JULIANE HÜBERT

MTNet

Space Weather, GICs and MT

Space weather impacts on ground technology and the role of the Solid Earth response

British Geological Survey

Three parts

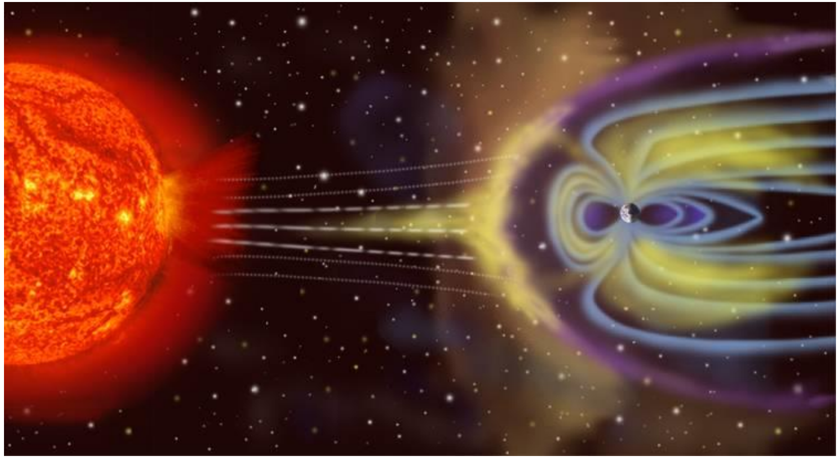
I Introduction to Space Weather
II The Geoelectric field and the solid Earth
III Measuring/modelling impacts of Space weather on ground technology

swigs
SPACE WEATHER IMPACT ON GROUND-BASED SYSTEMS

http://swigs.bgs.ac.uk/ http://www.geomag.bgs.ac.uk/

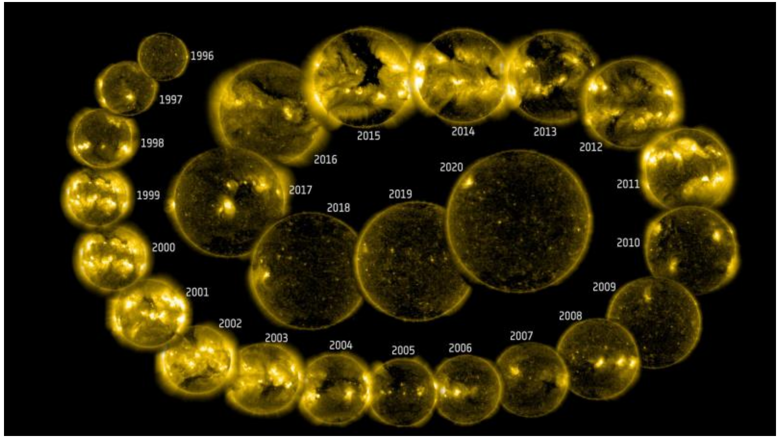
I Introduction to Space Weather

What is Space Weather?
- A novel natural hazard



“Solar wind disturbances that affect Earth’s space, atmosphere and surface environments and that can disrupt technology”.

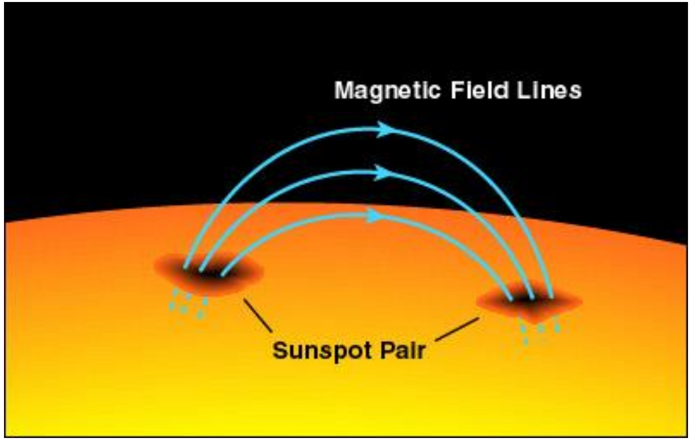
e.g. on the UK risk register since 2015 ->



Overall relative impact score	Between 1 in 20,000 and 1 in 2,000	Between 1 in 2,000 and 1 in 200	Between 1 in 200 and 1 in 20	Between 1 in 20 and 1 in 2	Greater than 1 in 2
5				Pandemic influenza	
4			Coastal flooding Widespread electricity failure		
3		**Major transport accidents** **Major industrial accidents**	Effusive volcanic eruptions Emerging infectious diseases Inland flooding	Severe space weather Low temperatures & heavy snow Heatwaves Poor air quality events	
2		Public disorder Severe wildfires	Animal diseases Drought	Explosive volcanic eruption Storms & gales	
1			**Disruptive industrial action**		

Relative likelihood of occurring in the next 5 years

Sunspots

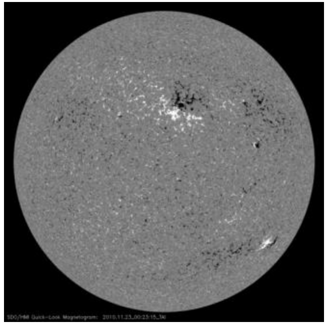


Sunspots change polarity every 11 years

– Full cycle takes 22 years

Consist of dark positive and negative regions (separated by a 'light bridge')

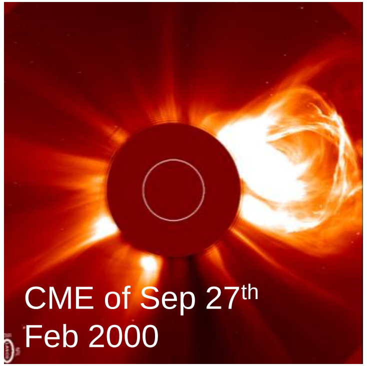
From the SDO HMI: 23 Nov 2010



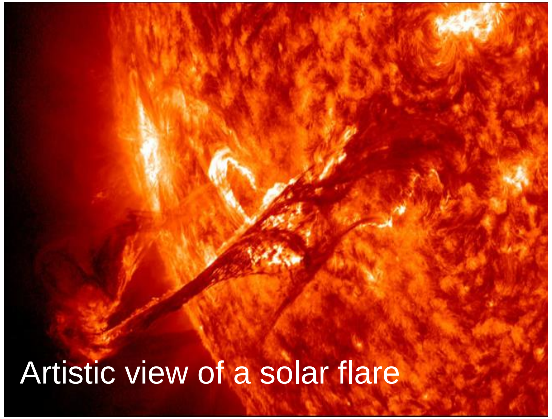
Solar Dynamic Observatory Heliospheric and Magnetic Imager

- White (negative polarity)
- Black (positive polarity)

Flares and Coronal Mass Ejections



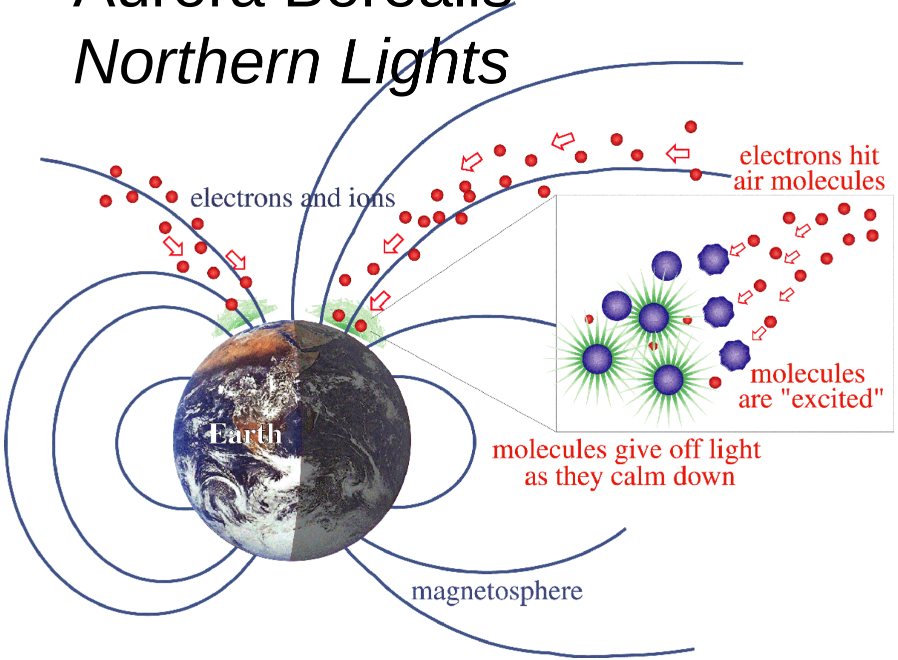
CME of Sep 27th Feb 2000



Artistic view of a solar flare

- Solar flares are bright and readily seen by astronomers (e.g. the great Carrington flare of 1859). Flares cause X-rays and SEPs.
- 'Coronal mass ejections', causing the worst space weather, were not discovered until the space age. CMEs cause charged particles and magnetic fields to escape from the Sun.

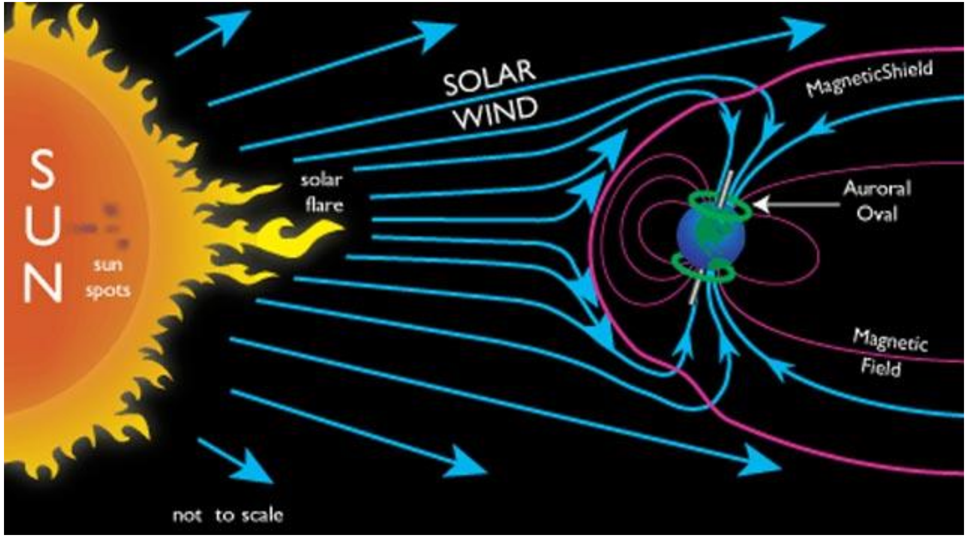
Aurora Borealis
Northern Lights



https://aurorawatch.lancs.ac.uk/alerts/

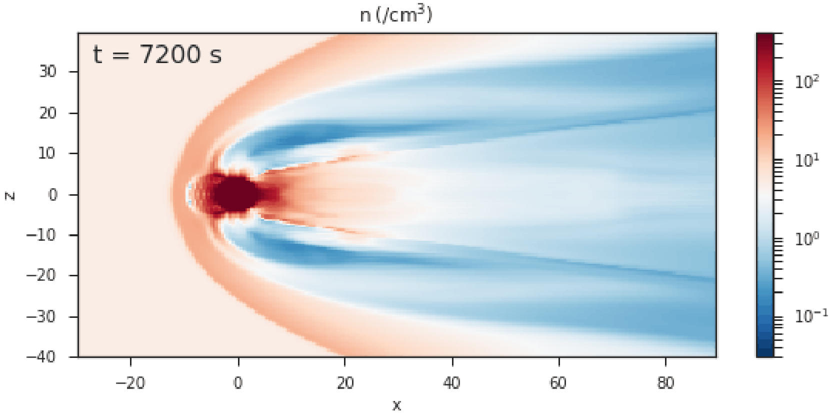
Above: STEVE over Scotland, March 2021.
Below: Aurora display on North Uist, Scotland

Interaction of solar wind with the magnetosphere



The Bz component of the Interplanetary magnetic field has to be negative to couple with the geomagnetic field, causing widespread disturbance of the field,

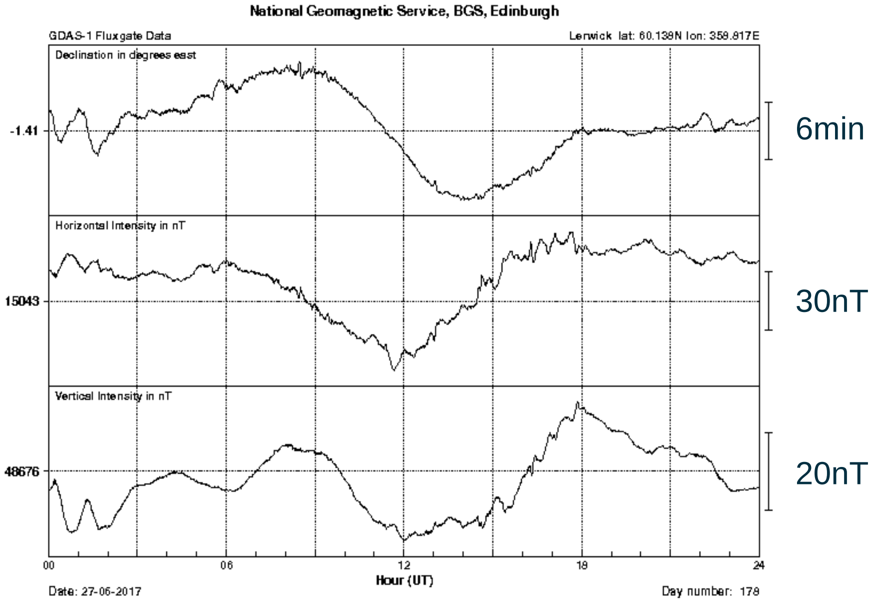
Simulation and prediction of the coupling of solar wind and magnetosphere is subject to a lot of research activity

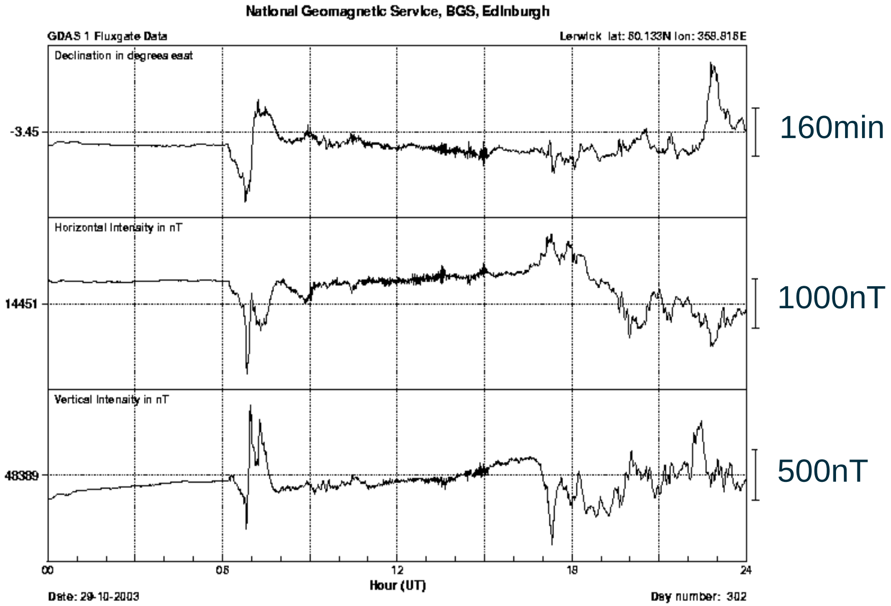


MHD modelling (Gorgon) of enhanced magnetospheric convection caused by interplanetary shock arrival (Eggington, 2020)

