Space weather impacts on the UK railway network

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Abstract

Some of the many manifestations of space weather's effects on ground-based infrastructure are hazards that affect the smooth and safe operation of railway networks, with the potential of signalling system failures, damage to locomotive on-board transformers and disruptions caused by interference to a plethora of interdependent systems such as radio, GPS and grid power supply.

This work focuses on the impacts on track circuits, signalling systems that use electrical currents to detect the presence or absence of a train in sections of a wider network, as such, they are affected by geomagnetically induced currents (GICs) arising from space weather.

The impact on track circuits of various designs has been investigated during the 2015 St. Patrick's Day storm, the first storm of solar cycle 24 to reach a level of "Severe" on the NOAA geomagnetic storm scale. This has been achieved by using the Spherical Elementary Current System (SECS) method of geomagnetic field interpolation, a conductivity model of the UK, estimations of the geoelectric field and track circuit modelling techniques developed by *Boteler (2021)*.

Geoelectric field estimations

Magnetic field interpolation using SECS

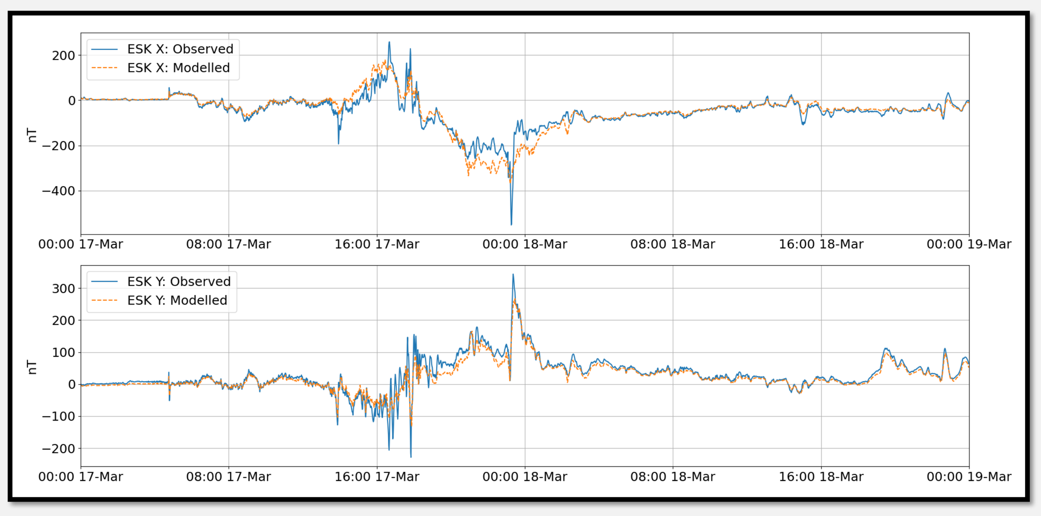

Fig 1. Comparison of observed and interpolated magnetic field variations at the location of Eskdalemuir (ESK) geomagnetic observatory for north (X) and east (Y) components.

As the UK railway network is widespread, many routes are distant from magnetometer sites, therefore, a method of interpolating the magnetic field is needed to determine the impact on individual track circuits.

The SECS method uses a network of magnetometers to simulate magnetospheric current elements, these elements can then be used to determine the magnetic field variations at any location within the confines of the network.

Figure 1 shows an SECS validation technique where one station is removed from the network and set as the point to be determined, the interpolated results are them compared with the observed data from the removed station.

