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Nonlinear plasma wave processes observed in the polar cusp

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We present observations of electric and magnetic field variations from proton (about few Hz) to electron cyclotron frequencies (about few kHz) obtained by STAFF instrument on Cluster satellites during two cusp crossings, at $\sim 6 R_E$ altitude, in September 2002. The cusp was identified by the presence of intensive fluxes of counter streaming electrons with low energies and broadband wave activity which is typical for this region.

Special attention is given for the interval of measurements when the wave-form of the magnetic field fluctuations was taken in this region by CLUSTER satellites. The wave has been processed using the wavelet and bispectral analysis. Results showing the cascade of turbulence and wave-wave interactions are pre-sented in this paper. A three wave process can be responsible for the broadening of the wave spectra in the polar cusp.

Key words: polar cusp, three waves processes, cascade of the energy, wavelet analysis, bispectral analysis.

1. INTRODUCTION

The main feature of the polar cusp is the direct inflow of the solar wind plasma from the magnetosheath into the interior of the magnetosphere. This plasma meets magnetospheric plasma with different characteristics. One can see a cold component upflowing from the ionosphere, warm plasma from the magnetosheath, and even energetic ions and electrons with energy up to several hundreds keV. This situation can lead to

the development of many different plasma instabilities. The observations done in the polar cusp indicate the permanent presence of plasma waves in this region (Pottelette *et al.* 1990, Pickett *et al.* 1999, Błęcki *et al.* 1998, 1999, 2005, 2006, Romanov *et al.* 1999, Savin *et al.* 1999, 2002a, b, 2005). These conditions indicate that cusp is an ideal region to study the development of different types of plasma instabilities and nonlinear interactions between different plasma modes. One can say that the polar cusp is an ideal laboratory to study key plasma processes interesting from the point of view of geophysics as well as astrophysics.

One of the most important problems with wave measurements in the dynamical regions of the magnetosphere, as in the case for the cusp, is the nonstationarity of the internal processes. Wave spectra given by satellite instruments are usually processed with the use of Fourier analysis.

An application of wavelet analysis allows us to avoid this problem. Moreover, this analysis gives much higher spatio-temporal resolution and can help to find nonlinear evolution of waves and cascade of energy between different wave modes. The wavelet used in this analysis is based on the Morlet wavelet. The SWAN package developed by Lagoutte *et al.* (1999a, b, c) has been used to obtain the presented results.

2. OBSERVATIONS AND ANALYSIS

Wavelet analysis

The criteria for wavelet function and the form of Morlet wavelet are the following:

$$\int_{-\infty}^{+\infty} \psi(t) dt = 0 , \quad \int_{-\infty}^{+\infty} \psi^2 dt < \infty .$$

Any localized function $\psi(t)$ can be chosen as a mother wavelet, if it satisfies these criteria.

The complex Morlet wavelet which will be used in this paper is represented by the following function:

$$\psi(t) = \exp(i\omega_0 t - t^2/2) - \sqrt{2} \exp(i\omega_0 t - t^2 - \omega_0^2/4) ,$$

where ω_0 is the central frequency and the Continuous Wavelet Transform (CWT) of the signal $x(t)$ is given by

$$\int_{-\infty}^{+\infty} x(t) \psi^* \left(\frac{t-\tau}{a} \right) dt = CWT(\tau, a) ,$$

where $*$ denotes the complex conjugate and a is a scaling parameter.

Bispectral analysis

This method (Kim and Powers 1978) allows us to find the wave modes nonlinearly interacting by three waves processes.

The resonance conditions for these processes are:

$$\omega_1 + \omega_2 = \omega_3 , \quad \mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 ,$$

where ω_1 , ω_2 and ω_3 are the wave frequencies and \mathbf{k}_1 , \mathbf{k}_2 and \mathbf{k}_3 are the wave vectors of the interacting waves.

Verification of these conditions is possible by computing the bispectrum of the signal $x(t)$ which is defined by

$$B(k, l) = E \left[X_k X_l X_{k+l}^* \right] ,$$

where X is the FFT of $x(t)$, and X_k , X_l , and X_{k+l} are the spectral components at frequencies k , l and $k+l$, respectively. $E[\]$ denotes an averaging over the time interval.

A quantitative measure of the phase coherency may be made using the bicoherence spectrum which is defined in terms of the bispectrum as

$$b^2(k, l) = \lim_{T \rightarrow \infty} \lim \frac{1}{T} \frac{|B(k, l)|^2}{X_k X_l X_{k+l}} .$$

where T is time interval of analysis.

Observations

The data used in this paper originate from the STAFF instrument on board the CLUSTER satellites (Cornilleau-Wehrlin *et al.* 2003).

