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# Statistical and spectral properties of the L'Aquila EQL in 2009

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***ABSTRACT*** A great number of earthquake lights (EQL) were observed in association with the L'Aquila earthquake of April 6, 2009. A previous comparison of EQL locations and the geology of the epicentres showed some possible association of EQL types with ground characteristics, while the association between sighting and shock times divided the co-seismic EQL types into pre-seismic and post-seismic ones. In this report, EQL colours are considered with respect to EQL types, positions and times. A digital method, taking into account witness distribution, to correct the statistical properties of EQL distribution was proposed. A Radial Distribution Function and time distribution were calculated. Accelerating EQL time distribution and correlation length fluctuations with earthquake were observed when approaching the principal shocks. The power law model produced good fits for the distributions.

**Key words:** earthquake lights, L'Aquila earthquake, central Italy.

## 1. Introduction

The L'Aquila earthquake of April 6, 2009 was the strongest event in a sequence of seismic shocks that had started a few months earlier in the Abruzzo region; local seismic activity began to increase in December 2008 (Pondrelli *et al.,* 2010). There were three significant foreshocks during the week preceding the main shock and seven strong aftershocks within the first week after the main shock. The most significant events prior to the earthquake, occurred on March 30 ($M$ = 4.4), at 15:38 Local Time (LT), April 5 ($M$ = 4.2), at 22:48 LT and April 6 ($M$ = 3.8), at 00:39 LT (Chiarabba *et al.,* 2009). The two strongest aftershocks occurred on April 7 ($M$ = 5.6), at 19:47 LT, and on April 9 ($M$ = 5.4), at 02:52 LT, (Bindi *et al.,* 2009). A summary of the L'Aquila seismic sequence was reported in Table 1 of Fidani (2010) to compare with earthquake lights (EQL).

A collection of testimonies about luminous phenomena related to seismic activity in and around L'Aquila before and after the main seismic event ($M$ = 6.3), at 03:32 LT on April 6, 2009 was presented with preliminary results (Fidani, 2010). The collection of testimonials began a few days after the main shock, on April 11, 2009 in the Amatrice area (Lazio region) of Italy, about 50 km north of L'Aquila. A systematic regional survey of the population was carried out using questionnaires (Soter, 1999). The statements made by witnesses were collected by visiting the 179 camps set up by the Italian Civil Protection service (Potezione Civile, 2009). Witnesses were also interviewed in meeting places such as schools, malls, hospitals, coffee shops and social clubs. In addition, data and supporting documents were collected from personnel from public and private institutions such as the police, firemen, and forest rangers. Interviews were done starting from the least hit areas in the Rieti province, to the most hit areas in L'Aquila. The main part of the data regards luminous phenomena observed in abdundance on this occasion. The questionnaire was compiled to collect information about public perception (Bird, 2009) to these phenomena, the format was based on previous works (Galli, 1910; Terada, 1931; Matteucig, 1985; Persinger and Derr 1990; Soter, 1999; St-Laurent, 2000; Stothers, 2004) that are listed in the supplementary material of the previous publication (http://www.nat-hazards-earth-syst-sci.net/10/967/2010/nhess-10-967-2010-supplement.pdf).

A total of about 1,200 interviews were carried out. While many witnesses did not see anything, many others reported multiple sightings. There were 1057 cases of macroscopic anomalies reported which occurred before, during and after the earthquake; 241 were possible EQL while the others were regarded as geophysical, atmospheric and biological phenomena (Fidani, 2010). Several photos that included luminous phenomena were also collected. At least 99 such phenomena occurred before the main shock and other strong events in the seismic sequence. Globular lights, luminous clouds and diffused light were more frequent before the quakes. Flashes were a characteristic at the time of the seismic events, while electric discharges and flames were observed principally after the shocks. Electrical discharges and flames were compared with respect to geological settings and geophysical dynamics. Electrical discharges that were observed mostly NW of L'Aquila, were sighted on the geological borders of the Aterno Valley which corresponds to the quake movement (Walters *et al.,* 2009). Flames were observed SE of L'Aquila, in the area of maximum negative vertical deformation.

Section 2 describes new sightings with the updated tables of types and colours. The statistical analysis of EQL space and time distributions are reported in Section 3. Conclusions are discussed in Section 4.

