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Short Note

An Empirical Procedure for Rapid Magnitude Estimation in Italy

by M. Olivieri and J. Schweitzer

Abstract Rapid estimates of source parameters are needed for reasons of civil protection in regions where destructive events often occur. This information can prevent further damage and casualties. A relation between the first seconds of a *P*-wave onset and the local magnitude M_L of the earthquake has been developed for the Italy region following results obtained in Japan and Southern California. The proposed dominant period estimate has been used in the present work and it gives reliable results from which to evaluate the size of the earthquake. The data set we evaluated consists of about 20,000 earthquakes that occurred in Italy and were well recorded by the stations of the MedNet Network. The proposed relationship will be one basis for developing and implementing an earthquake early warning system in Italy capable of delivering a rapid alert only a few seconds after the occurrence of a potentially destructive earthquake in the area. Recent extensive improvements of the Italian National Seismic Network, together with this new technique, will make possible the release of a robust magnitude estimate no later than 10 sec after the occurrence of the earthquake. However, no data are available for earthquakes with magnitudes $M_L > 6.0$, which poses some reliability limitations for the derived relationship in the case of larger earthquakes.

Introduction

Seismic activity is distributed all over Italy, and several large-magnitude earthquakes in recent years have caused casualties as well as huge damage to buildings and property. Lowering this seismic risk is an important task for seismologists and the Italian Civil Protection Agency needs to be quickly provided with accurate information about the hypocentral parameters: latitude, longitude, depth, and magnitude. New seismic equipment and a scientific and technological upgrading of the data-analysis system at Istituto Nazionale di Geofisica e Vulcanologia (INGV) have significantly cut down the average time needed for an automatic event location from approximately 20 to 5 minutes. Following the successful results obtained in Japan (Nakamura, 1998) and Southern California (Allen and Kanamori, 2003), real-time broadband data processing and the large number of new broadband stations have given us a chance to apply these recently developed methods for rapid magnitude estimations.

The traditional way of estimating an M_L magnitude requires the recording of the whole seismogram, including surface waves, which arrive very late. From these data the peak ground motion is measured and the magnitude of the earthquake can be estimated. From the point of view of risk, this means that the magnitude can only be estimated after the most damaging part of the wave field has traveled through the area surrounding the epicenter.

Nakamura (1998) first proposed a linear relationship between the magnitude of the source and the dominant period T_P of the seismic signal measured on a vertical component seismograph. This relationship is part of the Urgent Earthquake Detection and Alarm System (UrEDAS) that detects the first *P*-wave motion of an earthquake and estimates its location and magnitude within about 3 sec. The system requires adequate coverage of stations in the epicentral area.

Different relationships can then be used to rapidly estimate the magnitude. For example, Tsuboi *et al.* (2002), proposing an early warning system for tsunami monitoring, suggest using the proportionality between the seismic moment M_0 and τ^3, where τ is the source duration estimated from the *P*-wave first peak.

A slightly different technique (Kanamori, 2005) has been implemented at the TriNet network that monitors the seismicity in Southern California. Although the idea is similar, Kanamori's approach is based on a nonrecursive integration of ground displacement over a fixed window after the *P*-wave onset. Allen and Kanamori (2003) show that the linear relation between the dominant period and the magnitude can also be applied in this region, but, to obtain reliable estimates, it is important to gather a large number of observations.

The success of this system in these two cases and the availability of a reasonable data set of events of different magnitudes recorded by the broadband MedNet stations (Mazza *et al.*, in press) encouraged us to test this technique for Italy. Moreover, the recent conversion of the Italian National Network from short-period to broadband sensors increases the chances for success of this type of early warning system technique.

In this study, we have applied the approach of Allen and Kanamori (2003) for computing the dominant period of the signal. In discrete digitized nonmonochromatic signals the dominant period can be defined:

$$T_P^i = 2\pi\sqrt{X_i/D_i} \quad (1)$$

where

$$X_i = \alpha X_{i-1} + x_i^2 \quad \text{and} \quad D_i = \alpha D_{i-1} + (dx_i/dt)^2 \quad (2)$$

where x_i is the signal and α is the smoothing factor. We extrapolate an empirical relation for estimating the magnitude of an earthquake from the first seconds of a vertical broadband record. As a reference, we use the local magnitude M_L because a M_w catalog is not available for Italy. This is the first step toward building an earthquake early warning (EEW) system.

