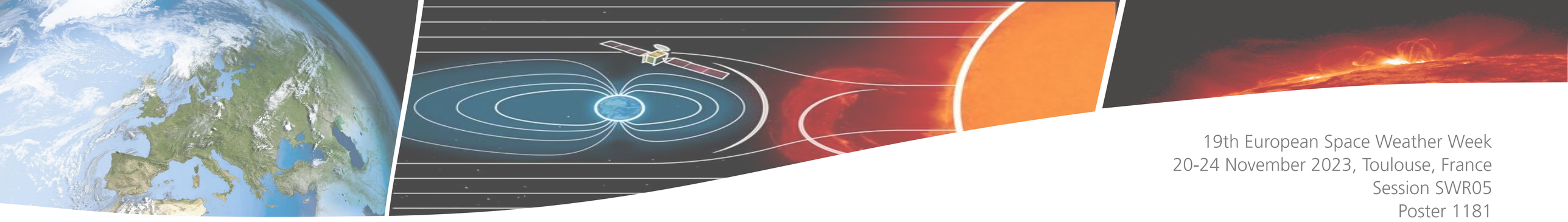

19th European Space Weather Week
20-24 November 2023, Toulouse, France
Session SWR05
Poster 1181

# Influence of ground conductivity models on GIC hazard estimation in Germany

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## ① Introduction

The hazard posed by Geomagnetically Induced Currents (GICs) to the regular operation of grounded infrastructure originates from the induced geoelectric field (GEF) under geomagnetically disturbed conditions. Here, we calculate GEF maps for Germany during 5 geomagnetic storms using three different conductivity models and evaluate their local agreement with independent electric field records, their differences across the country, and their role in driving GICs at selected substations.

Section ② provides the storm characteristics and illustrates the production of geomagnetic disturbance maps, which are ensured to reproduce the independent magnetic field records from the permanent magnetotelluric (MT) reference station in Wittstock.

Section ③ introduces the conductivity models and outlines their usage in the adopted GEF calculation scheme.

Section ④ shows the comparison of modeled and measured GEFs at Wittstock while section ⑤ explores the differences in modeled GEFs across Germany.

Section ⑥ adds calculated GIC time series driven by the modeled GEFs at a selected substation in the northwestern section of the German high-voltage transmission grid.

## ② Geomagnetic field

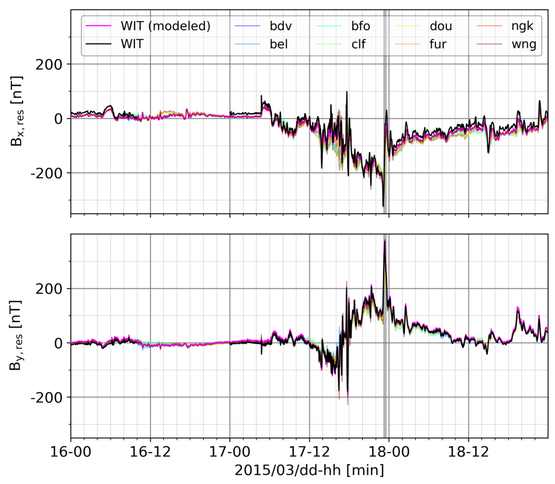
We obtain 1-min horizontal geomagnetic field observations from ≤11 INTERMAGNET stations in and around Germany (bdv,bel,bfe,bfo,clf,dou,fur,mab,ngk,wic,wng) for five 3-day geomagnetic storm intervals (Tab. 1) and apply the following processing steps:

1. Baseline removal [1] to isolate fast (<4h) variations (Fig. 1)
2. SECS fit [2] to produce disturbance map (Fig. 2)

| # | Center date (12pm) | Max Kp | # Obs. | DE Rank‡ | Max $\lvert B_X \rvert$ [nT] | Max $\lvert B_Y \rvert$ [nT] | Max $\lvert dB_X/dt \rvert$ [nT/min] | Max $\lvert dB_Y/dt \rvert$ [nT/min] |
|---|---|---|---|---|---|---|---|---|
| 1 | 2012-03-15 | 6+ | 9 | 56 | 109 | 127 | 31.7 | 21.0 |
| 2 | 2013-10-02 | 8- | 7◊ | 37 | 124 | 148 | 34.7 | 42.5 |
| 3 | 2015-03-17 | 8- | 8 | 14 | 328 | 342* | 40.9 | **95.6** |
| 4 | 2017-09-08 | 8+ | 10 | 33 | 203 | 259 | 61.7 | 75.2 |
| 5 | 2021-05-12 | 7 | 9 | 62 | 122 | 104* | 38.3 | 19.5 |

