Replies to Referees #1 and #2

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Dear Referee #1,

thank you for very useful and constructive comments. Please, see below for our point-by-point replies. The original review is written in *black* and our replies in blue. The line numbers refer to the original manuscript.

Review comments on the manuscript egusphere-2024-2831, entitled: Estimation of the 3-D geoelectric field at the Earth's surface using Spherical Elementary Current Systems

by Liisa Juusola et al.

The authors tried to derive the geoelectric field at the Earth's surface from magnetic field variations measured in the vicinity. The various components of the E-field are estimated with the help of the SECS approach and by using the 3-D induction model PGIEM2G. This approach is applied to IMAGE Magnetometer Network area. Convincing results are obtained in this way, which compare quite favorably with GIC measurements in gas pipelines. The computational design of the framework is suitable for running it in near-real time for estimating space weather hazards, resulting from GICs in the Fenno-Scandian region.

In spite of these generally positive ratings, the study would gain, when improvements were made in a number of cases.

Open issues

1. *One thing, the authors obviously have not taken into account is the effect of prompt penetrating electric fields on the geoelectric field. As shown by Brändlein et al. (2012) doi:10.1029/2012JA018008, the ionospheric Hall current, driven by the prompt penetration field, causes ground-based magnetic signatures, but it does not cause geoelectric fields on the ground. At mid-latitudes significant effects of this process can be observed. I am not aware that anyone has studied this effect at auroral latitudes. This point should be discussed.*

   Thank you for bringing this to our attention. We suggest to add at line 132:

   "This follows from neglecting the displacement current, as is usual in geoelectromagnetism. However, it should be noted that the displacement current may play a role in producing ground-based magnetic field signatures that do not cause a geoelectric field on the ground (Brändlein et al., 2012)."

   and at line 151:

   "Brändlein et al. (2012) discussed a waveguide transmission, where the wave mode on the ground has a non-zero horizontal magnetic field component but a zero horizontal electric field. In the vertical direction such a wave mode is expected to have a zero magnetic and non-zero electric field components. The SECS reconstruction is able to reproduce such a magnetic field as a superposition of the magnetic fields of ionospheric and telluric equivalent currents. Because the vertical magnetic field is zero, $\boldsymbol{E}_{DF}$ would also be zero."

2. *Table 3: Larges ground E-fields are predicted at the end of 7 Sep. 2017 for a location close to the transformer of Namsos. It should be checked if measurements of ground currents are available at that station. In case there are, they should be compared with the predictions. This would make the study much more convincing and relevant for application.*

   Unfortunately, the Namsos GIC measurement did not start until 2020. Furthermore, in order to predict the GIC, the network geometry and resistances would be needed. This information is generally classified.

3. *In the Introduction it is mentioned that a second layer is introduces below the Earth's surface. From the following sections it is not clear what this extra layer physically represents. How does it account for lateral conductivity variations?*

   This is a good point. We suggest to modify the text at line 78. The original text is

   "... a second layer just below the Earth's surface. This..."

   and the modified text would be

   "... a second layer just below the Earth's surface, to represent the magnetic field of the telluric currents. A ground conductivity model is not needed for the DF electric field calculation, because the conductivity distribution affects the telluric current distribution, and this is reflected in the magnetic field it produces. Using two layers instead of one..."

4. *Another statement is that the radial component of EDF is not required to be zero. What is the effect of that assumption? What does it physically imply? These two latter assumptions are pointed out as important assets of the presented approach. Therefore, they should be better explained to the readers.*

   We do not make any requirements about the radial direction of EDF, but show that, because of the geometry of the DF SECS, EDF only has a horizontal component between the ground surface and the ionospheric sheet current. In order to try to make this more clear, we suggest to modify the text at line 132. The original text is

   "Consequently, the induced electric field only has a ϕ' component,"

   and the modified text would be

   "Due to the geometry of the DF SECS magnetic field, the corresponding induced electric field only has a ϕ' component (see also the vector potential derivation in Amm and Viljanen (1999)),"

