Bollettino di Geofisica Teorica ed Applicata Vol. 52, n. 3, pp. x-xx; September 2011
DOI 10.4430/bgta0020

Rapid determination of the shakemaps for the L'Aquila main shock: a critical analysis

L. Faenza, V. Lauciani and A. Michelini
Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

(Received: April 7, 2010; accepted: October 15, 2010)

ABSTRACT This paper describes the progressive generation of the shakemap of the L'Aquila, M_w 6.3 April 6, 2009, main shock at the Centro Nazionale Terremoti of the INGV. Since 2006 and as part of the national projects funded by the Italian Civil Protection and by the EU SAFER project, the INGV has been determining shakemaps for $M \geq 3.0$ using the USGS-ShakeMap software package and a fully automatic procedure, based on manually revised location and magnitude. Focus of this work is on the importance that the data and the extent of the finite fault have in the determination of faithful ground motion maps. For the L'Aquila main shock, we have found that the data alone are not sufficient to replicate the observed ground motion in parts of the strongly affected areas. In particular, since the station coverage toward the SE where the earthquake rupture propagated is scantier, prompt availability of a rupture fault model would have been important to better describe the level of strong ground motion throughout the affected area. The final maps, obtained using all the data available and a likely estimate of the causative fault, appear to provide a faithful description of the ground motion experienced throughout a large region in and around the epicentral area. A critical review of the various aspects relevant to the generation of the maps indicates that availability of strong motion data in the near source region is critical not only to the generation of the shakemaps but also to more routinely seismological analysis. It follows that data exchange among those institutions acquiring strong motion data is of fundamental importance for rapid characterization of the seismic source and of the area affected by the strong ground motion.

Keywords: L'Aquila earthquake sequence, strong ground motion, macroseismic intensity.

1. Introduction

On April 6, 2009 a M_W 6.3 earthquake struck the Abruzzi region in central Italy (e.g., Chiarabba *et al.*, 2009; Pondrelli *et al.*, 2010). The event caused severe damage in the town of L'Aquila (about 73,000 inhabitants) and in dozens of villages located along the middle Aterno Valley. For its social impact-more than 300 casualties and about 40,000 people left homeless (47% of the edifices were damaged in the epicentral area), the Abruzzi earthquake can be considered one of the most disastrous to have occurred in Italy in the last one hundred years (Tertulliani *et al.*, 2009). The shaking was felt throughout central Italy and, for example, in the city of Rome about 90 km from the epicenter, about 3% g produced some light damage.

In this situation, civil defense agencies are indeed in great need of swift and accurate information on where earthquake damage is located, so they can promptly direct rescue teams and organize the emergency response. In Italy, the Dipartimento per la Protezione Civile (Italian Civil Protection Department - DPC) is in charge of emergencies and it has supported several scientific projects, in the last years in the field of seismology, aimed toward a better understanding of the occurrence of earthquakes on Italian territory, and the rapid quantification of the associated ground shaking. In particular, the DPC has founded two projects aimed toward the rapid assessment of ground-motion shaking in Italy-the project DPC-INGV S4 (2004-2006) and the project DPC-INGV S3 (2007-2009).

Since 2006, the USGS-ShakeMap software (Wald *et al.*, 1999b) has been operational at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) to generate maps of the peak-ground motion (*PGM)* parameters and of the instrumentally derived intensities for earthquakes occurring in Italy and neighbouring areas (Michelini *et al.*, 2008). The shaking is represented through maps of peak-ground acceleration (*PGA*), peak-ground velocity (*PGV*), 5% damped response spectral acceleration (*PSA*) at 0.3, 1.0 and 3.0 s periods, and ground-motion shaking intensity. In general, these maps have become adopted worldwide to provide quantitative, first order assessments of the level of shaking and of the extent of potential earthquake damage. In fact, intensities have been found informative by non-expert audiences unfamiliar with instrumental ground motion parameters.

The instrumentally derived intensity values are derived from the conversion of *PGM* into intensity values as proposed by Wald *et al.* (1999a). This regression is based on the Mercalli Modified scale and calibrated using intensity and *PGM* data collected in California. In Italy, the analysis of historical seismicity through the use of the macroseismic intensity data has a long tradition and the Mercalli-Cancani-Sieberg (MCS) Scale (Sieberg, 1930) has been long adopted. To attain homogeneity between the instrumentally derived intensity maps and the observed Italian macroseismic intensities, new regression relations between *PGM* and MCS intensity data have been recently proposed by Faenza and Michelini (2010) and, for the L'Aquila sequence, new MCS instrumentally derived macroseismic maps have been determined.

This paper presents a fairly detailed description of the generation of the shakemaps of the L'Aquila main shock. This is the first time in which, in Italy, during a major seismic crisis, maps of ground shaking have become available to DPC and published on the dedicated shakemap web portal (http://shakemap.rm.ingv.it, last accessed August 2010). First, we present a brief description of the implementation of shakemap at INGV [detail can be found in Michelini *et al.* (2008)] and a critical analysis of how things went, followed by a critical examination of the possible improvements that can be introduced into the routine monitoring and in the generation of the maps of strong ground shaking.

2. ShakeMap implementation at INGV

USGS-ShakeMap is a seismologically based *PGM* interpolation package, which combines recorded data of the ground shaking with seismological and geological information available for the area. Since it avails of observed instrumental data it incorporates information about both the seismic source and the wave propagation (Wald *et al.*, 1999b).

In Italy, the *PGM* data used to rapidly generate the maps of ground shaking are provided by

