Analysis of sub-ionospheric transmitter signal behaviours above L'Aquila region

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Abstract: We analyze the sub-ionospheric transmitter signals observed above L'Aquila by the electric field ICE experiment onboard the DEMETER micro-satellite. We consider the variation of the intensity level of the DFY transmitter station (Germany) during the occurrence of the L'Aquila earthquakes on April, 06th, 2009. We review the major methods based on the investigation of the ICE dynamic spectrum and the role of the time and the frequency profiles. We show that the drop of the German transmitter signal occurs nearly one week before the L'Aquila earthquakes. The origin of the decrease in the VLF transmitter intensity level is probably due to a lithospheric generation mechanism which indirectly disturbs the ionosphere. We discuss the behavior of the VLF sub-ionospheric transmitter signal and the models which might explain the origin of the transmitter signal attenuation above seismic regions.

1. Introduction

The seismo-electromagnetic effects are the electric and magnetic perturbations caused by natural geophysical activity such as earthquakes and volcanic eruptions. It includes: electromagnetic emissions in a large frequency range, perturbations of ionospheric layers, anomalies on the records of VLF transmitter signals, and night airglow observations (Parrot, 1995).

1.1. Ionospheric disturbances over the seismic regions

One important aspect of these seismic researches is the analysis of the ionospheric disturbances observed principally over the seismic regions. EQ precursory signatures appear not only in the lithosphere, but also in the atmosphere and ionosphere. Investigations are based on the analysis of radio signals, recorded by ground-based stations, associated to VLF (3–30 kHz) and LF (30–300 kHz) frequency bands. The original idea has been proposed by Gokhberg et al. (1989). The authors suggested the use of anomalies in the Earth-ionosphere waveguide propagation of VLF navigation signals for a short term earthquake prediction. The principal studies showed anomalies (amplitude and/or phase) in the radio signal few days (from 3 days to 10 days) before the occurrence of large earthquakes with a magnitude more than 5.5 in the case of VLF (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Yamauchi et al., 2007) and LF bands (Biagi et al., 2001, 2004). The conclusions of these authors are that the ionospheric D- and E-layers are affected by EQs occurrence. Recently Onishi et al. (2011) reported a detailed statistical study of the plasma waves observed by the DEMETER satellite over the Sichuan region during a period of 20 days encompassing the large earthquake of magnitude M = 7.9 that occurred on 12 May 2008. The authors suggested a statistical method to process and analyze plasma wave data and assist in detecting possible earthquake precursors among larger irregular disturbances arising from the natural variability of the ionized environment of the Earth. The initial results of this study show a deviation of the power spectrum of electrostatic turbulence in the epicentre zone about 6 days prior to the earthquake. However Onishi et al. (2011) concluded that the enhancement of electrostatic turbulence is associated with magnetospheric processes rather than with pre-seismic activity.

1.2. Sub-ionospheric transmitter signals over the seismic regions

The DEMETER micro-satellite was devoted to the study of electromagnetic pre-seismic emissions using a series of experiments that provide a more complete view of these phenomena (Parrot et al. 2006). The use of electric and magnetic field measurements on board the DEMETER micro-satellite have demonstrated that the intensity levels of transmitter signals decrease a few days before a seismic event occurrence (Molchanov et al. 2006). The authors estimated the variations in the VLF signals emitted by transmitters in Australia, France, Germany, and Japan. These showed drops in their VLF signals a few days before the occurrence of large earthquakes (magnitudes >5.5) in Europe and in Asia. Later, several investigations (Rozhnoi et al. 2007, Boudjada et al. 2008, Muto et al. 2008, Slominska et al., 2008, Rozhnoi et al. 2009, Akhoondzadeh et al., 2010, Boudjada et al., 2010) confirmed the finding of Molchanov et al. (2006). The influence of geomagnetic and also solar activities has been taken into consideration. Hence parameters, like the Kp-index, Ap-index, Dst-index and the sunspot numbers, are analysed with the aim to separate ionospheric anomalies that are associated with earthquakes from others that are principally linked to geomagnetic activity. In general, the selected earthquake events are analyzed during periods of relatively quiet geomagnetic activity. Rozhnoi et al. (2007) suggested that the effects of geomagnetic activity (described by the Dst-index) can be neglected, because such effects were absent in VLF transmitter signals in the Hawaii islands and in Australia for Japanese seismic events. Boudjada et al. (2012) considered four transmitter signals emitted by stations in Europe (France, FTU, 18.3 kHz; Germany, DFY, 16.58 kHz), Asia (Japan, JP, 17.8 kHz) and Australia (Australia, NWC, 19.8 kHz). Authors studied the variations of these VLF signals, taking into consideration: the signal-to-noise ratio, sunspots, and the geomagnetic activity. Boudjada et al. (2012) showed that the degree of correlation in periods of high geomagnetic and solar activities is, on average, about 40%. Such effects can be fully neglected in the period of weak activity as it is the case is several investigated earthquakes.

