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Observations of the anomalous third Schumann resonance peak during October 21 to 25, 2004 at Modra Observatory and a possible explanation

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Abstract: At the Astronomical and Geophysical Observatory of FMFI UK at Modra, the permanent monitoring of Schumann resonance (SchR) spectra has been performed for more than three years (in electric field component – the SchR magnetic field component spectra have been measured – up to now – only intermittently for a shorter time). During second half of October 2004, several cases of anomalously high third SchR mode amplitude were observed. Because the man-made artifacts as a cause can be (with high probability) excluded, we seek for the possible natural explanation. Two explanations appear to be physically plausible: the occurrence of multiple return strokes (MRS) or the very special geometrical source-receiver relations. We propose that the dynamical behavior of short-interval spectra can distinguish between them.

Key words: electromagnetic field, resonances, ionosphere, Schumann resonances, lightnings

1. Introduction

Schumann resonance phenomenon is now firmly established as a powerful experimental tool in the numerous parts of geophysics, e.g. ionospheric structure monitoring, lightning localisation, "global thermometer"

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etc. (*Nickolaenko and Hayakawa, 2002*). Shortly speaking, the Schumann resonances are the longitudinal eigenmodes of spherical electromagnetic resonator formed by Earth's surface and lower ionospheric layers at the height approximately 50 – 60 km. The first (fundamental) eigenfrequency lies about at 7.5 – 8 Hz, several higher ones at about 14, 20, 26, 32 Hz.

The eigenmodes can be observed due to very low attenuation of ELF electromagnetic waves propagating along the Earth's surface (*Galejs, 1972*). At normal circumstances, the global lightning activity covers most of energy needed for resonator excitation. Changes of principal SchR parameters (central frequency, halfwidth and amplitude of each eigenmode) reflect the variations of global lightning activity, Earth's surface impedance (down to the skin depth, which – for frequencies of 10 Hz order – is about 20 – 25 km for the solid Earth crust) and the variations of electrical parameters of the lower ionospheric layers.

Due to the longitudinal character of eigenmodes, the electromagnetic field in resonator consists mostly of vertical electric and horizontal magnetic field components irrespective of the details of excitation mechanism.

As a rule, the amplitudes of subsequent eigenmodes are monotonically decreasing with frequency. The opposite cases (very rare) therefore are of a substantial interest.

2. General background

2.1. Schumann resonance phenomenon and its geophysical significance

As generally known, the first theoretical studies of electromagnetic resonance phenomena in the Earth-ionosphere resonator originated by W. O. Schumann (*Schumann, 1952*) – but famous inventor Nikola Tesla suspected the qualitative existence of similar phenomenon as early as in 1893. The global eigenmodes in the electrical field component were experimentally confirmed firstly by *Balser and Wagner* (*1960*).

The detailed determination of electromagnetic eigenfields spatial distribution and the computation of eigenfrequencies were performed by numerous authors, e.g. (*Nickolaenko and Hayakawa, 2002; Sentman, 1990; Madden and Thompson, 1965; Pechony and Price, 2004*). Various models were

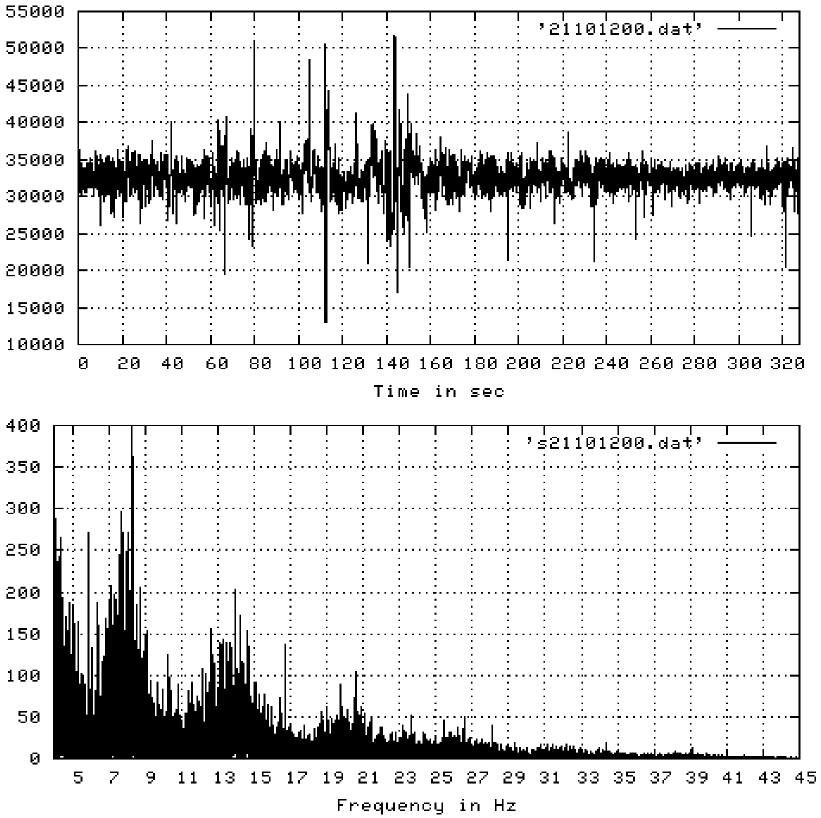

Fig. 1. Typical spectrum of the electric field component from October 21, 2004, 12:00 to 12:05:28 UT. Above: the amplifier output data. Vertical axis is in quantization levels – the level 00000 represents –2,5 V output, level 32768 – zero output and level 65535 corresponds to +2,5 V. Below: the raw spectrum from complete time series (65,536 samples). The vertical axis is in relative units.

used, from the initial simplest Schumann one (perfectly conducting Earth and spherically bounded lossless ionosphere layer with uniform scalar permitivity) to accounting for anisotropic complex conductivity of ionosphere and its height profile, day-night asymmetry, polar inhomogenities ("caps") etc. The geomagnetic field also affects the overall picture, because of gyrotropic nature of lower ionosphere permitivity. If considering so, the propagation constant becomes polarization-dependent (*Nickolaenko et al., 2004*). It is worth mentioning that the term "eigenfrequency" or "mode peak frequency" must be understood as not strictly constant from one place to another (even at the same time instant) (*Morente et al., 2004*).

