Location and size of the global source region of whistler mode chorus

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[1] We use multicomponent measurements of the four Cluster spacecraft and a backward ray tracing simulation to estimate the location and size of the global source of whistler mode chorus emissions in the magnetic equatorial plane. For the first time, analysis is made in a broad range of latitudes in both hemispheres along a single Cluster orbit. Our results show that for different time intervals, the sizes of the observed portions of the global chorus source region in the equatorial plane varied between 0.4 and 1.5 Earth radii. They were found at radial distances between 4.5 and 8.2 Earth radii during 2 h of measurements. Therefore, the superposed minimum width of the global source region of whistler mode chorus in the magnetic equatorial plane is approximately 4 Earth radii.

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1. Introduction

[2] Chorus emissions are among the most intense electromagnetic signals of natural origin observed in the inner part of the Earth magnetosphere. They attract increasing interest for their role in acceleration of electrons in the outer Van Allen belt to relativistic energies [*Horne et al.*, 2005]. Measurements by GEOTAIL [*Nagano et al.*, 1996], POLAR [*LeDocq et al.*, 1998], and CLUSTER [*Parrot et al.*, 2003a; *Santolík et al.*, 2003a, 2005a; *Santolík*, 2008] have shown that chorus comes from a region near the geomagnetic equatorial plane. Chorus is usually generated after an injection of energetic electrons into the magnetosphere after substorms [*Tsurutani et al.*, 1979; *Meredith et al.*, 2001]. The generation mechanism can be linked to the interaction of these injected energetic electrons with whistler mode waves [*Burton and Holzer*, 1974; *Trakhtengerts*, 1999] in the frequency range between a few hundred of Hz and a few kHz. The waves then move out of the equatorial plane. A chorus component has also been observed with the direction of propagation toward the equator, less intense and at lower frequencies [*Parrot et al.*, 2003b, 2004].

[3] For the investigation of chorus properties (in particular, the size and location of the chorus source) spacecraft observations combined with ray tracing calculations can be used. Using ray tracing simulations, *Parrot et al.* [2003b] for the first time simultaneously analyzed chorus waves emitted from the equator and chorus waves coming back through the same equatorial region after their magnetospheric reflection. *Parrot et al.* [2004] analyzed oppositely propagating chorus waves and applied the ray tracing simulation to the chorus component that comes back to the equator. The simulation results clearly show the magnetospheric reflection after which the waves return to lower latitudes and cross the equatorial plane. At the same time intense chorus directly propagates from the equator to the spacecraft. Computed wave-normal angles for the direct and reflected rays show that their wave vectors are inclined by approximately the same angle from the local magnetic field line.

[4] *Chum and Santolík* [2005] found that, depending on the initial wave-normal angle in its source, chorus can propagate to different maximum latitudes where its wave vector approaches the resonance cone and the waves are damped. They further found that, for different narrow intervals of initial wave-normal angles, chorus can also (1) magnetospherically reflect to lower L (McIlwain parameter) and penetrate into plasmasphere, (2) magnetospherically reflect outside of the plasmapause, (3) penetrate to low altitudes and into the subauroral ionosphere, and (4) magnetospherically reflect to the auroral region.

[5] *Bortnik et al.* [2006, 2007] calculated the Landau damping of chorus waves for different magnetospheric conditions. With the help of ray tracing simulations they estimated the effect of a varying wave-normal angle on maximum latitude to which chorus propagates and confirmed that chorus can propagate to very high latitudes and low altitudes. They also found that the final latitude of chorus propagation has the tendency to decrease with increasing L in the range between 3 and 7 owing to the lower ratio between the densities of the Landau resonant suprathermal particles and cold particles.

[6] *Santolík et al.* [2005b], based on data from 25 orbits of Double Star TC-1, have found chorus emission at different radial distances, reaching from the average plasmapause

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position up to regions close to the magnetopause. Significant occurrence rates of chorus at similar positions have been recently confirmed by *Li et al.* [2009]. These results are in agreement with the assumption of *Parrot et al.* [2004], that chorus can propagate to higher latitudes from its source locations distributed in a wide range of radial distances.

[7] This paper is a sequel of previous investigations of chorus emissions by *Parrot et al.* [2003b] and *Parrot et al.* [2004]. The aim of this paper is to estimate the minimum size of the global source region of chorus emissions by a ray tracing method. For this initial study, we have chosen a simple case of chorus waves, when spacecraft only observed chorus emissions directly emitted from the equator without a reflected component. These results can have broader implications for the physics of wave-particle interactions and global modeling of radiation belts. Section 2 describes the data from the four CLUSTER spacecraft and the analysis method. The analyzed event is shown in section 3. The results of the ray tracing analysis are presented in section 4. Section 5 contains a discussion whereas conclusions are given in section 6.

