Comparing three approaches to the ground geoelectric field modelling due to space weather event

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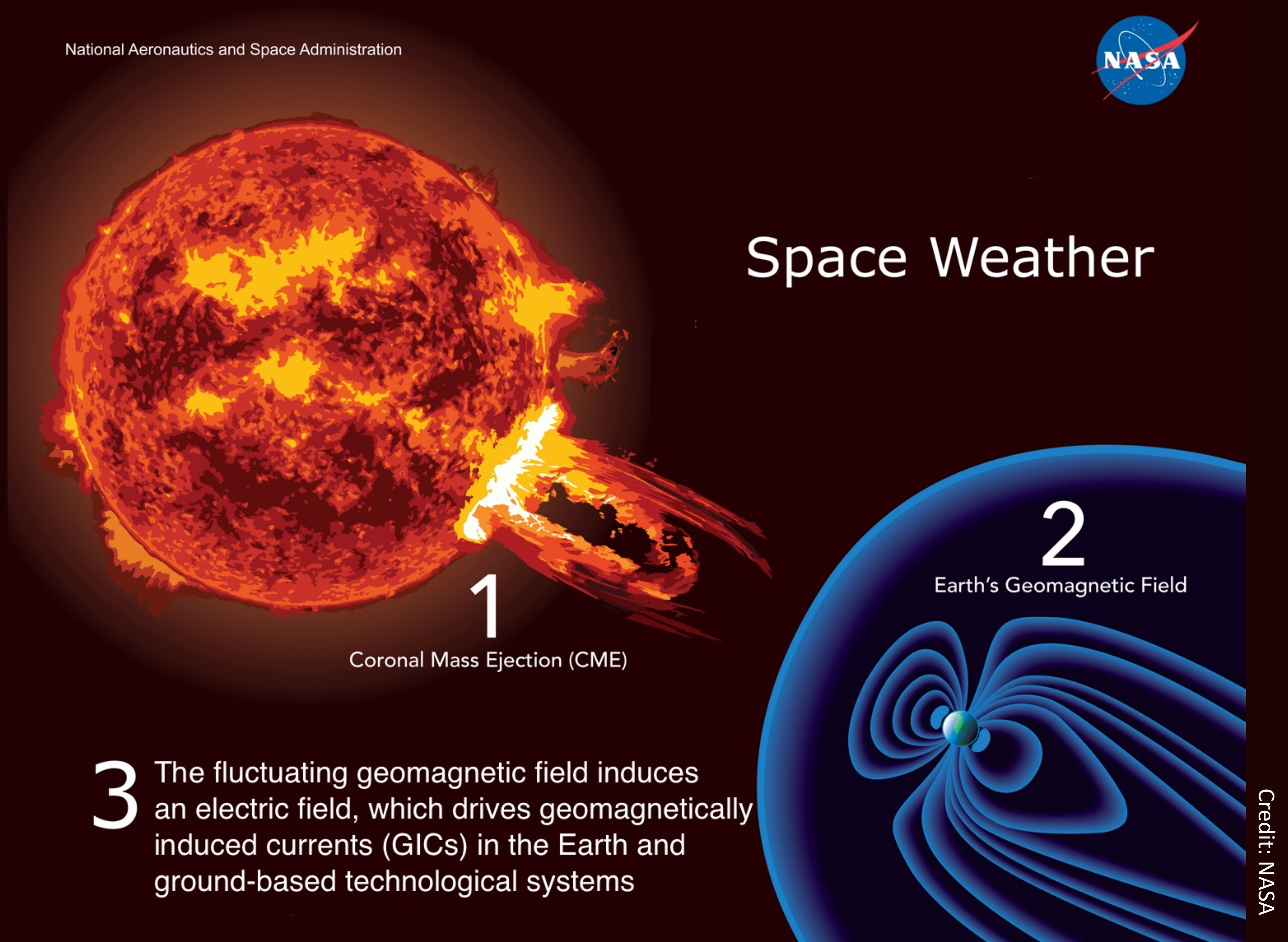
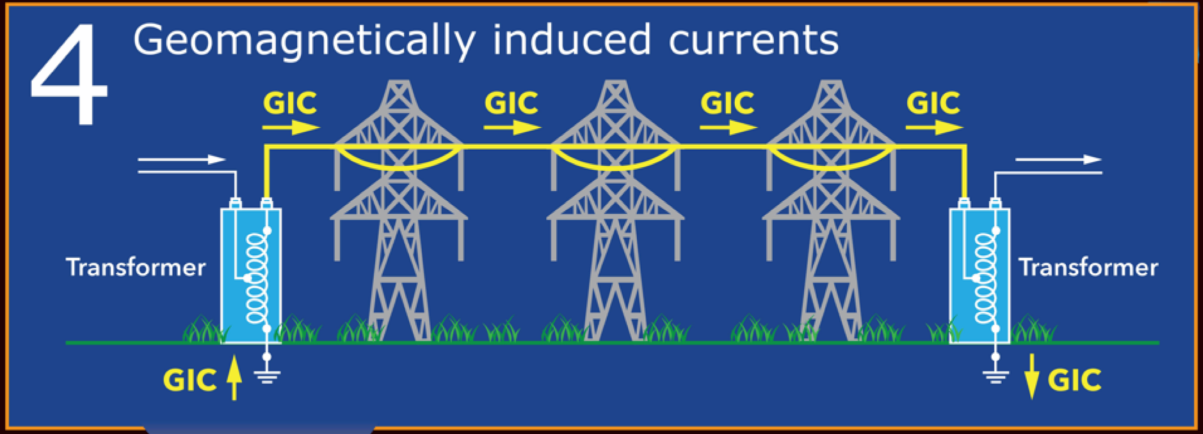
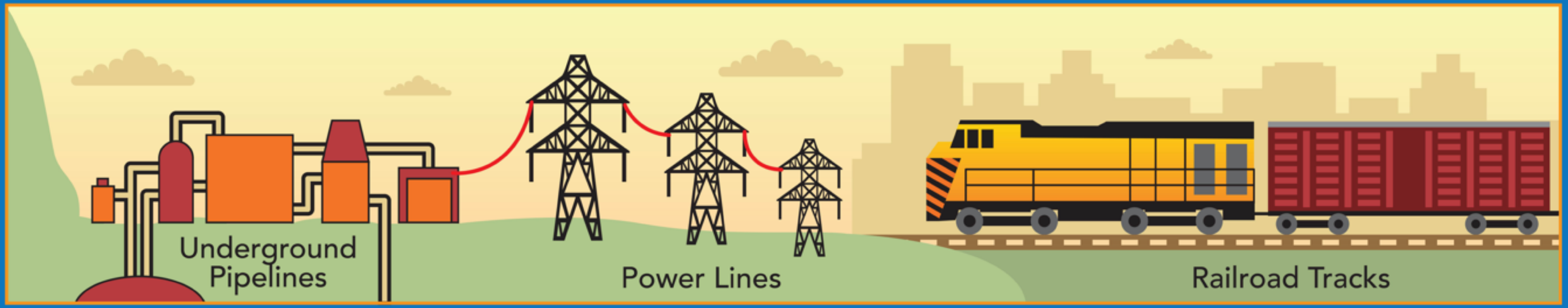

