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FINE SPECTRAL AND TEMPORAL STRUCTURE OF VLF–CHORUS OBSERVED BY CLUSTER

I.A. Kornilov[1], J.S. Pickett[2], D.A. Gurnett[2], O. Santolik[2,3], and O.I. Kornilov[4]

[1]*Polar Geophysical Institute, Apatity, Murmansk region, Russia*
[2]*Department of Physics and Astronomy, The University of Iowa, Iowa City, IA, USA*
[3]*Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic*
[4]*Institute of Physics, St.Petersburg State University, St.Petersburg,Petrodvorets, Russia*

Abstract

We analyze chorus VLF emissions measured by the four Cluster spacecraft (SC) Wideband Detectors (WBD) at close separations during geomagnetically disturbed periods. Data of electric field Cluster WBD antennas were used. Satellites space separation along magnetic field was 50-300 km, and cross field about 10-50 km. Direct waveform signal study revealed very fast variations of signal frequency and amplitude at the time scales about only several milliseconds without correlation for the different satellites. For chorus spectral analyses we used not only ordinary FFT, we mostly applied methods basing on autoregression (AR) models of signal, providing very high spectral and temporal resolution of spectrograms (better than 5-10 milliseconds and 10-20 Hz). All emissions (hiss, chorus, triggered and others) are structured at the scales less then 10 hertz and 10 milliseconds, and spectral details are rather different, even if satellites space separation is less than 100 km. Using correlation functions calculation for vertical and horizontal lines of AR-spectrogram matrix and constructing resulting two-dimensional pictures allowed measuring signals time shift for Cluster satellites, and so detecting the direction and velocity of emissions motion (and correspondingly frequency shifts). Cluster data for 27-11-2002 on chorus with decreasing frequency are shown. Wavelet spectral analysis demonstrates different interconnections and correlations between low (50-400 hertz) and high (3000-10000 hertz) components of spectra.

Introduction

VLF chorus emissions have been observed on the ground and space for many years [Gurnett and O'Brien, 1964], [Santolik and Gurnett, 2003], but generation mechanism is still not well understood. Chorus consist of discrete elements, each lasts for a time on the order of tenth to a few tenth of a second. In each element frequency changes with a typical rate of a few kHz/s, more often it increases, but falling tones are also observed. Chorus intensity is very high (10 – 100 nT), they are one of the most intense emissions in magnetosphere [Helliwell, 1965]. Poynting flux measurements [LeDocq et al, 1998] showed that chorus source is very close to equator, in agreement with modern theoretical studies [Trakhtengerts, 1999]. One surprising aspect of chorus was the discovery of Gurnett et al. [2001] that correlated chorus elements appear at different frequencies on the various Cluster spacecraft separated by distances of a few hundred km or less.

Data analyses

During many years people used FFT for VLF emissions spectral analyses, but in initial form it principally cannot provide high spectral and temporal resolution simultaneously. Much better results can be achieved by using different methods of modeling (forecasting forward and backward) of the data block (linear prediction, MEM, sliding average, etc). Tests with different model computer synthesized and real physical 'on table' generated signals having a priori known spectral structure demonstrate that for VLF emissions using of autoregression models (AR) of signal for data block prediction is the most effective.

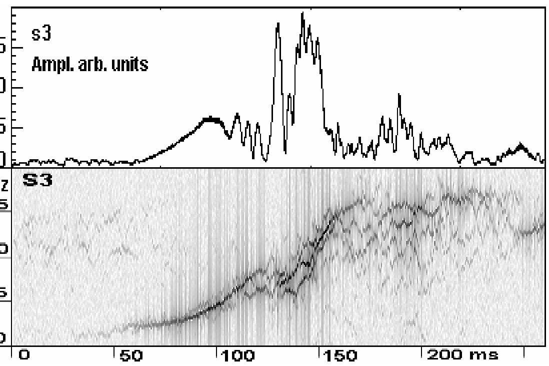

Fig. 1: Amplitude variations of chorus element (top), and corresponding AR-spectra.

Figure 1 demonstrates Cluster measurements of chorus on April 18, 2002. Spacecraft passed through their perigee at radial distance of 4.4 Re close to magnetic equatorial plane, moving from South to the North. WBD of all Cluster SC made continuous measurements using pass-band filter between 70 Hz and 10 kHz, sampling frequency 27.44 kHz, 8 – bit quantization mode. In the figure one can see process of chorus generation at time scale of individual chorus element (200 milliseconds). Initially process of generation started from mono-frequency regime with continuously growing amplitude. Rather slow amplitude increasing allows supposing that is amplification process of chorus wave from background emission. Then signal became two-frequency with strong amplitude oscillations. Large increasing of signal amplitude marks the beginning of multi-frequency generation. Interesting to note that frequency components are equidistant with frequency separation about 100 Hz.

