Reply to Referee 2

We thank the reviewer for careful reading of the manuscript and constructive suggestions. Below are our responses to the comments in red.

Review: High latitude, dayside ULF signals observed from ground in Greenland Eldor et al.

Summary

This paper attempts to address a gap in high latitude ULF wave observations using the upgraded West Greenland magnetometer chain. They find observations of ULF waves in the cusp region for the first time during the summer months. The work is concise and well presented, and the results are very interesting. I hope you find my comments useful.

Thank you for these encouraging words.

However, I do have some concerns regarding the measurements and interpretation of the results. Their study is based on presentation of a single broadband ULF metric [XULF]10. This could encapsulate a lot of different processes, and there is no attempt to separate them or address what they can't determine with this metric. There is also no evaluation of the frequency of their ULF waves due to the use of a very broadband filter, which would be interesting.

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 region, 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, as pointed out, 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 magneteometer 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 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 referee #1, we put too much emphasis on ULF waves. This should be remedied throughout the whole text and title, where we will move the 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. 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.

Secondly, there is a lot of speculation around the causes of their results which are not adequately backed up by data. There is discussion of electron precipitation without electron precipitation data,

We would like to address this statement. Indeed, we do not measure particle precipitation or use this kind of data in the study. We suppose that the reviewer is referring to the discussion on lines 125-155. However, it is a well known fact that the precipitation in the cusp is soft and hardly ionizes the E-region, where currents are flowing. This means that when we observe an enhanced magnetic signal, with a strong seasonal variation, the ionizing source is not precipitation, which we consider an important finding: There is a strong summer time ULF-like, daytime signal at the highest latitudes (Fig 1, very clear at THL, still visible at UPN). The implication is that the E-fields driving this signal are there all the time, but we need solar EUV to have them set up the necessary Hall-current to produce visible magnetic fluctuations on the ground. We bring this into context of other dayside studies, by introducing the work of Motoba et al, who, indeed, observe precipitation and ULF signals, and our main point is that they must then be looking at a different phenomenon, rather than what we observe at our highest latitudes. We will review this to ensure that it looks less like speculation and more like proper discussion, and that our point comes out clearly, and that all necessary citations are in place.

Kelvin Helmholtz instabilities without data and various effects in the conclusion not mentioned in the main body of the paper, such as the unspecified DPY effect.

The Kelvin Helmholtz instability (KHI) is mentioned 4 times in the manuscript (one time is in the reference list). One time related to flow in and around the magnetospheric cusp, and twice in relation to ionospheric flows. The former is related to speculation on the generation mechanisms of ULF waves, while the latter is related to KHI being seeded by our ULF-signals. We can easily remove the references to KHI, and make the text more general, which will be in line with the above comment, where we acknowledge that we, indeed, cannot separate between waves and other transients: Line 206: *The pulsed injection of plasma through the cusp by flux transfer events (FTEs), with a repetition rate between a few to about 15 minutes (Lockwood and Wild, 1993), and the role of multiple reconnection X-lines theorised by Lee et al. (1988) and observed e.g. by Hasegawa et al. (2010) and Fuselier et al. (2022), makes a very convincing basis for the generation of a wide band ULF signal.* We will remove the following sentence *The correlation of nightside FTEs and Pi 2 waves in the magnetospheric lobe (Keiling et al., 2006), furthermore, lends credibility to this notion.* Line 212-212 and 256-265: As discussed below, we will remove the whole paragraph. We will make sure that DPY is properly introduced, this we will do in the new section mentioned above. For the record here: The DPY current is the current associated with strong zonal ionospheric convection of newly reconnected field lines in the near the cusp footpoint owing to a dominant IMF By.

The study only uses two data sources: [XULF]10 and the Ap index. I think the paper overinterprets its data with the evidence they present.

We tend to disagree, we have tried to be specific about what are clear conclusions and what we feel are indications or speculations. However, we will review the text to moderate passages where over-interpretation might occur.

One of the simpler ways to add clarity to their results would be to use a simple open-closed field line model to be clear about when their stations were on open or closed field lines. At the moment, the only distinction is between summer and winter.

Location wrt the open-closed field line boundary is indeed central to what conclusion might be drawn. The challenge lies very much in the statistical treatment of our data. Cusp OCB is very dynamic wrt IMF conditions. In Figures 1 and 2, we show Figures 2 and 3 in the paper as polar plots, with the cusp OCB as indicated by Andersen and Bukowski. In their paper, the goodness of fit indicates a spread of between 2.5 and 3 degrees. This covers our high latitude population easily. If desirable, we could change the figures in the manuscript with these figures.

