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Evolution of the Ionospheric Plasma Turbulence over Seismic and Thunderstorm Areas

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Abstract: The authors report the observation of Extremely Low Frequency (ELF) plasma turbulence registered by DEMETER satellite in the ionosphere over the seismic and thunderstorm areas. The detail analysis of the electric field fluctuations for the selected strong earthquakes and thunderstorm is presented. Special attention is given to study of the characteristics of the spectra of these variations and searches of the nonlinear effects. This analysis is possible in the time interval when the waveform has been transmitted. Some attempt of this discussion is given in the paper.

Key words: Earthquakes, ionosphere, lightning, plasma turbulence, thunderstorms.

1. Introduction

The presence of the electromagnetic field disturbances before the earthquake is known since the end of 19th century, but the disturbances in the ionospheric plasma has been discovered only with satellite applications. The authors present in our paper disturbances registered by DEMETER satellite prior to the strong earthquakes and the authors try to find the relation between them and development of the turbulence in the ionospheric plasma.

Natural phenomena associated with strong electromagnetic emissions are thunderstorms, particularly sometimes occurred so called Transient Luminous Events (TLE's)-sprites, blue jets, halos and elves.

What is the turbulence? This question has no clear answer, but some essential features can be mentioned: many degrees of freedom (different scales), all of them in non-linear interaction (cross-scale couplings), creating cascade of energy from bigger sizes (lower frequencies) to smaller (higher frequencies). Main characterizations of the turbulence are related to the shape of the power spectrum and high order spectral analysis [1]. In authors' studies they use data gathered onboard of the DEMETER satellite. The short description of it is given in the next section.

Theory of the turbulence predicts the different slope of the spectra for the different types of the turbulence: noncompressible turbulence (K-1941) $k^{(5/3)-}$, noncompressible isotropic MHD (IK-1965) $k^{(3/2)-}$, noncompressible anisotropic MHD (SG-2000) k^{2-} and whistler turbulence (DB-1997) $k^{(7/3)-}$. The interaction between different spatial and temporal scales leads to transfer of the energy from bigger scales (spatial) to smaller ones. This process is called the turbulence cascade and authors will show the temporal development of this cascade in discussed phenomena. The spatial spectra characterized the type of the turbulence cannot be obtained from single satellite measurements, but they are directly related to the temporal variations described by spectra in the frequency domain. Further authors will present and discuss this type of turbulence characteristics.

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2. Experimental Results

2.1 Experiment Description

DEMETER is a low-altitude satellite launched in June 2004 onto a polar and circular orbit which measured disturbances of the electromagnetic field and plasma parameters. The altitude of the satellite orbit was 660 km. The orbit was Sun synchronized, it means that measurements were performed at almost constant local time in case of DEMETER around 10:15 and 22:15. Authors' attention is focused on the ELF (Extremely Low Frequency) range, which corresponds to range of the measurements of the electric field on DEMETER from DC up to 1,250 Hz. There are two modes of registrations: a survey mode where spectra of one electric and one magnetic component are onboard computed and a burst mode when, in addition to the onboard computed spectra, waveforms of one electric and one magnetic field component are recorded. The choice of the component is done by telecommand. The burst mode allows performing a spectral analysis with higher time and frequency resolution. Details of the wave experiment can be found in Refs. [2-4]. During the burst mode, the waveforms of the six components of the electromagnetic field are also recorded up to 1.25 kHz (sampling rate 2.5 kHz).

2.2 Wavelet Analysis

The traditional Fourier analysis is not relevant to studying the turbulence. The Fourier transform spreads information about the localized features over all scales making it impossible to study the evolution of different scale structures simultaneously. The important property of the wavelet transform is that the square of the wavelet coefficients can interprete as local energy and their statistics is easy to visualize and understand. The usefulness of wavelet analysis in studying the turbulence has been underlined by Farge [5] in the context of coherent structures. The main advantage of using the wavelet transform is that it preserves the information about local features (e.g. singularities) of the signal and allows reconstruction of the signal over a given range of scales. This property is of particular importance in studying turbulence, which often shows coherent structures apparently related to nonlinear processes. Applications of the wavelet analysis to study turbulence in the space plasma were discussed in Ref. [6]. The complex Morlet wavelet, which will be used in this paper is represented by Eqs. (1)-(2):

$$\psi(t) = \exp\left(i\omega_0 t - \frac{t^2}{2}\right) - \sqrt{2}\exp\left(i\omega_0 t - t^2 - \omega_0^2/4\right) \quad (1)$$

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

$$\int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-\tau}{a}\right) \mathrm{d}t = \mathrm{CWT}\,(\tau, a) \quad (2)$$

Where, *denotes the complex conjugate and "a" is a scaling parameter.