2. Experiment and Data Processing

[8] For our chorus analysis we have examined wave data measured by the Cluster spacecraft in different frequency ranges. Observations of three magnetic field components and two electric field components were made with the Spectrum Analyser (SA) which is a part of the STAFF (Spatio-Temporal Analysis of Field Fluctuations) experiment [*Cornilleau-Wehrlin et al.*, 1997, 2003]. The electromagnetic field has been analyzed between 8 Hz and 4 kHz.

[9] We have averaged the data with a time resolution of 20 s and we have used the PRASSADCO (Propagation Analysis of STAFF-SA Data with Coherency test) procedure [*Santolík*, 2001] to determine propagation characteristics of the observed emissions using different methods [e.g., *Santolík and Parrot*, 1998]. As a result, we obtain wave normal directions relative to the Earth's magnetic field for the four satellites during the same time interval and for a chosen frequency. Calculated wave normal directions (determined by a polar angle θ with respect to the Earth's magnetic field $\mathbf{B_0}$ and by the azimuthal angle φ with respect to the direction outward from the Earth) are then used as input data for a ray tracing program to trace all the rays back to the source.

[10] Our ray tracing procedure has been rewritten with substantial updates and modifications based on the original 3-D technique of *Cerisier* [1970] and *Cairo and Lefeuvre* [1986]. This modified version, used by *Parrot et al.* [2003b], has been described by *Santolík et al.* [2006, 2009a].

3. Observations

[11] Investigations of *Parrot et al.* [2003b] and *Parrot et al.* [2004] have shown the usefulness of the simultaneous measurements from at least two satellites to correctly estimate the propagation properties of chorus waves and their origin. We use chorus waves simultaneously observed by all CLUSTER spacecraft on 19 August 2003 between 0440 and 0710 UT (Figure 1) in the early afternoon sector. Our results will be applicable only to chorus in this region. The event takes place just after a disturbed period, with the DST index increasing from -140 nT 12 h before the observations to the values between −95 and −65 nT, with the AE index decreasing from 1000 nT to 80–500 nT (Figure 2), and with the Kp index decreasing from 7+ to 4− during 12 h before the observations.

[12] The spacecraft recorded directly emitted chorus on both sides of the equator. Figures 1a–1d show the electric power-spectral densities for Cluster 1-4 (SC1, SC2, SC3, and SC4), respectively. The spectrograms are obtained from the sum of power-spectral densities of the two electric components. Figures 1e–1h represent propagation characteristics of chorus emissions in frequency-time plots similar to spectrograms with intensities color-coded according to the scale on the right. Figures 1e–1h give an estimation of the sign of the parallel component of the Poynting vector relative to the Earth's magnetic field $\mathbf{B_0}$ [*Santolík*, 2001; *Parrot et al.*, 2003b]. In Figures 1e–1h, a blue color indicates that the Poynting flux is directed toward the south, whereas the red color shows flux directed toward the north (i.e., in the direction of $\mathbf{B_0}$). Orbital parameters are shown at the bottom of Figure 1 and relate to SC3.

[13] Chorus emission is seen between 100 Hz and 4 kHz, and the maximum frequency is near the magnetic equator at 0535 UT. The frequency of the chorus band of chorus decreases on both sides of the equator, as the spacecraft increase their latitude. By increasing their latitude, they also travel onto larger L shells. Equatorial cyclotron frequency decreases with increasing L, thereby causing a decrease in the frequencies of the observed chorus emission whose frequency is a fraction of the electron cyclotron frequency in their equatorial source region.

4. Ray Tracing Study

[14] For our study of chorus source it is very significant to see the evolution of chorus waves at the same frequency from their origin in the equatorial plane up to high latitudes. Taking into account this condition, we have analyzed chorus waves in the frequency band 800–1000 Hz. All the CLUSTER spacecraft measured chorus in this frequency band during the whole analyzed time interval, whereas measurements are not continuous at other frequencies (see Figures 1e–1h).