To study the wave processes in the polar cusp we use waveform of the magnetic field measurements recorded by this experiment, which can also provide spectra up to 4 kHz. The maximum measured frequency of the waveform is 12.5 Hz.

Two cases have been selected for further analysis, of Sept. 1 and Sept. 15, 2002. In both cases, CLUSTER was in the central cusp, which was identified by plasma measurements of instruments CIS and PEACE not shown here and the wave activity presented in Figs. 1 and 5. These figures show the overall spectrograms of the magnetic and electric components taken on September 1 and 15, 2002, by the 4 spacecrafts, respectively. The frequency range of these spectra is 10-4000 Hz. The spectra shown here were obtained by onboard processing. We use these spectrograms as the tool for selecting the time intervals of the most intense wave activity.

From the case of September 1, 2002, we choose the time interval 3:05–3:13 UT (Fig. 2). The further analysis is done for the satellite CLUSTER 3 data. Wavelet spectra show the strong enhancement of the wave intensity in the entire spectral range (0.1–12.5 Hz) at 3:11:24 UT. The duration of this event is about 80 s (Fig. 3). The wavelet analysis allows analyzing the different time resolutions at different frequencies. This leads to picture from which one can see the evolution of the observed event in the frequency domain. In this case, Fig. 3 shows that disturbance starts from the minimal registered frequency (0.15 Hz) at 3:10:58 UT (maximum of spectral density appears at the frequency ~ 0.2 Hz) and in the time interval of about 30 s the maximum of the spec-

