Reply to Referee

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Dear Professor Engebretson,

thank you for a positive and constructive review of our study (https://doi.org/10.5194/egusphere-2022-850). We are happy to carry out all the suggested corrections. Please see below for detailed replies to all comments. The original review is written in black and our replies in blue.

Review of Juusola et al., Drivers of rapid geomagnetic variations at high latitudes, submitted to EGUSphere, 2022

General Comments

This is a very well written study of five of the strongest geomagnetic variations observed by the IMAGE magnetometer array. It has a very good introductory review section, followed by tables showing the largest $|\Delta \boldsymbol{H}|$ and $|d\boldsymbol{H}/dt|$ at each of the IMAGE sites, separated into total (observed) and external and internal contributions. This is followed by a detailed analysis of five events that produced some of the most intense external $|d\boldsymbol{H}/dt|$ values. The authors provide plausible interpretations for the magnetospheric/ionospheric phenomena that drove these events, and also provide a careful discussion in section 4 of some of the limitations of this study (even though it is based on a large volume of data) and of continuing challenges to the successful prediction of intense (dangerous) $|d\boldsymbol{H}/dt|$ events. It concludes that the relevant scientific community is still far from a full understanding of the detailed physical pathway(s) leading to either modest or extreme $|d\boldsymbol{H}/dt|$ events, much less to the prediction of the time and place where these events will occur.

The content of this paper is of high quality and is certainly appropriate for publication in EGUsphere. This reviewer has only two substantive comments and four more minor comments.

Specific Comments

It is strongly suggested that throughout the paper the magnitude of the perturbations in the horizontal magnetic field that are denoted $|\boldsymbol{H}|$ should be replaced by $|\Delta \boldsymbol{H}|$. The magnitude of the total magnetic field or even its horizontal component (in a given coordinate system) is not what is physically important; it is rather the change in its value (during some appropriate time interval).

Re: OK

Lines 375–391: The manuscript cites a study by Viljanen et al. (2006) that showed peaks in occurrences of large $|d\boldsymbol{H}/dt|$ events 5 minutes after both non-storm and storm-time substorm onsets at Sodankylä (63.92° MLAT) and Nurmijärvi

(56.89° MLAT) during 1997 and 1999 (their Figure 3). However, there were no substorm onsets or sudden intensifications of the western electrojet during the five selected events. The authors may wish to contrast the observations of Viljanen et al. (2006) with those of Engebretson et al. (2021), who showed in their Figure 2 plots of maximum dB/dt events (all > 6 nT/s) vs. time delay after substorm onsets for five stations in Arctic Canada during 2015 and 2017, with MLATs ranging from 75.2° to 64.7°. There was no significant peak near 5 minutes after onset at any of these stations (the distributions were relatively flat during the first 30 minutes). The distribution at each station had a gradual and extended falloff that was roughly consistent with those shown in most panels of Figure 3 of Viljanen et al. (2006). The Engebretson et al. (2021) study also showed in panels B and C their Figure 11 that postmidnight dB/dt events that occurred greater than 30 minutes after substorm onsets at the lowest latitude station (KJPK, 64.7° MLAT) occurred during periods of gradual increases in the SML index (weakenings of the WEJ).

Engebretson, M. J., Ahmed, L. Y., Pilipenko, V. A., Steinmetz, E. S., Moldwin, M. B., Connors, M. G., et al. (2021). Superposed epoch analysis of nighttime magnetic perturbation events observed in Arctic Canada. Journal of Geophysical Research: Space Physics, 126, e2021JA029465. https://doi.org/10.1029/2021JA029465

Re: Thank you for reminding us of these results. We suggest to add after line 391: "The second alternative agrees with the results of Viljanen et al. (2006) and Engebretson et al. (2021). Viljanen et al. (2006) examined the occurrence of maximum $|d\boldsymbol{H}/dt|$ after substorm onsets at IMAGE stations during 1997 and 1999. They showed that the largest value of $|d\boldsymbol{H}/dt|$ during substorms occurs most probably at about 5 min after the onset at stations with CGM latitude less than 72°. At this time, the amplitude of the westward electrojet increases rapidly. Engebretson et al. (2021) showed the occurrence of maximum dB/dt events vs. time delay after substorm onset for five stations in Arctic Canada during 2015 and 2017, with MLATs ranging from 75.2° to 64.7°. There was no significant peak near 5 min after onset at any of these stations, and it was suggested that maximum dB/dt events are not typically associated with substorm onsets but times of the most intense westward electrojet. The key difference between these apparently contradictory results is that, whereas Viljanen et al. (2006) examined the occurrence of maximum $|d\boldsymbol{H}/dt|$ after all identified substorm onsets (with average maximum $|d\boldsymbol{H}/dt|$ typically less than 2.5 nT/s), Engebretson et al. (2021) only considered intense dB/dt events with maximum $dB/dt > 6$ nT/s. Thus, although the intensifying westward electrojet after substorm onset may be a typical source of moderate $|d\boldsymbol{H}/dt|$ values (Viljanen et al., 2006), the rarerer events with strong $dB/dt > 6$ nT/s tend to occur during times of the most intense westward electrojet (Engebretson et al., 2021). Engebretson et al. (2021) also showed that postmidnight dB/dt events that occurred greater than 30 min after substorm onsets at the lowest latitude station (KJPK, 64.7° MLAT) occurred during periods of gradual weakenings of the westward electrojet. These could be similar to our events with the undulating westward electrojet."

