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Detection and monitoring of earthquake precursors: TwinSat, a Russia–UK satellite project ☆

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Abstract

There is now a body of evidence to indicate that coupling occurs between the lithosphere–atmosphere–ionosphere prior to earthquake events. Nevertheless the physics of these phenomena and the possibilities of their use as part of an earthquake early warning system remain poorly understood. Proposed here is a programme to create a much greater understanding in this area through the deployment of a dedicated space asset along with coordinated ground stations, modelling and the creation of a highly accessible database. The space element would comprise 2 co-orbiting spacecraft (TwinSat) involving a microsatellite and a nanosatellite, each including a suite of science instruments appropriate to this study. Over a mission duration of 3 years $\sim$ 400 earthquakes in the range 6–6.9 on the Richter scale would be ‘observed’. Such a programme is a prerequisite for an effective earthquake early warning system.

Keywords: Earthquake; Ionosphere; Satellite

1. Introduction

Presented here is a proposal for coordinated experimental studies of lithosphere–atmosphere–ionosphere (LAI) coupling effects associated with seismic activity, particularly as precursors to earthquakes. The proposed programme would include the flight of TwinSat – 2 co-orbiting satellites that will make a range of measurements in the ionosphere, and coordinated ground-based observations. The proposed programme can be seen as the next step towards an ‘Earthquake early warning system’. The feasibility and design of such a system based on atmospheric and ionospheric signals can only come about after a more detailed study is made, both of the underlying physics and the practicalities.

The mitigation of earthquake damage and loss of life remains of great concern. It is argued that we can expect fatalities from a single event of more than 1 million in the next century. Economic impact can be enormous – it is estimated that the recent earthquake in Sendai caused ~$265 billion in damage and while much of that would have been unavoidable, many lives would have been saved and much secondary damage avoided if an early warning system had been in place.

A number of other missions have been proposed for study of LAI coupling effects but are not currently approved. The

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most sophisticated and successful of those flown has been Demeter, the first satellite dedicated to natural disaster and technologic effects on the ionosphere (Cussac et al., 2006). It has a circular sun-synchronised orbit, initial altitude ~710 km and operated in 2 modes, slow and burst (while above a seismically active region). While it is still in orbit, operations were ceased in December 2010.

A brief overview of experimental evidence of LAI phenomena is presented below. A description of the proposed program involving a TwinSat space sector, coordinated ground segments and an underlying modeling activity is then given.

2. Experimental evidence of LAI phenomena

Summarized below are several observations of LAI phenomena associated with seismic activity that have been reported.

Enhancement of seismic activity and typhoons produce DC electric field disturbances in the ionosphere with magnitudes up to 10 mV/m. These disturbances occur over an area of the order of several hundred km in diameter above the earthquake region. Also, the DC electric field enhancements may arise in the ionosphere from several hours to 10 days before an earthquake, (Chmyrev et al., 1989; Sorokin et al., 2005a, Gousheva et al., 2008, 2009).

Case studies and statistical analysis of plasma density variations observed from DEMETER satellite show that the plasma density increases in vicinity of epicenter of future earthquake days before the main shock (Pisa et al., 2011; He et al., 2011). It was noted that the intensity of the anomalies was enhanced when the earthquake magnitude increased and was reduced when the depth increased (He et al., 2011). Earlier the redistribution of plasma density in the upper ionosphere before earthquakes has been reported in several papers basing on the data of top-side ionosphere sounding (see Pulinets and Boyarchuk, 2004 and references therein).

Increase of light ions (H^+ and He^+) concentration in the ionosphere over impending earthquake region was first observed from the Intercosmos-24 satellite (Boskova et al., 1993, 1994) and later confirmed by the data from AE-C satellite (Pulinets et al., 2003).

The magnitude of ULF geomagnetic field oscillations detected in the seismically disturbed ionosphere prior to earthquakes lie in the range from 0.2 to 3 nT, (Chmyrev et al., 1989; Bilichenko et al., 1990; Bhattacharya et al., 2007, 2009).

The association of electromagnetic emissions with impending earthquakes was first reported by Gokhberg et al. (1982). Later it was shown that the small-scale (4–10 km) irregularities of plasma density with relative amplitudes of 10–30% and correlated electromagnetic ELF (Extremely Low Frequency) emissions with amplitudes 3–10 pT at frequencies ~450 and ~140 Hz respectively are excited within geomagnetic flux tubes (3–4° in latitudes) connected to the epicenter region several days prior to an earthquake (Nomikos et al., 1997; Serebryakova et al., 1992; Chmyrev et al., 1997). Similar ULF/ELF electric field and plasma perturbations have been registered recently by DEMETER satellite in connection with Chili earthquakes with magnitude $M>6.0$ (Zhang et al., 2011). Blecki et al. (2010, 2011) observed strong ELF emissions in the ionosphere 1–6 days before several large magnitude earthquakes. It was shown that such emissions were very well correlated in time and space with the thermal anomaly registered by the NOAA 18 satellite before the strong Sichuan earthquake of 2008.

Pre-earthquake VHF (Very High Frequency) electromagnetic radiation is generated in the atmosphere at altitudes 1–10 km over the quake zone, (Vallianatos and Nomicos, 1998; Ruzhin et al., 2000; Ruzhin and Nomicos, 2007).

Seismic-related disturbances in the troposphere create the conditions for over-horizon propagation of signals from ground-based VHF transmitters on the routes passing through the earthquake area, (Fukumoto et al., 2002; Fujiwara et al., 2004; Ohno et al., 2005).

Seismic-related disturbances of the lower ionosphere produce anomalous effect in Schumann resonance phenomena including unusual enhancement of the fourth harmonic and shift in frequency ~1 Hz from conventional value at this harmonic (Hayakawa et al., 2005; Nickolaenko et al., 2006).

Detection of seismic-related phase and amplitude disturbances of VLF/LF transmitter signals in the Earth-ionosphere waveguide a few days to a week before an earthquake is evidence of the lower ionosphere modification by an earthquake preparation processes, (Gokhberg et al., 1989; Gufeld et al., 1992; Rozhnoi et al., 2004, 2009). The most significant result in this field has been obtained from observations in three European VLF/LF stations – Moscow, Bari and Graz – for an earthquake in L'Aquila (Italy) on April 6, 2009 (Rozhnoi et al., 2009). Strong nighttime anomalies for long propagation paths together with a shift in the evening terminator for short paths have been found 5–6 days before the earthquake. Direction finding research has showed excellent coincidence with real position of the earthquake epicentre. In addition to a case study of L'Aquila event, the most important finding from subionospheric VLF/LF studies is the recent establishment on the statistical significant correlation between VLF/LF propagation anomalies and EQs with $M \sim 6$ and shallow ($d < 40$ km) depth (Hayakawa et al., 2010b).

First indication of seismic activity effects on outgoing infrared (IR) radiation was reported at the end of the eighties by Gorny et al. (1988). Later similar satellite observations made by various research groups in different countries confirmed appearance of thermal IR anomalies connected with impending earthquakes a week to a month before a shock (Quang et al., 1991; CORDIS RTD-PROJECTS/European Communities, 2000; Qiang and Du, 2001; Tramutoli et al., 2001; Tronin, 2002; Tronin et al., 2002; Saraf and Choudhury, 2003; Singh and Ouzounov, 2003; Ouzounov and Freund, 2003; Xiong et al., 2010).

Outgoing long wave (8–12 μm) radiation anomalies have been found on the ocean and the ground surface, mainly in the zones of large faults, and in the atmosphere (Ouzounov et al., 2007, 2008; Tronin, 2010). They showed change of the earth's surface temperature of 3–6° and an intensity of thermal radiation in the atmosphere up to 80 W per square meter.

Alterations in the total water vapor column and changes in aerosol parameters and ozone concentration in connection with large earthquakes have been reported, (Dey et al., 2004; Okada et al., 2004; Tronin, 2002, 2010).

