We thank both referees for the helpful comments. Point-by-point answers are given in blue.

Anonymous Referee #1

Received and published: 29 May 2020

Authors: N. Yagova et al.

Title: Even moderate geomagnetic pulsations can cause fluctuations of foF2 frequency of the auroral ionosphere.

The authors investigate the relation between colocated, simultaneous fluctuations in the F2 critical frequency and geomagnetic time series. They developed an automated method for inferring foF2 frequency from the ionograms. Events with foF2 frequencies modulated in the Pc5/Pi3 frequency range are analysed. The properties of a subset of events with coherence greater than 0.5 are compared to the average properties of the whole population of the events. The authors found that coherent events favour moderate geomagnetic conditions and show typical features of field line resonances. At the same time, it is noted that the automated detection of foF2 is not applicable to disturbed conditions. The paper, in general, is difficult to read and follow mainly because of its poor language. We strongly recommend the authors to use some spell-check tool to improve the quality of the presentation of their thoughts.

Thank you very much for your comments. We plan to improve the language.

A figure illustrating the automated detection of the critical frequencies would be helpful for the reader.

We plan to extend the Figure 1 and the capture to explain the detection procedure in a more clear way.

The focus of the paper is on coherent events, however, neither the 'event' is exactly defined, nor the significance level of the calculated coherence is given.

The significance levels will be added to the paper, and a more detailed classification of the events will be added. The more detailed classification will be added to clarify the basis for comparison of the coherent magnetic pulsations with the foF2 pulsations on each step of the data analysis.

There is also some inconsistency in the paper about at what frequency the coherence is taken (f1 vs f2: statistics in Fig 10 vs. case studies). Results presented in Fig 11 again suggest a link to f2 (at least based on the case studies).

This issue will be discussed in more details. While it is possible to analyze several frequencies in case studies, in statistics it can lead to an artificial enhancement of coherence between magnetic and foF2 pulsations. That is why, in the current version of the MS, we have used the comparison of only the first frequencies in statistics to obtain the lower boundary for the coherence estimates. In the next version, the data processing technique with both frequency maxima taken into account will be applied, and its influence on final statistical relationships will be considered.

The relative occurrence of coherent events is very low (_ 3%). The statistics support that coherent events tend to occur under moderately disturbed geomagnetic and interplanetary conditions. However, the significance of this result is not clear due to 1. the low relative occurrence of coherent events, 2.

the unknown significance level of coherence, 3. the limitations of foF2 detection under disturbed conditions, 4. the applied normalisation on which limited information is given. It was also not investigated how often the coherent events show up provided the conditions are favourable (moderate disturbance). Without this information the study is not complete and cannot be judged.

This summary of the problems in data analysis is really very important. We shall try to improve data analysis in accordance with the following plan.

1. A more detailed classification of the analyzed intervals will be applied, e.g. the intervals will be sorted into several sub-classes: in accordance with the 1) foF2 data availability ; 2) amplitudes of geomagnetic and foF2 pulsations; 3) coherence level between geomagnetic and foF2 pulsations

2. This will allow to estimate statistically the space weather effects for each group of intervals and to exclude the ambiguity which now exists in the analysis of highly disturbed intervals.

3. The number of analyzed events will be given for all the statistical studies and normalization procedure will be explained in more details.
4. Significance of the coherence estimate will be added

I recommend a major revision. Below I give a list
of my minor comments in two groups. The first group relates to science, the second to the language. The latter is far from being complete. It would have been a long list.
Minor comments on the scientific content

We shall try to improve the text in the accordance with the minor remarks listed below. Specific remarks are given below to some questions which need more explanations.
l 97: "about 10 nT and 0.08 MHz": Revise these values based on Fig 3!
l 100 what is the significance level for the coherence values in these calculations?
l 112: "about 80 nT and 0.08 MHz": although geomagnetic variations are several times greater here then for event 1, the foF2 variations are smaller. Comment?

The problem of different efficiency of geomagnetic pulsations in foF2 modulation will be discussed. This might be explained by different spatial scales of pulsations.

l 126: A MLT distribution of occurrence of the foF2 variations –> The MLT distribution of the occurrence of foF2 variations Under what conditions? What criteria define an event?
l 128: "frequency distributions of geomagnetic and foF2 pulsations": in general? I guess the distribution is based geomagnetic pulsation events simultaneous with foF2 events.

