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Seismo-induced effects in the near-earth space: Combined ground and space investigations as a contribution to earthquake prediction

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Abstract

The paper aims at giving a few methodological suggestions in deterministic earthquake prediction studies based on combined ground-based and space observations of earthquake precursors. Up to now what is lacking is the demonstration of a causal relationship with explained physical processes and looking for a correlation between data gathered simultaneously and continuously by space observations and ground-based measurements. Coordinated space and ground-based observations imply available test sites on the Earth surface to correlate ground data, collected by appropriate networks of instruments, with space ones detected on board of LEO satellites. At this purpose a new result reported in the paper is an original and specific space mission project (ESPERIA) and two instruments of its payload. The ESPERIA space project has been performed for the Italian Space Agency and three ESPERIA instruments (ARINA and LAZIO particle detectors, and EGLE search-coil magnetometer) have been built and tested in space. The EGLE experiment started last April 15, 2005 on board the ISS, within the ENEIDE mission. The launch of ARINA occurred on June 15, 2006, on board the RESURS DK-1 Russian LEO satellite. As an introduction and justification to these experiments the paper clarifies some basic concepts and critical methodological aspects concerning deterministic and statistic approaches and their use in earthquake prediction. We also take the liberty of giving the scientific community a few critical hints based on our personal experience in the field and propose a joint study devoted to earthquake prediction and warning.

Keywords: Earthquake prediction; Earthquake forecasting; Ground deformation; Electromagnetic emission; Satellite observation; Seismic precursor

1. Introduction

It has been shown that in the Earth's crust, rock microfracturing preceding a seismic rupture may cause local surface deformation fields, rock dislocations, charged particle generation and motion, electrical conductivity changes, gas emission, fluid diffusion, electrokinetic, piezomagnetic and piezoelectric effects. It has also been proposed that charge carriers could be activated in dry rocks mainly by the increasing external stress. These mechanisms have been considered as the main sources of the so-called seismo-electromagnetic emissions (SEME) consisting of broad band (from DC to a few tens of MHz) electromagnetic (EM) fields observed at the Earth's surface and in the near-Earth space (neutral and ionised atmosphere and magnetosphere). Therefore, earthquake-

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related ground strain deformation events and consequent EM emissions (EME) can be considered as coupling elements which affect the Earth-near-Earth Space interaction mechanisms. Within this framework, investigations of SEME-waves and their effects in the near-Earth space have mainly received an important help from satellite observations carried out in the privileged zone of the topside ionosphere. Low-Earth-Orbit (*LEO*) satellite observations gave information of ionospheric and magnetospheric perturbations caused by pre-seismic EM-waves and in particular of radiation belt particle precipitations, variations of temperature and density of the ionic and electronic components of the ionospheric plasma, electric and magnetic field fluctuations.

The main problem in these studies is to reconcile near-Earth space perturbations only with the propagation of SEME-waves through the atmosphere and magnetosphere, filtering from the data the impact of atmospheric EME-waves during thunderstorm activity, and effects of sun and cosmic rays in the geomagnetic cavity.

Up to now what is lacking is the demonstration of a causal relationship with explained physical processes and looking for a correlation between data gathered simultaneously and continuously by space observations and ground-based measurements. Coordinated space and ground-based observations imply available test sites on the Earth surface to correlate strain and EM data, collected by appropriate networks of instruments, with EM, plasma, and particle data detected on board of LEO satellites.

In this paper we aim at giving a contribution to earthquake prediction studies. At this purpose ground and space observations and modeling will be presented together with specific space projects. We will also take the liberty of giving the scientific community a few critical hints and propose a joint study devoted to earthquake prediction and warning. It is an intentionally synthetic and not exhaustive analysis of the problem, the aim being only to stimulate an answer by the scientific community. In doing this we have also been corroborated by important initiatives such as those carried out within the ESA Earth Observation Programme and the United Nations proclamation of the year 2008 as the International Year of Planet Earth. Note that the International Year's activities will span the three years 2007–2009. This could be the occasion to catalyse interest of scientific community to a largely shared specific project devoted to earthquake prediction.

The paper consists of three main parts. In the first, introductory, part we reconsider and clarify basic concepts (Section 1) and refer to reliable results reported in literature (Section 2). In the second part are described the ESPERIA space mission project (Section 3) together with description and testing of first ESPERIA instruments (EGLE and ARINA) in space (Section 4). In the third part (Section 5) we propose to the scientific community a new and common project devoted to the monitoring of mechanical and electromagnetic earthquake precursors in diverse seismic areas of our Planet and in space. The final goal should be to give a contribution to a deterministic method of earthquake prediction based on the physics of earthquake precursors.

1.1. Preparation focal zone and precursor area

As it is well known, earthquakes are a manifestation of significant ground rock deformation events, that is episodic deformations of the upper and, more or less, brittle layers of the Earth's lithosphere classified as *fast seismic ruptures, slow earthquakes* and *sub-seismic events*. The most familiar brittle lithospheric deformation event is defined as *ordinary* earthquake, that is a deformation, fracture, structure and phase transformation phenomenon, which releases suddenly a large amount of the elastic energy stored in the medium and is accompanied by a substantial fraction of energy radiated as elastic (seismic) waves. Seismic wave energy is a certain part (from about 1 to 10%) of total (radiated and not radiated) energy, and it is usually assumed as an estimate of the total energy of the earthquake. Moderate and strong earthquakes, with magnitudes from 5.0 to 9.0, have energy and seismic moment (Lay and Wallace, 1995) approximately in the range $10^{12}–10^{18}$ J and $10^{17}–10^{22}$ Nm, respectively, as given by the following well-known relationships (in cgs units) between energy (E), scalar seismic moment (M_0), and surface earthquake magnitude (M_S):

$$\log E = 11.8 + 1.5 M_S \quad (1)$$

$$\log M_0 = 1.5 M_S + 16.1 \quad (2)$$

But reducing "physics of the earthquake" only to the creation of fault rupture and consequent seismic wave radiation is to over-simplify the problem. It has been repeatedly observed that part of the accumulated *pre-seismic* elastic energy is also converted to other kind of energies (electromagnetic and acoustic ones, heat, etc.) and these (yet unknown) conversion mechanisms are probably similar as that of seismic energy. The understanding of such pre-seismic processes is fundamental to plan and design earthquake prediction techniques on a deterministic basis, that is based on the so-called *seismo-associated phenomena* or *earthquake precursors*.

The latter are phenomena of different types (seismic and nonseismic ones) accompanying the characteristic deformation of rocks during *earthquake preparation time* or *pre-seismic period*, and associated with changes in physical conditions in the so-called *preparation focal zone* (*volume*) as defined by standard *dilatancy–diffusion* and *crack–avalanche* "dilatancy" models (Nur, 1972; Myachkin et al., 1975; Scholz, 1977).

Until now, no exhaustive physical models have been proposed and accepted by the scientific community to be used for a deterministic earthquake prediction approach. What is known on the topic is that in the time interval preceding a seismic fracture, stress and strain energy are accumulated in a fault asperity. Most of the investigators consider reasonable to assume this increasing and concentrating stress at depth as a cause of the anelastic volumetric increase ("dilatancy") of a relatively small portion of rock, and consequent rock dislocation and microfracturing. This volume of cracked rock at depth (*preparation focal zone*) is considered as a primary local source of precursor signals. These signals propagating in the surrounding medium allow the earthquake precursors to be observed in a finite region of the Earth's surface (*precursor area*).

Then in principle earthquake precursors can be used to indicate the impending occurrence of a seismic event.

Characteristic sizes of the preparation focal zone and of the precursor area have been estimated by Dobrovolsky et al. (1979, 1989). They found the volume (V) of soft inclusion (cracked rock) at depth in the lithosphere versus magnitude (M), as follows:

$$V_{\max} = 10^{(1.24M-4.47)}\text{km}^3 \qquad (3)$$

which for a spherical volume of radius (r) gives:

$$r = 10^{0.414M-1.696}\text{km} \qquad (4)$$

The dimension of the precursor region at the earth surface is defined by the radius (R) of the Earth's surface area where pre-seismic strain changes exceed tidal strains ($\approx 10^{-8}$), as follows:

$$R = 10^{0.43M}\text{km} \qquad (5)$$

Relationships between pre-seismic strain ε, magnitude M, and distance R are:

$$\varepsilon = \frac{10^{1.5M-9.18}}{R^3} \quad \text{for } M<5.0$$
$$\varepsilon = \frac{10^{1.3M-8.19}}{R^3} \quad \text{for } M\geq 5.0 \qquad (6)$$

For comparison, we report in Table 1 the characteristic dimensions of the preparation focal zone at depth (i.e., the source of earthquake precursors) with those of the precursor region at the Earth's surface. Data are obtained for $4.0<M<7.0$ events, in the simple case of a preparation focal area modelled by a spherical volume and in the presence of a homogeneous medium. It can be seen that, characteristic sizes of preparation focal area at depth is relatively small (from a few hundreds meters to a few tens of kilometres) when compared with that of the precursor region at the Earth's surface (from a few tens of kilometres to about one thousand of kilometres).

We stress that this result is only valid for local deformation (tilt and strain fields). When other precursor phenomena than mechanical ones (for instance electric and magnetic fields) are considered and/or a more complicated geometry and structure is assumed, a new specific model must be proposed to calculate dimensions of these characteristic regions. A model is in preparation, which first results have been reported in international meetings (Sgrigna et al., 2001, 2002a; Conti et al., 2004).

1.2. Earthquake prevention and prediction

At present only two suitable approaches are available to defend society from destructive effects of earthquakes: the *prevention* and *prediction* methods.

Earthquake prevention implies to develop methods for the evaluation of *seismic risk*, in order to provide for *disaster assessment*.

In the prevention approach a great importance lies in the optimization of methods necessary to determine the three main factors (*vulnerability*, *value* and *hazard*), which define seismic risk.

On the contrary, earthquake prediction aims at giving the possibility to predict time of origin, hypocentral (or epicentral) location and magnitude of an impending earthquake. In our opinion, it is necessary to develop and apply both these two complementary methods, but it must be taken into account the fact that they are at a very different level of maturity and applicability.

Table 1
Sizes of earthquake preparation zone (r) and precursor region (R) for $4.0\leq M\leq 7.0$

M	r (km)	R (km)
4.0	0.1	52
5.0	2.5	141
6.0	6.0	380
7.0	41.3	1023

At present, techniques used to estimate seismic risk, with aim at reducing damages produced by earthquakes in a certain area of the Earth's surface, are reliable and applicability and prevention of damage is perfectly achievable with existing state of knowledge. On the contrary, techniques concerning a possible prediction of a seismic event are below standard.

A solution of the problem to reduce damages in a given region of known vulnerability and value (of real and personal properties, lost of people, infrastructures, etc.) is to design and build with opportune techniques (seismological engineering), buildings, hospitals, bridges, dams, museums, etc., which are able to resist to an earthquake of an assigned magnitude (defined on the basis of a seismic hazard estimation). In other words, prevention techniques seems mainly to lie in hands of administrators, engineers, specialists in applied geophysics and seismology, technicians of local and civil services, and authorities that can take adequate measures for protection of the population.

