Real-time simulation of the geoelectric field spatiotemporal evolution due to geomagnetic disturbances

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Abstract

We present a methodology that allows real-time simulation of the geoelectric field (GEF) spatiotemporal evolution in a given 3-D conductivity model of the Earth based on continuously augmented inducing source data. The presented concept is validated using Fennoscandia as a test region. The choice of Fennoscandia is motivated by several reasons. First, it is a high latitude region, where the GEF is expected to be particularly large. Second, there exists a 3-D ground electrical conductivity model of the region. Third, the regional magnetometer network, IMAGE, allows us to build a realistic model of the source for a given geomagnetic disturbance. Taking the 7-8 September 2017 geomagnetic storm as a space weather event, we show that real-time high-resolution 3-D modeling of the GEF is feasible and requires only a few tens of seconds.

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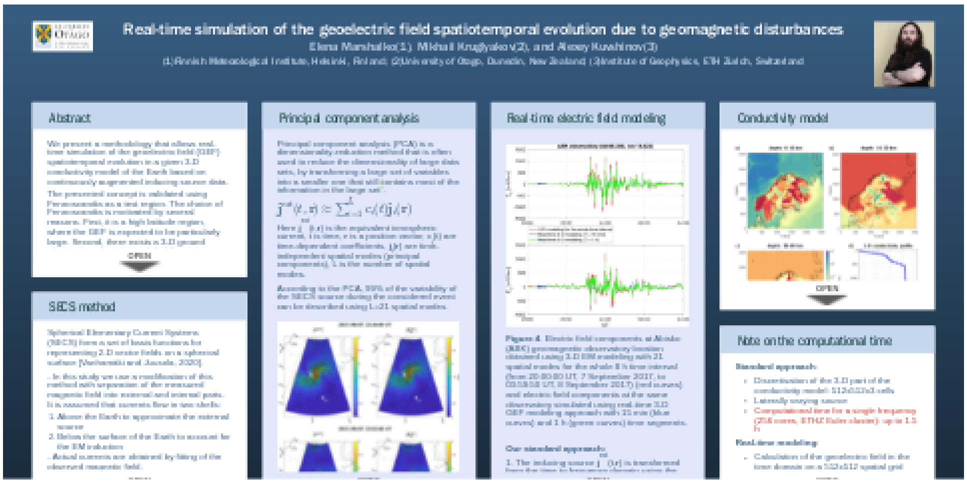

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ABSTRACT

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SECS METHOD

Spherical Elementary Current Systems (SECS) form a set of basis functions for representing 2-D vector fields on a spherical surface [Vanhamäki and Juusola, 2020].

- In this study we use a modification of this method with separation of the measured magnetic field into external and internal parts. It is assumed that currents flow in two shells:

1. Above the Earth to approximate the external source
2. Below the surface of the Earth to account for the EM induction

- Actual currents are obtained by fitting of the observed magnetic field.

Considered event: 2017/09/07 20:00:00 - 2017/09/08 23:59:50 UT.

Source of magnetic field data: IMAGE magnetometer array.

Magnetic field data cadence: 10 s.

