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Dynamical evolution of Schumann resonance spectra during a strong Q-burst on July 11, 2004

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Abstract: During permanent monitoring of Schumann resonances, numerous Q-bursts (strong transient ELF signals) were observed. In early morning of July 11, 2004, a very strong Q-burst was recorded and it was possible to analyze the dynamical evolution of electric field component spectra. The time evolution of the signal, together with dynamical behavior of frequency spectrum, enables to make conclusion about the spatial distribution of the field in the Earth-ionosphere resonator.

Key words: electromagnetic field, resonances, ionosphere, Schumann resonances, Q-burst

1. Introduction

Schumann resonance phenomenon is a subject of widespread and detailed investigations and has been widely elucidated in numerous literature, e.g. (*Bliokh et al., 1977*), (*Nickolaenko and Hayakawa, 2002*). In this paper, it is not necessary to quote the history of Schumann resonance discovery, their

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applications, and importance in geophysics. This subject – although very interesting – is also profoundly corroborated in literature.

In brief, Schumann resonances are the electromagnetic eigenmodes in spherical resonator of planetary dimensions. The conducting (at least partly) boundaries of this resonator are the Earth's surface and the lower ionospheric layers (starting at 50 – 60 km height).

The overwhelming majority of energy needed for (quasi-permanent) resonator excitation is supplied by global lightning activity. Because the principal parameters of each eigenmode (the amplitude, centre frequency and halfwidth) are dependent – at first – on the electrical parameters of the Earth's surface and ionospheric layers, the variations of Schumann eigenmodes parameters represent a unique geophysical data set. Nevertheless, the details of excitation source structure and geometrical relations source-observer – including the extraterrestrial ones, e.g. Solar proton events – see (*Ondrášková, 2003*) – have also a great influence on Schumann resonance parameters.

2. Details of excitation mechanism

As mentioned above, the dominant role belongs to the global thunderstorm (lightning) activity, see (*Nickolaenko and Hayakawa, 2002*, p. 269–282). About 95% of this activity concentrates into three tropical areas, namely central Africa, the Amazonia (the estuary of the Amazon river) and Sunda islands (Indonesia). At each of the three foci mentioned, the thunderstorm activity is culminating every day at about 14–15 UT, 20–21 UT and 9–10 UT, respectively (13–14 local time). For an European observer, the central African focus plays the superior role.

This permanent Schumann resonance "background" is sometimes overraised by short-time (transient) signals. These signals are stronger in amplitude, if we consider the direct (time-dependent) Schumann eigenmode field. But in spectrum, usually taken over a longer time interval, these "excursions" can be partly hidden. Among the terrestrial sources, the characteristic events called Q-bursts and flashes are typical.

