PSERC Tutorial: High Altitude Electromagnetic Pulse (HEMP) Impacts on the Grid

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PSERC

Introduction: HILFs

- The grid reliability is high, but there are some events that could cause large-scale, long duration blackouts
  - These include what the North American Electric Reliability Corporation (NERC) calls High-Impact, Low-Frequency Events (HILFs); others call them black swan events or black sky days
  - HILFs identified by NERC were 1) a coordinated cyber, physical or blended attacks, 2) pandemics, 3) geomagnetic disturbances (GMDs), and 4) high altitude electromagnetic pulses (HEMPs)
  - Another could be volcanic eruptions
- Presentation focuses on HEMPs

A Few Initial Thoughts

- “Ignorance is not always bliss”
- "All models are wrong but some are useful,“

  George Box, *Empirical Model-Building and Response Surfaces*, (1987, p. 424)
- “The use of nondisclosure agreements or NDA’s to obtain data, while useful in many instances, is not useful if the world community is to engage in research that adheres to the scientific principle of reproducibility of results by other qualified researchers and to use important findings to advance their own work“

  PSERC Founding Director Bob Thomas, 2015

Eletromagnetic Pulses (EMPs) Introduction

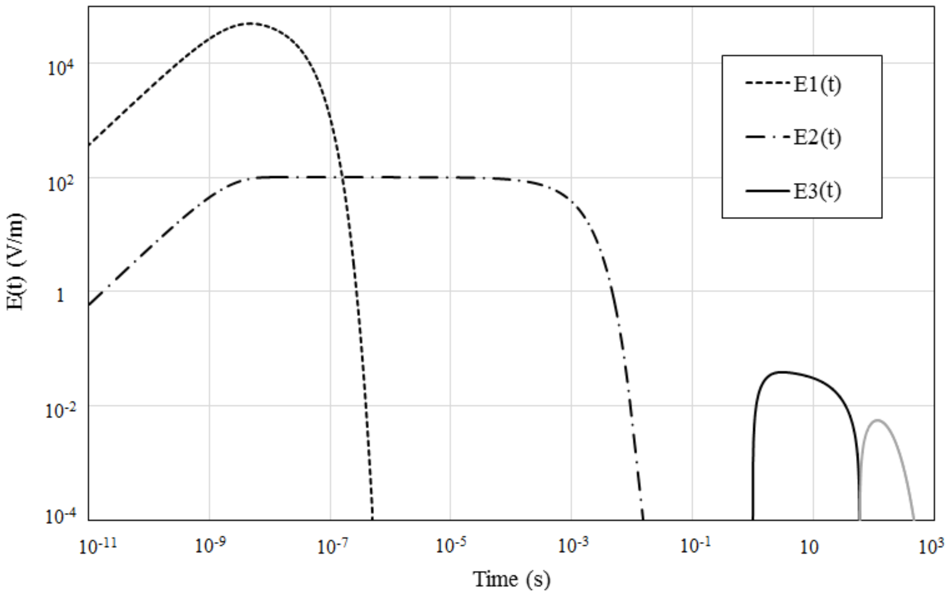
- Broadly defined, an electromagnetic pulse is any transient burst of electromagnet energy
- Characterized by their magnitude, frequencies, footprint, and type of energy
- There are many different types, such as static electricity sparks, interference from gasoline engine sparks, lightning, electric switching, geomagnetic disturbances (GMDs) cause by solar corona mass ejections (CMEs), nuclear electromagnetic pulses, and non-nuclear EMP weapons
- Talk focuses primarily on the impact of nuclear EMPs on the grid, mostly caused by high altitude explosions

Nuclear EMPs

- Much of the information on nuclear EMPs is classified
- Various public documents exist, including IEC 1000-2-9 (from 1996); some of the information presented here comes from this standard
- The primary concern about nuclear EMPS is the impacts caused by high altitude EMPs (HEMPs)
  - From 30 to 100's of km in altitude
  - For a high altitude explosion the other common nuclear impacts (blast, thermal, radiation) do not occur at the ground
  - Scope of HEMP impact can be almost continental
- More localized EMPs can be created by surface blasts; known as source region EMP (SREMP)

HEMP Time Frames

- The impacts of an HEMP are typically divided into three time frames: E1, E2 and E3
- The quickest, E1 with maximum electric fields of 10's of kV per meter, can impact unshielded electronics

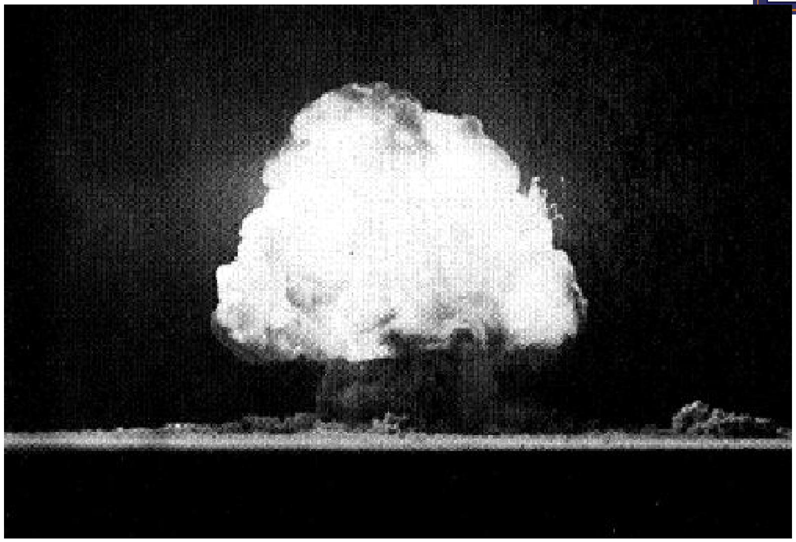


- E2, with electric fields of up to 100 volts per meter, is similar to lightning
- Much of talk is on E3, which is similar to GMDs

Image Source: IEC 1000-2-9 Figure

Nuclear EMP History

- The presence of EMPs was theorized by Enrico Fermi prior to the first explosion in July 1945
  - Many wires were shielded, but still data was lost due to EMP
- British called it "radioflash" in their tests in early 1950's due to the presence of "clicks" heard on radios
- Hardtack tests in 1958 (up to 80 km) further demonstrated HEMP impacts



Trinity Explosion, July 16, 1945,
20 kilotons of TNT
source: Los Alamos Lab

Nuclear EMP History: Starfish Prime

- Starfish Prime was an explosion of a 1.44 megaton nuclear weapon at an altitude of 400 km over the Pacific Ocean in July 1962
  - Part of series of tests known as Operation Fishbowl
  - The EMPs were much larger than expected, driving instruments off scale
  - Impacts seen in Honolulu (1445 km away), including knocking out about 300 street lights, setting off alarms, and damaging a microwave link
  - Some low earth orbit satellites were also damaged

Starfish Prime flash seen in Honolulu; source: Wikipedia

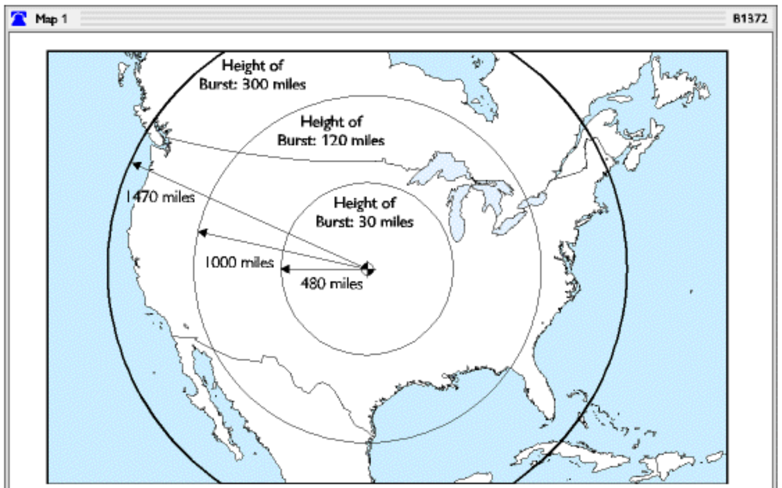
Nuclear EMP History

- Soviet HEMP tests in the early 1960's were reported to have damaged power equipment
- Nuclear tests in the atmosphere, space and under water were banned in 1963
  - There is a United Nations underground test ban from 1996, though not all countries have agreed to it
- Various countries have optimized nuclear weapons for HEMP impacts
  - Russian military writings claim to have a super EMP weapon that can generate 200 kV/m*

*Source: Congressional Research Service, Clay Wilson, High Altitude Electromagnetic Pulse (HEMP) and High Power Microwave (HPM) Devices: Threat Assessments," July 2008

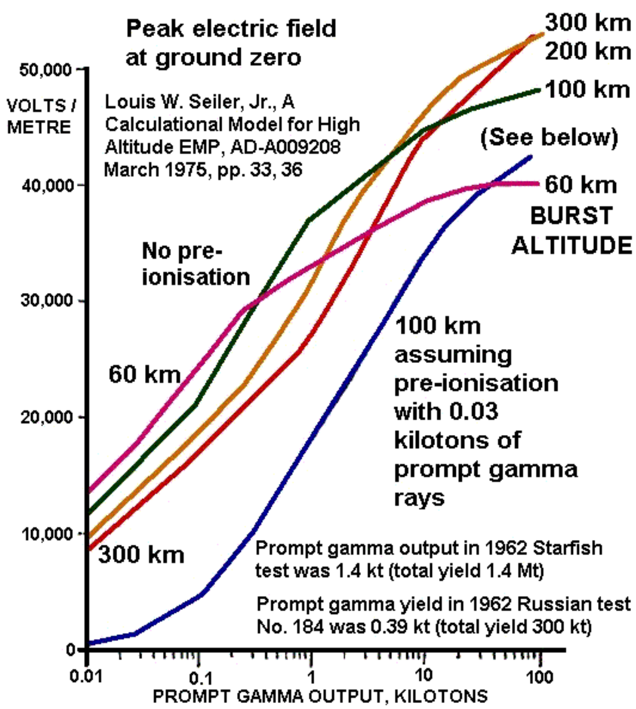
HEMP Impacts versus Size and Altitude

- EMP impacts do not scale linearly with weapon size
  - Even quite small weapons (such as 10 kilotons) can produce large EMPs



Area Effected by an Electromagnetic Pulse, by Height of Burst

Source: Gary Smith, "Electromagnetic Pulse Threats," testimony before the House National Security Committee, July 16, 1997.