On the contrary, the study of physical conditions which give rise to an earthquake, as well as of the processes that precede a seismic rupture, constitutes the basis of the earthquake prediction approach and the problem of prediction is an open scientific problem, which first attempts for a solution are at a very preliminary stage.

1.3. Earthquake forecasting

Since a reliable deterministic method of earthquake prediction, based on physics of earthquake precursors will presumably be available only in a far future, many investigators are attracted by a statistical prediction approach: the so-called *earthquake forecasting*, which is the probability of occurrence of an event in a given geographical location, within assigned values of magnitude and time ranges. But the earthquake forecasting concept overlaps with seismic hazard concept, one of the three factors used to estimate seismic risk. Typical examples of earthquake forecasting methods are those of the M8 and CN algorithms (e.g. Keilis Borok, 1996; Keilis Borok and Soloviev, 2003; Peresan et al., 2005).

This could result in a possible ambiguity in the application of earthquake prediction and earthquake prevention methods, which could give rise to a kind of "methodological noise".

All these statistical scientific approaches make use of sophisticated analyses of earthquake patterns, which may precede the earthquakes, and have reached a very good level of maturity. But, in our opinion more than within earthquake prediction studies they have to be addressed to the earthquake prevention field, where they can display all their importance and practical use.

1.4. Importance and reliability of earthquake precursors

In general earthquake precursors can be divided in the two classes of so-called seismic and nonseismic phenomena. In the class of seismic phenomena are included seismic gap, decreasing (seismic quiescence) and increasing background seismicity, and change in the seismic wave velocity. The list of nonseismic phenomena includes numerous earthquake precursors of very different types as phenomena directly reconciled with local deformations (ground elevations and tilts, strains in rock, water levels in wells, etc.) or of other kind as electric and magnetic fields, EM emissions, electric resistivity in rock, acoustic emissions, gas exhalations (mainly radon and helium), etc.

The time scale of an earthquake prediction attempt is by convention generally classified as short-term (≈hours–weeks), long-term (≈years–decades), intermediate-term (≈weeks–years), according to the expected time interval to the earthquake (*precursor time*).

Really, only short-term and intermediate-term time scales can be considered as true earthquake prediction deterministic methods, since long-term one, in practice, can be identified with the seismic assessment of the seismic hazard of a given zone and, then, associated with the statistical probability for the occurrence of large earthquakes.

According to previous considerations, a preliminary step for deterministic earthquake prediction is to collect, identify, and study *a posteriori* earthquake precursors. In the last decades the study of these phenomena was expected to give rise in a relatively short period of time to earthquake prediction. But this task was underestimated because the physics of earthquakes has demonstrated to be a very complicated matter and most of precursors have shown little reliability. Nevertheless, research with this aim continues with a critical view and with new ideas and deep investigations. In our opinion, for the reasons reported above, this activity should have a priority character with respect to earthquake forecasting.

Recent progress in the topic has been largely due not only to the increased amount and accuracy of ground field measurements, careful attention to errors in data, and improved understanding of earthquake source mechanics but also, and may be first of all, in a new approach including observations from space. In fact, seismic precursors detectable at the Earth's surface, include not only local mechanical deformations caused by dilatancy, but also many other phenomena associated with this rock micro-fracturing process and in particular EME signals. Effects produced by these signals revealed to be not limited to the surrounding medium, but demonstrated also to reach large distances, penetrating into the near-Earth space and producing perturbations in the neutral and ionised atmosphere, and in the magnetosphere. Concerning earthquake precursors, EME signals being observed both on the ground and in space act as a "link" (coupling element) between solid Earth and near-Earth pace.

Therefore, we think that it will be relevant to carry out systematic and continuous observations of pre-seismic EME signals at the Earth's surface and in near-Earth space, and of ground-based phenomena as local deformation events. As supported by references and results reported in Section 2, these two classes of pre-seismic signals have also demonstrated to be reliable earthquake precursors. Then we propose to consider them as earthquake precursors of priority importance for the study. This aims at being a contribution open to stimulate a discussion inside the scientific community. Of course, we hope to share our opinion with many colleagues, as well as we are also open for constructive discussions on the topic.

The previous scenario suggests to consider an earthquake as a coupling element between Earth and near-Earth space. In this sense, observations *a posteriori* of different ground and space seismic precursors and the development of theoretical models aim at seeing in perspective the phenomenon "earthquake" within the framework of a unified theory able to explain the causes of its genesis, and the dynamics, rheology, and micro-physics of its preparation, occurrence, post-seismic relaxation, and inter-seismic phases. The physical system to be considered includes solid Earth and near-Earth space with related couplings and perturbations.

2. Observation and modelling of earthquake precursors

Again it is important to underline that at present, there is not yet a method that allows medium-term and short-term earthquake predictions, but there are systematic observations of intermediate-term and short-term earthquake precursors, a few of which have demonstrated to be suitable for future applications.

2.1. Creep-related ground tilt intermediate-term precursors

A number of interesting results concerning anomalous surface tilt variations observed during earthquake preparation has been reported over the years. They include the observation and modeling of creep-related tilt perturbations (McHugh and Johnston, 1979; Bella et al., 1995; Sgrigna and Malvezzi, 2003) as well as precursory tilts detected before local and teleseismic earthquakes (Bilham, 1981; Bilham et al., 1985), coseismic and postseismic tilts (Thatcher and Fujita, 1984).

These anomalies are easily detectable by tiltmeters (Mortensen and Johnston, 1975; Bilham and Beavan, 1979; Nur et al., 1986; Bella et al., 1995; Sgrigna and Malvezzi, 2003) and considered by many authors (Ida, 1974; Bilham, 1981; Bilham et al., 1985; Bella et al., 1986a; Pevnev, 1988, 1989; Bella et al., 1993, 1995; Sgrigna et al., 2002b) as intermediate-term earthquake precursors.

Continuous hourly ground tilt data collected by the TELLUS tiltmeter network from 1981 by the present, in the seismic region of the Central Apennines of Italy, systematically gave evidence of intermediate term-earthquake tilt precursors (Sgrigna and Malvezzi, 2003). The main features of tilt signals observed in this seismic zone are:

1. Raw tilt data detrended by meteorological and secular tectonic effects revealed intermediate-term pre-seismic tilts with shape, amplitude, and time duration similar to those already obtained in the same area (Bella et al., 1986a, 1993, 1995).
2. Tilts are shifting in time relatively to each other, indicating a possible propagation of the pre-seismic strain field from the preparation focal area to the tilt sites, through the rigid blocks of the region (Salvini, 1993; Bella et al., 1998) separated by inclined transition zones, filled by fault viscoelastic material (Ida, 1974; Bilham, 1981; Bella et al., 1986b; Sgrigna and Malvezzi, 2003).
3. Experimental values for the velocity of propagation are in agreement with previous results.
4. The intermediate-term pre-seismic tilts have been interpreted as viscoelastic creep strains in the fault material, due to the propagation of stress–strain fields from the dilatant focal area to the observation sites.
5. 1-D and 2-D numerical models have been proposed to justify qualitatively the main features (tilt anomaly shape and onset time delay and decay of anomaly amplitude with distance from the earthquake preparation zone) of the pre-seismic ground tilt behavior (Bella et al., 1990, 1998; Sgrigna et al., 2002a). Horizontal movements of rigid crustal blocks were also considered by Gabrielov et al. (1990).

2.2. Ground and space short-term seismo-associated EME signals

The first systematic list of electric phenomena associated to earthquakes was made by Galli (1910) who reported 148 luminous phenomena that occurred in Italy: 52 before, 37 during and after the associated earthquake. The most frequent phenomena reported are flashes that occurred during the earthquake, the luminescent clouds and diffuse lights are reported before, during and after the earthquake.

In recent years, interest has been increasing in the SEME signals consisting of broad band (from ≈DC to a few tens of MHz) EM fields generated and transmitted by seismic sources into the near Earth's space, before, during, and after an earthquake. SEME characteristics and detectability have a very interesting and promising nature as a short-term earthquake predictor. To detail such an indication we outline in this section the main observations and models on the subject.

More recently, ground-based measurements revealed slow electrotelluric and magnetic field variations (Johnston and Mueller, 1987; Varotsos et al., 1993) as well as pre-seismic ground potentials. The latter are generated as streaming potentials when saline water moving through porous rocks entrains ionic charges (Draganov et al., 1991; Bernabé, 1998), or through stress applied to rocks containing or not piezoelectric minerals as quartz (Nitsan, 1977; Bishop, 1981; Varotsos et al., 1997; Freund, 2002). The transmission of substantial stress over large distances has been debated (Geller, 1996; Sgrigna et al., 2002a; Sgrigna and Malvezzi, 2003).

It has been shown (Areshidze et al., 1992; Guo et al., 1994; Bella et al., 1995; Molchanov and Hayakawa, 1998) that rock microfracturing releases gas (radon, helium) and causes electrical conductivity changes as a function of microcrack number and dimension and of pore fluids redistribution (saline pore fluids motion may cause the formation of intergranular water film). Recently, it has been proposed that also dry rocks can become a source of highly mobile electronic charge carriers, which increase the electric conductivity and may propagate through the rock as a charge cloud (Freund, 2003).

Ground low-frequency (ULF/ELF) EME-signals have also been documented in connection with relevant earthquakes (Kopytenko et al., 1993; Fraser-Smith et al., 1994; Ohta et al., 2001; Ismaguilov et al., 2001) and preliminary, though not exhaustive, explanations have been reported on the subject (Park et al., 1993; Merzer and Klemperer, 1997; Molchanov and Hayakawa, 1998; Surkov, 1999; Hayakawa et al., 2000).

A possible scenario is to consider these perturbations as due to SEME-waves generated by pre-seismic sources and transmitted into the near-Earth space (see, for instance Dobrovolsky et al., 1989; Guo et al., 1994; Fenoglio et al., 1995; Molchanov et al., 1995; Teisseyre, 1997; Grimalsky et al., 1999; Pulinets et al., 2000; Sorokin et al., 2001; Gershenzon and Bambakidis, 2001; Hayakawa et al., 2002; Fujinawa et al., 2002; Freund, 2003).

During the propagation from the hypocentral source to the Earth's surface, the higher frequency content of the ULF–HF EME-waves is attenuated and only ULF/ELF EME-waves are supposed to reach the Earth's surface and enter into the near-Earth space, where they cause perturbations (total electron content (TEC) changes, ionospheric motions, joule heating, etc.) in the atmosphere and ionosphere (Molchanov et al., 1995; Ohta et al., 2001). We think that only in the case of very shallow and strong earthquakes, when the size of preparation focal zone is greater than the hypocentral depth (see relations (4) and (5)), a higher frequency content of this EM radiation could be transmitted from the Earth's surface to the near space.