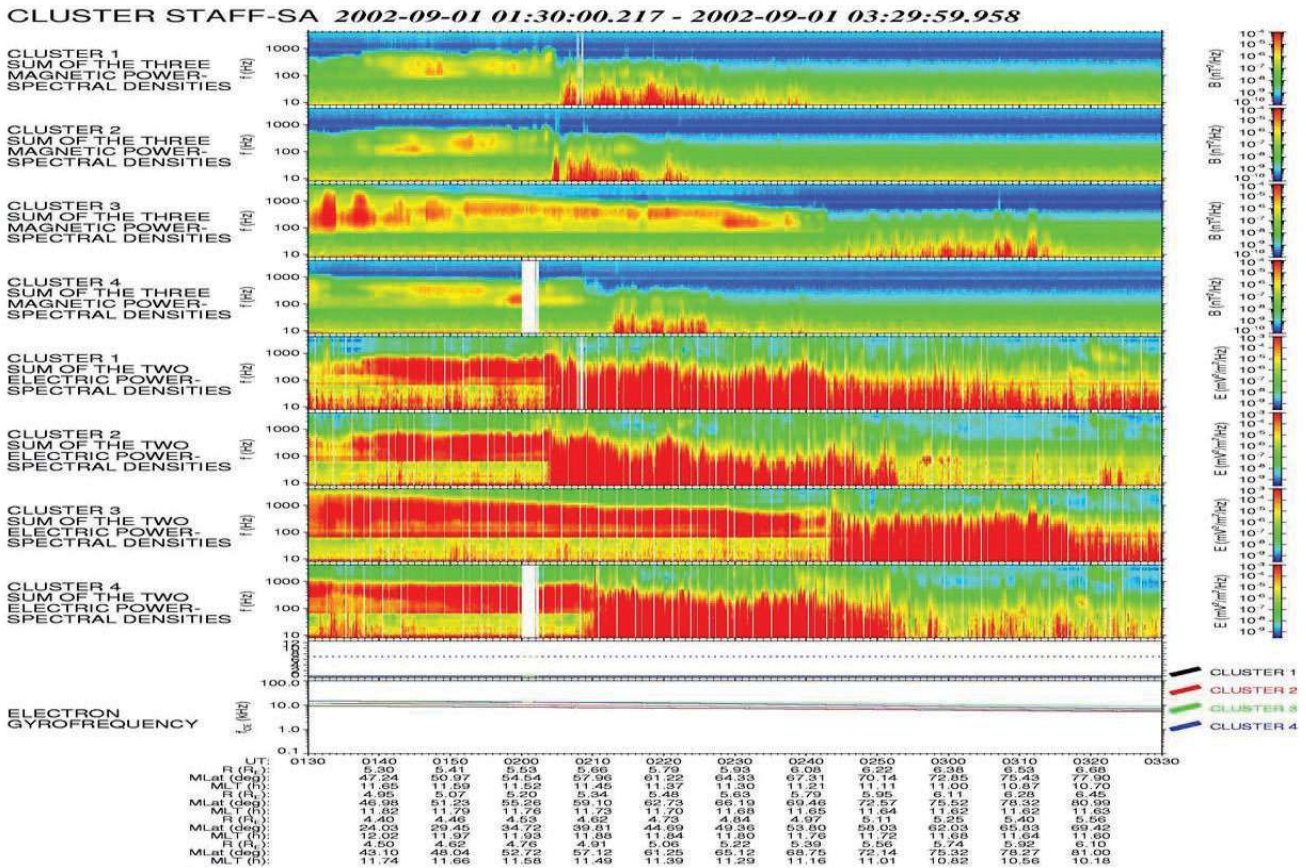


Fig. 1. Overall spectrogram of the magnetic and electric fields fluctuations in the frequency range 10-4000 Hz taken by the instruments STAFF installed on four CLUSTER satellites on September 1, 2002 in the time interval 01:30–03:30 UT. Four upper panels show the spectra of the magnetic field fluctuations, the next four the spectra of the electric field fluctuations. In the bottom part of the description, coordinates in the GSM system for 4 satellites are displayed. Cusp crossing is seen as a strong enhancement of the wave activity. Satellites CLUSTER 1, 2 and 4 are close to each other and crossing by them is seen almost at the same time. Satellite CLUSTER 3 is delayed and the cusp crossing by it is later.

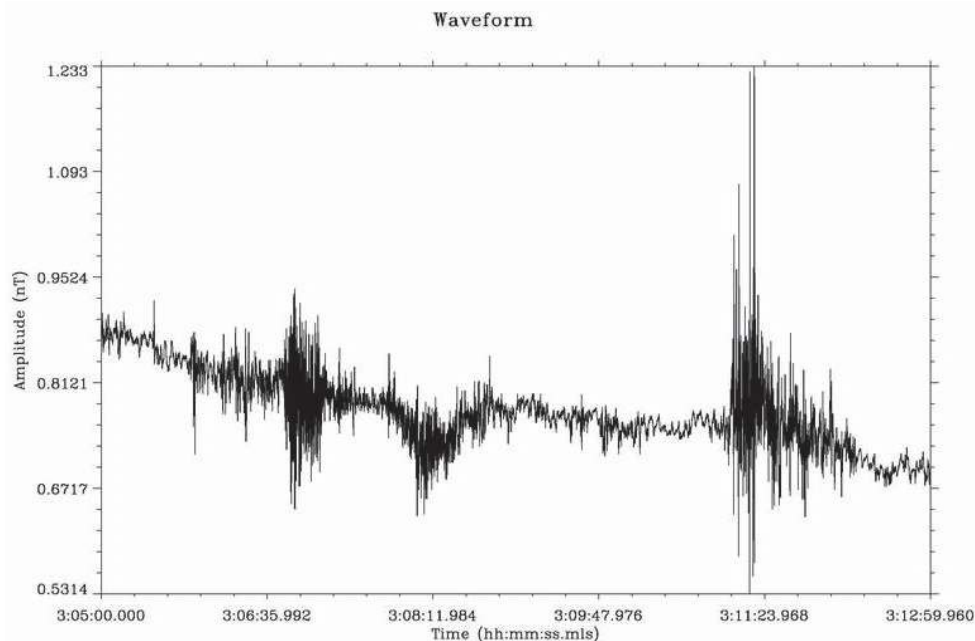


Fig. 2. Waveform of the magnetic field on 1 Sept. 2002 measured by STAFF instrument on CLUSTER 3 in the time interval 03:05–03:13 UT, when the strongest variations are registered.

