ARCHIVES OF MECHANICS
Arch. Mech. **76** (3), 277–290, 2024, DOI: 10.24423/aom.4492

The nonlinear effects in the ionospheric plasma generated by strong thunderstorms seen by DEMETER satellite

J. BŁĘCKI*), R. WRONOWSKI, P. JUJECZKO

Space Research Centre PAS, 00-716 Warsaw, Bartycka 18a, Poland,
*e-mail**)*: jblecki@cbk.waw.pl (corresponding author)*

The terrestrial ionosphere is mainly a plasma region which is very sensitive to different disturbances. A wide range of plasma instabilities can develop in this region, which are often nonlinear processes and leading to the development of plasma turbulence. Turbulence plays a crucial role in the dynamics of the space plasma processes. The turbulence appears when some physical parameter exceeds a certain level. It can have place during strong thunderstorms. The ionosphere is sometimes treated as plasma physics laboratory with unique possibility to study fundamental plasma processes. The use of ionospheric satellite gives the chance to perform insitu measurements of plasma parameters during dynamic processes.

For our analysis we used a set of selected data of the electric and magnetic fields variations in ELF (Extra Low Frequency 10–1250 Hz) and VLF (Very Low Frequency 100–20000 Hz) ranges originated from the French microsatellite DEMETER which was operating on the circular orbit with inclination of about 80° at altitude of 660 km from July 2004 until December 2010.

The Fourier, wavelet and bispectral analyses of these signals are given in this paper. Three wave processes have been identified during few very strong strokes. In some cases the nonlinear interactions of whistlers with the VLF signals of ground based transmitters have been registered. The character of spectra suggests the presence of Richardson's cascade. Our conclusion is that in few cases these results are related to whistler turbulence.

Key words: ionosphere, thunderstorms, nonlinear interactions, turbulence.

1. Introduction

The whistlers are cold plasma waves in the frequency range from the ion cyclotron up to the electron plasma frequency or electron cyclotron frequency. These waves are common in the space around the Earth and may be registered in the ionosphere and the magnetosphere by the satellite on-board receivers and by the ground-based systems.

The characteristic shape of the whistler spectrum, with falling frequency in time, is a result of its dispersion feature and propagation. The group velocity is greater for waves with higher frequencies than for lower ones. The whistlers propagate along magnetic field lines from the site of the thunderstorm. The arrival of the lower frequency waves is delayed in relation to a higher frequency. This characteristic type of waves occur in the VLF frequency range, which corresponds to the acoustic range. After transformation the electromagnetic signal into audio whistlers occur as declining tones. They were discovered during the First World War by a German radio operator who was trying to eavesdrop British radio transmissions. These waves are very common in the space around Earth, and may be registered in the ionosphere and the magnetosphere by the satellite onboard receivers as well as by the ground-based systems. The characteristic shape of the whistler spectrum with falling frequency in time is a result of its dispersion feature and propagation. Figure 1 gives the example of the whistler spectrogram registered by DEMETER satellite.

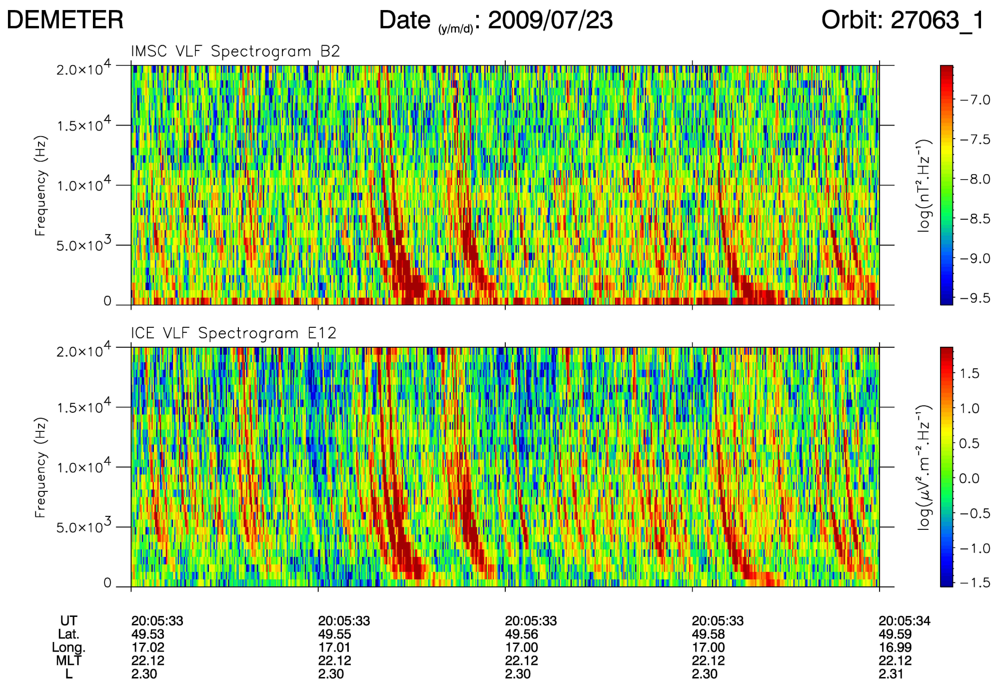

Fig. 1. Example of spectrograms of whistlers registered by DEMETER satellite. Horizontal line represents time, vertical frequency. Upper panel gives spectrogram of magnetic field lower electric field variations.

