Rotational effects associated with ground motion during the M_w 6.3 2009 L'Aquila (Central Italy) Earthquake

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ABSTRACT

The M_w 6.3 2009 L'Aquila (Central Italy) earthquake produced more than one hundred rotational effects on chimneys, pillars, capitals and gravestones. In this paper we focus on the 37 objects that can be more reliably considered as representative of pure rotational ground motion, and find a relation between the distribution of the observed rotations, the epicentral distance, the macroseismic intensities and the directivity effects that characterize the L'Aquila event. We also find sound relationships between the type of observed rotations and the geophysical, geotechnical and geomorphological characteristics of the site of observation. In downtown L'Aquila we find 1) a remarkable convergence between distribution of the rotations and of the damage; 2) 100% of the rotations occurred at sites characterized by high factors of amplification and poor geological setting; 3) the ground rotations are not strongly dependent on topographic

effects. Finally, from quantitative analyses of GPS data we find that the effect of the seismic arrival on an individual vertical object retrieved rotated is an overall rotation with a substantially unpredictable direction.

INTRODUCTION

Seismic actions are generally developed in terms of translational ground motion, as the rotational counterparts of motion are mostly ignored. This is the consequence of the fact that earthquake-induced ground rotations have always been considered too small and too difficult to measure with accuracy. Conversely, such rotational effects, often regarded as a weird and astonishing phenomenon, have been known and were widely reported for centuries. The first significant instances of earthquake-induced rotational effects were provided by the M~7 1783 Calabria event and the M~7 1857 Great Neapolitan Earthquake, both occurred in southern Italy. In particular, the occurrence of the 1857 event allowed Mallet (1862) to formalize a number of mechanisms that satisfactorily explained the observed rotations. Subsequent reports about earthquake-induced rotational effects described relevant rotational motions in the near fault region of the M=7.8 San Francisco (Jenista, 1906-1907), M=6.9 1974 Izu (Yamaguchi and

Odaka, 1974) and M=6.8 1988 Armenia (Yegian et al., 1994) earthquakes. Finally, Sargeant and Musson (2009) provided a compendium of observations of rotational effects from low to moderate earthquakes occurred in the United Kingdom.

In this paper we describe some of the rotational effects associated with the 2009 M_w6.3 L'Aquila earthquake (Figure 1). The L'Aquila event occurred at about 9.5 km depth on the Paganica Fault (Vezzani and Ghisetti, 1998), a NW-trending, SW-dipping seismogenic source quite clearly defined by the seismicity distribution (Chiarabba et al., 2009), the focal mechanism of the mainshock (Pondrelli et al., 2010), the GPS and DinSar modelling (Anzidei et al., 2009; Atzori et al., 2009; Papanikolaou et al., 2010), and the pattern of coseismic surface fractures (Boncio et al., 2010; Emergeo Working Group, 2010).

The macroseismic survey of the 2009 earthquake (Galli et al., 2009) showed that the largest damage was mainly distributed in a NW-SE direction and noticeably located SE of the instrumental epicenter, thus providing evidence of important directivity effects. During the macroseismic survey, we collected and classified an impressive number of rotational effects on buildings, monuments in villages and cemeteries and articles of furniture. The rotations

affected more than one hundred vertically organized objects such as chimneys, pillars, capitals and gravestones.

Cucci and Tertulliani (2011) first presented the whole dataset of rotational effects induced by the L'Aquila earthquake, finding a significant convergence between the distribution of the rotations and of the damage. They also put in evidence that some geological factors (lithology and site amplification) influence the rotational effects more than the seismological factors (slip distribution). In this work we try to establish more sound relationships between the type of observed rotations and the geophysical, geotechnical and geomorphological characteristics of the site of observation. Also, we focus on the particular situation in downtown L'Aquila where the extension of the settlement does not allow us to consider it as a single site. Moreover, in order to assess if the earthquake induced a specific direction of rotation, we analyze high frequency data of two GPS stations located in the area where earthquake-induced rotational effects have been observed (Figure 1).

ANALYSES OF ROTATIONAL EFFECTS

Past studies have emphasized the role played by a number of site and source effects in enhancing the earthquake-induced rotations. In particular, the changes of rupture velocity (Bouchon and Aki,

1982; Takeo and Ito, 1997) the local rheology (Huang, 2003; Spudich and Fletcher, 2008), and topographic effects (Stupazzini et al. 2009) have been called for as important contributors to local rotations. However, in the analyses of the observed rotational effects sometimes it can be difficult to discriminate between true rotational motion and translational motion (Hinzen et al., 2010). Asymmetrical distribution of mass and stiffness are quite common in buildings without anti-seismic design, and could cause rotational modes whose participating mass exceeds the one involved in translational modes. Rotational modes have also been observed at some given frequencies in a reinforced concrete building, explainable with irregularities and eccentricity in respect of the main geometrical axes (Mucciarelli et al., 2011). In some cases, the rotation observed on a particular object can likely derive from non-uniform frictions on its support. For this reason, starting from the two classes of rotational effects (free-field-based or building-based objects, see Figure 2) suggested by Cucci and Tertulliani (2011) we focussed our analyses only on the free-field-based (ffd hereinafter) objects. Ffd objects like tombstones, gate pillars and monuments (Figure 3) rest directly on the ground, are not affected by rotational modes of the underlying structure, and can be considered as representative of pure rotational ground motion.

