Geospace perturbations induced by the Earth: the state of the art and future trends

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Abstract

A systematic multi-parameter and multi-platform approach to study the slow process of earthquake preparation is fundamental to gain some insight on this complex phenomenon. In particular, an important contribution is the integrated analysis between ground geophysical data and satellite data. In this paper we review some of the more recent results and suggest the next directions of this kind of research. Our intention is not to detect a particular precursor but to understand the physics underlying the various observations and to establish a reliable physical model of the preparation phase before an impending earthquake. In this way, future investigation will search for suitable *fore-patterns*, which the physical model of multi-layers coupling predicts and characterizes by quasi-synchronism in time and geo-consistency in space.

1. Introduction

Earthquakes are among the most impressive natural phenomena frequently occurring on the planet: their impact on society is enormous because of the huge damages and loss of lives they cause. An earthquake is a dynamic phenomenon that usually happens because of a slow strain accumulation, lasting also several years, and culminating with a sudden rupture and displacement of blocks of rock in the lithosphere.

The evolutionary process of earthquakes is rich in complex features, from stochastic to chaotic or pseudo-periodic dynamics, often depending on the different geo-tectonic regime which reflects in the focal mechanisms. Fundamental research in the lithosphere, such as the study of fault rupture mechanics and seismic wave propagation, has been conducted in different regions in the past decades. Many case studies show that there are some seismic anomalies *before* earthquakes (commonly called *seismic precursors* although this term is largely criticised by many scholars) and associated phenomena *after* earthquakes in terms of ground deformation, active faults (slip rates and geometry), tectonic stress fields and geomagnetic fields (Cicerone et al., 2009). Nevertheless, there is no pragmatic approach to earthquake prediction, and the systematic understanding of the preparation process of earthquakes and their seismic cycles is very limited to date so that, at the moment, earthquake prediction is still considered a "mission - impossible", especially within the seismological community (e.g. Hough 2009 and references therein).

On the other hand, in very recent years, there is an increasing amount of evidence that during some last stages of the long term process of preparation, there could be a transfer of energy between lithosphere and the above layers of atmosphere and ionosphere. The corresponding variations of the atmospheric, ionospheric and magnetospheric parameters before the main earthquakes could give useful information regarding the earthquake preparation process and, if properly identified and isolated, can be used as hints for large impending earthquakes. A promising way to improve the current state of our knowledge on this complex phenomenon is to integrate ground (and possibly seafloor) studies with satellite Earth Observation (EO).

Recent studies have shown that numerous geophysical and geochemical parameters, mostly monitored from space, can be possibly associated with earthquakes (*Pulinets and Boyarchuk*, 2004; *Saradjian and Akhoondzadeh*, 2011). Fig. 1 shows a sketch of the concept of integrated (ground and satellite) earthquake monitoring system which can be put in practice by means of different kinds of satellites/payloads.

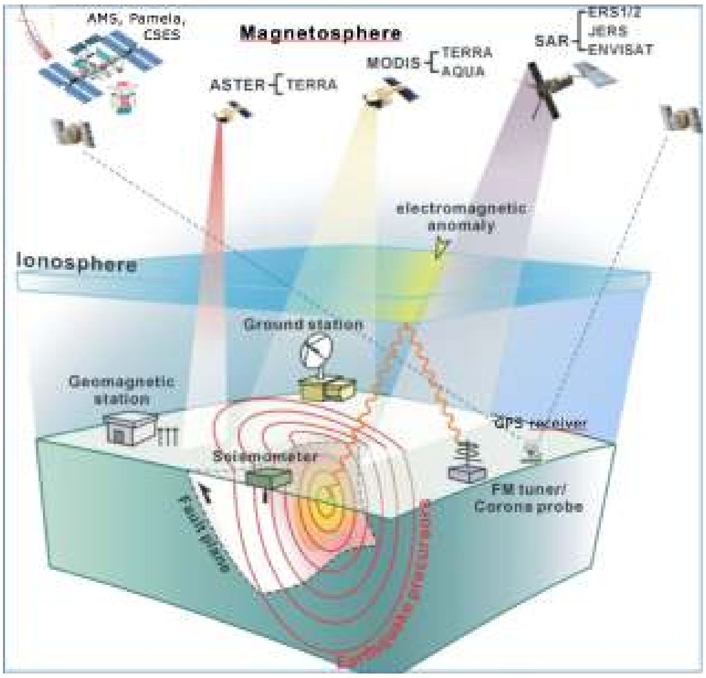


Fig. 1 - *The sketch of the concept of integrated (ground and satellite) earthquake monitoring system.*

EO by satellites provides the enormous capability of observing regional and global areas of our planet. Satellite sensors acquire a wide range and huge volumes of spatial-temporal measurements capturing- a variety of activities produced on Earth or in its interior. Meanwhile, EO provides new possibilities for scientists to investigate the earthquake behaviour by monitoring a broad range of abnormal phenomena reflected in ionosphere and ground displacement from space. This would allow us to improve our understanding of the earthquake preparation process at the global scale by observing the possible ionosphere coupling with lithosphere.

Main focus of this review is to survey the ionospheric and lower magnetospheric perturbations possibly induced by the lithosphere, identified by the analysis of ground-based and space-based data. The review describes the state of the art in the field and points out the scientific challenge to distinguish the different contributions and remove the effects coming from the outer space and man-made technologies. In Section 2 examples of geospace anomalies likely related to earthquakes are given. The list cannot be exhaustive but it is given to provide a sufficient "taste" of the importance of satellite EO for detecting seismic precursors. Section 3 deals with geospace anomalies mainly detected by ground based observations indicating the existence of the lithosphere-geospace link. Geospace signatures of other origins (man-made, atmosphere, outer-space) that can mask the solid earth-geospace interaction are faced in Section 4. Finally a discussion and some remarks are given in Section 5.

2. Geospace anomalies by EO satellites

Lower Magnetosphere

The study of the trapped particles belts stability is quite important, because these systems are very sensitive to energy releases from the space direction (Solar-terrestrial interaction, cosmic rays) and likely from the planet (lithosphere, atmosphere). The physics of the Van Allen Belts (VAB) trapping is well understood. Electrons with energies up to tens of MeV are stably trapped, forming a pair of belts (and sometimes more than two, see *Shprits et al*., 2013). A dominating source of instability for the inner electron belt is the Whistler-induced Electron Precipitation (WEP) (*Rodger et al*., 2003), where the resonant interaction between the gyrating electrons and circularly polarized VLF waves traveling along the magnetic field lines forces trapped electrons into the loss cone within a time scale of tens of seconds for 3-30 kHz VLF wave frequencies. The electrons precipitations are detected as sudden (few to tens of seconds) increases in the electron flux (electron bursts) by those satellites with orbits below the belts. The solar activity is one dominating cause for belts instability, whose effects should be carefully removed, in order to study possible effects of planetary energy release (lithosphere, atmosphere). Radiation belt electron precipitations were also produced in man-made experiments with ground VLF transmitters (*Sauvaud et al.* 2008).

Correlations between earthquakes and bursts of MeV electrons precipitating from the VAB were often reported in the past literature. Experimental data on relatively high-energy charged particle fluxes, obtained from various near-Earth space experiments (MIR orbital station, METEOR-3, GAMMA, SAMPEX, NINA and ARINA satellites) were processed and analyzed by Aleksandrin et al. (2003); a 2 to 5 h precursor effect resulted. A re-analysis of the SAMPEX database confirms a 4 h precursor effect (*Sgrigna et al*., 2005). Similar results have been recently found using data acquired by the NOAA-15 satellite during a period of 11 years (*Fidani and Battiston*, 2008).

Statistical evidences for a coupling mechanism between lithosphere and magnetosphere are reported in *Battiston and Vitale* (2012), in which correlations between the precipitation of low energy electrons (E>0.3 MeV) and earthquakes (above 5 Richter magnitude) have also been studied with data collected by the NOAA POES 15,16,17 and 18 satellites during a period of 13 years. The analysis shows that electron bursts follow earthquakes with a time delay of 1.25±0.25 hours: at these energies (300keV), the total drift period around the earth is of 4 hours and the absolute correlation timing depends on the burst being detected by the satellite, before or after having traveled one entire orbit. Fig. 2 shows that a few MeV electrons bursts are reported to have a correlation peak few (2-4) hours before large earthquakes: these bursts might be potentially a very interesting tool for “imminent” earthquake forecast.

Analogous results have been found with AGILE satellite data (*Tavani et al*., 2014). Fig. 3 shows Distribution of M5+ earthquakes in the L-shell vs. time diagram accessible by the AGILE satellite in the period August 5 - September 3, 2007. These results underline that operating with a satellite constellation would allow a much more effective coverage improving the correlation efficiency, currently at the level of 5-10%. Similarly, some new strategies must be studied to extract a useful spatial resolution on the position of the future epicenter, for example by applying a back-tracking of L-curves from satellites down to Earth surface.