[15] The whole period of observation was divided into shorter time intervals of 10 min. For each interval we have made multiple ray tracing analyses for each satellite. The ray tracing procedure uses a simple dipolar model of the geomagnetic field and a diffusive equilibrium density model. To initialize the ray tracing procedure, the polar and azimuthal angles θ and φ describing the wave vector direction at the point of observation were used. An example of the calculations is shown in Figures 3a and 3b. To have a better view of the ray trajectories, the 3-D plot has been projected on the three (*XY*, *XZ*, and *YZ*) planes defined by the axes of the solar-magnetospheric (SM) coordinates. Backward ray tracing calculation is started at the position of each spacecraft and stopped when the plane of the geomagnetic equator is reached ($Z_{SM} = 0$). Rays corresponding to each Cluster spacecraft are color-coded according to the

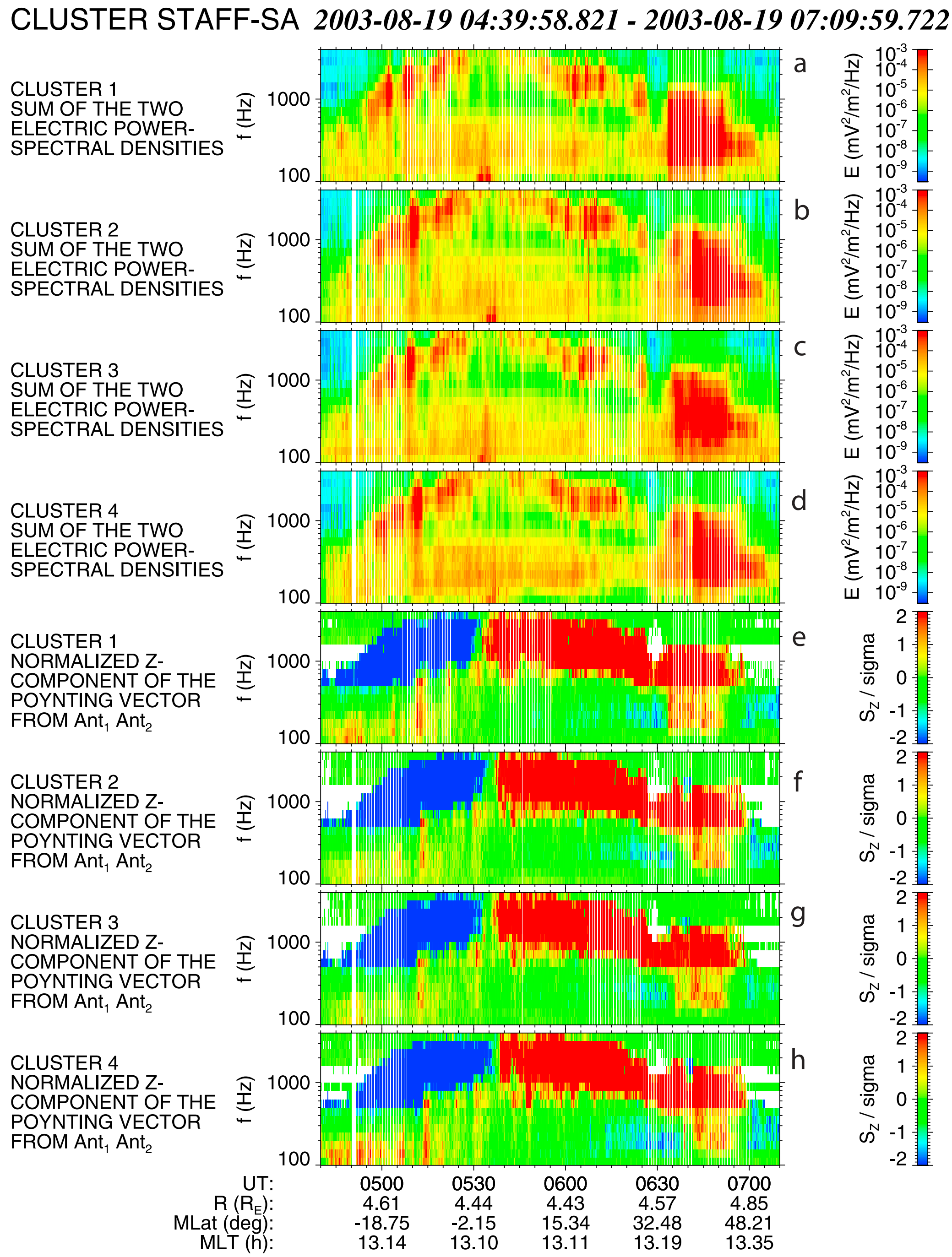

Figure 1. Data recorded by the STAFF-SA experiment on 19 August 2003 between 0440 and 0710 UT. Shown are (a–d) the electric power-spectral density and (e–h) the direction of the z component of the Poynting vector for each SC. The intensities of the spectrograms and the reliability of the sense of the Poynting vector are given by the color-coded scales on the right. Orbital parameters on the bottom are related to SC3.

dedicated spacecraft colors shown in the upper right corner of the image.

