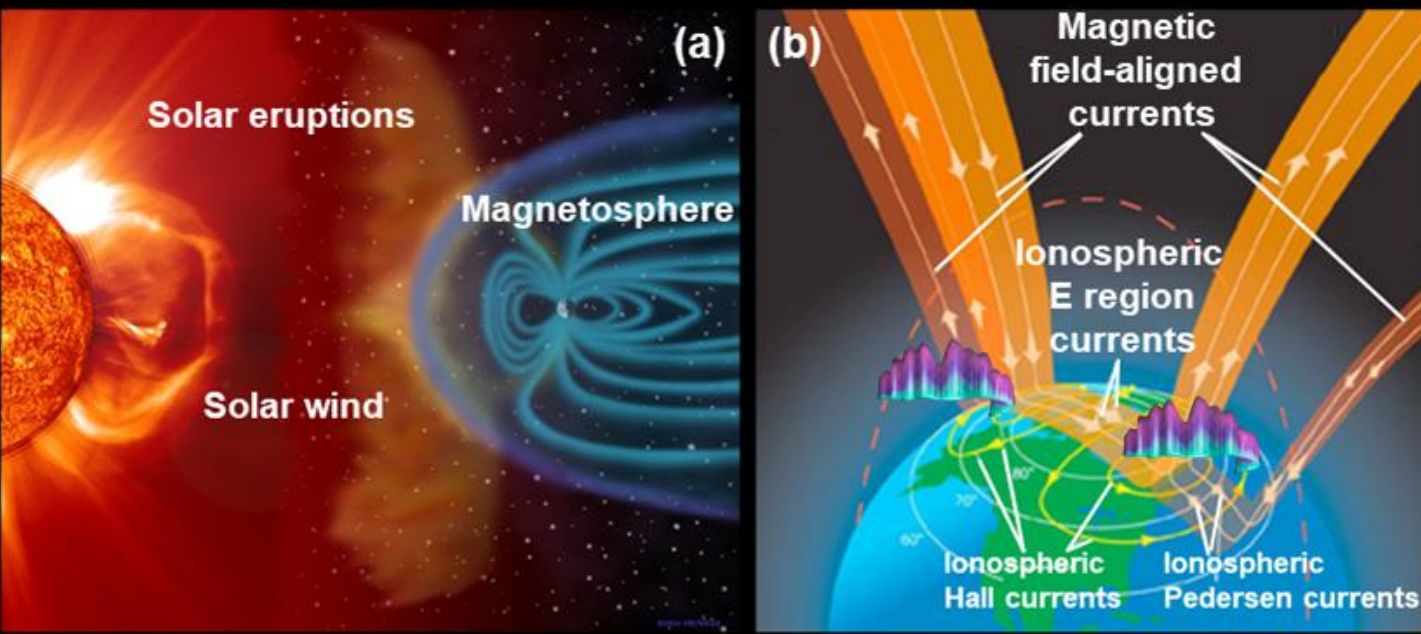


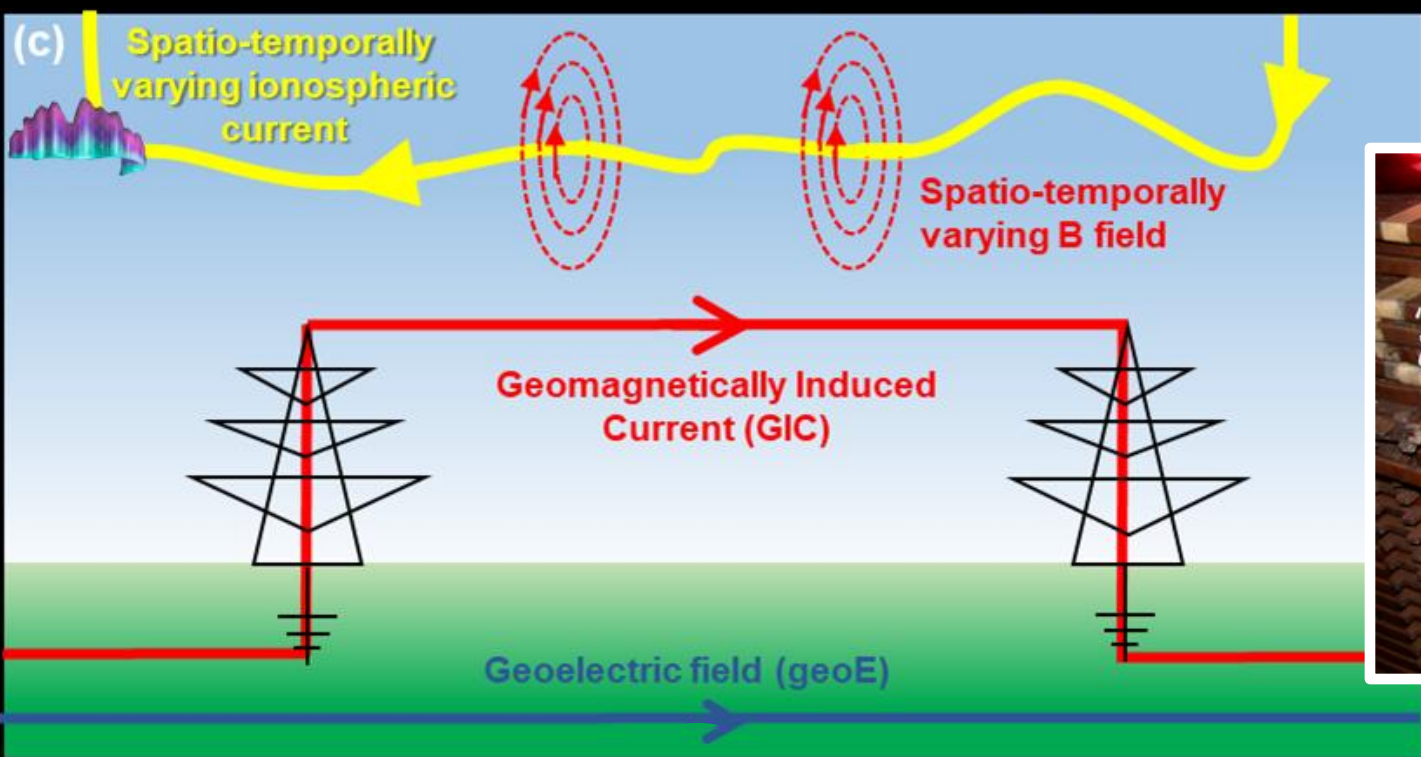
Question to the audience: What is the problem with auroras?





Space weather hazard:

- Sun → ... → Ionospheric currents
- Geoelectric fields & telluric currents
- Currents in power grid





Modeling geoelectric fields & geomagnetically induced currents

From ionospheric currents to currents in the Swedish power grid

Core team:

Maria Hamrin¹, Smilla Skarstind¹, (Jakub Vaverka¹), 
Juan Araújo^{1,2}, (postdoc) 

