FAST DETERMINATION OF MOMENT RUPTURE HISTORY: APPLICATION TO THE APRIL 6TH L'AQUILA EARTHQUAKE

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INTRODUCTION

On April 6th 2009, a magnitude Mw=6.1 earthquake strucks the Abruzzi region in central Italy**.** Despite its moderate size, the earthquake caused more than 300 fatalities and partially destroyed the city of L'Aquila and many villages in its surroundings. The main shock was preceded by an earthquake swarm which started at the end of 2008. The largest earthquakes of the swarm included a Mw=4.0, occurred on 2009/03/30 at 13:38 (UTC), and Mw=3.9 and Mw=3.5 events that occurred on 2009/04/05 at 20:48 and 22:39 (UTC) respectively. By the end of November 2009, more than 16,000 aftershocks with M_L>0.5 have been recorded by the INGV seismic network (Figure 1).

Current advances in data transmission and communication yield high quality broadband velocity and strong motion waveforms in near real-time. These data allow for the rapid characterization of earthquake sources in terms of fault geometry, focal depth and seismic moment. For the L'Aquila main shock, the velocimeter data of the Italian National Seismic Network (INSN, code IV), MedNet (code MN, station PDG), the North-East Italy Broadband Network (code NI, stations ACOM and PALA) and the SudTirol Province (code SI, station KOSI) were available in real-time. In the following days, the strong motion data of the RAN network ("Rete Accelerometrica Nazionale") and the displacement data recorded by the INGV GPS Network (Anzidei et al. 2009) also become available.

In this study we present the results of the rapid source parameters determination procedure developed at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) (Scognamiglio et al., 2009) as applied to the L'Aquila seismic sequence. Our approach consists of two stages – the near real-time determination of the seismic moment tensor, that is already routinely performed for all ML ≥ 3.5 earthquakes, and the rapid imaging of the rupture history on a finite fault for earthquakes with ML ≥ 6.0. We present the moment tensor solutions computed for all the earthquakes of the L'Aquila sequence with ML ≥ 3.5, and examine the effect of the velocity structure on the main shock moment magnitude. Then we provide a detailed description of the kinematic source model of the main event by inverting both strong motion and GPS data

Time Domain Moment Tensor Solutions (TDMT) for ML > 3.5 earthquakes.

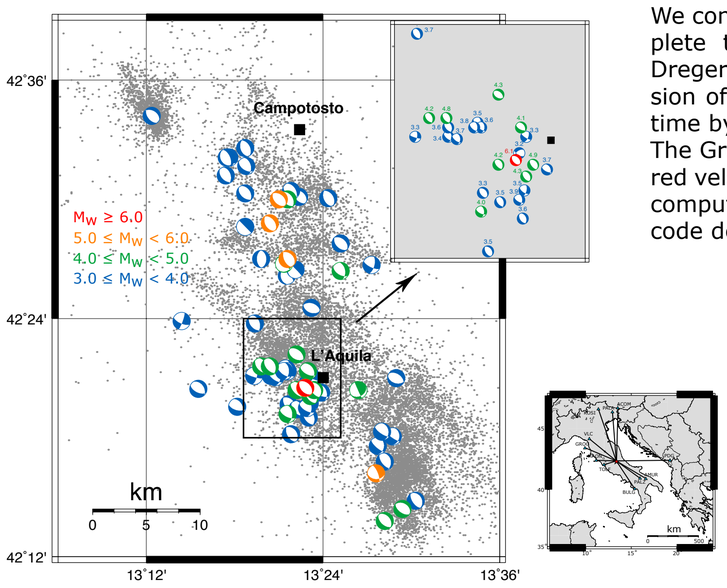

FIGURE 1

We compute **64** moment tensor solutions (Figure 1) using the complete time domain waveform inversion technique proposed by Dreger and Helmberger (1993). The algorithm performs an inversion of band-passed ground velocity waveforms gathered in real-time by the INSN.
The Green's functions (i.e., flat Earth, laterally homogeneous, layered velocity structures) used in this procedure have been previously computed and stored using frequency-wave number integration code developed by Saikia (1994).

Moment tensor inversion Parameters

Velocity Structure: TDMT model for ML≥ 4.0
nnCia.mod for 3.5 ≤ ML < 4.0
Inverted frequency: [0.02-0.05] Hz for ML ≥ 4.1
[0.02 - 0.1] Hz for 3.5 ≤ ML < 4.1
Inverted data: displacement waveforms for ML≥ 4.1
velocity waveforms for 3.5 ≤ ML < 4.1

The focal parameters were found to be strike 139°, dip 48°, rake -87 (Figure 2). A good waveform fit (variance reduction, VR, of 71.8%, and percentage of double couple, DC, of 94%) was found using 11 stations in the distance range of 113-489 km having a relatively small azimuthal gap (110°). The preferred depth, 9 km, agrees with the INGV-bulletin one, implying that hypocenter and centroid depths are consistent. The solution features a normal fault mechanism with a seismic moment of Mo=1.62e+25 dyne cm corresponding to a moment magnitude of Mw = 6.08 (Kanamori, 1977).