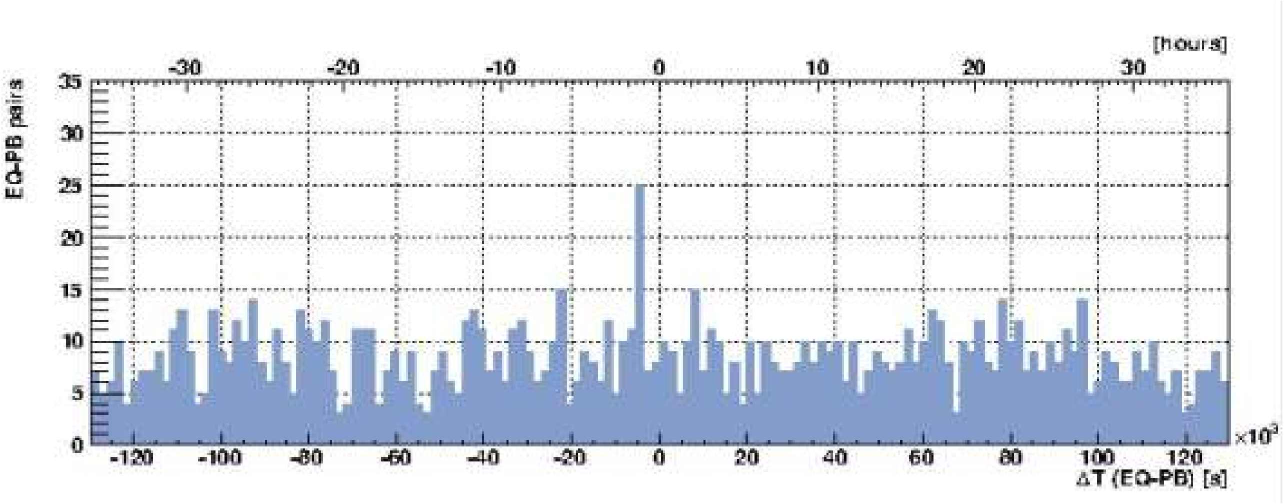


Fig. 2 - *Time Difference Distribution (Earthquake time - PB time) for M5+ seismic events and selected PB (NOAA-15,16,17-18; Battiston and Vitale, 2012).*

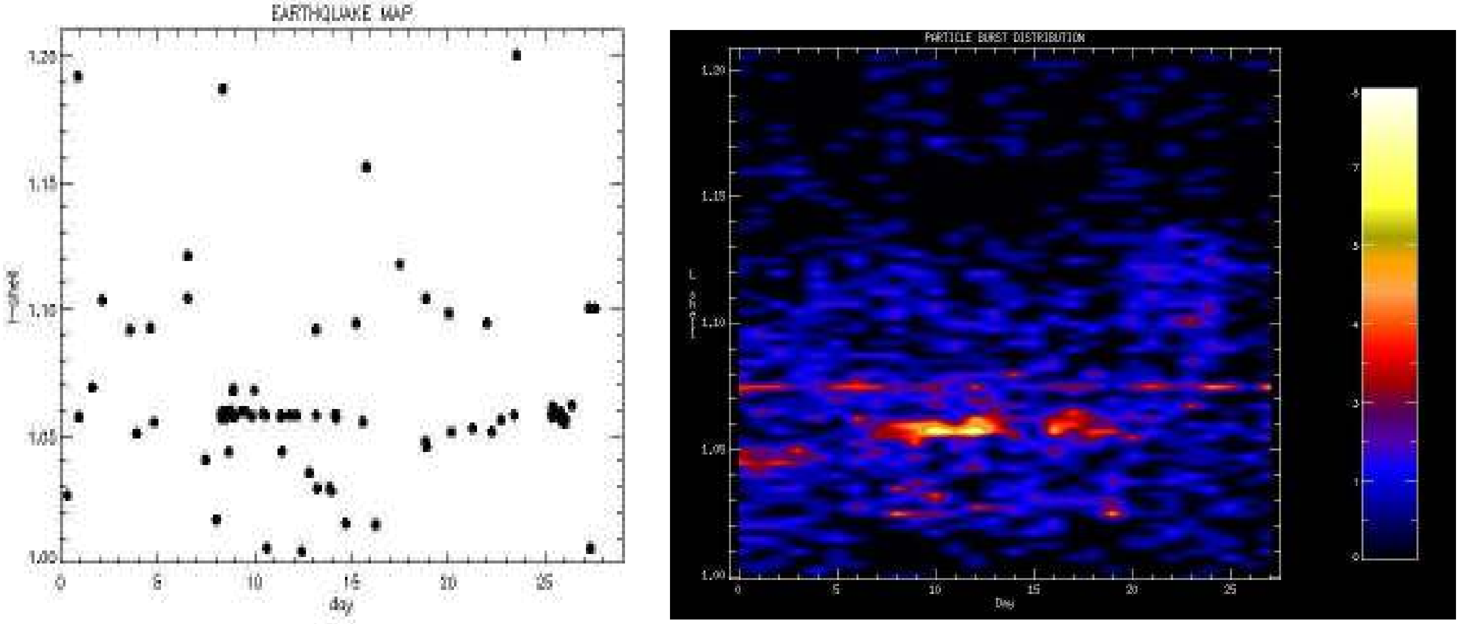
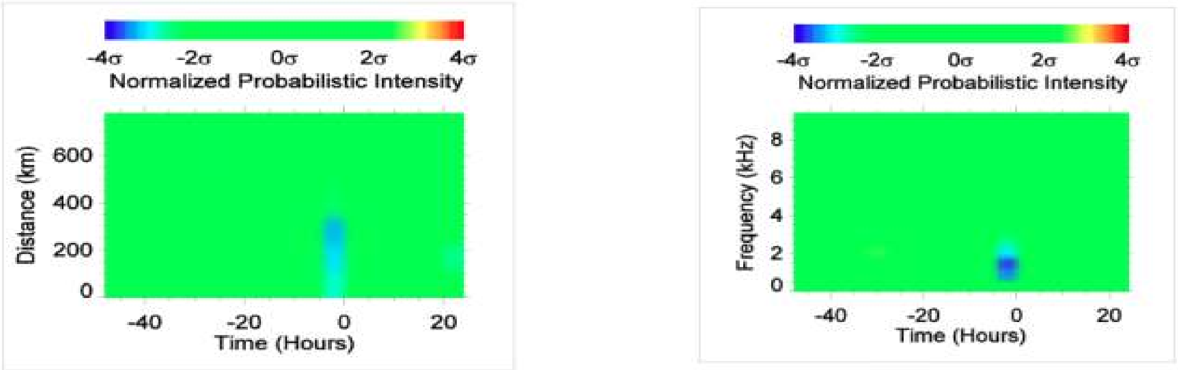


Fig. 3 (Left panel:) *Distribution of M5+ earthquakes in the L-shell vs. time diagram accessible by the AGILE satellite. The time period is August 5 - September 3, 2007.* (Right panel:) *an example of preliminary data on the distribution of normalized particle bursts detected by the AGILE satellite above 4 sigma during the same period of time (Tavani et al., 2014). The event enhancement is in apparent coincidence with the M8 Peru earthquake occurred on August 15, 2007.*

Ionosphere

DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) is a French micro-satellite operated by CNES and devoted to the investigation of the Earth ionosphere disturbances due to seismic and volcanic activities. Launched on June 29, 2004, it was turned off on 9 December 2010, after more than 6.5 years of scientific mission. Careful statistical studies were performed on the influence of seismic activity on the intensity of low frequency electromagnetic waves in the ionosphere, first based on the first 2.5 years survey of electromagnetic emissions (*Němec et al*., 2008), and then using the complete DEMETER data set (*Píša et al.* 2012, 2013),. Fig. 4 (right) shows that the normalized probabilistic intensity obtained from the night-time electric field data is below the “normal” level shortly (0 – 4 hours) before the shallow (depth < 40 km) M5+ earthquakes at frequencies of about 1 – 2 kHz. Clear perturbations are observed a few hours before the earthquakes, as another example of “imminent” forecast: they are real, although they are weak and so far only statistically revealed. No similar effects were observed during the day and for deeper earthquakes (*Němec et al.*, 2008). Fig. 4 (left) shows also that the spatial scale of the affected area is approximately 350 km confirming relatively well the size of the earthquake preparation zone estimated using the *Dobrovolsky et al.* (1979) formula ($r \leq 10^{0.43M}$ km, where r is the radius of the preparation zone and M is the earthquake magnitude).



2111 EQs
with M > 5.0 and d < 40 km

2111 earthquakes
with M > 5.0 and d < 40 km

Fig. 4 - *An example of a study of space-time correlation between satellite e.m. anomalies detected by DEMETER and earthquakes (Němec et al. 2008).*

It must be noted that the frequency of about 1.7 kHz, where the decrease is observed, corresponds approximately to the cut-off frequency of the first TM mode (i.e. transverse magnetic mode; EM wave lacks magnetic field component in the direction of propagation) of the Earth–ionosphere waveguide during the night time. An increase of this cut-off frequency effect would therefore necessarily lead to the decrease of the power spectral density of electric field fluctuations observed by DEMETER in the appropriate frequency range. Since this would also correspond to a decrease of the height of the ionosphere, these results would therefore indicate that the height of the ionosphere is statistically lower above the epicenters of imminent earthquakes. As the EM waves which are propagating in the Earth-ionosphere wave-guide are mainly whistlers, this means that it is not a change of their intensities but that their propagation is disturbed above the epicenters of future earthquakes.