2.3 Bispectral Analysis

When authors discuss the development of the plasma turbulence and cascade of the energy in the spectrum, the first step in this cascade and the fundamental process which is involved is the 3-wave interaction. The resonance conditions for these processes are $\omega_1 + \omega_2 = \omega_3$, $k_1 + k_2 = k_3$, where ω_1, ω_2 and ω_3 are the wave frequencies and k_1, k_2 and k_3 are the wave vectors of the interacting waves. Verification of these conditions is possible using the so-called bispectral analysis. The bispectrum of the signal gives the information about phase coherence of these waves. Kim, Y. C. and Powers, E. J. [7] first proposed this method for the studies of the plasma processes. The bispectrum of the signal x (t) is defined by Eq. (3):

$$B(k,l) = E(X_k X_l X_{k+l}^*) \quad (3)$$

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 quantitive measure of the phase coherency may make using the bicoherencespectrum, which define in terms of the bispectrum as Eq. (4):

$$b^2(k,l) = \frac{1}{T}\frac{/B(k,l)/^2}{P(k)P(l)P(k+L0} \quad (4)$$

Where, T is time interval of analysis.

The computer procedures for applications of the methods of wavelet and bispectral analysis have been developing in the package SWAN [8]. Authors of this paper earlier to study the nonlinear processes in the magnetospheric cusp [9] have applied these methods of analysis.

2.4 Results of the Measurements

Fig. 1 gives the global picture of the wave energy integrated over the frequency range 19.5-600 Hz (ELF-range) for the morning local time and night local time. The information presented in Fig. 1 gathered within one month-December 2007. DEMETER satellite was switched off in the high latitudes and only occasionally, measurements were performed in the auroral zones and in the polar cusps. In Fig. 1, authors have this exceptional case of observations in the polar cusp (left panel) and auroral zone (right panel). Strong enhancement of the wave intensity is present in the both regions. The strong wave activity is present in the ionosphere over regions of South Africa, Indonesia and Australia and is likely associated with the thunderstorms.

2.4.1 ELF Turbulence over Seismic Events

In the present part, authors give the examples of the registration of the electric field variations in the ELF range in the areas around the epicentres prior to the earthquake. Selected events correspond to the clear situation, when the geomagnetic indices are very low and no other disturbances of the ionosphere coming from the outer space could expecte.

First example originates from the registration over the epicentre of Japanese earthquake, which was on October 23, 2004 at 8:59 UT. The magnitude was M = 6.7. Five days before the earthquake DEMETER registered enhancement of the wave intensity in ELF range during closest approach to the epicentre. Projection of the satellite position on the orbit on the ground was in the distance of 114 km to the epicentre. Fig. 2 gives the spectrogram of the 3 components of the electric field variations for 3 minutes of registration (12:28-12:31) when the wave form was taken. Horizontal axis is a time, vertical- frequency and color the intensity of the waves. The characteristic broad

