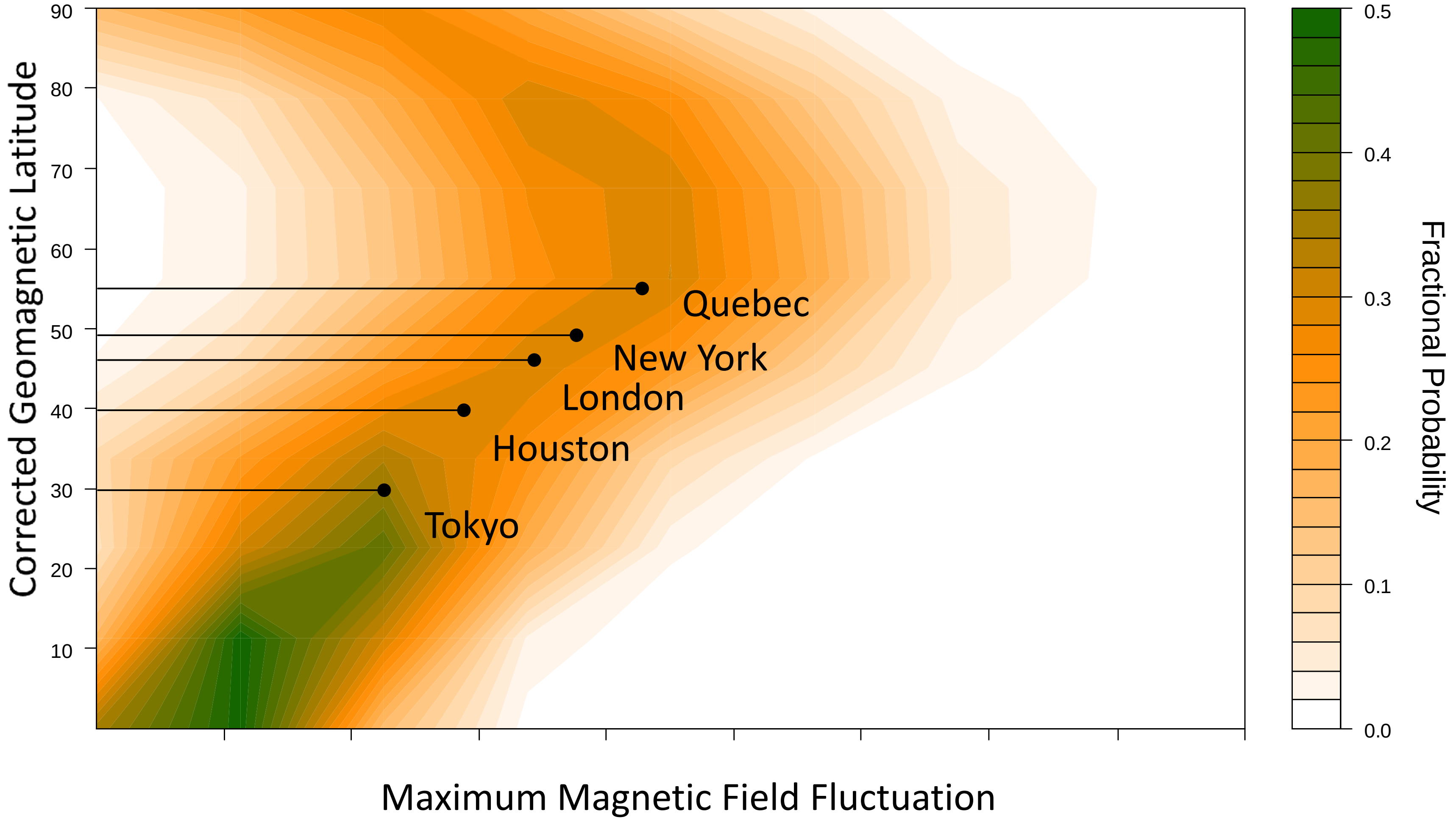
Given a geomagnetic storm of strength X, describe the risk of large B field fluctuations at a given latitude

- Statistical model for small-scale storm features
- SUPERMAG:
  - Magnetic observatory data from 1980-2010
  - 21 storms with Dst/Dxt < -250 nT
- Historical measurements



