

Statistical analysis of transverse size of lower band chorus waves using simultaneous multi-satellite observations

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Key Points:

- The average scale size of lower band chorus element is $\sim 315 \pm 32$ km at L shells over ~ 5 – 6 .
- Transverse scale size of chorus is larger at higher L shells and larger at higher latitudes, especially on the dayside.
- Transverse scale size of chorus is larger in the azimuthal direction than in the radial direction.

Abstract

Chorus waves are known to accelerate or scatter energetic electrons via quasi-linear or nonlinear wave-particle interactions in the Earth's magnetosphere. In this letter, by taking advantage of simultaneous observations of chorus waveforms from at least a pair of probes among Van Allen Probes and/or Time History of Events and Macroscale Interactions during Substorms (THEMIS) missions, we statistically calculate the transverse size of lower band chorus wave elements. The average size of lower band chorus wave element is found to be $\sim 315 \pm 32$ km over L shells of ~ 5 – 6 . Furthermore, our results suggest that the scale size of lower band chorus tends to be (1) larger at higher L shells; (2) larger at higher magnetic latitudes, especially on the dayside; and (3) larger in the azimuthal direction than in the radial direction. Our findings are crucial to quantify wave-particle interaction process, particularly the nonlinear interactions between chorus and energetic electrons.

Plain Language Summary

Chorus waves are known to play an important role in controlling energetic electron dynamics in the Earth's magnetosphere. The spatial scale of chorus waves is one of the most important parameters that determine the wave-particle interaction process and thus is critical for understanding the role of chorus waves in radiation belt dynamics. By applying simultaneous in situ waveform observations from multiple satellites, we statistically calculate the scale size of chorus wave elements, which is found to be $\sim 315 \pm 32$ (95% confidence interval) km on average. More specifically, we find that the scale size tends to be larger at higher L shells, at higher magnetic latitudes, and in the azimuthal direction than in the radial direction. Our findings are crucial for understanding and modeling wave-particle interactions driven by chorus waves.

1 Introduction

Whistler mode chorus waves are right-hand polarized electromagnetic waves with frequencies below the electron cyclotron frequency (f_{ce}). They are often observed outside the plasmasphere, where total electron density is relatively low and energetic electrons are injected from the plasma sheet particularly during disturbed geomagnetic activities (e.g., Bell & Buneman, 1964; Katoh & Omura, 2007; Omura et al., 2008; W. Li et al., 2009, 2010). An emission gap frequently exists at $0.5 f_{ce}$, dividing chorus waves into lower (0.1 – $0.5 f_{ce}$) and upper (0.5 – $0.8 f_{ce}$) bands (e.g., Koons and Roeder, 1990; Meredith et al., 2012). Chorus waves often exhibit rising and sometimes falling tone features in a sub-second time scale (defined as element scale hereafter) (e.g., Santolik and Gurnett, 2003; W. Li et al., 2011). Moreover, a group of chorus wave elements are often clustered together and are observed on a timescale of a few seconds to 10s of seconds (defined as cluster scale hereafter) (W. Li et al., 2012).

By accelerating or pitch angle scattering energetic electrons through quasi-linear or nonlinear interactions (e.g., Horne et al., 2003; Bortnik & Thorne, 2007; Summers et al., 2007; Bortnik et al., 2008; Tao et al., 2014; J. Li et al., 2015; Omura et al., 2015; da Silva et al., 2018), chorus waves provide a significant contribution to acceleration of highly relativistic electrons in the outer radiation belt, especially during storm times (e.g., Meredith et al., 2003; Thorne et al., 2013;

W. Li et al., 2007, 2014; Tu et al., 2014; Xiao et al., 2014; Shen et al., 2017; Bingham et al., 2018; Ma et al., 2018; Turner et al., 2019). Moreover, chorus waves are one of the most important loss mechanisms of plasma sheet electrons via pitch angle scattering (e.g., Horne et al., 2003). The scattered electrons into the upper atmosphere could then generate microbursts (e.g., Nakamura et al., 2000; Breneman et al., 2017, Shumko et al., 2018), pulsating aurora (e.g., Nishimura et al., 2010, 2011a, 2011b; W. Li et al., 2012; Ozaki et al., 2018, 2019) and diffuse aurora (e.g., Ni et al., 2008; Thorne et al., 2010).

In order to better understand the wave generation and wave-particle interaction processes, it is crucial to know the spatial extent of chorus waves. Several studies, focusing on analyzing individual events, revealed a typical scale size of chorus wave ranging from 100s to 1000s km (e.g., Santolik & Gurnett, 2003; Agapitov et al., 2010, 2017). For example, Santolik and Gurnett (2003) estimated the scale size of element scale chorus waves to be around 100 km by calculating the correlation coefficient of wave amplitudes measured by a pair of Cluster probes at $L \sim 4$ on the nightside. Using Van Allen Probes (RBSP) measurements, Agapitov et al. (2017) calculated the spatial extent of chorus elements to be 550–650 km (up to 800 km) at $L \sim 6$ on the dawnside (approximated by a Gaussian with the characteristic scale around 300 km). At a higher L shell, i.e., $L \sim 11$, Agapitov et al. (2010) showed a case with a larger scale size of chorus element, around 3000 km, using THEMIS observations. Moreover, the scale size of chorus waves is estimated by mapping the size of microburst and pulsating aurora onto the equatorial plane (e.g., Nishimura et al., 2011a, 2011b; Breneman et al., 2017; Shumko et al., 2018; Ozaki et al., 2018, 2019). On the nightside at $L \sim 8$, the latitudinal (longitudinal) size of pulsating aurora is found to be a few 10s (100s) kilometers, which is roughly 3000–7000 km when mapping onto the equatorial plane (Nishimura et al., 2011b). Using a similar method, Ozaki et al. (2018) estimated the scale size of chorus wave to be smaller, ~ 900 km at $L \sim 5$. Shumko et al. (2018) showed the scale size of microburst to be ~ 50 km and 30 km in the latitudinal and longitudinal directions respectively (from two points FIREBIRD CubeSat measurements of bouncing microburst at $L = 4.7$) and the corresponding chorus spatial extent at the geomagnetic equator is estimated to be 500–550 km. More recently, Agapitov et al. (2018) statistically analyzed the scale size of chorus waves by utilizing chorus wave amplitudes from the THEMIS filter bank data (FBK) dataset. They found that the scale size of chorus wave is largest from the dawn to noon sector, while the overall scale size is estimated to vary from 250 to 800 km, which is defined as the correlation coefficient drop to 0.5. It should be noted that due to the limitation of the 4-s time resolution of FBK data, the estimated scale size is more relevant to cluster scale chorus waves.

In spite of the recent advances, many outstanding questions regarding the scale size of chorus waves still remain, especially for the chorus element scale. More specifically, (a) what is the overall scale size of chorus elements? (b) How does it vary with L shell, MLT and magnetic latitude (MLAT)? (c) What is the relative size of chorus wave in the radial and azimuthal direction? To address these questions, in this letter, we statistically analyze the transverse scale size of lower band chorus elements using simultaneous wave measurements from RBSP and THEMIS.

