Coordinated registration of seismogenic effects in the ionosphere by means of remote ground-based and local satellite measurements

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Abstract. The proposed goal of the project is to carry out the synchronous ground based and satellite study of the ionospheric earthquake precursors. A huge data array about the variations of upper atmosphere airglow, electromagnetic emissions, generation of plasma inhomogeneities and other ionospheric phenomena preceding an earthquake have been collected earlier. All these phenomena were considered as physically independent. Another standpoint is that the whole set of phenomena is mutually dependent. For instance, the generation of the electromagnetic earthquake precursors might be result of the trapping of natural VLF emissions into the seismogenic plasma ducts appearing above an earthquake epicenter. The goal of our project is to prepare a joint coordinated experiment onboard SICH-1M satellite ("Variant"-mission) supported by the ground observations in frames of the AIRUS project and active sounding of the ionosphere. Such synchronized experiment will allow to collect the database necessary for the verification of existing hypotheses. The high sensitivity of onboard scientific instrumentation will promote to the rise of reliability of the data, especially as to the separation of seismogenic "signals" from various ionospheric perturbations.

1. Introduction

There is a wide range of ionosphere-seismogenic phenomena, which are described in the literature. A part of these phenomena have been acquired by of *in situ* satellite measurements. Another part has been registered by remote sensing methods from the Earth surface (ionosounding, detecting of the subionospheric radio signal propagation, observation of the night sky optical emission, etc). These phenomena detected by ground-based and satellite-born methods are different. On ground we can explore the signatures showing the ionospheric plasma inhomogeneities generation in D, E, F layers. At the heights typical for satellites – above ionospheric F layer and in the magnetosphere – such signatures were not observed. Instead, satellites register specific density variations, electromagnetic emissions as well as the fluxes of precipitating energetic particles that can not be observed from the ground. Therefore, the data relating to the ionospheric earthquake precursors constitute two heterogeneous groups: the data of satellite-born and the data of ground-based remote observations.

The natural assumption is that these various types of ionospheric earthquake precursors are interconnected appearing as a signature of a single physical process. Unfortunately, database collected is not sufficient to reveal the nature of this process. It is essentially incomplete because only *isolated ionospheric effects of individual seismic events* have been detected until recently. Moreover, all these effects have been recognized retrospectively as an additional output of experiments aimed at the study of the other phenomena, mainly the signatures of solar-terrestrial events. The latter are best noticeable in auroral zones of the magnetosphere where the weak seismogenic impact is practically impossible to extract. At the middle latitudes the solar activity is lower and masks less the seismogenic effects, however at these latitudes payload instrumentation is switched on only occasionally. Besides, the sensitivity of instrumentation designed for the measurements in the polar ionosphere is not sufficient for mid-latitude measurements. Therefore, the satellites only in rare cases registered the earthquake effects.

Still one problem is the “seismogenic signals" extraction from the ionospheric perturbations of the other nature. Today we can’t be certain whether we have regular manifestations of lithosphere-ionosphere coupling or some accidental coincidences of seismic and ionospheric activities occurred (Parrot, 1999). The only way toward the progress in this direction is to prepare and carry out high sensitive regular satellite observations in the ionosphere over seismically active and seismically quiet regions supported by on-ground observations and active sounding what will allow to create a database for the statistical study of slight seismogenic effects and their comparison with the statistical background noise.

In the nearest future several satellite missions will be launched forming a cluster of ionospheric satellites, namely, DEMETER, SICH-1M and the TIMED mission. The two first missions are dedicated to the search of ionospheric earthquake signatures. The scientific payload of the TIMED mission also permits to detect seismogenic perturbations (although this is not a claimed goal of the mission). Other opportunity is the project AIRUS (Atmosphere and Ionosphere Radio-wave-sounding Using Satellites) proposed in order to investigate the mechanism and characteristics of density perturbations in the upper atmosphere associated with the sources beneath the ground surface. The main attention will be given to the following sources:

- seismic events and tsunamis,
- volcano eruptions and typhoons,
- cloud-ionosphere discharges (sprite phenomena),
- pollution of the atmosphere from nuclear plant accidents.

The basic idea to analyze simultaneously the reflected sounding signals at the ground stations and the signals observed about the satellite, penetrated through the atmosphere and ionosphere. Such correlative analyses could improve the accuracy of density determination the especially could be important for the positioning of perturbation region.

