

CONFERENCES AND SYMPOSIA

PACS number: 01.10.Fv

Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (29 May 1996)

On May 29, 1996 the Scientific Session of General Physics and Astronomy Department of Russian Academy of Sciences was held at the P L Kapitza Institute for Physical Problem. Following reports were presented.

(1) **Zaliznyak I A, Ren'o L P, Petrov S V** (P L Kapitza Institute for Physical Problems RAS, Moscow) *Experimental confirmation of differences in spin dynamics of quasi-one-dimensional antiferromagnets with integer and half-integer spin*;

(2) **Buchachenko A L, Oraevskiĭ V N†, Pokhotelov O A, Sorokin V M, Strakhov V N, Chmyrev V M** (Institute of Terrestrial Magnetism, Ionosphere and Radio-wave Propagation RAS, Moscow) *Ionospheric precursors to earthquakes.*

Brief presentation of the second report is given below.

PACS numbers: 91.30.Px, 94.20.Vv

Ionospheric precursors to earthquakes

A L Buchachenko, V N Oraevskiĭ, O A Pokhotelov, V M Sorokin, V N Strakhov, V M Chmyrev

1. Introduction

Earthquakes, volcanic eruptions, tsunami and other large-scale natural catastrophes bringing numerous destructions every year take away hundreds of human lives; millions of dollars are needed to overcome the impact of these natural calamities. Therefore, prognosis and timely warning of approaching disasters remains one of the most important unsolved problems of modern geophysics and space physics.

When elaborating the warning system one needs to account, along with seismic processes, also for the entire variety of physical phenomena occurring in various media on preparatory phases of an earthquake. Currently, there is a bulk of experimental facts which point at existence of electromagnetic and plasma precursors to earthquakes, or, in other words, at perturbations in parameters of fields and plasma, occurring in the atmosphere and ionosphere hours, days, or weeks prior to earthquakes. This report is devoted to the main results found experimentally when investigating these phenomena as well as to the development of the program to explore the processes taking place in the epicentral zone of earthquake and physical principles underlying the formation of precursors of various types. The program is aimed at the elaboration of the methodology of the short-term prognosis and at substantiation of the structure and composition of the experimental system for earthquake precursor monitoring.

2.Experimental results

For the last decade in a number of satellite experiments new phenomena which occur prior to earthquakes were discovered in the ionosphere and the magnetosphere. In particular, these include anomalous bursts of electromagnetic radiation in the ULF/ELF/VLF ranges detected with satellites IC-18, IC-19, IC–Bulgaria-1300, Aureole-3, Cosmos-1809, IC-24, OGO-6, DE-2 and with several other spacecrafts [1 – 10]. A distinct connection of these anomalous electromagnetic phenomena with specific earthquakes was noted. The existence of ELF radiation of seismic origin in the ionosphere is supported by the results of statistical analysis of satellite data over hundreds of earthquakes [10].

There are convincing data on DC electric fields in ground and ionospheric plasma [4, 11, 12], anomalous airglow of the atmosphere in different wavelength ranges [13, 14], perturbations in main parameters of E and F regions of the ionosphere [15 – 19], changes in the ion composition, plasma temperature, and fluxes of high-energy particles in the upper ionosphere [20, 21, 35], perturbations of phase and amplitude of signals from VLF and LF radio stations on the paths crossing the earthquake zones [22, 23, 29], geomagnetic pulsations and whistlers [24 – 26], variations in the composition of the atmospheric gas, formation of aerosol clouds of definite type and increase in concentration of heavy elements in water basins near earthquake epicentral zones, and on a number of other phenomena [19, 36].

The processes listed above were observed from space or with ground-based instruments before earthquakes, preceding them by hours, days, or weeks depending on the type of the phenomena. Just for that reason they may be considered as precursors and used as a physical basis for creating earthquake forecasting and warning system.

In addition to precursors to large-scale natural calamities, there were recently discovered and are now intensively studied the perturbations in the parameters of electromagnetic fields and plasma sensitive to technological disasters, such as accidents at atomic power plants, atomic explosions in various media and other impacts on the environment brought about by human activity [27 – 33].

Consider several examples of perturbations in electromagnetic fields and plasma, associated with seismic activity and observed with ionospheric satellites before earthquakes.

Figure 1b shows variations in two horizontal components of the magnetic field B_x and B_y in the frequency range of

† The author is also known by the name V N Oraevsky. The named used here is a transliteration under the BSI/ANSI scheme adopted by this journal.