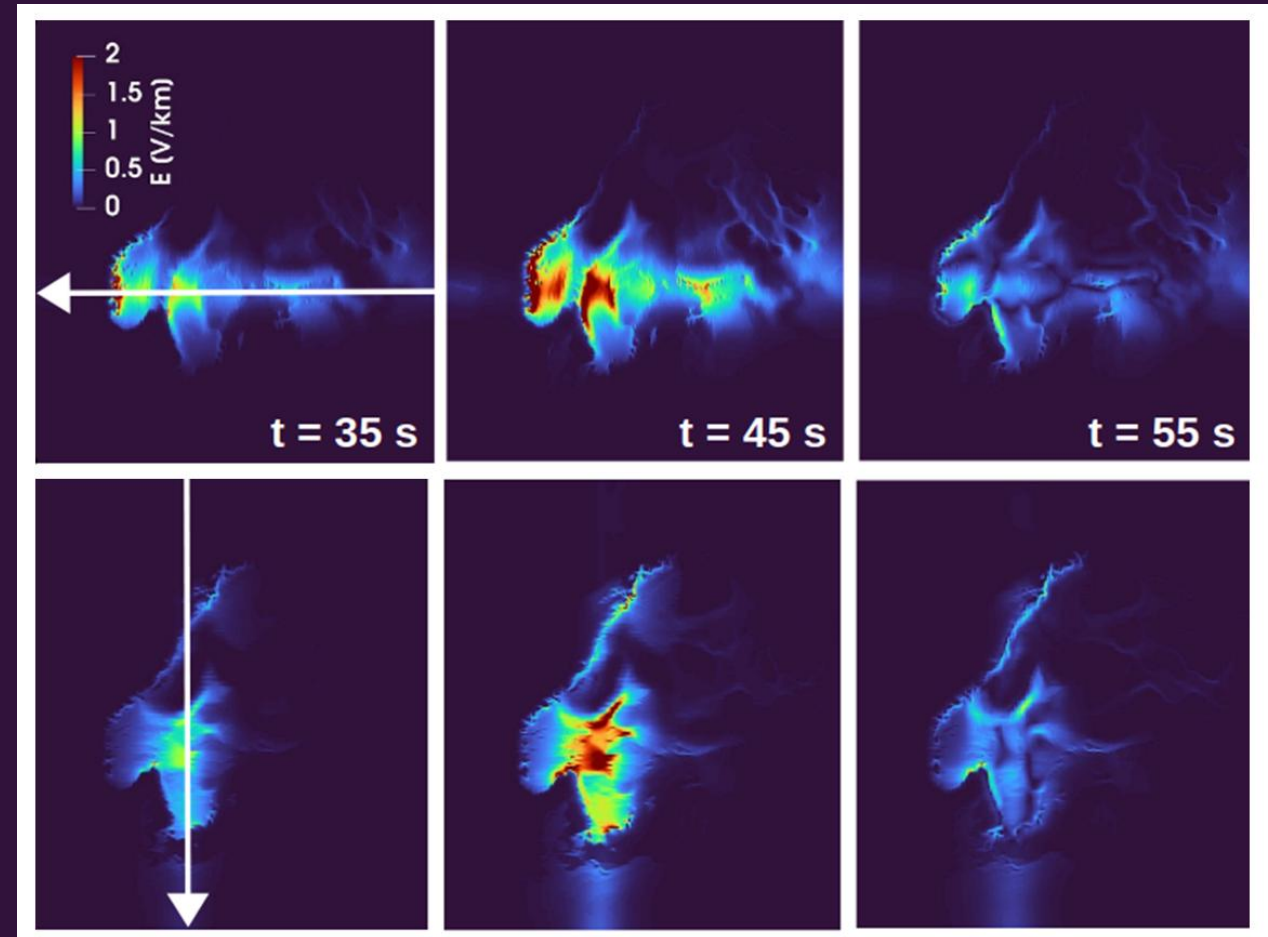
¹Umeå University

²Swedish Institute of Space Physics (IRF)