Uses solar wind modelling and observed data at L1

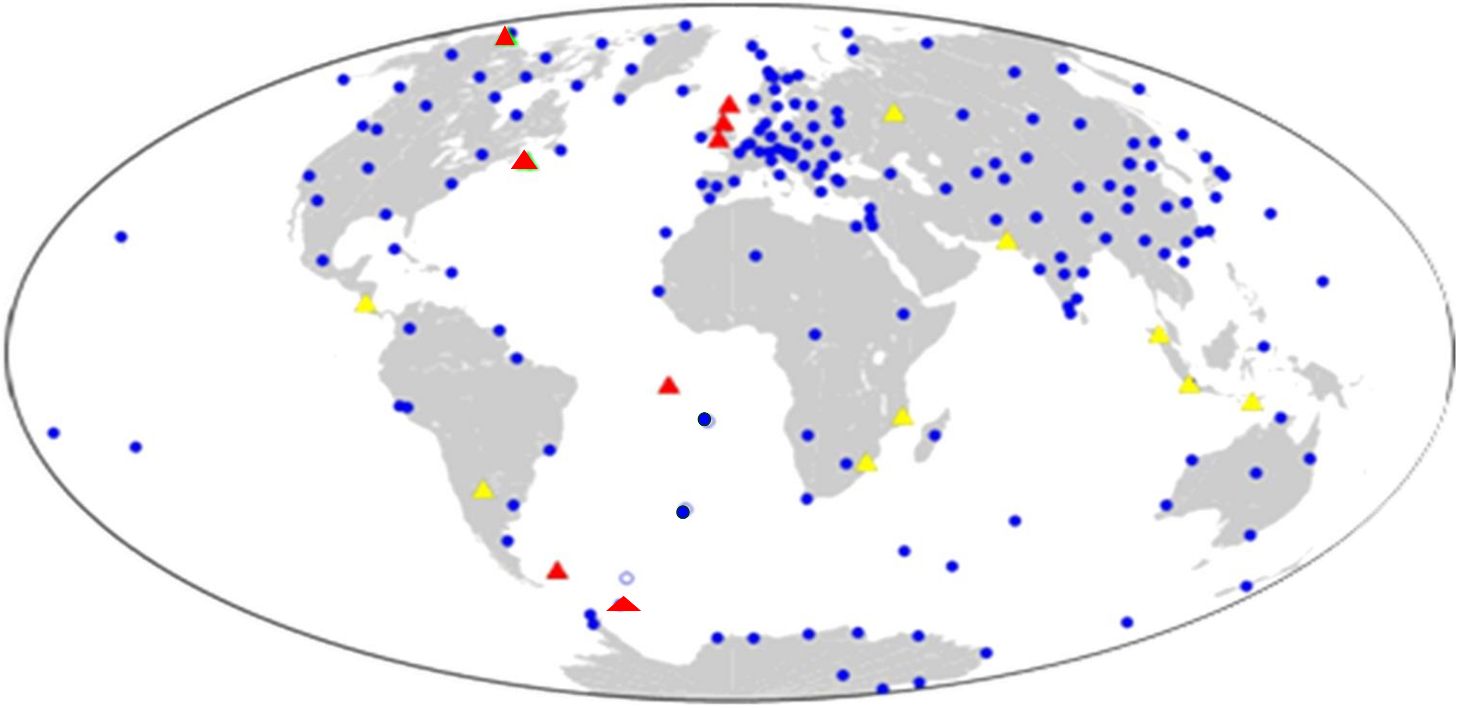
How does Space Weather impact the Geomagnetic field?





Magnetogram at Lerwick observatory, UK for a quiet day (left) and a stormy day (right)

Geomagnetic observatories and Intermagnet



Global network of observatories, monitoring the Earth's magnetic field.
Many of them deliver real-time data. Sampling rates 1s -1min.

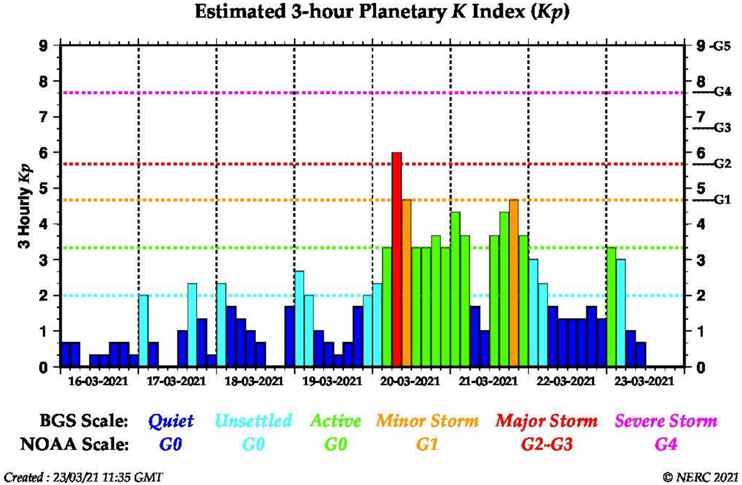
INTERMAGNET

Magnetic indices and scales:

NOAA G scales and Kp are widely recognized:

- BGS use them to forecast and to categorise past activity
- Based on Kp, the 3-hourly geomagnetic index

Kp	BGS categories since 2014		NOAA G-scales	
	Category	Description	Category	Description
<3+	QUIET	Kp < 3+		
3+	ACTIVE	3+ < Kp < 5-		
4-				
4o				
4+				
5-	STORM G1	5- < Kp < 5+	G1	Kp = 5
5o				
5+				
6-	STORM G2	6- < Kp < 6+	G2	Kp = 6
6o				
6+				
7-	STORM G3	7- < Kp < 7+	G3	Kp = 7
7o				
7+				
8-	STORM G4	8- < Kp < 9-	G4	Kp = 8
8o				
8+				
9-				
9o	STORM G5	Kp = 9o	G5	Kp = 9



BGS Global Geomagnetic Activity Forecast for Met Office

Forecast period (noon-to-noon GMT)	Forecast Global Activity level	
	Average	Max
28 SEP-29 SEP	ACTIVE	STORM G2
29 SEP-30 SEP	QUIET	STORM G1
30 SEP-1 OCT	QUIET	ACTIVE

For more information about the forecast and activity categories see geomag.bgs.ac.uk/education/activitylevels.html

Activity during last 72 hours

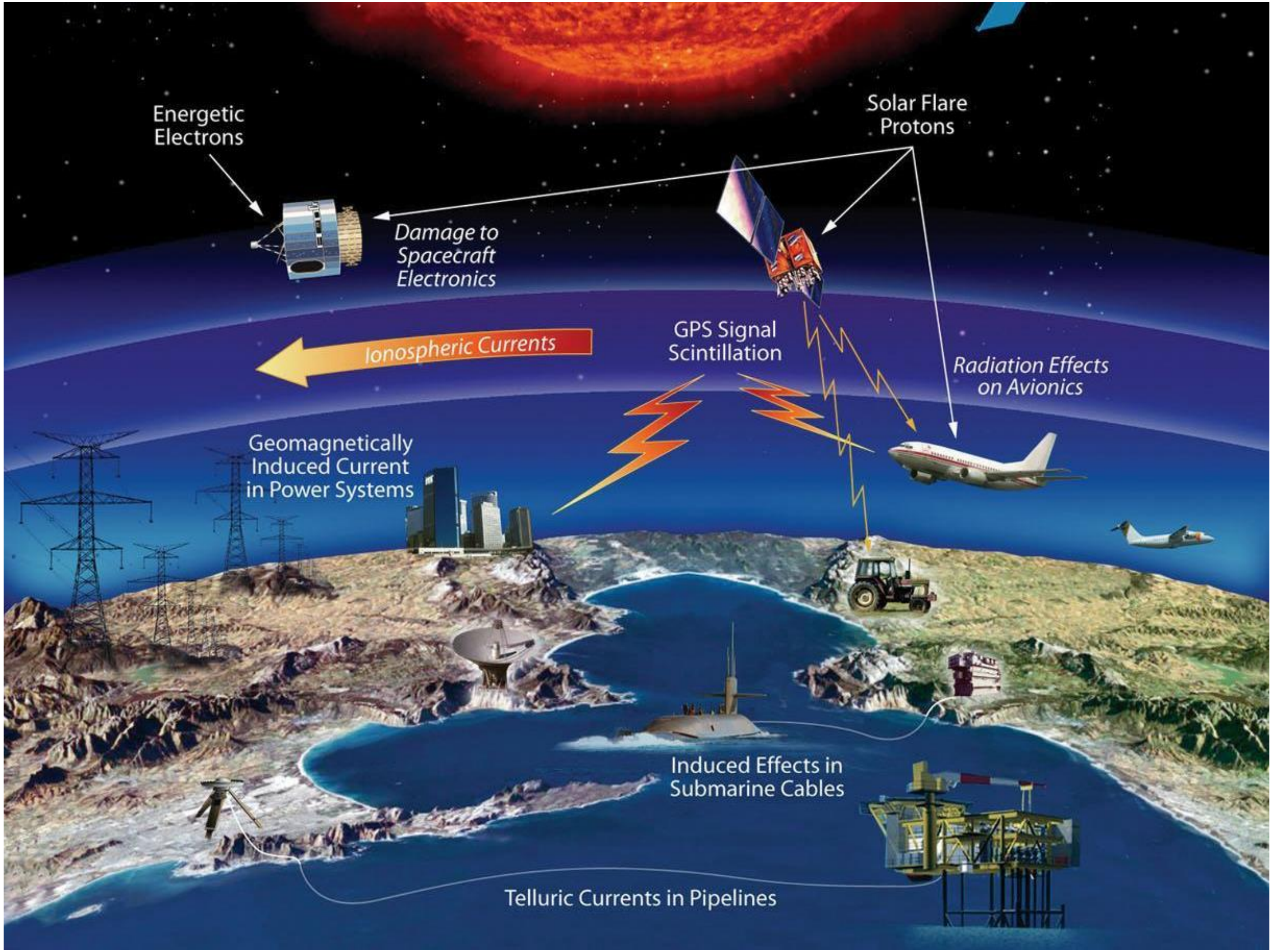
	Global			Local (UK)		
Date	Average	Max	At time (UT)	Average	Max	At time (UT)
25 SEP-26 SEP	ACTIVE	STORM G2	03:00-06:00	ACTIVE	STORM G1	21:00-00:00
26 SEP-27 SEP	QUIET	STORM G1	12:00-15:00	QUIET	ACTIVE	12:00-15:00
27 SEP-28 SEP	ACTIVE	STORM G1	18:00-21:00	ACTIVE	STORM G1	18:00-21:00
					STORM G1	03:00-06:00

Additional Comments

Geomagnetic conditions are still ACTIVE as the Earth remains under the influence of the high speed stream from the extension south of the Northern polar coronal hole. This is predicted to continue throughout the first forecast period with possibility of STORM G1 spells or even a STORM G2 as the solar wind stream speeds remain elevated. Activity is predicted to ease going into the second forecast period but there still remains the chance of STORM G1 intervals as coronal hole influence slowly wanes with chances of ACTIVE periods during day 3 as the coronal hole moves away from being Earth facing.

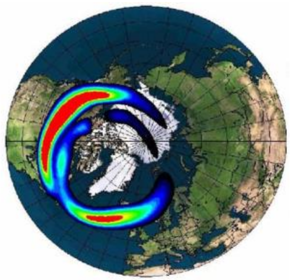
Tweets by @BGSspaceWeather

BGS Space Weather
@BGSspaceWeather
Next 24hrs - QUIET overall with chance of an occasional ACTIVE period due to residual Coronal Hole effects. Possible glancing blow from a CME on the 19th may further enhance activity if it arrives, with a chance of a brief STORM G1, although there is some uncertainty about this.

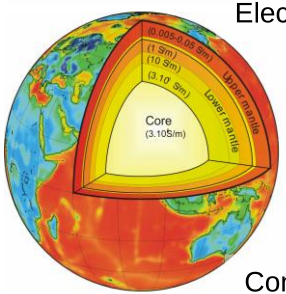


Effects strongest in *higher latitude* countries like Canada, Sweden, Finland, UK
But under ‘surveillance’ in the US and NZ,
Reports also from Spain, Portugal, South Africa

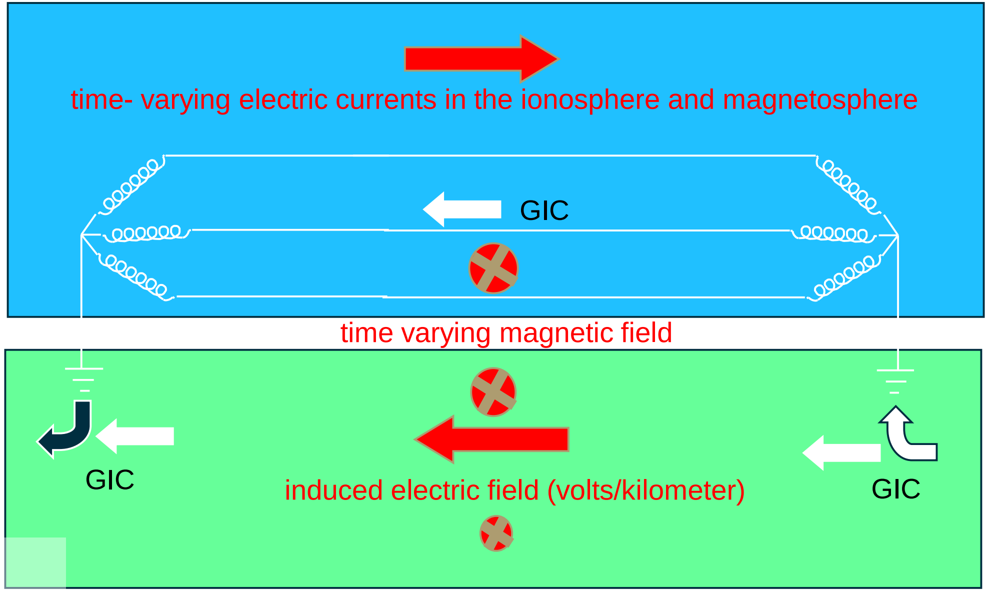
Why Does Space Weather Cause Grid Problems?