## 2. EQL witnesses and colours

Through web facilities such as e-mail, Facebook and Blogs, it was possible to collect further testimonies of EQL from many Abruzzo residents, who had read the first publications and thus recalled their impressive sightings. Testimonials were collected using the same questionnaire as was used in the previous year (Fidani, 2010). Eight cases can be summarised as follows:

1) soon after the main shock several people observed shooting star-like phenomena in the sky;
2) a flash on April 5, 2009 that was low in the sky from behind the mountain towards L'Aquila, was observed on the road between San Valentino and Scafa in the province of Pescara, at about 19:30 – 20:00 LT;
3) red clouds were observed from the historical centre of L'Aquila at about 1:00 -1:30 LT on April 6, 2009, towards Bagno;
4) ongoing blue electric discharges were seen to the east of Pile at about 4:00 LT on April 6, 2009, soon after a quake;
5) from the historical centre of L'Aquila three red spheres were observed from 23:30 to 00:30 on April 3 and 4, 2009, towards Paganica; initially, the spheres moved slowly, then faster and then slowly again, then they stopped and vanished;
6) flashes from a window in the direction of Monteluco were observed between the two strong foreshocks on April 5, 2009;
7) in the afternoon of April 5, 2009, around sunset the atmosphere and sky were permeated by

a red fog, the red was more intense in the Aterno Valley, and
8) on June 22, 2009, at about 23:30 LT, clear white reddish flashes, floating on clouds, were observed from Tollo in the province of Chieti.

Testimonial 5 is integrally reported as an example, analogous to the previous article (Fidani, 2010). From the Students' Bar located in Piazza San Pietro in the historical centre of the city of L'Aquila, Francesco Bisignani and his friend suddenly saw three big red lights in the sky towards Paganica. The lights were each moving separately in the sky. Initially, they moved slowly then faster and then slowly again; they seemed to dance. The lights looked like balls of fire. In the end, they stopped in the sky, the lights dwindled and then disappeared. The sightings lasted for about a minute.

According to Table 2 of a previous article (Fidani, 2010), cases 2 and 8 were observed at distances greater than 20 km ("Far"), while the others were "Near" observations. According to Table 3 of the same article, case 1 can be considered like "sparks" while the others are well identified. The time correlation of such EQL with the shocks are in accordance with previous reports. Cases 1, 4, and 8 were observed after the main shock, while case 3 before; cases 2 and 7 were observed before the $M$ = 4.2, 22:48 LT on April 5, 2009 shock; finally, cases 5 and 6 were observed before the $M$ = 3.8, 00:39 LT on April 6, 2009 shock. The updated classification is shown in Table 1. The results of Table 4 of the previous article remained unchanged, since case 1 was high in the sky, undetermined in shape and had a vertical movement; case 2 was ground-based, undetermined in shape and still; case 3 was above the horizon, undetermined in shape and still; case 4 was ground-based, stretched vertically, with a vertical movement; case 5 was high in the sky, globular and had a vertical movement; cases 6 and 7 were unclassifiable and case 8 was high in the sky, stretched horizontally with a horizontal movement. In Table 1, at least 104 of the phenomena occurred before the main shock and other strong events in the seismic sequence, whereas globular lights, luminous clouds and diffused light were more frequent before the quakes.

A new classification based on colours was considered for L'Aquila EQL which gives further important information on the physical nature of such phenomena. EQL colours ranged over the whole spectrum with bright and dark aspects, but they were not uniformly distributed among the EQL types. Only 137 of 249 EQL witnesses recorded colours, while 13 sightings at undetermined times were omitted from Table 2. Red is the dominant colour, particularly for clouds and diffused lights which happened before the earthquake. Fireballs ranging in colour from white to red preceded the earthquake. All the colours were nearly, uniformly distributed for flashes. A colour summary distribution with respect to the time correlation between EQL and earthquake appears at the bottom of Table 2: yellow and red coloured EQL were observed before the earthquake while white and blue were observed after the earthquake. The coloured lights are mapped according to space distribution in Fig. 1. Red lights appeared principally near the epicentre in the Aterno Valley. Sky radiation measurements indicated anomalous values several days before another strong earthquake, both in the red and the green parts of the spectrum (Araiza-Quijano and Hernández-del-Valle, 1996). Such measurements could have been due to radiation in the visible spectrum which originates in the Earth and is reflected by haze and cloud cover. More recently, a red glow at 630 nm was hypothesized by electronically excited oxygen atoms (Freund, 2011), after accidentally recording a red light during the failure of rock cylinders using a low-light video