The terrestrial ionosphere is mainly a plasma region which is very unstable medium. A wide range of plasma instabilities exist in various regions of the terrestrial ionosphere, which are often nonlinear processes and leading to the development of plasma turbulence. Turbulence is one of the most universal events phenomena in nature. It appears in the Earth's atmosphere, in the oceanic flows and in many technical problems as well as in the studies of the plasma environment of the Earth and other planets. It plays a crucial role in the dynamics of the astrophysical processes, among others in the processes taking place on the Sun. Nevertheless, the time-varying, structured, burst and highly nonlinear nature of turbulence makes the analysis very complex and many aspects are poorly understood. Indeed, some aspects which appear universal in both neutral fluid and plasma turbulence, such as intermittency, remain enigmatic after decades of study. The turbulence appears when a physical parameter exceeds a certain level. The onset of turbulence may be gradual or it may occur with explosive suddenness; it may occur with relative spatial homogeneity or in local and periodic bursts. These different characteristics reveal compliance with different non-linear causative factors underlying the appearance of turbulence. One suspects, and this is confirmed in many cases, that the origins of turbulence lie in latent instabilities that are called into play at appropriate levels of excitation. Since there are numerous types of instabilities, both microscopic and macroscopic, it is to be anticipated that there will be different types of turbulence. Another distinctive feature, also traceable to the nature of the underlying instabilities, is associated with the relative suddenness of the transition to turbulence; if it occurs gradually the turbulent excitation process is said to be "soft", whereas if it develops discontinuously it is "hard". In spite of its universality it is difficult to describe it and understand turbulence. Even a clear definition of turbulence does not exist neither in the case of fluid mechanics nor the dynamics of plasmas. Description of the plasma behaviour is much more difficult than the description of a neutral medium. Apart from variation of parameters such as density, temperature and velocity, the electric and magnetic fields and the current density change in time.

Our analysis is related to the special range of nonlinear interactions which are an immanent feature of turbulent processes – three wave interactions being the first step in developing of the turbulence. We analyse very strong electromagnetic signals in ELF/VLF range registered by DEMETER in the ionospheric plasma generated by extremely powerful thunderstorm strokes.

2. Methodology

DEMETER satellite

Our goal is to discuss registrations, originating from the French microsatellite DEMETER, of wave processes gathered in the ionosphere related to the strong thunderstorms. DEMETER operated on the circular orbit with inclination of about 80° at altitude of 660 km from July 2004 until December 2010. The scientific payload of Demeter consists of: ICE − Instrument for electric field variation measurements ULF/ELF/VLF (ULF = Ultra Low Frequency up to 10 Hz) range from DC (constant field) up to 20 kHz, high frequency analyser measures these variations up to 4 MHz, IDP (ion spectrometer) ion density: $5 \cdot 10^2$–$5 \cdot 10^6/\text{cm}^3$ and ion temperature: 1000–5000 K, ISL (Langmuir probe) electron density: 10^2–$5 \cdot 10^6/\text{cm}^3$ and electron temperature: 500–3000 K, IAP (spectrometer for high energy electrons) energetic electrons 30 keV–10 MeV, IDP ion composition H^+, He^+, O^+, NO^+, IMSC magnetic field measurements from DC up to 20 kHz.

There were two modes of operation: a survey mode where spectra of one electric and magnetic component are computed onboard up to 20 kHz and a burst mode where waveforms of electric and magnetic fields are recorded up to 20 kHz [1, 2].

The main goal of this satellite was the search for the possible ionospheric effects prior to the earthquakes, but because of its orbit and the instrumentation used, the collected experimental material has a fundamental value for the studies of the plasma processes, among others plasma turbulence, plasma instabilities and nonlinear interactions.

Wavelet analysis

The traditional Fourier analysis is not relevant for turbulence study. 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 be interpreted as local energy and their statistics is easy to visualize and understand.

The usefulness of the wavelet analysis in turbulence studies has been underlined by Farge [3] in the context of coherent structures. Main advantage of using the wavelet transform is that it preserves the information about local features (e.g. singularities) of the signal and allows signal reconstruction 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 by [4, 5]. A more detailed description of methods used for the analysis can be found in [6, 7].