Analyzed Data Set

The data used in this study are based on about 20,000 events that occurred in Italy and the surrounding regions between 1996 and 2002. These data were recorded at broadband MedNet stations and local magnitudes (M_L) were computed for each observation. By restricting the epicentral distance to 100 km and removing events with an origin time preceded within 5 minutes by another earthquake, we obtained a data set of about 4000 events with M_L ranging from 1.0 to 5.9. The locations of these events are shown in Figure 1 on the right. Unfortunately, the distribution of stations does not allow sampling all of Italy, but all regions where most of the recent relevant earthquakes occurred are well covered. The last large earthquake, the so-called Irpinia earthquake, M_s 6.9, 23 November 1980 (Bernard and Zollo, 1989), occurred before the beginning of digital broadband seismology era in Italy. This limits our study to magnitudes not greater than 6.0. However, in the past decades several moderate (magnitude <6.0) but destructive earthquakes have occurred in Italy. Some extrapolation may also be justified because Allen and Kanamori (2003), G. Wurman, R. M. Allen, and P. Lombard (personal comm., 2007) and Olson and Allen (2006) show the existence of linearity between M_L and $\log(T_P)$ in a broad range of magnitudes between magnitudes 3.0 and 8.0.

Data Processing and Results

The data set used in this study consists of vertical broadband recordings with 20-Hz sampling. This gives a Nyquist frequency of 10 Hz, which is reasonable for observing corner frequencies of events in Italy down to M_L 2 at epicentral distances from 10 to 100 km. However, when computing the discrete sampled integral of the signal and of its derivative required for the method of Allen and Kanamori (2003), this sampling rate is too low for retrieving the correct dominant period of a sinusoidal signal with a frequency higher than 2 Hz. Figure 2 shows the effect of this computation with a 5-Hz sinusoidal signal digitized once with 100 samples/sec and once with 20 samples/sec. In the first case (100 samples/sec), the observed dominant frequency (i.e., the first minimum after the transient) has a value of exactly 5 Hz, whereas the undersampled signal with 20 samples/sec gives the wrong value of 2.6 Hz.

This is not an aliasing effect of the time series itself but of its derivative: the recursive algorithm must use at least two samples to calculate the signal's derivative at one sample. This reduces the effective resolution of the algorithm by an additional factor of two. To avoid any further problem due to this effect, we oversampled the data by applying the *sinc* interpolation method (see, e.g., Hoffmann, 2002) and transformed the signal into a 100 samples/sec trace. This sampling rate is also used for the data stream transmitted from the new broadband Italian National Network to INGV. The only "disturbance" introduced by oversampling is some noise before the sinusoid onset that broadens the peak but does not affect the estimated dominant period, the time elapsed from the moment of *P*-onset, and the stabilization of the function.

Different time-window lengths and filters were tested to find the most stable estimate of the dominant period and to minimize the 25 percentile around the median values obtained for each magnitude. This search was performed with a trial-and-error approach since an *a priori* behavior of the data processing cannot be predicted because we do not know any simple relationship between window length and scattering of T_P estimates.

The best relationship between T_P and M_L is obtained by using two different filters: one for smaller and one for larger magnitudes. This implies that two different linear relations between T_P and M_L were derived. For small earthquakes with magnitudes between M_L 2.0 and 4.0 the broadband vertical-component waveforms were high-pass filtered at 1.0 Hz. In Figure 3 we show the dominant frequency (i.e., the reciprocal of the dominant period) as function of time together with the high-passed filtered seismogram. For larger events, that is, with magnitudes between M_L 3.5 and 6.0, the data were low-pass filtered at 2.5 Hz (Fig. 4).

