Answers to referee 1

The authors thank referee 1 for careful reading of the manuscript and for the constructive comments. Below, are the point-to-point answers to the specific comments and the technical corrections.

1. *Line 10 and elsewhere – "small-scale ULF waves..." Here or somewhere early in the manuscript, please further clarify the definitions of small-scale versus large-scale (e.g., m-number below or above 10, small scale is ~<100 km in ionosphere in north-south or east-west sense, >~500 km for large scale, etc.). There is always confusion in the literature on scale size definitions (small-, meso-, large-), and clarifying this would help place the results in context with other studies. Lines 45-46 propose that m-number can be used to divide large from small-scales, but no threshold for large versus small m-number is given and there are no m-number measurements in the manuscript.*

   We appreciate the referee's request for a clearer definition of spatial scales. In the original manuscript, we avoided specifying azimuthal wave numbers, *m*, as our datasets do not allow for a direct determination of the *m-number*. However, we agree that explicit characterization improves clarity of the manuscript and have thus added this.

   For clarity, we have also specified that we are defining the azimuthal wave number in the ionosphere instead of in the equatorial plane and we have changed our equation for m accordingly, such that it now reads $m = \frac{2\pi R_E \cos(\theta)}{\lambda_{az}}$, where θ is the geographic latitude. In our case, the event centers around Hornsund ($\theta = 77°$). This results in an azimuthal wavelength of $\lambda_{az} > 900$ km for large scale ($m < 10$) and $\lambda_{az} < 600$ km for small-scale ($m > 15$).

   The revised manuscript now reads (line 43 onward):

   The azimuthal scale size of ULF waves is described by the m-number ($m = \frac{2\pi R_E \cos(\theta)}{\lambda_{az}}$, where R_E is the Earth's radius, θ the geographic latitude, and λ_{az} the azimuthal wavelength in the ionosphere). Waves can be classified according to their m number, where low-m waves have large spatial scales and are predominantly toroidally polarized. Although there are no strict definitions regarding scale sizes, low-m waves typically have m numbers between 1–10 and include FLRs, which are most effectively driven by fast mode waves when m ≈ 3 (Menk and Waters, 2013; Rubtsov et al., 2018). High-m waves, on the other hand, have small spatial scales and show poloidal polarization. Waves are generally considered *high-m when m > 15 (Yeoman et al., 2010), but in other cases even higher values such as 50 < m < 150 are used for the high-m classification (Mager et al., 2019; Michael et al., 2024). In between low-m and high-m waves, there is a class of intermediate-m waves (10 ≲ m ≲ 15) which can show characteristics of either low-m or high-m waves (Mager et al., 2019). Above Svalbard, at ϑ = 77°, large-scale waves (m < 10) correspond to azimuthal length scales of $\lambda_{az} > 900$ km, while small-scale waves (m > 15) are characterized by $\lambda_{az} < 600$ km.*

2. *Line 181 – "The Lompe analysis are based on 5 min windows…" 5-min windows are an appreciable fraction of the 10- and 15-minute wave periods (1.1-1.67 mHz), thus this approach could smooth and/or average out contributions of the waves to the overall results. If the window is using a snapshot rather than averages (e.g., Lompe calculations based on instantaneous ground magnetometer values every 5-min rather than a 5-min average), this issue could be mitigated, but other issues may arise if there are timing offsets between ground magnetometer snapshots, DMSP snapshots, etc. Please add some discussion on how the Lompe calculation window does (or doesn't) affect the wave properties. This is not a major issue because the study validates Lompe results by making direct comparisons with individual Iridium satellites and cross-comparisons with other datasets, but it's still important to discuss whether the 5-minute window could affect e.g., the absolute numbers for FAC intensity, heating rate, etc.*

   We thank the referee for raising this important point. We agree that the relationship between the Lompe time window and ULF wave periods requires clarification.

   Lompe performs a regularized least-squares inversion using all available measurements within the selected time window. Thus, while it does not explicitly compute time averages, multiple measurements within a window effectively contribute to a weighted fit, resulting in a solution that represents the system over that time interval.

   We have explored shorter time windows (1–2 minutes) to assess the robustness of the results. While these shorter windows preserve more of the temporal variability, they also lead to increased noise and less stable inversion results due to reduced data coverage. In particular, reliable conductance estimates require sufficient spatial sampling, which is strongly constrained by the availability of DMSP measurements. Since a full DMSP pass spans more than 5 minutes, shorter Lompe windows would introduce an inconsistency between the temporal resolution of the electrodynamic inversion and the conductance input. In addition, the longer time windows provide better spatial coverage for satellite-based magnetometer measurements, improving the inversion calculations.

Based on these considerations, we retain the 5-minute Lompe window and clarify in the discussion of the revised manuscript that the resulting patterns should be interpreted as resulting an average over a part of the ULF wave cycle. The temporal limitation is now explicitly discussed as:

Lastly, it should be noted that the Lompe solutions represent the electrodynamic state over a 5-minute window, which is a significant part of the observed ULF wave periodicity of 15 minutes. As a result, the derived convection and current patterns correspond to an average over a fraction of the ULF wave cycle. This temporal smoothing may reduce the apparent amplitude of rapid variations and should be taken into account when interpreting the relationship between the electrodynamic response and ULF wave periodicities. Shorter time windows for the Lompe models are not feasible due to increased noise due to a reduction in mainly space based measurements and inconsistency of the temporal resolution of Lompe and the conductance as obtained using the DMSP spacecraft.