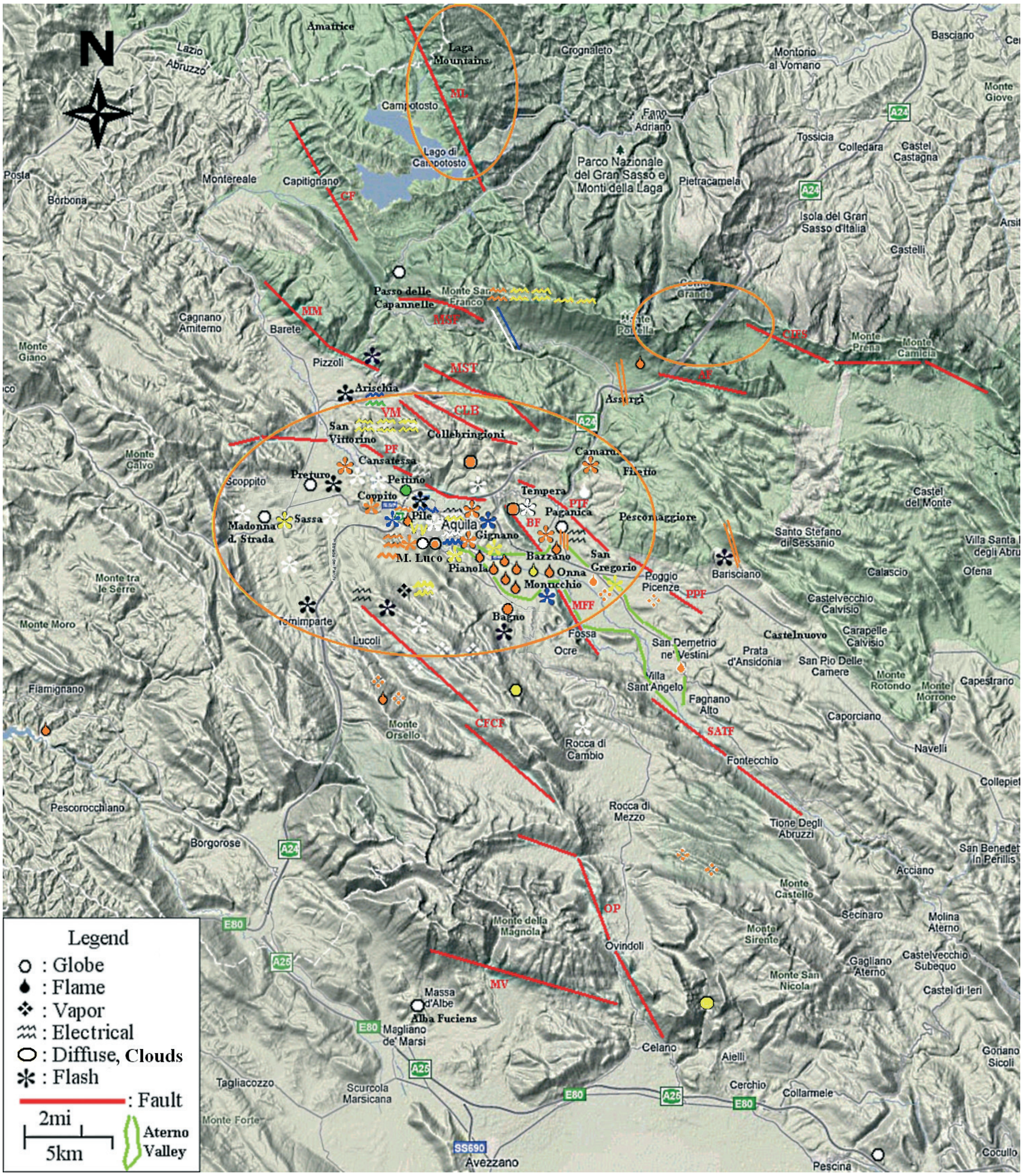


Fig. 1 - Geographical distributions of EQL with their colours on the map retrieved from Google Maps website http://maps.google.pt/; the symbols are specified in the legend; black indicates non specific colours. Primary active faults in the region of the sightings are indicated with red lines: ML, Monts of Laga Fault; CF, Capitignano Fault; MM, Mount Marino Fault; MSF, Mount San Franco Fault; MST, Mount Stabbiata Fault; CLB, Collebringioni Fault; VM, Valle del Machione Fault; AF, Assergi Fault; CIFS, Campo Imperatore Fault System; PF, Pettino Fault; PTF, Paganica-Tempera Fault; BF, Bazzano Fault; PPF, Poggio Picenze Fault; MFF, Monticchi-Fossa Fault; CFCF, Campo Felice-Colle Cerasitto Fault; SATF, Sant'Angelo-Tione Fault; Ovindoli-Pezza Fault; MV, Mont Velino Fault. Fault location from EMERGEO Working Group (2010).

Table 1 - The uploaded L'Aquila collection ordered according to the Galli (1910) classification.

| Types (shape and size) | Before (#) | During (#) | After (#) | Sum (#) | Uncertain (#) | Total (#) |
|---|---|---|---|---|---|---|
| Undetermined | 2 | 6 | 1 | 9 | - | 9 |
| Flashes | 19 | 25 | 23 | 67 | 6 | 73 |
| Electrical discharges | 1 | 5 | 9 | 15 | - | 15 |
| Thin strip of light | 1 | 1 | 1 | 3 | - | 3 |
| Fire balls | 19 | - | 6 | 25 | 2 | 27 |
| Fire columns | 1 | 1 | - | 2 | - | 2 |
| Fire beams | 1 | 1 | 1 | 3 | 1 | 4 |
| Luminous funnels | 5 | - | 2 | 7 | - | 7 |
| Flames | 4 | 6 | 12 | 22 | 1 | 23 |
| Small flames | - | 2 | - | 2 | - | 2 |