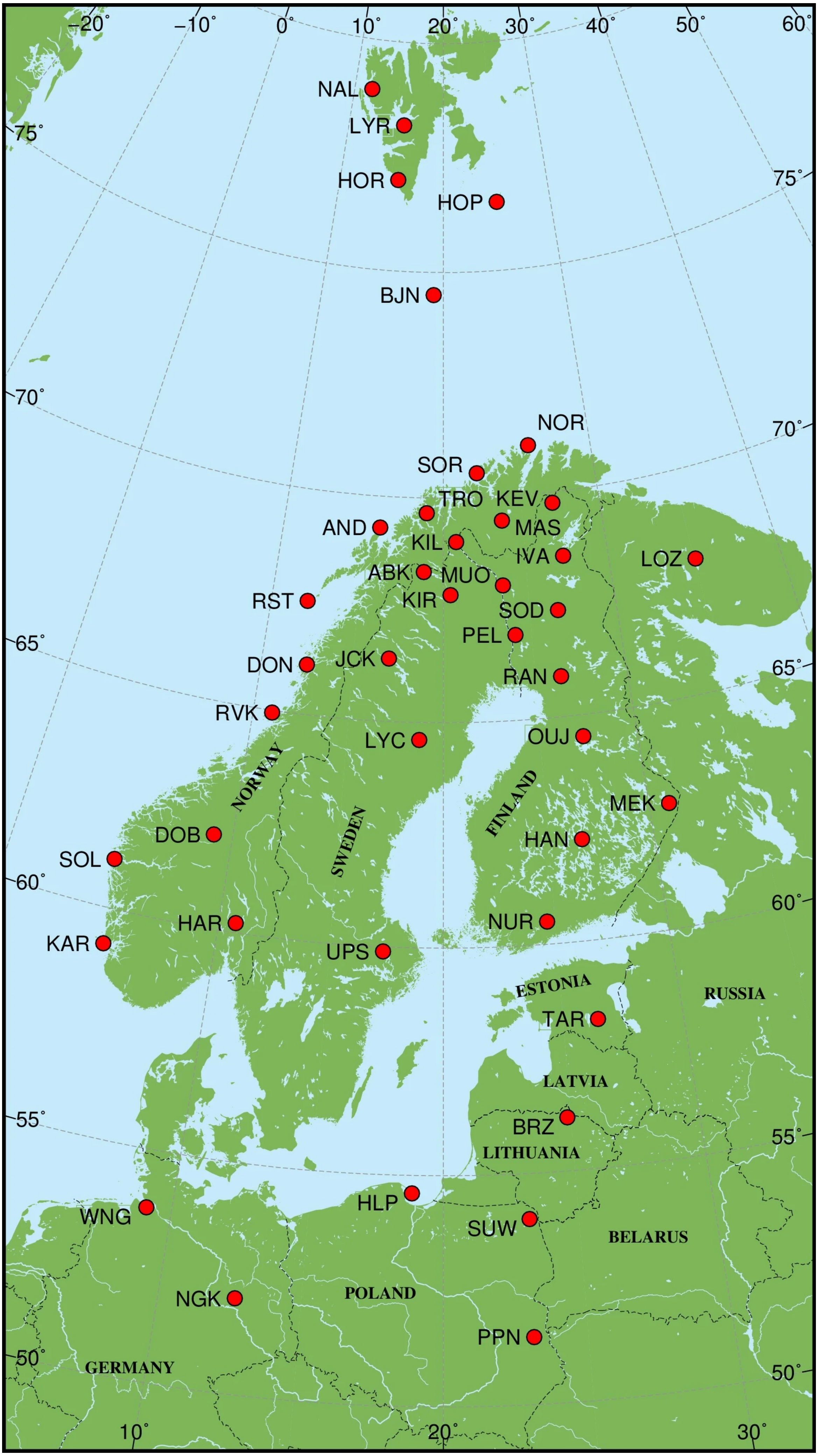
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Figure 1. IMAGE magnetometer array. Source: Finnish Meteorological Institute.

PRINCIPAL COMPONENT ANALYSIS

Principal component analysis (PCA) is a dimensionality-reduction method that is often used to reduce the dimensionality of large data sets, by transforming a large set of variables into a smaller one that still contains most of the information in the large set[1] (https://builtin.com/data-science/step-step-explanation-principal-component-analysis).

$$\mathbf{j}^{ext}(t,\mathbf{r}) \approx \sum_{i=1}^{L} c_i(t)\mathbf{j}_i(\mathbf{r})$$

Here $\mathbf{j}^{ext}(t,\mathbf{r})$ is the equivalent ionospheric current, t is time, $\mathbf{r}$ is a position vector, $c_i(t)$ are time-dependent coefficients, $\mathbf{j}_i(\mathbf{r})$ are time-independent spatial modes (principal components), L is the number of spatial modes.

According to the PCA, 99% of the variability of the SECS source during the considered event can be described using L=21 spatial modes.

