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Real-time modelling, nowcasting and forecasting ground electric field due to Space Weather events using satellite and ground-based data

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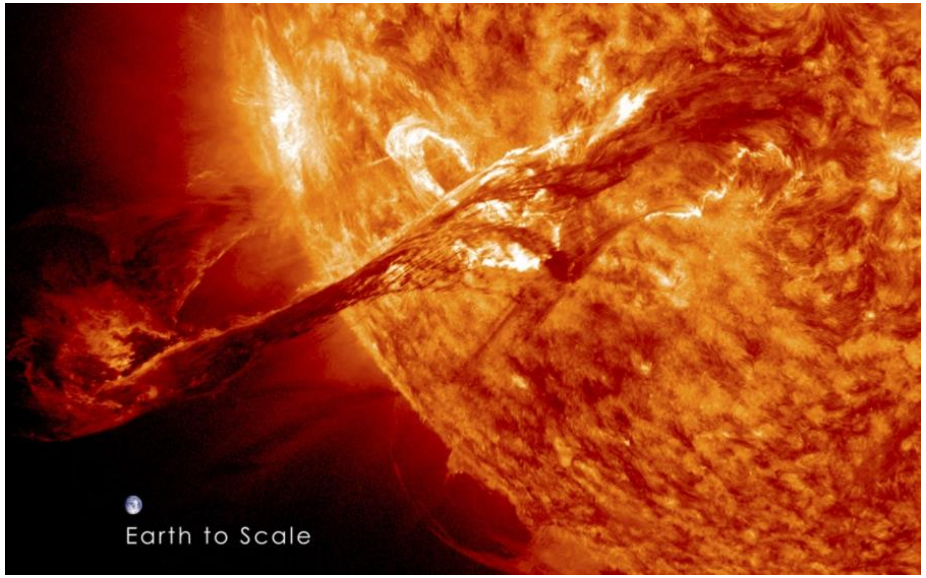
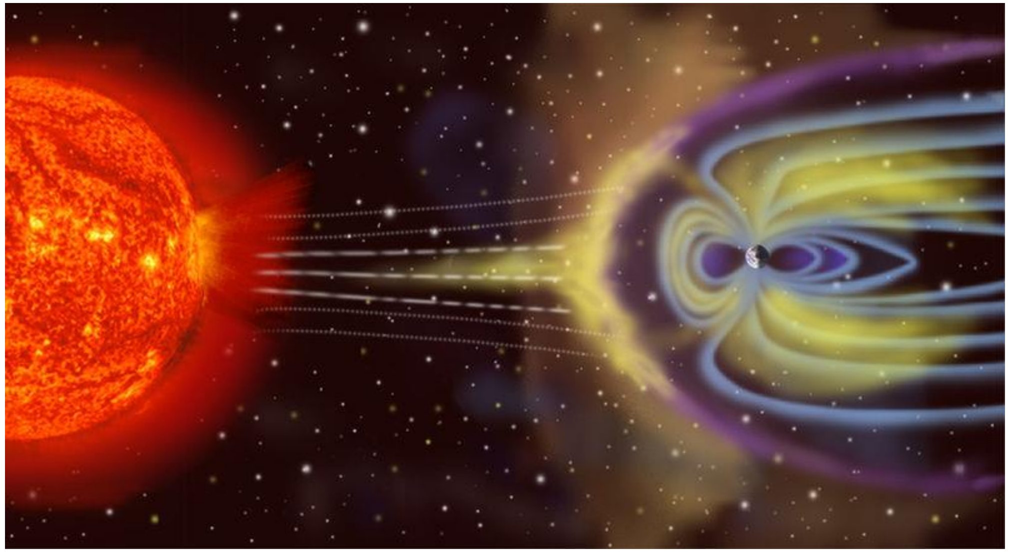
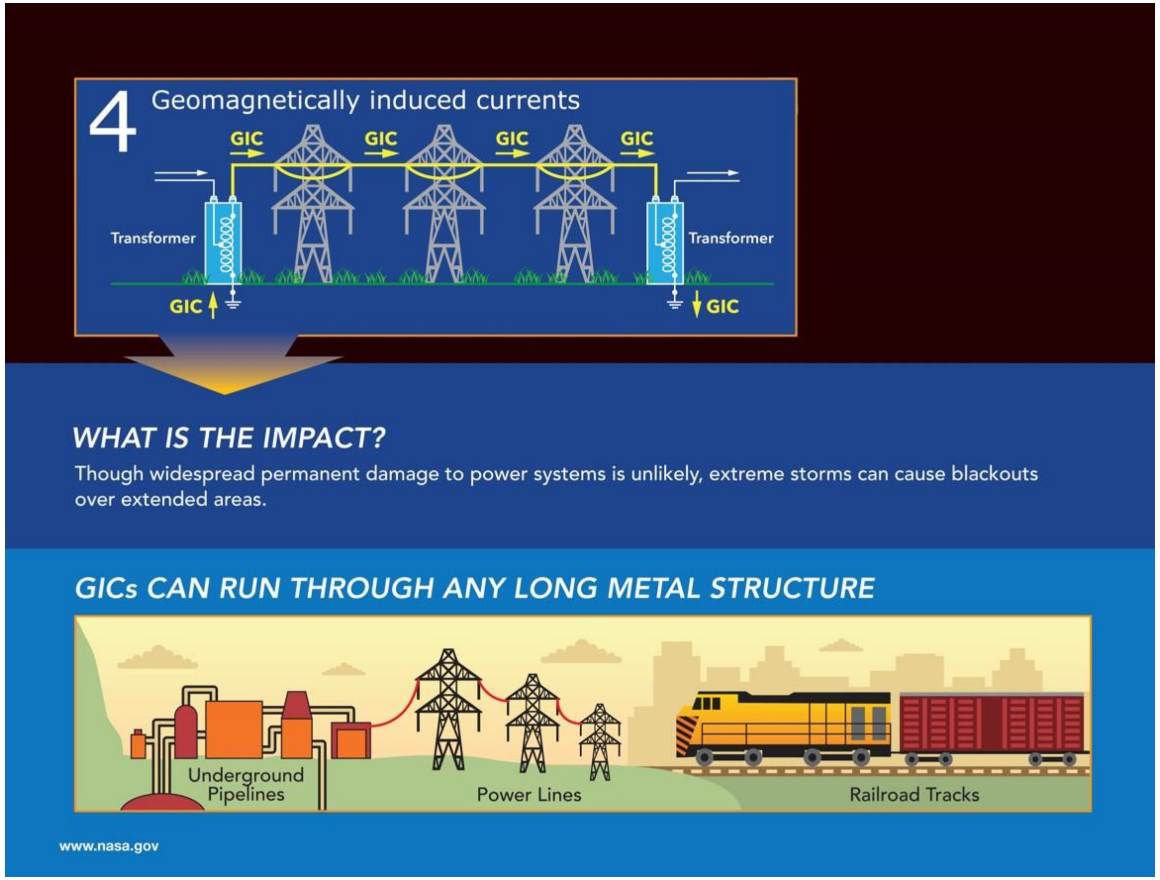
Context:





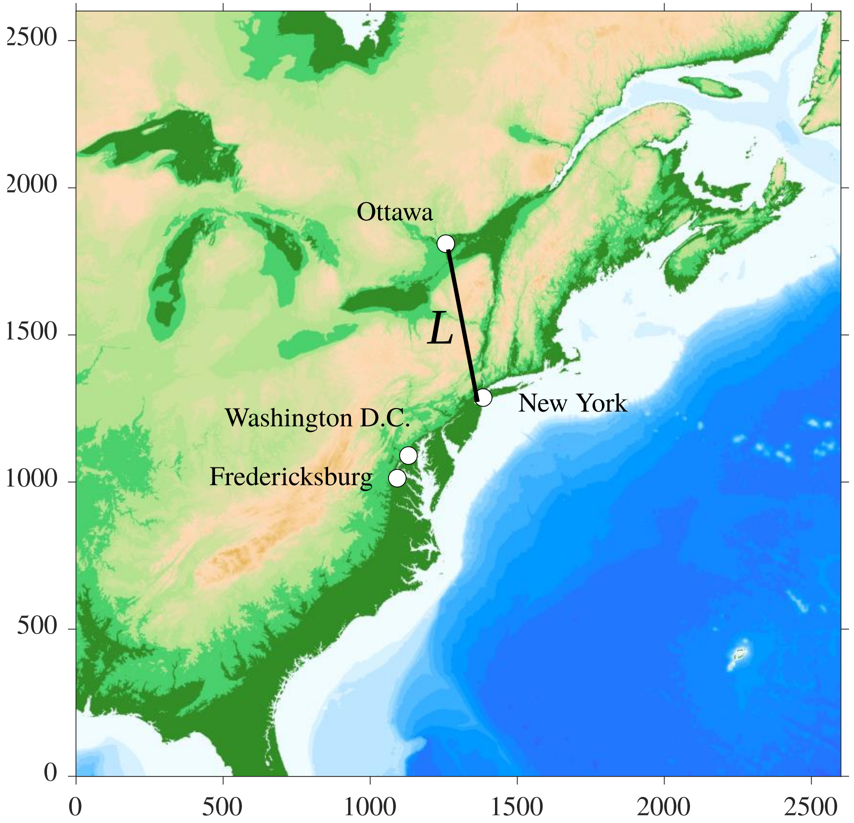
- Coronal mass ejections produce large release of plasma
- Plasma (with a speed of 400 km/s and higher; solar wind) flows into interplanetary space
- The interaction of the wind with Earth's magnetosphere/ ionosphere leads to storms/substorms