Magnetic Latitude Risk





Credit: AER

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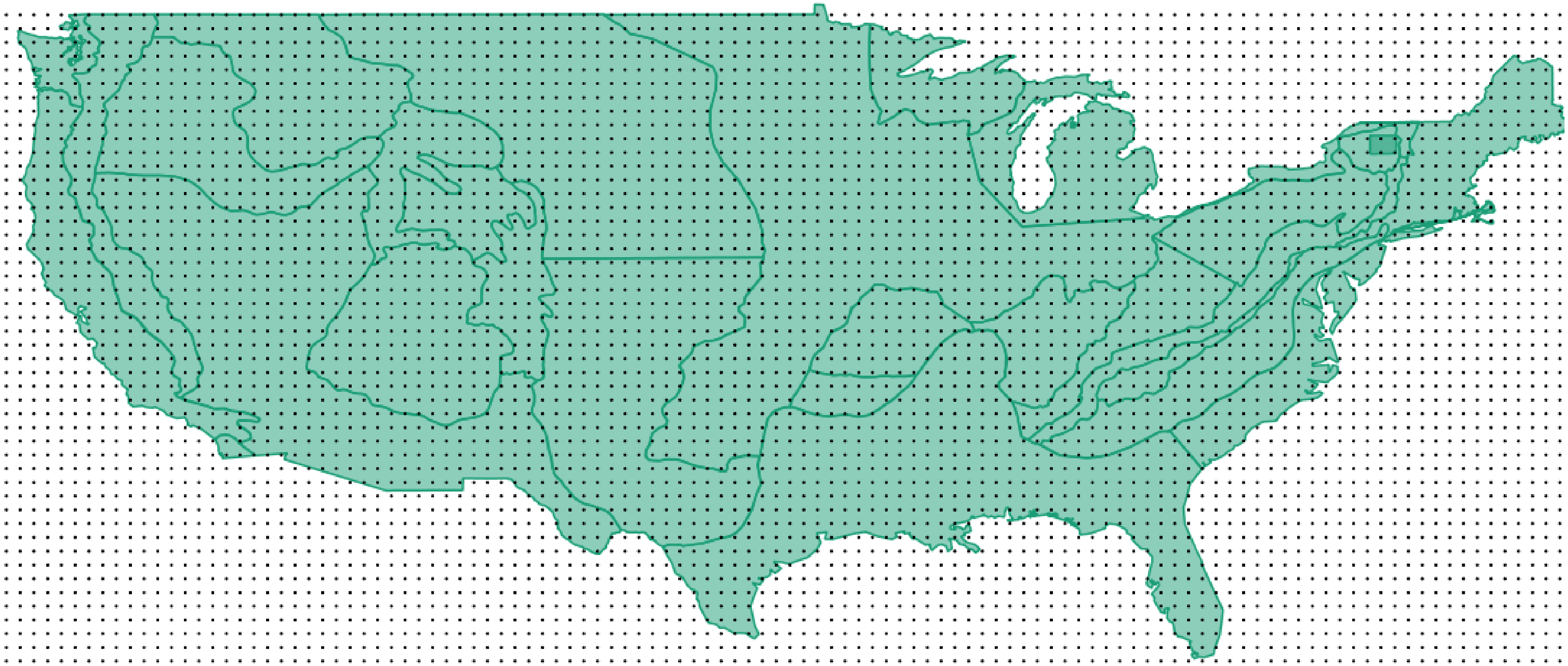
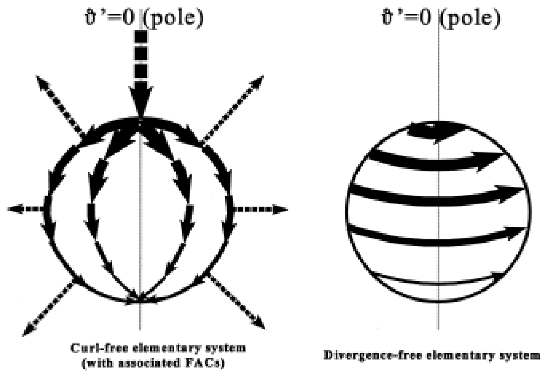
B-field Extrapolation



- Grid with 0.5° longitude and latitude spacing (dots) across the continental US.
- Lines demarcate physiographic regions from the USGS.

Spherical Elementary Current Systems



Surface Electric Fields for North America during Historical Geomagnetic Storms

Wei, Homeier, & Gannon – submitted to Space Weather Journal

Ground magnetic field mapped to ionospheric equivalent currents

$$\underline{\underline{T}} \cdot \underline{I} = \underline{Z}$$

$$\vec{J}_{eq,Ion}(\vec{r}) = \iint_{\text{Ionosph.}} \frac{[\operatorname{curl} \vec{J}(\vec{r}\,')]_r}{4\pi R_I} \cot(\tilde{\vartheta}/2) \underline{e}_{\tilde{\varphi}} d^2 r'$$

$$B_{r'}(r, \vartheta') = \frac{\mu_0 I_0}{4\pi r} \left(\frac{1}{\sqrt{1 - \frac{2r\cos\vartheta'}{R_I} + \left(\frac{r}{R_I}\right)^2}} - 1 \right)$$