The concentration of charged soil aerosols in the atmosphere above a seismic region increases by 1–2 orders of magnitude the days to a week before an earthquake. A similar effect was observed in intense outbursts of radon (Rn222) and other radioactive substances on the eve of large earthquakes (Alekseev and Alekseeva, 1992; Virk and Singh, 1994; Heincke et al., 1995; Pulinets et al., 1994; Yasuoka et al., 2006; Omori et al., 2007).

3. Model of phenomena

A major part of theoretical models of the lithosphere–atmosphere–ionosphere interaction is that a DC electric field is assumed as an underlying cause of numerous electromagnetic and plasma disturbances excited in the ionosphere and the atmosphere on the eve of earthquakes. Liperovsky et al. (2008) have analyzed the generation mechanism of localized electric field spikes with magnitude up to 10^3 V/m and characteristic time scales from 1 to 100 min in the near ground atmosphere before earthquakes. These spikes are generated in a process of upward convectional transport and gravitational sedimentation of charged aerosols of different sizes in the earthquake area. The aerosols become charged through their interaction with ions which in turn are the product of the radioactive decay of radon that is injected into the atmosphere before earthquake. Such spiky vertical electric fields have been observed in the near ground atmosphere in seismically active areas (Vershinin et al., 1999; Smirnov, 2005). An interesting effect, which is important from the point of view of search for earthquake precursors, was predicted by Liperovsky et al. (2008) and involves the generation of non-equilibrium IR emissions due to excitation of CO_2 and CH_4 molecules by electrons accelerated in the electric field spikes. However, since the time scale of these spikes does not exceed 100 minutes the model postulated (Liperovsky et al., 2008) does not explain pre-earthquake DC electric fields and related phenomena observed in the ionosphere.

Pulinets et al. (2000) have suggested a mechanism for the electric field modification near the Earth surface and its penetration into the ionosphere. The electric field disturbances in this model are generated by the separation of large and small charged drops of mist through convection motion and gravitational sedimentation. Drops are charged by coupling with atmospheric ions, generated, as above, through radon decay. This model can be used to compute the upward transfer of the excited electric field and predicts a magnitude of this field in the ionosphere ~0.07 mV/m if the near ground electric field is 100 V/m in the area with diameter ~200 km. To obtain the ionospheric field at least at the background level of ~1 mV/m a near ground field ~1000 V/m is needed. It is therefore evident that the DC electric field of ~10 mV/m experimentally observed in the ionosphere during several days before an earthquake cannot be explained by this model.

The nature of seismic related DC electric field in the ionosphere has been investigated in numerous papers (Pulinets et al., 2003; Grimalsky et al., 2003; Denisenko et al., 2008; Ampferer et al., 2010). Authors of these papers used a well-known model of the electric field penetration into the ionosphere, which assumed that the field source is situated in the lithosphere and the field is transferred through the atmospheric layer with altitude dependent electric conductivity. This layer is a part of the closed global atmosphere–ionosphere electric circuit. It is assumed that the homogeneous Ohm's law for a part of circuit without electro motive force is fulfilled in this layer. The maximum magnitude of DC electric field in the ionosphere E_1 can be estimated by formula $E_1 = \sigma_0 E_0/\sigma_1$ where σ_0 *and* E_0 are the conductivity and the electric field near the Earth surface and σ_1 is the ionosphere conductivity. A mean value of the electric field in a seismic region does not exceed the background level ~100 V/m on a time scale of several days. Taking into account that $\sigma_0 \approx 10^{-14}$ S/m, $\sigma_1 \approx 10^{-5}$ S/m and $E_0 \approx 100$ V/m we find $E_1 \approx 10^{-4}$ mV/m, i.e. four orders of magnitude lower than the background ionospheric field. Such a value was obtained in all above mentioned papers utilizing this model. Thus their results are not compatible with the well published experimental data which indicated the pre-earthquake DC electric fields ~10 mV/m in the ionosphere (Chmyrev et al., 1989; Gousheva et al., 2008; Gousheva et al., 2009).

This contradiction was removed in the electrodynamic model of the atmosphere–ionosphere coupling described in Sorokin et al. (2001, 2005b, 2007), Sorokin and Chmyrev (2010). Their model is based on the assumption that the source of ionospheric DC electric field is Electro Motive Force (EMF) formed in the near ground atmosphere. The maximum magnitude of DC electric field in the ionosphere can be estimated in this case as $E_1 = (\sigma_0 E_0/\sigma_1)(1 + j_e/\sigma_0 E_0)$ where j_e is a density of the EMF external electric current near the Earth surface. If we suppose, that the external current is caused by the movement of aerosols with concentration N and charge Ze under the action of vertical atmospheric convection with the velocity v, then the current density can be estimated as $j_e = ZeNv$. Assuming $Z = 300$, $N = 8\times10^9$ m^{-3}, $v = 0.3$ m/s, we obtain the electric field in the ionosphere $E_1 = 10^{-7}(1 + 10^5)$ V/m ≈ 10 mV/m, which corresponds to satellite observations over the seismic regions (Chmyrev et al., 1989; Gousheva et al., 2008; Gousheva et al., 2009). Basing on the analysis of total electron content data Zolotov et al. (2008) have shown that the ionosphere disturbance observed during

6 days before the Peru earthquake of September 26, 2005 has been caused by the enhancement of DC electric field in the ionosphere up to 6–8 mV/m. This finding strongly supports the approach developed in Sorokin et al. (2001, 2005b, 2007), Sorokin and Chmyrev (2010). A key factor of this approach is the formation of an external electric current. The charged aerosols and radioactive elements are injected into the atmosphere due to intensified soil gas elevation in the lithosphere during enhanced seismic activity. Molchanov et al. (2004) considered the enhanced injection of soil gases into the atmosphere as one of the most important factors for the seismic influence on the ionosphere. Among other mechanisms they analyzed the effects of soil gas injection on the generation of acoustic-gravity waves, which reach the ionosphere and forms there the plasma irregularities that influence the propagation of radio waves and the depression of geomagnetic pulsations.

According to the electrodynamic model of the atmosphere–ionosphere coupling the electro motive force works between the Earth surface and near ground atmospheric layers. EMF is formed as a result of convective and turbulent transport and gravitational sedimentation of charged aerosols at the injection of which by soil gases causes the Earth's surface to acquire a charge of the opposite sign. External current and charge are defined by a set of nonlinear equations describing the kinetics of electrons, ions and charged aerosols and their interaction in the atmosphere. The perturbation of current flowing in the atmosphere–ionosphere electric circuit leads to growth of DC electric field in the ionosphere up to 10 mV/m and in the near ground atmosphere ~100 V/m (Sorokin et al., 2001, 2005b, 2007; Sorokin and Chmyrev, 2010).

Basing on the electrodynamic model it was shown that under particular conditions the seismic related DC electric field in the atmosphere below 10 km can reach the breakdown value in 1 or 2 layers ~1–2 km in thickness (Sorokin et al., 2011). Since the breakdown field depends on the atmosphere density and turbulent atmospheric vortices are accompanied by the density fluctuations, turbulence in these layers leads to appearance of random electrical discharges. (Tertyshinikov, 1996) have reported on the growth of ozone concentration in the atmosphere over an earthquake area which is consistent with the excitation of seismic related electrical discharges in the atmosphere. Besides this ozone generation effect we can expect the stimulation of following phenomena as a result of a pre-earthquake DC electric field reaching the breakdown value:

- Heating of the atmosphere in the discharge region and the generation of outgoing long wave (8–12 μm) radiation;
- Broadband electromagnetic VHF emission;
- Airglow in visible range;
- Refraction and scattering of VHF radio waves in the troposphere providing the over-horizon reception of ground-based VHF transmitter signals.