2 Data Set and Methodology

2.1 Instrumentation

We use measurements from the twin RBSP satellites (Mauk et al., 2013) and three of the five THEMIS probes (THEMIS-A, D and E) (Angelopoulos, 2008) in this study. High time resolution magnetic field measurements are from Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) (Kletzing et al., 2013) onboard RBSP and search coil magnetometer (SCM) (Le Contel et al., 2009) onboard THEMIS with the sampling frequency of ~ 35 kHz and ~ 8192 Hz, respectively. These high time resolution waveform data are used to calculate chorus wave properties. Background magnetic field measurements from the FluxGate Magnetometers (FGM) from the two missions (Kletzing et al., 2013; Auster et al., 2008) are used to calculate local electron gyrofrequency, which is then mapped to the equator using a dipole field model.

2.2 Criterion and Calculation Method

Conjunction criteria between a pair of probes (among RBSP and/or THEMIS missions) are set as: (1) $\Delta L < 0.3$, (2) $\Delta \text{MLT} < 0.3$ h, and (3) $\Delta_{\parallel} < 1500$ km, where ΔL , ΔMLT , and $\Delta_{\parallel}$ are the separation between the two probes in L shell, MLT, and the distance along the field line. Moreover, both probes were required to be located between the magnetopause and the plasmapause, please see the Supporting Information for more details (Meredith et al., 2004; Li et al., 2014; Hartley et al., 2015), and operate the burst mode simultaneously. Note that we used the criterion of $\Delta_{\parallel} < 1500$ km, since the statistical distribution of correlation coefficients does not vary significantly within ~ 1500 km in the parallel direction, as shown in Supporting Information Figure S4. This value is consistent with the previously reported parallel scale ranging from 1200 to 3000 km (Santolik et al., 2004; Breneman et al., 2009; Agapitov et al., 2011).

We applied the linear Pearson correlation method to calculate the correlation coefficient between the radial components (pointing away from the center of the Earth) of magnetic field waveform observed by a pair of probes in the field-aligned coordinates, where background magnetic field is calculated as the 10-minute running average. The correlation coefficient is calculated using the following equation:

$$\Gamma = \frac{\sum_{i=1}^n (\Psi_{x_i} - \overline{\Psi_x})(\Psi_{y_i} - \overline{\Psi_y})}{\sqrt{\sum_{i=1}^n (\Psi_{x_i} - \overline{\Psi_x})^2} \sqrt{\sum_{i=1}^n (\Psi_{y_i} - \overline{\Psi_y})^2}} \quad \#(1)$$

where Γ is the correlation coefficient, Ψ_x is the radial component of magnetic field waveform recorded at one of the two probes (Probe X), and Ψ_y is the radial component of magnetic field waveform recorded at the other probe (Probe Y). It is worth noting that although radial

components of wave magnetic fields are used to represent the chorus wave and calculate the correlation coefficient, a comparison of radial and azimuthal components of wave magnetic fields, as shown in Figure S3 of Supporting Information, indicates that the calculated correlation coefficients are very similar.

It is known that the background magnetic field decreases with increasing L shells in the Earth's equatorial magnetosphere. If one uses a fixed time window, one would take less wave cycles into the Γ calculation at higher L shells and hence obtain a higher correlation coefficient. Therefore, in this study, we use a varying time window based on the equatorial electron gyro frequency, specifically, 5 times of the wave cycle of $0.1 f_{ce}$ wave, to ensure that time window contains 5 (for $0.1 f_{ce}$) to 25 (for $0.5 f_{ce}$) wave cycles at various locations. A time lag τ is incorporated into the calculation considering the propagation effects and associated phase differences observed by the two probes:

$$\Gamma = \frac{\sum_{i=1}^n (\Psi'_{x_i} - \overline{\Psi'_x})(\Psi_{y_i} - \overline{\Psi_y})}{\sqrt{\sum_{i=1}^n (\Psi'_{x_i} - \overline{\Psi'_x})^2} \sqrt{\sum_{i=1}^n (\Psi_{y_i} - \overline{\Psi_y})^2}} \quad \#(2)$$

where Ψ'_x is the time shifted (with time lag τ) radial component of magnetic field waveform. Using a set of different time lags, we calculate a set of different Γ . It is worth noting that, for periodic waves, calculated Γ would periodically change with time lag τ between -1 and 1. While occasionally correlated signals may have a maximum value close to 1, it hardly drops close to -1. Therefore, in order to remove these occasionally correlated signals, we apply:

$$\Gamma_w = \frac{\text{Max}(\Gamma) - \text{Min}(\Gamma)}{2} \quad \#(3)$$

where $\text{Max}(\Gamma)$ is the maximum Γ with a set of time lags, while $\text{Min}(\Gamma)$ is the minimum. In this way, the calculated Γ_w for periodic waves almost stays the same, however, Γ significantly decreases for occasionally correlated signals.

2.3 Case study on 22 Jan 2016

Figure 1 shows an example of simultaneous observations of chorus waves from RBSP-A and B. On 22 Jan 2016, RBSP-A and B were closely located with the separation distances of 226, 183, and 447 km in the radial, azimuthal and parallel direction relative to the ambient field line, respectively. Both probes observed strong lower band rising tone chorus emissions, as shown in Figures 1a, 1b, 1h and 1i. Many weak chorus emissions exhibit slightly oblique wave normal angles, while large amplitude emissions are very parallel to the background magnetic field line (Figures 1c, 1d, 1j and 1k).

Figure 1e shows Γ as a function of universal time (UT) and time lag. The time lag shown here is limited to ± 2 ms to visualize the periodic structures at each time slice more clearly. However, the actual time lag considered in calculating Γ could be up to 0.1 s. It is evident that with different time lags, correlation coefficient shows periodic changes, which is clearer in a zoom-in view shown in Figure 1l. Γ_w calculated from Equation (3) is shown in Figure 1g. In this study, we

focus on lower band chorus emissions which exhibit rising or falling tone features with magnetic wave amplitudes (B_w) over $0.1\text{--}0.5 f_{ce}$ well above the noise level. Therefore, we select Γ_w with B_w greater than the larger value between 5 pT and 2 times of the median of B_w in the 6-sec time window from 07:47:00 UT to 07:47:06 UT (marked with black dots in Figures 1g and 1n). It is worth noting that weak chorus elements have similar wave amplitudes to the hiss-like waves around 1 kHz, thus are not included in calculating correlation coefficients by applying the B_w criterion.

During this time interval, the median, upper quartile (75th percentile) and maximum of the selected Γ_w are 0.56, 0.66 and 0.86, respectively. We select the 75th percentile, i.e., 0.66, to represent the correlation coefficient for this conjunction event. The reason why we use a relatively large percentile is that even when the satellite separation is smaller than the chorus scale size, one of the probes may possibly be located outside the chorus region leading to a low correlation coefficient, which is likely more obvious when the satellite separation is comparable to the chorus scale size. Nevertheless, the calculated statistical scale size of chorus wave elements using median values (see section 3 below) is similar to that using 75th percentile values, indicating that our calculation is robust.

3 Statistical Results

3.1 Overall Transverse Scale Size

After applying all the criteria described above, we identified more than two thousand conjugate events during five years from January 2013 to December 2017. Figures 2a and 2b show distributions of these events in the L -MLT and L -MLAT planes. The majority of events are collected from the twin RBSP conjunctions, which are mostly distributed at L shells between 5 and 6. On the duskside, only a few conjugate events are observed, which is reasonable since the dusk-side magnetosphere is not favorable for chorus generation (Meredith et al., 2003, 2012; W. Li et al., 2010).