CHAMP (CHAllenging MinisatellitePayload) is a German small satellite mission (2000-2010) managed by GFZ for geoscientific and atmospheric research and applications, providing highest quality data for the investigation of geomagnetic and gravity field. Balasis and Mandea (2007) examined, for the first time, CHAMP satellite magnetic and electron density data using a wavelet analysis technique to find out electromagnetic signatures possibly related to the 26/12/2004 Sumatra megathrust (M9.3) earthquake. The authors conclude that, due to the complexity of the ionospheric system, further investigations are required in order to answer the question of whether a series of anomalous signals (“events”) found in the data can be associated with the earthquake and to assign their possible usefulness with respect to earthquake development. They strongly envisaged further statistical analysis of CHAMP satellite magnetic and electron density data using highly sensitive signal processing techniques based on linear (wavelet transforms) and nonlinear analysis methods (e.g., Tsallis entropy, Tsallis 1988).
Recently automated methods of deriving the characteristics of Ultra Low Frequency (ULF) waves in the magnetosphere have been developed (Balasis et al., 2012, 2013a) and applied to CHAMP data. In Figure 5 we see some events automatically detected. Moreover, in the same papers a useful software platform based on a combination of wavelet transforms and artificial neural networks has been developed to monitor the wave evolution from the outer boundaries of Earth’s magnetosphere through the topside ionosphere down to the surface. The time-frequency analysis tool can be used to detect subtle changes in the spectral properties of the space-borne electromagnetic data that are neither related to magnetospheric signals and ionospheric plasma bubbles (see for instance Stolle et al., 2006) nor to

main and lithospheric geomagnetic field anomalies but are of seismogenic origin. Additionally, complexity information measures like entropies (including non-extensive Tsallis entropy; Tsallis, 1988) and the Hurst exponent (see for instance the recent review by Balasis et al., 2013b and Balasis et al., 2006, 2008, 2009 and Eftaxias et al., 2009, 2010) can be used to discriminate between normal and abnormal periods in the data, which can be related to quiescence and earthquake event epochs.

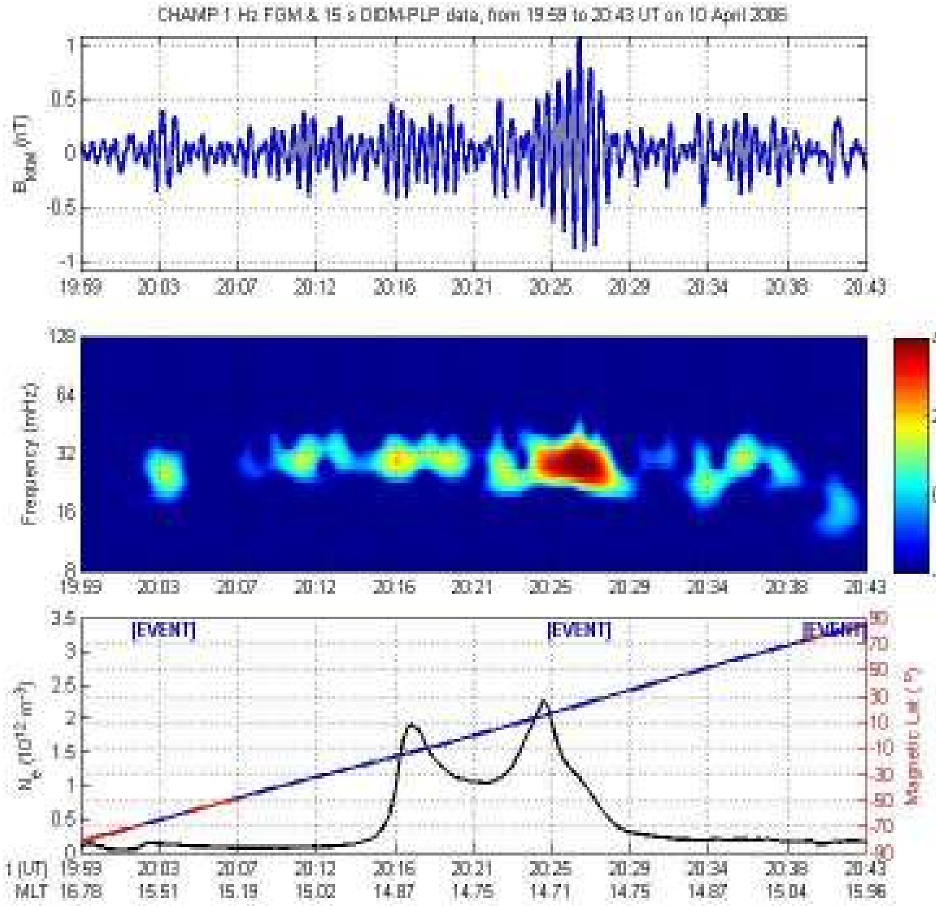


***Figure 5**. CHAMP track with a magnetospheric ULF Pc3 wave event (frequency range of Pc3 pulsations: 20-100 mHz). From top to bottom, CHAMP filtered magnetic field time series, its corresponding wavelet power spectrum and the combined planar Langmuir probe (PLP) data / magnetic latitude plot, all with respect to time (UT) for a satellite pass from 19:59 to 20:43 UT on 10 April 2006. The bottom row provides additional information about the satellite's magnetic local time (MLT) position. The wave activity is marked with '[EVENT]' (in blue) flags in the lower panel. The latitudes where the ULF activity is observed are also given in blue in the same panel.*

Such studies will be important in view of the recently launched ESA's Swarm mission. Swarm is a constellation of three satellites, providing precise simultaneous measurements of the magnetic field over different regions of the Earth. Two of these 3 satellites are at a quite short distance, namely 150 km, in a lower orbit. This fact will allow us to observe the small space-scale variations of the geomagnetic field, with particular attention to the lithospheric field. The past satellites were single satellite systems and so, before the launch of Swarm, we could observe just the large space-scale geomagnetic field. Swarm can, thus, offer a new, exciting and unique opportunity for distinguishing seismogenic emissions from non-seismic external (ionospheric and / or magnetospheric) electromagnetic signals, providing that proper analysis tools will be applied in order to extract the wealth of information that underlies the data.

Neutral atmosphere

The process of earthquake preparation is accompanied by the exchanges of mass and energy, which can change the energy budget in the earth-atmosphere system over the seismogenic zone. Many types of infrared physics parameters can be used to identify possible pre-earthquake anomalies. Brightness Temperature (BT), Outgoing Longwave Radiation (OLR), Surface Latent Heat Flux (SLHF), atmospheric temperature at different altitudes, could change before earthquakes and all these parameters are regularly recorded by satellite at regional and global scales. BT corresponds to the temperature of a black body that emits the same intensity as measured. OLR is the emission of the terrestrial radiation from the top of the earth's atmosphere to the space; it is controlled by the temperature of the earth and the atmosphere above it, in particular, by the water vapor and the clouds. SLHF describes the heat released by phase changes and depends on meteorological parameters such as surface temperature, relative humidity, wind speed, etcetera. If the detected IR anomaly is a real change of temperature or just an emission in the IR frequency band is debated. A recent paper (Piroddi et al. 2014) shows a clear thermal IR anomaly preceding the 2009 L'Aquila (Italy) earthquake. The authors proposes a mechanism the generation of electric currents in the lithospheric rocks when they are under stress and a consequent IR irradiation with no actual temperature change (*Freund et al.*, 2007; *Freund*, 2011). However, some recent works found SLHF (*Qin et al.*, 2011) and surface temperature anomalies (*Qin et al.*, 2012) before some large earthquakes, so supporting the possibility for some actual change of temperature too. Fig. 6 shows a comparison between skin temperature deduced from satellite and ground temperature from a meteorological station for the 2012 Emilia earthquake (*Qin et al.*, 2012): a thermal anomaly is seen also in the ground station, although its value is much less than the anomaly detected by the satellite.