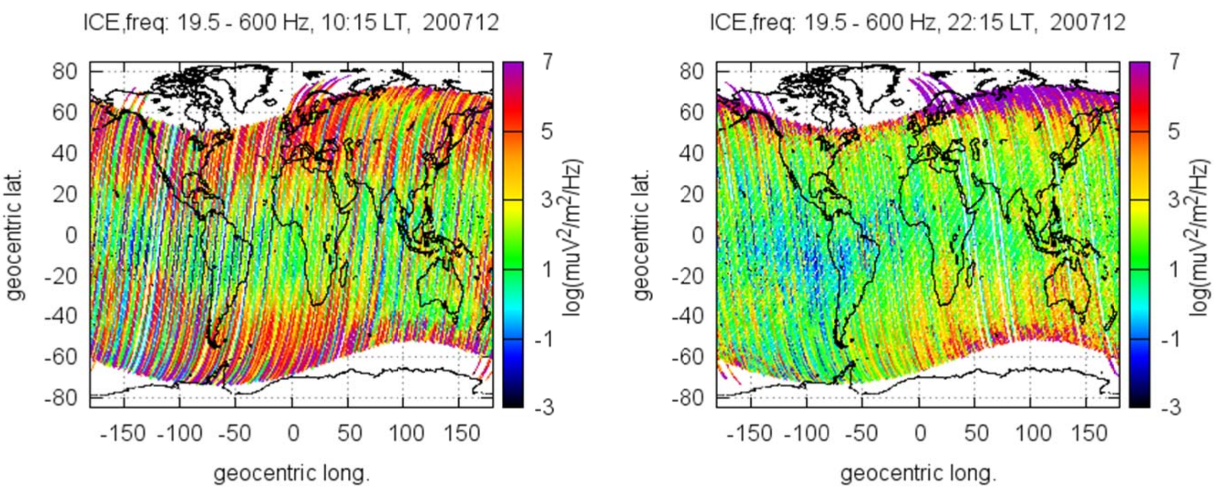

Fig. 1 The global picture of the wave energy integrated over the frequency range 19.5-600 Hz (ELF-range) for the morning local time (left panel) and night local time (right panel). The colour scale presents the strength of the turbulence measured as an integrated power of the waves. The strong enhancement of it is seen in the polar cusp, auroral zones in the ionospheric trough, but also some local activity over South Africa, Indonesia and Australia one can see.