Uspekhi Fizicheskikh Nauk **166** (9) 1023 – 1029 (1996)
Translated by S D Danilov

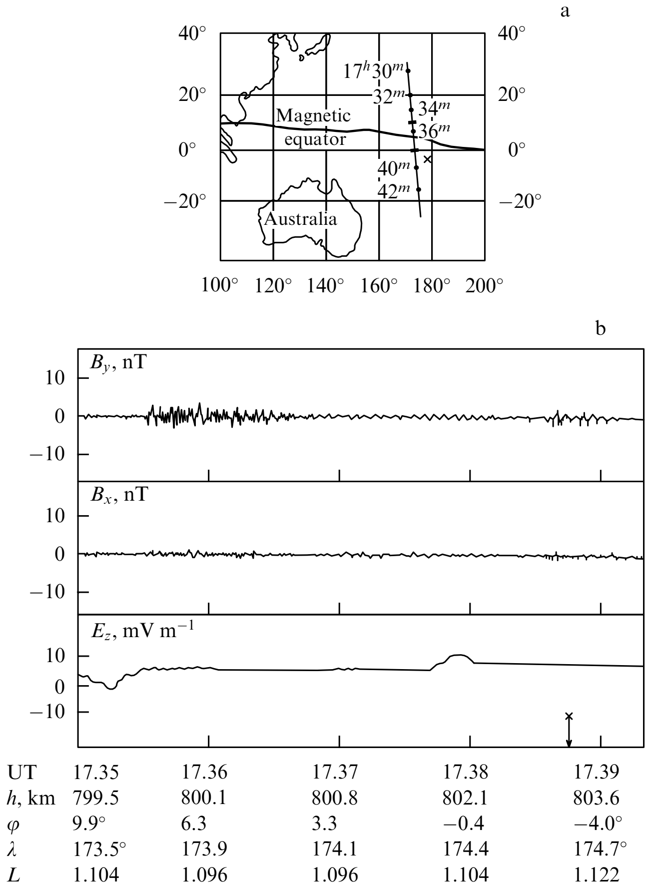

Figure 1.

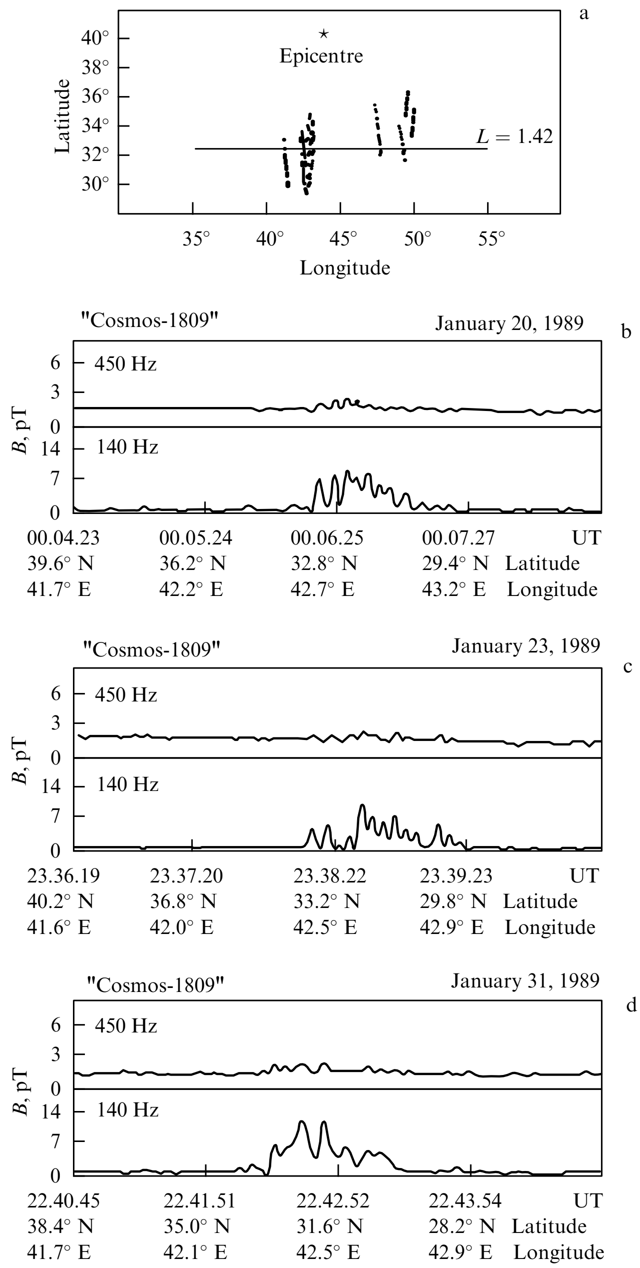

Figure 2.