More in general, results of local ground-based SEME observations have been obtained on a larger (ULF–HF) frequency band (see, in addition to the above-mentioned authors, also Warwick et al., 1982; Oike and Ogawa, 1986; Johnston, 1997; Bella et al., 1998; Uyeda et al., 1999; Eftaxias et al., 2003). Recently, Nardi and Caputo (2006), reported observations of electric signals, recorded in the laboratory and in the field experiments. They showed that these signals are generally of the same type and particularly in the VLF band.

Another scenario for SEME disturbances is to consider them as a secondary effect produced by other mechanisms induced by seismic activity (Molchanov et al., 1993).

Fair weather currents have also been proposed to justify variations in the atmospheric conductivity profiles (Pulinets et al., 2000). Pre-seismic changes of the tropospheric conductivity profiles have also been associated with modifications of the spectral content of ELF–VLF radio noise during lightning discharges (Hayakawa et al., 2002).

Research of disturbances in radio-wave propagation produced by seismic activity has also been carried out (Hayakawa and Sato, 1994; Morgounov et al., 1994; Gufeld et al., 1994; Bella et al., 1998). The analysis is based on the amplitude and phase variations of radio-signals propagating in the earth-ionosphere wave-guide and emitted by diverse transmitting stations.

Significant short-term earthquake precursors were obtained by investigating the propagation of Omega and Loran VLF radio-waves used for world-wide navigation (Hayakawa and Sato, 1994; Morgounov et al., 1994;

Gufeld et al., 1994). Also a short-term attenuation in the electric field strength of the LF radio-signal emitted by Radio Monte Carlo (RMC) broadcasting station, was observed at a receiver of Central Italy prior to local earthquakes (Bella et al., 1998).

These short-term pre-seismic variations of several days have been explained by the abnormal ionisation in the lower ionosphere (Morgounov et al., 1994) and tropospheric radio defocusing mechanisms (Bella et al., 1998).

2.3. Short-term seismo-associated precursors in space

Results of satellite measurements in the near-Earth space pointed out short-term earthquake precursors constituted by electric and magnetic anomalies and EME signals, which were accompanied by perturbations of comparable duration in the temperature and density of ionospheric plasma and radiation belt high-energy particle fluxes.

Space observations of ionospheric perturbations over seismic regions have been reported and discussed on the occasion of several strong earthquakes (Gokhberg et al., 1979; Larkina et al., 1989; Parrot and Mogilevsky, 1989; Bilichenko et al., 1990; Serebryakova et al., 1992; Parrot et al., 1993; Chmyrev et al., 1997; Rodger et al., 1999; Lee et al., 2000; Pulinets et al., 2000; Hayakawa et al., 2002; Aleksandrin et al., 2003; Sgrigna et al., 2005a).

Satellite observations seem to confirm the above-illustrated scenarios. Indeed, pre-seismic changes of electric and magnetic fields (Molchanov et al., 1993; Parrot, 1994; Rodger et al., 1999) and of ionospheric plasma temperature and density (Parrot and Mogilevsky, 1989; Parrot et al., 1993; Chmyrev et al., 1997) have been observed from a few minutes to several days prior to EQs of moderate or strong magnitude (generally greater than 4.0).

A relatively new result is that pre-seismic EM disturbances produced in a seismic area with one of the above-described mechanisms, are thought to reach the inner Van Allen radiation belt, where they may interact with trapped particles (Galperin et al., 1992). In confirmation of this hypothesis, in the last two decades, a very interesting and new phenomenon has been observed in the ionosphere–magnetosphere transition region. It consists of anomalous particle fluxes detected by several space experiments and reconciled with the earthquakes occurrence (Galper et al., 1989; Voronov et al., 1990; Aleshina et al., 1992; Pustovetov and Malyshev, 1993). These particle fluxes are characterized by an anomalous short-term and sharp increase of high-energy particle counting rates (CRs). In the following, they are referred to as ‘‘particle bursts’’ (PBs). Most of PBs have been collected near the South Atlantic Anomaly (SAA) at altitudes generally between about 400 and 1200 km, by several satellites (Pustovetov and Malyshev, 1993; Ginzburg et al., 1994; Galper et al., 1995).

Larkina et al. (1989), and more recently, Aleksandrin et al. (2003) and Sgrigna et al. (2002b,a) also made attempts to confirm the pre-seismic character of these PBs, by using PBs–EQs statistical correlations, and under the hypothesis that pre-seismic ULF/ELF EME wave-trapped particle interaction may cause the precipitation of Van Allen belt electrons and protons.

With this purpose in mind several authors (Aleshina et al., 1992; Galperin et al., 1992; Galper et al., 1995; Krechetov, 1996) proposed that in a certain portion of the ionosphere–magnetosphere transition zone such a low-frequency content of SEME radiation (from DC to some hundred Hz) can propagate as Alfven waves along the geomagnetic field lines. Near the radiation belt boundary, the waves may resonantly interact with trapped particles (electrons and protons from a few MeV to several tens of MeV) causing particle precipitation as a result of pitch angle diffusion. The lower limit of the above-mentioned portion of the ionosphere–magnetosphere transition zone (i.e., the altitude where pre-seismic EME-waves may be captured in the geomagnetic field lines and, then, propagate up to the inner radiation belt) has been estimated from PBs space observations and resulted to be around 300–500 km (Aleksandrin et al., 2003; Sgrigna et al., 2005a). A qualitative representation of this model is presented in Fig. 1.

Lifetime of PBs longitudinal drift is determined by the particle loss rate during particle interaction with the residual atmosphere of the Earth, and a lifetime of the order of several tens of minutes is obtained for electrons and protons of several tens of MeV (Walt, 1994). During this time, particles (drifting longitudinally) may move around the Earth along the L-shell corresponding to the EME ground source location (Aleshina et al., 1992; Galper et al., 1995). This is a crucial factor for a possible use of pre-seismic PBs as an earthquake predictor, since the longitudinal drift makes the PB detection easier by particle detectors installed on board of satellites. Another important factor is the opposite drift direction of positive and negative charged particles, which in principle could allow the location of EME wave-particle interaction zone (i.e., the PBs space source location) to be identified. Indeed, the above-reported LEO observations seem to confirm the possibility to detect these PBs caused by ULF SEME.

Also VLF EM waves were observed from Intercosmos-24 satellite measurements (Molchanov et al., 1993). Data collected by this mission demonstrated that ULF emissions of ~0.2 nT can penetrate through the

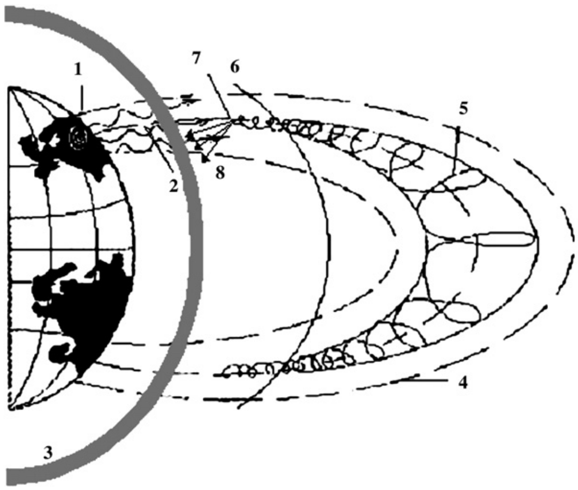


Fig. 1. Seismic EME-waves generation in the crust and their propagation and interaction with ionospheric plasma and magnetospheric trapped particles. Trajectories of charged particles trapped by the geomagnetic field lines are represented in a meridian plane. (1) Earthquake hypocentral ''dilatant'' area, where pre-seismic EME waves are emitted during the earthquake preparation, (2) EME-waves propagation from the preparation focal area to the ionosphere, (3) ionospheric interaction region, (4) geomagnetic field lines, (5) stationary trajectory of trapped particles, (6) stationary lower boundary of the radiation belt, (7) mirror points lowering, and (8) particle bursts precipitation and consequent longitudinal drift.

ionosphere and interact with energetic protons of 0.5–5 MeV near the magnetic equatorial plane. As a consequence of this cyclotron interaction, the proton distribution function can become unstable for Cherenkov radiation of VLF waves in the frequency interval 0.1–20 kHz (Krechetov, 1996).

Nevertheless, there is still an open debate about the mechanism to be invoked in order to justify the entire phenomenon under study and, in particular, whether the very low amplitude ULF/ELF EM waves may reach the inner Van Allen radiation belt and cause the above-mentioned coupling phenomena. In fact, the electric and magnetic components of these EME-waves are estimated to be of only some fraction of $mV/m(Hz)^{1/2}$ and some fraction of $nT/(Hz)^{1/2}$ or less, respectively (Parrot et al., 1993).

This science background gives an idea (though not exhaustive) of the state-of-the-art in the topic.

3. The ESPERIA space project

ESPERIA (Sgrigna, 2001; Sgrigna et al., 2005b) is an equatorial magnetic, plasma and particle mission planned with a LEO small satellite and mainly concerned with detecting any tectonic and pre-seismic related signals. It has been proposed for monitoring perturbations in the topside ionosphere and for defining the near-Earth magnetic environment. The project aims at reconciling these phenomena with seismic related signals from the Earth's surface. In particular, electromagnetic emissions related to strong earthquakes and possibly caused by stress changes in the crust, are a main scientific objective of this mission project.

To identify electromagnetic emissions of seismic origin, the impact of anthropogenic electromagnetic radiation in the near-Earth space, atmospheric electromagnetic emissions during thunderstorm activity, and effects of sun and cosmic rays in the geomagnetic cavity were also taken into account during the Phase A Study, performed for the Italian Space Agency (ASI).

ESPERIA has the same scientific objectives and a similar payload as DEMETER mission. ESPERIA includes a modular multi-instrument science payload constituted by a Magnetic Field Analyzer (two, fluxgate and search-coil, vector magnetometers), an Electric Field Analyzer (a constellation of ten Electric Probes), a Particle Detector (constituted by 6 silicon telescope), and an Ionospheric Plasma Analyzer (Langmuir Probe and Retarding Potential Analyzer).

Most of these instruments are of large use in near-Earth Space investigations, therefore ESPERIA, with some relatively small changes and/or augmentation of its payload, can easily be adapted to extend the study to other applications in the ionosphere–magnetosphere transition zone. Therefore, ESPERIA can also be seen as an equatorial coordinated and simultaneous complement to polar missions like SWARM, or NASA "Living with a Star" Program.

A description of the ESPERIA space mission concept is reported in Sgrigna (2001) and Sgrigna et al. (2005b). We give here only a synthesis of this space project.

3.1. ESPERIA mission concept

The ESPERIA instruments are planned to provide a cost-effective survey of earthquake forecasting. Instruments and orbital parameters are structured to reach the final goals on the basis of general and specific requirements concerning scientific, technical and methodological aspects of the mission.

The fundamental aspects concerning the ESPERIA mission are synthesized in the following sub-sections.

3.1.1. General requirements

- Coordinated space and ground measurements
- Simultaneous and continuous measurements of the different parameters with an excellent capability in detecting particles over a broad energy range, as well

as in revealing plasma instabilities and electromagnetic fluctuations
- Repeatability and maximum density of ground tracks over selected Earth's surface regions with high-accuracy and short revisit time for a continuous ground monitoring of local and short-term earthquake precursor phenomena.

