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Utilizing magnetotelluric and differential magnetometer measurements for the validation of geomagnetically induced current models in a complex power network

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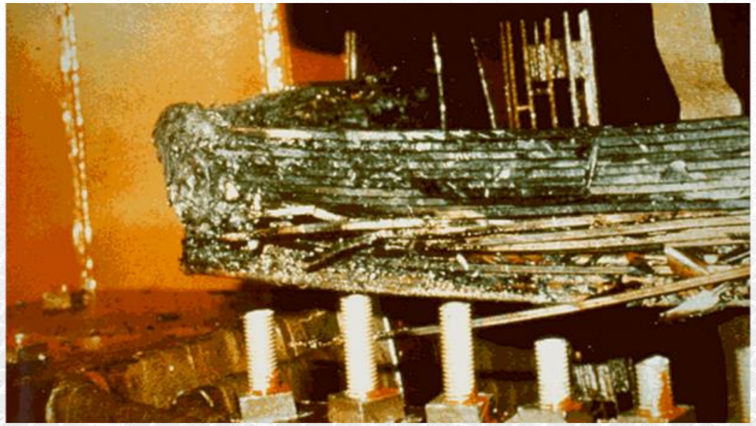
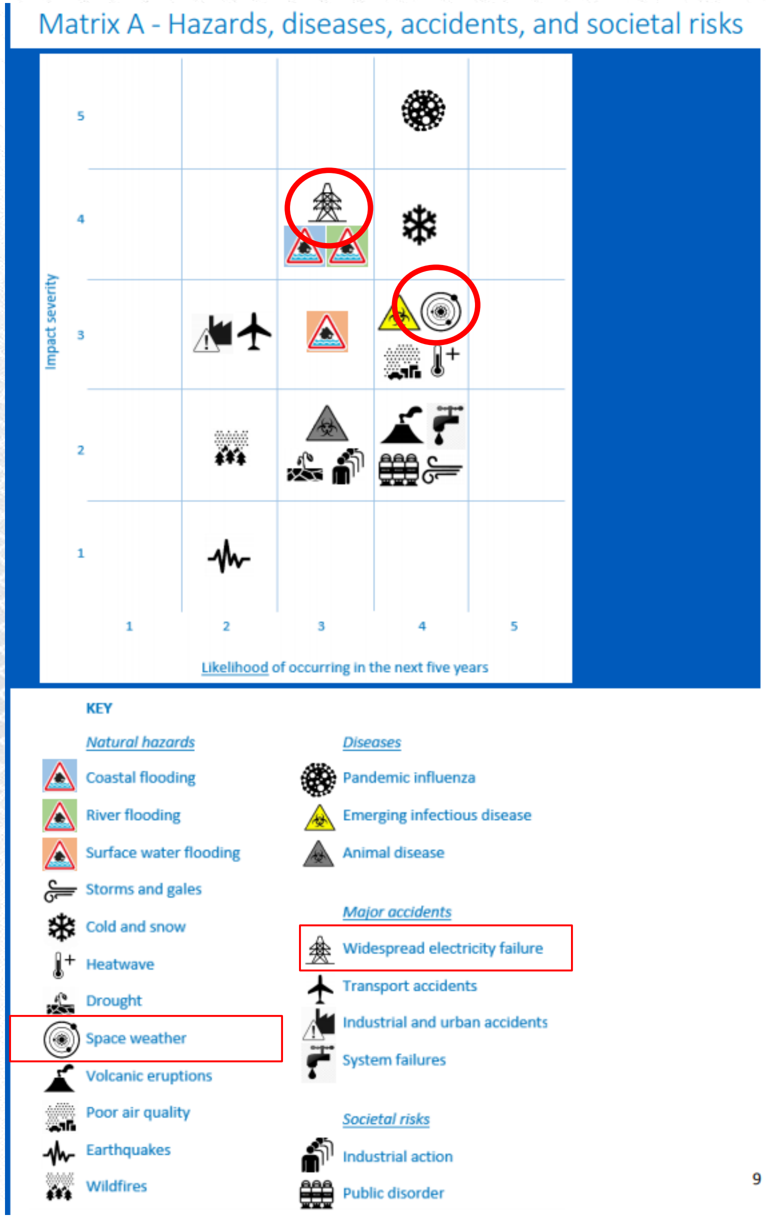
SWIGS
SPACE WEATHER IMPACT ON GROUND-BASED SYSTEMS

Geomagnetically induced currents (GIC)

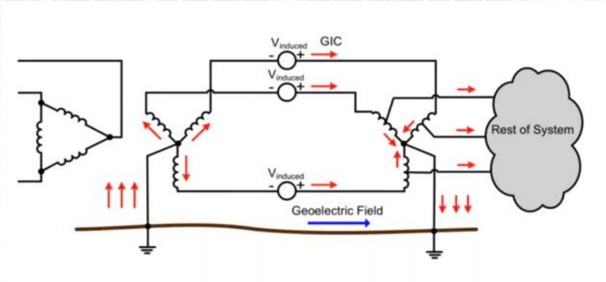


• mainly a risk for higher geomagnetic latitude countries, but also reports from South Africa

• historic events: 1989 Hydro-Quebec reported failure of transformer network – major power out for 2 days, 2003 Malmö blackout due to transformer failure

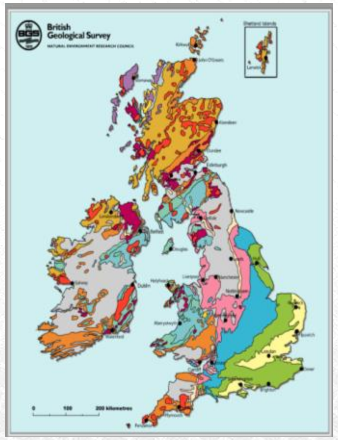


From the UK National Risk Register for Civil Emergencies 2017

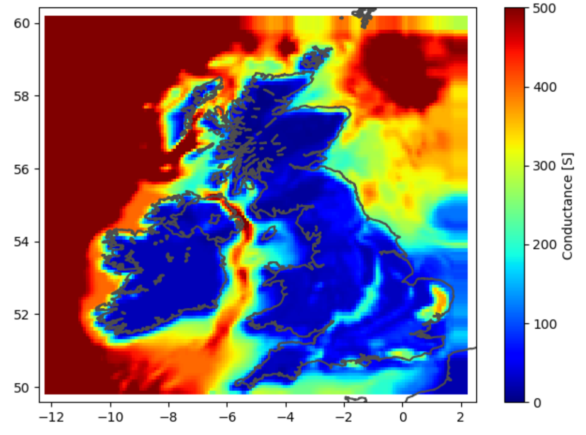


GIC modelling in the UK

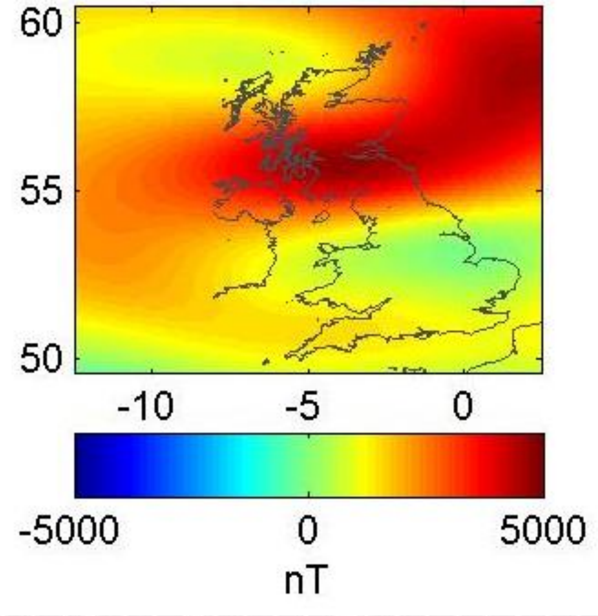
- Requires a knowledge of
  - a) Earth's conductivity (geology)
  - b) Anomalous magnetic field which induces electric field
  - c) Grid topology & characteristics (in the UK some information publicly available)



