Reply to Referee #1

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We thank Referee #1 for constructive comments and agree with almost all of them. Please, see below for our point-by-point replies. The original review is written in *black* and our replies in blue.

This paper presents a thorough and mathematically rigorous analysis of the relation between ground magnetic perturbations and ionospheric conductances measured by the EISCAT radars. The statistics are carefully performed, and the separation of the equivalent currents into divergence-free and curl-free parts is a significant improvement over prior similar studies.

There are several drawbacks to the model that should be addressed in more detail in the discussion section as noted in the attached annotated file. Nevertheless, the model described here can be very useful for the study of individual events localized over suitably spaced ground magnetometers.

Overall, this paper represents a significant contribution that will facilitate future studies and improved insights on auroral electrodynamic processes. I consider the paper publishable after the comments in the attached file are addressed.

The comments extracted from the file:

Line 26: difficult 'to' obtain

We will correct the typo.

Line 96: What was the intrinsic range resolution of the radar measurements?

Range resolution of the fitted plasma parameters depends on altitude and may vary between radar modes. The resolution is typically about 3 km in the lower E region (below 110 km altitude) and about 20 km at 330 km altitude.

We will add this explanation to the text.

Line 96: This is rather arbitrary. What percentage of the profiles were eliminated by this test, and how would that percentage change with different thresholds. Is the test done only in the altitude range up to 330 km? Does the presence of satellite echoes above this altitude affect the electron densities measured at other altitudes?

The limit was chosen to be close to, but clearly above, the largest density one may realistically expect in the F region. The test was done only for the interpolated data up to 330 km altitude. Also satellites above 330 km altitude may affect the densities measured below 330 km, because satellite echoes from above may be aliased below 330 km in the radar signal processing.

The fraction of profiles rejected based on this criterion was 0.066% for the UHF and 0.035% for the ESR. Fraction of rejected points as function of the threshold is shown in the attached Figure 1. The deep decline at thresholds smaller than