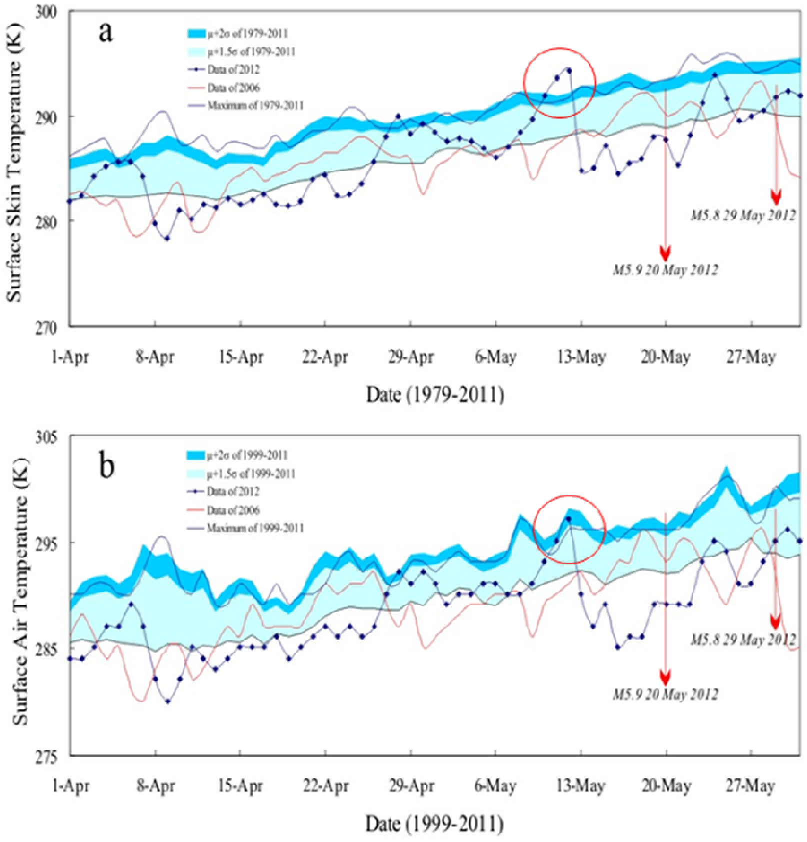


Fig. 6- *Surface skin temperature (above) detected by satellite and surface air temperature (below) measured by a ground meteorological station in the area above Emilia major Earthquakes on 20 and 29 May 2012.*

Particular techniques must be applied to identify the anomalous signal in the thermal IR data. For instance, *Tramutoli* (2007) proposes some Robust Satellite techniques that take into proper account the past behavior of the signal under investigation.

An interesting although controversial study concerns the earthquake clouds, suggesting their formation because of some local weather conditions caused by energy and particle exchanges between crust and

atmosphere that locally modify the global electric circuit during the earthquake preparation phase (e.g. *Guangmeng and Jie*, 2013; *Harrison et al.*, 2014).
Due to the relevance of the role of the atmosphere in the lithosphere-ionosphere interaction, it is greatly important in the next future to systematically study atmospheric parameter variations in the context of earthquake forecast. For example, air temperatures are available and can be quickly downloaded from the National Centers for Environmental Prediction (NCEP) Global reanalysis dataset, which is generated by assimilation with ground weather station and satellite data.

3. Geospace anomalies by ground based observations

The ionospheric anomalies can be registered up to one month in advance (middle – term precursors) as well as with lead times from some hours up to one day (short-term precursors) (*Gufeld and Gusev*, 1998). Various parameters to detect the ionospheric anomalies can be monitored by ground based equipments such as ionosondes and GPS receivers: F2-layer critical frequency (foF2), Total Electron Content(TEC), electron temperature(Te), at F2-layer heights, and LF radio signals (see e.g. *Ondoh,* 2009; *Trigunait et al.,* 2004; *Hobara and Parrot*, 2005; *Liu et al.*, 2006; *Maekawa et al.*, 2006; *Ondoh and Hayakawa*, 2006; *Dabas et al.*, 2007).
The degree of reliability of the revealed associations is different in the diverse analyses. *Hobara and Parrot* (2005) analysed the foF2 variations recorded by the ionosonde stations in the Asian longitudinal sector to study the isolated and very powerful M8.3 Hachinohe earthquake occurred on 1968. The foF2 decrease was registered in the vicinity of the epicenter and not further than 1500 km apart: a pronounced ionospheric reaction to the event was detected. *Liu et al.* (2006) have analyzed the association between foF2 and 184 earthquakes with M5+ which took place during the period 1994-1999 in the Taiwan area. They observed a decrease in foF2 by > 25% within 5 days before the earthquakes. As expected, the effect increases with the earthquake magnitude but decreases with the distance from the epicenter to the ionospheric station: in practice, only the M5.4+ earthquakes and within the distance of 150 km have a significant chance to result in a pronounced foF2 decrease.

Also the sporadic E layer (Es), occurrence was found interesting: its occurrence probability and the frequency (foEs) increase in the semi-transparency range have been considered by *Silina et al.* (2001). *Ondoh and Hayakawa* (2006) observed an anomalous foEs increase together with unusual ELF radio noises in the daytime on January 15, 1995 at Shigaraki and Kokubunji of epicentral distances within 500 Km from the Hyogo-ken Nambu earthquake (M=7.2) occurred later in the same day. An analogous investigation has been carried out by searching for anomalous variations of Es and F2 layers parameters from Rome (Italy) ionosonde data occurring before Italian earthquakes (1979-2009) with magnitudes M ranged between 5.5 and 6 (*Perrone et al.*, 2010). The results are similar to those obtained for the Japanese earthquakes but large lead times for the precursor occurrence (up to 34 days for M=5.8–5.9) tells about a longer preparation period.

On May 12th 2008, the devastating M8 Wenchuan earthquake struck the eastern edge of the Tibetan plateau, collapsing buildings and killing thousands people in major cities aligned along the western Sichuan basin in China. The energy released by the earthquake was so huge that the tremors could be felt several thousand kilometers away from the epicenter. By means of a network of 58 ground-based GPS receivers in China and nearby, *Zhao et al.* (2008) estimated the Total Electron Content (TEC). On one hand, Fig. 7 (left) shows that, on 3 May the ionosphere was disturbed at a global scale because of a geomagnetic storm during the period 00:00–10:00 UT, so the large enhancement in TEC around the East Asian region was not actually associated with the earthquake. On the other hand, Fig. 7 (right) shows the case of May 9th, i.e. 3 days prior to the main shock: the anomalous enhancement over southern China is now likely a seismic precursor because there was no magnetic activity. The presence of its conjugate point in the southern hemisphere, confirms a characteristics trait of an ionospheric coupled to VAB phenomenology (*Zhao et al.*, 2008).

Another ionospheric indicator has been recently considered in looking for ionosphere-lithosphere coupling. The ionosphere may exhibit plasma irregularities of different sizes. The effects of these irregularities on the propagation of radio waves may be treated by diffraction and refraction theory. As a wave travels through a heterogeneous and anisotropic medium, it will accumulate changes of amplitude and phase, the so called ionospheric scintillations. Some preliminary results (e.g. *Kandalyan and Alquran*, 2010) indicate that the correlation between the occurrence of strong earthquakes and ionospheric scintillation is worth being investigated.

The above results highlight that proper data selection and caution are needed to better discriminate between real seismo-ionospheric anomalies, outer space causes, and even artifacts (*He et al.*, 2014) revealing that sometime the *coversphere* (vegetation, soil state and composition, etc.) could contrast the lithosphere-atmosphere-ionosphere coupling.

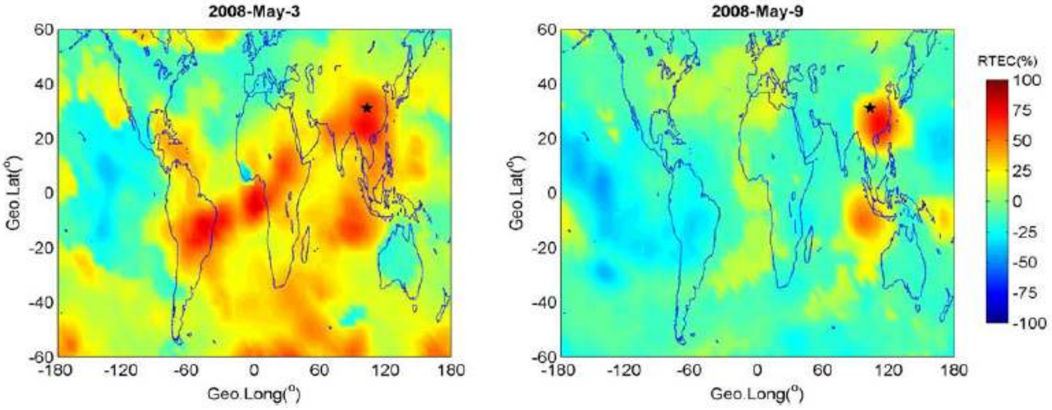


Fig. 7- *Two-dimensional maps for relative differential TEC (RTEC) obtained from superposition of the GIM maps during interval 00:00–10:00 UT on 3 (storm disturbed) and 9 May (not disturbed) 2008, respectively. The latter is clearly more related to a possible seismic effect to ionosphere (Zhao et al., 2008).*

Geomagnetic field

The Information Theory (*Shannon* 1948) can be applied with success to satellite geomagnetic data for extracting eventual anomalies. This technique has high time-space resolution using a preliminary wavelet analysis (e.g. see *Balasis and Mandea*, 2007 for wavelets applied to satellite geomagnetic data) in order to detect shorter-wavelength anomalies. *Cianchini et al.* (2009) computed the wavelet entropy content of CHAMP satellite magnetic data, taken over periods including the times of two large earthquakes occurred in the Sumatra region, revealing an anomalous period some minutes before the largest earthquake occurrence.

