Investigation of the ULF electromagnetic phenomena related to earthquakes: contemporary achievements and the perspectives

Yuri Kopytenko (1), **Valery Ismagilov** (1), **Masashi Hayakawa** (2), **Natalia Smirnova** (3), **Vladimir Troyan** (3) **and Thomas Peterson** (4)

(1) *SPbF IZMIRAN, St. Petersburg, Russia*
(2) *The University of Electro-Communications, Chofu Tokyo, Japan*
(3) *Institute of Physics, St. Petersburg University, St. Petersburg, Russia*
(4) *TFPLAB, Cleveland, Ohio, U.S.A.*

Abstract
The results of ULF electromagnetic signal observations in seismoactive regions prior to earthquakes are presented and discussed. The new differential measurement technique developed in SPbF IZMIRAN for location of the ULF emission sources of space and lithosphere origin is described. The MVC-2DS geophysical instrumentation is introduced as a promising tool for registration of ULF signals related to earthquakes (both seismic and electromagnetic ones). Methods are proposed for ULF data processing to investigate the preparation processes in the earthquake source regions and to distinguish seismogenic signals on the background of space pulsations. Some examples of application of those methods for study of the earthquake precursory signatures are presented. Perspectives of seismo-electromagnetic tomography experiments in seismoactive regions, using MVC-2DS technique, are discussed in relation to the development of earthquake prediction methods.

Key words *earthquake precursors – ULF emissions – fractal analysis – self-organized criticality – geophysical tomography*

1. Introduction

Extraction of the earthquake precursory signatures from geophysical time series is now considered to be a promising tool in the development of earthquake prediction methods. A large amount of geophysical data has been analyzed by researchers of different countries around the world, using a variety of mathematical methods (see, for example, Di Bello *et al.*, 1996; Cuomo *et al.*, 1997, 1998; Lapenna *et al.*, 1998; Vallianatos and Tzanis, 1999 and also the proper papers in the recent monographs by Hayakawa and Fujinawa, 1994, and Hayakawa, 1999). Here we introduce our experience in the study of the ULF electromagnetic effects related to earthquakes. This presentation can be considered as a summary of our recent papers on that subject (see Kopytenko *et al.*, 1999a,b,c, 2001; Hayakawa *et al.*, 1999, 2000; Troyan *et al.*, 1999; Smirnova, 1999; Smirnova *et al.*, 1999).

2. Justification of the ULF emission study in relation to earthquakes

It is now widely accepted that the earthquake preparation processes consist of not only seis-

Mailing address: Dr. Yuri Kopytenko, SPbF IZMIRAN, St. Petersburg 191023, Russia; e-mail: galina@gh5667.spb.edu

mic (tectonic, elastic) but also electromagnetic events (Hayakawa and Fujinawa, 1994; Hayakawa, 1997, 1999). Such electromagnetic phenomena could appear in a wide frequency range, from DC up to MHz frequencies. In our approach, we direct attention to ULF (0.005-10 Hz) electromagnetic waves, since in ground-based observations we consider this band as a most promising frequency range where electromagnetic earthquake precursors might be found. The following supporting arguments can be considered:

1) The skin-depths for ULF waves cover all expected earthquake source depths. Actually the skin depth for the plane ULF wave with period T in the Earth's crust of resistivity ρ may be written as $\delta = \sqrt{10^7 \rho \cdot T/2\pi}$ (Kovtun, 1980). Taking into account that the resistivities normally encountered in the Earth are in a range from 1 to 10000 $\Omega \cdot$m, one can conclude that the ULF waves with periods from 0.1 to 200 s can cover the depth from 0.2 to 700 km which includes all depths of earthquake sources. These ULF waves of space origin (geomagnetic pulsations) have been successfully used in magnetotelluric methods for remote sensing of the Earth's crust conductivity. Since the earthquake preparation process can lead to a change in the crust resistivity, it can affect behavior of the ground observed ULF fields. The higher frequency waves (ELF, VLF emissions) cannot deeply penetrate the Earth's crust and are not affected by the alteration processes of the earthquake focal zone. The lower frequency fluctuations of space origin (geomagnetic variations) can penetrate to the earthquake depths (and even deeper), but their fields integrate electromagnetic effects over a wide space region in the Earth's crust. So, effects of local earthquake sources could be masked by such low frequency geomagnetic variations.