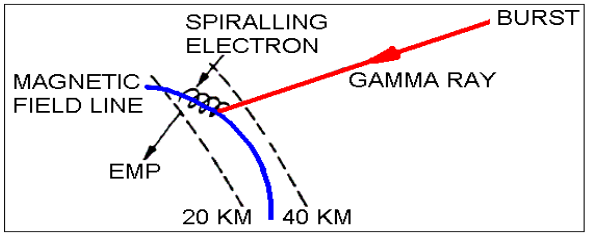


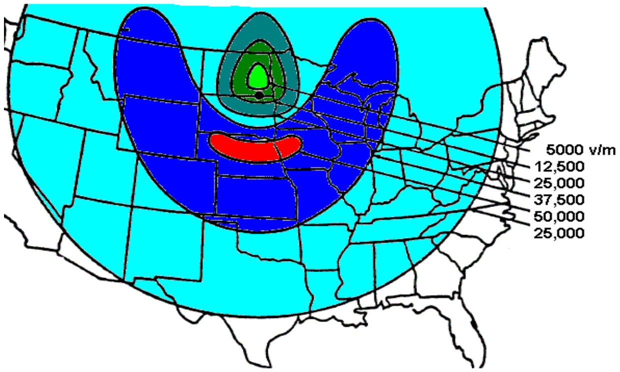
Low altitude EMPs can still have large footprints

Image Sources: en.wikipedia.org/wiki/Nuclear_electromagnetic_pulse

EMP E1 and E2 Mechanisms

- In a nuclear explosion, the E1 pulse is produced by the gamma radiation stripping electrons from atoms in the upper atmosphere
  - Known as the Compton effect; explained by Conrad Longmire at Los Alamos in 1963
  - Electron flow is diverted by earth's magnetic field
  - Mostly line of sight impacts; highest impacts south of detonation in Northern Hemisphere





urce: Nuclear Environment Survivability, S. Army, report AD-A278230 (1994)

Known as Smile Diagrams

- The E2 pulse is created by scattered gamma rays and neutron gamma rays

Source: "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, MetaTech-R-320, January 2010

EMP E1 Protection

- Because of large footprint, small energy density in the E1, so devices can be protected by Faraday cages
  - The allowable size of apertures depends on the wavelength and hence the frequency (λ=c/f); a ballpark figure is no larger than 1/10 the wavelength; for 1 GHz this is about 3 cm
  - Incoming wires are also an issue
- Military Standard 188-125-1 ("HIGH-ALTITUDE ELECTROMAGNETIC PULSE (HEMP) PROTECTION FOR GROUND-BASED C41 FACILITIES PERFORMING CRITICAL, TIME-URGENT MISSIONS PART 1 FIXED FACILITIES") provides useful guidance
- Another useful reference is MetaTech Report R-320, "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid"

Source: "The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid, MetaTech-R-320, January 2010

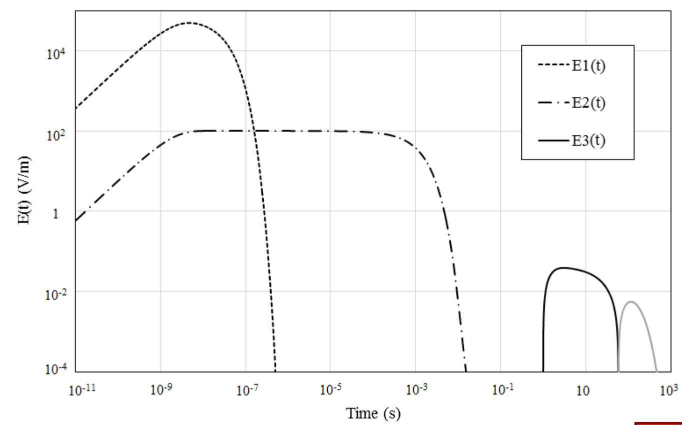
Non-Nuclear EMP (NNEMP) Generators

- E1 EMPs can be generated by non-nuclear sources
  - It is easy to find “how to” manuals on-line
- The magnitude of the pulses produced by NNEMPs can exceed that of nuclear EMPs
- However, the range is greatly reduced – perhaps up to several dozen meters for nonmilitary, mobile systems
  - Can be used for stopping many types of automobiles, and destroying electronics

Source: spectrum.ieee.org/aerospace/military/electromagnetic-warfare-is-here, August 2014

HEMP E3

- The earth's magnetic field is disturbed by 1) the fireball generated by the blast and 2) energized metallic debris
- E3 causes a geoelectric field induced by the earth's changing magnetic field
- E3 is very similar to CME caused GMD s except faster rise times and larger magnitudes
  - Time frames range from seconds to several minutes
  - A useful reference is Metatech report R-321, "The Late-Time (E3) HEMP and Its Impact on the US Power Grid," January 2010



Amplitude Spectrum of Each HEMP Component

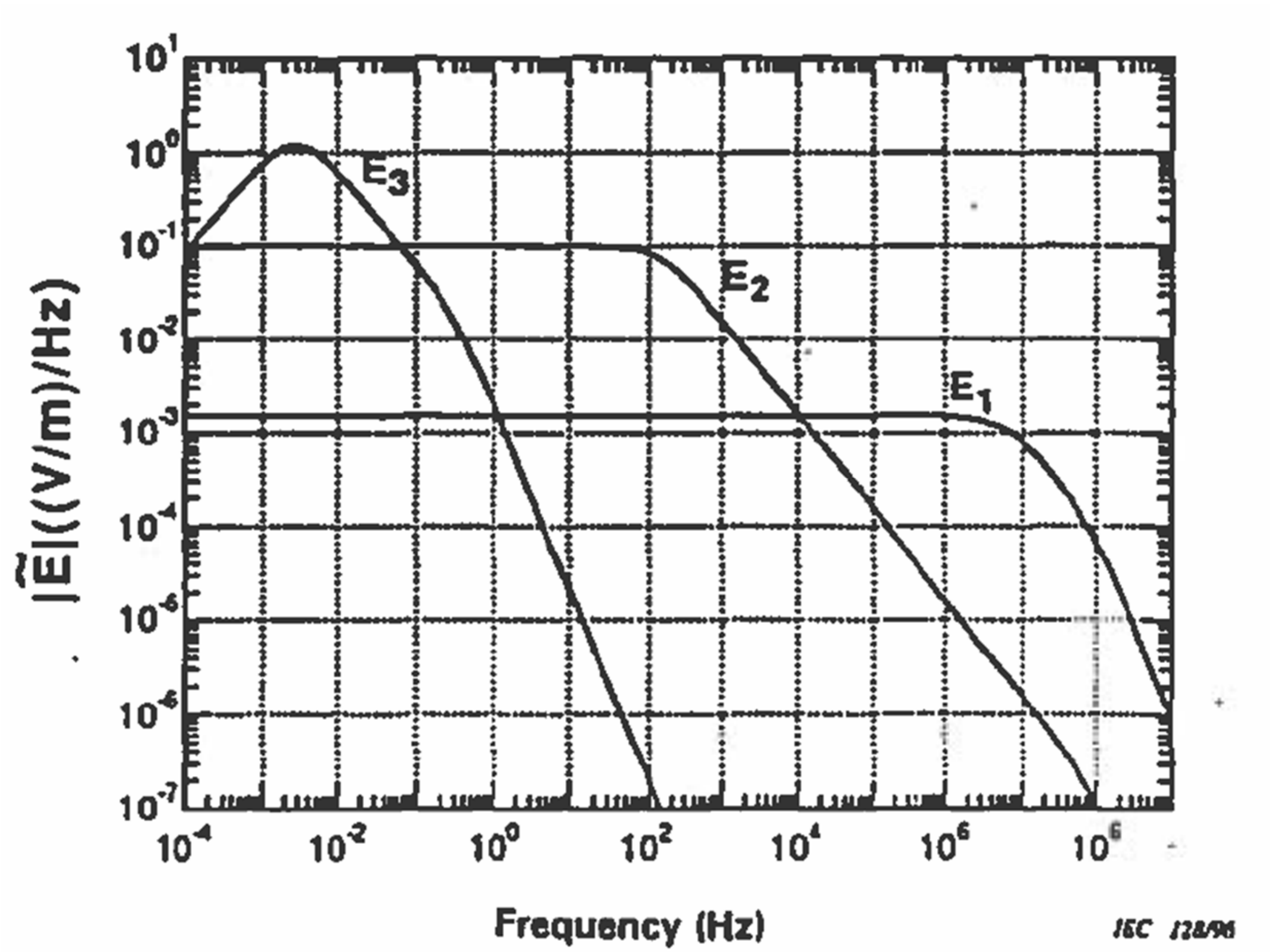
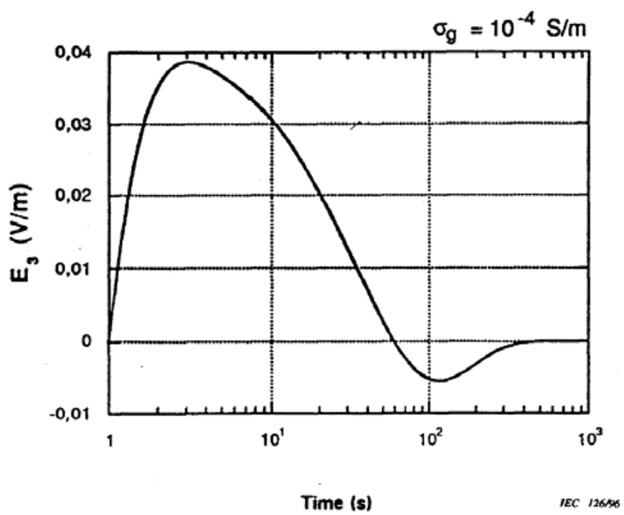
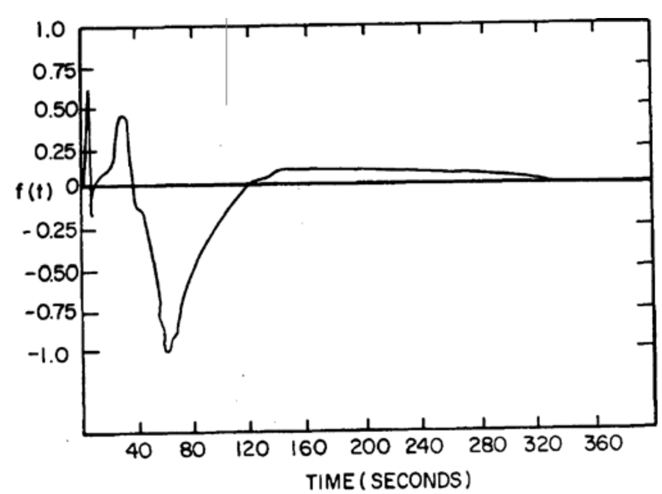


Image Source: IEC 1000-2-9, Figure 11

HEMP E3A and E3B

- The E3 is usually broken into two components
  - the E3A "Blast Wave" (seconds) caused by the expansion of the nuclear fireball, expelling the Earth's magnetic field
  - the E3B "Heave" as bomb debris and air ions follow geomagnetic lines at about 130 km, making the air rise, which gives rise to a current and an induced electric field





Left Image: IEC 1000-2-9, Figure 9, Right Image: ORNL "Study to Assess the Effects of Magnetohydrodynamic Electromagnetic Pulse on Electric Power Systems Phase I Final Report," May 1985, Figure 8