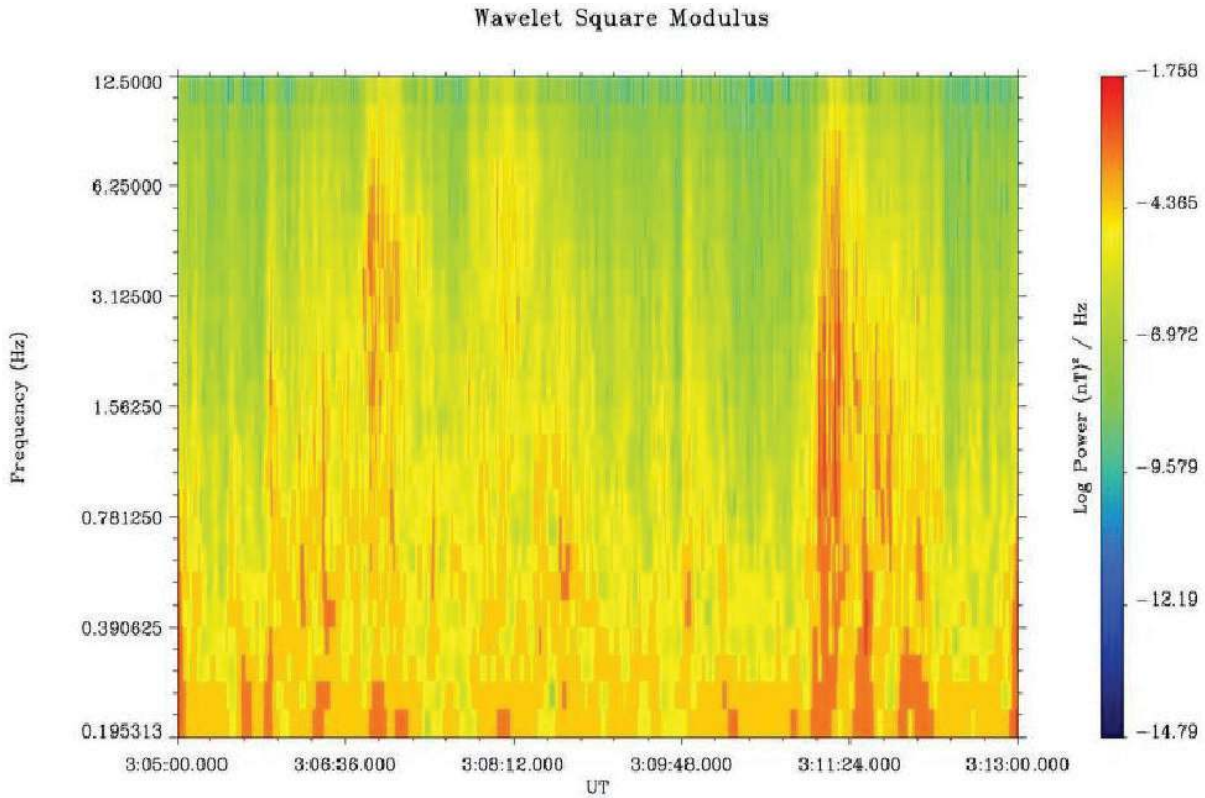


Fig. 3. Wavelet spectrogram of the magnetic field on 1 Sept. 2002 registered by STAFF instrument on CLUSTER 3. Frequency range is 0.2-12.5 Hz. Strong enhancement of the wave activity is seen at 3:11:24 UT. During 18 second drift of the frequency related to the maximum of the spectral density is seen from the lowest part of spectrum to higher one. It can be discussed as a cascade of energy.