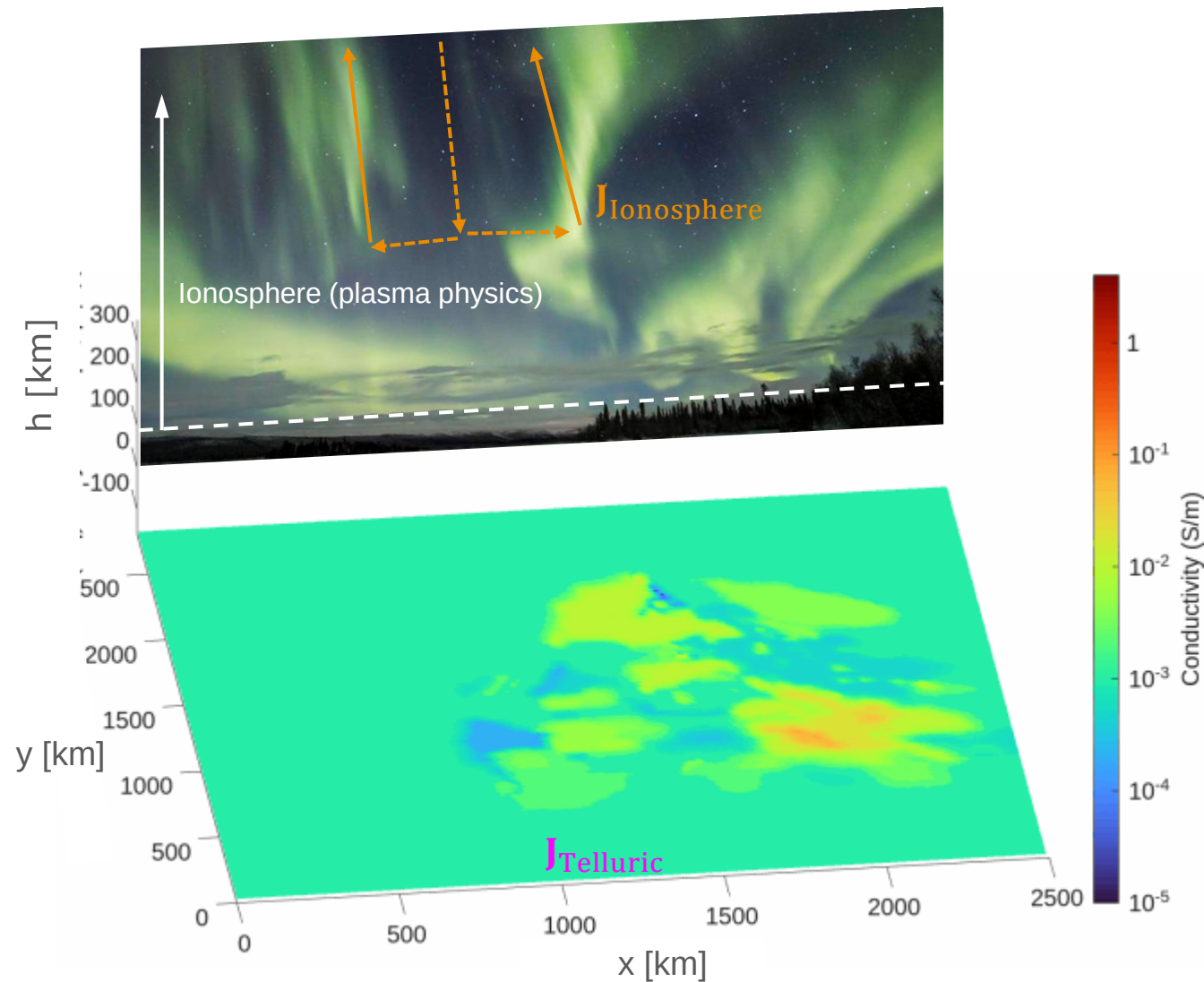
HPC collaborator: Eddie Wadbro (Karlstad University)