Therefore, the original dataset with 105 observations at 37 different sites (see Table 1 in Cucci and Tertulliani, 2011 for the full description of the whole dataset) is now reduced to 37 effects observed at 15 localities. To check for correlation between distribution of ffd rotations and local geological pattern, we superimpose our data on a map (Figure 4) prepared merging data from i) the geological map by Vezzani and Ghisetti (1998), that provides the background geological information; ii) the seismic microzonation map by the Italian Civil Protection (http://www.protezionecivile.it/jcms/it/microzonazione_aquilano.wp?toptab=1 - top-content), that shows the sites prone to amplification of the seismic signal on the bases of geomorphological observations and geotechnical prospections, and iii) a detailed geological survey of the sites of observations. On this basis the terrains are divided in two different classes according to their characteristics, either 'stable' (e.g. unfractured outcrops of limestone/flysch bedrock not affected by amplification) or 'not stable' (e.g. artificial landfills, fluvial and lacustrine deposits, alluvial fans, slope deposits, fractured/weathered bedrock with evidence of amplification) sites.

Figure 4 and Table 1 show the results of the comparison between the distribution of ffd effects and the geological characteristics of

the sites of observation. Two rotations out of 37 observations (5%) were observed on stable sites, 35 were observed on not stable sites (95%). Performing our calculations on the number of localities where at least one rotation was observed, we find that the not stable sites are 13 out of 15, the 87% of the total. We also checked the classification stable/not stable for all the other 33 sites, located in the near fault region, where rotational effects did not occur. In this case the occurrence provides percentage rates remarkably balanced between stable and not stable sites (48% and 52% respectively, Table 1).

ROTATIONS OBSERVED DOWNTOWN L'AQUILA

A particular case we examine in this study is that of downtown L'Aquila, where severe damage occurred (Imcs VIII-IX) and where we retrieved many rotated objects. Within the historical centre of L'Aquila we observed 24 rotated objects, 15 of which are ffd. They are columns, pillars, statues, chimneys and ornamental marble blocks (Figure 5) retrieved rotated after detailed surveys. The extension of the settlement and the fact that a remarkable number of rotations were observed in the old city required a more detailed approach in terms of geological/geomorphological survey and seismic microzonation. Therefore, we conveyed to Figure 6 all the

information available from the geology of the area (Gruppo di lavoro MS_AQ, 2010) and from the map of the amplification factors (Milana et al., 2011).

The historical centre of L'Aquila is settled on a fluvial terrace formed by Quaternary breccias ("Megabrecce" *sensu* Demangeot, 1965) of variable thickness and stiffness (Blumetti et al., 2002). In the southern part of the city a formation of reddish silts (L'Aquila Red Silts (Gruppo di lavoro MS_AQ, 2010) outcrops over the marly breccias. The terrace is carved by fluvial incisions filled by colluvial deposits of limited thickness. Instrumental measurements of seismic noise and microtremors (De Luca et al., 2005; Milana et al., 2011) highlighted the presence of amplification of the ground motion throughout the historical centre, with particular emphasis in the areas where Red Silts outcrop. Amplification factors higher than 2 have been determined. Microzonation activities (Gruppo di lavoro MS_AQ, 2010), performed during and after the 2009 sequence have also enlightened that the breccias do not continuously extend and are substituted in places by the Red Silts. Ground motion analyses confirmed that all the historical centre of L'Aquila is prone to local amplification, with amplification factors bigger in the area of the city where the Red Silts outcrop and

where a velocity reversal due to geological conditions was demonstrated by Bordoni et al., (2011).

The analysis of the ground motion is in good agreement with the distribution of the damage, more severe in the Red Silts zone, and in general in the central and south-western parts of the city (Tertulliani et al., 2011). In fact several total collapses of reinforced concrete buildings occurred in that area as opposed to the north-eastern sector of the city.

If we consider the trace of the watershed in the old town (represented by the main NNE-SSW street, see Figure 6), all the rotations are placed in the western sector of the city where also the major damaged areas are located. It is interesting to note that within the downtown we retrieved several multiple observations (observations of rotated objects in the same place, for instance Palazzo Camponeschi and San Pietro a Coppito square) with non-coherent directions of rotation (both clockwise and counter-clockwise, see Figure 5). This observation would suggest that the direction of the rotation was not affected by any other factor than the frictions and the physical constraints of the object itself.