**Tab. 1: Geom storm overview** Characteristics of selected geomagnetic storms based on INTERMAGNET observatory data.

‡ Rank in sorted list of max. |dB/dt| averaged over ≥3 German obs. for each day since 2000
◊ No data at BFO
* At NGK (all other at WNG)



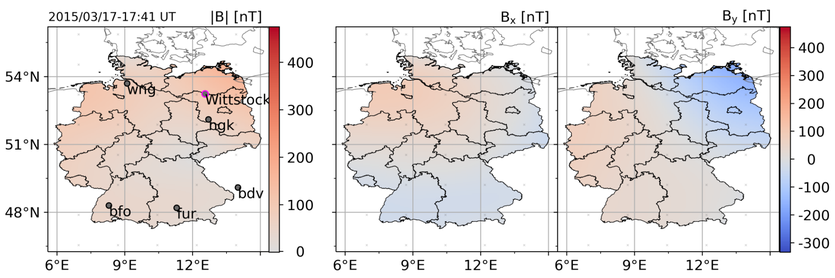




**Fig. 1 (above): St. Patrick's Day storm at Wittstock** Northward (X, top) and eastward (Y, bottom) geomagnetic disturbance from Wittstock MT station (black, see location in Fig. 1) [3] compared to modeled disturbance (magenta) based on INTERMAGNET records from 8 different locations (colored, lowercase).

**Fig. 2 (left): SECS-based disturbance map** Snapshot of modeled absolute (left) and vector magnetic disturbance (right) at time of max. $\lvert dB_Y/dt \rvert$ during St. Patrick's Day storm (see Fig. 1 gray vertical line).

## ③ Conductivity models

The induced electric field is calculated in frequency space (0.1-8.3mHz) under the plane-wave assumption,

$$\vec{E}(\omega) = \frac{\underline{Z}(\omega)}{\mu_0} \vec{B}(\omega) \text{ [V/m]},$$

where $\vec{B}$ is taken to be the magnetic disturbance field (see Fig. 2) and $\underline{Z}$ is the impedance tensor [Ω], calculated from three different conductivity models (Tab. 2, Fig. 3).

| # | Name | Horizontal resolution | Dim | Max. depth [km] | Components | Impedance calculation |
|---|---|---|---|---|---|---|
| 1 | EuRhoM [5] | irregular 100s km | 1 | ≤202 | Divers | 1D [4] |
| 2 | Global Conductivity [6] | 1°x1° | 3 | 100 | Ocean, sediments, crust, top of mantle | 1D [4] |
| 3 | EuSigma (A. Grayver, under develop.) | irregular ~0.025° | 3(+1) | ≤15 (~1800) | Ocean + sediments [7], land sediments [8], crust (100 Ωm), mantle (1D) | 3D Cartesian induction solver [9] |

**Tab. 2: Conductivity models** Overview of conductivity model specifications and impedance extraction methods.

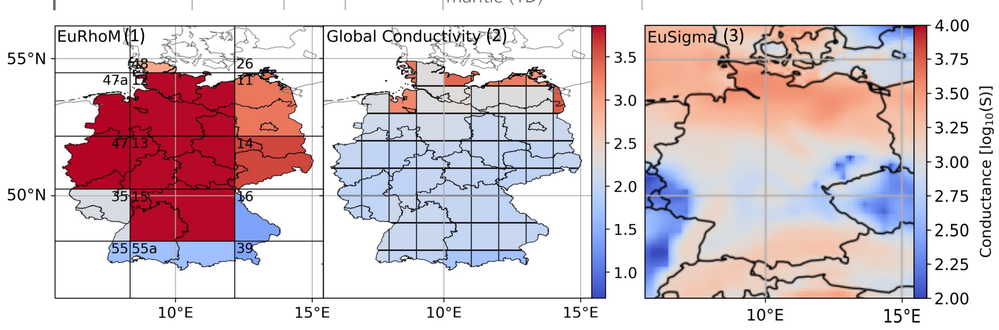



**Fig. 3: Surface conductance maps** Surface conductance (depth-integrated conductivity) from three different conductivity models covering Germany (see Tab. 2).

