EARTHQUAKE FORECASTING: A POSSIBLE SOLUTION CONSIDERING THE GPS IONOSPHERIC DELAY

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ABSTRACT:

The recent Italian earthquake of L'Aquila has dramatically emphasized the problem of the natural disasters and their correct forecasting. One of the research community aims is, therefore, to find a possible and reliable indicator, considering all the available technologies and tools. Starting from the recent developed researches concerning this topic and considering that the number of GPS/GNSS permanent station around the world is continuously increasing, this study tries to investigate if it is possible to take some advantages from the GPS/GNSS data in order to find a correlation between the GPS signal delays and the earthquake activities. In some case in fact, the level of ionospheric activity increases nearness to an earthquake shock, describing a different behavior 5-10 days before the event, in particular when the seismologic event has a magnitude greater than 4-4.5 degrees. Considering the GPS data from the permanent stations located close to L'Aquila, an analysis about the daily variation of ionospheric signal delay is carried out in order to evaluate a possible correlation between seismic events and unexpected variation of ionospheric activities. Many scenarios have been tested, in particular considering the elevation angles, the lengths of visibility and the time of the day (morning, afternoon or night) of the satellites. The importance of the ionospheric impact in the case of this kind of natural disaster has been shown. In particular, a realistic correlation between the two parameters can be seen about a week before the seismologic event.

1. INTRODUCTION

Earthquake physics is a very complex and broad topic. It involves many scales of the Earth's crustal structure starting from tectonic plates and finishing with the microscopic processes involved in the friction, generation of electric charge and chemical reactions. Earthquake occurrence is connected with the Earth' crustal dynamics. All these movements lead to a strain accumulation within the Earth's crust, to mechanical deformations and crust rupture when the deformation exceeds the limit of mechanical strength. The process of rupture is the earthquake itself. It is natural to expect a difference in earthquake characteristics for every type of tectonic plate contact.

For over the last half a century many attempts have been made to identify ionospheric precursors of strong earthquakes, and in most cases, some ionospheric variability relative to a sort of reference, observed for hours to days before the earthquake is suggested as an ionospheric precursor

Moreover, there are also studies which put forward likely mechanisms to justify the association between observed precursor ionospheric variability and seismic activity occurring before strong earthquakes. However, even today the possibility to identify ionospheric precursors is somewhat controversial.

One of the key points is whether it is possible to screen solar, geomagnetic and even tropospheric from the observed ionospheric variability so as to identify likely precursor ionospheric signatures. The purpose of this paper is to evaluate the efficacy of the ionospheric TEC as additional Earthquakes precursor, considering a dramatic Italian event: the L'Aquila Earthquake (6 April 2009, Magnitude=6.3). In the paper will be presented the results obtained in comparison to the Earthquake's map.

2. EARTHQUAKE FORECASTING: SOME POSSIBLE PRECURSORS

The classical approach of seismic prediction was based on the so-called seismic cycle implying the periodical storing and release of the seismic stress taking into account the continuous tectonic plate movement. Of course, it is difficult to expect from the Earth's crust the ideal homogeneous structure but sometimes the earthquake sequence has a strikingly regular periodicity.

The process of earthquake preparation within one period of the seismic cycle was divided into five stages starting from the moment of the previous earthquake. The first one (which actually put forward the dilatation theory) is the change of the P-wave velocity. The build of dilatation is detected by the velocity diminution in the second stage. Other precursors are ground uplift and tilt, radon emanation, electric resistivity and a number of small earthquakes within the area of earthquake preparation. Basing on present knowledge, we can say that these are not the only precursors registered. Most likely they are representatives of different groups of precursors, namely: mechanical deformation, geochemical and hydrological precursors, electromagnetic precursors, and naturally, the seismic ones.

First of all the precursors should be ranked in two categories: the time of appearance before the earthquake, and their confidential merit. All available seismic information should be used, starting from the seismic regioning, calculation of the seismic risk, and finishing with the most recent techniques based on the self-organized criticality.

Then the middle-term precursors should be tracked such as radon flux, water level etc. The cumulative principle should be used, adding every new appearing indication to the expert alarm system. And finally, the short-term precursors should be processed, including all types of physical, geochemical, electromagnetic and biological monitoring.