0.1 – 8 Hz and the vertical component of DC electric field E_z observed from the satellite IC-Bulgaria-1300 15 min prior to the earthquake which took place on January 21, 1982 [4]. The projection of the satellite orbit and the location of the epicentre, denoted by the cross, are shown in Fig. 1a. The magnetic equator is depicted by a solid line. The earthquake began at 17.50.26 UT, with the geographic coordinates of the epicentre being 3.39° S, 177.43° E, the depth of 33 km, and the magnitude $M = 4.8$. An arrow in Fig. 1b denotes the moment when the satellite passed at the minimum distance (2.8° westward) from the epicentre. Zones near 17.35.15 and 17.37.50 UT correspond to the projection of the earthquake epicentral zone from the lower ionosphere to the satellite altitude along the magnetic field lines. It is seen that the vertical DC electric field of 3 – 7 mV m^{-1} was observed in two zones: approximately at 17.38 UT over the epicentre and at about 17.35.15 UT in a magnetically conjugate zone. The width of these zones was 1 – 1.5° by latitude. The amplitude of geomagnetic pulsations observed was 3 nT at the frequency of about 1 Hz. Reference [4] demonstrates that electric and magnetic fields observed are not of ionospheric or magnetospheric origin but are connected with the earthquake.

Figure 2 illustrates ionospheric manifestations of strong aftershocks of the destructive Spitak earthquake (Armenia, 40.7° N, 44.0° E, 7 December 1988, $M = 6.7$) which were analyzed in Ref. [8]. The observations were implemented from the satellite Cosmos-1809 at the altitudes of $\sim$ 970 km during the period of high seismic activity from January 20 to February 17, 1989. Panels a – d of Fig. 2 show following: (a) the localisation of the epicentre and fragments of the satellite orbits at which electromagnetic ELF radiation was detected; (b) records at frequencies of 140 and 450 Hz 2.5 h prior to the earthquake (universal time UT, the latitude and longitude are given in the figure); (c) records obtained 10 min and 2.9 h prior to the aftershocks; (d) records obtained during a long series of weaker but frequent shocks. These data together with other ELF/VLF measurements carried out by Cosmos-1809 in the Spitak region proved that intense ELF radiation is generated in a zone less than, or of the order of, 6° by longitude and 2 – 4° by latitude relative the earthquake epicentre. The radiation intensity was about 10 pT at the frequency of 140 Hz (in a 25 Hz frequency band) and about 3pT at the frequency of 450 Hz (in a 75 Hz frequency band). Subsequent processing of the Cosmos-1809 data revealed small-scale (4 – 10 km along the orbit) irregularities in plasma density $\delta N/N = 3 - 8\%$ which occur in just the same regions as the anomalous ELF radiation [34]. An example of such an

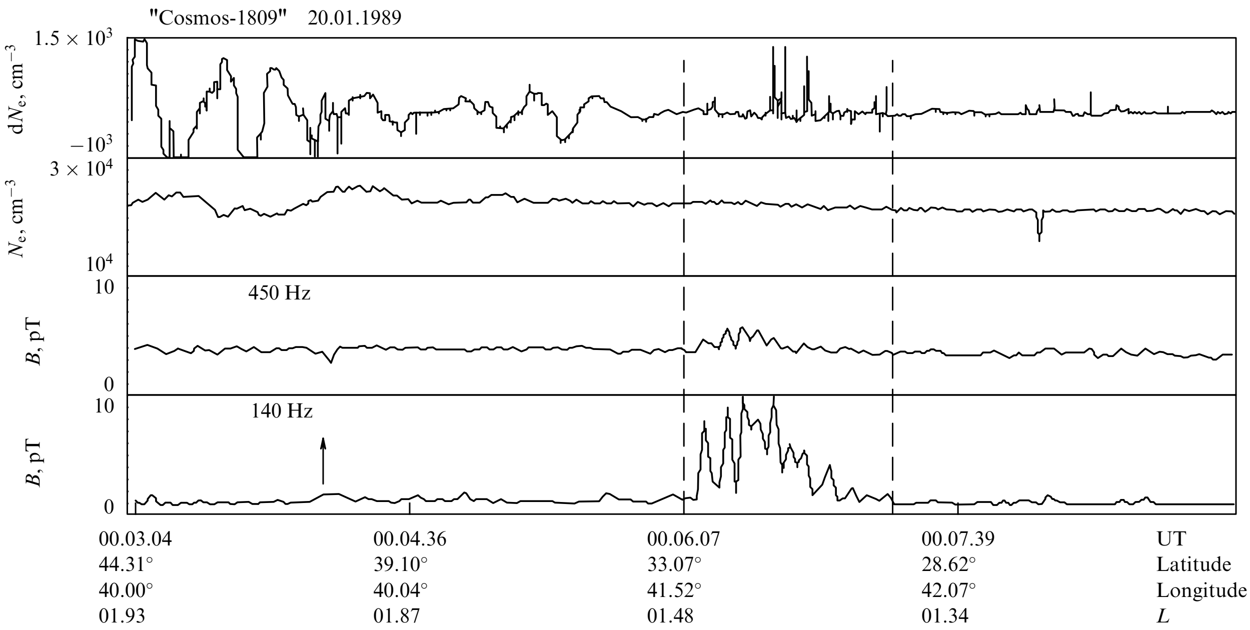

Figure 3.

irregular structure is shown in Fig. 3 for the case presented in Fig. 2b.