Using this favorable situation we propose to prepare a joint coordinated experiment onboard SICH-1M satellite (electromagnetic measurements according to the VARIANT program) supported by the AIRUS program as well as the ground-based radiophysical sounding of the ionosphere.

The main types of ionospheric anomalies referred in the literature to the signatures of seismogenic phenomena are discussed in the chapter 2. In this part of the work our goal is to outline a hypothetical pattern of ionospheric earthquake precursors. In the chapter 3 we describe the program of experiments proposed for VARIANT satellite mission. The program of ground based supporting experiments is described in the chapter 4.

2. Hypothetical pattern of the ionospheric earthquake precursors

Let's consider data set of the ionospheric earthquake precursors that have been acquired last years by means of the ionosounding and in situ satellite observations. According to Liperovsky et al. (1992) let's mark the following types of seismogenic effects: (i) whistler belts – electromagnetic and quasi-electrostatic ELF-VLF hisses filling large regions of the ionosphere and magnetosphere, (ii) MHD oscillations of a segment of L-shell initiating at the earthquake epicenter, (iii) the large scale inhomogeneities of the plasma density, and (iv) the variations of precipitating particle fluxes. All these effects have been revealed retrospectively in connection with earthquakes. They started few hours (sometimes, few days) before the main shock and lasted after earthquake termination approximately the same time.

(i) Whistler belts. These type of emission fills a wide part of L-shell conjugated with earthquake epicenter. The emission is localized along the geomagnetic latitude in comparatively narrow angle range dF ~ 5÷20° but it is widely spread in longitude: dL ~ 100°. A certain image of whistler belt is displayed in Figure 1 (according to the data of Liperovsky et al. (1992)). The idea about the whistler belt spatial structure appeared due to the scanning of the belt at every satellite pass. At heights 600÷1000 km the "typical" whistler belt takes about 1000 km in the latitude direction and about several thousands km in the longitudinal direction. The vertical distribution of the emission can not be reconstructed on the base of single satellite measurements but the fact that whistler belts are often observed by pairs, at opposite edges of geomagnetic field lines, suggests that emission propagates along the L-shell through magnetosphere and reaches the conjugated ionospheric area.

The last fact doesn't mean that electromagnetic emission comes into the ionosphere from the bottom or that emission is generated above earthquake region in the lower ionosphere. The mode composition of whistler belts is appeared to be rather complex and consists of a mixture of waves propagating in various directions (Mikhailova et al., 1991, Mikhailov et al., 1997). Some data indicate that the generation of whistler belts may be explained as a result of the trapping of natural VLF emissions into the ionospheric plasma ducts, and these ducts have seismogenic nature.

The spectral composition of these signals shows that whistler belts are hisses. The spectrum occupies the broad band in the range from hundreds Hz up to tens kHz (ELF and VLF wave bands) without pronounced maximums or minimums. Characteristic emission spectral density is E_f ~10 μV/m·Hz$^{1/2}$. The collections of spectra measured by various satellites have been given by Liperovsky et al. (1992), Henderson et al. (1993), Molchanov et al. (1993). These measurements don't allow determining the emission mode constitution. Nevertheless, the wave polarization (namely, the presence of both electrostatic $dE = -\nabla j$ and vortex dB components) as well as the outlook of frequency spectra (particularly, the absence of peculiarities at points of plasma resonance w_{pi}, nw_{ci}) lead us to the conclusion about whistler nature of observed emissions.

Due to the huge spatial scale of whistler belts the satellites have registered them more often than other types of earthquake precursors. There are whistler belts that have been identified as earthquake precursors for the first time (Gokhberg et al., 1983, Larkina et al., 1983). The whole number of observations of whistler belts amounts already to one hundred.

(ii) Alfven waves structures. In contrast with the previous case this type of emission is rather well localized in space. It represents the MHD oscillations of a part of L-shell initiated earthquake epicenter zone (more exactly, at epicenter projection to the height of ionospheric E layer). Alfven waves occupy a sector that is rather wide in the longitudinal direction dL ~ 10° but is extremely localized within latitudes dF ~ 0.5÷1°. At heights 600÷1000 km this structure looks like a wide but thin "film". The thickness of the film is about 40÷100 km, the length along the geomagnetic parallel is about 1000 km. Due to the good spatial localization and clear conjunction with earthquake this kind of earthquake precursor may be considered as a perspective for the earthquake prediction one. At the same time, good localization hampers this effect detection; only about 20 satellite observations of Alfven wave structures have been described in the literature.