ROTATION ANALYSIS BY HIGH FREQUENCY GPS DATA

Just a few days before the M_w 6.3 earthquake, five GPS stations acquiring data at different sampling rates (30 s, 1 s and 0.1 s) were installed in the epicentral area; these stations recorded the mainshock and permitted to properly resolve the near-field coseismic deformation pattern (Anzidei et al., 2009).

The GPS monuments can be rightly considered as ffd objects since they are concrete pillars funded on limestone outcrops and not installed on buildings. In order to deeply investigate if the earthquake triggered a specific direction of rotation, at least for this kind of objects, here we considered data at the highest available frequency (10 Hz) of GPS stations CADO and ROIO, both located in the area where earthquake-induced rotational effects have been observed (Figure 1).

We started from the horizontal components of motion (East, North) at CADO and ROIO in a topocentric Cartesian reference frame (Serpelloni et al., 2009), relating to a few minutes around the mainshock epoch (1:32:40 UTC). For each observation epoch (sampling 0.1 s) we calculated the signed curvature of the planar trajectory, defined as

$$k = \frac{\dot{x}\ddot{y} - \dot{y}\ddot{x}}{(\dot{x}^2 + \dot{y}^2)^{3/2}}$$

where $\dot{x}, \dot{y}$ and $\ddot{x}, \ddot{y}$ are the first and second time derivatives of the two horizontal components *x* and *y* (in our case East and North), respectively. The sign of the signed curvature *k* indicates the direction in which the tangent vector rotates: if it rotates counter-clockwise, then $k > 0$, if it rotates clockwise, then $k < 0$.

The absolute value of *k* is the reciprocal of the radius of curvature *R*, i.e. the radius of the osculating circle to the trajectory

$$|k| = \frac{1}{R}$$

The computed curvatures of the two GPS planar trajectories turn out to be very noisy and to constantly change their sign, thus indicating continuous variations in the direction of the rotation (from clockwise to counter-clockwise and viceversa). Figure 7 (a, b) shows the 10 Hz-time series of the East and North components and a moving average of the curvature (used to partly smooth out short-term fluctuations) for the two GPS sites, in the time span from 1:32:10 to 1:33:30 (UTC).

Despite the high background noise, it is nevertheless possible to highlight some particular features related with the earthquake occurrence. At the first seismic arrivals (earlier at ROIO than at CADO as ROIO is closer to the epicentre) there are not large amplitude pulses at both GPS stations and both the corresponding

curvatures do not show particular variations in their behaviours, keep being noisy, with large values (corresponding to little curvature radii), and constantly changing sign.

The large amplitude portion of GPS signals (which cannot be modelled as a source effect, but probably as a fault zone resonance (Avallone et al., 2010)) occurs about 5 s after the beginning of the deformation at each site and spans about 7 s (Avallone et al., 2011); in this time span the curvatures seem to change their trend: values suddenly become close to zero, indicating almost infinite curvature radii, i.e. straight trajectories.

High frequency GPS data seem to highlight that the first seismic arrivals didn't induce rotations with a well-defined direction, whilst they put in evidence that the following large amplitude effects probably triggered a rectilinear motion. Likely, the resulting effect on ffd objects is an overall rotation with an unpredictable direction.

DISCUSSION AND CONCLUSIONS

The first main purpose of this paper was to check whether and how some geophysical observables influence a number of objects retrieved rotated following the 2009 L'Aquila earthquake. To this aim we preferred to reduce the original dataset investigated by Cucci and Tertulliani (2011) from about 105 to 37 rotational effects

(ffd rotations) more reliably affected by pure ground rotational motion. The analysis of our data confirms and corroborates a series of distinctive features of the L'Aquila earthquake-induced rotations that were first glimpsed by Cucci and Tertulliani (2011) with the large dataset. The relationship between the distribution of the observed rotations, the epicentral distance, the macroseismic intensities and the directivity effects are further put in evidence when referred to ffd-type objects. As a matter of fact, the great majority of the ffd rotations are located in the epicentral area (within ~20 km from the instrumental epicenter) and where the MCS intensity is between VII and VIII-IX. Moreover, the evident asymmetry in the distribution of the ffd rotations (observed only SE of the epicenter) closely resembles the southeastward directivity of the macroseismic effects.

As for the geological and seismological parameters that can influence the occurrence and the distribution of the rotational effects, Cucci and Tertulliani (2011) already put in evidence that the relation between rotations and pattern of slip distribution on the fault plane is quite feeble, in particular for those objects that are potentially affected by rotational modes of the underlying structure. For this reason we chose to focus on the geological aspects of the question. Actually, what was an absolute majority (82-83%) of data

where the geological factors affect the site of observation in Cucci and Tertulliani (2011), now becomes a overwhelming majority of 95%. If we consider each locality as a single datum independently from the number of rotations observed (a very conservative choice that does not take into account the frequent case of multiple observations at a same site) this percentage is still 87%. Conversely, a quick look at the partition stable/not stable (48%/52%) of those sites where rotational effects did not occur further strenghtens our results. The result of this first part of investigation is that scarce geophysical and/or geotechnical characteristics or unfavourable geomorphological conditions at the site deeply influence the occurrence of earthquake-induced rotations.