3.1.2. Specific requirements

a. Optimization of orbital parameters
  - Continuous monitoring (no need of "survey" and "burst" modes)
  - Efficiency and low costs of the ground segment operativeness, including optimization in the use of mass memory by frequent down-link procedures
  - High-sensitivity measurements in zones with relatively minimum temporal and spatial field changes
  - Maximum density of measurements and a continuous monitoring of EM emissions over seismic areas
  - Necessity to detect particles affected by EM emission waves of terrestrial origin and generated by seismotectonic processes: Particle Detector Analyser must skim L-Shells just beneath the inner radiation belts with $L \approx 1.2$.

b. Model payload
  - Multi-instrument payload to detect ULF–HF electric and magnetic fields; ionospheric plasma temperature and density; particle fluxes, pitch angle, and energy
  - High instrumental sensitivity, signal-to-noise ratio, and dynamic range for all the parameters to be studied
  - Continuous data acquisition
  - No interaction and disturbances between different instruments
  - No differential photoemission from the external surface of platform and payload
  - No influence of electric field distortion in EM emission measurements caused by the satellite metallic structure and geometry.

c. Ground-based measurements
  - Seismic activity, coordinated and continuous pre-seismic mechanical (tilt and strain) and electromagnetic fields in test areas
  - Comparison and integration of space observations with ground-based ones.

Taking into account of the above-mentioned requirements, and in particular the necessity to be inside the ionosphere–magnetosphere transition zone and to carry out a high-accuracy Earth's surface monitoring, mission demands for a geo-synchronous magnetic equatorial orbit with an altitude between about 600 and 1000 km (topside ionosphere). To perform a high-accuracy ground monitoring is requested a ground track repetition of a fixed (integer) number of orbits per day, that is by a fixed orbit altitude. At this purpose a FEEP (*Field Electric Emission propulsion*) system is applied to the ESPERIA platform, so that if necessary, also some changes in the orbit can be adopted during the mission. For 14 orbit/day the corresponding altitude will be 813 km, therefore, a *LEO* orbit is requested. This orbit altitude corresponds to a field of view of ±39° with a revisit time of ≤24 h. Note that when the orbit has inclination 0°, the revisit time coincides with the orbit period (110 min). Moreover, the satellite trajectory oscillates around the magnetic equator up to geomagnetic latitudes of ±23°. This condition guarantees a good field of view and a short revisit time for a good ground monitoring of local short-term earthquake precursor phenomena. The observation geometry implies nadir pointing.

Summarizing all the above-mentioned requirements and comments, the following orbit, mission, spacecraft, and payload instrument characteristics have been adopted for ESPERIA.

3.2. ESPERIA main features

1. Orbit characteristics
   - Ground track repetition with accuracy of 10 km
   - Revisit time ≤24 h; geosynchronous orbit: 14 orbits/day
   - Altitude = 813 km; inclination = 11°.5, eccentricity = 0; Orbit period: 110′
   - Orbit knowledge and time resolution ≈100 m and 1 s, respectively
   - Field of view: ±39°
   - Maximum oscillation around the magnetic equator: ±23°.
2. Spacecraft
   - Platform MITA with Nadir pointing
   - FEEP thrusters applied to the platform (constant altitude).
3. Mission duration ≥2 years
4. Payload instrument
   a. Electric Field Analyser (EFA)
      - frequency range: ~DC–10 MHz
      - accuracy: 300 nV/m
      - dynamic range: 120 dB.

   b. Magnetic Field Analyser (MAFA)
      - ○ Flux-gate:
        - frequency range: ~DC–10 Hz
        - accuracy: a few (6–8) pT; resolution: 24 bit.

- ○ Search-coil:
  - ● frequency range: ~10 Hz–100 kHz
  - ● sensitivity: 10^{-2} pT /$(\mathrm{Hz})^{1/2}$ (at 1 kHz).

c. Langmuir Probe (LP) and Retarding Potential Analyser (RPA)
LP: electron temperature: 300–15,000 K; electron density:10^2–$10^7 \mathrm{cm}^{-3}$
RPA: ionic temperature: 300–10,000 K; ionic density: 10^2–$10^7 \mathrm{cm}^{-3}$.

d. Particle Detector Analyser (PDA)
Energy range: 300 KeV–2 GeV
Pitch angle precision <4° with particle identification
Geometry: 5 silicon strip telescope +1 calorimeter 1 silicon strip telescope +1 calorimeter.

An overview of the ESPERIA satellite illustrating the location of the different instruments of the scientific payload is reported in Fig. 2. As it can be seen, located at the top of the satellite are PDA, LP, and RPA instruments. Each MAFA sensor system is at one different end of the two primary expanding booms (of ≈5 m), so that search-coils are separated by about 10 m from flux-gate sensors and each sensor system is at a distance of about 5 m from the satellite body. Electric probes with preamplifiers inside are located at the end of secondary booms (of ≈2 m), so that each electric sensor system is about 2 m from the nearest magnetic sensor system. Instead of magnetic torques, the attitude control is implemented by 3 reaction wheels (of known EM spectra). In this way, magnetic disturbances are less than 2 pT at a distance of 5 m (deployed booms/magnetic probes accommodation), that is magnetic disturbances are less than instrumental sensitivity.

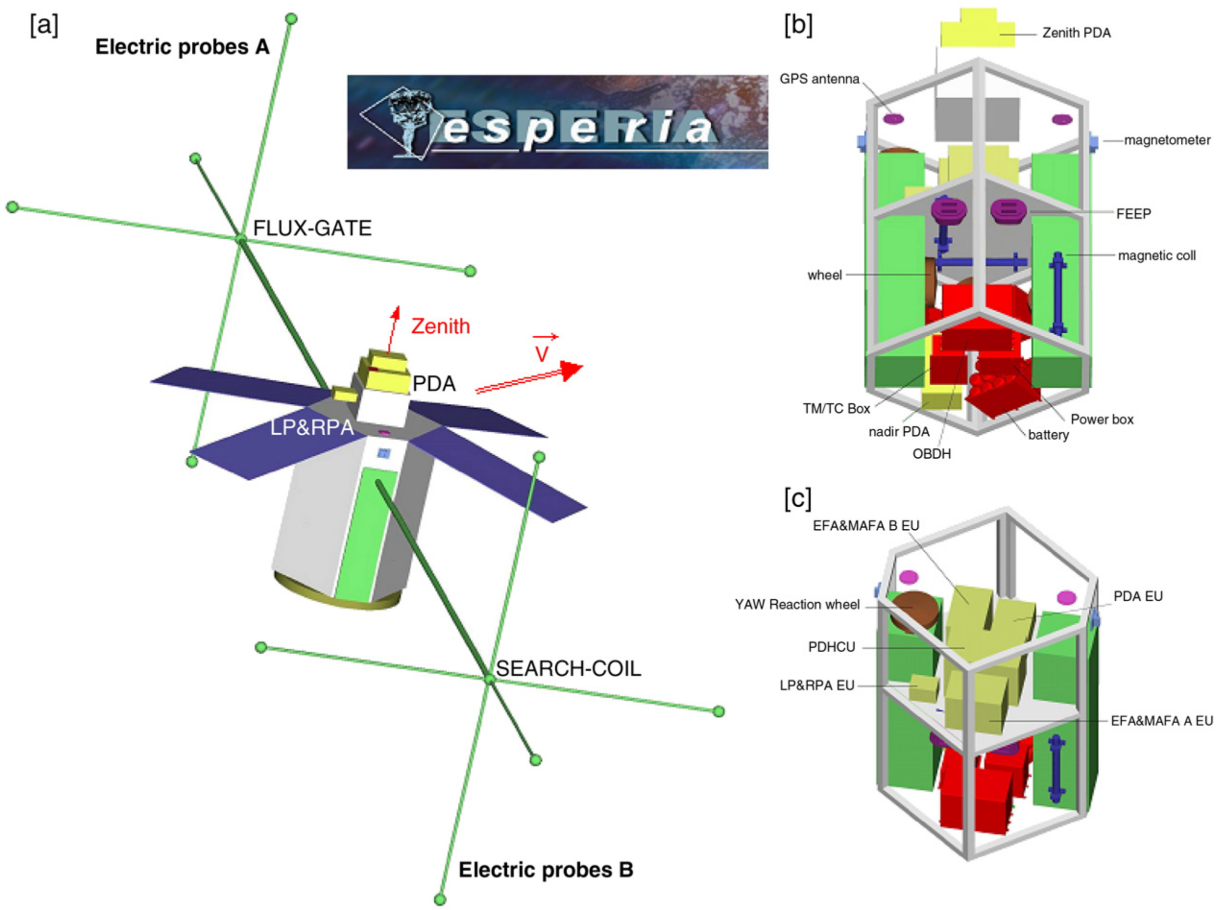


Fig. 2. [a] Schematic external view of the ESPERIA satellite with deployed booms and relative systems of antennas for electric (EFA) and magnetic (MAFA) field measurements. Particle detector (PDA) and Plasma Langmuir probe and Retarding potential analyzer (LP and RPA (yellow)) as well as solar panels (top) are also shown. [b and c] ESPERIA Spacecraft internal configuration including the multi-instrument payload EFA/MAFA, PDA, and LP and RPA, FEEP and other platform instruments.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For electromagnetic cleanness all probes will be switched off during the desaturation of reaction wheels or when (for short periods) FEEP will be active. To guarantee the equipotentiality of external satellite surfaces, we also planned a surface plating of spacecraft and a special solar panels design. This requires uniform electrical and optical characteristics of the external surfaces of the satellite and equal to that of areas of electric EFA probes. The velocity vector of the satellite is perpendicular to the direction of primary booms.

ESPERIA was planned and designed by an International Consortium led by the Roma Tre University of Rome (Vittorio Sgrigna, *Principal Investigator*).

3.3. Relation with other missions and science teams

ESPERIA may be considered as a second generation of the DEMETER concept and can profit by the information from previous missions. The equatorial character of ESPERIA and some augmentation or changes in its payload allow to extend the original scientific objectives of this mission for geo-electric and magnetic field mapping, for studying sun activity and cosmic rays, and investigating structure and dynamics of the magnetospheric cavity.

First ESPERIA instruments (EGLE and ARINA) have been launched in space. ARINA (Sub-section 4.2) and DEMETER (Parrot, 2002) are two simultaneous polar missions which allow comparisons of particle data within the DEMETER Guest Investigation Programme (Sgrigna, 2005).

4. The EGLE and ARINA space experiments

Two ESPERIA instruments (particle detector ARINA and search-coil magnetometer EGLE) have been built and have been tested in space (Sgrigna, 2004, 2005; Conti et al., 2005).

EGLE has been installed on board the International Space Station (ISS) last April 2005, within the LAZIO-SiRad experiment of the ENEIDE mission, which has been coordinated by the European Space Agency (ESA) and received contributions from the Italian National Institute of Nuclear Physics (INFN) and Regione Lazio (Italy).