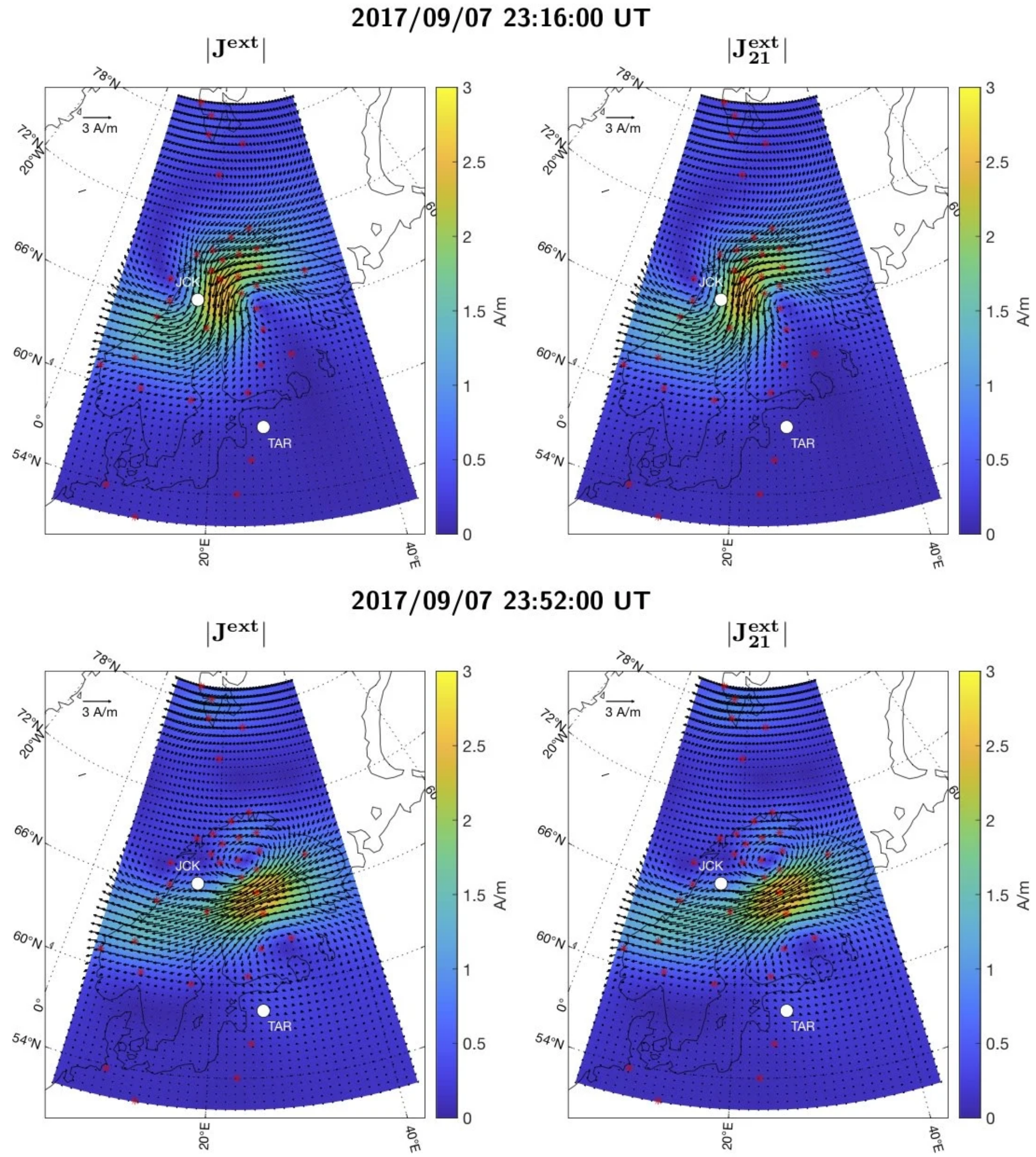

Figure 2. Left: the original external equivalent current; right: the external equivalent current constructed using 21 spatial modes. The results (in A/m) are for two time instants: 23:16:00 (top row) and 23:52:00 (bottom row) UT on September 7, 2017.