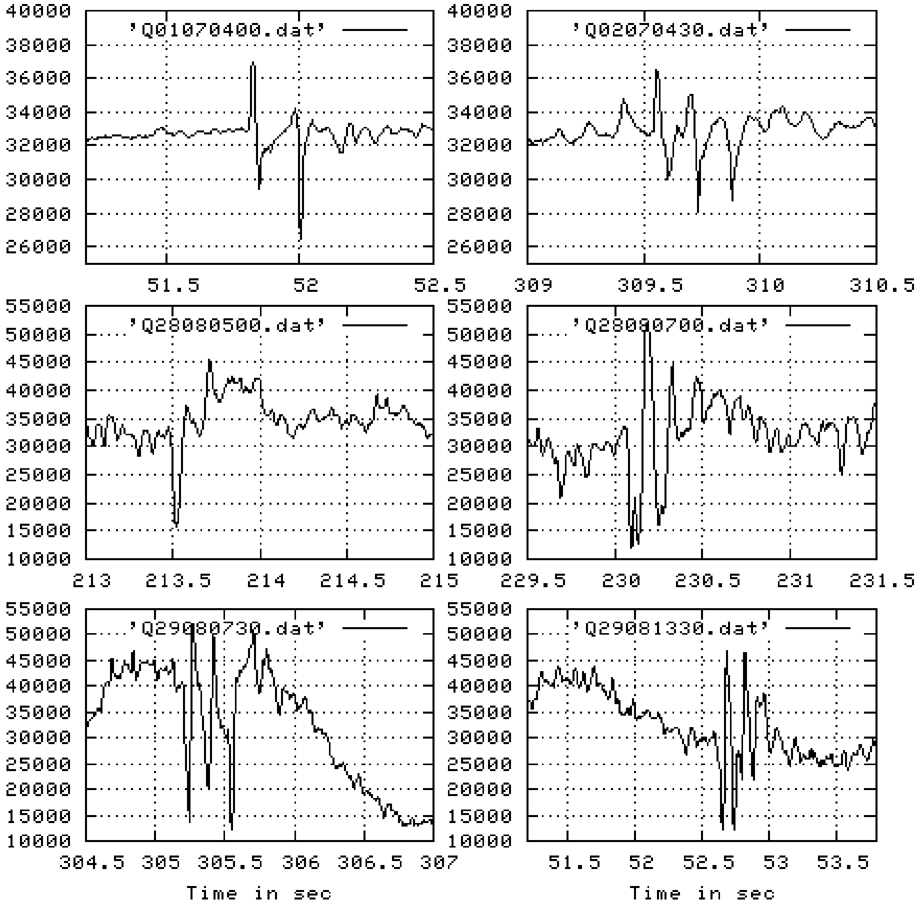

Fig. 1. Some examples of observed Q-bursts waveforms (during July and August 2004) in electric field components. The horizontal axis marks represent time (in seconds) from the beginning of measurement interval. The vertical axis is graduated in quantization sample number (the range from 00000 to 65535 correspond to output voltage from –2.5 to +2.5 V).

2.1. The Q-bursts

Their name was adopted from "quiet burst", because their onset was very abrupt, without any signs of "precedence phase". But the principal feature of Q-bursts is their "two-peak" time structure. Their typical time waveforms are illustrated in Fig. 1. This time dependence is obviously most prominent in the vertical electric field component, as the “quasi-oscillatory” part of waveform between the maxima.

The time difference between the maxima is a very important characteristic. Usually this quantity does not exceed $0.25-0.3$ s. On the contrary, the flashes usually manifest themselves (in time waveform) as oscillatory processes with approximate exponential damping, lasting a longer time (up to $1-2$ s). The amplitude of a flash signal exceeds the “normal” Schumann resonance background by orders of magnitude. The sources of such transient signals (flashes) are mostly the near centres of lightning activity (up to $1000-1500$ km), whereas Q-bursts originate from more distant powerful strokes.

For such sources, it is possible to resolve the inverse problem, therefore, it is possible to compute the frequency spectrum from the moment of excitation current.

To calculate the electric and magnetic field in the resonator excited by a vertical current with momentum M_c

$$\vec{j}(r,\theta,\varphi) = \frac{\vec{r}}{|\vec{r}|} M_c \frac{\delta(r-r_s)\,\delta(\theta)\,\delta(\varphi)}{r^2 \sin\theta},$$

situated at the pole of spherical coordinate system ($\theta = 0$), it is convenient to use scalar Stratton-Chu integral equation (*Stratton, 1961*, p. 538, 562), (*Galejs, 1972*, p. 139). This equation can be, in the case of longitudinal (TEM) waves, written in the form:

$$\begin{aligned} E_r(\vec{R}) = &- \frac{i\omega\mu_0}{4\pi} \int_V j_r(\vec{r_s}) G(\vec{R}-\vec{r_s}) d\vec{r_s} - \oint_S \Big[E_r(\vec{r_s}-\vec{r}) \mathrm{grad}_r G(\vec{R}-\vec{r}) - \\ &- E_\theta(\vec{r_s}-\vec{r}) \mathrm{grad}_\theta G(\vec{R}-\vec{r}) \Big]\, d\vec{r}, \end{aligned} \tag{1}$$