More recently, *Cianchini et al.* (2012) have analysed the components of the geomagnetic field variations, measured at the ground based magnetic observatory of L'Aquila (Central Italy), introducing the Transfer Function Entropy. This approach allowed these authors to detect specific anomalous periods in the magnetic data: this analysis pointed out clear temporal burst regimes of a few distinct harmonics corresponding to lower crust skin depths and preceding the main shock of the seismic sequence. The results obtained by means of other more conventional techniques applied to magnetic observatory data have been strongly criticized (e.g. *Masci and Di Persio*, 2012).

Integration with ground seismic data

Earthquakes can be in principle considered as elements of a statistical point process. Thus all tools of analysis for this kind of process are worth applying to time/space distributions of earthquakes. An empirical law is well known in seismology: the Gutenberg-Richter law (*Gutenberg and Richter*, 1944).

It provides a statistical frame to represent all earthquakes occurred in given area (or even worldwide) and time as a simple log-linear function relating the number *N* of earthquakes with magnitude equal to or greater than *M*, and the magnitude itself: $Log\ N = a - bM$, where *a* and *b* are two constant parameters. It has always been recognized the importance of the *b*-value for understanding the state of stress in a certain seismic area. Recently *De Santis et al.* (2011) have shown that the *b*-value is directly connected with the Shannon entropy of earthquakes. Seismic entropy aims at characterizing the past and present seismicity, extracted from the Catalogs, affecting a seismogenic area and is a central concept of Geosystemics (*De Santis*, 2009, 2014).

Interesting results have been obtained by the use of the so-called Accelerated Strain Release (ASR) approach (*Bufe and Varnes*, 1993) that consists in fitting the cumulative value of a specific quantity related to the magnitude of each foreshock, e.g. the scalar Benioff strain, $s(t)$, with a power law in the time to failure t_f, i.e. the theoretic time of occurrence of the sequence main shock (e.g. *De Santis et al.*, 2010): $s(t)=A+B(t_f-t)^m$, where A, B and m are appropriate empirical constants. The fitting process gives as an outcome the time t_f together with the expected magnitude, which is related to either A or B. Although this approach has been strongly criticized (*Hardebeck et al.*, 2008), *De Santis et al.* (2010) applied this approach to the 2009 L'Aquila (Central Italy) seismic sequence as a means to highlight its intrinsic chaotic features. In practice, the fitting process is performed day-by-day and the results obtained are investigated for their behavior in time. A stable outcome in time of the different parameters can be a reliable indication for an impending earthquake (*De Santis et al*., 2010 and 2011).

A systematic research in the worldwide seismic catalogs, together with simultaneous remote sensing analysis over the same area, would disclose the local to regional chaotic characteristics of the seismic sequences in order to better understand the earthquake phenomenon from the classic to the new systemic point of view.

4. Anthropogenic, atmospheric and outer-space effects

Most of the geospace anomalies are not of lithospheric origin, they are rather due to human activities, or induced by the atmosphere , or can originate from the outer space. Below we describe them with some detail.

Perturbations from Power Lines

PLHR's (Power Line Harmonic Radiation) are the ELF and VLF waves emitted by the power lines at the harmonics of 50 Hz (or 60 Hz in USA). But these lines are not alone to radiate harmonics. Direct observations of PLHR by satellites are rather rare (*Parrot*, 1995) and shown in few papers (indirect effects are more often reported). Non linear interactions between electrons and PLHR can participate in the precipitation of electrons from the slot region in the radiation belts, on the other hand, main part of the PLHR energy dissipates in the lower ionosphere and modifies the ionospheric currents. This problem now requires serious attention because the electrical power consumption is always increasing in the world.

A systematic research on PLHR's has been performed using all burst DEMETER data. From VLF spectrograms, it is easy to find at the satellite altitude, the spectral lines separated by 50 Hz in Europe and by 60 Hz in USA (*Němec et al.*, 2007 and references therein). Examples of PLHR's have been published by *Parrot and Němec* (2009) and the Fig. 8 shows one of these events.

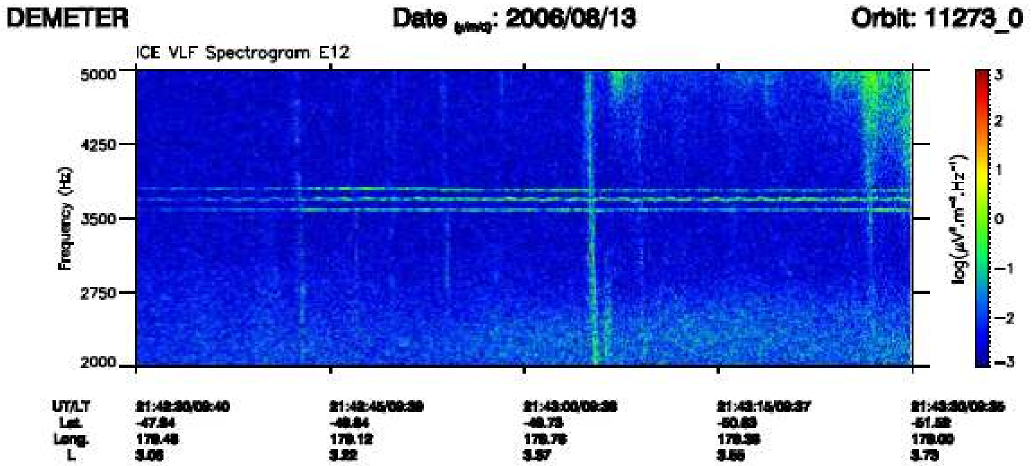


Fig. 8: *VLF spectrogram of an electric field component recorded on 13 August 2006 during one minute between 21:42:30 and 21:43:30 UT. The frequency range is 2 -5 kHz. The intensity is color-coded according to the scale on the right. A set of three lines can be observed just above 3.5 kHz. The frequencies of lines are close to 3603, 3711, and 3808 Hz, which means that the frequency interval is approximately equal to 100 Hz. There is no apparent frequency shift of the lines during the observation. The event was measured close to the New Zealand and from 21:41:30 UT until 21:46:00 UT when the satellite stops the registration at high latitudes. Relatively thin lines forming the event and frequency spacing close to the multiple of base power system frequency (50 Hz at New Zealand) represent a good indication that the event is caused by PLHR.*

Perturbations from VLF Transmitters

At VLF frequencies between 10 and 20 kHz, the ground based transmitters are used for radio navigation and communications. Their ionospheric perturbations include: the triggering of new waves, ionospheric heating, wave electron interactions, and particle precipitation. At HF frequencies, the broadcasting stations utilize powerful transmitters which can heat the ionosphere and change the temperature and the density. All these wave dissipations in the ionosphere could participate to the global warming of the Earth because the change in global temperature increases the number of natural lightning discharges in the atmosphere. Then the supplementary lightning discharges produce more magnetospheric whistlers which could produce heating and ionization in the lower ionosphere.

The ground-based VLF transmitters are mainly used for communications by the army. They emit at fixed frequencies and their waves are propagated and bouncing in the Earth-ionosphere waveguide. But the ionosphere is not regular and these waves can also cross the ionosphere and be observed by a satellite. DEMETER has shown that the most powerful transmitter NWC in Australia can perturb and heat the ionosphere on a vast scale. The Fig. 9 shows an example of these ionospheric modifications which are observed at the satellite altitude. The waves, which cross the ionosphere and propagate in the opposite hemisphere, can also perturb the particles of the radiation belts due to wave-particle interaction as it has been studied by *Sauvaud et al*. (2008).

Furthermore, it is a feedback mechanism because two different processes could be involved. First, lightning is a source of NOx, and NOx affects the concentration of ozone in the atmosphere which contributes to the greenhouse effect. Second, precipitation of energetic electrons by man-made waves may trigger other lightning discharges. It explains the importance of the study of such man-made waves (*Parrot and Zaslavski*, 1996).

