British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Applied geoscience for our changing Earth

Prediction of Extreme Geomagnetically Induced Currents in the UK high-voltage network

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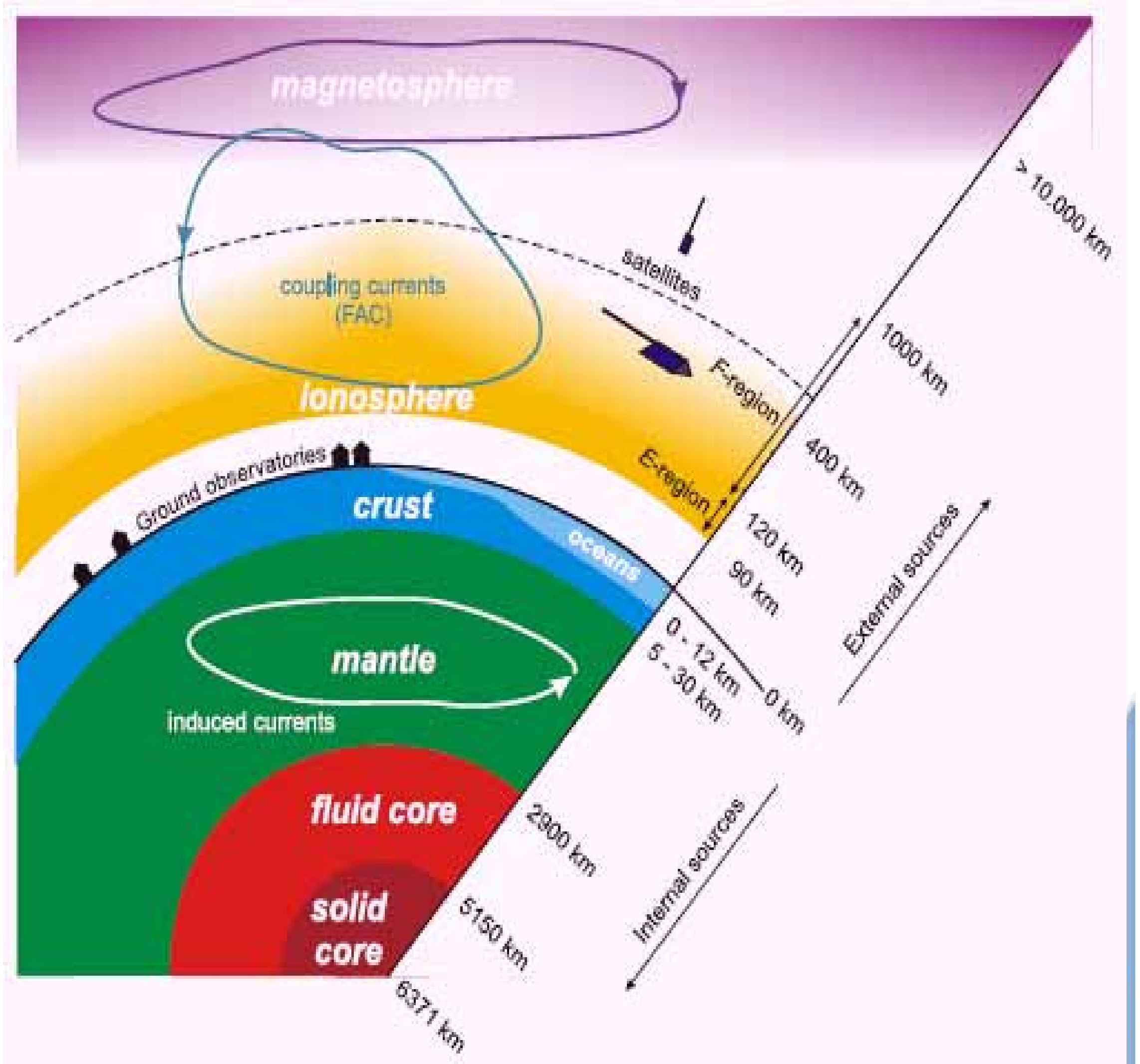
www.geomag.bgs.ac.uk

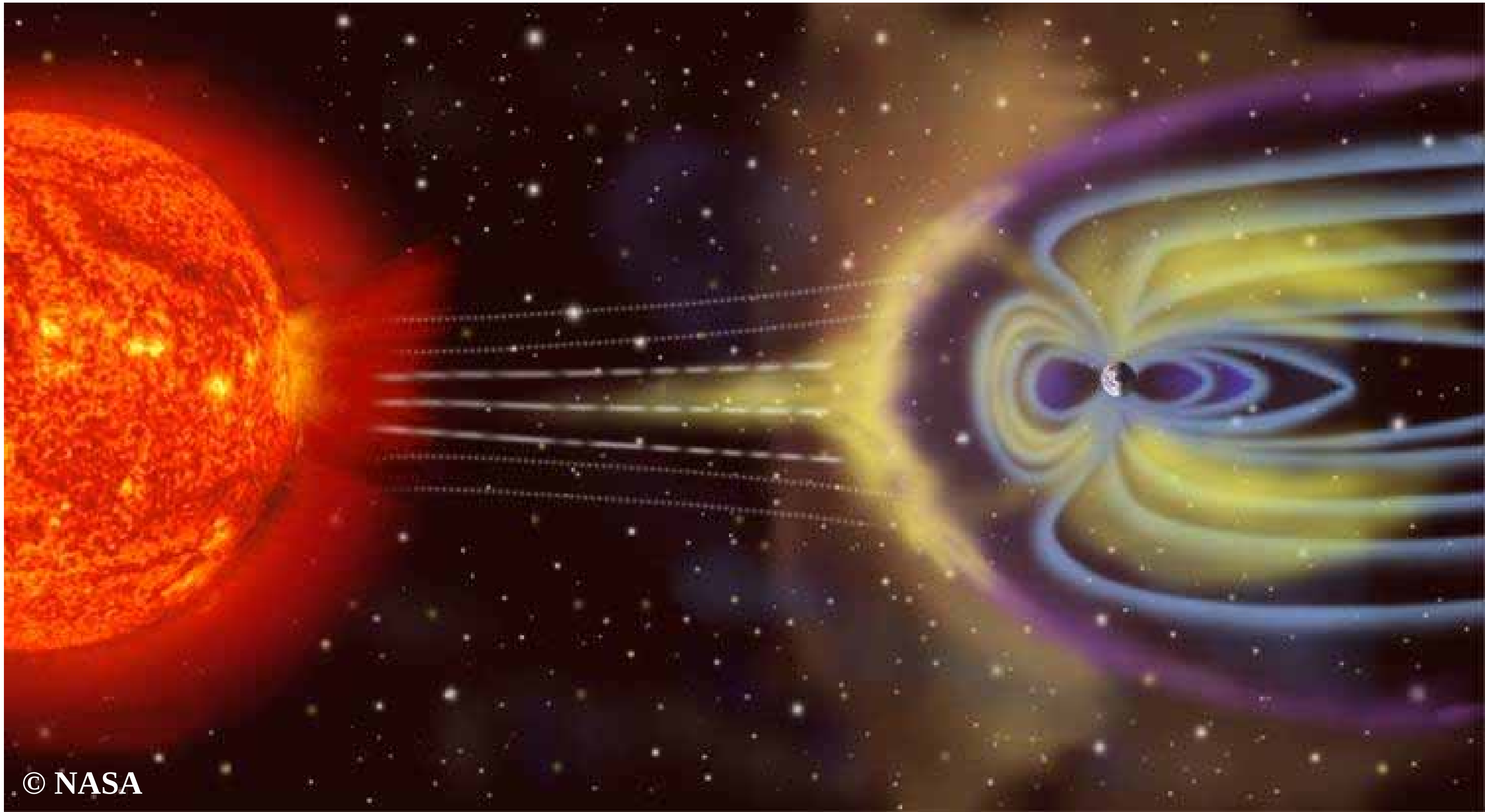
BGS Geomagnetism

- **Long-term geomagnetic monitoring and allied research to improve our understanding of the Earth and its natural environment**
- **Knowledge exchange and provision of data products**
- **26 staff; 3 UK observatories plus 5 overseas**