E3 Assumed Electric Field Magnitude and Direction for a Uniform Earth Model

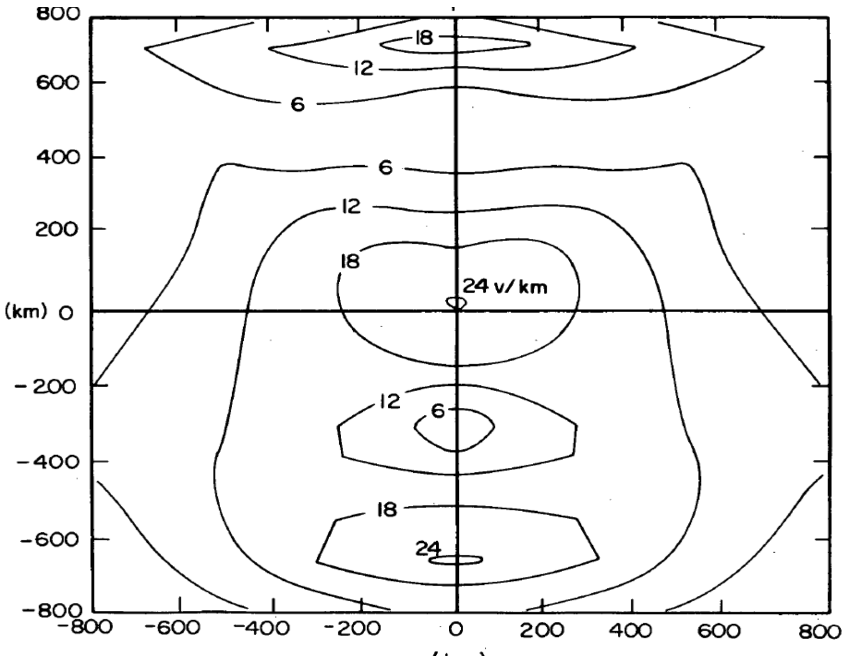


Fig 9: Electric Field Magnitude

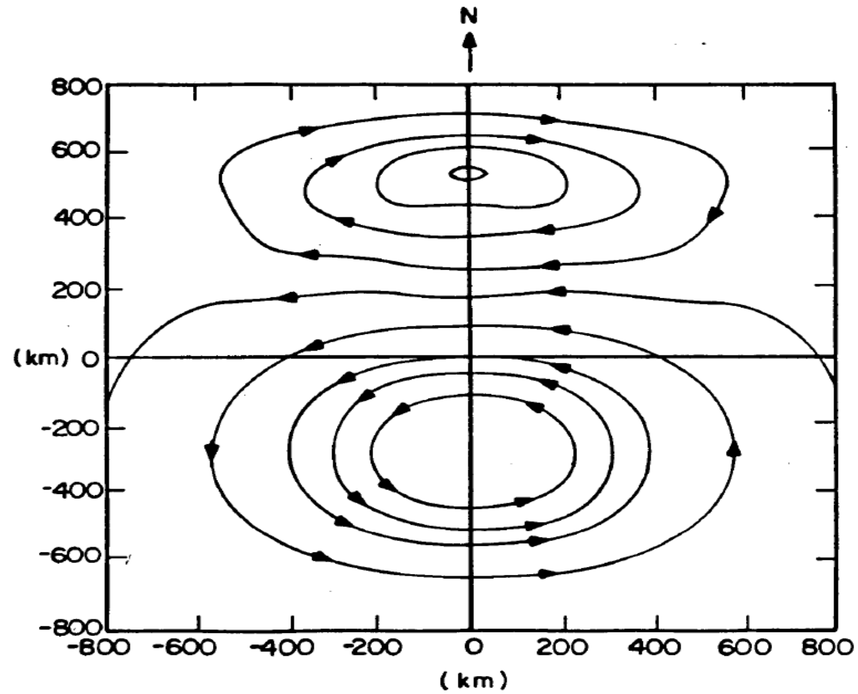


Fig 10: Electric Field Direction

The 1985 ORNL suggests modeling the electric field as the product of a spatially independent time function (fig 8), and time independent spatial magnitude and directions (fig 9 and 10)

Images: ORNL 1985 Report, Figures 9 and 10

Measured Change in B During Fishbowl Tests

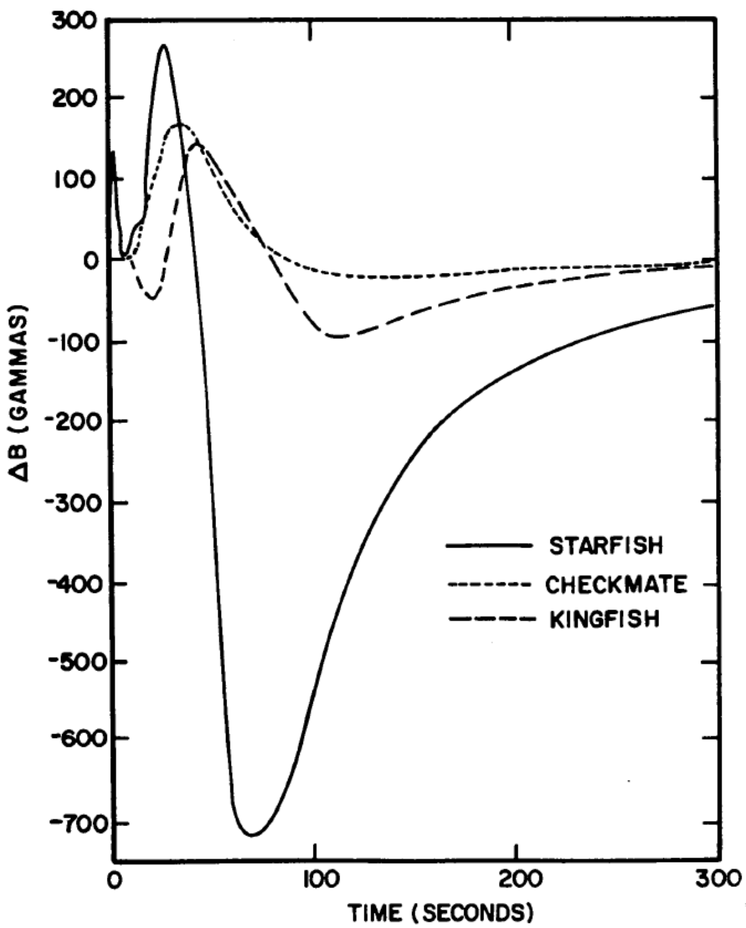
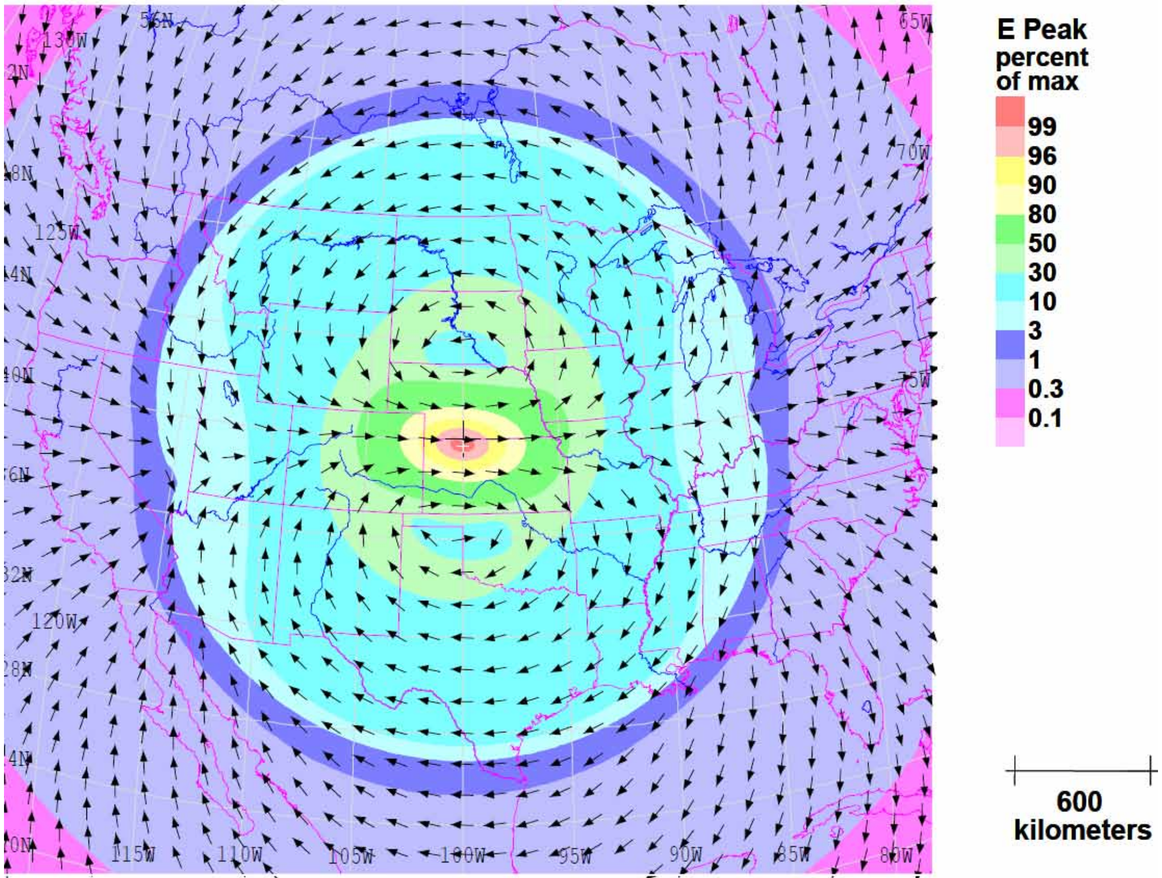


Image: ORNL 1985 Report, Figure 1

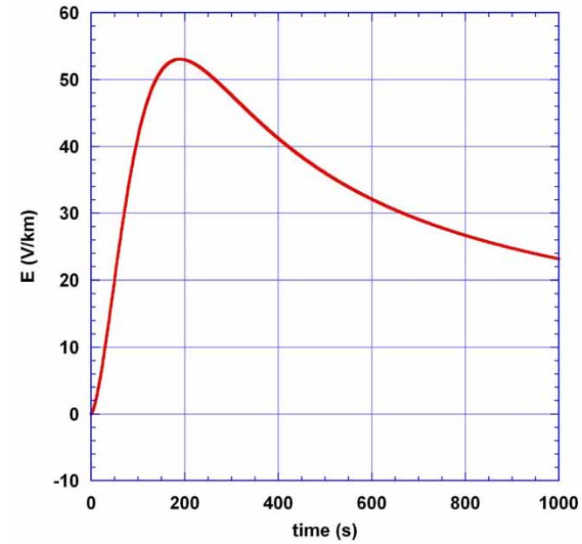
Checkmate and Kingfish were nuclear tests that were part of Operation Fishbowl. Checkmate was at 147 km, with a classified yield (less than 20 kilotons). The Kingfish yield is classified, but believed to be about 400 kiloton at 97 km.

