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# *Interactive comment on* "Statistical study of ULF waves in the magnetotail by THEMIS observations" *by* Shuai Zhang et al.

**Shuai Zhang et al.**

tamin@sdu.edu.cn

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First of all, we would like to thank the reviewer for the helpful comments and suggestions. We are very appreciative of that. Our responses to the comments are in blue font. In the revised manuscript, the modifications are highlighted in red font.

This paper presents a statistical analysis of ULF waves in the nightside magnetosphere including the tail region up to geocentric distances of 32 Re. The wave events are identified using plasma bulk velocity data to capture fundamental field line oscillations. The wave events are classified into radial and azimuthal type and standing and nonstanding modes. The most important result is the finding that standing waves are



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Discussion paper

hardly detected beyond 16 Re. I find this result to be very interesting and significant. I recommend publication of the manuscript after the authors have considered minor comments listed below.

Line 78. Please change “Susumu Kokubun" to “Kokubun"

Revised.

Line 136. “quasi monochromatic" Is this judgement made by visual inspection of the time series data? If so, it may explain some discrepancies between the present and previous studies (see my comment on line 267 below).

Thanks for your suggestions. In this study, the “Quasi monochromatic" is not exactly made by visual inspection of the time series data. We conduct Fast Fourier Translation (FFT) analysis to all the candidate time series as to the event shown in Fig. 2(l-n). Then, we judge whether there is an obvious spectral peak in FFT spectrum by visual inspection. Only events with an obvious single spectral peak are considered as “quasi monochromatic" wave. We added one sentence in lines 158-159.

Line 169, Figure 2. I recommend using a common amplitude scale for the components of each vector quantity. It makes easier to visually grasp the amplitude difference between the toroidal and poloidal components.

Ok. Figure 2 has been re-plotted by using the same y-axis limit for each component in the revised manuscript.

Line 171. The Ez component is not zero. This should be pointed out in the main text and explained in relation to how you define the field line coordinate system.

Thanks for your suggestion. The sentence has been added in lines 163-166 in the revised manuscript: “Note that the magnetic field vector used for calculating **E** ($\mathbf{E} = \delta\mathbf{V} \times \mathbf{B}$) at each moment may be deviate from the z-axis determined by 30 minutes sliding average of the magnetic field data. Therefore, the Ez component will have a





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little deviation from zero in the FAC coordinate system as shown in Fig. 2g.".

Line 232. The phase difference can be ~-90 degrees, depending on the magnetic latitude (or distance from the tail midplane where Bx = 0). I hope that events exhibiting this phase delay are also included.

Thanks for your comments. The events with $-90^{\circ}$ phase difference have already been included in our list of events. Because either the phase deference of $\sim 90^{\circ}$ or $-90^{\circ}$ is considered as the characteristic of a standing wave. We rephrased the words “the phase differences" as “the absolute value of the phase differences" in lines 238 and 243 in the revised manuscript.

Line 239. I guess that this probability means the probability that a given azimuthal or radial wave event shows signatures of a standing wave, not the probability that you find a standing wave at a given time. Please clarify.

Yes, the sentence has been rephrased as “Figure 7 shows the radial distribution of the probability that a given azimuthal or radial oscillating wave event shows signatures of a standing wave." in lines 249-250 in the revised manuscript.

Line 240. Change “deep" to something like “dark"

Revised. See line 250 in the revised manuscript.

Line 259. “fundamental eigenmode". You can justify this mode identification by examining the relationship between the sign of the Er-Ba phase difference and the magnetic latitude of the spacecraft. You can also identify second harmonic from the phase difference. Have you found any second harmonic waves? Second harmonic poloidal (radial) waves have been reported at R $<$ 10 (e.g., Hughes et al., 1979), and I wonder if you have encountered any at R $>$ 10.