Electrical currents



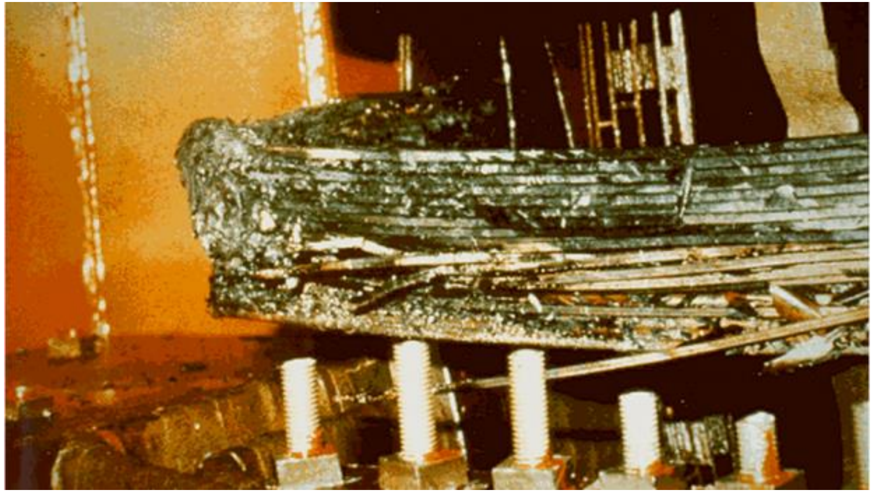
Conducting Earth



Geomagnetically induced currents (GIC) cause

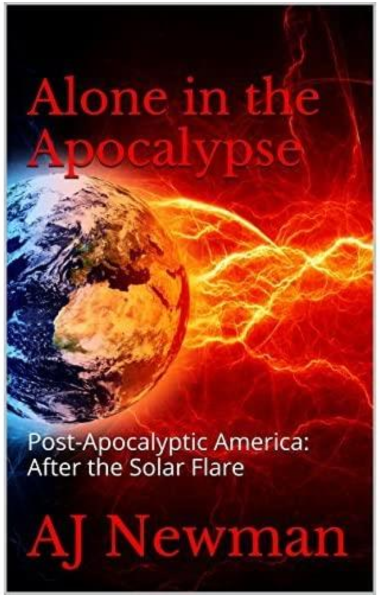
- Half-cycle saturation of transformers, voltage harmonics, overheating, increased reactive power demand, and/or drop in system voltage, in NZ GICs of >40A are reported
- Leading to transformer burn-out (big storm) or shortened lifetime (many smaller storms)
- Accumulative effects in gas pipelines (pipe-to-soil potentials, PSPs) and disturbances in railway communications possible

Geomagnetically induced currents

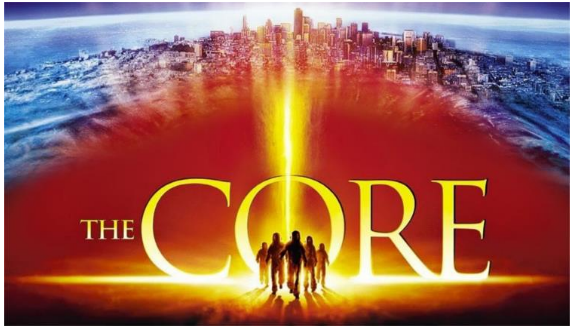


Reported impacts on power grids:

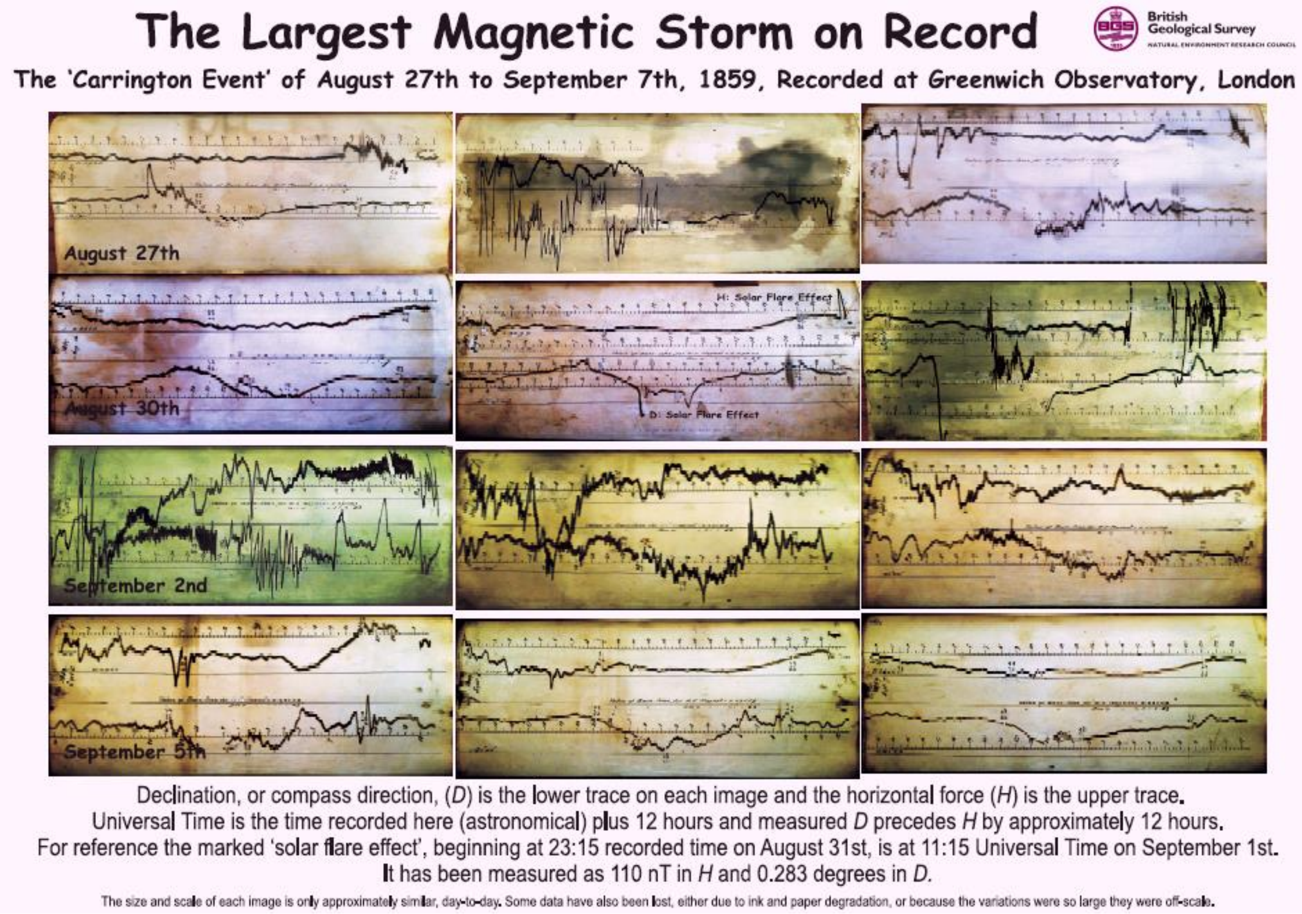
• 1989 Hydro-Quebec, Canada reported failure of transformer network – major power out for 2 days
• 2003 Malmö, Sweden blackout due to transformer failure



How bad could it get?



Space Weather events – 1859

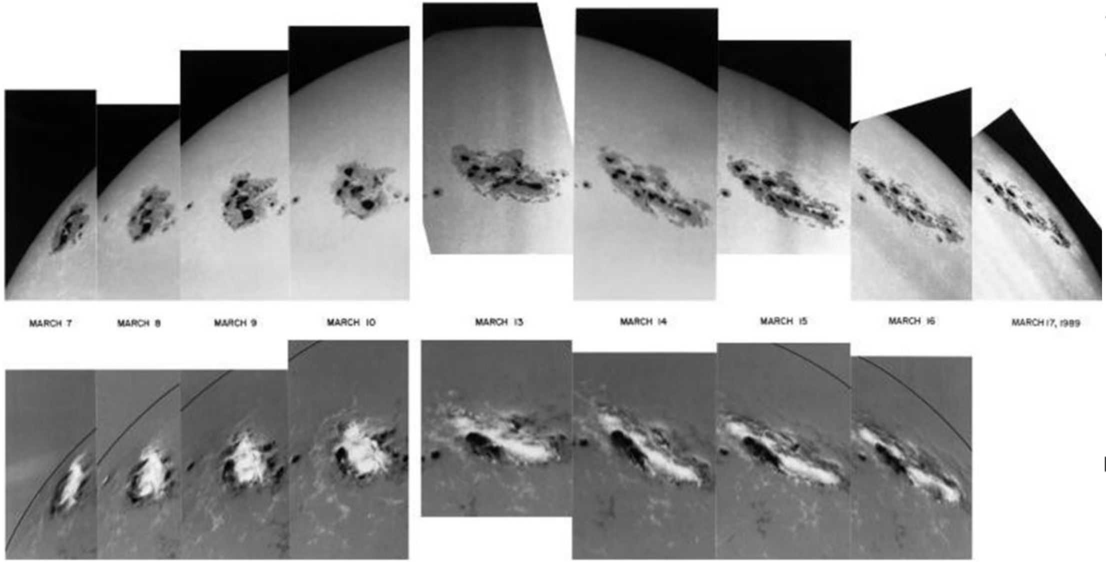


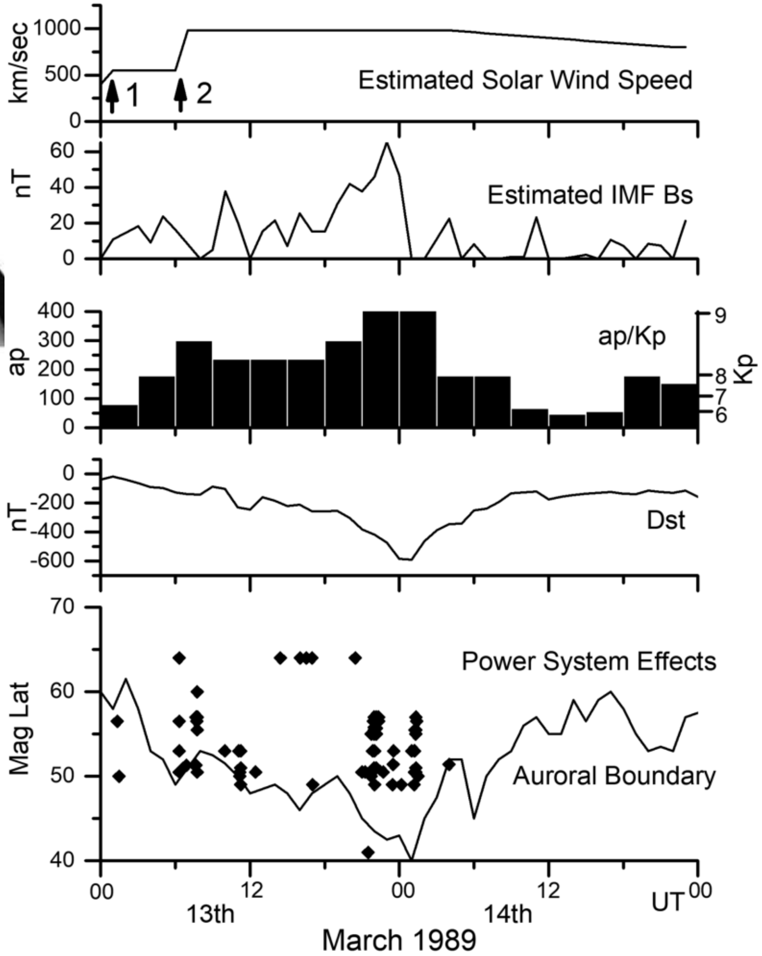
'Carrington event'
Large CME
Effected telegraph lines
Auroras visible as far south as Hawaii,
Only few geomagnetic observations
many off-scale

Oughton et al. (2019):
UK 4% transformer failure probability and a gross domestic product los £15.9 billion for the effects of Carrington size event without mitigation

To compare: £339bn deficit for 20/21 because of Covid-19 (according to think tank 'Institute for government')

Space Weather events – March 1989





Up: Images of the Sun's surface (top) and magnetograms (lower)

Right: Timeline for the magnetic disturbance of 13–14 March 1989 (Boteler, 2019), two CMEs (X4.5, M7.3) caused large GIC in the Hydro – Quebec power system resulting in system collapse

What data is needed to quantify the ground effects?

- Topology of the power grid/pipe network
- The integrated **ground electric field** along power lines / pipelines

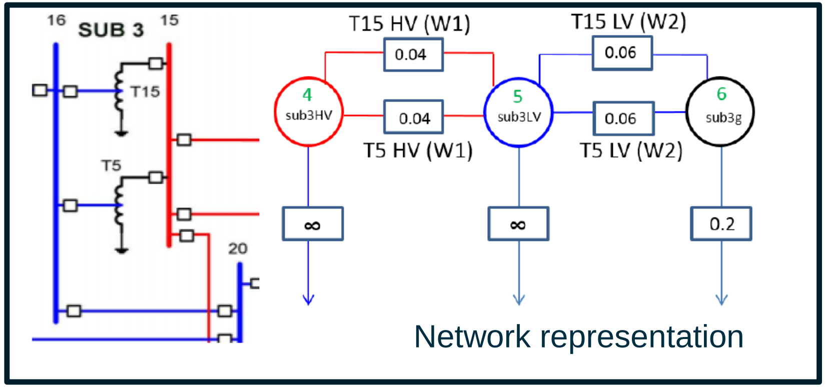
- GIC estimation: $I = (1+Y.Z)^{-1} \cdot J$

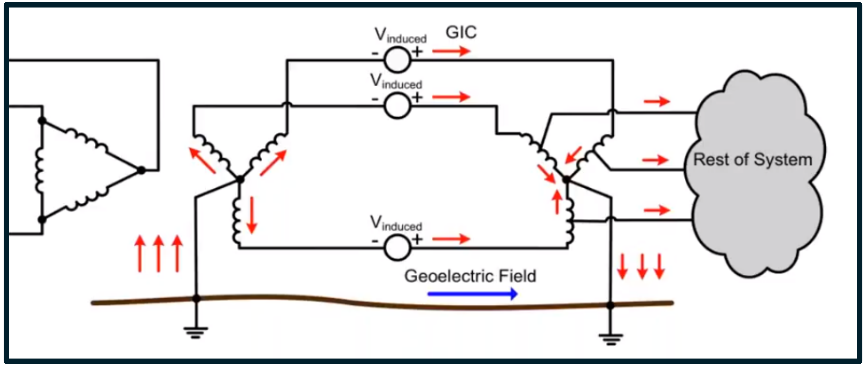
network admittance matrix

impedance matrix

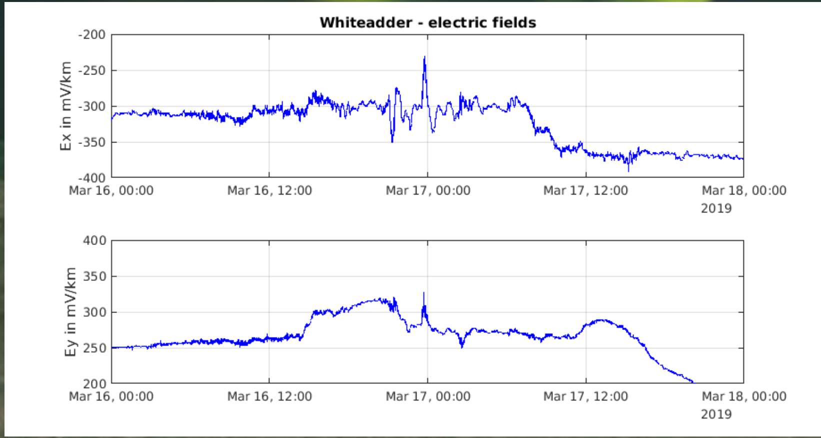
geo-voltage between nodes

(Lethinen & Pirjola, 1985)

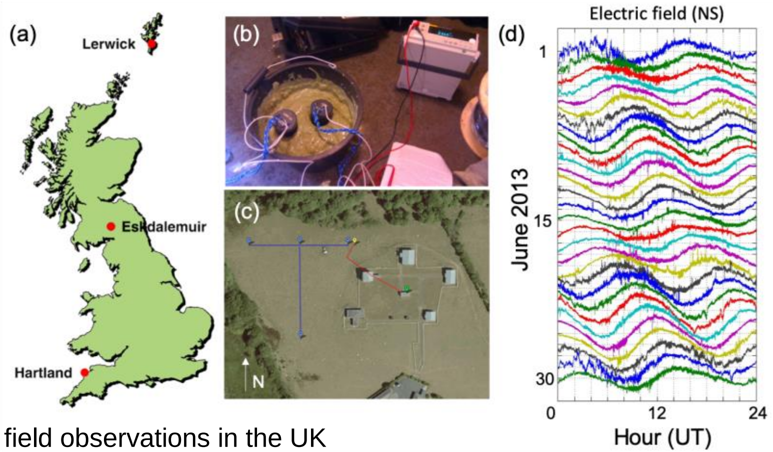




II Geoelectric field



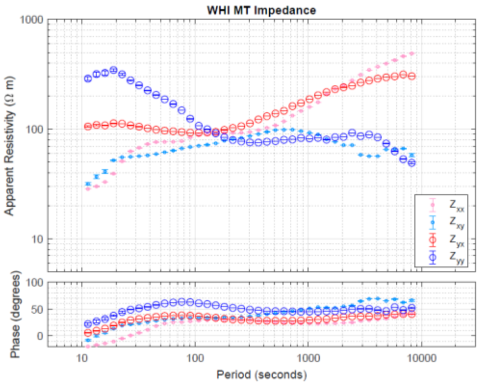
Ways to derive the ground electric field (GEF)

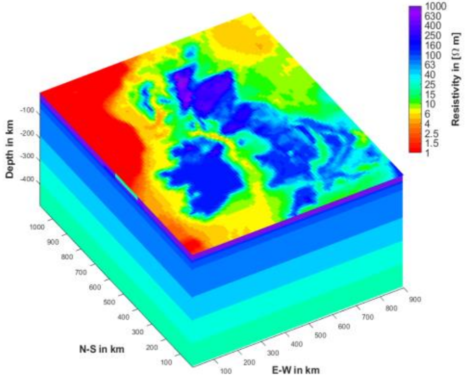


Electric field observations in the UK

1. Measurements: permanently currently at all three UK observatory sites since 2013
2. Calculate from (ideally 3D) models of electrical conductivity
3. Using magnetotelluric (MT) impedance transfer function Z

$$E(\omega) = Z(\omega) \cdot B(\omega)$$





Thin-sheet model of electrical resistivity after Beamish et al. (2012) based on airborne EM data and bedrock lithology and 1-D lithosphere.