(a) Geology of UK and Ireland



Electrical conductivity model of the UK – **thin sheet model** derived from airborne data and geology



(b) Anomalous magnetic field, Recorded at UK observatories and aurorawatch stations

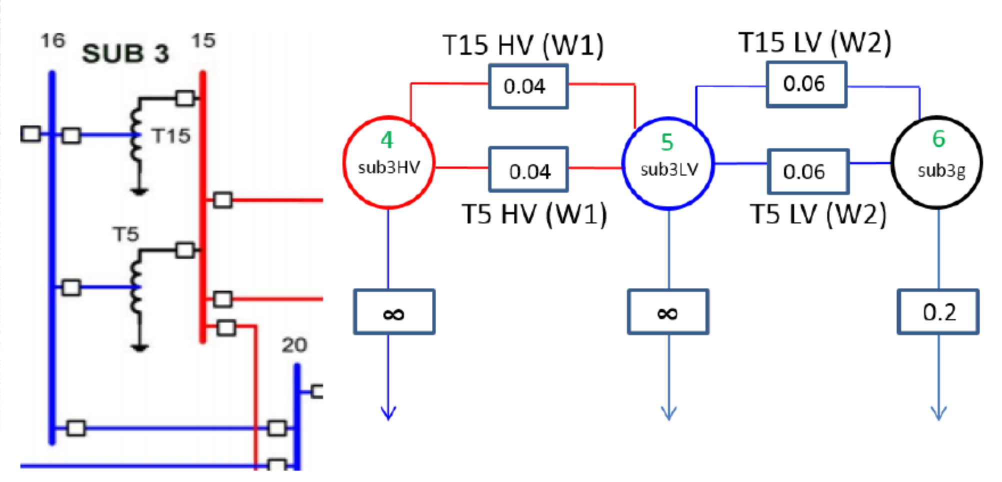
- GIC calculated through integration of line resistances along line length divided by network topology matrices i.e.