For example, radon monitoring is one of the widely used techniques in geological studies. As is known, radon is the product of radium decay. Radon is an ideal indicator in geological research because it is generated continuously in any geological structure. Its concentration loss due to decay (period of semi-decay is 3.825 days) and due to migration into the atmosphere is always compensated by new production.

Radon migration is determined by the macroscopic diffusion coefficient which depends on the mode of geological structure deformation. It is obvious that under compression the diffusion coefficient decreases, and under unloading – increases. The loading-unloading process during earthquake preparation is the reason of the radon concentration variations before the earthquakes.

Earthquake preparation is usually accompanied by electromagnetic phenomena in different frequency bands starting from DC up to VHF radio emissions .

Due to the ability of electromagnetic emissions to propagate in the ambient environment, these emissions are registered at different distances from the earthquake epicentre. But one phenomenon, namely the anomalous vertical constant electric field is registered just within the area of the earthquake preparation.

Summarizing the aforesaid, we can state that before the strong earthquakes in fair weather conditions the anomalies of atmospheric electric field have been observed in the form of electric field increase.

The ionospheric precursors are part of the more general physical process of earthquake preparation and it is probably the youngest precursor method.

Ionospheric effect can be estimated considering different source of data, but the use of GNSS data deriving from permanent station is a conventional mode.

In fact, It is possible to elaborate TEC (total content electron) map, where several permanent station data are elaborated.

This kind of analysis is quick and fast, because the permanent stations are ever working and the density is very high.

In the past, many important and dramatic earthquakes have been analyzed considering the TEC variation, bring to have interesting results and confirming the capability of the ionospheric activity to be one of the earthquake precursor.

Recently, this approach has been used considering the Sumatra's Earthquake, which has caused many died at the end of 2006.

Some studies has demonstrated the correctness of forecasting due to TEC analysis, even describing the earthquake phenomenon 8-10 days before.

How is it possible define the Earthquake intensity?

The earthquake's intensity is estimated from the oscillation created by different kinds of seismic waves (usually, the surface and body waves). The seismic waves are registered by seismographs and the largest vertical displacement A of the seismograph arrow was selected by Charles Richter in the 1930s to characterize the earthquake intensity by a parameter called the "local magnitude" M_L:

$$M_L = \log_{10} A + 2.56 \log_{10} \Delta - 1.67 \qquad (1)$$

where

A is the amplitude of known reference event,

Δ distance to the source of seismic wave.

Here A is expressed in millimeters, and Δ in kilometers.

An graphical idea how much energy is released during strong earthquakes and to imagine the relationship between the number and energy released by small, moderate, and strong earthquakes, the Figure 1 can be considered. One can see that the most destructive and dangerous earthquakes have a magnitude higher than 7.

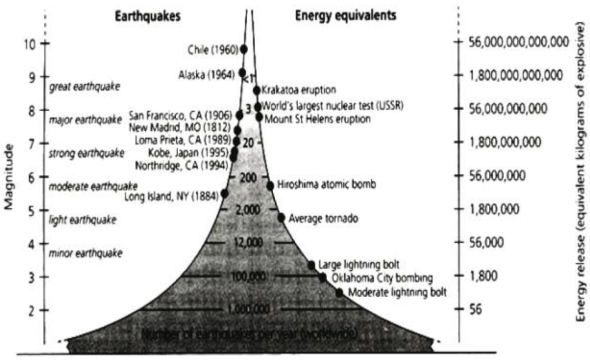

Figure 1. The number of events per year (horizontal axis), magnitude (*left axis*) and energy in trinitrotoluol equivalent (*right axis*) released yearly by Earth's seismic activity

3. THE IONOSPHERIC PROPAGATION DELAY

Total electron content (or TEC) is an important descriptive quantity for the ionosphere of the Earth. In particular, TEC is the total number of electrons present along a path between two points, with units of electrons per square meter, where 10^{16} electrons/m² = 1 TEC unit (TECU).

Ionospheric TEC is characterized by observing carrier phase delays of received signals transmitted from GNSS satellites. Therefore, TEC is directly correlated to the signal ionospheric propagation delay, that can be computed, for example, using a "one-way" positioning.

The "one-way" positioning, or "precise point positioning" (PPP) is an absolute positioning, made without differential techniques, using data collected by only one receiver (pseudoranges, carrier phases and Doppler observables), accurate orbital and satellite clock data and error models of atmospheric delays.

