Analysis of the Ionospheric Perturbations Prior to the 2009 L'Aquila and 2002 Molise Earthquakes from Ground- and Space-Based Observations

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Abstract – The ionospheric responses to the 2009 L'Aquila (local magnitude M_L 5.8 main shock on April 6, 2009) and 2002 San Giuliano di Puglia (M_L 5.4 and 5.3, major shocks on October 31, 2002, and November 1, 2002; also known as 2002 Molise earthquakes) seismic sequences, both in central Italy, were investigated in a combined ground satellite study. A multiparametric method based on ionosonde observations of sporadic E and F2 ionospheric layers and an appropriate algorithm for the analysis of the Earth's magnetic field and electron density satellite measurements were applied to the Rome ionosonde and Challenging Minisatellite Payload satellite data, respectively, looking for middle-term precursory ionospheric anomalies within the preparation zone of the corresponding earthquakes under quiet geomagnetic conditions. Some interesting anomalies were detected prior to the 2009 L'Aquila main shock, including ionosonde anomalies during the same day of the larger foreshock (7 days before the main shock) and the previous day, in coincidence with a magnetic field anomaly by satellite. Less consistent results were obtained for the 2002 Molise seismic sequence, likely due to the lower magnitude of the corresponding events, generating a weak pre-earthquake ionospheric response. In this case, only one variation in the magnetic field measured by satellite 9 days prior to the first major shock met the conditions to be considered anomalous.

1. Introduction

Earthquakes are very impressive phenomena due to the accumulation of some potential energy in the lithosphere, largely released in a very short time along fault-generating seismic waves that can be very destructive. Because the rest of this energy is liberated some time before the fault rupture, great interest is directed to the study of the earthquake preparatory phases. In particular, the role of FlUids in the pReparaTory pHase of EaRthquakes in Southern Apennines (FURTHER) Strategic Project by the Earthquake Department of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) aims to establish the role of fluids in the preparatory phase of earthquakes in the Southern Apennines, Italy, using a cross-disciplinary approach. In this framework, some project activities are devoted to study the coupling among the lithosphere and the top geolayers before intermediate to large earthquakes, usually defined as *lithosphere–atmosphere–ionosphere coupling* (LAIC), which can reveal relevant anomalies in geophysical parameters from a few days to some months before the earthquake occurrence [1, 2].

In this study, ionospheric data from the Rome ionosonde and the Challenging Minisatellite Payload (CHAMP) [3] recorded prior to the two seismic sequences of L'Aquila (2009) and San Giuliano di Puglia (2002), central Italy, were analyzed to validate the methodologies to be applied to the seismic events in the regions of specific interest within the FURTHER project.

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2. Data and Methods

For this study, data from the Advanced Ionospheric Sounder INGV ionosonde [4] of Rome (41.8°N; 12.5°E) and those recorded at around 400 km by the CHAMP satellite during the periods of 2 months to 3 months before each main shock of the two seismic sequences (i.e., September 1, 2002, to November 1, 2002, and January 6, 2009, to April 6, 2009) were used.

A multiparametric method based on hourly measurements of sporadic E (Es) and F2 ionospheric layers parameters [5–7] was applied to the ionosonde data. Pre-earthquake anomalies are defined from the observation for at least two consecutive hours of an abnormally high Es layer, followed by strong deviations of two control parameters, at least 2 h persistence each. The following conditions are then considered:

$$\Delta h'\mathrm{Es} = h'\mathrm{Es} - (h'\mathrm{Es})_{\mathrm{med}} \geq 10 \text{ km} \tag{1}$$

$$\delta f_b\mathrm{Es} = \frac{f_b\mathrm{Es} - (f_b\mathrm{Es})_{\mathrm{med}}}{(f_b\mathrm{Es})_{\mathrm{med}}} \geq 0.2 \tag{2}$$

$$\delta f_o F2 = \frac{f_o\mathrm{F2} - (f_o\mathrm{F2})_{\mathrm{med}}}{(f_o\mathrm{F2})_{\mathrm{med}}} \geq 0.1 \tag{3}$$

where $(*)_{\mathrm{med}}$ represents the 27 day running median, h'Es is the Es virtual altitude, f_bEs is the Es blanketing frequency, and f_oF2 is the F2-layer critical frequency.