A gamma is one nT.
For reference the Quebec GMD had 500 nT/minute and the 1859 Carrington is estimated to be 5000 nT/minute

E3B Electric Field Magnitude and Direction



The heave electric fields are largest for blasts at about 130 km altitude

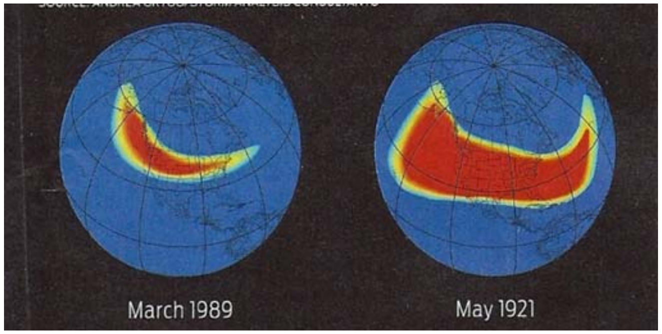


The assumed time duration and footprint is larger than in the 1985 ORNL report

Image Source: Left is Figure 2-11 from R-321, Right is Figure 2-8 form R-321

Analysis is Then Similar to Solar GMDs: Brief GMD Review

- Solar corona mass ejections (CMEs) can cause changes in the earth's magnetic field (i.e., dB/dt). These changes in turn produce a non-uniform electric field at the surface
  - Changes in the magnetic flux are usually expressed in nT/minute; from a 60 Hz perspective they produce an almost dc electric field



  - 1989 North America storm produced a change of 500 nT/minute, while a stronger storm, such as the ones in 1859 or 1921, could produce 5000 nT/minute variation
  - Storm "footprint" can be continental in scale
  - Earth's magnetic field is normally between 25,000 and 65,000 nT, with higher values near the poles

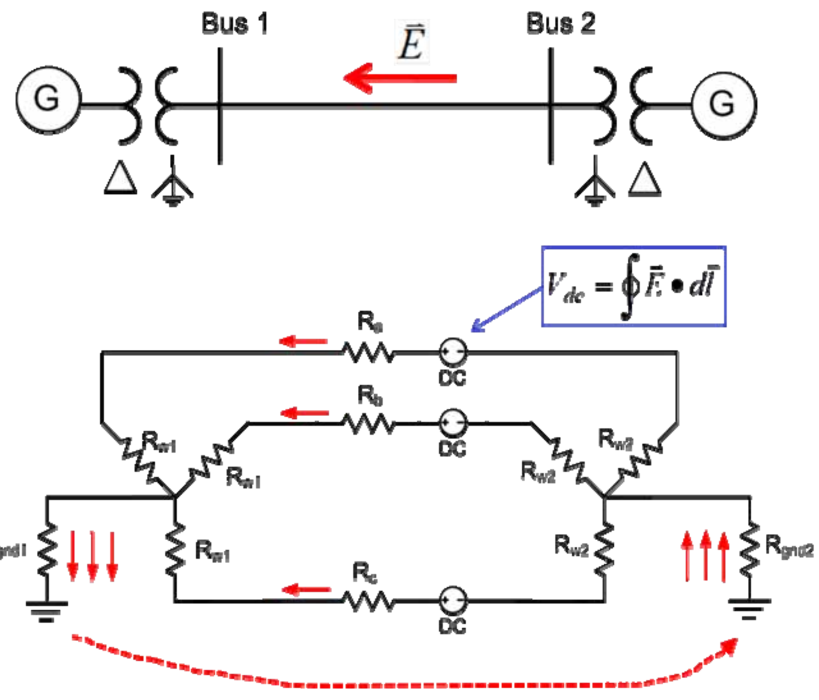
Image source: J. Kappenman, "A Perfect Storm of Planetary Proportions," *IEEE Spectrum*, Feb 2012, page 29

Electric Fields and Geomagnetically Induced Currents (GICs)

- The induced electric field (whether from a CME or HEMP) at the surface is dependent on deep earth (hundreds of km) conductivity
  - Electric fields are vectors (magnitude and angle); values expressed in units of volts/mile (or volts/km);
  - A 2400 nT/minute storm could produce 5 to 10 volts/mile.
- The electric fields cause GICs to flow in the high voltage transmission grid
- The induced voltages that drive the GICs can be modeled as dc voltages in the transmission lines.
  - The magnitude of the dc voltage is determined by integrating the electric field variation over the line length
  - Both magnitude and direction of electric field is important

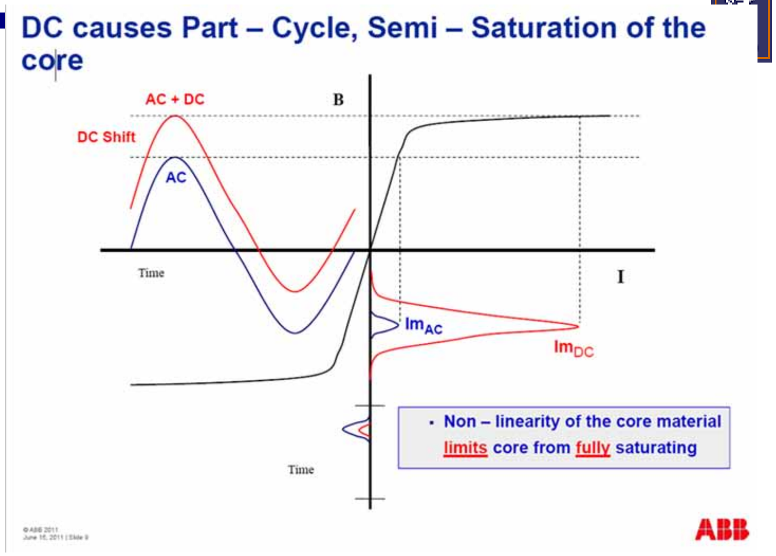
Geomagnetically Induced Currents (GICs

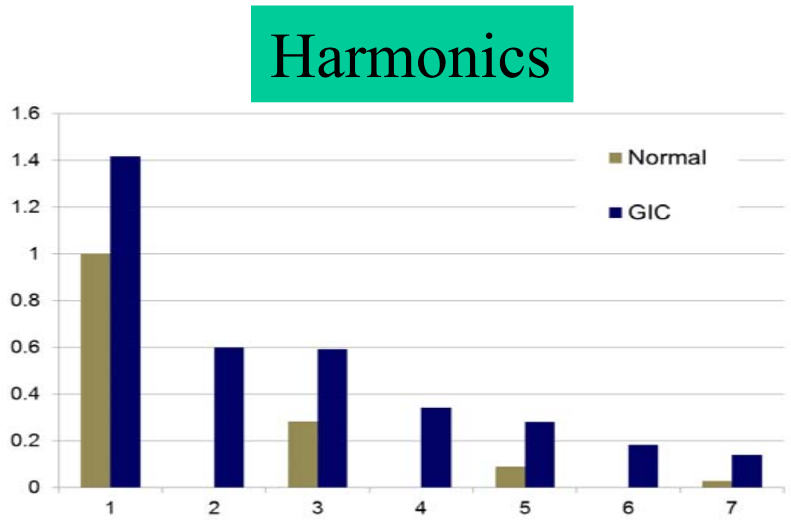
- GMDs cause slowly varying electric fields
- Along length of a high voltage transmission line, electric fields can be modeled as a dc voltage source superimposed on the lines
- These voltage sources produce quasi-dc geomagnetically induced currents (GICs) that are superimposed on the ac (60 Hz) flows



Transformer Impacts of GICs

- The superimposed dc GICs can push transformers into saturation for part of the ac cycle
- This can cause large harmonics; in the positive sequence (e.g., power flow and transient stability) these harmonics can be represented by increased reactive power losses in the transformer





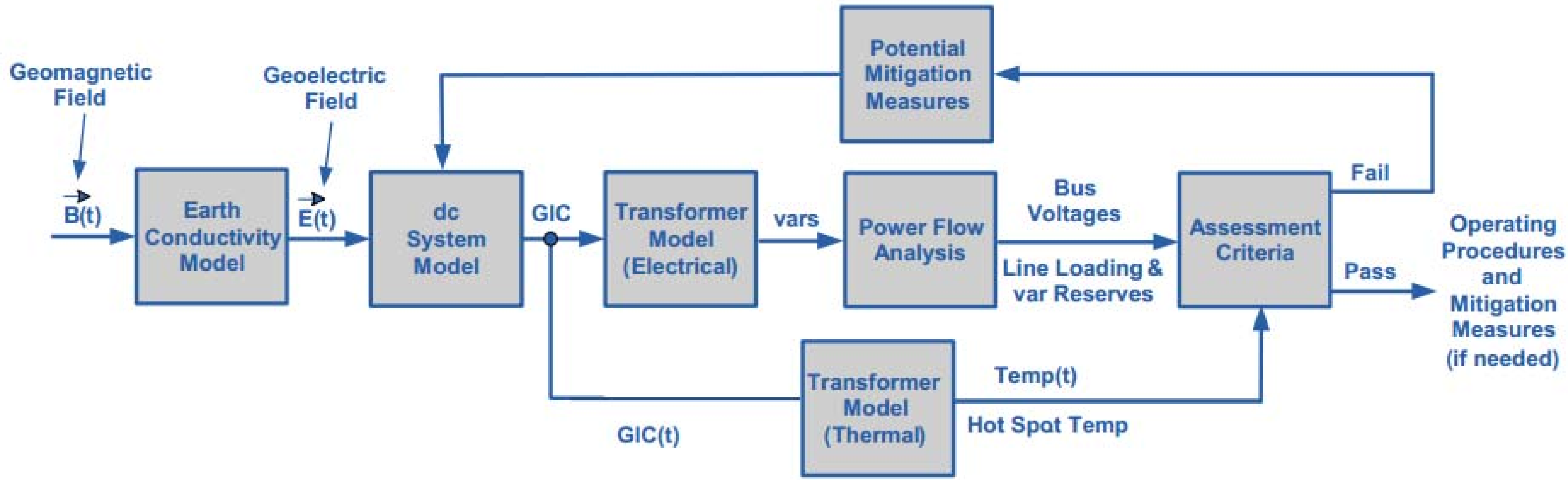
Images: Craig Stiegemeier and Ed Schweitzer, JASON Presentations, June 2011

GMD Enhanced Power Analysis Software

- By integrating GIC calculations directly within power flow and transient stability engineers can see the impact of GICs on their systems, and consider mitigation options
  - Models can provide assumed scenarios, either from a solar event or HEMP
- GIC calculations use many of the existing model parameters such as line resistance. Some non-standard values are also needed; either provided or estimated
  - Substation grounding resistance
  - transformer grounding configuration, transformer coil resistance, auto-transformer, three-winding transformer