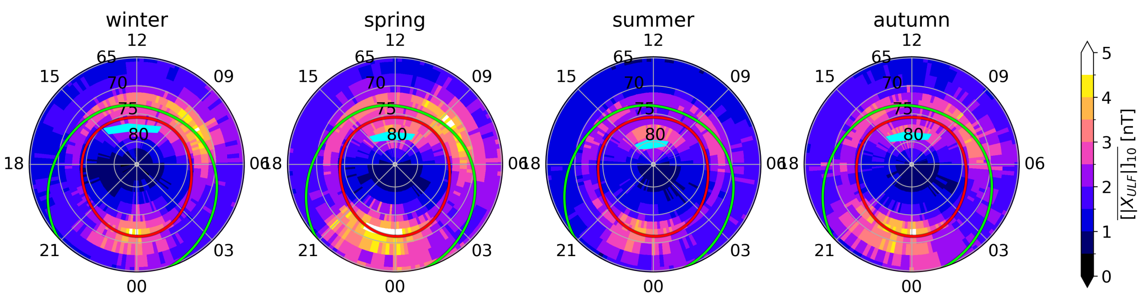

Figure 1. Polar plots of the average ULF signal amplitude for the different seasons. The Feldstein model is represented by red (polar boundary) and green (equatorward boundary) lines. The statistical location of the cusp is marked with a cyan-coloured area computed using the equations set forth by Anderson and Bukowski (2024).

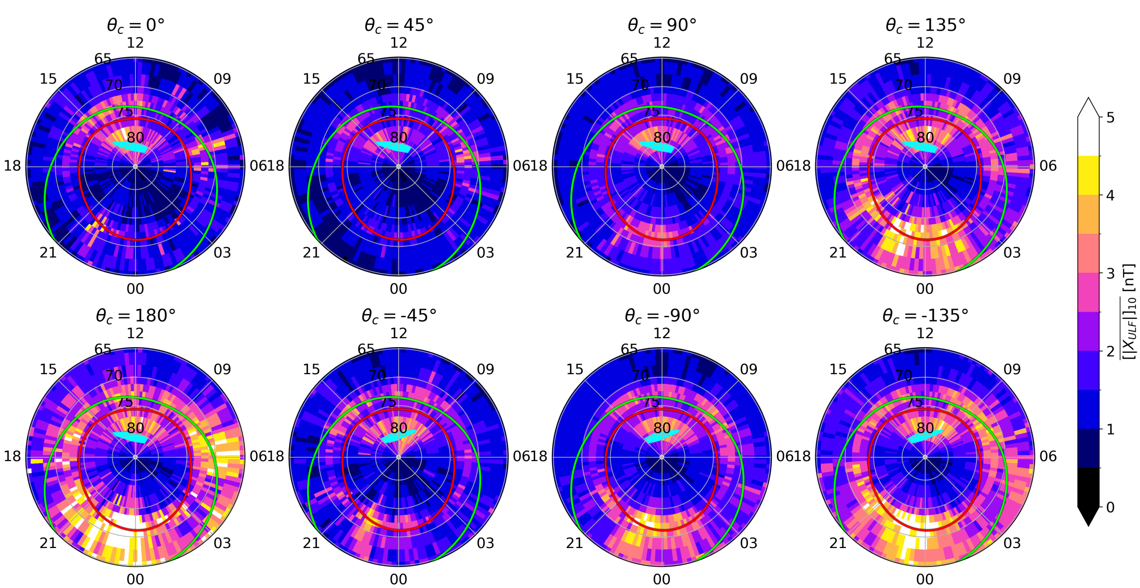

Figure 2. Similar to Figure 1 but for different IMF clock angles during the summer months.

For example, I would expect the results for the STF magnetometer to look different if binned by open or closed field line. This would resolve some ambiguity about the sources of the ULF waves, which they do discuss in detail.

We are unsure what exactly the referee means. As can be seen both in Figure 2 and 3 of the manuscript, the population centred on STF does not change much in latitude throughout the year or as a function of clock angle as opposed to the Northern population, which moves with the Anderson and Bukowski cusp equatorward boundary.

I do think the paper would be worthy of publication, especially as the results are really interesting. However, I think either more data needs introducing from other sources to back up their speculation, or the speculation should be toned down and investigated more thoroughly in a subsequent paper. I also think they could do more with the data already presented. Combining the data in this paper with say SuperDARN data or electron precipitation data in a future study would yield very interesting results.

Thank you for these encouraging words. Since this study was motivated for making a statistical investigation of "ULF signals" as seen from ground based magnetometers, we believe that adding more data from other instruments would be outside the scope of the current work. However, we will tone down the speculative parts and add a sentence in the conclusion, where we state: *We have identified several interesting features connected to the presence of ULF signals at very high latitudes in the vicinity of the cusp. These deserve further investigation through case studies as well as statistical studies where ground based radars are used as well as satellites.*

Comments:

1. I think a Figure showing the output of your butterworth filter would be useful. You have a very broad range of frequencies here, which implies your filtered spectrum could just look like noise. This could also affect your interpretation of your metric as finer frequency structures like FLRs will be mixed with spectrally broad features.