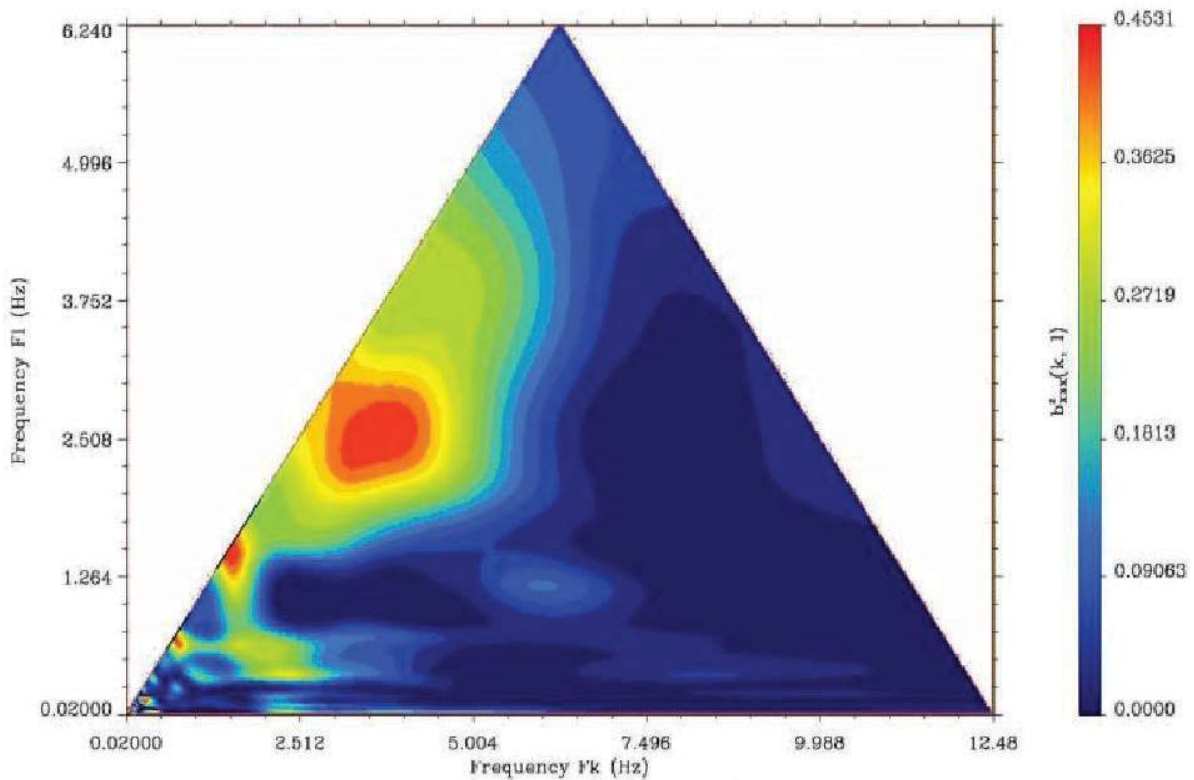


Fig. 4. The bicoherence of the magnetic field variations on 1 Sept. 2002 registered by STAFF instrument on CLUSTER 3 in the time interval 03:10:50–03:12:20 UT. The maxima of the bicoherence correspond to the frequencies of the waves interacting in the 3 waves processes.

tral density moved up to frequency ~ 3 Hz. The same process is also present in the time interval 3:06:07–3:06:42 UT. The duration of event around 30 s means that the satellite is in the same region of the cusp. The distance crossed in this time interval, of about 100 km, is small in comparison to the characteristic scale of the outer cusp and structures inside the cusp. This evolution of the spectra is likely to be associated with the cascade of energy between the modes, which is typical for the developing turbulence. The bispectral analysis gives us average information from the 90 s time interval. The bispectra presented in Fig. 4 are obtained from averaging over the time interval 3:10:50–3:12:20 UT. One can see in Fig. 4 the presence of the “islands” of the strongest three waves interactions. The frequencies of the interacting waves are: ~ 1.1 and 1.2 Hz, ~ 3 and 2.5 Hz, 3.0 and 6 Hz. Each of them represents interaction of two waves and the result of this nonlinear interaction is the wave with frequency being the sum of the frequencies of the interacting waves. Interactions of these waves lead to generation