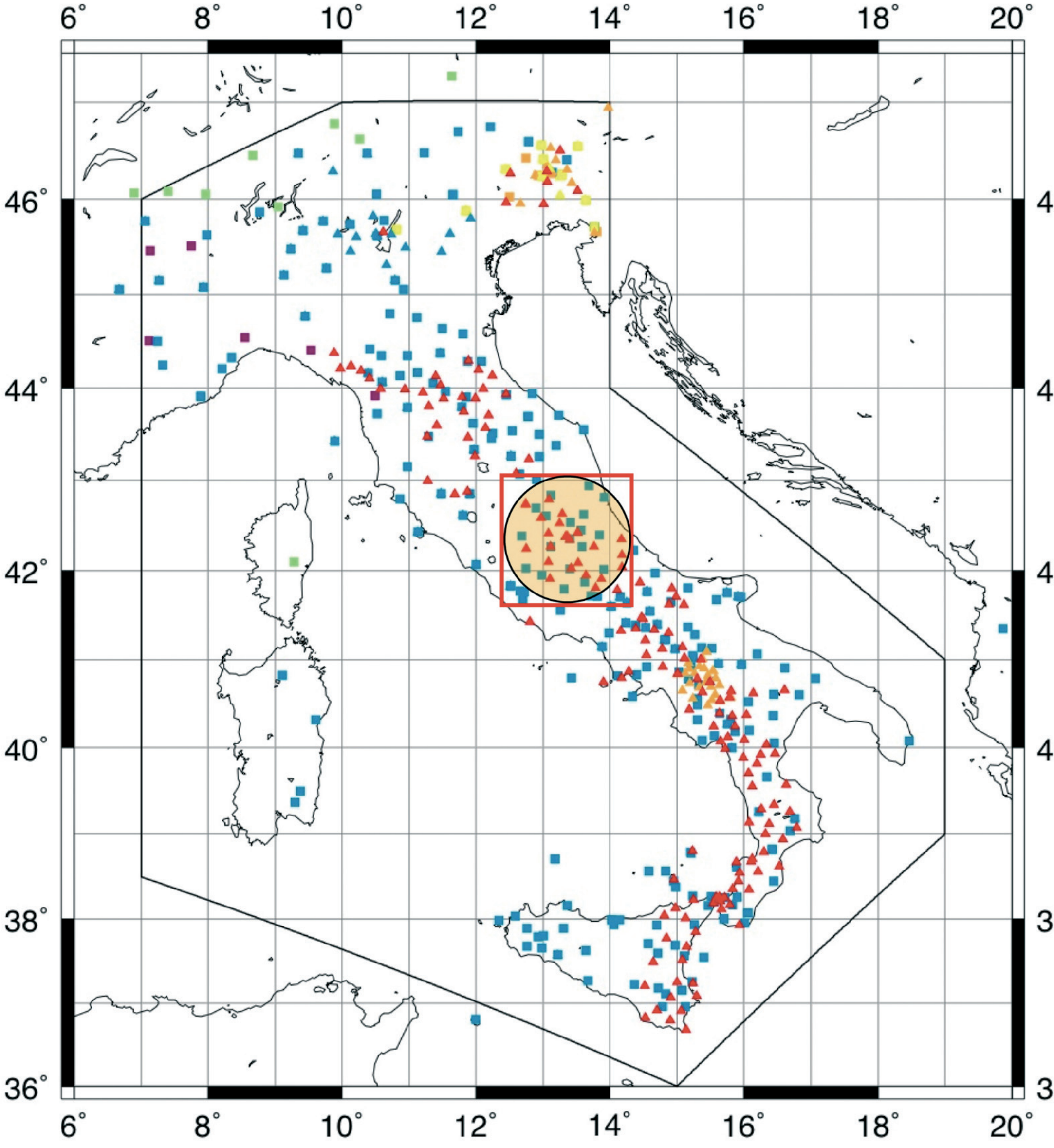


Fig. 1 - Map of Italy with the location of the stations operating on Italian territory. The saturation area corresponding to Fig. 2 is shown as a 90 km radius, orange circle. Distribution of broadband (squares) and accelerometer (triangles) stations in Italy. The stations of the Italian National Network and the MedNet are in blue, both of which are maintained by INGV; the RAN stations are in red; in the North-East of Italy, the stations maintained by the University of Trieste are in yellow and those of the OGS in orange; in the South of Italy, the Amra network is in yellow; in North-West Italy, the stations of the University of Genoa are in violet; the stations maintained by ETH in the north are in green.

the INGV seismic networks and by the partners of the project DPC-INGV S3: OGS, the universities of Genova, Naples (Federico II) and Trieste. A rapid procedure for data exchange among all the partners is operative within the S3 project. In detail, the National Italian Seismic Network (international code IV) and the MedNet network (MN), both belonging to INGV, span the whole national territory, whereas the other networks have regional or local spatial distribution: the Irpinia area for the ISNet network (Naples), north-eastern Italy for the stations belonging to the University of Trieste and OGS and the NW of Italy for the University of Genoa (see Fig. 1). Network IV is mainly composed of broadband (BB) stations and strong-motion recorders co-located at some of the BB stations sites (i.e., about 60 BB stations are paired with strong-motion sensors).

In addition to the networks listed above, the DPC runs the Rete Accelerometrica Nazionale (RAN, national strong-motion network), a dense network consisting of more than 300 stations and covering the whole territory. Unfortunately and although these data can be of great importance not only for the purpose of determining maps of *PGM* but also for more standard seismological analysis, they are not available in real time to the participating institutions of the DPC supported S3 project[1]. A real-time procedure for data exchange between DPC and INGV has been proposed but it has not been implemented yet owing to technical reasons.

With regard to the seismological information required for the “proper interpolation” of the real data where no observations are available, the procedure adopted by INGV follows the USGS-ShakeMap standards by relying on previously determined predictive relationships for the ground motion, and on estimates of the site amplifications based on the average S-wave velocity in the uppermost 30 m (V_{S30}).

In the INGV shakemap implementation, the regionalized predictive relationships for ground motion (GMPEs), proposed in the framework of the National Seismic Hazard Working Group (Gruppo di Lavoro 2004), are adopted for $M<5.5$ earthquakes. The need for regionalized GMPEs is, however, under debate (Bragato, 2009). The relations used are those determined by Malagnini and colleagues (Malagnini *et al.*, 2000, 2002; Morasca *et al.*, 2006) who proposed a partition of the Italian territory into 6 areas, using 3 different GMPEs [see Fig. 2 in Michelini *et al.* (2008)]. Because of the lack of strong-motion records in the Italian region for larger magnitudes ($M \geq 5.5$), the regressions of Akkar and Bommer (2007a) for *PGV*, and Akkar and Bommer (2007b) for the *PGA* and *PSA* are used.

The last ingredient for a shakemap interpolation is the correction for site amplification. For the Italian territory, we have implemented a classification based on the 1:100,000 geological map of Italy [see Fig. 3 in Michelini *et al.* (2008)] compiled and published by the Servizio Geologico Nazionale (see http://www.apat.gov.it/Media/carta_geologica_italia/default.htm, last accessed August 2010). In this case, the geological units have been gathered into five different classes A, B, C, D, and E according to the EuroCode8 provisions, EC8, after Draft 6 of January 2003 on the base of the ground acceleration response (e.g., http://www.eurocodes.co.uk/EurocodeDetail.aspx?Eurocode=8, last accessed August 2010). The procedure used to include the site correction within the USGS-ShakeMap relies on the calculation of a rock-site grid, passing through the reduction of recorded *PGM* amplitudes to rock-site conditions; the amplitude-dependent (and frequency - dependent, for *PSA*) amplification factors are applied to the rock-site estimates using the V_{S30} map [see Fig. 3 in Michelini *et al.* (2008)]. It is important to note that this site correction procedure is designed to return the original, observed data at each station.

---

[1] In NE Italy, however, the DPC stations are effectively acquired through a cooperation with the University of Trieste which is also an S3 partner.

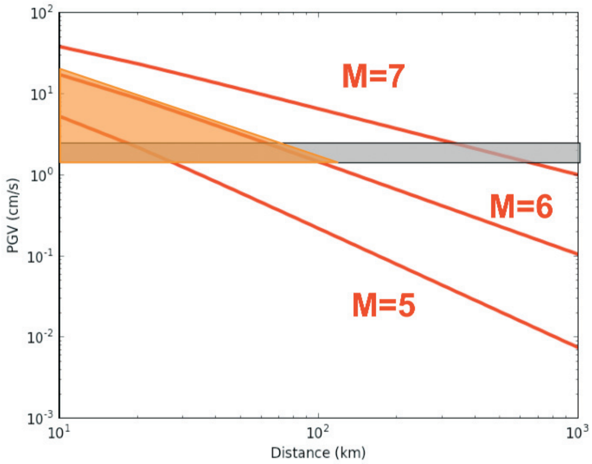


Fig. 2 - Saturation threshold for BB stations of the INGV IV network. The Akkar and Bommer (2007a) *PGMEs* for *PGV* and for different magnitude (i.e., magnitude equals 5.0, 6.0 and 7.0) are shown. The grey horizontal bar is the BB station saturation threshold. The interception point occurs at about 90 km. Analogously, the saturation distance for magnitude 5 and 7 earthquakes is 20 and 140 km, respectively. The orange triangle is the "saturation area" for a magnitude 6 earthquake, i.e., the stations located within this area saturate and cannot be used.

The generation of ShakeMaps at INGV relies on SAC format waveforms assembled for each event. The procedure is triggered by the manual location of the seismologist on duty at the INGV seismic center and the resulting maps become available within 15-30 minutes after the earthquake occurrence. For $M \leq 4.5$, the maps are published on the public server (http://shakemap.rm.ingv.it, last accessed August 2010). For larger magnitudes, the maps are first visioned by DPC for publication approval. This approval procedure stage was removed about ten days after the L'Aquila main shock and therefore all maps are now published regardless of the earthquake magnitude.

An alternative procedure is also being tested at INGV, based on the automatic EarthWorm earthquake monitoring system (Johnson *et al.*, 1995), for routine shakemap calculation. When using this second procedure, shakemaps for each earthquake are available within about 5 minutes from the event occurrence.

3. L'Aquila main shock: how it went

In this section, we present a concise situation of the evolution of the shakemap determination for the main shock.

1. The automatic final earthquake location [01:32:39.47 Origin Time (OT); 42.33°N; 13.34°E and 1.4 (km) depth] was available at 01:37 GMT, that is, about 5 minutes after origin time[2].
2. The manual main shock location became available after about 15 minutes from OT; the geographic location was the same but the hypocenter depth was determined at 9 km.
3. For the magnitude estimation, the first automatic determination, available with about 5 minutes after OT, was equal to M_L=5.9. After manual revision, about 15 minutes after the origin time, a magnitude value of M_L=5.8 resulted. Two hours later, the first moment magnitude value became available with M_W =6.3.
4. The first ShakeMaps, based on revised location and magnitude were calculated within 30

minutes from the earthquake occurrence and were available on the internal INGV shakemap server.