Electric field estimations using ground conductivity and a 1D model

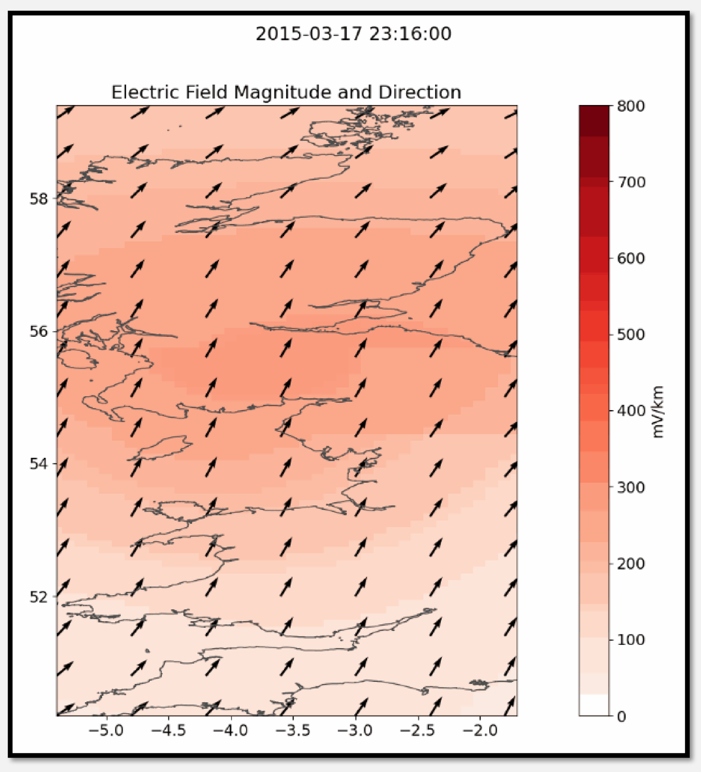

Fig 2. Estimated geoelectric field across a section of the United Kingdom during the 2015 St. Patrick's Day storm.

Using the ground conductivity data from *Ádám (2012)*, a magnetotelluric forward modelling solution is conducted over a homogeneous 1D layered earth with n layers.

Repeating this method for a range of frequencies, we can obtain an array of apparent resistivities, the interpolated magnetic field values can be combined with these values to estimate the electric field in the frequency domain. With the application of the fast Fourier transform (FFT), the estimation of the E-field in the time domain can be obtained.

Track circuit principles

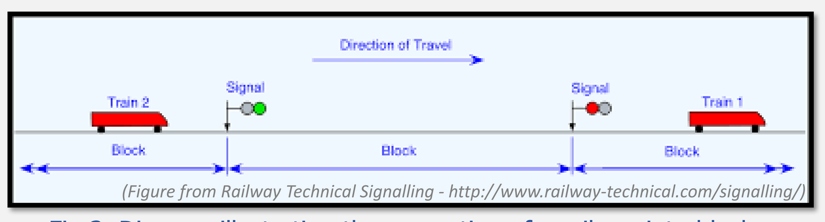

Fig 3. Diagram illustrating the separation of a railway into blocks, each controlled by one or more signalling systems.

In the case of track circuits, insulating rail joints (IRJs) separate railways into individual blocks, each one comprising of an electrical circuit containing a power source and a relay to detect changes in the current. With no train present, the relay is energised by the power source and a green (clear) signal is displayed; when a train enters a block, the wheels and axles short circuit the relay, with the current no longer flowing through it, the relay is de-energised and a red (stop) signal is displayed.

As these rails are conductors, the geoelectric fields generated by space weather cause electric currents to flow through them, these geomagnetically induced currents (GICs) can confuse the track circuit relays into displaying false signals, as the currents can energise and de-energise the relays.