Table 1. Ionospheric anomalies identified during March 2009 by the ionosonde multiparametric method applied to the Rome ionosonde data before the 2009 L'Aquila earthquake UT = Universal Time

Day (March 2009)	UT (h)	$\Delta h'$Es (km)	δf_bEs	δf_oF2	A_p	AE (nT)
2	17 to 18	17	0.22[a]	0.09[a]	2	<100
3	6 to 7	30	0.24	0.13[b]	7	<100
				0.21[b]		>100
6	7 to 8	27	0.33[b]	0.10[b]	2	<100
29	7 to 8	39	0.15[c]	0.11	4	<100
30	6 to 8	48	0.21[a]	0.15[a]	4	<100

[a] Occurred only for 1 h.
[b] Occurred some hours later.
[c] Slightly lower than the threshold.

All these ionospheric characteristics were obtained by manual interpretation of vertical incidence ionograms. Only pre-earthquake anomalies detected under geomagnetically quiet conditions are considered possibly related to the impending earthquake. This is assessed by applying the following conditions on the three hourly geomagnetic index a_p, its daily average A_p, and the auroral electrojet index AE: $a_p \leq 12$ during the previous 24 h, $A_p \leq 9$, and AE ≤ 100 nT during the previous 6 h.

An updated version of the MAgnetic Swarm anomaly detection by Spline analysis (MASS) method [8] was applied to the magnetic field (B) and electron density (N_e) data from the CHAMP satellite. For all the satellite tracks in each day, the local time (LT) and the geomagnetic latitudes are evaluated, selecting only night orbital tracks (between 22:00 to 06:00). The first-time derivatives of B and N_e were estimated from the first difference values divided by the time interval between two consecutive samples, and a fit with cubic splines was applied to remove the long-term trend. Overlapping windows of 1° to 3° latitude length (l_w) sliding along the tracks within $\pm 50^\circ$ geomagnetic latitude are considered, to limit the effects due to the high latitude ionosphere. We define as anomalous those windows for which rmse$>k_t \cdot$RMSE, where rmse and RMSE are the *root mean square errors* computed for the specific window and for the whole track, respectively, and k_t is an appropriate threshold (1.5 to 3). To limit the effects of perturbations coming from outer space, only tracks recorded under quiet magnetic conditions in terms of D_{st} and a_p indices ($|D_{st}| \leq 20$ nT, $a_p \leq 10$) are considered.

3. Analysis and Results

The two seismic sequences of L'Aquila (2009) and San Giuliano di Puglia (2002), Italy, were analyzed in this work to study the ionospheric response during the corresponding preparation phases.

The stronger main shock was in L'Aquila and occurred on April 6, 2009 (01:32:40 Coordinated Universal Time [UTC]) in an extensional tectonic regime along a normal fault at the coordinates (42.34°N; 13.38°E), 94 km apart from the Rome ionosonde. The hypocentral depth was 8 km, and the local magnitude M_L was 5.8. The corresponding Dobrovolsky radius (or *strain radius*) [9], which defines the estimated circular extension of the earthquake preparation zone, was 312 km. For this event, ionospheric anomalies were searched up to 3 months before the main shock.

Table 2. Ionospheric anomalies identified during January 2009 by the MASS method applied to N_e CHAMP data within the preparation area of the 2009 L'Aquila earthquake

Day (January 2009)	Track number	Mean LT (h)	D_{st} (nT)	a_p
9	7	05:46:47	−9	5
18	6	05:06:56	−8	0
22	6	04:44:43	−5	3

Table 3. Ionospheric anomalies identified during February 2009 and March 2009 by the MASS method applied to B_y CHAMP data within the preparation area of the 2009 L'Aquila earthquake

Date (2009)	Track number	Mean LT (h)	D_{st} (nT)	a_p
February 23	2	01:47:11	4	2
March 29	29	22:33:13	7	4

In 2002, two different major shocks shook the San Giuliano di Puglia region [10]. The first one occurred on October 31 (10:33:00 UTC) at the coordinates (41.70°N; 14.93°E) (202 km from Rome), while the second one on November 1 (15:09:02 UTC) at (41.72°N; 14.84°E; 194 km from Rome), both with a 10 km deep hypocenter. Both earthquakes occurred in the tectonic context of dextral (right-lateral) strike-slip faulting; M_L was 5.4 and 5.3, respectively, with a corresponding strain radius of 210 km and 190 km. In this case, ionospheric anomalies were analyzed within the 2 months before the occurrence of the second shock.

The analysis of the 2009 L'Aquila seismic sequence through the ionosonde multiparametric method was already included in a previous work [5] and a subsequent reanalysis [7] of all the M5.5+ earthquakes occurred in central Italy since 1984. As a choice was made to associate only one anomaly to each earthquake, a single anomaly detected on March 3, 2009, was associated with this event. As reported in Table 1, under the present analysis, four additional ionospheric precursory anomalies were identified during March 2009, although some criteria were not strictly satisfied.