We agree that the paper would benefit from a more thorough description and a figure of the output of the Butterworth bandpass filter. We will add one of the figures below (A version/combination of Figure 3 or 4 with the appropriate description in section two) and include the following text (to be adapted to the final figure): *The Butterworth bandpass filter yields the signal shown by the blue curve in Figure xx. As illustrated, the filtered signal oscillates around zero. To obtain a representative measure of the signal amplitude, a 10-minute boxcar filter is applied to the absolute values,* $|X_{ULF}|$*. The resulting smoothed signal, denoted* $[|X_{ULF}|]_{10}$*, is presented as the red curve in Figure xx.*

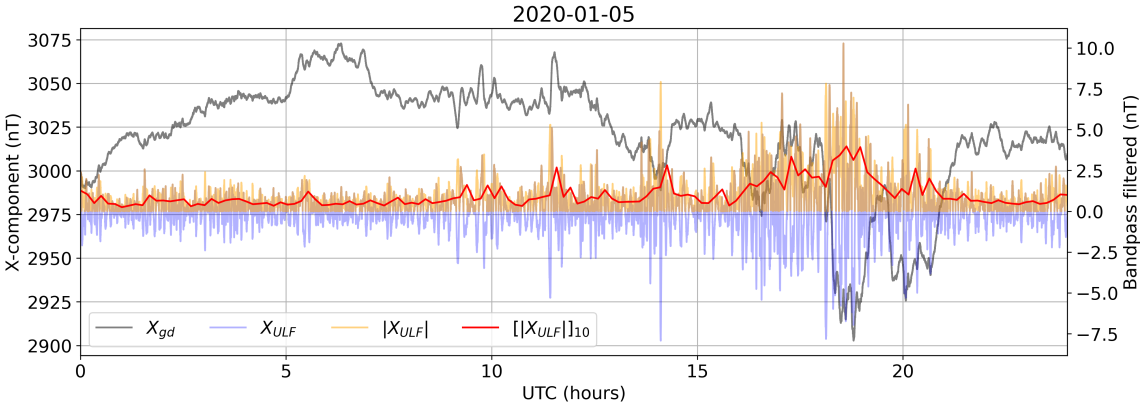

Figure 3. Example of a 10-minute smoothed ULF signature ($[|X_{ULF}|]_{10}$, right axis) at TAB alongside the local northward component (X_{gd}, left axis), the bandpass filtered northward component (X_{ULF}, right axis), and the absolute of the bandpass filtered northward component ($|X_{ULF}|$, right axis).

In Figure 4 below, we show an example of the bandpass filtered X-component for more narrow bands. The plots display that signals across multiple frequencies are present, and thus, while FLRs could appear in the Pc 5 range in our data, the signals we are investigating are also broadband signatures. Notice how the spectrum in the lower panel, resembles that of a Heaviside function, i.e. a step function, which is indicative of the presence of transients