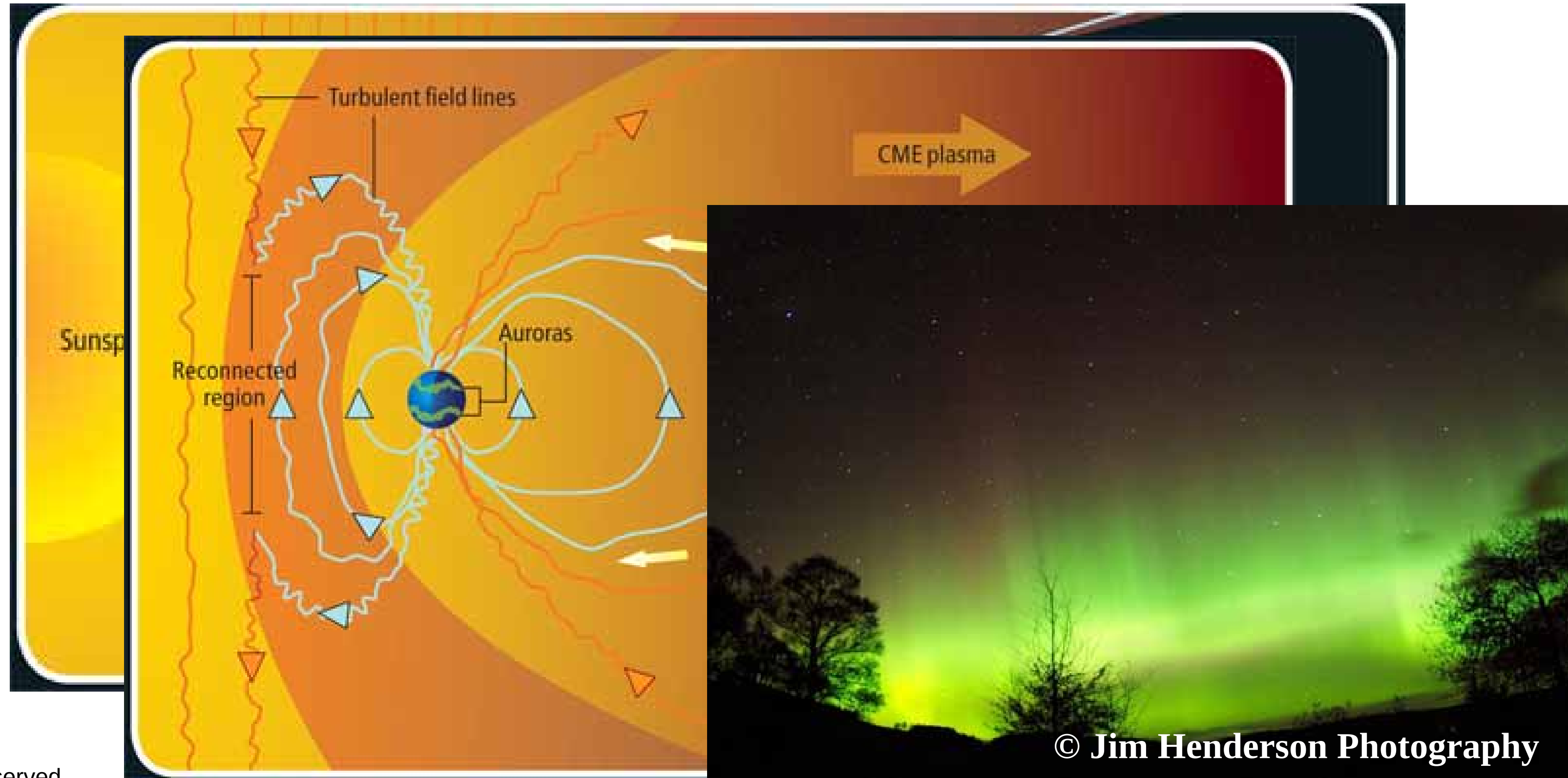
What is Space Weather?

Hopefully, we've already covered this …



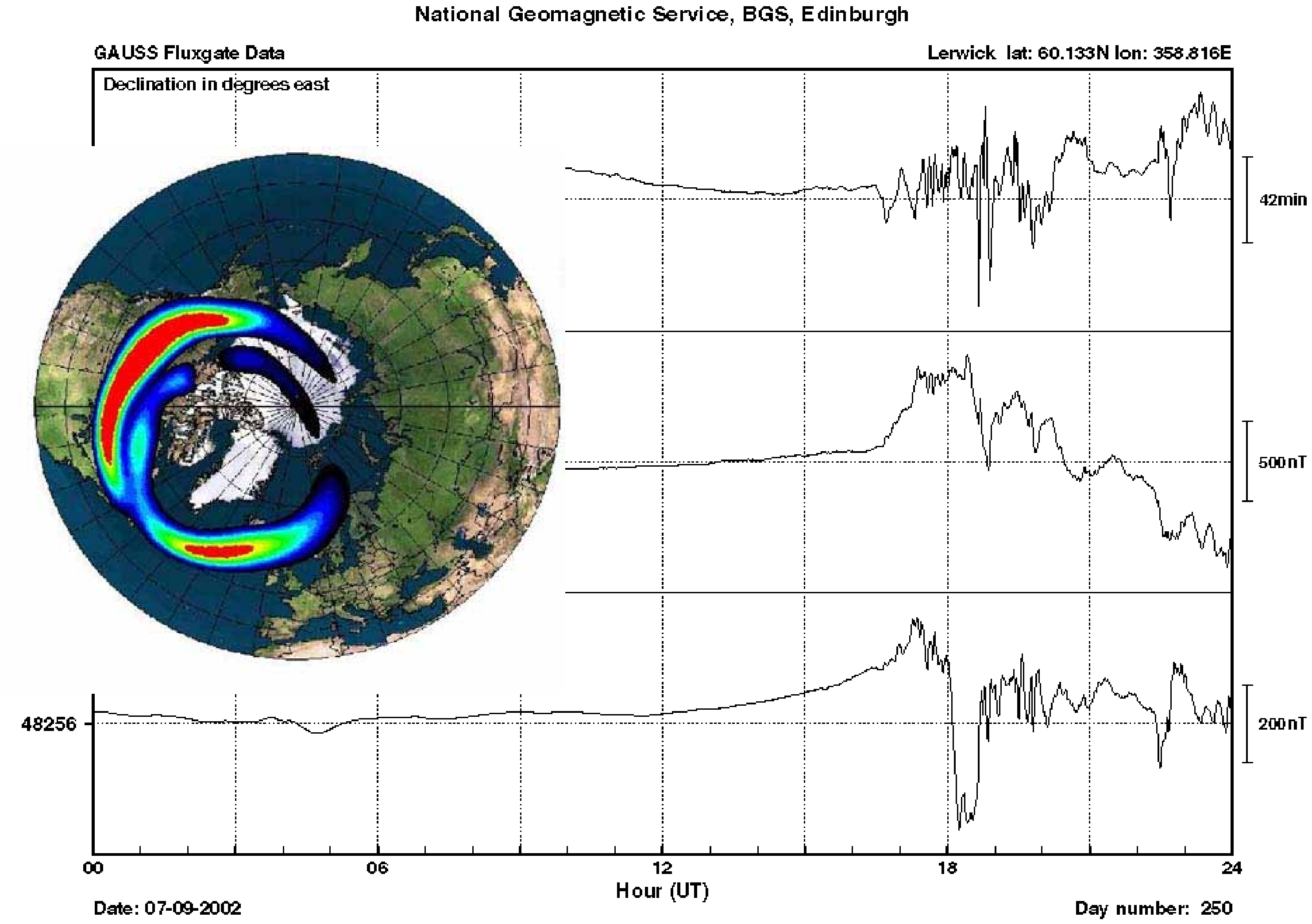
Effects of CME at Earth

- Embedded North or South directed magnetic fields
- Reconnection with Earth’s field (geo-effectiveness)
  - Large amounts of energy pumped into the magnetotail and the field aligned currents (FAC)

