JGR Space Physics

RESEARCH ARTICLE
10.1029/2019JA026496

Key Points:
- Observation of the Arase satellite with an all-sky imager revealed a long-lasting correlation between pulsating aurora and chorus waves
- The high-correlation region sometimes changed abruptly, which could have resulted from the discrete spatial structure of plasma
- The cross-correlation analysis can be used for monitoring the local link between the ionosphere and magnetosphere

Supporting Information:
- Supporting Information S1
- Movie S1

Correspondence to:
S. Kawamura,
suguru.kawamura@uec.ac.jp

Citation:
Kawamura, S., Hosokawa, K., Kurita, S., Oyama, S., Miyoshi, Y., Kasahara, Y., et al. (2019). Tracking the region of high correlation between pulsating aurora and chorus: Simultaneous observations with Arase satellite and ground-based all-sky imager in Russia. *Journal of Geophysical Research: Space Physics*, *124*, 2769–2778. https://doi.org/10.1029/2019JA026496

Received 14 JAN 2019
Accepted 16 MAR 2019
Accepted article online 25 MAR 2019
Published online 23 APR 2019

Tracking the Region of High Correlation Between Pulsating Aurora and Chorus: Simultaneous Observations With Arase Satellite and Ground-Based All-Sky Imager in Russia

S. Kawamura[1], K. Hosokawa[1], S. Kurita[2], S. Oyama[2,3,4], Y. Miyoshi[2], Y. Kasahara[5], M. Ozaki[5], S. Matsuda[6], A. Matsuoka[6], B. Kozelov[7], Y. Kawamura[1], and I. Shinohara[6]

[1]Graduate School of Communication Engineering and Informatics, University of Electro-Communications, Chofu, Japan, [2]Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan, [3]National Institute of Polar Research, Tachikawa, Japan, [4]Ionosphere Research Unit, University of Oulu, Oulu, Finland, [5]Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa, Japan, [6]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Chofu, Japan, [7]Polar Geophysical Institute, Murmansk, Russia

Abstract The temporal modulations of magnetospheric chorus waves are one of the candidates for explaining quasiperiodic precipitation of energetic electrons causing pulsating aurora (PsA). To confirm fully the direct association between PsA and chorus, an extended interval of PsA (~1 hr) simultaneously observed by the Arase satellite and a ground-based all-sky imager in Apatity, Kola Peninsula, Russia was examined. In particular, a region of high correlation between PsA and chorus was continuously tracked within the field of view of the all-sky imager. The result showed that the high-correlation region and the modeled footprint of Arase moved in tandem. This strongly implies that the chorus and PsA electrons originated from the same local interaction region. In addition, the location of the high-correlation region showed sudden jumps, which were probably associated with the motion of the satellite through discrete spatial structures of plasma in the region of wave-particle interaction.

Plain Language Summary Pulsating aurora (PsA), which consists of luminous patches/arcs blinking with various periodicities ranging from a few to a few tens of seconds, is known to occur very frequently during the recovery phase of auroral substorms. It has been suggested that the luminosity variation of PsA is controlled by natural electromagnetic waves in space, which are called *chorus waves*. There have been several studies that demonstrated one-to-one correspondence between the temporal variations of PsA and chorus waves. However, it is still unclear how long such a good correlation between PsA and chorus is preserved. In this study, an extended interval of PsA (~1 hr) simultaneously observed by a newly launched magnetospheric satellite, Arase, and a ground-based high-speed all-sky imager in Apatity, Kola Peninsula, Russia was investigated. As a result, not only was the correspondence between PsA and chorus verified but also the motion of the high-correlation region (correlation coefficient > 0.5) was successfully tracked in a continuous manner. The obtained long-lasting reasonable correlation proves that the chorus waves control the luminosity variation of PsA. In addition, the region of high correlation between PsA and chorus showed sudden jumps, which could be caused by the motion or variation of the fine-scale structure of the wave-particle interaction region in space.

1. Introduction

Pulsating aurora (PsA), which consists of diffuse patches/arcs blinking with various periods ranging from a few to a few tens of seconds (this primary period is called *main pulsation*; Yamamoto, 1988), are known to occur very frequently in a local time sector from the magnetic midnight to dawn (Jones et al., 2013). It has been suggested that the luminosity variations of PsA are controlled by the intensity modulation of chorus waves often appearing near the equatorial plane of the magnetosphere (Nishimura et al., 2010; Li et al., 2012, and references therein). Chorus waves typically occur in two distinct frequency ranges below and above half the gyrofrequency and are respectively called lower-band chorus (LBC) and upper-band chorus (e.g., Burtis & Helliwell, 1969). Especially, LBC waves can resonate with PsA electrons (Davidson, 1990) whose energy typically ranges from a few to a few tens of kiloelectron volts (Sandahl et al., 1980), which is one of the reasons why the modulation of LBC has been considered as an agent causing the characteristic luminosity variation of PsA (Miyoshi et al., 2015; Ozaki, Shiokawa, et al., 2018).

To date, there have been several studies that demonstrated one-to-one correspondence between the temporal variations of PsA and modulations of chorus observed near the magnetic equator (e.g., Jaynes et al., 2013; Kasahara, Miyoshi, et al., 2018; Nishimura et al., 2010; Nishimura, Bortnik, Li, Thorne, Chen, et al., 2011; Nishimura, Bortnik, Li, Thorne, Lyons, et al., 2011) or propagating to the ground (e.g., Ozaki et al., 2012, 2015; Tsuruda et al., 1981). However, the durations of the events considered by these previous studies were relatively short, mostly less than 5 min, even in the ground-based observations, because long-lasting (>30 min) simultaneous observation is rarely obtained. Hence, it is still unclear how long such a good correlation between PsA and chorus is preserved. Among the previous studies, only a recent work by Nishimura et al. (2018) investigated a long-lasting period of PsA and chorus whose duration was ~3 hr. However, the temporal resolution of their observations was insufficient for detecting the temporal variations of PsA and chorus (the cadence was 3 s for the optical observation, and the temporal resolution was 6 s for the chorus observation by the satellite). When carrying out a cross-correlation analysis between two time series, the temporal resolutions must be conformed to the lower temporal resolution one. In this case, the cadence of optical observation conformed to 6 s (the Nyquist period is 12 s). This is clearly insufficient for detecting the primary periodicity of PsA, which is typically ~5–10 s (Duncan et al., 1981). Additionally, during the event studied by Nishimura et al. (2018), there were several intermittent intervals in which the correlation between PsA and chorus was low.