[16] Experimental uncertainties of this analysis are linked to experimental errors of determination of the initial wave vector direction. These errors are determined by direct experimental uncertainties of the measurement and by statistical properties of the data and analysis methods. The accuracy of the measurements is a few degrees, as we estimate it from uncertainties of boom directions, antenna directions, and from the accuracy of the vector measurements of the static magnetic field by the FGM instrument [*Balogh et al.*, 2001]. The random errors induced by the

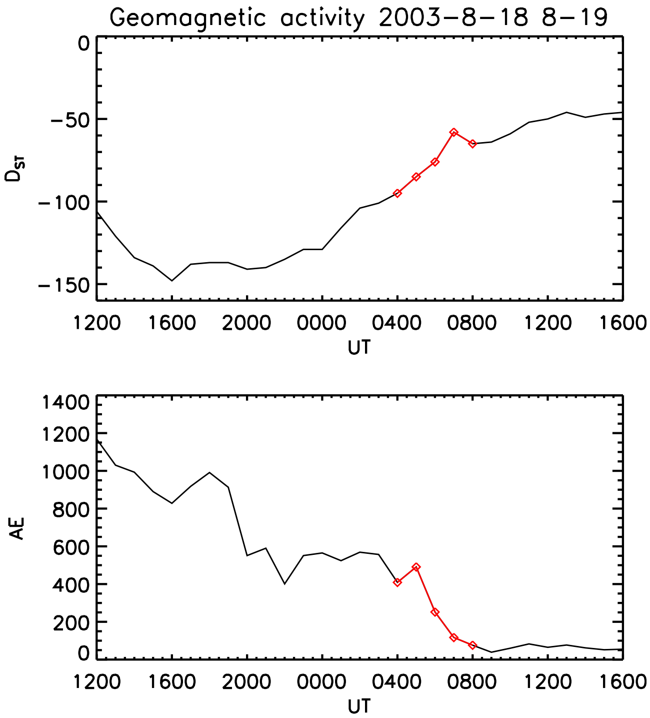

Figure 2. Geomagnetic activity on 18–19 August 2003: (top) the D_{ST} index and (bottom) the AE index.

statistical properties of the data and analysis methods have been estimated using five different independent analysis methods [*Means*, 1972; *McPherron et al.*, 1972; *Samson*, 1973; *Samson and Olson*, 1980; *Santolík et al.*, 2003b] on the same data set and by finding minimum and maximum values of θ and φ obtained by these methods. From these results we estimate that the typical error in θ is around 10° and the typical error in φ is around 10–20°. These uncertainties have effect on the results of the backward ray tracing calculation. Typically, the position of the point at which the plane of the geomagnetic equator is reached have an uncertainty of the order of 0.1 Earth radii (R_E).

[17] Figure 3a presents results of chorus analysis from 0450 until 0500 UT. This time interval corresponds to chorus measurements in the Southern Hemisphere. It is clearly seen that the waves observed on different spacecraft originate in the same region in the equatorial plane (i.e., in the source region of chorus). Figure 3b shows measurements on the opposite side of the equatorial plane between 0650 and 0700 UT. The data coverage is better in the Northern Hemisphere because chorus was slightly more intense (see the electric field spectrograms in Figure 1). Moreover, intensity of chorus varies with distance from the source.

[18] Our calculation can give the approximate spatial size of the chorus generation zone in the equatorial plane. As the spacecraft do not cover the whole source region we can calculate only the size of its observed part. Figures 3c and 3d show the obtained dimensions of the observed part of the chorus source region in the X_{SM} and Y_{SM} directions, respectively. Red triangles indicate the source limit closest to the Earth while black diamonds indicate the outer limit. The pairs of points at the beginning and at the end of the time interval correspond to Figures 3a and 3b, respectively. Figure 3e presents the geomagnetic latitude of the Cluster spacecraft for each interval of calculations.

[19] The separation on each pair of points represents the minimum size of the observed portions of the global chorus source region in the equatorial plane. The distances between rays in each pair are changing while the spacecraft moves off the source. This separation varies between 0.4 and 1.5 R_E for different pairs. It is logically smallest close to the equator where the spacecraft move in the vicinity of the source plane and thus they are reached by rays from a small part of the global chorus source region.

[20] If we suppose that the dimensions of the chorus source do not change significantly during our observations, the minimum size of the global source region corresponds to the difference between positions of the two outermost rays in the equatorial plane for the whole period of observation. The source regions of these rays are observed at radial distances of 4.5 and 8.2 R_E. The superposed minimum size of the source region of whistler mode chorus in the magnetic equatorial plane is thus approximately 4 R_E.