Figures 2c and 2d show the number of events and correlation coefficients as a function of transverse separation distance ($\Delta_\perp$), which is calculated in the field-aligned coordinate system. Here, the field-aligned coordinate is defined based on a 15-min running average of the background magnetic field observed by RBSP-A or RBSP-B, depending on which one of the two probes is located closer to the equator during the event. As shown in Figure 2d, the calculated correlation coefficient tends to decrease with increasing $\Delta_\perp$. The dark blue line is a Gaussian fitting for the averaged correlation coefficient within each $\Delta_\perp$ bin (magenta dots):

$$f(x) = A_0 e^{-\frac{x^2}{2A_1^2}} + A_2 \#(4)$$

where $(A_0 + A_2)$ is the peak of the Gaussian distribution and A_1 is the half width of the fitting. Center of the fitting is set to be zero, where the separation is the smallest and the correlation coefficient is expected to be the largest. The peak and half width of the Gaussian fitting are around 0.68 and 315 ± 32 (95% confidence interval) km, respectively. The peak is below 1 which may be due to the parallel separation. The overall scale size of chorus elements is $\sim 315 \pm 32$ km,

which is defined as the half width of the Gaussian fitting, and is up to 450 km where the correlation coefficient drops to 0.5. It should be noted that if we use median values of correlation coefficients (rather than 75th percentiles) in each 6-s time window, the scale size of chorus wave is ~306 km, which is slightly smaller but is very close to the value using 75th percentiles, indicating the robustness of our calculation.

3.2 L , MLT and MLAT Dependence

The dependences of chorus wave scale size on L shell, MLT and MLAT are further evaluated and shown in Figure 3. Figure 3a shows the averaged correlation coefficient sorted by various L and MLT bins. Note that only events with $\Delta_{\perp} \leq 800$ km are included, which is roughly the transverse size when the fitted correlation coefficient drops to 0.4 in Figure 2d, to reduce the transverse separation influence. It is also worth noting that we did not use the half width value (315 km) as the threshold value due to the limited event samples within that transverse separation. Bins with the number of events less than ten are excluded on the top row in Figure 3 due to the relatively low statistical significance. Average correlation coefficients are relatively larger over 6–12 MLT, compared to other MLT bins. Interestingly, average correlation coefficient tends to be larger at higher L shells for all the four MLT bins, which suggests a trend that chorus scale size tends to increase at higher L shells. This feature is reasonable, since the magnetic field intensity decreases with increasing L shells, leading to increasing Larmor radius of source electrons, which may be relevant to increasing transverse scale size of chorus waves. It is worthwhile to note that the correlation coefficient shown in the bottom-left (5.5–5.6 L shell and 0–6 MLT) and top-right bins (5.8–5.9 L shell and 18–24 MLT) of Figure 3a may not be statistically significant since the top-right (bottom-left) bin has a few conjugate events whose transverse separations are small (large), respectively.

Figures 3c and 3d (Figures 3e and 3f) show the binned correlation coefficient and number of events in each MLT- $\Delta_{\perp}$ bin for magnetic latitude within 7 degrees (larger than 7 degrees). The average correlation coefficient tends to decrease with increasing transverse separation distance in both $|\text{MLAT}| < 7^{\circ}$ (Figure 3c) and $|\text{MLAT}| > 7^{\circ}$ (Figure 3e). Interestingly, averaged correlation coefficients are typically larger at higher latitudes ($|\text{MLAT}| > 7^{\circ}$) than those at lower latitudes ($|\text{MLAT}| < 7^{\circ}$), especially closer to the noon. A possible mechanism for the MLAT dependence of chorus scale size could be the geometrical spreading of wave power, since the waves tend to become more oblique and thus deviate from the original L shell during their propagation from the equator towards higher latitudes, as revealed from ray tracing simulations (e.g., Breuillard et al., 2013; Chen et al., 2013). This effect is more distinct closer to the dayside, indicating that a compressed magnetic field topology (e.g., Keika et al., 2012) may be more favorable for the wave power spreading than a stretched field line at least within $\sim 20^{\circ}$ of magnetic latitude where RBSP/THEMS wave measurements are available.

3.3 Azimuthal Versus Radial Size

Furthermore, we divide the transverse separation into the azimuthal and radial directions to compare the scale size of lower band chorus elements in these two directions. Figures 4a and 4b

show averaged correlation coefficient and number of events in each $\Delta r \times \Delta \phi$ bin, where Δr is the radial separation and $\Delta \phi$ is the azimuthal separation. Bins with fewer than ten event samples are not shown. Due to the fact that the burst mode operates more frequently when the dual Van Allen Probes are getting closer, more event samples are obtained at smaller separations. From Figure 4a, as expected, a larger correlation coefficient is found for a smaller separation in both directions. More interestingly, the binned correlation coefficient decreases faster in the azimuthal direction than in the radial direction within ~ 600 km. However, it remains above 0.4 within ~ 1000 km in the azimuthal direction, which is larger than that in the radial direction. This finding suggests that chorus waves may remain phase coherent in a larger spatial extent along the azimuthal direction, which may be caused by the azimuthal drift motion of source electrons after their injection from the plasma sheet. It is also important to note that, in the azimuthal direction, the correlation coefficient does not show smooth variations which may also be influenced by the drift motion of source particles, whose drift speed depends on energy.

4 Summary and Discussion

We use simultaneous multi-probe observations (i.e., at least a pair of probes from Van Allen Probes and/or THEMIS missions) of chorus waveforms to calculate the transverse scale size of lower band chorus waves in the element scale. Main findings are summarized as follows.

1. Overall, at L shells over 5–6 an average transverse scale size of lower band chorus wave, calculated based on the half width of Gaussian fitting of correlation coefficients, is about 315 ± 32 km and is up to 450 km where the correlation coefficient drops to 0.5.
2. Averaged correlation coefficient tends to become larger at higher L shells at all MLT bins (Figure 3a), suggesting that transverse scale size of lower band chorus wave tends to be larger at higher L shells.
3. Averaged correlation coefficient is larger at higher latitudes (Figures 3c and 3e), suggesting that the scale size tends to become larger at higher latitudes. This feature is more significant on the dayside, where the magnetic field is more compressed.
4. The scale size of chorus waves is slightly larger in the azimuthal direction than in radial direction, which may be caused by the drift motion of source electrons in the azimuthal direction.

Interestingly, from THEMIS FBK statistics, Agapitov et al. (2018) found that cluster scale chorus waves with larger B_w have smaller scale sizes, which may be consistent with our results, since larger B_w chorus waves are more likely observed near the equator region, especially in the nightside magnetosphere (W. Li et al., 2009). Moreover, the scale size of cluster scale chorus waves is larger on the dayside than on the nightside, which is suggested to be caused by the fact that injected energetic electrons spread wider as they drift from the nightside to the dayside (Agapitov et al., 2018). Thus, it is not surprising that a relatively small scale size of chorus waves, ~ 100 km, was reported by Santolik et al. (2003) near 21 MLT. This effect may also contribute to the MLT dependence of element scale size of chorus waves in our statistical study that the scale size becomes larger away from the nightside where energetic electrons are closer to the initial injection region. The number of samples is small on the duskside, thus the result that

the scale size decreases after 12 MLT needs further validations in future studies.