At this purpose, ARINA particle data and EGLE magnetic data, together with fault creep events from the TELLUS ground tilt network of central Italy and magnetic and EM data from ground-based networks located in other Countries, should be available. All these data may be studied together with those obtained from DEMETER instruments, through the Demeter Guest Investigation Programme.

4.1. The EGLE magnetic experiment on board the International Space Station

The monitoring of electromagnetic environment on board the International Space Station (ISS) needs both of an appropriate observation methodology and of the corresponding experimental equipment design. The continuous monitoring of EM environment on board the ISS by an advanced magnetic experiment in the ULF–HF band is important in the following areas:

a. Geophysical research of plasma-wave processes connected to solar–magnetosphere–ionosphere–atmosphere–lithosphere interactions.
b. Investigation of space weather phenomena in equatorial, middle-latitude and sub-auroral ionosphere.
c. Investigation of the possible relationships between seismic activity and ULF–VLF phenomena that may be related to earthquakes.
d. Continuous monitoring of ULF–ELF–VLF activity in the near-Earth space including ELF–VLF pollution.
e. Monitoring of natural and man-made variations of the plasmasphere caused by whistlers.
f. Investigation of the effects of the large ISS structure on the propagating wave-front.

LAZIO-SiRad-EGLE experiment aims at performing measurements involving:

1. the radiation environment at the ISS altitude;
2. the magnetic environment inside the ISS.

The experiment includes magnetometer EGLE (Esperia's Geo-magnetometer for a Low-frequency wave Experiment).

EGLE is used to measure the intensity and variations of the magnetic field within the ISS, and to correlate these measurements with those of particle fluxes. The study of these effects is important to detect electromagnetic field variations and particle pitch angle distribution of the precipitating particles.

EGLE experiment is also the first test in space of a data acquisition system based on the 1-Wire® technology.

The EGLE magnetometer is constituted by:

- a single axis search coil probe, the EGLE Magnetometer Head (MH), which has been developed in collaboration with Valery Korepanov (Lviv Centre of Space Research),
- an electronic interface with amplifiers, filtering and data acquisition unit (EGLE MB box),

- a 2 m long cable to connect LAZIO MEB and EGLE MB,
- a 1-Wire® to RS232 serial adapter on the LAZIO pc tower.

EGLE has been built for automatic measurements of the low-frequency magnetic field component. The instrument performs high accuracy measurements. The advantages in using such a device are:

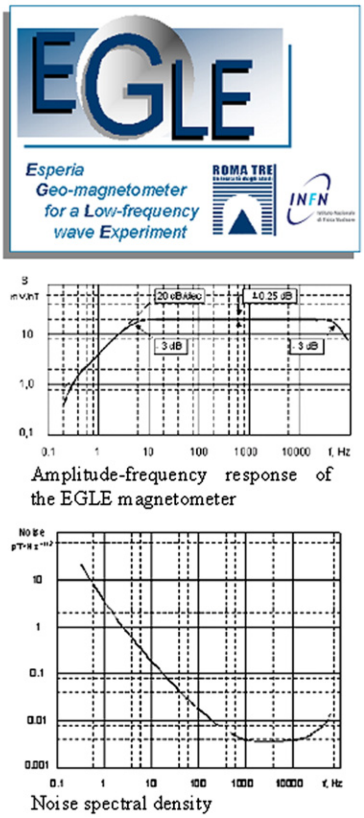
- small dimensions and mass;
- low power consumption;
- data acquisition via 1-Wire® technology.

A schematic representation of EGLE magnetometer and characteristic frequency response are reported in Fig. 3. An example of data recorded on board ISS is shown in Fig. 4.

4.2. The ARINA particle experiment on board a LEO satellite

The ARINA experiment consists of a proton–electron telescope to be installed on board the polar *LEO* Russian satellite RESURS-DK1, which launch occurred on June 15, 2006 within the PAMELA mission. The orbit is elliptic with 959 altitude ranging from 300 km to 600 km and inclination of 70.4°. The duration of the mission will be ≥3 years. The scientific objective of the experiment is to detect fluxes of high-energy charged particles (3–100 MeV), from the inner radiation belt and correlate them with seismic activity.

Main features of the ARINA instrument are reported in Fig. 5. As it can be seen, the instrument consists of a set of scintillation detectors C1–C12 made on the basis of polystyrene, which are viewed by photomultipliers (PMTs), the event recording system, the data acquisition and processing system (DAPS), the power supply system (PSS), and the command unit (CU). Detectors C1–C12 are functionally combined into three systems: the hodoscopic trigger system HTS (detectors C1–C3), the scintillation calorimeter SC (detectors C4–C9), and the anticoincidence system ACS (detectors C10–C12). Each of the detectors C1 and C2 consists of four strips directed perpendicularly and positioned just one under another. Detector C3 is situated below detectors C1 and C2 and has a mosaic structure (6 elements). Each



Basic technical specifications of the EGLE probe MH	
Frequency band of receiver signals	0.5 ÷ 50000 Hz
Shape of transfer function	linear – flat
Type of output	Symmetrical
Transformation factor at both output terminals: • at linear part (0.5 – 5 Hz) • at flat part (5 – 50000 Hz)	f*4 mV/(nT*Hz) 20 mV/nT
Transformation factor error: ▪ at flat part of band pass without edges ▪ at flat part band pass edges	≤ ±0.25 dB ≤ 3 dB
Magnetic noise level, pT*Hz$^{-1/2}$: ▪ at 5 Hz ▪ at 100 Hz ▪ at 5 kHz ▪ at 50 kHz	≤ 0.4 ≤ 0.02 ≤ 0.004 ≤ 0.02
Nominal output load	≤ 200 pF ≥ 50 kΩ
Power supply voltage	± (15 ± 0.2) V
Power consumption	300 mW
Temperature range of operation	-30 °C ÷ +50 °C
Outer dimensions (without prominent parts)	l = 400 mm d = 32 mm
Length of the output cable	0.7 m
Weight	≤ 320 g

Fig. 3. EGLE sensor characteristics.

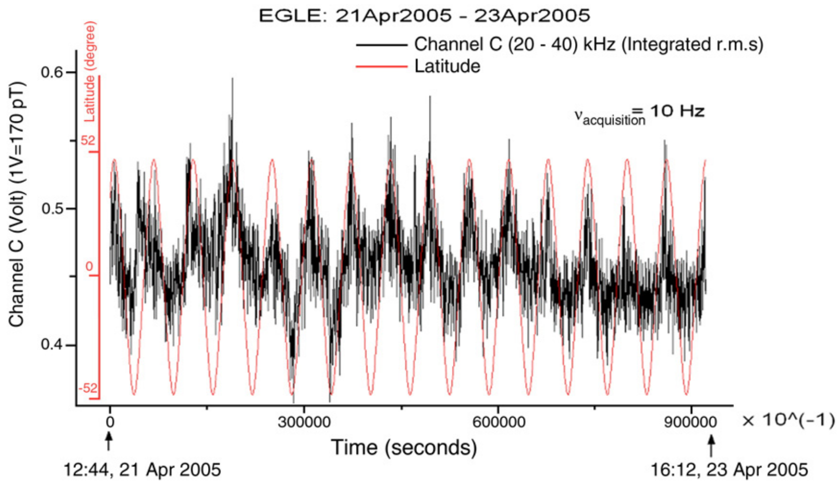


Fig. 4. An example of magnetic data in the frequency band (20–40) kHz, recorded by the EGLE instrument on board the ISS. Superimposed to the signal is shown the latitude variation of the ISS.

mosaic element is viewed by its own PMT. Such detector's assembly allows to determine the angle of incident particle. The geometry and dimensions of detectors C1–C3 define the instrument aperture and the geometric factor. The scintillation calorimeter can comprise the detector C3 in addition to a set of detectors C4–C9. It provides the separation of the protons and electrons and allows to measure the particle energy by the number of detectors, passed by the particle up to its stop. That is, it used the range of the particle in stack of detectors. The ACS consists of the detector C10 and lateral detectors C11 and C12, and it is needed to exclude from recording the particles moving in the opposite direction "from the bottom upward" as well as all directions beyond the aperture.

5. Combined ground and space experiments: a proposal to the scientific community for a joint study devoted to earthquake prediction and warning

According to the considerations and results of previous Sections 1 and 2 and to the projects designed and/or made (Sections 3 and 4), we propose to the scientific community a joint research project devoted to study

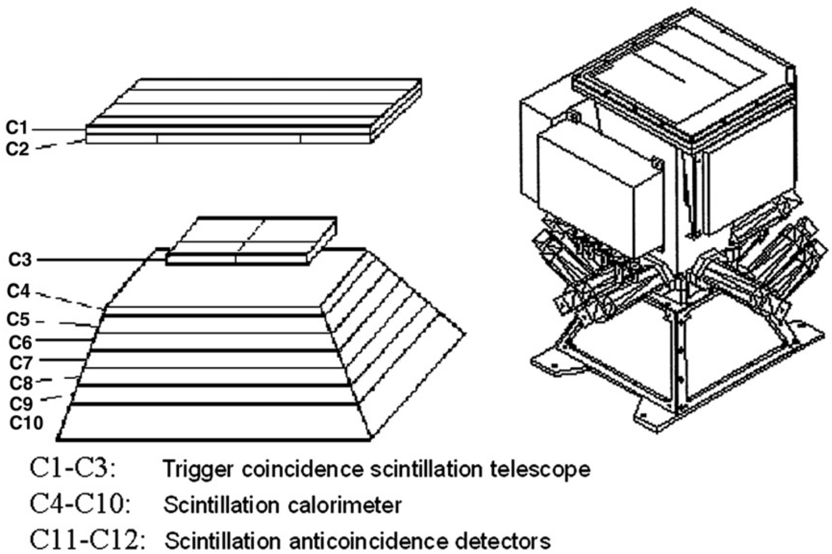


Fig. 5. ARINA space instrument layout.

the earthquake prediction problem on a deterministic basis.

The strategy is based on concepts largely accepted by investigators. In particular, we propose:

1. to define a physical model of earthquake precursors on a deterministic basis,
2. to propose a method for future applications and services of early warning on the basis of this model;
3. to validate such a model, and consequent method, through coordinated and continuous ground-based and space observations of the more reliable earthquake precursor phenomena. The more promising current ground-based detection methods and their output must be also identified in the light of data fusion with space-borne sensors.

On the basis of the previous items the study should also outline a global mission scenario with options and related trade-off's on the following items:

– Science return
– Early warning and coverage
– Technical feasibility and readiness
– Resources needed.

In the joint study we propose to the scientific community, we should like to demonstrate consistently a causal relationship with explained physical processes and look for a correlation between data gathered simultaneously and continuously by space observations and ground-based measurements. From an objective standpoint, once these relationship and correlation should be demonstrated, we will be confident that the combination of data from both Earth and near-Earth space, with their inherent analysis, could provide the scientific basis to establish a coherent interpretation of the assumed earthquake forerunners and, consequently, to enable and pave the way to future applications and services on a sound scientific basis.