where $E_r(\vec{r})$ is the vertical electric field component, $j_r(\vec{r})$ is the vertical component of source current, and $G(\vec{r}-\vec{r'})$ stands for the Green's function, which must be appropriate to the boundary conditions. The first integral is taken over the resonator volume, the second one over the lower resonator boundary (the Earth's surface). The Green's function can be (in the case of a spherical cavity) expanded into spherical harmonic functions. For a uniform cavity, the n-th term is:

$$G_n(\vec{r}-\vec{r_s}) = \pi n(n+1) \frac{w_n(kr,ka)\, w_n(kr_s,kb)\, P_n(\cos\theta)}{4n\pi r r_s \epsilon_0 \mu_0 \omega^2 \sin(n\pi)} \tag{2}$$

where, for the sake of brevity, the quantity $w(r_1, r_2)$ is assumed:

$$w(r_1, r_2) = r_1 h_n^{(1)}(r_1) \frac{d}{dr_2}[r_2 h_n^{(2)}(r_2)] - r_1 h_n^{(2)}(r_1) \frac{d}{dr_2}[r_2 h_n^{(1)}(r_2)]. \tag{3}$$

Notations $h_n^{(1)}$ and $h_n^{(2)}$ are the spherical Bessel functions of the first and second kind, a is the radius of the (spherical) Earth, b is the radius of the lower ionosphere boundary, $\vec{r}$ is the radius vector of the integration point, $\vec{r_s}$ is the same for the source, and $\vec{R}$ for the observer.

The scalar integral equation (1) describes originally the diffraction of electromagnetic waves on a sphere. This is relevant to the existence of two terms in (1): the volume integral and the surface one. To express the field of eigenmodes in a spherical cavity, the Stratton-Chu integral equation can be used with the appropriate Green's function.

For a general non-uniform cavity (with variations of surface impedance or variations of the effective ionospheric height – provided that it is very small compared to Earth's radius – or both) it is impossible to express the Green's function of the problem in the closed form.

The only possibility is to use numerical solution or to employ some simplified analytical method (*Nickolaenko and Hayakawa, 2002*, p. 191–199).

2.2. The distance to the source

The result of the analysis shortly described in Section 2.1 states that the distance to the isolated source of the event (Q-burst) can be estimated:
– from the time interval between the two maxima of the signal (see Fig. 1);
– from the period of oscillations at waveform between these maxima;
– from the spectrum of Poynting vector (only in the case when the electric field component and two orthogonal magnetic field components are recorded simultaneously).

The first estimate is based on the fact, that two subsequent maxima in time represent arrivals of wavefronts propagating directly to the observer (direct wave) and around the globe (antipodal wave). It is worth mentioning that, due to the wide spectrum of the original signal, there was a significant difference from the case of a narrow-band signal (*Makarov et al., 1994*). The second, less reliable estimate can use the "quasi-sinusoidal" oscillations in time waveform between the direct and antipodal signal maxima. Such