The relevance of the velocity model on scalar moment

To verify the effect of the velocity structure on the scalar moment we invert the same 11 waveforms used for computing the main-shock TDMT solution, at depth of 9 km, in the frequency band 0.02-0.05 using the other two different velocity models shown in Figure 3.
Red curve is the velocity model routinely adopted by the TDMT procedure, blue curve is the nnCIA.mod (Hermann *et al.* 2009), while green curve is the PREM81 velocity model.

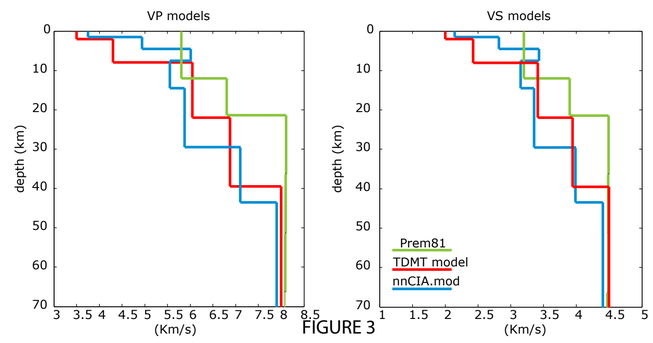

FIGURE 3

The resulting moment tensors (Figure 2 and 4A-B) show comparable fault geometry, a good fit (VR > 58% and DC > 85%), and MW of 6.08, 6.09 and 6.28, respectively.