While the procedure to generate the main shock shakemap worked successfully, the same cannot be said for the *PGM* data, which only partially became available in real time.

3.1. Data availability during the L'Aquila main shock

For the main shock, INGV encountered a number of problems regarding the availability of the data to generate the shakemaps. Some of these problems had been known beforehand and opportune countermeasures had been implemented. In summary, there are three main sources for the data availability impasse mentioned above:

i) broadband data saturation of nearby stations,

ii) failure of data transmission for the on-demand strong motion stations, and

iii) unavailability of the RAN data.

The first two causes are really the two sides of the same coin. In the INGV implementation of ShakeMap, the data used for the maps consist, primarily, of the broadband recordings of the IV network. These stations were nearly all saturated within the 80-90 km distance range from the earthquake epicenter as could have been already expected for an earthquake with magnitude around 6. For this reason, many IV stations have been equipped with strong motion sensors, but technical problems related to the satellite transmission, inhibited the data transfer and availability. The only exception was represented by the AQU (MN) strong motion recordings. These data, in fact, do not rely on satellite communication but on a high-speed, dedicated, Internet network connection and they became available to the INGV headquarters in near real-time and accessible to users within a few hours after the main shock. It should be noted, however, that the station spacing of the IV network is targeted toward regional earthquake monitoring and that for the L'Aquila main shock the number of INGV strong motion stations would have been not larger than 5 stations within 50 km from the epicenter.

However, what can be considered as the major failure is the lack of a real-time data exchange between INGV and the RAN network. The RAN network has more than 20 stations between Abruzzo and the neighboring regions and its data would have been extremely valuable to constrain the strong ground motion in the epicentral area as seen below.

To better explain the current situation of the seismic networks in Italy, in Fig. 1, we present the station distribution for the entire Italian territory. The red square identifies the area of the L'Aquila main shock. In this area, only the IV network (in blue) and the RAN (in red) are operational. The semi-transparent, 90 km radius circle indicates the area where the BB stations saturated.

Fig. 2 shows a graph useful to explain the saturation of the stations as function of the epicentral distance and magnitude. We use the ground motion prediction equations of Akkar and Bommer (2007a) to calculate the estimated *PGVs* as function of distance for earthquake magnitudes of 5, 6 and 7. We have also drawn a grey shaded area corresponding to the approximate saturation level of the BB stations of the INGV IV network. It can be appreciated

---

[2] The automatic procedure determines the hypocenter and the magnitude progressively and the early determinations using fewer stations just around the epicenter were available from ~1 minute after the earthquake OT.

from this graph that for *M* about 6 earthquakes such as that of L'Aquila, the BB stations are expected to saturate up to distances of about 90 km from the epicenter and this is what actually occurred. Clearly, the lack of strong motion data in the early minutes/hours after the main shock severely affected the generation of the shakemaps.

3.2. Shakemaps of the main shock

The first shakemap became available at about 2:00 GMT about half an hour after the earthquake occurred. The only data used for this map are those from the INGV IV BB network and the location and magnitude are those provided by the INGV seismic center (M_L=5.8). Fig. 3 displays the first maps published on the INGV internal web portal. In the epicentral area, there are no data, and therefore the contour is based only on the values provided by the GMPEs and the site corrections. At the epicenter, the maximum *PGM* is about 20% g, while the intensity level is around VI-VII for the MM scale and VII-VIII for the MCS scale. Use of the MM scale leads to a general underestimation of the potential damage, when compared to the MCS scale. This peculiarity occurs naturally in all shake maps presented in this article; the reasons are fully explained in Faenza and Michelini (2010). As in Italy, the intensity scale used is the MCS, using maps based on regression in terms of MM scale, must be made with caution.

In mid-morning of April 6, the RAN data become available upon request and could be included in the shakemap calculation. Since many RAN stations are close to the epicenter, their inclusion resulted in much better constrained ground shaking in the close-in region. In fact, if the values provided in Fig. 3 substantially underestimate the shaking at the epicenter, we see that in Fig. 4, published at around 11:00 GMT of April 6, the gross features of the ground shaking experienced at the epicenter (about 30% g) are now shown. The associated, instrumentally derived intensity now reaches values of about VII and about VIII for the MM and MCS intensity maps, respectively.

Several days later, the first models of the finite fault extension become available mainly from the analysis of GPS and InSAR data (Atzori *et al.*, 2009; Walters *et al.*, 2009). Inclusion of the fault improved the representation of the ground shaking in the epicentral area considerably, as can be appreciated in Fig. 5. When the finite fault is inserted in the calculation, the maximum *PGAs* attain values around 40% g matching those recorded by the stations. In terms of intensity, the MCS map provides values of about VIII-IX in overall agreement with those reported by the QUEST macroseismic survey for the L'Aquila main shock (Galli *et al.,* 2009) (see Fig. 6).

Fig. 7 shows the difference between the first shakemaps published (Fig. 3) and the final ones (Fig. 5). As already pointed out, inclusion of all the data - especially of that close to the epicenter RAN data - and of fault finiteness resulted in a substantial improvement of the determination of the ground shaking in the epicentral area, with differences of the order of 20% g, in terms of *PGA* and up to 2 intensity units for MCS intensity (see also Worden *et al.*, 2010). In any case, part of the shaking remains nevertheless unaccounted for by the shakemaps since the GMPEs are unable to predict, correctly, the near field of the earthquake, which for L'Aquila ensued due to the complexity of the source (e.g., Cirella *et al.*, 2009; Pino and Di Luccio, 2009) and the local site effects (Cultrera *et al.*, 2009) which cannot be properly replicated by the simple and rough inclusion of site effects as in the USGS-ShakeMap.

In Fig. 6, we present the comparison between the MCS intensity shakemap determined using