In this study, an extended interval of PsA (~1 hr) simultaneously observed by the Arase satellite and a ground-based high-speed all-sky imager (ASI) in Apatity, Kola Peninsula, Russia, both of which have a temporal resolution of 1 s, was investigated. By performing a cross-correlation analysis between the time series of PsA luminosity and chorus intensity, not only was the correspondence between PsA and chorus verified but also the motion of the high-correlation region (correlation coefficient > 0.5) was successfully tracked in a continuous manner.

2. Data Sets

Panchromatic optical observation using an ASI without any optical filter has been carried out in Apatity, Kola Peninsula, Russia (67.58°N, 33.31°E, L-shell value = 5.15) since January 2009 with a temporal resolution of 1 s (Kozelov et al., 2012), which made it possible to detect the main pulsation (the main contributing emission is the green line emission at 557.7 nm since we do not use any optical filters) whose periodicity ranges from a few to few tens of seconds. Chorus wave observations by the Arase satellite, which was launched on 20 December 2016 (Miyoshi et al., 2018), were also employed. During the interval of interest (0000–0100 UT on 31 March 2017), the satellite was located in the Southern Hemisphere slightly off the magnetic equator, and the magnetic local time of the satellite position was 3–4 MLT. The observation of chorus was made by the Plasma Wave Experiment/Onboard Frequency Analyzer (PWE/OFA; Kasahara, Kasaba, et al., 2018; Matsuda et al., 2018; Ozaki, Yagitani, et al., 2018) onboard the Arase satellite. From the PWE/OFA observations, it was possible to obtain dynamic spectra of waves in the electric field and magnetic field with a temporal resolution of 1 s. In addition, the Magnetic Field Experiment (MGF; Matsuoka et al., 2018) onboard the Arase satellite was used to observe changes of the magnetic field configuration in the magnetosphere during the interval of interest.

3. Results

An extended interval of PsA was analyzed from 0000 to 0100 UT on 31 March 2017 (the corresponding local time was 3–4 MLT). During the entire interval, the magnetic footprint of the Arase satellite was located within the field of view of the ASI. Figure 1a shows an all-sky image at 0040:05 UT, which has been mapped onto the geographic coordinate system by assuming an emission altitude of 100 km. At this time, blobs of PsA elongating more in the east-west direction were seen in the equatorward half of the field of view. In this panel, the magnetic footprint of Arase estimated by using the Tsyganenko 04 (T04) empirical magnetic field model (Tsyganenko & Sitnov, 2005) is superimposed. The spacecraft footprint entered the field of view of the ASI at approximately 0000 UT and traversed the region of PsA from east to west until the end of the interval