2) Dynamic processes in the earthquake preparation zones can produce current systems of different kinds (see *e.g.*, Molchanov and Hayakawa, 1995 and references therein) which can be local sources for electromagnetic waves at different frequencies, including ULF. High-frequency waves attenuate so rapidly that they cannot be observed on the Earth's surface, whereas ULF waves can propagate through the crust and reach the Earth's surface. So, in ground-based observations, we could expect some ULF signals of seismic origin. In both cases ULF waves carry information on the alteration processes in the Earth's crust. Therefore, the probability of earthquake signature manifestation seems to be much higher in the ULF range than in the other frequency ranges. That is why we focus on the study of ULF emissions.

3. Specific ULF electromagnetic signals before the earthquakes: former studies

Pronounced ULF emissions, presumed to be of lithosphere origin, were first independently registered by Kopytenko *et al.* (1990, 1993) before the Spitak (Armenia) earthquake of 8 December 1988 ($M_s = 6.9$) and by Fraser-Smith *et al.* (1990) prior to the Loma Prieta earthquake of 17 October 1989 ($M_s = 7.1$). The measurement techniques used by Russian and American groups differ by their respective use of: a three-component «magneto-variational» instrument, and a one-component induction coil magnetometer. Distances from their observation points to the epicenters also differ (130 km for Spitak EQ and 7 km for Loma Prieta EQ). Nevertheless, the authors reported a nearly similar behavior of the ULF emissions relating to both earthquakes. The signals appeared as burst-like emissions or broadband noise in the frequency range of 0.01-10 Hz with amplitudes near 1 nT. The precursory times were of the order of a few hours. There were also some differences in the signal properties, which have been discussed in details by Molchanov *et al.* (1992). Later, similar specific ULF signals were detected in Georgia before the $M = 6.9$ Racha earthquake of 29 April 1991, prior to its strong aftershock of 15 June 1991, and even before the moderate aftershocks (see Kopytenko *et al.*, 1994b). The authors referred to these ULF emissions as ULE – Ultralow-frequency electromagnetic Lithospheric Emissions. These emissions were observed up to 200 km from the epicenter as noise-like bursts or quasisinusoidal signals in the range 0.1-10 Hz with amplitudes varying up to 2 nT. The duration of ULE ranged from several minutes to several hours. The most prominent feature of ULE, which distinguishes them from ULF emis-

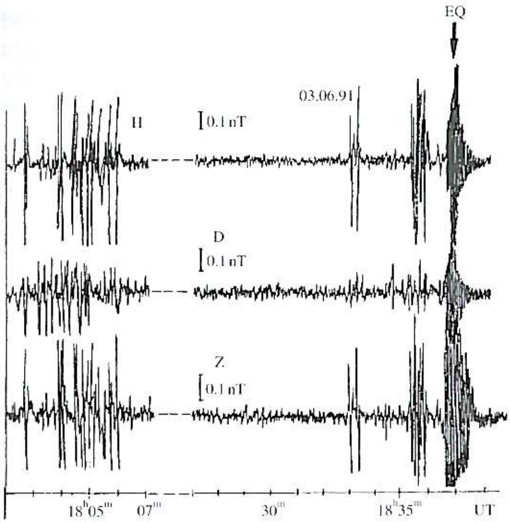


Fig. 1. An example of the ULE - Ultra-low frequency Lithospheric Emissions registered prior to the moderate ($M = 4$) Racha aftershock of 3 June 1991 (marked as EQ). The observation point (Nikortsminda station) was located about 40 km from the epicenter.

sions of space origin, is their rather high polarization ratio Z/H ($Z/H > 1$). Hence, the ULE are mainly Z- (vertical) polarized, whereas in the ULF emissions of space origin the H- (horizontal) polarization is more typical. In fig. 1 an example of such ULF emissions registered at the Georgian station Nikortsminda prior to one of the aftershocks of the Racha earthquake is shown.