National Aeronautics and Space Administration
NASA
Space Weather
1
Coronal Mass Ejection (CME)
2
Earth's Geomagnetic Field
3 The fluctuating geomagnetic field induces an electric field, which drives geomagnetically induced currents (GICs) in the Earth and ground-based technological systems
Credit: NASA



WHAT IS THE IMPACT?

Though widespread permanent damage to power systems is unlikely, extreme storms can cause blackouts over extended areas.

GICs CAN RUN THROUGH ANY LONG METAL STRUCTURE



www.nasa.gov

Credit: NASA

GICs can be calculated from the geometry of a technological network and system design parameters using the geoelectric field data

In this study we focus on the geoelectric field modelling

The modelling is performed for the region of Fennoscandia and 8 hours of the geomagnetic storm on 7-8 September 2017: 2017/09/07 20:00 – 2017/09/08 03:59 UT

Geoelectric field modelling approach

The geoelectric field $\vec{E}(t,r)$ (and magnetic field $\vec{B}(t,r)$) is obtained by solving Maxwell's equations numerically

$$\frac{1}{\mu_0}\nabla\times\vec{B} = \sigma\vec{E} + \vec{j}^{ext}$$

$$\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

for given:

1. Inducing source $\vec{j}^{ext}(t,\vec{r})$

2. Earth conductivity distribution $\sigma(\vec{r})$

t – time, $\vec{r} = (x,y,z)$ – position vector, μ_0 - magnetic permeability of free space

Geoelectric field modelling approach, continued

1. The inducing source $\vec{j}^{ext}(t,\vec{r})$ is transformed from the time to the frequency domain using the FFT

2. Maxwell's equations in the frequency domain

$$\frac{1}{\mu_0}\nabla\times\vec{B} = \sigma\vec{E} + \vec{j}^{ext}$$
$$\nabla\times\vec{E} = i\omega\vec{B}$$

are numerically solved for the corresponding frequencies ω, using EM forward modelling code *extrEMe* (Kruglyakov et al., 2016), based on a contracting integral equation approach

3. $\vec{E}(t,r)$ (and $\vec{B}(t,r)$) is obtained by means of the IFFT of the frequency domain fields

Kruglyakov, M., Geraskin, A. & Kuvshinov, A. 2016. Novel accurate and scalable 3-D MT forward solver based on a contracting integral equation method. *Computers and Geosciences*, 96, 208–217.

Three approaches to the electromagnetic induction source setting

Common:

All approaches are based on the numerical solution of Maxwell's equations in Earth models with a 3-D conductivity distribution.

Difference:

Different setting of the electromagnetic (EM) induction source:

1. Laterally varying sheet current flowing above the Earth. The current is constructed on the base of a 3-D magnetohydrodynamic (MHD) simulation of near-Earth space (**physics-based approach**).

2. Laterally varying sheet current flowing above the Earth. The current is constructed using ground-based magnetometers' data (**data-based approach**).

3. Laterally uniform (plane wave) excitation. The geoelectric field is calculated using magnetotelluric (MT) impedances and ground-based magnetometers' data (**data-based approach**).

Advantages and disadvantages of the considered methods

	Advantages	**Disadvantages**
Laterally-varying source constructed on the base of an MHD simulation	1. The ability to forecast the EM field evolution as MHD simulations are run on the base of the satellite solar wind data 2. Equivalent current and, subsequently, EM field can be calculated for any point on Earth	1. The lowest accuracy among the considered methods 2. The most computationally expensive method, as both MHD and EM simulations should be carried out
Laterally-varying source constructed using the SECS method	The most accurate method among all the considered methods	The method relies on the data from ground-based magnetometers. In the high-latitude regions a dense grid of geomagnetic observatories is required to capture the source evolution properly
Plane wave method	The least computationally expensive method, as MT impedances can be precomputed and then convolved with magnetic field	1. The method also relies on the data from ground-based magnetometers 2. In the high-latitude regions the plane wave assumption is violated, which leads to less accurate results compared to modelling with laterally-varying source