Components of the complex & frequency dependent Magnetotelluric transfer function

Estimating the GEF– many different techniques


Surveys in Geophysics (2020) 41:115–166
https://doi.org/10.1007/s10712-019-09579-z

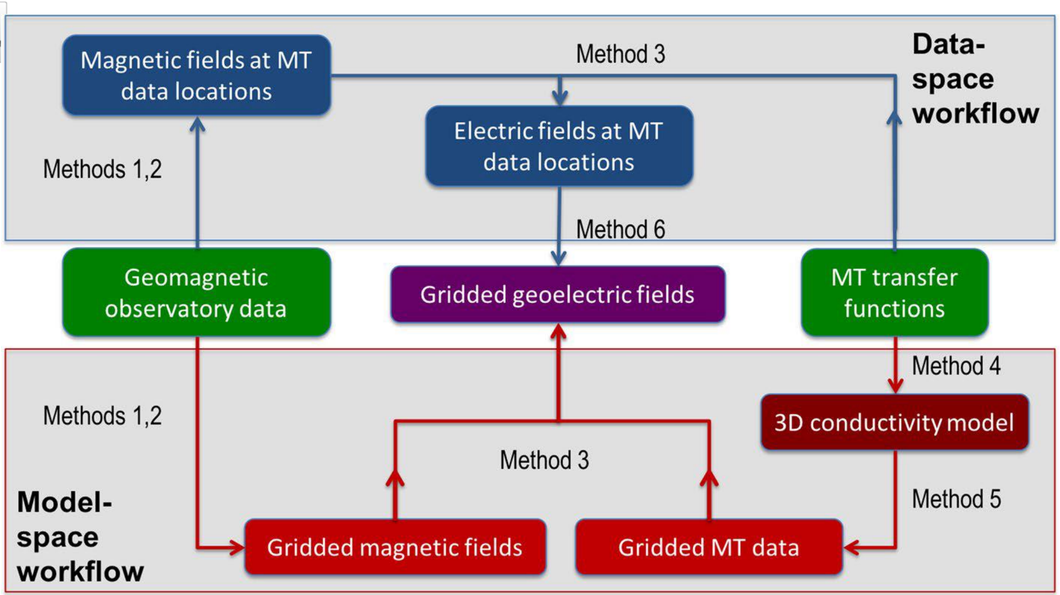
The Role of Global/Regional Earth Conductivity Models in Natural Geomagnetic Hazard Mitigation

Anna Kelbert[1]

Received: 5 February 2019 / Accepted: 15 October 2019 / Published online: 27 December 2019

Input data:

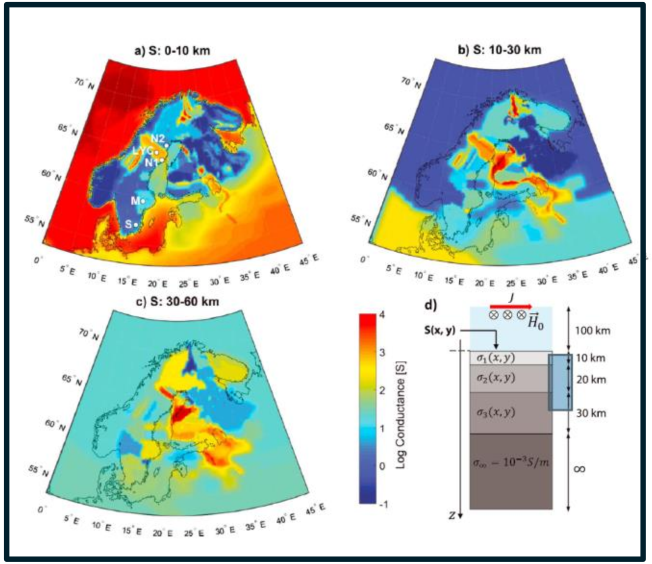
- **Magnetic** field data during storm time (measured or modelled)
- Some sort of **electrical conductivity** information (either conductivity model or MT impedance)



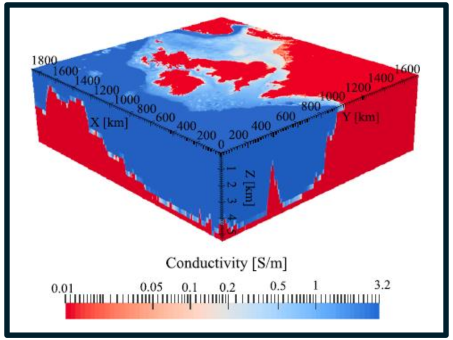
Kelbert (2020): Work flows for different approaches to estimate the GEF

What kind of electrical conductivity model?

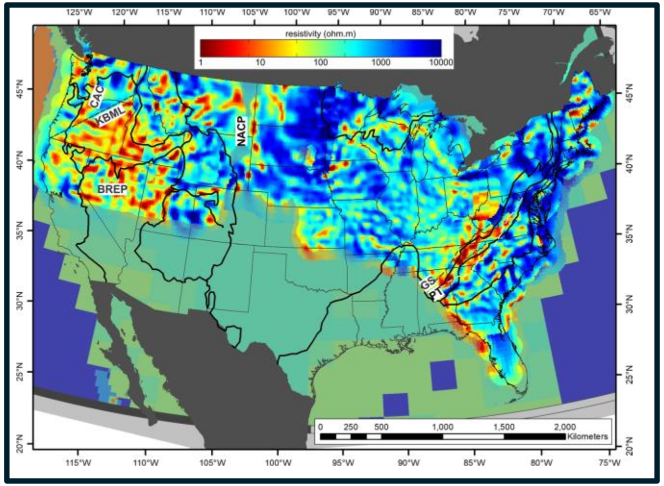
- Depends on the scale and what data is available:1-D, 2.5-D (thin-sheet), 3-D



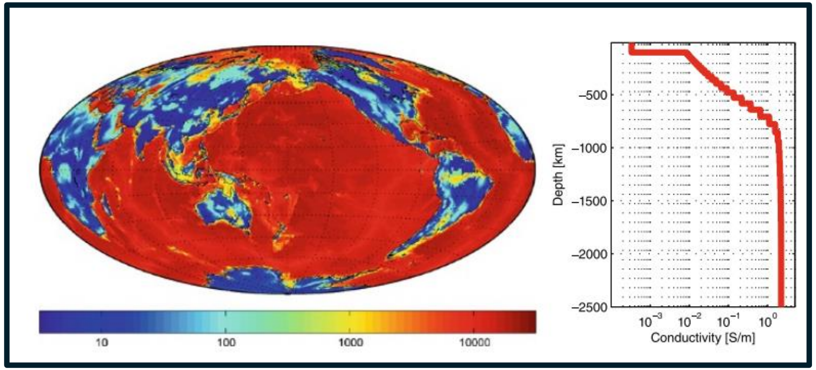
Rosenqvist et al., 2019



Ivannikova, 2018



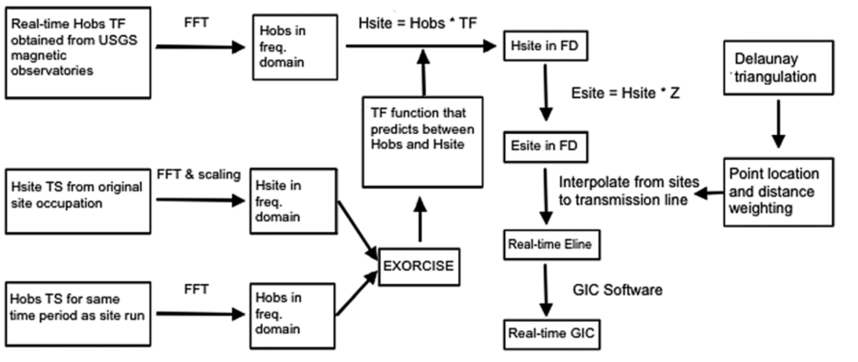
Kelbert et al., 2019



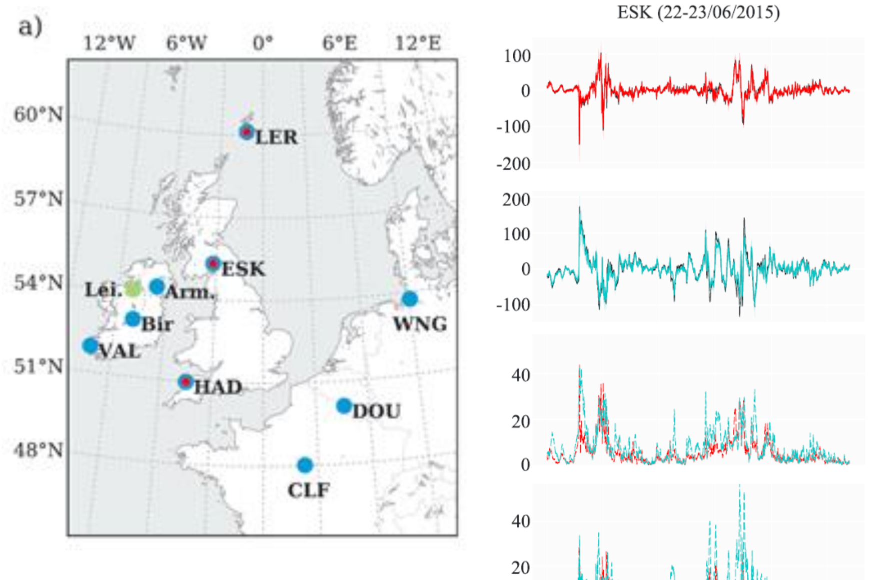
Püthe et al., 2014

Using the MT impedance

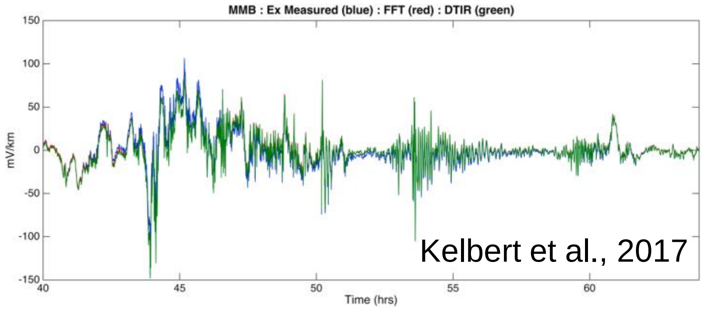
- Avoids ambiguities of inverse modelling
- Quick computations
- High accuracy



Bonner & Schultz, 2017



Campanyà et al., 2019

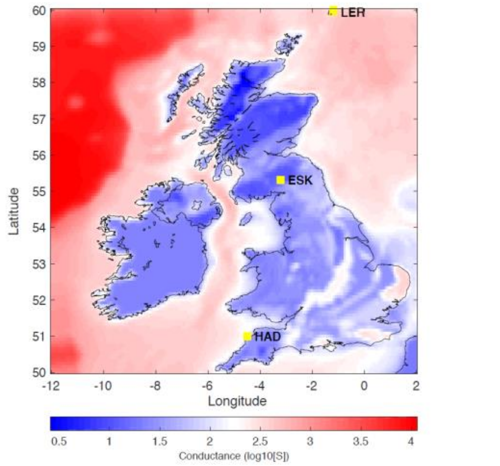


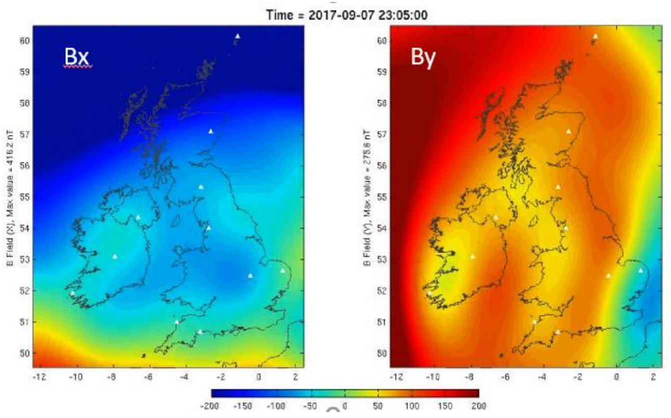
Kelbert et al., 2017

Ground electric field modelling in the UK

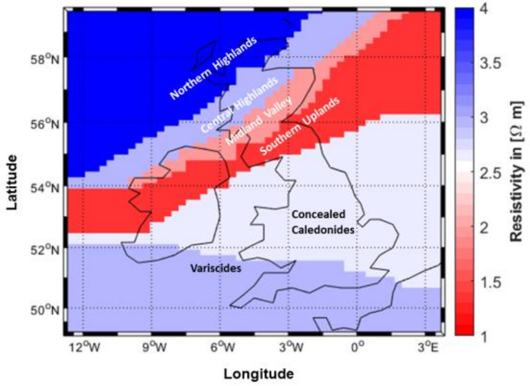
a) The **anomalous magnetic field** which induces electric field (SECS)

b) 2.5D thin-sheet model (after Vasseur&Weidelt, 1997). Thin-sheet of upper 3 km is characterized from bedrock conductivity maps, derived from airborne EM and laboratory data (Beamish et al. 2012).