The MASS method applied to the CHAMP satellite data before the 2009 L'Aquila earthquake revealed three nocturnal tracks during January 2009 with N_e anomalies within the earthquake preparation region, and two tracks with anomalies in the Y (east) component of B (B_y) in February and March 2009. Such anomalies, reported in Tables 2 and 3, were detected considering different l_w and k_t values.

From the analysis of the 2002 Molise seismic sequence, no anomalies from ionosonde data were detected under quiet geomagnetic conditions. As shown in Table 4, the AE index reached values greater than

Table 4. Ionospheric anomalies identified during September 2002 and October 2002 by the ionosonde multiparametric method applied to the Rome ionosonde data before the 2002 Molise seismic sequence UT = Universal Time

Date (2002)	UT (h)	$\Delta h'$Es (km)	δf_bEs	δf_oF2	A_p	AE$_{max}$ (nT)
September 21	7 to 9	30	0.44	0.18	6	309
September 26	6 to 7	24	0.42	0.17	5	560[a]
October 2	1 to 4	18	0.96	0.17	53	1489
October 14	14 to 16	31	0.53	0.19	23	1077
October 27	7 to 8	21	1.80	0.19	25	1131

[a] AE peaked after the ionospheric anomaly, but reached approximately 350 nT during it

300 nT, up to almost 1500 nT. Some anomalies were also detected under A_p index values greater than 20.

Before this latter seismic sequence, some CHAMP N_e anomalies were detected under geomagnetically quiet conditions, but none of them were located within the earthquake preparation area, and only one of the corresponding tracks (on October 22, 2002, mean LT 22:59:03) was recorded at night. However, on the same track, B_y anomalies from a satellite were detected also within the seismic preparation zone (Figure 1).

The anomalies identified by the ionosonde multiparametric method were also studied in relation to the earlier obtained empirical relations between the anticipation time Δt, the epicenter–ionosonde distance R, and the magnitude M of the impending earthquakes [5, 7]. In particular, in Figure 2, the anomaly revealed on March 6, 2009, and the ones detected from September 2002 to October 2002 are superimposed to the $\log(\Delta t \cdot R)$ versus M plot obtained in [7].

4. Discussion and Conclusions

From the combined analysis of ground-based ionosonde and the CHAMP satellite data prior to the 2009 L'Aquila (M_L 5.8 main shock) and the 2002 San Giuliano di Puglia (M_L 5.4 and 5.3, major shocks) seismic sequences, some remarks can be highlighted.

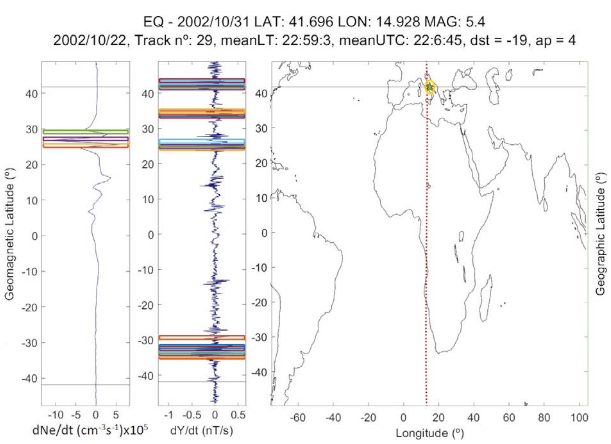

Figure 1. Electron density (first panel) and Y-component magnetic (second panel) anomalies detected on October 22, 2002 by the MASS method applied to CHAMP satellite data, with $l_w = 1.0$ and $k_t = 1.5$. In the third panel is shown the geographical map of the region of interest, where the red dotted line represents the satellite path and the yellow circled zone corresponds to the Dobrovolsky area of the first main shock of the 2002 Molise seismic sequence.