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

network admittance matrix

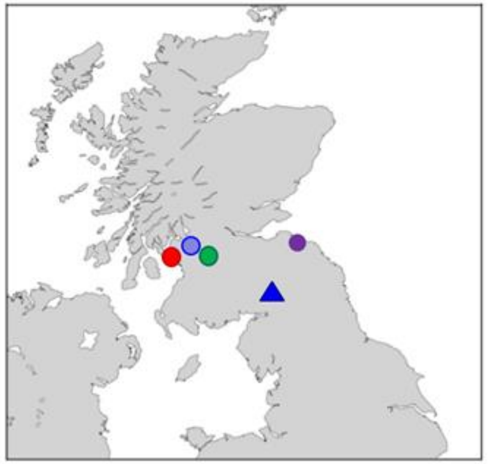
impedance matrix

geo-voltage between nodes



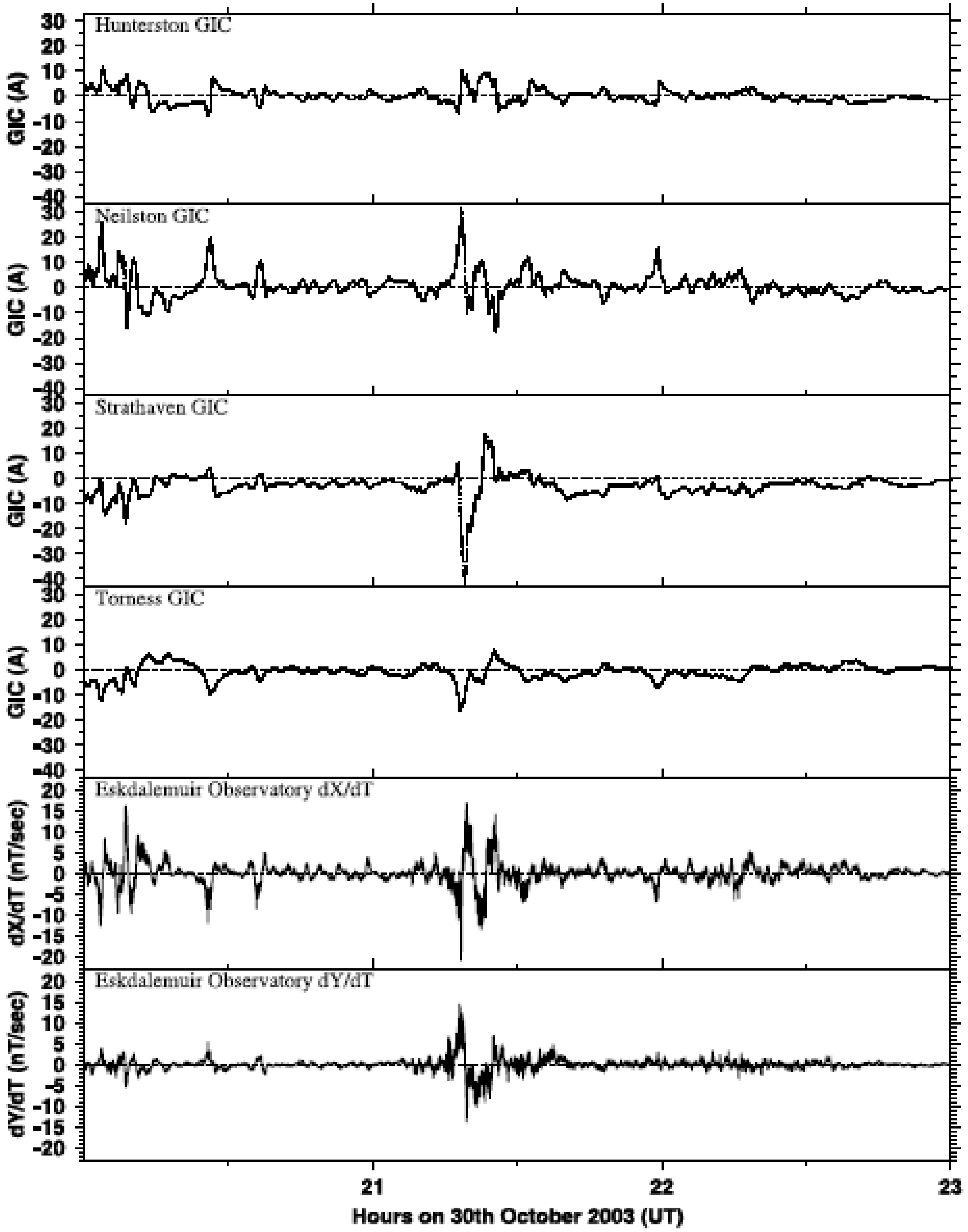
(c) Network representation

GIC measurements: Hall effect probe

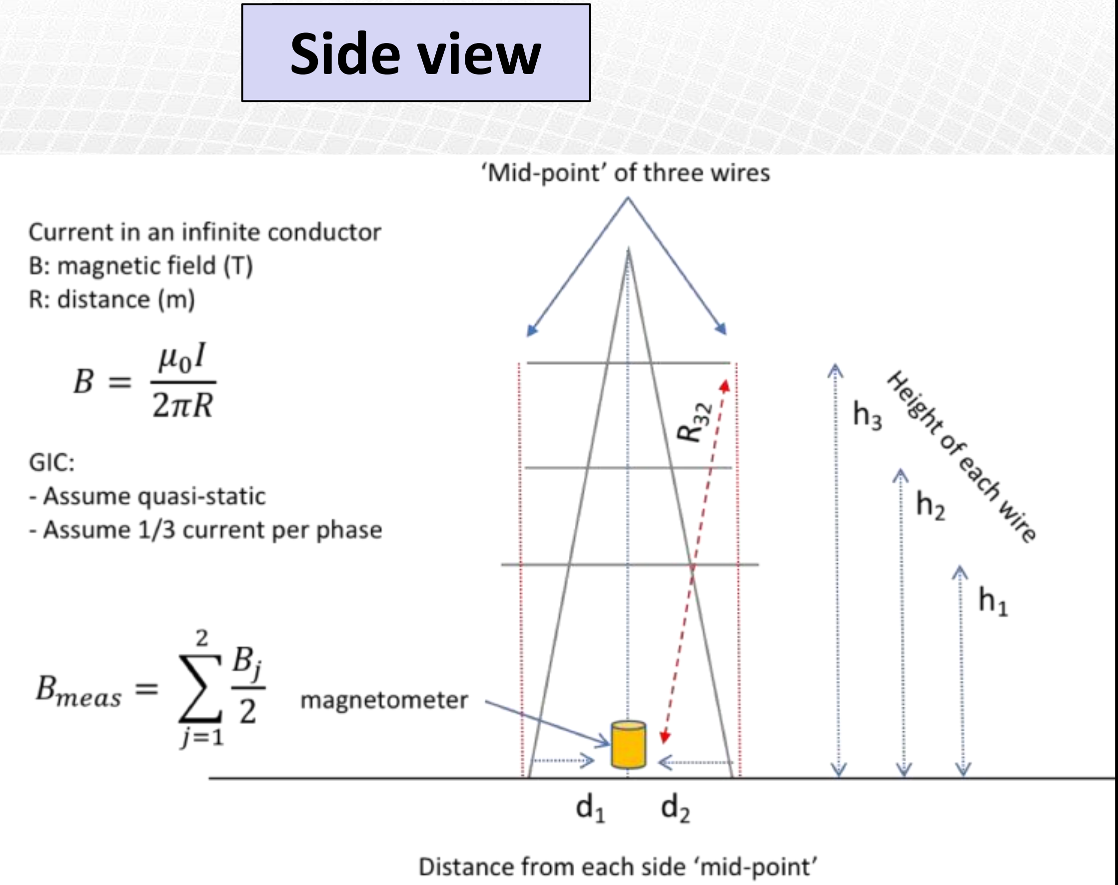


Up: Location of GIC direct observations in the network (Hall effect probes) at four locations in the UK, presently only data from *four* available

Right: Thomson et al. (2005) Measured GIC and field rates of change at Eskdalemuir for 30 October 2003.



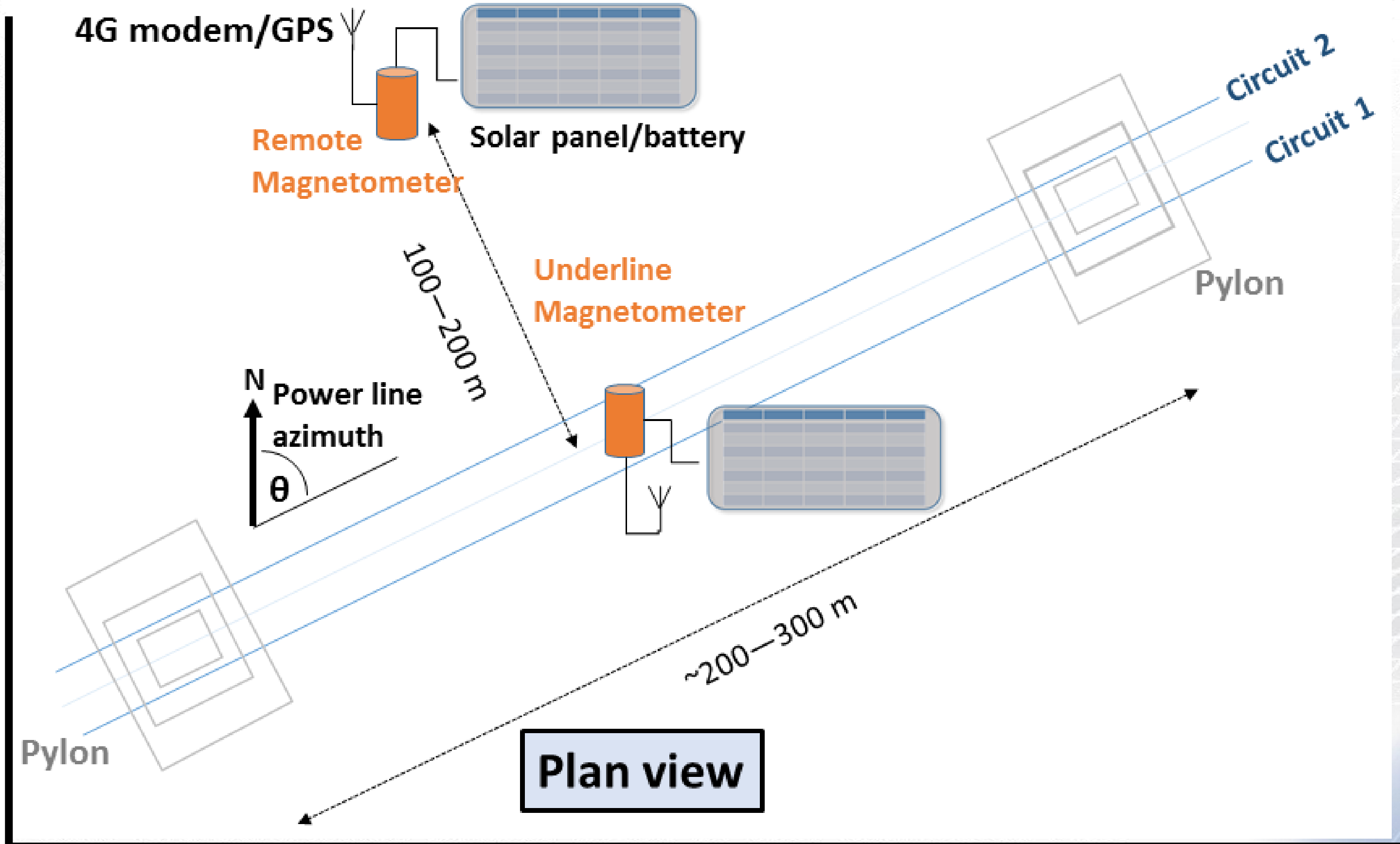
GIC measurements: Differential Magnetometer Method (DMM)



$$B_j = \frac{\mu_0 I}{3 \cdot 2\pi R_{1j}} + \frac{\mu_0 I}{3 \cdot 2\pi R_{2j}} + \frac{\mu_0 I}{3 \cdot 2\pi R_{3j}}$$