Figure 9: What is D (vertical axis)? Relative occurrence

Figure 10: Why the distribution of the first spectral peaks is presented. In your example events f2 has the higher coherence and corresponding Psw fluctuations. Are not your examples presented typical for the coupling between foF2 and geomagnetic variations?

In the present version, we have chosen this variant for statistical studies, because the analysis of different combinations of frequency maxima in foF2 and geomagnetic pulsations can lead to an overestimation of common features in their spectra. We understand, that our variant gives the underestimated level of similarity. We have used this variant to obtain an estimate from the bottom for the similarity between the two types of pulsations. . In the next version, we will apply the data processing technique with both frequency maxima taken into account.

l 131: "spectral coherence at SOD" : at what frequency? coherence at f1?
l 132: Give the significance level!
Figure 10 b) Mark the significance level in this plot!
l 142: some information on the derivation of the weight functions and how they applied to normalize the data is needed
This information will be included into the text

l 153: "the 4-day minimum Dst and 6-hour maximal AE": intervals centred or preceding the coherent event?

All the parameters are given for the preceding intervals

l 158-162 Do coherent events occur under severely disturbed conditions, just they cannot be observed? Or they do not occur under those conditions at all? How does this observational limitation affect your conclusions?

This question will be answered using a more detailed classification of events (see our answer to the last point of the major comments). As for the ionosonde data, Pc5s in the F layer can be recorded under extremely disturbed conditions only rarely, because of blanketing or absorption below. This leads to the situation when case studies of rare Pc5 events may be possible, but the amount of data is not enough for statistical analysis.

l 165: "3-hour mean values of BZ and V and 3-hour maximal value of _Psw": in which interval? (same issue as above)

Again, the preceding intervals are used

l 181: "Amplitude of SW dynamic pressure fluctuations show an association with occurrence of coherent foF2 _ B pulsations": only 2 examples were presented in favour of this statement. Figure 13 b) does not yield any information on the spectral content of the pressure variations, and hence their relation to the coherent frequency. You seem to focus your statistics on f1 (first peak, e.g. Fig 10 a; coherence at f1), while your 2 examples had their relation with the SW pressure variations at f2.

The data of SW dynamical pressure have many gaps. That is why we only qualitatively consider some example events. In the future, we plan to study the cross-spectra of IMF and SW dynamic pressure fluctuations with foF2 pulsations based on an extended data set.

l 185: refer to your observations relevant presented in Fig 11. and show how they support the FLR nature of the coherent subset

We plan to add an example of FLR properties of coherent b-foF2 pulsations l 193: "The picture changed dramatically": be more specific!

Thank you very much for the help with the text. We shall take all the comments into account.
Further comments:
l 1: "variations of the critical frequency": maybe "modulation" of the critical frequency could also be used here
l 1: o-mode radiowave –> o-mode radio waves
l 2: in 1–5â ˘ AL’mHz –> in the 1–5â ˘ AL’mHz
l 4: delete "daytime Pc5/Pi3 geomagnetic pulsations and" [foF2 is obviously not detected in geomagnetic pulsations]
l 6: at SOD station –> observed at SOD station
l 6: with the data of a station pair located at the same magnetic meridian –> using the data of a station pair located along the same magnetic meridian
l 8: Meanwhile, –> "At the same time," OR "However,"
l 8: "the analysis of geomagnetic and foF2 variations show intervals with noticeable coherence for both horizontal components" –> "the analysis of geomagnetic ad foF2 variations shows intervals of significant [OR remarkable] coherence with both horizontal geomagnetic components" [foF2 does not have any components]
l 11: averaged –> the average
l 11: coherent to –> coherent with
l 13: show –> shows
l 14: show –> shows [I suggest to use some synonym of ’show’, such as ’reveal’, ’indicate’. Use an online Thesaurus for finding synonyms]
l 19: Majority of publications are based on the radar observation –> Majority of publications on the topic are based on radar observations
l 20: of electron concentration at certain altitude –> of the electron concentration at a certain altitude
l 23: with mainly compressional mode of MHD wave in the magnetosphere –> with mainly compressional mode magnetospheric waves
l 26: An effect of TEC modulation by ULF wave –> The effect of TEC modulation by a ULF waves
l 27: and zones –> and also from zones
l 28: observed pulsations –> the observed pulsations [a large number of articles are missing from the text, check!]
l 31: the recovery phase of the magnetic storm –> the recovery phase of a magnetic storm
l 33: aimed on variations –> aimed at comparing variations
l 37: It makes an ionogram –> It obtains an ionogram recording
l 40: 10 s sampling rate –> 10 s sampling period/interval
l 40: and we also use the data of the MAS station, which is a part of IMAGE –> we also use data of recorded at MAS station of the IMAGE network
l 42: To analyzed –> To analyze
l 43: and also Dst and AE indexes are used –> as well as Dst and AE indexes
l 46: with quality and time resolution enough –> with good quality and time resolution is enough
l 56: for the reader’s sake refer to your Fig 1 here.
l 58: Lorentsian –> Lorentzian
l 60: 235 km –> 235 km.
l 60: Coefficients f1, _f = f2 _ f1, k, and _ are found as a result of fitting procedure,