2.2. Schumann resonance observations

At Modra Observatory, the electrical field SchR component has been picked up by 5 m high ball antenna. The signal is fed to high-input impedance amplifier (about 82 dB gain), followed by high- and lowpass filters and 50 Hz notch. The signal is digitized by a 16-bit bipolar 3-channel ADC, 200 samples per second. At the beginning of every half an hour, the 5.5-minute sample train (65,536 samples) is accumulated and then spectrum is obtained by standard FFT algorithm. The spectra in the frequency band $5-45$ Hz, as a moving averages smoothed by 50 spectral samples wide window, are available in real time at: http://147.175.143.11/. Fig. 1 shows the typical spectrum of electric field component. The spectrum given there (as well as in all subsequent figures) are the square root of power one.

Except the intervals of heavy rain, snow or icing, the spectra are relatively clear and, at least for the first 4 peaks, the triple of parameters – central frequency, quality factor and peak amplitude – is determined by Lorentz function fitting and subsequently stored.

The magnetic field component measurements are in testing phase now. Two orthogonal search coils are used as sensors. Each coil has 150,000 turns, on a 1 m long open core (50 sq. cm cross-section). The outputs of symmetrical winding are connected to the amplifier (gain about 52 dB at 10 Hz) with ultra-low noise instrumentation amplifier input stage. Next stages are interleaved with four sharp bandstop filters on 50 Hz, output signal is processed in the same way as for the electrical component case. The amplifiers are located immediately at coils, all under the double electrostatic shielding.

The complete assembly is protected from moisture by plastic housing. During long experimental campaign, it was definitely proved that the observatory site is not suitable for magnetic component monitoring.

Typical magnetic component spectrum is in Fig. 2. The two (possibly three) eigenmodes clearly emerge from averaged spectra, but the magnetic noise level is very high. Moreover, the artificial disturbance from Austrian

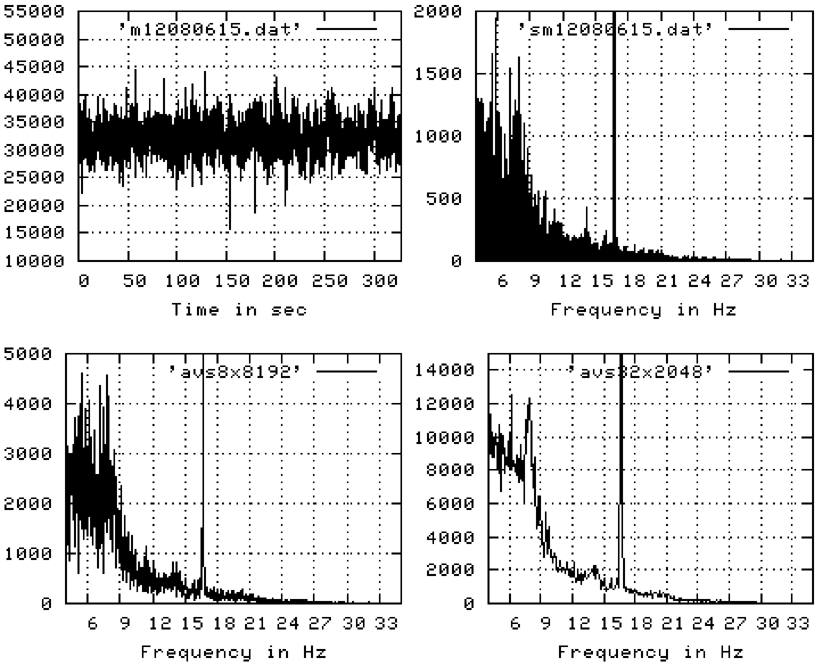

Fig. 2. Typical spectrum of magnetic field component (testing phase), obtained at August 12, 2004, 06:15 to 06:20:28 UT. Above, from left to right: raw data; the non-smooted spectrum from complete time series. Below, left to right: The spectrum averaged from 8 frames; spectrum averaged from 32 frames.

railways is present as a narrow 16.67 (50/3) Hz peak. Therefore, an extensive search of a better site is under way.

More detailed description of the whole experimental assembly can be found in (*Kostecký et al., 2000*) and the details of signal processing in (*Rosenberg, 2004*).

3. The description of eigenfields

3.1. The spherical harmonics expansion

As a direct consequence of resonator geometrical symmetry, the amplitudes of electric and magnetic fields can be expressed as linear combinations of *spherical harmonics* (eigenfunctions of angular part of Laplace operator), multiplied by *radial function.* All field quantities are expressed in a spherical coordinate system, with polar axis identical with the rotational axis of the Earth. Moreover, their time dependence is taken as harmonic, with angular frequency ω. Within this section, the initial conditions and the excitation mechanism would be disregarded.

The field vectors $\vec{E}(\vec{r}, t)$ and $\vec{H}(\vec{r}, t)$ must fulfill Maxwell equations together with appropriate boundary conditions. Simply stated, at the Earth's surface the tangential components of $\vec{E}$ and $\vec{H}$ must be zero, whilst at the upper (ionospheric) boundary must be continuous, plus the radiation condition in external space, i.e. the absence of waves coming from infinity.