$$R_{ij} = \sqrt{{h_i}^2 + {d_j}^2}$$

i = 1:3 # of wires
j = 1:2 # of sides

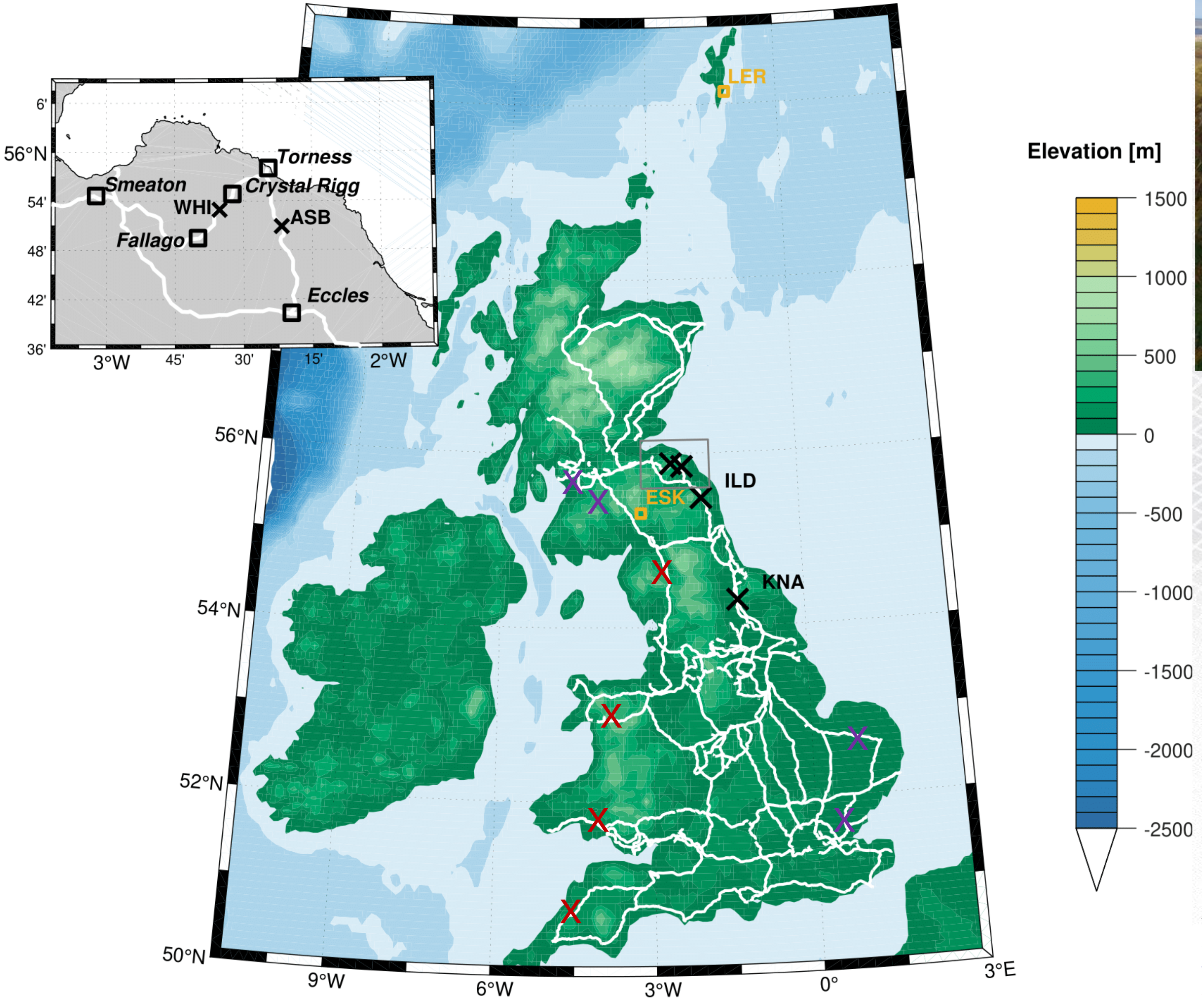


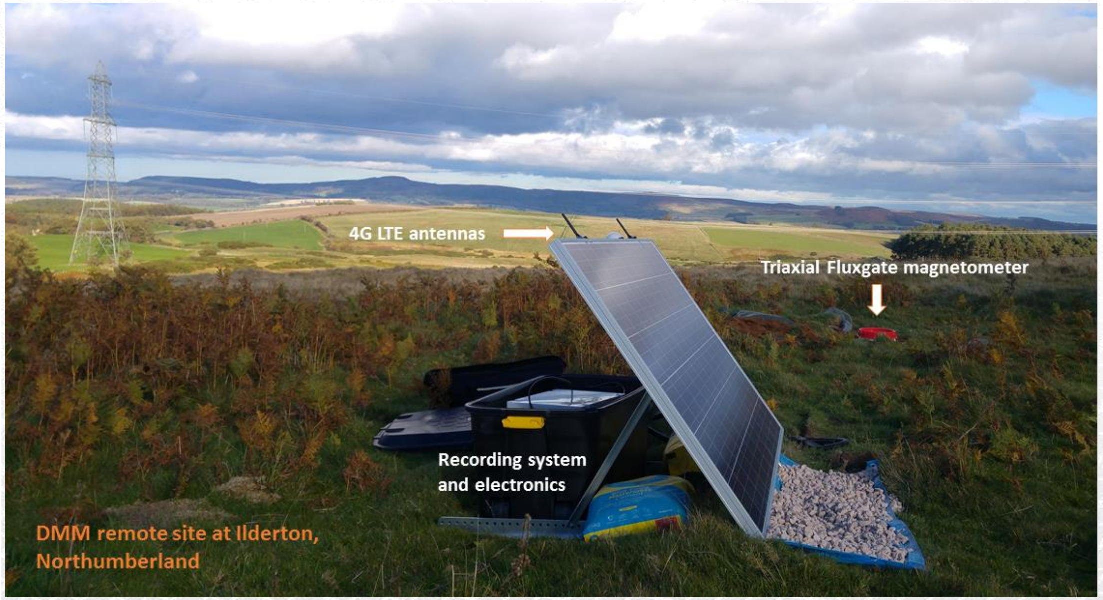
- Requires two variometers measuring 3-component B-fields
  - One under HV line
  - One > 100 m away
  - Use Ampere's law to derive current

DMM BGS Hardware

- *Sensys* 3-axis fluxgate magnetometer
- Kenda *EarthData* 24bit Digitiser
- Calibrated system on absolute pillar in Eskdalemuir observatory
- Solar panel/battery
- 3/4G mobile network modem
- 1-second sampling
- Real-time data return to data entre in Edinburgh via seedlink protocol
- <1 nT accuracy over 30 minutes
- Buried for temperature stability and protection