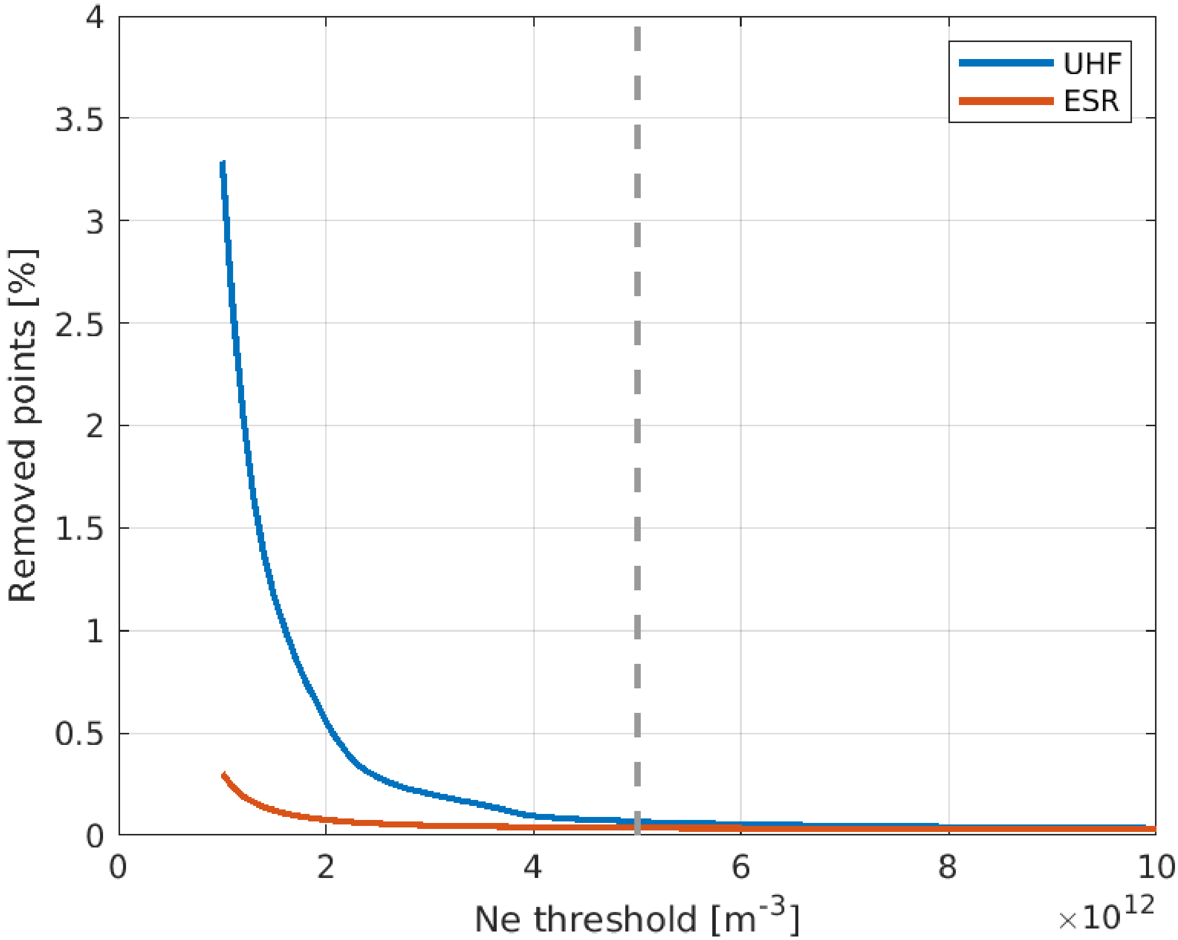

Figure 1. Fraction of rejected points as function of the electron density threshold.

$3 \cdot 10^{12}$ m^{-3} is believed to be from largest real electron densities, while $5 \cdot 10^{12}$ m^{-3} is close to beginning of a plateau probably caused by satellite echoes and other outliers.

We will add this explanation (without the figure) to the text.

Line 260: Why are there so many conductance values below that given by the Moen and Brekke model? Weren't they also based on EISCAT measurements?

Yes, the Moen and Brekke (1993) model is based on EISCAT measurements, but only on nine days of data (cf. line 56). Most likely the limited amount of data causes the model to be less than ideal for describing the larger data set we now have. This observation was part of the motivation for the current study (cf. line 69).

Line 409: The

We will correct the typo.

Line 416: The authors should consider comparing the field-aligned current determinations from those derived from AMPERE. This would help highlight the importance of spatial scales in the conductances and electrodynamic modeling results.

Thank you for a very good suggestion, we will add AMPERE data to Fig. 13 (Figure 2 of this document).

Line 436: There is no discussion of the effects of a neutral wind on the calculations.

Thank you for pointing this out. We suggest to add the following discussion:

"Neutral wind $\boldsymbol{v}_n$ perpendicular to the ionospheric background magnetic field $\boldsymbol{B}_0$ generally needs to be considered in ionospheric electrodynamics (e.g., Hatch et al., 2024). For example, in a coordinate system where the neutral wind is not zero, Ohm's law (Eq. 3) becomes

$$\boldsymbol{J} = \Sigma_P(\boldsymbol{E} + \boldsymbol{v}_n \times \boldsymbol{B}_0) + \Sigma_H(\boldsymbol{E} + \boldsymbol{v}_n \times \boldsymbol{B}_0) \times \hat{\boldsymbol{e}}_r. \quad (1)$$

Neutral wind is not required to estimate the electron density N_e from EISCAT observations and, thus, to estimate the conductivities with Eqs 6 and 7. The Ebec model is parametrized with electric current, which is independent on the frame of reference determined by the neutral wind. Thus, neutral wind is not expected to introduce errors to the conductances given by Ebec, and the electric field estimated from equivalent current density and Ebec conductances is given in the frame of reference where the neutral wind is zero."

Line 459: While artificially introducing gradients improves the agreement with Swarm, this represents an ad hoc solution that cannot be used in the absence of satellite measurements.

This is true, and for this reason we have included the demonstration as part of the discussion only.

Line 477: Some discussion should be added of the recent models that correlate conductances with field-aligned currents, thus ensuring the gradients are self-consistent with the parallel currents. The difference in spatial resolution between the EISCAT measurements and the equivalent currents derived from magnetometers is a significant drawback to the model presented here.

Thank you for the suggestion, we propose to add the following dicussion and figure:

"Recent models by Robinson et al. (2020) and Wang and Zou (2022) correlate conductances from the Poker Flat Incoherent Scattering Radar (PFISR) with field-aligned currents from AMPERE and Swarm, respectively, thus ensuring the conductances and their gradients are self-consistent with the parallel currents. The latitudinal scale of AMPERE field-aligned currents is about 3^o (Waters et al., 2020) and field-aligned current variations with a latitudinal scale of $150\ \mathrm{km}$ were used by Wang and Zou (2022). Thus, although the difference in spatial resolution between the EISCAT measurements and the equivalent currents derived from IMAGE magnetometers is a significant drawback to the Ebec model, the models parametrized by field-aligned currents also have similar limitations.