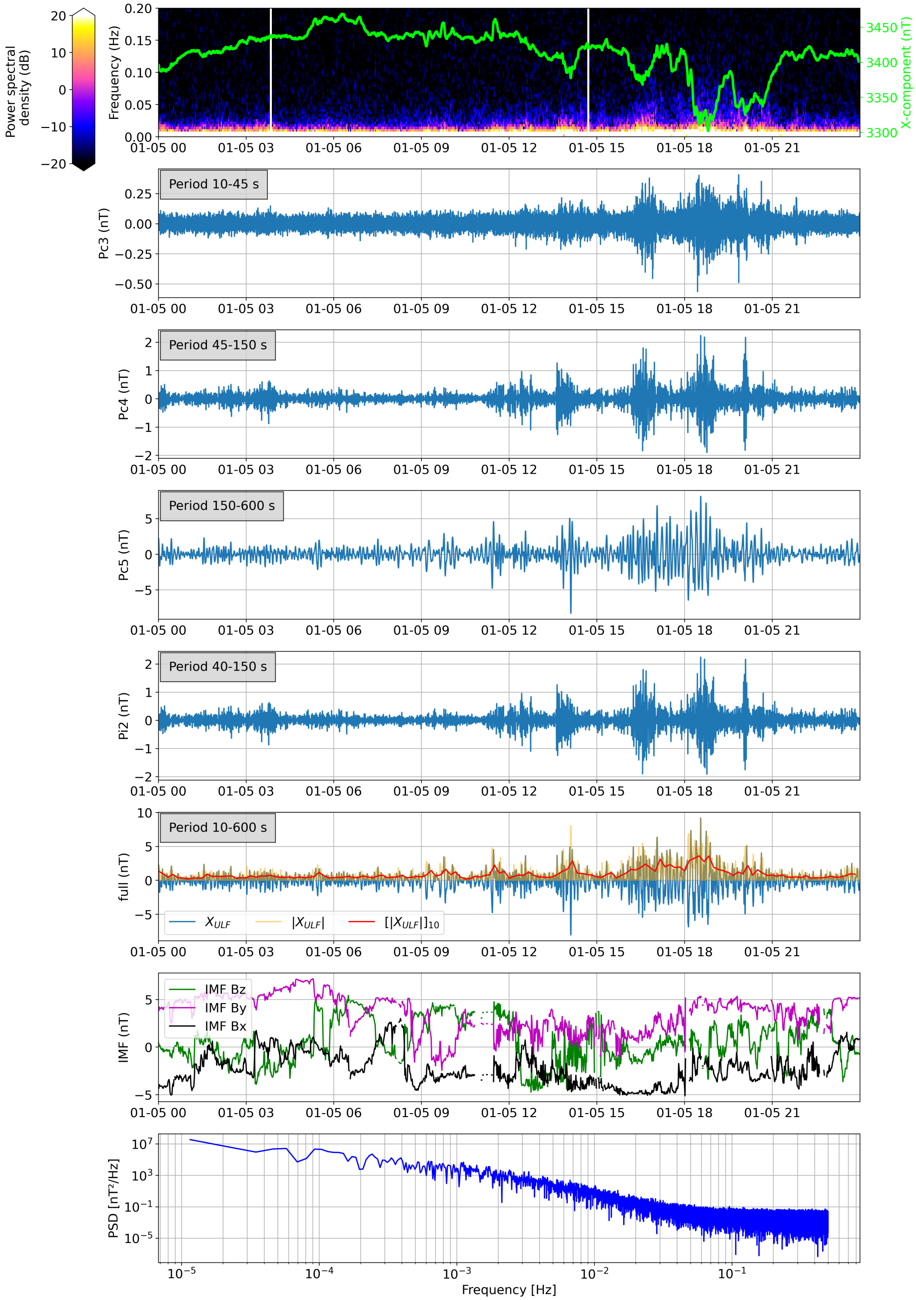

Figure 4. First panel: Plot of the spectrum at TAB on the 1st of June 2020, where the green curve represents the magnetic northward component (X). Second-fifth panel: outputs of a bandpass filter in the period range stated in the top left corner for Pc 3-5 and Pi 2 (X_{ULF}). Sixth panel: The output of the bandpass filter, used in the paper (X_{ULF}), the absolute values ($|X_{ULF}|$), and the 10-minute smoothed signal ($[|X_{ULF}|]_{10}$). Seventh panel: IMF parameters for the given date. The eighth panel: The power spectral density w.r.t. frequency for the given day at TAB.

2. You should define [XULF]10 more explicitly, say with an equation of how it is calculated. It's not clear why it's just measured in nT either. From your description, it's not obvious if [XULF]10 represents a single number of not.

We will add the following text in "section 2": *The applied boxcar filter uses a custom edge strategy that replaces zero-padding at the start with progressively growing averages.* We would be happy to include the following equation as well:

$$[|X_{ULF}(n)|]_{10} = \frac{1}{M} \sum_{k=0}^{M-1} |X_{ULF}(n-k)|, \tag{1}$$

where M is 600s corresponding to the 10-minute boxcar window and n is time in seconds.

3. L60 – You mention that you apply a 10 minute moving average filter to get rid of spurious 0 values. Why are there 0 values? Is this just the instrument dropping out? How does the 10 minute average get rid of this. Don't you need to do this anyway to produce [XULF]10, regardless of the 0 values? Please clarify.

We can see how this phrasing is confusing. The spurious zero values stem from the bandpass filter that returns a pulsed signal (pulsating around 0), e.g. the blue curve in Figure 3. When we then take the absolute value of the bandpass filtered data, values that marked the transition between a positive and negative peak are now a value of zero (see the orange curve in Figure 3). This will not reflect the degree of activity, and that's why we smooth the signal (red curve in Figure 3). We think this will become clearer as we add Figure 3 that displays the output of the bandpass filter and the $[|X_{ULF}|]_{10}$. Since we will add a figure of the output of the bandpass filter, we will adapt the description of the spurious zero values (lines 60-62), to fit with the Figure and bandpass filter descriptions outlined in the above answers.

4. L55 – Why the northward component? The polarisation of a ULF wave often depends on the process, so why did you pick this component? Are your results only specific to this polarisation?

Looking at scatter plots of the horizontal components in Figure 5, we see that the scatter of X and Y is more or less isotropic for all stations in the study. This can be interpreted as no mutual dependence between the components, and we therefore regard it as safe to use only one component. However, as has been shown in other studies, there is a relationship between polarisation and the presence and location of the substorm current wedge, and the nature of certain field line resonance induced waves (poloidal vs toroidal waves). We therefore acknowledge the potential of a follow up statistical study where polarization could be the focus.