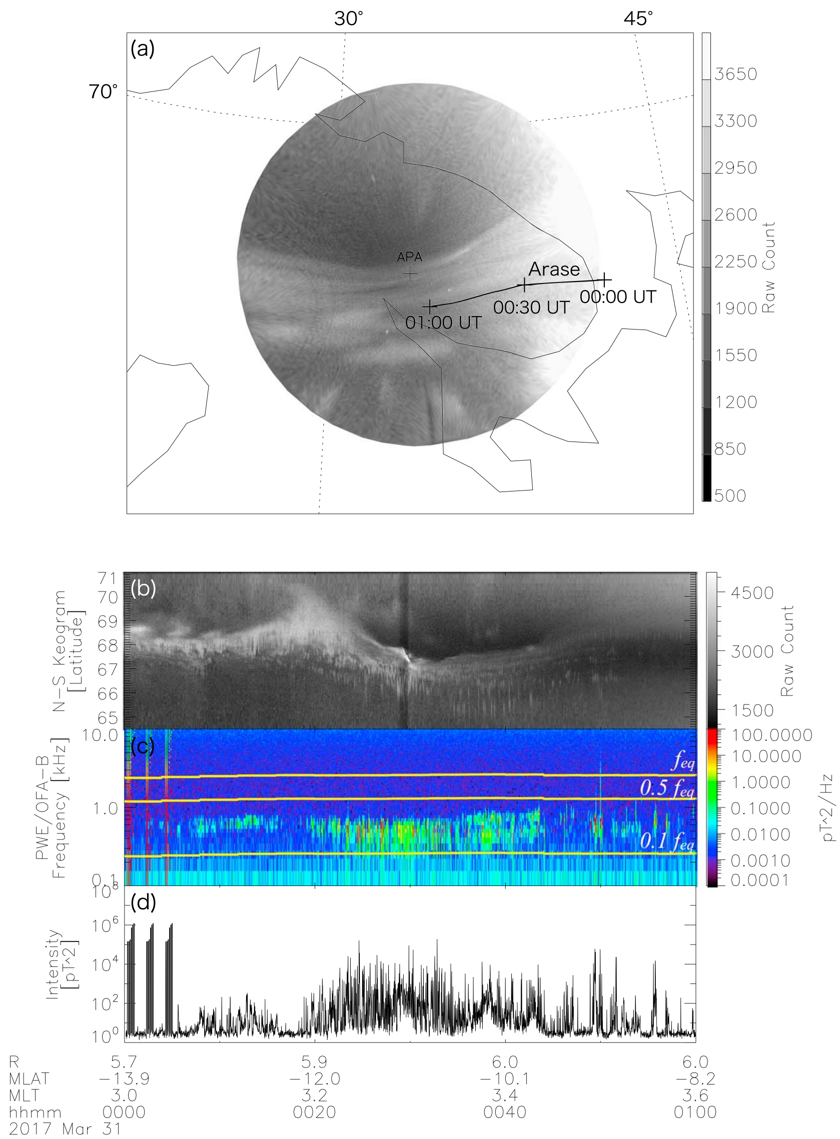

Figure 1. Overview of an event of pulsating aurora from 0000 to 0100 UT on 31 March 2017, during which the footprint of Arase satellite was located within the field of view of the all-sky imager at Apatity (marked at center of field of view): (a) all-sky image at 0040:05 UT mapped onto the geographic coordinate system by assuming an emission altitude of 100 km, (b) south-to-north keogram of the optical intensity, (c) frequency-time diagram of magnetic field from PWE/OFA, and (d) temporal variation of integrated chorus intensity in the lower-band chorus frequency range (three spikes of chorus intensity seen during 0000 to 0005 UT are calibration signals). PWE/OFA = Plasma Wave Experiment/Onboard Frequency Analyzer.

at 0100 UT. Figures 1b and 1c, respectively, show the south to north keogram of the ASI and frequency-time diagram (i.e., dynamic spectra) of the magnetic field from PWE/OFA. Prominent activities of PsA and intense chorus were simultaneously observed at least until 0045 UT. After that, PsA and chorus became somewhat sparse, and the ground-based observation was terminated at 0100 UT by significant contamination from the sunlight. Figure 1d shows the time series of the chorus intensity. To derive this time series, the power of the dynamic spectra in the LBC frequency range from 0.192 to 1.088 kHz was averaged, and then a high-pass filter with a 30-s cutoff period was applied to extract the pulsating component in the chorus intensity.

Next, the optical intensity of PsA and the amplitude of chorus were compared by performing a cross-correlation analysis between the two time series. This analysis was applied to all the pixels within the

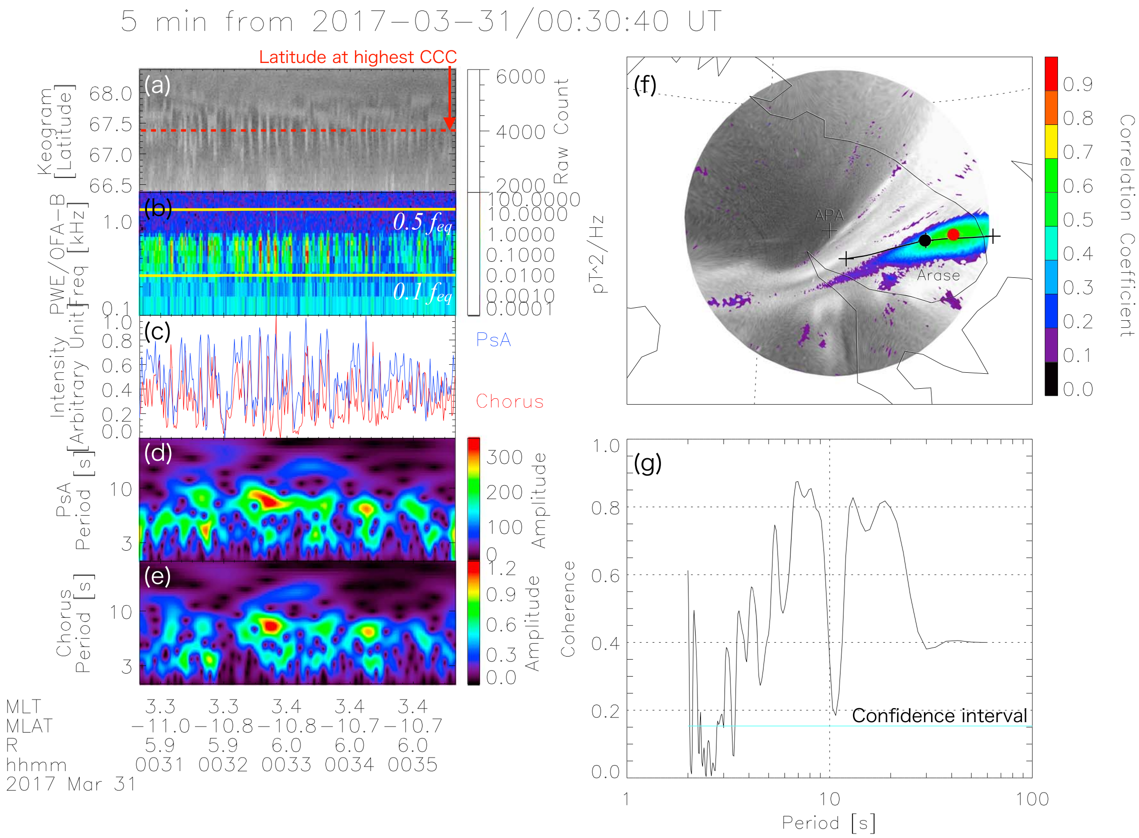

Figure 2. Summary of the cross-correlation analysis of PsA luminosity and chorus intensity during a 5-min interval from 0030:40 to 0035:40 UT: (a) south-to-north keogram of the optical intensity, (b) frequency-time diagram of magnetic field from PWE/OFA, (c) time series of integrated chorus intensity (red) and optical intensity (blue) at the point of maximum cross correlation, and (d, e) S transform dynamic spectra of the optical data and chorus data, respectively. (f) All-sky image at the beginning of the 5-min analysis interval onto which the distribution of the cross-correlation coefficient is superimposed (the black and red dots, respectively, give the magnetic footprint of Arase calculated by using T04 and the location of the point of highest correlation coefficient) and (g) coherence between PsA luminosity and chorus intensity showing good correspondence at 6- to 9-s and 11- to 20-s periods. PsA = pulsating aurora; PWE/OFA = Plasma Wave Experiment/Onboard Frequency Analyzer.

field of view of the ASI, and, eventually, a point where the cross-correlation coefficient is maximized was identified. Figure 2 illustrates an example of the analysis using a 5-min data set from 0030:40 to 0035:40 UT. Figure 2a shows the time series of the optical intensity along the south-to-north cross section, including the estimated point of maximum correlation. Figure 2b gives the frequency-time diagram of the magnetic field from PWE/OFA. It is clearly seen that periodic bursts of chorus (Figure 2b) have their counterparts in the main pulsation of PsA (Figure 2a). Figure 2c displays the temporal variations of the optical intensity at the point of maximum correlation (blue) and the LBC intensity (red). As shown in Figures 2a–2c, there is a remarkable one-to-one correspondence between PsA and chorus.