$$B_{\vartheta'}(r, \vartheta') = -\frac{\mu_0 I_0}{4\pi r \sin\vartheta} \cdot \left(\frac{\frac{r}{R_I} - \cos\vartheta'}{\sqrt{1 - \frac{2r\cos\vartheta'}{R_I} + \left(\frac{r}{R_I}\right)^2}} + \cos\vartheta' \right)$$

$$\underline{\underline{T}} = \begin{pmatrix} T_{11,\vartheta} & T_{12,\vartheta} & \cdots & T_{1n_{el},\vartheta} \\ T_{11,\varphi} & T_{12,\varphi} & \cdots & T_{1n_{el},\varphi} \\ T_{21,\vartheta} & T_{22,\vartheta} & \cdots & T_{2n_{el},\vartheta} \\ T_{21,\varphi} & T_{22,\varphi} & \cdots & T_{2n_{el},\varphi} \\ \vdots & & & \vdots \\ T_{n_{obs}1,\varphi} & T_{n_{obs}2,\varphi} & \cdots & T_{n_{obs}n_{el},\varphi} \end{pmatrix} \quad \underline{I} = \begin{pmatrix} I_{0,df,1} \\ I_{0,df,2} \\ \vdots \\ I_{0,df,n_{el}} \end{pmatrix} \quad \underline{Z} = \begin{pmatrix} Z_{1,\vartheta} \\ Z_{1,\varphi} \\ Z_{2,\vartheta} \\ Z_{2,\varphi} \\ \vdots \\ Z_{n_{obs},\vartheta} \\ Z_{n_{obs},\varphi} \end{pmatrix}$$

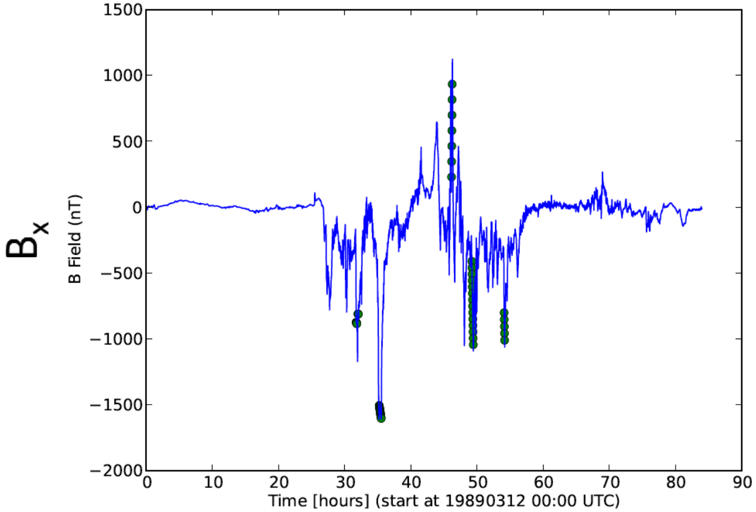
T = ground mag effect, Includes rotation from SECS frame to observation frame

