Reply to Referee

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Dear Reviewer,

thank you for a constructive and thorough review. We are happy to carry most of the suggested corrections. Please see below for detailed replies to all comments. The original review is written in black and our replies in blue.

A review of the manuscript entitled

"Drivers of rapid geomagnetic variations at high latitudes",

submitted to the journal EGUsphere by Liisa Juusola et al.

This is a very promising research paper. It exploits the large and comprehensive data resource that is the IMAGE archive. It employs an under-utilized, if not particularly new, analysis technique with 2-layer 2DSECS. It uses these to separate "internal" from "external" equivalent current sources driving geomagnetic disturbance at Earth's surface, and therefore to better understand the impact and scale of magnetosphere/ionosphere dynamical phenomena without worrying that "large" geomagnetic disturbances are simply due to much more localized earth conductivity structure. It is also very interesting to see how "internal" sources contribute to the interpretation of space weather phenomena, although perhaps this topic was covered in more detail by a recent paper by the same 1st author, and is only a secondary consideration in the present manuscript. Altogether, this manuscript offers a novel perspective on what influences ground magnetic disturbance the most, for the most impactful space weather events, and therefore should be published and added to the scientific literature base through EGUsphere.

That said, the presentation of this material lacks a certain focus, and is, at times, difficult to read, even for a scientist who is well-acquainted with the analysis techniques and scientific subject matter. The comments below are offered in the constructive hope that the overall clarity and readability of this research paper will be improved, and ultimately appeal to a wider and possibly more scientifically diverse audience.

These critiques/recommendations are offered in a loosely prioritized order:

1. There is a considerable review of the underpinning theory in the Introduction. It ends with an overly brief statement of the question being asked/answered, and it is not especially clear how this relates to the material presented prior to that.
   - most of the theory could be migrated into a more fleshed out Section 2.2, including Figures 1 and 2;
   - the introduction could then more clearly and succinctly articulate the motivation behind this study, possibly hinting at the more comprehensive explanation of techniques coming up later.

We suggest to move most of the text at lines 21–60 and Fig. 1–2 to Section 2.2. The sentence "The amplitude of the time derivative of the horizontal ground magnetic field ($|d\boldsymbol{H}/dt|$) has often been used as a proxy for the geoelectric field and GIC risk (Viljanen, 1998; Viljanen et al., 2001)." at lines 21–23 would remain in the Introduction and the expression "external $|d\boldsymbol{H}/dt|$" at line 108 would be replaced by "external (due to ionospheric and magnetospheric currents) $|d\boldsymbol{H}/dt|$".

2. There are too many figures (18!), and many figures include multiple labeled panels, sometimes up to the letter "l" (i.e., 12 panels!). This alone is very distracting, but the real problem is that it is not obvious that all the panels are discussed in the body of the manuscript. The authors should reconsider whether all these are necessary, and if so, could some be migrated to supplementary material. If the authors choose to keep most or all figures, they should make almost all of them larger, probably full-page.

   We appreciate the Reviewer's point. It is true that not every single panel is thoroughly discussed for each event. There are two reasons we decided to show all these panels: to make it possible for the reader to compare various features of the different event types, and to avoid the need to introduce new figure layouts for all events. Because of these reasons, we would prefer to keep the panels as they are. However, Fig. 2–3 could be replaced by a reference to the IMAGE webpage, where the same information can be found. We might also remove Fig. 7 and Fig. 8b and the related text section, according to the Reviewer's suggestion below. We would like to keep Fig. 8a, because it demonstrates the important fact that sudden impulses are very fast events, whose details can be partly lost when using 10-s or sparser data. The size of the final figures is probably decided by the copyeditors, but we will try to ensure that they are large enough in case the paper is accepted.

3. There are too many inline mathematical relationships. The authors should consider changing some of these to numbered equations that are visually separated from the main text, then cross-referenced when needed.

   We suggest to separate the equations at lines 36 and 121–123 and replace the equation at line 124 by a reference to the equation of line 36.

4. Similarly, there are too many statistics and other data presented inline that would be more clearly presented in numbered, tables, then cross-referenced when needed.

   We suggest to replace the statistics at lines 188–191 by a table.

(some specific comments and questions that should be addressed)

5. Authors should expand on, or cite specific literature that justifies, the statement in the Introduction: "The down component (Bz) cannot be included in the fitting, because it cannot be represented in terms of ionospheric equivalent currents only".

   We suggest to cite Untiedt and Baumjohann (1993) and Vanhamäki and Juusola (2018).

6. Authors should explain, or cite relevant literature justifying, why the internal 2DSECS was defined at only 1m depth? This certainly deviates from much of the previous literature (e.g., Pulkkinen et al., 2003 — EPS), and it seems likely to bias results toward nearby geomagnetic measurements.

   Induced currents can flow at any depth below the Earth's surface and an internal equivalent current layer that has been placed deeper than this will not be able to model the currents flowing above it. In reply to the comments by Referee 2, we have suggested to add the following text at line 25 (to be moved to section 2.2, according to the Reviewer's suggestion above): "Both current systems are 3D, but they can be replaced by divergence-free currents on two spherical shells (e.g., Haines and Torta, 1994). These equivalent currents produce the same magnetic field at the Earth's surface as the true 3D currents. The locations of the equivalent current layers are based on physical arguments: the upper layer is at 90 km altitude, practically below all currents in space, and the lower layer is just below the Earth's surface to represent all

induced currents which can flow at any depth. The two-dimensional Spherical Elementary Current Systems (2D SECS) (Vanhamäki and Juusola, 2020) (SECS) method is one option for deriving the divergence-free equivalent currents and separating the variation magnetic field into its external and internal parts. It is based on explicit current distributions from which the magnetic field is calculated according to the Maxwell equations. In real-life applications, availability of the measured magnetic field from a finite set of points in a limited area instead of the whole globe causes some uncertainty, as discussed by Vanhamäki and Juusola (2020). Similar issues naturally concern other methods as well, such as those based on spherical harmonics or Fourier analysis." This topic has also been investigated by Juusola et al. (2016) and 1 m depth was found to produce good results.

7. The authors should explain better how the results presented in Figures 7 and 8, and related discussion about the data's time resolution, tie into discussion of internal and external sources, and localization of $|dH/dt|$. Frankly, while this is an important point, it seems like a topic for a different paper.

   We suggest to remove lines 237–257, Fig. 7–8, and to modify the conclusions and abstract accordingly.

8. All references to the supplemental animations/movies should make it clear that these are supplemental material. If they could by hyperlinked, even better, at least for the online version of this manuscript.

   We suggest to add "supplementary" before any reference to an animation in the text. The hyperlinking is a very good idea, but will probably be up to the copyeditors.

(typos, grammatical errors, and ambiguities I noticed)

9. Line 43 — "in order to be able to produce–d– the highly structured..."

   OK

10. Line 73 — "...by solar wind perturbations, or internally." Clarify "internally".

    We suggest to add "inside the magnetosphere" after "internally".

11. Line 87 — "...rapid dB/dt spikes..." — maybe quote dB/dt, assuming it is taken from the cited paper, since the authors consistently use $|dH/dt|$ in this manuscript.

    OK

12. Line 375 — "What is noteworthy in our five –of– events is..."

    OK

References

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Untiedt, J. and Baumjohann, W.: Studies of polar current systems using the IMS Scandinavian magnetometer array, Space Science Reviews, 63, 245–390, https://doi.org/https://doi.org/10.1007/BF00750770, 1993.

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