The second main purpose of this work was to verify if the same kind of investigations carried out at the scale of the mesoseismic area (~500 km^2) provide similar results when applied at the local scale as in the case of downtown L'Aquila (~2 km^2). Also in this case we find a remarkable convergence between distribution of the rotations and of the damage, as 14 rotational effects out of 15 are located in the southern and western most severely damaged part of the old town (Figure 6). In addition, all the rotations are distributed west of the local watershed, that runs in a ~N-S

direction and roughly divides the historical centre in two specular halves that are topographically very similar. From this observation we can deduce as a first order evidence that ground rotation is not strongly dependent on topographic effects, at least in the case of L'Aquila. Moreover, our studies in downtown L'Aquila emphasized the influence of bad characteristics of the terrain on the rotational effects, as 100% of the rotations occurred at sites classified 'not stable' and characterized by high factors of amplification and poor geological setting.

Finally, the third purpose of the paper was to find specific relationships between the direction of rotation and the site of observation, i.e. if the clockwise or counterclockwise sense of rotation observed is predictable at a certain site. The results of this first attempt of a quantitative analysis of the data confirm that the clockwise/counterclockwise datum can not be reliably associated with any seismological observables, as already suggested by the inconsistent sense of rotation witnessed sometimes at a same site. Indeed very high frequency GPS data seem to confirm that the earthquake didn't bring about a particular direction of rotation on objects: this direction would not be affected by any other factor than the frictions and physical constraints of the object itself.

ACKNOWLEDGEMENTS

We want to thank R. Devoti and F. Riguzzi for fruitful discussions, and E. Serpelloni for having provided the high frequency time series of the GPS coordinates. We also thank A. Rebez and an anonymous reviewer for several suggestions that improved the paper.

Figure 1

Map of the study area (modified from Cucci and Tertulliani, 2011). The focal mechanism by Pondrelli et al. (2010) indicates the position of the epicenter of the 2009 L'Aquila earthquake. Aftershock distribution from ISIDe, the Italian Seismic Instrumental and parametric Data-basE (http://iside.rm.ingv.it/iside/standard/index.jsp). A solid curved line encircles the area where earthquake-induced rotational effects (both building-based objects and free-field objects, see below in the main text) have been observed. Triangles mark the location of the two GPS stations CADO and ROIO. We also indicate the surface expression of the normal Paganica Fault (hachures on the hanging wall).

Figure 2

The sketch represents the two main typologies of rotations observable in the field. (a) Building-based object: chimney in Pianola (3 km from the epicenter). Building-based objects like chimneys, furniture and some pillars are usually placed on top of a building or a construction and can be affected by rotational modes of the underlying structure. (b) Free-field object: pillar at the L'Aquila University (2 km from the epicenter). Free-field objects like tombstones, gate pillars, capitals, monuments and some statues rest directly on the ground, are considered reliably representative of pure rotational ground motion, and constitute the dataset of this work.

Figure 3

Examples of ffd rotations observed following the L'Aquila earthquake.

Figure 4

Distribution of ffd rotational effects induced by the L'Aquila earthquake and geological characteristics of the sites of observation (numbers in parenthesis indicate multiple observations associated to the same location). The terrains are divided in either 'stable' or 'not stable' according to their geophysical/geotechnical/geomorphological characteristics. Crossed circles indicate sites where rotational effects did not occur. A black star shows the location of the epicenter of the L'Aquila earthquake. Triangles mark the location of the two GPS stations CADO and ROIO.

Figure 5

Examples of ffd rotations observed in downtown L'Aquila.

Figure 6

Distribution of the ffd rotational effects, geology and amplification factors in downtown L'Aquila. Circles mark the sites of the observed rotations (numbers inside the circles indicate multiple observations associated to the same location). Differently grey shaded areas represent the main geological outcrops in the old town (simplified from Gruppo di lavoro MS_AQ, 2010). Legend: Ba, breccias of L'Aquila (middle Pleistocene); Lr, red silts (middle-upper Pleistocene); Fd, fluvial and colluvial deposits (upper

Pleistocene-Holocene). Squares indicate the AF evaluated from aftershocks in the 2-10 Hz range by Milana et al., (2011). A black curve separates the area of more severe damage localized southwest in the map. A dashed line marks the local watershed.

Figure 7

10 Hz-time series of the East and North components (top) and curvature (moving average) (bottom) for the two GPS sites, CADO (a) and ROIO (b), in the time span from 1:32:10 to 1:33:30 (UTC) of April 6, 2009.