2. Dynamic Spectral Analysis

In the following we introduce first the ICE experiment onboard DEMETER microsatellite. Then we review the methods we have used to process the recorded electric field measurements above the earthquakes region. Those methods lead us to estimate the VLF transmitter signal variations above specific points of the Earth.

2.1. Instrument Champ Electrique (ICE) Experiment

This experiment consists of 4 spherical sensors with embedded pre-amplifier electronics mounted on the ends of 4 booms. The component of the electric field is determined along the axis defined by two sensors. Any pair of sensors among the four can be used for this objective which enables the 3 components of the DC and AC vector electric field to be measured. Four frequency ranges have been defined, DC/ULF (0–15 Hz), ELF (15 Hz–1 kHz), VLF (19 Hz–20 kHz) and HF (3.25 kHz–3.3 MHz). In the survey mode, used in this study, the power spectrum is stored with a 19.53 Hz frequency resolution and averaged over 2.048 s.

2.2. Time and frequency profiles

We use in this study the half-orbit dynamic spectrum recorded by ICE experiment. It indicates the VLF flux density variation versus the time (in UT) and the frequency (in Hz). The high spectral resolution of the experiment (size pixel is 2.048 s × 19.53 Hz) leads to record the fine features which occur during one half-orbit which is about 35 minutes. The observed ionospheric components are principally the hiss, the chorus, the whistlers, and the artificial signals, e.g. calibration and transmitter signals. A dynamic spectrum has 980 spectra and 1024 channels in time and frequency range, respectively. The total number of pixels for one given dynamic spectrum is about 10^6 points. This huge collected information needs to be processed in the way to derive the variation of the ELF/VLF ionospheric components during each half-orbit.

In a first step, we investigate the flux density variation versus the observed time, the so-called time profile. For this we consider for each spectrum the averaged intensity **$\langle I(t) \rangle$** using the following relation:

$$\langle I(t)\rangle = \frac{1}{N_f}\sum_{i=0}^{i=1023} I(t,i)$$

where ***t*** is the observed time, ***i*** is the index related to the frequency channel, and N_f is the total number of channels. The advantage of the time profile is to get a quick look on the time occurrence of the observed components. However it is not possible to distinguish between the hiss and the chorus components in particular to define their corresponding respective frequency ranges.

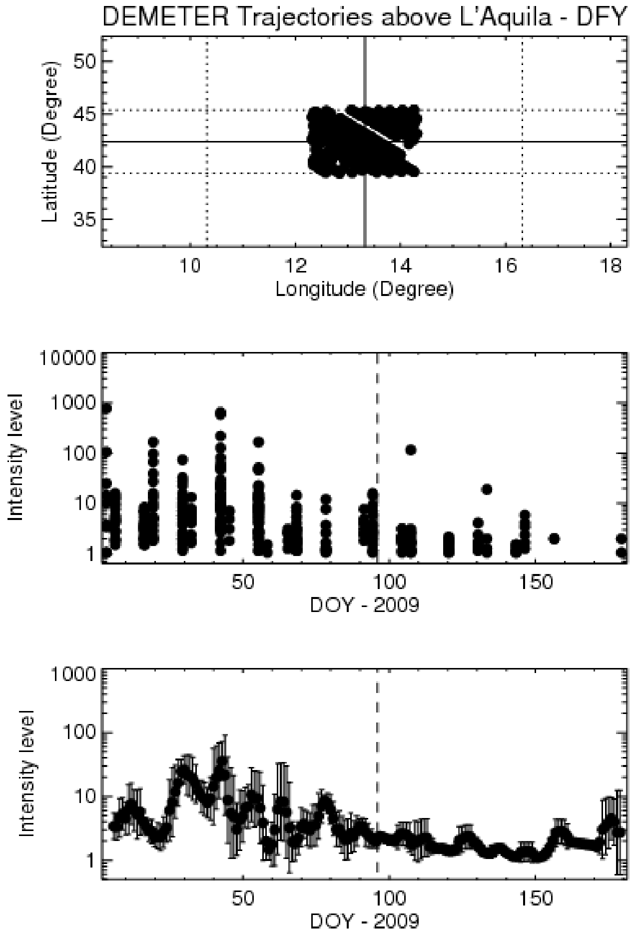

Figure 1. Variation of the DFY transmitter signal at the frequency of 16652.5 Hz (the closest frequency to the German transmitter signal 16560 Hz) above L'Aquila region: (a) first panel shows the orbits the DEMETER micro-satellite above L'Aquila region versus geographic and latitude coordinates, (b) second panel displays the variation of the DFY transmitter signal versus the day of the year 2009 (from Jan., 01st, to June, 30th, 2009.) and (c) third panel shows the VLF intensity mean and the corresponding standard deviation.