Both the carrier phase and pseudorange observables are important to PPP. In fact, referring to a single receiver r and a single satellite s, it is possible to write the following equations, in meters:

$$\begin{cases} P_1 = \rho + I + c(dt - dT) + Tr + m_{P1} + e_{P1} \\ P_2 = \rho + \alpha \cdot I + c(dt - dT) + Tr + m_{P2} + e_{P2} \\ \Phi_1 = \rho - I + \lambda_1 N_1 + c(dt - dT) + Tr + m_{\Phi 1} + e_{\Phi 1} \\ \Phi_2 = \rho - \alpha \cdot I + \lambda_2 N_2 + c(dt - dT) + Tr + m_{\Phi 2} + e_{\Phi 2} \end{cases} \qquad (2)$$

where ρ = range between the receiver and the satellite;

dt = satellite clock error;

dT = receiver clock error;

Tr = tropospheric propagation delay;

I = ionospheric propagation delay;

N = integer carrier phase ambiguity;

m_P = code multipath delay;

m_Φ = carrier phase multipath delay;

ε_P = random errors on pseudorange observables;

ε_Φ = random errors on carrier phase observables;
α = quadratic ratio between the two frequencies.

In matrix notation, the equations above become (Leick, 2004):

$$\begin{bmatrix} P_1 \\ P_2 \\ \Phi_1 \\ \Phi_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & \alpha & 0 & 0 \\ 1 & -1 & \lambda_1 & 0 \\ 1 & -\alpha & 0 & \lambda_2 \end{bmatrix} \begin{pmatrix} \rho + Tr + \ldots \\ \ldots + c \;\; dt - dT \\ I \\ N_1 \\ N_2 \end{pmatrix} + \begin{pmatrix} m_{P1} + e_1 \\ m_{P2} + e_2 \\ m_{\Phi 1} + e_3 \\ m_{\Phi 2} + e_4 \end{pmatrix} \qquad (3)$$

The matrix notation enables to observe that it is possible to isolate the ionospheric propagation delay from the geometry-dependent terms and the carrier phase ambiguities.

Therefore, it is possible to compute the state vector solving the system at each epoch ("step by step"), or using a Kalman filter procedure. In addition, the observations can be weighed with the satellite elevation angle, in order to reduce the influence of noise at low elevation angles: this calculation is very important for a single receiver positioning. The elevation-dependent weight proposed by (Huber, 2003) is used:

$$w(z) = \cos^2 z + a \cdot \sin^2 z \qquad (4)$$

where z = satellite zenith distance;
a = coefficient $0 < a << 1$. In this case $a = 0.3$.

4. CASE STUDY: THE L'AQUILA EARTHQUAKE

Italy frequently experiences earthquakes, but it is uncommon for them to be very deadly. The last major earthquake was the 5.9-magnitude 2002 Molise earthquake which killed more than 25 people and was the deadliest in 20 years.
The 6th of April 2009 the middle of Italy was invested by a catastrophic event: a violent earthquake has seriously damaged the city of L'Aquila and the closest towns, with a radius equal to 70 kms (Figure 3).

Figure 2. Damages due to the L'Aquila earthquake

Figure 3. The L'Aquila earthquake: localization

This earth tremor has had the intensity of $6.3M_L$ of Richter scale and it was announced by a series of previous tremors, started since the 14/12/2008, with an intensity of 4.8 M_L Richter.
After the earthquake, 256 others tremors have been registered.
The main event has caused 308 died and about 1500 injuries.
A lot of people are homeless and jobless, and the cultural heritage has also suffered a heavy damage.
Earthquakes mark the history of L'Aquila, a city built on the bed of an ancient lake, providing a soil structure that amplifies seismic waves. The city was struck by earthquakes in 1315, 1349, 1452, 1501, 1646, 1703, and 1706. The earthquake of February 1703, which caused devastation across much of central Italy, largely destroyed the city and killed around 5,000 people.
While most of L'Aquila's medieval structures suffered damage, many of its modern buildings suffered the greatest damage, for instance, a dormitory at the university of L'Aquila collapsed. Even some buildings that were believed to be "earthquake-proof" were damaged. L'Aquila Hospital's new wing, which opened in 2000 and was thought capable of resisting almost any earthquake suffered extensive damage and had to be closed.
Italy is classified in four earthquake zones, which are defined in relation to the risk. In Figure 4 there are the classification and it is possible to recognize L'Aquila in the zone more risky (4th).