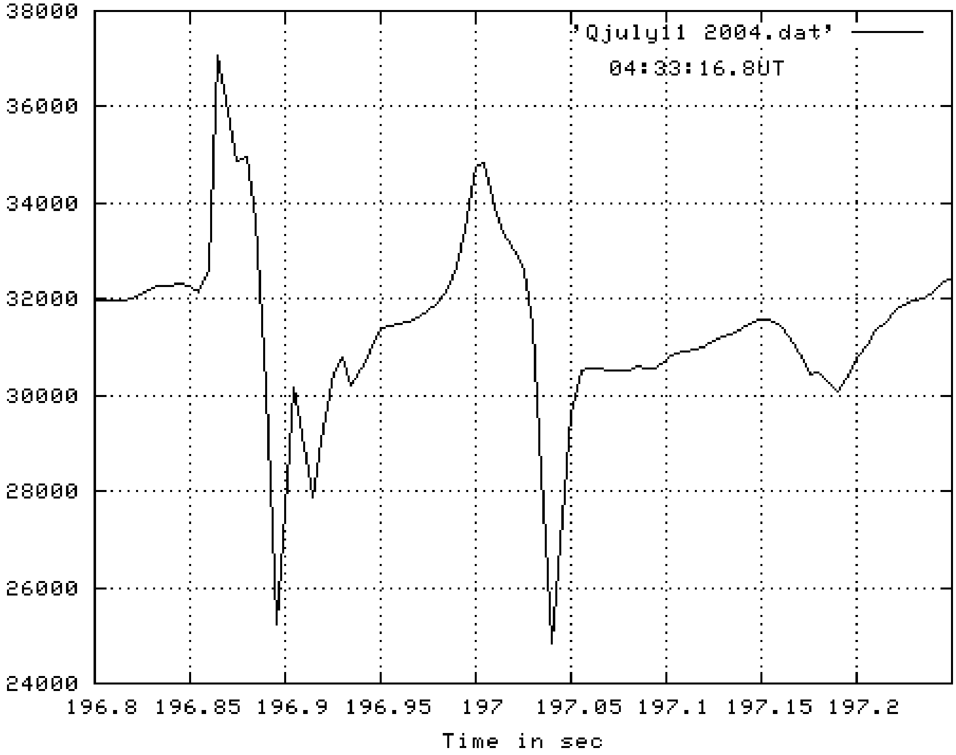

Fig. 2. The July 11, 2004 Q-burst waveform. The horizontal width is 0.5 s, starting from 04:33:16.8 UT, the vertical marking is analogical to Fig. 1.

oscillations are very often observable during Q-burst (see Figs 1, 2) and are related to the periodic variations of propagation (wave) impedance. In fact, it is difficult to determine frequency from several (3–4) periods of wave impedance oscillations, even with moderate accuracy. The semi-empirical formula (*Burke and Jones, 1996*) gives the estimate of the source distance D in the Earth's circumference units:

$$D/L = 0.5(1 - 6/f_0), \tag{4}$$

where D is the estimated source-observer distance, L is the Earth's circumference and f_0 the frequency of wave impedance oscillations in Hz.

Analogical, but more reliable, estimate can be made from Poynting vector frequency spectrum. Moreover, if the both orthogonal magnetic field components are recorded simultaneously, the approximate direction (bearing) to the source can be determined.

2.3. Records of Q-bursts at Modra observatory

At the Modra observatory, during more than two years of regular Schumann resonance observations (the vertical electric field component), numerous Q-bursts have been detected. For the overall description of hardware and the signal processing methods, see (*Kostecký et al., 2000*) and (*Rosenberg, 2004*). The spectra were produced from the time series of 65,536 samples taken at 200 Hz sampling frequency. The corresponding time interval is about 5.5 minutes.

In order to study the dynamical (in time) evolution of spectra, we used the method of division of the complete time series into 16, 32, 64 and 128 adjacent subintervals (frames). The spectra (with poorer frequency resolution, naturally) were determined for each subinterval and results have been compared. The use (and results) of such technique is described in the next section.

2.4. The strong Q-burst on July 11, 2004

On July 11, 2004, an extraordinary strong Q-burst (with all characteristic features) was detected. The appropriate part of the time waveform is shown in Fig. 2. The first (negative in Fig. 2) maximum occurred at 04:33:16.9 UT, the interval between direct and antipodal wave arrival was almost exact 0.135 s. The record of the complete time series is shown in Fig. 3 (above left), the Q-burst waveform itself (in finer time resolution) is given in Fig. 3 (bottom left). The third maximum, somewhat blurred, but clearly distinguishable, delayed by 0.290 s after the first one, corresponds to the original pulse after two orbits around the Earth. The traces of wave impedance oscillations are also visible (immediately after the first negative maximum), but, in this case, it would be impossible to determine the relevant period even with minimal precision. To achieve this, it would be necessary to pick up and analyse both the horizontal magnetic components simultaneously. Such measurements at Modra observatory are only in a testing phase now.