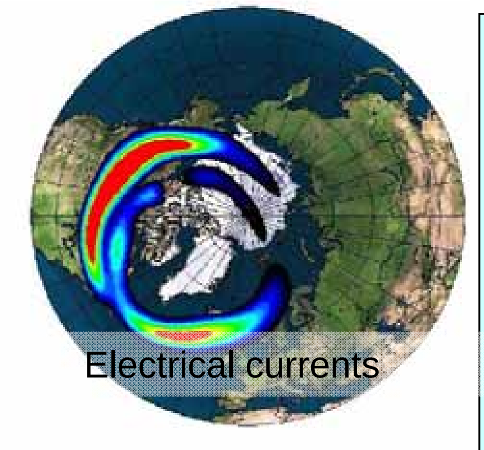


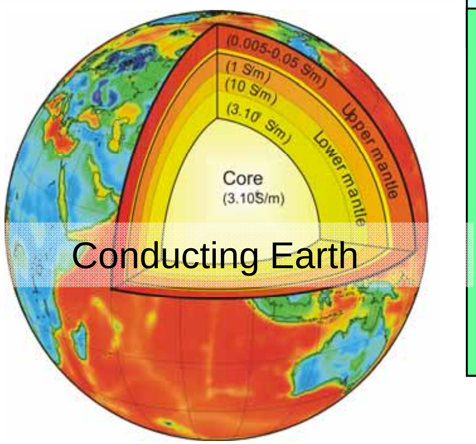
Images: © NASA

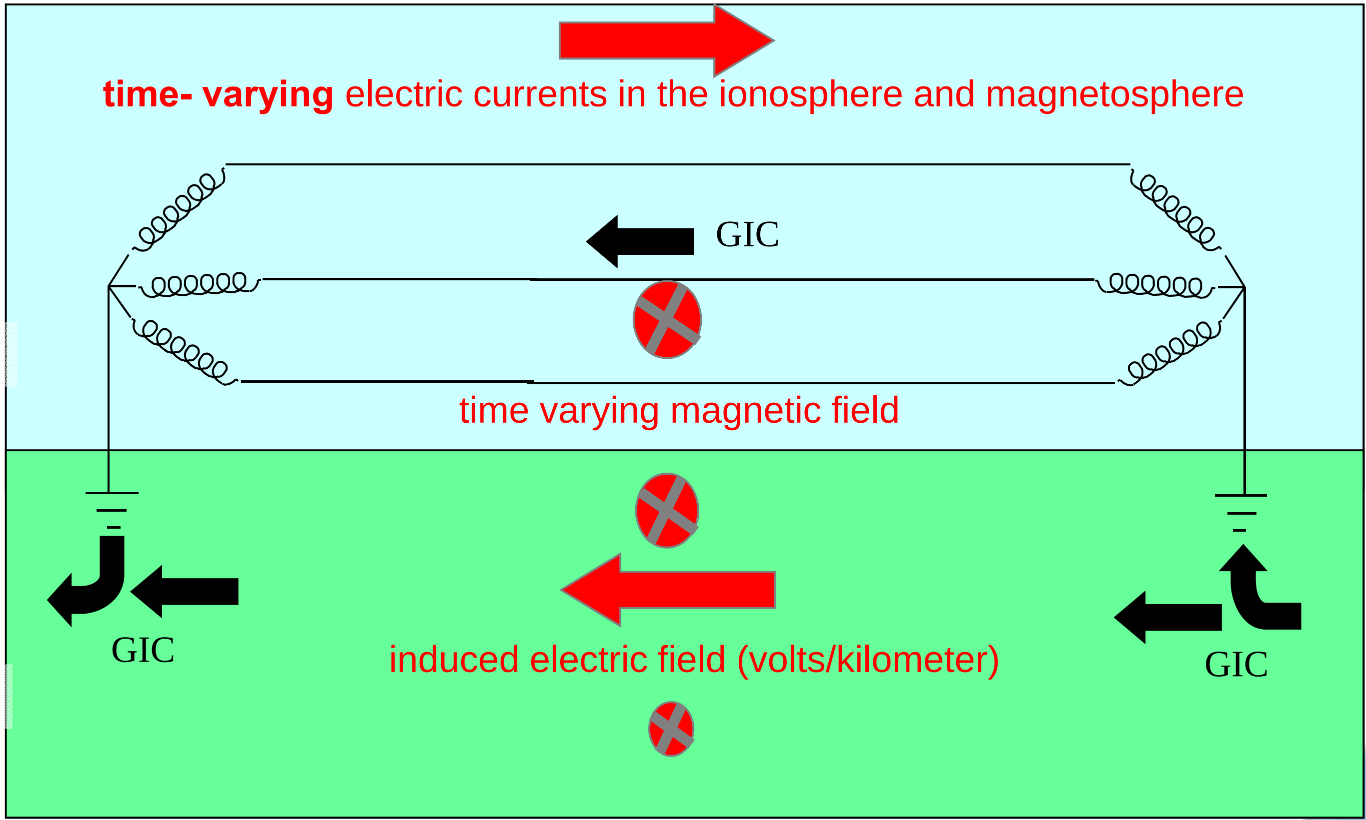
Example magnetogram



Why Does Space Weather Cause Grid Problems?







DC offset in transformer causes: voltage harmonics; loss of reactive power; flux escape from core; overheating; destruction of insulation

Impact – Power Grids

- Failure of Hydro-Quebec system in March 1989
  - Cascaded shutdown of entire grid in 90 seconds
  - 9 hours to restore 80% of operations
  - 5 million people without power (in cold weather)
  - Estimated C$2Bn economic cost
    (incl. C$12M directly to power company)
- Other known impacts
  - 2003: UK, Sweden (1 hour blackout), Finland, Canada, South Africa (8 transformers failed), Japan, Spain, New Zealand …
  - Some evidence of effect on pricing movements in electricity supply markets
- Mitigation Strategies?
  - DC blocking devices, power re-routing(?),
    maintenance re-scheduling,
    load adjustment, ‘turn on all the taps’

GIC modelling approaches

1) Transfer functions from geomagnetic observatories to transformers

- Rate of change of horizontal field (d*H*/dt) is an excellent proxy for GIC
- Requires local magnetic observatory or variometers and calibration for each transformer

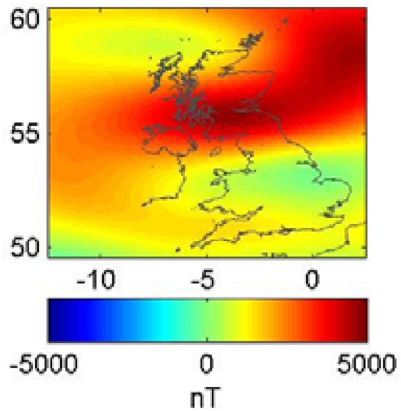
2) Modelling of regional induced electric field from magnetic field

- Computation of integrated voltage within the network
- Relatively computationally intensive

E-field modelling

- Requires a knowledge of:
  - **a) Ground conductivity (i.e geology)**
  - **b) Anomalous magnetic field**
  - **→ induced electric field**
  - **c) Grid topology & characteristics**

(a) Geology of UK and Ireland



(b) Anomalous magnetic field

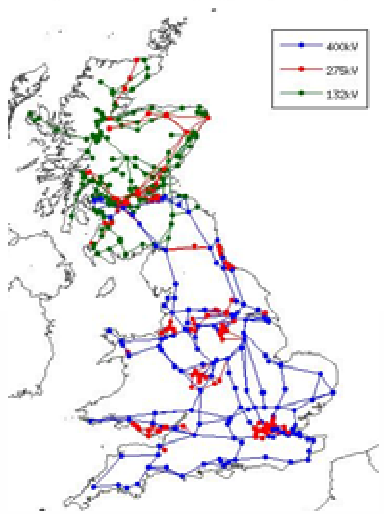
- GIC calculated through integration of line resistances along line length divided by network topology matrices:

$$\text{GIC: } I = (1+Y.Z)^{-1} \cdot J$$

network admittance matrix

geo-voltage between nodes

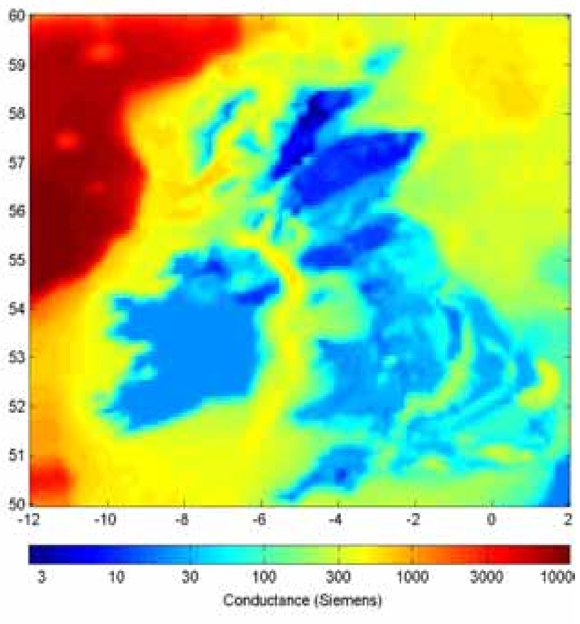
impedance matrix

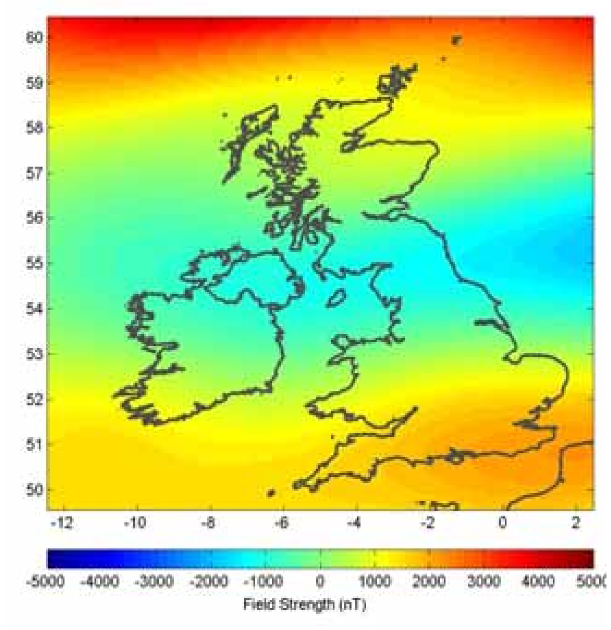


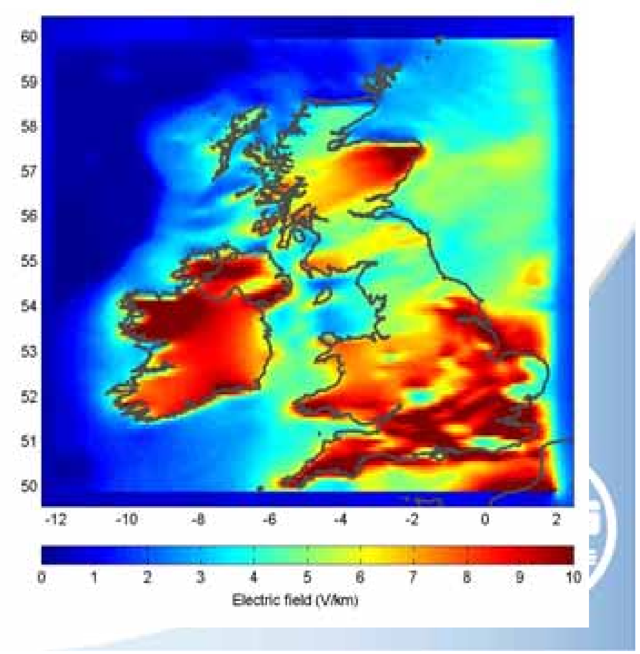
(c) UK grid model

Computing an induced Electric field

- Induced Electric field computed using:
  - Conductivity model
  - Anomalous Magnetic field
  - ‘Thin-sheet’ modelling used to convert magnetic field changes to electric field induced in the ground
    - Magnetic field in N-S direction induces E-W electric field
    - Computed E-field is *frequency-dependent*

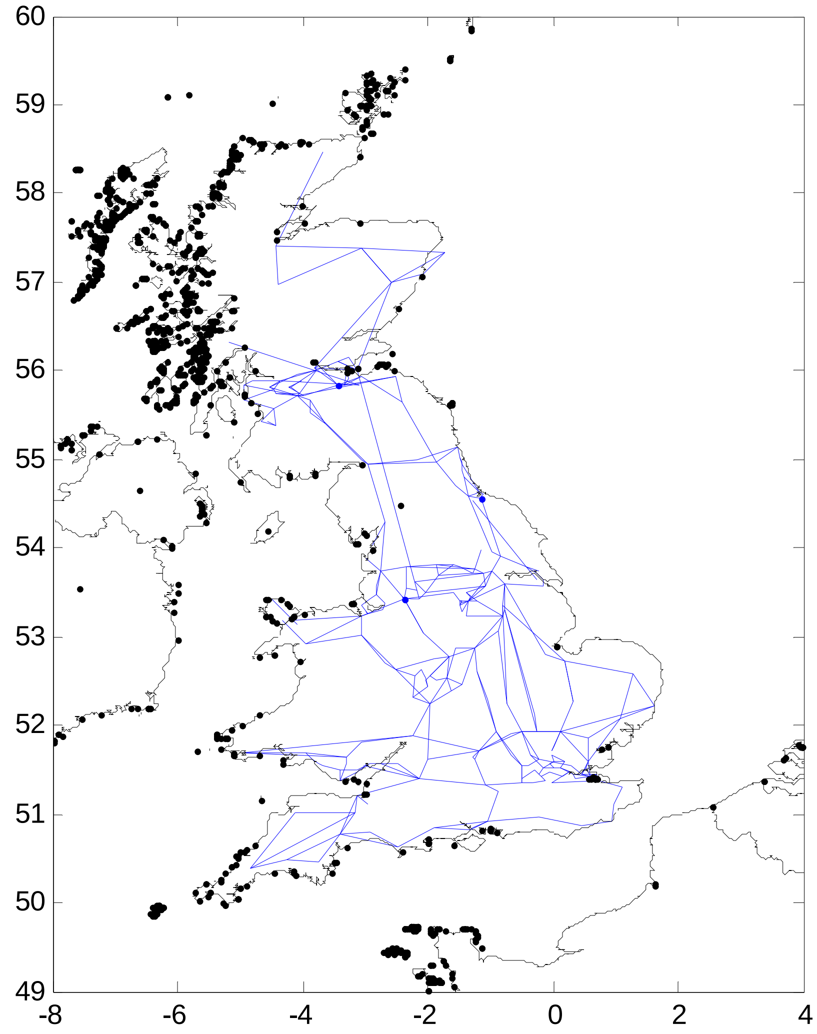






UK power network: 2007

- Simplified 400/275 kV system
- One transformer per location (simplified)
- One connection between linked nodes (simplified)
- Transformer and earthing resistances assumed identical across all transformers (simplified)
- Line resistances calculated using estimated transmission line impedances
- 252 nodes with 379 connections