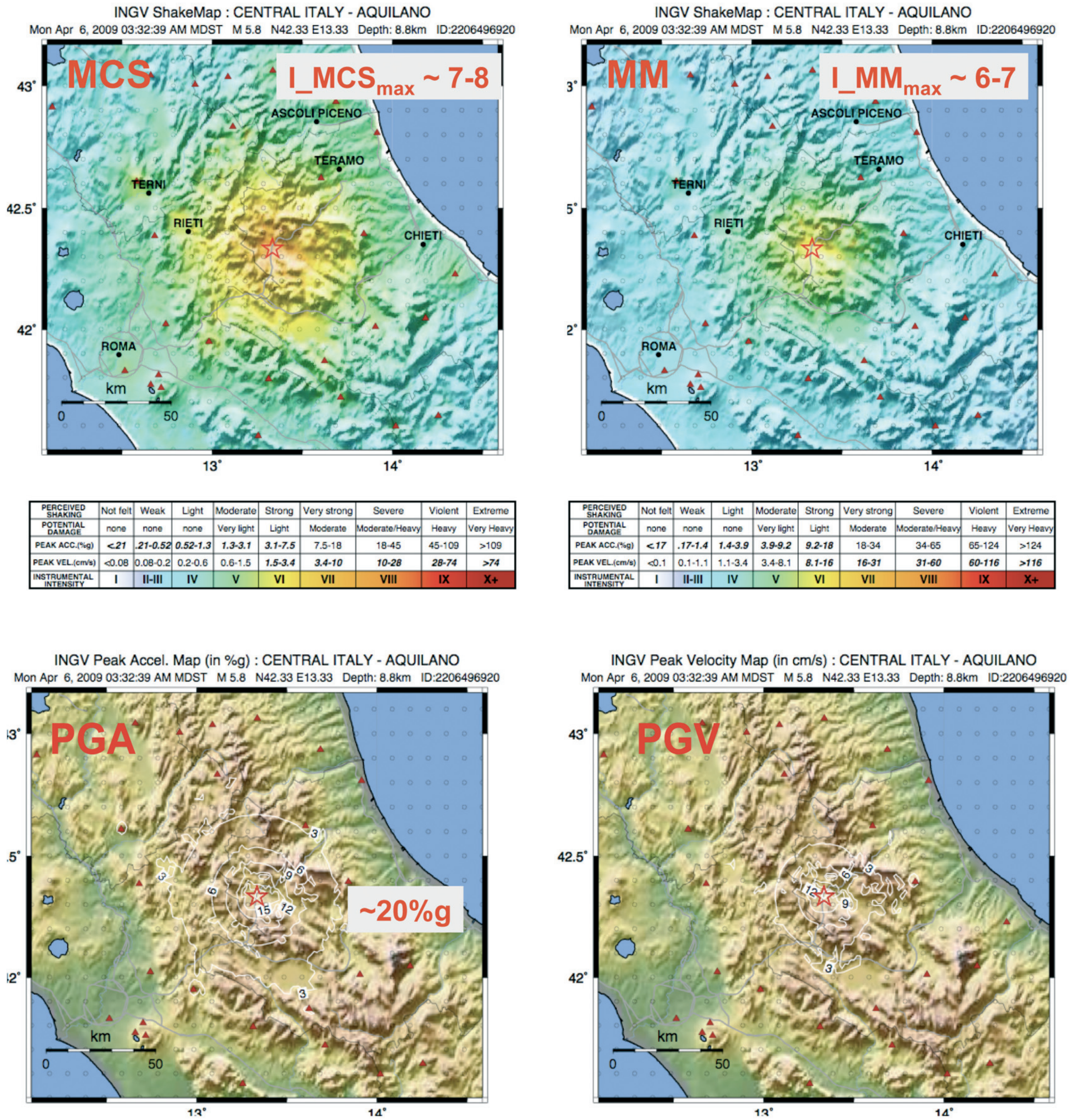
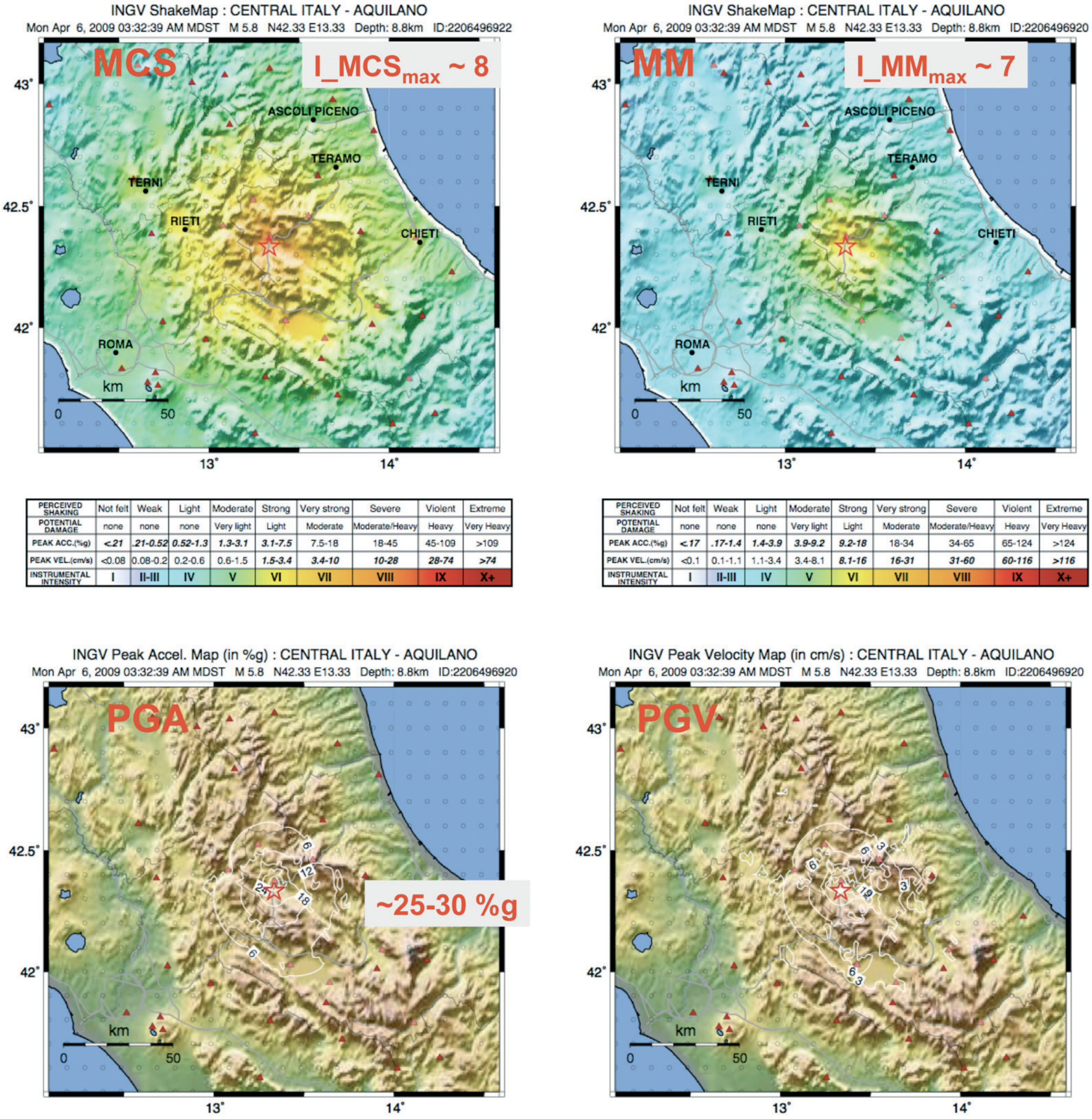


Fig. 3 - First version of the shakemaps published in the INGV internal (not public) web portal, based on the location and magnitude of the INGV seismic center and the *PGM* data of the INGV BB stations. Bottom panels: *PGA* (left) and *PGV* (right) maps. Top panels, instrumental intensity maps. Right: the published map, using the equation of Wald *et al.* (1999a) to convert *PGM* into intensity (Mercalli Modified scale). Left: the instrument intensity map used to convert *PGM* into intensity the equation of Faenza and Michelini (2010) in MCS intensity scale.

all the *PGM* data, adopting the relations recently proposed by Faenza and Michelini (2010), and the MCS intensity values reported by the QUEST team (Galli *et al.,* 2009). Note that to generate the shakemap from the macroseismic data, the intensity data are converted into *PGM* and then analyzed using the USGS-ShakeMap package. Furthermore, this process does not modify the values at the observation points since they are re-converted into intensity using the same biunique



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.21	.21-0.52	0.52-1.3	1.3-3.1	3.1-7.5	7.5-18	18-45	45-109	>109
PEAK VEL.(cm/s)	<0.08	0.08-0.2	0.2-0.6	0.6-1.5	1.5-3.4	3.4-10	10-28	28-74	>74
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 4 - Second version of the shakemaps published in the INGV internal web portal at around 11 GMT of April 6, 2009, based on the location and magnitude of the INGV seismic center and the *PGM* data of the INGV BB and the RAN accelerometers (same format as in Fig. 3).

relations of Faenza and Michelini (2010). Fig. 6 clearly shows the overall similarity between the two maps obtained from totally different types of data thus highlighting the significance of the ShakeMap procedure for rapid quantification of the experienced ground motion and, perhaps more importantly, the importance of strong motion data and of the rapid data exchange. Fig. 6, also provides an independent validation of the accuracy of our instrumental-intensity based on shakemap, since the data set of Faenza and Michelini (2010) do not include the L'Aquila event.