DMM field installation in the UK

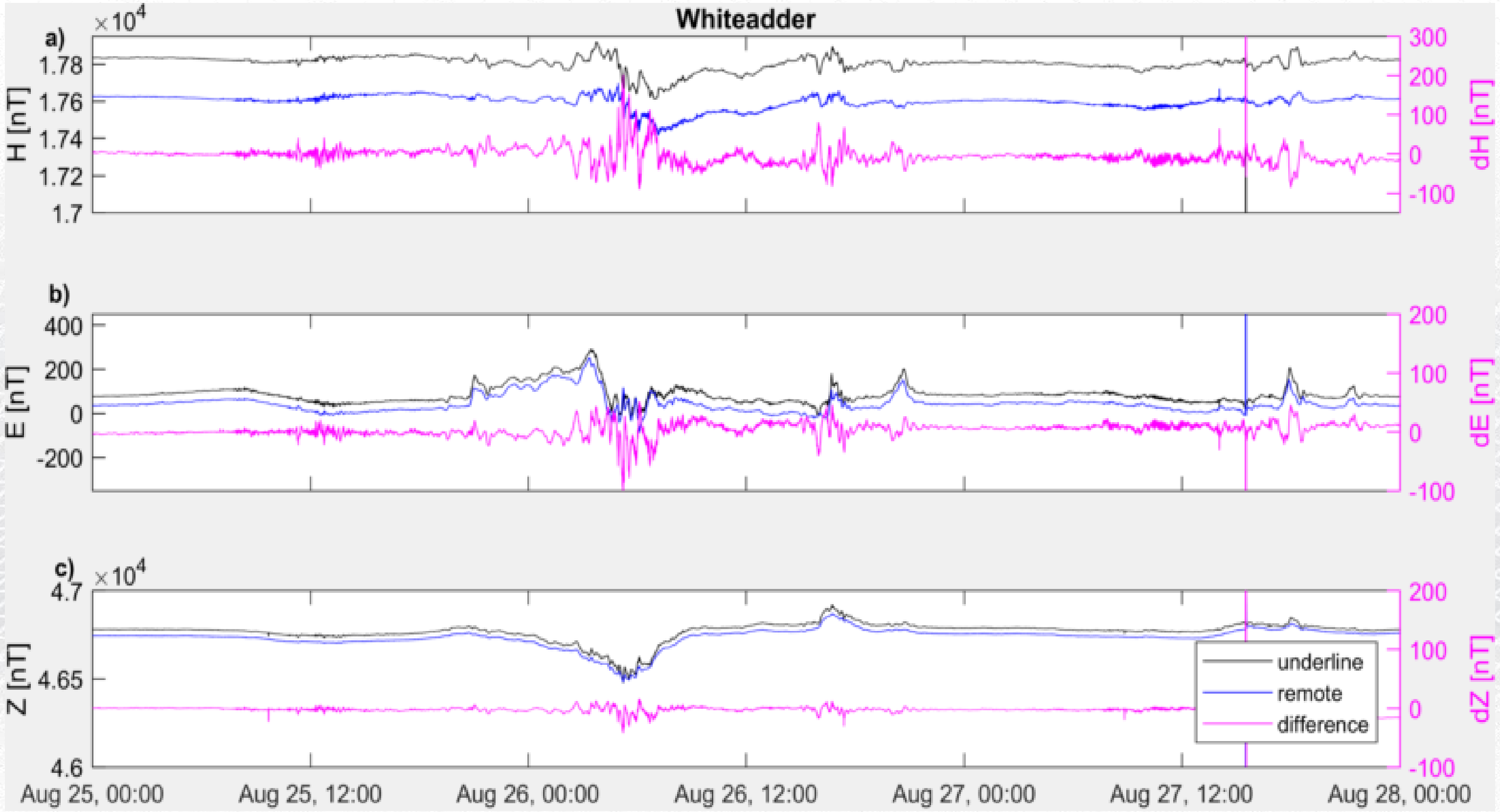


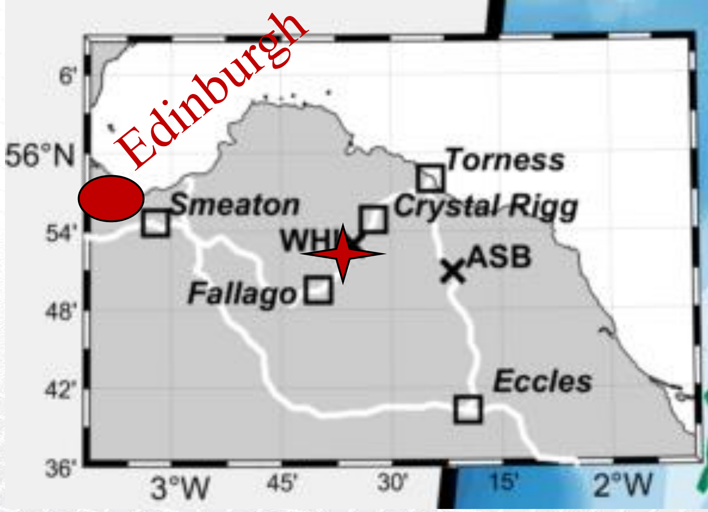


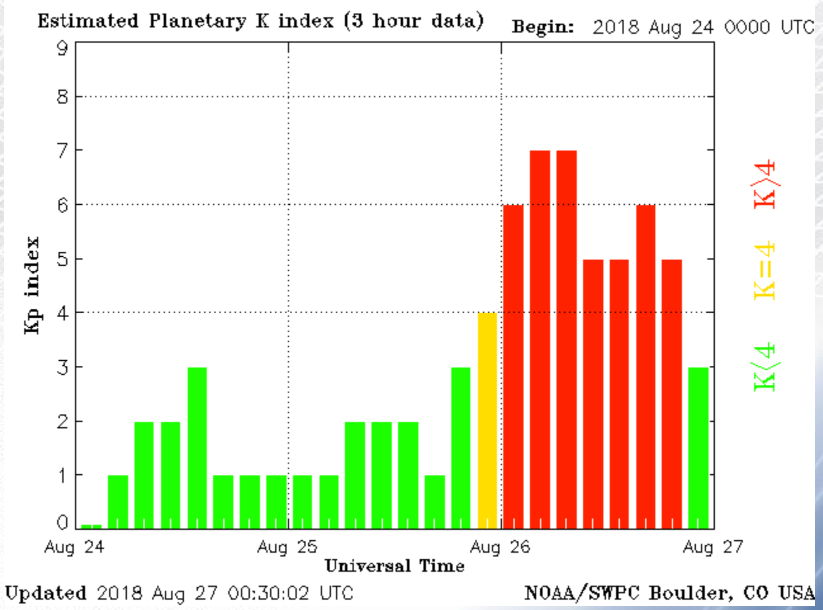
Map of the GB HV transmission power grid and DMM installations
4-5 systems running simultaneously