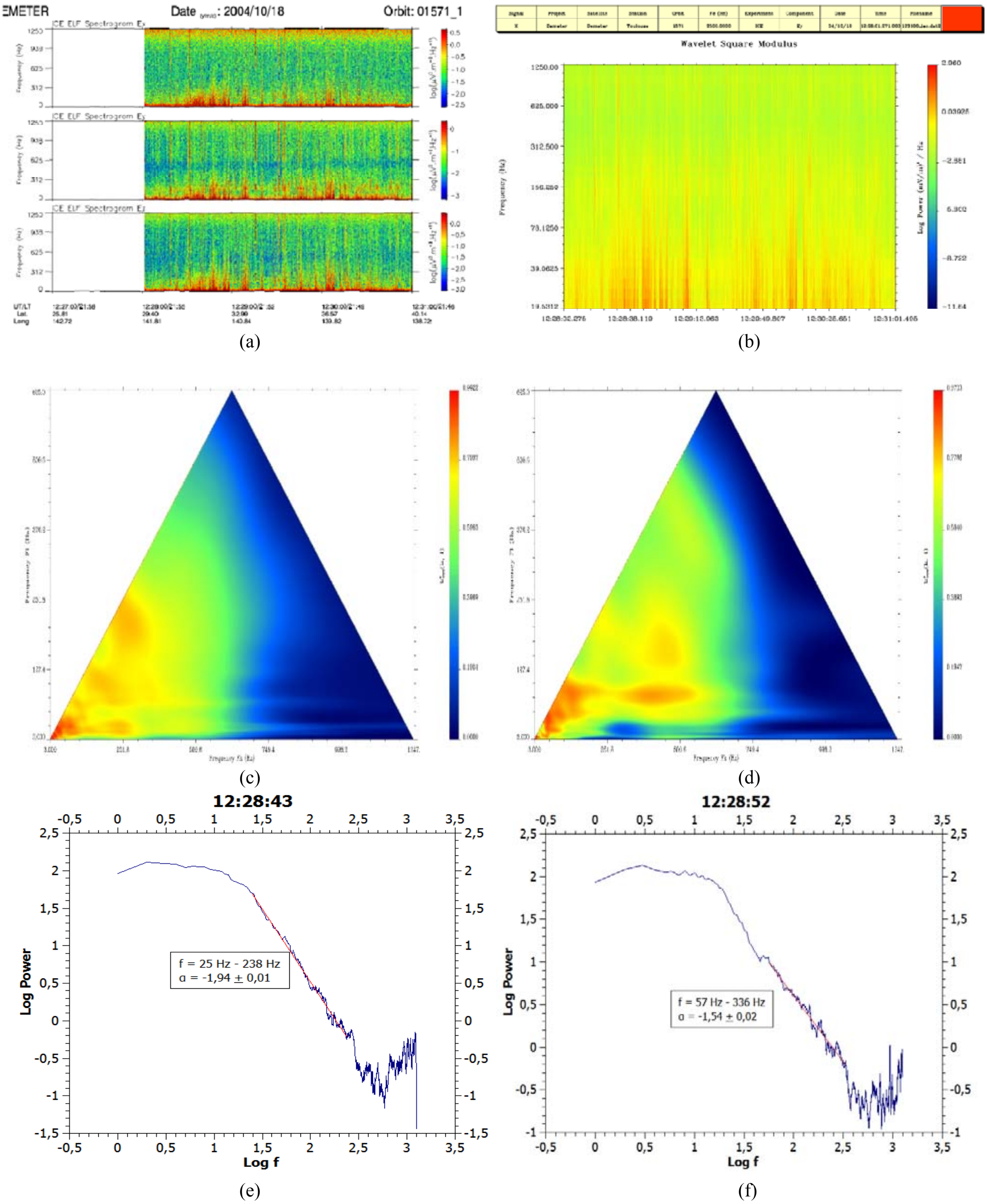

Fig. 2 The spectrogram of the 3 components of the electric field variations for 3 minutes of registration (12:28-12:31) when the wave form was taken registered 5 days before the earthquake in Japan (a). The variability of the spectrum is clearly seen in the wavelet spectrogram (b). The panels in the middle row represent the bicoherentspectra. The panel (c) shows the strong three waves' interactions in the lowest range of the frequency. This interval of interactions evolutes into higher frequency range as it is seen in the panel (d). Bottom panels show the single spectra with slopes-1.94 (e) and 1.54 (f). The earthquake took place on 23 October 2004 at 8:59 UT.

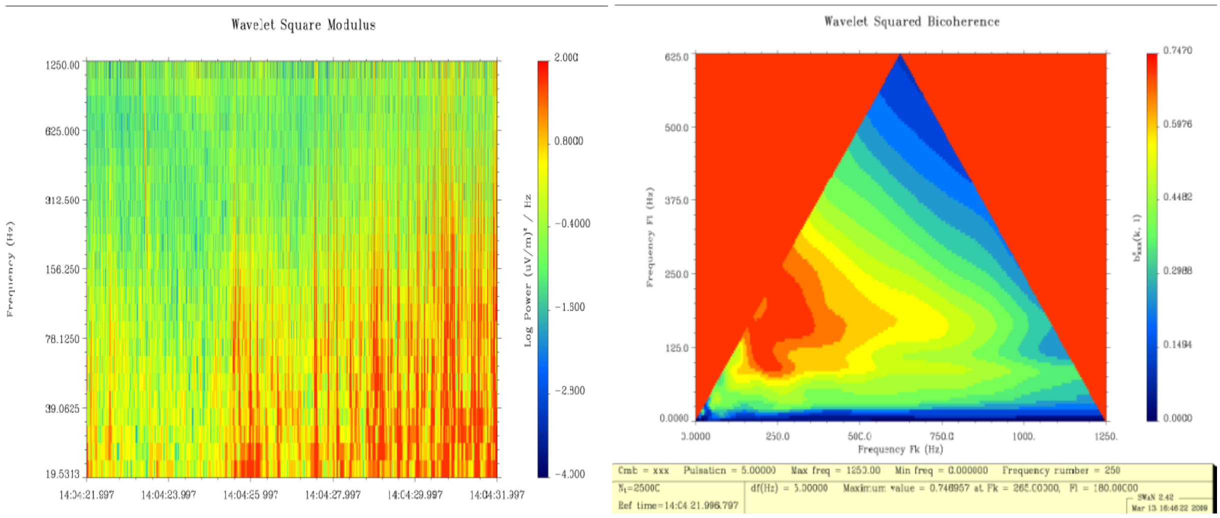

Fig. 3 The bispectrum and wavelet spectrogram of the electric field variations registered one day to the Ping Tong earthquake (see text for details).