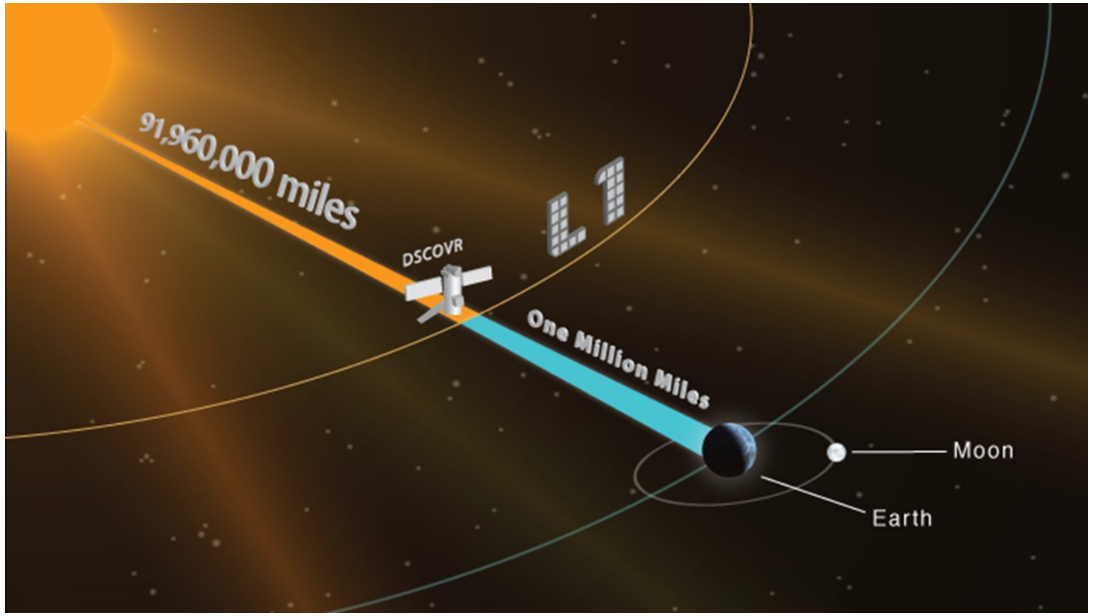
1. Construction of the source model on the base of an MHD simulation

3-D magnetohydrodynamic (MHD) models of near-Earth space, such as Space Weather Modelling Framework (SWMF; Toth et al., 2005), are used for the construction of the source model. We use the MHD models available at the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center.

Inputs: solar wind parameters (density, temperature, velocity, magnetic field) from a satellite located at the L1 Lagrangian point (ACE, DSCOVR)

Outputs: time-varying 3-D currents in the magnetosphere, horizontal currents in the ionosphere and field-aligned currents

As MHD simulations are run on the base of the satellite solar wind data, this approach allows to forecast the space weather impact on Earth.



Credit: NOAA

Toth, G., Sokolov, I.V., Gombosi, T.I., Chesney, D.R., Clauer, C.R., De Zeeuw, D.L., Hansen, K.C., Kane, K.J., Manchester, W.B., Oehmke, C., Powell, K.G., Ridley, A.J., Roussev, I.I., Stout, Q.F., Volberg, O., Wolf, R.A., Sazykin, S., Chan, A., & Yu, B. 2005. Space Weather Modeling Framework: A new tool for the space science community. *Journal of Geophysical Research,* 110.

1. Construction of the source model on the base of an MHD simulation, continued

The CalcDeltaB tool (Rastätter et al., 2014) is used to calculate the external magnetic field perturbations on the ground from the snapshots of the current systems via Biot-Savart law:

$$\vec{B}^{ext}(t,\vec{r}_s) = \frac{\mu_0}{4\pi}\int_V \frac{\vec{j}^{MHD}(t,\vec{r}\,')\times\vec{r}\,'}{|\vec{r}\,'|^3}\,dV$$

$\vec{j}^{MHD}(t,\vec{r})$ – current density on a 3-D MHD grid

$\vec{B}^{ext}(t,\vec{r})$ is computed on a 5×5 degrees global grid at the surface of the Earth with 1-minute temporal resolution

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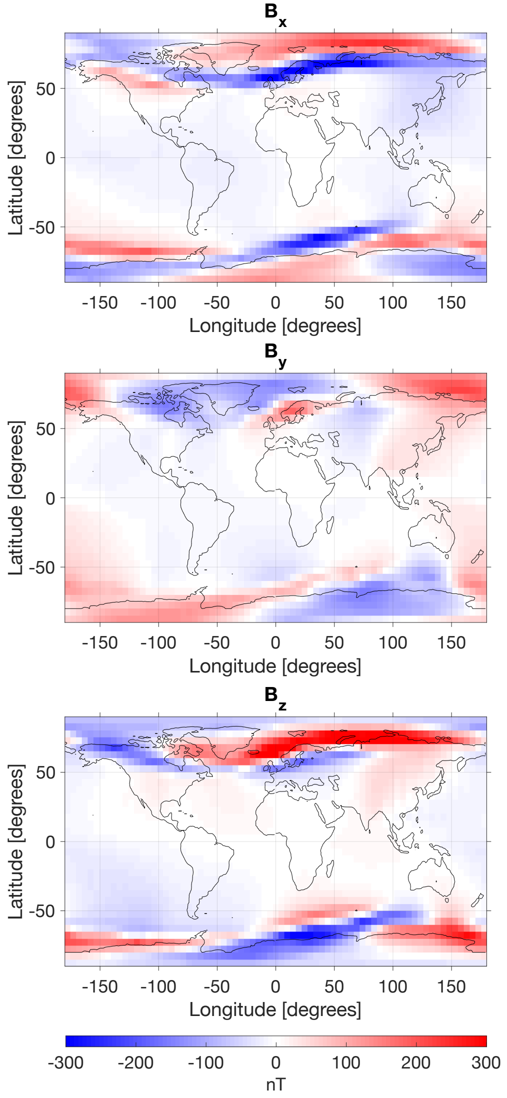


Rastätter, L., Toth, G., Kuznetsova, M.M., & Pulkkinen, A.A. 2014. CalcDeltaB: An efficient postprocessing tool to calculate ground-level magnetic perturbations from global magnetosphere simulations. *Space Weather,* 12, 553-565.