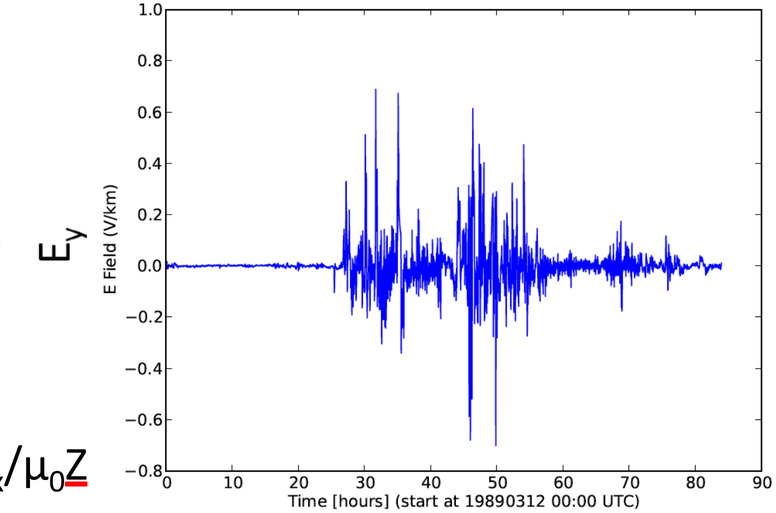
I = scaling factors

Z = measurements

Amm and Viljanen 1999

Magnetic Field --> Electric Field

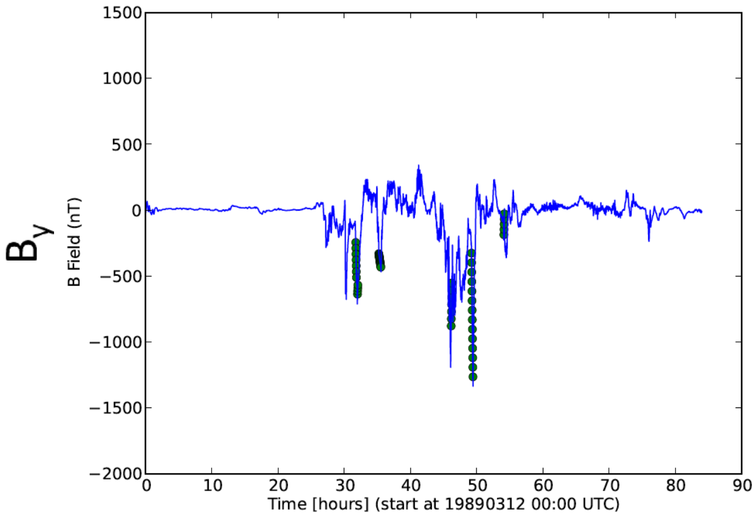


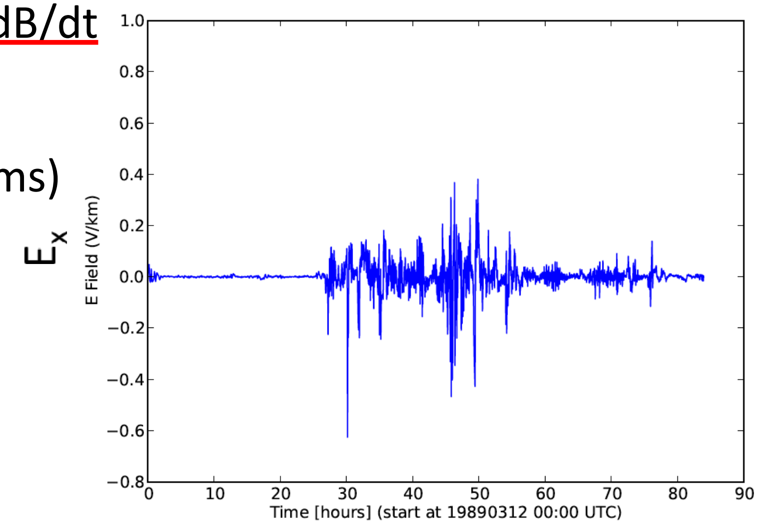


$$\underline{E}_{x,y} = \pm\underline{B}_{y,x}/\mu_0\underline{Z}$$

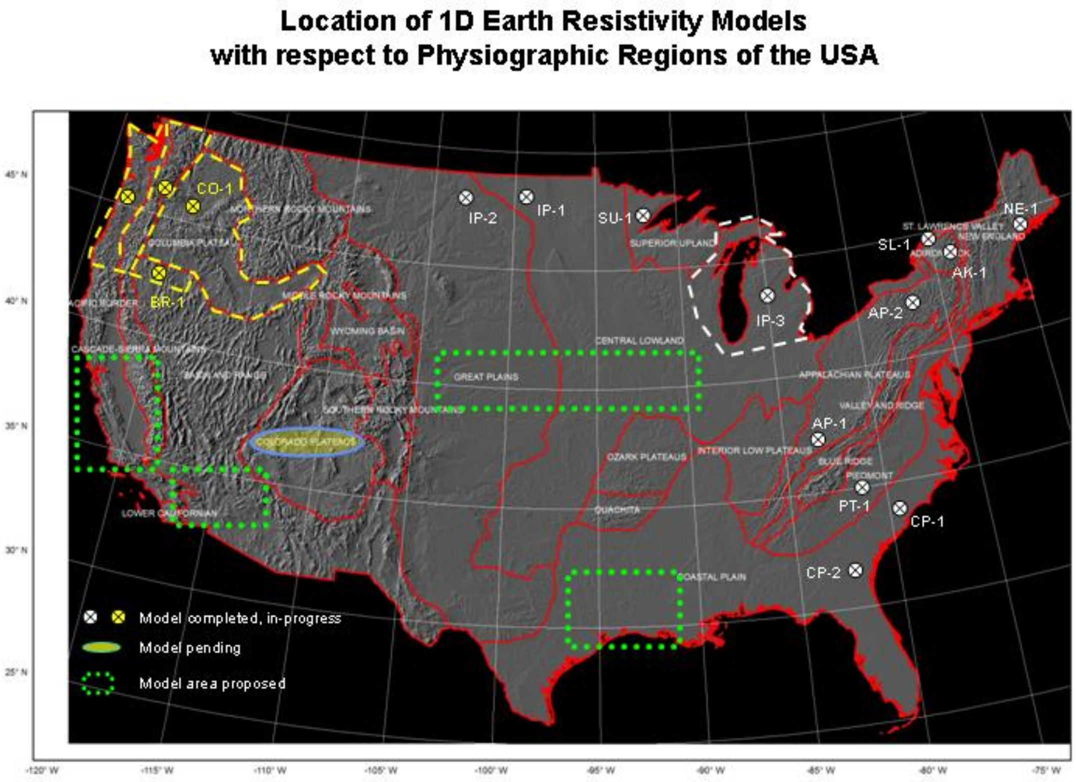
$$\underline{B} = (1/i\omega)\underline{dB/dt}$$