Bispectral analysis

When we discuss the development of plasma turbulence and cascading of the energy in the spectrum, the first step leading to this cascade, and the fundamental process which is involved, is the 3-wave interaction. Resonance conditions for these processes are: $\omega_1 + \omega_2 = \omega_3$, $\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3$, where ω_1, ω_2 and ω_3 are wave frequencies and $\mathbf{k}_1$, $\mathbf{k}_2$ and $\mathbf{k}_3$ are wave vectors of interacting waves. Verification of these conditions is possible using the so called bispectral analysis. This method for the studies of the plasma processes was first proposed by [8]. It allows to find the nonlinearly interacting wave modes by computing the bispectrum of the signal which gives the information about phase coherence of these waves.

The computer procedures for applications of wavelet and bispectral analysis methods have been developed in the SWAN package [9]. These methods of analysis have been applied by authors of this paper earlier to study the nonlinear processes in the magnetospheric cusp [6]. We try to find a set of parameters which can characterize turbulence in the ionosphere. Very important results related to the turbulence have been obtained with DEMETER registrations in the ionosphere over seismic areas [10]. Earlier works show that turbulence in the ionosphere is present before earthquake, even few days, but how to distinguish it from other turbulence is not clear.

Power spectral density analysis

Power spectral density (PSD) describes how the power of the signal is distributed along frequencies. It takes the Fourier-transformed signal defined as

$$\hat{\chi}(f) = \int_{-\infty}^{\infty} e^{-i2\pi f t} x(t)\, dt,$$

where $x(t)$ is the input signal, f is the frequency and t is the time. Then, the power spectral density is $\mathrm{PSD}(f) = |\hat{x}(f)|^2$. For a discrete signal, the corresponding equation is

$$\mathrm{PSD}(f) = 1/T\,\Delta t^2 \Big[\sum_{n=-N}^{n} x_n e^{-i2\pi f n \Delta t}\Big]^2,$$

where T is the duration of the sample, Δt is the time step and x_n is the sampled signal. The selection of sampling limits is done manually with the use of a rectangular window (signal trimming). For the VLF data of DEMETER, sampling frequency is $1/\Delta t = 40\,000$ Hz. By measuring the slope of the PSD in the region of interest (the Richardson cascade) one is able to fit a function in a form $y(f) = Cf^{\alpha}$, where C is a constant and the steepness factor α describes the turbulent process. The fitting procedure is done with the Matlab *fit* function. The spectrum is smoothed using an averaging, rectangular filter to get rid of ripples.

3. Results

Two different phenomena of three waves interactions are presented in this section. One is related to interaction between waves being a product of the thunderstorm stroke and other is related to interaction of waves generated by a thunderstorm with waves from VLF transmitter. Two cases of the nonlinear interactions are related to registrations of DEMETER satellite taken over the African thunderstorm centre another three over Southern France.

3.1. African thunderstorm centre

Among the top 500 places with the highest lightning frequency Africa is represented by 283, followed by Asia with 87, South America with 67, North America with 53, and Oceania with 10. It indicates that Central Africa is the most intensive thunderstorm site. Figure 2 shows the distribution of the total number of lightnings in the period 1998–2013 registered by the NASA Lightning Imaging sensor.

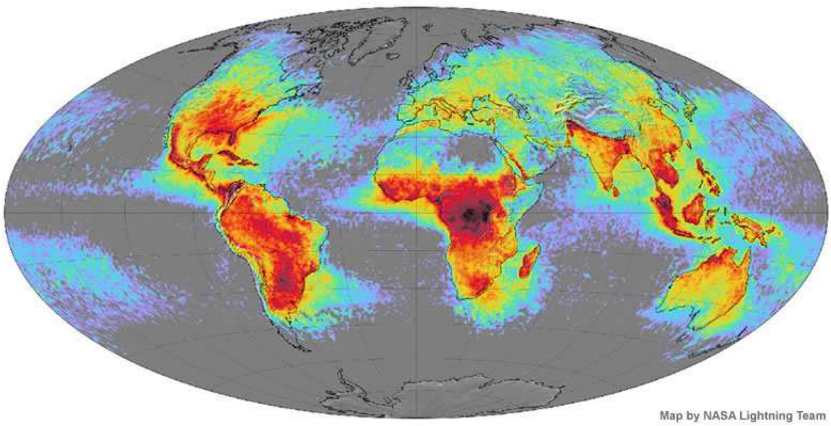

Fig. 2. Global lightning strokes from January 1998 to February 2013 from the NASA/MSFC Lightning Imaging Sensor on the Tropical Rainfall Measuring Mission satellite.

DEMETER satellite flew by over this centre many times, but we selected two very representative cases of registration strong disturbances in the ionosphere. First was on January 06, 2008, morning.

Figure 3 presents the wave form of an electric field (upper left panel), the spectrogram – intensity versus time and frequency in the VLF range (bottom left panel), the single Fourier spectrum of a signal taken for the most intensive variations (upper right panel) and the bispectrum for the same moment (bottom right panel).