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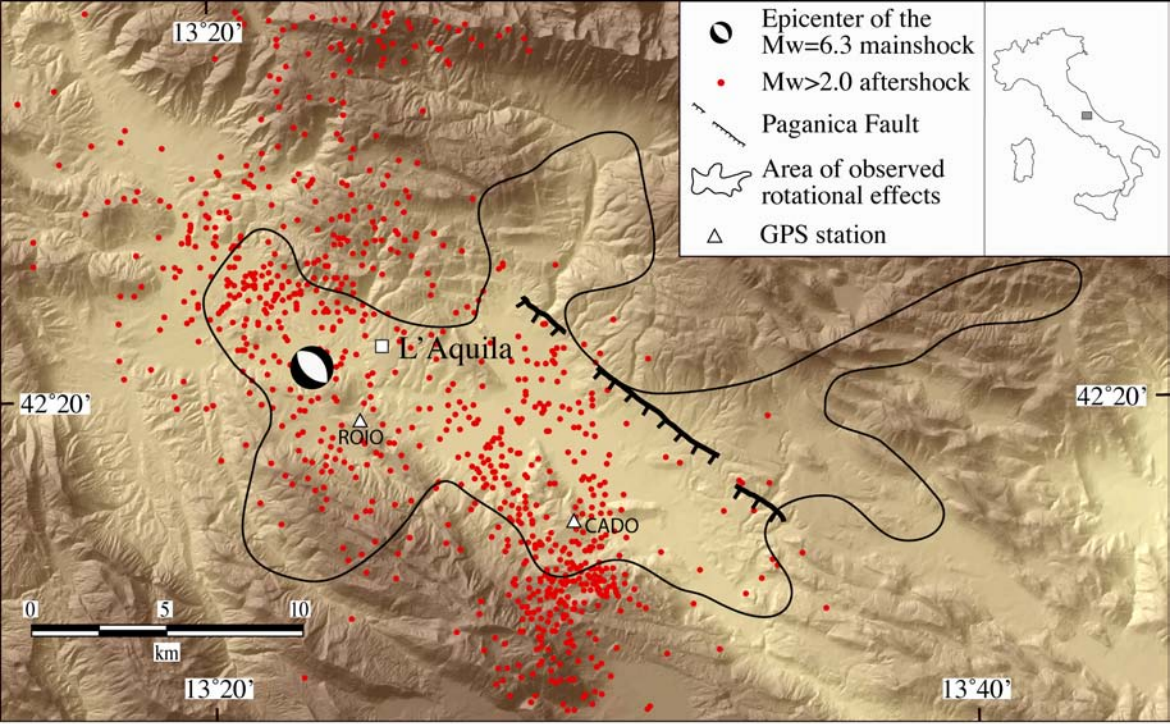

Epicenter of the Mw=6.3 mainshock
Mw>2.0 aftershock
Paganica Fault
Area of observed rotational effects
GPS station
13°20'
13°40'
42°20'
L'Aquila
RQIO
CADO
0
5
10
km