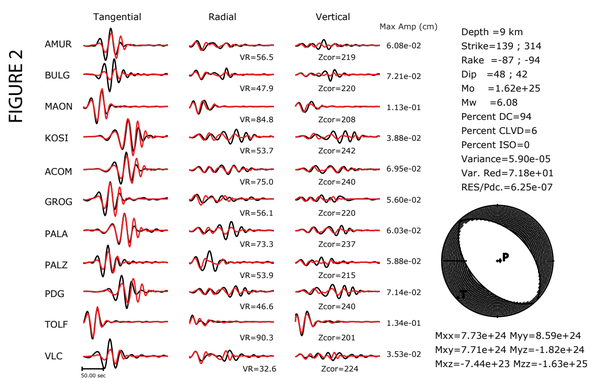

FIGURE 2

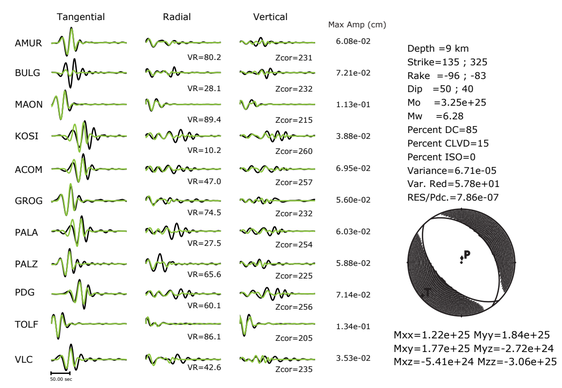

FIGURE 4A

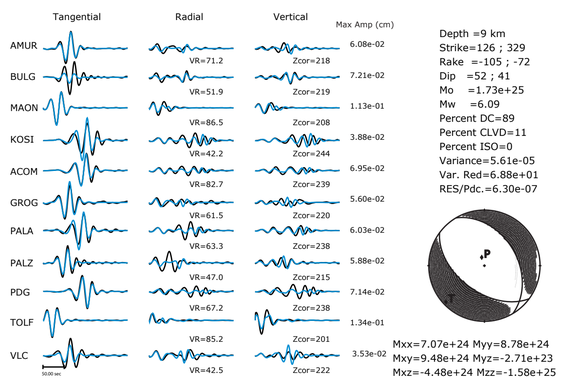

FIGURE 4B

Finite Fault Solution for the Main Shock

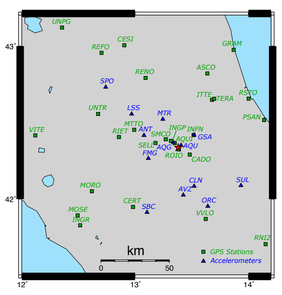

FIGURE 5

We use the L'Aquila main shock as a case study to test the potential of the procedure recently implemented at INGV to rapidly determine finite fault rupture models. The code, based on the work of Hartzell and Heaton (1983) and subsequently developed by Dreger and Kaverina (2000), consists of a non-negative least-square inversion method with simultaneous smoothing and damping.
In order to determine the extended fault model for the L'Aquila main shock, we have inverted the recordings from 13 three-component digital accelerometers of the RAN Network and the AQU (MedNet) accelerogram; moreover, in the final inversion attempts, we have also inverted 27 GPS horizontal displacements retrieved by the permanent stations of the INGV geodetic Network (Figure 5). The hypocentral distances of the selected recording sites and GPS benchmarks are less than ~100 km. The code inverts for slip and rake distributions, while we explored rise time and rupture velocity between 0.6 - 2.3 s and 1.6 - 4.0 km/s respectively.

Strong motion inversion

This model is characterized by a rise time of 0.7 s, a rupture velocity of 2.2 km/s, and a seismic moment of 2.238e+25 dyne cm corresponding to a Mw 6.17. It features a large, main slip patch located 2 km up-dip from the hypocenter and a second slip patch located ~8 km southeast from the hypocenter (Figure 6). We find also a deeper and smaller patch of slip located at 4 km down-dip from the hypocenter. The main patch up-dip from the hypocenter has a maximum slip of 88.5 cm, an average rake of -100°. Figure 7 shows the resulting fits to the recorded velocity time histories. The synthetic seismograms match better the recorded waveforms and the variance reduction is 68%.

Adopted Fault Parameters
Strike: 139°
Dip: 48°
Fault dimension: 16 km x 26 km
Top of the fault: 0.85 km
Subfault dimensions: 2 km x 2 km
Inverted frequencies: 0.02 - 0.5 Hz
Explored rise time: 0.6 - 2.3 s
SourceTimeFunction for slip velocity: triangle
Explored constant rupture velocity: 1.6 - 4.0 km/s
Rake variable on the fault plane: [-135 ÷ -45]
Velocity Structure: nnCIA.mod (Figure 3)