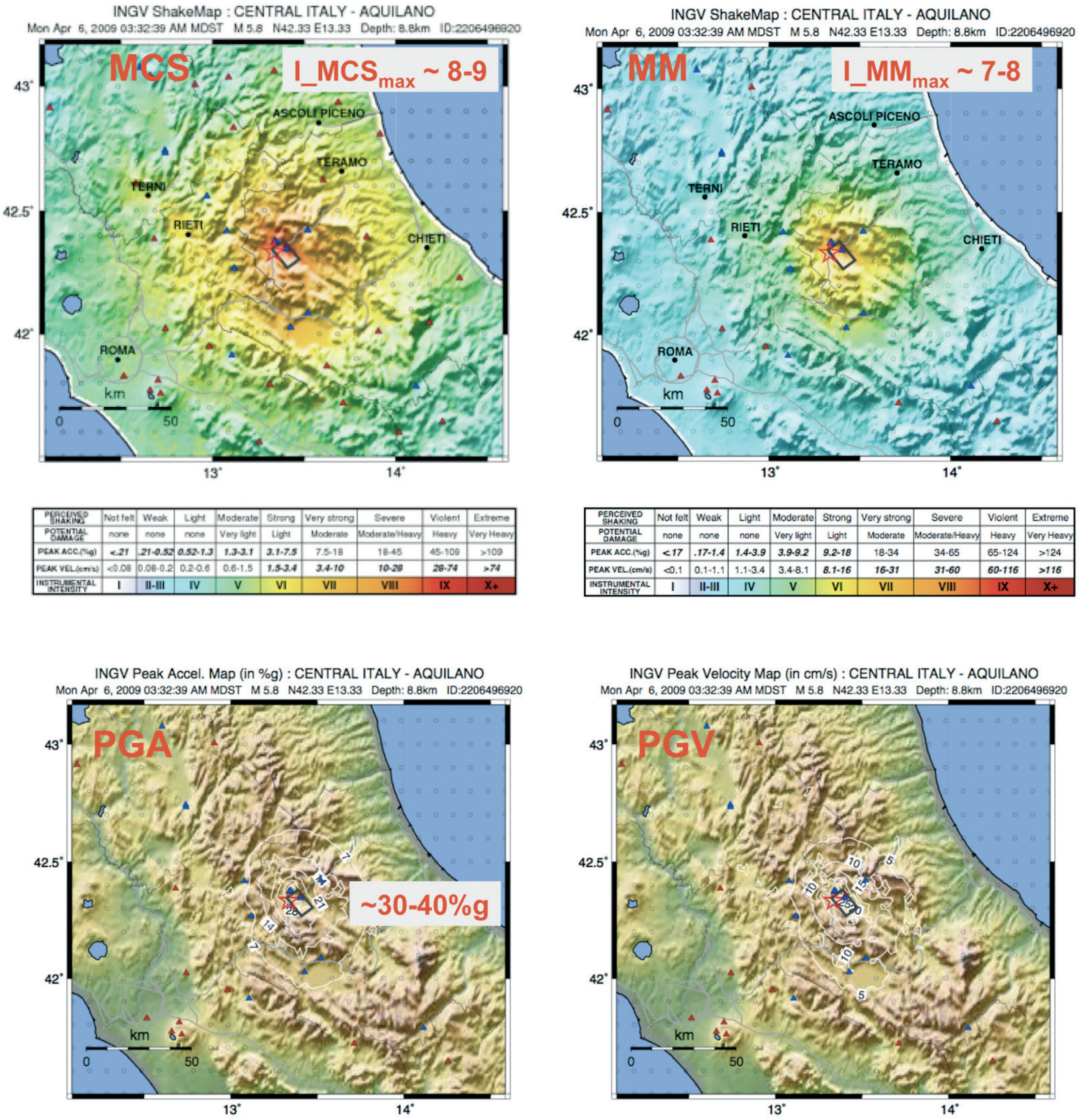
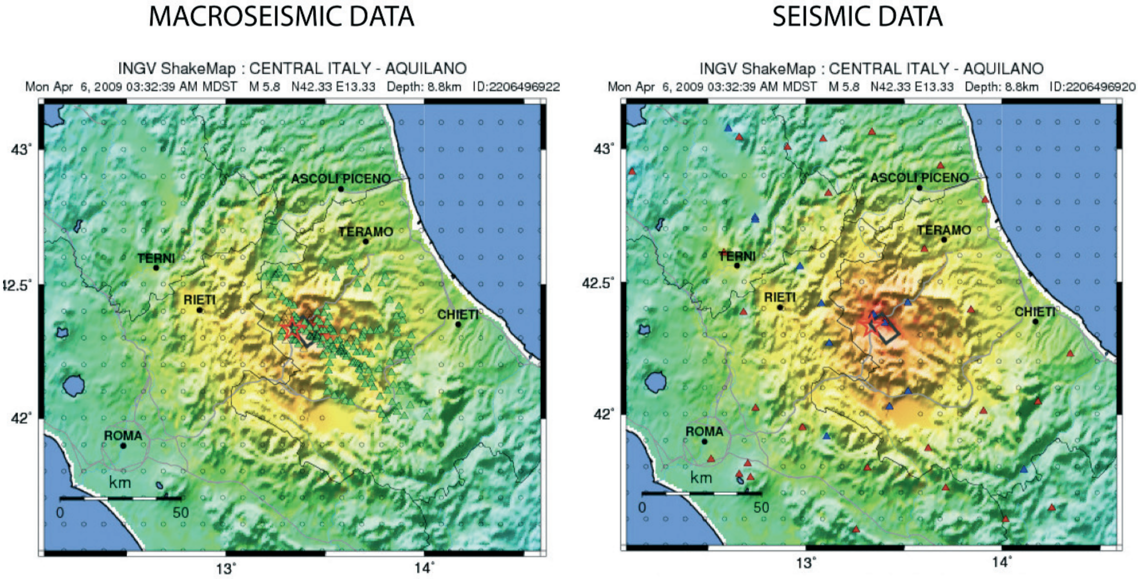


Fig. 5 - Final version of the shakemaps published on the INGV web portal (public) several days after the main shock, based on the location and magnitude of the INGV seismic center, the *PGM* data of the INGV BB and the RAN accelerometers, and the finite fault from GPS inversion (same format as in Fig. 3).

4. L'Aquila main shock - how it can go: a critical analysis

The previous section provided a concise description of the evolution of the shakemaps produced by INGV for the main shock. It has been shown that more accurate shakemaps were determined as additional data and information about the source became available. In this section, we propose some improvements that could lead to a better and faster generation of shakemaps and of the earthquake characterization overall. We, thus, do not restrict the analysis to the



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.21	.21-0.52	0.52-1.3	1.3-3.1	3.1-7.5	7.5-18	18-45	45-109	>109
PEAK VEL.(cm/s)	<0.08	0.08-0.2	0.2-0.6	0.6-1.5	1.5-3.4	3.4-10	10-28	28-74	>74
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 6 - Left Panel: ShakeMap using macroseismic data, using the equations of Faenza and Michelini (2010); Right Panel: shakemap using all data available and the finite fault, as in Fig. 5.

shakemap generation alone but, rather, we provide a critical assessment of the various phases that lead to the generation of the maps including both data availability and analysis such as location and magnitude determination. We have chosen to list and describe the various activities while keeping in mind that they all play a significant role for the seismic monitoring and the rapid notification of the results.

4.1. Data acquisition and exchange

We find that much can be learnt from the L'Aquila main shock experience. Here there are two aspects. The first consists of the real-time data flux from the stations to the acquisition headquarters. The second involves the data sharing between the DPC strong motion network, RAN, and the INGV acquisition center and, in general, data sharing with all the other institutions participating in the rapid estimation of earthquake damage and source characterization objective, for example, the DPC-S3 project.

For the first aspect, it has been found that the BB data flux functioned properly since they were all transferred with minimum delays. By contrast, the "on-demand" strong motion data relying on the satellite connection (as the BB) did not function as expected, being impeded by the effective free band available. This all hints at the fact that either a larger bandwidth must be reserved to the satellite channels to insure that the data are properly transferred or - the solution we prefer - continuous strong motion data transfer on dedicated satellite channels must be guaranteed. In the latter case, it is indisputable that data of little seismological value will be acquired during times of normal background seismicity but, in contrast, it will ensure that the relevant strong motion data become available immediately on occurrence of larger earthquakes, that is, when these are really the only data that provide prominent information whereas all the others saturate.

The second aspect involves the rapid, real-time, data exchange among institutions. In this regard, given that i) if the data transfer is properly tuned (see comments above) the current transmission technology can provide all data in real-time, ii) there is an ever increasing demand for rapid assessment and characterization of earthquake impact on population and man-made constructions in a broader sense (e.g., public and private edifices, monuments, roads, aqueducts, pipelines, etc.), and since several scientific and civil protection institutions are concurrently involved exploiting their own monitoring networks, it appears essential to assure data exchange and inter-institution coordination. More specifically and for the rapid generation of maps of the strong ground motion, we note that a procedure for data exchange has been designed and implemented among the participating institutions within the DPC-S3 project. Unfortunately, for technical reasons, this procedure had not been implemented by DPC, currently the major player in Italy for the acquisition of strong motion data.