Overview of GMD Assessments

In is a quite interdisciplinary problem

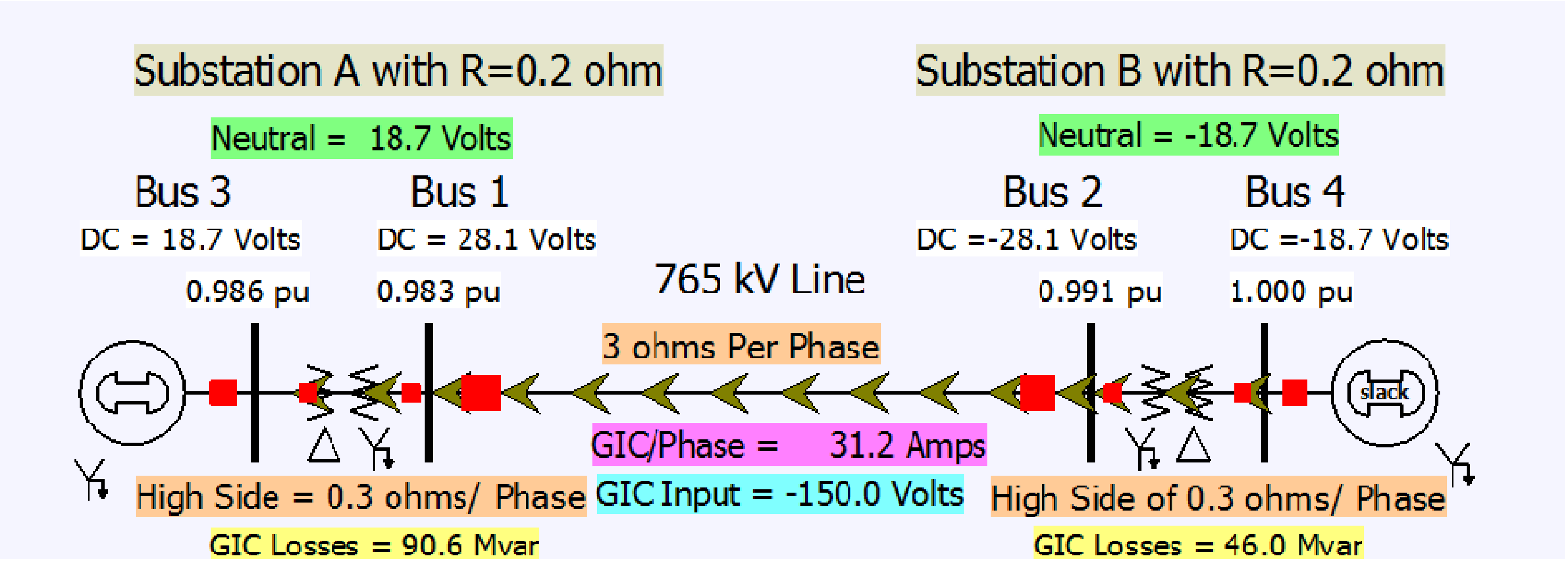


The two key concerns from a big storm or an HEMP are
1) large-scale blackout due to voltage collapse,
2) permanent transformer damage due to overheating

Image Source: http://www.nerc.com/pa/Stand/WebinarLibrary/GMD_standards_update_june26_ec.pdf

Four Bus Example

$$I_{GIC,3Phase} = \frac{150\text{ volts}}{(1+0.1+0.1+0.2+0.2)\Omega} = 93.75\text{ amps or }31.25\text{ amps/phase}$$



The line and transformer resistance and current values are per phase so the total current is three times this value. Substation grounding values are total resistance. Brown arrows show GIC flow.

Power Flow Embedded GIC Calculations: The G Matrix

- With knowledge of the pertinent transmission system parameters and the induced dc line voltages, the dc bus voltages and flows are found by solving a linear equation

$$\mathbf{I} = \mathbf{G}\,\mathbf{V}$$

  - The **G** matrix is similar to the $\mathbf{Y}_{\mathbf{bus}}$ except 1) it is augmented to include substation neutrals, and 2) it is just resistive values (conductances)
  - The current vector contains the Norton injections associated with the GMD-induced line voltages
- Factoring the sparse **G** matrix and doing the forward/backward substitution takes about 1 second for the 60,000 bus Eastern Interconnect Model

Input Electric Field Considerations

- The current vector (**I**) depends upon the assumed electric field along each transmission line
- With a uniform electric field determination of the transmission line's GMD-induced voltage is path independent
  - Just requires geographic knowledge of the transmission line's terminal substations
- With nonuniform fields, such as during an HEMP, an exact calculation would be path dependent, but just a assuming a straight line path is probably sufficient (given all the other uncertainties!)

Impact of Earth Models: Background on Relationship Between dB/dT and E

- The magnitude of the induced electric field depends upon the rate of change in the magnetic field, and the deep earth (potentially 100's of km) conductivity
- The relationship between changing magnetic fields and electric fields are given by the Maxwell-Faraday Equation

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{dt} \qquad \text{(the } \nabla \times \text{ is the curl operator)}$$

$$\oint_{\partial\Sigma} \mathbf{E} \cdot d\ell = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S} \qquad \text{Faraday's law is } V = -\frac{d\lambda}{dt}$$

Background on Relationship Between dB/dT and E

- The magnetic field variation in the atmosphere induces currents in the earth that somewhat cancel the magnetic field variation
  - Lenz's law says the direction of any induced current is always such that it will oppose the change that produced it
- The induced fields tend to cancel the magnetic field variation, leading to decreased fields. This gives rise to a frequency dependent skin depth

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

where f is the B field variation in Hz

μ is the magnetic permeability ($4\pi \times 10^{-7}$ H/m here)

σ is the conductity in S/m

As an example, at 0.01 Hz and conductivity of 0.01 S/m the skin depth is 50.3 km

Frequency Domain Analysis With Uniform Conductance

- If the earth is assumed to have a single conductance, σ, then

$$Z(\omega) = \frac{j\omega\mu_0}{\sqrt{j\omega\mu_0\sigma}} = \sqrt{\frac{j\omega\mu_0}{\sigma}}$$

- The magnitude relationship is then

This was the assumption in the 1985 ORNL report

Recalling $B(\omega) = -\mu_0 H(\omega)$

$$|E(\omega)| = |Z(w)\,\mathrm{H}(\omega)|$$

$$= \left|\sqrt{\frac{j\omega\mu_0}{\sigma}}\,\frac{B(\omega)}{\mu_0}\right|$$

For example, assume σ of 0.001 S/m and a 500nT/minute maximum variation at 0.002 Hz.

Then B(ω) =660×10^{-9} T and

$$E(\omega) = \sqrt{\frac{2\pi\times0.002\times\mu_0}{0.001}}\,\frac{660\times10^{-9}\text{ T}}{\mu_0}$$

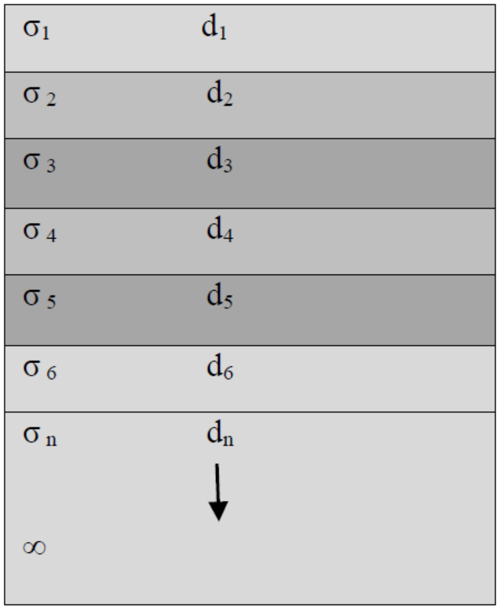
$$E(\omega) = 0.00397\times0.525 = 2.1\text{ V/km}$$

1-D Earth Models

- With a 1-D model the earth is model as a series of conductivity layers of varying thickness
- The impedance at a particular frequency is calculated using a recursive approach, starting at the bottom, with each layer m having a propagation constant

$$k_m = \sqrt{j\omega\mu_0\sigma_m}$$

- At the bottom level n $Z_n = \dfrac{j\omega\mu_0}{k_n}$



1-D Layers

Image: Figure 3.1 from NERC Application Guide: Computing Geomagnetically-Induced Current in the Bulk-Power System, December 2013

1-D Earth Models

- Above the bottom layer, each layer m, has a reflection coefficient associated with the layer below

$$r_m = \frac{(1-k_m)\dfrac{Z_{m+1}}{j\omega\mu_0}}{(1+k_m)\dfrac{Z_{m+1}}{j\omega\mu_0}}$$

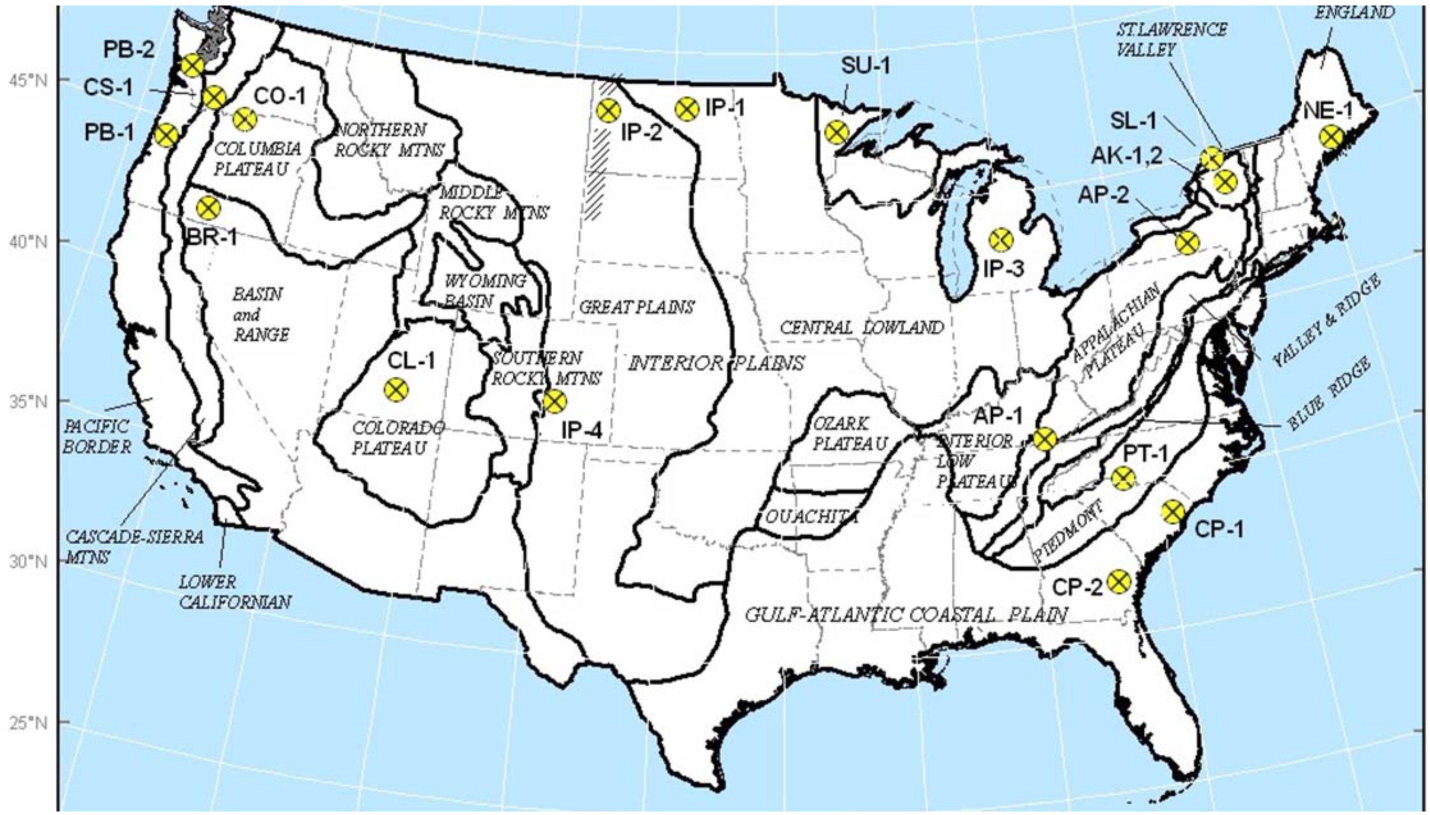
- With the impedance at the top of layer m given as