The storms/substorms generate geomagnetically induced currents (GICs) in the power grids; strong GICs can damage these technological systems



Topical task of Space Weather studies is a real-time forecasting of GICs and, ultimately, elaboration of an alerting system(s) for power companies

Modelling GICs



Based on known power line design parameters

$$\text{GIC}(t) = f\left[V(t)\right]$$

$$V(t) = \int_L \bar{E}(l,t)\,dl$$

Thus, to model GICs one needs to model (preferably in real-time) ground electric field (GEF)

To model GEF in real time (globally or regionally) one needs:

(1) Adequately parameterize the source of geomagnetic disturbances

(2) Specify the spatiotemporal evolution of the source

(3) Build electrical conductivity model of the Earth's subsurface

(4) Perform – in a given conductivity model – real-time modelling of GEF, i.e., compute as fast as feasible the spatio-temporal progression of the GEF from continuously augmented data on the spatio-temporal evolution of the source

(5) Convert the predicted GEF into GIC

Real-time 3-D modelling of GEF*

- Factorize the source via spatial modes $\bar{j}_i(\bar{r})$ and corresponding time series of the expansion coefficients $c_i(t)$

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

L – number of spatial modes

- Then GEF can be written as

$$\bar{E}(\bar{r},t;\sigma) = \sum_{i=1}^{L} \int_0^T c_i(t-\tau)\bar{E}_i(\bar{r},\tau;\sigma)\,d\tau$$

σ – Earth's conductivity, $\bar{E}_i$ - electric field corresponding to $\bar{j}_i$, *T* – "memory"

* Kruglyakov M., A. Kuvshinov, E. Marshalko, 2022, Real-time 3-D modeling of the ground electric field due to space weather events. A concept and its validation, Space Weather.