[21] Evolution of the calculated wave vector direction defined by the θ and φ angles during ray tracing simulations are presented in Figures 4a and 4b and Figures 4c and 4d, correspondingly. Figures 4a and 4c present measured values of angles for all satellites at these locations, whereas Figures 4b and 4d contain calculated values of both angles in the anticipated source region of chorus close to the equatorial plane. The values of the measured θ angles indicate that the wave vectors are close to parallel or antiparallel directions with respect to $\mathbf{B_0}$. The values of the θ angles at the end of the backward rays mean that chorus waves inside their source region have obliquely directed wave vectors at approximately 50 degrees from the Earth's magnetic field lines. Their azimuthal angles φ are close to +/− 180 degrees. This shows that the wave vectors are directed toward the Earth.

[22] Assuming that the position of the chorus source does not change with time, distribution of L values can be explained by an extended chorus source region in the equatorial plane. We observe chorus coming from the same global source region, but originating from its different parts. To define the position of the observed part of the chorus region during the event, we represent the McIlwain parameter L as the radius and the magnetic local time (MLT) as the polar angle (Figure 5a). The results from different spacecraft are superposed. Black, red, blue, and green points are color-coded for each Cluster spacecraft in the same way as for the ray tracing results.

[23] Spatial location in L of the source is presented as a histogram in Figure 5b. The obtained distribution has two maxima at 5 and 7.8 R_E that can be associated with local generation zones inside the larger source region. It means that, in this particular case, it is highly probable to observe chorus sources at distances near 5 R_E.

[24] Analysis of the correlation between the chorus frequency and location of its source region shows a small decrease of L for increasing frequency (Figure 6). For this estimate, we have made ray tracing analysis and then calculated L for four frequency bands: 500–630 Hz, 630–800 Hz, 800–1000 Hz, and 1000–1300 Hz for a particular time interval from 0500 to 0510 UT on 19 August 2003.