The ULF-response of the ionosphere to the earthquake preparation processes was discovered in Ref. [6]. Measurements implemented by the satellite IC-Bulgaria-1300 [6] brought in the evidence that electromagnetic radiation at frequencies above and on the order of 8 Hz, having amplitude of 0.2 – 0.4 nT, is excited in the ionosphere several hours prior to and during an earthquake. The width of the zone where the radiation was detected was 40 – 100 km along the satellite orbit, whereas maximum intensity was observed on L-shell of the earthquake epicentral zone projection onto an altitude of 100 km in the ionosphere. An example of the dynamic spectrum of ELF emission of seismic origin is given in Fig. 4. The arrow on the temporal scale there indicates the instant of time when the satellite crossed the L-shell of the epicentre.

Figure 5 demonstrates the two-dimensional distribution of the deviation of electron density from its median value in maximum of the ionospheric F-layer (in terms of critical frequency, MHz) as recorded by the satellite IC-19 with the help of its onboard ionosonde. Negative variations of electron density were observed 2 days and a day prior to the earthquake (Fig. 5a, b). The modification of the ionosphere of that kind occurring in the height range from 60 km in D-layer to the upper ionosphere (up to 1000 km), is caused by a combined action of electromagnetic and chemical factors on the ionospheric plasma [19].

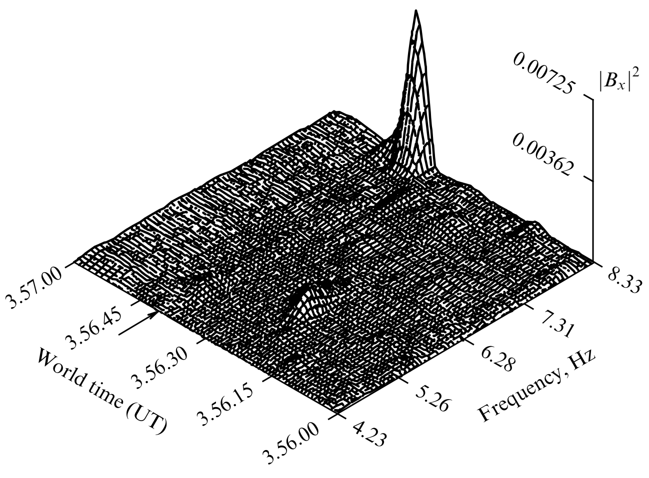

Figure 4.

Therefore, there exists a reliable experimental basis for organising a special program of works aimed at integration and further development of the whole set of known experimental data and physical models in order to elaborate methods of application of ionospheric observations to forecasting and monitoring large-scale catastrophes from space. A variant of such programme is presented below.

It is noteworthy that available experimental data on seismic and technological effects in the ionosphere were obtained as concomitant results of experiments originally planned to solve quite other tasks having no relation to the earthquakes. This points at the necessity of implementation of experimental space program specially intended for exploration of ionospheric precursors of earthquakes. Basic directions of works in the framework of this program could be formulated in the following way:

(1) A complex of instruments capable of exploring specific physical processes which are or could be caused by earthquake preparation processes has to be created. Subsequent researches would help to learn cause-and-effect links in the sequence of occurring phenomena and in spatial-temporal characteristics of perturbations of seismic origin in the ionosphere which may be employed in the system of early warning.

(2) The program of experiments should allow for coordination of space and ground-based observations, as well as data reception from autonomous 'buoy' stations in seismically active regions. These data should be delivered with the help of satellites to united centre of data processing for subsequent systematic analysis of the material from all sources.