described below. –> A fitting procedure described below is used to find f1, _f = f2 _ f1, k, and _. [f1,_f, _ are not coefficients] What are the meaning of f1 (I guess f at h1)
and f2?
l 61: boundary is determined as a line –> boundary consists of a set of (h,f) points
l 62: Signal intensity I at the boundary should be high –> Signal intensity I is high
l 63: Amplitude ratio R of the signal intensity at the boundary line to the power above it should also be high –> The contrast between the peak and the background (characterized by the amplitude ratio R) is high [or similar, your version is confusing. Intensity to power ratio called amplitude ratio... It is not clear what is ’above’. At higher frequency?]
l 64: As four fitting factors are used –> We then fit Eq(1) to the detected boundary points. As four fitting factors are used
l 64: organized and a parameter –> organized. A parameter
l 65: over the "cross" in space of parameters –> over the parameter space [?]
l 65: where x is a point in the space of parameters, and i is a parameter number –> where ’x’ is a point in the parameter space, and ’i’ identifies the parameter [and what is c?]
l 64: Give a representative example, e.g. the values of the parameters used to derive the fits presented in Fig 1!
l 68: time dependence f(t): Do you mean the time dependence foF2(t)?
l 69: give a typical value of t1!
l 71: the other [??? or another]
l 73: Examples of approximation curves are given in Figure 1:
Figure 1: Complete the figure caption by including "the fitted curves are plotted over the ionograms in yellow" or similar. Add a reference to the fitting curves in Fig 1 in the main text, as well.
l 76: pictures –> plots
l 79: Note, that the ionograms are rotated by 90â °U ¸e in respect to usual f _ H presentation: This sentence should come earlier! (with respect to)
l 80: foF2 –> foF2 values
l 84: Statistical analysis: Statistical analysis of what?
l 84: interval –> intervals
l 85: We studied –> We studied the effect/influence of .... on...
l 87: resolution, enough –> resolution high enough
l 90: Cross-spectra are calculated for foF2 variations, on one hand, and components of the geomagnetic field pulsations, on the other hand. –> Cross-spectra are calculated between foF2 variations and components of the geomagnetic field pulsations.
l 100: "at low frequency part of spectrum f < 2 mHz" –> "in the low frequency part (f < 2 mHz) of spectrum"
l 101: peak with maximal y2 = 0.6 –> peak with y2 = 0.6
l 129: "with frequencies (f1 > 3.7 mHz)" –> "with frequencies above 3.7 mHz
l 130: "The distribution of Pc5/Pi3 intervals over foF2 _ b spectral coherence at SOD are shown in Figure 10b for two" –> "The histogram of the foF2 _ b spectral coherence at SOD is shown in Figure 10b for the two"
l 137: "a question arises about the pulsation properties and external parameters, favorable for their occurrence": rephrase!
l 138: "the geomagnetic pulsations" –> "a subset of the geomagnetic pulsations"
l 139: " with all the intervals, selected" –> " with all the events selected"
l 142: "calculated with the weight functions, which are found from" –> "calculated with weight functions derived from"
l 143: "coherent and pulsations and averaged" –> "coherent pulsations and averaged"