The formation of large enough DC electric field in the ionosphere exceeding a threshold value leads to instability of acoustic-gravity waves and generation of periodic or localized ionospheric structures in a form of solitary dipole vortices or vortex chains and associated plasma density and electric conductivity disturbances in the ionosphere. The excitation of horizontal spatial structure of conductivity in the lower ionosphere results in the formation of magnetic field-aligned currents and plasma layers stretched along the geomagnetic field. Excitation of these horizontal small-scale irregularities of electric conductivity in the lower ionosphere is a key factor for the generation mechanism of ULF magnetic field oscillations, electron number density fluctuations and ELF electromagnetic emissions observed on satellites and Schumann-resonance-like anomalous line emissions observed on the Earth surface before earthquakes (Sorokin et al., 1998; Borisov et al., 2001; Sorokin and Hayakawa, 2008; Hayakawa et al., 2010a; Chmyrev and Sorokin, 2010).

Heating of E layer of the ionosphere through the enhancement of current in a global electric circuit leads to an altitude profile of electron density in F layer and the perturbation of light ions density in the upper ionosphere (Sorokin and Chmyrev, 1999). Growth of electric current flowing into the ionosphere from the atmosphere results in electron density redistribution in E region including the formation of anomalous sporadic E layers (Sorokin et al., 2006). Additional electric current in D layer of the ionosphere initiates the formation of electron density disturbances by changing the charge carriers from electrons to negative ions and by electron heating (Laptukhov et al., 2009).

A major part of earlier theoretical models was devoted to separate descriptions of the various precursor signals observed by different experiments. Thus, for example Molchanov et al. (1995), Molchanov (1999), Surkov and Pilipenko (1999), Vallianatos and Tzanis (1999), Tzanis and Vallianatos (2001, 2002), Uritsky et al. (2004) considered the formation by the lithosphere sources of ULF radiation and its penetration into the ionosphere, Kim and Hegai (1999) tried to explain the modification of height ionospheric profile by plasma drift in growing DC electric field and Gokhberg et al. (1996) and Liperovsky et al. (1997) analyzed the possible effects of internal gravity waves and infrasonic waves on the ionosphere. All these models constructed a chain of processes developed from the supposed source to the observed parameter. Different approach consists in joint analysis of the whole set of observed phenomena and search for their common nature. Such an approach is aimed at the development of unified model, which explains a range of satellite and ground experimental data by a single underlying cause and outline the interconnection between the observed parameters. This approach is realized in electrodynamic model of the lithosphere–atmosphere–ionosphere coupling (Sorokin et al., 2001, 2005b, 2007; Sorokin and

Chmyrev, 2010), which is illustrated by a scheme in Fig. 1.

TwinSat work program foresees continuation of theoretical modeling of the atmosphere–ionosphere interaction at the preparatory phases of earthquakes. This program includes the following tasks:

Task 1: The development of numerical methods for finding 3D-distribution of DC electric field in the closed atmosphere–ionosphere electric circuit, which is generated by external electric current excited in the lower atmosphere in a process of vertical atmospheric convection and gravitational sedimentation of charged aerosols injected into the atmosphere before an earthquake. Effects of the ionization of lower atmosphere by radioactive sources (radon, etc.), the adhesion of electrons to molecules and the interaction of charged ions with charged aerosols will be taken into consideration.

Task 2: The development of the theoretical model for the disturbances of the *D*-, *E*- and *F*- layers of the ionosphere connected with the generation of external electric current. For the *D*- layer we will consider the effect of the replacement of the charge carriers type at the inflow of external current from the atmosphere into the ionosphere and the redistribution of charged particle density leading to the formation of large-scale horizontal inhomogeneities and influencing the ULF-VLF electromagnetic wave characteristics in the Earth-ionosphere waveguide. For the *E*-region the computation of anomalous sporadic layers will be performed.

Task 3: The further development of the theory of internal/acoustic-gravity wave instability in the ionosphere under influence of DC electric field will be made that takes into account the relative movement of ionized and neutral plasma components and the inclination of the geomagnetic field.

Task 4: The development of the theory of nonlinear vortex structures and related disturbances in the ionosphere influenced by the electric field and some other factors caused by earthquake and volcanic activities. This will include the generation of nonlinear Internal Gravity Wave (IGW) structures and related electric current and plasma density perturbations in the ionosphere. Analysis of Drift-Alfven Wave (DAW) instability in the ionosphere disturbed by nonlinear IGW will be carried out. 2 detectable effects of this instability will be investigated. First is the formation of DAW vortex structures and small-scale current filaments and second is connected with nonlinear evolution of DAW turbulence into the relatively large-scale zonal winds.

Task 5: The development of the theory for the formation of breakdown electric fields and electrical discharges in the troposphere and stratosphere over seismic and volcanic activity zones. As a result of this study we expect to obtain the radiation characteristics of these discharges in different

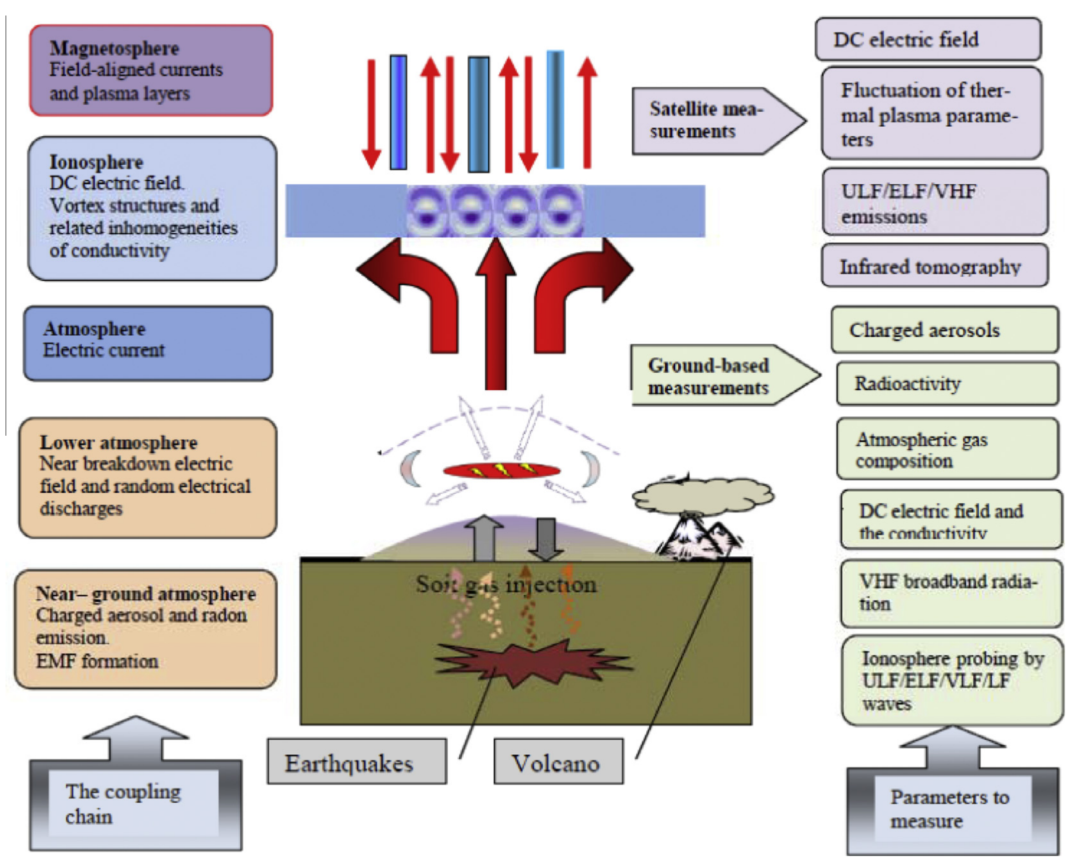

Fig. 1. A schematic of the Lithosphere–Atmosphere–Ionosphere electrodynamic coupling.

frequency ranges and their influence on the electric and thermodynamic parameters of the atmosphere. Special attention will be paid to runaway breakdown in the pre-earthquake/volcanic activity electric field and associated phenomena in the atmosphere and the ionosphere of the Earth.