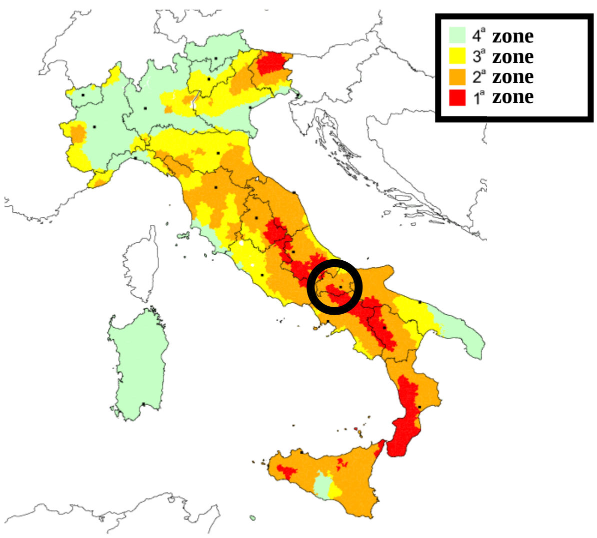

Figure 4. Italian Seismic classification

The characteristics and the magnitude of this tragic event allows to investigate if the analysis of ionospheric delay could be an effective earthquake precursor in this case.

5. TESTS

In order to study the trend of ionospheric propagation delay near the seismic event of L'Aquila, data from GPS permanent stations placed near the earthquake epicenter have been used. In particular, the following stations are considered:

Permanent Station	Approx. coordinates	
	Latitude	Longitude
L'Aquila (AQUI)	42.34	13.38
Ascoli Piceno (ASCO)	42.82	13.64
Atri (ATRA)	42.55	14.01
Castel del Monte (CDRA)	42.37	13.72
Montereale (MTRA)	42.53	13.24
Monterotondo (MORO)	42.05	12.62
Oricola (OCRA)	42.05	13.04
Ovindoli (OVRA)	42.14	13.51
Sulmona (SMRA)	42.05	13.92
Sora (SORA)	41.71	13.60
Terni (TERI)	42.57	12.65

Table 1. Coordinates of permanent stations

These stations were chosen according to the earthquake preparation zone radius with respect to the distance from the epicenter, as described in Table 2 (Dobrovolsky et al., 1979):

Magnitude	Earthquake preparation zone radius ρ [km]
3	19.5
4	52.5
5	141
6	380
7	1022
8	2754
9	7413

Table 2. Earthquake preparation zone radius for different magnitudes

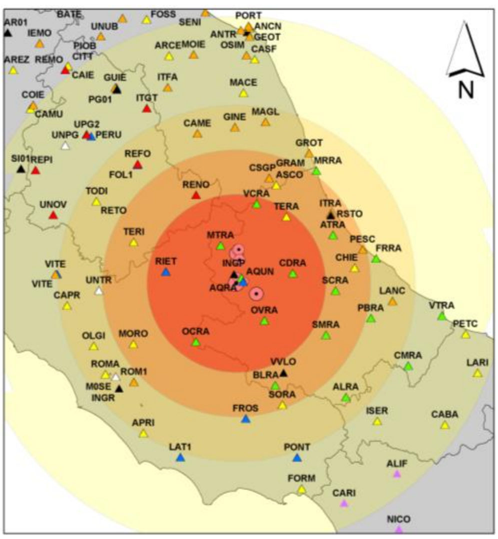

Figure 5. Map of the GNSS permanent stations in the middle of Italy

For each station, data from March 15 (JD 74/2009) to April 17 (JD 107/2009), that are 15 days before and 15 days after the earthquake, were taken into account.

The tests with the "one-way" positioning were performed for all stations and all days, considering three different satellites (PRNs 8 /11 and 29) of the GPS constellation. The choice of these three satellites is need to monitor the behavior of the ionospheric propagation delay at three different times of day (morning, afternoon and night) as shown in Figure 6. In particular, the figure represents the position of the three satellites on the day of the highest earthquake (JD 96/2009), but it can be considered roughly equivalent for the other days of the analysis, being the temporal displacement of the satellites equal to 4 minutes per day.