Numerical implementation

$$\bar{E}(\bar{r},t_k;\sigma)=\sum_{i=1}^{L}\sum_{n=0}^{N_t}c_i(t_k-n\Delta t)W_{\bar{E}_i}(\bar{r};\sigma)$$

t_k - current time instant

Δt - sampling rate of time series

$\bar{r}$ - positions where one needs the field

N_t - number of samples in the past ($T = N_t\Delta t$)

$W_{\bar{E}_i}(\bar{r};\sigma)$ - weights precomputed for a given conductivity model and a given source $\bar{j}_i$

L – number of spatial modes

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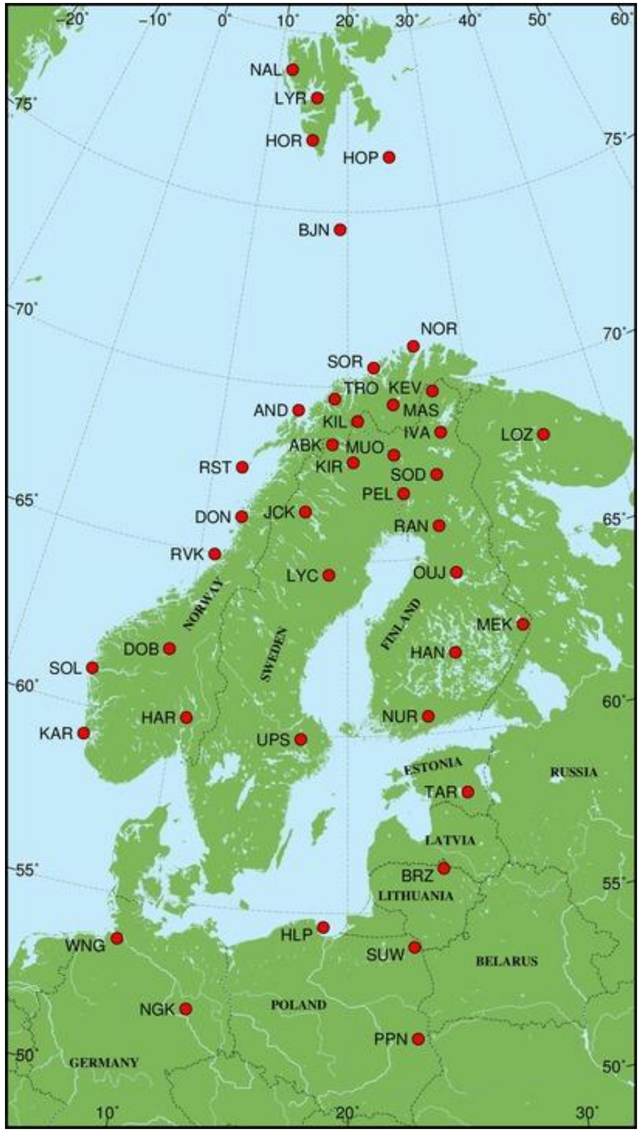
Validation: data, event and (regional) source