(a) Anomalous magnetic field, recorded at UK observatories and
aurorawatch variometer stations

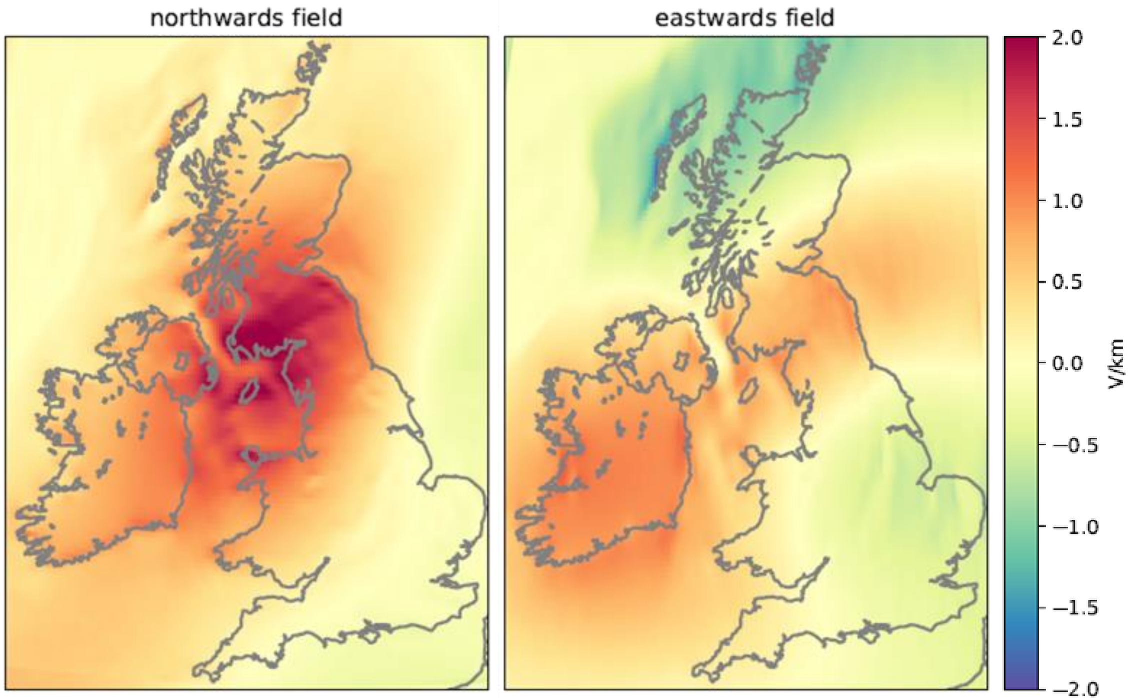


(b) Electrical conductance model of the UK **(**from airborne data and geology)

March 1989 electric field from thin-sheet model

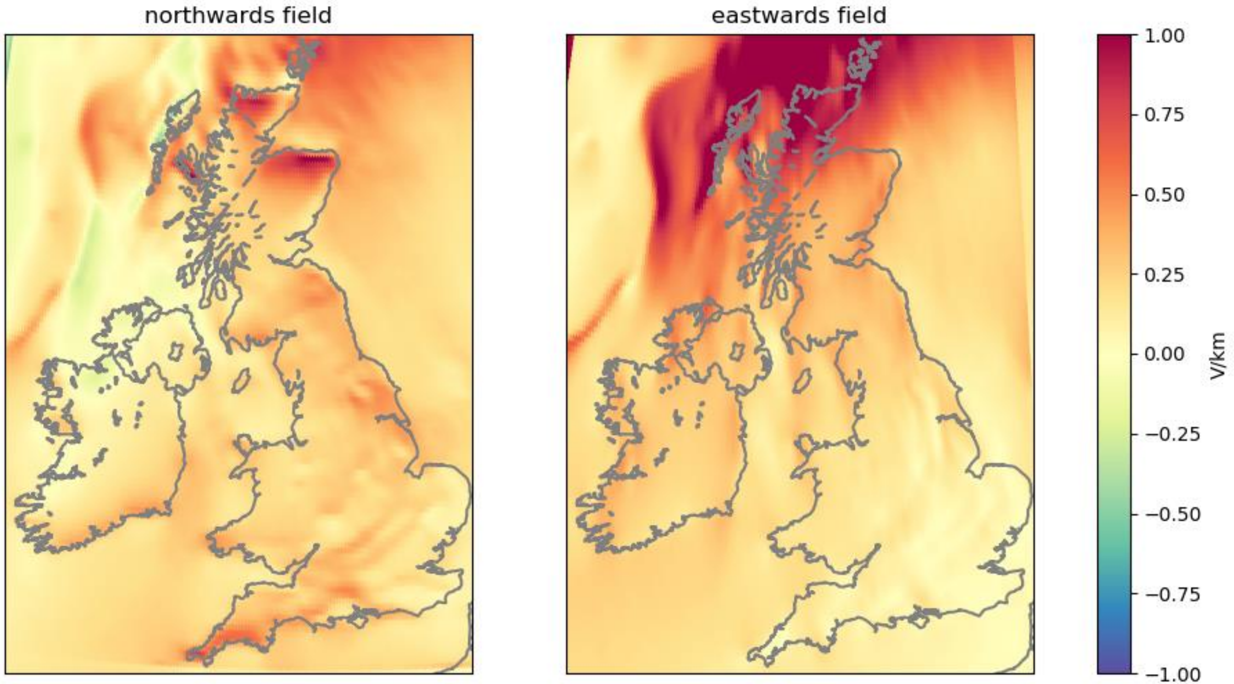
- 21:46 UT on 13th March 1989
- Largest Ex (N-S) 2.4 V/km
- Largest Ey (E-W) 1.8 V/km

Thin-sheet model allows for a very quick computation of electric field across the British isles, used for alerts



September 2017 electric field from thin-sheet model

- 00:25 UT on 8th September 2017
- Largest Ex (N-S) 1.12 V/km
- Largest Ey (E-W) 1.91 V/km



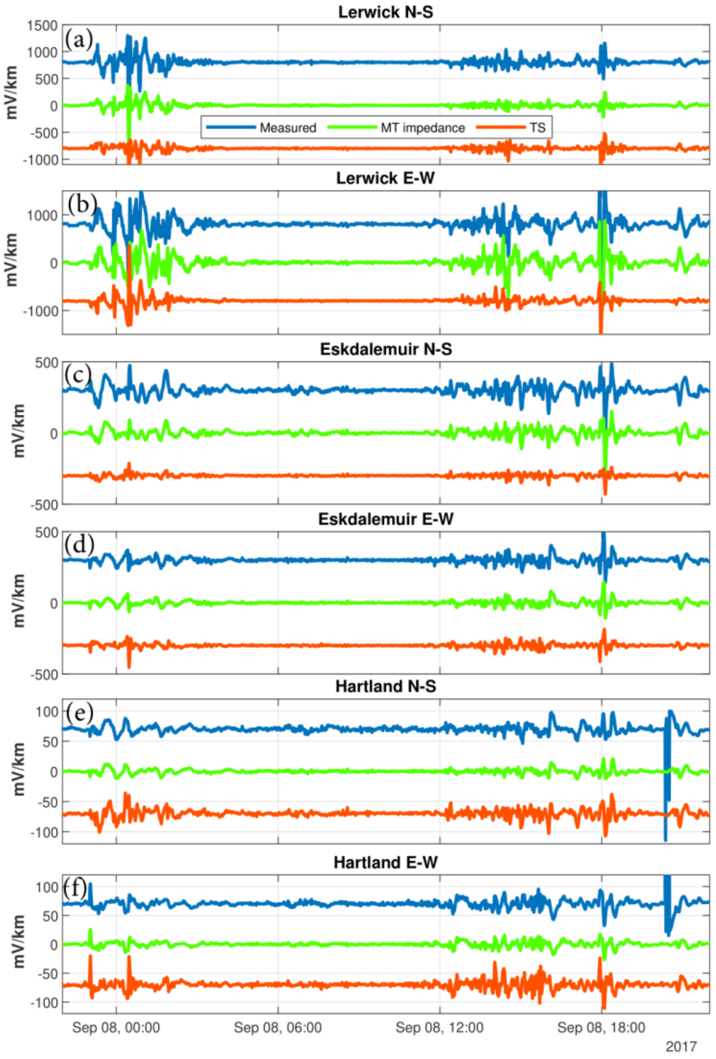
Thin-sheet model allows for a quick computation of electric field across the British isles

GROUND ELECTRIC FIELD

Comparison of electric field measurements and modelling (thin sheet and MT impedance) for September 2017 storm

-> good fit for TS, better for MT

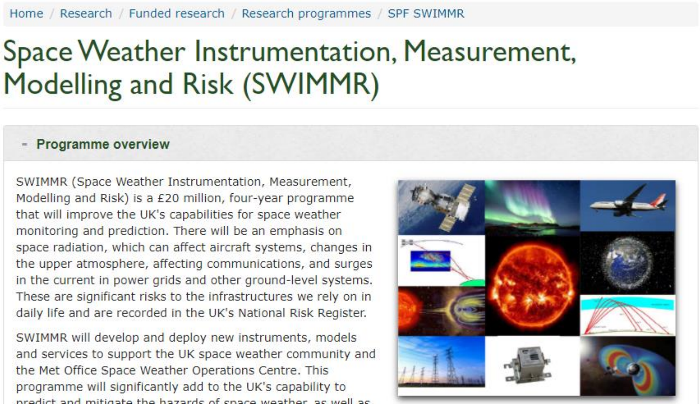
	Corr obs/TS	Corr obs/MT
LER(N-S)	0.58	0.91
LER(E-W)	0.32	0.92
ESK(N-S)	0.59	0.97
ESK(E-W)	0.66	0.95
HAD(N-S)	0.44	0.88
HAD(E-W)	0.46	0.94



Beggan et al., *under review*

To update conductivity model and GEF computation

-> collect more MT data!
Funded under SWIMMR

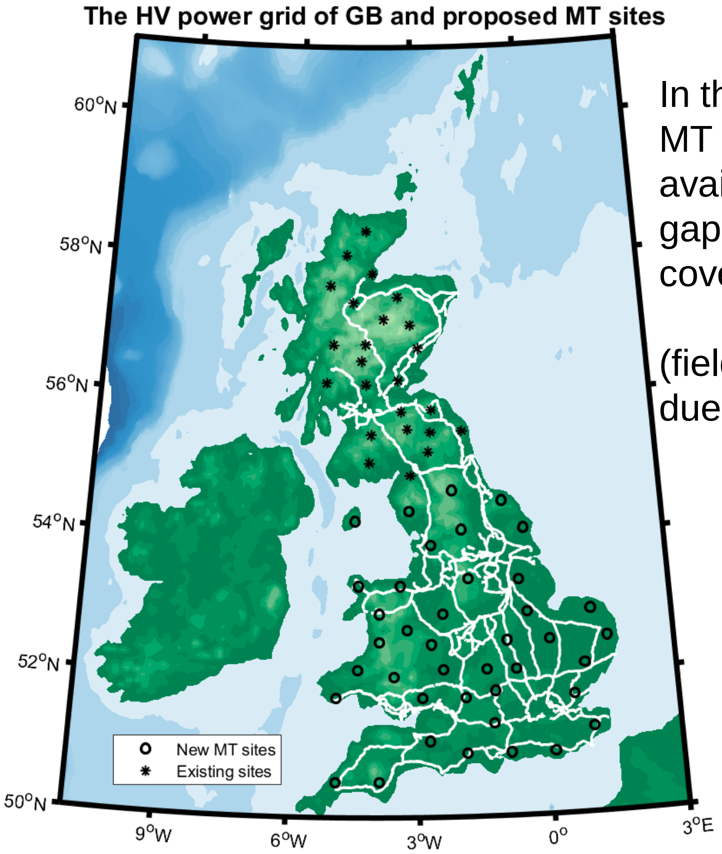

Home / Research / Funded research / Research programmes / SPF SWIMMR

Space Weather Instrumentation, Measurement, Modelling and Risk (SWIMMR)

- Programme overview

SWIMMR (Space Weather Instrumentation, Measurement, Modelling and Risk) is a £20 million, four-year programme that will improve the UK's capabilities for space weather monitoring and prediction. There will be an emphasis on space radiation, which can affect aircraft systems, changes in the upper atmosphere, affecting communications, and surges in the current in power grids and other ground-level systems. These are significant risks to the infrastructures we rely on in daily life and are recorded in the UK's National Risk Register.

SWIMMR will develop and deploy new instruments, models and services to support the UK space weather community and the Met Office Space Weather Operations Centre. This programme will significantly add to the UK's capability to



In the UK: Some new MT and legacy data available -> need to fill gaps for countrywide coverage

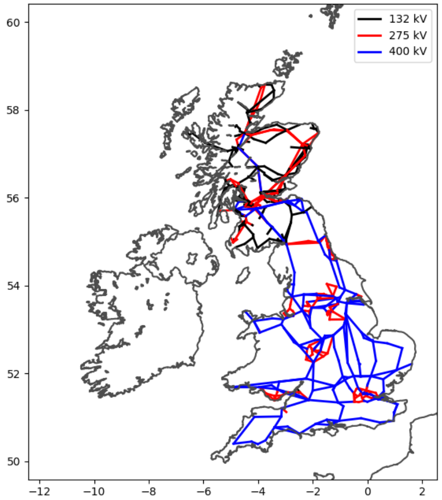
(field work postponed due to pandemic)

III Monitoring and modelling ground effects:

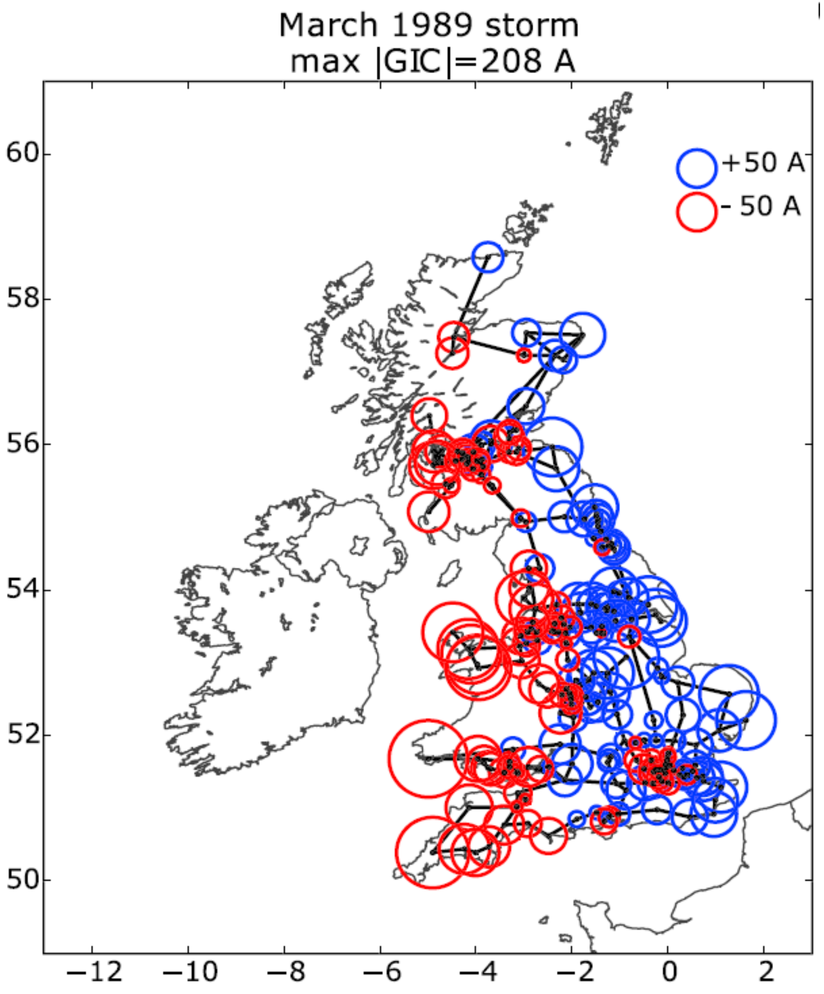
GICs in power lines and pipe-to-soil potentials

GIC modelling in the UK

- Only public domain data availble about topology (ETYS)
- 1501 total nodes (446 earthed nodes/substations)
- 1706 connections (1183 lines including parallel) (reduces to 784 when parallel lines combined)
- Shapefile to include true position of line segments



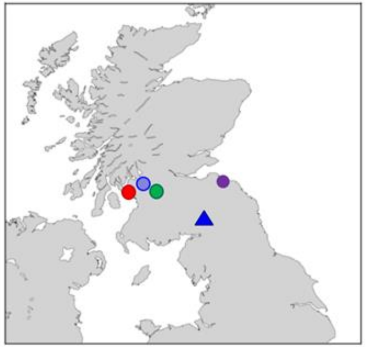
Kelly et al. (2017): GIC in the UK grid during the March 1989 storm