$$Z_m = j\omega\mu_0\left(\frac{1-r_m e^{-2k_m d_m}}{k_m\left(1+r_m e^{-2k_m d_m}\right)}\right)$$

- Recursion is applied up to the surface layer

USGS 1-D Conductivity Regions

- The USGS has broken the continental US into about 20 conductivity (resistivity) regions

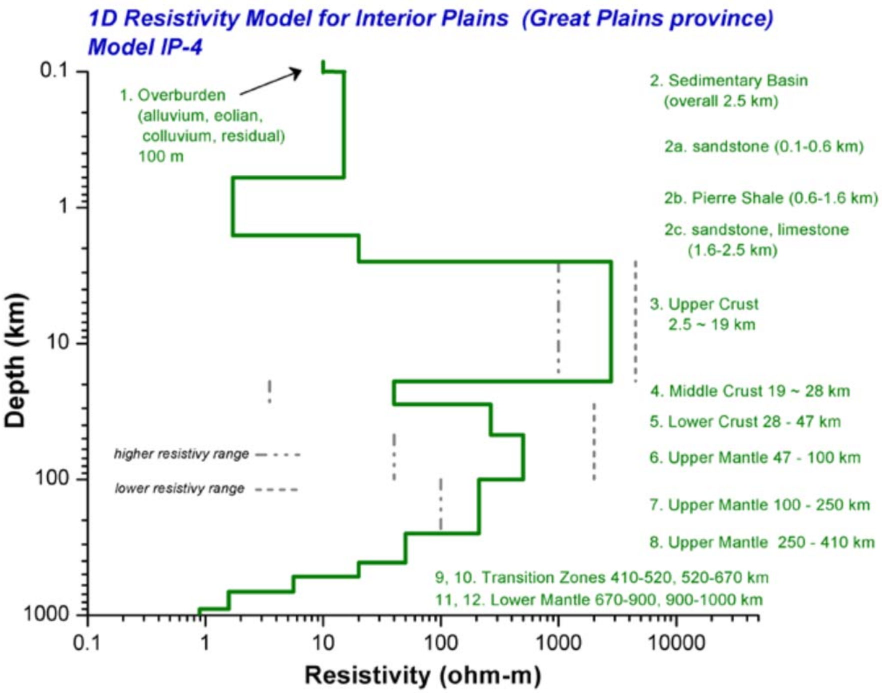


These region scalings are now being used for power flow GMD analysis

Image from the NERC report; data is available at http://geomag.usgs.gov/conductivity/

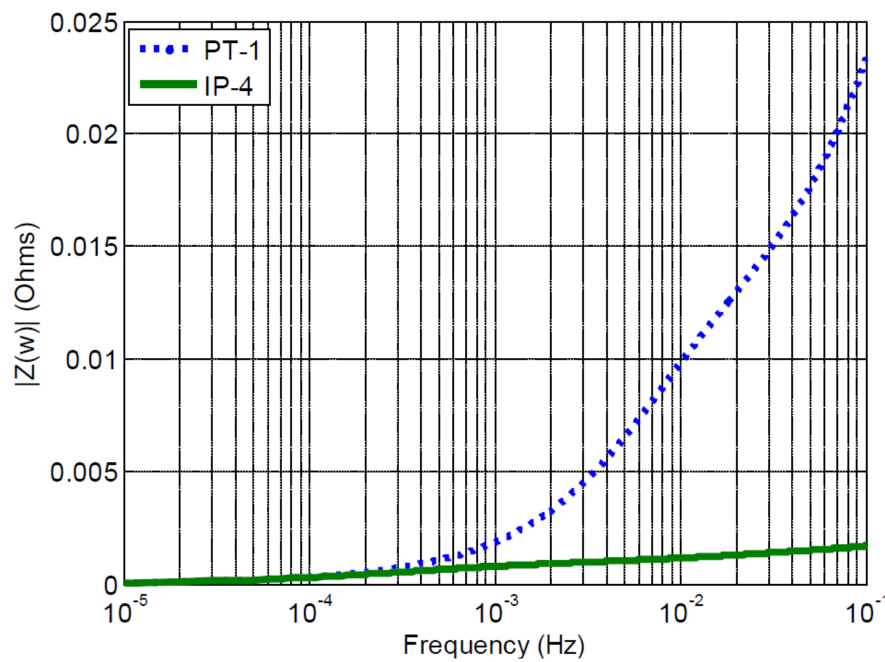
1-D Earth Models

- Image on left shows an example 1-D model, whereas image on right shows the Z(ω) variation for two models

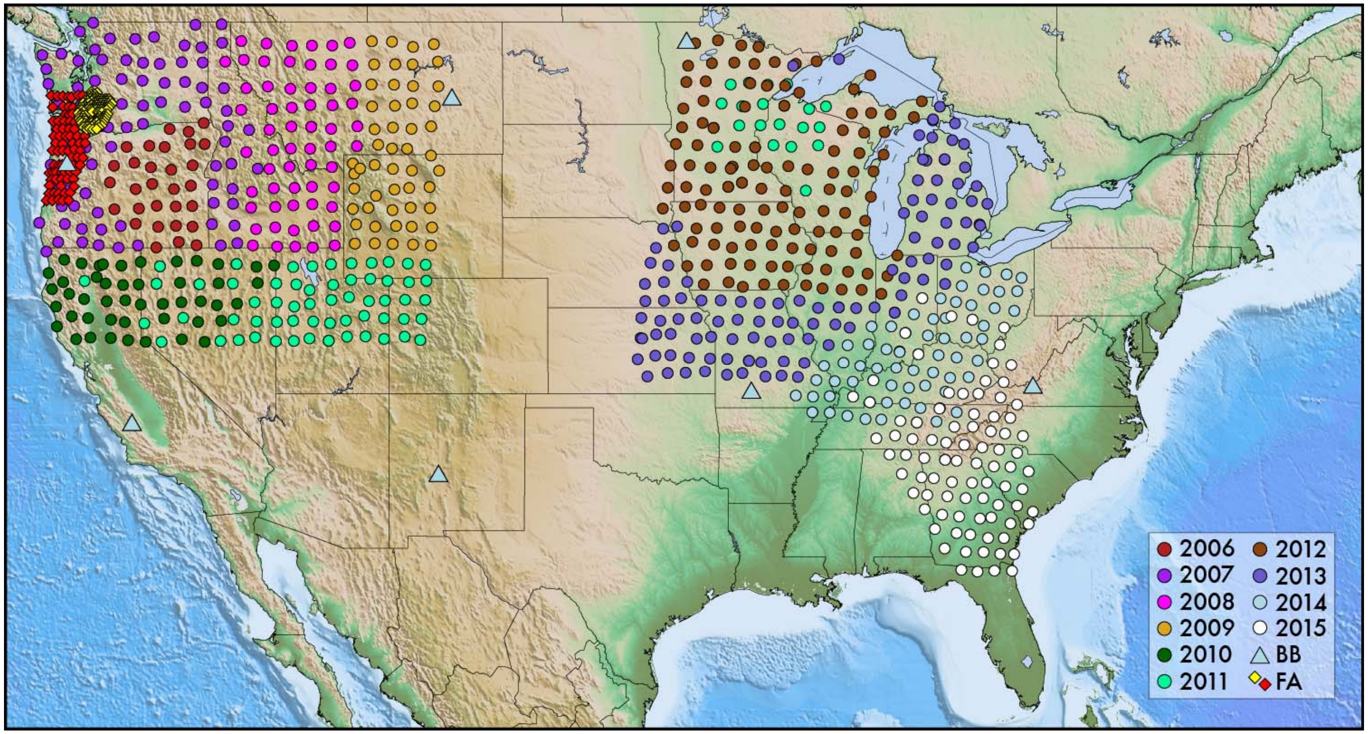


Resistivity values and depths have been interpreted from published geological reports and maps, and may differ from actual conditions measured by a geophysical survey and/or borehole.

Figure 9: Frequency response of two layered Earth conductivity models.



