

Reply to Referee 1

We thank the reviewer for careful reading of the manuscript and constructive suggestions. Below are our responses to the comments in red. We have found that both reviewer 1 and 2 share many of the same concerns, we therefore ask the referee to consider both replies.

This paper reports an interesting property of geomagnetic perturbations at cusp latitudes, based on a statistical analysis of four years of ground-based magnetometer data obtained from 13 stations along the west coast of Greenland. In the analysis presented by the authors, they apply a 10-min moving average to the band-pass-filtered data in the period range of 10-600 s and suggest that this method identifies a population of cusp-related "ULF signals" that is most prominent during summer.

Thank you for these encouraging words.

While the dataset analyzed in this study is valuable and the authors' results may represent a potentially important indication of a certain type of temporal variability in the Hall current system in the cusp, it is difficult to interpret the authors' result as evidence for cusp-related "ULF signals", at least within the scope of the data presented. The authors use the terminology "ULF signal/signature" with some caution when referring to the magnetic responses measured by ground magnetometers. Nevertheless, the analysis appears to rely on an implicit assumption that the magnetic perturbations extracted by their method are associated with ULF waves. The possibility that these perturbations instead reflect reconnection-related dynamic variations of the Hall current system, independent of ULF wave activity, is not adequately considered or discussed.

We understand the reviewer's concern here, and agree that indeed transient features in the cusp region, such as flux transfer events or pulsed reconnection, would introduce frequency components in the ULF regime to our analysis.

In the view of this referee, the dominant contribution to the large amplitudes observed in the band-pass-filtered data is more likely to arise from magnetic perturbations associated with either the passage of localized reconnection-related enhancements of the Hall current system or the rapid temporal changes in the Hall current system driven by variations in reconnection. Within the scope of the data presented, these possibilities cannot be ruled out. The authors' attempt to relate the obtained properties to cusp-related ULF wave phenomena requires further justification. Alternatively, the manuscript should be revised throughout the whole text to ensure that the detected magnetic perturbations are consistently interpreted as more widely accepted cusp phenomena, namely, reconnection-related, dynamic variations of the Hall current system intrinsic to the cusp, rather than as ULF wave signatures.

Indeed, we agree with the referee in this statement. In fact, after studying simulated spectra of various impulsive phenomena, such as Flux-transfer-events with repetition rates of 10 minutes, delta functions, and step functions, we acknowledge that it is, indeed, impossible to discern signals from ULF waves and other fast changes with our XULF parameter. In our revision, we need to address these different phenomena and emphasise the distinction between a wave induced magnetic signal and other similar signals. In particular, in the cusp, or high latitude noon sector, abrupt changes in the solar wind giving rise to

reorganisation or enhancements in the convection and associated currents, as well as the presence of FTEs, will be embedded in the signal. We thereby need to tone down the discussion of what mechanisms might give rise to ULF waves in the cusp. In fact, in order to justify our "ULF-signal" as a true ULF wave signature, we would need additional measurements such as flow measurements using radar, optical measurements, and space based measurements, an expansion that would be outside the scope of this statistical analysis of Greenland magnetometer data. We will introduce a new sub-section in section 2, where we discuss the interpretation of $[XULF]$ ¹⁰ Here, we will underscore that we are unable to separate between ULF waves and other phenomena. We will, furthermore, address how our parameter makes narrowband, such as FLRs, and broadband signals impossible to discern. As also pointed out by the referee, we put too much emphasis on ULF waves. This will be remedied throughout the whole text and title, where we will move emphasis from ULF wave generated signals, to "geomagnetic response to transient, impulsive, and wave like magnetospheric phenomena". Already in the abstract, we will remove ULF waves from the first sentence. Furthermore, we will early on in the paper define the term "ULF signal" as "a non-zero value of $[XULF]$ ¹⁰" and emphasize that this should not be interpreted solely as the presence of a PC1-6 or Pi1-5 wave, but also other transient and impulsive phenomena. The introduction will be expanded to include a short review of high latitude dayside transient phenomena, such as FTEs, DPY, TCVs, sudden impulses, etc. The number of changes made in the text will be too numerous to include here, we therefore hope that the reviewer will stay with us for another iteration of the paper. We also refer to the response to referee 2, which was written before this one.

Detailed comments:

(1) As noted above, this referee considers that one of the dominant contributions to the large amplitudes observed in the band-pass-filtered data in the period range of 10–600 s arises from the inclusion of numerous events associated with the passage of the localized enhancements of the Hall current system, which are believed to be related to intermittent reconnection. The passage of such current structures over a ground station would naturally produce quasi-periodic magnetic perturbations with periods of 10 min or so.

We completely agree. In fact, the spectrum of a bandpass filtered Heaviside function (i.e., step function) will look the same as that of a broadband ULF wave signal. Please see the response to referee #2 for details about which changes we intend to implement.