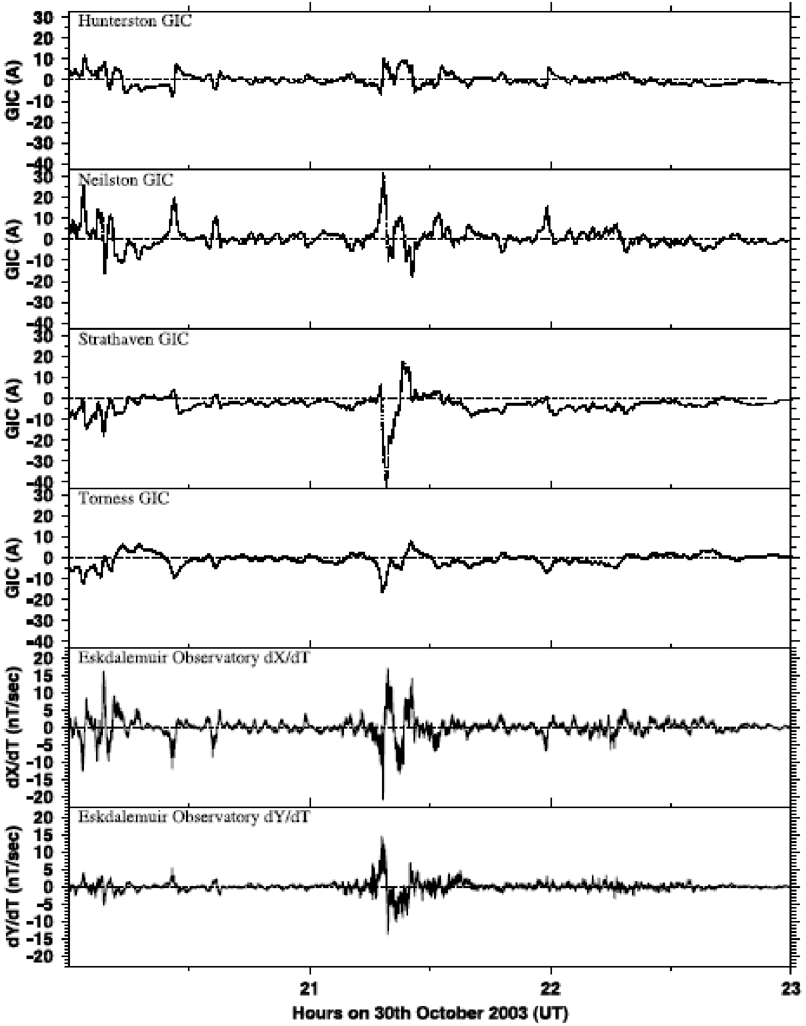


GIC measurements: Hall effect probe

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

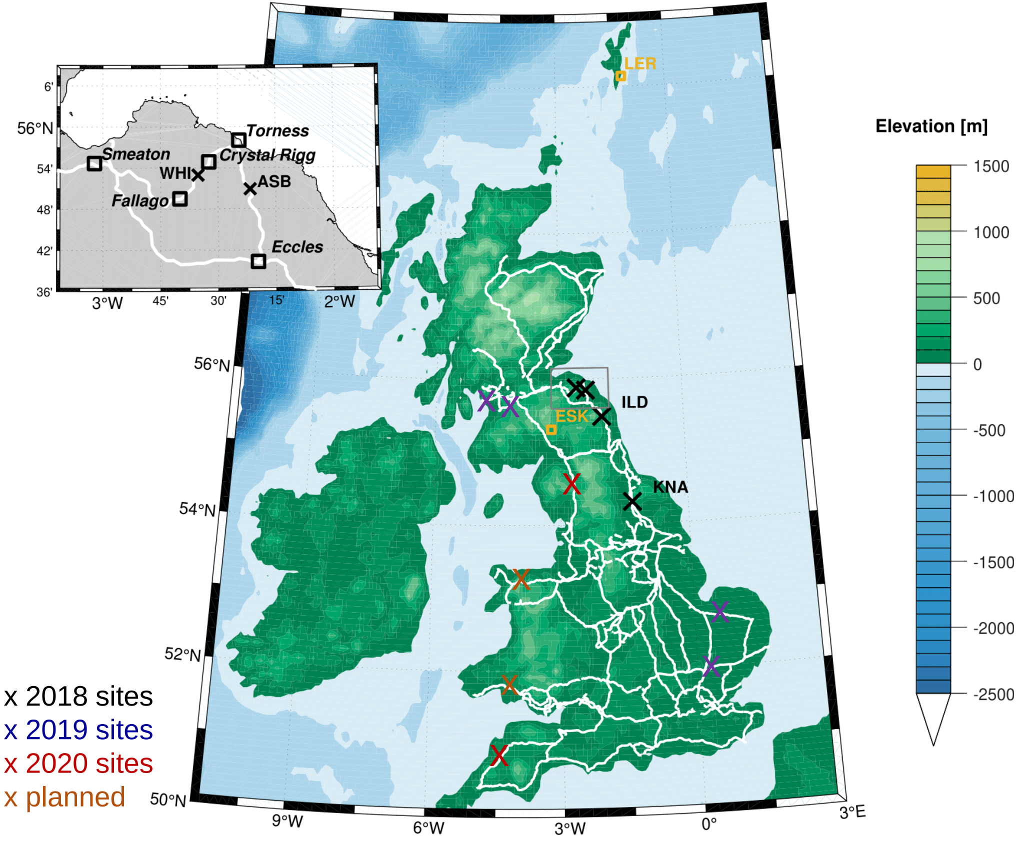
-> need to expand data set



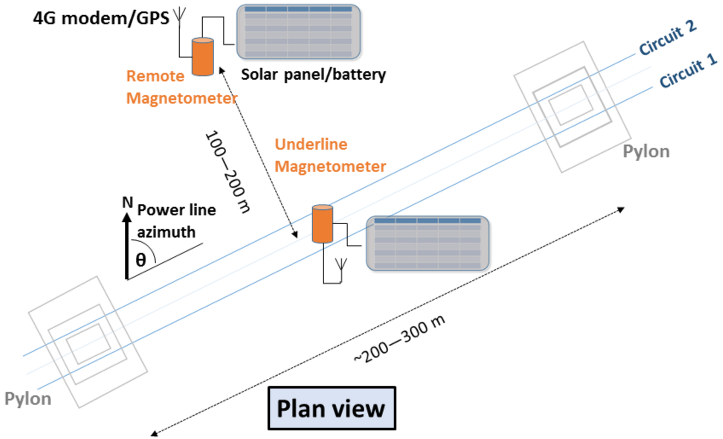


Right: Thomson et al. (2005) Measured GIC and field rates of change at Eskdalemuir for 30 October 2003.

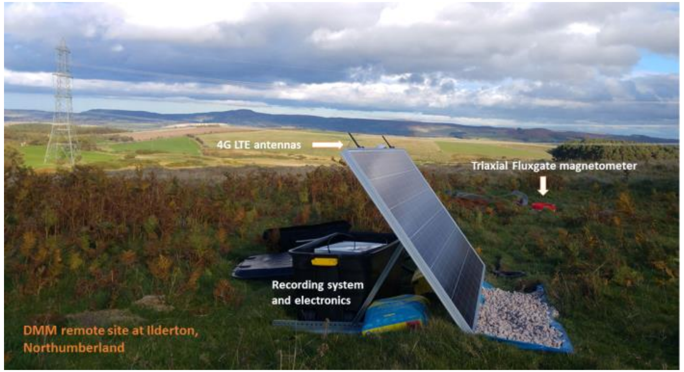
DMM field installation in the UK



x 2018 sites
x 2019 sites
x 2020 sites
x planned



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

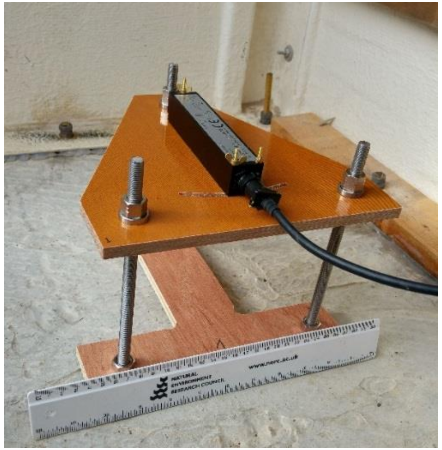


BGS

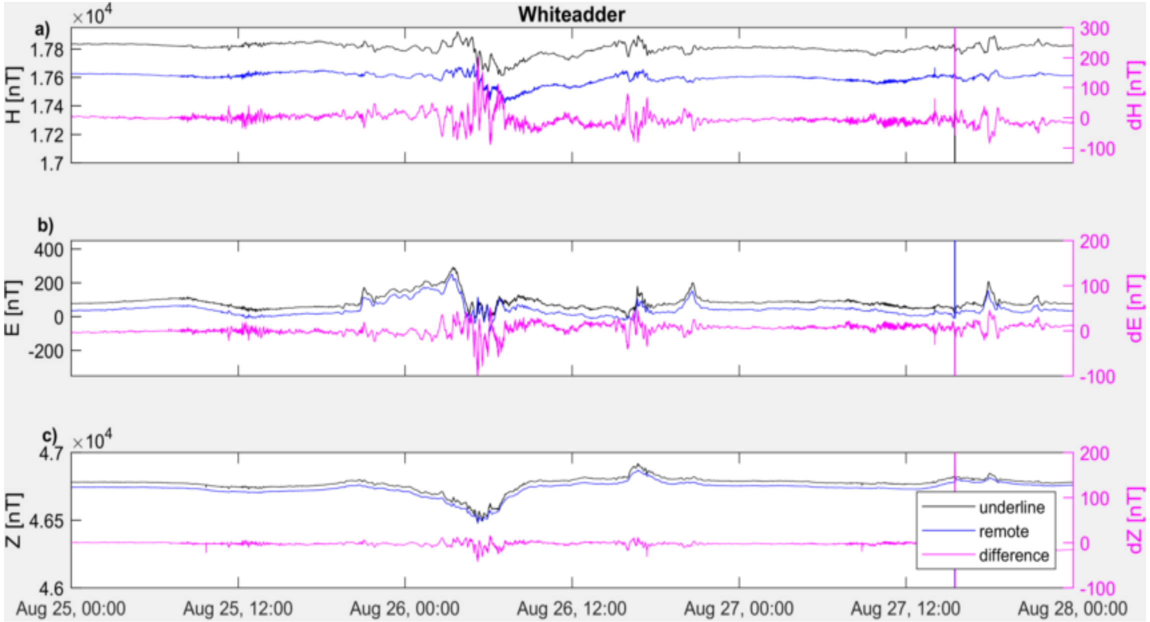
DMM Hard ware components

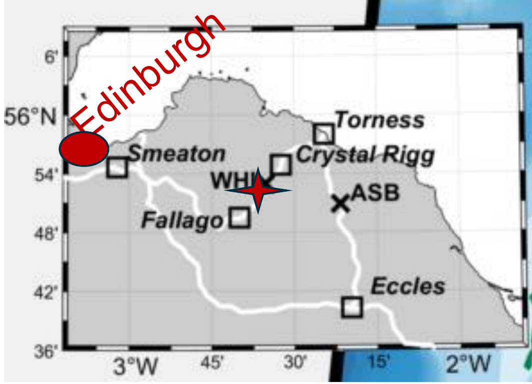
- *Sensys* 3-axis fluxgate magnetometer
- Kenda *EarthData* 24bit Digitiser
- Calibrated system on absolute pillar in Eskdalemuir observatory
- Solar panel/battery
- 3/4G mobile network modem

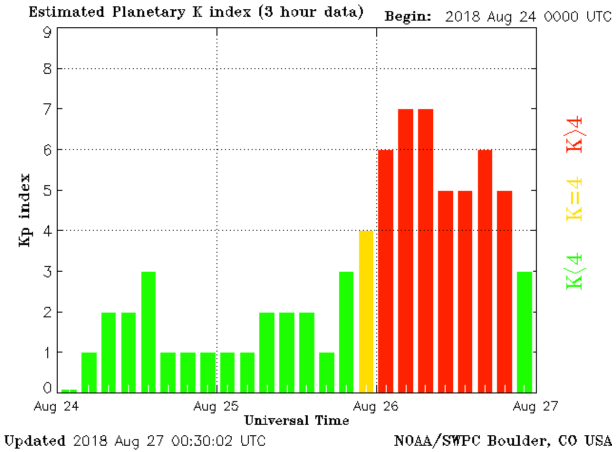
- 1-second sampling
- Real-time data return to data entre in Edinburgh via seedlink protocol
- <1 nT accuracy over 30 minutes
- Buried for temperature stability and protection



G3 Storm on 26 August 2018 DMM first data



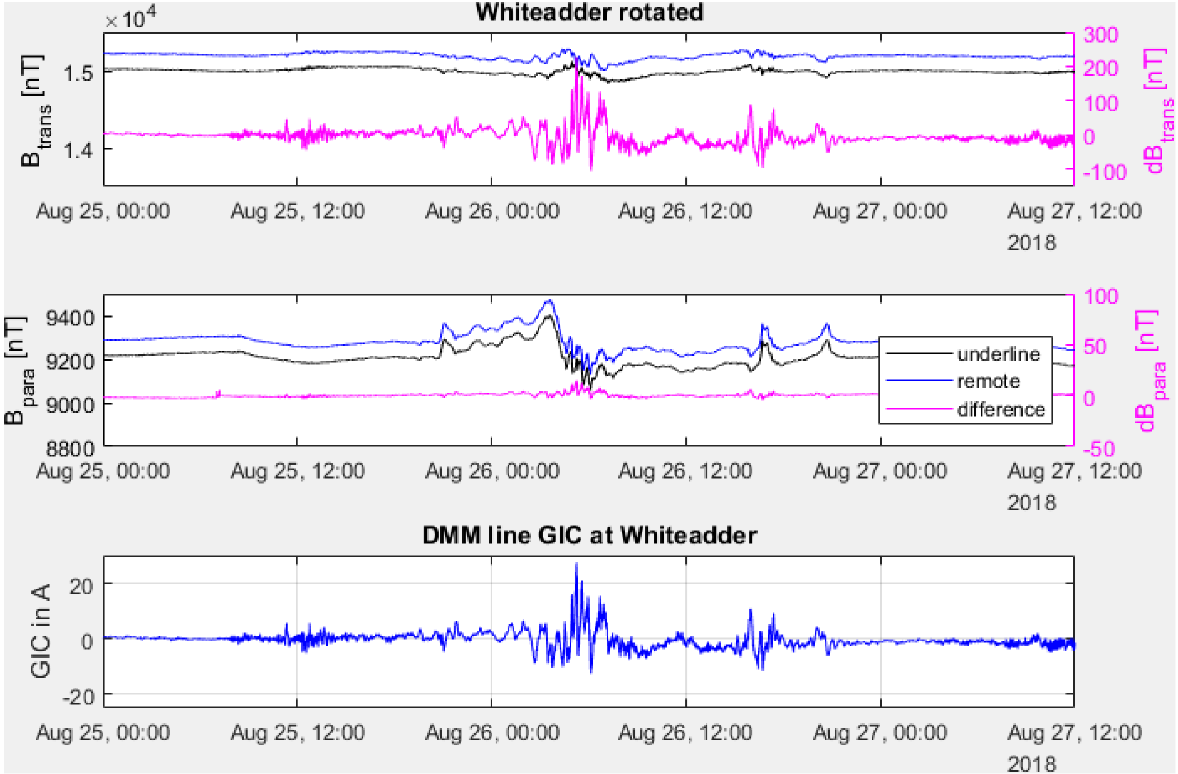


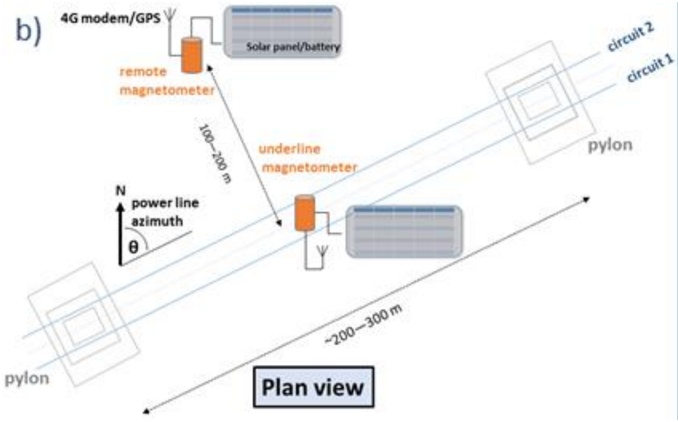


Measured magnetic field components at underline and remote systems and the difference between them. Max. difference in fields ~225nT.