Fourier's spectrum has two different slops in different frequency ranges. For 900–2200 Hz it is equal around 2, for 4000–6500 Hz about 1.95 for 7000–11000 Hz about 8.4. The bispectrum has not very high value, maximum is around 0.3, but it clearly indicates nonlinear 3 wave interactions in a wide frequency band from 6 kHz till 20 kHz.

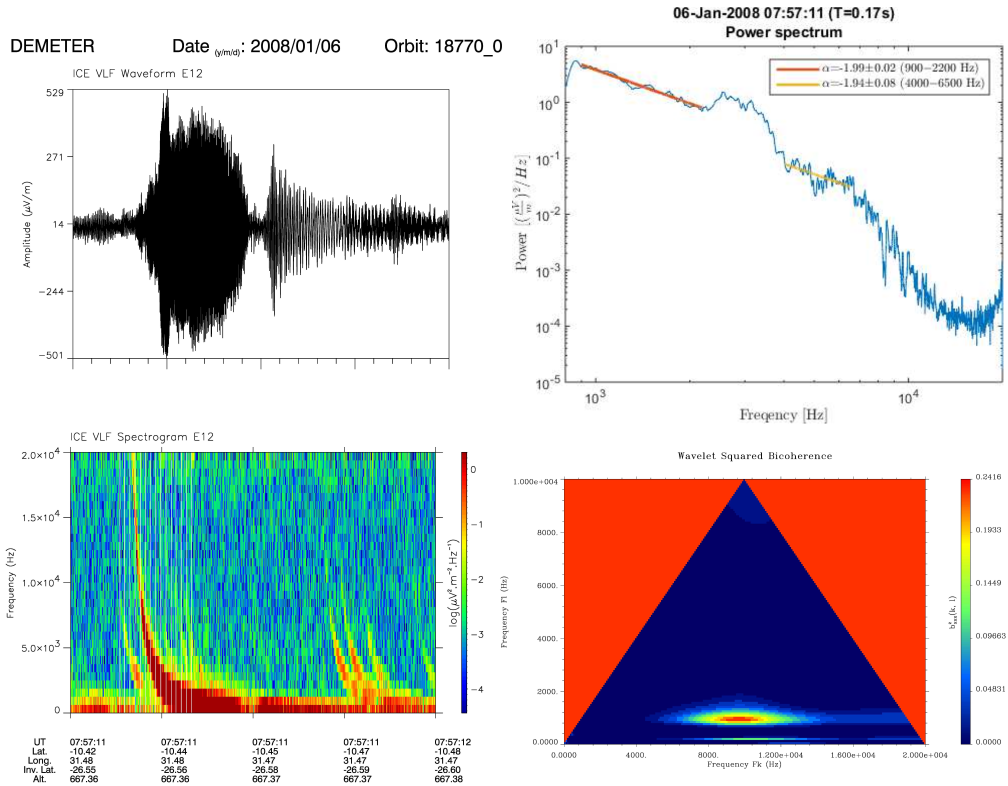

FIG. 3. Wave form, spectrogram, single Fourier spectrum and bispectrum of electric field variations registered by DEMETER satellite over area of intensive thunderstorms in central Africa on January 06, 2008, at 07:57:11 UT.

3.2. Castres (Southern France) strong thunderstorm

On August 8 the very strong thunderstorm took place in the vicinity of Castres, in Southern France close to Toulouse. DEMETER just flew by over the area of this thunderstorm. Table 1 gives the information about strongest strokes. The first column of it contains the day of an event, the second shows the exact time of strokes, the geographical coordinates of a stroke are shown in

TABLE 1. Data on the strokes over Castres.

Day	Time	Latitude	Longitude	Current [kA]
2009/10/08	21:05:59	43.2771	3.9276	52.5
2009/10/08	21:06:26	43.4709	3.9191	−118.4
2009/10/08	21:06:28	43.0593	4.0521	−155.0

columns third and fourth, the last one informs about the intensity of current in strokes. The first stroke is weaker than second and third but they are positive so it suggests that sprites could follow it, but there was no optical registrations and there is no evidence of presence of it, but effects registered by DEMETER were so strong that it is worth to analyse.

First we discuss the case of the third event. The current in this stroke had the intensity −155.0 kA on 21:06:28UT.