Figures 2d and 2e, respectively, show the S transform dynamic spectra of the temporal variation of PsA and chorus intensity plotted in Figure 2c. Both the time series commonly have prominent peaks at 6–10 s, which is in the typical range of PsA periods (Yamamoto, 1988). In addition, coherence derived from cross-spectral analysis between PsA and chorus (Figure 2g) indicates that the correlation was high at 6- to 9-s and 11- to 20-s periodicities. However, the variation of 11- to 20-s periodicities does not correspond to the main pulsation of PsA, because the S transform amplitude at 11–20 s is obviously weak (Figures 2d and 2e). Figure 2f shows the spatial distribution of the cross-correlation coefficient superimposed on the all-sky image. The black and red dots, respectively, give the magnetic footprint of Arase calculated by using T04 and the location of the point of highest correlation coefficient. The correlation coefficient was high (correlation coefficient > 0.5) only around the modeled footprint of the Arase satellite. This indicates that electrons scattered by

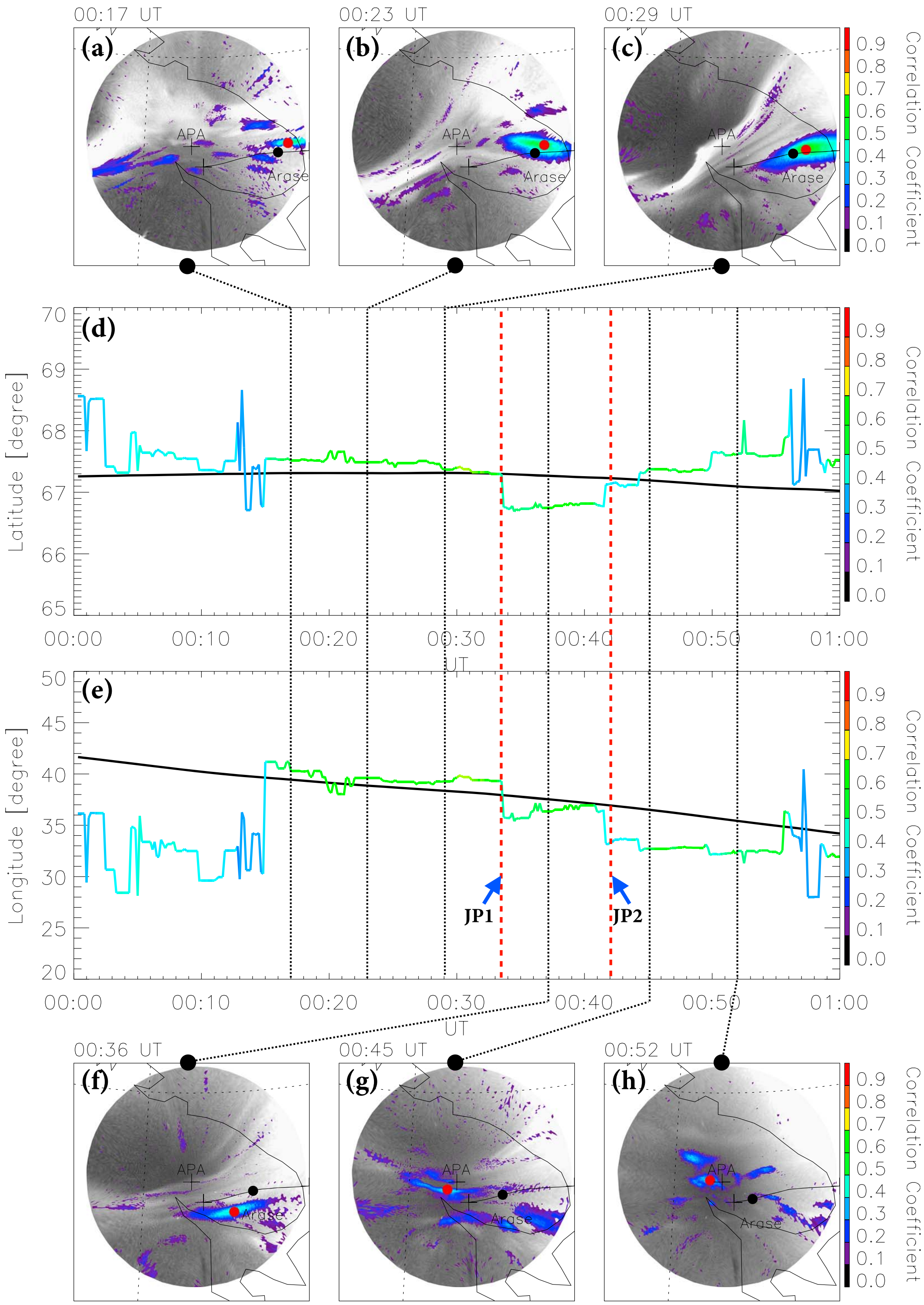

Figure 3. (d, f) Temporal variation of the latitude and longitude of the high-correlation region, where the color of the line indicates the value of the correlation coefficient (black curves show the latitude and longitude of the magnetic footprint of the satellite derived from the Tsyganenko 04 magnetic field model) and (a, b, c, f, g, h) some selected snapshots of the optical data from the interval where the distribution of the correlation coefficient is overplotted (the black circle indicates the modeled footprint of Arase, and the red circle gives the point of the maximum cross-correlation coefficient).

wave-particle interaction precipitated into a localized region near the footprint and caused the characteristic luminosity variation of PsA. The result of the cross-correlation analysis for the entire 1-hr interval is given in the supporting information Movie S1.