If the scalar electric (U) and magnetic (V) potentials are introduced, the solution for potentials can be expressed as (*Bliokh et al., 1977*):

$$U(r,\theta,\varphi,t) = \sum_{n,m} kr \left[A_{nm} h_n^{(1)}(kr) + B_{nm} h_n^{(2)}(kr)\right] Y_{nm}(\theta,\varphi) \exp^{i\omega t} \tag{1}$$

inside the resonator, and

$$U(r,\theta,\varphi,t) = \sum_{n,m} kr C_{nm} h_n^{(2)}(kr) Y_{nm}(\theta,\varphi) \exp^{i\omega t} \tag{2}$$

in the ionosphere. The same formal expressions are valid for magnetic scalar potential V. In case of E-modes, $U \neq 0$ and $V = 0$, for H-modes the situation is opposite. The double-indexed constants A_{nm}, B_{nm}, C_{nm} reflect the boundary conditions as well as the excitation conditions.

In Eqs (1) and (2), Y_{nm} represent the spherical harmonics of the order n and degree m. The radial functions $h_n^{(1)}$, $h_n^{(2)}$ are the well-known spherical Bessel functions of argument $(\omega r/c)$.

The field amplitudes $\vec{E}(\vec{r})$, $\vec{H}(\vec{r})$ can be calculated from potentials U (or V) by obvious way (*Bliokh et al., 1977*, p. 14−15) and it is possible to expand them into the series of spherical harmonics:

$$\vec{H} = \sum_{n,m} \alpha_{nm} \vec{H}_{nm}$$
$$\vec{E} = \sum_{n,m} \beta_{nm} \vec{E}_{nm}. \tag{3}$$

The wave number $k = (\omega/c)$ must be determined from characteristic – dispersion – equation (system of equations) which reflects the fact, that field solution must fit the boundary conditions. (For details, see *Nickolaenko and Hayakawa, 2002*, p. 13 – 14 and 22).

In this simplified model, the characteristic wave numbers, corresponding to the eigenfrequencies, are parametrized by two indices n and p. Roughly speaking, the first one is equal to the number of waves along the Earth's circumference, whilst the second one is equal to the number of halfwaves transversally between resonator boundaries. For Schumann resonances, the second index $p = 0$.

Because the spherical harmonics Y_{nm} have two indices, the eigenmodes are degenerated in this simple model (any intermodal coupling).

In the high-quality resonator (narrow eigenmode peaks) the system of spherical harmonics represents nearly adequate functional base, and convergence of (2) is pretty good, practically irrespective of excitation mechanism details. The case of SchR is opposite – the quality factor Q is lower than 10 for all eigenmodes. Therefore, for modelling of fields with sufficient precision it is necessary to take into account a great number of terms, even if we try to calculate fields in the ELF range (for frequencies up to 60 Hz at least 200 terms are necessary – *Bliokh et al., 1977, p. 98 – 99*). As a partial remedy the well-known Kummer transformation can be used, or it is possible to separate the electrical dipole field in the near zone. The rest of series converges more rapidly.

3.2. Mode coupling

Leaving the simple model of homogenous lossless ionospheric layer, the boundary condition – continuity of tangential field components – must be substituted by much more complicated one. Under plausible geometrical conditions, it is justified to approximate the exact boundary condition with the Leontovich impedance condition (*Weinstein, 1957*):

$$[\vec{n_r} \times \vec{E}] = \overline{\overline{\mathbf{Z}}} \circ [\vec{n_r} \times [\vec{n_r} \times \vec{H}]], \tag{4}$$

where $\vec{n_r}$ is the unit radial vector, $\overline{\overline{\mathbf{Z}}}$ represents the second-order surface impedance tensor (frequency dependent in general). This is relevant if the skin depth of electromagnetic wave is substantially smaller than the curvature radius of the boundary, which is just the SchR case.

Now it is necessary to introduce the excitation. If we take into account the spectral component $\vec{I}(\omega, \vec{r})$ of the driving current, and expand the field amplitudes into the spherical harmonics (3) (for details see *Nickolaenko and Hayakawa, 2002*, p. 32 − 33) we obtain a system of algebraic equations for the coefficients of expansion:

$$\omega_n \alpha_{nm} - \omega \beta_{nm} = -I_{nm},$$

$$\omega_n \beta_{nm} - \omega \alpha_{nm} + ic \sum_{p=1}^{\infty} \sum_{q=-p}^{p} \alpha_{pq} \Lambda_{nmpq} = 0, \tag{5}$$

where the source term I_{nm} is simply given by integration over the resonator volume V_{Res}:

$$I_{nm} = \frac{i}{J} \int_{V_{Res}} (\vec{I}(\omega, \vec{r}) \cdot \vec{E}^{*}_{nm}) dV, \tag{6}$$

where the asterisk denotes complex conjugate and the "mixing parameter" Λ_{nmpq} is given by the expression:

$$\Lambda_{nmpq} = \frac{\mu_0}{J} \oint_S (\vec{H}^{*}_{nm} . Z[\vec{n_r} \times [\vec{H}_{pq} \times \vec{n_r}]]) dS. \tag{7}$$

The integration in (7) is performed over the lower ionospheric boundary. Normalization factor J (total field energy density) is given by:

$$\int_{V_{Res}} \epsilon_0 |\vec{E}_{nm}|^2 dV = \int_{V_{Res}} \mu_0 |\vec{H}_{nm}|^2 dV = J.$$

After system (5) is solved, it is possible to find the relative "abundance" of subsequent eigenmodes in the resulting electromagnetic field.