In general, when the issue consists of fast characterization of large earthquakes, we feel that the distinction between seismological and engineering data is somewhat artificial since the major difference is really with the instrumental gain. Accelerometric data carry along with them a wealth of seismological information about the source that is extremely important to define an earthquake in the near-field swiftly. It follows that all efforts should be made to ensure data exchange and avoid, among other things, the replication by different institutions with similar instrumentation in the same area, with the associated dissipation of public funds.

Finally, an additional aspect that makes the prompt availability of the strong motion desirable is that these data can be integrated with displacement recordings.

For the L'Aquila strong motion data, it has been found that the values of displacements obtained from the strong motion recordings matched those obtained from GPS data very closely (Fig. 8). The prompt availability of static displacements is very appealing, for example, to engineers operating in the epicentral area in the immediate hours after the earthquake when assessing the structural damages.

4.2. Automatic location

The final, automatic earthquake location of the main shock in the INGV seismic center became available within about 5 minutes from the earthquake origin time. This time lag must be improved as current location methodologies can provide similar results in a much shorter time. For example, the location provided by the EarthWorm seismic monitoring package (Johnson *et al.*, 1995) that was being tested at INGV when the L'Aquila main shock occurred, provided the location in less than two minutes and novel methodologies that rely on continuous waveform processing can provide locations in 15-25 seconds from the origin time depending on station coverage (e.g., Maggi and Michelini, 2009), or even faster locations can be obtained using techniques designed for early warning (e.g., Olivieri *et al.*, 2008; Satriano

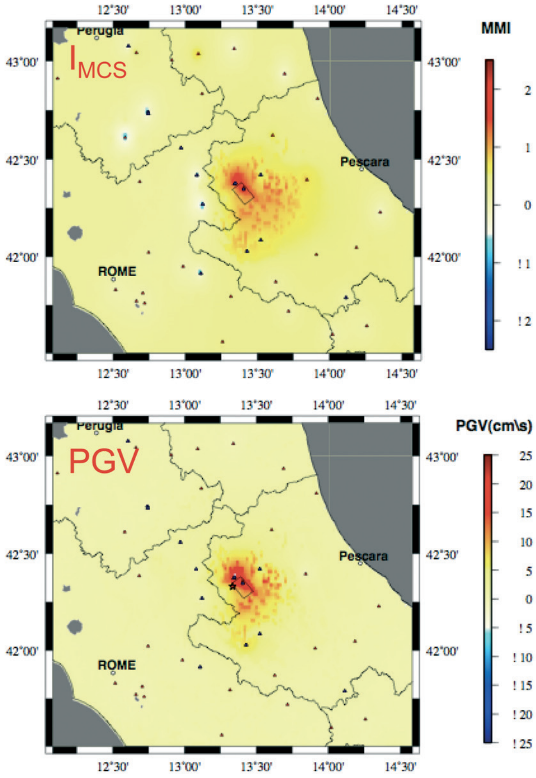


Fig. 7 - Difference between the final shakemaps published, as reported in Fig. 5, minus the first shakemaps published, as reported in Fig. 3, for the MCS intensity map, the *PGA* and the *PGV*.

et al., 2008).

4.3. Manual location

Manual revision of the earthquake location is certainly of great importance since it allows the seismologist on duty to verify the stations to be included in the location and the onset readings to be used. Availability of strong motion waveform data recorded near the epicenter in real-time can be very advantageous to this revision process.

4.4. Magnitude determination

The determination of magnitude is in some manner even more important than that of location. While for the location it is important to provide the general area where the earthquake occurred, we note that for an extended finite fault, the exact location of the hypocenter is less relevant. For example, the L'Aquila earthquake main shock focus differs by more than 5 km from the main release of seismic energy (Cirella *et al.*, 2009; Pino and Di Luccio, 2009) and there are many similar cases in the literature. Conversely, the estimation of magnitude can be prone to criticism since different types of magnitudes can be determined and, in general, it is difficult to explain to the public and the media what the differences are. In addition, when using the software ShakeMap and when only a few stations are available, incorrect values of magnitudes can condition the selection of the most appropriate GMPE relation for the interpolation of the ground motion on

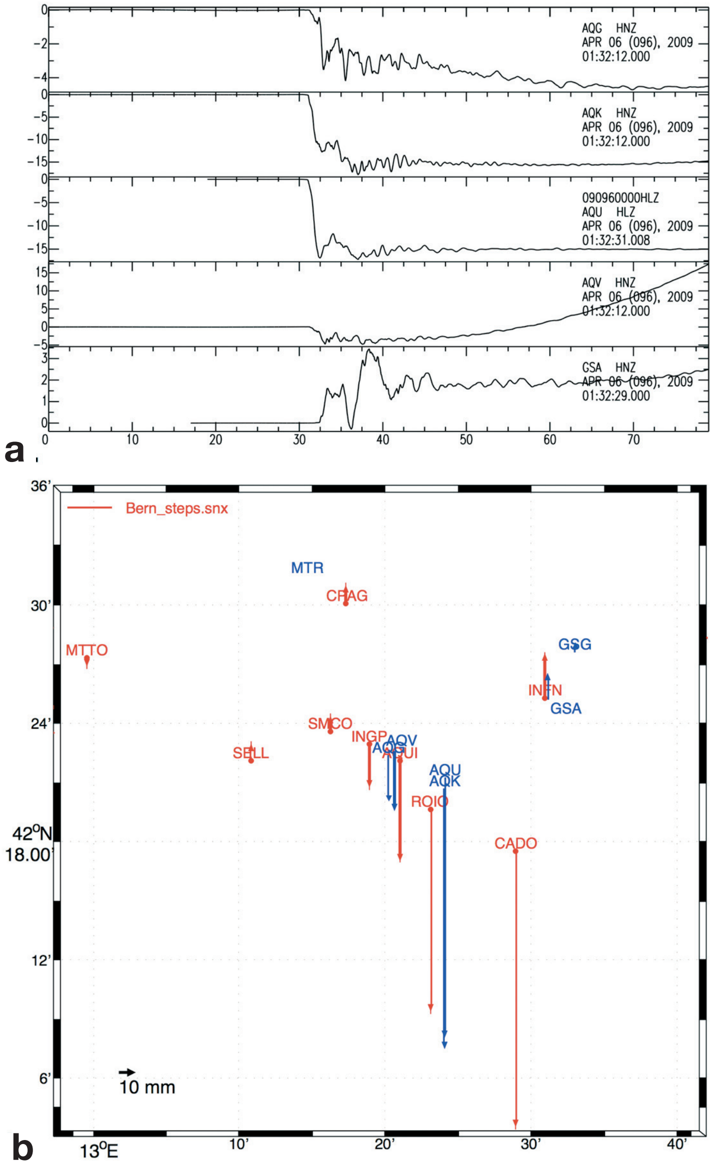


Fig. 8 - a) Integration to displacement of vertical component accelerometric recordings; b) comparison between static displacements obtained from accelerometric records and from GPS data (blue and red lines, respectively).

the geographical grid[3].

Another aspect of importance regards what type of magnitude is best representative of the actual earthquake size. Moment magnitude (M_W) is determined directly from the scalar value of the moment tensor and provides an estimate of the static dislocation on the causative fault by its very nature. It is therefore, the best estimate of the earthquake size but, as for L'Aquila, it

---

[3] This problem becomes almost negligible when the data coverage is sufficient because a correction for the level of ground shaking is applied to the GMPEs adopted.

becomes available only after some time. Moment magnitude follows from the inversion of the recorded seismograms for the moment tensor. Current procedures implemented at INGV (Scognamiglio *et al.*, 2009) require data time windows of some minutes and are triggered by the manual location of the seismic center. It takes somewhere in the order of at least 15 minutes before a moment tensor solution can be obtained automatically using the Time Domain Moment Tensor (TDMT) procedure of Dreger and Helmberger (1993). As for the case of L'Aquila, a manual revision of the moment tensor can require up to several hours. It thus follows that in the immediate moment after the earthquake, it is necessary to rely first on fast, but less accurate, magnitude determinations and progressively update the estimates as more reliable determinations are made. In this regard, it is important to mention that fast, scalar moment, magnitude determinations at teleseismic distances from P-waves [e.g., M_{wp}: Tsuboi *et al.* (1995)] can be very valuable since they can provide approximate estimates of moment magnitude within 10-15 minutes. For the L'Aquila earthquake this procedure was not active but in its off-line calculation, it provided an estimate of $M_{wp} = 6.3$.