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

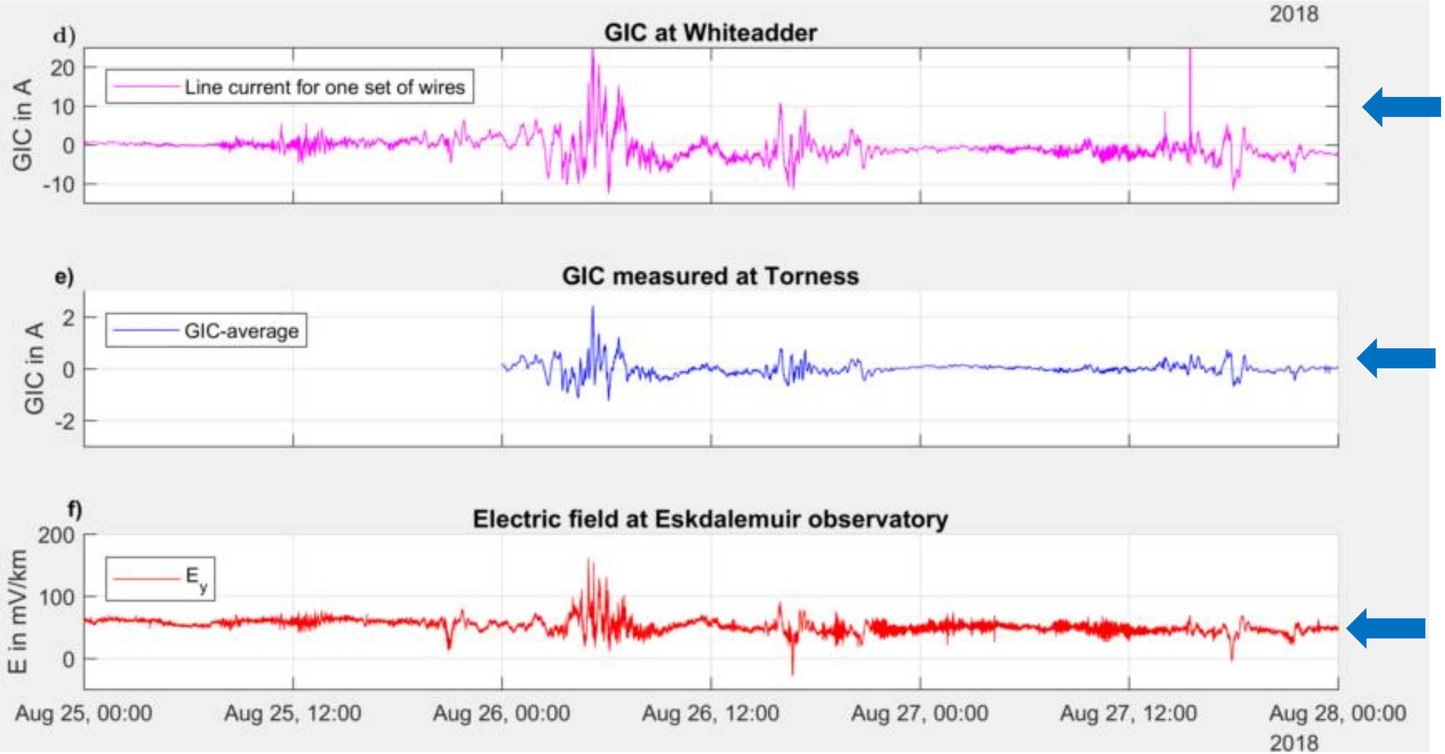
Storm 26 August 2018 – Line GIC measured at station WHI (East Scotland)





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).

G3 Storm on 26 August 2018 – Line GIC comparison to Hall probe data



Line GIC measured with DMM

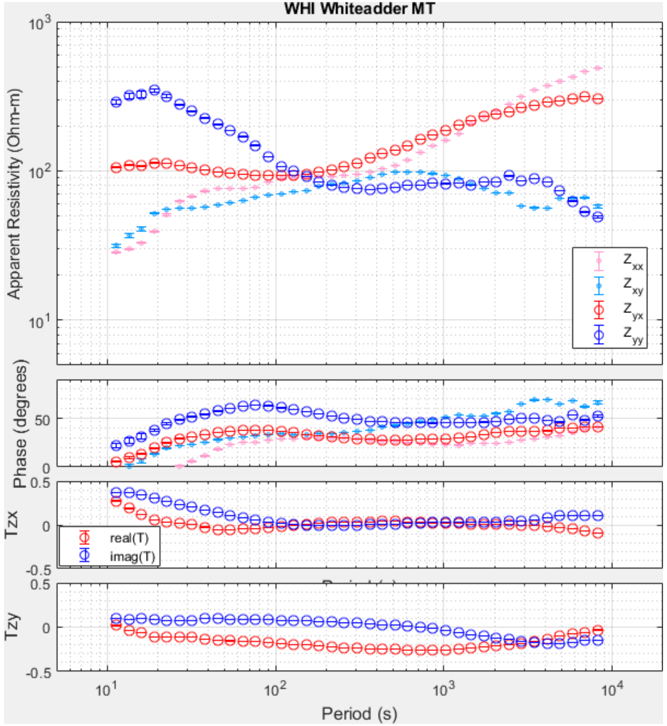
Hall probe data at nearby substation (provided by Scottish Power Ltd)

E-field data from Eskdalemuir observatory

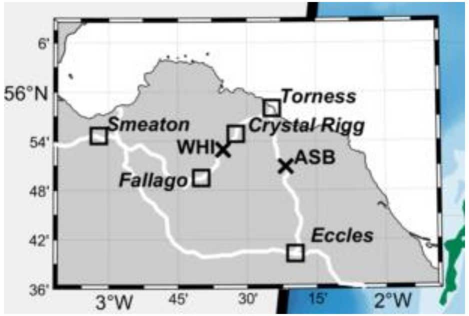
Proof of concept in *Hübert et al. (2020)*

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



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



Thanks to DIAS for instrument loan

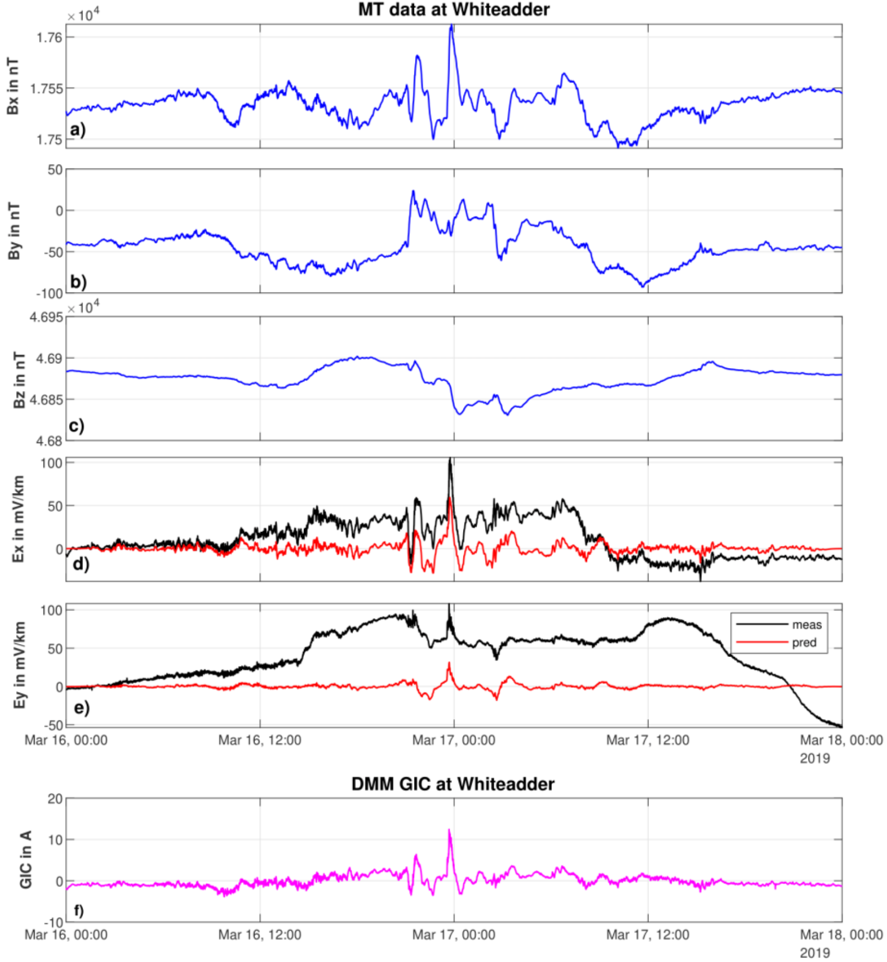
Institiúid Ard-Léinn Bhaile Átha Cliath | Dublin Institute for Advanced Studies

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)

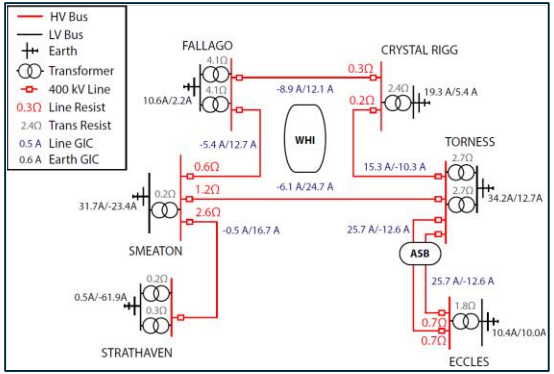
d-e) Computed electric field using MT impedance, capturing most of the variation, but not long-term trends/drift

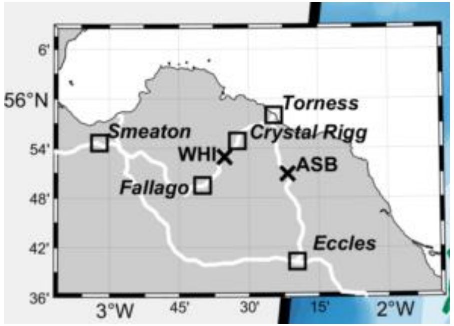
f) and line GIC at WHI station



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

Storm 26 August 2018 using MT impedance derived electric field and detailed subgrid

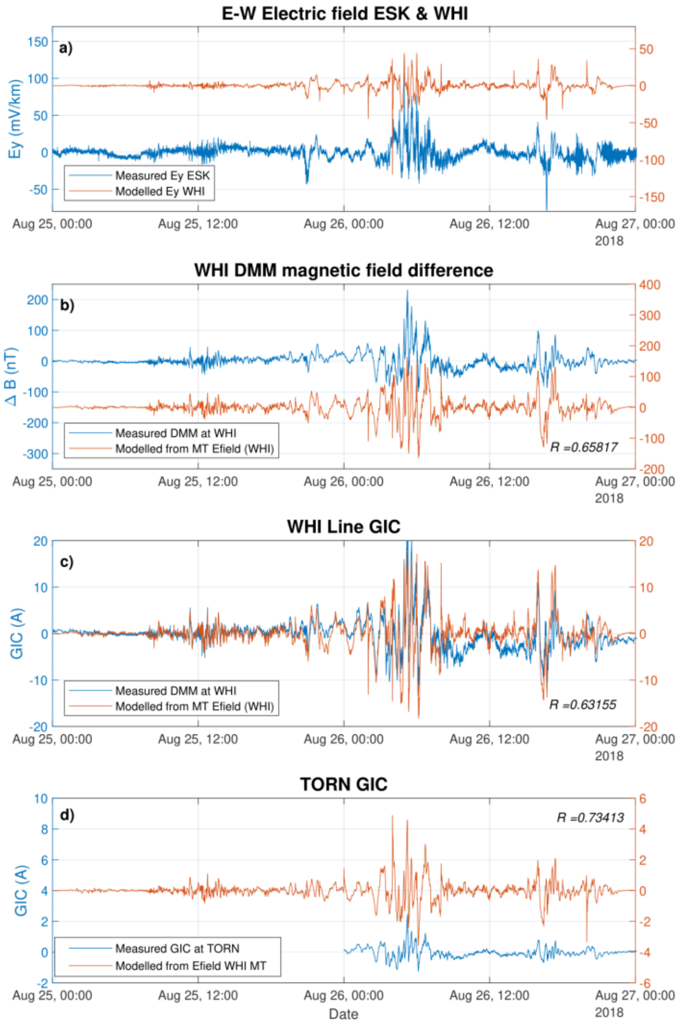


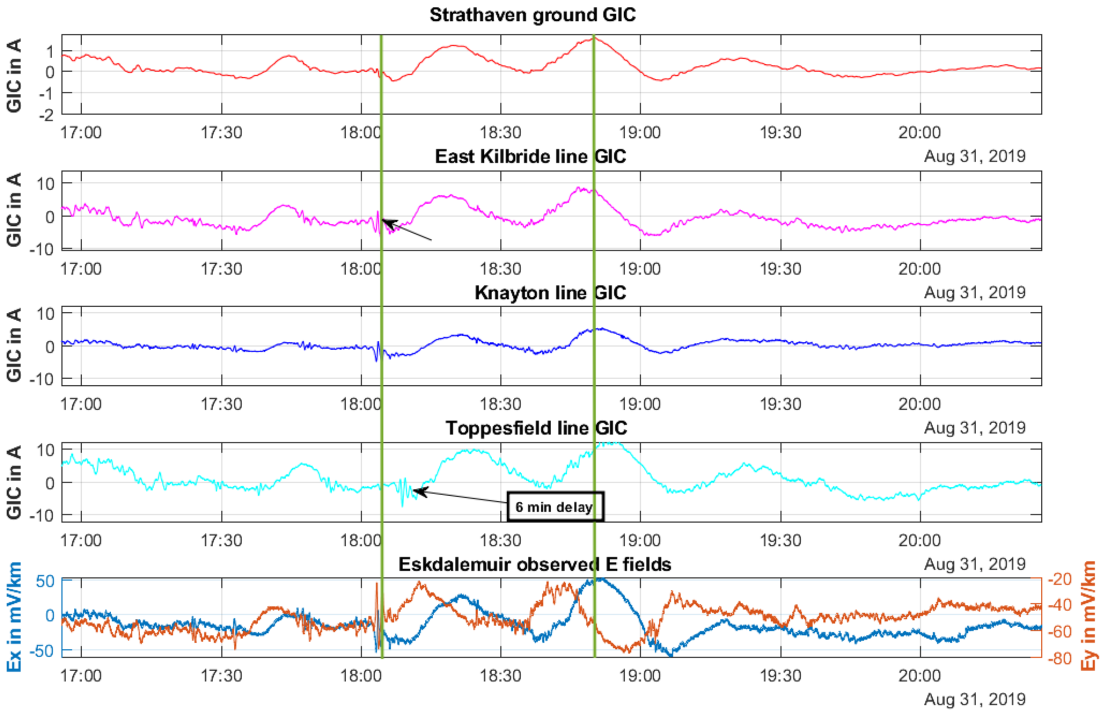


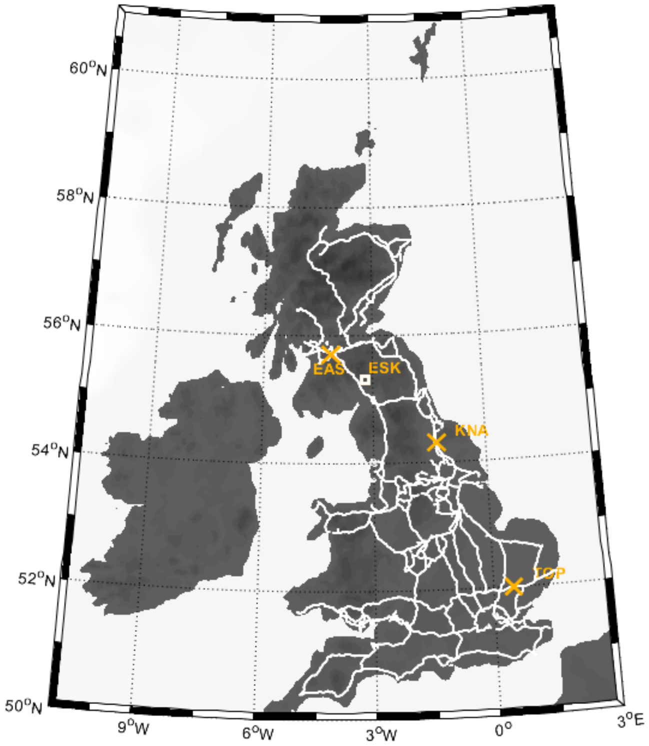
Schematics after Horton (2012) of HV power grid in East Scotland with location of substations

-> repeat for all DMM sites

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.