In a second step, we estimate the variation of the intensity level versus the observed frequency range, from 20 Hz to 20 kHz, the so-called frequency profile. We calculate for each frequency (i.e. each channel) the variation of the intensity level during the half-orbit. This leads us to get 1024 curves associated to the observed frequency range. Then we deduce for each channel an averaged intensity ***<I(f)>*** value as:

$$\langle I(f)\rangle = \frac{1}{N_t}\sum_{j=0}^{i=977} I(t,j)$$

where $\boldsymbol{f}$ is the channel frequency, $\boldsymbol{j}$ the index related to the time spectrum number, and $\boldsymbol{N_t}$ the total spectrum number.

It is possible to estimate the spectral envelope of the VLF emission using the frequency profiles. Boudjada et al. (2008) analysed the maximum, the median and the minimum levels for one given frequency channel. Authors showed that the "maximum curve" displays more features than the other ones. Hence the ionospheric substructures which occurred in the lower part of the dynamic spectrum (i.e. between 1 kHz and 2 kHz) are absent on the "average-curve", and all details are nearly lost on the "medium- and minimum-curves". The "maximum-curve" gives a more realistic idea about the spectral envelope associated to the observed emissions. This method has been principally used to investigate the earthquakes which occurred in Italia peninsula in Nov. 2004 (Boudjada et al., 2008) and in April 2009 (Boudjada et al., 2010).

The characteristic orbits of Demeter micro-satellite allow observing during few minutes a specific point on the Earth's geoids. This feature leads us to collect measurements of ICE experiment mainly when the satellite is above specific point of the Earth. In this analysis, we select two "rectangle" areas centred on L'Aquila (42.38° N, 13.32° E) region and the DFY transmitter station (52.5° N, 13° E) in Germany. For the L'Aquila and DFY station we consider, respectively, the following latitude and longitude intervals: 32.38° to 52.38° N and 8.32° to 18.32° E, and 62.5° to 42.5° N and 8.0° to 18.0° E.

3. Drop of DFY transmitter signal before L'Aquila earthquakes occurrence

We estimate the variation of the DFY transmitter signals above the L'Aquila region and DFY transmitter station in the period from 01st Jan. 2009 to 30th June 2009.

The first panels of Fig.1 and Fig.2 show the two 'rectangle' areas and the corresponding DEMETER orbits centered, respectively, on L'Aquila region (left-upper panel) and DFY transmitter (right-upper panel). We can see that the coverage of both areas is quasi-similar because the geographical longitude values are nearly equal (i.e. ~ 13°). The recorded VLF intensity variations are displayed in the second panels of Fig.1 and Fig.2 where the dashed vertical lines refer to the day of

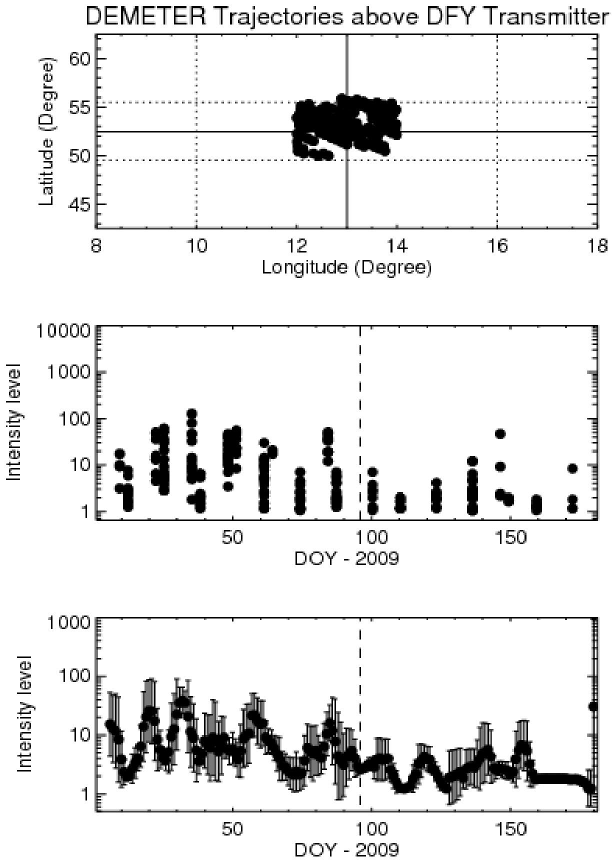

Figure 2. Like in Fig.1 when the DEMETER micro-satellite was above DFY transmitter station (Germany).