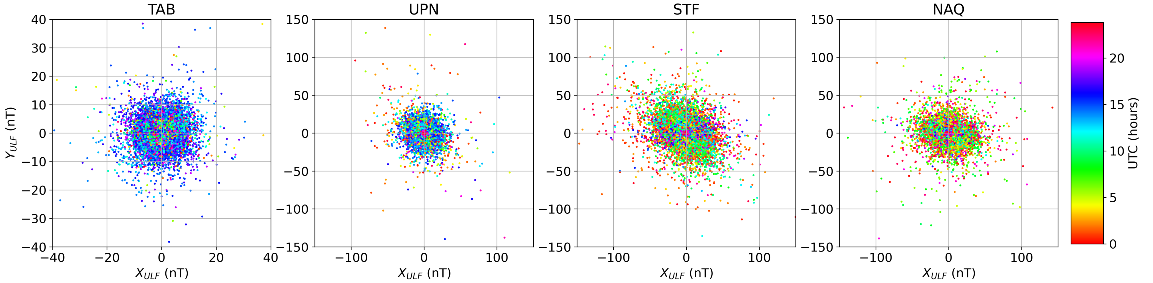

Figure 5. Polarisations plots of the difference between the two components X_{ULF} and Y_{ULF} for four stations with respect to UTC.

5. Figure 1e. As a colourblind reviewer, I have to say this subplot looks very psychedelic to me, making it hard for me to decide if I agree with your interpretation about the ULF activity being proportional to AP. Could you please use a colour scale that just goes from dark to light, through say just one colour? (You choose).

Thank you for making us aware of this problem, we will make use of the colourmap "viridis", which is better suited for colourblindness, to represent the ap index instead. The new figure is seen below in Figure 6:

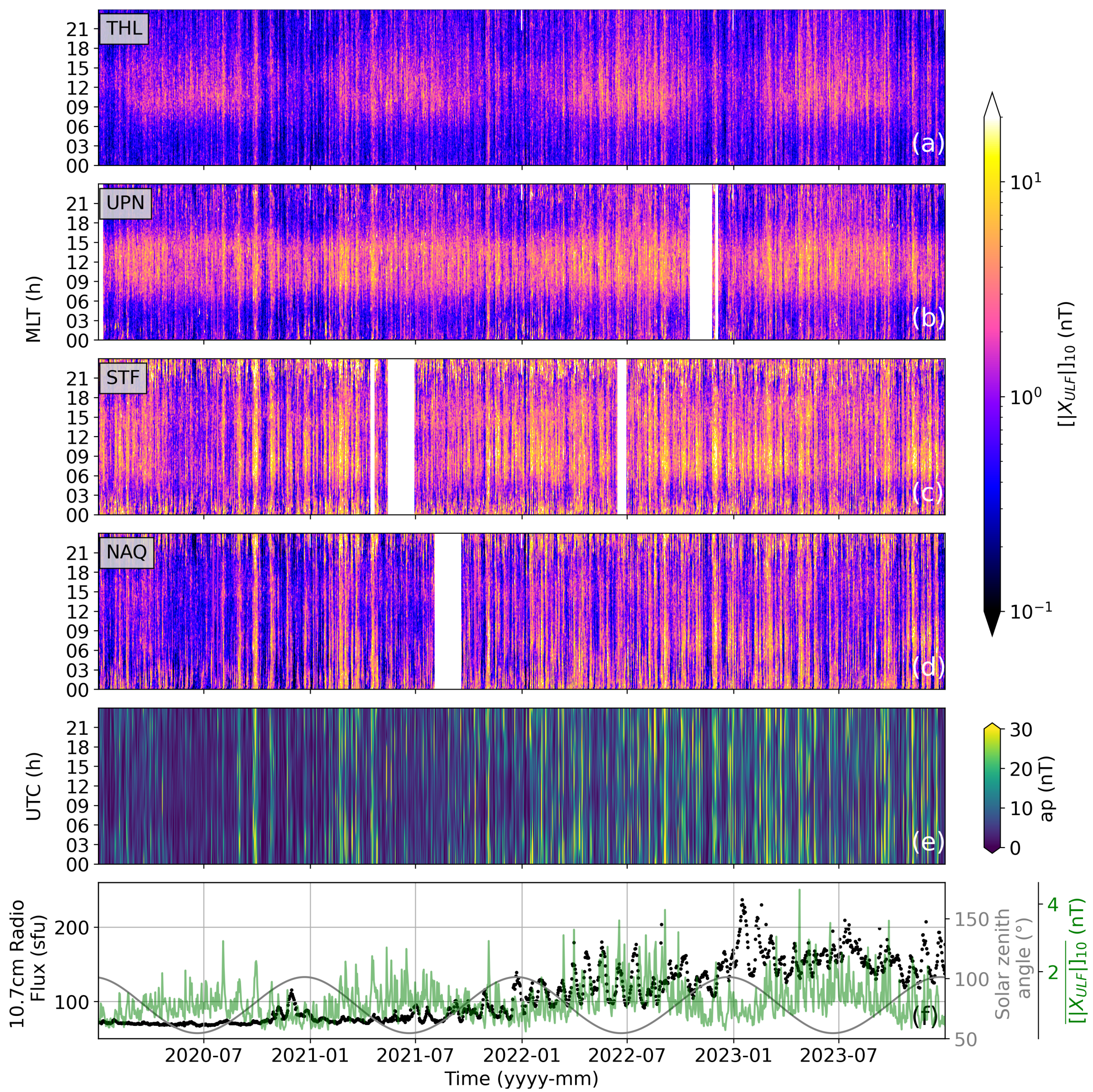

Figure 6. (a)–(d): ULF signals at the four stations THL, UPN, STF, and NAQ for four years, as a function of MLT. (e): Geomagnetic activity *ap* index as a function of UTC. (f): The daily average ULF signal measured at THL (green), the solar zenith angle (grey), and the daily solar flux F10.7 (black).

6. Figure 1c. You seem to get minima in ULF wave activity at 3 and 18 MLT. Any ideas why? It even looks like it minimises at 12 MLT. Is this addressed by L116?

Yes, this is addressed in L116. Considering the latitude of STF, it will be south (but close to) of the auroral oval at magnetic noon and north of it at magnetic midnight. This means it will cross the oval on both sides of noon, but quite close in time to noon (reading off Figure 1 at 6 MLT and 15 MLT). The minimum the referee refers to is the station being inside the polar cap, and at midnight, experience that substorm expansion brings the oval/activity over the station before it retracts back south. Hence, a minimum on both sides of midnight, rather than a "long" nightside minimum.

7. In your equatorward station, you don't seem to have any dayside ULF wave activity. I would have expected you might pick up some Field Line Resonances in the outer magnetosphere, but you don't seem to have detected this. Is this related to your butterworth filter or choice of [XULF]10 metric? Or do you think they really are absent, and do you have a suggestion?

If an equatorward station, e.g. NAQ are exposed to Field Line Resonances (FLRs), we would be able to see it in the bandpass filtered data since these often appear as Pc 4-5 pulsations (which are included in the period range of our bandpass filter 10–600s). As mentioned above, the polarisation of the waves formed by an FLR can have an influence on how the ULF signals appear in our analysis. Figure 7 displays the ULF signals observed at NAQ for the two components X and Y. Only a slight difference between $[|X_{ULF}|]_{10}$ and $[|Y_{ULF}|]_{10}$ is seen, where the signal from 15-18 MLT is not present in $[|Y_{ULF}|]_{10}$. We therefore believe that it is not the choice of the X-component that affects the amount of magnetic signals from FLRs we can observe in our statistical study. In addition, considering that the station is in the very southern part of the auroral zone (64 degrees geomagnetic latitude), we do not expect this location to see the bulk of FLRs. They would appear more frequently deeper inside the auroral zone, towards the poleward edge of the aurora oval, where field lines map to regions close to the magnetopause in the dawn and dusk sectors. Only during enhanced geomagnetic activity would we see them, and by scrutinizing the Figure we in fact see a weak indication of this at around 6 and 18 MLT.