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It ain't even a plasma



Governing equations:

$$\left\{ \begin{array}{l} \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0 \\ \nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}_{\text{Ionosphere}} + \mathbf{J}_{\text{Telluric}} \\ \mathbf{J}_{\text{Telluric}} = \sigma(\mathbf{r})\mathbf{E} \end{array} \right.$$

$$\nabla \cdot \mathbf{B} = 0 \quad \nabla \cdot \mathbf{D} = 0 \quad (\text{no free charges})$$

$$\mathbf{D} = \epsilon(\mathbf{r})\mathbf{E} \quad \mathbf{B} = \mu_0\mathbf{H} \quad (\text{non-magnetic})$$

Solve in or **time domain** or **frequency domain**?

$$\mathbf{E}(t) \rightarrow \mathbf{E}(t + \Delta t) \rightarrow \mathbf{E}(t + 2\Delta t) \rightarrow \dots$$

$$\mathbf{E}(t) \xrightarrow{\text{Fourier}} \hat{\mathbf{E}} e^{-i\omega t} \xrightarrow{\text{Fourier}^{-1}} \mathbf{E}(t)$$

Brief history of geoE modeling

- ❑ ~1990 first models
- ❑ Frequency domain
 - Simple to analyze (the "physics way", one frequency at a time...)
 - Less time consuming

- ❑ 1-2D → 3D, often simplified ground conductivities

➤ 2019: 1st Swedish model with realistic 3D conductivity

- State-of-the-art
- Frequency domain
- Driver: Observed ground **B**
- Ground response: 3D impedance, $\hat{\mathbf{E}} = \mathbf{Z}(\omega)\hat{\mathbf{H}}(\omega)$
Simple — but many assumptions for $\mathbf{Z}$
- Takeaway: 3D conductivity matters
Southern Sweden particularly exposed
...
- But: Phase shift
...



Space Weather

RESEARCH ARTICLE
10.1029/2018SW002084

Regional 3-D Modeling and Verification of Geomagnetically Induced Currents in Sweden

L. Rosenqvist¹ and J. O. Hall^{1,2}

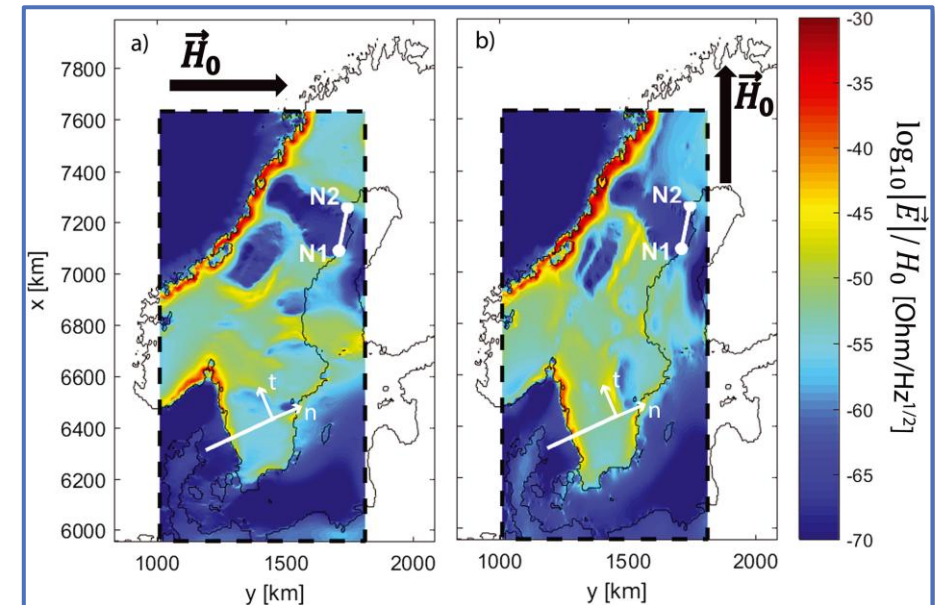
¹Swedish Defence Research Agency, Stockholm, Sweden, ²Now at Swedish Nuclear Fuel and Waste Management Company, Solna, Sweden