band emissions in the frequency range 0-320 Hz were seen. The irregular character of these spectra—strong variability in timeseen in the wavelet spectrogram (upper, right panel)—can be interpreted as one of the features of the turbulence called intermittency. Bicoherentspectra in the middle row show the evolution of the 3 waves interactions regions from very low frequency (left panel) to higher frequency (right panel). This evolution corresponds to the fundamental process in the turbulence development called *cascade.* The bottom panels in Fig. 2 present the single spectra with shown slope 1.94 (left panel) with value close to the characteristic of the noncompressible, anisotropic MHD turbulence and 1.54 related to noncompressible isotropic MHD. It means that during 9 seconds time the character of the turbulence changed, probably due to isotropisation caused by evolution of the turbulence.

The second example presented in Fig. 3 is associated with the earthquake close to Ping Tong in Taiwan region. The magnitude M = 7.1, main shock occurred on December 26, 2006 at 12:26 UT. This figure presents the wavelet spectra and corresponding bispectra of the electric field variations in the ELF range during flight of DEMETER over the earthquake region one day before the main shock. The distance between epicentre and projection of the satellite position was 350 km. The wavelet spectra indicate strong variability in time, but also evolution of the position in the frequency of the maximum of the intensity from lower to higher frequency (from 30 Hz up to 300 Hz). The bispectrum shown in left panel of Fig. 3 gives the information on the intensive interaction between waves with frequency around 100 Hz and 200 Hz, the value of the bispectrum in this frequency range attains so high level as 0.75 what is indicator of strong 3 wave's process being fundamental process in the development of the weak turbulence. All these facts are signature of the existence of the energy cascade in discussed frequency range. With one satellite (single point measurements) authors can say nothing more about development of the turbulence.

The last event presented in Fig. 4 was registered 9 days before the earthquake on February 27, 2010 in Chile. The results presented here have been obtaining when DEMETER was about 600 km from the epicentre in the horizontal direction.

The upper left panel of Fig. 4 shows the Fourier spectrogram of the electric field variations. The right panel shows the wavelet spectrogram for the interval when strongest variations were seen. These emissions appear in the lowest part of the frequency band (below 150 Hz). Middle panels contain the information on