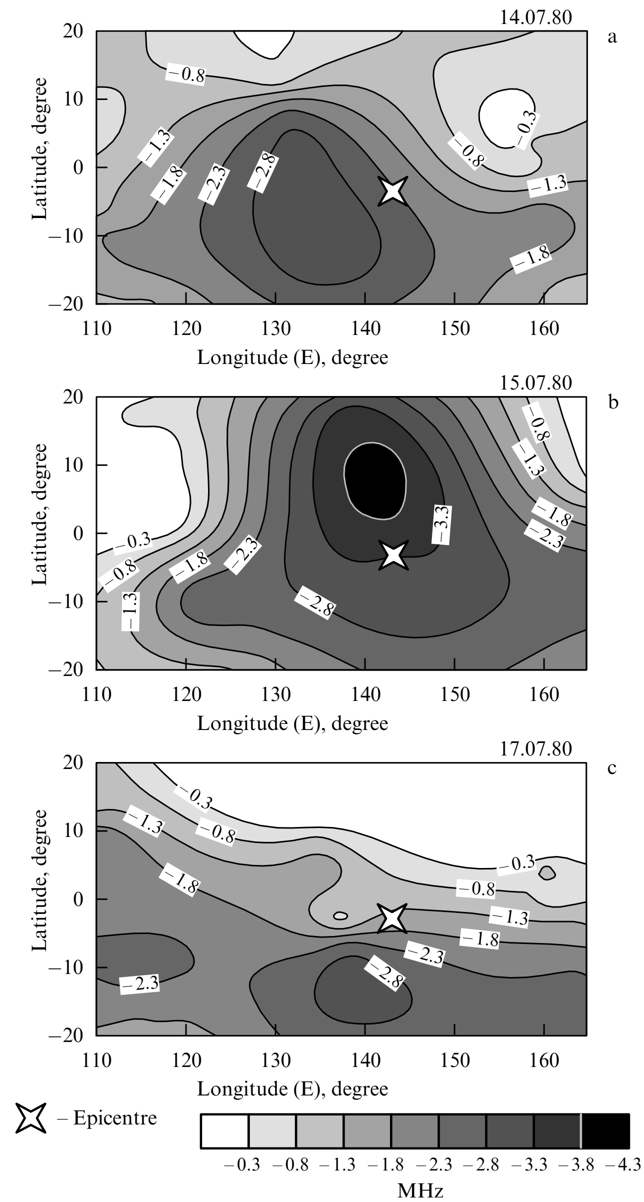

Figure 5.

(3) There should be constructed a series of relatively inexpensive microsatellites and subsatellites capable of working either autonomously or in the infrastructure of large spacecrafts which could launch them into an orbit as an additional useful payload. Since the level of seismic related perturbations in the ionosphere is extremely low a special care should be taken to provide appropriate electromagnetic cleanness and electromagnetic compatibility of instruments and experiments onboard.

3. Substantiation of the structure and composition of experimental space system for monitoring of earthquake precursors

3.1 Structure of the system. From experimental data it follows that there exist three typical sizes of the zone where ionospheric imprints of pre-earthquake situation could be detected from a satellite:

(1) large zone, $\pm 30^\circ$ relative the earthquake epicentre. *Observed effects*: the modification of the vertical profile of electron concentration, change in the ion plasma composition, appearance of fluxes of precipitating high-energy particles and pulse VLF signals with anomalous dispersion in the upper ionosphere. *A typical feature*: seismically induced perturbations of electron concentration profile are observable in local time sectors 03 – 06 LT and 15 – 18 LT; sounding of the ionosphere should be accomplished from the altitudes of 1000 km or more;

(2) medium zone, $\pm 10^\circ$ relative the earthquake epicentre. *Observed effects*: the generation of electromagnetic radiation in ELF range, formation of small-scale irregularities in plasma density, perturbation of DC electric field, generation of geomagnetic pulsations at the frequencies ~ 1 Hz, and modification of vertical profile of hydroxyl emissions. *A typical feature*: ELF radiation, electric fields and small-scale plasma irregularities are localized in the magnetic field tube of an epicentral region and can be observed onboard the satellites in magnetically conjugate zones;

(3) small zone: $\leqslant 3^\circ$ relative the earthquake epicentre. *Observed effects*: the generation of electromagnetic ULF radiation and modification of atmospheric emission at 5577 and 6300 A. *A typical feature*: the zone of ULF radiation is conjugated with the epicentre by magnetic field lines.

We note that the subdivision presented, as concerns certain parameters, is based on a rather limited experimental material. Consequently itself it is an object of investigations and should be ascertained at the experimental stage of works on creation of the prognosis system.

The zones and features observed within them, as specified above, in essence define the structure of the experimental satellite system for development of the methods of earthquake prognosis. When designing the system we shall depart from the following criteria:

dividing the Earth's surface into equal longitudinal sectors of width 60° and 20° in compliance with sizes of large and medium zones, we will require for at least one satellite supplied with necessary instruments for observation of processes typical for these zones be present within each of them once per 1.5 – 2 h;

the orbit height and inclination should provide the presence of the satellites over regions where earthquake preparation features have maximum intensity and probability;

measurements of local parameters of fields and plasma in each sector are to be accomplished with pairs of satellites having identical instruments and distinguishing only in the time of equator crossing by a quarter of orbital period, in order to discern spatial and temporal variations of perturbations, exclude random signals and in this manner reduce the probability of error.

The system should provide a possibility of measurements and analysis of seismic oscillations, ULF/ELF/VLF waves, atmospheric emissions and other feasible precursors to earthquakes on the net of ground-based 'buoy' stations accessed from satellites. Performing the direct local measurements of field and plasma parameters; information from 'buoys' for a period elapsed is stored and then transmitted to satellites in a compressed form; simultaneously online data are transmitted synchronous to the onboard measurements.

In addition to space-based and ground-based measuring systems of great importance is also using the drifting and tethered balloons supplied with instruments for measurements of electric fields and conductivity variations, molecular gas composition and content of rigid particles (aerosols) in the atmosphere, as well as variations in atmospheric emissions in various wavelength ranges. The balloon instruments should be accessed from satellites of the lower array (see below) in the same manner as ground-based 'buoy' systems.