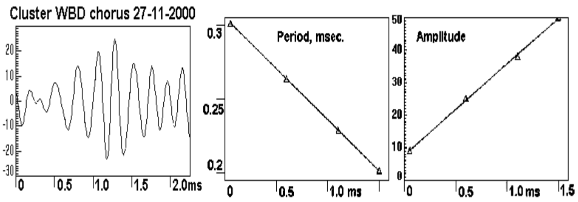

Fig.2. Fast frequency and amplitude modulation of chorus waveform.

Very many examples of extremely fast variations of chorus wave frequency and amplitude can be found in analyzing fragments of chorus waveforms. Figure 2 shows one example. During only 4 periods (1.5 milliseconds) wave frequency increased twice and amplitude 5 times. It is very difficult to believe that only gyroresonance mechanism can be responsible for this process. Interesting to note that period of wave decreases and amplitude increases with a good linearity.

Figure 3 presents some AR-model spectrograms for different Cluster spacecrafts. Bottom case is the same, as in figure 1. For three panels (top) SC is above equator (Mlat = 0.21^o), and two others below (Mlat=-0.07^o). Top pictures present the case of clear two-frequencies generation (especially for S1). Note, that difference between signals for S2 and S3 is much more than for S1 and S2, though S2 is closer to S3. Along magnetic field distance between S1-S2=200 km, S2-S3=70 km. Cross B separations are S1-S2=10 km, S2-S3=60 km. In all the figures we can see initial stage of chorus generation as a slow amplification of some weak background signal. Small fragments of the bottom panels, marked by vertical lines, are shown in figure 4 in more details.

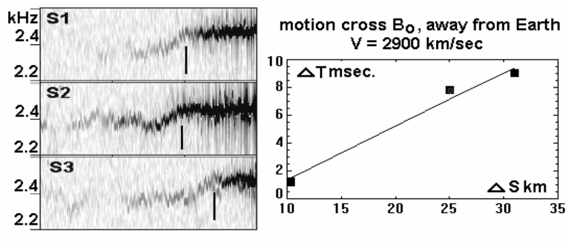

Fig.4. Fragment of initial stage of chorus generation, cross- field spreading.

One characteristic element (small sharp jump of frequency) is well visible, though for three SC only. Time delays for different satellites definitely can be noticed, allowing drawing summarizing picture with using information about spacecraft positions along and cross magnetic field. It was found that signal delays do not correlate with satellites positions along magnetic field, but correlate rather well with their positions cross field. Cross-field correlation possibly reveals some away from Earth cross-field spreading of generation area with a speed about 3000 km/s.

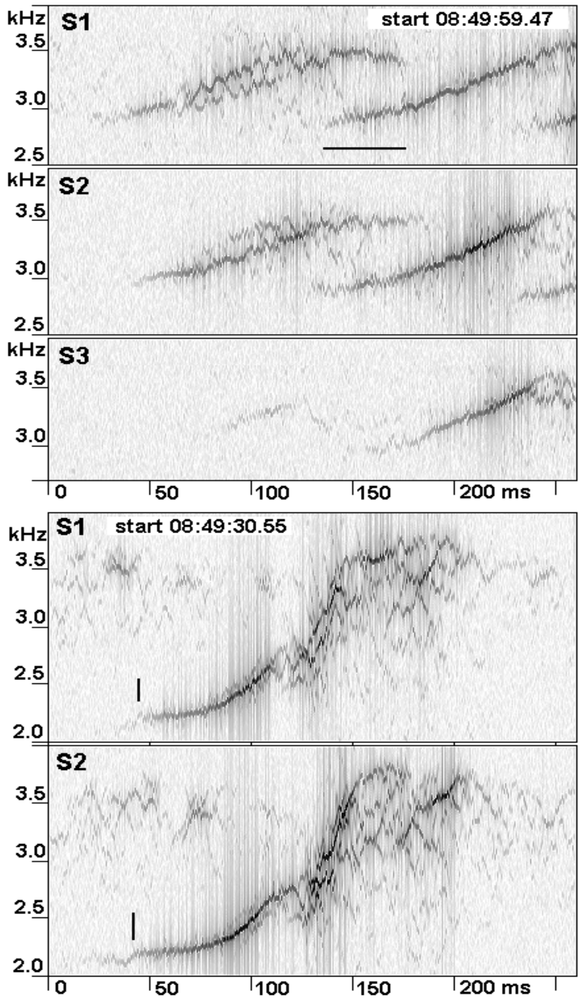

Fig.3. Examples of mono, double, and multi-frequency generation modes.