But we also like to stress a few critical issues, and in particular:

1. The intrinsic difficulty of having repeatable observations
2. The different geological and seismic characteristics of the observed sites
3. The different nature and location of the observed EM phenomena (ULF, ELF, VHF etc.)
4. The lack of a well-defined inherent physical model
5. The non-sufficiently applied multidisciplinary approach as requested by the problem. In several cases teams of researchers investigate the phenomenon studying the effects produced on one single parameter or field and in most cases with different methods of analysis. Also partial and different frequency bands are often considered for the same parameter (for instance ULF or VLF–HF SEME signals).

Consequences of these issues are that in some cases pre-seismic anomalies are detected with different sensors, at different times in different places and analyzed with different methods. So, it is evident that on this basis is not always possible to correlate the collected data in a consistent way.

The approach we propose is to combine together information from:

- local ground deformation intermediate-term precursors, as those reported in Section 2
- EM shorter-term signals by ground and satellite observations

and to use a common method of analysis.

All the above measurements aim at:

- checking the causality (or the non-causality) of the electromagnetic/plasma effects resulting from seismic events
- and/or validating the postulated energy transport mechanisms from the earth surface to space, with the relevant scientific justification
- making attempts of a space localization of the forthcoming earthquake.

Concerning reliability of ground-based earthquake precursors, data collected up to now (Section 2) suggest that the most significant ones are:

1. local deformations. Creep strain episodes seem to be particularly informative and reliable;
2. EM emissions in the broad ULF–VHF frequency band.

A few contacts occurred with teams that manage the following networks and that we invite to participate to our proposal. In this way four ground-based different networks of instruments for local strain and EM measurements will be available for the beginning. They are:

– the SEGMA magnetometer array of four wave magnetic stations (headed by Prof. Villante of the L'Aquila University of Italy in collaboration with the Institut fuer Weltraumforschung (Graz, Austria));

– the ULF magnetic network at Panagyurishte (headed by Prof. Villante in collaboration with the Geophysical Institute of the Bulgarian Academy of Science (Sofia, Bulgaria));
– the VLF–VHF EM network of twelve stations in Greece (headed by Prof. Eftaxias of the University of Athens (Greece);
– the ULF wave stations working in Antarctica, one at Terra Nova Bay (headed by Prof. Villante) and another at the Ukrainian Akademik Vernadsy (headed by Prof. Korepanov of the Lviv Centre of Space Research (Ukrainian Space Agency, Lviv, Ukraina);
– the TELLUS tilt network of four stations (headed by Prof. Sgrigna, University of Rome, Roma Tre) operational in the seismic central Apennines area of Central Italy.

In space (topside ionosphere) the best earthquake precursors have shown to be:

1. EM emissions in the ULF–HF frequency band
2. Temperature and density of the ionospheric plasma (both in its electronic and ionic components)
3. High-energy particle fluxes precipitating from the inner Van Allen radiation belt (from about a few tens to a few hundreds of MeV).

Note that EM emissions may be detected both on the ground and in space, of course with different techniques and receiving complementary information. So, they are a common and very important element for the study. The importance of these phenomena lies not only on their reliability as earthquake precursors but also on the different precursor time duration, which (Sub-section 5.1) could help in solving the problem of timing. Another important factor is the presence of fault creep signals and their relative onset time-shifts, which may help in determining space and magnitude of an impending earthquake, as synthesised in the following.

5.1. Magnitude evaluation, space localization and timing problem

We suggest to perform in ground-based networks, simultaneous and continuous measurements of local deformation (tilt and strain) events and of EME signals, at least in the ULF–HF frequency band. Coordinated space observations of EME signals in the same frequency band, and of temperature and density of the ionospheric plasma, as well as fluxes of high-energy radiation belt particle, are also suggested to be carried out in the topside ionosphere.

On the basis of data collected in this way, a first, rough, and overpreliminary attempt to determine magnitude, space, and time of an impending earthquake could be performed.

An estimation of the relevant order of magnitude of interest for time and space scale of the phenomena under investigation could be attempted as follows.

When in an enough large monitoring network zone an earthquake is in preparation, only a certain number of instruments (tiltmeters and strainmeters) installed in the zone to monitor local deformations are expected to be activated by the phenomenon, and begin to record anomalous signals (as creep strains described in Subsection 2.1). The space location of these instruments will allow to recognize the portion of the zone affected by the pre-seismic deformation field (i.e. the precursor area). On the basis of relationships (5) and (6) of Section 1, a rough estimate of the dimension of this area will allow to determine the magnitude of the impending earthquake.

Moreover, by the time-shift in the onset times of the precursor signals detected by tiltmeters or strainmeters, and on the basis of simple space–time (velocity) calculations, we should attempt a localization of the epicentral area of the forthcoming seismic event.

Also space measurements could in principle be used, and compared with that from ground observations, for a rough estimate of the precursor area of an impending earthquake. In fact, LEO satellites with a payload similar to that designed for ESPERIA could give additional and complementary information by its position when recording over the precursor area anomalous variation of EM signals, temperature and density of the ionospheric plasma, or fluxes of radiation belt particles. Moreover, as reported in the previous Sub-section 2.3, the opposite longitudinal drift of anomalous burst of positive and negative charged particles in principle could be used to determine the location of EME wave–particle interaction zone (i.e., the PBs space source location). In this way, using particle measurements, it would be possible to detect earthquake precursors also when satellite is not over seismic regions. Of course it should be verified that wave–particle interaction zone reconstructed by the data is located, or not, over the precursor area of the impending earthquake.

In the same monitoring network zone, the first onset times in earthquake precursor ground-based deformation signals (tilts, creep strains) may be considered and assumed as a warning for an impending earthquake in the zone. Since this type of precursors are of intermediate-term characters (up to several months), this information could be used as a first early warning.

From this moment we must wait for a variable period of time (which depends upon the earthquake magnitude) the afterwards onset times of short-term pre-seismic EM emission signals detected in the same instrumental network. When these EM emissions will begin we could attempt a rough information of the time occurrence of the impending seismic event. The uncertainty in this estimate being of hours–days, which is the characteristic precursor time associated with EM short-term precursor phenomena.

Reliable information from these ground-based intermediate- and short-term precursors, recorded together in the same test area, could be used for a second warning. Space-based evidences of EM emissions in the same frequency band of those recorded in the ground, temperature and density of the ionospheric plasma, and high-energy radiation belt particle fluxes, obtained on board of a LEO satellite flying over the same ground monitoring network, could corroborate the validity of the second warning. In the case that space observations will confirm recent results reported in literature on their shorter-term character of a few hours, they could be used as a third (and last) warning, just before the occurrence of the seismic event.

Note that by a time-shift analysis, all the onset times of tilt and strain signals should be compared relatively to each other and results used not only for a rough estimate of the location of the forthcoming earthquake but also for the time occurrence of this event. The latter estimate can be attempted by calculating the slow-propagation of the pre-seismic strain field.

Also note that a great importance of space monitoring lies in the possibility to compare ground-based data with space ones, and this can be used as a kind of calibration for the physical model we aim to define, as well as to compare relatively to each other results from different monitoring networks, operational in diverse seismic areas of the Earth.

This proposal is mainly addressed to investigators involved in earthquake precursor studies who already manage and use existing ground-based networks of instruments and/or are involved in near-Earth space experiments, or in laboratory and theoretical studies in the field. Also other investigators who are interested and are going to be involved in the field are welcome.

6. Conclusions and outlook

Natural disasters are of serious concern to mankind and the earthquake is one of the most dangerous of them. Therefore any plausible approach suitable to reduce the impact of these disasters deserves great attention. In the paper we focus our attention to seismic activity. Of course, in this frame earthquake prediction becomes the most important goal.

Hence, our proposal to the scientific community aims at giving a contribution in the light of an earthquake prediction method to be constructed on a deterministic basis. Of course, it is not meant to achieve in the next future an explicit solution to the problem, that is of an immense complexity. In fact, some attempts to build a theory of earthquake prediction are far from being defined and generally accepted. But numerous earthquake related phenomena, the so-called earthquake precursors of mechanical and/or EM origin, have been observed prior to catastrophic earthquakes.

Signals associated with seismic events have been observed from both ground-based and space measurements and have indicated some degree of positive statistic correlation with the earthquake preparation and occurrence.

The study we propose for a deterministic approach in the field is based on the detection of the most significant earthquake precursors and related physical explanation. Both near-Earth space and ground-based continuous observations of the most significant pre-seismic changes are proposed to be carried out in the so-called topside ionosphere and in different seismic areas of the Earth within a “unified” physical model of earthquake precursors.

This “unified” model will:

- describe the preparation phase of an earthquake (pre-seismic accumulation of elastic strain energy) and involved physical mechanisms (dilatancy and consequent precursor phenomena);
- justify the genesis and characteristics of the selected pre-seismic and co-seismic EM and mechanical anomalies giving their relative and absolute reliability as earthquake precursors;
- perform a preliminary quantitative estimation of the possible SEME signals based on credible assumptions of the parameters involved;
- allow a better understanding of the physics of the lithosphere–atmosphere–ionosphere–magnetosphere coupling mechanisms, which result in EM and plasma effects in the ionosphere or other seismo-induced phenomena that can be better studied in space;
- identify credible energy transport mechanisms from the Earth surface to space that could explain the alteration of plasma and EM parameters at satellite altitudes, to assess the applicability of space-based assets;
- devise a set of space-based sensors capable of giving added value to the current understanding of the detected seismic precursors;
- allow to define a method for earthquake prediction.

Results, observations and modelling should be used to validate a method for possible future applications in earthquake prediction.

At this purpose a method has been proposed to the scientific community for a joint collaboration between groups of investigators involved in earthquake prediction studies and working in diverse seismic areas of the Earth. The purpose is to put these investigators together around a table for defining a common line of conduct and a concrete collaboration in the field. The United Nations 2008 International Year of Planet Earth could be a good occasion to begin.

References

Aleksandrin, S.Yu., Galper, A.M., Grishantzeva, L.A., Koldashov, S.V., Maslennikov, L.V., Murashov, A.M., Picozza, P., Sgrigna, V., Voronov, S.A., 2003. High-energy charged particle bursts in the near-Earth space as earthquake precursors. Ann. Geophys. 21, 597–602.

Aleshina, M.E., Voronov, S.A., Galper, A.M., Koldashov, S.V., Maslennikov, L.V., 1992. Correlation between earthquake epicenters and regions of high-energy particle precipitations from the radiation belt. Cosm. Res. 30 (1), 79–83.

Areshidze, G., Bella, F., Biagi, P.F., Caputo, M., Chkuaseli, V., Della Monica, G., Ermini, A., Manjgaladze, P., Melikadze, G., Sgrigna, V., Slavina, L., Zilpimiani, D., 1992. Anomalies in geophysical and geochemical parameters revealed in the occasion of the Paravani (M=5.6) and Spitak (M=6.9) earthquakes (Caucasus). Tectonophysics 202, 23–41.