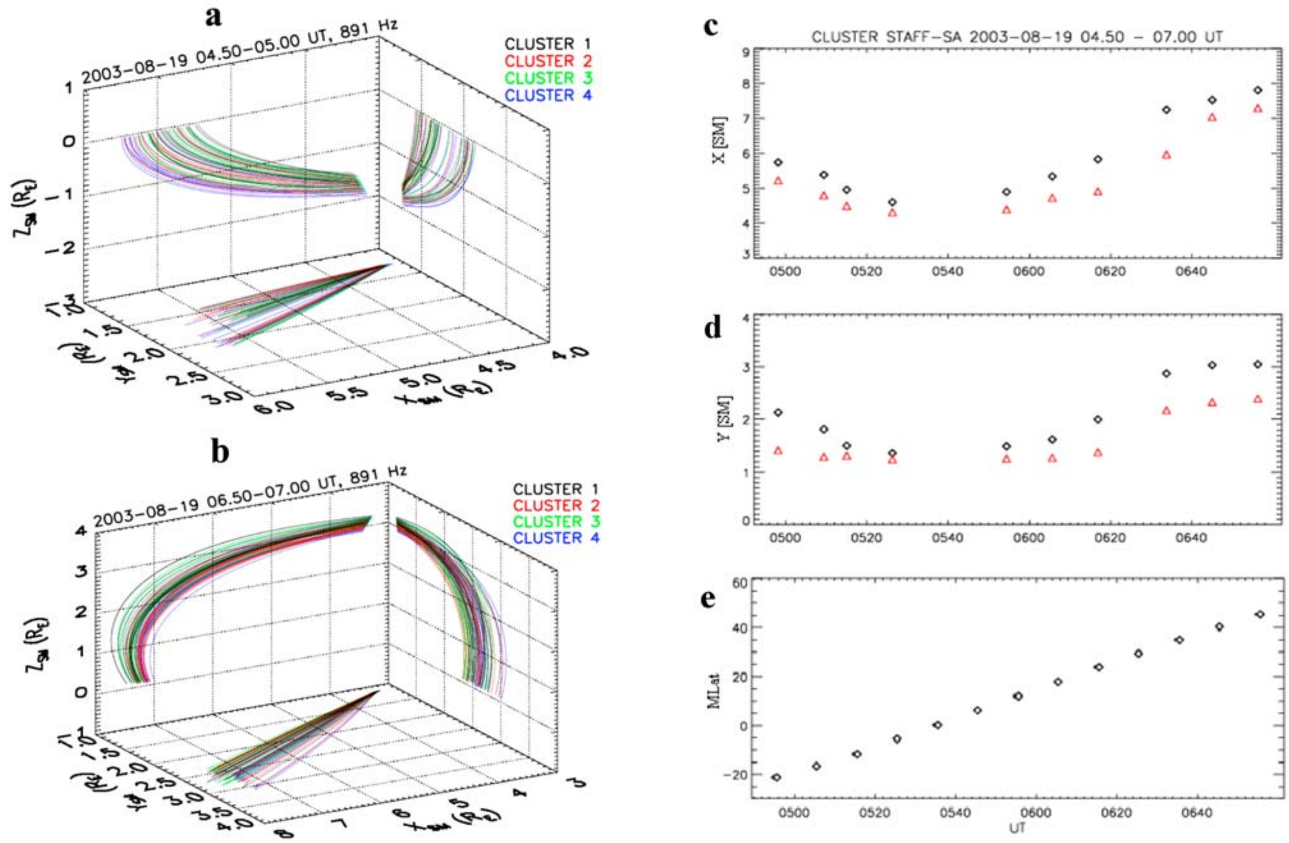

Figure 3. Backward ray traces in three dimensions for a frequency of 891 Hz based on the data from the frequency interval 800–1000 Hz. The curves are color-coded according to each spacecraft: (a) at the beginning of chorus observation in the Southern Hemisphere on 19 August 2003 between 0450 and 0500 UT, (b) at the observation of chorus at the end of the selected interval in the Northern Hemisphere on 19 August 2003 between 0650 and 0700 UT, and the minimum dimensions of the observed parts of the chorus source obtained from the results of the ray tracing method in the coordinates (c) X_{SM} and (d) Y_{SM}. Black and red symbols indicate the calculated boundaries of the chorus source region. (e) The positions of the measurements as 10 min averages of the geomagnetic latitudes of the Cluster spacecraft.

However, the difference between the median L for different frequencies is not significant compared to the global extent of the chorus source.

5. Discussion

[25] A simplified dipolar model of the geomagnetic field and a diffusive equilibrium density model are used in the ray tracing procedure. Results of the ray tracing method may be biased by inaccuracies of both models. *Santolík et al.* [2006] studied low-altitude electromagnetic ELF hiss on the dayside of magnetosphere that is similar to the region of our study. The authors used reverse ray tracing simulation and several plasma density models which showed chorus generation region at L close to 5. However, no strong differences of the ray tracing calculations for the different density models were indicated. It is thus probable that our results would not depend strongly on the density model. It is clear, however, that the obtained L values would be different with different magnetic field models. We use here the dipole model to be able to compare our results with previous studies [e.g., *Bortnik et al.*, 2007] which use the same simple model of the magnetic field.

[26] An implicit assumption in the ray tracing study is that chorus originates directly from the magnetic equator on the first pass of the waves, with no bouncing back and forth. In the light of previous results of *Parrot et al.* [2003b, 2004], this appears to be a justifiable assumption. The chorus that returns to the equator after a magnetospheric reflection has been observed at lower frequencies and at approximately two orders of magnitude lower intensities compared to chorus that propagated directly from the equator. The observations described in this paper also showed Poynting fluxes directed from the equator in the analyzed frequency band.

[27] Figure 5a shows that during the period of observations the MLT of the spacecraft did not significantly change (rises from 0100 to 0300) and positions of all four Cluster spacecraft were close to each other, but L changes with spacecraft moving in latitude. The chorus source of selected events is located at L between 4.5 and 8.2 on the dayside. This agrees with the theory [*Bortnik et al.*, 2007] and recent observations [e.g., *Li et al.*, 2009]. The obtained values of L are also in agreement with previous results of the chorus