1. Construction of the source model on the base of an MHD simulation, continued

The global external magnetic field perturbations $\vec{\boldsymbol{B}}^{ext}(\boldsymbol{t}, \mathbf{r})$ at the surface of the Earth are converted into global equivalent current function $\boldsymbol{\Psi}$ (Ivannikova et al., 2018):

$$\Psi(t, a, \vartheta, \varphi) = \int_{\Omega} G(\vartheta, \vartheta', \varphi - \varphi') B_r^{ext}(t, a, \vartheta', \varphi')\, d\Omega'$$

The inducing source $\vec{j}^{ext}(t, \vec{r})$ has a form of spatially distributed electric current flowing in a thin shell above the surface of the Earth:

$$\vec{j}^{ext}(t, \vec{r}) = -e_r \times \nabla_\perp \Psi$$

e_r – radial (outward) unit vector, $\nabla_\perp$ – angular part of the gradient, a – mean radius of the Earth

Ivannikova E., Kruglyakov, M., Kuvshinov, A., Rastaetter, L. and Pulkkinen, A.A. (2018), Regional 3-D modeling of ground electromagnetic field due to realistic geomagnetic disturbances, *Space Weather*, 16.

2. Construction of the source model using ground-based magnetometers' data

Construction of the ionospheric equivalent current is carried out for Fennoscandia with separation of the geomagnetic variation field on the ground into external and internal parts using the spherical elementary current system (SECS) method (Pulkkinen et al., 2003) on the base of IMAGE magnetometers' data.

SECS ionospheric equivalent current

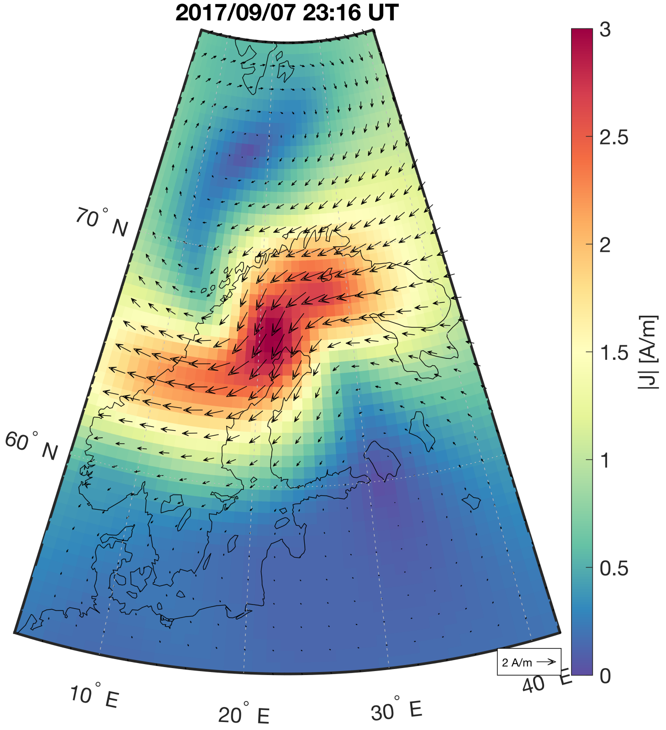
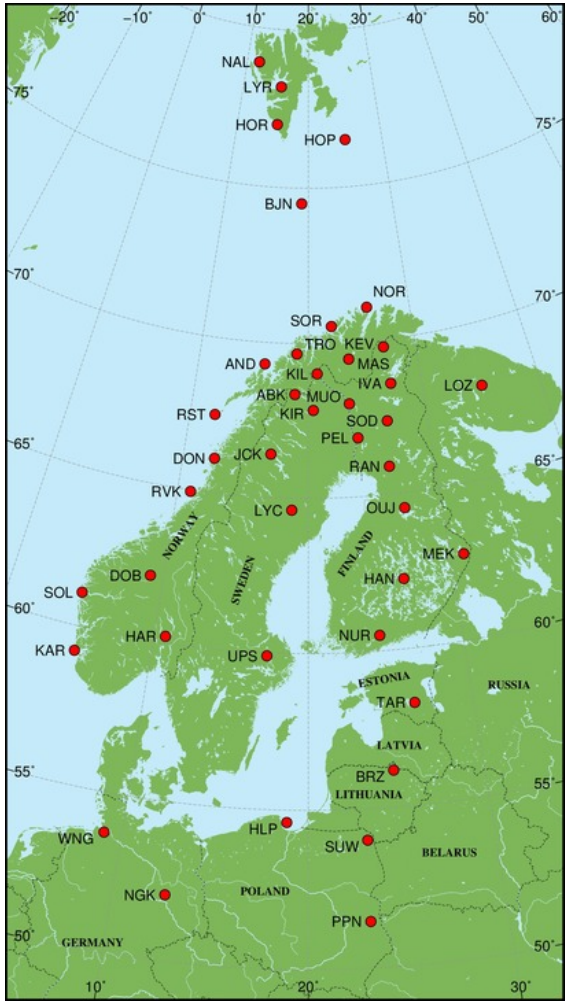


IMAGE magnetometer array



Credit: Finnish Meteorological Institute

Vanhamäki, H. and Juusola, L.: Introduction to Spherical Elementary Current Systems, in: Ionospheric Multi-Spacecraft Analysis Tools, pp. 5-33, ISSI Scientific Report Series 17, 2020.

3. Plane wave excitation

1. 3-D EM forward modelling is carried out with two (laterally uniform) plane wave sources at FFT frequencies (corresponding to periods from 2 min to 8 hr in case of this study). 3-D MT impedances $Z(\omega, \mathbf{r})$ that relate the surface horizontal electric to surface horizontal magnetic field at each grid point $\mathbf{r}$ of the conductivity model

$$Z(\omega, \mathbf{r}) = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

are then calculated for each FFT frequency ω.