## ④ Electric field at Wittstock

| # | $MAE_X$ [mV/km] 1 | 2 | 3 | $MAE_Y$ [mV/km] 1 | 2 | 3 |
|---|---|---|---|---|---|---|
| 1 | 0.8 | 2.5 | 0.4 | 0.5 | 1.8 | 0.3 |
| 2 | 0.7 | 1.9 | 0.4 | 0.4 | 1.5 | 0.3 |
| 3 | 2.0 | 5.9 | **1.0** | 1.1 | 3.7 | **0.8** |
| 4 | 1.4 | 3.9 | 0.7 | 1.0 | 3.3 | 0.7 |
| 5 | 0.5 | 1.2 | 0.3 | 0.7 | 1.7 | 0.6 |

**Tab. 3: GEF model errors** Mean absolute Error (MAE) between modeled GEFs and electric field observations from Wittstock MT station [3] in north (X) and east (Y) directions for all conductivity models (numbered columns, see legend of Fig. 4) and storms (rows).

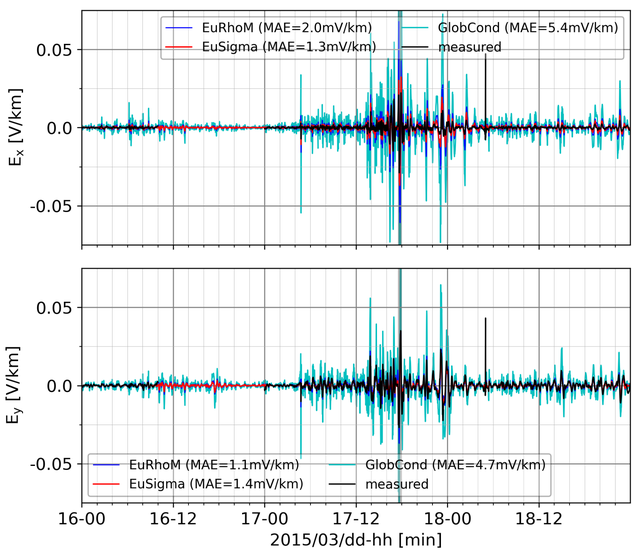



**Fig. 4: St. Patrick's Day storm electric field at Wittstock** Measured (black) and modeled GEFs in north (top) and east (bottom) directions at Wittstock (location in Fig. 1) for three conductivity models (colored, see Tab. 2).

## ⑤ Electric field across Germany

| | Max $\lvert E_X \rvert$ [V/km] 1 | 2 | 3 | Max $\lvert E_Y \rvert$ [V/km] 1 | 2 | 3 | Max $\lvert \Delta E_X \rvert$ [V/km] 13 | 23 | 12 | Max $\lvert \Delta E_Y \rvert$ [V/km] 13 | 23 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #3 | .310 | .195 | .131 | .131 | .134 | .103 | .245 | .155 | .227 | .099 | .101 | .116 |
| #5 | .064 | .038 | .040 | .100 | .084 | .080 | .055 | .028 | .048 | .082 | .063 | .071 |
| Mean [1] | .194 | .151 | .372 | .221 | .177 | .430 | .183 | .328 | .354 | .192 | .391 | .395 |
| Std [1] | .065 | .039 | .069 | .091 | .032 | .132 | .061 | .055 | .086 | .092 | .092 | .118 |

**Tab. 4: Extreme & mean GEFs.** Extreme GEFs (left) and GEF differences (right) for all conductivity models (see legend of Fig. 4) and 2 out of the 5 storms (top rows). Spatial means and standard deviations of storm-time averaged (5 snapshots per component), [0,1]-normalized GEFs and GEF differences (bottom rows).