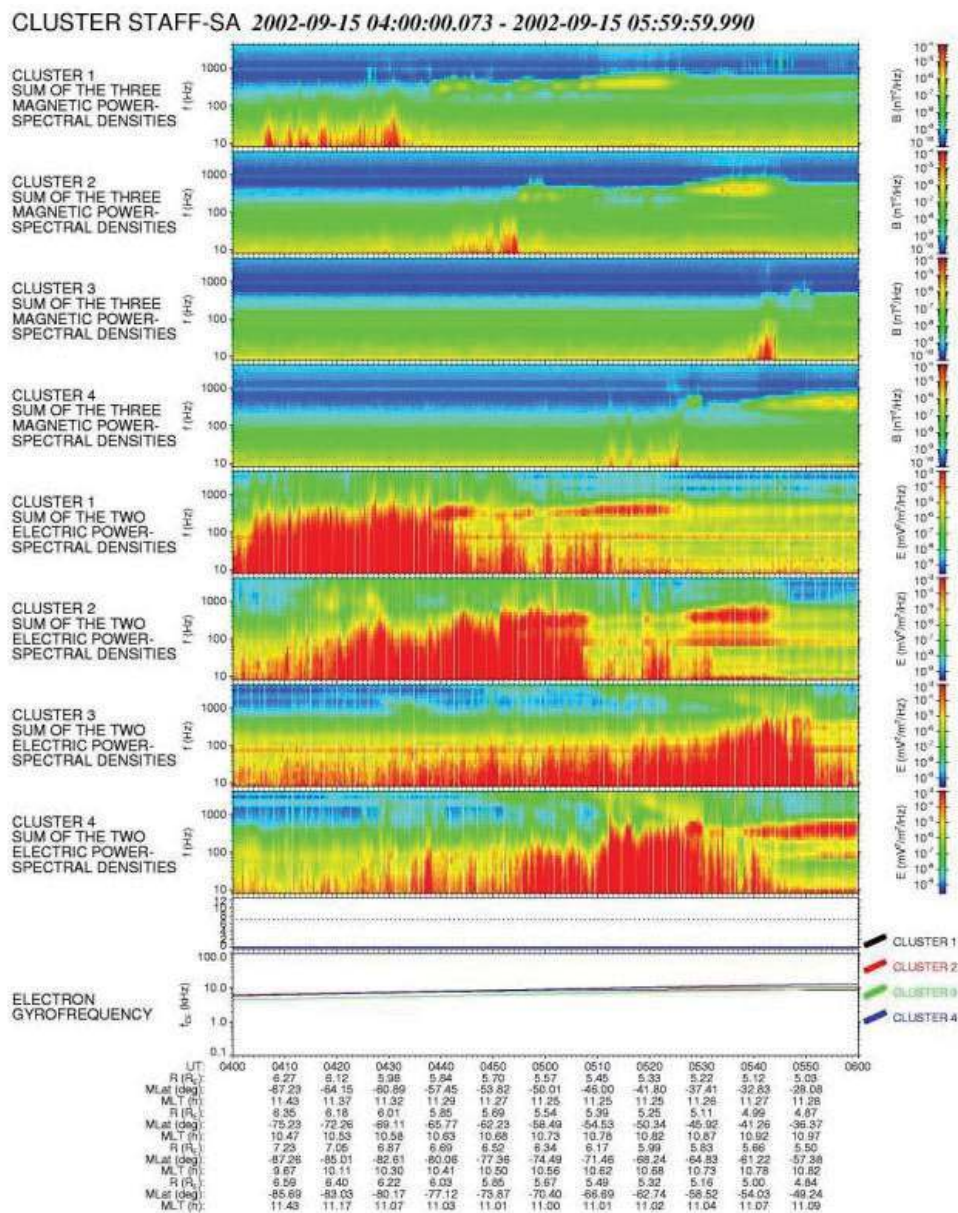


Fig. 5. The same as in Fig. 1, but for cusp crossing on 15 Sept. 2002 (in the time interval 04:00–06:00 UT) in the middle polar cusp.

of the broad band spectra seen in Fig. 3, but also confirm the picture given by the wavelet analysis showing the cascade of energy from low frequency to higher. All these frequencies lie below or close to the proton gyrofrequency and the observed process can be assumed as cascade of the Alfvén turbulence.

The second selected case of the turbulence observations in the polar cusp is of September 15, 2002. It is shown in Figs. 5-8. The big difference between the magnetic field variations registered on 4 spacecrafts is present in this case. The overall spectrogram (Fig. 5) allows choosing the interval of most intensive turbulence. It is seen on CLUSTER 2 around 4:50 UT. Figure 6 presents the waveform of the magnetic component for the selected time interval from CLUSTER 2 registrations.

Figure 7 shows the wavelet spectrogram for the time interval 4:48–4:56 UT. The constant maximum at frequency 0.5 Hz is associated with satellite rotation period of 2 s. The main intensification is present at 4:49:30 and 4:51:00–4:54:30 UT. The cascades can be distinguished in the wavelet spectra from 4:53:00 till 4:53:30 and 4:53:50 till 4:54:20 UT and in frequency band from 0.15 up to 3 Hz in the first case and from 0.15 up to 6 Hz in the second interval.

The bispectral analysis has been performed over both intervals, but the significant indicator for 3 waves interaction has been found only in the first one. Figure 8 shows the bispectral diagram obtained by averaging over the time interval 4:48:00–4:49:30 UT, which indicates strongest interactions at the frequencies 0.3, 1.3, 2.8 Hz and in the ranges 1.5-5.0 Hz and 5.0-10.0 Hz. The interactions of the waves in these particular ranges lead to broad band spectra, but also to the creation of the maxima of some particular frequencies (see Fig. 7). Also in this case, the discussed frequency domains correspond to the Alfvén turbulence.