For example, Figure 4 of the paper by Øieroset et al. (1997, JGR, doi: 10.1029/96JA03716) shows that periodic magnetic perturbations with amplitudes of roughly 100 nT are observed in the cusp. Such perturbations would be expected to appear as large-amplitude events in the author's analysis, which is based on a moving average of band-pass-filtered data covering periods from 10 s to 10 min. Although the authors briefly mentioned in the Conclusions a possible relation between their identified "ULF signatures" and magnetic perturbations associated with flux transfer events, this acknowledgement is too limited. Instead, it would be more appropriate to place this relation at the core of the paper and to interpret the reported results primarily in terms of reconnection-driven, dynamic variations of the Hall current system.

Thank you for pointing towards this reference, we will use it. As described in the other reply, we will include text regarding this in both the introduction as well as a subsection of Section 2, where the interpretation of our XULF parameter is described.

65 Another potentially dominant contribution to the large amplitudes observed in the band-pass-filtered data may arise from the inclusion of events reflecting rapid temporal changes in the large-scale Hall current system driven by variations in reconnection. Taguchi et al. (2015, JGR, 2015, doi:10.1002/2015JA021002) showed, using magnetic field data from the Greenland magnetometer chain, that the near-noon Hall current distribution can remain in a transition state for approximately 10 min. Their Figure 6 shows that the H components at SVS, KUV, and UPN change from about +200 nT to -200 nT over a time interval of 10 min. Although such variations are not inherently periodic, the application of a band-pass filter covering periods from 10 s to 10 min is likely to extract magnetic perturbations with an amplitude on the order of 10 nT. These filtered perturbations could therefore make a significant contribution to the large-amplitude events identified in the authors' analysis.

We agree, see above and in the response to reviewer #2.

75 Considering the results presented in the previous studies, the authors' reported population of the cusp-related "ULF signal" may be explained without invoking ULF wave activity in the cusp. In fact, Figure 6 of the paper by Taguchi et al. shows that the magnetic perturbations of the three stations, SVS, KUV, and UPN, are relatively large, whereas those at THL and UMQ is much smaller. This behavior is consistent with the authors' results shown in Figures 2 and 3, in which the relatively small amplitudes at UMQ lead to a clear separation of the cusp signatures.

Indeed, it fits very well into our results, we appreciate the referee pointing this out.

80 This referee suggests that the manuscript should be revised throughout the whole text to focus on temporal variations in the cusp Hall current system associated with reconnection at the dayside magnetopause under southward, eastward, or westward IMF conditions, as well as the lobe reconnection under northward IMF, with only limited invocation of ULF wave activity on open magnetic field lines. In this context, this referee believes that the inclusion of the term "ULF" in the paper's title may be misleading. If the authors wish to retain this term in the title, they should clearly present at least one representative example of a well-defined ULF pulsation in the manuscript and explicitly quantify the corresponding magnetic amplitude as detected using their analysis method based on the moving average of band-pass-filtered data.

We agree that the usage of the term ULF is misleading. Suggested alternative title of the paper: *High latitude, dayside rapid variations observed with ground magnetometers in Greenland*

90 (2) Figures 1 and 4 do not appear to be particularly useful for supporting the main conclusions of this paper. For Figure 1, the authors may consider replacing it with some representative case examples showing the time series of the moving average values of the band-pass-filtered data together with the corresponding raw magnetic field data, at least for the stations THL, KUV, UPN, and UMQ. The contrast between the relatively large amplitudes observed at KUV and UPN and the much smaller amplitudes at UMQ and THL appears to be central to the authors' result, and would be more effectively illustrated through such case studies.

95 We agree that the paper would benefit from a figure displaying the output of the Butterworth bandpass filter and the boxcar-smooth $[|X_{ULF}|]_{10}$ as was also pointed out by referee #2. Please see the response to referee #2.

In regards to Figure 1 in the paper, we still believe that it is necessary to prove our point wrt. the Hall conductance plots and the argument that the magnetic perturbations are not caused by particle precipitation at the polar cap stations. It underscores the notion that the signals observed are originating from cusp related processes.

100 With regard to Figure 4, it is not surprising that the Hall conductance from the Moen and Brekke model (1993) is broadly consistent with the amplitudes of the observed magnetic perturbations at stations located well away from the auroral oval, such as THL (Figure 1a). This behavior simply reflects the fact that the enhancement of the Hall conductance due to electron precipitation is weak in the very high-latitude ionosphere, such as that above THL. In the view of this referee, the conductance model plotted in Figure 4 does not play a significant role in the interpretation of the authors' results, although the model itself is
105 valuable. As noted above in connection with Figure 1, the magnetic perturbations at KUV and UPN appear to be more directly relevant to key results presented in Figures 2 and 3, and the discussion would benefit from placing greater emphasis on the behavior of the magnetic perturbations at these stations.

We agree with the referee in the comments about conductivity generation. However, on the contrary, we believe that showing the striking similarity between Figure 4 and Figure 1 (top two panels of both) is important. This is in order to emphasize that
110 the disappearance of magnetic signatures during the boreal winter does not mean that the associated E-fields in the ionosphere disappear. A surprising number of ground based cusp studies have been performed during wintertime, probably because optical data (studies centered on Svalbard) are available. This could potentially create "false truths" or erroneous notions locked to one particular season or magnetic longitude, while our results actually underpin that there are differences and still work to be done related to these phenomena, especially during Summer.