Wave spectra consist of the Alfvenic and magnetosonic modes with frequencies from a few Hz up to hundreds Hz (ELF band). Frequency spectra are sharply cut-of from below (accordingly to the observations of "Intercosmos-Bulgaria-1300" satellite: $f_{\min} \approx 8$ Hz) but have no definite limit from above being spread within the ELF band with gradual intensity decreasing (if the frequency varies from 10 Hz to 100 Hz the emission intensity falls two orders of the magnitude). Observed amplitudes of Alfven emission peaked up to the dB=0.3÷3nT at f=1÷10Hz. The directional pattern of Alfven waves enlarges at high frequencies: dF~6° at f~500 Hz (Molchanov et al., 1993). Representative collections of Alfven wave spectra have been gathered by Liperovsky et al. (1992), and Molchanov et al. (1993).

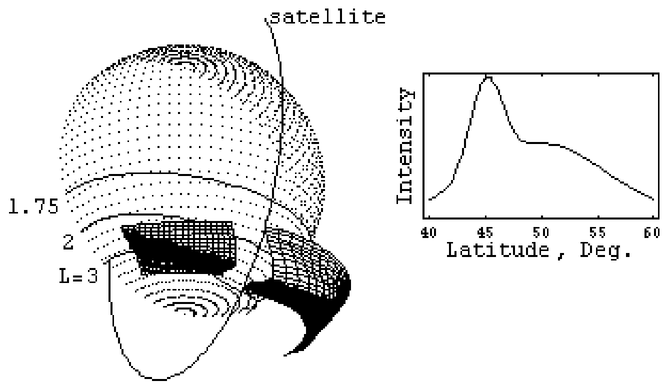

Fig. 1. Hypothetical structure of a whistler belt. On the left − intensity distribution of ELF-VLF waves in the horizontal section of whistler belt (intensity is proportional to the relief height). The geomagnetic parallels L=1.75, 2, 3 are indicated on the globe. On the right − the emission intensity along a satellite trajectory.

(*iii*) *Plasma inhomogeneities.* The distribution of plasma density as well as the macroscopic motions of the ionospheric layers is precisely detected from the Earth by ionosounding methods up to the heights of absolute maximum of the ionospheric concentration $h_{\max} = 250 \div 300$ km. A large data set about the seismogenic perturbations of lower ionosphere, particularly, the perturbation of vertical plasma profile n_p(z) have been collected in the literature. Satellite observations ($h >> h_{\max}$) usually don't reveal the plasma density perturbations. Probably, plasma inhomogeneities might be generated in the lower ionosphere and their further transportation into the upper ionosphere connected with non-linear stage of Rayleigh-Taylor instability.

Let us summarize the data about the lower ionosphere anomalies acquired by ionosounding techniques. The character of perturbations appeared to be different in the cases of powerful and weak earthquake. The following effects have been detected in the case of powerful earthquake:

- The stable modification of the ionosphere both at and above the F layer peak height (Depuev et al., 2000, Parrot, 1999). Electron density is gradually reduced and its spatial distribution looks like a funnel located either immediately over the epicenter or from its one side.
- The increasing of the frequency of sudden and quick E_s layers spreading (in time interval < 15 minutes),
- The generation of the drifting ionospheric inhomogeneities (accordingly to (Sorokin and Fedorovich, 1982), of the slow MHD waves with periods T~2÷3 hours),
- The turbulent motion of plasma layers and the generation of small-scale plasma inhomogeneities (with inhomogeneity scale about ten meters and more and plasma density

variations $d\ n_p / n_p$ ~ 0.01).

In the case of weak earthquake the only noticeable feature is the ionosphere heating which causes the plasma flowing out of the region of increased pressure. As a result the F_2 layer density decreases around the epicenter ($-d\ n_p \sim 0.2 n_p$) in a zone with radius of a few hundred kilometers. All mentioned phenomena have been detected in one-three days before shocks. The notions "powerful" and "weak" earthquake here are conditional because it is clear that ionospheric response depends on many factors, not only on the magnitude of future shocks. The conditional threshold accepted in the literature has been chosen at the magnitude M=5: M>5 means powerful earthquake, M<5 – weak earthquake.