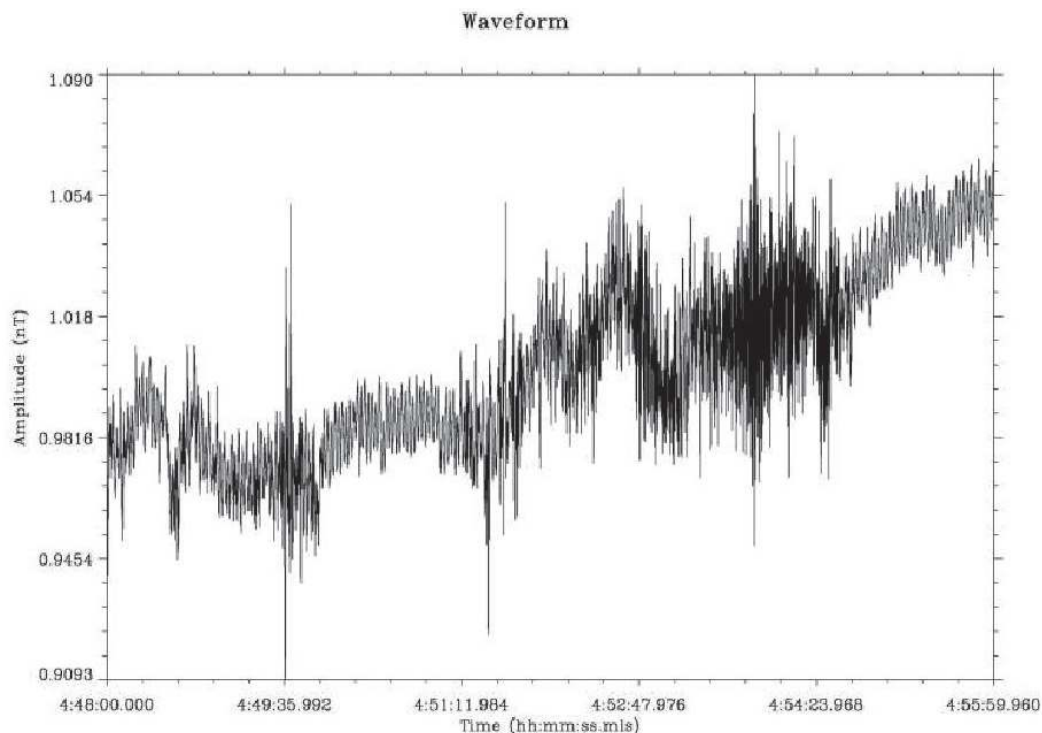


Fig. 6. Waveform of the magnetic field variations registered in the middle polar cusp by CLUSTER 2 on 15 Sept. 2002 (04:48-04:56 UT).

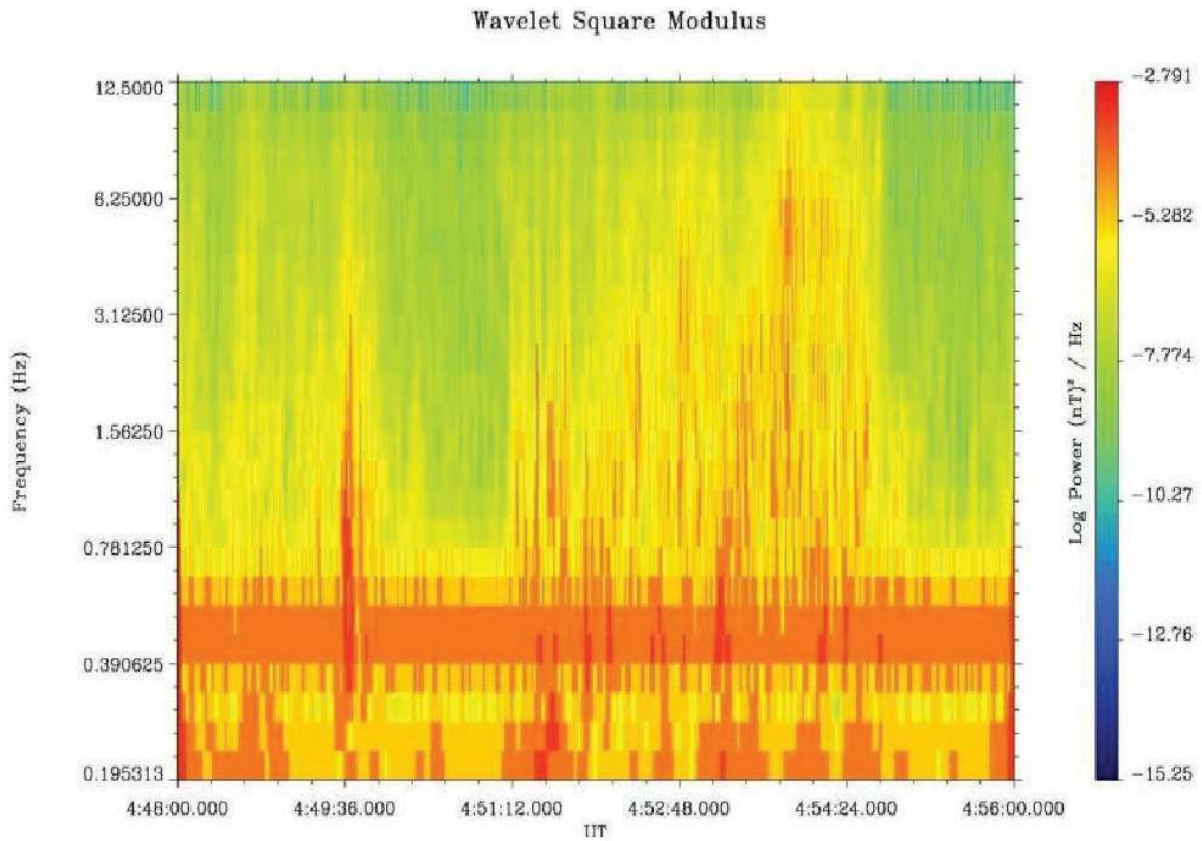


Fig. 7. Wavelet spectrogram of the magnetic field variations for time interval 04:48–04:56 UT on 15 Sept. 2002 CLUSTER 2. Frequency range is 0.2–12.5 Hz.