The time of the earthquake (EQ) of magnitude $M = 4$ is marked by an arrow. One can see the intensive ULF electromagnetic bursts prior to the seismic shock. The first bursts (which cannot be seen in the figure) appeared approximately 1.5 h before this event and then receded around 0.5 h prior to the earthquake, as seen in fig. 1. They reappeared just before the shock as noise-like bursts with duration of nearly one minute. One can see also that the burst intensities in Z and H components are comparable (which are not typical for ULF emissions of space origin). Such specific behavior of the ULE allows us to consider these signals as short-term earthquake precursors.

4. The advanced ULF measurement technique and MVC-2DS instrumentation

The problem of the ULF emission source location is one of the principal problems in connection with study of the ULF electromagnetic phenomena related to earthquakes. Its solution would allow us to distinguish the inputs of magnetospheric and lithospheric sources into the ground-observed ULF fields. The common sources for ground-observed geomagnetic pulsations of space origin could be pulsating current systems in the ionosphere E regions. Such current systems are usually localized and connected with the resonance field tubes of the magnetosphere, where the eigenfrequency of the local field line coincides with the frequency of the initial ULF waves generated far away, presumably in the solar wind, on the magnetopause or inside the magnetosheath (for details of theoretical and experimental studies of the field line resonance see, for example, Kivelson and Southwood, 1986; Ziesolleck *et al.*, 1993; Pilipenko and Fedorov, 1993 and references therein).

A new method for locating such ULF emission sources has recently been developed at SPbF IZMIRAN. It is based upon differential measurements of the amplitudes and phases of geomagnetic field variations using a group of three magnetic stations. A detailed description of the method is presented by Kopytenko *et al.* (1999a,c). Using this method, it is possible to determine the direction of the ULF field gradient, and thus the direction to the ionospheric (or lithospheric) ULF current system. A diagram of gradient measurement experiment is shown in fig. 2. A gradient measurement technique consists of two sets of gradient magnetometer instrumentation separated by a distance of 100-500 km. This distance is chosen to be consistent with both the wavelengths of ULF geomagnetic pulsations and the typical distances to ULF ionospheric current systems. Each instrumentation consists of three high-sensitivity digital geophysical stations MVC-2DS for measurements of the H, D, and Z components of the ULF geomagnetic fields. MVC-2DS instrumentation is placed on the Earth's surface at the corners of a triangle with sides of 4-6 km length (points

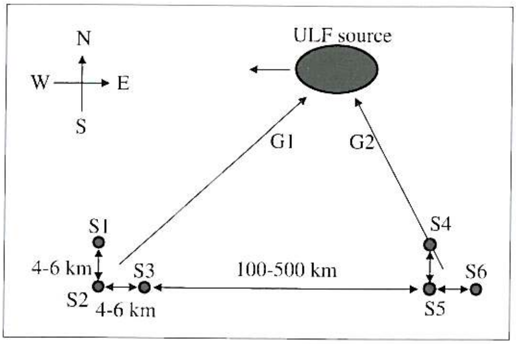


Fig. 2. Diagram of a gradient measurement experiment to determine the location of the ULF emission source. The points S1-S6 show the positions of the measuring MVC-2DS stations. G1 and G2 are the directions of the ULF magnetic field gradients, which point to the projection of the ULF source on the Earth's surface.

S1-S3 and S4-S6 in fig. 2). Since the distance to the ULF source current system is much greater than the distance between observation sites, the wave phase fronts, in the vicinity of each MVC-2DS instrumentation, can be approximated as plane surfaces.