"Atmospheric Explorer-C" satellite has been launched to the extremely elongated orbit with altitude of perigee 160 km and apogee 4300 km. The satellite has detected the anomalies of ion density n_i and electron temperature T_e below and near the main ionospheric maximum. Gaivoronskaya (1996) subdivides the observed n_i, T_e-variations on three types: 1) the exhaustion of F_2 layer ($-d\ n_i \sim 0.5 n_i$ in a region about 1000 km along the satellite trajectory), 2) the long-periodic wavelike perturbations of n_i, T_e – the drifting ionosphere inhomogeneities, 3) the weak quasi-periodic variations n_i, T_e, which are supposed to be a result of ionosonic waves interference. These results completely agree with the scheme described above.

Analysis of the "Atmospheric Explorer-C" satellite observations in the upper ionosphere ($h >> h_{\max}$) doesn't reveal any anomalies of plasma parameters. We could make the same conclusion about all other satellite missions. The possible exclusion relates to the "ISIS-2" satellite, which had found the exhaustions of ionospheric plasma correlating with earthquake (only in one or two cases). Observed variations have been about $-d\,n_p \sim 0.1 n_p$; plasma caverns had been extended in a few hundreds km along the satellite trajectory. Liperovsky et al. (1992) have suggested that there were plasma bubbles rising from the ionospheric E-layer. We suppose that the available experimental data are not enough to make the definite conclusion.

The next kind of satellite probing relates to the measurement of the total electron content (TEC)of ionosphere under satellite $N_e = \int_{-\infty}^{h_s} n_e\ dh$ (where h_S is the satellite altitude). Parrot (1999) has analyzed the N_e-variations basing on the data of "TOPEX-POSEIDON" two-frequency altimeter. Since the measurements above the dry land cannot be interpreted the shelf earthquakes have been selected. Among 706 shelf earthquakes the 238 events demonstrate TEC-variation (or 34% of events). Control analysis of TEC-variations without earthquake revealed 85 events at 540 satellite passes (or 16% of events).

(*iv*) *The variations of the fluxes of precipitating energetic particles*. The small but statistically reliable increments of the particles number precipitated from radiation belts were registered by satellites – 100 keV electrons and 100 MeV protons. Precipitation events were localized in a wide zone which configuration is more or less similar to the configuration of whistler belts described above (Galper et al., 1986). The processes of hiss generation and particles precipitation are probably interconnected because just the interaction with whistlers leads to the pitch-angle diffusion of trapped particles and to the falling into lose-cone. If so, the precursor (iv) appears as a secondary effect in respect of the electromagnetic precursor (i) and has no independent value.

Table 1 summarizes the available data used in this work.