Figure 4 contains the wave form and spectrogram (left panels), bispectrum (left bottom panel) and single spectrum (right bottom panel) of the electric field variations in the ionosphere registered during the DEMETER flight over this event. The wave form presents an extremely high amplitude that reached a value of 44 mV/m in the centre of the time interval. At the same moment the spectrogram of a whistler shape is also extremely intensive. One can see the characteristic horizontal line in the spectrogram at a frequency around 18 kHz, which is an emission of the ground based VLF transmitter in Rosnay with a position

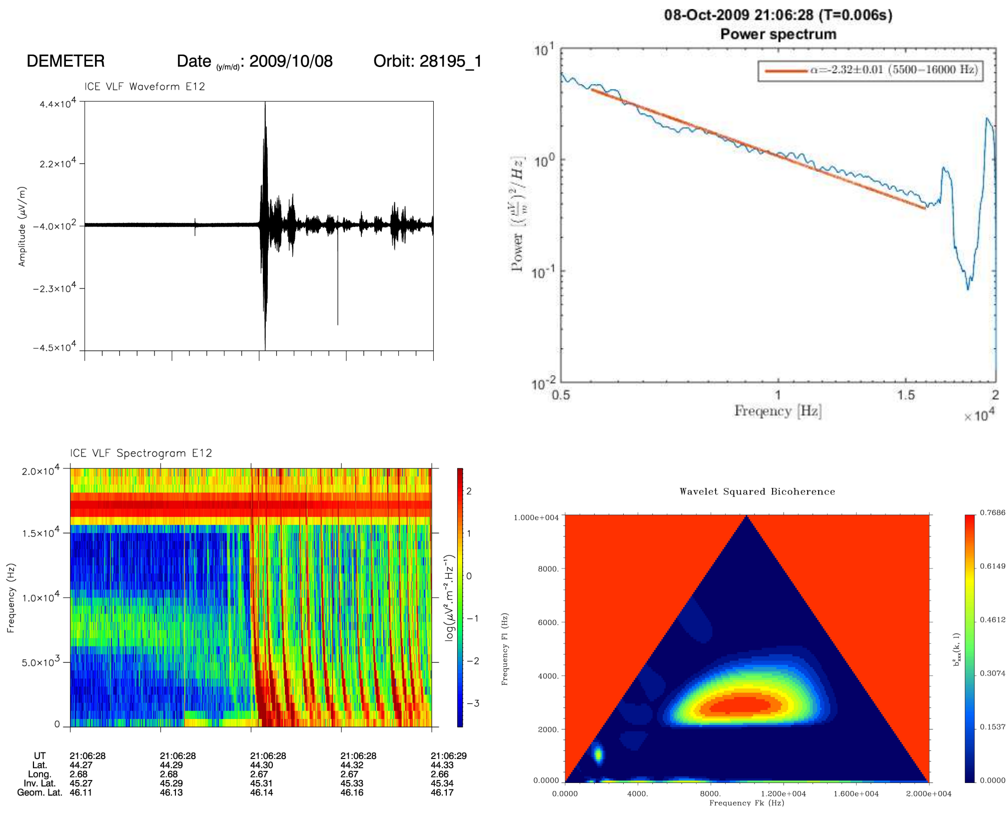

FIG. 4. The same as in Fig. 3 for the case of thunderstorm in vicinity of Castres (France) on 8.10.2009 at 21:06:28 UT, case 3 in Table 1. Details in text.

of 46.71° N, 1.24° E lying about 400 km north from Castres. This transmitter emits waves at frequency 18.3 kHz. During the strongest whistler in a spectrogram there is clearly seen the broadening of the spectrum – shift to a higher frequency. It is also seen in a single spectrogram where 2 peaks are present, one corresponding to frequency of an original signal of transmitter and the second