l 151: indexes –> indices
l 159: "limited by" –> "limited to"
l 186: "in coherent foF2 _ Bx pulsations" : delete. This information is already given earlier in the sentence.
l 197: "For the first time, a statistical study of foF2 variations in Pc5/Pi3 range and their relation to geomagnetic pulsation in the conjugated position at SOD station and its spatial distribution along a magnetic meridian." Check the sentence (missing predicate).

Anonymous Referee #2

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In their manuscript "Even moderate geomagnetic pulsations can cause fluctuations of foF2 frequency of the auroral ionosphere", Yagova et al. explore variations of the ionosphere F2 region critical frequency (foF2) and ultra-low frequency (ULF) waves in the Pc5 and Pi3 frequency bands detected at auroral latitudes.
Using ground magnetometer and ionosonde data spanning years 2014 and 2015, the authors examine the power, coherence and phase difference of perturbations in the daytime ionosphere and Pc5/Pi3 geomagnetic pulsations, distinguishing a subset of events during periods of magnetic quiescence and moderate magnetic storms with coherence greater than 0.5 from ULF wave signatures in the ionosphere observed under conditions favourable to strong geomagnetic storms. This extends previous studies by Pilipenko et al. (2014a and 2014b) that considered ULF wave-driven oscillations in the ionosphere F2 region during strong and small magnetic storms.
Furthermore, the manuscript presents a new methodology to the automated detection of the foF2 critical frequency from ionograms that could be of interest for the research community working on determining factors that influence the amplitude and phase of perturbations in the ionosphere as these are detected on the ground. There are, however, several issues that hinder my recommendation of this manuscript for publication in Annales Geophysicae in its present form.
There are major issues with the English language use, several typographical errors and in general, it is poorly written making it difficult to understand the scientific rationale behind this study.

Thank you very much for the comments. We are working on improvement of the language of the MS.

For example, in line 19, it reads: "Modulation of ionospheric parameters by Pc5 pulsations was reported : : :", without detailing which parameters are meant here. In the same line, it goes on to say: "Majority of publications are based on the radar observation : : :" (which would more correctly read "The majority of publications are based on radar observations : : :"), without making it clear to which publications the authors refer.

These points will be clarified

It would be worthwhile to establish in the Introduction the need for a study such as the present by listing past publications focused on perturbations in the ionosphere driven by ULF waves. Early results on geomagnetic pulsations in the ULF wave frequency range associated with total electron content (TEC) fluctuations date back to 1976 and include the following:

- Davies & Hartmann (1976), Short-period fluctuations in total columnar electron content, Journal of Geophysical Research, https://doi.org/10.1029/JA081i019p03431
- Okuzawa & Davies (1981), Pulsations in total columnar electron content, Journal of Geophysical Research, https://doi.org/10.1029/JA086iA03p01355

In the previous version, we have briefly mentioned only auroral Pc5 pulsations, while the papers by Davies (1976) and Okuzawa (1981) were devoted to Pc3-4 pulsations at lower latitudes. In the revision we plan to extend the Introduction section and include these and some other references.

Total electron content variations have been proven a powerful tool in the detection of ionospheric signatures of ULF waves at high latitudes as well as data from ionosondes exploiting the radio-wave reflecting properties of the ionosphere, as it is detailed by Watson et al. (2015). It is not clear to me and perhaps the reader how the results of Watson are different from those of Kozyreva et al. (2019) briefly mentioned in line 29. Nor the difference with those of Pilipenko et al. (2014b) derived from data collected during a different magnetic storm.

This analysis will be included into the Introduction section and to Discussion. We plan to give a more thorough analysis of observational results in the Introduction section and of physical mechanisms in the Discussion.