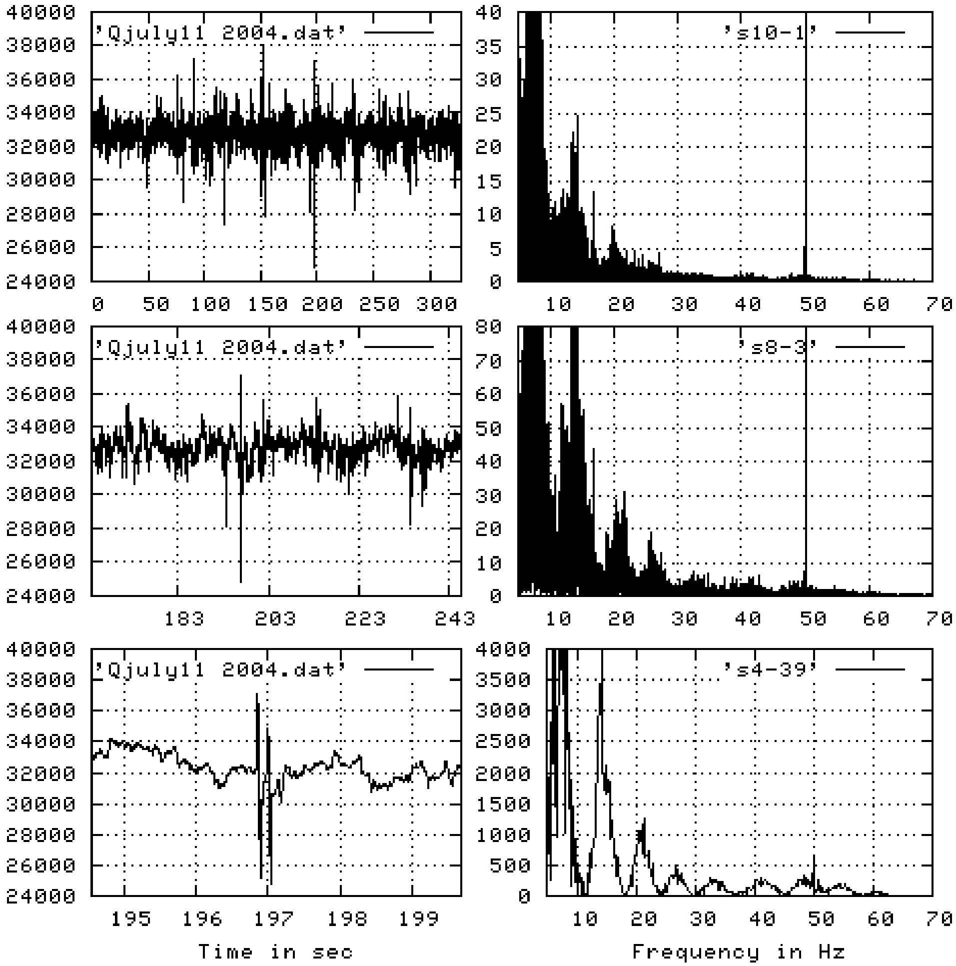

Fig. 3. The partial time waveforms and associated frequency spectra for the studied Q-burst. Left from above: the complete time waveform (327.7 s long) the third frame (out of 4 ones), 82 s long; the 39th frame (out of total 64), 5.12 s long. Right from above: the corresponding spectra (in the same order).

Therefore, an attempt to estimate the source distance can be based only on the time difference between the arrivals of the direct and (first orbit) antipodal waveform, which is highly unreliable (the bandwidth of the analog part of signal processing chain is about 80 Hz, the sampling interval is 5 ms). Very crude estimate is about 4000–6000 km. If we adopt this value, together