x 2018 sites
x 2019 sites
x 2020 sites

DMM first data: Storm 26 August 2018 – Fields measured at WHI



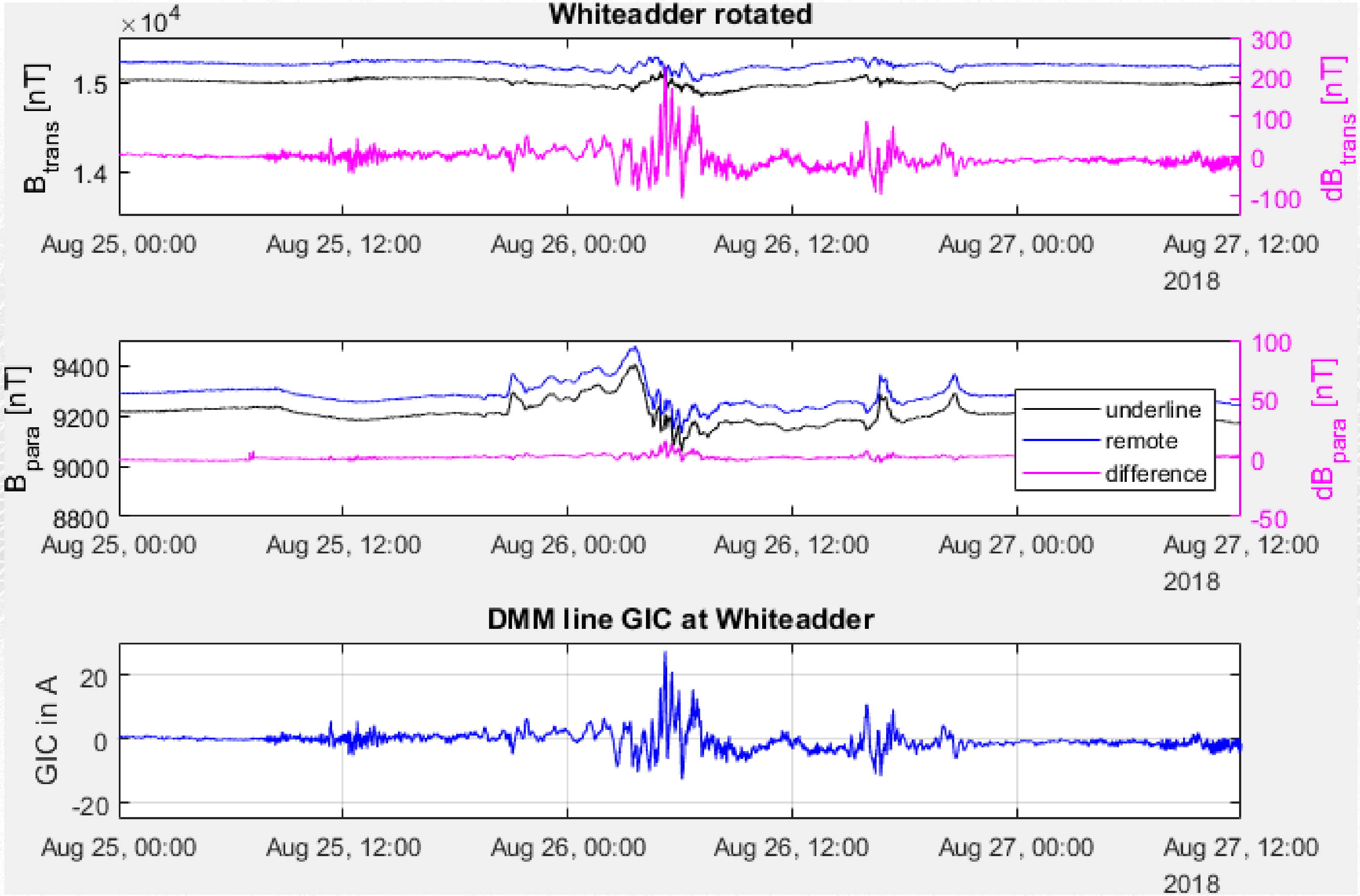


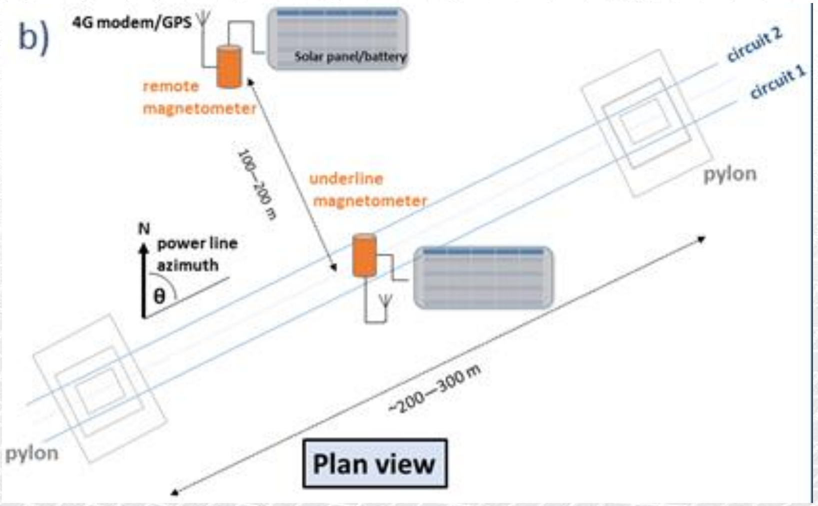


Measured magnetic field components at underline and remote systems and the difference between them. Max. difference in fields ~225nT.

CME on 20 Aug 2018
IMF fell southward ~-15 nT and stayed there for 20 hours

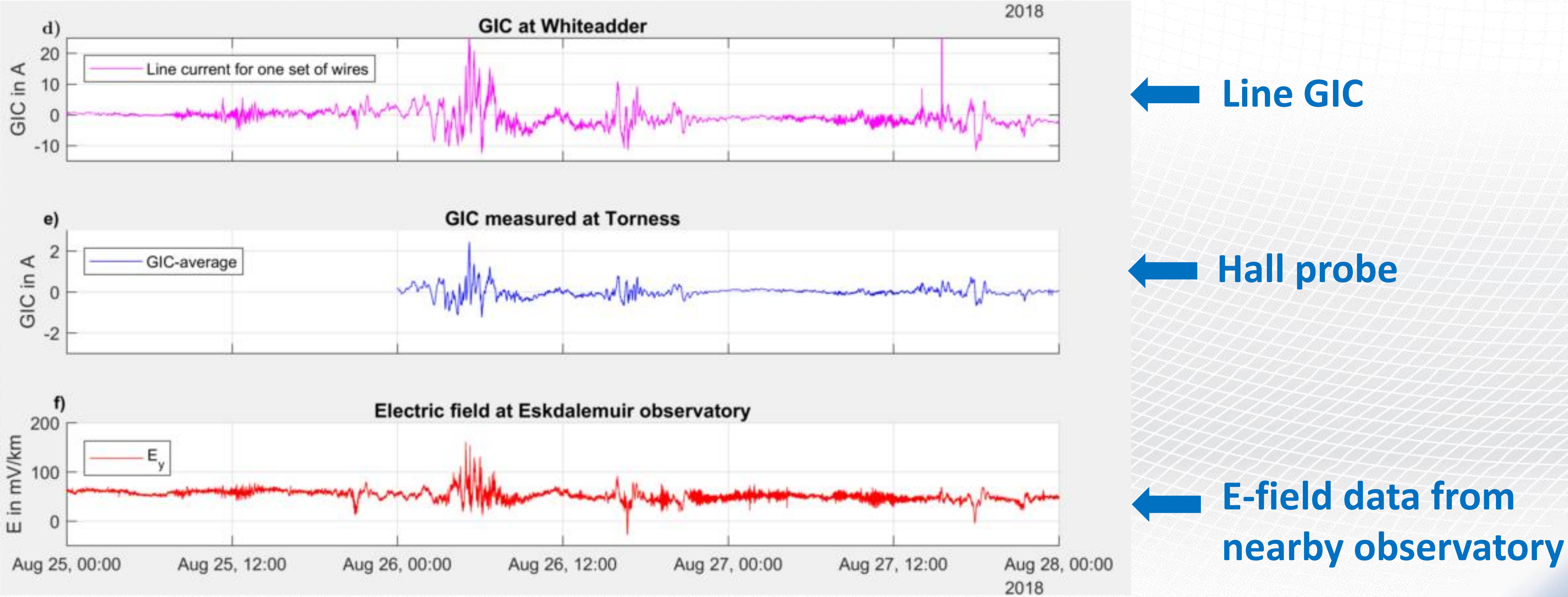
Storm 26 August 2018 – Line GIC measured at station WHI (East Scotland)





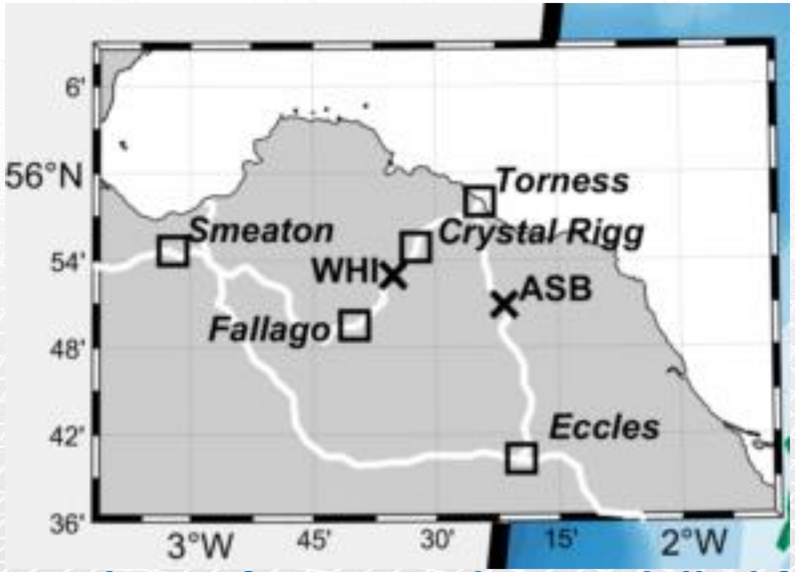
Rotated data into power line coordinate system to get maximum difference in one field component, then GIC computation with pylon model assuming *balanced circuits* (25 A).