In this case the directions of field gradients G1 and G2, from two observation points, vector toward the ULF source. Those directions can be located with two methods: from the wave phase delays (eq. (4.1)) and from differential values of the ULF magnetic field components (eq. (4.2)):

$$\mathrm{tg}(\alpha) = \frac{(y_3 - y_1)t_{12} - (y_2 - y_1)t_{13}}{(x_2 - x_1)t_{13} - (x_3 - x_1)t_{12}} \tag{4.1}$$

$$\mathrm{tg}(\beta) = \frac{(y_3 - y_1)\Delta B_{12}(t) - (y_2 - y_1)\Delta B_{13}(t)}{(x_2 - x_1)\Delta B_{13}(t) - (x_3 - x_1)\Delta B_{12}(t)} \tag{4.2}$$

Here x_1, y_1, x_2, y_2, x_3, y_3 represent the coordinates of three magnetic stations of the gradientometer; $t_{12} = t_2 - t_1$, $t_{13} = t_3 - t_1$ are the time delays of the wave front arrival to magnetic stations 2 and 3 in relation to the base station 1; α is the angle between the geomagnetic north direction and the wave propagation vector. ΔB_{12} and ΔB_{13} are the corresponding differences of the magnetic field components (H, D, Z) measured at stations 2 and 3 in relation to station 1; β is the angle between the direction to the geomagnetic north and the direction of magnetic field component gradient.

It is important to use the GPS system and numbering frequency of the order of 50 Hz to provide the precise measurements of the ULF wave phase delays. According to Saka and Kim (1985), the phase difference for *Pc* 3-4 would be of the order of one degree, which corresponds to time delays of 140 ms for the typical pulsation period $T = 50$ s. The recent measurements made in the field conditions of Karelia (Russia), using this technique, showed its efficiency and allowed to estimate the horizontal velocities of the ULF wave from the ionospheric source. Those velocities appeared to be of the order of 10-50 km/s.

A more detailed description of the gradient method and results of its application are presented in Kopytenko *et al.* (1994a, 1999a,c).

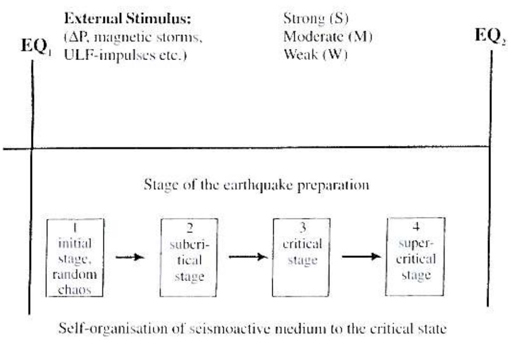
We consider this gradient measurement technique and the MVC-2DS instrumentation, as promising tools for the study of earthquake precursory signatures. The MVC-2DS measuring system provides high sensitivity over a wide frequency range from 0 to 10 Hz, under observatory and field conditions, without requiring a special antiseismic pillar (see Kopytenko *et al.*, 1997, for details).

The MVC-2DS instrumentation has recently been installed in Japan in a seismoactive region of Izu peninsula. Preliminary results of the ULF data analysis in relation to the swarm of local earthquakes of April-May 1998 have been reported by Kopytenko *et al.* (1999b, 2001). Some of these results will be presented and discussed in the next section.

5. Electromagnetic earthquake precursory signatures in the ULF range: recent studies

The pronounced ULF signals registered before earthquakes by the groups of Kopytenko and Fraser-Smith, as described above in Section

3, may be presumed to be of seismic origin and could be considered as short-term precursory phenomena. Nevertheless, for seismic hazard evaluation and earthquake prediction, it is also of great importance to study the long-time evolutionary processes in the potential earthquake focal zone, in order to understand the earthquake preparation dynamics. For this, the SOC (Self-Organized Criticality) concept developed by Per Bak (Bak *et al.*, 1987; Bak, 1997), contemporary models of earthquakes (the dilatancy-diffusion model (Anderson and Whitcomb, 1973), and the model of avalanche-unstable crack formation (Mjachkin, 1978) as well as kinetic theory of fracturing and crack dynamics by Czechowski, 1991, 1995, could all supply the background for interpretation of scaling characteristics of the ULF fields and the search for the long-term precursory signature of earthquakes in the ULF time series. Considering an earthquake as the critical phenomenon, we suggest a phenomenological model of large-scale evolutionary processes between two violent earthquakes (see Troyan *et al.*, 1999 for model details). We consider four stages in the earthquake preparation process: initial (random chaos), sub-critical, critical and supercritical (see fig. 3, the middle part).