Figure 15 (Figure 3 of this document) shows Σ_P and Σ_H as given by the conductance models of Robinson et al. (2020) and Wang and Zou (2022) when applied to the AMPS field-aligned current density (Fig. 10d). Note that due to the large differences in conductance amplitudes, the color scales are not the same as those in Fig. 9b–e. Apart from the amplitudes, the most obvious difference in the conductances given by Robinson et al. (2020) and Wang and Zou (2022) compared to SWIPE and Ebec is the latitudinally wide double oval structure caused by parametrizing by both upward and downward field-aligned current density. The coefficients of the COMPASS model by Wang and Zou (2022) are defined for three-hour MLT sectors, resulting in the discontinuous conductance distributions that could be smoothed, e.g., by interpolation."

Line 486: The authors should note that the overall agreement with Ahn et al. suggests that these relations are not dependent on the geographic locations of the magnetometer measurements.

Do you mean that this indicates that the internal contribution to magnetometer measurements is not significant?

The internal part is typically some tens of percent of the total horizontal variation magnetic field amplitude, and directed such that it strengthens the external horizontal field. However, this depends much on geographic location. For example, it is possible that the internal contribution to the magnetometer data used by Ahn et al. may have been particularly small. Without a more thorough investigation, we do not think that an overall agreement between the Ahn et al. (1998) and our model indicates that the internal contribution to magnetometer measurements in general can be considered insignificant.

Line 497: The authors should discuss whether this method can help model the extreme magnetic perturbations associated with GICs. Is it possible these GIC events are associated with large EDF values?

Indeed, this is the case as discussed in Juusola et al. (2025). We suggest to add:

"Especially, the possibility of extracting $\boldsymbol{E}_{DF}$ on the ground surface (Juusola et al., 2025) allows detailed studies of extreme magnetic perturbation events associated with GICs."

Figure 8: The vertical scale should be adjusted to better show the spread in conductance values.

We will adjust the scale.

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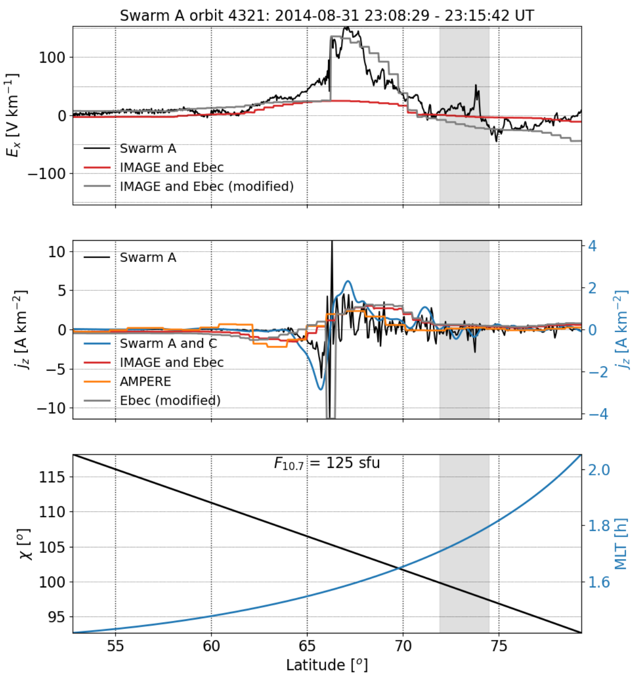
(a)