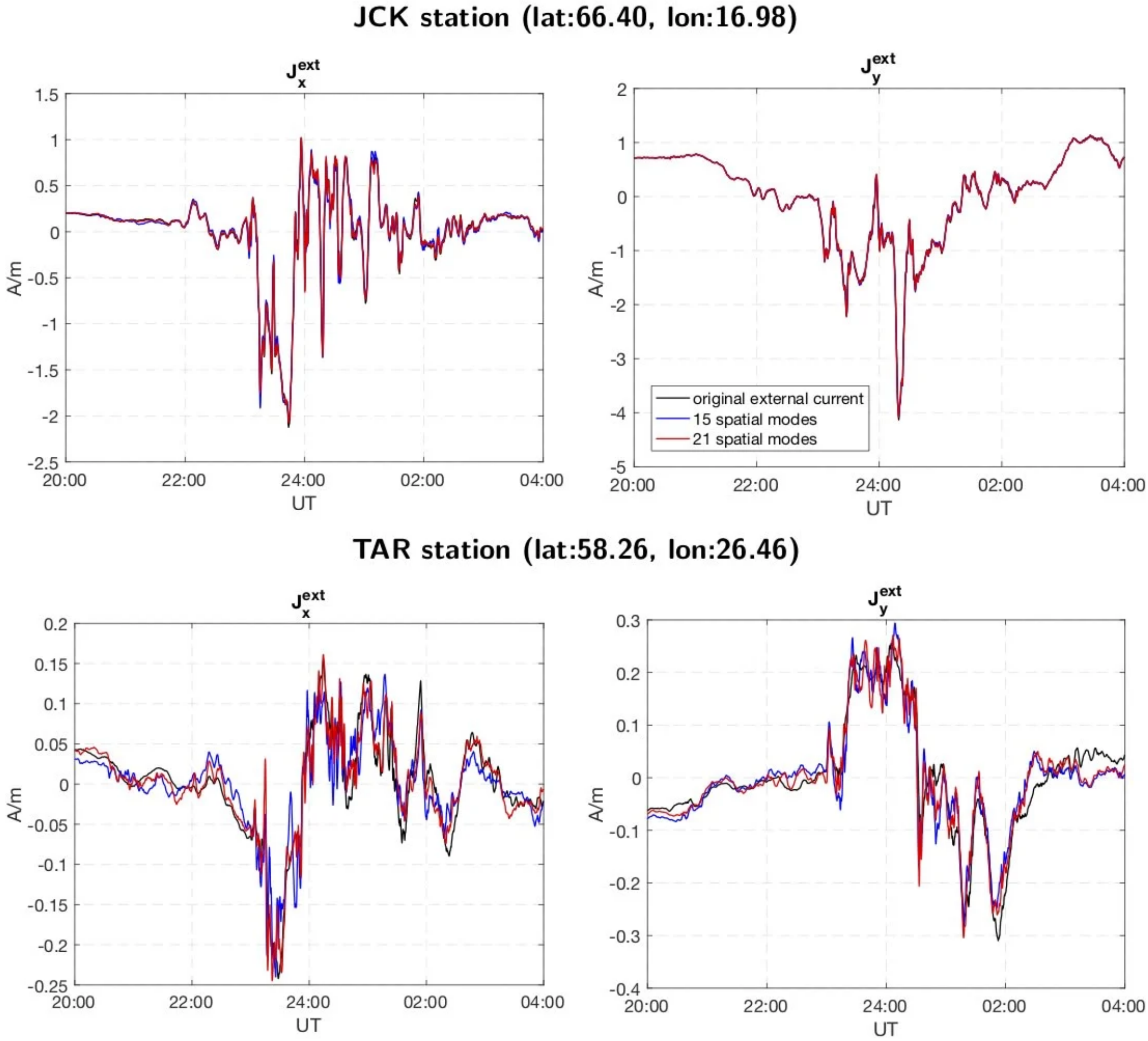

Figure 3. Time series of the original external equivalent current (black curves) and external equivalent current constructed using 15 (blue curves) and 21 spatial modes (red curves) above two exemplary sites (Jäckvik (JCK) and Tartu (TAR)). The results are in A/m. Left and right panels show x- and y-components of the currents, respectively. Note different scales in the panels. Locations of the sites are shown in Figure 2 as white circles.