   Furthermore, we suggest to add at line 151, after the addition suggested in our reply to point 1:

   "Although the combination of ionospheric and telluric DF current densities always produces a DF electric field that has a zero vertical component between the ionspheric and telluric equivalent current sheets, this does not necessarily mean that $\boldsymbol{E}_{DF}$ cannot have a vertical component in this region. This issue was investigated in detail by Pirjola and Viljanen (1998). In addition to the parts described by the DF current densities, the 3D current distributions in the ionosphere and in the ground include a part that has a zero magnetic field between the ionosphere and ground surface. However, the corresponding vector potential $\boldsymbol{A}$ may not be zero, although $\nabla \times \boldsymbol{A}$ must be zero. The corresponding DF electric field is a Laplace field that has its sources above the ionosphere and inside the ground. A similar Laplace electric field could also be produced with electric charges in these regions. According to the results by Pirjola and Viljanen (1998), valid up to neglecting the displacement current, any horizontal part of this DF field is cancelled by charges accumulated on the ground surface, leaving only an insignificant vertical component. Thus this part of the induction process does not drive any GIC."

Dear Referee #2,

thank you for very useful and constructive comments. Please, see below for our point-by-point replies. The original review is written in *black* and our replies in blue. The line numbers refer to the original manuscript.

The authors describe a new set of techniques to model the geoelectric field using curl free as well as the divergence free geomagnetic field. They work through a series of simplification of Maxwell's equations to derive the relationships and point out interesting insights into the induced geoelectric field properties. The model does require a good representation of the ground conductivity which can be a limitation for many other locations. Overall this is an excellent contribution to the research area and will be interesting to apply in locations outside the Scandinavian region.

Minor comments:

Abstract: I would not have a citation embedded in the abstract ((Kruglyakov & Kuvshinov, 2018)

We will remove the citation.

Line 9: coefficients

Will be corrected.

Line 17: with orders of magnitude

Will be corrected.

Line 24: , a solid understanding

Will be corrected.

Line 25: scarce

Will be corrected.

Line 28: A couple of more linking sentences would be useful. E.g. To achieve an intercomparison of results we ... "do things ..."

We suggest to add: "We will approach the modelling problem by separating the different contributions to the geoelectric field."

Line 52: surface

Will be corrected.

Line 150: You make an excellent point about the induced fields tending to cancel each other out.

Thank you!

Line 188: geoelectric

Will be corrected.

Line 300: It is not entirely clear at this point that the SMAP model with PGIEM2G is a prerequisite for the modelling to work to compute CF from DF. Can you clarify that here?

We suggest to modify the original sentence

"In principle, it should be enough to to determine the time-independent coefficients from a single active interval."

by adding the clarification at the end of it:

"In principle, it should be enough to to determine the time-independent coefficients from a single active interval modelled using SMAP and PGIEM2G."

Line 347: good data are available

Will be corrected.

Figure 3 caption: Last sentence says Bx, By, Bz but that is -B_theta, B_phi, -B_r rather than r, theta, phi as written.

Will be corrected.

Figure 5: Conductivity is in a diverging blue-white-red color scale - could you change it to a linear one (i.e. no white in the middle). This applies to other figures or plots with linear increasing rather than positive/negative variations

If it is acceptable, we would like to keep the current color scale. The diverging scale makes it easy to separate small and large values, which is important for the electric field amplitude and conductances. Furthermore, the combination of red and blue should be suitable for the colorblind, whereas many other color scales are not. As suggested by the editor, we will add explanations for where the white is and why in the relevant figure captions. We will also change the colormap of Fig. 18c (Fig. 2c of this document), because the original version contained colors that were not accessible, as pointed out by the editor.

Figure 10: similar comment about linearly increasing colors. Also there doesn't seem to be any red in the plots.

There are very small areas of red, mainly at some coast lines. However, as this is not clear, we suggest to saturate the plots further, as shown in the attached Figure 1.