Swarm A orbit 4321: 2014-08-31 23:08:29 - 23:15:42 UT
E_x [V km^{-1}]
Swarm A
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j_z [A km^{-2}]
Swarm A
Swarm A and C
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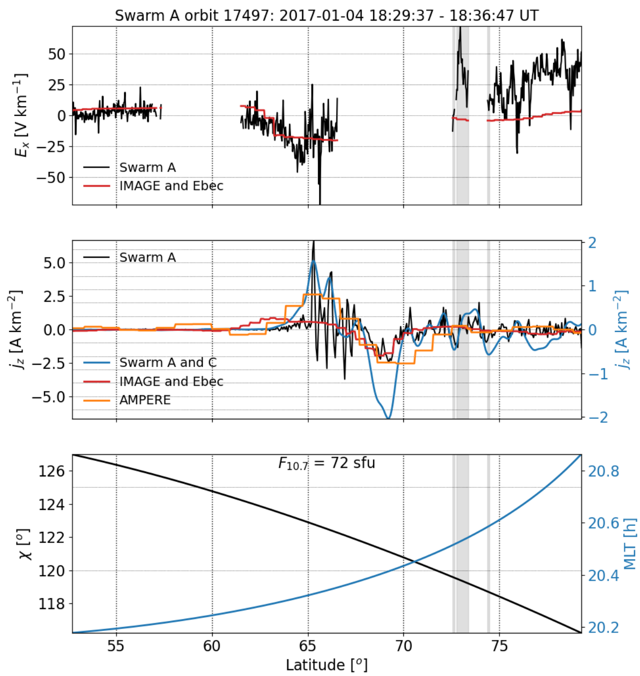
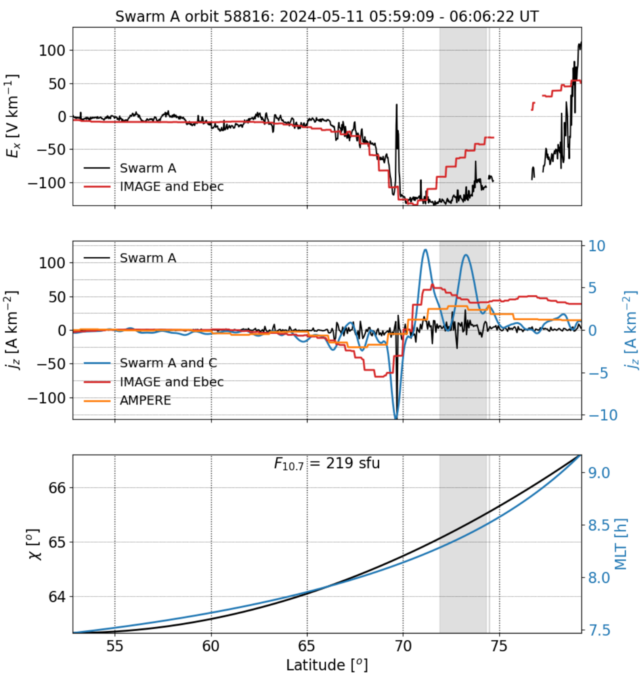
AMPERE
Ebec (modified)
$F_{10.7}$ = 125 sfu
χ [°]
MLT [h]
Latitude [°]

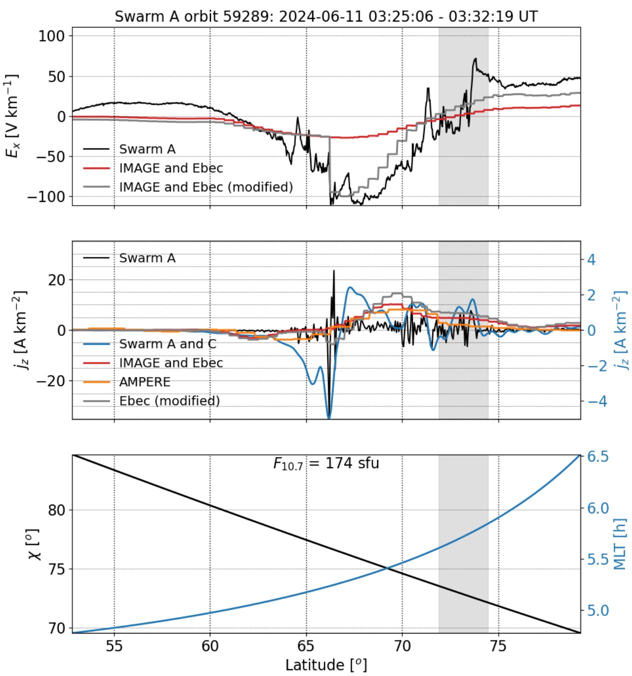
(b)


Swarm A orbit 17497: 2017-01-04 18:29:37 - 18:36:47 UT
E_x [V km^{-1}]
Swarm A
IMAGE and Ebec
j_z [A km^{-2}]
Swarm A
Swarm A and C
IMAGE and Ebec
AMPERE
$F_{10.7}$ = 72 sfu
χ [°]
MLT [h]
Latitude [°]