REAL-TIME ELECTRIC FIELD MODELING

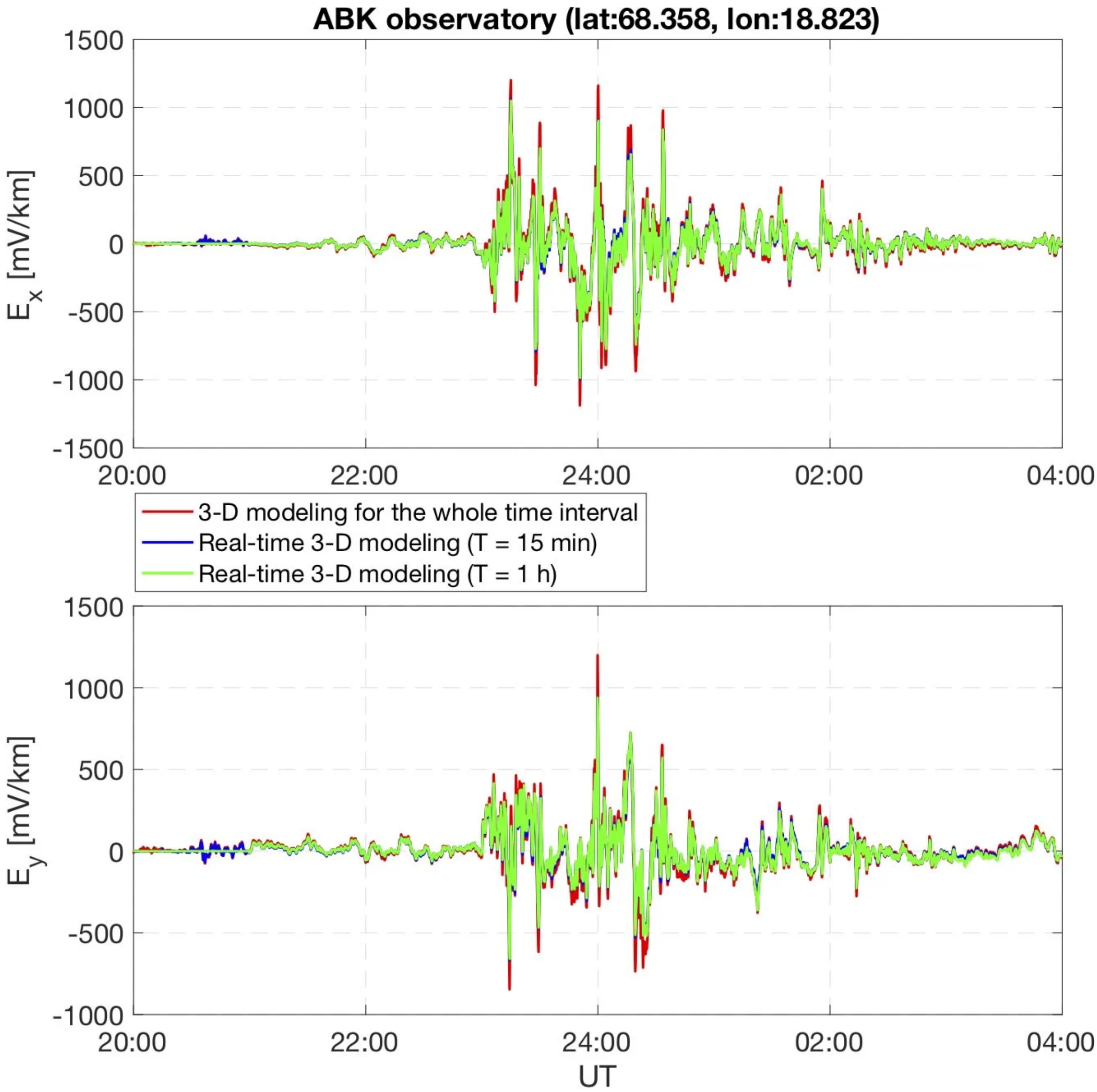

Figure 4. Electric field components at Abisko (ABK) geomagnetic observatory location obtained using 3-D EM modeling with 21 spatial modes for the whole 8 h time interval (from 20:00:00 UT, 7 September 2017, to 03:59:50 UT, 8 September 2017) (red curves) and electric field components at the same observatory simulated using real-time 3-D GEF modeling approach with 15 min (blue curves) and 1 h (green curves) time segments.

Our standard approach:

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

2. Maxwell's equations in the frequency domain are numerically solved for the corresponding frequencies ω using 3-D EM modeling code PGIEM2G based on the volume integral equation approach [Kruglyakov and Kuvshinov, 2018]

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

where μ_0 is the magnetic permeability of free space; ω is angular frequency; $\mathbf{B}(\mathbf{r},\omega;\sigma)$, $\mathbf{E}(\mathbf{r},\omega;\sigma)$ are magnetic and electric fields, respectively. $\sigma(\mathbf{r})$ is the spatial distribution of electrical conductivity.

3. Electric field **E**(t,**r**) and magnetic field **B**(t,**r**) in the time domain are obtained by means of the inverse Fourier transform.

Real-time electric field modeling:

1. Precompute electric field $\mathbf{E}_i(\mathbf{r}_s,\omega;\sigma)$ for selected PCA-recovered spatial modes for a set of frequencies using PGIEM2G
2. Calculate convolution integrals: $\mathbf{E}(\mathbf{r}_s,\tau;\sigma) = -\frac{2}{\pi}\int_0^\infty \mathrm{Im}\,\mathbf{E}_i(\mathbf{r}_s,\omega;\sigma)\sin(\omega\tau)\,\mathrm{d}\omega$
3. Calculate electric field in the time domain using following convolution integrals: $\mathbf{E}(\mathbf{r}_s,t;\sigma) \approx \sum_{i=1}^{L}\int_0^T c_i(t-\tau)\mathbf{E}_i(\mathbf{r}_s,\tau;\sigma)\mathrm{d}\tau$

$c_i(t-\tau)$ are obtained using the PCA of the SECS source and can be a continuously augmented nowcasted or forecasted time series.

Electric field at a time step t will be calculated based on the data for the previous time segment of length T. According to out analysis T=15 min is a reasonable choice (see Figure 4).