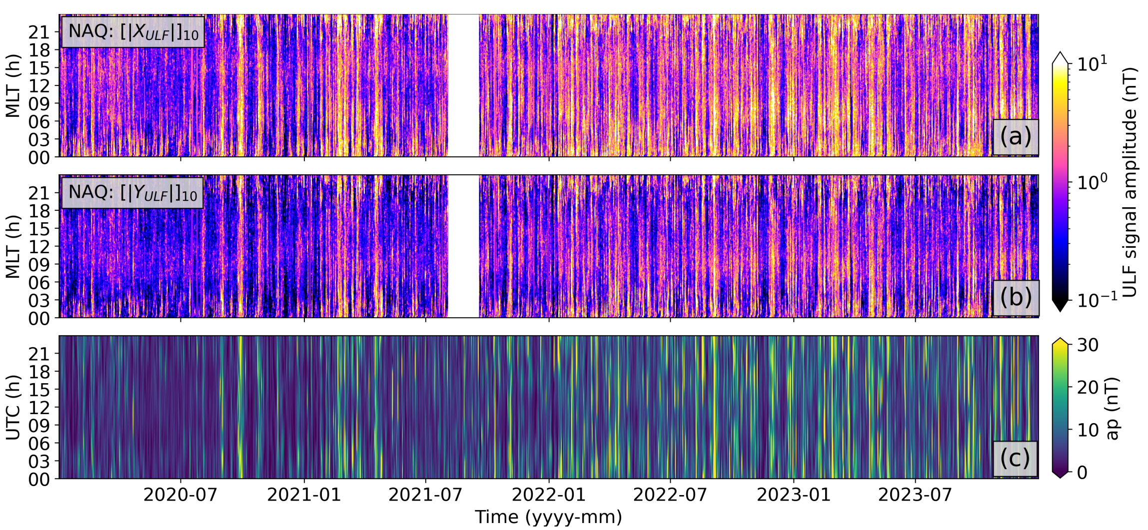

Figure 7. ULF signals at NAQ detected in the X- (a) and Y-components (b), and corresponding interpolated ap index (c).

8. L88 – What is Q? And why is Q 3?

Q corresponds to the Feldstein model input and is a geomagnetic activity index. We have selected "3" since that corresponds to moderate geomagnetic conditions, which are likely most representative for our statistical study. We will add the following to the text at line 88: *Q refers to the 15 min geomagnetic activity index as introduced by Bartels and Fukushima (1956)*

9. L115 – 'is well studied in the literature.' You should put some example references to back up this claim.

Yes, you are right, we will add to line 115: *(e.g. Sakurai and McPherron (1983), Lester et al. (1983), and Takahashi and Kan (2004).*

10. L128 – When introducing figure 4, you imply it is similar to all the results in figure 1, which doesn't like right. It only correlates with the two poleward stations. You seem to backtrack on this later in the paragraph. Maybe just put it correlates with Figures 1a and 1b.

Indeed, it is particularly Fig 1a and b that have similarities. In the sentence that the referee refers to, we write: *The resulting Hall conductances, presented in Fig. 4, show great similarity with the ULF power plots of Fig. 1, especially at THL; ....* We are too modest here, and will change the sentence to: *The resulting Hall conductances, presented in Fig. 4, show in particular great similarity with the ULF power plots of Fig. 1a and 1b (THL and UPN); ...*

11. In Figure 4, you hall conductance significantly increases each year. You haven't put in an explanation for this. Is it solar cycle related?

Yes, this is due to the increasing solar luminosity, which follows the solar cycle, as we approach solar maximum in these years. The calculation of the Hall conductance uses the F10.7 as an input parameter, which is why we see this increase; see also Figure 1F. We will add on line 130: *The steady increase in the conductivity from year to year is caused by the simultaneous increase in the solar illumination as described by F10.7 (see Fig. 1F) as we approach solar maximum.*

12. L140 – You compare your results to Motoba et al. 2019, but you don't state how their ULF observations are taken. This could be significantly different to yours, which are very wideband observations, mixing three different categories of ULF waves together (Pc3-5). You should confirm how they measured ULF waves to see if it's comparable to your method before making any comparisons. Indeed, their measurements are significantly different. They use Themis spacecraft magnetometers and particle detectors, as well as ground based optics. We do not attempt a one-to-one comparison of their results vs. ours, the point is rather that they see their ULF signals in precipitation that has significantly higher energies than what we expect in the cusp. We believe it is clear from the text that their observations fit well into the results provided by other authors, but they do not fit for the case of ULF signals further poleward, where there is a significant seasonal variation.

13. L151 – ' there is a local minimum around 75 deg' . Local minimum in what?

Text improvement: *The ULF signal strength yields a clear minimum around 75 degrees in Figure 2, separating a northern and southern ULF signature population.*

14. L182 – 'the physical distance along the Sun-Earth line between magnetic noon and midnight is small.' Do you mean along the surface of the earth? Or out in the equatorial plane of the magnetosphere? Please clarify, it could make a big difference!

We acknowledge that this statement is somewhat unclear. Yes, we mean along the surface, or in the ionosphere. The reviewer is absolutely right about the ambiguity, in the magnetosphere, this distance is quite enormous. What we try to point out here is that when THL is located at magnetic midnight, its physical location on the sun-earth line is quite close to where it was 12 hours earlier at noon, but the magnetic field lines map to a completely different part of the magnetosphere. I.e. mapping to the mantle rather than the magnetopause or its vicinity. See also the next comment below.

15. L184 – 'when the local magnetic field lines start convecting into the interior magnetosphere/mantle.' I'm a bit confused what you're talking about here. Are you referring to the Dungey cycle convection which moves magnetic flux into the tail and causes nightside reconnection? That only happens during southward IMF. And what is the relevance of the mantle to this discussion?