Hughes, W. J., McPherron, R. I., Barfield, J. N., & Mauk, B. H. (1979). A compressional Pc4 pulsation observed by three satellites in geostationary orbit near local midnight. Planetary and Space Science, 27(6), 821-840. doi:10.1016/0032-0633(79)90010-2

Thanks for your suggestions. According to your suggestion, we try to identify the second harmonic waves by the E-B phase difference and the magnetic latitude. Figure S1 is a schematic diagram describing the latitude dependence of phase difference for the fundamental waves and second harmonic waves. The green dashed line P1 (P2) indicates a fixed point slightly on the north (south) side of the magnetic equator plane. Panel b (c) shows the temporal variation of B, V and E at the P1 (P2) point. We can see that the sign of E-B phase difference between the fundamental waves and second harmonic waves is opposite at the same observation latitudes. The azimuthal oscillating wave could be second harmonic wave if Er lead (lag) Ba by $\sim 90^{\circ}$ when MLAT$<$0 (MLAT$>$0), and the radial oscillating wave could be second harmonic if Ea lead (lag) Br by $\sim 90^{\circ}$ when MLAT$>$0 (MLAT$<$0). In total, we find that about 3.03% (33) azimuthal oscillating wave events may be second harmonic waves and 2.65% (15) radial oscillating wave events may be second harmonic waves, as shown in Figure S2. The above analysis result is not contradictory to our opinion that most of our standing wave events are fundamental waves. We added two sentences about the harmonic mode in lines 270-272 in the revised manuscript.

Line 267. This is different from the Geotail result obtained by Kokubun (2013, Figure 15) and Takahashi et al. (2014, doi:10.1002/2014ja020274, Figure 5). Please comment on this difference and offer explanation if possible.

Kokubun (2013, Figure 15) shows that the number of waves is higher on the dawnside than duskside, at first glance, it is different from our results. We noticed that, in his work, the orbit normalization was not conducted and the events they focused on mainly occur in the dayside. The number of events (153) observed in the nightside is less in his work, which is probably because the amplitude of waves is required to be greater than 30 km/s in his work, while the amplitude of waves should be greater than 25 km/s in our study.

Takahashi et al. (2014, Figure 5) shows that the occurrence rate of toroidal waves is higher on the dawnside than duskside and the occurrence rate is zero in the midnight





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Discussion paper

region, which are different from our results. The possible reason is that they only focused on the pure toroidal wave, while azimuthal oscillating waves with comparable power in Va and Vr are also included in our list of events. Thus, more azimuthal oscillating waves could be observed in the duskside in our study, because of the possible coupling between azimuthal oscillating waves and radial oscillating waves (with higher occurrence in the dusk sector). Another possible reason for these differences is that their waves were identified automatically by program using a 60 min data window and there was no precise beginning and ending time. A quantitative standard is used in our study to determine the beginning and ending time of each event, which may lead to a different list of events between our than their works. We added some additional comments in lines 287-292 in the revised manuscript.

Line 287. “Poulters" means “Allan and Poulter?"

Yes, revised.

Line 298, “Highly stretched field lines". Is it possible that some events are observed on open field lines?

It is an interesting question. However, we can only say statistically that the events we studied were happened on closed magnetic field lines. We have calculated the elevation angle of the magnetic field line for all wave events as shown in Fig. S3. It found that 61.70% of the events have an elevation angle larger than $45°$ and only 2.48% events with an elevation angle $<10°$. It suggests that most of our events are observed near the magnetic equatorial plane. In addition, we mainly use ion velocity data to identify ULF waves, which are usually reliably measured in the plasma sheet. Therefore, it is unlikely that the events studied in this work were occurred on open magnetic field lines. We added some additional comments in lines 269 and 273-277 in the revised manuscript.

Line 331. Figure 8. It would be better if the vertical axis shows the probability of detecting a wave event (instead of the number of events) in each bin for the solar wind velocity and AE index.

Thanks for your suggestion. we have re-plotted Fig. 8. The new vertical axis shows the probability of detecting a wave event instead of the normalized number of events in each bin. The detailed calculation formula for the probability is as follows (take the solar wind Vx as an example):

$$Normalized\ event\ number = \frac{the\ number\ of\ events\ in\ a\ given\ bin}{the\ duration\ proportion\ of\ solar\ wind\ Vx\ in\ a\ given\ bin}$$

$$= \frac{the\ number\ of\ events\ in\ a\ given\ bin}{\frac{duration\ of\ background\ Vx\ in\ a\ given\ bin}{total\ duration\ of\ background\ Vx}}$$

$$Probability = \frac{the\ normalized\ event\ number\ in\ a\ given\ bin}{the\ total\ normalized\ event\ number\ of\ all\ bins}$$

The sentence has been rephrased to “The Y-axis indicates the probability of detecting one wave event in each bin. The background solar wind data is obtained from OMNI from 2008 to 2015." in lines 338-339 in the revised manuscript.

Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2018-39/angeo-2018-39-AC2-supplement.pdf

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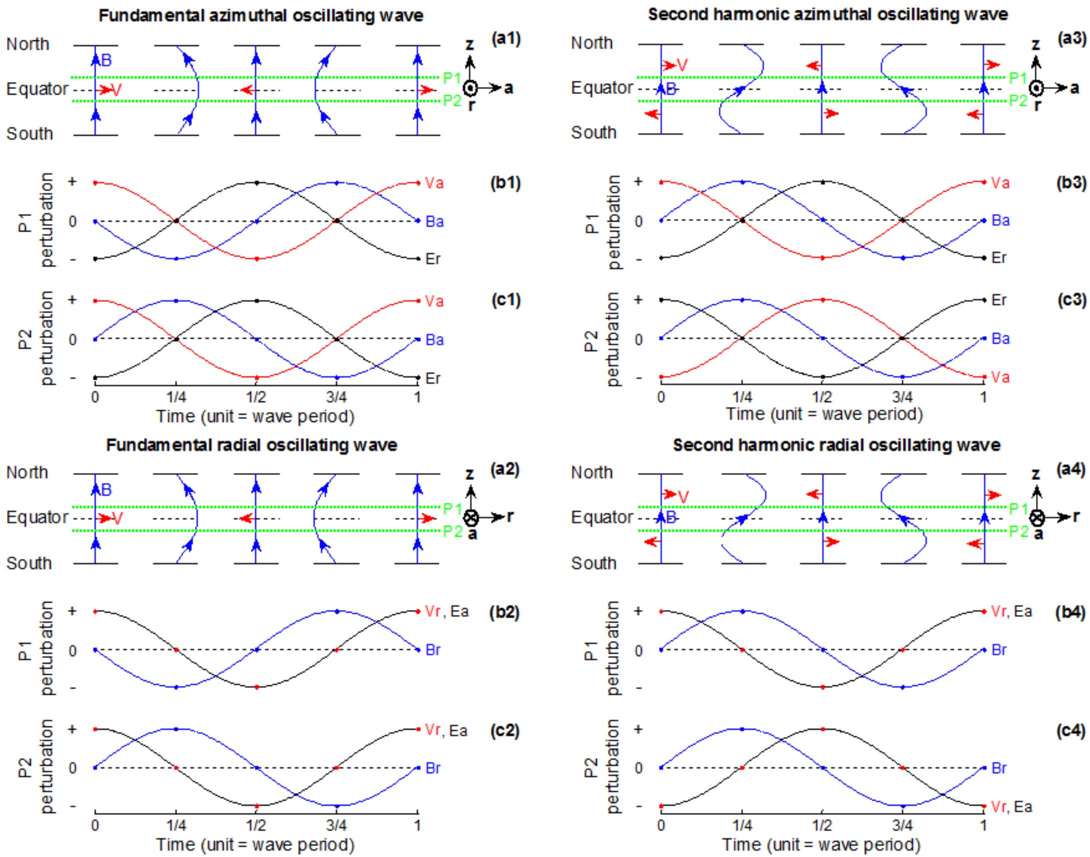


**Fig. 1.** Figure S1. Schematic illustration of magnetic field, velocity and electric field for the fundamental wave and second harmonic waves in the magnetic meridian plane. Refer to Fig. 3 of Takahashi et al.