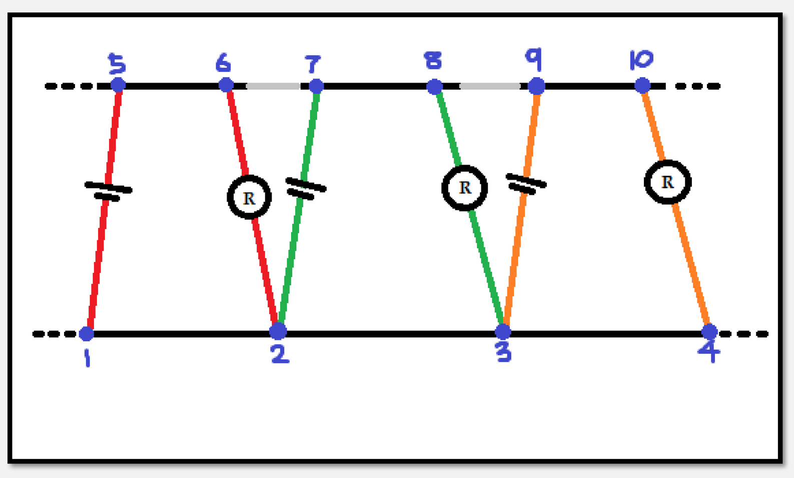

Fig 4. Diagram illustrating the track circuit blocks in an electrified railway, showing the continuous rail carrying the return current.

As track circuits on non-electrified railways are symmetrical, equal currents are induced in both rails, cancelling out the effect on the relay, hence this interference only occurs on electrified railways where a single continuous rail is needed to return the currents that power the locomotive to the power grid.

Figure 4 shows the top rail being interrupted by IRJs (shown in grey), splitting the section into three separate track circuits, whereas the bottom rail is the continuous.

Modelling a section of railway

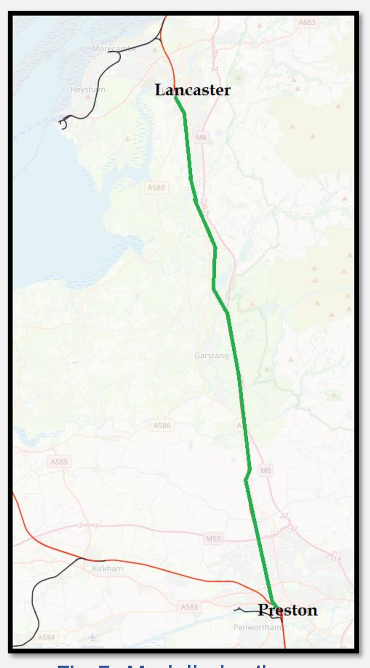

Fig 5. Modelled railway section between Preston and Lancaster (shown in green).

The track circuit modelling techniques used in this work were developed by *Boteler (2021)*.

The section of railway chosen for this initial modelling test is a section of the West Coast Mainline (WCML) between Preston and Lancaster, while specific data on this region is being obtained, simplifications will be used, as detailed below:

- Electrical characteristics of the rail and track circuit components are based on values given in *Boteler (2021)* and sources therein.
- The railway line is considered to be a straight line orientated 12° counter clockwise from North.
- The 35km section of railway is considered isolated from prior and subsequent sections, it is split into 35 track circuit blocks each 1km in length.
- The geoelectric field is assumed to be constant over the length of the railway.

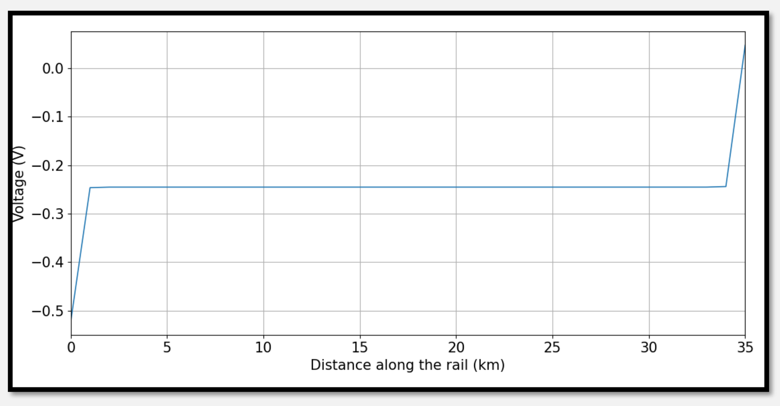

Fig 6. Voltage profile along the continuous rail in a section of an electrified railway network containing 35 track circuit blocks each 1km in length.