| Sparks | 1 | 1 | 3 | 5 | - | 5 |
| Luminous vapors | 5 | - | 4 | 9 | - | 9 |
| Luminous clouds | 21 | 2 | 4 | 27 | 2 | 29 |
| Diffused lights | 24 | 4 | 9 | 37 | 1 | 38 |
| Streamers | - | - | 3 | 3 | - | 3 |
| **All** | **104** | **54** | **78** | **236** | **13** | **249** |

Table 2 - The L'Aquila EQL colours were sorted according to the Galli (1910) classification. Where b: before, d: during and a: after the quake.

| Types (shape and size) | White b d a | yellow b d a | red b d a | blue b d a | green b d a | noting b d a |
|---|---|---|---|---|---|---|
| Flashes | - 5 3 | 2 2 3 | 4 3 5 | 1 2 2 | - - - | 13 19 12 |
| Electrical discharges | - - 2 | - - 2 | - 1 1 | - 1 2 | - - - | 1 3 2 |
| Thin strip of light | - - 1 | - - - | - - - | - - - | - - - | 1 1 - |
| Fire balls | 5 - 2 | 3 - - | 4 - 3 | - - - | - - 1 | 7 - - |
| Fire columns | - - - | - - - | 1 1 - | - - - | - - - | - - - |
| Fire beams | - - - | - - - | 1 1 1 | - - - | - - - | - - - |
| Luminous funnels | - - - | 4 - - | - - - | - - - | - - - | - 1 2 |
| Flames | - - - | - - 1 | 1 2 9 | - - - | - - - | 3 3 3 |
| Small flames | - - - | - - - | - - - | - - - | - - - | - 2 - |
| Sparks | - - - | - 1 - | - - - | - - - | - - - | 1 - 3 |
| Luminous vapors | - - - | - - - | 5 - 2 | - - - | - - - | 1 - 3 |
| Luminous clouds | - - - | - - - | 16 2 2 | - - - | - - - | 4 - 1 |
| Diffused lights | - - - | - - - | 17 2 4 | - - - | - - - | 7 2 4 |
| Streamers | - - - | - - 1 | - - 2 | - - - | - - - | - - - |
| All | 5 5 8 | 9 3 7 | 49 12 29 | 1 3 5 | - - 1 | 38 31 30 |