Expected Earthquake Effect

(S = strong earthquake, M = moderate earthquake, W = weak earthquake)

Stage / Ext. Stimulus	I random chaos	II subcritical stage	III critical stage	IV supercritical stage
Strong	—	M	S	S
Moderate	—	W	M, S	M, S
Weak	—	—	W, M	M, S
No	—	—	—	W, M, S

Fig. 3. Sketch to explain the phenomenological model of large-scale evolutionary processes occurring between two violent earthquakes $EQ_{1,2}$.

The expected earthquake effect, which depends on the stage of the earthquake preparation and on the intensity of the external stimulus, is marked in the table at the bottom of fig. 3. Many anomalous environmental phenomena, such as sharp atmospheric pressure gradients across fault zones, or geomagnetic storms, can be considered as stimuli for earthquakes (Sytinsky, 1985). The initial stage (or relaxation phase) is characterized by the state of random chaos, since the stress energy accumulated before the first earthquake is completely released during the earthquake. In this stage any external stimulus cannot cause earthquakes. In the process of self-organized evolution of the system to the critical state, it reaches step-by-step sub-critical, critical and super-critical stages. In the last stage it is not necessary to stimulate the system – it explodes by itself. All earthquake intensities, from weak to violent, are very probable in this super-critical stage (see the last column in the table at the bottom of fig. 3).

A principal feature of the SOC is a fractal organization of the output parameters, both in space (scale-invariant structure) and in time (flicker noise or 1/f noise). Therefore, we expect the possibility to use fractal methods to investigate dynamic processes in the hazard system of earthquakes – at different stages of the catastrophic event preparation. We can also analyze the dynamics of polarization characteristics in ground-observed ULF pulsations, since they can reflect resistivity changes in the Earth's crust beneath the observation site.

The most detailed analysis of such a long-term evolution of the ULF emission parameters has been fulfilled for the strong ($M_s = 8.0$) Guam earthquake of August 8, 1993 (Hayakawa *et al.*, 1996, 1999; Smirnova *et al.*, 1999). The epicenter of the earthquake was located in the sea near Guam Island at a depth of 60 km. ULF magnetic data were obtained at the Guam observatory which was located only 65 km from the earthquake epicenter. Three components of magnetic variations (*H*, *D*, and *Z*) are usually recorded on a digital cassette tape, at a sampling rate of 1 s. More than a half-year period has been studied to investigate the evolution of the ULF characteristics (ULF activity, *Z/H* polarization, spectral structure and fractal properties) before and after the earthquake.

A typical daily record of geomagnetic field variations at Guam observatory is presented in fig. 4. The original ULF signals (with one-second sampling rate) are shown in the insertion for the noon 1-h interval.

Comparison of ULF activity with the planetary index of geomagnetic activity K_p (see K_p dynamics in the upper part of fig. 5) showed that rather high ULF wave activity occurred one month before the earthquake without any pronounced geomagnetic activity. It has been supposed by Hayakawa *et al.* (1996) that those emissions could be of seismic origin and related to earthquake preparation processes, since the previous ULF emissions, registered 3-4 months before the earthquake, were usually in correlation with geomagnetic activity. Such correlation is typical for ULF emissions of space origin.