(c)


Swarm A orbit 58816: 2024-05-11 05:59:09 - 06:06:22 UT
E_x [V km^{-1}]
Swarm A
IMAGE and Ebec
j_z [A km^{-2}]
Swarm A
Swarm A and C
IMAGE and Ebec
AMPERE
$F_{10.7}$ = 219 sfu
χ [°]
MLT [h]
Latitude [°]

(d)


Swarm A orbit 59289: 2024-06-11 03:25:06 - 03:32:19 UT
E_x [V km^{-1}]
Swarm A
IMAGE and Ebec
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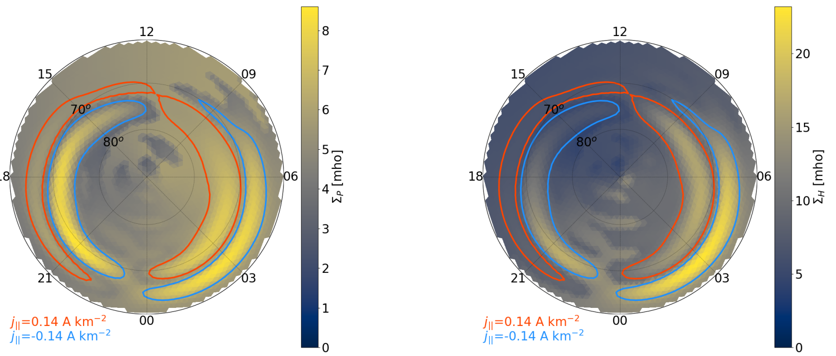
j_z [A km^{-2}]
Swarm A
Swarm A and C
IMAGE and Ebec
AMPERE
Ebec (modified)
$F_{10.7}$ = 174 sfu
χ [°]
MLT [h]
Latitude [°]

Figure 2. Four Swarm crossings of IMAGE (a–d). Top: Ionospheric electric field component corresponding to the ion drift measured by Swarm A perpendicular to the satellite orbit (black) and IMAGE+Ebec estimate of the same component (red). Middle: Radial current density estimated from Swarm A using the single satellite method (Ritter et al., 2013) (black, left scale), from the Swarm A and C satellite pair using the dual-satellite method (Ritter et al., 2013) (blue, right scale), from AMPERE using spherical harmonic fits (Waters et al., 2020) (orange, right scale), and the IMAGE+Ebec estimate (red, right scale). Bottom: Sun zenith angle χ (black, left scale) and MLT (blue, right scale). The gray curves in the top and middle panels of crossings (a) and (d) are otherwise the same as the red curves except that a modified conductance model (Section 4.2) is used.

(a) AMPS and Robinson et al. (2020) Σ_P (b) AMPS and Robinson et al. (2020) Σ_H



(c) AMPS and Wang and Zou (2022) Σ_P (d) AMPS and Wang and Zou (2022) Σ_H

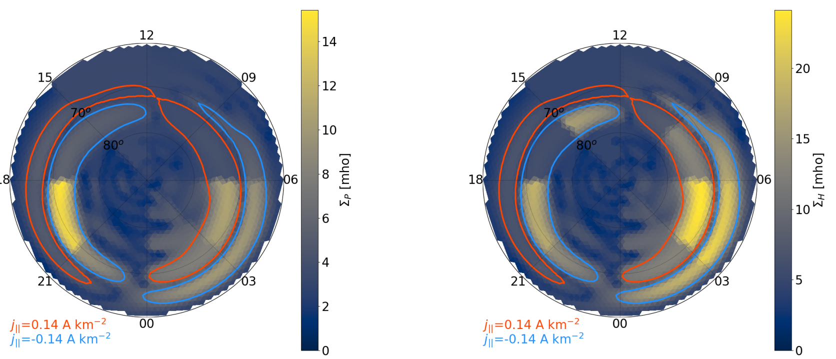


Figure 3. The same as Fig. 9b–c except for the Robinson et al. (2020) (a–b) and Wang and Zou (2022) (c–d) conductance models parametrized with AMPS field-aligned current density (Fig. 10d) instead of the Ebec model parametrized with AMPS $|\boldsymbol{J}_{DF}|$ (Fig. 9a). Note that due to the large differences in conductance amplitudes the color scales are not the same as those in Fig. 9b–e.