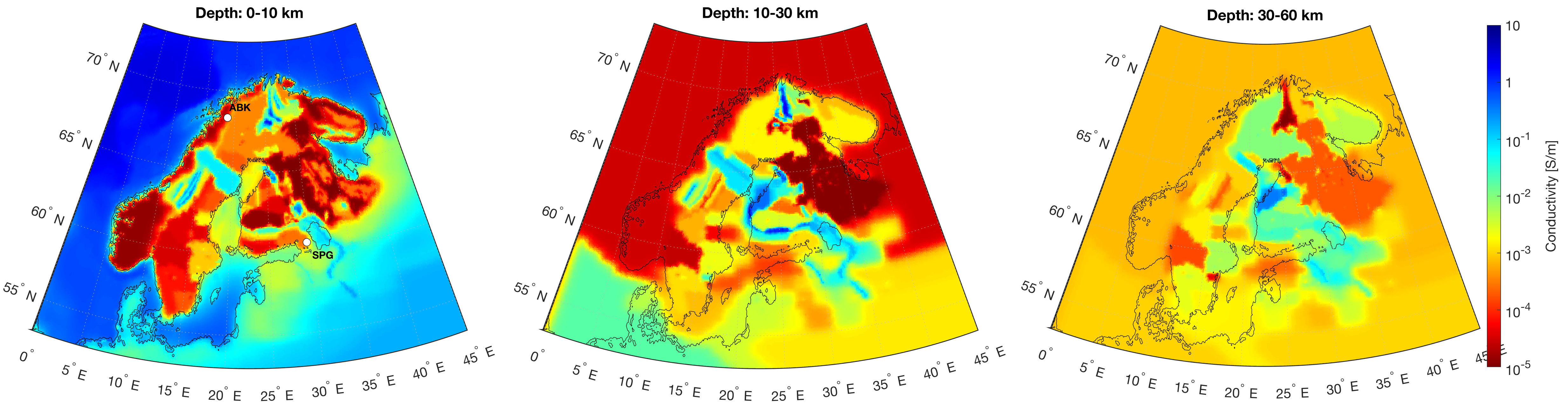
2. The horizontal electric field is calculated for each frequency and each grid point $\mathbf{r}$ of the conductivity model using the magnetic field $B_h^{SECS}(\omega, \mathbf{r})$, which was obtained via 3-D EM modelling with laterally varying SECS source, and impedances pre-computed at step 1

$$E_h^{pw}(\omega, \mathbf{r}) = \frac{1}{\mu_0} Z(\omega, \mathbf{r})\, B_h^{SECS}(\omega, \mathbf{r})$$

3. An inverse FFT is performed for the frequency domain geoelectric field to obtain the geoelectric field in the time domain.

Modelling region and conductivity model

In this study we carry out 3-D EM forward modelling for the region of Fennoscandia using SMAP model (Korja et al., 2002)



3-D part of the model is underlain by 1-D conductivity profile obtained by Grayver et al. (2017)

Korja, T., et al. (2002). Crustal conductivity in Fennoscandia - a compilation of a database on crustal conductance in the Fennoscandian Shield. *Earth Planets Space*, 54, 535-558.

Grayver, A. V., Munch, F. D., Kuvshinov, A. V., Khan, A., Sabaka, T. J., and Tøffner-Clausen, L. (2017), Joint inversion of satellite-detected tidal and magnetospheric signals constrains electrical conductivity and water content of the upper mantle and transition zone, *Geophys. Res. Lett.*, 44, 6074-6081.

Summary of model discretisation

The lateral discretization of the original SMAP model is 10x10 km^2. Vertically the 3-D part of the model is discretized by 3 layers with the following thicknesses: 10, 20 and 30 km.

We increased the lateral and vertical discretisation of the model in the following way:

The lateral discretisation of the model is 5x5 km^2. The size of the model in lateral directions is 2550x2550 km^2.

3 layers of the SMAP model were rediscretised by 21 layers of variable thickness.

We increased the lateral and vertical discretisation of the conductivity model, because higher discretization is required for accurate modelling of the EM field in high-contrast models like the SMAP.

Results of magnetic field modelling with MHD (SWMF) and SECS sources

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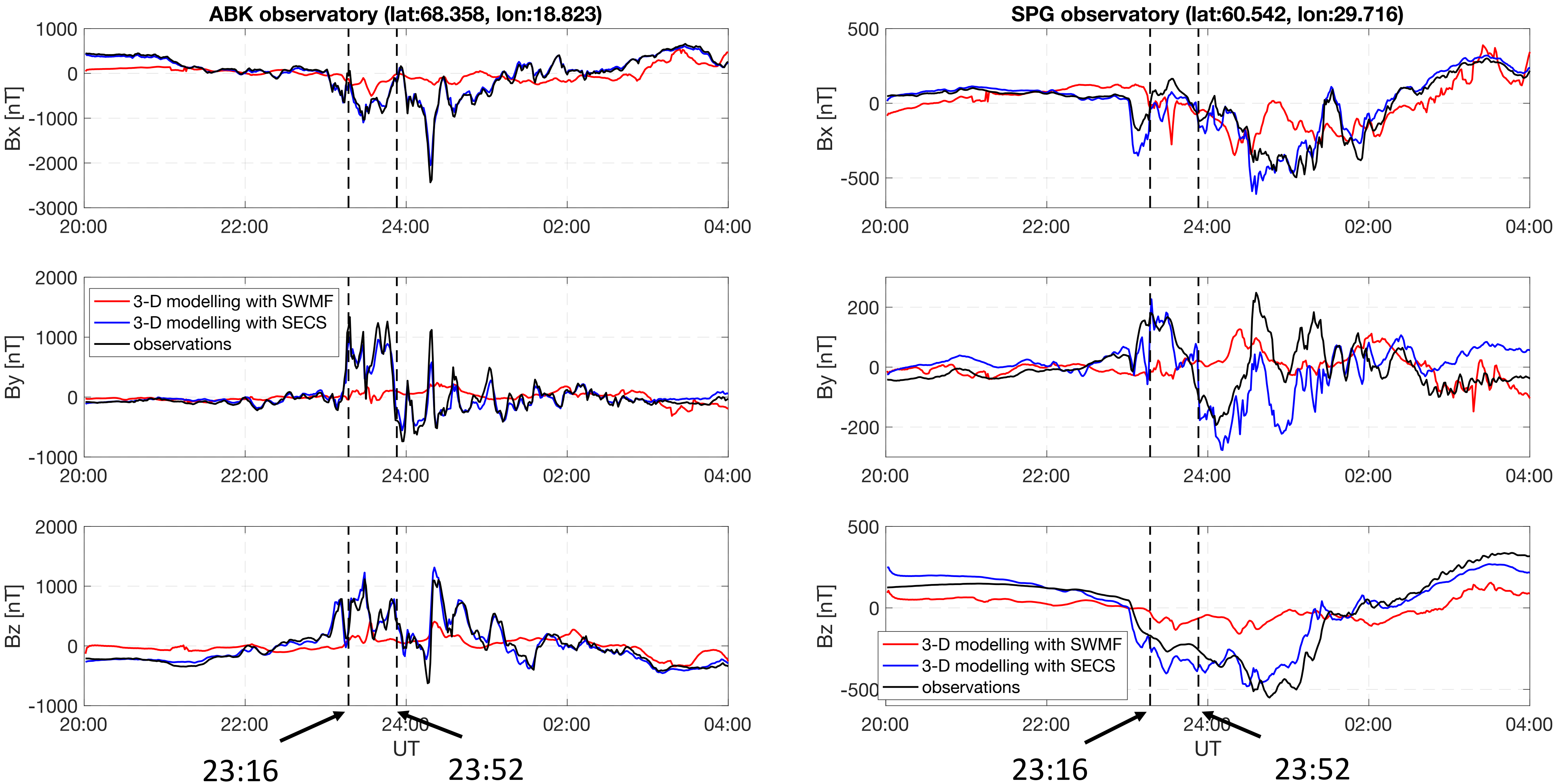