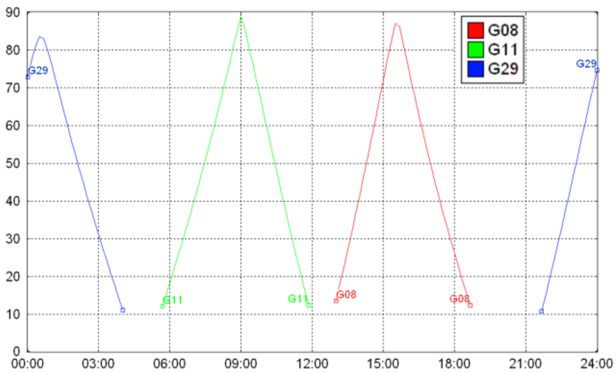

Figure 6. Visibility of satellites PRN 08 / PRN 11 / PRN 29

The "one way" positioning in equation (3) has been implemented in a Kalman filter, by a dedicated software developed in FORTRAN language. The results were analyzed by means of some toolboxes developed in MATLAB® language.

In the next section, the results of the performed analysis are shown.

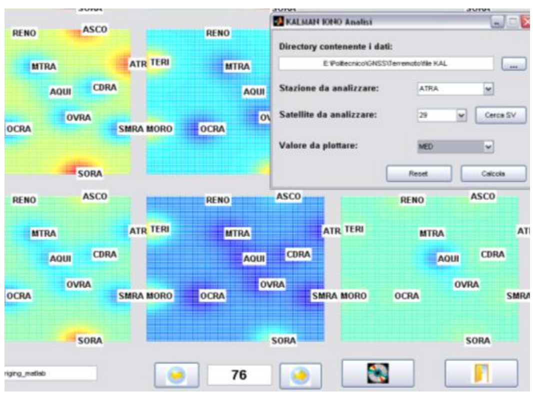

Figure 7. Screenshots of the developed software

6. RESULTS

For each permanent station the ionospheric propagation delay, considering the three GPS satellites PRNs 8,11 and 29 was computed using the "one-way" positioning described in the paragraph 3. The AQUI station (L'Aquila) was analyzed for a time period longer than the one mentioned in the previous section, in order to have a longer and more significant time series.

In particular, it was considered a time period between February 9 (JD 40/2009) and April 17 (JD 107/2009). In the following, figures shows the trend of the daily average value of the ionospheric propagation delay for the GPS station of L'Aquila, for each chosen satellite. The week before the earthquake of April 6 (JD 96/2009) is represented with red color.