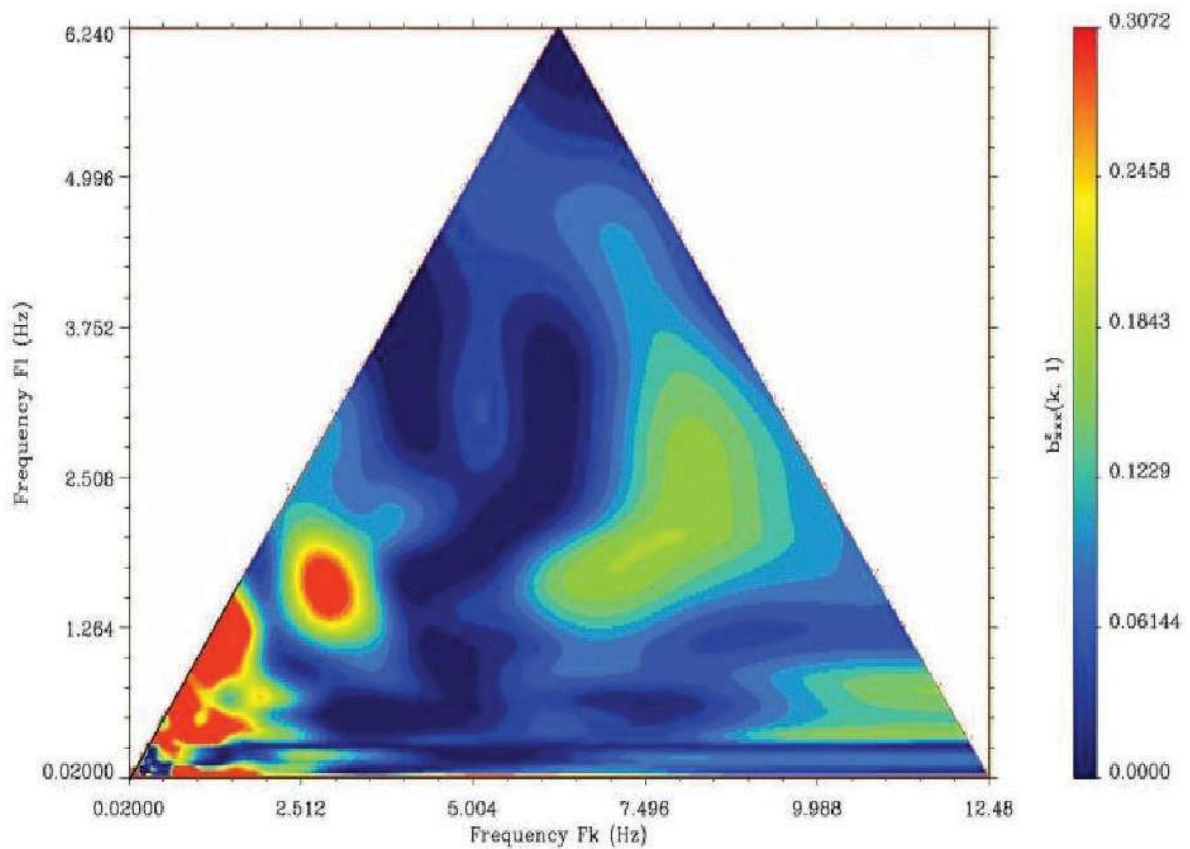


Fig. 8. The bicoherence of the magnetic field variations registered in the middle polar cusp by CLUSTER 2 on 15 Sept. 2002 from time interval 04:49:30–04:51:00 UT. Frequency range is 0.02–6.24 Hz.

3. CONCLUSIONS

The wavelet and bispectral analysis presented here show that nonlinear processes are present in the polar cusp plasma.

Three waves processes in the Alfvén range lead to redistribution of the energy and broadening the wave spectra. This process can be a good explanation of the observed feature in the polar cusp wave spectra. The turbulence which is one of the main characteristics of the polar cusp has broad band spectra with some maxima at particular frequencies. Both these features are the result of nonlinear interaction which can produce additional maxima in the frequency domain in the wave spectra. In the collision free polar cusp plasma, this turbulence is the main factor of the plasma dynamics.

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