Strictly speaking, the system (5) is of infinite dimension. Naturally, we must limit ourselves to finite number of unknowns in (5). For the uniform (but possible lossy) ionospheric layer the system matrix is diagonal, due to special form of "mixing parameter" (7). In general, the system matrix is non-diagonal and, moreover, non-symmetric due to ionospheric gyrotropy. The methods of solution are profoundly discussed in (*Nickolaenko and Hayakawa, 2002*, Sec. 5.1, p. 173 − 187).

4. The excitation mechanism

4.1. The relative amplitude of modes

For frequencies of principal SchR eigenmodes in interest (about 5–40 Hz) the principal field components are vertical (transversal) E_r, horizontal (longitudinal) components H_φ and H_θ. The last one is of the order of magnitude $|Z \cdot E_r|$, because in real situation the modul of Z is of the order of magnitude 10^{-2}, the vertical electric component E_r dominates (TEM – wave in microwave terminology).

Due to the scalar product in the source term (6), the vertical driving currents as field sources are prefered. The vertical driving current prevail in most lightning strokes, sprites and elves.

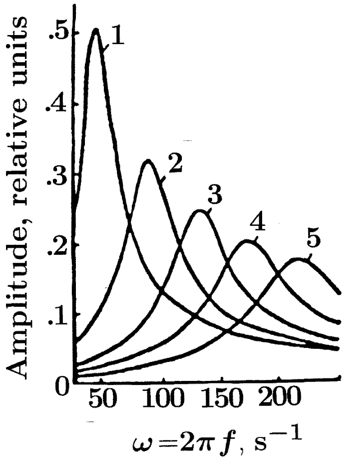

Fig. 3. The teoretical amplitude-frequency curves for the first five Schumann eigenmodes (taken from *Bliokh et al., 1977*, Fig. 22a). Horizontal axis is in angular frequency (in s^{-1}), the vertical axis in relative units.

In the normal situation, amplitudes of subsequent eigenmodes are monotonically decreasing, beginning from the fundamental one. This is a direct consequence of field solution. In the simple model of homogenous ionosphere with scalar surface impedance $Z(\omega)$ according to the standard ionospheric model (*Nickolaenko and Hayakawa, 2002*, p. 50, Tab. 2.2.) the frequency dependence of radial electric field E_r is given by:

$$E_r = \frac{4\pi i I ds(\omega)}{a^2(b-a)} \sum_{n=0}^{\infty}(2n+1)\frac{\omega - \frac{icZ(\omega)}{(b-a)}}{\omega_n^2 - \omega^2 + \frac{icZ(\omega)}{(b-a)}} P_n(\cos\theta), \tag{8}$$

where a, b are the radii of the inner and outer resonator spherical boundaries, respectively. Eq. (8) holds for simple vertical driving current with momentum $I.ds$, eigenfrequencies ω_n are calculated after inserting Eq. (3) into boundary conditions.

The normalized amplitude-frequency curves for the first five eigenmodes are given in Fig. 3. This general conclusion is also valid in the more complicated ionospheric models, but only for simple (isolated) driving source.

4.2. The influence of source distance

As follows from detailed calculations (*Bliokh et al., 1977*, p. 106 – 113), the distribution of eigenmode amplitudes (over the whole Earth) is strongly inhomogeneous, especially if the ionospheric gyrotropy is taken into account. From observations of a single field component, only very approximate source distance can be estimated, based on the time difference between the incoming direct and antipodal wave (if they can be resolved in time). The formal solution for time propagation of a single pulse (in both the field components) is given in (*Nickolaenko and Hayakawa, 2002*, p. 156 – 160).

5. The situation on October 21 to 25, 2004

During the second half of October 2004, we recorded several cases when the amplitude of the third eigenmode (at about 20.5 Hz) was greatly exaggerated. Sometimes the third peak was maximal in amplitude. Moreover, in this cases the permanent “wideband podium” of exponential form (which is clearly visible e.g. in Fig. 1) was enhanced starting at 13 – 14 Hz.

In the next paragraphs, the situation will be described and possible explanations discussed.