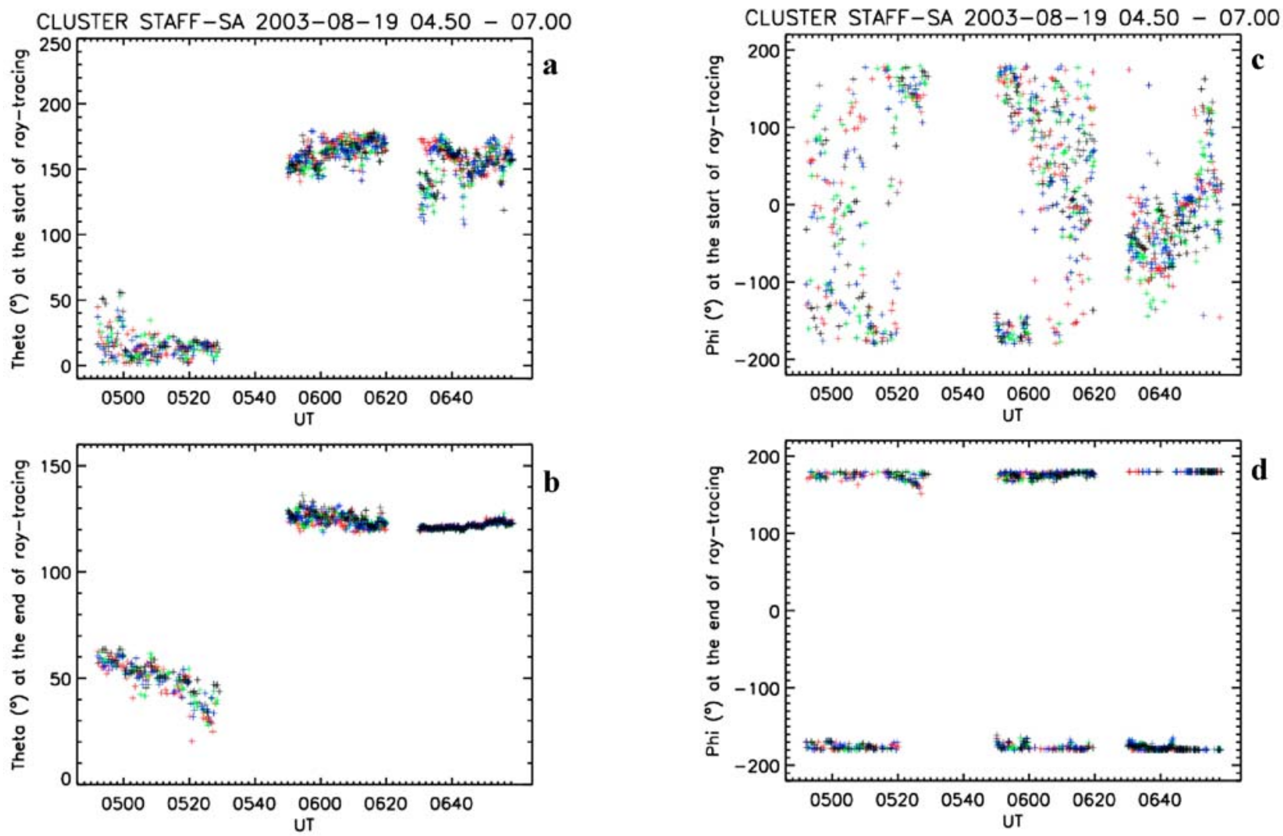

Figure 4. Values of (a and b) the θ angle and (c and d) the φ angle at the beginning and at the end of the ray tracing simulation. Initial values of the angles are measured by spacecraft (Figures 4a and 4c), and then they are computed by the ray tracing procedure when the rays reach the geomagnetic equator (Figures 4b and 4d).