Satellite	Yr	*h*, km	Earthquake: M, D*t*	Phenomena
OGO-6	1969	400-1100	1) Earthquakes haven't been identified 2) M=5.4, Δt = hours	1) Electromagnetic emissions E=10÷100 mkV/m, f=10 Hz÷3 kHz. Emissions occupy spatial belts spread in dL ~ 100° (in longitude), and dF ~ 5÷20° (in latitude) 2) Magnetic field perturbations at the L-shell conjugated with the epicenter (f=0.1÷1 kHz)
ISIS-2	1979	1400	M>6, Δt = 2÷6.5 hr	10 % plasma density depletion in the region conjugated with earthquake (single observation)
AE-C	1973	140-4300	M=6, Δt<14 hr	20 % plasma density depletion at the height 150 km over epicenter, wavelike n_e,T_e perturbations
GEOS-1	1977	2050-38000	M>5, Δt = 1÷2 hr	Electromagnetic hiss f=150÷1000 Hz
GEOS-2	1978	36000	M>4, in 2 hr before the shock and in the shock moment	Electromagnetic hiss dB<10^{-3}nT, f=150 Hz÷3 kHz at the L-shell conjugated with earthquake
Intercosmos-19	1979	600-1000	39 earthquakes with M>5, Δt = from tens hr before up to tens hr after the shock	Quasi-electrostatic emissions E=10÷100 mkV/Hz$^{1/2}$m, f=140 Hz÷15 kHz in a spatially localized belts: 300-500 km in geomagnetic latitude, and 5000 km in geomagnetic longitude.
Intercosmos-Bulgaria-1300	1981	825	1) M=4.8, Δt = 15 min., 2) M=3.4÷5.2, in 3 hr before and in the moment of the shock	MHD waves at the L-shell conjugated with epicenter: 1) dB=3nT, f=1Hz. 2) dB=0.2÷0.4 nT, f=8Hz. 3) Variations of the fluxes of protons with the energy > 100 MeV
Aureol-3	1981	400-2000	1) M>5, Δt = hrs ÷ tens min 2) M=3.4, Δt = -8 hr, 0, +40 min	1) Electromagnetic hiss E~0.1 mV/Hz$^{1/2}$m, dB~0.4 nT/Hz$^{1/2}$, f=150 Hz÷15 kHz. Emissions localized in belts dL ~ 100° (longitude), dF ~ 10° (latitude). 2) Simultaneously with the "Intercosmos-Bulgaria-1300" satellite, the registration of MHD waves at the earthquake L-shell f=10÷1000 Hz, dL ~ 120°, dF ~ 13°. 3) Variations of the proton fluxes with energy >100 MeV
Meteor-3	1985	1200	M>4, Δt = 2.5 ÷ 3 hr	Variations of the fluxes of energetic particles: 1) of electrons E_e>5 MeV and E_e>20 MeV, 2) of protons E_p>90 MeV and E_p>400 MeV
Salyut-7, MIR	1985-1987		M>4, Δt = 2.5 ÷ 3 hr	Enhancement of the energetic particle fluxes
Cosmos-1809	1988	970	M>4, Δt = hrs	MHD waves at the L-shell conjugated with an epicenter: dL ~ 120°,dF ~10°,dB=0.1 nT, f=140 Hz
DE-2	1982	300-1300	63 earthquakes with M≥5, Δt = -12,+6 hr	Emissions: 1) ELF E~0.1 mV/Hz$^{1/2}$m, f=4 Hz÷128 Hz. 2) VLF E~0.1 mV/Hz$^{1/2}$m, f=1÷10 kHz. Conclusion about the *absence* of the correlation between emissions and earthquakes
Intercosmos-24 (ACTIVE)	1989	500-2500	28 earthquakes with 5.2<M<6.1, Δt = -2,+2 day, Max in 12÷24 hr *before* earthquake	1) Electrostatic hisses E~0.1 mV/Hz$^{1/2}$m, f=10÷15 kHz in "belts" dL ~ 300°,dF ~10° and in the conjugated ionosphere. 2) MHD-waves: E_{max}~0.2 mV/Hz$^{1/2}$m, f=10Hz in belts dL ~ 50°,dF ~6°

Table 1. Satellite observations of the ionospheric earthquake precursors. Here *h* is an altitude of satellite orbit, M is earthquake magnitude, Δt is a time of precursor registration before earthquake. If an effect has been observed both *before* and *after* the main shock the sign '–' means 'before', and the sign '+' means 'after'.

3. "Variant"-mission onboard SICH-1M satellite

"Variant" is a joint international space experiment on current density and electromagnetic field measurements in ionospheric-magnetospheric plasmas. The experiment will be performed as an additional payload of the Ukrainian remote sensing satellite SICH-1M (designed and manufactured by "Yuzhnoye" Design Office). The satellite will be launched in 2002 yr. at the circular orbit with the inclination of around 80° and altitude 670±30 km. It should cross the main morphological structures of the ionosphere: middle latitude throat, polar cusps, auroral oval etc. Composition of the "Variant" mission scientific instrumentation is given in the Table 2. The instrumentation as well as the telemetry system allows to perform the monitoring of the electromagnetic earthquake precursors described in the previous section.

Several new ideas have been proposed to explore during the "Variant" mission in order to get more exact and complete information about the seismogenic perturbations in the ionosphere. The onboard satellite instrumentation includes three instruments for the registration of electric current density which is the main “agent” of ionosphere-magnetosphere coupling and, accordingly to Pokhotelov et al. (1994), of the lithosphere-ionosphere coupling. The simultaneous measurements of the electric and magnetic field fluctuations should allow to perform the separation of the spatial and temporal variations onboard of the single satellite (Vaisberg et al, 1989). The scientific equipment devoted to the electric current measurements includes split Langmuir probe (WZ), Rogovsky coil (ZF) and Faraday cup (FC). Detailed description of these instruments is given by Korepanov and Dudkin (1999). While FC is well known device that is often used in space experiments, the Rogovsky coil ZF will be in space flight for the first time; the wave probe WZ is completely new instrument. WZ has been designed in result of close collaboration between Lviv Center of Space Research Institute NASU-NSAU (Ukraine) and Institute for Space Research RAN (Russia) on the base of former successful experiment onboard Prognoz-10 satellite aimed at the simultaneous measurements of spatial current density and magnetic field fluctuations in the Earth’s bow shock region. This instrument can detect simultaneously the fluctuations of spatial electric current density, magnetic field and electric potential. Also the simultaneous measurements of the electromagnetic field fluctuations in ELF/VLF frequency band will be performed making use of the electric and magnetic fields sensors (instruments EZ and WZ). The waves in this frequency range are supposed to be the most typical signatures of the seismogenic effects.