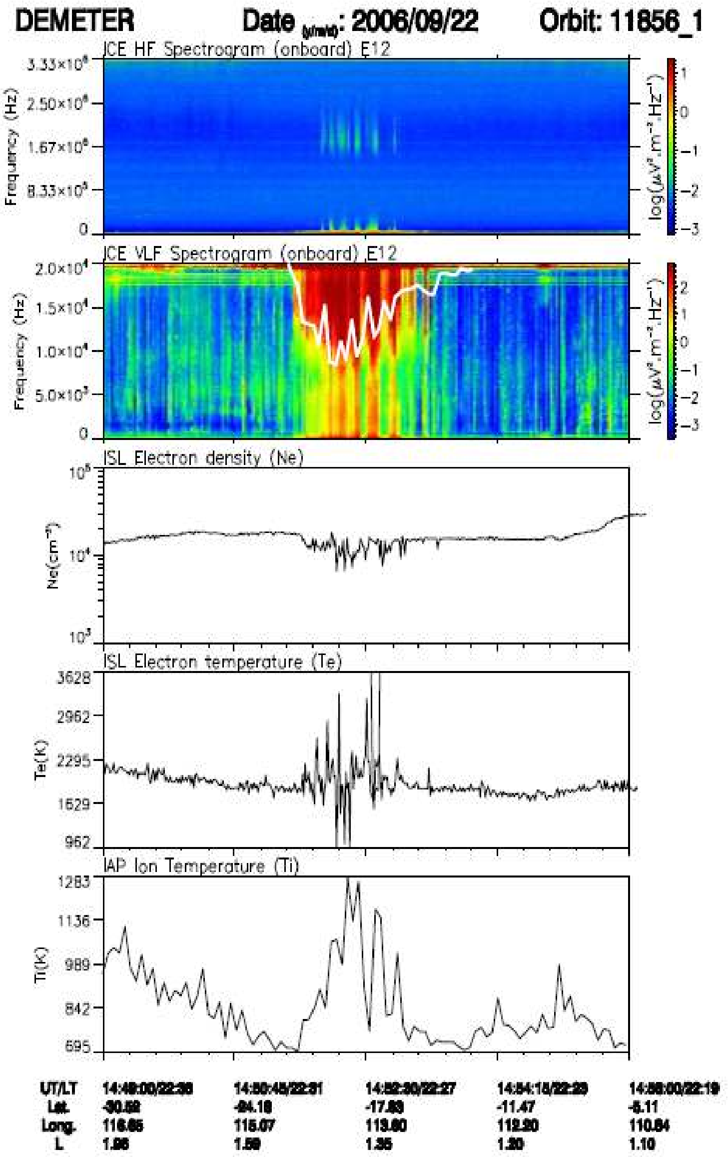


Fig. 9: *Data recorded on September 22, 2006 between 14.49.00 and 14.56.00 UT. From the top to the bottom the panels show: - the HF spectrogram of an electric component up to 3.33 MHz, - the VLF spectrogram of the same component up to 20 kHz (the white line represents the lower hybrid frequency), - the electron density, - the electron temperature, and – the ion temperature as function of the time. A large perturbation is observed in the North of the transmitter NWC (21°47'S, 114°09'E).*

Ionospheric perturbations driven by the outer space

The ionospheric perturbations from above are due to other sources, such as solar activity, acoustic gravity waves, travelling ionospheric disturbances, plasma dynamics, and large meteorological phenomena. In particular the solar activity induces magnetic storms. On these occasions, a flow of particles (energetic electrons and ions) forming the so called *solar wind* is injected in the near-Earth's environment affecting the state of the ionosphere-atmosphere system.

At the beginning of the DEMETER satellite mission, the solar activity cycle was just at the start of its decreasing phase and the satellite has suffered very intense magnetic storms which allowed to reveal new phenomena which were not observed before. The Figure 10 shows an example of plasma bubbles close to the equator.

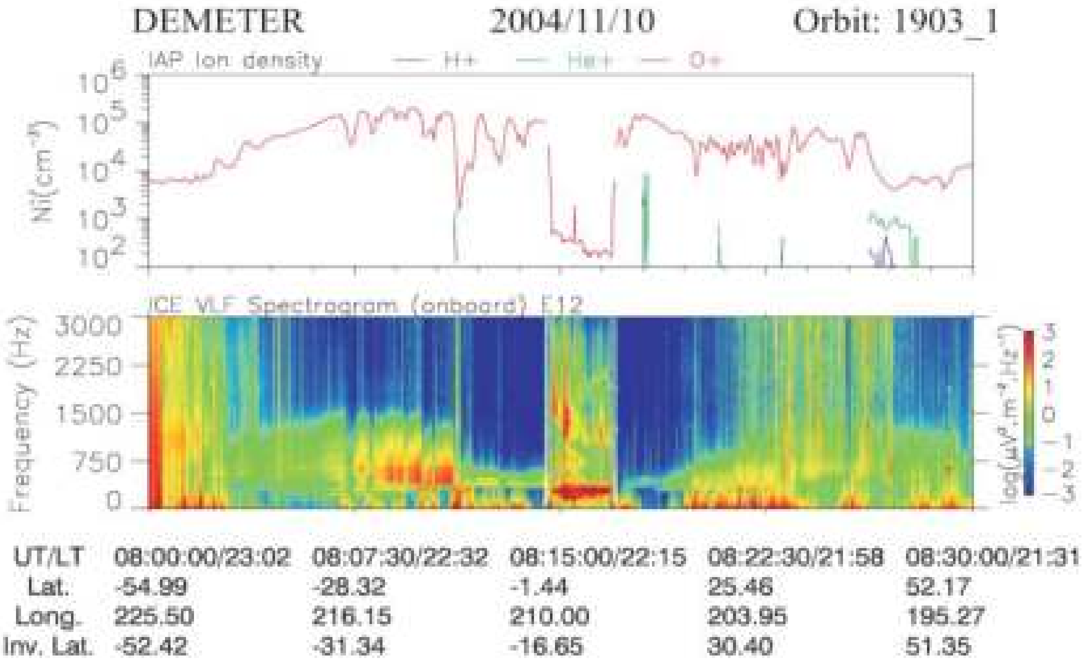


Fig. 10: *Variation of the O^+ density and spectrogram showing the night emissions on a part of the orbit 1903. O^+ is the majority ion but one can see a large decrease close to the equator which is known as plasma bubble. The plasma and wave measurement performed by DEMETER inside these bubbles during the very intense storm on 7-11 November 2004 show an important turbulence at the low hybrid frequency triggered by electromagnetic whistlers coming from the atmosphere below the satellite. This discovery reveals for the first time the coupling which could exist between the thunderstorms and the ionospheric plasma in the equatorial plasma bubbles.*

One must also pay attention to the plasma dynamics. In the equatorial and low mid-latitude ionospheric regions, the distribution of plasma is controlled by the coupled processes of plasma diffusion, **E**x**B** drifts, thermospheric neutral winds, and chemical processes. The daytime (nighttime) F region plasma is transported by a vertical upward (downward) $\boldsymbol{E} \times \boldsymbol{B}$ drift, created by interaction between the ionospheric $\boldsymbol{E}$ field and the geomagnetic $\boldsymbol{B}$ field, over the dip equator, and by field-aligned diffusions on both sides of the dip equator. This is commonly known as the Equatorial Ionospheric Anomaly (EIA).

These processes have a tendency to create a plasma distribution symmetric to the dip equator and local TEC gradients. As already stated, if TEC gradients are present, a trans-ionospheric signal propagating through them could encounter distortion of the original wave front, giving rise to a randomly modulated wave, i.e. the ionospheric scintillation. If received by specially modified GNSS multi-frequency multi-constellation receivers at ground, we are able to measure the ionospheric scintillation parameters associated with the TEC gradients.

During the equinoctial and summer months, the ionospheric scintillation induced by EIA is a daily phenomenon in the equatorial regions. It occurs mainly in the local post sunset hours (*Spogli et al.*, 2013 and references therein) and must be taken into account when investigating ionospheric/inner magnetospheric perturbations coming from below.

Fig. 11 reports the ionospheric scenario over Brazil due to the EIA derived from a GNSS network in Brazil (CIGALA/CALIBRA projects, funded by EC-FP7): on the left, the occurrence of moderate/strong amplitude scintillation (S4 index) is mapped, while on the right the corresponding standard deviation of the TEC rate of change (ROT) is shown (Spogli et al., 2013).

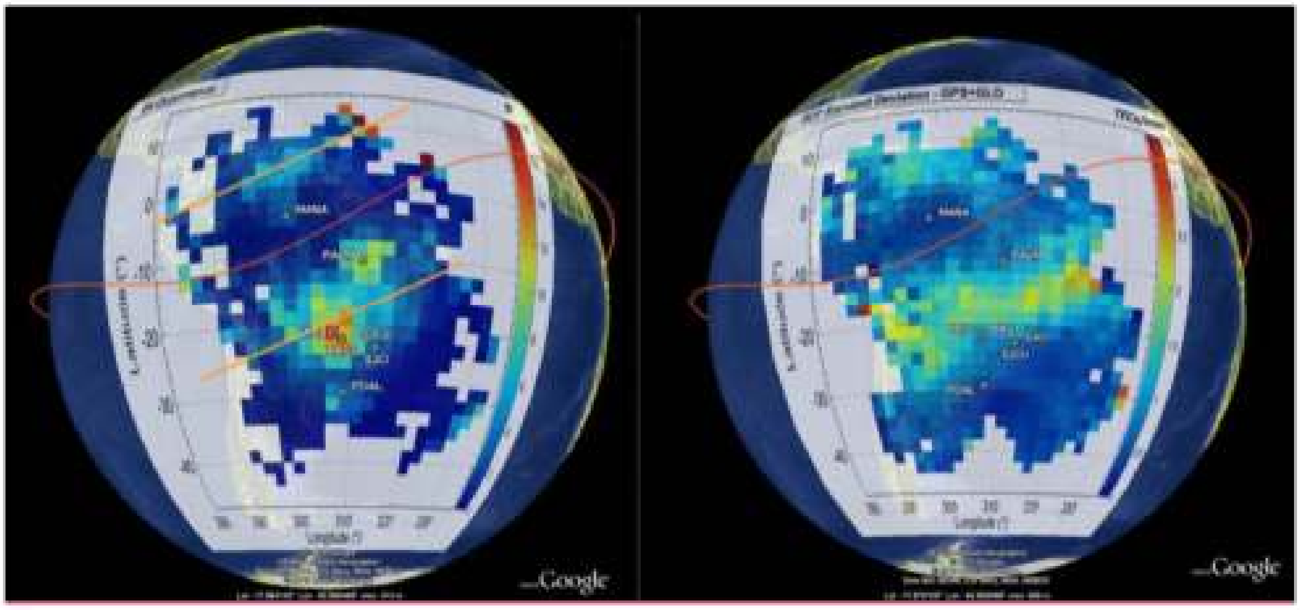


Figure 11. *(Left) Occurrence of moderate/strong amplitude scintillation (S4 index). (Right) Standard deviation of the TEC rate of change (ROT). Both these quantities identify regions where TEC gradients due to the EIA are present (Spogli et al., 2013).*