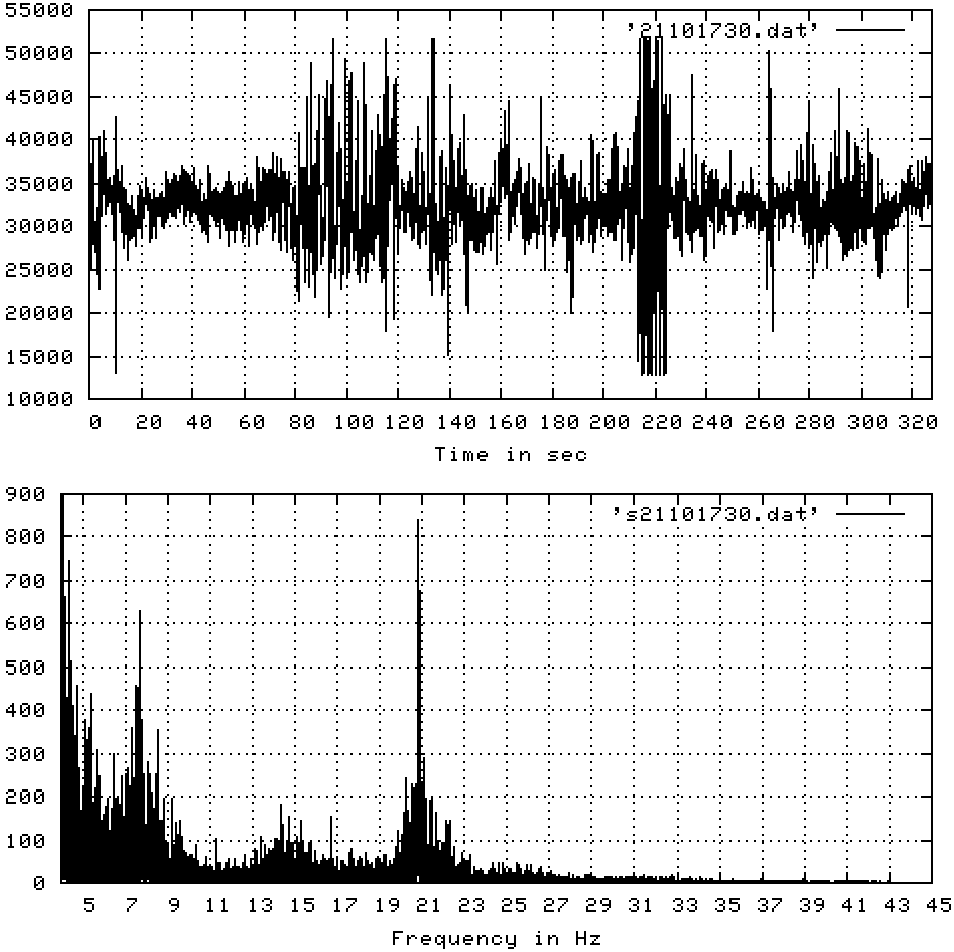

Fig. 4. The same as in Fig. 1 but for the data from October 21, 2004, 17:30 to 17:35:28 UT. The Q-burst is visible at approx. 17:34:25 UT.

5.1. The overall situation and SchR data

Some of the anomalous spectra (and also the original data) are shown in Figs 4–6 (taken on Oct. 21, at 17:30, 18:00, Oct. 24, 21:30, Oct. 25, 18:30, 20:00 – all times in UT). The first, second and fourth spectrum is characterized by the third peak as the most prominent one and relatively sharp increase in baseline amplitude at about 13 Hz. The third peak is not so elevated at the second and fifth spectrum, but it is still anomalously high in amplitude.

To complete the experimental situation, at first we examined the data from digitized amplifier output – for the interval 17:30 – 17:35.5 UT of October 21 and the corresponding data record is given in Fig. 4. The examination would reveal the occurence of flashes or Q-bursts (*Ševčík et al., 2005*). Within the time interval 17:30 to 17:35.5 UT, October 21, 2004, an isolated Q-burst occurred with the onset at 17:30:09.9 UT (the first maximum). The spacing between the direct and antipodal wave maxima was 0.13 s. According to *Nickolaenko and Hayakawa* (*2002*, 160 – 161), a very crude estimate of

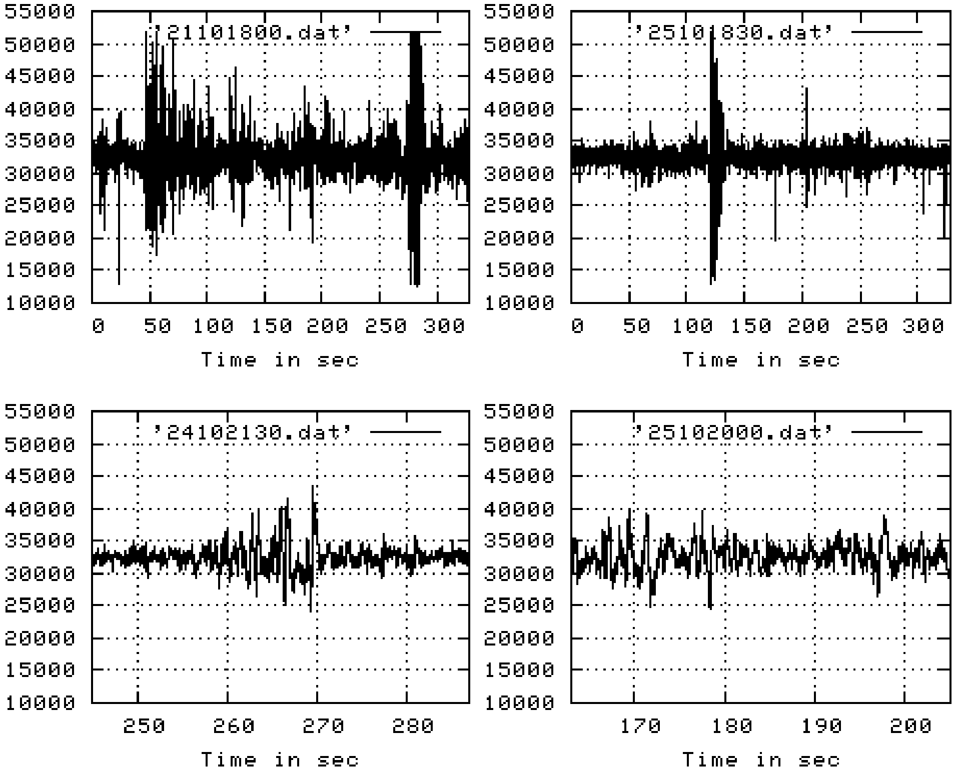

Fig. 5. The time waveforms, from which the anomalous spectra were obtained. Above, left to right: October 21, 2004, 18:00–18:05:28 UT; October 25, 2004, 18:30 – 18:35:28 UT. Below, left to right: October 24, 2004, 21:30 – 21:35:28 UT; October 25, 2004, 20:00 – 20:05:28 UT (vertical axis as in Fig. 1).