Note that SPG observatory is not a part of the IMAGE array, so its magnetic field data were not used for the SECS source construction. Note also that not all IMAGE magnetometer stations are geomagnetic observatories.

Results of electric field modelling with plane wave excitation, MHD (SWMF) and SECS sources

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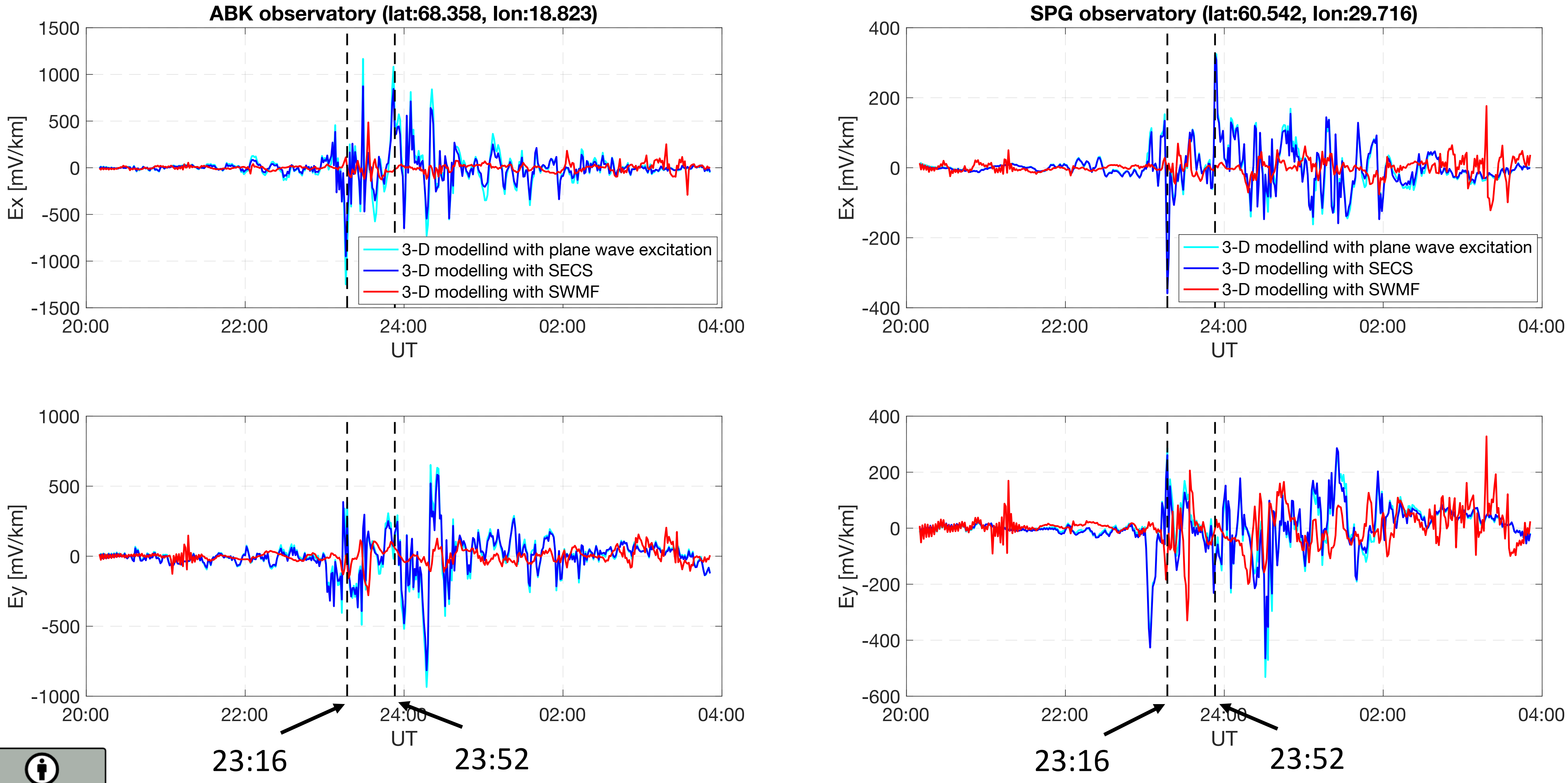

Results of 3-D geoelectric field modelling: SECS vs MHD (SWMF)