- Data: three components of magnetic field at IMAGE network

- Event: 7-8 September 2017 storm

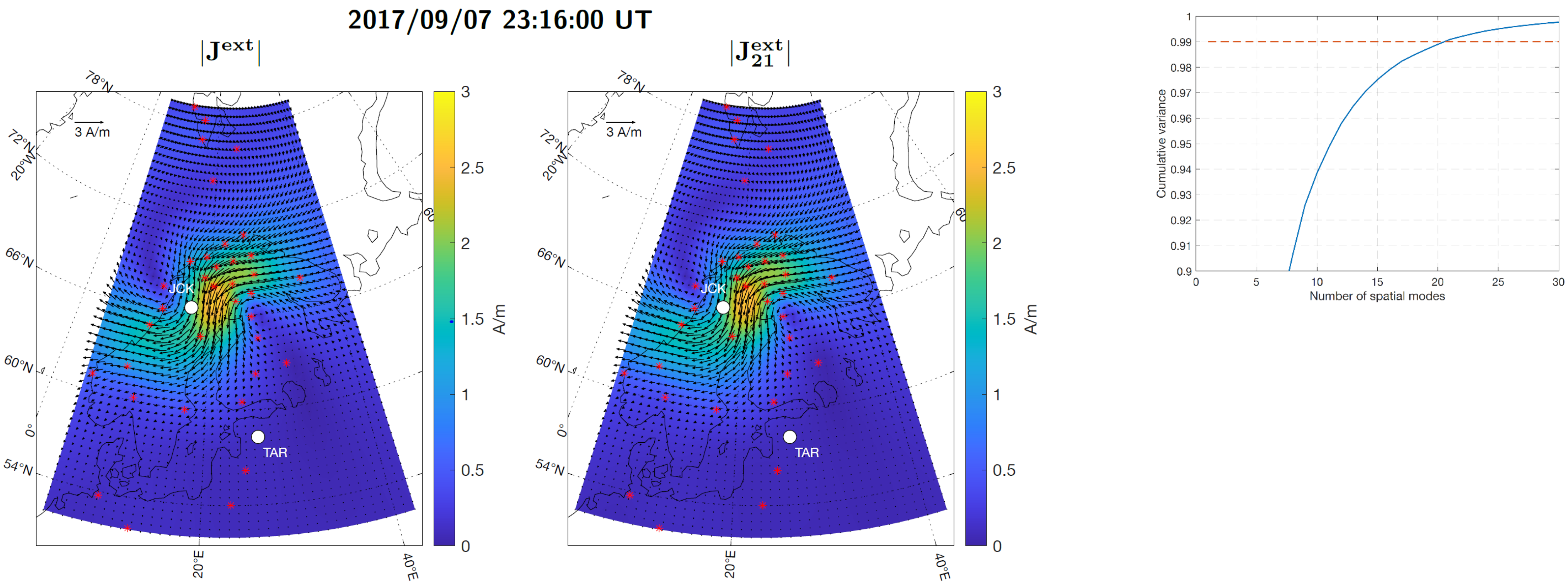
- Spatial modes and corresponding time series are obtained by Principal Component Analysis (PCA) of SECS-recovered* source

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



Vanhamaki, H., & Juusola, L., 2020. Introduction to Spherical Elementary Current Systems. In M. W. Dunlop & H. Luhr (Eds.), Ionospheric multi-spacecraft analysis tools.

Factorization of the source



$$\bar{j}^{ext}(\bar{r},t) = \sum_{i=1}^{L} c_i(t)\,\bar{j}_i(\bar{r}), \quad L = 21$$

(instead of original 3456 SECS-based currents)