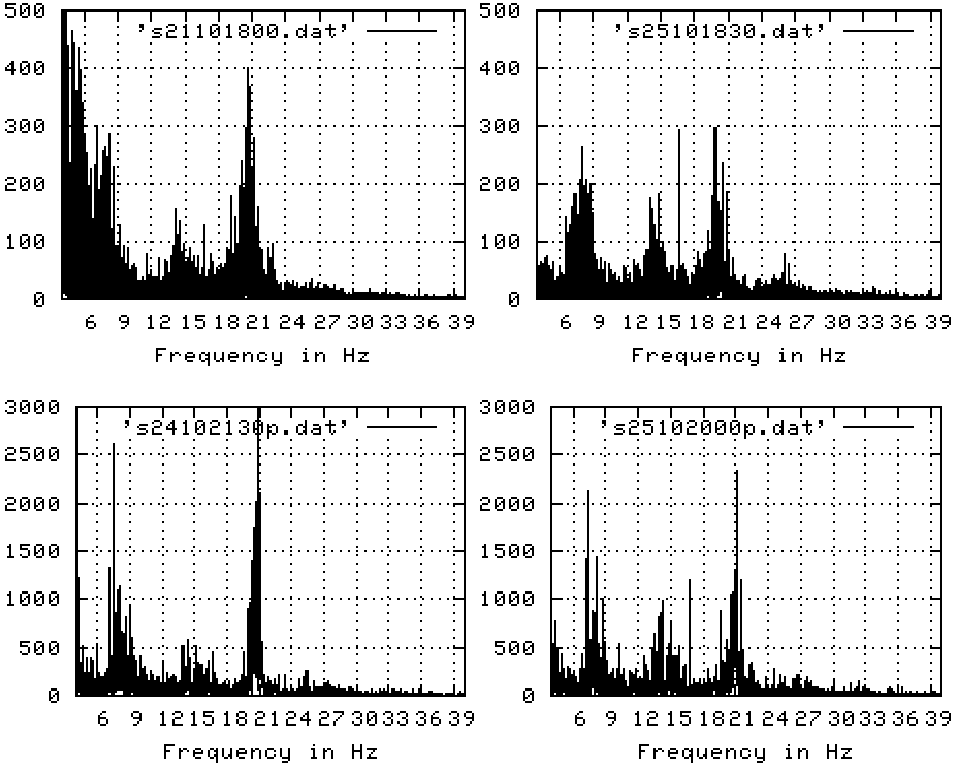

Fig. 6. Frequency spectra corresponding to the time intervals in Fig. 4. Vertical axis is in relative units. The anomalous amplitude of the third eigenmode is clearly observable at all spectra shown.

the source distance would be in a range of 2,000 – 3,000 km, clearly outside the European continent.

The second important parameter is the dynamical behavior of spectrum. To determine this, each 5.5-minute interval was divided into 16 subsequent subintervals (frames of length 20.5 s) which were separately FFT-transformed. As an example, the dynamical (time) evolution of the first four eigenmodes during the time interval 17:30 – 17:35.5 UT, October 21, 2004 is depicted in Fig. 7. The analogical computation was performed for all intervals in question.

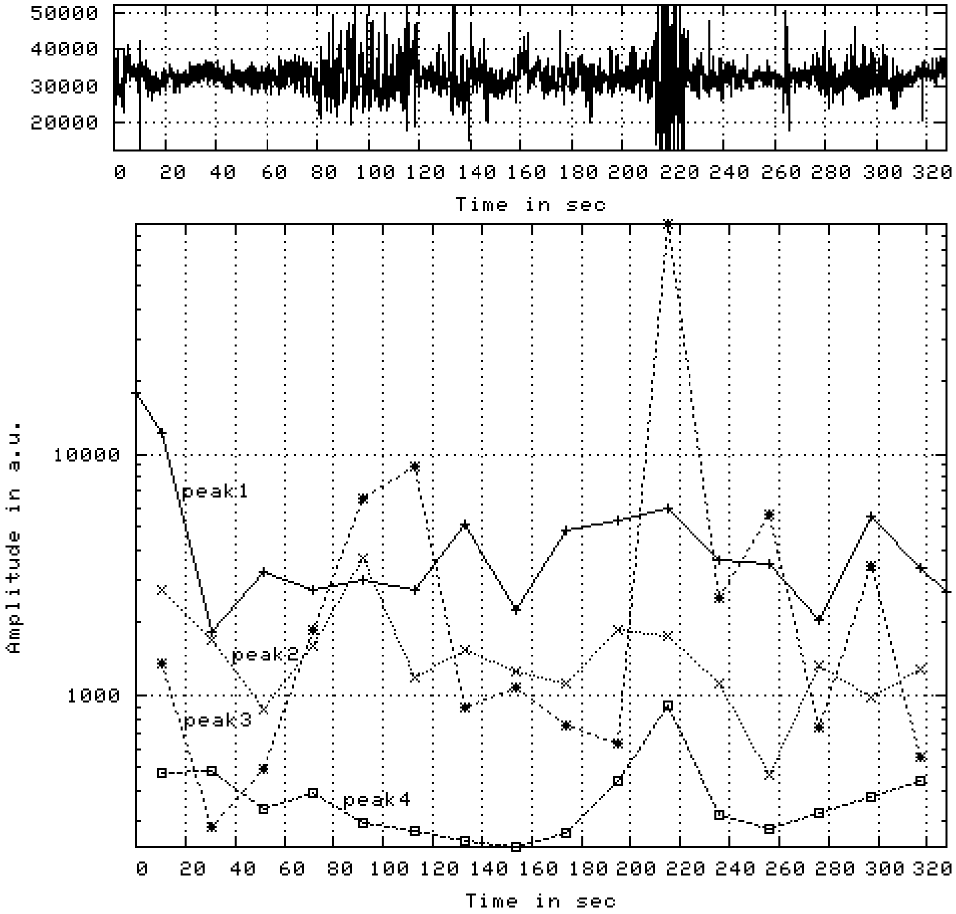

Fig. 7. The dynamical evolution of the spectrum from October 21, 2004, 17:30 – 17:35:28 UT data. Above: the complete time sequence of data output. At vertical axis, the voltage interval is from approx. –1.0 V to +1.5 V; Below: for 32 data frames (each 10.24 second wide) the average amplitudes of the first four eigenmodes are displayed in relative logarithmic units.