Task 6: The theoretical modeling of the intensification of outgoing long wave (8–12 μm) radiation and its possible interconnection with strong electromagnetic ELF emissions in the ionosphere over the epicenter of an impending earthquake.

Task 7: Finally, we will systemize the generation mechanisms and interrelations of separate precursor signals in the framework of unified self-consistent physical model, which describes the chain of processes arising in the atmosphere and the ionosphere on the eve of volcanic eruptions and strong earthquakes.

4. Proposed TwinSat programme

The objectives of the proposed programme are:

- To validate current experimental findings and theoretical models addressing the short-term earthquake precursors through specialized and coordinated 2-satellite and ground based observations;
- To develop a comprehensive theoretical model describing the formation and interconnection of the precursor signals and the causal mechanism(s) (if present) between the driving seismic activity and the ionospheric signatures;
- To search for new precursory signals and estimate potential for accuracy improvement of forecasting the time and position of impending earthquakes;
- To determine the feasibility of a follow-on satellite constellation for reliable earthquake prediction taking into consideration the danger of false alarms and ambiguity;
- To evaluate possible ‘earthquake occurrence probability algorithms’ based on the above results.

The links between the seismo-tectonic processes and atmosphere/ionosphere earthquake precursors remain poorly understood. While the complex and dynamic nature of the earthquake precursor phenomena requires spatial, spectral, and temporal coverage that is beyond any single payload, we believe a dedicated space mission of the form described below, together with coordinated ground stations, could make considerable progress in this area.

A major part of the programme would involve the correlation of space and ground-based observations so as to optimize the ability to distinguish earthquake precursor signals from signals of an anthropogenic, magnetospheric or other non-seismic origin.

For the proposed polar orbit, the passage over a particular region will occur approximately 5 times in a 2 day period. The expected number of earthquakes with magnitude 6–6.9 in the Richter scale in 3 years for which data will be taken is ∼400.

The space segment consists of 2 platforms in a mother/daughter arrangement – the microsatellite TwinSat-1M and the nanosatellite TwinSat-1N, operating at a controlled separation (see Figs. 2 and 3). An inter-satellite radio link provides transmission of scientific information from TwinSat-1N to TwinSat-1M, where it is stored in high capacity onboard memory for the subsequent delivery of the whole data set from the 2 satellites to an appropriate ground telemetry station.

TwinSat will be a significant advance over other missions in that it involves 2 satellites with controlled separation. 2 satellites enable synchronous measurements of the precursor signals in separated points along the orbit to determine their spatial structure and the dynamic characteristics such as their propagation velocity, temporal/spatial variations, etc. This will allow significantly improved recognition and discrimination of earthquake precursor signals from a background of other sources. In addition, the development and test of a scheme of joint operation and in-orbit information exchange between 2 very small platforms will enable future cost effective satellite constellation for monitoring of large-scale natural disasters.

After launch and orbital insertion, the TwinSat-1N would be separated from TwinSat-1M with a relative velocity of ∼3 cm/s. Differences in the ballistic coefficients of the 2 satellites will cause the TwinSat-1N to lose altitude more quickly (and therefore speed up) and so some orbital control will be needed to maintain a useful separation between the 2 spacecraft. It is foreseen that this control will be on the TwinSat-1M spacecraft in the form of, for instance, a thruster. It is proposed to maintain a separation of <400 km (varying during the mission with the TwinSat-1N being either ahead or behind the TwinSat-1M). The attitude of the TwinSat-1N is fixed with respect to the direction of motion and so to accommodate the 2 relative directions of the TwinSat-1M, 2 patch antennae will be used on TwinSAT-1N. The possibility of keeping the

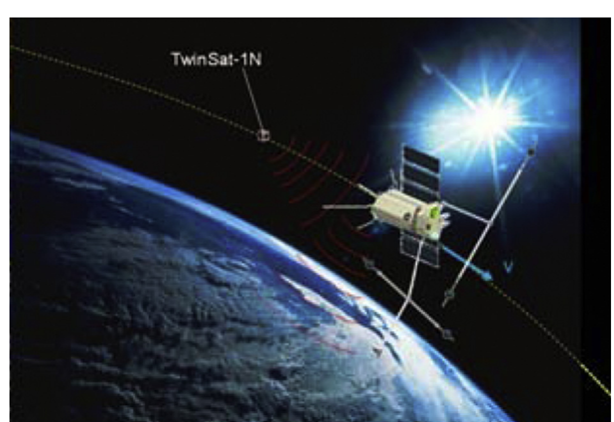

Fig. 2. Twin satellite orbital configuration.

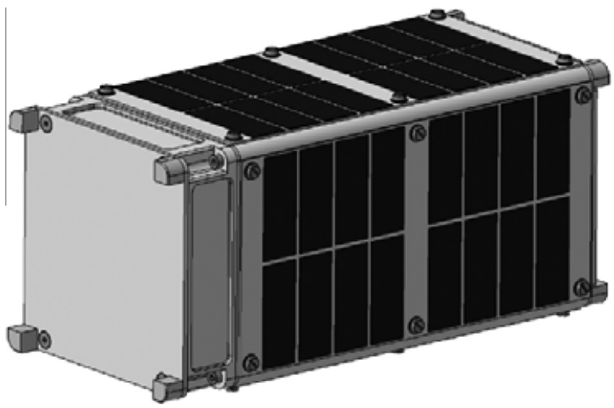

Fig. 3. TwinSat-1N.

TwinSat-1N permanently ahead of the TwinSat-1M is being studied.

The launch configuration of TwinSat-1M has the form of a compact hexahedral prism. The lower plate is used for fastening the micro satellite to the separation system and for installation of the separation contacts and the Orbital Control Complex (OCC) strip antennas. The upper plate accommodates the digital solar sensors, GLONASS/GPS devices and the antennas and booms, both deployed after orbit insertion. A truss construction is mounted on the upper plate for fastening the sensor booms, deployment mechanisms and fittings. Screen-vacuum thermal insulation provides for the thermal control of TwinSat-1M. TwinSat-1M construction provides the possibility of piggy-back delivery to orbit by any launch vehicle.

The TwinSat-1M will comprise the following sub-systems (see also Table 1):

- Onboard Control Complex (OCC) including the radio channel unit with antennas, central controller, user navigation device with antenna, power module, telemetry commutation, optional GLOBALSTAR modem interface modules and harness;
- Attitude Control System (ACS) including; the actuator unit with the ACS controller, driver-flywheels (6 units) module, and the electromagnetic devices, startracker, 2 digital sun sensors and 6 sensors for the preparatory orientation on the Sun, fluxgate magnetometer and harness;
- Power supply system (PSS) including the Gallium Arsenide solar cell array, Ni-MH battery, controller and harness;
- Temperature Control System (TCS) including electrical heater, heat insulation, radiation surfaces, temperature sensors and harness;
- Spacecraft structure including frame and booms;
- TwinSat-1N separation system.

The TwinSat-1M payload instruments and TwinSat-1N are additional sub-systems. (see Table 2)

The TwinSat-1N will be configured as a 2U CubeSat (Heidt et al., 2000) with additional deployed solar panels. Since a conventional CubeSat deployment device is not proposed for this mission, deployment of these panels will occur prior to satellite release (either while attached to TwinSat-1M or prior to launch). In addition a pre-deployed boom will be provided for the ULF/ELF magnetic sensors.

The baseline communication strategy between satellites in normal operations would be communications from TwinSat-1N via an S-band link to TwinSat-1M. In addition, a VHF/UHF link would allow independent communications between TwinSat-1N and the ground which would be particularly important while the attitude of TwinSat-1N is being stabilized after separation.