(Fourier Transforms)





Calculate E-field at Specific Locations



- Magnetic field data from Intermagnet
- Interpolate with SECS
- Surface impedance (Z) information from USGS
- Coast effect from Gilbert (2005) and Pirjola (2012)

Relative E-field Risk

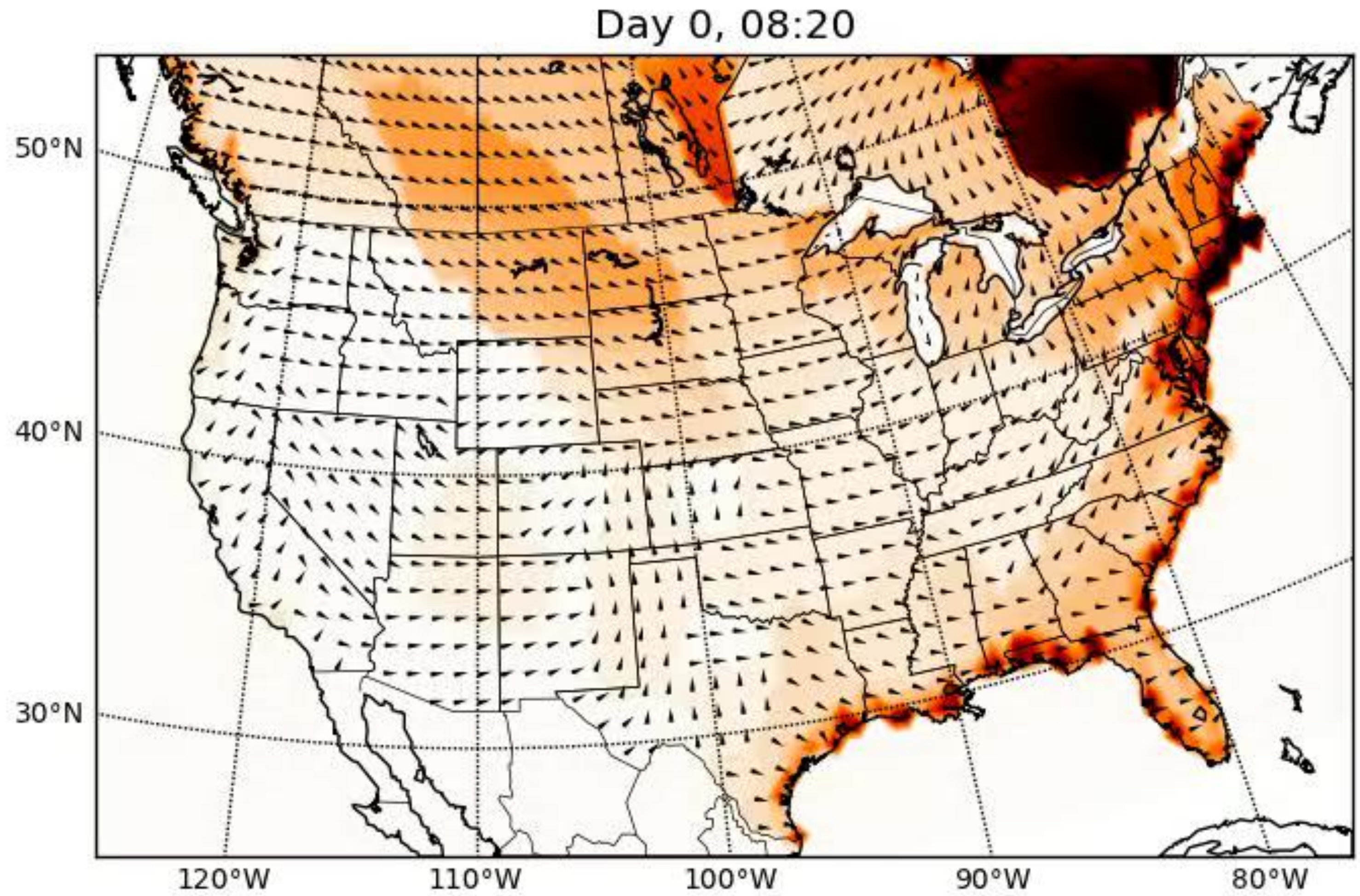
Same magnetic field time-series induces a different surface electric field time-series