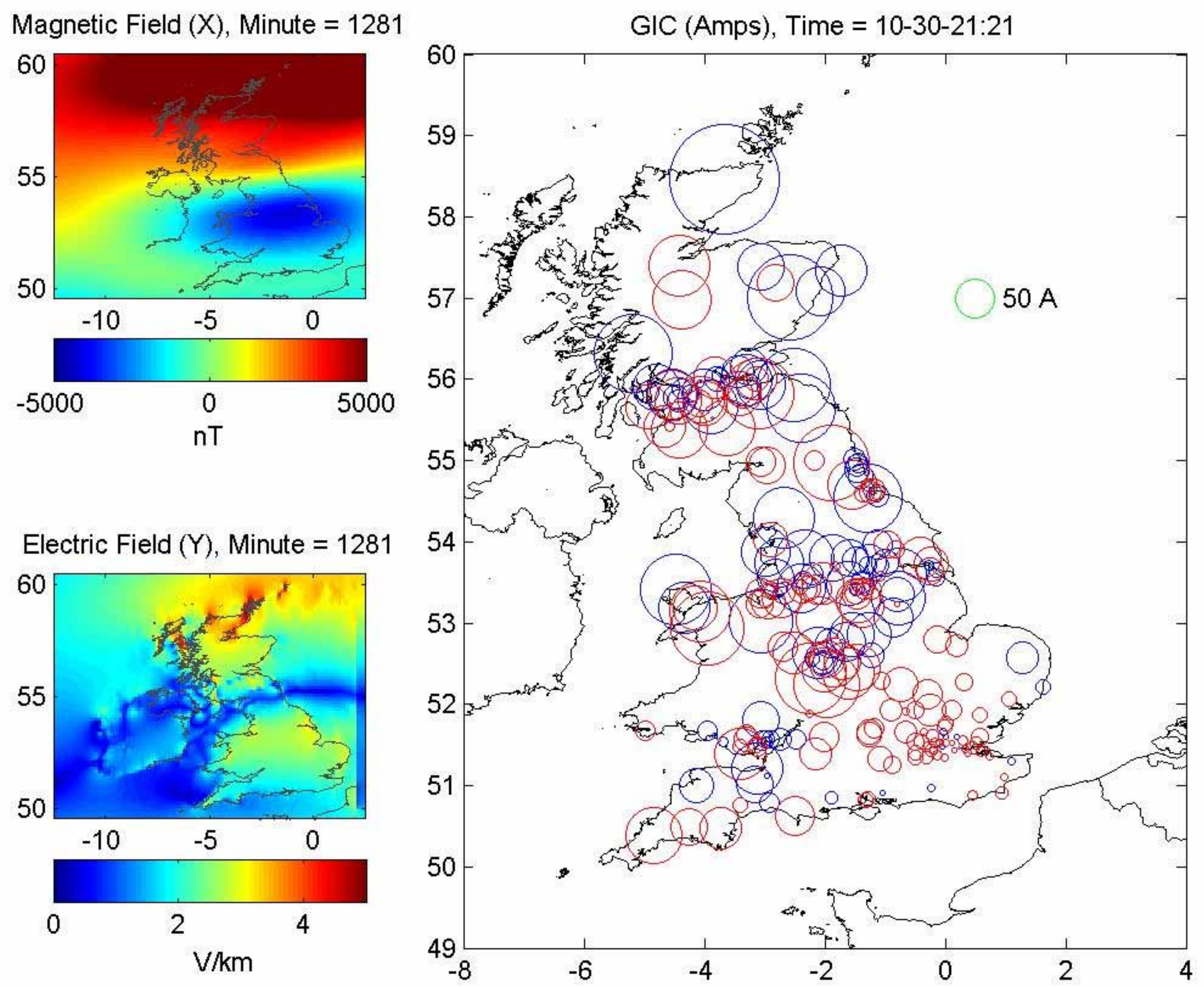
Halloween Storm: October 2003

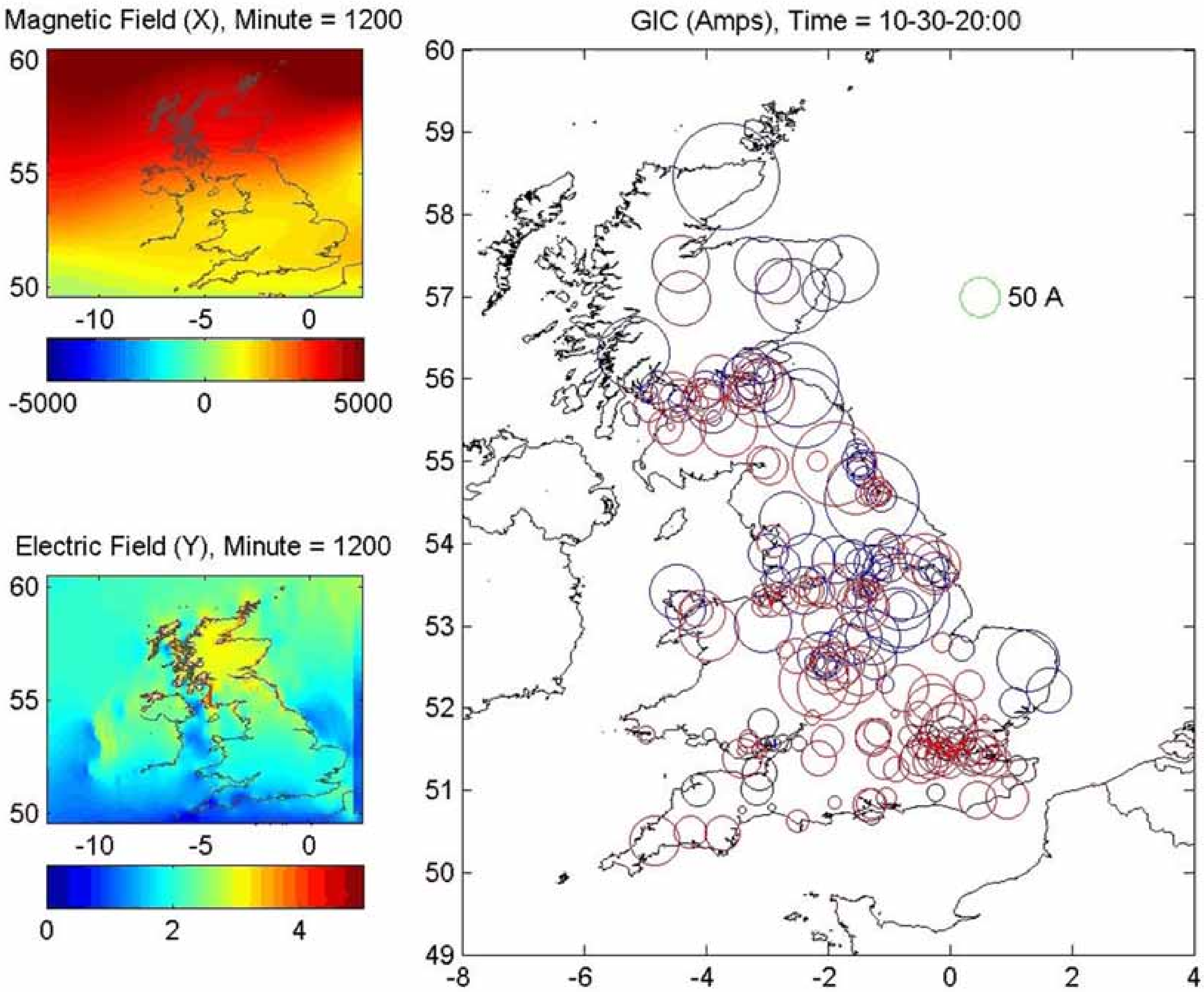
Notes:

Two large CMEs arrived at Earth simultaneously

- Storm lasted ~3 days
- Oct 30th at 21:21 was storm peak in UK
- Simplified 400 kV model (252 nodes, 379 connections)
- Assumed six minute frequency of dH/dt
- Red (into ground) Blue (into grid)