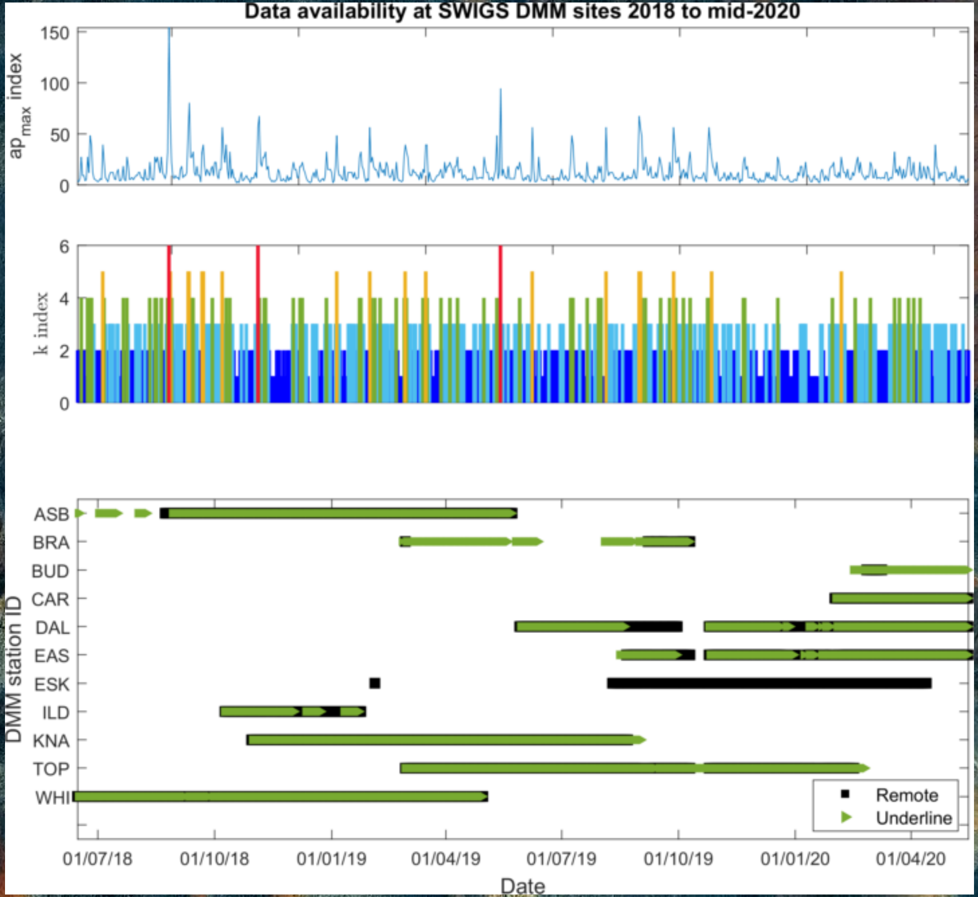
DMM, electric field and ground GIC observations for 31 August 2019, G2 storm – observed time delay across the network

Several of the DMM site data have been deposited in the National Geoscience Data Centre (NGDC)

Magnetic time series for Differential Magnetometer site Whiteadder Moor (WHI). https://www.bgs.ac.uk/services/ngdc/accessions/index.html#item134025

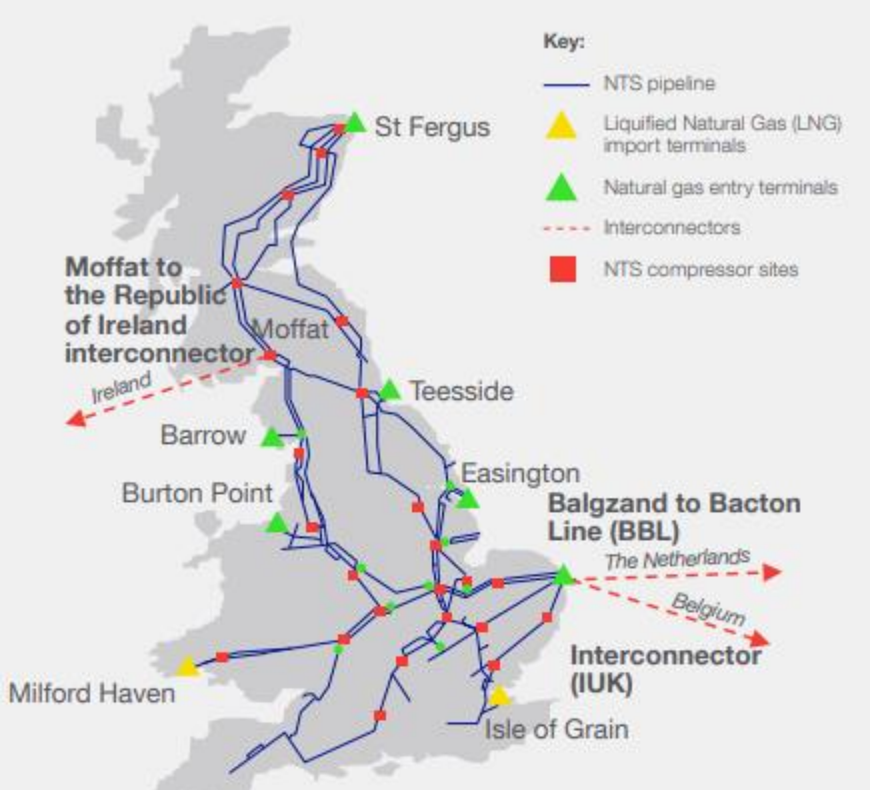
Magnetic time series for Differential Magnetometer site Abbey St.Bathans (ASB). https://www.bgs.ac.uk/services/ngdc/accessions/index.html#item133965

Rest to come



British pipeline network

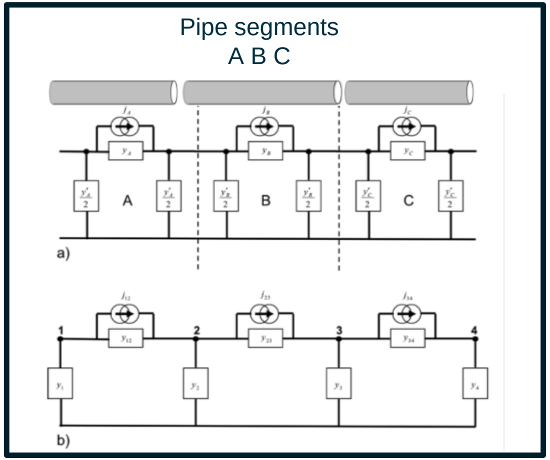
- The national transmission system in mainland Great Britain has ~7660km of pipelines
- Most of the network built between 1960 and 1990
- Typical design life ~40 years so much of network beyond original life expectancy by 2021
- Cathodic protection of at least 0.85mV is used to control galvanic current and reduce corrosion
- Induced electric fields cause differences in potential between the pipeline and surrounding soil which can override this galvanic protection
- Damage is not thought to be instantaneous but results from the cumulative action of many disturbances



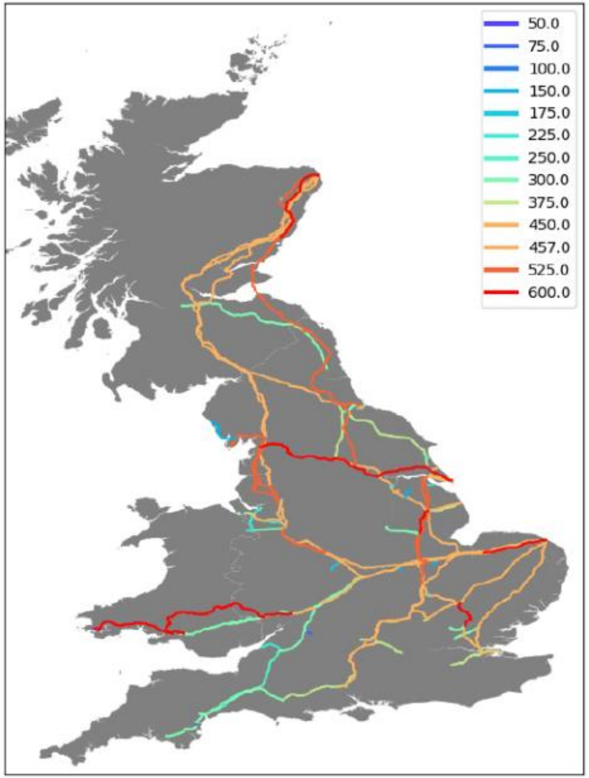
Richardson & Thomson, in prep.

Construction of the model

- Shapefiles describing the network are available on the National Grid website
- These contain:
  - An ID for each section of line
  - Outer pipe diameter
  - Geometry of each section
- However we also need:
  - Pipe resistivity – assume 0.18 10^{-3} Ωm
  - Coating Conductance – assume 5 10^{-6} Sm^{-2}
  - Pipe wall thickness – set at 5% of outer radius



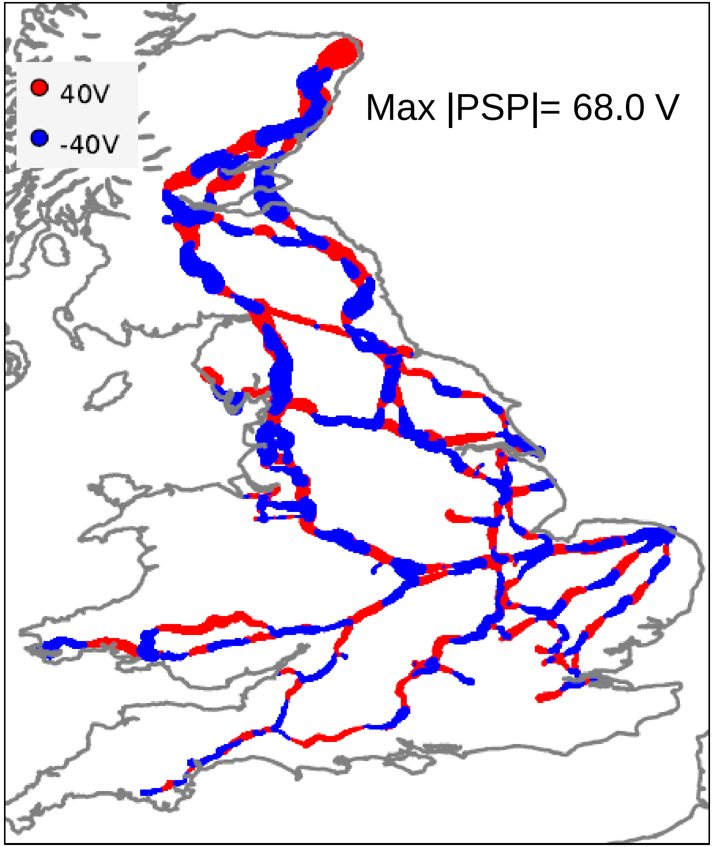
Pipeline model after Boteler et al. (2013)



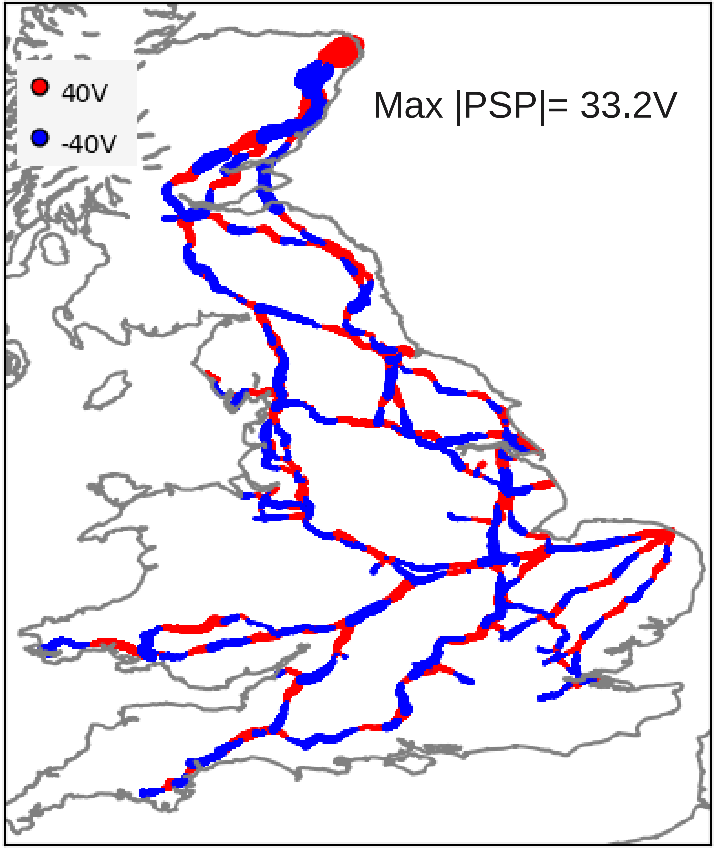
Colours are pipe diameter in mm

Modelled PSPs

MARCH 1989 STORM

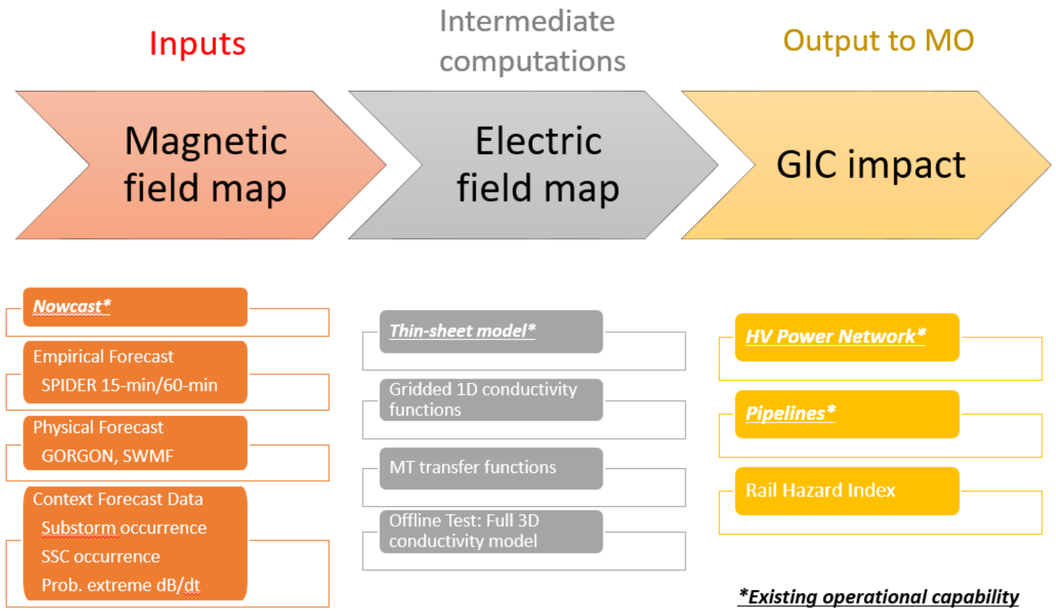


SEPTEMBER 2017 STORM



SWIMMR- Activities in ground effects (SAGE) Nowcasting+Forecasting of GICs/PSP

- Bringing it all together to provide forecast service to industry stakeholders (UK MetOffice)



Some conclusions

- Extreme Space Weather events are hazardous to modern infrastructure like HV powerlines, gas pipeline and railway communications through the coupling of the solar wind with the Earth's magnetic field, which gives rise to induced currents in the ground

- Space Weather research draws from many different areas of science and engineering – new possibilities for collaboration, but also challenges, especially for communication

- To model these impacts detailed knowledge of the magnetic field, the electric field and the infrastructure topology are needed

- Estimating realistic ground electric fields depends on good MT data

BGS

Rosemary Oakeshott - *Gas pipeline internment* CC BY-SA 2.0

British Geological Survey

THANK YOU

Thanks to the BGS Geomagnetism team and SWIGS/SAGE collaborateurs

Smeaton substation, Edinburgh

DMM site, North Ayrshire with views towards Aran