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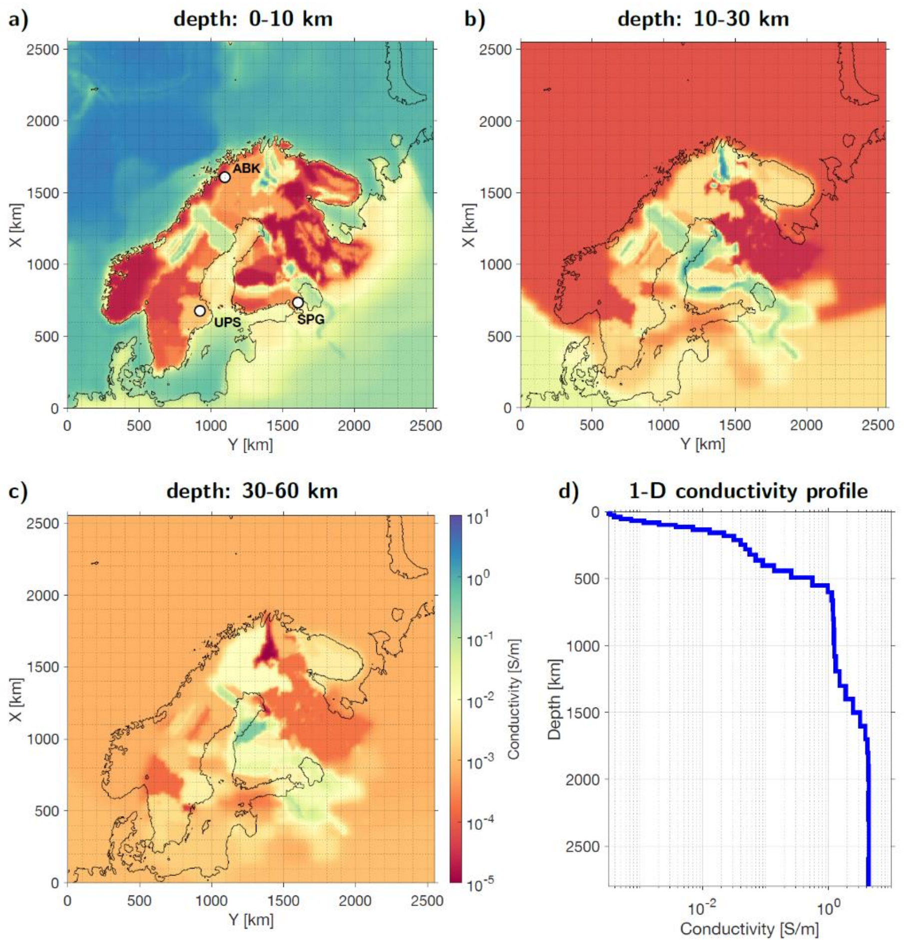
Building 3-D conductivity model*



Korja, T., Engels, M., Zhamaletdinov, A. A., Kovtun, A. A.,Palshin, N. A., Smirnov, M. Y., . . . BEAR Working Group, 2002. Crustal conductivity in Fennoscandia. Earth, Planets and Space

How fast?

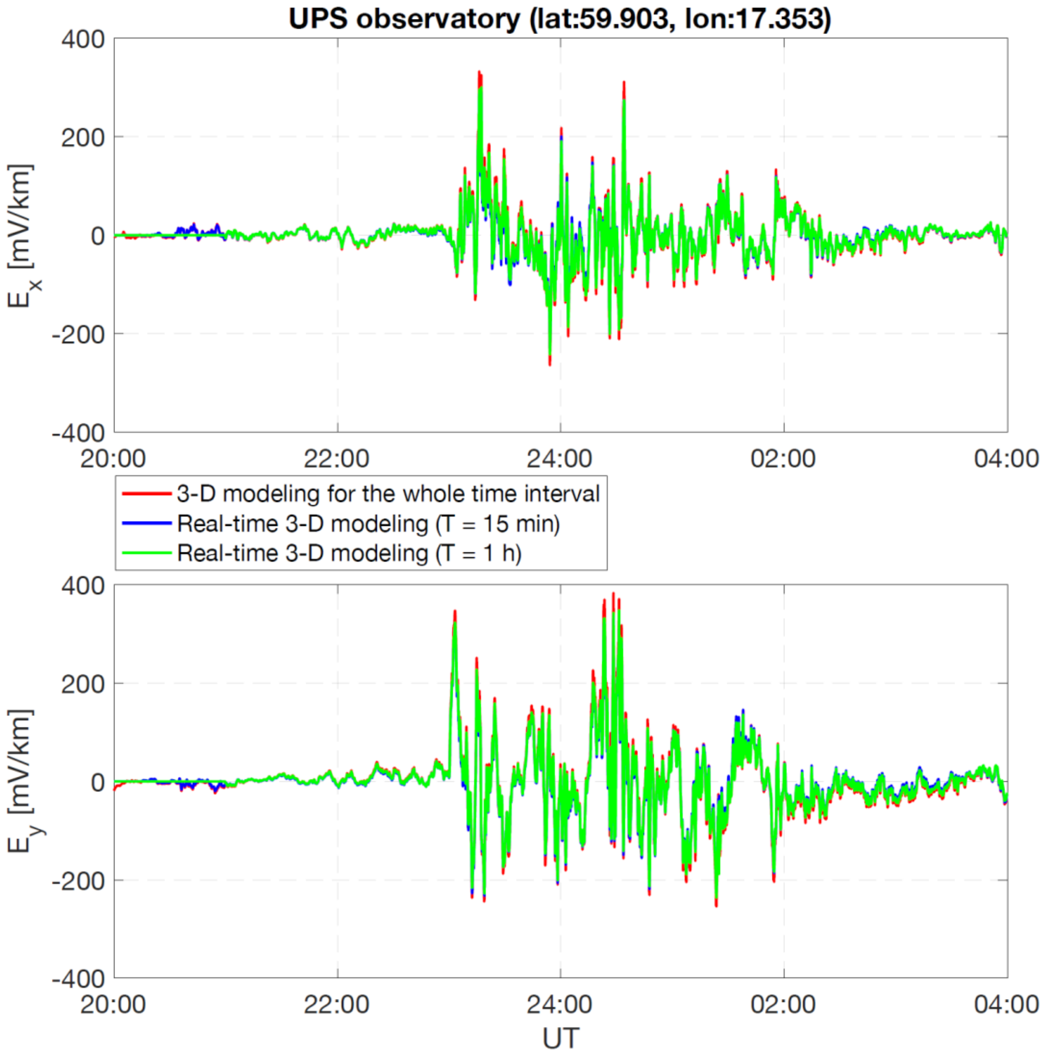
$$\bar{E}(\bar{r},t_k;\sigma)=\sum_{i=1}^{L}\sum_{n=0}^{N_t}c_i(t_k-n\Delta t)W_{\bar{E}_i}(\bar{r};\sigma)$$