Here the temporal variation of the high-correlation region every 10 s is derived by applying the above-mentioned analysis to the entire 1 hr of data (i.e., by sliding the 5-min window with an interval of 10 s). Figure 3d plots how the latitude of the point of maximum correlation moved during the interval, where the color of the line indicates the value of maximum correlation coefficient. The superimposed black curve gives the latitude of the magnetic footprint derived by T04 for comparison. The format of Figure 3e is the same as that of Figure 3d, but the lines show the change in longitude. These two panels demonstrate that the positions (i.e., latitude and longitude) of the model footprint and the point of maximum correlation have almost similar values, at least for 45 min from 0015 UT to 0100 UT. However, the offset between the two lines was large, and the correlation coefficient was less than 0.5 in the first 15 min from 0000 UT to 0015 UT. One of the reasons for this deviation is a relatively weaker chorus during the interval (Figure 1c). In addition, the point of maximum correlation (i.e., the actual footprint) might be outside the field of view of the ASI, because the model footprint of the satellite was inaccurate during this interval due to relatively high magnetic activity (the Kp index was 5-).

Figures 3a–3c and 3f–3h display several selected snapshots of all-sky images with the spatial distribution of the correlation coefficient. Because the Arase satellite was near its apogee during this conjunction event, the magnetic footprint (black circles in the snapshots) traversed the field of view in the longitudinal direction (i.e., from east to west). Interestingly, the point of maximum cross correlation, shown by the red circle in the images, moved almost in tandem with the footprint of the satellite. In the time interval covered by these images, the cross-correlation coefficient was greater than 0.5 in a limited region in both the latitude and longitude near the footprint. That is, the high-correlation region closely followed the eastward motion of the footprint of Arase. In addition, the deviation from the model footprint was less than 3° in longitude during the period. Even though the model footprint might be somewhat inaccurate and distorted, the tandem motion between the high-correlation region and model footprint implies one-to-one correspondence between PsA and chorus. In addition, this result indicates that the correlation analysis between the PsA luminosity and the chorus intensity can be used for accurate tracing of the magnetic field line, as first suggested by Nishimura, Bortnik, Li, Thorne, et al. (2011). At the same time, however, it was found that the temporal variation of the high-correlation region was sometimes not smooth. The latitude and longitude of the high-correlation region showed abrupt jumps—for example, at around 0034 UT and 0042 UT—which are indicated by the blue arrows in Figures 3d and 3e (hereafter, they are called "JP1" and "JP2"). This may be associated with the motion or variation of the discrete spatial structure of plasma in the region of wave-particle interaction. In the next section, what process caused these two jumps in the location of the high-correlation region is discussed.

4. Discussion and Conclusion

As described in section 1, previous studies have claimed a close relationship between the PsA luminosity and the chorus intensity by showing multiple case examples (e.g., Nishimura, Bortnik, Li, Thorne, Chen, et al., 2011). However, most of the cases were short-duration events; thus, it has still been uncertain how long such a good correlation continues. Recently, Nishimura et al. (2018) analyzed a long duration (~3-hr) event of PsA that was simultaneously observed by the Radiation Belt Storm Probes-B (RBSP-B) satellite and the Time History of Events and Macroscale Interactions during Substorms (THEMIS) ASI. Although the correspondence was generally good during the entire 3-hr interval, there were several intermittent periods of poor correlation coefficient. This might have been caused by the insufficient temporal resolution of the ground-based ASI (3-s cadence) and wave spectra data from the satellite (6-s resolution), which are sometimes close to the primary periodicities of PsA and chorus. In this study, by employing relatively higher temporal resolution data (1 s), the motion of the high-correlation region was successfully tracked for an ~1-hr interval. Such a long-duration cross-correlation analysis showed that a good correlation (correlation coefficient > 0.5) between PsA and chorus was obtained only in a spatially limited region near the model footprint of the satellite. Also, it was clearly demonstrated that the high-correlation region moved well in tandem with the model footprint. These results prove that the chorus and the flux of PsA electrons originated from the same local