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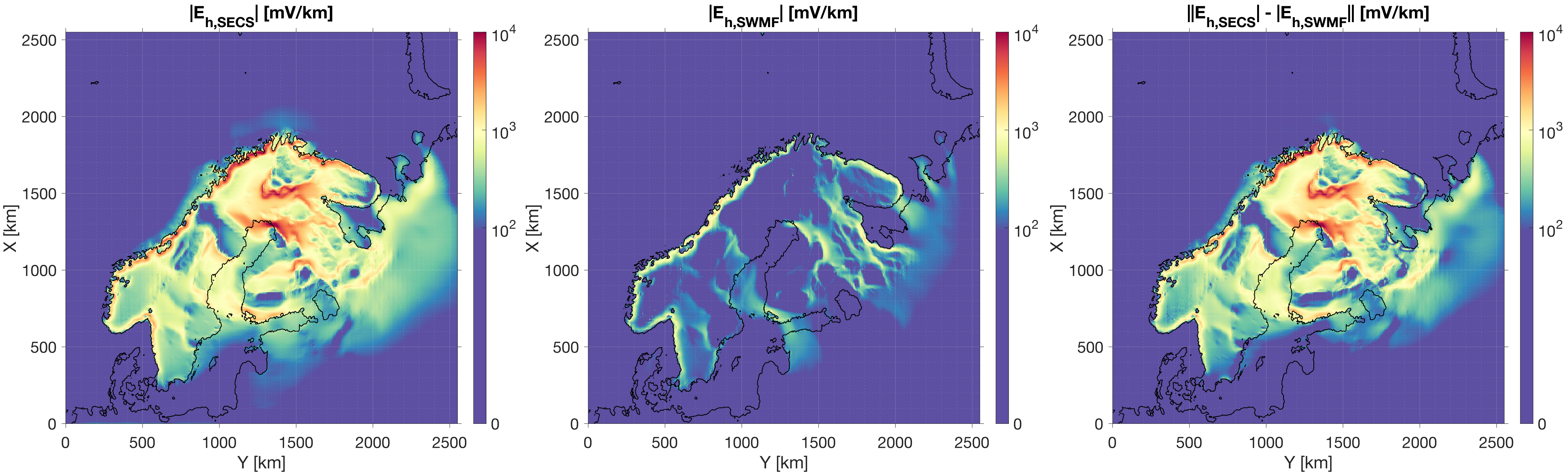

$|E_{h,SECS}|$ - magnitude of horizontal electric field obtained via 3-D EM modelling and equivalent current calculated using the SECS method

$|E_{h,SWMF}|$ - magnitude of horizontal electric field obtained via 3-D EM modelling and equivalent current calculated using the SWMF

Results of 3-D geoelectric field modelling: SECS vs MHD (SWMF)

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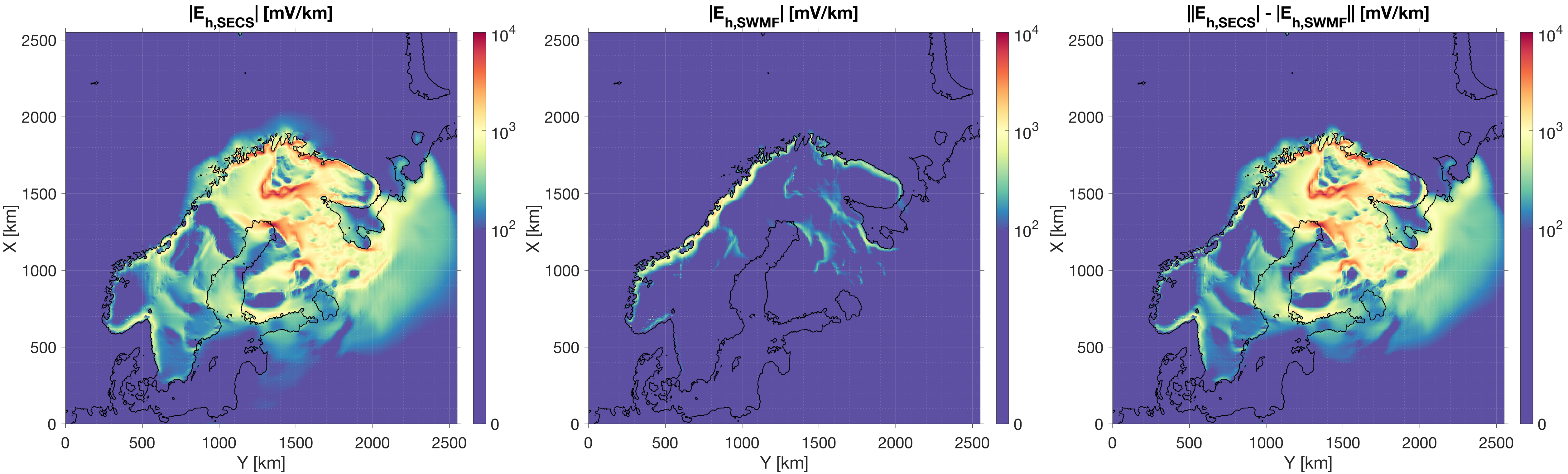

$|E_{h,SECS}|$ - magnitude of horizontal electric field obtained via 3-D EM modelling and equivalent current calculated using the SECS method

$|E_{h,SWMF}|$ - magnitude of horizontal electric field obtained via 3-D EM modelling and equivalent current calculated using the SWMF