Conceptually, for baseline operations, from the systems view, TwinSat-1N will be configured as a subsystem of TwinSat-1M rather than an independent entity. In this way inflight re-configuration of the TwinSat-1N would be natural, straight forward and synchronized with other operations. The close integration of the 2 satellites and relatively high bandwidth available to the TwinSat-1N compared with other CubeSat missions affords considerable research potential.

5. Science payloads

The TwinSat-1M spacecraft will measure the following parameters:

- DC electric field vector
- Spectral and wave characteristics of 6 electromagnetic field components in ULF/ELF range (0.5–500 Hz)
- Spectrum and sample waveforms of electric field oscillations in VLF/LF (0.5–300 kHz) range
- Amplitude and phase variations of ground based VLF/LF transmitter signals
- Spectrum and sample waveforms of electromagnetic waves in VHF range (22–48 MHz)
- Variations of thermal and supra thermal (0.3–20 eV) plasma parameters
- Energy distributions of electron and ion fluxes with energies 3–300 eV for 2 directions
- Lightning activity in the sub-satellite regions (optical measurements) – needed to discriminate against lighting-related events, ionospheric plasma disturbances and some atmospheric emissions.
- IR emission in the range 10.5–12.5 μm

The TwinSat-1N spacecraft will measure the following parameters:

- Variations of thermal and supra thermal (0.3–20 eV) plasma parameters*
- Energy distributions of electron and ion fluxes with energies 0.3–300 eV for 2 directions*

Table 1
TwinSat-1M characteristics.

Characteristic	Value
Satellite dimensions (without booms)	Ø46 × 53 cm
Mass (including payload)	~50 kg
Power	
Average	90 W
Maximum	140 W
TwinSat-1N separation	
velocity	3 cm/s
Linear	<6°/s (TBD)
Angular	
Attitude control	3-axis, 8 arc min stability
Orbit	Sun-synchronous, 700–800 km altitude, ~100 min period
Telemetry to ground	
Fast channel (8.2 GHz)	~60 Mbit/s
Onboard memory	~5 Gbyte
Inter-satellite link frequency	~2.4 GHz (TBD)
Active lifetime	>3 years

Table 2
TwinSat-1N characteristics.

Characteristic	Value
Dimension	10 × 10 × 22.7 cm
Mass	2.5 kg
Power	
Average	2.2 W
Peak	4.0 W
Attitude control	3 axis stabilized, ~1° accuracy
Intersatellite link frequency	2.4 GHz
Telemetry to TwinSat-1M	
Fast channel	64 Kbit/s
Telemetry to ground	
Slow channel (145/435 MHz)	4.8 Kbit/s
Active lifetime	>3 years

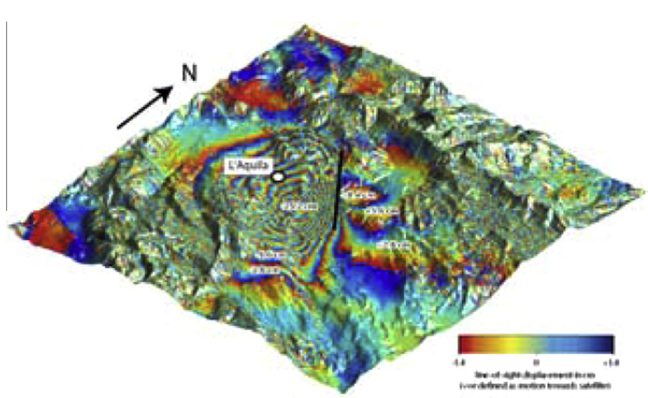

Fig. 4. InSAR image for the L'Aquila EQ, courtesy of Richard Walters.

- Wave form of ULF/ELF magnetic field oscillations (0.5–500 Hz), 1 or 2 components

*TwinSat-1M and TwinSat-1N instruments will be the same design.

6. Data from other satellites

To augment the TwinSat science return it will be advantageous to have data from other space assets including:

- Spatial strain maps of potential earthquake areas from InSAR data, e.g. see Fig. 4.
- Outgoing IR (8–12.5 μm) radiation intensity and thermal images of seismically active zones, e.g. see Fig. 5.
- Space Weather monitoring to be able to take account of magnetospheric effects.

In all cases existing and planned space assets can provide this data.

7. Ground stations

The ground segment consists of the network of geophysical stations situated in several zones of high earthquake and volcanic activity. The 2 satellites will be in a fast operation mode during the passages over these zones, where supporting ground-based measurements of relevant electromagnetic field and the atmosphere parameters should be performed. Comparison of the ground-based and 2-satellite observation results with seismic data will allow us to define the existence (or absence) of correlation between the measured parameters and their cause-sequence links with seismic activity. Measurements to be made by ground stations include:

- Atmospheric gas composition;
- Radon emission and variations of radioactivity;
- Dynamics of aerosol injection;
- Atmospheric DC electric field and current variations;
- Spectral and wave characteristics of ULF/ELF/VLF/VHF electromagnetic emissions including the arrival direction finding and locating the radiation sources;
- Remote sensing of ionospheric disturbances through the registration of amplitude and phase variations of VLF/LF signals from ground-based transmitters at appropriate propagation routes;
- Debit, temperature and chemical composition of underground water sources and holes;
- Air temperature and humidity, wind velocity and atmospheric pressure;
- Seismic and magnetic field oscillations.

The most attractive is the deployment of a multi-discipline ground network in the Kamchatka/Kuril region, which is characterized by the strongest earthquake and volcano activities in the world. 29 active Kamchatka volcanoes annually produce 3–4 eruptions of explosive type. Taking into account the high occurrence rate of eruptions in the selected area, we can expect the formation of a unique set of data on the precursory signals obtained from coordinated ground and twin-satellite observations. Use could also be made of the existing networks in Greece, Italy

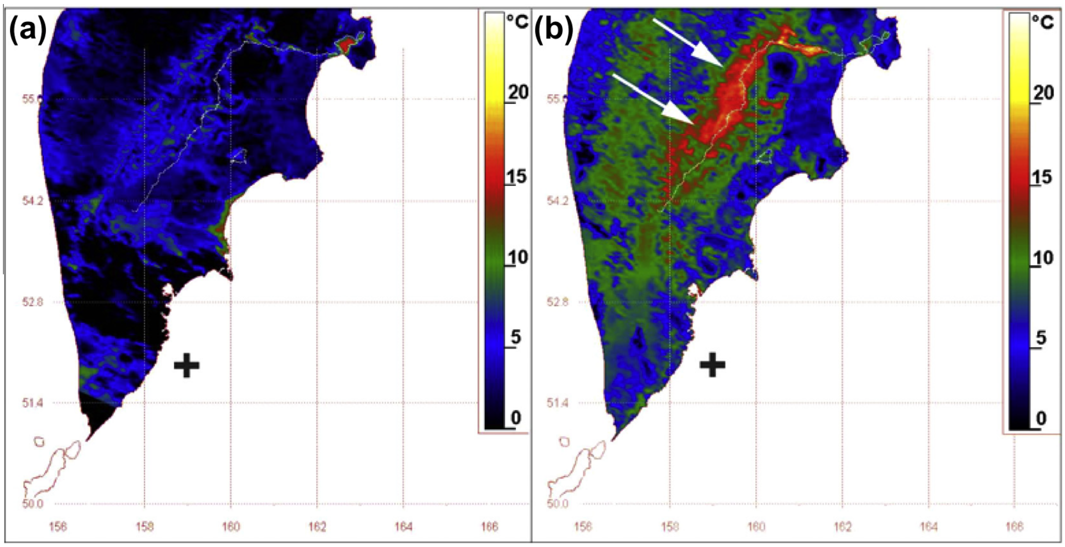

Fig. 5. Thermal anomaly associated with Kamchatka earthquake, June 21, 1996 as seen by satellite NOAA-14. Left indicates background situation. Right, immediately after earthquake. Tronin 2010.

and Iceland after corresponding adaptation of these networks for the TwinSat experiments.