The dynamics of the polarization ratio Z/H for the Guam ULF data, is presented in the lower part of fig. 5. It is easy to see a long-period variation of the *Z/H* ratio, and its gradual increase, one to two months before the earthquake. Such dynamics is independent of geomagnetic activity (as it is seen from fig. 5) and may therefore indicate the gradual increase in resistivity beneath Guam Island, due to the process of new crack formation, starting approximately two months before the earthquake. Recent measurements carried out in Japan (Izu Peninsula) using the MVC-2DS system, also showed the specific variations of the polarization ratio *Z/H*, *Z/D* in relation to the nearby earthquake swarms of April-May 1998. In fig. 6 the dynamics of *Z/G* ratio (*G* is the total horizontal component of pulsations $G = \sqrt{H^2 + D^2}$) is presented on a background of the swarms of earthquakes with magnitudes $M > 2.5$.

The corresponding dynamics of geomagnetic activity is shown in the upper part of fig. 6.

The observation point (Kamo) was situated about 30-40 km off the earthquake epicenters.

It is seen from fig. 6 that the seismoactive period of April-May 1998 consists of two earthquake swarms divided by a calm, lasting nearly four days. The largest earthquakes of the first and second swarm occurred on April 26 ($M_S = 4.7$) and May 3 ($M_S = 5.7$) correspondingly. Around

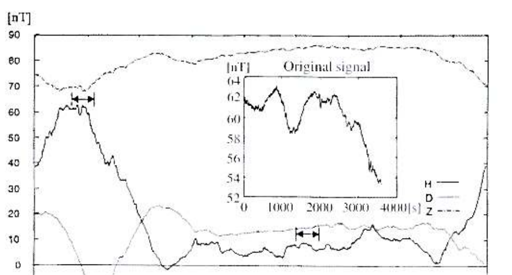


Fig. 4. A typical daily record of geomagnetic field variations (*H*, *D*, *Z* components) at Guam observatory (one-minute sampling). Two local times (noon and midnight) are indicated for further analysis. The original ULF signals (one-second sampling) at noon are shown in the insertion.

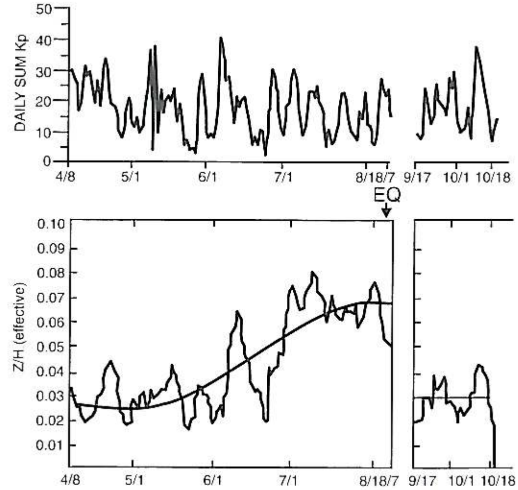


Fig. 5. Dynamics of the K_p index (upper part) and the ULF emission polarization ratio *Z/H* (lower part) before and after the Guam earthquake of August 8, 1993. The ULF data are the 5-day running averaged over midnight (22-02 LT) interval. An arrow marks the time of the earthquake (EQ).

these dates the sharp increase in geomagnetic activity took place also. So, effects of the earthquakes and geomagnetic activity can be manifested together in the properties of ULF emissions.

The detailed description of the field experiment in Japan and its result is presented in Kopytenko *et al.* (2001). The principal peculiarities revealed can be summarized as follows:

1) The ULF magnetic activity increased sufficiently just before the main shock of $M_s = 5.7$ on 3 May 1998, which can be connected both with earthquake preparation processes and with sharp increase of geomagnetic activity.