3-D Models and EarthScope



The magnetotelluric (MT) component of USArray, an NSF Earthscope project, consists of 7 permanent MT stations and a mobile array of 20 MT stations that will each be deployed for a period of about one month in regions of identified interest with a spacing of approximately 70 km. These MT measurements consist of magnetic and electric field data that can be used to calculate 3D conductivity deep in the Earth. The MT stations are maintained by Oregon State University's National Geoelectromagnetic Facility, PI Adam Schultz. (www.earthscope.org)

3-D Models and EarthScope

- Earthscope data is processed into magnetotelluric transfer functions that:
  - Define the frequency dependent linear relationship between EM components at a single site.

$$\frac{E_x(\omega)}{B_y(\omega)} = \xi_{xy}$$

(simplified for the 1D case)

- Can be used to relate a magnetic field input to and electric field output at a single site

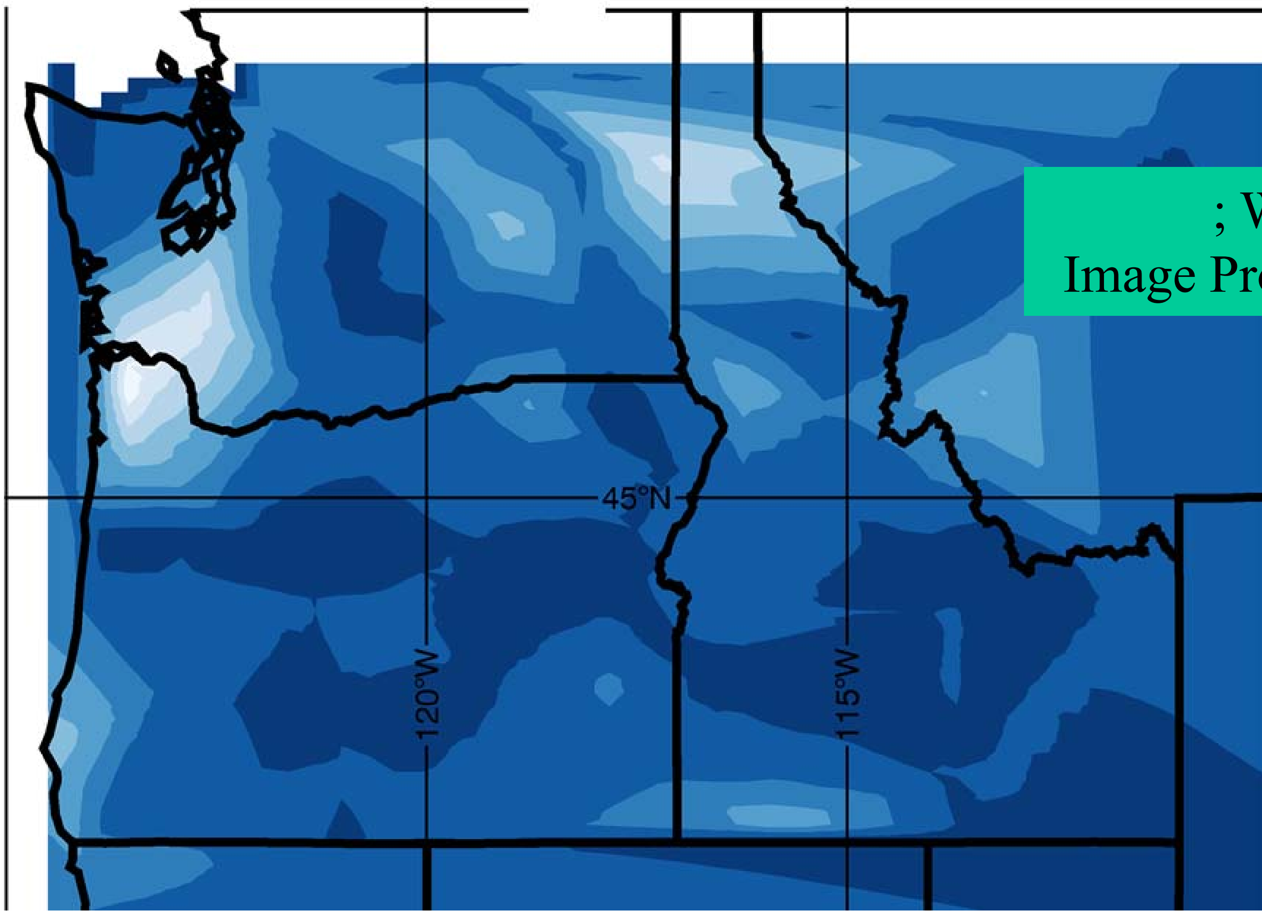
$$\begin{bmatrix} Ex \\ Ey \end{bmatrix} = \begin{bmatrix} \xi_{xx} & \xi_{xy} \\ \xi_{yx} & \xi_{yy} \end{bmatrix} \cdot \begin{bmatrix} Bx \\ By \end{bmatrix}$$

- Are provided in 2x2 impedance tensors by USArray

Reference: Kelbert et al., IRIS DMC Data Services Products, 2011.

Example 3-D Earthscope Model Results

- Image provides a snapshot visualization of the time-varying surface electric fields using Earthscope data



; White ~ 10 V/km
Image Provided by Jenn Gannon

Large-Scale Studies Require Geo-mapped Buses

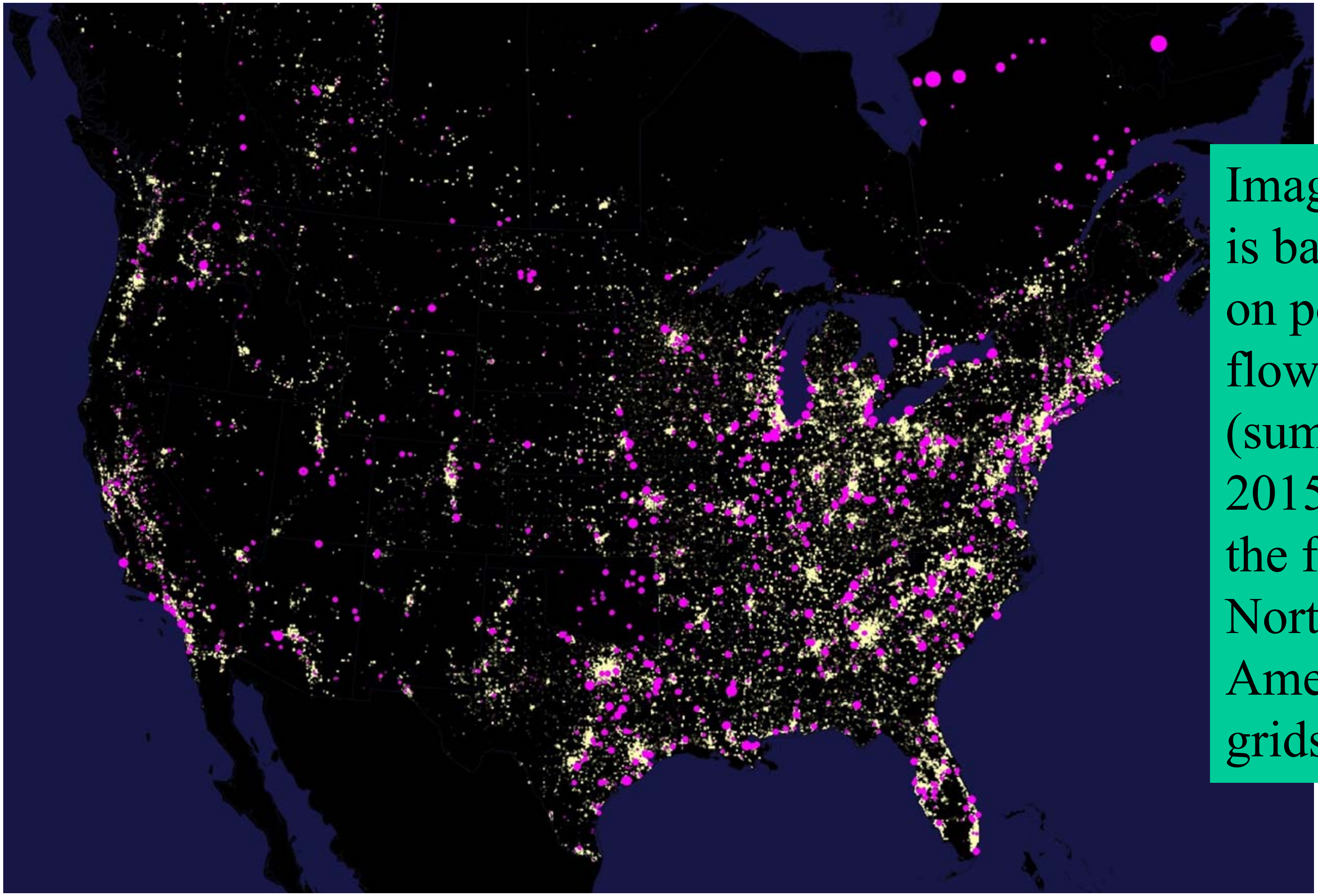
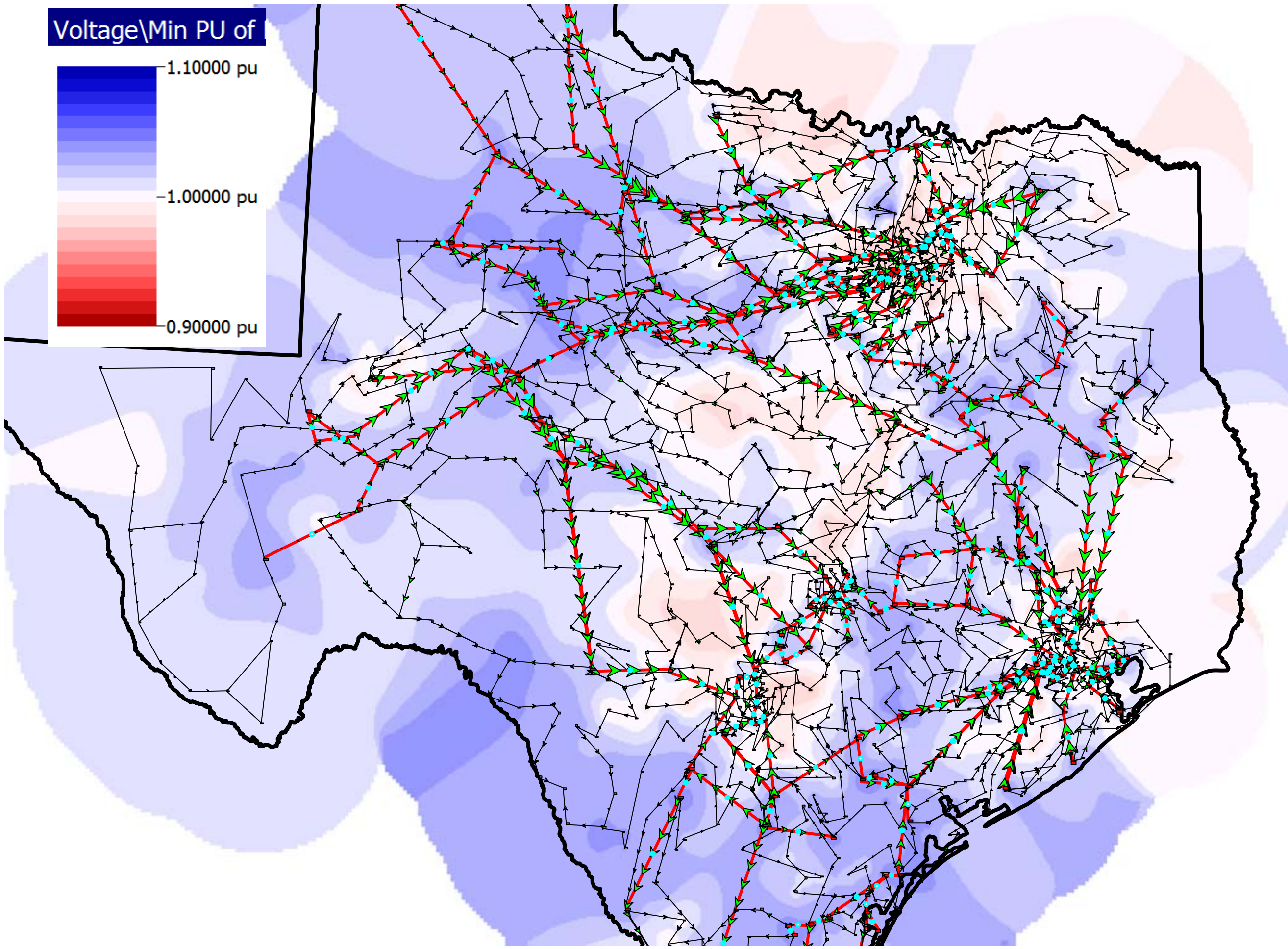