At high latitude, the formation of scintillation-driving irregularities can result from patches of plasma density the steep edges of which are unstable, so that smaller scale density structures develop along these edges. Within the auroral oval and cusp, precipitating energetic particles produce enhanced electron densities in correspondence of the auroral oval boundaries. Within the polar cap, ionospheric irregularities are associated with patches, as discrete electron density enhancements in the F layer.

The features of the scintillation patterns at high latitude is mostly characterized by the interplay between the interplanetary magnetic field (IMF) and the geomagnetic field. As an example, figure 12 shows the occurrence of moderate/strong phase scintillation above European high latitude region along year 2008 (low solar activity) as a function of the magnetic latitude and magnetic local time. Top plot is for IMF Bz positive conditions, while bottom plot is for negative conditions. Black and red curves reproduce the modeled auroral ovals (Feldstein model) for quiet (IQ=0) and moderately disturbed (IQ=3) geomagnetic conditions, respectively (extracted from *Alfonsi et al*., 2011). This shows how the orientation of the IMF influences the scintillation patterns in magnetic local time, highlighting the important role of the plasma inflow and outflow from and to the magnetosphere in the noon and midnight hours. Thus, also when high latitudes ionospheric data are considered, scintillation effects could mask other signatures (as the ones eventually due to lithosphere coupling) and should be removed.

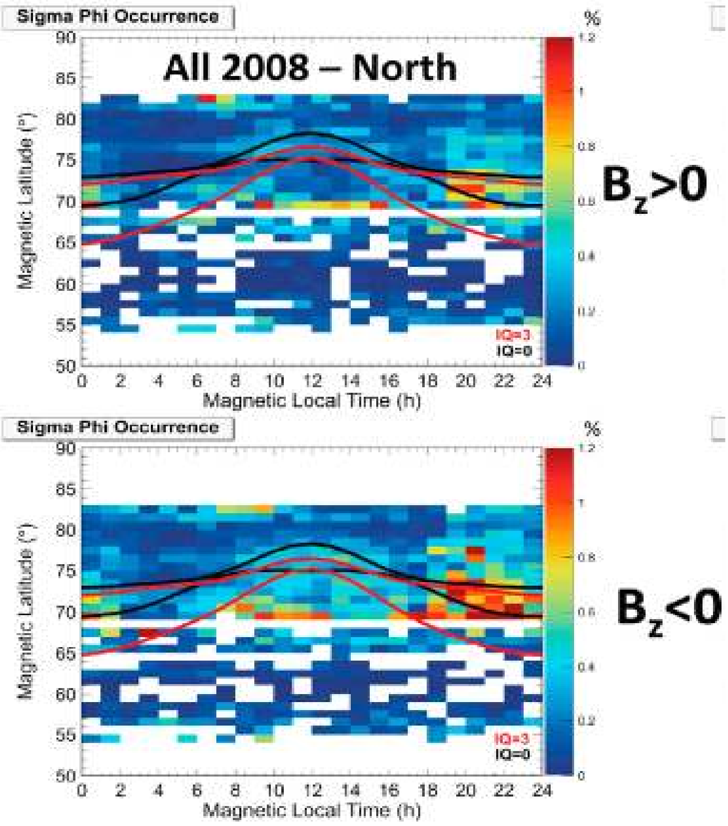


Fig. 12. *Occurrence of moderate/strong phase scintillation above European high latitude region along year 2008 (low solar activity) as a function of the magnetic latitude and magnetic local time. Top plot is for IMF Bz positive conditions, while bottom plot is for negative conditions. Black and red curves reproduce the modeled auroral ovals (Feldstein model) for quiet (IQ=0) and moderately disturbed (IQ=3) geomagnetic conditions, respectively (extracted from Alfonsi et al., 2011).*

Perturbations from the atmosphere

Atmospheric perturbations, such as thunderstorms, lightning, polar auroras, etc., are known to produce large electric fields, wave (whistler) production and particle acceleration (e.g. *MacGorman and Rust*, 1998). Our interest in wave/particle production and acceleration in the atmosphere is connected with the study of the physical processes producing high-energy phenomena. From this point of view, gamma-ray production and particle acceleration by waves are all interconnected.

An outstanding issue is the assessment of the possible correlation between wave/particle phenomena detected in the ionosphere/inner magnetosphere with large atmospheric storms and thunderstorms/lightning.

DEMETER satellite registered the electromagnetic emissions induced by the atmospheric lightning strokes and thunderstorm in all frequency ranges (*Parrot et al*., 2008a, *Parrot et al*., 2008b).

An example of particle perturbations is given in Fig. 13, which shows the simultaneous comparison of VLF spectrograms with the data of the particle detector IDP as measured by DEMETER. This allowed to reveal the precipitation of the particles in the radiation belts induced by the waves emitted by the lightning stroke which are propagated along the magnetic field lines from one hemisphere to another (*Inan et al*., 2007).

Recently, *Parrot et al*. (2013) have shown that intense thunderstorm activity (where transient luminous events are often associated) can perturb the ionospheric density as illustrated in Fig. 14.

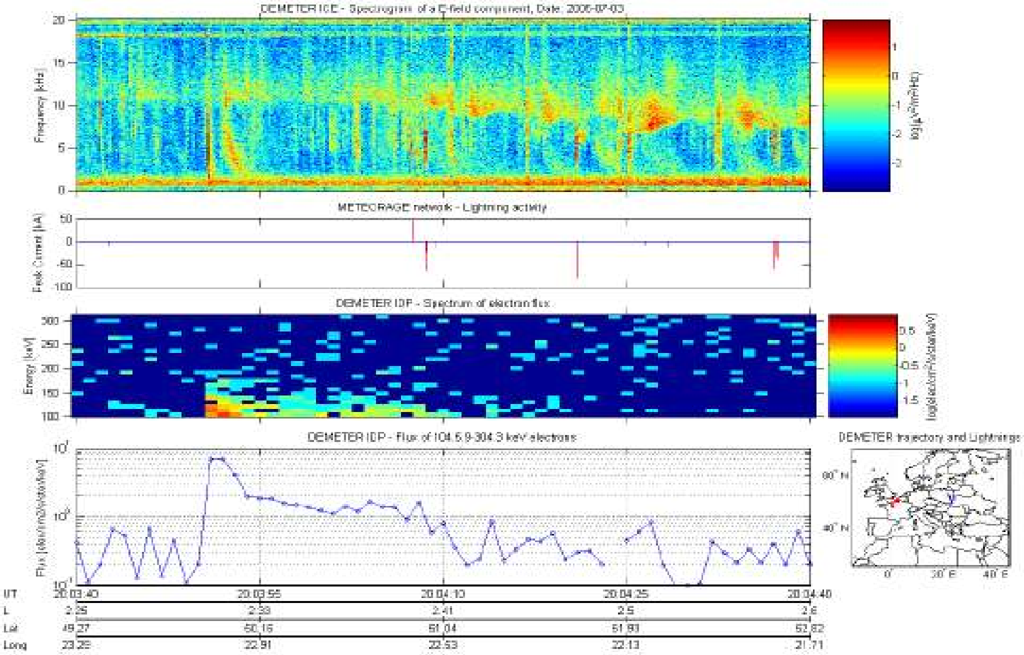


Fig. 13: *Example of particle precipitation induced by a lightning stroke. The top panel shows a spectrogram between 0 and 20 kHz obtained with an electric component. The vertical trace around 20:03:50 UT is the electromagnetic mark of a lightning stroke which occurred in the atmosphere. At the same time one can see on the two bottom panels which display the IDP data an increase of the particle flux up to 200 keV.*