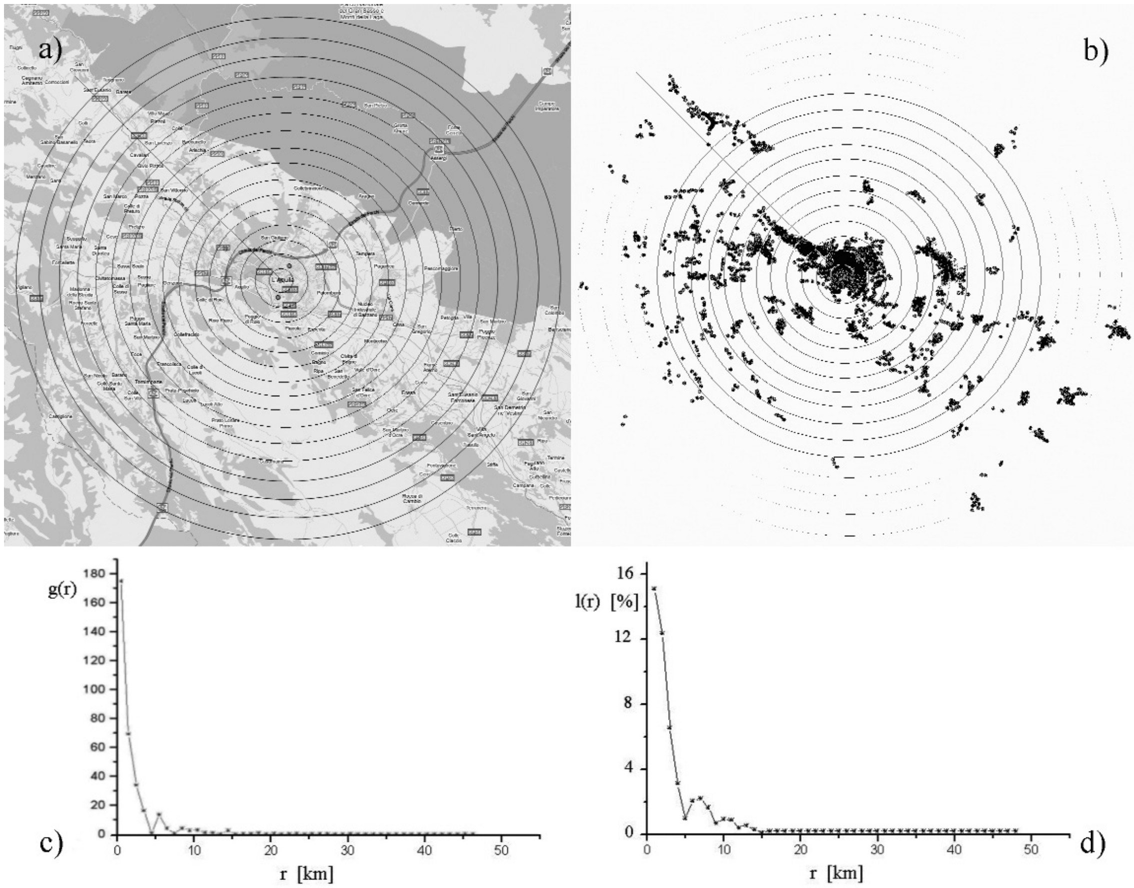


Fig. 2 - The L'Aquila territory with a circular subdivision (a) which was extracted from the picture with the house positions (b). The radial distribution of houses (d) is similar and explains the distribution density *g(r)* in (c).

camera (Kato *et al.,* 2007). Yellow electrical discharges concentrated on the mountain tops where electric charges can be better concentrated.

## 3. Space and time distribution statistics

Although the processes which cause the luminous phenomena of earthquake are not known and the hypotheses that can be formulated depend on unknown subterranean settings, the observed EQL variables suffer from unpredictable random evolution. However, considering the large number of observations that were reported in relation to the L'Aquila earthquake, a statistical analysis of the data can provide some well-founded information that is important for the further study of the EQL phenomena. Thus, starting from the considerations in Section 2, the Radial Distribution Function (RDF) *g(r)* is an important statistical function that should be considered. This function is the measure of the probability of finding an EQL at a distance, *r*, from the epicentre of the main shock. The *g(r)* is usually determined by the radial distribution of