The following publications could be added to improve the placement of this work in the context of existing literature:
- Baddeley et al. (2005), On the coupling between unstable magnetospheric particle populations and resonant high-m ULF wave signatures in the ionosphere, Annales Geophysicae, https://doi.org/10.5194/angeo-23-567-2005
- Buchert et al. (1999), Ionospheric conductivity modulation in ULF pulsations, Journal of Geophysical Research, https://doi.org/10.1029/1998JA900180

The references will be added to the MS

In lines 31 and 32, the authors note that the association of waves with moderate amplitudes with variations of the foF2 critical frequency have not been studied. However, how their amplitude is defined as moderate is not described nor later in the manuscript. As mentioned in the title of the manuscript, the reader is waiting for more details on these moderate geomagnetic pulsations, in my mind.

Thank you very much for this comment. In the next version the data analysis will be improved and a classification of the intervals in accordance with spectral power density at frequencies of PSD local maxima will be added. This will allow to quantify such terms as “moderate”.

In lines 62 and 63, could the authors explain in quantitative terms how high the signal intensity at the reflection boundary should be as well as the amplitude ratio of the signal intensity at the reflection boundary to the power above it?
Later, in lines 68 and 71, the authors note that a threshold for the time derivative of the foF2 critical frequency is calculated from the variance over a time interval of length t1. Is the variance of the foF2 critical frequency meant? How is the length of the time interval t1 defined?

The description of the approximation procedure will be extended. Besides, the parameters values used as the initial point of approximation will be added as a supplementary file.

Section 2.2 would benefit from an ionogram on which the described method has been used to detect the ionosphere F2 region critical frequency, clearly illustrating the new method for the foF2 critical frequency automated detection.

Figure 1, its capture, and the text explaining the procedure will be improved to make the detail of the approximation procedure clearer.

In Figures 4 and 7, it would be worthwhile to note the frequency of the primary and secondary maximum in power and provide further explanation at which frequency the coherence is taken for the statistics provided in Section 3.1.2.

The explanations will be added. Actually, in the present version, there is a difference in the examples, where 2 frequencies are used and statistical results where only the first spectral maxima are analyzed. This point will be improved in the revised version.

In Section 3.1.1, in addition to the details offered for the two intervals in March and July 2015, the two examples could be utilised to introduce the criteria set for selecting similar events for subsequent statistical analysis.

The classification of events will be improved. Really, in the present version, not identical criteria are used at different stages of data analysis. The choice of event class is not random but it may be difficult to discriminate between different types of events taken for comparison with coherent b-foF2 events in each case. The explicit classification will be given in the beginning of the Data processing section.

In Figures 9, 10, 12 and 13, as these are described in Section 3.1.2, what does “occurrence” and the symbol “D” mean in this context? Do the authors refer to “probability of occurrence”?

Yes, that is the empirical probability density, the term will be explicitly explained in the text

As they stand, the conclusions reached and briefly summarised in the first paragraph of Section 4 of this manuscript are a bit vague. Although it is suggested that this study is focused on variations of the ionosphere’s critical frequency foF2 during quiet and moderately disturbed geomagnetic conditions, the most favourable values of the Dst index lay between -100 and -50 nT. Under such conditions, how often would it be expected to detect events are associated with ULF geomagnetic pulsations? How would the low occurrence rate (3%) of coherent events change if periods of highly disturbed conditions or quiescence were excluded? Please also consider commenting on the solar wind conditions that are favourable for the occurrence of coherent events and specifically, provide the range of solar wind speed and dynamic pressure values.

The new classification of all the intervals analyzed will give answers to all these questions. You are absolutely right, that in the previous version of our MS, the problems caused by the method of foF2 detection from the ionogram in the disturbed ionosphere can hardly be discriminated with the ionospheric Pc5/Pi3 occurrence probability. In the next version we shall limit ourselves with the disturbance levels, for which the detection procedure is valid and concentrate only on the intervals when quality of foF2 detection allows for the spectral analysis. For these intervals, we shall analyze the specific features of high coherent b-foF2 pulsations and space weather conditions favorable for their occurrence. Probabilities of coherent b-foF2 pulsations under favorable conditions will be given explicitly in the text.

Lastly, there are inconsistencies in the referencing style and specifically, on page 9 and 10, the year of publication in Mager et al. (2013), Min et al. (2017) and Viall et al. (2009) should be moved to the end of each reference.

The references will be corrected