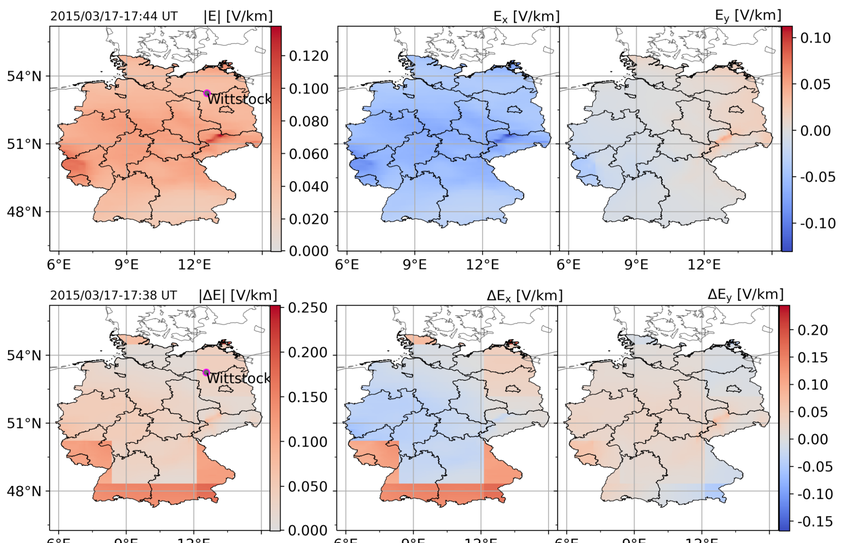



**Fig. 5: St. Patrick's Day storm GEF maps.** Snapshots of modeled absolute (left) and vector (right) GEF (for EuSigma, top) and GEF differences (between EuRhoM and EuSigma (Δ13), bottom) at times when extreme values are reached.

## ⑥ GIC at substation

The GEF drives a quasi-DC current through power lines and connected grounded transformers, which we calculate based on an ohmic model of the high-voltage grid (Fig. 6 & 7).

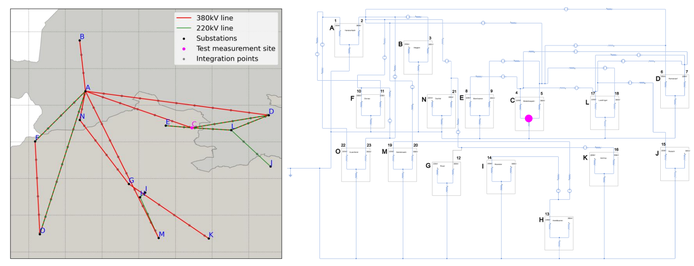



**Fig. 6: High-voltage grid section** High-voltage lines and substations (labeled dots) in northwestern Germany (left) and corresponding circuit diagram including all direct connections to substation C (magneta).

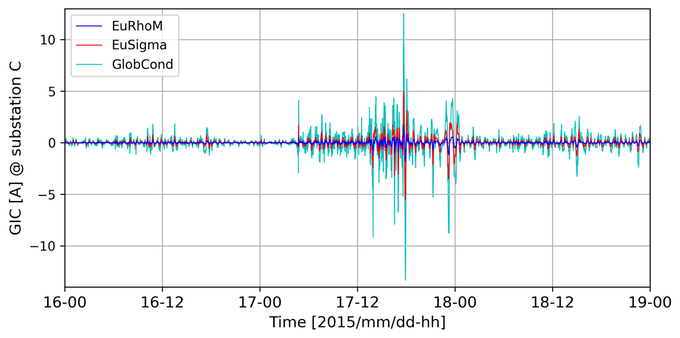



**Fig. 7: St. Patrick's Day Storm GIC at substation in northwestern Germany** GEF-driven transformer neutral point current at substation C in northwestern Germany considering all direct connections in the high-voltage transmission grid (see Fig. 6).

## ⑦ Conclusions

- EuSigma-based GEF agrees best with measured electric field at Wittstock in northeastern Germany ($MAE_X \leq 1$mV/km, $MAE_Y \leq 0.8$mV/km).
- EuSigma-based GEF shows smallest local extremes ($|E_{X,Y}|_{max} = 0.13$ V/km), but largest storm-time means across Germany with relative standard deviations $\sigma_X \approx 19\%$, $\sigma_Y \approx 31\%$.
- GEF difference amplitudes are comparable to GEF amplitudes and smallest between EuSigma and EuRhoM on average.
- GICs at northwestern substations reflect GEF amplitude ranking at Wittstock ($GIC_{max} \approx 5$A EuSigma).

## ⑧ Outlook

- Incorporate 1s-data from German geomagnetic observatories for selected events
- Explain uncertainties in modeled GEF: inaccuracies in impedance vs. magnetic field representation
- Update EuSigma
- Generate GIC threat map based on historic GEF
- Extend the grid model and update its parameters (esp. winding and grounding resistances)
- Verify complete GIC modeling chain by comparing results to measured GICs for 2023 storms

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**Acknowledgments**
We thank the operators of the INTERMAGNET geomagnetic observatories, Oliver Ritter and his colleagues from GFZ Potsdam for providing the Wittstock MT-Data, the providers of EuRhoM and Global Conductivity models, and a German TSO for cooperation.

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