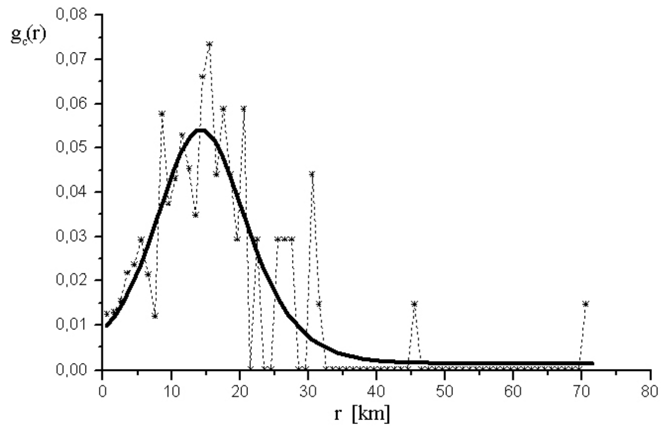


Fig. 3 - The corrected RDF shows a maximum near 15 km, it was fitted by an Asymmetric Double Sigmoidal law.

the sightings *n(r)*, by calculating the distance between the earthquake epicentre and all the EQL, and combining the results in a histogram. The histogram is then normalized with respect to an ideal flat distribution $\rho$, with $\rho = N/\pi R^2$, where $N = \Sigma_{r=1}^{R}\, n(r) = 249$ is the total number of EQL and $R$ is the maximum discrete distance of EQL from the chosen centre equal to 70 km. For two dimensions, this normalization is the density number of the system multiplied by the area of the radial shell. If integer values of distances in km are considered, given that this is the level of precision of many of the EQL positions, the radial shell area can be expressed as $\pi(2r+1)$. As can be seen in Fig. 2c, the RDF decay of EQL reflects the size of the fault, which is centred near 0 km with a length of about 12 km (Walters *et al.,* 2010), and shows a strange interference pattern approximately in correspondence to the borders of the fault.

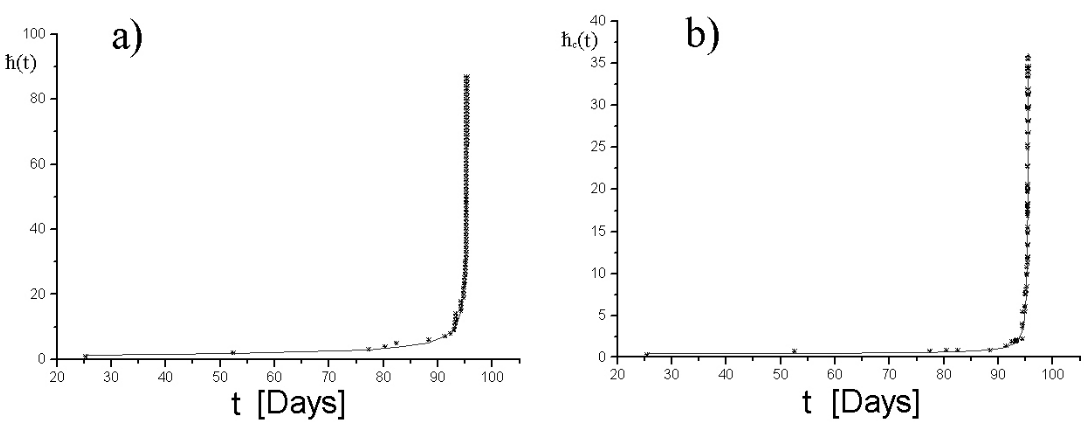


Fig. 4 - Cumulative EQL time distributions and fits according to Eq. (3), before (a) the correction of Eq. (2) and after it (b). Days are the time sum $t_E - t_L + t_M$, where $t_E$ are the earthquake times listed in the supplement of Fidani (2010), $t_L$ is the luminosity time which was associated with the earthquake at $t_E$ and $t_M$ is the main shock time.