In this example, each track circuit has identical length and components, this means that GICs will have the same effects on each track circuit in the network, with the exception of the first and last. As such, a single track circuit in the centre will be chosen to determine the effects over each block in the network.

Figure 6 shows the voltage profile along the continuous rail, as stated above, excluding the first and last blocks, the voltage at each 1km node along the rail is equal.

Results from the railway model

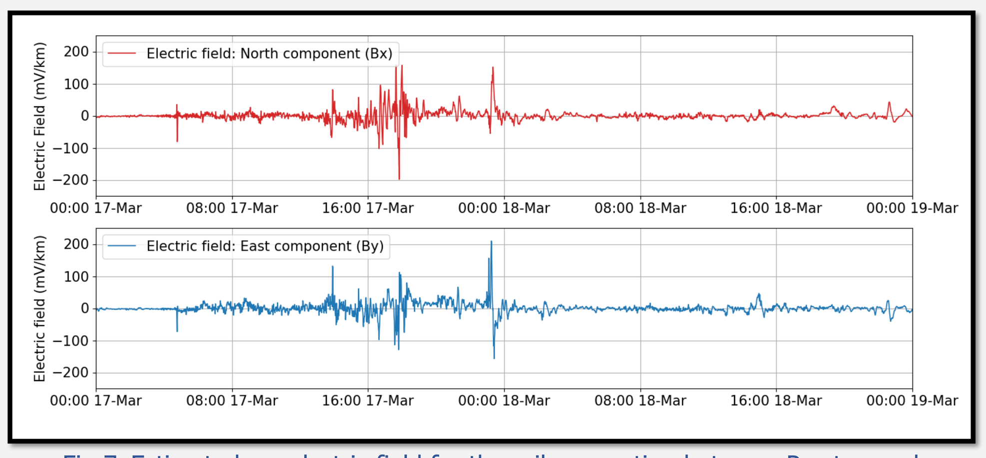

Fig 7. Estimated geoelectric field for the railway section between Preston and Lancaster during the 2015 St. Patrick's Day storm.

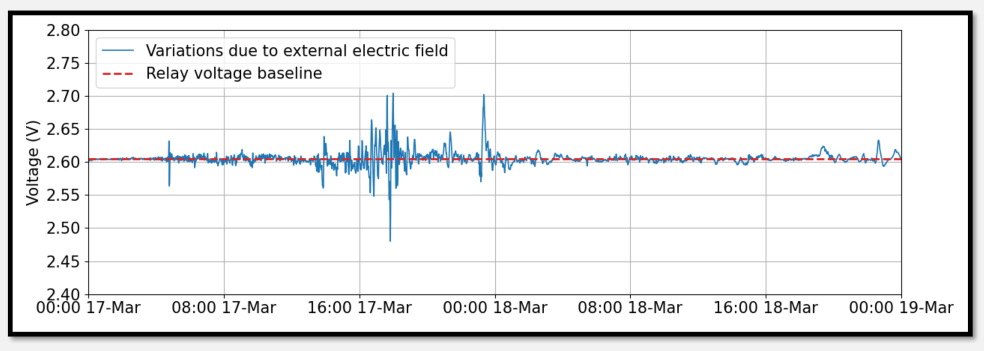

Fig 8. Deviation in the voltage across a track circuit relay from the baseline operating voltage due to an external geoelectric field caused by space weather.