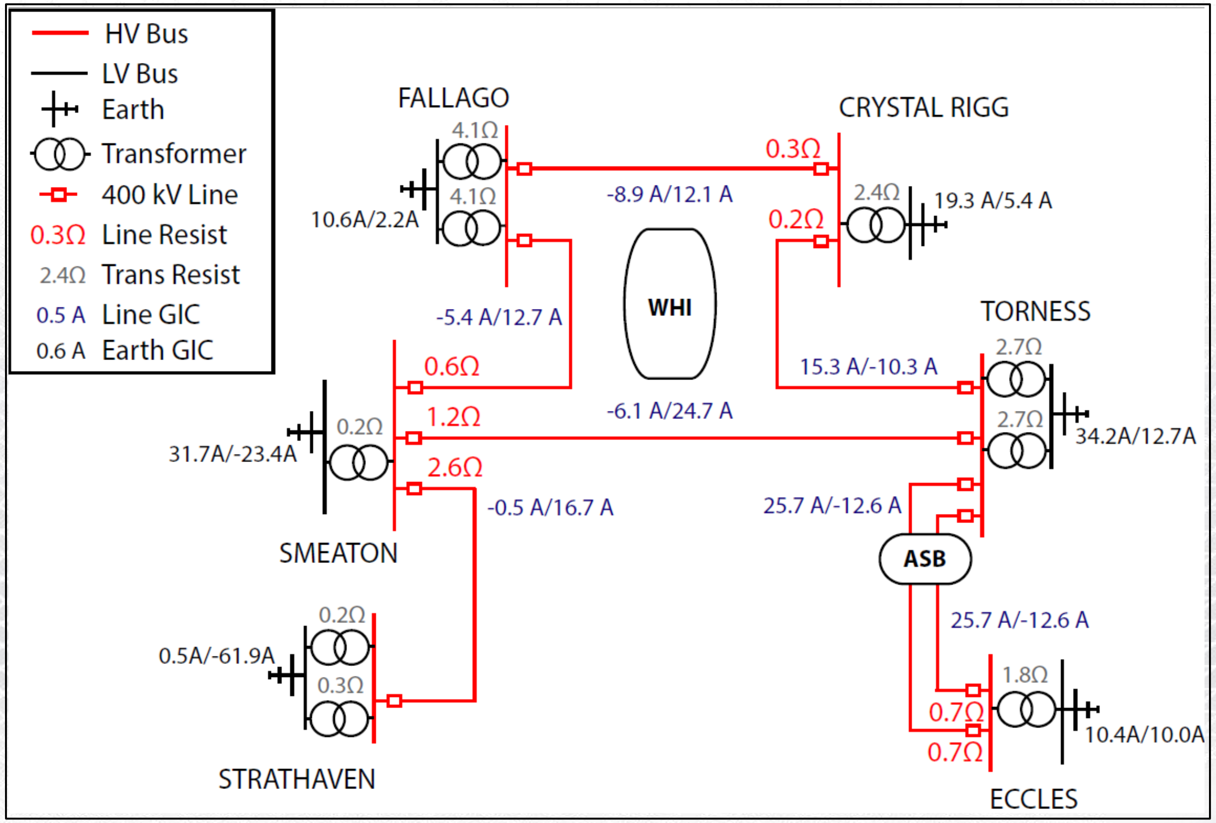
Storm 26 August 2018 – Line GIC comparison to Hall probe data



- GIC measurement at a transformer at Torness power station 30km away (provided by Scottish power Ltd.)
- -> very similar signal shape, but different amplitude- > difference between line GIC and measurement in transformer (multiple lines)
- E-W Electric field measured at Eskdalemuir observatory peak ~140 mv/km (70km away).

GIC of Storm 26 August 2018 – qualitative analysis using a detailed network subgrid





Analysis of measured vs modelled for East Scotland

Measured

At ESK; geoelectric field (E-W) peak: ~140 mV/km

At WHI DMM; peak B field: ~225 nT

At TORNESS Hall probe; 2 A

Modelled (using network representation of

At TORNESS substation*:* 12.7 A * 0.140 = ~2 A ✓

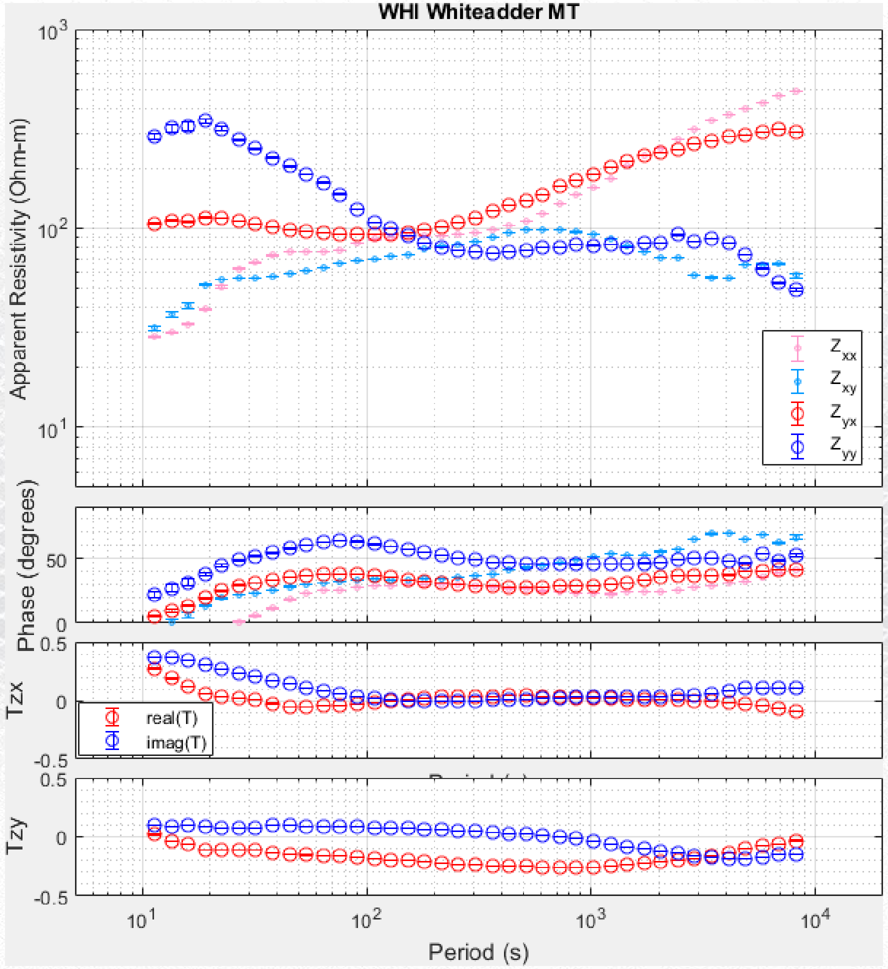
Along WHI *Line:* (24.7 * 3 + 12.1 * 3) A * 0.140 * distance to wires ~ 225 nT ✓

Schematics after Horton (2012) of HV power grid in East Scotland with location of substations, DMM sites and line parameters from ETYS 2010, line GICs are computed for *1V/km* homogenous E-fields. Line GIC are per phase, substation GIC are totals.

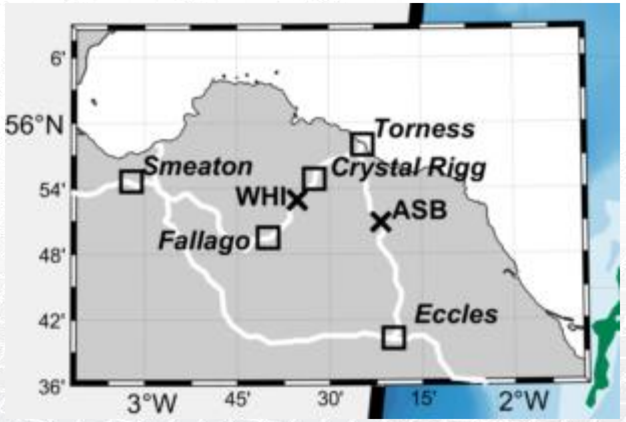
Getting better Electric field estimates using MT

LMT installation next to DMM remote site at Whiteadder, East Lothian Recorded 14 March – 30 April 2019 (six weeks with one minor geomagnetic activity on 16 March 2019

Technique used already by e.g., Bonner & Schultz, 2017; Campanya et al., 2019; Kelbert et al., 2017



Smooth impedance transfer function 10-10^4 s using remote reference with observatory data at Eskdalemuir