Key Points:

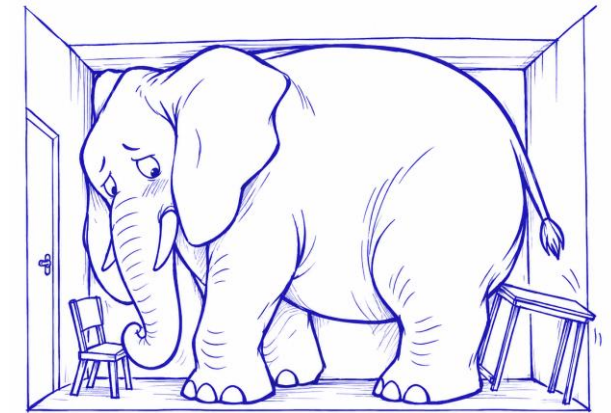
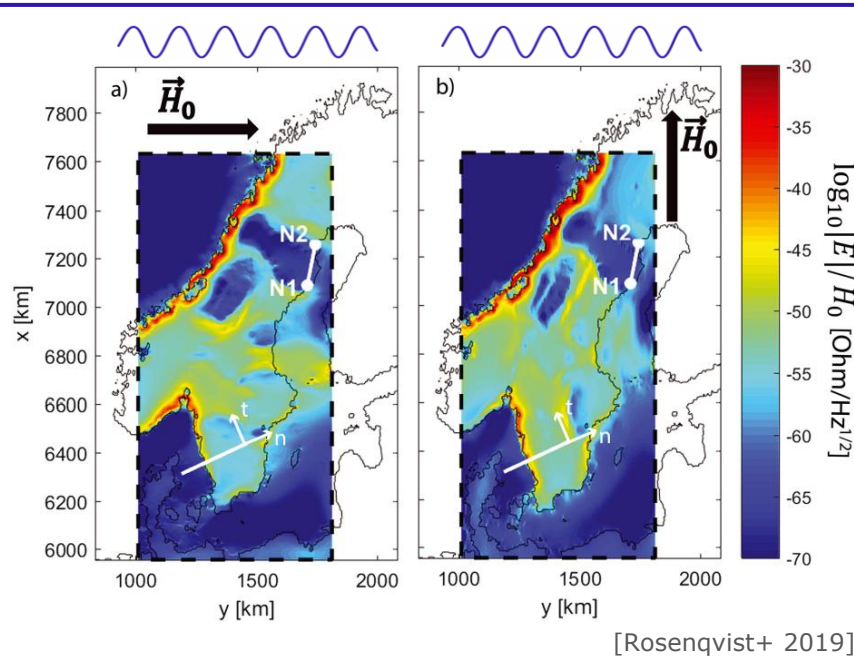
- Three-dimensional modeling of the geoelectric field in Sweden is performed based on a crustal conductivity map for the Fennoscandian shield
- Southern Sweden is exposed to stronger electric fields due to a combined effect of a lower crustal conductivity and the coastal effect
- GICs calculated based on the 3-D modeling, nearby magnetic field observations, and a power grid model are verified by measured GICs

Abstract Geomagnetically induced currents (GICs) flowing in long conductors can pose a threat to critical infrastructure such as the power grid in cases of extreme geomagnetic activity. Geomagnetic activity is more pronounced at high latitudes; thus, Nordic countries, such as Sweden, can potentially be vulnerable to GIC. Previous studies have identified the southern region of Sweden as the most vulnerable to extreme

[Rosenqvist+ 2019, 2022, 2025; Dimmock+ 2019, ...]



Frequency domain models – Basics



Space weather is non-harmonic!

$$\mathbf{E}(t) \xrightarrow{\text{Fourier}} \hat{\mathbf{E}} e^{-i\omega t}$$

$$\nabla \times \nabla \times \hat{\mathbf{E}} + \dots = \mathbb{A} \hat{\mathbf{E}} = f_{\text{"forcing"}}$$