Image is based on power flow data (summer 2015) for the four North American grids

Example EMP Results: 2000 Bus Synthetic Texas Footprint Model



The next few slides illustrate the impact of an EMP on an entirely synthetic (fictitious) 2000 bus model located on the Texas footprint. The ORNL scenario is used with an impact over lat 32.5N, long 97.5W

Example EMP Results: 2000 Bus Synthetic Texas Footprint Model

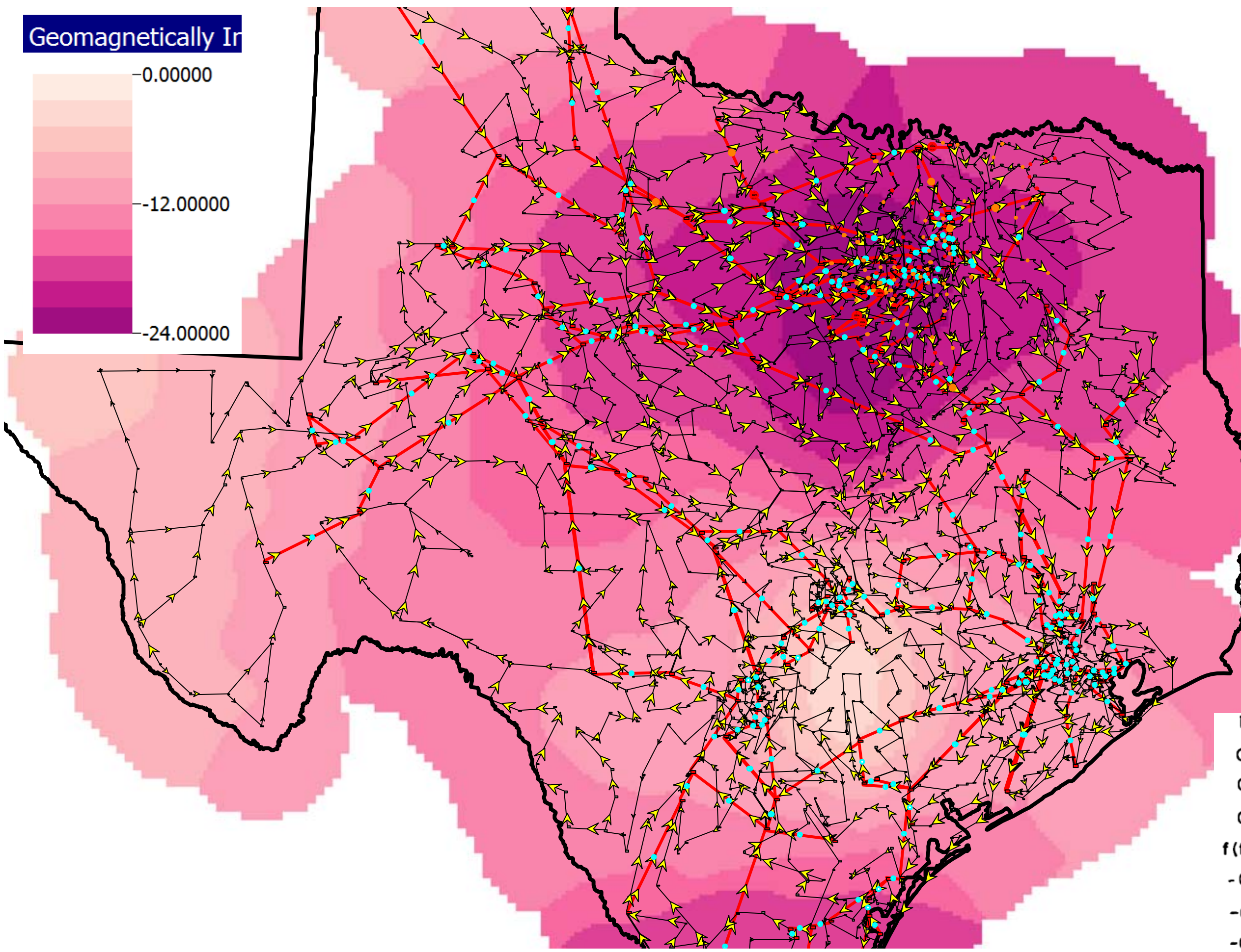
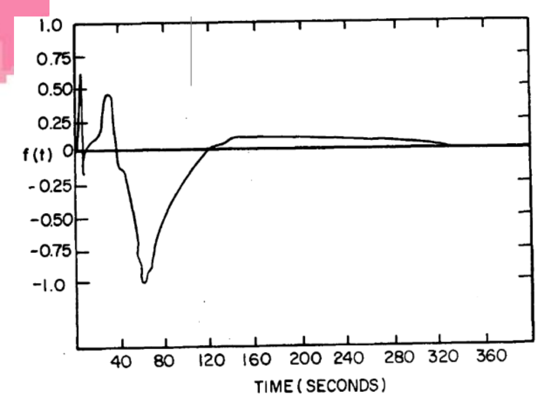
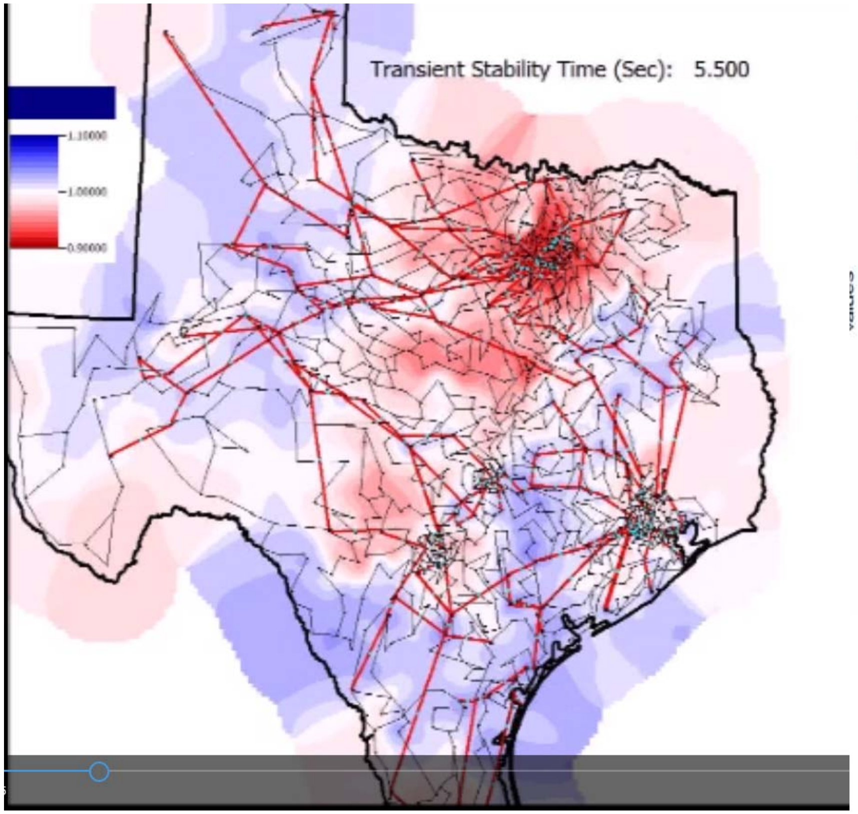


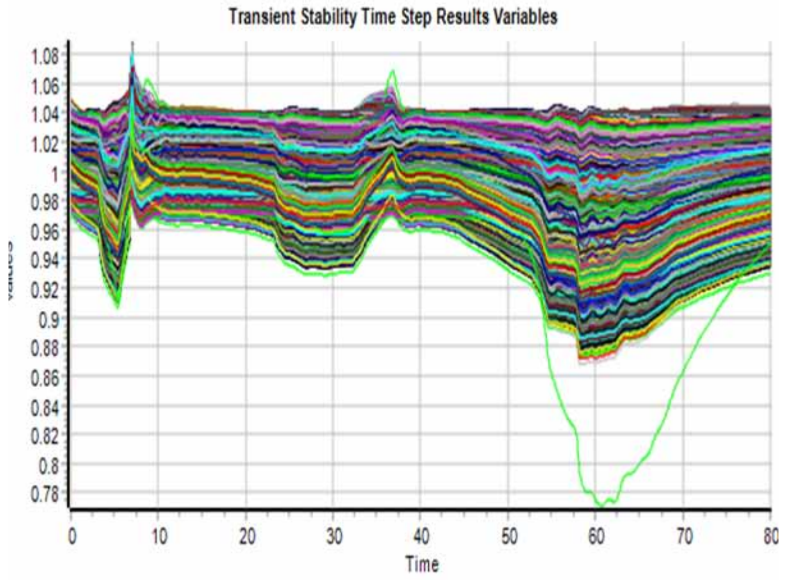
Image shows the assumed electric field 60 seconds after the attack; the below graph shows the assumed time variation in the electric field



Example EMP Results: 2000 Bus Synthetic Texas Footprint Model

- This movie and graph show the variation in the bus voltages for the first 80 seconds using a transient stability solution with PowerWorld Simulator





Power Flow Convergence Issues

- Integrated GIC modeling can impact power flow convergence since the GIC induced reactive power losses simultaneously add lots of reactive power.
- Several techniques can help prevent divergence
  - Just calculating the GICs without solving the power flow
  - Gradually increasing the assumed electric fields to avoid simultaneously adding too much reactive power
  - Only calculating the GIC transformer reactive power losses for specified areas; reactive power doesn't travel far
  - Freezing reactive control devices such as LTC taps
- Transient stability solutions can avoid many issues and are useful especially for HEMP analysis

GIC Mitigation

- Engineers need tools to determine mitigation strategies
  - Cost-benefit analysis
- GIC flows can be reduced both through operational strategies such as opening lines, and through longer term approaches such as installing blocking devices

- Redispatching the system can change transformer loadings, providing margins for GICs
- Algorithms are needed to provide power engineers with techniques that go beyond trial-and-error

Conclusions

- Building on the modeling work done for GMD, tools exist for doing HEMP assessment on large-scale power systems
  - There is certainly lots of uncertainty in this analysis
- Getting started with GIC assessment (either GMD of HEMP) can be relatively straightforward, consisting of doing GIC enhanced power flow studies
  - Can be used to determine mitigation strategies and locations for monitoring equipment
- Integration into transient stability is straightforward, and can be leveraged HEMP studies
- Lots of research opportunities!!

Thank You!

Questions?