Relative risk is a factor of ~5 across the continental United States

$E_{x,y} = \pm B_{y,x}/\mu_0 Z$

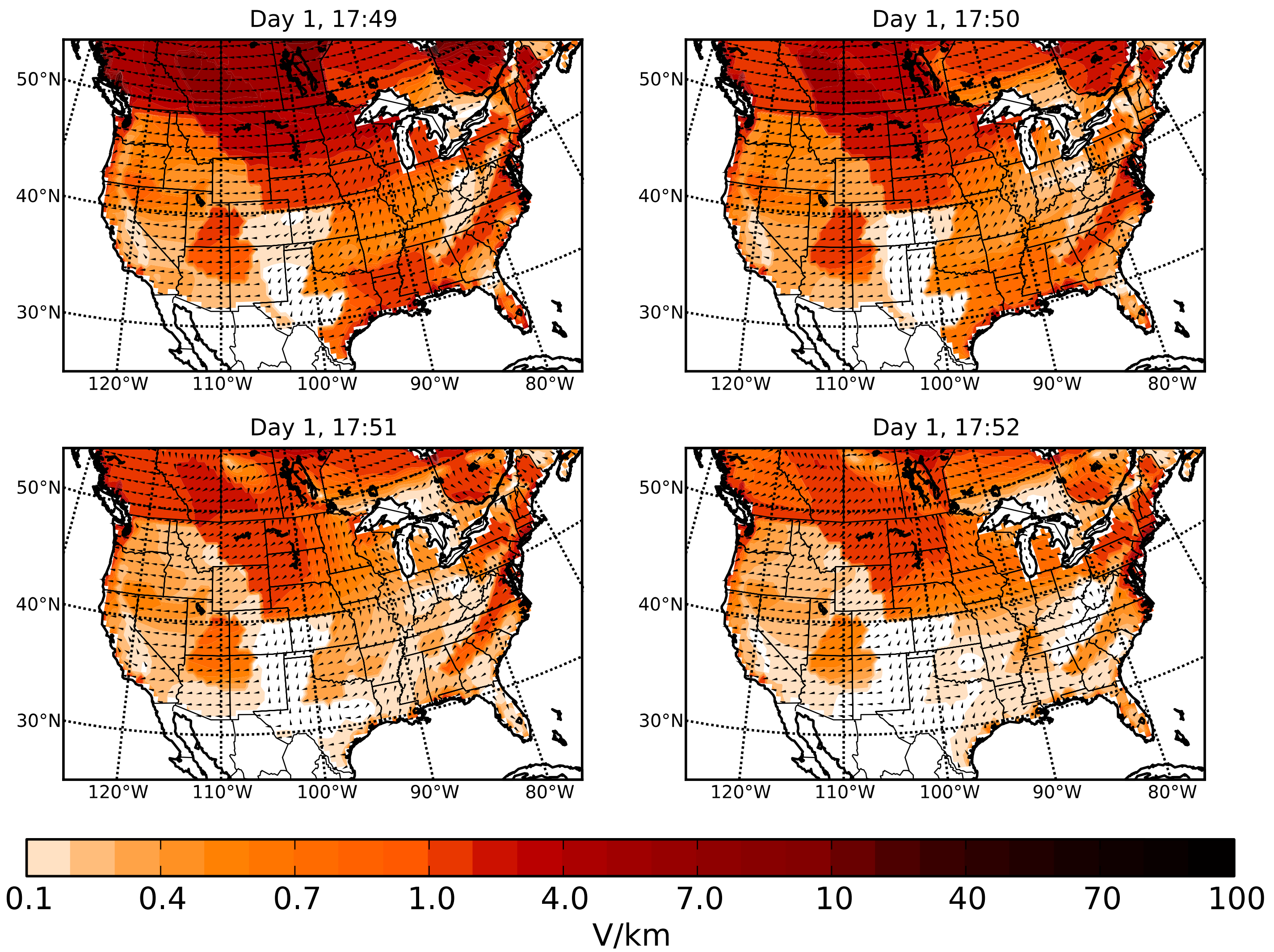
Wei, Homeier, Gannon; submitted

Realistic GMD scenarios can be integrated into PowerWorld power flow solution software