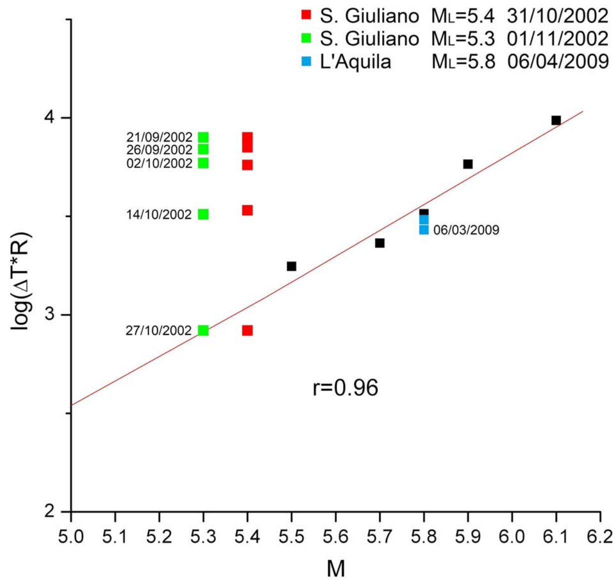

Figure 2. The dependence obtained in [7] for $\log(\Delta t \cdot R)$ on the earthquake magnitude M, in comparison to some of the anomalies revealed in this study prior to the 2009 L'Aquila and the 2002 Molise earthquakes. Here, the same anomalies detected within September 2002 to October 2002 are related to both the main shocks of the Molise seismic sequence.

Before the 3 months preceding the 2009 L'Aquila earthquake, no N_e satellite anomalies within the Dobrovolsky area were detected in coincidence with the ionosonde ones. However, the B_y anomaly was revealed during the same day of the ionosonde anomaly of March 29, 2009 (8 days before the main shock; Tables 1 and 3), although the latter did not exceed the threshold for δf_bEs. The subsequent day, at 13:38:38 UTC, the major foreshock (M_L 4.1) of that sequence occurred, along with another ionosonde anomaly with short duration of anomalous δf_bEs and δf_oF2 (Table 1). Note that among the N_e satellite anomalies identified during January 2009 (Table 2), one (January 22) occurred during the sudden stratospheric warming (SSW) of January 18 to 23 (SSW) [11]. Finally, another interesting aspect is the frequent detection of anomalies close to the geomagnetically conjugate point (with minor effect) of N_e satellite anomalies within the earthquake preparation area and of the B_y anomaly occurred on February 23, 2009 (Figure 3).

The analysis of the 2002 Molise seismic sequence gives less consistent results, likely due to the more magnetically disturbed period of study but also to the rather lower earthquake magnitudes, which are expected to generate a weak or even negligible precursory LAIC response in such a small region. Moreover, the Rome ionosonde was located quite far from the epicenters of the two corresponding Molise major earthquakes. As a consequence, no coincident anomalies by ionosonde and satellite were found for this latter case, and only the

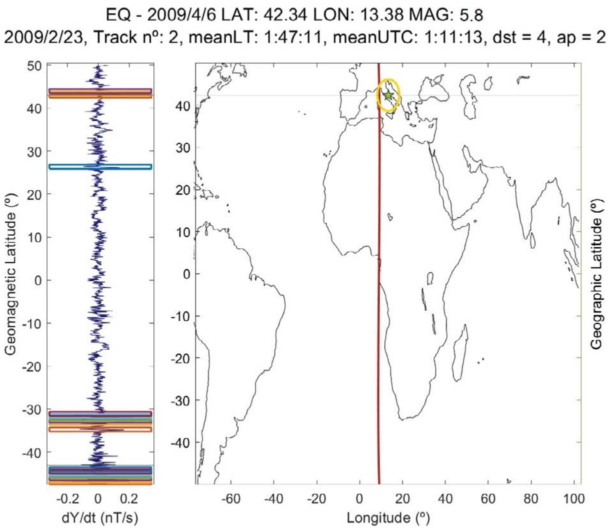

Figure 3. Same as Figure 1, for the Y residual component of the Earth's magnetic field (first panel) recorded on February 23, 2009. The yellow circled zone in the second panel corresponds to the Dobrovolsky area of the 2009 L'Aquila earthquake.

last found ionosonde anomaly (October 27, 2002; Table 4) seems to be consistent with the relationship between $\Delta t \cdot R$ and M previously found in [7] (Figure 2). However, the strong geomagnetic perturbation that occurred before such anomaly does not allow us to exclude the origin from outer space. Regarding the N_e satellite anomalies, none of them were found within the Dobrovolsky area, although a clear nocturnal one was detected over North Africa on October 22, 2002 (9 days before the main shock), when B_y anomalies were also found near the epicenter (Figure 1) but not at the conjugate point, unlike those detected at around 35° of magnetic latitude.

This study demonstrates the difficulty in obtaining coherent results from different methods to reveal the ionospheric response to the preparation phase of earthquakes with low to intermediate magnitudes ($M < 6.0$). However, some anomalies were detected 7 days to 9 days before both the investigated seismic sequences, along with others more in advance, with interesting characteristics to be better investigated, including the connection between magnetic conjugate regions and the possible influence of other global phenomena, such as SSWs.

5. Acknowledgment

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6. References

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