It is worth noting that since most conjunction events were collected by the dual RBSP satellites near their apogee (L shells between 5 and 6), although we use THEMIS and RBSP satellite constellations, the scale size may be more representative for the lower band chorus waves over the L shells of 5–6. Nevertheless, the extensive waveform data set in this region provided an excellent opportunity to statistically evaluate the dependence of chorus scale size on L shell, MLT, and magnetic latitudes. The L shell dependence covering a broader range of L shells is beyond the scope of the present study, and is left for future investigations.

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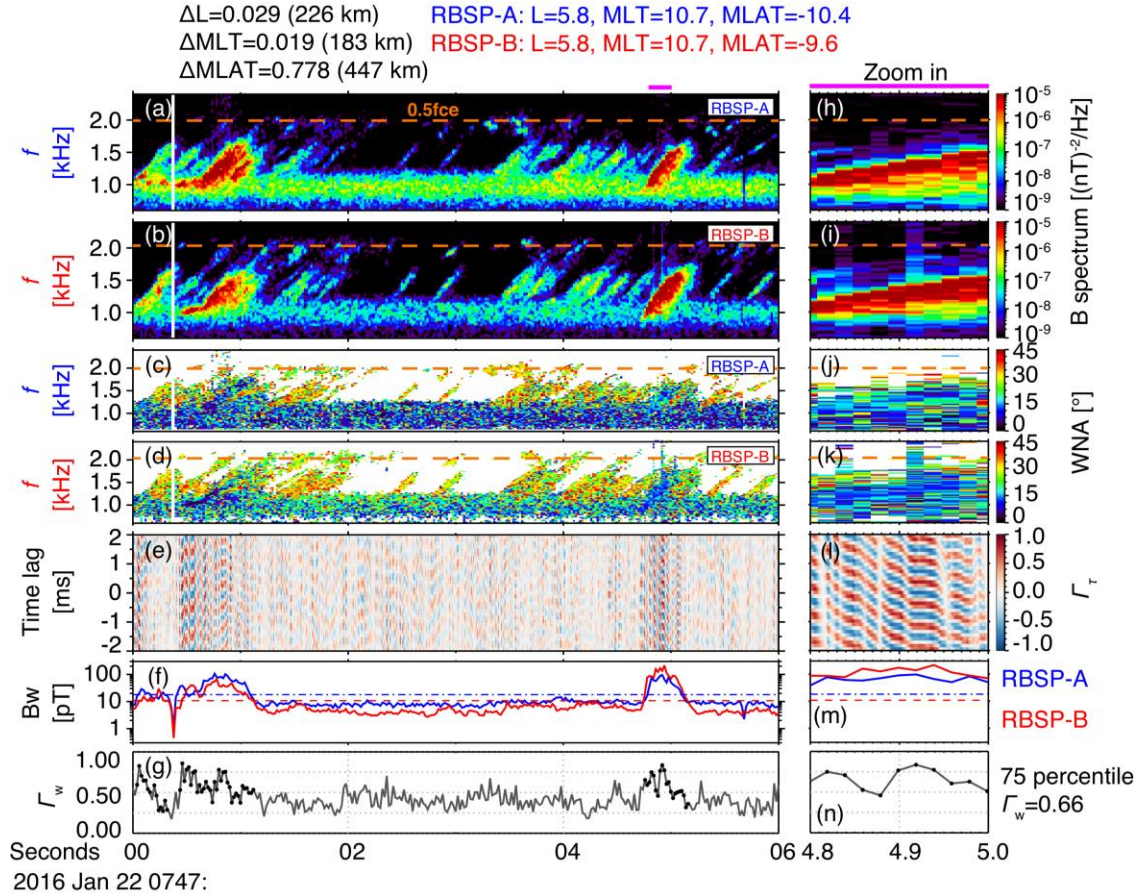


Figure 1. Example case on 22 January 2016 observed by RBSP-A and B. (a) Magnetic spectral density measured by RBSP-A and (b) RBSP-B. (c) Wave normal angles measured by RBSP-A and (b) RBSP-B. Orange dashed lines indicate $0.5 f_{ce}$. (e) The correlation coefficient (Γ_τ) between waveforms observed by the two probes as a function of universal time and time lag. (f) Integrated magnetic wave amplitude (B_w) from the magnetic spectral density in the lower band chorus frequency range from RBSP-A (RBSP-B) in blue (red). Blue (red) dashed line represents the larger value between 5 pT and two times of the median of B_w in the 6-s time window for RBSP-A (RBSP-B). (g) Correlation coefficient (Γ_w) of waveforms observed by the two probes, shown in black line. Selected Γ_w based on the wave amplitude criteria are shown in black dots. (h)-(n) Similar formats to (a)-(g), but zoomed in to 07:47:04.8-07:47:05.0 UT.