Thus one may anticipate the following optimal variant of experimental system construction which accounts for practically all recently known phenomena and effects that are considered as precursors (or potentially could be considered as these) to earthquakes and reveal themselves at different temporal scales prior to earthquakes:

Upper satellite array composed by four satellites on circular solar-synchronous orbits of height ~ 1000 km with orbital planes oriented at 90° relative each other, and one satellite on an elliptic orbit (350 – 3500 km) inclined at $\sim 83°$. These satellites are to carry out a global survey of three-dimensional (latitude, longitude, and height) distribution of electron concentration in the ionosphere based on making use of onboard ionosonde and instruments of transionospheric sounding, mass-spectrometry of ionised and neutral gas components in the ionosphere, measurements of plasma temperature, atmospheric emissions at altitudes of *F*-region of the ionosphere, pitch-angle and energy distributions of high-energy particle fluxes, and, provided all instruments are electromagnetically compatible, the analysis of VLF radiation.

The satellite on an elliptic orbit is needed for investigations of altitude distribution of ion composition, collection of reference information for discriminating false signals, as well as to searching new precursors and exploring both their generation mechanisms and dependence on local time and altitude.

Lower satellite array composed by nine pairs of small satellites on circular orbits of altitude ~ 400 km and inclination 65 – 83°. Two satellites forming a pair should be on identical orbits lying in the same plane and distinguishing only in the time of equator crossing by a quarter of orbital period. The orbit planes of nine pairs of satellites should be equidistributed over longitude with a step of 40°. These satellites are supposed to implement measurements of ULF/ELF/VLF waves, DC electric fields, plasma density and small-scale fluctuations, mass composition of ion and neutral components of ionospheric plasma, jets of high-energy particles, atmospheric emissions in different oxygen and nitrogen lines from regions below the satellite and hydroxyl emissions when observing in the direction of Earth's limb.

Balloon array composed of tethered balloons at altitudes of 6 – 10 km in seismically most dangerous zones and of drifting balloons at altitudes of 30 – 40 km launched under appropriate wind conditions in zones of augmented seismic hazard. On balloons, measurements of electric fields and conductivity variations, molecular gas composition and the content of rigid microparticles (aerosol) in the atmosphere, as well as variations of atmospheric emissions in various wavelength bands are to be accomplished. Balloon instruments should be accessed from lower array satellites in a regime similar to that for ground-based 'buoy' complexes.

Ground-based array consisting of autonomous 'buoy' stations arranged in zones of high seismic hazard at points free of industrial interference in ULF/ELF/VLF and optical frequency ranges, and of basic geophysical and radiophysical test sites and observatories. 'Buoy' stations are to be equipped with compact instruments having low energy consumption. The instruments should be capable of measuring and analyzing seismic oscillations, geomagnetic pulsations, ULF/ELF/VLF waves, atmospheric emissions and other feasible earthquake precursors, operate autonomously and not require the energy source replacement more often as once or twice a year. At lower array satellite passing above a 'buoy' station the latter conveys, in a compressed form, the data stored for elapsed time interval and transmits online measurement data synchronous to onboard measurements. Basic geophysical and radiophysical test sites acquire the telemetry information from satellites in the regime of stored data transmission as well as in the regime of direct data transmission if onboard measurements are conducted within the test site visibility range. They also perform continuous monitoring of earthquake precursors by means of vertical sounding of the ionosphere, radio-beacon measurements, amplitude-phase measurements of signals from VLF radio stations on paths crossing the region of seismic hazard, measurements of electrotelluric fields and currents, the atmospheric composition, and other types of measurements admissible at the present background noise level. At test sites, regular observatory measurements are also performed in the standard configuration.

The satellites of upper and lower array should work continuously in one of two regimes: (1) the regime of monitoring, in which in between the intervals of communications, the data are recorded continuously (with a preliminary processing) and stored into a storage unit which is sampled in the visibility zone of the receiving telemetry station, or (2) in the regime of experiment when a direct data transmission is performed to the ground-based telemetry station at maximum sampling rate of measuring instruments.

The tracking stations are to be distributed more or less uniformly over the Earth' surface offering a possibility to transmit information from a satellite and control the regime of its operations no less that once per 3 h. At late stages of system development, when algorithms of automated recognition of potential earthquake will be settled the need in large number of ground-based telemetry stations will become less vital. Perhaps in this case all work on information collecting could be performed by one or several high-apogee satellites.