Bella, F., Bella, R., Biagi, P.F., Ermini, A., Sgrigna, V., 1986a. Possible precursory tilts preceding some earthquakes ($3.0 \leq M \leq 3.8$) occurred in Central Italy between February 1981 and June 1983. Earthq. Predict. Res. 4, 147–154.

Bella, F., Biagi, P.F., Ermini, A., Sgrigna, V., Manjgaladze, P., 1986b. Possible propagation of tilt and strain anomalies: velocity and other characteristics. Earthq. Predict. Res. 4, 195–209.

Bella, F., Biagi, P.F., Caputo, M., Della Monica, G., Ermini, A., Sgrigna, V., 1990. Very slow-moving crustal strain disturbances. Tectonophysics 179, 131–139.

Bella, F., Biagi, P.F., Caputo, M., Della Monica, G., Ermini, A., Sgrigna, V., 1993. Ground tilt anomalies accompanying the main earthquakes occurred in the Central Apennines (Italy) during the period 1986–1989. Nuovo Cim. 16C, 393–406.

Bella, F., Biagi, P.F., Caputo, M., Della Monica, G., Ermini, A., Manjgaladze, P.V., Sgrigna, V., Zilpimiani, D.O., 1995. Possible creep-related tilt precursors obtained in the Central Apennines (Italy) and in the Southern Caucasus (Geirgia). Pure Appl. Geophys. 144, 277–299.

Bella, F., Caputo, M., Della Monica, G., Lisi, A., Plastino, W., Scandone, R., Sgrigna, V., 1998. Crustal blocks and seismicity in the Central Apennines of Italy. Nuovo Cim. 21C, 597–607.

Bernabé, Y., 1998. Streaming potential in heterogeneous network. J. Geophys. Res. 103, 20827–20841.

Bilham, R.G., 1981. Delays in the onset times of near-surface strain and tilt precursor to earthquakes. In: Simpson, P.J., Richards, P.G. (Eds.), Earthquake Prediction: An International Review. Geophysical Union, Washington, D.C., pp. 411–421.

Bilham, R.G., Beavan, R.J., 1979. Strains and tilts on crustal blocks. Tectonophysics 52, 121–138.

Bilham, R.G., Beavan, J., Evans, K., Hurst, K., 1985. Crustal deformation metrology at Lamont–Doherty Geological Observatory. Earthq. Predict. Res. 3, 391–411.

Bilichenko, S.V., Iljin, F.S., Kim, E.F., Pokhotelov, O.A., Puschaev, P.P., Stanev, G.A., Streltsov, A.V., Chmyrev, V.M., 1990. ULF response of the ionosphere for earthquake preparation processes. Dokl. Acad. Nauk, USSR 311, 1077–1080.

Bishop, J.R., 1981. Piezoelectric effects in quartz-rich rocks. Tectonophysics 77, 297–321.

Chmyrev, V.M., Isaev, N.V., Serebryakova, O.N., Sorokin, V.M., Sobolev, Ya.P., 1997. Small-scale plasma inhomogeneities and correlated ELF emissions in the ionosphere over an earthquake region. J. Atm. Solar-Terr. Phys. 59, 967–974.

Conti, L., Cirella, A., Malvezzi, V., Sgrigna, V., 2004. A model for the propagation of preseismic electromagnetic fields through lithosphericand atmospheric media, 2004. Proc.1st General Assembly, European Geosciences Union, Nice, France, 25–30 April 2004, EGU04-A-04927; NH4.02-1FR4P-0430, p. 337.

Conti, L., Buzzi, A., Sgrigna, V., Stagni, C., Zilpimiani, D., 2005. The EGLE experiment. 10th Scientific Assembly of the International Association of Geomagnetism and Aeronomy (IAGA 2005), Toulose, France, July 18–29, 2005. Session Division II, C085: Low Latitude Atmosphere–Ionosphere–Magnetosphere Coupling, Dynamics and Energetics; IAGA2005-A-01522, p. 83.

Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimantion of the size of earthquake preparation zones. Pure Appl. Geophys. 117, 1025–1044.

Dobrovolsky, I.P., Gershenzon, N.I., Gokhberg, M.B., 1989. Theory of electrokinetic effects occurring at the final stage in the preparation of a tectonic earthquake. Phys. Earth Planet. Inter. 57, 144–156.

Draganov, A.B., Inan, U.S., Taranenko, Y.N., 1991. ULF magnetic signatures at the Earth surface due to the ground water flow: a possible precursor to earthquakes to earthquakes. Geophys. Res. Lett. 18, 1127–1130.

Eftaxias, K., Kapiris, P., Polygiannakis, J., Peratzakis, A., Kopanas, J., Antonopoulos, G., Rigas, D., 2003. Experience of short term earthquake precursors with VLF–VHF electromagnetic emissions. Nat. Hazard Earth Syst. Sci. 3, 217–228.

Fraser-Smith, A.C., McGill, P.R., Helliwell, R.A., Villard Jr., O.G., 1994. Ultra-low frequency magnetic field measurements in southern California during the Northridge earthquake of 17 January 1994. Geophys. Res. Lett. 21, 2195–2198.

Freund, F., 2002. Charge generation and propagation in igneous rocks. J. Geodyn. 33, 543–570.

Freund, F., 2003. On the electrical conductivity structure of the stable continental crust. J. Geodyn. 35, 353–388.

Fenoglio, M.A., Johnston, M.J.S., Byerlee, J.D., 1995. Magnetic and electric fields associated with changes in high pore pressure in fault zones: application to the Loma Prieta ULF emissions. J. Geophys. Res. 100, 12951–12958.

Fujinawa, Y., Takahashi, K., Matsumoto, T., 2002. Modeling confined pressure changes inducing anomalous electromagnetic fields related with earthquakes. J. Appl. Geophys. 49, 101–110.

Galli, I., 1910. Raccolta e classificazione di fenomeni luminosi osservati nei terremoti. Boll. Soc. Ital. Sismologia 14.

Gabrielov, A.M., Levshina, T.A., Rotwain, I.M., 1990. Block model of earthquake sequence. Phys. Earth and Planet. Inter. 61, 18–22.

Galper, A.M., Dimitrenko, V.B., Nikitina, N.V., Grachev, V.M., Ulin, S.E., 1989. Interrelation between high-energy charged particle fluxes in the radiation belt and seismicity of the Earth. Cosm. Res. 27, 789.

Galper, A.M., Koldashov, S.V., Voronov, S.A., 1995. High energy particle flux variations as earthquake predictors. Adv. Space Res. 15, 131–134.

Galperin, Yu.I., Gladyshev, V.A., Jordjio, N.V., Larkina, V.I., 1992. Precipitation of high-energy captured particles in the magnetosphere above the epicenter of an incipient earthquake. Cosm. Res. 30, 89–106.

Geller, R.J., 1996. Debate on VAN. Geophys. Res. Lett. 23 (11) (whole issue).

Gershenzon, N., Bambakidis, G., 2001. Modeling of seismo-electromagnetic phenomena. Russ. J. Earth Sci. 3, 247–275.

Ginzburg, E.A., Malishev, A.B., Proshkina, I.P., Pustovetov, V.P., 1994. Correlation of strong earthquakes with radiation belt particle flux variations. Geomagn. Aeron. (Engl. Transl.) 34, 315–320.

Gokhberg, M.B., Morgounov, V.A., Aronov, E.L., 1979. On the high frequency electromagnetic radiation during seismic activity. Dokladi Acad. Sci. USSR 248, 1077–1081.

Grimalsky, V.V., Kremenetsky, I.A., Rapoport, Yu.G., 1999. Excitation of EMW in the lithosphere and propagation into magnetosphere. In: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. TERRAPUB, Tokyo, pp. 777–787.

Gufeld, I., Gusev, G., Pokhotelov, O., 1994. Is the prediction of earthquake dates possible by the VLF radiowave monitoring method? In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic Phenomena Related to Earthquake Prediction. TERRAPUB, Tokyo, pp. 381–389.

Guo, Z., Liu, B., Wang, Y., 1994. Mechanism of electromagnetic emissions associated with microscopic and macroscopic cracking in rocks. In: Hayakawa, M. (Ed.), Electromagnetic Phenomena Related to Earthquake Prediction. TERRAPUB, Tokyo, pp. 523–529.

Hayakawa, M., Sato, H., 1994. Ionospheric perturbations associated with earthquakes, as detected by subionospheric VLF propagation. In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic Phenomena Related to Earthquake Prediction. TERRAPUB, Tokyo, pp. 391–397.

Hayakawa, M., Kopytenko, Yu., Smirnova, N., Troyan, V., Peterson, Th., 2000. Monitoring ULF magnetic disturbances and schemes for recognizing earthquake precursors. Phys. Chem. Earth, Part A Solid Earth Geod. 25, 263–269.

Hayakawa, M., Molchanov, O.A., Nikolaenko, A.P., 2002. Model variations in atmospheric radio noise caused by preseismic modifications of tropospheric conductivity profile. In: Hayakawa, M., Molchanov, O.A. (Eds.), Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. TERRAPUB, Tokyo, pp. 349–352.

Ismaguilov, V.S., Kopytenko, Yu.A., Hattori, K., Voronov, P.M., Molchanov, O.A., Hayakawa, M., 2001. ULF magnetic emissions connected with under sea bottom earthquakes. Nat. Hazard Earth Syst. Sci. 1, 23–31.

Ida, Y., 1974. Slow moving deformation pulses along tectonic faults. Phys. Earth Planet. Inter. 9, 328–337.

Johnston, M.J.S., 1997. Review of electric and magnetic fields accompanying seismic and volcanic activity. Surv. Geophys. 18, 441–475.

Johnston, M.J.S., Mueller, R.J., 1987. Seismomagnetic observations during the 8 July 1986 magnitude 5.9 North Palm Springs earthquake. Science 237, 1201–1203.

Keilis Borok, V.I., 1996. Intermediate term earthquake prediction. Proc. Nat. Acad. Sc. USA 93, 3748–3755.

Keilis Borok, V.I., Soloviev, A., 2003. Non Linear Dynamics of the Lithosphere and Earthquake Prediction. Springer-Verlag, Berlin.

Kopytenko, Yu.A., Matiashvili, T.G., Voronov, P.M., Kopytenko, E.A., Molchanov, O.A., 1993. Detection of ultra-low-frequency emissions connected with the Spitak earthquake and its aftershock activity, based on geomagnetic pulsations data at Dusheti and Vardzia observatories. Phys. Earth Planet. Inter. 77, 85–95.

Krechetov, V.V., 1996. Cerenkov radiation of protons in the magnetosphere as a source of VLF waves preceding an earthquake. Geomagn. Aeron. (Engl Transl.) 35, 688–691.

Larkina, V.I., Migulin, V.V., Molchanov, O.A., Kharkov, I.P., Inchin, A.S., Schvetsova, V.V., 1989. Some statistical results on very low frequency radiowave emissions in the upper ionosphere over earthquake zones. Phys. Earth Planet. Inter. 57, 100–109.