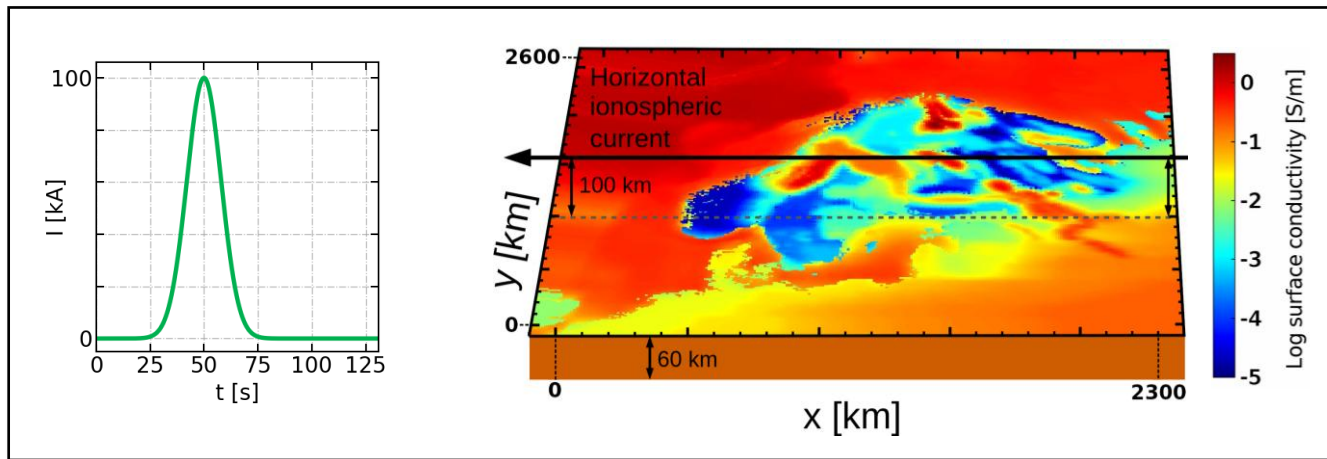
$$\hat{\mathbf{E}} = \mathbb{A}^{-1} f_{\text{"forcing"}}$$

$$\left(\hat{\mathbf{E}} e^{-i\omega t} \xrightarrow{\text{Fourier}^{-1}} \mathbf{E}(t) \right)$$



TIGR: Time-domain Ionosphere–Ground Response model

- ❑ Time domain, 1st article in review
- ❑ Driver:
 - Prescribed ionospheric 3D currents
 - or observed ground **B**
- ❑ Self-consistently solves Maxwell's eqs.
- ❑ Impedance matching not needed



[Araujo+ 2025, in review]

- ❑ 3D conductivity
- ❑ 250×280×50 cells, 10 km resolution
- ❑ GPU accelerated
- ❑ 100 s → ~25 min on NVIDIA H100
- ❑ gprMax [Warren+, 2016] → C++/MATLAB (in-house)