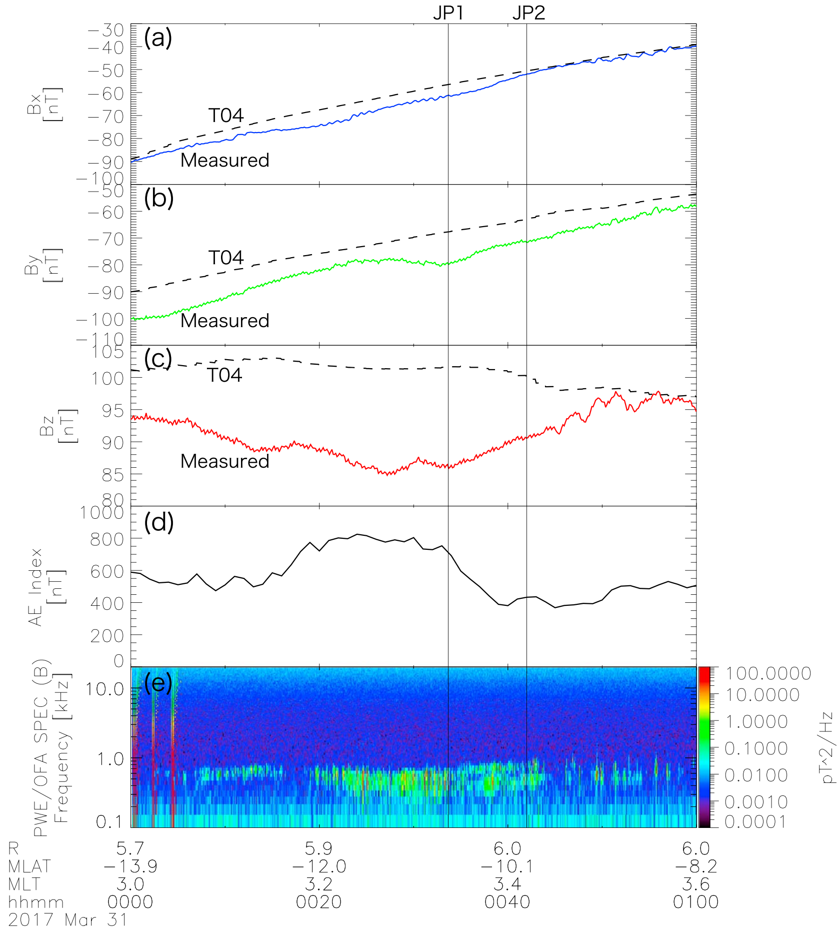

Figure 4. (a–c) B_x, B_y, and B_z components of the magnetic field in geocentric solar magnetospheric coordinate observed by the Magnetic Field Experiment instrument onboard the Arase satellite (the solid line and dashed lines show the measured magnetic field and model magnetic field, derived from Tsyganenko 04 model, respectively), (d) AE index from the OMNI-2 database, and (e) frequency-time diagram of the magnetic field observed by PWE/OFA onboard the Arase satellite. AE = auroral electrojet; PWE/OFA = Plasma Wave Experiment/Onboard Frequency Analyzer.

interaction region; thus, the correlation analysis of PsA and chorus can be used for assessing the accuracy of the magnetic field tracing from the satellite to the ionosphere, as first suggested by Nishimura, Bortnik, Li, Thorne, Lyons, et al. (2011).

In addition to the main finding described above, it was found that the location of the high-correlation region showed two abrupt jumps, which are indicated by the blue arrows (JP1 and JP2) in Figures 3d and 3e. Such changes in the position of the high-correlation region could be caused by sudden reconfiguration of the background magnetic field associated with substorms. Figures 4a–4c show the measured (solid) and modeled (dashed) magnetic field in the geocentric solar magnetospheric coordinates at the location of Arase. The modeled one was derived from the T04 model driven by input parameters from the OMNI-2 database. The measured magnetic field basically followed the gradual change of the modeled magnetic field, but the deviation of the B_z component from the model reaches 10–25 nT. These deviations were possibly associated with ongoing substorm activities inferred from the continuous high auroral electrojet index values shown in Figure 4d. The measurements indicate that a gradual change in the magnetic configuration actually happened during the interval. However, there were no sudden changes in the background field at the timings of JP1 and JP2. This suggests that the jumps of the high-correlation region were not directly caused by sudden reconfigurations of the background magnetic field.

Another possibility is that the observed sudden jumps of the high-correlation region were related to the motion of the satellite through the fine-scale structures in the region of chorus generation and

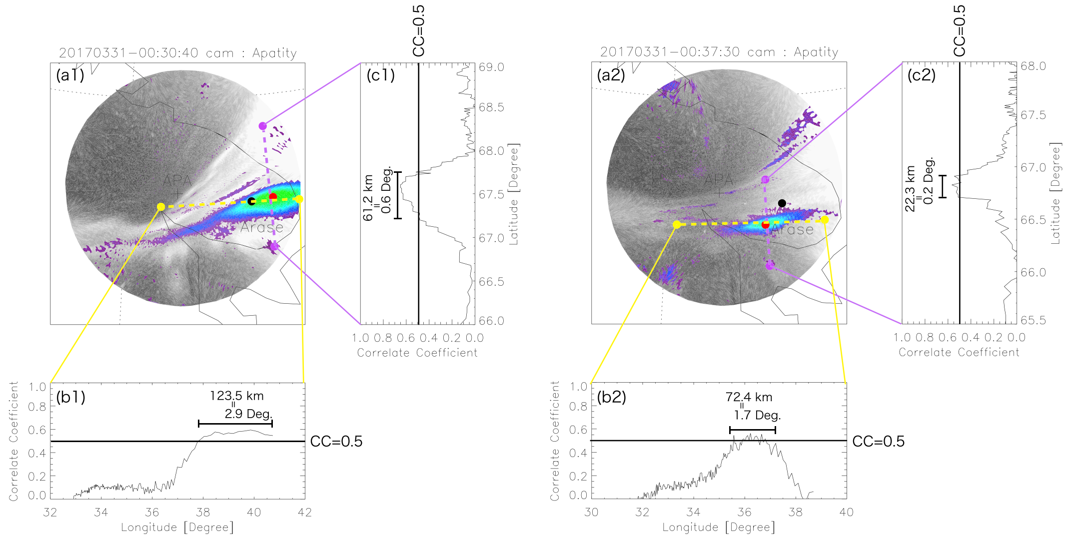

Figure 5. Longitudinal and latitudinal distribution of high-correlation region at two selected time intervals: (a1, a2) all-sky images, respectively, at 0030:40 UT and 0037:30 UT onto which the distribution of the cross-correlation coefficient is superimposed (the black and red dots, respectively, give the magnetic footprint of Arase calculated by using T04 and the location of the point of the highest correlation coefficient—the distance between model footprint, black dot, and the point of maximum correlation, red dot, is 61.94 km [a1] and 76.55 km [a2]), (b1, b2) longitudinal cross section of the cross-correlation coefficient along the horizontal yellow dashed line, and (c1, c2) latitudinal cross section of the cross-correlation coefficient along the vertical purple dashed line.

propagation. Although it was gradual, the reconfiguration of the magnetic field might have caused changes of the spatial structure and location of field-aligned ducts, which are regions of an increased electron density extending along the magnetic field lines. Very low frequency waves, such as chorus waves, can be trapped and propagate along such field-aligned ducts. Thus, the jump-like variations imply that Arase observed other chorus waves that propagated along other ducts because of the magnetic reconfiguration and motion of the satellite through the region of wave-particle interaction. In addition, Arase might have observed chorus that propagated from the other source region, because chorus waves sometimes propagate obliquely to the magnetic field (Santolík et al., 2009).