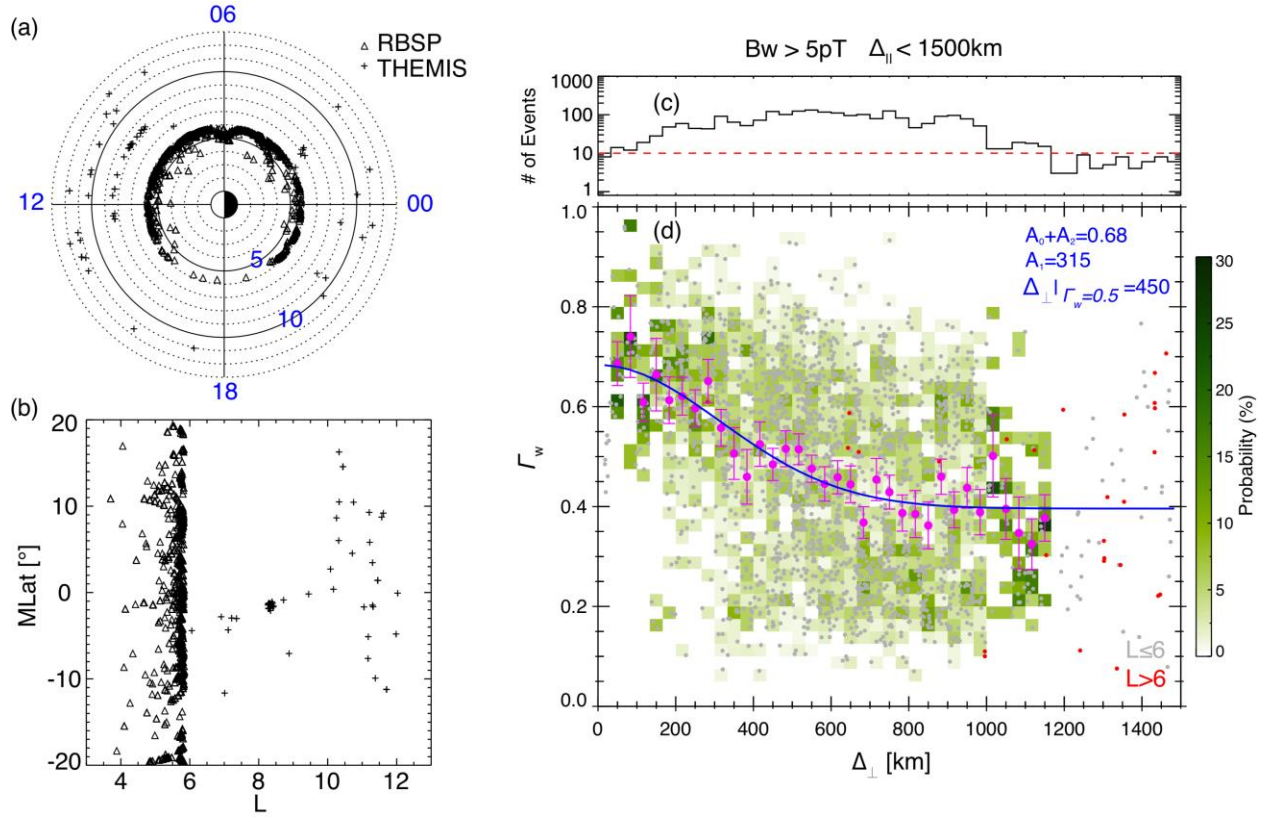


Figure 2. Event distribution and overall result of calculated correlation coefficients. (a) Event distribution in L -MLT and (b) L -MLAT planes. Events observed by a pair of RBSP (THEMIS) are marked as triangles (crosses). (c) Number of samples as a function of transverse separation distance. (d) Correlation coefficient as a function of transverse separation distance. Grey (red) dots are calculated correlation coefficients at $L < 6$ ($L > 6$). Greenish bins are probabilities of correlation coefficients in each $\Delta_{\perp} \times \Gamma_w$ bin. Magenta dots are averaged correlation coefficients in each $\Delta_{\perp}$ bin with error bars indicating the standard error (σ). Blue line is the Gaussian fitting for the magenta dots and the corresponding fitting parameters are labeled in the right-top corner in panel (d).

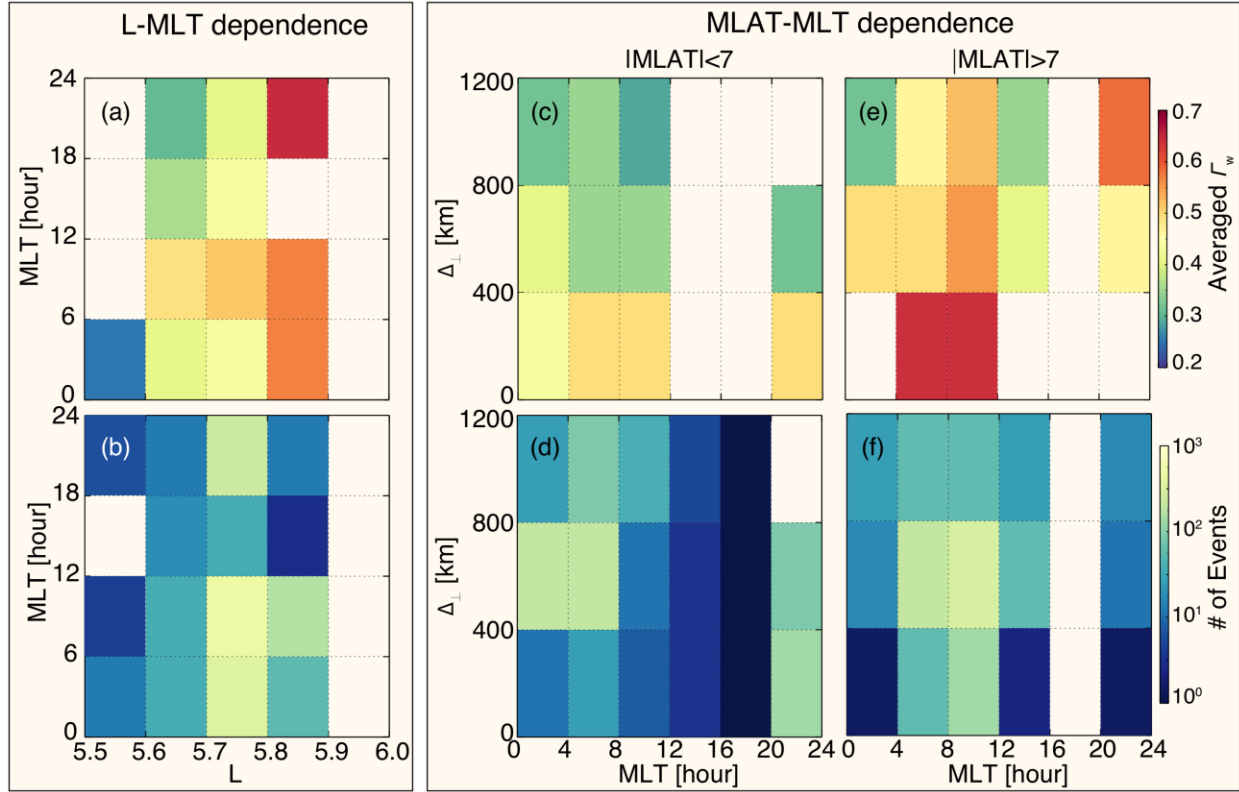
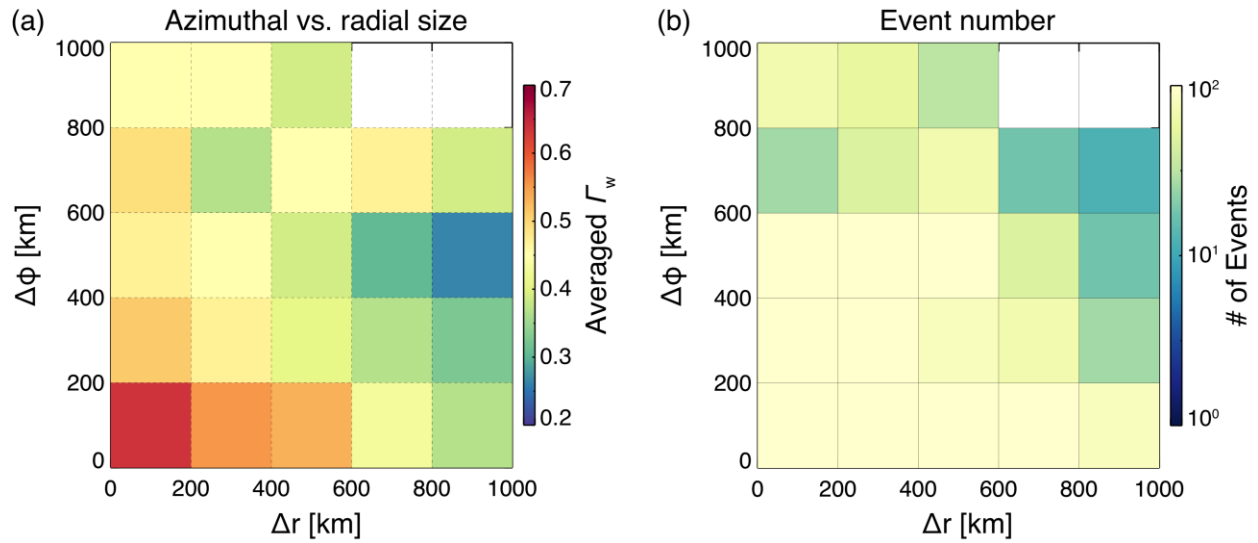


Figure 3. Dependencies of correlation coefficients of chorus waveform on L shell, MLT and MLAT. (a) Averaged correlation coefficient and (b) number of events in each $L \times$ MLT bin. (c) Averaged correlation coefficient and (d) number of events in each MLT $\times$ $\Delta_\perp$ bin with $|MLAT| < 7^\circ$ in both northern and southern hemispheres. (e)-(f) are in the same format as (c)-(d), but for $|MLAT| > 7^\circ$. For top panels, bins with fewer than ten event samples are not shown.