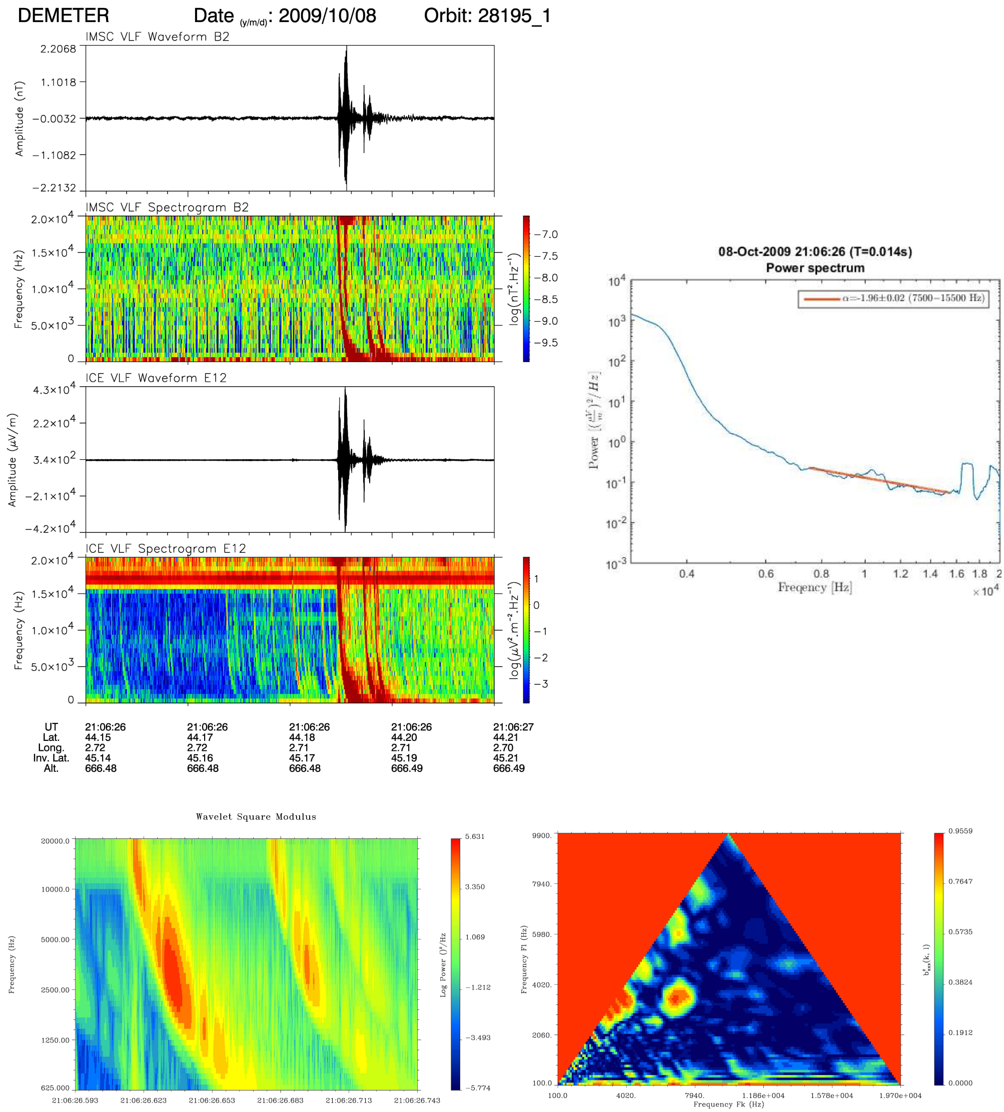

FIG. 5. The same as in Fig. 4 but for the stroke number 2 in Table 1, with additional information presented in the left bottom panel being result of wavelet analysis. Details in text.

is a result of nonlinear interaction of it with a whistler. The same effect is clearly seen in a spectrogram as broadening and intensification of whistlers at frequencies close to 20 kHz. The bispectrum shown in the left bottom panel confirms the presence of 3 wave processes in the frequency range from 6 kHz to 14 kHz. The maximum value of bispectrum is equal 0.7690 and it testifies about strong 3 waves interactions in this frequency range. These interactions are the first step in developing turbulence. The slope of a spectrogram in this frequency range equal to 2.32 suggests the presence of whistler turbulence which according to the theory [11–14] has spectrum with a slope 7/3.

The second event also associated with the thunderstorm in Castres is related to a little weaker lightning with a current −118.4 kA, but all effects described in the previous case are present also in the registrations done by DEMETER on 21:06:26 UT. The electric signal has a maximum value of 22 mV/m. The amplitude of magnetic field variations reached value 22 nT (see left upper panel in Fig. 5). The power spectrum of an electric field has a slope of 2.87 which is higher than 7/3 but not too much and again we assume that these variations are related to the whistler turbulence. Two peaks in the upper part of a frequency range are likely to picture the nonlinear interaction of the whistler with the VLF signal from the Rosnay transmitter.

It is also present in spectrograms of electric and magnetic fields variation as intensification of spectral density in the part of the highest frequency range. The process shown in Fig. 5 is non-stationary and the use of the Fourier analysis is not adequate, more suitable in this case is the use of the wavelet analysis which gave the good resolution in time and frequency simultaneously. The wavelet spectrogram shown in the left bottom panel of Fig. 5 represents detail frequency-time evolution of electric field variation. It was calculated with the Morlet wavelet, which has a shape close to the Gaussian function. The uncertainty principle $\delta t \delta f \geq 1$ relevant to this function gives the relation between time and frequency resolution. These values are equal to 0.01 second and 100 Hz, respectively, in the most interesting case at 21:06:26.638 UT when the separation in time of the spectrogram at frequencies between 1000 and 8000 Hz for two branches and broadening of it in time and frequency is seen. So high time frequency resolution is not achievable with the Fourier analysis as we can see in the spectrogram in the left upper panel of Fig. 5. The details of the wavelet applications can be found in the papers and books mentioned in the paragraph "Methodology" of this paper. This is probably the result of nonlinear interactions between different frequencies. The figure in the right bottom panel contains few regions in the frequency with a sufficiently high bispectrum value indicating these interactions.

The last discussed case is related to the event number 1 in Table 1. The stroke at 21:05:59 had much weaker current with a value of 52.5 kA, but it was positive.