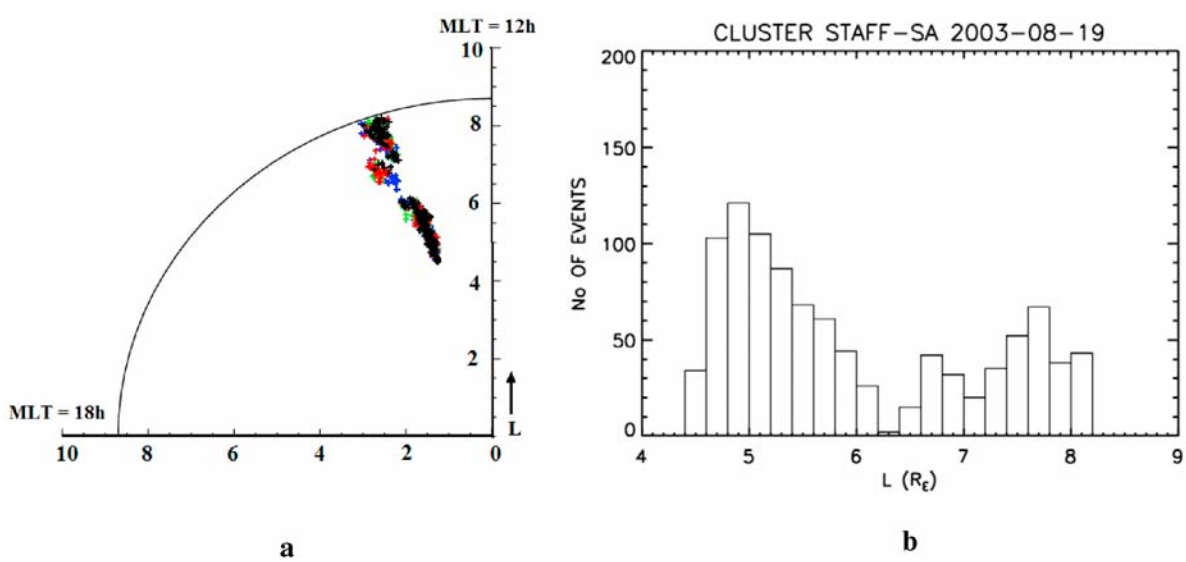

Figure 5. (a) Reconstructed positions of chorus sources during the analyzed event as a function of the McIlwain parameter L and the magnetic local time (MLT). (b) Spatial distribution of L for the whole period of observation on 19 August 2003 between 0440 and 0710 UT. Each event corresponds to the ray tracing results based on the 20 s averages of measurements of the four Cluster spacecraft.

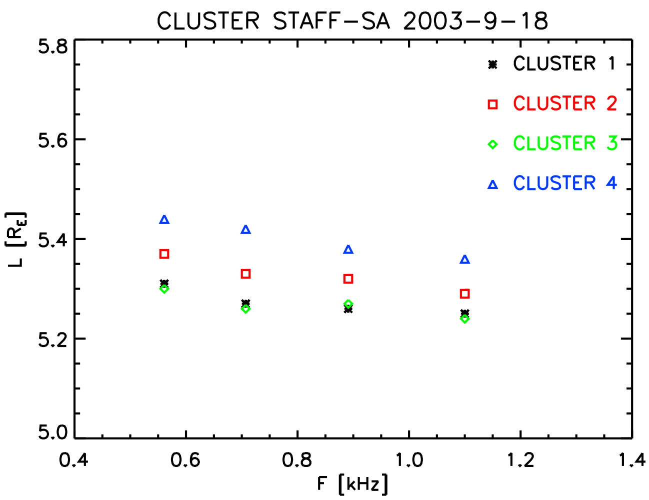

Figure 6. Median McIlwain parameter L of the chorus source as a function of the frequency of chorus on 19 August 2003 between 0500 and 0510 UT. Calculated positions of the origin of the rays corresponding to each Cluster spacecraft are color-coded according to the dedicated spacecraft colors shown on the top right.

measurements from the Double Star equatorial spacecraft [*Santolík et al.*, 2005b] that show higher intensities of chorus at L above 6 on the dayside. It is necessary to note that the orbit of the Double Star TC-1 spacecraft is located at low geomagnetic latitudes with an apogee of 13.3 R_E while CLUSTER spacecraft cross the chorus source region at a nearly constant radial distance (4 – 5 R_E).

[28] Figures 4b and 4d show that the calculated wave vectors in the source region are highly inclined toward the Earth. This corresponds well to the conclusions of the theoretical study by *Chum and Santolík* [2005]. This results is also consistent with some recent studies [*Tsurutani et al.*, 2009; *Verkhoglyadova et al.*, 2009; *Chum et al.*, 2009; *Santolík et al.*, 2009b] suggesting that oblique propagation might be important in the chorus source region.

6. Conclusions

[29] In this paper we have analyzed continuous observations of a chorus event seen on both sides of the geomagnetic equatorial plane. Simultaneous measurements by all Cluster spacecraft and a ray tracing procedure allow us to estimate the minimum size of the chorus source region located in the equatorial plane. These parameters can be important for global modeling of radiation belts.

[30] Our results show that in separate 10 min time intervals we have observed small portions of this region that were 0.4–1.5 R_E wide and changed their position and size as the spacecraft moved along their orbit through the equatorial plane from the south to the northern latitudes. Assuming that this effect is mainly due to the spacecraft motion and that the position and size of the source do not substantially change at time scales of 1 h, we conclude that the global source region is at least 4 R_E wide in the equatorial plane and that it is localized at radial distances between 4 and 8 R_E.

[31] In the future a larger volume of Cluster data will be used for a statistical study of chorus source region to compare with other studies.

[32] **Acknowledgments.** We acknowledge discussions of the STAFF data with N. Cornilleau-Wehrlin of LPP/CNRS, Velizy, France, C. Harvey of CESR Toulouse, M. Maksimovic of the Meudon Observatory, and other colleagues from the STAFF team. We acknowledge the access to the spin-resolution data of the FGM magnetic field experiment (provided by A. Balogh and E. Lucek). We thank the reviewers for their helpful comments. This research was supported by ESA PECS contract 98025 and grants ME9107, GACR 205-09-1253, IAA 301120601 and by PICS grant 3725 from CNRS/DREI.

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