512

513 **Figure 4.** Azimuthal versus radial scale size of chorus waves. (a) Averaged correlation
 514 coefficient and (b) number of events in each $\Delta r \times \Delta \phi$ bin, where Δr is the radial separation and
 515 $\Delta \phi$ is the azimuthal separation of a pair of satellites.
 516

Figure 1.

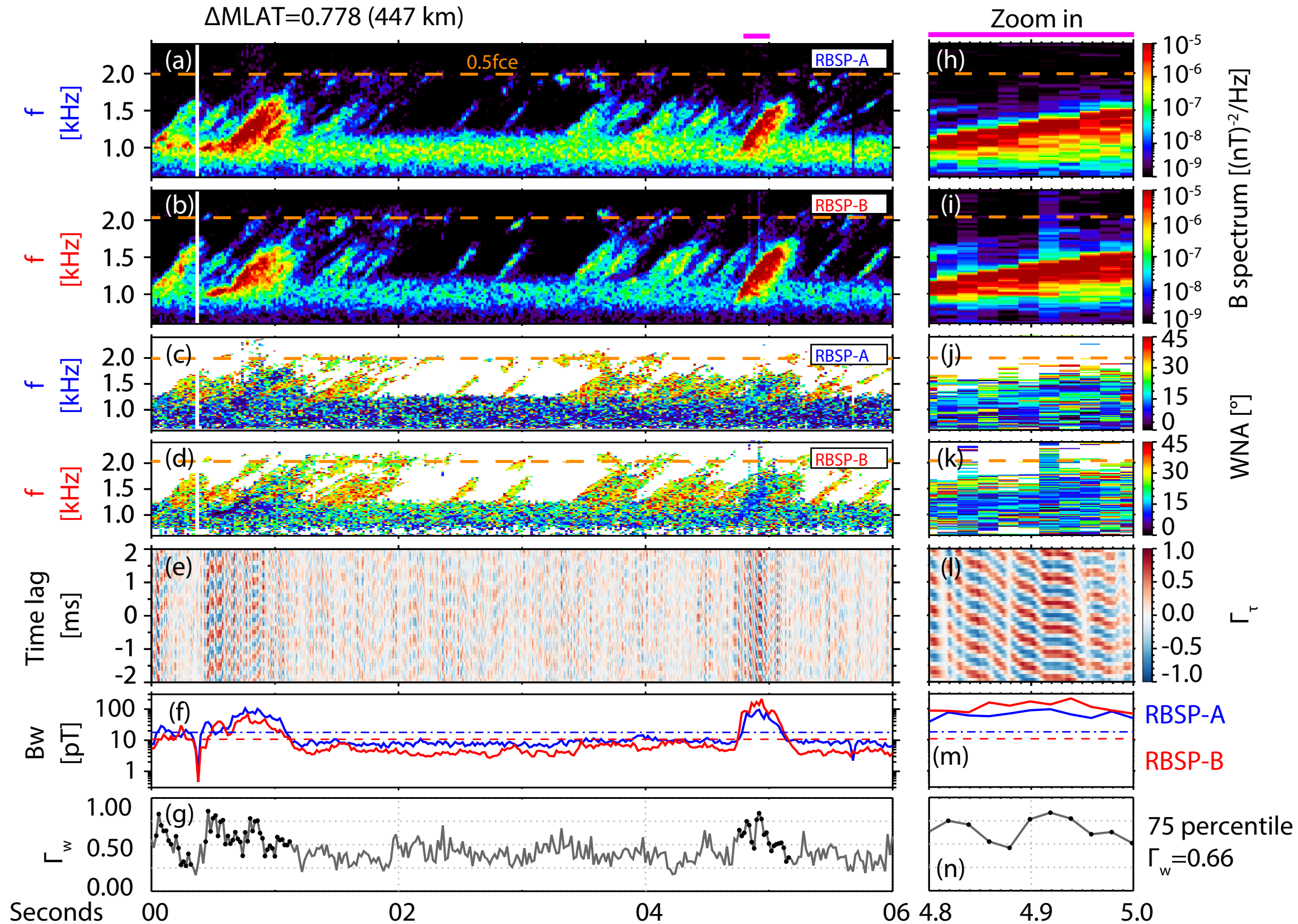
$\Delta L=0.029$ (226 km)

RBSP-A: $L=5.8$, $MLT=10.7$, $MLAT=-10.4$

$\Delta MLT=0.019$ (183 km)

RBSP-B: $L=5.8$, $MLT=10.7$, $MLAT=-9.6$

$\Delta MLAT=0.778$ (447 km)



2016 Jan 22 0747:

Figure 2.