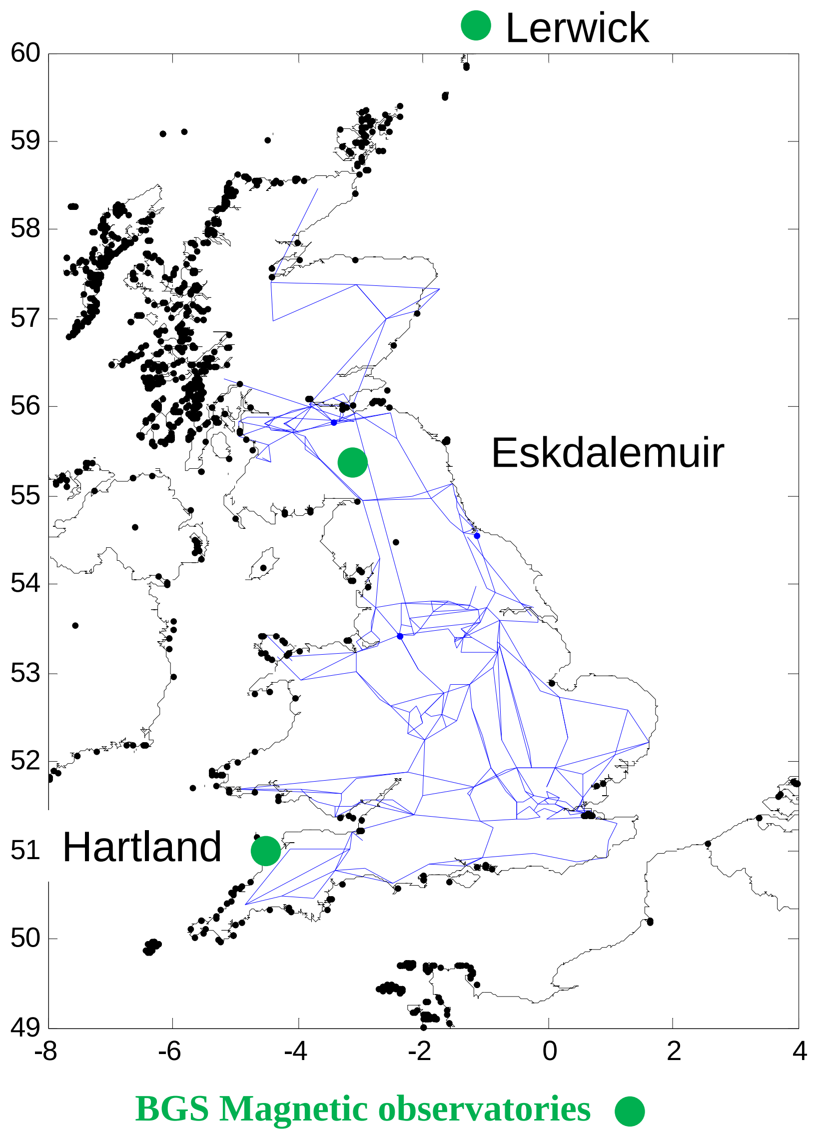
All 3 phases summed




Magnetic Field (X), Minute = 1200
60
55
50
-10
-5
0
-5000
0
5000
Electric Field (Y), Minute = 1200
60
55
50
-10
-5
0
0
2
4
GIC (Amps), Time = 10-30-20:00
60
59
58
57
56
55
54
53
52
51
50
49
-8
-6
-4
-2
0
2
4
50 A

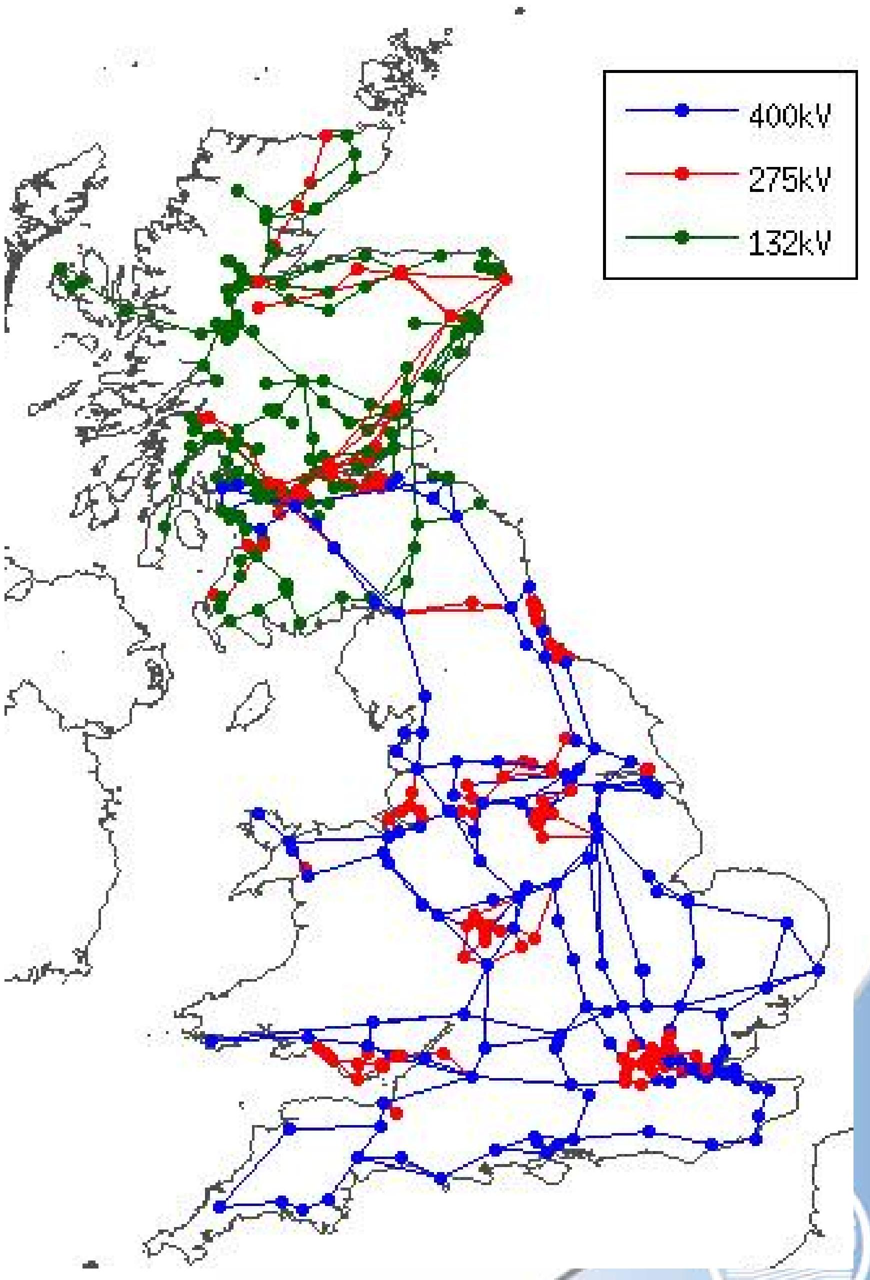
Transformer 'Hotspots'

- Top 'hotspots' in **2007** representation of the UK power network were analysed
- Typically:
  - end of long lines
  - geologically resistive regions
  - corner nodes,
  - isolated sectors