5.2. Possible explanation

It seems that there are three possible (physically relevant) explanations for the anomalous situation described above:

- an artificial origin (some man-made signal near to the third eigenmode frequency or the result of frequency aliasing or amplifier non-linearity);

- a signal generated by a near multiple-return stroke (MRS);
- a consequence of special sources-observer geometry.

The first possibility cannot be firmly excluded, but this origin seems to us hardly probable. During the whole observation time (more than three years for electric component, at exactly the same experimental conditions except the weather – and short time, but multiple campaigns for measuring magnetic component at various sites) we have never observed artifacts in the vicinity of the third eigenmode. Concerning the possibility of aliasing effect, this is practically excluded. Firstly, the numerous calibration runs, including the non-linearity tests (known in the field of low frequencies as "two-tone tests") were performed with good results. Secondly, the simultaneous experimental runs employing slightly different ADC sampling frequencies (from 180 to 220 Hz) were made with good results, too. Finally, the origin of possible man-made signals at 20 – 21 Hz remains obscure (the only possibility known to us would be the submarine ELF communication system – see http://www.vlf.it/zevs/zevs.htm – but it seems again very improbable.

Concerning a single Q-burst as a source, this possibility cannot be excluded a priori. But several other observations, e.g. in *Ševčík et al.* (*2005*), showed that during and immediately after such a burst, the spectrum enhancement is practically frequency independent (at least in the interval of our observations) with clearly no sign of lifting of the only particular mode.

The phenomenon of MRS is widely described in literature (*Bliokh et al., 1977*, p. 76 – 81; *Nickolaenko and Hayakawa, 2002*, p. 70 – 72), including modeling "synthetic spectra" of such a source. In this case, the frequency spectrum of source current is apparently "modulated" with maxima spaced by reciprocal value of (average) time interval between single strokes. According to the literature data, the most frequent value of this interval is about 40 millisec., which corresponds exactly to 25 Hz period of "frequency modulation" of spectrum.

This value is close to the frequency of the third eigenmode (20 – 21 Hz). In addition, the literature data suggest that a small, practically continuous current is flowing between the subsequent strokes and this component of current is responsible for the enhancement of exponential "pedestal" in spectrum. This is just what we can see in Figs 4, 6 and 7. Nevertheless, the explanation of the observed anomalous spectra as a consequence of a single

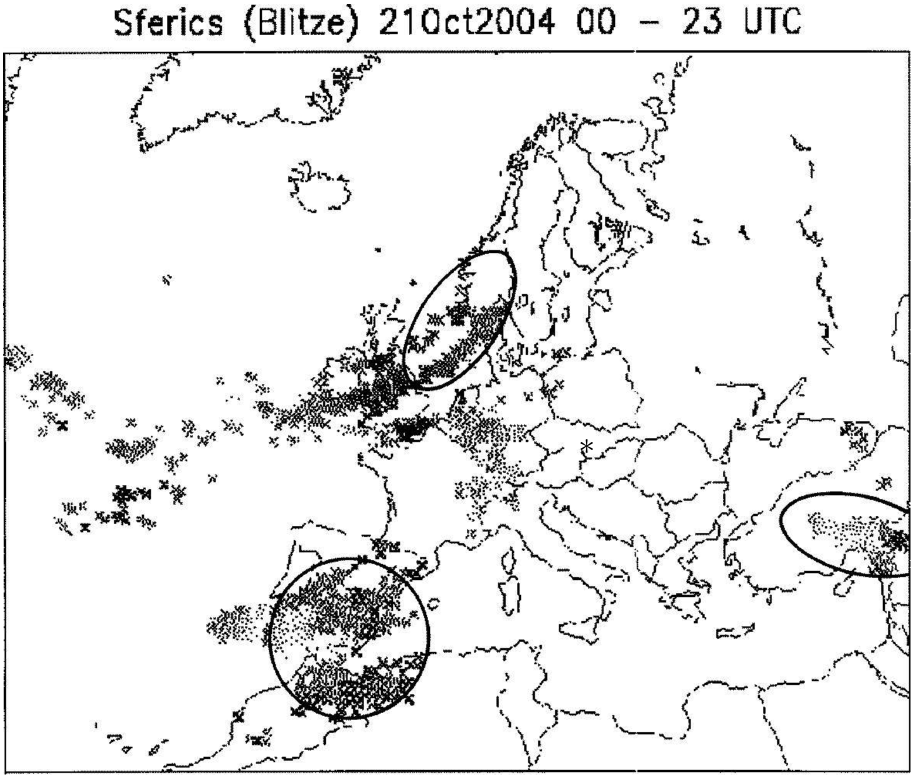

Fig. 8. The map of lightning activity over the whole day of October 21, 2004 (taken from http://www.wettercentrale.de). Positions of activity in time intervals studied are marked by circles or ovals. ∗ – Observatory Modra–Piesok.

MRS seems again very improbable.

One explanation still remains, the existence of multiple sources arranged (by chance) in special geometry with respect to the observer. From the archives of the German Meteorological Service (http://www.wetterzentrale.de) it is possible to obtain maps showing the distribution of lightning activity during days under question.