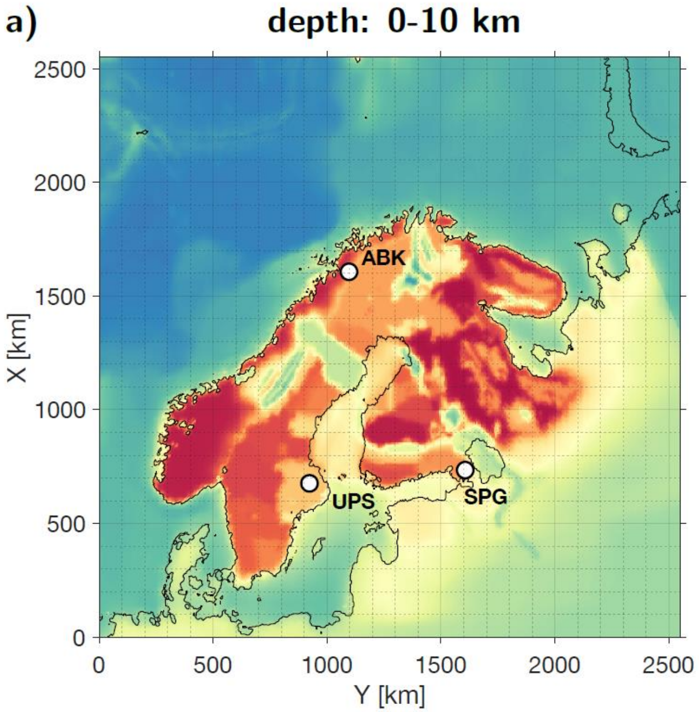
The above operation requires fraction of secs to get electric field at a grid of 512x512 sites at a current time instant provided $W_{\bar{E}_i}(\bar{r};\sigma)$ are precomputed and stored (and c_i is known in the past)

NB: computation of $W_{\bar{E}_i}(\bar{r};\sigma)$ requires numerical solution of Maxwell's equations at a set of frequencies and for *L* spatial modes; such computations take a few days but are performed only once (and in advance) and stored