Another approach toward the very fast determination of magnitude exploits the potential of real-time strong motion recordings and it consists in using the techniques developed for early warning by, for example, Festa *et al.* (2008) and Lancieri and Zollo (2008). These authors have shown, in an off-line analysis that very accurate estimates of earthquake magnitude can be obtained within a few seconds from the first station recordings.

A possible progressive magnitude determination schema would include the following analysis sequence:

- if strong motion data are available in real-time, automatic determination of M using early warning techniques (< 20 s);
- automatic determination of M_L (about 4-5 minutes);
- automatic determination of M_{wp} (about 5-10 minutes depending on station coverage);
- automatic TDMT calculation (about 20-30 minutes) (Dreger and Helmberger, 1993; Scognamiglio *et al.*, 2009) and/or Quick Regional CMT (QRCMT) (Pondrelli *et al.*, 2006, 2010).

In the procedural schema above, each new calculation supersedes the previous one. For our purposes, moment tensor determination provides a first indication on the planes along which the rupture occurred. This information is important since the extended fault inversion (see below) tests both planes to select the most likely one (e.g., Scognamiglio *et al.*, 2010).

4.5. First ShakeMaps

The initial shakemaps can be generated as soon as the data, an initial location and magnitude are available. These initial maps of ground motion can rely on the automatic location and magnitude and we have found that it can be made available within 5-6 minutes. Since they are supposed to include the strong motion data, they will likely provide some initial, but realistic, estimates of the ground motion experienced. With the exception of areas where the strong motion station coverage is particularly dense, experience has shown that more accurate maps can be obtained, for $M \geq 5.5$ earthquakes, only after inclusion of fault finiteness.

4.6. Preliminary determination of the fault finiteness

Incorporation of fault finiteness requires fast inversion for the extended fault using either the locally available strong motion data or/and teleseismic data. In the latter case, however, the attainable fault resolution is hampered by many factors such as teleseismic station coverage and frequency range adopted for the inversion. For earthquakes of the size of the L'Aquila main shock (i.e., about 20×15 km^2), we expect that the adoption of inversion techniques such as those developed by Kikuchi and Kanamori (1991) can provide indications on possible rupture directivity, preferential position and extension of the fault relative to the hypocenter. This information is probably sufficient for generating maps using the USGS-ShakeMap package, which requires only the position of the vertices of the fault in its current implementation.

In contrast, the use of local strong motion data can, in principle, provide more information on the rupture history of the fault. A limitation is imposed, however, by the availability of proper Green functions (GFs) capable to model faithfully the seismograms at the frequencies required by the finite fault inversion (Scognamiglio *et al.*, 2010).

In any event and for both approaches, the local data procedure starts by testing which of the two faults resulting from the moment tensor mechanism is more likely to have ruptured. Once selected, it seeks determination of the rupture history with the aim of pin pointing the areas where the largest slip has occurred. It has been found in a study that analyzed the whole procedure (Scognamiglio *et al.*, 2010) that the entire processing can be automated until a preliminary result using regional GFs is obtained. Afterward, it has been found that knowledge of the GFs is very important to avoid incorrect mapping of the information contained in the seismograms in the rupture model. That is, the local velocity structure may have to be re-determined locally in order to improve the quality of the GFs.

In summary, it appears that a preliminary and somewhat reliable fault model cannot be obtained earlier than a few hours (2-3) from earthquake occurrence in the best case and that accurate and reliable rupture models cannot be obtained before velocity model local refinement. In addition, in order to generate maps of shaking in almost real-time, a methodology aimed at rapid setting of the size of the faults, based, for example, on scaling laws and/or tectonic settings could be implemented in the near future.

4.7. Final ShakeMaps

As explained above, inclusion of the fault is the last step in determining the shakemaps. It has been explained above that inclusion of the fault can require somewhere in the order of some hours using conventional inversion procedures such as those tested by Scognamiglio *et al.* (2010), which rely on the procedure in place at UC Berkeley Seismological Lab. (Dreger *et al.*, 2005). In addition, it appears of relevance to mention that prior information on the tectonics of the area where the earthquake occurred can aid the identification of the fault that likely ruptured during the main event.

5. Discussion and conclusions

The aim of this work was to describe and appraise the process of generation of the shakemaps of the L'Aquila earthquake main shock at INGV.

Rapid availability of maps of *PGM* (shakemaps) can be a useful tool for civil defense organizations, citizens and media because it can provide a first evaluation of the shaking and the resulting damage caused by a destructive earthquake. It is important to stress that the rapid assessment of ground-motion shaking obtained through the calculation of the shakemaps does not allow to accurately resolve possible local site amplifications unless local recordings are available. For this reason, the shakemaps are a useful tool in the first minutes to hours after an earthquake has occurred when it is of primary importance to correctly assess the gross impact that the earthquake has. Their relevance, however, progressively decreases as information about the actual damage becomes available.

Perhaps one of the most important lessons learnt from the L'Aquila main shock and its aftershock sequence is the relevant role that real-time, accelerometric data can play. These data, especially if close to the epicenter, are useful for the determination of the finite fault, the location of the main shock, the near field static displacements and the maps of peak ground shaking. For L'Aquila the strong motion data became available only some hours after the main shock, and the lack of a well tested data format and exchange procedure further delayed the insertion of the *PGM* data in the shakemaps. These additional data, however, were not sufficient to describe, comprehensively, the strong ground motion in the epicentral area. Only after the insertion of the finite fault within the calculation of the shakemaps some days after the main shock, did the maps appear to replicate more faithfully the level of ground motion indicated by the reported macroseismic field. Specifically, it was found that the difference between the first shakemaps, published using only the distant INGV stations (i.e., greater than ~80 km from the epicenter), and the last, which included all available seismic data in L'Aquila and the finite fault, accounts for about 2 degrees in the MCS intensity scales within the near-source area (Fig. 7).

In the second part of this study, we have listed a number of analyses that can lead to improvements in the rapid estimation of earthquake size and affected areas. These include procedures to rapidly obtain location and magnitude, moment tensor and finite fault. These should be implemented as standard routine operations and should include analysis tools at both regional and teleseismic scale.

In conclusion, we believe that the USGS-ShakeMap implementation at INGV worked satisfactorily during the seismic crises. Since April 6, more than 260 shakemaps in the area around L'Aquila (20 of which with $M_L \geq 4.0$; on average within 10-15 minutes from earthquake occurrence) have been published. In this regard and to overcome the described lack of strong motion data from the epicentral area, from the very first days after the main shock, INGV installed several strong motion instruments which were telemetered to the central headquarters in Rome. These data became quite valuable for the generation of the shakemaps.

Acknowledgments. The work has been partially founded by 2007-2009 DPC S3 Italian Civil Protection project. The authors would like to thank Antonella Gorini, Elisa Zambonelli e Fabio Sabetta of the Italian Civil Protection (DPC) for proving the RAN data during the seismic sequence. The V_{S30} classification of the Italian territory was kindly provided by Marco Moro and Giuliano Milana of INGV.

REFERENCES

Akkar S. and Bommer J.J.; 2007a: *Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East*. Bull. Seismol. Soc. Am., **97**, 511-530, doi: 10.1785/0120060141.

Akkar S. and Bommer J.J.; 2007b: *Prediction of elastic displacement response spectra in Europe and the Middle East*. Earthquake Eng. Struct. Dyn., **36**, 1275-1301.