3.2 Basic requirements on the satellites of experimental system. In the preceding section we formulated main constraints on the parameters of orbits of upper and lower array satellites and the rules of their grouping for monitoring continuously all ionospheric earthquake precursors known so far. Now, let us formulate the requirements to spacecrafts (SC) themselves and to the onboard equipment:

(1) each satellite should possess its own systems of power supply, thermal control, spatial stabilisation and orientation, determination of spatial position, orbit correction (or maintenance), telemetry and control systems which should ensure normal functioning of the SC and the useful payload *not less than for 2 years*;

(2) each satellite should comply with requirements of electromagnetic cleanness and electromagnetic compatibility of instruments and experiments onboard;

(3) the mass of satellite must fill into 50 – 100 kg interval to make possible its launching by relatively inexpensive rockets, simultaneous launching of several SC with subsequent trimming of their orbits (if necessary) to required ones with the help of correcting engines (thrusters), or launching into an orbit as an additional useful payload by other SC to reduce the cost of the project;

(4) the rate of telemetry information transmission must be higher that 2 Mbit c^{-1} and the capacity of the onboard storage unit should be not less than 100 Mbytes;

(5) a satellite is to be stabilised by all three axes with one being directed to the Earth centre; the accuracy of stabilisation is not worse than 10° with respect to each of axes, and that of determination of orientation parameters is not worse than 1°;

(6) thermal stabilisation system should ensure the temperature at scientific equipment sites in instrumental section of the satellite $20 \pm 10\,°C$;

(7) power supply system should provide 40 W on average per day for a period not less than 2 years;

(8) correcting engine (thruster) should ensure the maintenance of given orbital parameters for 2 years;

(9) the determination of spatial position of satellite should be implemented with an accuracy not worse than 300 m.

3.3 Requirements to onboard scientific instruments. *The set of instruments for the upper array satellites includes*:

— ionosonde-spectrometer of IS-1000 type and the equipment for transionospheric sounding to detect earthquake precursors by variations of electron density through the total column of the ionosphere;

— equipment for local measurements of concentrations, ionic and neutral plasma composition, and the distribution function of thermal electrons;

— spectrometers of charged particles with working ranges of 5 eV – 20 keV and 20 keV – 2 MeV;

— scanning photometer;

— magnitometer;

— ULF/VLF receivers;

– an instrument to measure DC electric fields, or that to measure plasma drift velocities.

The set of instruments for the lower array satellites includes:

— an instrument to measure three components of DC electric field;

— an instrument to measure parameters of thermal plasma (including the temperature, density, density oscillations and drift velocity);

— five-component ULF receiver;

— five-component ELF and VLF receivers;

— optical installation including TV-camera and photometer for limb observations and a photometer oriented to nadir;

— mass-spectrometer of ionised and neutral components of ionospheric plasma;

— spectrometer of electrons and protons with energies of 20 keV – 2 MeV;

— DC magnitometer;

— a set of coherent transmitters for ionospheric tomography;

— a system of data acquiring from 'buoy' stations;

— a thruster for maintenance of required parameters of the satellite orbit.

4. Basic sections of the program aimed at investigation of lithosphere-ionosphere interactions and elaboration of methodology of short-term earthquake prediction

A. Concept of lithospheric mechanochemical reactor

A.1. Development of theoretical model to describe processes of mechanical stress accumulation, generation and breeding of microcracks in an elastically inhomogeneous medium.

A.2. Learning the mechanisms giving rise to critical stresses and responsible for their relaxation into a macroscopic (giant) crack with shear shift.

A.3. Implementation of laboratory modelling of mechanochemistry of rocks, including the processes of formation and transport into the atmosphere of gaseous and aerosol fractions in the reactor products and the processes of electromagnetic field and current generation coupled with them; development of the theory for these processes.

A.4. Conduction of experiments on exploring the chemical composition of the reactor products, performing chemical monitoring in seismically active regions to settle the methods of chemical diagnosis and prognosis of the earthquake activity.

A.5. Development of theoretical models for radiation generation in X-ray, optical and radio frequency ranges during the crack formation.

B. Dynamics of the products of mechanochemical reactor in the atmosphere, their transport into the ionosphere and modification under the influence of cosmic ionising radiation and thunderstorm discharges

C. Chemical-physical impact of the reactor products on the atmosphere and the ionosphere

C.1. Investigations of changes in ground water chemical composition, gas composition of the atmosphere, and aerosol cloud formation over the earthquake epicentral zone.

C.2. Study of the atmospheric conductivity and atmospheric electric fields, formation of the thunderstorm cells and stimulation of thunderstorm activity, the role of vertical electric discharges in transport of seismically produced ions to the ionosphere.

C.3. Analysis of changes in distributions of density, temperature, and ion composition in the ionosphere.

D. Geophysical effects of mechanochemical reactor work at the preparatory stages of earthquake

D.1. Studying principal mechanisms of large-scale field and current formation, their modulation by different sources, and generation of electromagnetic radiation in frequency ranges of geomagnetic pulsations, ULF and ELF in the epicentral region.

D.2. Study of stimulated (secondary) electromagnetic radiation and geomagnetic pulsations.

D.3. Investigation of stimulated plasma irregularities in the ionosphere.

D.4. Exploration of processes involving ionospheric D-region modification, perturbation of far atmospherics parameters, amplitude and phase characteristics of VLF and LF radio stations in the Earth-ionosphere waveguide.