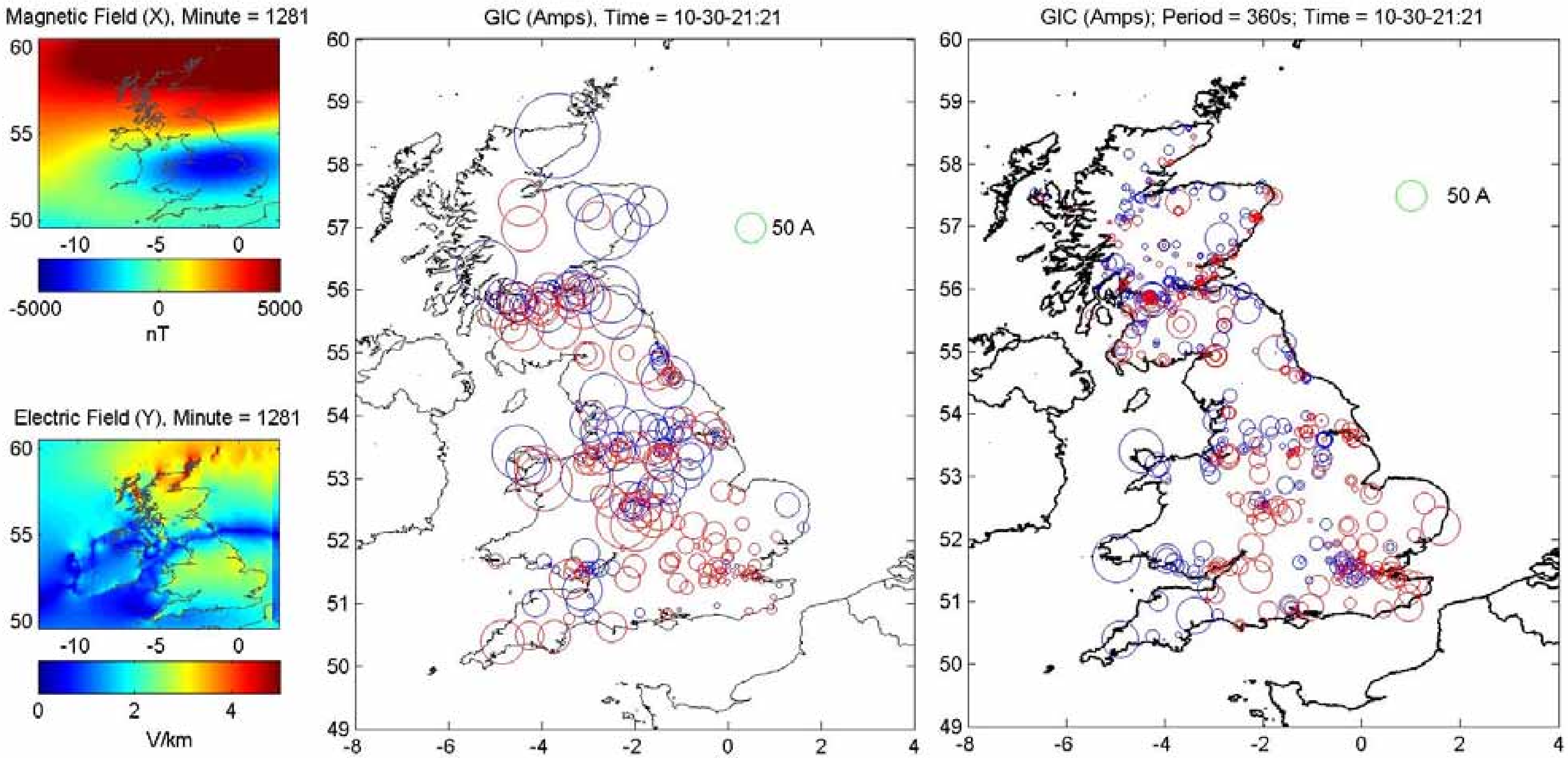


UK power network: 2012

- Multiple transformers per location
- One connection between linked transformers (simplified)
- Transformer and earthing resistances provided by National Grid
- Line resistances calculated using transmission line impedances provided by National Grid
- 701 transformers with 1269 connections



Network differences: 2007/2012



Simplified *More complex*

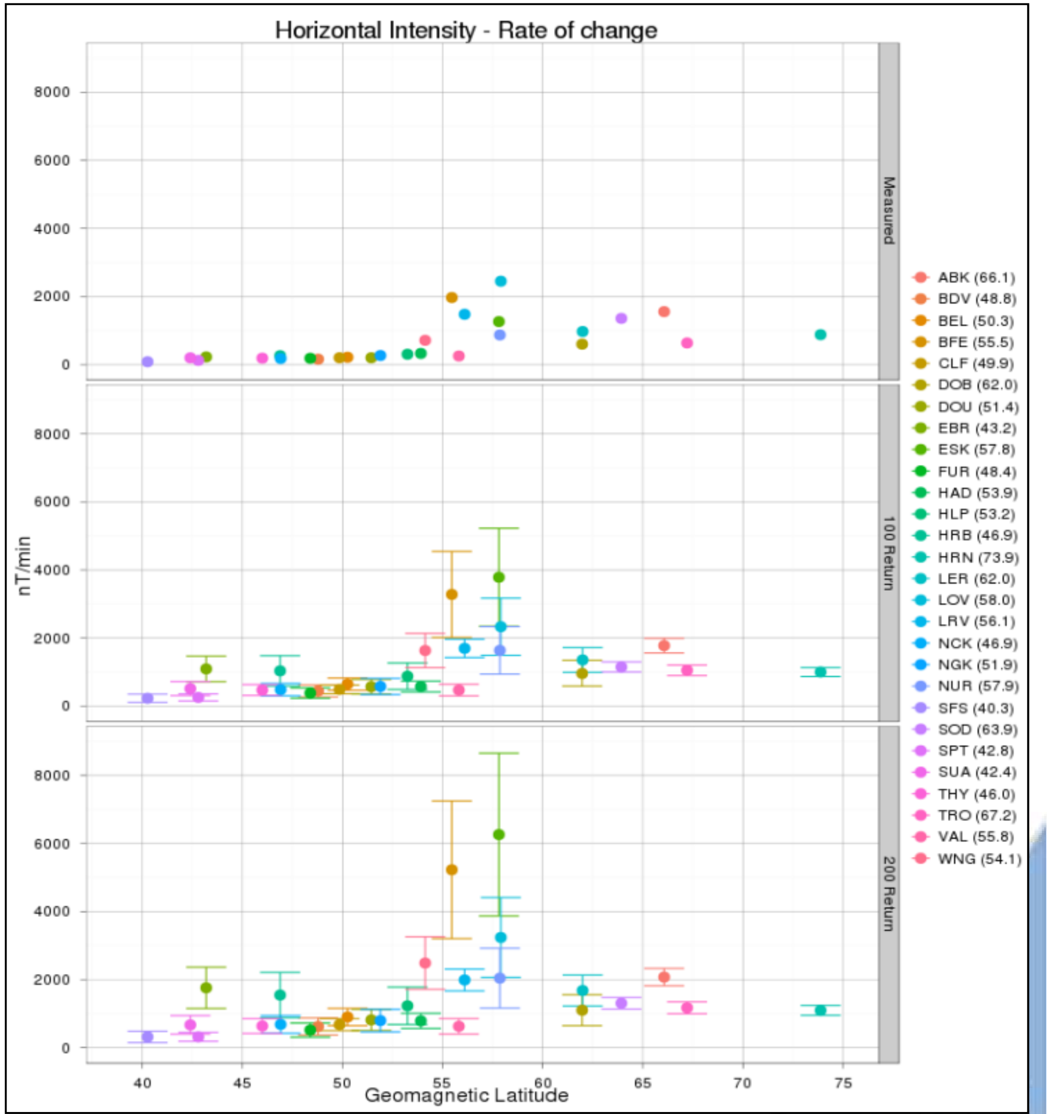
Extreme Events

- September 1859: ‘Carrington’ Event
  - Large solar flare observed by Richard Carrington at Kew
  - Estimated solar wind speed of ~2000 km/sec (17hr transit)
  - Off-scale at Greenwich and Kew magnetic observatories
  - Reports of aurorae very far south (e.g. Rome)
  - Telegraph network of UK adversely affected
    - Fires, electric shocks
  - People can read their papers at night time by auroral light

- How likely is this to happen again?

Extreme Geomagnetic Values

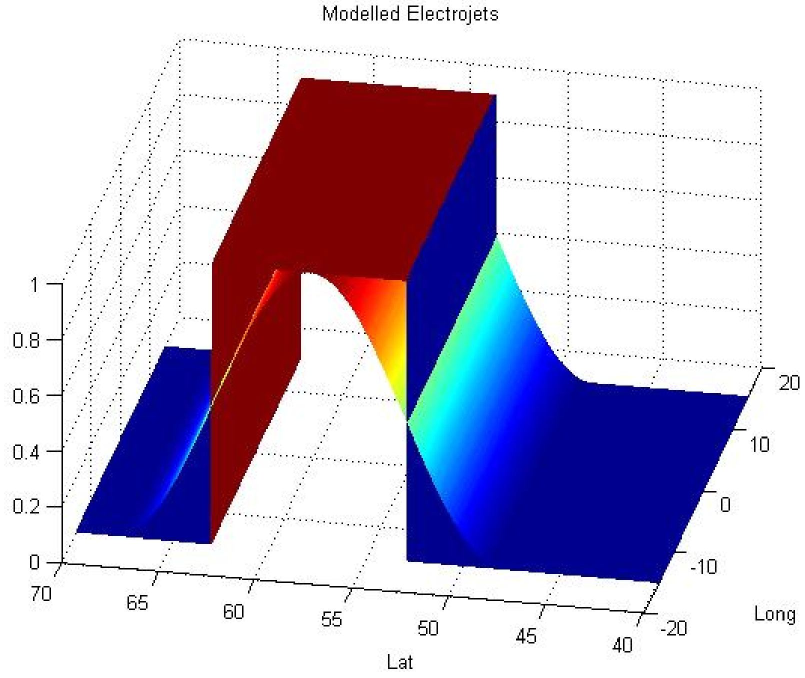
- Use Extreme Value Theory to estimate bounds on return events (e.g. flooding/banking …)
- Extrapolation of 30 years of digital data across Europe using EVT
- Many caveats etc…
  - Weak trend with latitude
  - ‘Bulge’ in activity level between ~54-62 degrees
- Return magnitudes:
  - 100 Year: 1500-4000 nT/min
  - 200 Year: 2000-6000 nT/min
  - Carrington Event: 1 in 500 year?