Results of 3-D geoelectric field modelling: SECS vs plane wave

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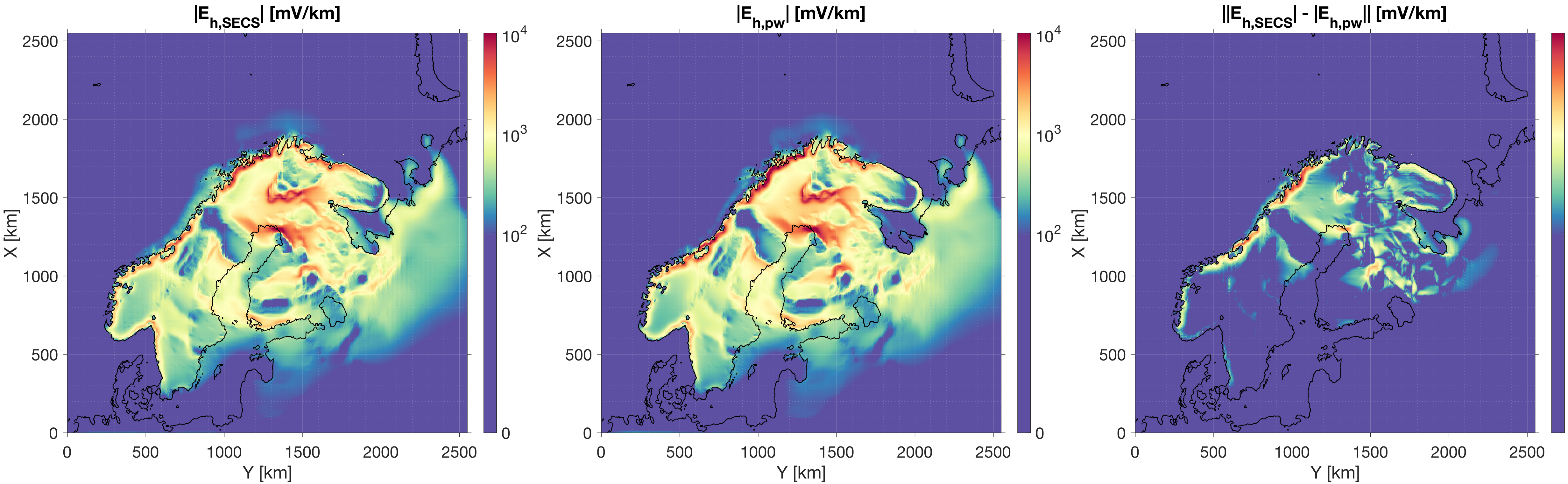

$|E_{h,SECS}|$ - magnitude of horizontal electric field obtained via 3-D EM modelling and equivalent current calculated using the SECS method
$|E_{h,pw}|$ - magnitude of horizontal electric field obtained via plane wave 3-D EM modelling

Results of 3-D geoelectric field modelling: SECS vs plane wave

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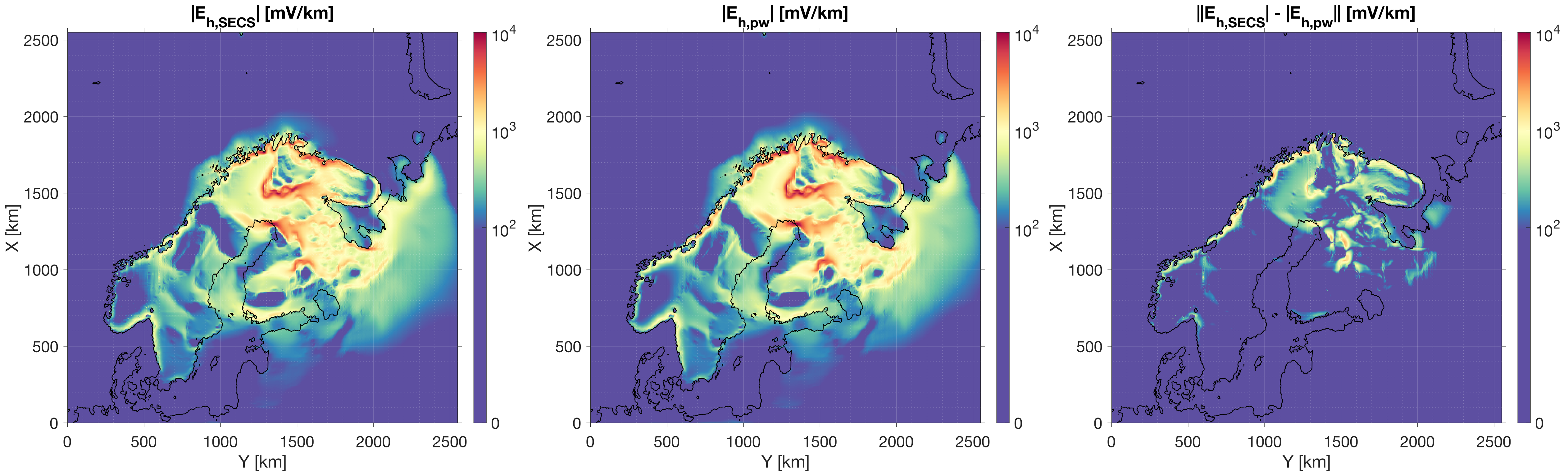

$|E_{h,SECS}|$ - magnitude of horizontal electric field obtained via 3-D EM modelling and equivalent current calculated using the SECS method
$|E_{h,pw}|$ - magnitude of horizontal electric field obtained via plane wave 3-D EM modelling

Conclusions

1. The magnitude of magnetic field perturbations in the Fennoscandian region is underestimated, when performing 3-D EM modelling of magnetospheric substorm event on the base of a SWMF simulation

   Ways to improve modelling results:

   - Computation of the external magnetic field perturbations on a denser grid
   - Search for an alternative (potentially more accurate) MHD solution: Lyon-Fedder-Mobarry (LFM) global MHD model (Lyon et al., 2004)?

2. The difference between geoelectric field modelling results for laterally nonuniform source and plane wave excitation is substantial in the Fennoscandian region. The largest differences occur a) in the areas of strong lateral contrasts of conductivity (e.g., at the coasts), and b) at higher latitudes.

Lyon, J. G., J. A. Fedder, and C. M. Mobarry (2004), The Lyon-Fedder-Mobarry (LFM) global MHD magnetospheric simulation code, J. Atmos. Sol. Terr. Phys., 66, 1333–1350.