No, we are referring to the different magnetospheric regions field lines are mapping to, while moving northwards at noon. In other words, when you move below the cusp and out of it northwards, into the polar cap, field lines immediately map to the interior of the magnetospheric lobes/mantle. Indeed, it is true that in the Dungey cycle description, with IMF Bz < 0, they do convect, while the picture is more static for Northward IMF. We will rephrase to make it clearer, suggestion: *Especially at very high latitudes (at THL), the physical distance in the ionosphere along the Sun-Earth line between magnetic noon and midnight is small. Although we do not have more stations north of THL, this station at midnight could be viewed as an extension of the magnetometer chain at noon in a statistical treatment; the absence of ULF waves close to magnetic midnight at this latitude indicates that the ionosphere north of the station stops receiving ULF signals when the local magnetic field lines map into the mantle. We should therefore, at noon, expect a relatively fast decay of dayside ULF signals north of this latitude.*

16. L190 – There is quite a lot of discussion about your cusp region linking to magnetopause processes, but you've got no data about the magnetopause here. You also state your ULF waves are on open field lines. Where do you think these map too. The magnetosheath which is turbulent? Could this be your source? Are they recently opened field lines, but these would only occur here for southward IMF. You suggest the waves aren't generated by reconnection, which I agree with from your data. In the following paragraph, you mention these could be related to Alfven waves in the outer magnetosphere, but you've just said you think your waves are on open field lines. There's also a mention of magnetopause surface waves for the first time at the end of this paragraph on L201. In summary, I'm confused what your argument is on page 8. Please revise and make it clearer what you are trying to say.

Indeed, we are of the opinion that our "high latitude ULF signal" is on open cusp field lines. This contrasts, the conclusion of Kozyreva et al. However, as we also discuss, they are making their conclusions based on winter conditions, where we from our study expects the high latitude signal to be weak or merged with the more southern dayside signal, see manuscript Fig. 3 upper panel. For better clarity, we propose removing the two sentences from line 198 onwards: *Our results represent higher temporal resolution, but considering the broadband nature of the dayside high latitude ULF signals, on the other hand, do show a clear presence of ULF waves on open magnetic field lines. This lends a hand to the argumentation by Kozyreva et al. (2019) in support of magnetopause surface waves.*

17. L212 – A reference or two about generating ULF signals in the ionosphere would be good. Say Huges and Southwood (1976).

Excellent suggestion, thank you, we will include Hughes and Southwood

18. I didn't understand the relevance of the paragraph starting around L215 to this study. Please clarify why a discussion about KHI is needed.

Indeed, it is simply a speculation motivated by one of the outstanding problems regarding the generation of ionospheric irregularities giving rise to GNSS scintillations. Our ULF signals could easily be the seeding mechanism to initiate the build up of KHI in the cusp ionosphere. However, since the relevance to the current paper is lacking, we are happy to remove the paragraph. It follows from this that we should also remove the paragraph starting on line 256.

19. L235 – I don't see how you can make this claim without any data. You have no electron precipitation data. In fact you only have broadband ULF data and Ap.

We believe that the premise for this claim is laid out in the first sentence. We do not need to re-discover the energy levels of cusp electron precipitation. Already, Newell and Meng (1988) established that a sound definition of electron precipitation in the cusp is energies less than 200 eV. Studies by Mantas and Walker (1974) and Banks et al (1975) show that electrons of energies below 0.48 kEv, do not reach below 200 km. We will include these references in the manuscript. Furthermore, we will modify the sentence starting on line 237: *Therefore, the ULF signatures observed on the ground, that are results of alternating/oscillating Hall currents in the E-region, are the result of an alternating E-field when precipitation lacks or is soft, rather than an alternating conductivity.*

20. L252 - What is DPY? There are several phenomena mentioned in this paragraph for the first time. What is the Svalgaard Mansurov effect? You haven't mentioned this before either.

We will give a brief description of these effects in the introduction and also the implications of these to our XULF in the new subsection of section 2.

Typographic Comments 1. In the title, 'from ground' > 'from the ground' is better.

Agreed, we will make the change. Although, we are proposing a new title based on referee 1's suggestion...

2. L14 – delete 'many to come' from example references.

this is a matter of personal taste, analogue to "and references within" in other contexts. However, if necessary, we would be happy to exchange "many to come" with a selection of references to publications covering a larger timespan.

3. Figure 1 – the white subplot labels are a bit unclear. It would be clearer if your subplot labels were not actually on top of the data. They could go on the left say, you have a little highlighted box over them. You choose, just make them more readable.

This will be done. We can solve this as has been done in Figure 7.

4. $Theta_c$ in Figure 1 is not explicitly defined in the caption or text. Is this the IMF clock angle?

We believe that the referee means Figure 2. Yes, it is the clock angle, we will add this to the caption.

5. L129 – No need for a semicolon. Just make this two sentences.

This will be done.

6. L129 – No need for the semi colon here. Split into two sentences.

This will be done.

7. L168 – 'an ULF' > ' a ULF'

This will be done.