Validation of the concept

$$\bar{E}(\bar{r}, t_k; \sigma) = \sum_{i=1}^{L} \sum_{n=0}^{N_t} c_i (t_k - n\Delta t) W_{\bar{E}_i}(\bar{r}; \sigma)$$

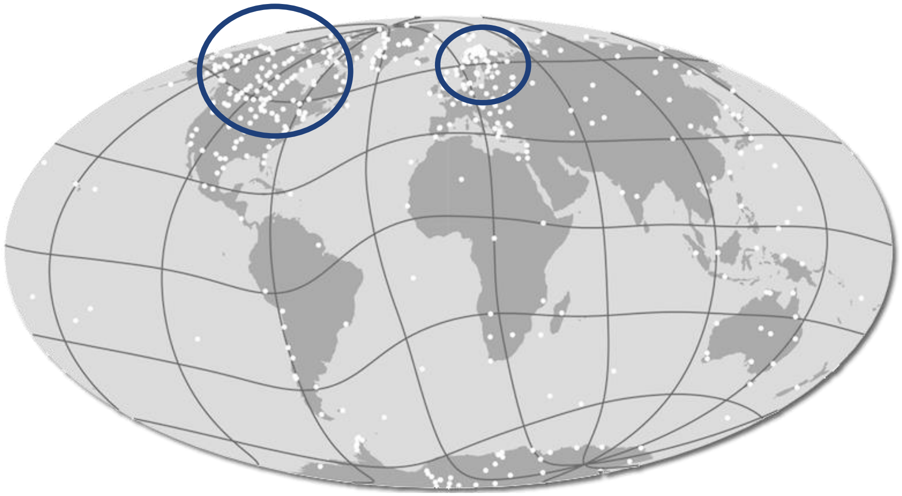




GEF nowcasting

(1) From *Swarm* and ground-based data for historical (past) event(s) one obtains spatial modes $\bar{j}_i(\bar{r})$ and coefficients $c_i(t)$ (using PCA)

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



(2) One calculates GEF as

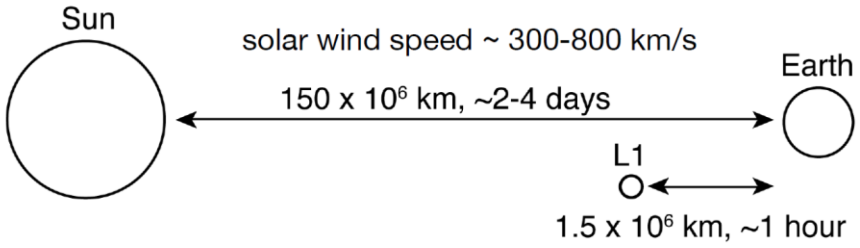
$$\bar{E}(\bar{r},t_k;\sigma) = \sum_{i=1}^{L}\sum_{n=0}^{N_t} c_i(t_k - n\Delta t)\,W_{\bar{E}_i}(\bar{r};\sigma)$$

GEF forecasting

(1) From *Swarm* and ground-based data for historical (past) event(s) one obtains spatial modes $\bar{j}_i(\bar{r})$ and coefficients $c_i(t)$ (using PCA)

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

(2) One trains NN using as input - the solar wind data from ACE/DSCVR satellites (located in L1 point) and as output - $c_i(t)$



(3) One forecasts $c_i(t)$ using trained NN, and then forecasts GEF as

$$\bar{E}(\bar{r},t_k;\sigma) = \sum_{i=1}^{L}\sum_{n=0}^{N_t} c_i(t_k - n\Delta t) W_{\bar{E}_i}(\bar{r};\sigma)$$

Concluding remarks

- Nowcasted ground electric field (in a form of global/regional maps progressed in time) could be a valuable Swarm-based product

- Accurate nowcasting requires realistic and detailed 3-D conductivity model(s) of the Earth’s (ongoing ESA-funded project) and realistic model(s) of the source (Macao and NanoMagsat satellite missions would help)

- Forecasting GEF (essentially forecasting the realistic source) remains very challenging task