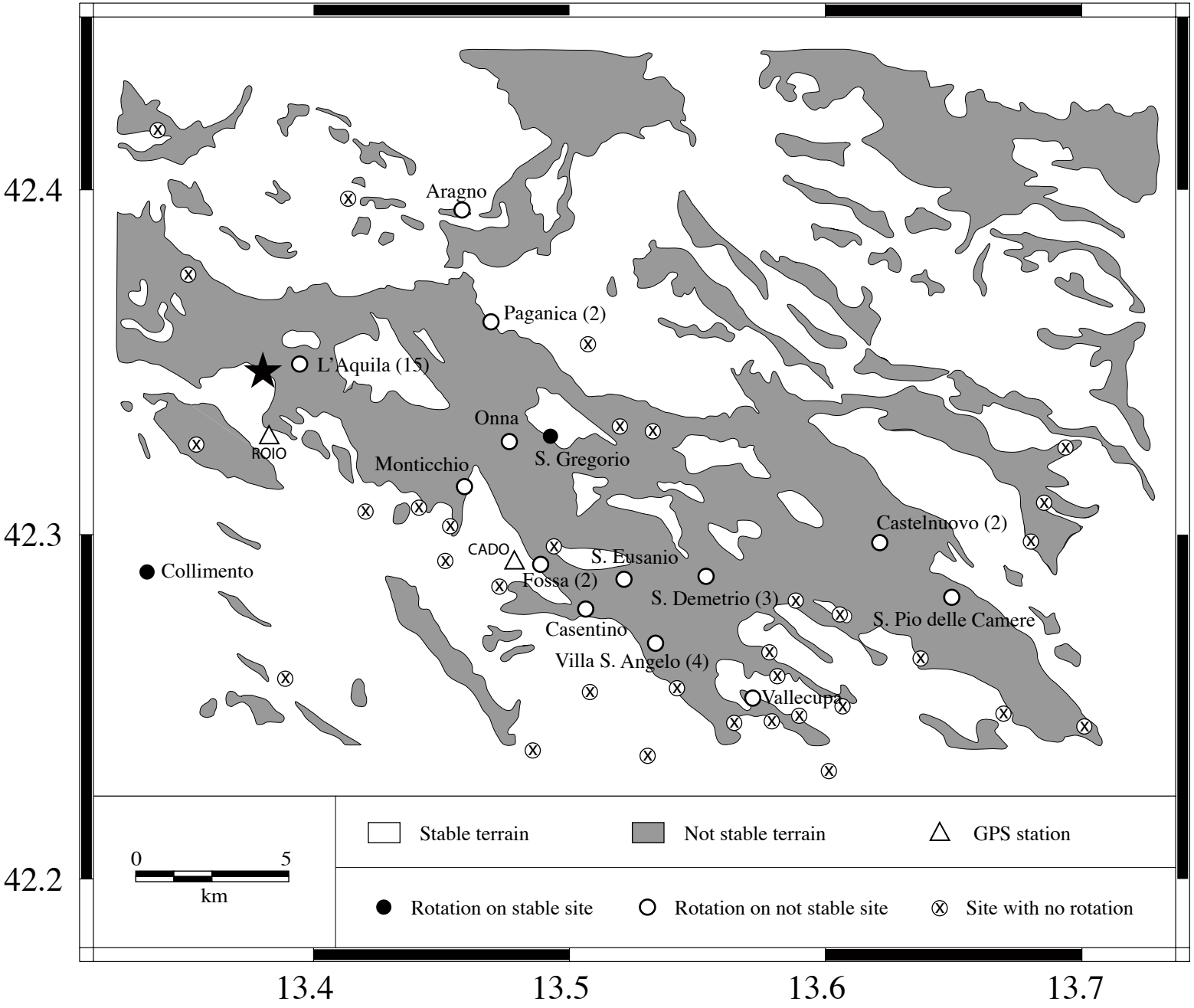
Figure 1

Figure 2


Sant'Eusanio
Castelnuovo
San Gregorio
RIPOSO
Villa Sant'Angelo
CONSACRANO
Castelnuovo
FIGLI DI PAGANICA
CONSACRATI ALLA GLORIA
DALLA SANTA OFFERTA
ALLA PATRIA
FIATE BENEDETTI
CADUTI GUERRA 1940-45
Paganica

Figure 3

Figure 4


42.4
42.3
42.2
13.4
13.5
13.6
13.7
Aragno
Paganica (2)
L'Aquila (15)
ROIO
Onna
S. Gregorio
Monticchio
Castelnuovo (2)
CADO
S. Eusanio
Collimento
Fossa (2)
S. Demetrio (3)
S. Pio delle Camere
Casentino
Villa S. Angelo (4)
Vallecupa
0
5
km
Stable terrain
Not stable terrain
GPS station
Rotation on stable site
Rotation on not stable site
Site with no rotation