The whistlers related to this stroke are seen in spectrogram at 21:05:59.250 and it was not very intensive (see Fig. 6 left upper panel), but about 60 msec later very strong variations in the VLF range were registered. The wave form of an electric field shown in the right bottom panel of Fig. 6 has achieved a huge value of 48.4 mV/m. The Fourier spectrum of this extremely strong signal is given in the upper right panel and the slope of it in the frequency range 8000–16 000 Hz is equal 2.58+/−0.04 which again is close to 7/3 typical for whistler turbulence. The bispectrum presented in the right bottom panel has "island" of maximal values of it around 7000 to 14 000 Hz. It means that in these frequency ranges strong 3 wave interaction occurs. They lead to developing whistler turbulence. This event is not related to the registered lightning, but occurs 60 msec after a 50 kA positive stroke. It can suggest, that it is associated with the sprite which usually follows a positive stroke. There were not optic registrations so we have no evidence that this event is related to a sprite and the registered turbulence is generated by it, but it is highly probable. So strong emission in ELF/VLF ranges has been reported for the registration done by DEMETER when a camera

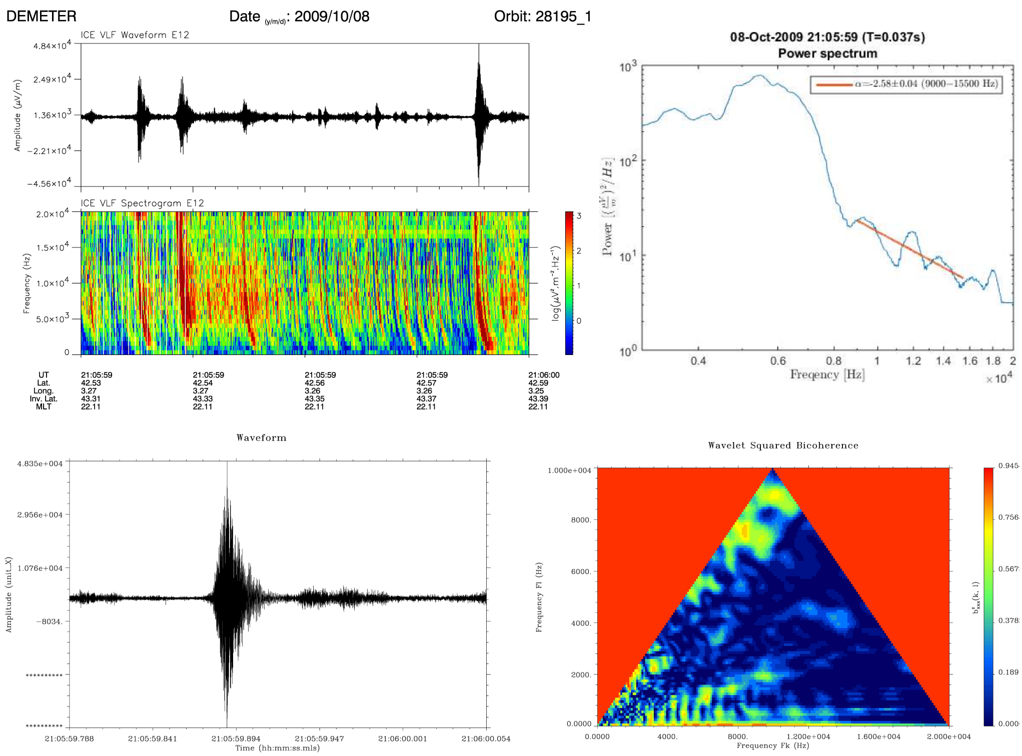

FIG. 6. The same as in Fig. 5. Details in text.

installed on the Śnieżka Mountain took photos of the sprite and the DEMETER satellite flying some distance away from it [6].

4. Conclusions

The observations discussed in this paper are related to a study of nonlinear effects in very strong whistlers and nonlinear interactions of them with the VLF ground based transmitter.

One of the cases discussed concerns the lightnings in the Central African thunderstorm area. The whistler registered there had a very high intensity with an unusual long duration in the lowest part of spectrogram. These emissions are different from the ones recorded in the days of classical whistlers because they last several tens of milliseconds after the occurrence of the parent lightning.

Next, three discussed cases are related to the strong thunderstorm in the vicinity of Castres in southern France. Two cases are caused by extremely intensive negative lightnings with the current intensity respectively 118.4 kA and 155.0 kA. At the same time, DEMETER registered very intense whistlers. The detailed analysis with the wavelet and bispectral tools shows nonlinear 3 wave interactions within whistlers themselves but also these interactions with the VLF signal emitted by the ground-based transmitter in Rosnay, which emitted a signal at 18.4 kHz.