see: Thomson *et al.*, (2011), *Space Weather*

Extreme scenarios

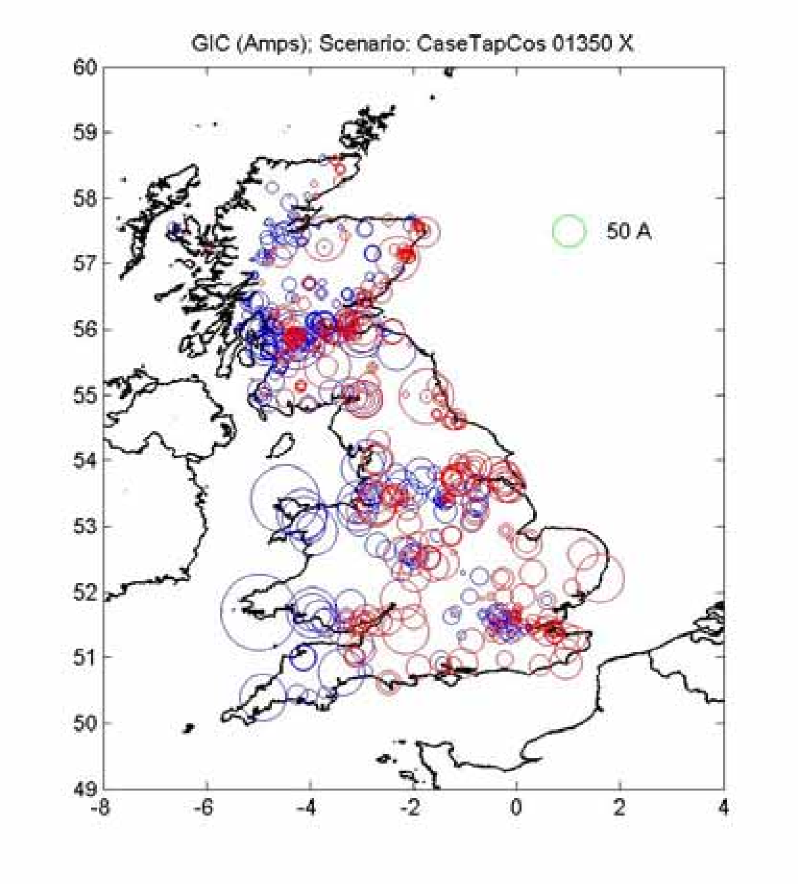
- Idealised Electrojet generates d*H*/dt
  - Scaled according to 100 or 200 year extreme event
  - Various frequencies (2, 10, 30 minutes)
  - Compute E-field and related GIC for each scenario

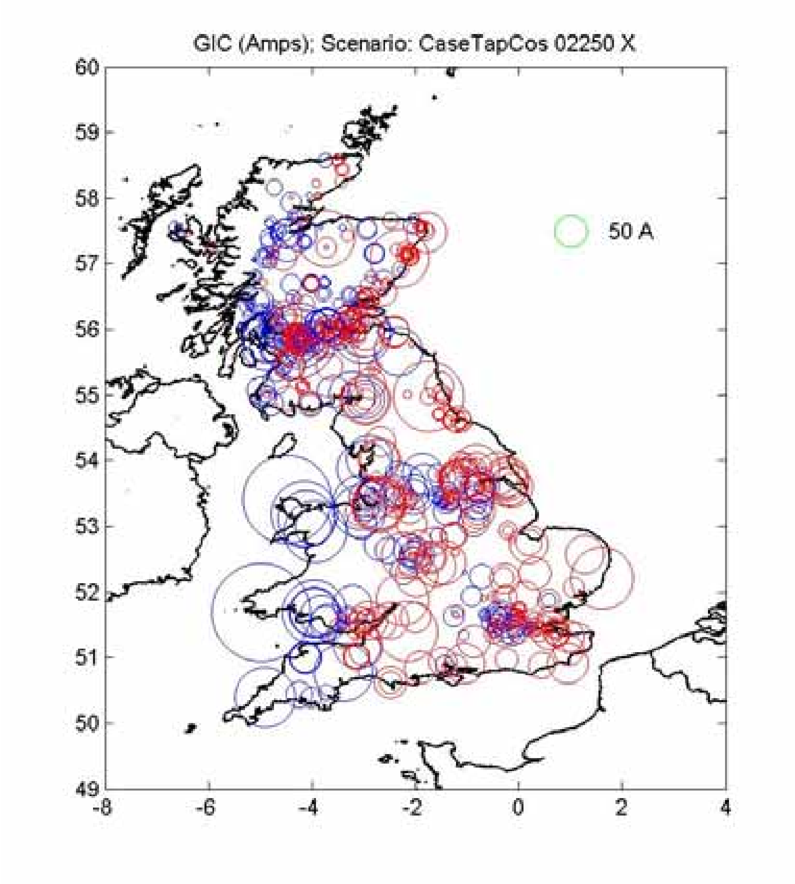


- Also: x5 scaled version of October 2003 storm

N.B. for USA examples, see Pulkkinen *et al*., (2012), *Space Weather*

Example GIC: 100 & 200 year





Note: 2 minute period used

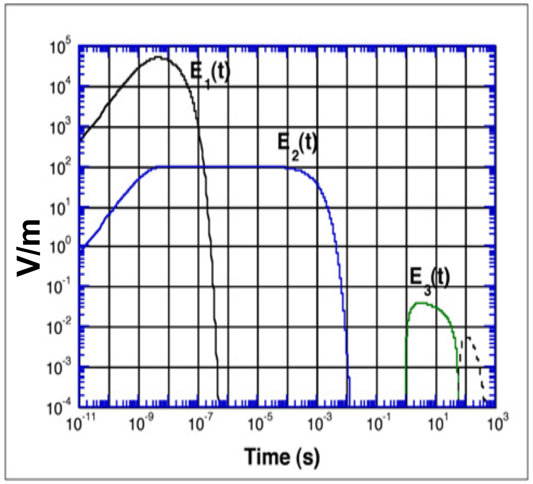
Beggan et al., *Space Weather*, 2013, *in prep.*

Applications to HEMP

- E3 impulse (10s – 100s long)
- Analogous to (very?) severe magnetic storm

- Can be modelled by electric field technique
- GIC dependent on B-field generated:
  - Proximity
  - Magnitude
  - Period
  - Duration

- However, short duration suggests relatively little damage in transformers due to direct heating effects, though other effects (e.g. imbalances in reactive power) could occur



Primary components of an EMP

Starfish glow seen in Honolulu (1957)
(from www.wikipedia.com)

Thank you for listening

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References:

Beggan, C.; Beamish, D.; Kelly, G.; Richards, A.; Thomson, A.W.P., 2013, Prediction of Extreme Geomagnetically Induced Currents in the UK high-voltage network, *Space Weather, in prep.*

Pulkkinen, A.; Bernabeu, E.; Eichner, J.; Beggan, C.; Thomson, A.W.P.. 2012, Generation of 100-year geomagnetically induced current scenarios, *Space Weather*, **10**, S04003. 10.1029/2011SW000750

Thomson, Alan W.P.; Dawson, Ewan B.; Reay, Sarah J.. 2011, Quantifying extreme behaviour in geomagnetic activity, *Space Weather*, **9**, S10001. 10.1029/2011SW000696

Some future work

- Validate electric field and GIC models with National Grid and Scottish Power GIC measurements
  - Some Scottish GIC data available
  - Installing E-field monitoring equipment at three UK observatories

- Detailed models of individual transformer electrical characteristics
  - Beyond the common earthing resistances

- Within the FP7 EURISGIC project
  - Re-examine extreme events
  - Compare GIC for UK and Ireland (tests model assumptions)

Geo-Electric Field Monitoring

Project Summary

- Long-term measurements at UK observatories
- N-S & E-W electrode lines
- Electrode line length: 50 –100 m
- Electrodes installed depth: 0.5–1.0 m
- Monitoring period: 2 -5 years

Objectives

- Comparison of measured and modelled data to aid numerical model developments
- Longer term, project will provide magneto-telluric data for study of deep Earth conductivity