8. Post launch operations

The TwinSat mission is planned to operate for 3 years during which a database of results, both space- and ground-generated, will be set up. Prior to launch and during the mission search and analysis tools will be developed so that the database can be used to systematically assess the feasibility of creating an early warning system for earthquakes and volcanic eruptions including estimates of false alarm rates and metrics of warning (for instance a likelihood estimate based on a balanced scorecard of observed phenomena and correlations).

Together with an early warning systems feasibility will come also its configuration (number and nature of satellites, optimum orbits and orbital configuration such as inclination, height and separation, ground stations and control and dissemination centre assets).

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References

Alekseev, V.A., Alekseeva, N.G. Investigation of metal aerosols transfer in the biosphere during gaseous emission in zones of tectonic activity using methods of nuclear physics. Nucl. Geophys. 6, 99–105, 1992.

Ampferer, M., Denisenko, V.V., Hausleitner, W., Krauss, S., Stangl, G., Boudjada, M.Y., Biernat, H.K. Decrease of the electric field penetration into the ionosphere due to low conductivity at the near ground atmospheric layer. Ann. Geophys. 28, 779–787, 2010.

Bhattacharya, S., Sarkar, A., Gwal, A.K., Parrot, M. Observation of ULF/ELF anomalies detected by DEMETER satellite prior to earthquakes. Indian J. Radio Space Phys. 36, 103–113, 2007.

Bhattacharya, S., Sarkar, A., Gwal, A.K., Parrot, M. Electric and magnetic field perturbations recorded by DEMETER satellite before seismic events of the 17th July 2006 M 7.7 earthquake in Indonesia. J. Asian Earth Sci. 34, 634–644, 2009.

Bilichenko, S.V., Inchin, A.S., Kim, E.F., Pokhotelov, O.A., Puschaev, P.P., Stanev, G.G., Streltsov, A.V., Chmyrev, V.M. ULF response of the ionosphere to earthquake preparation processes. Dokl. Akad. Nauk SSSR 311 (5), 1077–1081, 1990.

Blecki, J., Parrot, M., Wronovski, R. Studies of electromagnetic field variations in ELF range registered by DEMETER over the Sichuan region prior to the 12 May 2008 earthquake. Int. J. Remote Sens. 31 (13), 3615–3629, 2010.

Blecki, J., Parrot, M., Wronovski, R. Plasma turbulence in the ionosphere prior to earthquakes, some remarks on the DEMETER registrations. J. Asian Earth Sci. 41 (4–5), 450–458, http://dx.doi.org/10.1016/j.jseaes.2010.05.016, 2011.

Borisov, N., Chmyrev, V., Rybachek, S. A new ionospheric mechanism of electromagnetic ELF precursors to earthquakes. J. Atmos. Sol. Terr. Phys. 63, 3–10, 2001.

Boskova, J., Smilauer, J., Jiricek, F., Triska, P. Is the ion composition of the outer ionosphere related to seismic activity? J. Atmos. Sol. Terr. Phys. 55, 1689–1695, 1993.

Boskova, J., Smilauer, J., Triska, P., Kudela, K. Anomalous behavior of plasma parameters as observed by the Intercosmos 24 satellite prior to the Iranian earthquake of 20 June 1990. Studia Geophy. Geod. 38, 213–220, 1994.

Chmyrev, V.M., Sorokin, V.M. Generation of internal gravity vortices in the high-latitude ionosphere. J. Atm. Terr. Phys 72, 992–996, 2010.

Chmyrev, V.M., Isaev, N.V., Bilichenko, S.V., Stanev, G.A. Observation by space – borne detectors of electric fields and hydromagnetic waves in the ionosphere over on earthquake center. Phys. Earth Planet. Inter. 57, 110–114, 1989.

Chmyrev, V.M., Isaev, N.V., Serebryakova, O.N., Sorokin, V.M., Sobolev, Ya.P. Small-scale plasma inhomogeneities and correlated ELF emissions in the ionosphere over an earthquake region. J. Atmos. Sol. Terr. Phys. 59, 967–973, 1997.

CORDIS RTD-PROJECTS/European Communities, 2000. Regular update of seismic hazard maps through thermal space observations. Project Reference: ENV4980741.

Cussac, T., Clair, M.A., Ultré-Guerard, P., Buisson, F., Lassalle-Balier, G., Ledu, M., Elisabelar, C., Passot, X., Rey, N. The DEMETER microsatellite and ground segment. Planet. Space Sci. 54, 413–427, 2006.

Denisenko, V.V., Boudjada, M.Y., Horn, M., Pomozov, E.V., Biernat, H.K., Schwingenschuh, K., Lammer, H., Prattes, G., Cristea, E. Ionospheric conductivity effects on electrostatic field penetration into the ionosphere. Nat. Hazards Earth Syst. Sci. 8, 1009–1017, 2008.

Dey, S., Sarkar, S., Singh, R.P. Anomalous changes in column water vapor after Gujarat earthquake. Adv. Space Res. 33, 274–278, 2004.

Fujiwara, H., Kamogawa, M., Ikeda, M., Liu, J.Y., Sakata, H., Chen, Y.I., Ofuruton, H., Muramatsu, S., Chuo, Y.J., Ohtsuki, Y.H. Atmospheric anomalies observed during earthquake occurrence. Geophys. Res. Lett. 31, L17110, http://dx.doi.org/10.1029/2004GL019865, 2004.

Fukumoto, Y., Hayakawa, M., Yasuda, H. Reception of over-horizon FM signals associated with earthquakes, in: Hayakawa, M., Molchanov, O.A. (Eds.), Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. Terra Scientific Publishing Co., Tokyo, pp. 263–266, 2002.

Gokhberg, M.B., Morgunov, V.A., Yoshino, T., Tomizawa, I. Experimental measurement of electromagnetic emissions possibly related to earthquakes in Japan. J. Geophys. Res. 87, 7824–7828, 1982.

Gokhberg, M.B., Gufeld, I.L., Rozhnoy, A.A., Marenko, V.F., Yampolsky, V.S., Ponomarev, E.A. Study of seismic influence on the ionosphere by super long wave probing of the Earth-ionosphere waveguide. Phys. Earth Planet. Inter. 57, 64–68, 1989.

Gokhberg, M.B., Nekrasov, A.K., Shalimov, S.L. Influence of unstable outflow of greenhouse gases in seismic regions on the ionosphere. Phys. Earth 8 (8), 52–57, 1996.

Gorny, V.I., Salman, A.G., Tronin, A.A., Shilin, B.V. The earth's outgoing IR radiation as an indicator of seismic activity. Proc. Acad. Sci. USSR 301 (1), 67–69, 1988.

Gousheva, M., Danov, M., Hristov, P., Matova, M. Quasi-static electric fields phenomena in the ionosphere associated with pre- and post earthquake effects. Nat. Hazards Earth Syst. Sci. 8, 101–110, 2008.

Gousheva, M., Danov, M., Hristov, P., Matova, M. Ionospheric quasi-static electric field anomalies during seismic activity in August-September 1981. Nat. Hazards Earth Syst. Sci. 9, 3–10, 2009.

Grimalsky, V.V., Hayakawa, M., Ivchenko, V.N., Rapoport, Yu.G., Zadorozhnii, V.I. Penetration of an electrostatic field from the lithosphere into the ionosphere and its effects on the D–region before earthquakes. J. Atmos. Sol. Terr. Phys. 65, 391–407, 2003.

Gufeld, I.L., Rozhnoy, A.A., Tyumentsev, S.N., Shersttuk, S.V., Yampolsky, V.S. Radio wave disturbances prior to Rudbar and Rachinsk earthquake. Phys. Solid Earth 3, 102–106 (in Russian), 1992.