Since the population distribution is not uniform over the region and every person could be a potential witness, the RDF should be corrected for such witness distribution. In recent works (Atzori *et al.,* 2009), it can be observed that the hypocenter of the earthquake was directly under the town of L'Aquila and the nearby villages. Due to the increasing area, the radial density of the population decreases gradually as the distance from the city increases. Consequently, it was necessary to describe the witness distribution. This was done by considering the distribution of houses as observed on Google Maps (http://maps.google.com/), and then dividing the map into concentric circles with a unitary radius of 1 km, see Fig. 2a. By using GIMP software (http://www.gimp.org/), the building area was marked off in black and extracted from the map, see Fig. 2b. From the concentric circles, it was possible to calculate the percentile of black area in every loop of Fig. 2b by the colour option histogram of GIMP software. The distribution is depicted in Fig. 2d. It can be seen that the shape is the same as that of the RDF in Fig. 2c. The peaks which appear at about 6 km and 10 km can now to be interpreted as the presence of villages with large populations such as Paganica, Coppito, Arischia and Pizzoli. If we call the population distribution $l(r)$, where $L = \Sigma_{r=1}^{R}\, l(r)$ is the total percentile population within the distance $R$, then the Population Distribution Function (PDF) $f(r)$ can be defined with respect to the population density $\sigma = L/\pi R^2$ through the same shell areas $\pi(2r+1)$, where $L$ = 100% of the population in that area, i.e. about 100,000 people. Finally, the corrected and normalised RDF is

$$g_c(r) = c\, g(r)/f(r) = (cL/N)\, n(r)/l(r) = 0{,}022\, n(r)/l(r), \qquad (1)$$

where the normalization coefficient is $c = 1/\Sigma_{r=1}^{R}\, g(r)/f(r) = 0.055$; $g_c(r)$ is shown in Fig. 3. To have a better estimation of the average of the distribution, a fit of RDF was performed by using the Asymmetric Double Sigmoidal Function. This allowed an average of 15 km from the chosen centre to be used for the analysis. This is important because many EQL were large phenomena, extending perhaps 10 km, the same as for the diffuse lights and clouds, which were more visible in the periphery of L'Aquila than from the city centre because the outlying areas have fewer artificial lights. On the other side, the distribution tail of the RDF in Fig. 3 should also be investigated to have more information on the physical processes behind EQL and earthquake (Bak *et al.,* 1987). However, the distribution fluctuations increase as the distance $r$ increases due to the fact that the sampling was less uniform and less abundant in the area from L'Aquila. Since the fit to determine the true character of the process (Laherrere and Sornette, 1998) must be very robust, the tail of this distribution cannot be used.

In analogy with the studies of cumulative seismic moment as the most direct measure of seismic strain (Main, 1999), it was of interest to calculate the cumulative EQL time distribution with respect to the times of the principal shocks. As described above, the witnesses were not uniformly distributed throughout the territory and there is no proof that the manifestation of EQL was space-independent. Furthermore, the greater number of possible witnesses corresponds to a greater probability of more than one reported sighting of any one EQL. Given the interest in finding a physical link between earthquake and EQL, it is necessary to search for an EQL distribution, witness-independent result. Considering the EQL space-time distribution $h(r,t)$, the EQL spatial sum should be weighted with the PDF as in Eq. (1). Therefore, the corrected cumulative EQL time distribution $h_c(T)$ can be obtained by using

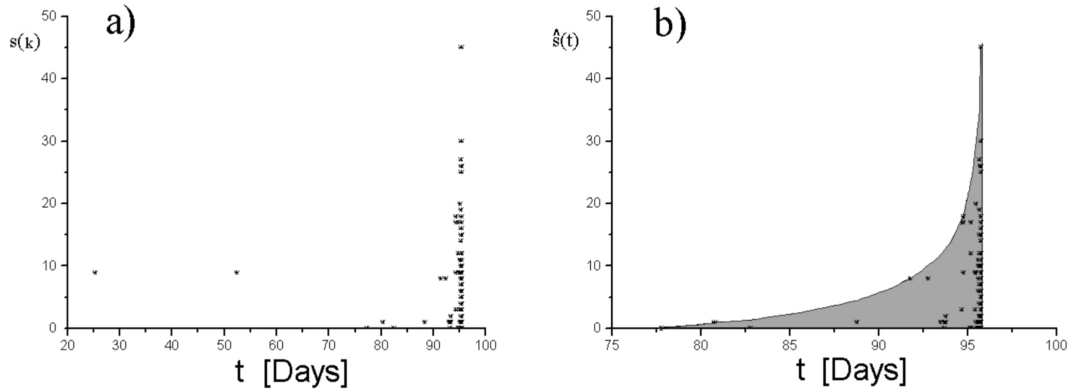


Fig. 5 - The maximum correlation length distribution of EQL with all the data before the principal shocks a); in b) the data for the last two weeks before EQ, the maximum correlation length is limited in the grey area by the power law in Eq. (4). Days are the time sum $t_E - t_L + t_M$, which corresponds to a index $k$ for the EQL events, where $t_E$ are the earthquake times listed in the supplement of Fidani (2010), $t_L$ is the luminosity time which was associated with the earthquake at $t_E$ and $t_M$ is the main shock time.