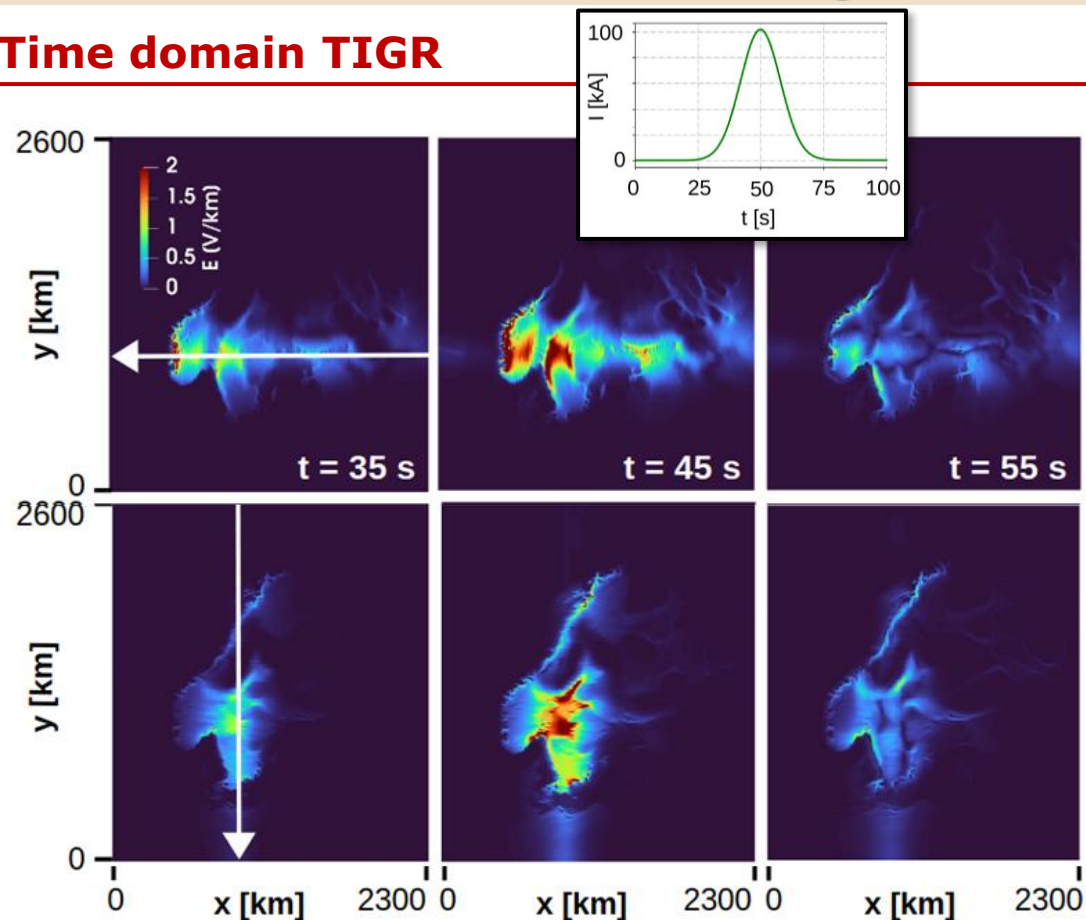


Juan Araújo



TIGR: First results

Time domain TIGR



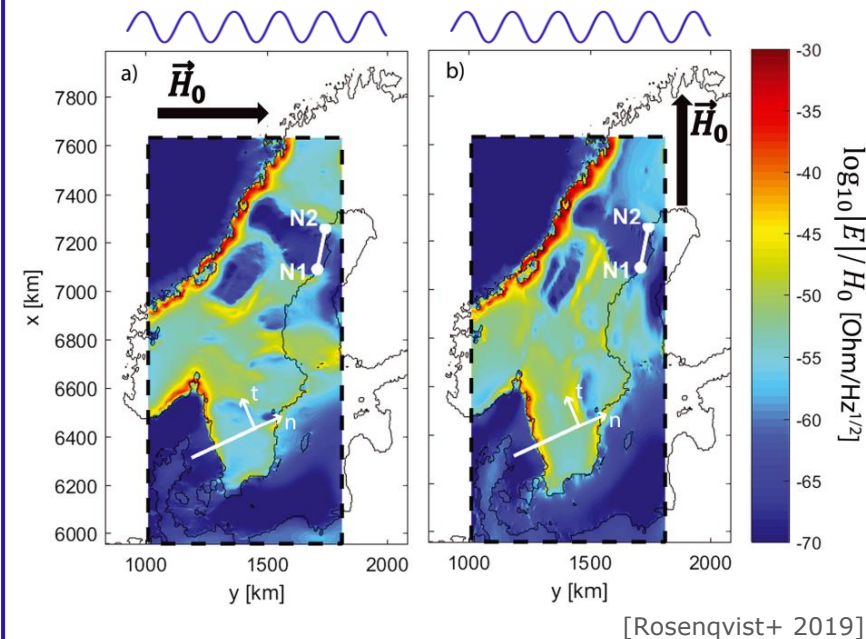
➤ Response:

- Localized
- Lagged

➤ Intuitive/easy to analyze:

- No inverse Fourier transform
- Transients, phase shifts, ...
- 3D time-varying telluric currents
- ...

Frequency domain



$$\mathbf{E}(t) \xrightarrow{\text{Fourier}} \hat{\mathbf{E}}e^{-i\omega t}$$

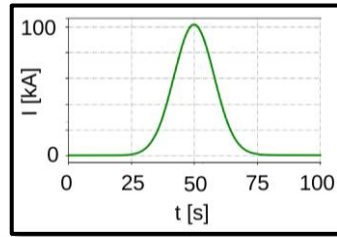
$$\nabla \times \nabla \times \hat{\mathbf{E}} + \dots = \mathbf{A}\hat{\mathbf{E}} = f_{\text{forcing}}$$