Figure 18: the label on the colorbars are not legible

We will make them larger as shown in the attached Figure 2.

Additional corrections

In addition, we will remove some extra ϵ_0 from Eq. 22 and Eq. 24. This is just a typo and does not affect the results. We will also remove references to Kruglyakov and Bloshanskaya (2017) as this paper is about the predecessor of PGIEM2G.

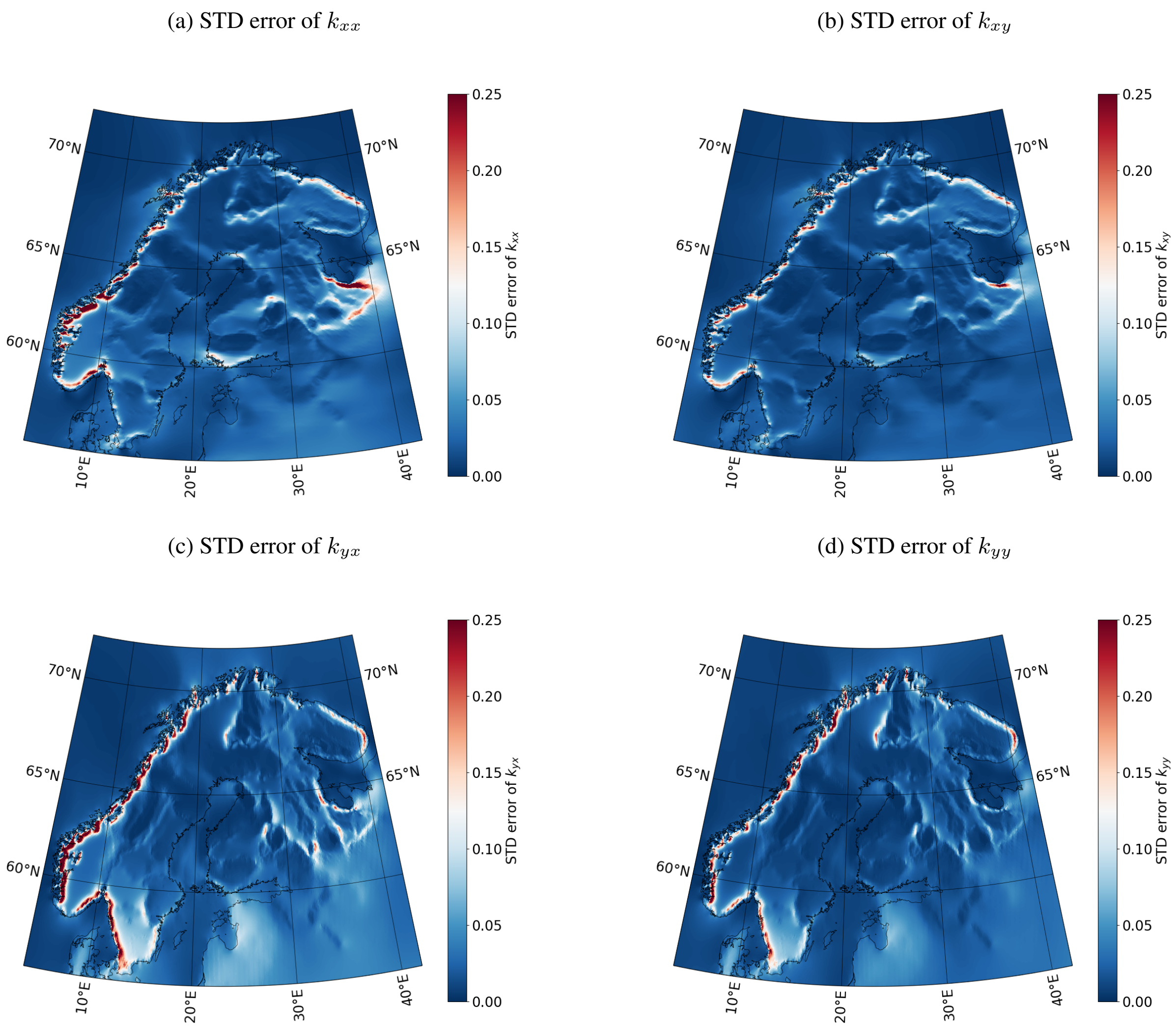


Figure 1.