L'Aquila earthquakes (April, 06th, 2009, day of the year 96). We note in the second panel of Fig.1 that the transmitter VLF signal above L'Aquila decreases of about one order of magnitude between the beginning of March 2009 and the day of the earthquakes, after that the signal increases again.

This variation is less evident above DFY transmitter station (the second panel of Fig.2). We only select the night-side orbits of the micro-satellite. The full-circles in Fig.1 and Fig.2 indicate the time and the intensity level recorded during a specific day. The time interval between the two close VLF signals, shown in middle panels of Fig1, is about 3 days, followed by a gap of about 10 days. This means that the same signal is recorded again each 13 days. In the lower panels of Fig.1 and Fig. 2, we compute the VLF intensity mean and the corresponding standard deviation derived from a sample population of 5 elements around the interpolated point. The decrease is clearly seen above L'Aquila region. The combine of DFY transmitter signals above L'Aquila and above the DFY transmitter stations leads us to find, first, that the intensity level is decreasing few days before the earthquakes. The drop is evident above L'Aquila region but less clear over the DFY transmitter. Second we note that the days of DFY signal occurrence above L'Aquila and DFY signal station are different with a delay of about 3 days. This may explain the discrepancy in intensity levels between both locations.

4. Discussion and Conclusion

The intensity level drop of the DFY transmitter signals above earthquakes regions have been confirmed by several studies, since the pioneer work of Molchanov et al. (2006). In this analysis we show that different methods provide similar results. It is clear that above seismic regions the ionosphere is disturbed. We illustrate in this analysis that the VLF transmitter signal is subject to attenuation few days before the earthquakes occurrence. The geomagnetic activity is found to progressively decrease up to two days before L'Aquila earthquakes. The drop in intensity above the L'Aquila can not be related to the geomagnetic activity because the daily Kp-index is low. Also we note that VLF transmitter signal above the DFY station is regularly detected. It is very probable that the weak Kp-index value has allowed us to see more easily the attenuation of the transmitter signal above L'Aquila. The recent studies of Boudjada et al. (2012) found that the drop in the VLF transmitter over seismic regions, as reported in several studies, might be related to the preparatory zone. The model proposed by Liperovsky et al. (2000) and Molchanov (2004) might explain how the gas water release from the earthquake preparatory zone can disturb the ionosphere. These studies showed that an upward energy flux of atmospheric gravity waves can disturb the ionospheric electron density above seismic regions. Stangl et al. (2011) found that for the L'Aquila earthquake, there were anomaly enhancements in the Total Electron Content (TEC) measurements. This study concluded that the paths of the VLF signals are deviated during their propagation in the turbulent ionosphere. The VLF signals drop because they only occasionally reach the DEMETER satellite. Other models have suggested that the ionospheric disturbances are linked to the changes in the atmospheric electricity (conductivity and vertical field) due to air ionization produced by radon released from an active tectonic fault before an earthquake. Space observations have reported electric fields of about 3 mV/m to 7 mV/m (Chmyrev et al., 1989). Recent investigations of Ampferer et al. (2010) and Denisenko et al. (2008) proposed much lower fields at the ionosphere level. This suggests that a further comparison of models and observations is recommended for the prediction of pre-seismic electromagnetic phenomena.

Other models suggested a local time effects which expresses a dependence on the time of day, and a different condition between day and night periods. Duma and Vilardo (1998) showed occurrence probability of earthquakes per hour origin time in the L'Aquila region (Italy) using a seismicity data base recorded between 1972 and 1996. They found that the most seismic events occurred in the time interval between 22 LT and 04 LT, as L'Aquila event, i.e. 03:32 LT. on April, 06^{th}, 2009. A further paper of Duma and Ruzhin (2003) reported that the daily variation of the seismicity at L'Aquila have similar behaviours as the horizontal magnetic field component measured by L'Aquila geomagnetic observatory. The authors came to the conclusion that seismicity LT occurrence is related to the 'magnetic quiet-day solar daily variations', so-called Sq-variations (Chapman and Bartels, 1940). These variations are generated in the Earth's ionosphere mainly by solar radiation and tidal forces. This seismicity LT dependence should be re-discussed in the frame of EQ electromagnetic precursor.

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