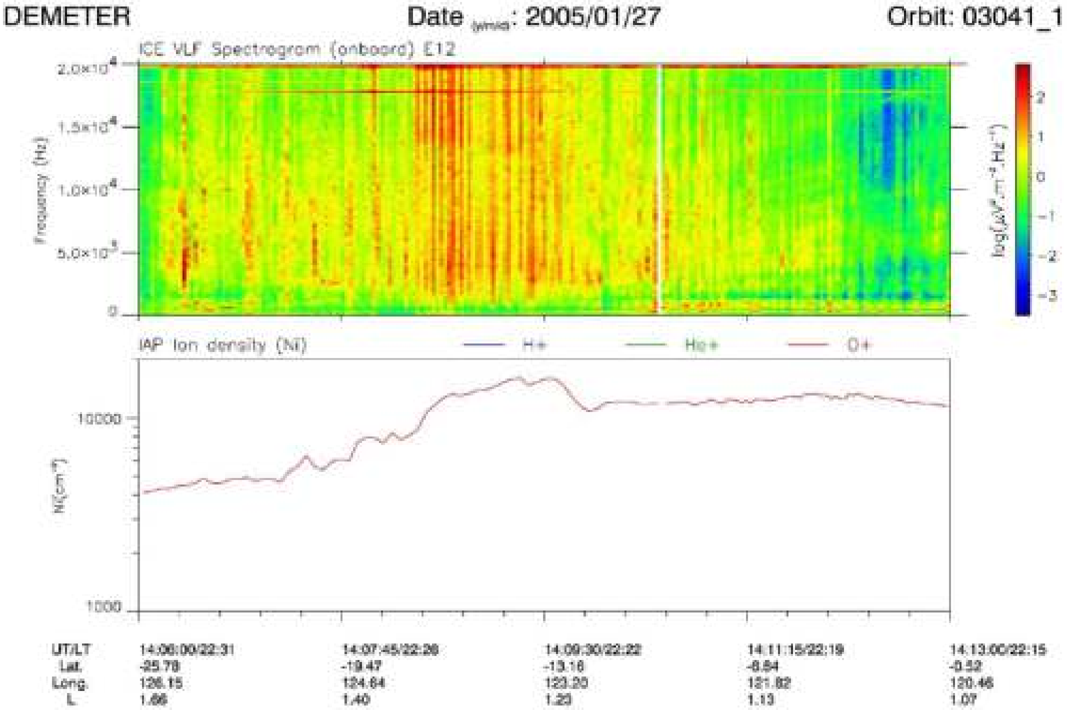


Fig. 14: *The top panel represents the spectrogram of an electric field component from 0 to 20 kHz on January 27, 2005 between 14:06:00 and 14:13:00 UT. The intensity is color-coded according to the color scale on the right. The bottom panel represents the variation of the O^+ ion density (the densities of the other ions are much lower). The information at the bottom of the figure is related to the Universal Time, the Local Time, the geographic latitude and longitude, and the McIlwain parameter L.*

5. Discussion

A general approach to the problem of identifying an ensemble of temporal quasi-synchronous and spatial organised anomalies, possibly associated with an impending earthquake, should be multi-parametric and multi-sensor, and the investigation must be multi-disciplinary.

Based on data for selected events from earthquake catalogues (time, geographical position, depth, magnitude, eventually also focal mechanism), geophysical parameters (e.g. ionospheric density, electron temperature, e.m. fields, TEC, scintillation, etc) from LEO satellites (e.g. DEMETER, CHAMP, Swarm) and ground based observations should be systematically analysed in order to detect anomalous variations. Different time intervals, e.g of about 45 days before the earthquake time and at least one week after, should be also considered to investigate different steps of the earthquake preparation phase. In all cases, even for single case study, data of the same period of time in previous years need to be considered, in order to evaluate some statistics to assess if special conditions are at play during the earthquake preparation phase (see, e.g., *Qin et al.,*2012) . The analysis can be statistical or (almost) deterministic. The former requires to see how many earthquakes are preceded by the geospace anomalies (and vice versa) under investigation and which is the time in advance (e.g. *Němec et al.*, 2008; *Píša et al.*, 2012): this kind of study aims at establishing the degree of confidence about the presence of a significant statistical correlation between lithospheric and ionospheric events. The latter focuses on some specific case studies, especially for large earthquakes to establish if the geospace anomaly is unequivocally of lithospheric origin (e.g. *Píša et al.*, 2011; *He et al.*, 2014): this latter kind of study aims at searching for the most appropriate model of lithosphere-atmosphere-ionosphere coupling.

In addition, the use of the high-energy particle data generated by satellites (e.g. NOAA satellites, AGILE) will allow a deeper investigation on possible enhancements of activity (particle bursts, flux increases) geomagnetically related with lithospheric events.

As stated in section 4, the impact of phenomena of anthropogenic, atmospheric and outer-space origin should be seriously taken into account when searching the lithospheric signatures in the geospace. A best practice to remove (or avoid) outer-space contribution in the ground based as well satellite data is a proper data selection, based on periods with low geomagnetic indices (the most useful are *Kp* and *Dst*) and at particular local time, so removing most of the aperiodic and periodic magnetic variation of external origin. When considering the data selection, it is necessary to take into account also the characteristics of the region under study such as, for example the magnetic latitude. Climatology of scintillation over a specific area indicating where and when ionospheric perturbations are more likely to occur, man-made sources of disturbances, period of solar and magnetic storms, thunderstorms should be taken into account in discussing the analysis results if they impact in the lithospheric phenomena under investigation.

Once the multi-parametric/sensor/disciplinary analysis results will be assessed, efforts should be addressed in modelling the lithosphere-atmosphere-ionosphere coupling in order to improve the knowledge on the earthquake cause-effect.

There are many theories that attempt to describe the physical processes manifesting some anomalous behaviours in some parameters before earthquakes and try to explain why these precursors may occur. A review of these processes can be found in *Pulinets and Boyarchuk* (2004), *Freund* (2011), Pulinets and Ouzounov (2011) and the references therein. A process that can explain many observations is based on the emission of a radioactive gas or metallic ions before an earthquake (e.g., *Sorokin et al.*, 2001), which may change the distribution of electric potential above the surface of the Earth and then up to the ionosphere. Penetration of the electric field to the ionosphere could induce anomalies in the ionospheric plasma density and/or conductivity, which are observed above seismic zones (see e.g., *Liu et al.*, 2006; *Kon et al.*, 2011, 2014). *Harrison et al.* (2010) proposed that radon emitted before an earthquake would increase the conductivity of air at ground level and that the ensuing increase of current in the fair weather global circuit would lower the ionosphere. However, *Freund et al.* (2009) have estimated that even if radon is coming out the ground in seismic areas, its contribution to the air conductivity is of minor importance relative to the air ionization rate which can be expected from charge carriers from the rocks. They have shown experimentally that these mobile electric charge carriers flow out of the stressed rocks (see *Freund et al.*, 2009, and references therein): at the Earth's surface, they cause extra ionization of the air molecules. It has also been shown by *Kuo et al.* (2011, 2014) that ionospheric density variations can be induced by changes of the current in the global electric circuit between the bottom of the ionosphere and the Earth's surface where electric charges associated with stressed rocks can appear. The interaction of the anomalous electric current with the geomagnetic field can even amplify the effect in the higher atmosphere (*Kuo et al.*, 2014).

As a further effect of an earthquake, it is also known that just after the occurrence of a sufficiently large event the possibility of observing the effect of the propagation of AGW in the ionosphere exists.

6. Conclusions and future directions

There is no well established model of the lithosphere-atmosphere-ionosphere coupling (e.g. *Pulinets and Boyarchuk* 2004, *Liperovsky et al.* 2008, *Freund* 2011). The main research of scientists working on it will be dedicated to find a final answer. To do that, they will investigate space-borne data from a series of low-Earth orbit (LEO) European satellites, as the recently launched Swarm constellation (Olsen and Haagmans, 2006) and the past CHAMP and DEMETER missions, along with an ongoing magnetospheric mission (ESA's Cluster four multi-spacecraft 2000-to date mission) in order to detect and identify possible signatures in magnetometer, electric field and particle detector recordings on-board these satellites of electromagnetic perturbations related to earthquakes. These perturbations can be pre-, co- or post-seismic signals and will constitute *an ensemble* of *sequentially time ordered, spatially organised and physically related anomalies*, and their correlations with seismic cycles will be assessed. The emphasis must be put on the analysis of the measurements from the three topside ionosphere missions and Cluster can be used to separate from signals originated in the magnetosphere. Ground data from seismic and geomagnetic stations, together with ionosondes, nearby a corresponding earthquake epicenter can be used, whenever a nearby ground station exists, in order to compare them with the satellite observations. The rich datasets of CHAMP (2000-2010) and DEMETER (2004-2010) can be used for statistical analyses of past earthquake events, while Swarm constellation of three satellites will serve for the study of seismic events after its launch (22 November 2013), as well as the next satellite CSES (Chinese Seismo-Electromagnetic Satellite), specifically designed for finding em signatures related to earthquakes (Shen et al., 2011) and to be launched in 2016. Thermal IR data from other satellites (eg. EUMETSAT consortium etc.) will provide an integrated dataset to be included in any interdisciplinary study of lithosphere-atmosphere-ionosphere coupling in the search of the best physical model explaining the available ground and satellite based observations.

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