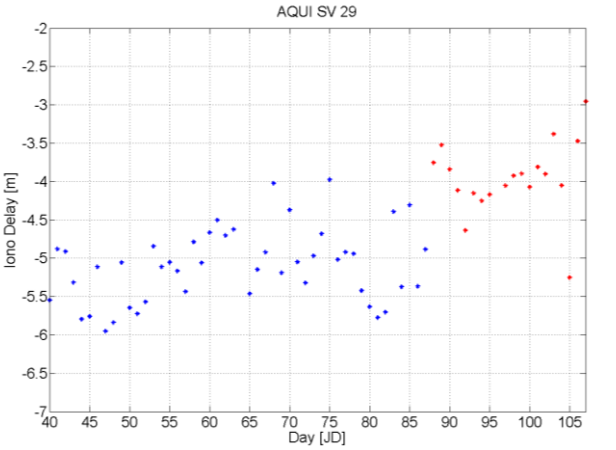

Figure 8. Time series of ionospheric delay in AQUI – PRN 29

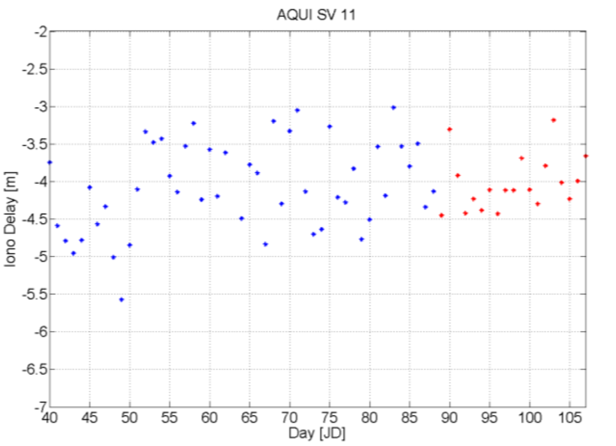

Figure 9. Time series of ionospheric delay in AQUI – PRN 11

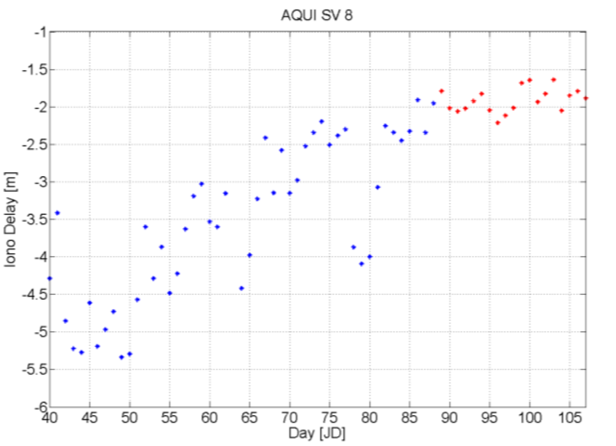

Figure 10. Time series of ionospheric delay in AQUI – PRN 8

Analyzing the figures above, it is possible to identify, about a week before the seismic event (JD 88/2009), an anomalous variation in patterns of ionospheric propagation delay, especially for the satellite PRN 29. In fact, the ionospheric propagation delays computed for satellites PRNs 11 and 8 suffer from noise due to solar activity during the morning and the afternoon, and therefore does not allow to detect the possible disturbance caused by the incoming of the earthquake.

Table 3 shows the median and RMS values computed for the AQUI station, and relating to the period before and after the JD 88/2009.

GPS Satellite	Before JD 88/2009		After JD 88/2009	
	Median [m]	RMS [m]	Median [m]	RMS [m]
PRN 29	-5.06	0.48	-3.93	0.34
PRN 11	-4.13	0.60	-4.11	0.39
PRN 08	-3.47	1.04	-1.93	0.14

Table 3. Values of TEC in AQUI, expressed in m

The comparison with the average values of ionospheric propagation delay computed for the other GPS permanent stations provides additional points of interest. Figure 11 shows the time series computed for the GPS station of Castel Del Monte (CDRA) in the range from JDs 74 to 107. The Table 4 summarizes the median and RMS values computed for each station considering the satellite PRN 29.

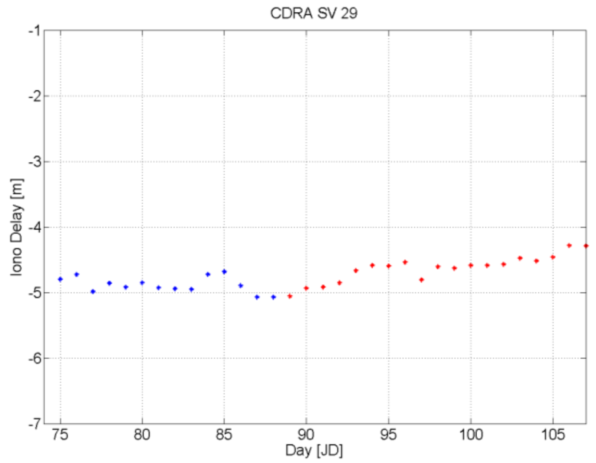

Figure 11. Time series of ionospheric delay in CDRA – PRN 29

Permanent Station	Before JD 88/2009		After JD 88/2009	
	Median [m]	RMS [m]	Median [m]	RMS [m]
L'Aquila (AQUI)	-5.06	0.48	-3.93	0.34
Ascoli Piceno (ASCO)	-2.93	0.10	-2.89	0.07
Atri (ATRA)	-5.15	0.10	-5.01	0.11
Castel del Monte (CDRA)	-4.91	0.12	-4.59	0.19
Montereale (MTRA)	-5.22	0.10	-5.00	0.13
Monterotondo (MORO)	-0.51	0.10	-0.45	0.06
Oricola (OCRA)	-5.87	0.12	-5.59	0.72
Ovindoli (OVRA)	-5.04	0.11	-4.73	0.11
Sulmona (SMRA)	-5.52	0.11	-5.30	0.12
Sora (SORA)	-1.45	0.09	-1.38	0.07
Terni (TERI)	0.03	0.09	0.15	0.06

Table 4. Values of TEC for satellite PRN29

Analyzing the results reported in Table 4, it can be seen, even more than the median value, that the RMS of the stations can be used as interest parameter for the detection of a precursor to earthquakes. In fact, the RMS obtained for the station of L'Aquila, located a short distance from the epicenter of the earthquake, are not comparable with those obtained for the other ones.