Technical Corrections

In line 185, the phrase "optimal temporal development" does not seem appropriate. "Optimal" approximates to "best", so this part of the sentence is confusing.

Re: We suggest to remove "optimal".

Figure 4 needs to be much larger in the final published paper, and some of the fine print in the figure could be moved to the figure caption. Figures 5, 6, 9, 11, 13, 14, 16, and 17 would also be easier to read if they made use of the full width of the available space on a page.

Re: We suggest to make a new Fig. 4 (attached Figure 1), which only covers the relevant period 1994–2018, only includes the relevant stations, and does not include any of the fine print or mention the EISCAT magnetometers. 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.

In line 285, "possible" should be changed to "possibly."

Re: OK

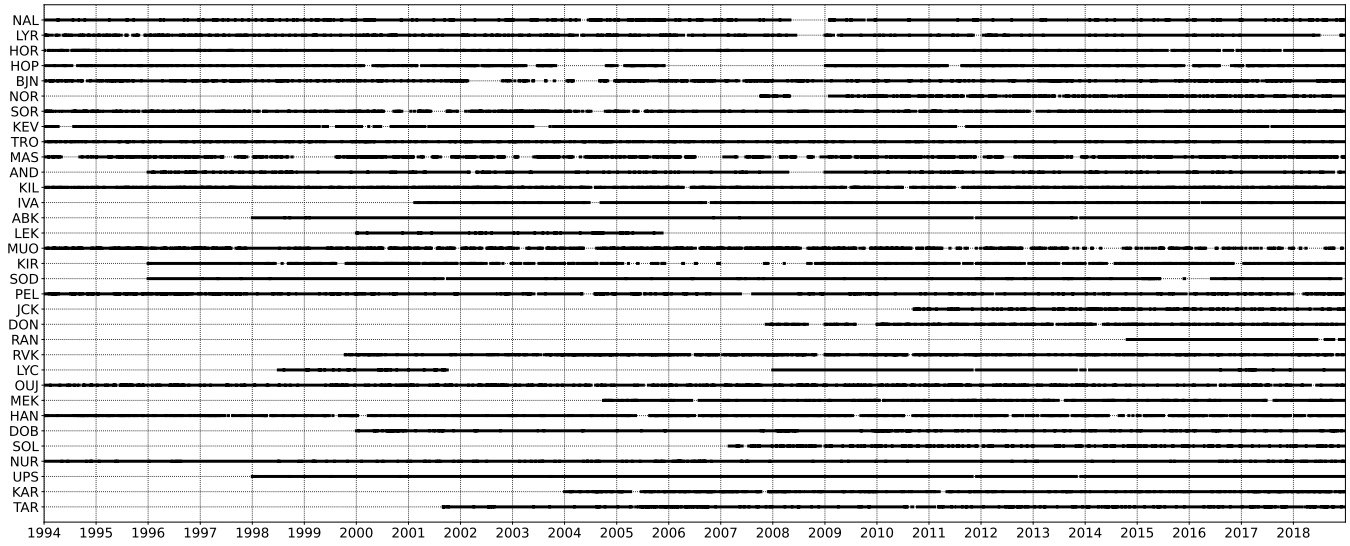

Figure 1. Availability of data from IMAGE magnetometer data.

In line 375, remove “of” after “five.”

Re: OK

References

Engebretson, M. J., Ahmed, L. Y., Pilipenko, V. A., Steinmetz, E. S., Moldwin, M. B., Connors, M. G., Boteler, D. H., Weygand, J. M., Coyle, S., Ohtani, S., Gjerloev, J., and Russell, C. T.: Superposed epoch analysis of nighttime magnetic perturbation events observed in Arctic Canada, J. Geophys. Res.: Space Physics, 126, e2021JA029 465, https://doi.org/https://doi.org/10.1029/2021JA029465, 2021.

Viljanen, A., Tanskanen, E. I., and Pulkkinen, A.: Relation between substorm characteristics and rapid temporal variations of the ground magnetic field, Ann. Geophys., 24, 725–733, https://doi.org/https://doi.org/10.5194/angeo-24-725-2006, 2006.