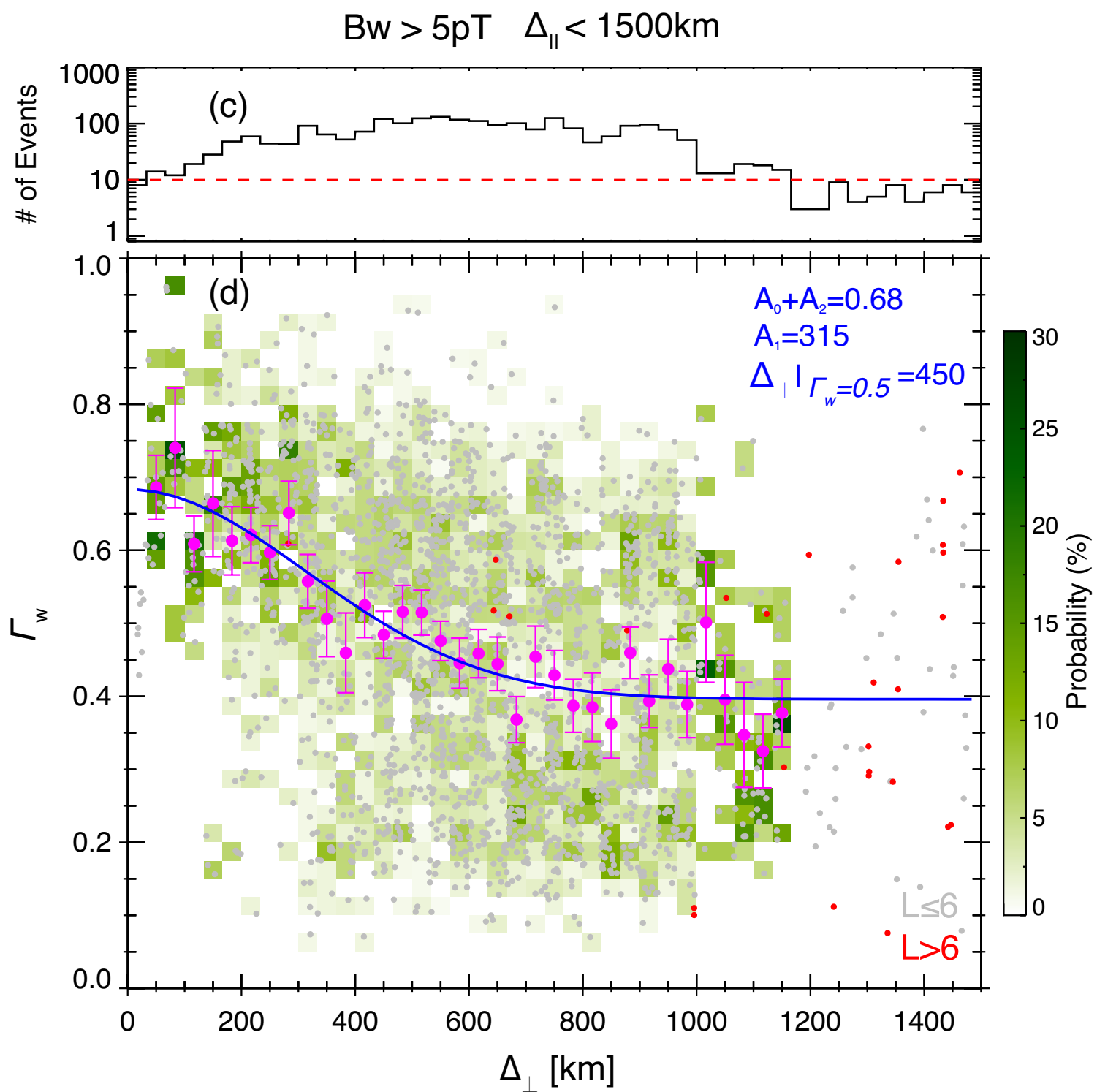
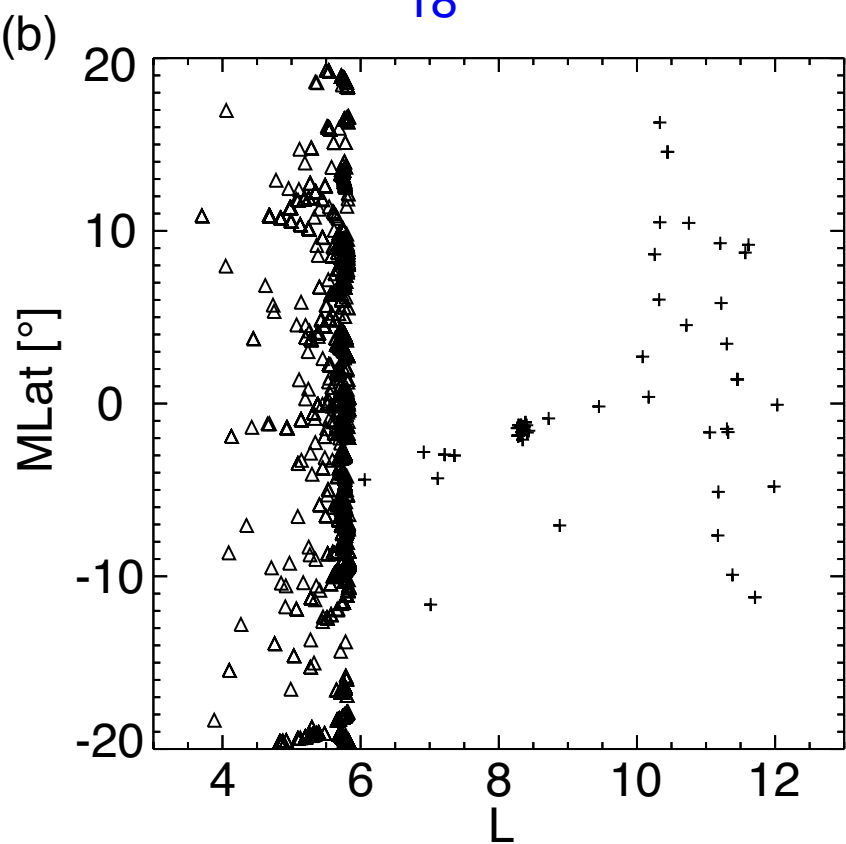
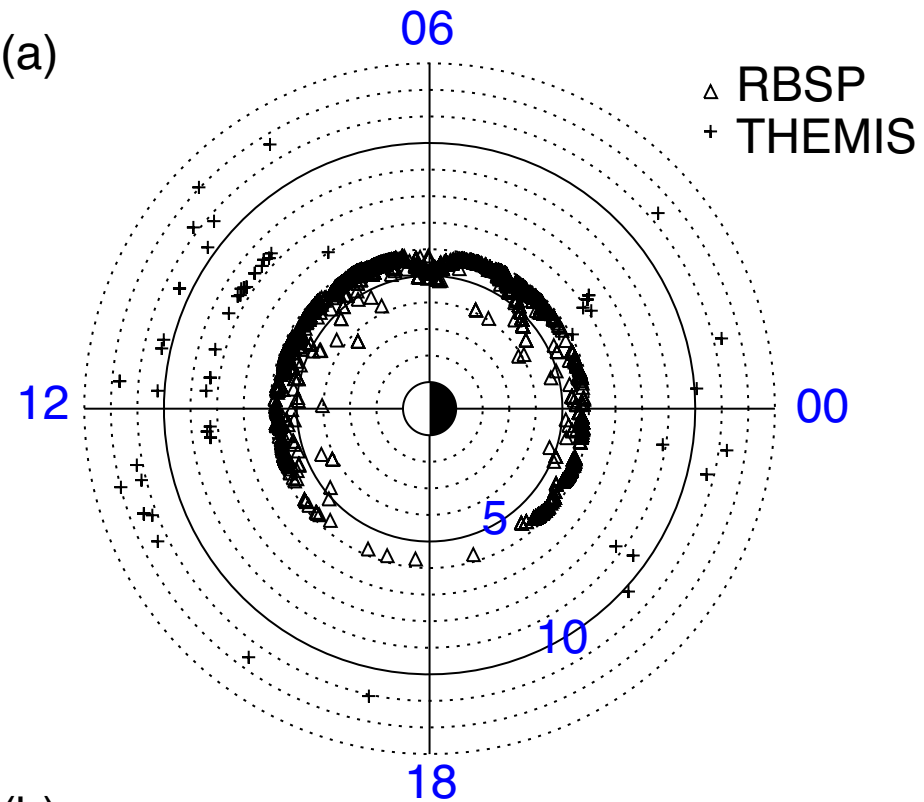
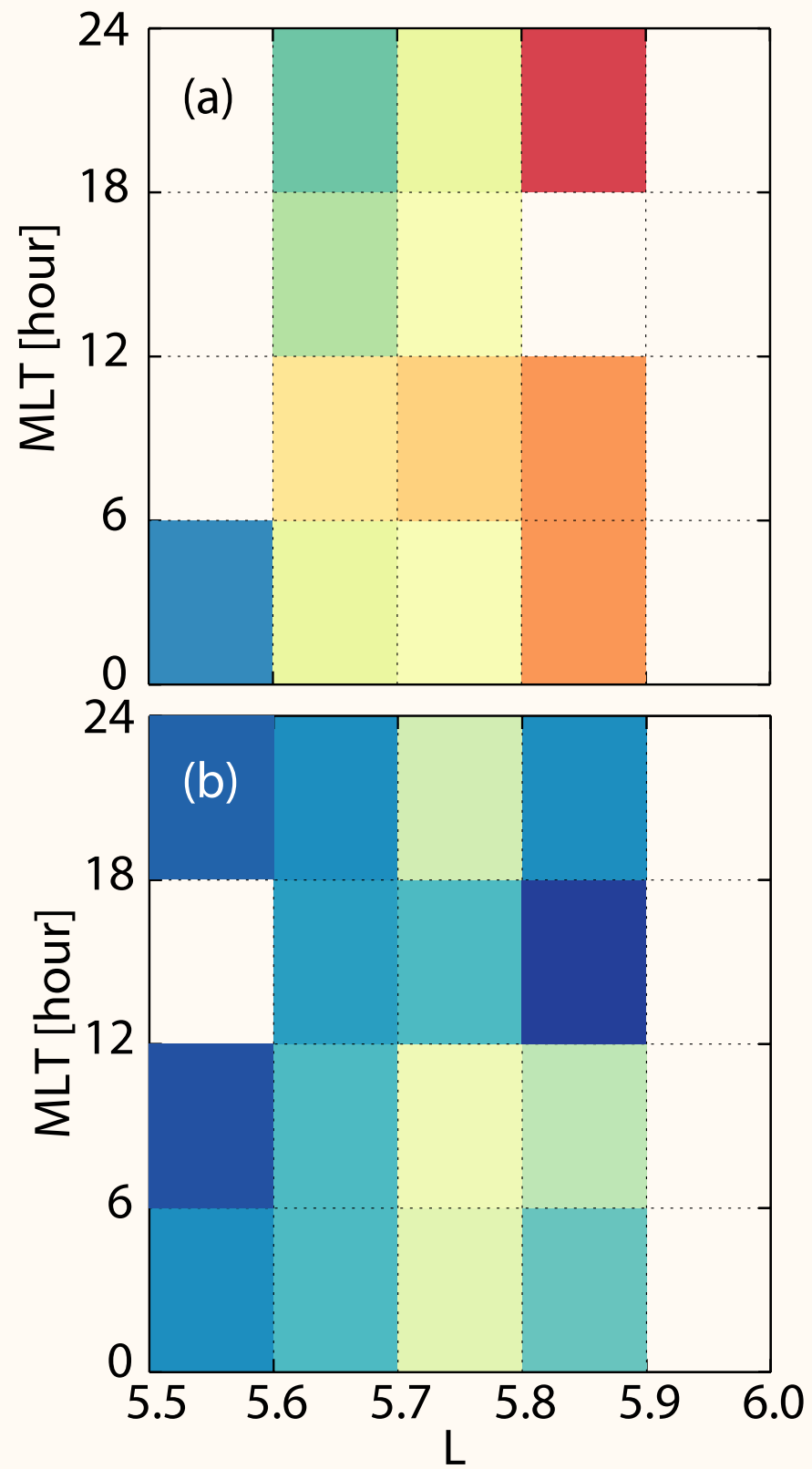