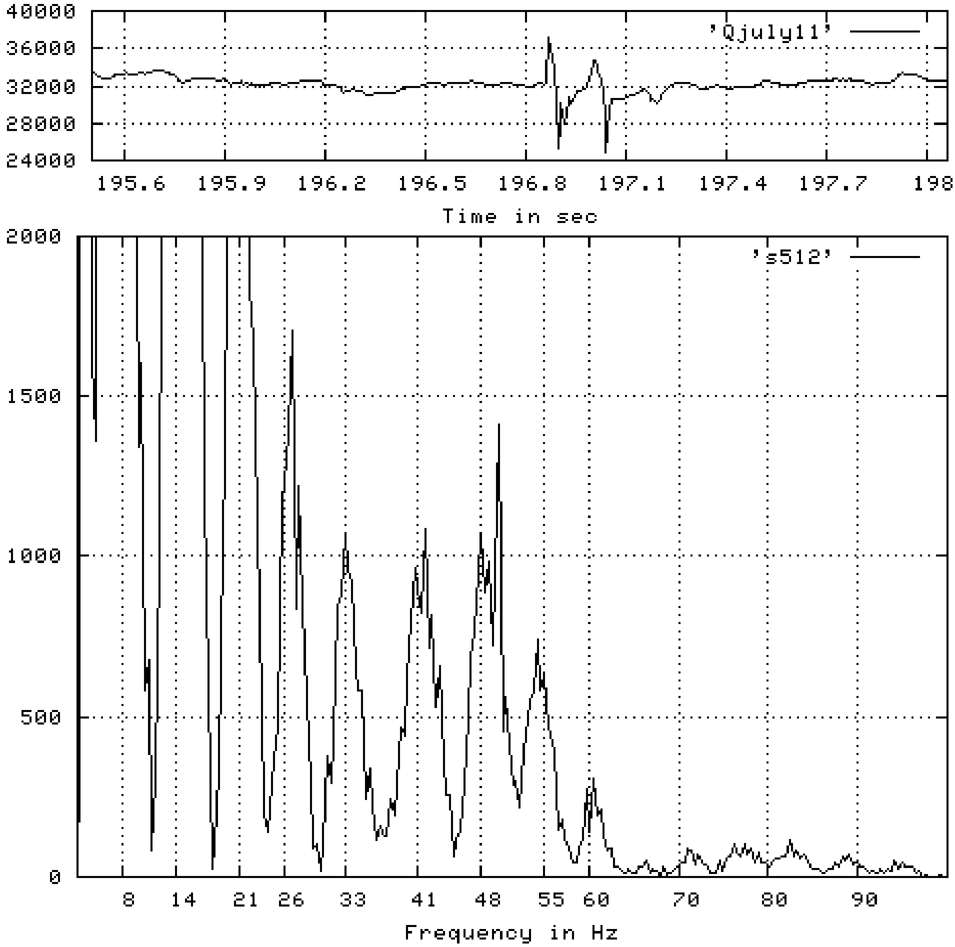

Fig. 4. Above: the partial time waveform – frame 78/128, 2.54 s long. Below: the corresponding frequency spectrum (the vertical axis in relative units). On horizontal axis, the approximate frequencies of individual eigenmodes are marked. The eigenmodes up to the 10th are present, except the 6th (at approx. 36 Hz).

with the time of the event 04:30 UT, one can guess that the responsible source was a very powerful discharge over the western part of the Indian ocean. This is only a guess. The only thing that can be stated is that the source was well outside the European continent and adjacent seashelf.

As mentioned before, the complete time interval 327.68 s wide was divided subsequently into 16, 32, 64 and 128 frames. For each frame, the frequency spectrum and relative amplitude of subsequent (discernible) eigenmode peaks were computed. Some results are shown in Figs 3 and 4. During the burst (the frame 39/64 and 78/128) all eigenmodes up to the 10th were excited, except the 6th eigenmode (frequency about 36 Hz). It is worth mentioning that, irrespective of the number of modes excited, their peak amplitudes are still monotonically decreasing with mode number. It seems that it is possible to explain the absence of one mode by the geometrical relations between the source and observer.

3. Conclusion and prospection for future

We confirm that by means of the system for monitoring Schumann resonances at Modra observatory it is possible to detect and analyse Q-bursts (at present, in the electric field component), together with their fine structure. During enhancement of part-time spectra due to Q-burst phenomena, the monotonic decrease of eigenmode amplitudes with respect to their order is preserved. Some of eigenmodes can be even more suppressed or virtually absent, and this fact can be attributed to geometrical relations between the source and observing site.

Concerning the directions of future research, these will be focused into two principal directions: to upgrade the observatory SchR hardware and software for simultaneous recording and analysis of all three principal field components (with sufficient precision) and to perform numerical modeling of the Earth-ionosphere resonator as a non-homogeneous one, with a special emphasis on the source-observer geometry.

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