2) Specific variations of the ULF pulsation polarization ratio (*Z/H*, *Z/D*, and *Z/G*) were revealed before, during, and after the earthquake swarms. The following behavior of that ratio has been observed: First, the ratio increased gradually, starting approximately 20 days before the earthquake swarms and reaching its maximum two days before the first swarm (see fig. 6). Then, the ratio decreased gradually during the time of the first earthquake swarm and reached its minimum just at the time of the main seismic shock of $M_s = 5.7$. After that, the relaxation process took place as a return of the polarization ratio to nearly its initial value. One can also see the short-term (2-3 days) enhancement of *Z/G* ratio at the end of the first swarm and its local maximum during the calm between the earthquake swarms. So, the largest earthquake of magnitude $M_s = 5.7$ occurred during the deep minimum in the ULF polarization ratio.

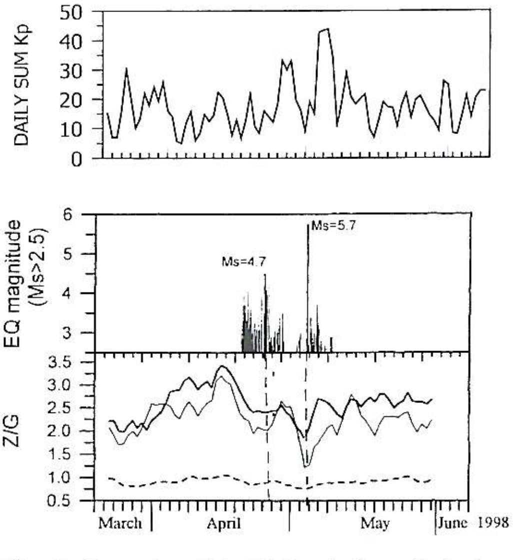


Fig. 6. Dynamics of the ULF emission polarization ratio *Z/G* (lower part) in relation to the nearby earthquake swarms of April-May 1998 (middle part) and geomagnetic activity variation (upper part). The ULF data (Kamo station, Izu Peninsula, Japan) are the 5-day running average over 00-04 LT interval. The frequency bands: $f = 0.002$-0.01 Hz - bold curve; $f = 0.01$-0.05 Hz - thin curve; $f = 0.05$-0.2 Hz - dashed curve.

3) Variations of the polarization ratio relating to earthquakes depend significantly upon frequency range. This is clearly seen in fig. 6. They are the most pronounced in the lower frequency bands of $f = 0.002$-0.01 Hz (bold curve) and $f = 0.01$-0.05 Hz (thin curve). Variations of the *Z/G* ratio are almost masked in the higher frequency range of $f = 0.05$-0.2 Hz (see the dashed curve in fig. 6).

Variations of the ULF emission polarization ratio could be connected with variations of the crust resistivity. This can be interpreted in the framework of the above mentioned earthquake models, if we take into account self-organized processes of crack formation and the porosity of the medium (see Hayakawa *et al.*, 2000). So, the decrease of the *Z/G* ratio before the main seismic shock (fig. 6) may correspond to an increase in the Earth's crust conductivity. This could be related to the process of filling in of porous space by fluids. In this condition the fracture threshold becomes lower and the probability of a strong earthquake increases. Variations of crust resistivity, in relation to earthquakes, have been mentioned by a number of other authors (see Park *et al.*, 1993).

It should be mentioned also that the above described dynamics of conductivity would be manifested in the ULF emission polarization ratio independent on the pulsation origin, even if we attribute the enhancement of the ULF emission activity before the main seismic shock to intensification of space pulsations in response to the sharp increase of geomagnetic activity.

The corresponding explanation can be found in Section 2. As it is seen from fig. 5, near the same dynamics of the polarization ratio is observed also before the Guam earthquake on the background of weak geomagnetic activity.

The other method, which was applied for the Guam ULF data processing, was a fractal analysis (Feder, 1988; Turcotte, 1997). It was found that the ULF spectrum manifests, on average, the inverse power law behavior $S(f) \sim f^{-\beta}$ which is typical for the SOC dynamics. The evolution of the ULF spectrum slope β in relation to the earthquake date for the noon sector (running average values over ± 5 days) is shown in fig. 7. One can see that β exhibits a tendency to decrease gradually while approaching the earthquake date.