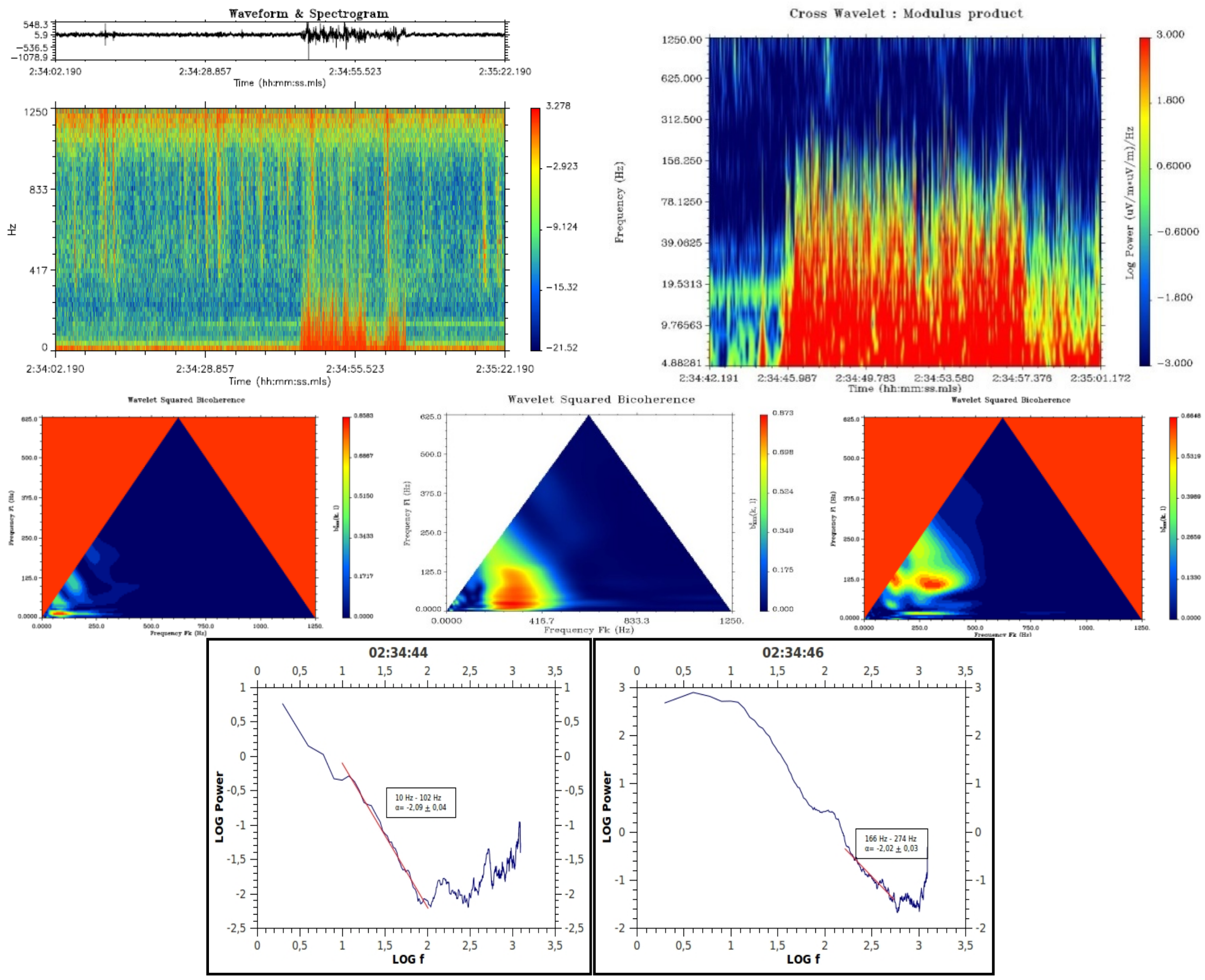

Fig. 4 The example of the ionospheric turbulence registered by DEMETER satellite before Chile earthquake (see text for details).

three waves' interaction process and one can see the area of the frequency corresponding to the strongest interactions where this process is most effective. The three figures represent 3 bispectra from 3 one second intervals of measurements shifted by 0.5 secondone to another. One can see the evolution of the range of the wave-wave interactions from the lowest frequency to higher. This is related to the turbulent cascade. The lowest panels give the shape of the spectra for the time interval corresponding to the previous panels and the slope of it is close to two, what is characteristic for magnetohydrodynamic (mhd) type of the turbulence.

More events related to the turbulence in the ionospheric plasma over seismic regions registered by DEMETER can be found in Refs. [10-12].

2.4.2 ELF Turbulence over Thunderstorms

The thunderstorms belong to the most powerful natural phenomena. The power of single lightning can be over 10^{11} Watts. A lightning in fact is a strong electric current and it can be treated as a huge antenna system from which electromagnetic waves of all frequencies are radiated. Transients' electric currents during lightning are the main sources for the generation of impulse-type electromagnetic radiation known as sferics (atmospherics). These waves propagating in the ionospheric and magnetospheric plasma along the geomagnetic lines indicate that dispersion with higher frequency waves propagate faster than lower ones and they are in acoustic range so receivers can register them as a falling tone remaining whistler. The ionospheric and magnetospheric Very Low Frequency (VLF) plasma whistler waves have been known since the 1950s and 1960s. Smith and Brice reported first satellite registration in 1964 [13]. The nova day with ground base registration of whistlers in VLF/ELF ranges are reviewed in Ref. [14]. DEMETER satellite registered many of these kind emissions [15].

Another even more energetic events associated with thunderstorm activity are so called Transient Luminous Events (TLE)—sprites, blue jets, gigantic jets, halos and other appearance in the upper atmosphere 40 km-100 km discovered in 1989 [16]. They are also the source of the strong electromagnetic emissions registered both on ground [17] and in space [18].

Further, the one event registered by DEMETER satellite over area of strong thunderstorm is presented. This event has been selected for discussion, because strong electromagnetic emissions registered during it lead to nonlinear interaction between two types of waves electron and ion whistler.The ion whistlers can be registered only onboard of the satellite. First report about it was given in 1965 by Garnet, D. A., at al. [19].