Thanks to DIAS for instrument loan

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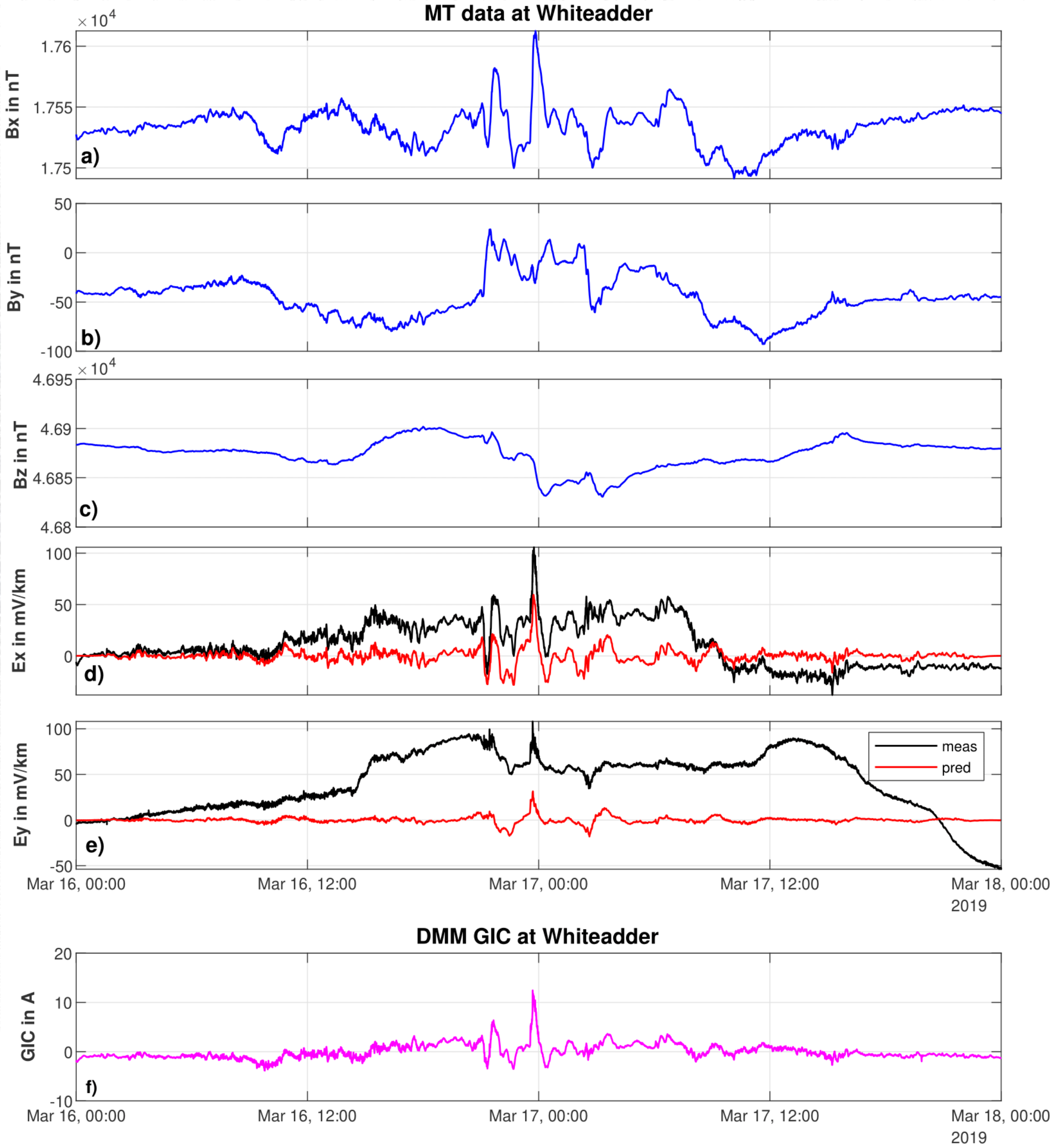
Getting better Electric field estimates using MT

a-e) MT time series recorded at WHI station for minor geomagnetic activity 16-17 March 2019 (G1)

d-e) Computed electric field using MT impedance, capturing most of the variation, but not long-term trends/drift

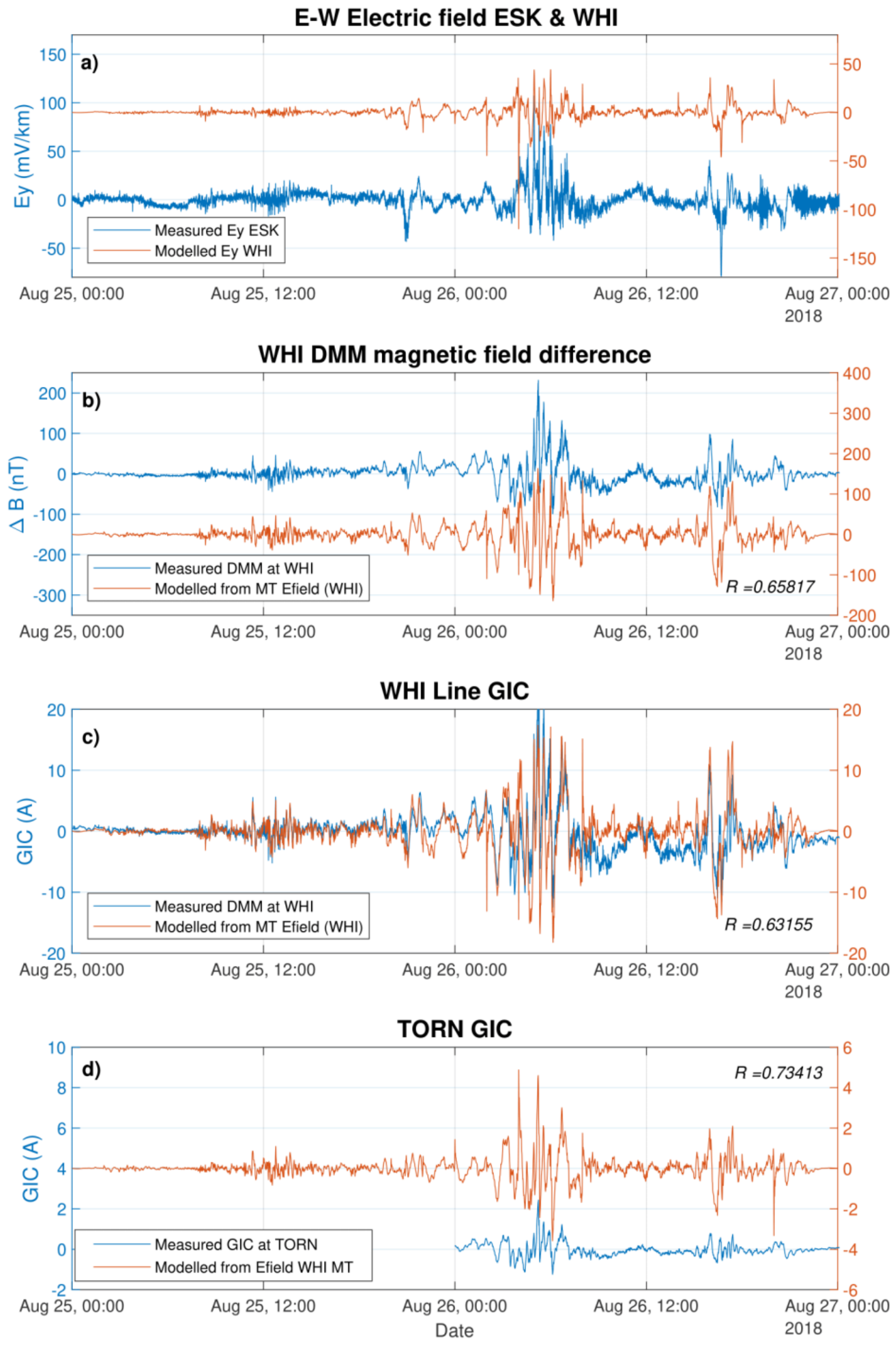
f) and line GIC at WHI station



Storm 26 August 2018 using MT impedance derived electric fields

Comparison of measured and modelled data:
a) Electric field times series during
the G3 geomagnetic storm on 25-26 August 2018
measured at Eskdalemuir and modelled at Whiteadder
(WHI),
b) DMM magnetic field differences at WHI,
c) Line GICs at site WHI and
d) GICs at Torness substation
with correlation coefficients R for the modelled and
measured time series.

-> Reasonable fit for observed and modelled line and
ground GICs, validation successful!



Summary

- Designed, assembled and tested of Differential Magnetometer Method (DMM) system for line GIC measurements in the UK HV power grid. So far installed 10 DMM systems with real-time data collection.
- Data set will be available on the National Geoscience Data Centre (some is already).
- Compared and validated GIC modelling in one subset of the network grid -> needs very detailed information needed for network parameters.
- Improvements can be made with better estimates for the electric field using MT impedances over larger areas, not just single locations

Acknowledgments

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Photo by H. Buxel

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