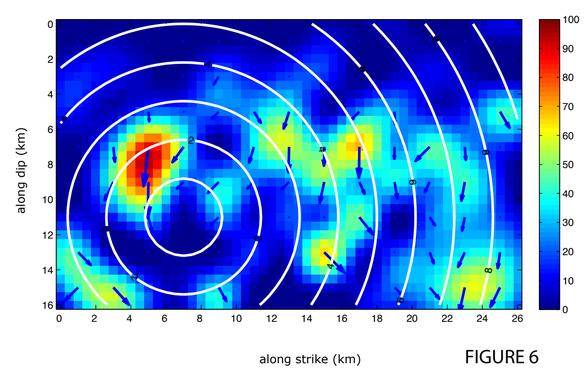

FIGURE 6

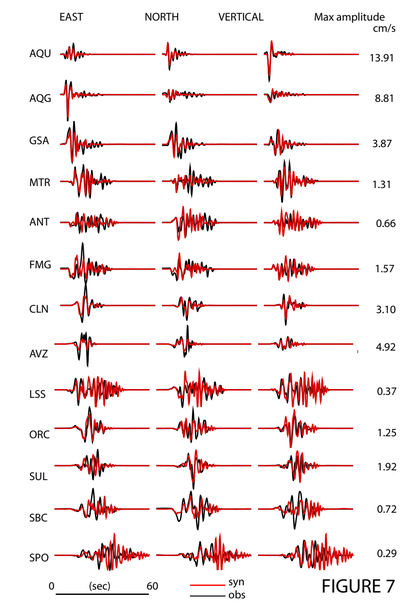

FIGURE 7

Strong motion and GPS inversion

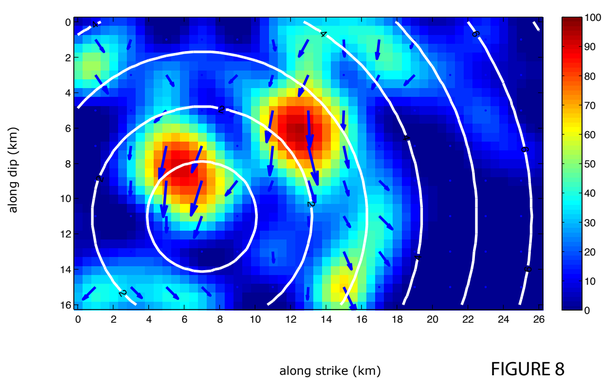

FIGURE 8

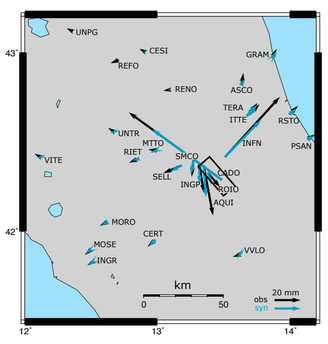

FIGURE 9

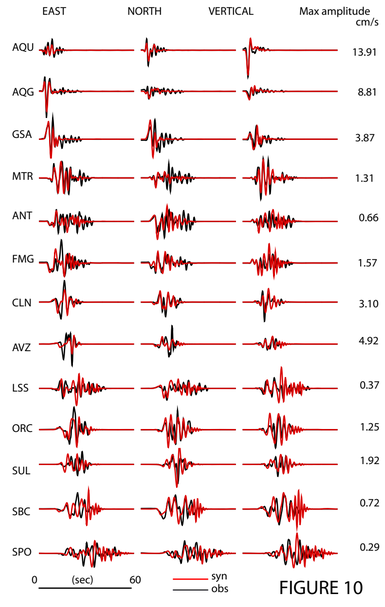

FIGURE 10

Our final rupture model shows well-constrained rupture directivity both up-dip from the hypocenter and SE along strike propagation.

In particular, the slip patch located southeast of the hypocenter and rupturing between 3 and 5 seconds is found to be a main feature of the rupture model and it is consistent with both the slip models obtained using similar data sets (Cirella et al., 2009; Piatanesi et al., 2009) and those that rely solely on satellite data of various types (Atzori et al., 2009; Cheloni et al., 2009).
In addition, focusing on the other main slip patch rupturing between 1 and 2 seconds and up-dip from the hypocenter, we have found that it is mostly required to fit the ground motion time histories recorded at AQU and AQG which are located nearly above and to the N-NW of the patch, respectively.
With regard to the rupture velocities, our two best fitting inversions (with and without GPS data) suggest similar and alternative fits using two different rupture velocities. This result can be explained by a heterogeneus distribution of these parameters on the fault plane. That is, we can account fot the variability and the uncertainties in constraining rupture velocity only if we introduce dynamic heterogeneities and/or geometrical complexities.

Figure 8 shows the retrieved best-fitting rupture model, corresponding to a variance reduction of 73.2%. This model has a rise time of 2.1 sec and a rupture velocity of 3.1 km/s. The scalar seismic moment is 2.515e+25 dyne cm corresponding to Mw 6.2. Figures 9 and 10 display the comparison between recorded and synthetic ground velocity time histories and the coseismic GPS horizontal displacements, respectively. The maximum slip is 88 cm. The average rake angles are 103° and 92° for the for the up-dip and southeast patches, respectively. The inferred slip pattern might suggest a smaller fault plane, roughly 20 km long and 16 km wide.

CONCLUSION

The obtained Moment Tensor solutions demonstrate that the adopted procedure represents an applicable tool for real time determinations. The differencies in fault geometry and scalar seismic moment shown in Figures 2 and 4A-B indicate that for the Italian region the moment tensor computation needs regionalised velocity models.

The rupture history of the L'Aquila main shock looks very complex. The adopted procedure catches the main energy releases of the kinematic rupture. The heterogeneities in rupture velocity and rake highlight a likely heterogeneous distribution of dynamic parameters driving the rupture process, or a complex geometry of the fault.

References:

Hermann B. and L. Malagnini (2009). *Systematic determination of moment tensor of the April 6th, 2009 L'Aquila earthquake sequence*. AGU Meeting U23A-0029.
Cirella A., A. Piatanesi, M. Cocco, E. Tinti, L. Scognamiglio, A. Michelini, A. Lomax and E. Boschi, (2009). *Rupture history of the 2009 L'Aquila earthquake from non-linear joint inversion of strong motion and GPS data,* Geoph. Res. Lett., 36, 2009.
Dreger D.S., and Kaverina A., (2000), *Seismic remote sensing for the earthquake source process and near-source strong shaking: a case study of October 16, 1999 Hector Mine earthquake*, Geoph. Res. Lett., 27,13,1941-1944.
Dreger D. S., and D. V. Helmberger D.V. (1993). *Determination of source parameters at regional distances with 3-component sparse network data,* J.Geophys. Res., 98, 8107-8125.
Scognamiglio L., E. Tinti, and A. Michelini, (2009), *Real-time determination of seismic moment tensor for the Italian region,* Bull. Seismol. Soc. Am., 99, 4, doi:10.1785/0120080104.