On October 8, 2009, strong thunderstorm was active over Castres in southern France. DEMETER flew in the distance of 50 km away from the centre of the thunderstorm activity in the horizontal direction on 21:06 UT. But strongest emissions were registered 21:05:10 and 21:06:10. Fig. 5 shows an overall wave form and spectrogram of ELF electric field variations recorded by DEMETER during the flight over the thunderstorm. The frequency range is from 19 Hz up to 1,250 Hz, and the power spectral density is color-coded according to the scale on the right. Sferics and whistlers are clearly seen during entire time of registration over the thunderstorm area. Fig. 6 contains 2-second interval of the waveform (upper part of the graph) and the corresponding two second spectrogram of the field variations in the right panel. The waveform at around 21:05:39 indicates strong negative jump related to strong (150 kA) negative stroke. In the spectrogram broad, band reactions were seen. Immediately after that, electron whistler is developed and lasts about half a second. When the

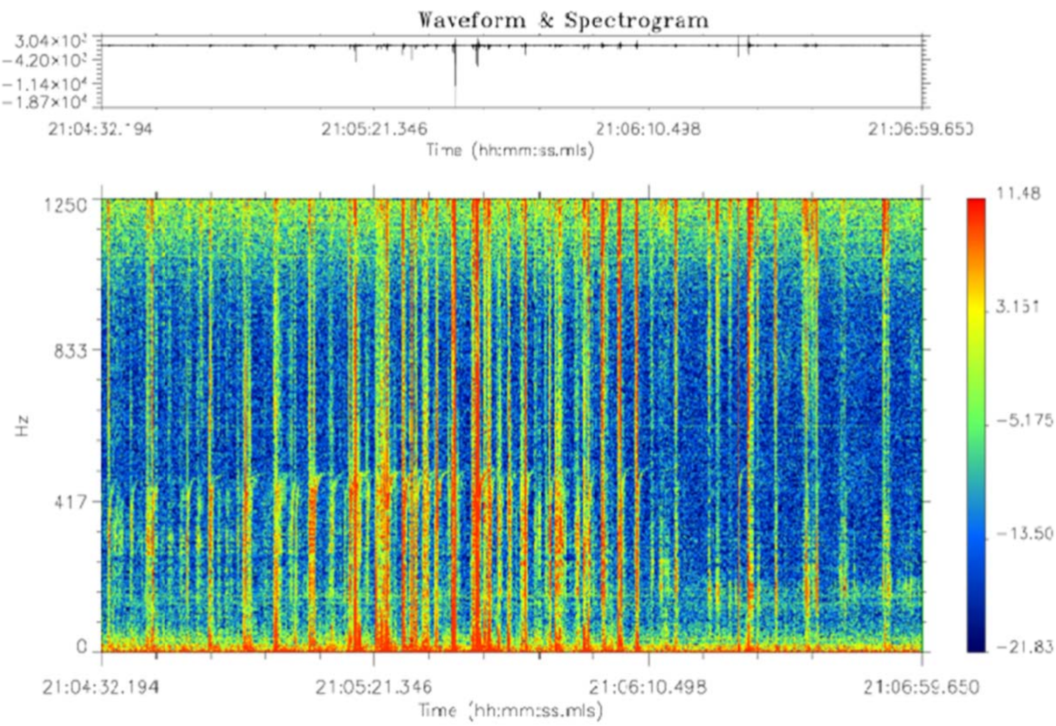

Fig. 5 Theoverall waves form and corresponding spectrogram of the electric field variation registered over thunderstorm in the vicinity of Castres.