In Figs 8, 9, 10 we reproduce these maps (the distributions for the time intervals of anomalous amplitude of the third eigenmode are specially marked). It is easy to see, that in all cases the three foci of lightning activity lay approximately at the vertices of an equilateral triangle. The observing site is close to the barycenter of such triangle.

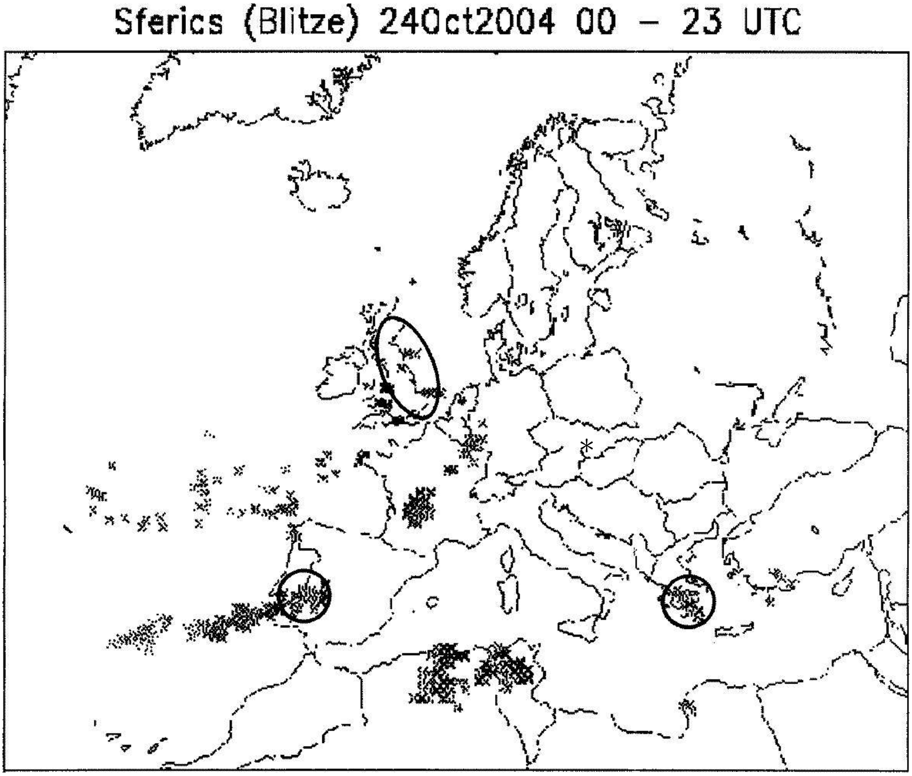

Fig. 9. The same map as in Fig. 8 but for October 24, 2004. * – Observatory Modra–Piesok.

Preliminary model calculations show that in this special sources-observer geometry, the strong enhancement of the third eigenmode is possible, fairly irrespective of detailed ionospheric structure above.

6. Conclusion and prospection for future

It may be preliminarily stated, that the special geometrical relations between multiple source and observing site can be regarded as possible cause of amplitude enhancement of some higher eigenmode. To justify this, the numerical modeling of eigenmodes field distributions in Earth-ionosphere resonator must be performed for the multiple source cases and for (at least

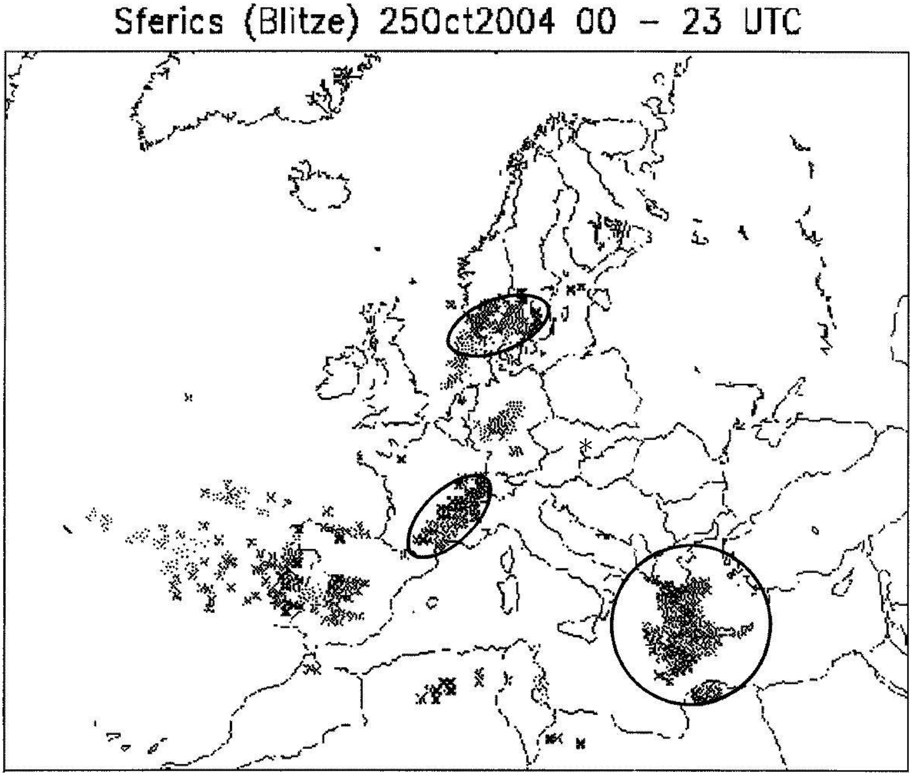

Fig. 10. The same map as in Fig. 8 but for October 24, 2004. ∗ – Observatory Modra–Piesok.

simple) model of day-night ionospheric asymmetry. This would be the subject of future investigation.

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