It was difficult to find some fine common details in chorus spectrograms during multi-frequency stage of generation. For precise delays detection, and so for measuring the speeds of wave motion another method has been developed. We calculated cross-correlation functions for every horizontal line of AR spectra and then plotted a two-dimensional picture of delays versus frequency. Example of this procedure for the time moment presented at the bottom part of figure 3 one can see in figure 4. Delays obviously are well correlating with satellites positions along magnetic field. Chorus move away from equator with a speed about 60,000 km/sec. Note that time shifts became larger, and so the speed of chorus motion smaller after multi frequency mode generation starting (changes from 2-3 ms in frequency range 2.2-2.6 kHz, to 8-12 ms for 2.6-3.7 kHz range). When satellites are above equator (top plots in figure 3), chorus move in opposite direction, again towards equator with a velocity about 30,000 km/sec (not presented in the figure).

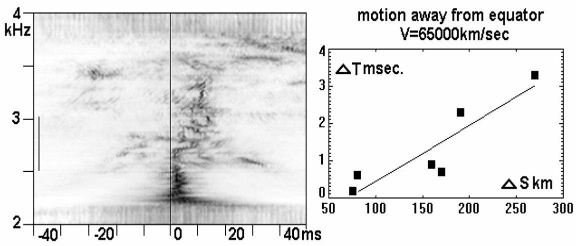

Fig.5. Applying of cross-correlation analyses for every horizontal line of AR spectra.

Chorus with decreasing frequency (falling tones) can also be observed. Example of Cluster data for 27-11-2000 is shown in figure 6. We can see mostly mono frequency generation, though some ‘splitting’ to higher frequencies can be seen as well. SC separation along magnetic field was about 700 km, cross B – 150 km. For this case there were absolutely no any chorus correlation for different SC (even approximately).

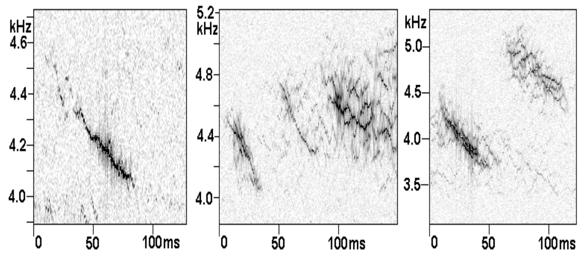

Fig.6. Example of falling-tone chorus (27-11-2000).

Wavelet spectrograms are very useful for emissions study because they can represent very broad range of frequencies simultaneously with an extrimally good time resolution. One example is shown in figure 7.

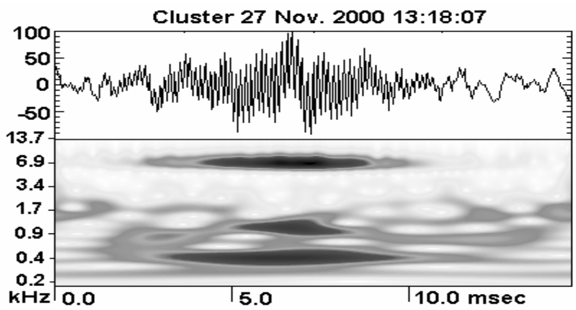

Fig.7. Wave form and Wavelet spectrogram.

Top panel presents direct signal waveform, and bottom figure is a Wavelet spectrogram. We can see short chorus type activation at frequency about 7 kHz with simultaneous signal intensifications at 400 Hz and 1000 Hz). Preliminary study revealed real existence of high and low frequencies correlation in chorus Wavelet spectrograms, but this correlation can be rather different (can be both positive and negative, depending on chorus amplitude, etc), and definitely need more detailed investigation.

Correlation with pulsating aurora

Very often chorus are well correlated with pulsating electron precipitation, observed on the ground and by balloons as pulsating aurora and X-ray microbursts. Typical energies of precipitating electrons are about 10 –100 kev. [Burtis and Helliwell, 1975]. The most widely held view of pulsating aurora generation is a type of relaxation oscillator involving trapped electrons and VLF wave-producing instabilities in the equatorial region of the magnetosphere [Trakhtengerts et al., 1986; Demekov and Trakhtengerts, 1994]. It was also found that bouncing between hemispheres electrons could produce effect of some global magnetospheric synchronization for chorus emissions generation process [Kornilov and Lubchich, 2000].