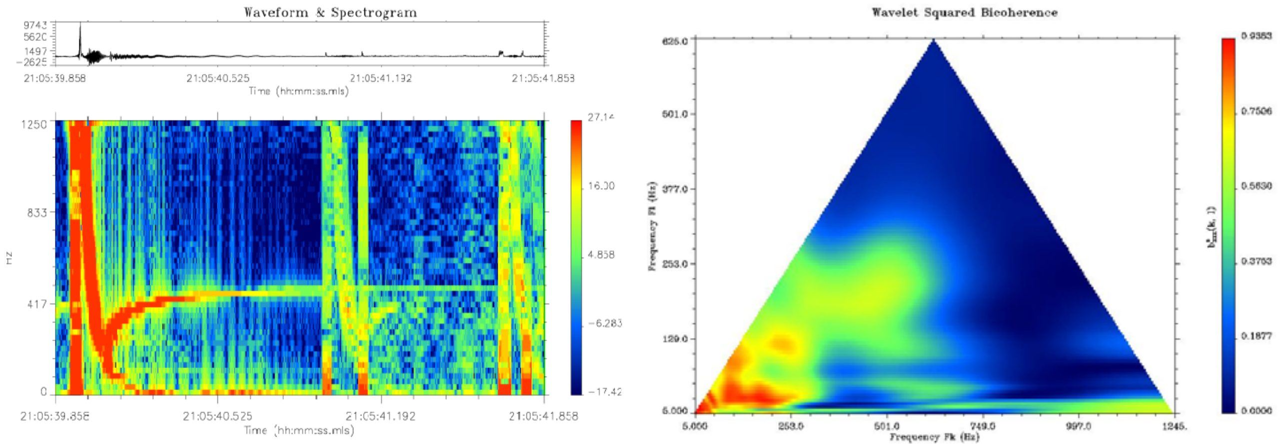

Fig. 6 The wave form and corresponding spectrogram of the electric field variations (left panel) registered by DEMETER satellite over thundrstorm area and bicoherence (right panel) for these event. Details in the text.

frequency reaches the value close but below the ion gyrofrequency, ion cyclotron whistler starts to develop. The right panel of Fig. 6 presents the bicoherence function calculated from measurements in interval for which spectrogram is shown in left panel of the same figure. As Figs. 2-4, the horizontal and vertical axis represent the frequency of interacting waves, the colour scale represents the value of the bicoherence. When this value is higher than 0.5, we assume that three waves' interactions occurs. As one can see the value of the bicoherence exceeds the critical value in many frequency bands. The strongest interactions occur in the lowest frequency range, but also we see strong interaction ($b \approx 0.8$) for frequencies 250 Hz and 60 Hz, what is related to ion whistler's interactions. Weaker ($b \approx 0.65$), but also enough strong interactions are seen between waves with frequence of about 250 Hz and frequence of about 500 Hz. This shift in frequency of interacting waves again indicates the presence of the cascade of energy from bigger spatial scales (lower frequency) to smaller (higher frequency). This process is fundamental in development of the turbulence [1].

3. Conclusion

The plasma turbulence is a common feature of the ionospheric plasma. It occurs in the equatorial anomaly region, in the ionospheric through, in the auroral oval. It is present constantly in mentioned regions, but it is present also over the seismic and thunderstorm areas. In the present paper the electromagnetic effects observed by DEMETER satellite have been shortly discussed and are prior to the strong earthquakes in Japan, Taiwan and Chile and over strong thunderstorm in the vicinity of Castres in southern France. The analysis of the wave form in ELF frequency range with Fourier, wavelet and bispectral methods has shown the presence of the strong emissions in this frequency range in the ionosphere several days before the earthquake and during thunderstorm. The discussed results were obtained during very quiet time and therefore no ionospheric and magnetospheric sources of perturbations were expected. However, these turbulence behaviours are not specifically related to the occurrence of earthquakes and can be met in other regions of the ionosphere particularly at equatorial and high latitudes. But the closest occurrence in space and in time suggests that the observed effects at mid-latitudes are related to a perturbation of the ionosphere which could be associated with the preparation of the discussed earthquakes and also indicate the influence of the thunderstorm on the ionospheric plasma. Presented examples show the presence of the variation of the electric field in ELF range indicating the features of the turbulence. Authors can say that effect is present few days prior to the earthquake, but the very similar variations can be observed in the ionosphere not associated with the earthquake. In the case of disturbed magnetosphere, it will be very difficult to distinguish the disturbances originated from the earthquake from the other. Authors can conclude that only complex measurements, not only plasma, can give in the future positive method of forecasting of the earthquakes. Nevertheless, electromagnetic effects associated with the plasma turbulence in the ionosphere can be one of significant indicators. Comparison of the global distribution of the lightnings and TLE [20] with the global maps of the ELF turbulence presented in Fig. 1 shows the direct connection between these phenomena.

Acknowledgements

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