In conclusion, by analyzing simultaneous observations of PsA with Arase and an ASI in Russia, a long-lasting high correlation between PsA and chorus near the footprint of the satellite was found. The region of high correlation was identified only in a localized area, and, more importantly, its location followed well the magnetic footprint of the satellite estimated by the empirical model. Such a long-lasting high correlation between PsA and chorus evidences that the chorus and the flux of PsA electrons originated from the same local interaction region (Nishimura et al., 2010; Nishimura, Bortnik, Li, Thorne, Lyons, et al., 2011; Nishimura, Bortnik, Li, Thorne, Chen, et al., 2011). Furthermore, tracking the tandem motion of the high-correlation region and the model footprint makes it possible to estimate the magnetic field mapping accuracy, which was first suggested by Nishimura, Bortnik, Li, Thorne, Lyons, et al., (2011). In this case, the deviation between the model footprint and the point at maximum correlation (e.g., the actual footprint) is always less than 3°, as shown in Figure 3. This means that the model footprint had good accuracy within a hundred kilometers during this event. As shown in Figures 3d and 3e, the temporal variation of the correlation coefficient was continuously high (greater than 0.5) for the 45 min in the central part of the interval. This indicates that this method can be used for tracking the footprint during relatively longer time period.

In addition, detailed analyses of the high-correlation region could be used to estimate the spatial extent of the region of wave-particle interaction in the magnetosphere. Figure 5 shows the latitudinal and longitudinal distributions of the high-correlation region at two specific times. The longitudinal and latitudinal extent of the high-correlation regions reached 123.5 km (Figure 5b1) and 61.2 km (Figure 5c1), respectively. The longitudinal extent was 2 times larger than the latitudinal extent (Figures 5a1 and 5a2). This spatial distribution of high-correlation regions corresponds to the shape of the chorus source region at the equatorial plane of the magnetosphere. During this event, the PsA showed an arc-like structure extending more in the east-to-west direction. These results imply that the cross-correlation analysis between PsA and chorus can be used for continuous monitoring of the size of the region of local interaction between chorus and energetic magnetospheric electrons as a source of PsA.

Major Topic or Scientific Question

This study demonstrates that the main pulsation of the pulsating aurora (PsA) is a result of modulations of the magnetospheric chorus waves thorough wave-particle interactions.

New Scientific Knowledge

Good correlation between temporal variations of PsA and chorus waves continued for about an hour. This suggests not only that the main pulsation of PsA is a result of modulation of chorus but also that a PsA-chorus comparison can be used for monitoring of the local link between the ionosphere and magnetosphere.

Broad Implications

Chorus waves are known as one of the drivers of electron acceleration in the magnetosphere; thus, the PsA-chorus connection indicated by this study is particularly important for auroral physics and broad aspects in space weather applications.

Acknowledgments
This work was supported by JSPS KAKENHI (Grants JP15H05747, JP15H05815, JP16H06286, JP16H04056, and JP16H01172). This work was also supported by the International Space Science Institutes Beijing (ISSI-BJ) International Team program. Science data of the ERG (Arase) satellite were obtained from the ERG Science Center operated by ISAS/JAXA and ISEE/Nagoya University (https://ergsc.isee.nagoya-u.ac.jp/index.shtml.en). The present study analyzed the MGF L2 v.01.01 data and the PWE/OFA L2 v.02.01 data. The operation of the all-sky imager in Russia, Apatity (http://aurora.pgia.ru/), was supported by the Polar Geophysical Institute. The work of B. K. was supported by the Russian Science Foundation under project 15-12-20005P.

References

Burtis, W. J., & Helliwell, R. A. (1969). Banded chorus—A new type of VLF radiation observed in the magnetosphere by OGO 1 and OGO 3. *Journal of Geophysical Research*, *74*(11), 3002–3010. https://doi.org/10.1029/JA074i011p03002

Davidson, G. T. (1990). Pitch–angle diffusion and the origin of temporal and spatial structures in morningside aurorae. *Space Science Reviews*, *53*, 45–82. https://doi.org/10.1007/BF00217428

Duncan, C. N., Creutzberg, F., Gattinger, R. L., Harris, F. R., & Vallence Jones, A. (1981). Latitudinal and temporal characteristics of pulsating auroras. *Canadian Journal of Physics*, *59*(8), 1063–1069. https://doi.org/10.1139/p81-140

Jaynes, A. N., Lessard, M. R., Rodriguez, J. V., Donovan, E., Loto'aniu, T. M., & Rychert, K. (2013). Pulsating auroral electron flux modulations in the equatorial magnetosphere. *Journal of Geophysical Research: Space Physics*, *118*, 4884–4894. https://doi.org/10.1002/jgra.50434

Jones, S. L., Lessard, M. R., Rychert, K., Spanswick, E., Donovan, E., & Jaynes, A. N. (2013). Persistent, widespread pulsating aurora: A case study. *Journal of Geophysical Research: Space Physics*, *118*, 2998–3006. https://doi.org/10.1002/jgra.50301

Kasahara, S., Miyoshi, Y., Yokota, S., Mitani, T., Kasahara, Y., Matsuda, S., et al. (2018). Pulsating aurora from electron scattering by chorus waves. *Nature*, *554*(7692), 337–340. https://doi.org/10.1038/nature25505

Kasahara, Y., Kasaba, Y., Kojima, H., Yagitani, S., Ishisaka, K., Kumamoto, A., et al. (2018). The Plasma Wave Experiment (PWE) on board the Arase (ERG) satellite. *Earth, Planets and Space*, *70*, 86. https://doi.org/10.1186/s40623-018-0842-4

Kozelov, B. V., Pilgaev, S. V., Borovkov, L. P., & Yurov, V. E. (2012). Multi-scale auroral observations in Apatity: Winter 2010–2011. *Geoscientific Instrumentation, Methods and Data Systems*, *1*(1), 1–6. https://doi.org/10.5194/gi-1-1-2012