3. *Line 286 – "This would indicate a generation mechanism internal to the Earth's magnetosphere" Externally driven ULF waves can also exhibit a non-FLR nature due to, for example, phase-mixing after the external driving concludes (e.g., the transition from large to small scale waves via phase mixing can occur in an MHD approximation, Rankin et al., 2021 Figure 5), non-stationary driving more generally, presence of multiple drivers/wave modes, etc. Is it possible that these scenarios could fit the non-FLR/small-scale wave observations, in addition to the internal driving mechanism? If so, it would help to mention some alternate possibilities in the text.*

   We thank the referee for this insightful suggestion. We agree that phase mixing may contribute to the observed non-field line resonance (non-FLR) signatures. Due to the lack of longitudinal spaced data, we cannot derive the azimuthal propagation direction, thus making it impossible to provide further evidence as to an internal or external driving mechanism. We have, however, extended the discussion to include the possibility of phase mixing. The added paragraph now reads:

   "In addition to internal generation mechanisms, phase mixing could contribute to the observed non-FLR nature of the ULF wave event. Characteristically, a FLR shows a narrow resonant frequency peak on the resonant field line that matches eigenfrequency of the wave. Wave growth on adjacent field lines is slower, causing broadening of the peak and phase mixing (Mann et al., 1995; Rankin et al., 2021). Phase mixing can thus redistribute wave energy and change its signature."

In addition, a sentence about the possibility of phase mixing has also been added to the conclusion:

"Phase mixing may play a role in the apparent conflicting observations, in which case the frequency peak of an initial, externally generated FLR is broadened and the wave exhibits characteristics more aligned with internally driven small-scale wave signatures."

Technical corrections:

a. *Line 40 – "ULF waves are magnetohydrodynamic oscillations…" It might be better to say something like "ULF waves are oscillations that can often be described with a magnetohydrodynamic approximation…" since later in the paragraph parallel electric fields (not an MHD feature) associated with FLR are mentioned.*

   Thank you for this suggestion. We fully agree with this comment and have changed it accordingly in the manuscript.

b. *Line 150 – "The UAA event does not have a classic FLR nature" Would it be possible to include the original magnetometer time series as a Figure in the Appendix? This would be useful for future studies to investigate the possibility of ground conductivity effects, presence of other wave activity, etc., as well as for future studies seeking to model this event.*

   We have chosen to add an extra panel to Figure 4 showing the median filtered X- and Y-components of the magnetometer data.

c. *Line 244 – Rankin et al. 2021 is cited but missing from the reference list. I think this refers to the following reference (which is also mentioned in comments above): Rankin, R., Gillies, D.M. & Degeling, A.W. On the Relationship Between Shear Alfvén Waves, Auroral Electron Acceleration, and Field Line Resonances. Space Sci Rev 217, 60 (2021). https://doi.org/10.1007/s11214-021-00830-x*

   Thank you for pointing this out. Something had gone wrong in the manuscript file which we have now corrected. The paper is now cited correctly.

Answers to referee 2

We thank the referee for the positive assessment of our manuscript and for the thoughtful and physically insightful comments regarding the possible drivers of the observed ULF wave activity and their relationship to the auroral precipitation and ion upflow.

We agree that the geomagnetic location of the event (near the open–closed field line boundary in the afternoon sector) makes external driving mechanisms, such as magnetosheath or mantle flow interactions and shear-driven processes, plausible contributors to the observed ULF wave activity. We also appreciate the referee's suggestion that the auroral precipitation may represent the primary driver of the ion upflow, with the ULF wave acting more as a framework than the direct driver.

Possible sources of ULF wave activity are briefly introduced in the manuscript (lines 45–46), followed by a discussion of field line resonance formation (lines 49–50). To point the reader towards additional information sources, we have now added two references in the discussion (line 288) regarding the Kelvin–Helmholtz instability as a potential source of ULF wave activity. Since a detailed investigation of wave generation mechanisms would require additional data and analysis that are not available within the current dataset, we consider this level of detail to be sufficient for the scope of the present study, which focuses on the ionospheric response and energy dissipation associated with the observed event. This, after careful consideration, we have therefore decided not to expand the discussion of potential ULF wave drivers further.

We note that the relationship between ULF waves, electron acceleration, and auroral precipitation is already partly addressed in the manuscript (lines 243–254). There, we discuss that wave energy is likely partitioned into particle acceleration, leading to periodic electron precipitation into the ionosphere. In this interpretation, the ULF wave modulates the acceleration of electrons, which in turn produces the observed periodic auroral features.

At the same time, we agree that the auroral precipitation itself is the most likely driver of the observed type 2 ion upflow, as it provides the necessary enhancement in electron temperature and density to generate ambipolar electric fields. Thus, while the particles are required to drive the upflow, the ULF wave may play an important role in controlling the temporal modulation of the precipitation and associated auroral dynamics.

We believe that this interpretation, already outlined in the manuscript, is consistent with the referee's suggestion and adequately reflects the coupling between ULF wave activity, auroral processes, and ion upflow without extending beyond the scope of the present work.