D.5. Analysis of mechanisms of formation and modification of sporadic layers in E-region of the ionosphere.

D.6. Investigation of airglow of the atmosphere in the region around the earthquake epicentre and of the ionosphere above the earthquake epicentral zone.

E. Cause and effect links between the phenomena observed and the earthquake prognosis methodology

E.1. Elaboration of phenomenological model to assess the impact of mechanochemical reactor on the near-Earth space.

E.2. Development of a physical model of impact of the mechanochemical reactor on the Earth's atmosphere, ionosphere, and magnetosphere.

E.3. Elaboration of basic physical-chemical principles of the methodology of short-term earthquake prognosis using chemical, electromagnetic, and plasma monitoring of earthquake precursors by ground-based and satellite-borne means.

References

1. Migulin V V et al., Preprint No. 25 (390) (Moscow: IZMIRAN, 1982) p. 28
2. Gokhberg M B et al. *J. Geophys. Res.* **8** 7824 (1982)
3. Larkina V I et al. *Geomagnetizm i Aeronomiya* **28** 812 (1988)
4. Chmyrev V M et al. *Phys. Earth Planet. Inter.* **57** 110 (1989)
5. Parrot M, Mogilevsky M M *Phys. Earth Planet. Inter.* **57** 86 (1989)
6. Bilichenko S V et al. *Dokl. Akad. Nauk SSSR* **311** 1077 (1990)
7. Mikhailova G A, Golyavin A M, Mikhailov Yu M *Geomagnetizm i Aeronomiya* **31** 80 (1991)
8. Serebryakova O N et al. *Geophys. Res. Lett.* **19** 91 (1992)
9. Molchanov O A et al. *Ann. Geophys.* **11** 431 (1993)
10. Parrot M *J. Geophys. Res.* **99** 23339 (1994)
11. Varotsos P, Alexopopoulos K *Tectonophys.* **110** 73 (1984)
12. Varotsos P, Alexopopoulos K *Tectonophys.* **136** 335 (1987)
13. Fishkova L M et al. *Ann. Geophys.* **3** 679 (1985)
14. Toroshelidze T I, Fishkova L M *Dokl. Akad. Nauk SSSR* **302** 313 (1988)
15. Gokhberg M B et al. *Izv. Akad. Nauk SSSR Ser. Fiz. Zemli* (4) 12 (1988)
16. Fatkullin M N, Zelenova T G, Legenka A D *Phys. Earth Planet. Inter.* **57** 82 (1989)
17. Alimov O A et al. *Dokl. Akad. Nauk SSSR* **305** 1335 (1989)
18. Liperovskiĭ V A et al. *Izv. Akad. Nauk SSSR Ser. Fiz. Zemli* (12) 77 (1990)
19. Pulinets S A, Legenka A D, Alekseev V A, in *Dusty and Dirty Plasmas, Noise and Chaos in Space and in the Laboratory* (New York: Plenum Publ., 1994) p. 545
20. Boskova J et al. *J. Atm. Terr. Phys.* **55** 1595 (1993)
21. Boskova J et al. *Studia Geoph. et Geod.* **38** 213 (1994)
22. Ralchovsky Tz, Komarov L *Bulgarian Geophys. J.* **14** 78 (1988)
23. Liperovskiĭ V A, Pokhotelov O A, Shalimov C A, in *Ionosfernye Predvestniki Zemletryaseniĭ* (Ionospheric Earthquake Precursors) (Moscow: Nauka, 1992) p. 304
24. Fraser-Smith A C et al. *Geophys. Res. Lett.* **17** 1465 (1990)
25. Kopytenko Yu A et al., Preprint No. 3 (888) (Moscow: IZMIRAN, 1990) p. 25
26. Hayakawa M, Yoshino T, Morgounov V A *Phys. Earth Planet. Inter.* **77** 97 (1993)
27. Blanc E, Rickel D *Radio Science* **24** 279 (1989)
28. Gokhberg M B et al. *Dokl. Akad. Nauk SSSR* **313** 586 (1990)
29. Fuks I M, Shubova R S *Geomagnetizm i Aeronomiya* **34** 130 (1994)
30. Mendillo M, Hawkins G S, Klobuchar J *J. Geophys. Res.* **80** 2217 (1975)
31. Galperin Yu I et al. *Izv. Akad. Nauk SSSR Ser. Fiz. Zemli* (11) 88 (1985)
32. Chmyrev V M et al. *Kosmicheskie Issledovaniya* **27** 248 (1989)
33. Imhof W L et al. *Geophys. Res. Lett.* **10** 361 (1983)
34. Chmyrev V M et al. *J. Atm. Terr. Phys.* (in press) (1996)
35. Galperin Yu I et al. *Kosmicheskie Issledovaniya* **30** 89 (1992)
36. Alekseev V A, Alekseeva N G, Jchankuliev J *Radiation Measurements* **25** 637 (1995)