CONDUCTIVITY MODEL

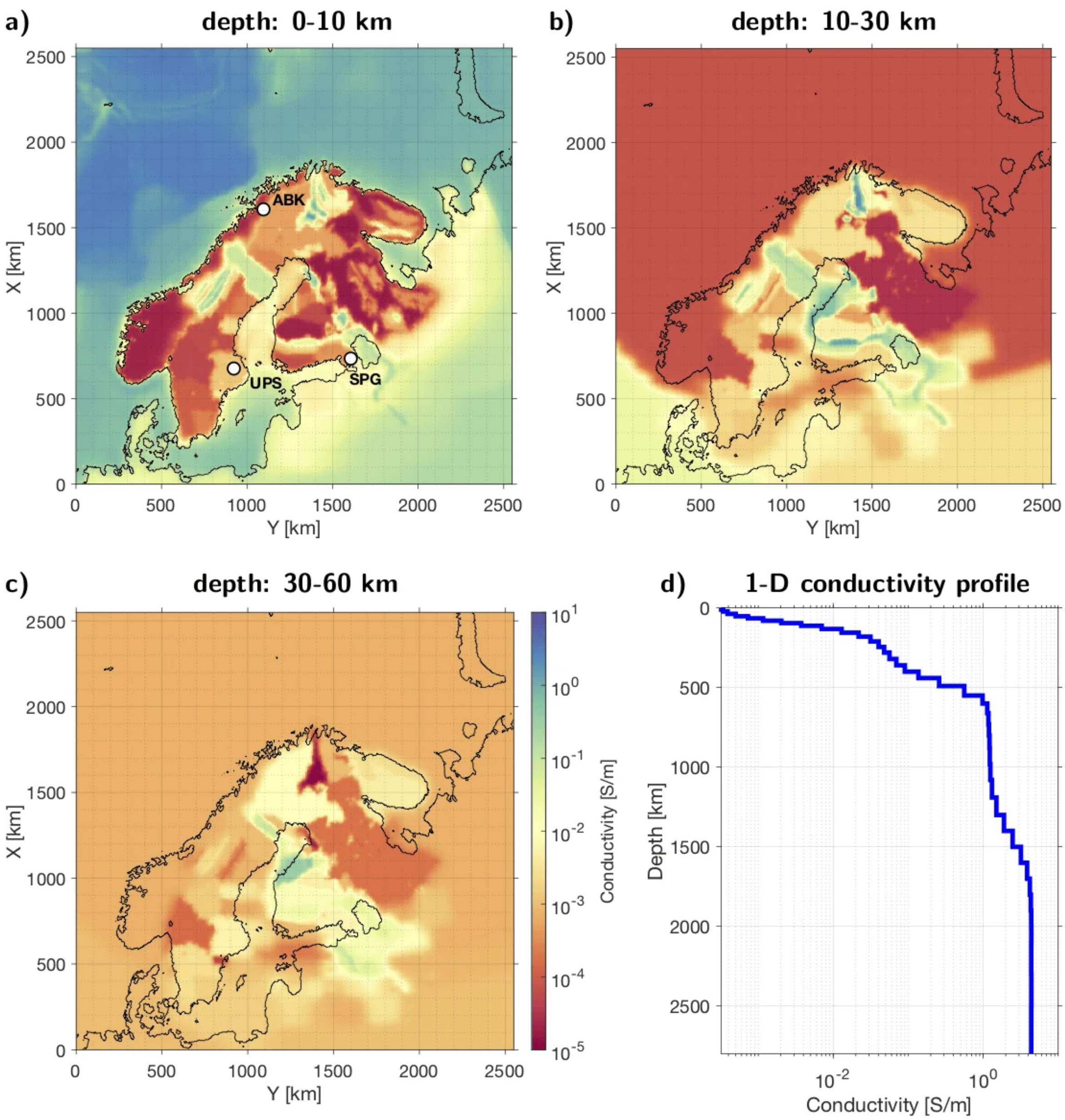

Figure 5. Conductivity distribution [S/m] in the model of Fennoscandia: (a)-(c) Plane view on 3 layers of the 3-D part of the model; (d) global 1-D conductivity profile from Kuvshinov et al. [2021] used in this study. Locations of geomagnetic observatories Abisko (ABK), Uppsala (UPS), and Saint Petersburg (SPG) are marked with circles in plot (a).

Conductivity model:

1. Based on SMAP model [Korja et al., 2002]
2. 3-D part of the model consists of 3 layers and is underlain by 1-D conductivity profile from Kuvshinov et al. [2021]
3. The size of the modeling region: 2550x2550 km
4. Lateral discretization: 5x5 km^2

NOTE ON THE COMPUTATIONAL TIME

Standard approach:

- Discretisation of the 3-D part of the conductivity model: 512x512x3 cells
- Laterally varying source
- Computational time for a single frequency (256 cores, ETHZ Euler cluster): up to 1.5 h

Real-time modeling:

- Calculation of the geoelectric field in the time domain on a 512x512 spatial grid
- 21 spatial modes, 15 min time segments
- Computational time: <0.025 s (depending on the computational environment)

Modeling details are presented in:

Kruglyakov, M., Kuvshinov, A., and Marshalko, E. (2021). Real-time 3-D modeling of the ground electric field due to space weather events. A concept and its validation. *Space Weather* (in review). Preprint available at the *Earth and Space Science Open Archive.* https://doi.org/10.1002/essoar.10507931.1 (https://doi.org/10.1002/essoar.10507931.1)

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