Fractal dimensions of the ULF time series, calculated from the spectrum slopes β by using the relation $\beta = 5\text{-}2D$ (Turcotte, 1997), increase toward the value $D = 2$ prior to the earthquake. The appearance of both the higher-frequency fluctuations (appearance of the flicker noise in the ULF frequency range) and the increase in the fractal dimension D of the ULF time series can be considered as an earthquake precursory signature. More detailed analysis of the Guam ULF data, on the basis of a fractal approach, is reported in Hayakawa *et al.* (1999).

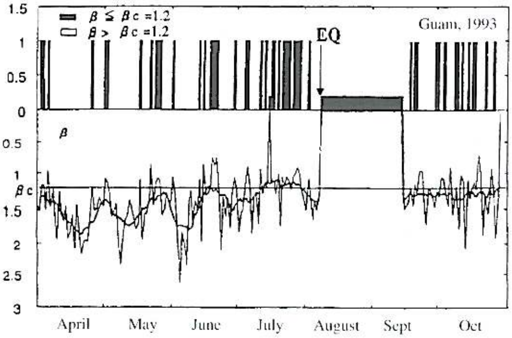


Fig. 7. Dynamics of the spectrum slope in the noon (12 h-13 h) sector (lower part). The black fields in the upper part denote intervals with slopes smaller than (or equal to) the critical one ($\beta = 1.2$).

6. Discussion: perspectives of the ULF emission studies in relation to earthquakes

The results presented here show that analysis of ULF geomagnetic data may provide important information on evolutionary processes in the earthquake region. Such information is expected to be more complete if we monitor not only ULF geomagnetic variations but also the ULF telluric currents and ULF seismic activity. This can be done using the geophysical system MVC-2DS. The current series of the MVC-2DS system provides additional inputs to carry out simultaneous measurements of electromagnetic and seismic variations. The MVC-2DS instrumentation provides a way to perform a seismic-electromagnetic tomography experiment in earthquake hazard regions. A theoretical and methodological basis for such an experiment could be geophysical diffraction tomography developed by one of the authors (see Troyan, 1999; Troyan *et al.*, 1999). Geotomography is an effective method for solving inverse geophysical problems for different types of geophysical fields (seismic, electromagnetic, and acoustic). The principal notion of geotomography is the tomographic functional, which has a sense of the influence function of various spatial regions on the measurement's geophysical data. The reconstruction algorithm of geotomography allows reconstruction of medium parameters (elastic, electric, etc.) from the set of measurement data for the network of geophysical stations. In our case of ULF study, the use of diffraction tomography methods, instead of a ray tomography approach, is of major importance, since in the ULF range, the wavelength is comparable with the characteristic value of the medium inhomogeneity.

Summarizing our experience, we outline the following perspectives for the investigation of ULF emissions relating to the study of earthquake preparation processes and catastrophic event prediction.

– Location of the ULF lithosphere current systems in seismoactive regions by use of MVS-2DS instrumentation and the gradient measurement technique. This allows us to distinguish the ionospheric and lithospheric ULF current systems.

– Development of mathematical methods for solving inverse geophysical problems (mainly geophysical diffraction tomography) and for ULF time series analysis (nonstationary fractal and other methods).

– Development of the methodology for ULF seismo-electromagnetic tomography experiments across fault zones, and for reconstruction of the elastic and electromagnetic parameters in potential earthquake focal zones.

– Modeling SOC processes and crack dynamics during the earthquake preparation stage.

– Continuous monitoring of meteorological and helio-geophysical conditions that could also be affecting earthquake zones.

On the basis of our experience we conclude that the ULF electromagnetic precursors do exist and that the development of suitable observational techniques and analysis methods is a promising research direction for earthquake precursor study.

Acknowledgements

The research was supported by NASDA's Earthquake Remote Sensing Frontier Project and by Russian Foundation for Basic Research under grants 98-05-65554 and 99-05-64127. At the final stage the work was supported also by Grant INTAS 99-1102.

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