In general, the noise increase cannot be seen only for the AQUI station, but also for all the stations placed in the proximity of the earthquake epicenter. A representation of this phenomenon can be obtained interpolating (e.g., through a simple Kriging) the values daily computed for each station.

In the following, the spatial variation of ionospheric propagation delay (calculated with respect to the median value of the period before JD 88/2009), obtained in MATLAB® using the toolbox developed by (Lophaven et al., 2002) are shown.

In particular, the figures below describe the trend on JDs 88/2009 and 94/2009, where it is shown the area of influence immediately after the variation of ionospheric delay, and the behavior of the ionospheric propagation delay variation near the epicenter (AQUI, CDRA OVRA stations, two days before the earthquake).

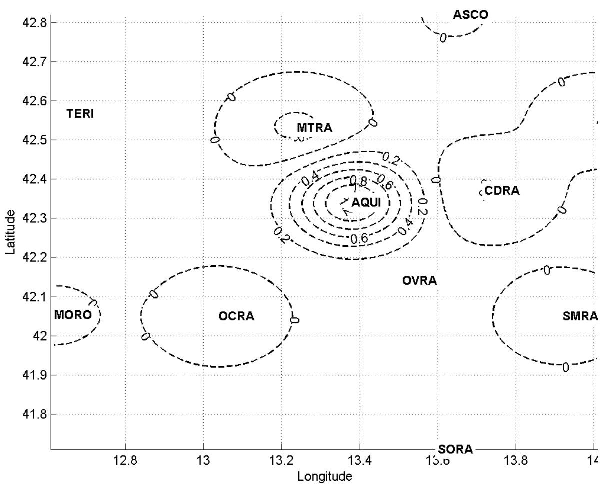

Figure 12. Contour plot of global ionospheric delay variation – JD88

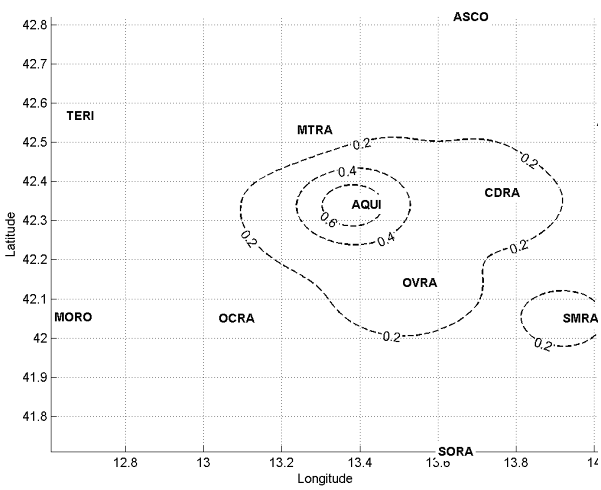

Figure 13. Contour plot of global ionospheric delay variation – JD94

7. CONCLUSIONS AND FUTURE TESTS

The tests developed and the relative analysis demonstrate that the ionospheric delay can be an additional precursors of earthquakes.
As demonstrate above, before L'Aquila's Earthquake the study of ionospheric anomalies could be significant especially around 7 days before. Ionospheric variation and RMS values have been effective precursor of the dramatic event of April 6th. In particular few days before, strange variations were be denoted around the epicentre.
The Earthquake preparation zone is also correct as the site external of the radius equal to 100 kms.
In fact, the precursor's characteristics are different in different seismically active regions. So these regional peculiarities should be studied.
The TEC analysis is an appreciable precursor but it demonstrate its limit when the value of magnitude is not quite high (< 5.5). The tremors occurred before and after the main tremors are not detected by this approach.
The last conclusion is about the precursors variation with the season and solar cyclephase. It is well known that there are strong variations of the ionosphere parameters as a function of season and solar cycle. It is quite possible that ionosphere sensitivity to the seismic events and the overall precursor's characteristics may also change with the season and solar cycle phase. The seasonal dependencies can be revealed not only as a result of ionospheric variations, but also as the weather conditions change with the season. Winds, rain, snow, and fog everything may contribute to the electric field generation mechanism. In order to give an answer about this question, it is necessary to more investigate, making other tests and considering other factors.

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