Figure 3.

L-MLT dependence



MLAT-MLT dependence

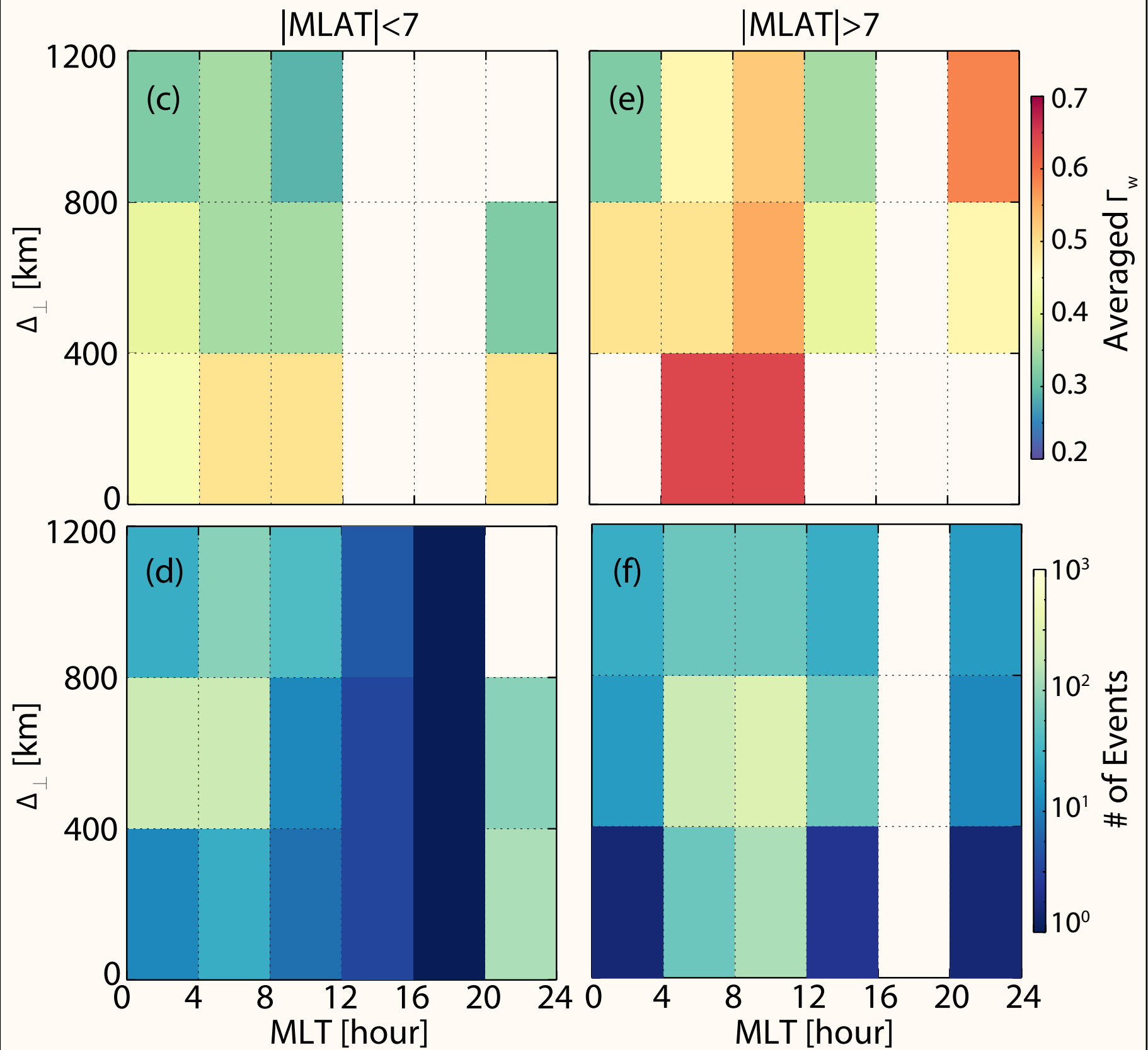


Figure 4.