Atzori S., Hunstad I., Chini M., Salvi S., Tolomei C., Bignami C., Stramondo S., Trasatti E., Antonioli A. and Boschi E.; 2009: *Finite fault inversion of DInSAR coseismic displacement of the 2009 L'Aquila earthquake (central Italy)*. Geophys. Res. Lett., **39**, L15305.

Bragato P.L.; 2009: *Assessing regional and site-dependent variability of ground motions for ShakeMap implementation in Italy*. Bull. Seismol. Soc. Am., **99**, 2950-2960.

Chiarabba C., Amato A., Anselmi M., Baccheschi P., Bianchi I., Cattaneo M., Cecere G., Chiaraluce L., Ciaccio M.G., De Gori P., De Luca G., Di Bona M., Di Stefano R., Faenza L., Govoni A., Improta L., Lucente F.P., Marchetti A., Margheriti L., Mele F., Michelini A., Monachesi G., Moretti M., Pastori M., Piana Agostinetti N., Piccinini D., Roselli P., Seccia D. and Valoroso L.; 2009: *The 2009 L'Aquila (central Italy) M_W 6.3 earthquake: Main shock and aftershocks*. Geophys. Res. Lett., **36**, L18308, doi: 10.1029/2009GL039627.

Cirella A., Piatanesi A., Cocco M., Tinti E., Scognamiglio L., Michelini A., Lomax A.J. and Boschi E.; 2009: *Rupture history of the 2009 L'Aquila (Italy) earthquake from non-linear joint inversion of strong motion and GPS data*. Geophys. Res. Lett., **36**, L19304.

Cultrera G., Luzi L., Ameri G., Augliera P. and Azzara R.; 2009: *Evaluation of the local site effects in the upper and middle Aterno Valley*. <www.earth-prints.org>.

Dreger D.S. and Helmberger D.V.; 1993: *Determination of source parameters at regional distances with three-component sparse network data*. J. Geophys. Res., **98**, 8107-8125.

Dreger D.S., Gee L., Lombard P., Murray M.H. and Romanowicz B.; 2005: *Rapid finite-source analysis and near-fault strong ground motions: Application to the 2003 M_w 6.5 San Simeon and 2004 M_w 6.0 Parkfield earthquakes*. Seismol. Res. Lett., **76**, 40-48.

Faenza L. and Michelini A.; 2010: *Regression analysis of MCS intensity and ground motion parameters in Italy and its application in ShakeMap*. Geophys. J. Int., **180**, 1138-1152.

Festa G., Zollo A. and Lancieri M.; 2008: *Earthquake magnitude estimation from early radiated energy*. Geophys. Res. Lett., **35**, L22307.

Galli P., Camassi R., Azzaro R., Bernardini F., Castenetto S., Molin D., Peronace E., Rossi A., Vecchi M., and Tertulliani A.; 2009: *Il terremoto aquilano del 6 aprile 2009: rilievo macrosismico. effetti di superficie ed implicazioni sismotettoniche*. Il Quaternario, **22**, 235-246.

Gruppo di Lavoro; 2004: *Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003.* Rapporto conclusivo per il Dipartimento della Protezione Civile, INGV, Milano-Roma, 65 pp. + 5 App.

Johnson C., Bittenbinder A., Bogaert B., Dietz L. and Kohler W.; 1995: *Earthworm: a flexible approach to seismic network monitoring*. IRIS Newsletter, **14**, 1-4.

Kikuchi M. and Kanamori H.; 1991: *Inversion of complex body waves-III*. Bull. Seismol. Soc. Am., **81**, 2335-2350.

Lancieri M. and Zollo A.; 2008: *A Bayesian approach to the real-time estimation of magnitude from the early P and S wave displacement peaks*. J. Geophys. Res., **113**, B12302.

Maggi A. and Michelini A.; 2009: *Continuous waveform data stream analysis: Detection and location of the L'Aquila earthquake sequence*. In: Trans. Am. Geophys. Union, **90**, Fall Meeting Supplement, Abstract U12A-01.

Malagnini L., Akinci A., Herrmann R.B., Pino N.A. and Scognamiglio L.; 2002: *Characteristics of the ground motion in northeastern Italy*. Bull. Seismol. Soc. Am., **92**, 2186-2204.

Malagnini L., Herrmann R. and Di Bona M.; 2000: *Ground-motion scaling in the Apennines (Italy)*. Bull. Seismol. Soc. Am., **90**, 1062-1081.

Michelini A., Faenza L., Lauciani V. and Malagnini L.; 2008: *ShakeMap implementation in Italy*. Seismol. Res. Lett., **79**, 689-698, doi: 10.1785/gssrl.79.5.689.

Morasca P., Malagnini L., Akinci A., Spallarossa D. and Herrmann R.; 2006: *Ground-motion scaling in the western Alps*. J. Seismol., **10**, 315-333.

Olivieri M., Allen R.M. and Wurman G.; 2008: *The potential for earthquake early warning in Italy using ElarmS*. Bull.

Seismol. Soc. Am., **98**, 495-503.

Pino N.A. and Di Luccio F.; 2009: *Source complexity of the 6 April 2009 L'Aquila (central Italy) earthquake and its strongest aftershock revealed by elementary seismological analysis*. Geophys. Res. Lett., **36**, L23305.

Pondrelli S., Salimbeni S., Ekstrom G. and Morelli A.; 2006: *The Italian CMT dataset from 1977 to the present*. Phys. Earth Planet. Int., **159**, 286-303.

Pondrelli S., Salimbeni S., Morelli A., Ekstrom G., Olivieri M. and Boschi E.; 2010: *Seismic moment tensors of the April 2009, L'Aquila (central Italy), earthquake sequence*. Geophys. J. Int., **180**, 238-242.

Satriano C., Lomax A.J. and Zollo A.; 2008: *Real-time evolutionary earthquake location for seismic early warning*. Bull. Seismol. Soc. Am., **98**, 1482-1494.

Scognamiglio L., Tinti E. and Michelini A.; 2009: *Real-time determination of seismic moment tensor for the Italian region*. Bull. Seismol. Soc. Am., **99**, 2223-2242.

Scognamiglio L., Tinti E., Michelini A., Dreger D., Cirella A., Cocco M., Mazza S. and Piatanesi A.; 2010: *Fast determination of moment tensors and rupture history: what has been learned from the 6 april 2009 L'Aquila earthquake sequence*. Seismol. Res. Lett., **81**, 892-906.

Sieberg A.; 1930: *Geologie der erdbeben*. Handbuch der Geophysik, **2**, 552-555.

Tertulliani A., Rossi A., Cucci L. and Vecchi M.; 2009: *L'Aquila (central Italy) earthquakes: The predecessors of the April 6, 2009 event*. Seismol. Res. Lett., **80**, 1008-1013.

Tsuboi S., Abe K., Takano K. and Yamanaka Y.; 1995: *Rapid determination of Mw from broadband P waveforms*. Bull. Seismol. Soc. Am., **85**, 606-613.

Wald D.J., Quitoriano V., Heaton T.H. and Kanamori H.; 1999a: *Relationships between peak ground acceleration, peak ground velocity, and Modified Mercalli intensity in California*. Earthquake Spectra, **15**, 557-564.

Wald D.J., Quitoriano V., Heaton T.H., Kanamori H., Scrivner C.W. and Worden C.B.; 1999b: *Trinet "ShakeMaps": Rapid generation of peak ground motion and intensity maps for earthquakes in southern California*. Earthquake Spectra, **15**, 537-555.

Walters K.T., Elliott J.R., D'Agostino N., England P.C., Hunstad I., Jackson J.A., Parsons B., Phillips R.J. and Roberts G.P.; 2009: *The 2009 L'Aquila earthquake (central Italy): A source mechanism and implications for seismic hazard*. Geophys. Res. Lett., **36**, L17312.

Worden C.B., Wald D.J., Allen T.I., Lin K. and Cua G.; 2011: *Integration of Macroseismic and Strong-Motion Earthquake Data in ShakeMap for Real-Time and Historic Earthquake Analyses*. Bull. Seismol. Soc. Am, in press.

Corresponding author: Licia Faenza
Istituto Nazionale di Geofisica e Vulcanologia
Via di Vigna Murata 605, Roma, Italy
Phone: +39 06 51860608; fax: +39 06 51860541; e-mail: licia.faenza@ingv.it