Lay, T., Wallace, T.C., 1995. Modern Global Seismology. Academic Press, San Diego, CA, p. 384.

Lee, C.C., Liu, J.Y., Pan, C.J., 2000. The height of sporadic-E layer simultaneously observed by the VHF radar and ionosondes in Chung-Li. Geophys. Res. Lett. 27, 641–644.

McHugh, S., Johnston, MJ.S., 1979. A review of observations and dislocation modeling of some creep-related tilt perturbations from Central California. In: Vogel, A. (Ed.), Terrestrial and Space Techniques in Earthquake Prediction. Vieweg and Sohn, Braunschweig, pp. 181–201.

Merzer, M., Klemperer, S.L., 1997. Modeling low-frequency magnetic-field precursors to the Loma Prieta earthquake with a precursory increase in fault–zone conductivity. Pure Appl. Geophys. 150, 217–248.

Molchanov, O.A., Hayakawa, M., 1998. On the generation mechanism of ULF seismogenic electromagnetic emissions. Phys. Earth Planet. Inter. 105, 201–210.

Molchanov, O.A., Mazhaeva, O.A., Golyavin, A.N., Hayakawa, M., 1993. Observation by the Intercosmos-24 satellite of ELF–VLF electromagnetic emissions associated with earthquakes. Ann. Geophys. 11, 431–440.

Molchanov, O.A., Hayakawa, M., Rafalsky, V.A., 1995. Penetration characteristics of electromagnetic emissions from an underground seismic source into the atmosphere, ionosphere and magnetosphere. J. Geophys. Res. 100, 1691–1712.

Morgounov, V.A., Ondoh, T., Nagai, S., 1994. Anomalous variation of VLF signals associated with strong earthquakes $M \geq 7.0$. In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic Phenomena Related to Earthquake Prediction. TERRAPUB, Tokyo, pp. 409–428.

Mortensen, C.E., Johnston, M.J.S., 1975. The nature of surface tilt along 85 km of the San Andreas fault: preliminary results from a 14-instrument array. Pure Appl. Geophys. 113, 237–249.

Myachkin, V.I., Brace, W.F., Sobolev, G.A., Dieterich, J.H., 1975. Two models for earthquake forerunners. Pure Appl. Geophys. 113, 169–181.

Nitsan, U., 1977. Electromagnetic emission accompanying fracture of quartz-bearing rocks. Geophys. Res. Lett. 4, 333–336.

Nardi, A., Caputo, M., 2006. Perspective electric earthquake precursors observed in the Apennines, Eighth Workshop on Non Linear Dynamics and Earthquake Prediction, ICTP, SMR.1676-20, Trieste, 03–15 October 2005. Also in: Boll. Geofis. Teorica e Appl. 47, 3–12.

Nur, A.M., 1972. Dilatation, pore fluids and premonitory variation of TP/TS traveltime. Bull. Seismol. Soc. Am. 62, 1217–1222.

Nur, A.M., Ron, H., Scotti, O., 1986. Fault mechanisms and the kinematics of block rotation. Geology 14, 746–749.

Ohta, K., Umeda, K., Watanabe, N., Hayakawa, M., 2001. ULF/ELF emissions observed in Japan, possibly associated with the Chi-Chi earthquake in Taiwan. Nat. Hazard Earth Syst. Sci. 1, 37–42.

Oike, K., Ogawa, T., 1986. Electromagnetic radiations from shallow earthquake observed in the LF range. J. Geomagn. Geoelectr. 38, 1031–1040.
Park, S.K., Johnston, M.J.S., Madden, T.R., Morgan, F.D., Morrison, H.F., 1993. Electromagnetic precursors to earthquakes in the ULF band: a review of observations and mechanisms. Rev. Geophys. 31, 117–132.
Parrot, M., 1994. Statistical study of ELF/VLF emissions recorded by a low-altitude satellite during seismic events. J. Geophys. Res. 99, 23339–23347.
Parrot, M., 2002. The micro-satellite DEMETER. J. Geodyn. 33, 535–541.
Parrot, M., Mogilevsky, M.M., 1989. VLF emissions associated with earthquakes and observed in the ionosphere and the magnetosphere. Phys. Earth Planet. Inter. 57, 86–99.
Parrot, M., Achache, J., Berthelier, J.J., Blanc, E., Deschamps, A., Lefeuvre, F., Menvielle, M., Plantet, J.L., Tarits, P., Villain, J.P., 1993. High frequency seismo-electromagnetic effects. Phys. Earth Planet. Inter. 77, 65–83.
Peresan, A., Kossobokov, V., Romashkova, L., Panza, G.F., 2005. Intermediate-term middel-range earthquake prediction in Italy: a review. Earth-Sci. Rev. 69 (97).
Pevnev, A.K., 1988. Earthquake prediction: geodetic aspects of the problem. Izv. Akad. Nauk SSSR., Fiz. Zemli 12, 88–98.
Pevnev, A.K., 1989. Deterministic geodetic prediction of preparation areas of strong crustal earthquakes. Earthq. Predict., Dushanbe, Donish 11, 11–23.
Pulinets, S.A., Boyarchuk, K.A., Hegai, V.V., Kim, V.P., Lomonosov, A.M., 2000. Quasi-electrostatic model of atmosphere–thermosphere–ionosphere coupling. Adv. Space Res. 26, 1209–1218.
Pustovetov, V.P., Malyshev, A.B., 1993. Space–time correlation of earthquakes and high-energy particle flux variations in the inner radiation belt. Cosm. Res. 31, 84–90.
Rodger, C.J., Dowden, R.L., Thomson, N.R., 1999. Observations of electromagnetic activity associated with earthquakes by low-altitude satellites. In: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. TERRAPUB, Tokyo, pp. 697–710.
Salvini, F., 1993. Block tectonics in thin-skin style-deformed regions: examples from structural data in the Central Apennines. Ann. Geofis. XXXVI, 97–109.
Scholz, C.H., 1977. A physical interpretation of the Haicheng earthquake prediction. Nature 267, 121–124.
Serebryakova, O.N., Bilichenko, S.V., Chmyrev, V.M., Parrot, M., Rauch, J.L., Lefeuvre, F., Pokhotelov, O.A., 1992. Electromagnetic ELF radiation from earthquake regions as observed by low-altitude satellite. Geophys. Res. Lett. 19, 91–94.
Sgrigna, V. (Principal Investigator), Esperia Science Team, 2001. ESPERIA Phase A Report, Italian Space Agency (ASI), Program for Scientific Missions Dedicated to Earth Sciences, Rome, July 2001, pp. 194.
Sgrigna, V., 2004. Description and testing of ESPERIA instruments (ARINA and LAZIO-SIRAD) in space. EOS Trans., AGU 85 (47), F1795 T53C-03.
Sgrigna, V., 2005. Description and testing of ARINA and LAZIO/EGLE instruments in space within the ESPERIA mission project and the DEMETER guest investigation programme. DEMETER Guest Investigator Workshop. CNES, Paris, France. 2–4 May 2005.
Sgrigna, V., Malvezzi, V., 2003. Preseismic creep strains revealed by ground tilt measurements in central Italy on the occasion of the 1997 Umbria–Marche Apennines earthquake sequence. Pure Appl. Geophys. 160, 1493–1515.
Sgrigna, V., Conti, L., Corsi, M., Galper, A., Malvezzi, V., Picozza, P., Scrimaglio, R., Stagni, L., Zilpimiani, D., 2001. Ionospheric perturbations possibly caused by preseismic electromagnetic emissions. EOS Trans., AGU 82, S52A-14 (20), S272.
Sgrigna, V., D'ambrosio, C., Yanovskaya, T.B., 2002a. Numerical modeling of preseismic slow movements of crustal blocks caused by quasi-horizontal tectonic forces. Phys. Earth Planet. Inter. 129, 313–324.
Sgrigna, V., Console, R., Conti, L., Galper, A., Malvezzi, V., Parrot, M., Picozza, P., Scrimaglio, R., Spillantini, P., Zilpimiani, D., 2002b. Preseismic natural emissions from the Earth's surface and their effects in the near Earth space. A project for monitoring earthquakes from space. EOS Trans., AGU 83, T22B-10 (19), S356.
Sgrigna, V., Carota, L., Conti, L., Corsi, M., Galper, A., Picozza, P., Stagni, L., 2005a. Correlations between earthquakes and anomalous particle bursts from SAMPEX/PET satellite observations. J. Atmos. Sol.-Terr. Phys. 67, 1448–1462.
Sgrigna, V., Console, R., Conti, L., Galper, A.M., Malvezzi, V., Parrot, M., Picozza, P., Scrimaglio, R., Spillantini, P., Zilpimiani, D., 2005b. The ESPERIA project: a mission to investigate the near-Earth space. In: Reigberg, C., Luhr, H., Schwintzer, P., Wickert, J. (Eds.), Earth Observation with CHAMP, Results from Three Years in Orbit, Potsdam, August 2004. Springer Geosciences Series, Berlin, pp. 407–412.
Sorokin, V.M., Chmyrev, V.M., Yaschenko, A.K., 2001. Electrodynamic model of the lower atmosphere and the ionosphere coupling. J. Atmos. Sol.-Terr. Phys. 63, 1681–1691.
Surkov, V., 1999. ULF electromagnetic perturbations resulting from the fracture and dilatancy in the earthquake preparation zone. In: Hayakawa, M. (Ed.), Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. TERRAPUB, Tokyo, pp. 371–382.
Teisseyre, R., 1997. Generation of electric field in an earthquake preparation zone. Ann. Geofis. 40, 297–304.
Thatcher, W., Fujita, N., 1984. Deformation of the Mikata Rhombus: strain buildup following the 1923 Kanto Earthquake, Central Honshu, Japan. J. Geophys. Res. 89, 2102–2106.
Uyeda, S., Sulaiman Al-Damegh, K., Dologlou, E., Nagao, T., 1999. Some relationship between VAN seismic electric signals (SES) and earthquake parameters. Tectonophysics 304, 41–55.
Varotsos, P., Alexopoulos, K., Lazaridou, M., Nagao, 1993. Earthquake predictions issued in Greece by seismic electric signals since February 6, 1990. Tectonophysics 224, 269–288.
Varotsos, P., Sarlis, N., Lazaridou, M., Kapiris, P., 1997. Transmission of stress induced electric signals in dielectric media. J. Appl. Phys. 83, 60–70.
Voronov, S.A., Galper, A.M., Koldashov, S.V., Maslennikov, L.V., Mikhailov, V.V., Nikitina, N.V., Popov, A.V., 1990. Increases in high energy charged particle fluxes near the South Atlantic magnetic anomaly and the seismicity of the Earth. Cosm. Res. 28, 789–791.
Walt, M., 1994. Introduction to Geomagnetically Trapped Radiation. Cambrige University Press.
Warwick, J.W., Stoker, C., Meyer, T.R., 1982. Radio emission associated with rock fracture: possible application to the great Chilean earthquake of May 22, 1960. J. Geophys. Res. 87, 2851–2859.