nearby Corso Vittorio E.
13


San Pietro a Coppito


Palazzo Camponeschi


Porta Napoli

Figure 5

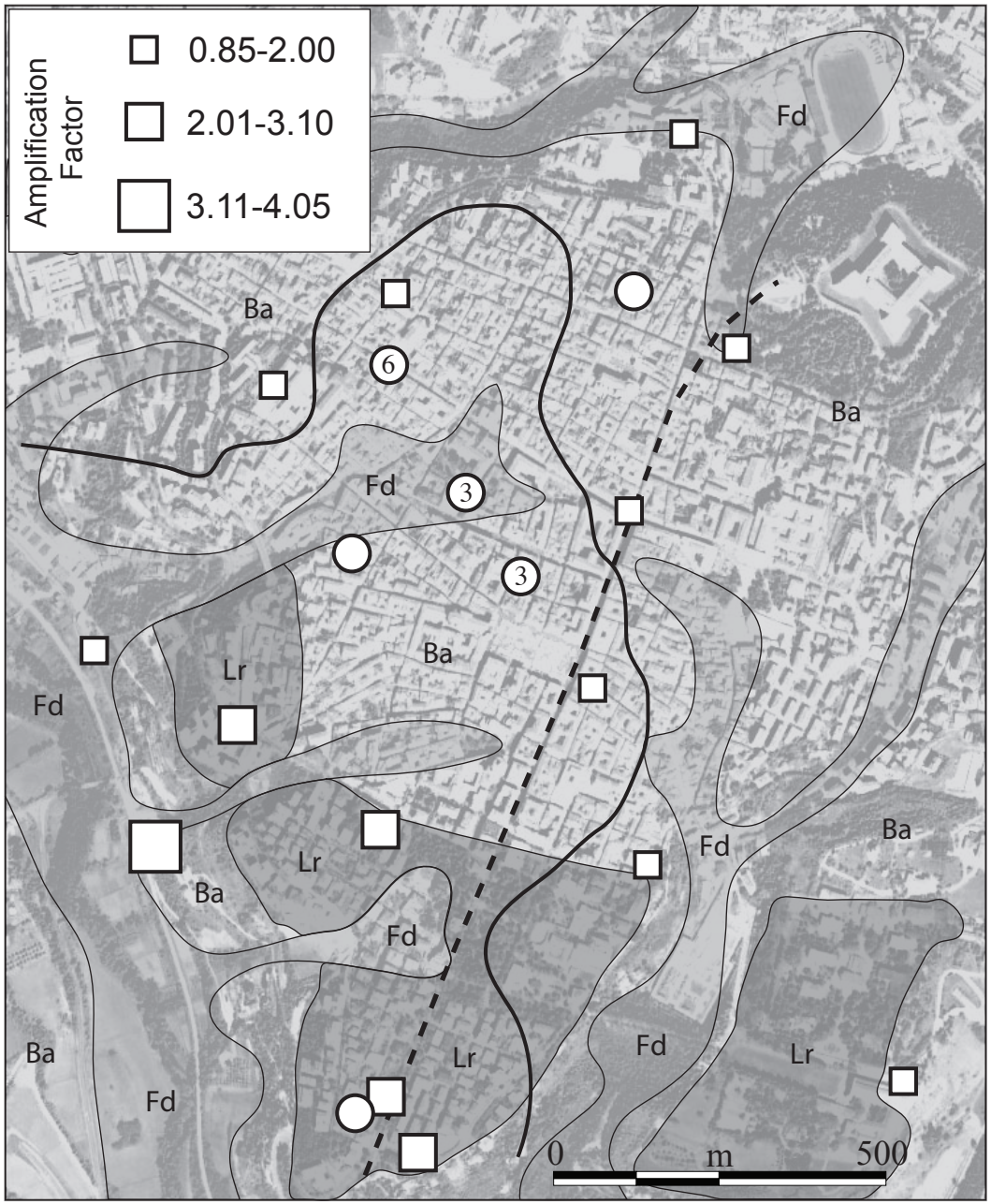
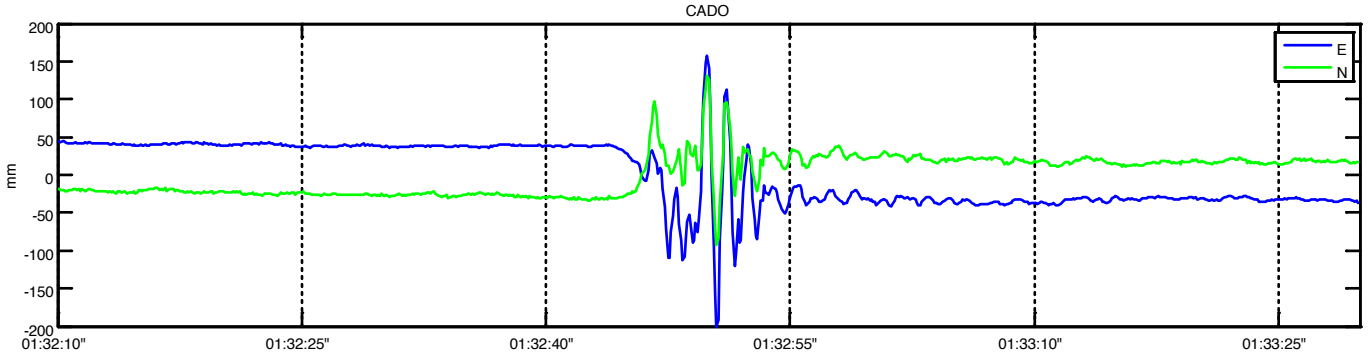
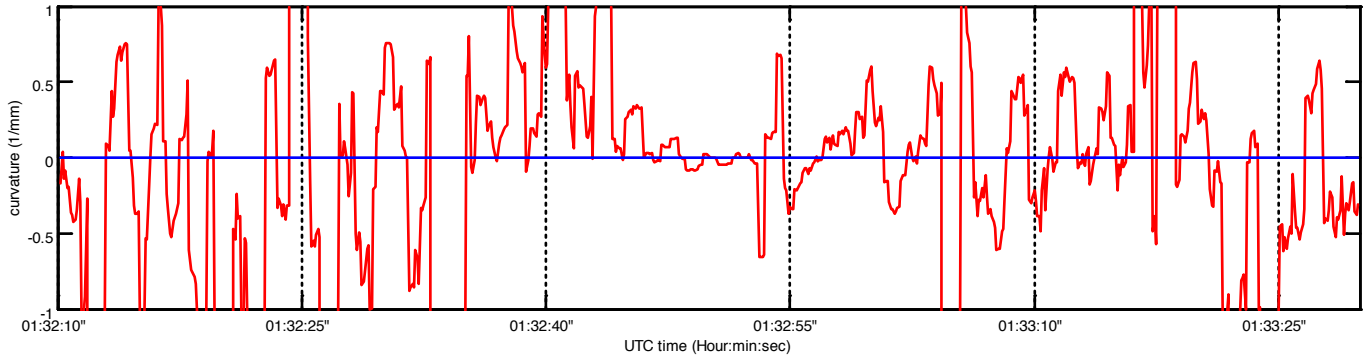
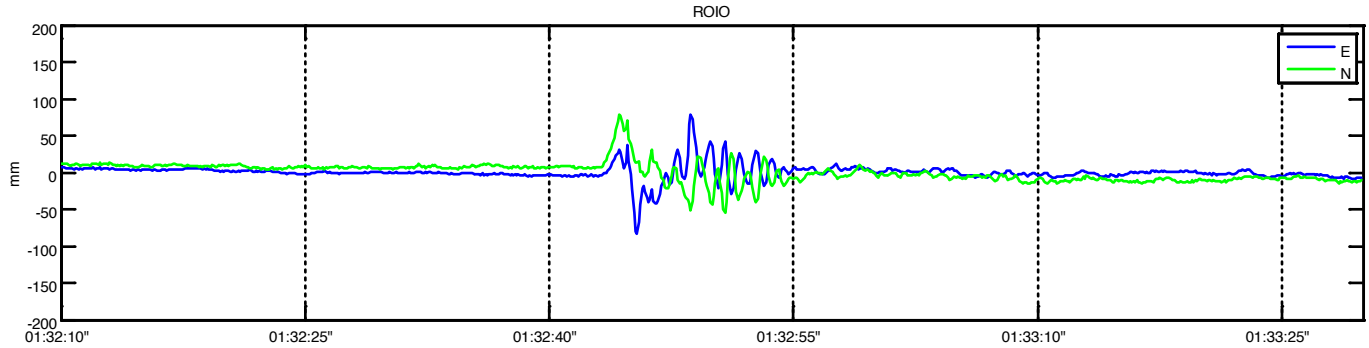