The third case is related to relatively weaker lightning with a current intensity of 52.5 kA, but it was a positive current, which could generate a sprite. Unfortunately, there was no optical registration so we have no direct evidence of the sprite occurrence. Bell *et al.* [15] and Reising [16] have shown that the strong ELF sferic energy could be an indicator of a sprite, but presented in this paper and our earlier studies [5] also the VLF very strong signal can be related to a sprite. So, having this in mind it is quite reasonable to assume, that so strong emission with an amplitude of 48,35 mV/m is produced by a sprite and nonlinear effects seen in this event are also produced by a sprite. Analysis of the single spectra for the discussed events has a slot close to 7/3 which is the signature of whistler turbulence.

Acknowledgements

This work is based on observations with the electric field experiment ICE and the magnetic field experiment IMSC embarked on DEMETER. The authors thank J. J. Berthelier the PI of the electric field experiment for the use of the data and M. Parrot PI of the magnetic field experiment. We also thank H. D. Betz (LINET) and G. Diendorfer (EUCLID) for the information on the thunderstorm activity. This work has been partly supported by the National Science Centre, Poland (NCN), through grant No. 2021/41/B/ST10/00823.

References

1. J.J. Berthelier, M. Godefroy, F. Leblanc, M. Malingre, M. Menvielle, D. Lagoutte, J.Y. Brochot, F. Colin, F. Elie, C. Legendre, P. Zamora, D. Benoist, Y. Chapuis, J. Artru, R. Pfaff, *ICE-the electric field experiment on DEMETER*, Planetary and Space Science, **54**, 456–471, 2006.

2. M. Parrot, D. Benoist, J.J. Berthelier, J. Błęcki, Y. Chapuis, F. Colin, F. Elie, P. Fergeau, D. Lagoutte, F. Lefeuvre, M. Lévêque, J.L. Pinçon, H.-C. Seran, P. Zamora, *The magnetic field experiment and its data processing onboard DEMETER: scientific objectives, description and first results*, Planetary and Space Science, **54**, 441–455, 2006.

3. M. Farge, *Wavelet transforms and their applications to turbulence*, Annales Review Fluid Mechanics, **24**, 395–457, 1992.

4. G.J. MacDonald, *Spectral analysis of time series generated by nonlinear processes*, Reviews of Geophysics, **27**, 4, 449–469, 1989.

5. A.W. Wernik, *High-latitude ionospheric plasma turbulence: advanced analysis methods and results*, Acta Geophysica Polonica, **50**, 1, 119–134, 2002.

6. J. Błęcki, M. Parrot, R. Wronowski, S. Savin, *Nonlinear Interactions of the Low Frequency Plasma Waves in the Middle-altitude Polar Cusp as Observed by Prognoz-8, Interball-1 and Cluster Satellites*, Acta Geophysica, **55**, 459–468, 2007.

7. J. Błęcki, M. Parrot, R. Wronowski, *ELF and VLF signatures of sprites registered onboard the low altitude satellite DEMETER*, Annales Geophysicae, **27**, 2599–2605, 2009.

8. Y.C. Kim, E.J. Powers, *Digital bispectral analysis of self-excited fluctuation spectra*, Physics of Fluids, **21**, 8, 1452–1453, 1978.

9. D. Lagoutte, J.Y. Brochot, P. Latremoliere, *SWAN Software for Waveform Analysis, Analysis Tools version 2.3*, LPCE/NI/003.D – Part 1–3, 1999.

10. J. Błęcki, M. Parrot, R. Wronowski, *Plasma turbulence in the ionosphere prior to earthquakes, some remarks on the DEMETER registrations*, Journal of Asian Earth Sciences, **41**, 450–458, 2011, doi: 10.1016/j.jseaes.2010.05.016.

11. D. Shaikh, *Density fluctuation spectrum in whistler turbulence*, Physics Letters A, **374**, 2551–2554, 2010, doi: 10.1016/j.physleta.2010.04.024.

12. Y. Narita, S.P. Gary, *Inertial-range spectrum of whistler turbulence*, Annales Geophysicae, **28**, 597–601, 2010, doi: 10.5194/angeo-28-597-2010.

13. Y. Narita, T.N. Parashar, J. Wang, *The Gary Picture of Short-Wavelength Plasma Turbulence – The Legacy of Peter Gary*, Frontiers in Physics, **10**, 2022, doi: 10.3389/fphy.2022.942167.

14. A. Yoshizawa, S.I. Itoh, K. Itoh, N. Yokoi, *Turbulence theories and modelling of fluids and plasmas*, Plasma Physics and Controlled Fusion, **43**, 3, 2001, R1-R144, doi: 10.1088/0741-3335/43/3/201.

15. T.F. Bell, S.C. Reising, U.S. Inan, *Intense continuing currents following positive cloud-to-ground lightning associated with red sprites*, Geophysical Research Letters, **25**, 8, 1285–1288, 1998.

16. S.C. Reising, U.S. Inan, T.F. Bell, *ELF sferic energy as a proxy indicator for sprite occurrence*, Geophysical Research Letters, **26**, 7, 987–990, 1999.

Received February 21, 2024; revised version April 20, 2024.
Published online June 21, 2024.