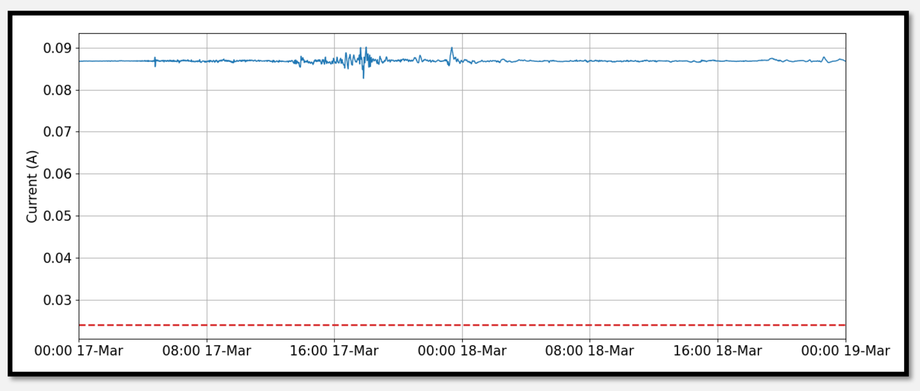

Fig 9a. Deviation in the voltage across a track circuit relay from the baseline operating voltage due to an external geoelectric field caused by space weather.

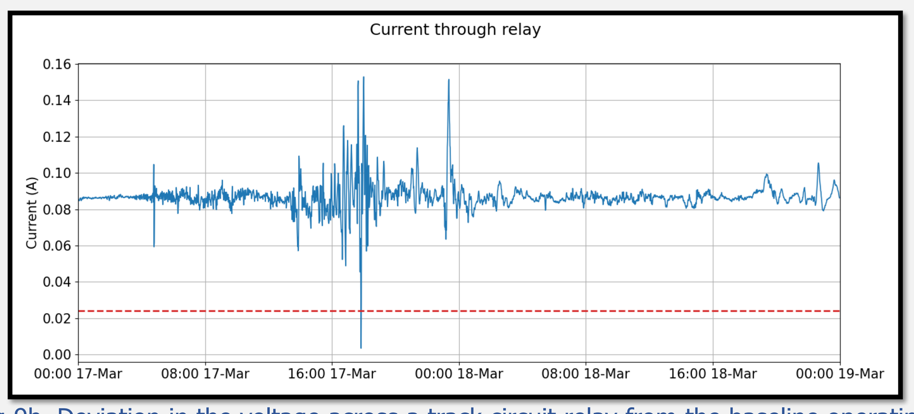

Fig 9b. Deviation in the voltage across a track circuit relay from the baseline operating voltage if the external geoelectric field from Figure 9a was 20 times stronger.

Following the steps detailed in the previous sections, the geoelectric field at the location of railway is estimated, this is shown in Figure 7.

The geoelectric field is then applied to the network model to determine the effects on individual track circuits within the railway section.

As shown in Figure 8, without any outside interference, the normal operating voltage (baseline) across the track circuit relay is 2.61V; during the course of the storm, the GICs induced in the track circuit cause the voltage across the relay to fluctuate, deviating a maximum of 0.1V from the baseline at its most intense period.

For the track circuit parameters used in this example, the current across the relay needs to drop below 0.024A for the relay to be de-energised, this is designed to only occur when a train is present and the wheels and axles short circuit the relay. As shown in Figure 9a, the geoelectric field caused by space weather during the 2015 St. Patrick's Day storm is not sufficient enough to affect the normal operations of a track circuit of this design in a location between Preston and Lancaster.

Figure 9b shows that if the geoelectric field was 20 times stronger, GICs would be sufficiently strong to cause an empty track circuit block to display a red (stop) signal.

Further Work

The strength of the current through the relay and the susceptibility of the relay to the effects of GICs are dependent on many factors including: the strength of the geoelectric field, which varies widely across the geological terrains of the UK; the electrical characteristics of the rail, dependent on the profile and resistivity of the steel; the components of the track circuit, such as relay internal resistors and power supply.

In future iterations of the model, these effects will be investigated further, with region specific data being used to determine the impacts on track circuits in those locations. The investigation will also be expanded to include other regions of the UK with different ground conductivity and under various space weather scenarios.