In figure 9 very rare case of synchronous 10-seconds TV observations of pulsating patch in keogram form (top) and chorus (second plot) are shown. At the bottom of plot short fragments of chorus at the time scale about hundred of milliseconds having similar with Cluster observed emissions fine spectral structure one could see. To find at least weakest traces of fine chorus time-spectral details in pulsating precipitating electrons fluxes we have used so called integral projection function (IP). Integral projection is widely used for compression of video information, and calculated as a special sum of rows and columns of TV frame matrix. IP allows revealing the weakest

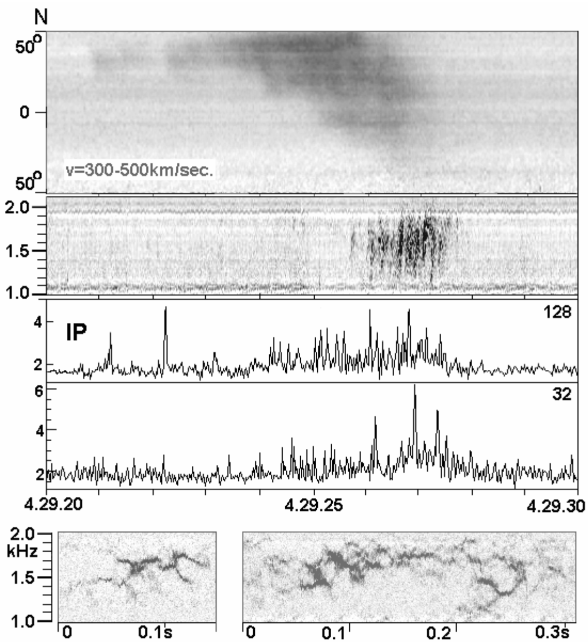

Fig 8. Case study of individual pulsating patch and chorus emissions (10-seconds time interval).

changes in the neighbour TV frames. In compare with other methods of TV frames comparison (for example, sum of absolute differences of corresponding pixels), IP has very low sensitivity to the image noises. IP calculation with using ordinary and averaged frame with different levels of averaging allows approximately estimate characteristic sizes of image elements for which the largest differences in the neighbour TV frames are achieved. Numbers in the two middle panels (128 and 32) present initial frame without averaging (128*128 pixels), and frame averaged for 8 pixels (32*32). IP were calculated for the all 500 TV frames of presented time interval. Small-scale luminosity variations (and so, precipitating electron flux modulation) are more pronounced in the initial stage of pulsating patch development (picks for the moments 04.29.26 and 04.29.27 for the frames without averaging). These variations have characteristic scale in ionosphere about 2 – 3 km. The largest frames differences are visible for IP – 32 (8 points averaging), and correspond to the scales about 5 – 10 km. So, we can preliminary conclude, using IP gives some proof that extremely weak modulation of precipitating electrons at the time scale of TV fields (0.02 seconds) really could exist. Of course, direct measurements of fast electron fluxes modulation at time scales of milliseconds exactly in the region of chorus generation would be much more informative.

Discussion

Spectrograms and waveforms revealed extremely fine structure and some other properties of chorus (consequent changes from mono towards two and multi-frequency generation modes, initial stage of wave amplification, etc) that hardly can be explained by traditional gyroresonance interaction between waves and particles. On the other hand, it is well known, that in thermonuclear study, solar radio emissions physics, astrophysics, radio astronomy, etc, mechanisms of electromagnetic energy generation and amplification basing on direct analogy with a processes taking place in powerful microwave electronics are broadly discussed. For VLF waves physics two microwave devices seem to be very interesting. One is traveling-wave tube, using for signal amplification, and backward-wave tube (carcinotron), mostly using for generation. These two tubes do not use any gyro effects (like, for example, so called gyrotrons), and operate using principle of direct velocity modulation of moving along magnetic field electrons, leading to space modulation of charge density. This spatially bunching electron flux effectively interacts with electromagnetic wave being in phase, realizing the process of wave amplification and generation as a self-organizing spatially distributed oscillating system. Only 4 requirements need to be fulfilled, and they are acquitted inside magnetosphere:

1. Existence of focusing magnetic field preventing electrons to move away from the region of generation.
2. Strong enough electron fluxes along magnetic field (analog of starting current in microwave tube).
3. Presence of slowing structure, necessary for electrons and wave to be in phase, in other words, electrons speed and phase velocity of wave should be almost the same. In magnetosphere background cold plasma plays this role.
4. Presence of abnormal dispersion medium for the backward wave mode (group and phase velocity of wave should have opposite directions). Cold plasma has namely those properties.

So, some analogs of microwave devices definitely can operate inside magnetosphere. Probably, we can suppose that in some monofrequency emissions (for example, triggered emissions, chorus with decreasing frequency, initial stage of rising tone chorus, etc) amplification mode of the traveling wave tube is realized and multi-frequency chorus are generated by backward wave oscillator regime.

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