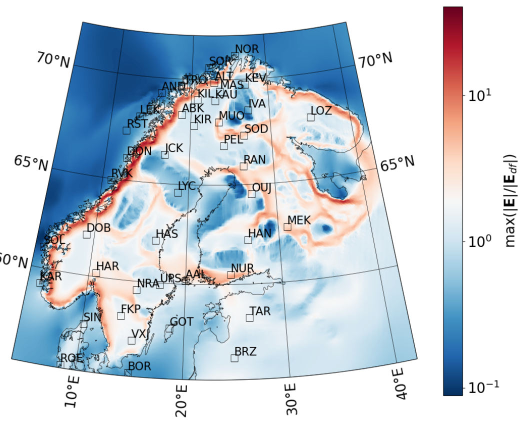
References

Amm, O. and Viljanen, A.: Ionospheric disturbance magnetic field continuation from the ground to ionosphere using spherical elementary current systems, Earth Planets Space, 51, 431–440, https://doi.org/https://dx.doi.org/10.1186/BF03352247, 1999.

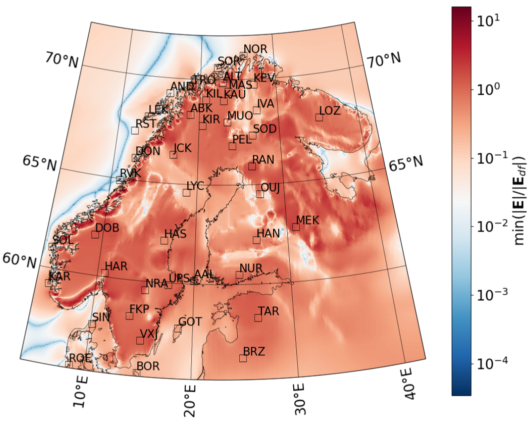
Brändlein, D., Lühr, H., and Ritter, O.: Direct penetration of the interplanetary electric field to low geomagnetic latitudes and its effect on magnetotelluric sounding, J. Geophys. Res., 117, A11314, https://doi.org/https://doi.org/10.1029/2012JA018008, 2012.

Pirjola, R. and Viljanen, A.: Complex image method for calculating electric and magnetic fields produced by an auroral electrojet of finite length, Ann. Geophys., 16, 1434–1444, https://doi.org/https://doi.org/10.1007/s00585-998-1434-6, 1998.

(a) Maximum $|\boldsymbol{E}|/|\boldsymbol{E}_{DF}|$



(b) Minimum $|\boldsymbol{E}|/|\boldsymbol{E}_{DF}|$



(c) $\boldsymbol{E}_{DF}$ direction for maximum $|\boldsymbol{E}|/|\boldsymbol{E}_{DF}|$

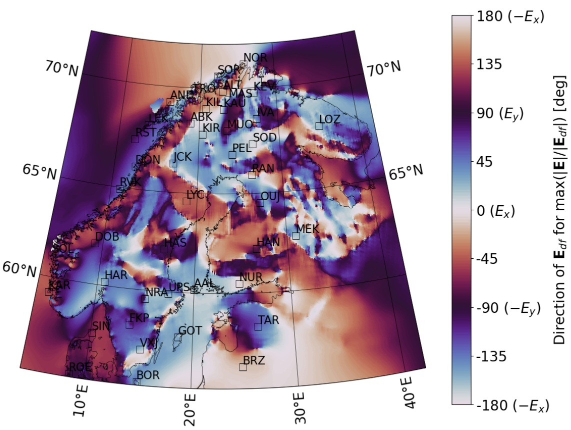


Figure 2.