4. Sub-satellite ionosphere sounding

In frames of the AIRUS project it is supposed to carry out the synchronous sounding of the atmosphere-ionosphere boundary region by VLF subionospheric signals. It is a well-known method for registration of ionospheric inhomogeneities induced by magnetospheric sources (e.g., energetic particles precipitation), solar radiation bursts or by whistlers (Trimpi-effect). Recently, this method was applied for the search of short-term ionospheric perturbations associated with sprite phenomena (Dowden et al., 1996, 1997, Molchanov et al., 1998a) as well as of the long-term inhomogeneities possibly related to earthquakes (Gufeld et al., 1994, Hayakawa et al., 1996 a,b, Molchanov et al., 1998b). At present the network of the 7 VLF reception stations is operated in Japan and signal of following powerful VLF transmitters are analyzed: CHI (China, f=22.2 kHz), NWC (Austria, 19.8 kHz), NPM (Hawaii, 21.4 kHz), NSS (USA, 23.4 kHz), and JJY (Japan, 40 kHz). In frames of the AIRUS project the data of these observations will be used for the seismogenic ionosphere inhomogeneities diagnostics. As it has been mentioned above, to have a complete picture of phenomena arisen in the ionosphere in order to recognize them as seismic is very important. That is why we suppose to supplement electromagnetic satellite-born observations with the data of ground-based radio sounding. Ionosounding data also will be used for this purpose.

	Device	Measurement	Designed by
1.	Wave probe WZ	Electric current density **J**: Frequency range 0.1 Hz … 40 kHz, Noise 10^{-12} A/cm^{2}Hz$^{1/2}$ Magnetic field vector **B**: Frequency range 0.1 Hz … 40 kHz Noise 10^{-13} T/Hz$^{1/2}$ Electric potential φ: Frequency range 0.1 Hz … 40 kHz Noise 10^{-6} V/Hz$^{1/2}$	LC ISR, Ukraine (V. Korepanov) IKI, Russia (S. Klimov)
2.	Rogovsky coil ZF	Electric current density **J**: Frequency range 0.1 Hz … 400 Hz, Noise 10^{-12} A/cm^{2}Hz$^{1/2}$	LPCE/CNRS, France (F. Lefeuvre, V. Krasnosselskikh)
3.	Electric probe EZ	Electric field vector **E**: Frequency range 0.1 Hz … 200 kHz Noise 10^{-6} V/Hz$^{1/2}$	LC ISR, Ukraine (V. Korepanov)
4.	Faraday cup FC	Electric current density **J**: Frequency range 0.1 Hz ... 1 kHz, Noise 10^{-10} A/cm^{2}Hz$^{1/2}$	Sheffield University, United Kingdom (H. Alleyne, M. Balikhin)
5.	DC magnetometer FZM	Magnetic field vector **B** Frequency range DC - 1 Hz	LC ISR, Ukraine (R. Berkman, S. Belyayev)

Table 2. Scientific Payload Proposed for SICH-1M Mission

5. Conclusion

Summarizing, we emphasize that in spite of a great number of publications and increasing practical interest to the works in the branch of earthquake forecast the results obtained in this field are rather pure: separated experimental facts, some attempts of data systematization and some theoretical hypotheses. Existing experimental background does not permit to outline the more or less reliable picture of the seismogenic phenomena occurring in the ionosphere. We have to realize what is already established and what is necessary to ascertain first of all in the next satellite experiments. For this purpose some tentative patterns of the ionospheric earthquake precursors have been constructed in this article. These patterns are mostly working hypotheses that must be examined in future.

To verify the basic ideas about the nature of lithosphere-ionosphere coupling we propose to combine the local satellite and remote sensing ground-based measurements ("Variant" mission onboard SICH-1M satellite and AIRUS radiophysical subionospheric sounding with Japanese network of VLF receivers). The proposed project will be also helpful for the investigation of non-seismogenic types of the ionospheric perturbations.

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