Hayakawa, M., Ohta, K., Nickolaenko, A., Ando, Y. Anomalous effects in Schumann resonance phenomena observed in Japan, possibly associated with the Chi-chi earthquake in Taiwan. Ann. Geophys. 23, 1335–1346, 2005.

Hayakawa, M., Ohta, K., Sorokin, V.M., Yaschenko, A.K., Izutsu, J., Hobara, Y., Nickolaenko, A.P. Interpretation in terms of gyrotropic waves of Schumann-resonance-like line emissions observed at Nakatsugawa in possible association with nearby Japanese earthquakes. J. Atmos. Sol. Terr. Phys. 72, 1292–1298, 2010a.

Hayakawa, M., Kasahara, Y., Nakamura, T., Muto, F., Horie, T., Maekawa, S., Hobara, Y., Rozhnoi, A.A., Solovieva, M., Molchanov, O.A. A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes. J. Geophys. Res. 115, A09305, http://dx.doi.org/10.1029/2009JA015143, 2010b.

He, Y., Yang, D., Qian, J., Parrot, M. Response of the ionospheric electron density on different types of seismic events. Nat. Hazards Earth Syst. Sci. 11, 2173–2180, 2011.

Heidt, H., Puig-Suari, J., Moore, A., Nakasuka, S., Twiggs, R., 2000. CubeSat: a new generation of picosatellite for education and industry low-cost space experimentation. In: Proc. 14th Annual AIAA/USU. Conference on Small Satellites, Logan, UT.

Heincke, J., Koch, U., Martinelli, G. CO_2 and Radon measurements in the Vogtland area (Germany) – a contribution to earthquake prediction research. Geophys. Res. Lett. 22, 774–779, http://dx.doi.org/10.1029/94GL03074, 1995.

Kim, V.P., Hegai, V.V. A possible presage of strong earthquakes in the night-time mid-latitude F2 region ionosphere, in: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Co., Tokyo, pp. 619–627, 1999.

Laptukhov, A.I., Sorokin, V.M., Yashchenko, A.K. Disturbance of the ionospheric D region by the electric current of the atmosphere–ionosphere electric circuit. Geomag. Aeron. 49, 768–774, 2009.

Liperovsky, V.A., Meister, C.-V., Schlegel, K., Haldoupis, Ch. Currents and turbulence in and near mid-latitude sporadic E-layers caused by strong acoustic impulses. Ann. Geophys. 15, 767–774, 1997.

Liperovsky, V.A., Meister, C.-V., Liperovskaya, E.V., Bogdanov, V.V. On the generation of electric field and infrared radiation in aerosol clouds due to radon emanation in the atmosphere before earthquakes. Nat. Hazards Earth Syst. Sci. 8, 1199–1205, 2008.

Molchanov, O.A. Fracturing as an underlying mechanism of seismo-electric signals, in: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Co., Tokyo, pp. 349–356, 1999.

Molchanov, O.A., Hayakawa, M., Rafalsky, V.A. Penetration characteristics of electromagnetic emissions from an underground seismic source into the atmosphere, ionosphere, and magnetosphere. J. Geophys. Res. 100, 1691–1699, 1995.

Molchanov, O., Fedorov, E., Schekotov, A., Gordeev, E., Chebrov, V., Surkov, V., Rozhnoi, A., Andreevsky, S., Iudin, D., Yunga, S., Lutikov, A., Hayakawa, M., Biagi, P.F. Lithosphere–atmosphere–ionosphere coupling as governing mechanism for preseismic short-term events in atmosphere and ionosphere. Nat. Hazards Earth Syst. Sci. 4, 757–767, 2004.

Nickolaenko, A.P., Hayakawa, M., Sekiguchi, M., Ando, Y., Ohta, K. Model modifications in Schumann resonance intensity caused by a localized ionosphere disturbance over the earthquake epicenter. Ann. Geophys. 24, 567–575, 2006.

Nomikos, K., Vallianatos, F., Kaliakatsos, J., Sideris, S., Bakatsakis, M. Latest aspects of telluric and electromagnetic variations associated with shallow and intermediate depth earthquakes in South Aegean. Ann. Geofis. XL (2), 361–374, 1997.

Ohno, N., Fujiwara, H., Chuo, Y.J., Muramatsu, S., Nagao, T., Kamogawa, M., (2005). Atmospheric anomalies before 2004 M 7.4 Kii peninsula earthquake. In: International Workshop on Seismo Electromagnetics, IWSE-2005. March 15–17, Tokyo, Japan, Programme and Extended Abstracts, 2005, p. 491.

Okada, Y., Mukai, S., Singh, R.P. Changes in atmospheric aerosol parameters after Gujarat earthquake of January 26, 2001. Adv. Space Res. 33, 254–258, 2004.

Omori, Y., Yasuoka, Y., Nagaham, H., Kawada, Y., Ishikawa, T., Tokonami, S., Shinagi, M. Anomalous radon emanation linked to preseismic electromagnetic phenomena. Nat. Hazards Earth Syst. Sci. 7, 629–635, 2007.

Ouzounov, D., Freund, F. Mid-infrared emission prior to strong earthquakes analyzed byremote sensing data. Adv. Space Res. 33 (3), 268–273, 2003.

Ouzounov, D., Liu, D., Chunli, K., Cervone, G., Kafatos, M., Taylor, P. Outgoing long wave radiation variability from IR satellite data prior to major earthquakes. Tectonophysics 431, 211–220, 2007.

Ouzounov, D., Habib, S., Ambrose, S. Multisensor approach analyzing atmospheric signals for possible earthquake precursors. Application of remote sensing for risk management, "Risk Wise", in: International Disaster and Risk Conference (IDRC) Davos. Tudor Rose, Switzerland, pp. 162–165, 2008.

Pisa, D., Parrot, M., Santolik, O. Ionospheric density variations recorded before the 2010 M_w 8.8 earthquake in Chile. J. Geophys. Res. 116, A08309, http://dx.doi.org/10:1029/2011JA016611, p. 8, 2011.

Pulinets, S., Boyarchuk, K. Ionospheric Precursors of Earthquakes. Springer Berlin, Heidelberg, New York, p. 323, 2004.

Pulinets, S.A., Legen'ka, A.D., Alekseev, V.A. Pre-earthquake effects and their possible mechanisms, in: Kikuchi, H. (Ed.), Dusty and Dirty Plasmas, Noise and Chaos in Space and in the Laboratory. Plenum Publishing, New York, pp. 545–557, 1994.

Pulinets, S.A., Boyarchuk, K.A., Hegai, V.V., Kim, V.P., Lomonosov, A.M. Quasielectrostatic model of atmosphere–thermosphere–ionosphere coupling. Adv. Space Res. 26, 1209–1218, 2000.

Pulinets, S.A., Legen'ka, A.D., Gaivoronskaya, T.V., Depuev, V.K. Main phenomenological features of ionospheric precursors of strong earthquakes. J. Atmos. Sol. Terr. Phys. 65, 1337–1347, 2003.

Qiang, Z., Du, L.-T. Earth degassing, forest fire and seismic activities. Earth Sci. Front. 8 (2), 235–245, 2001.

Quang, Z., Xu, X., Dian, C. Thermal infrared anomaly – precursors of impending earthquakes. Chin. Sci. Bull. 36 (4), 319–323, 1991.

Rozhnoi, A.A., Slovieva, M.S., Molchanov, O.A., Hayakawa, M. Middle latitude LF (40 kHz) phase variations associated with earthquakes. Phys. Chem. Earth 29, 589–598, 2004.