$$\hat{\mathbf{E}} = \mathbf{A}^{-1}f_{\text{forcing}}$$

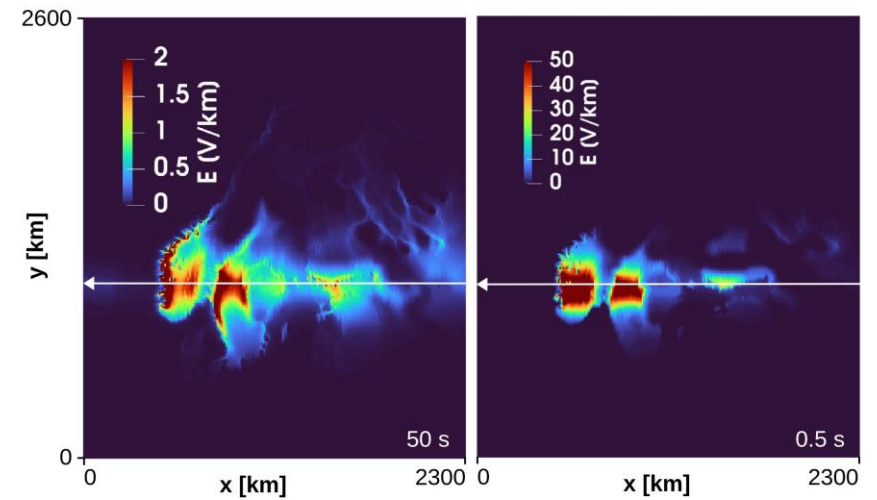
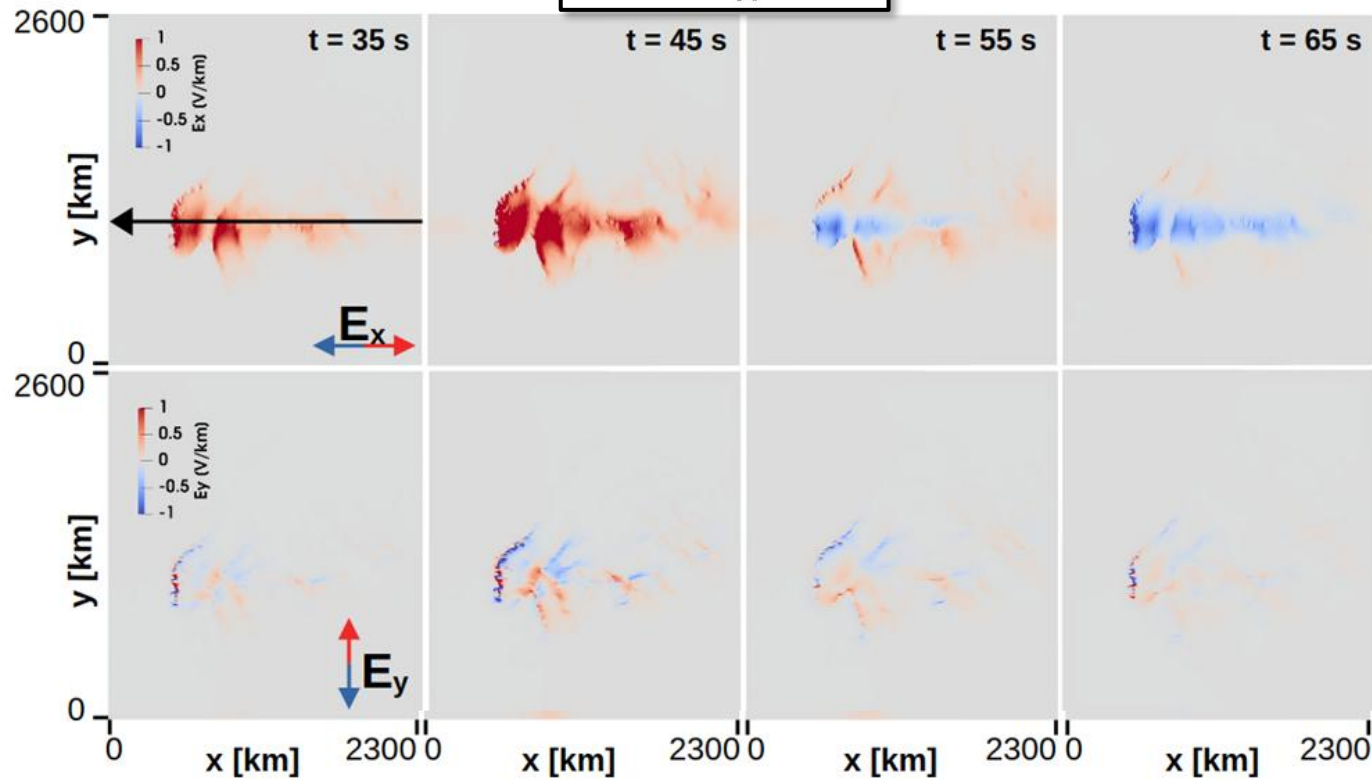
$$\left(\hat{\mathbf{E}}e^{-i\omega t} \xrightarrow{\text{Fourier}^{-1}} \mathbf{E}(t) \right)$$



TIGR: First results



➤ Conductivity gradients → perpendicular geoE



➤ Faster forcing → stronger & more localized |geoE|



TIGR: Where can we go from here?



For societal resilience:

- Power-grid planning & risk mitigation (security, stakeholders)
- GIC hotspots (realistic disturbances, optimization problem)
- Transients & timing (previous phase issue)
- Understand previous grid trips

EISCAT_3D @Skibotn



Fundamental research:

- Enhance ground-based observations
- Exploit TIGR flexibility
- Vision: Long-term space weather forecasting



HPC opportunities & challenges:

- Growing computational demands
- More opportunities for HPC & scientific computing
- Manpower (funding) & computing resources

Question to the audience: What is the problem with auroras? **Space weather is non-harmonic!**

Thank you!

**Special thanks to
eSSENCE & HPC2N!**