Extreme GMD Scenarios

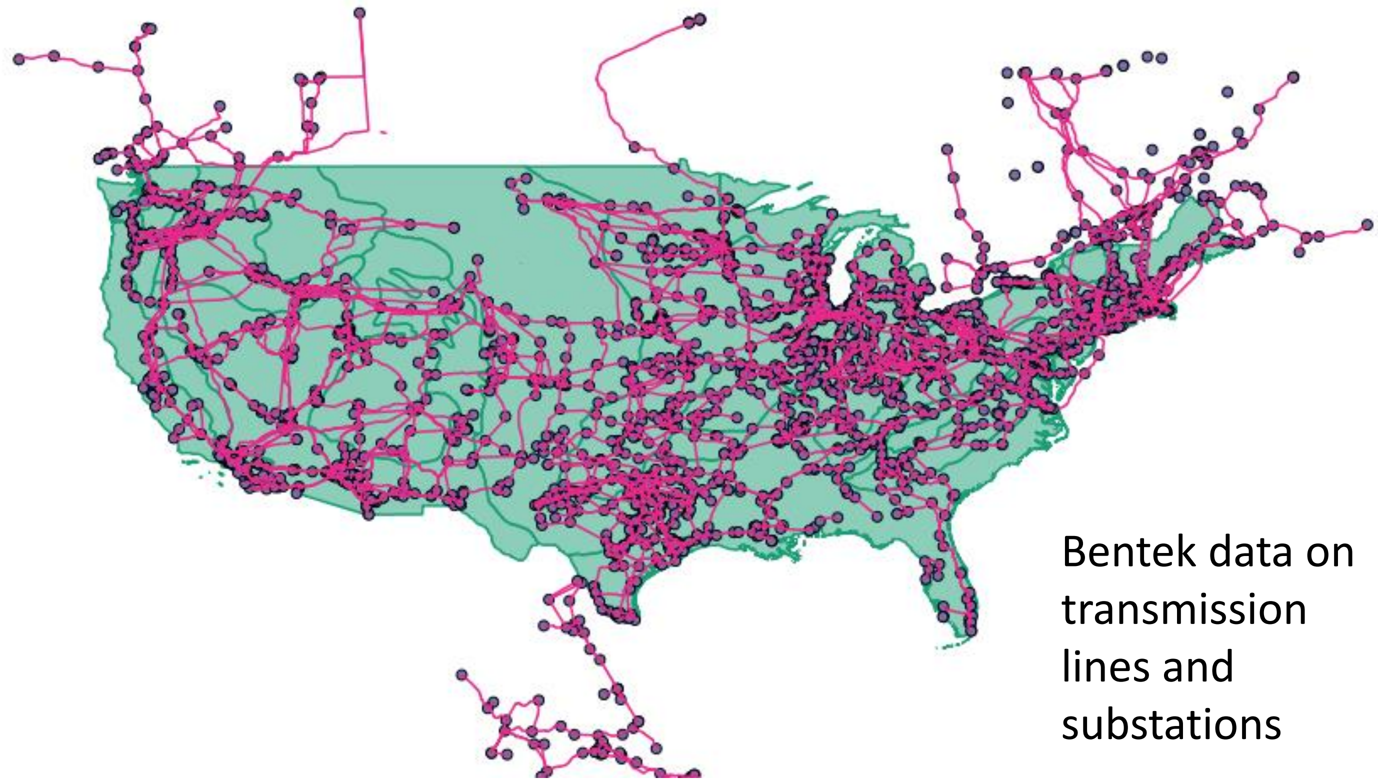
Also see the poster by Lisa Wei



E fields to Currents

PowerWorld sells a GIC add-on, other vendors as well

Can code your own if comfortable with matrix calcs



Bentek data on transmission lines and substations

$$V_{im} = \int_i^m \mathbf{E} \cdot d\mathbf{s}$$

$$J_{e,m} = \sum_{i=1, i \neq m}^{N} \frac{V_{im}}{R_{im}^{n}}$$

$$\mathbf{I_e} = (\mathbf{1} + \mathbf{Y_n Z_e})^{-1} \mathbf{J_e}$$

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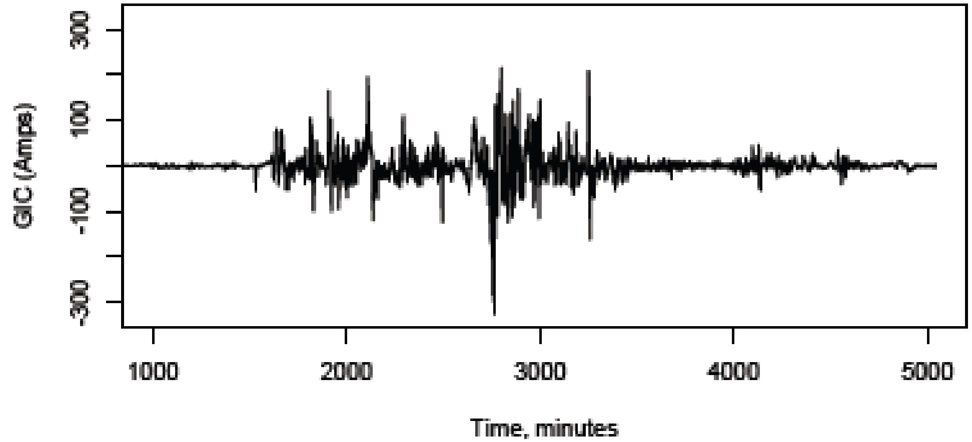
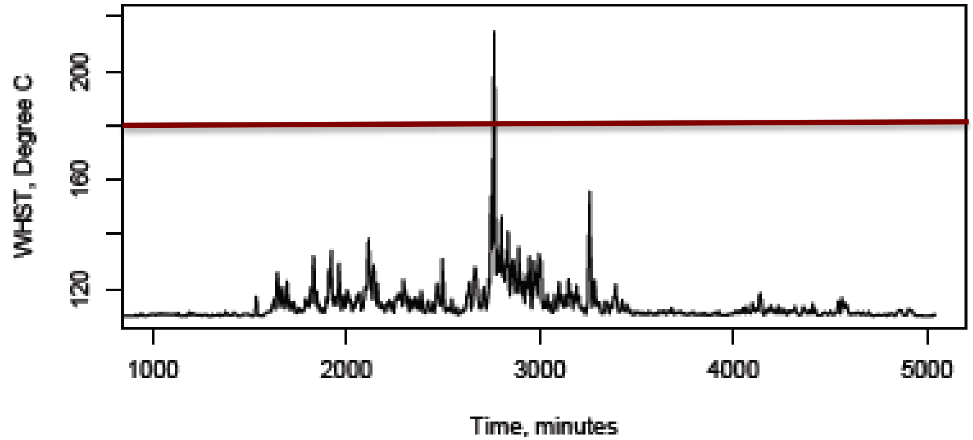
E fields to Currents

Any effect that can be translated to GIC per node per timestep can be modeled

Parameterized temperature models follow the winding hot spot temperatures through the storm

Can get the total population and locations of transformers with WHST's that exceed a given threshold





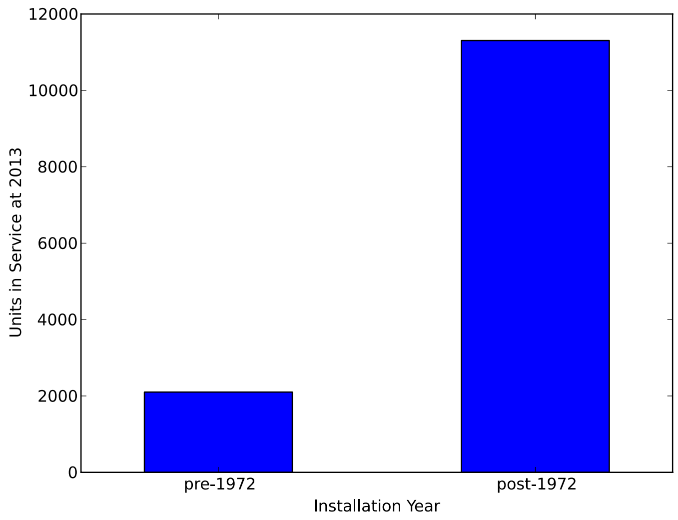
Loss of Life

Transformer age distribution derived from the installation rate (excluding replacements) and failures described by the hazard function:

$$H_{(t)} = \frac{\alpha e^{\beta t}}{1+\alpha e^{\beta t}}$$

Perks formula: HSB

Expected at 2013



Failures are reinstalled in the same year and the calculation is integrated forward

Multiple hazard functions were used and the hazard function choice does significantly affect the 2013 age distribution and subsequent loss of life

GMD Risk Assessment

- GMD stress test scenarios
  - Geophysical model
    - Magnetic latitude
    - Ground conductivity
    - Coast effect (boundary effect)
- Couple with GIC software/code
  - When is voltage collapse likely to occur, if at all
    - Snapshots of extreme E amplitudes
    - Snapshots of extreme GIC
      - calculate GIC per node at each time step, identify GIC metrics of concern, run those specific time steps
  - Effects of an unmitigated storm
    - Follow heating effects through entire time-series, identify vulnerable transformers

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