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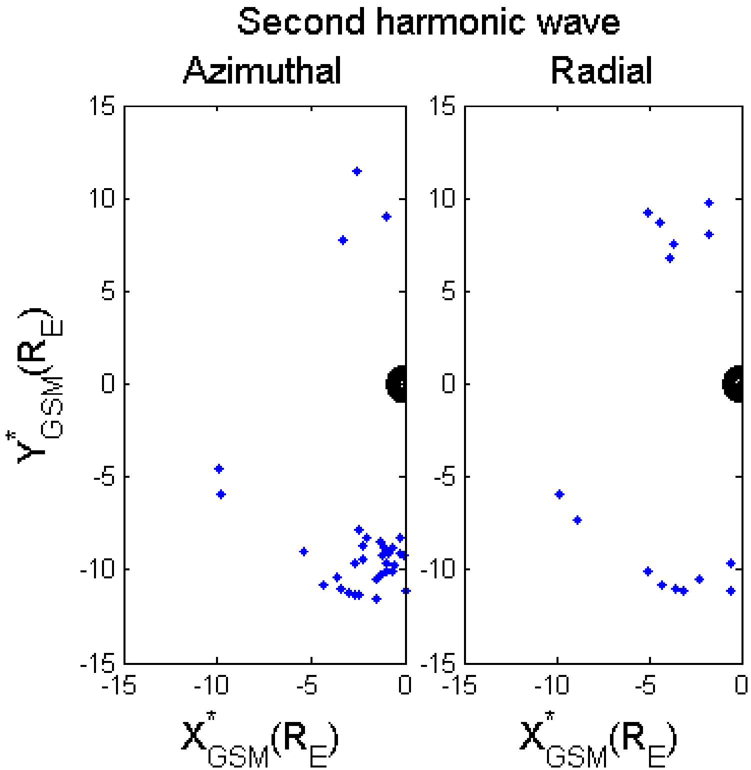


**Fig. 2.** Figure S2. The distribution of second harmonic waves in the GSM* X-Y plane.



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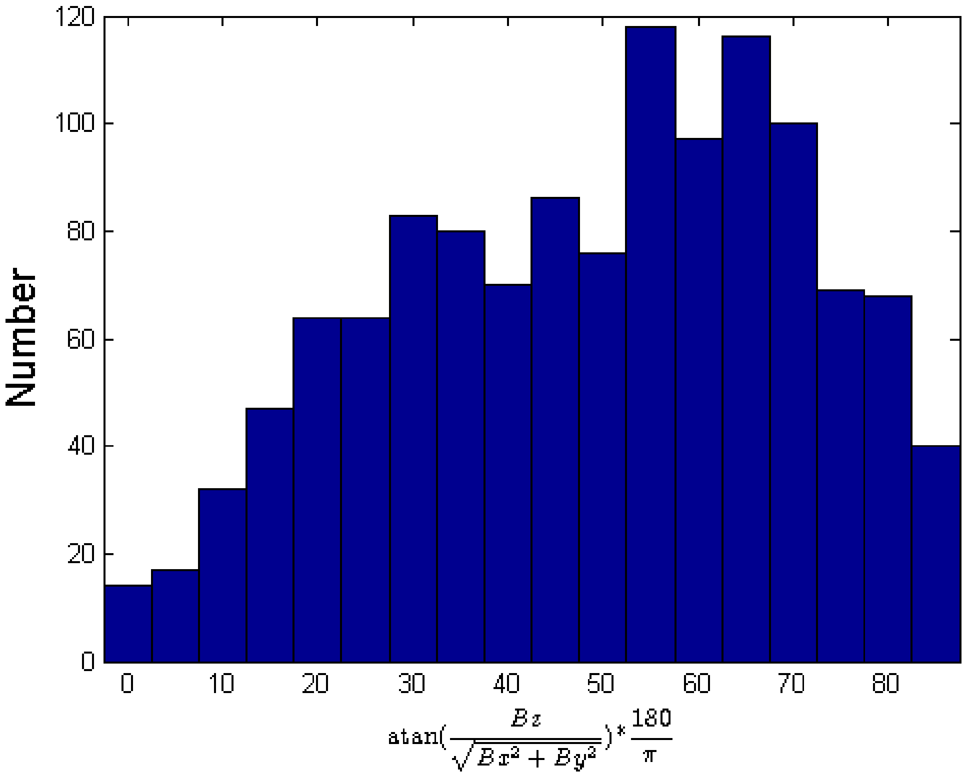


**Fig. 3.** Figure S3. The distribution of elevation angle of the magnetic field line.