Li, W., Bortnik, J., Nishimura, Y., Thorne, R. M., & Angelopoulos, V. (2012). The origin of pulsating aurora: Modulated whistler mode chorus waves. In A. Keiling, E. Donovan, F. Bagenal, & T. Karlsson (Eds.), *Auroral phenomenology and magnetospheric processes: Earth and other planets*, *Geophysical Monograph Series* (Vol. 197, pp. 379–388). Washington, DC: American Geophysical Union. https://doi.org/10.1029/2011GM001164

Matsuda, S., Kasahara, Y., Kojima, H., Kasaba, Y., Yagitani, S., Ozaki, M., et al. (2018). Onboard software of Plasma Wave Experiment aboard Arase: instrument management and signal processing of Waveform Capture/Onboard Frequency Analyzer. *Earth, Planets and Space*, *70*(1), 75. https://doi.org/10.1186/s40623-018-0838-0

Matsuoka, A., Teramoto, M., Nomura, R., Nosé, M., Fujimoto, A., Tanaka, Y., et al. (2018). The ARASE (ERG) magnetic field investigation. *Earth, Planets and Space*, *70*(1), 43. https://doi.org/10.1186/s40623-018-0800-1

Miyoshi, Y., Saito, S., Seki, K., Nishiyama, T., Kataoka, R., Asamura, K., et al. (2015). Relation between fine structure of energy spectra for pulsating aurora electrons and frequency spectra of whistler mode chorus waves. *Journal of Geophysical Research: Space Physics*, *120*, 7728–7736. https://doi.org/10.1002/2015JA021562

Miyoshi, Y., Shinohara, I., Takashima, T., Asamura, K., Higashio, N., Mitani, T., et al. (2018). Geospace Exploration Project ERG. *Earth, Planets and Space*, *70*(1). https://doi.org/10.1186/s40623-018-0862-0

Nishimura, Y., Bortnik, J., Li, W., Angelopoulos, V., Donovan, E. F., & Spanswick, E. L. (2018). Comment on "Pulsating auroras produced by interactions of electrons and time domain structures" by Mozer et al. *Journal of Geophysical Research: Space Physics*, *123*, 2064–2070. https://doi.org/10.1002/2017JA024844

Nishimura, Y., Bortnik, J., Li, W., Thorne, R. M., Chen, L., Lyons, L. R., et al. (2011). Multievent study of the correlation between pulsating aurora and whistler mode chorus emissions. *Journal of Geophysical Research*, *116*, A11221. https://doi.org/10.1029/2011JA016876

Nishimura, Y., Bortnik, J., Li, W., Thorne, R. M., Lyons, L. R., Angelopoulos, V., et al. (2011). Estimation of magnetic field mapping accuracy using the pulsating aurora-chorus connection. *Geophysical Research Letters*, *38*, L14110. https://doi.org/10.1029/2011GL048281

Nishimura, Y., Bortnik, J., Li, W., Thorne, R. M., Lyons, L. R., Angelopoulos, V., et al. (2010). Identifying the driver of pulsating aurora. *Science*, *330*(6000), 81–84. https://doi.org/10.1126/science.1193186

Ozaki, M., Shiokawa, K., Miyoshi, Y., Hosokawa, K., Oyama, S., Yagitani, S., et al. (2018). Microscopic observations of pulsating aurora associated with chorus element structures: Coordinated Arase satellite-PWING observations. *Geophysical Research Letters*, *45*, 12,125–12,134. https://doi.org/10.1029/2018GL079812

Ozaki, M., Yagitani, S., Ishizaka, K., Shiokawa, K., Miyoshi, Y., Kadokura, A., et al. (2012). Observed correlation between pulsating aurora and chorus waves at Syowa Station in Antarctica: A case study. *Journal of Geophysical Research*, *117*, A08211. https://doi.org/10.1029/2011JA017478

Ozaki, M., Yagitani, S., Kasahara, Y., Kojima, H., Kasaba, Y., Kumamoto, A., et al. (2018). Magnetic Search Coil (MSC) of Plasma Wave Experiment (PWE) aboard the Arase (ERG) satellite. *Earth, Planets and Space*, *70*(1). https://doi.org/10.1186/s40623-018-0837-1

Ozaki, M., Yagitani, S., Sawai, K., Shiokawa, K., Miyoshi, Y., Kataoka, R., et al. (2015). A direct link between chorus emissions and pulsating aurora on timescales from milliseconds to minutes: A case study at subauroral latitudes. *Journal of Geophysical Research: Space Physics*, *120*, 9617–9631. https://doi.org/10.1002/2015JA021381

Sandahl, I., Eliasson, L., & Lundin, R. (1980). Rocket observations of precipitating electrons over a pulsating aurora. *Geophysical Research Letters*, *7*(5), 309–312. https://doi.org/10.1029/GL007i005p00309

Santolík, O., Gurnett, D. A., Pickett, J. S., Parrot, M., & Cornilleau-Wehrlin, N. (2009). Oblique propagation of whistler mode waves in the chorus source region. *Journal of Geophysical Research*, *114*, A00F03. https://doi.org/10.1029/2009JA014586

Tsuruda, K., Machida, S., Oguti, T., Kokubun, S., Hayashi, K., Kitamura, T., et al. (1981). Correlations between the very low frequency chorus and pulsating aurora observed by low-light-level television at $L = 4.4$. *Canadian Journal of Physics*, *59*(8), 1042–1048. https://doi.org/10.1139/p81-137

Tsyganenko, N. A., & Sitnov, M. I. (2005). Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms. *Journal of Geophysical Research*, *110*, A03208. https://doi.org/10.1029/2004JA010798

Yamamoto, T. (1988). On the temporal fluctuations of pulsating auroral luminosity. *Journal of Geophysical Research*, *93*(A2), 897–911. https://doi.org/10.1029/JA093iA02p00897