$$h_c(T) = (L/N)\ \Sigma_{k=1}^{T}\ \Sigma_{r=1}^{R}\ h(r,k)/l(r), \qquad (2)$$

where $h(r,k)$ is the function which gives the observed EQL number at distance $r$, with the integer index $k$ referred to the discrete time $t_E - t_L + t_M$. Such time was defined referring to Table 1 and the supplement of Fidani (2010) with $t_L$ the EQL time, $t_E$ the earthquake time associated to the EQL and $t_M$ the main shock time. $\Sigma_{k=1}^{T} h(r,k) = n(r,T)$ is the cumulative number of EQL at distance $r$ up to event $T$. The corrected cumulative EQL time distribution is plotted in Fig. 4b; it is very well fitted by the power law

$$h_c(t) = h_o + a\ (t_o - t)^{-\alpha}, \qquad (3)$$

with $h_o$ = -0.31, $a$ = 15.85, $t_o$ = 95.15 and $\alpha$ = 0.54. Fig. 4a shows the EQL time distribution before the PDF correction, the fit can be also made by the power law in Eq. (3) with $h_o$ = 0.45, $a$ = 3.11, $t_o$ = 95.18 and $\alpha$ = 0.95. The power law (3) describes an acceleration in the EQL phenomena which does satisfy the critical point hypotheses (Sornette and Sornette, 1989). An exponential law was also used to describe acceleration but no good fit was obtained.

Finally, the maximum correlation length $s(k)$ between the $k$ EQL positions and the principal shock epicentre was analysed for precursory EQL. In this case, the maximum correlation length was not calculated between EQL positions in analogy to the correlation length of the seismic case (Zoller *et al.,* 2001), this was based on the hypotheses that EQL phenomena could be in strict relation with underground physical conditions that produces the earthquake (St-Laurent *et al.,* 2006; Freund *et al.,* 2009). The maximum correlation is depicted in Fig. 5a. Based on the assumption that the growth of the correlation length is only observable in the last time interval, where the signal exceeds the noisy background (Zoller *et al.,* 2001), the data considered started on March 15, 2009. The shadow area of Fig. 5b is the area covered by maximum correlation length. The maximum correlation length increases until it reaches a singularity point as the time approaches that of principal shocks. Such an increase can be evaluated by considering the fit of the limiting curve of the shadow, this was obtained through the power law

$$s(t) = s_o + d\,(t_o - t)^{-\lambda} \quad (4)$$

with $s_o$ = -17.59, $t_o$ = 95.20, $d$ = 36.39 and $\lambda$ = 0.25. The value for the exponent $\lambda$ was found to be equal to that suggested from a theoretical point of view clarifying the physics of the frictional sliding processes (Rundle *et al.,* 1996).

## 4. Conclusions

In this work eight sightings were added to the L'Aquila EQL collection based on information collected in the same manner as in the past. Colour and distance information was added to the past description, where red lights appeared in greater number. A geographical distribution of EQL colours was also shown.

A digital method that takes into consideration the non-uniform distribution of eyewitnesses is proposed for the first time. It was used to obtain the corrected EQL spatial and temporal distributions. This makes data less dependent on the population distribution and suitable for further statistical analysis. The corrected RDF was calculated and showed that two things are important when collecting witness information: 1) a denser sample number up to a distance of five fault lengths is necessary in order to describe the EQL distribution tail and 2) the spatial extension of the EQL.

Acceleration was reported in EQL time distributions and in EQL maximum correlation length which were modelled by power laws, the critical exponents were near to that theoretically found by physical hypotheses. However, to have a definitive result on the nature of the EQL as critical phenomena is necessary to define an EQL amplitude and to calculate the already defined correlation length (Zoller *et al.,* 2001). This work is a stimulus to study in depth this possibility. As it is due principally to the limited accuracy of data collected by interviews, a previously proposed (Fidani, 2010) instrumental observation system is desirable.

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