Rozhnoi, A., Solovieva, M., Molchanov, O., Schwingenschuh, K., Boudjada, M., Biagi, P.F., Maggipinto, T., Castellana, L., Ermini, A., Hayakawa, M. Anomalies in VLF radio signals prior the Abruzzo earthquake (M = 6.3) on 6 April 2009. Nat. Hazards Earth Syst. Sci. 9, 1727–1732, 2009.

Ruzhin, Yu., Nomicos, C. Radio VHF precursors of earthquakes. Nat. Hazards 40, 573–583, 2007.

Ruzhin, Yu., Nomicos, C., Vallianatos, F., 2000. High frequency seismoprecursor emissions. In: Proc. 15th Wroclaw EMC, Symposium. pp. 512–517.

Saraf, A.K., Choudhury, S. Earthquakes and thermal anomalies. Geospatial Today 2 (2), 18–20, 2003.

Serebryakova, O.N., Bilichenko, S.V., Chmyrev, V.M., Parrot, M., Rauch, J.L., Lefeuvre, F., Pokhotelov, O.A. Electromagnetic ELF radiation from earthquake regions as observed by low-altitude satellites. Geophys. Res. Lett. 19, 91–94, 1992.

Singh, R.P., Ouzounov, D. Earth processes in wake of Gujarat earthquake reviewed from space EOS. Trans. Am. Geophys. Union 84, 244, 2003.

Smirnov, S.E. Peculiarities of negative anomalies of the quasi-static electric field in the near-Earth atmosphere on Kamchatka. Geomag. Aeron. 45 (2), 282–287, 2005.

Sorokin, V.M., Chmyrev, V.M. Modification of the ionosphere by seismic related electric field, in: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Co., Tokyo, pp. 805–818, 1999.

Sorokin, V.M., Chmyrev, V.M. Atmosphere–ionosphere electrodynamic coupling, in: Bychkov, V.L., Golubkov, G.V., Nikitin, A.I. (Eds.), The Atmosphere and Ionosphere: Dynamics, Processes and Monitoring. Springer, pp. 97–146, 2010.

Sorokin, V.M., Hayakawa, M. On the generation of narrow-banded ULF/ELF pulsations in the lower ionospheric conducting layer. J. Geophys. Res. 113, A06306, 2008.

Sorokin, V.M., Chmyrev, V.M., Isaev, N.V. The generation model of small-scale geomagnetic field-aligned plasma inhomogeneities in the ionosphere. J. Atmos. Sol. Terr. Phys. 60, 1331–1342, 1998.

Sorokin, V.M., Chmyrev, V.M., Yaschenko, A.K. Electrodynamic model of the lower atmosphere and the ionosphere coupling. J. Atmos. Sol. Terr. Phys. 63, 1681–1691, 2001.

Sorokin, V.M., Isaev, N.V., Yaschenko, A.K., Chmyrev, V.M., Hayakawa, M. Strong DC electric field formation in the low latitude ionosphere over typhoons. J. Atmos. Sol. Terr. Phys. 67, 1269–1279, 2005a.

Sorokin, V.M., Chmyrev, V.M., Yaschenko, A.K. Theoretical model of DC electric field formation in the ionosphere stimulated by seismic activity. J. Atmos. Sol. Terr. Phys. 67, 1259–1268, 2005b.

Sorokin, V.M., Yaschenko, A.K., Hayakawa, M. Formation mechanism of the lower ionosphere disturbances by the atmosphere electric current over a seismic region. J. Atmos. Sol. Terr. Phys. 68, 1260–1268, 2006.

Sorokin, V.M., Yaschenko, A.K., Hayakawa, M. A perturbation of DC electric field caused by light ion adhesion to aerosols during the growth in seismic-related atmospheric radioactivity. Nat. Hazards Earth Syst. Sci. 7, 155–163, 2007.

Sorokin, V.M., Ruzhin, Yu.Ya., Yaschenko, A.K., Hayakawa, M. Generation of VHF radio emissions by electric discharges in the lower atmosphere over a seismic region. J. Atmos. Sol. Terr. Phys., http://dx.doi.org/10.1016/j.jastp.2011.01.016, 2011.

Surkov, V., Pilipenko, V. The physics of pre-seismic electromagnetic ULF signals, in: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Co., Tokyo, pp. 357–370, 1999.

Tertyshinikov, A.V. The variations of ozone content in the atmosphere above strong earthquake epicenter. Phys. Solid Earth 31, 789–794, 1996.

Tramutoli, V., Bello, G.D., Pergola, N., Piscitelli, S. Robust satellite techniques for remote sensing of seismically active areas. Ann. Geofis. 44, 295–312, 2001.

Tronin, A. Atmosphere–lithosphere coupling. Thermal anomalies on the Earth surface in seismic processes, in: Hayakawa, M., Molchnov, O. (Eds.), Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. Terra Scientific Publishing Co., Tokyo, pp. 173–176, 2002.

Tronin, A. Satellite remote sensing in seismology. A review. Remote Sens. 2, 124–150, 2010.

Tronin, A.A., Hayakawa, M., Molchanov, O.A. Thermal IR satellite data application for earthquake research in Japan and China. J. Geodyn. 33, 519–534, 2002.

Tzanis, A., Vallianatos, F. A critical review of ULF electric earthquake precursors. Ann. Geofis. 44 (2), 429–460, 2001.

Tzanis, A., Vallianatos, F. A physical model of electrical earthquake precursors due to crack propagation and the motion of charged edge dislocations (monograph), in: Seismo Electromagnetics (Lithosphere–Atmosphere–Ionosphere Coupling). Terra Scientific Publishing Co., pp. 117–130, 2002.

Uritsky, V., Smirnova, N., Troyan, V., Vallianatos, F. Critical dynamics of fractal fault systems and its role in the generation of pre-seismic electromagnetic emissions". Phys. Chem. Earth 29, 473–480, 2004.

Vallianatos, F., Nomicos, K. Sesmogenic radioemissions as earthquake precursors in Greece. Phys. Chem. Earth 23 (9–10), 953–957, 1998.

Vallianatos, F., Tzanis, A. A model for the generation of precursory electric and magnetic fields associated with the deformation rate of the earthquake focus, in: Hayakawa, M. (Ed.), Seismic Atmospheric & Ionospheric electromagnetic Phenomena. Terra Scientific Publishing Co., Tokyo, pp. 287–306, 1999.

Vershinin, E.F., Buzevich, A.V., Yumoto, K., Saita, K., Tanaka, Y. Correlations of seismic activity with electromagnetic emissions and variations in Kamchatka region, in: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Scientific Publishing Co., Tokyo, pp. 513–518, 1999.

Virk, H.S., Singh, B. Radon recording of Uttarkashi earthquake. Geophys. Res. Lett. 21, 737–741, 1994.

Xiong, P., Shen, X.H., Bi, Y.X., Kang, C.L., Chen, L.Z., Jing, F., Chen, Y. Study of outgoing long wave radiation anomalies associated with Haiti earthquake. Nat. Hazards Earth Syst. Sci. 10, 2169–2178, 2010.

Yasuoka, Y., Igarashi, G., Ishikawa, T., Tokonami, S., Shinogi, M. Evidence of precursor phenomena in the Kobe earthquake obtained from atmospheric radon concentration. Appl. Geochem. 21, 1064–1072, 2006.

Zhang, X., Zeren, Z., Parrot, M., Battiston, R., Qian, J., Shen, X. ULF/ELF ionospheric electric field and plasma perturbations related to Chile earthquake. Adv. Space Res. 47, 991–1000, http://dx.doi.org/10.1016/j.asr.2010.11.001, 2011.

Zolotov, O.V., Namgaladze, A.A., Zakharenkova, I.E., Shagimuratov, I.I., Martynenko, O.V., 2008. Simulation of the equatorial ionosphere response to the seismic electric field sources. In: Proceedings of the 7th International Conference Problems of Geocosmos. St. Petersburg, Russia, 26–30 May 2008, pp. 492–496.