Amplification Factor
0.85-2.00
2.01-3.10
3.11-4.05
Fd
Ba
6
Ba
Fd
3
3
Ba
Lr
Fd
Ba
Lr
Ba
Fd
Fd
Ba
Ba
Fd
Lr
Fd
Lr
0
m
500

Figure 6


CADO
E
N
mm
200
150
100
50
0
-50
-100
-150
-200
01:32:10"
01:32:25"
01:32:40"
01:32:55"
01:33:10"
01:33:25"

a)


curvature (1/mm)
1
0.5
0
-0.5
-1
01:32:10"
01:32:25"
01:32:40"
01:32:55"
01:33:10"
01:33:25"
UTC time (Hour:min:sec)


ROIO
E
N
mm
200
150
100
50
0
-50
-100
-150
-200
01:32:10"
01:32:25"
01:32:40"
01:32:55"
01:33:10"
01:33:25"

b)

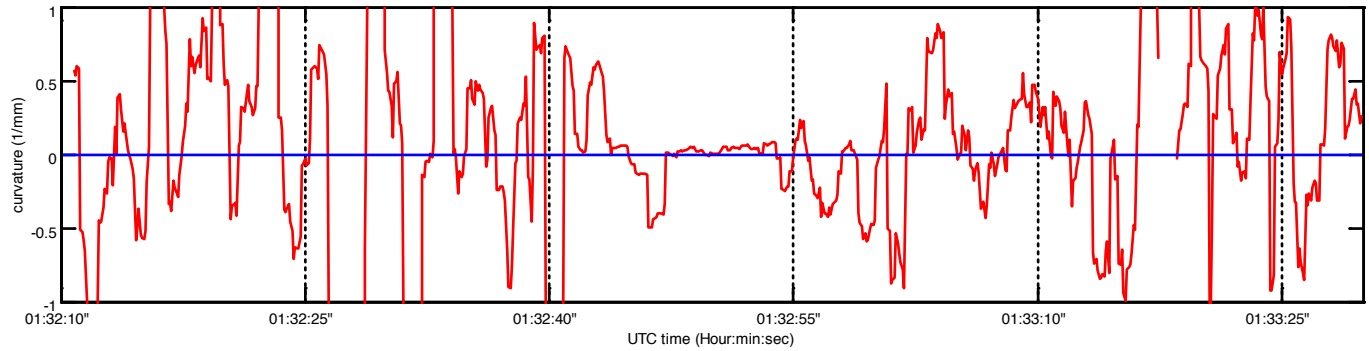

curvature (1/mm)
1
0.5
0
-0.5
-1
01:32:10"
01:32:25"
01:32:40"
01:32:55"
01:33:10"
01:33:25"
UTC time (Hour:min:sec)

Figure 7

Table 1 Comparison between observed rotational motions and geological characteristics of the site

	Number	Stable	Not stable
Observed rotations*	37	2 (5%)	35 (95%)
Sites with rotations†	15	2 (13%)	13 (87%)
Sites without rotations#	33	16 (48%)	17 (52%)

* Dataset of rotations: reports the total number of observations.
† Dataset of rotations: reports the total number of localities with at least one rotation.
# Sites where rotational effects did not occur.