In both cases, the T_P maximum was retrieved in a 1-sec-

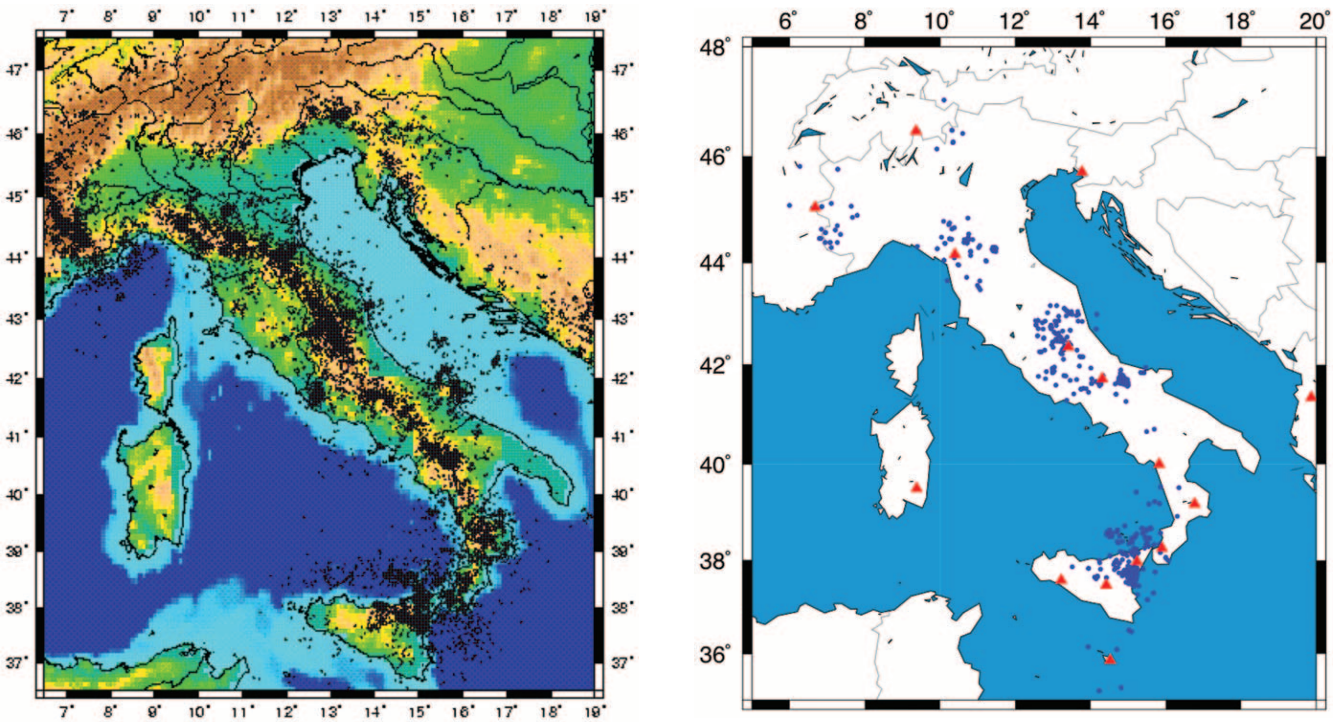


Figure 1. (Left) Map of the crustal seismicity in Italy. (Right) A map of all events (blue dots) selected for this study observed at distances less than 100 km with MedNet stations (red triangles).

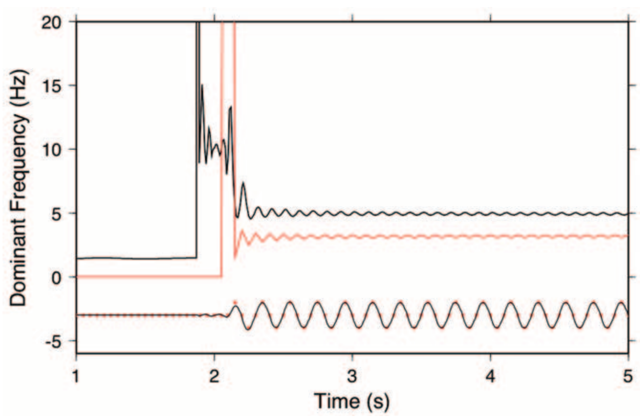


Figure 2. Synthetic test for a 5-Hz signal, sampled at 20 samples/sec (red) and 100 samples/sec (black). Note that the 20 samples/sec signal gives a dominant frequency far too low.

long time window after a 0.5-sec transient from the *P* onset. Although it is known that larger events have a more complex source radiation and that this lasts for more than 1.5 sec, in our data set of events with $M_L < 6.0$, we do not see larger T_P maxima after the 1-sec time window. The measured T_P maxima and the corresponding M_L observations are shown in Figure 5 for each of the two filter options. In addition, we show the two linear relations that best fit the distribution of the observed M_L values as a function of the maximum predominant T_P. The two relations are:

$$M_L = 8.69 + 10.66 \log(T_P) \quad \text{for } 2.0 < M_L < 4.0$$

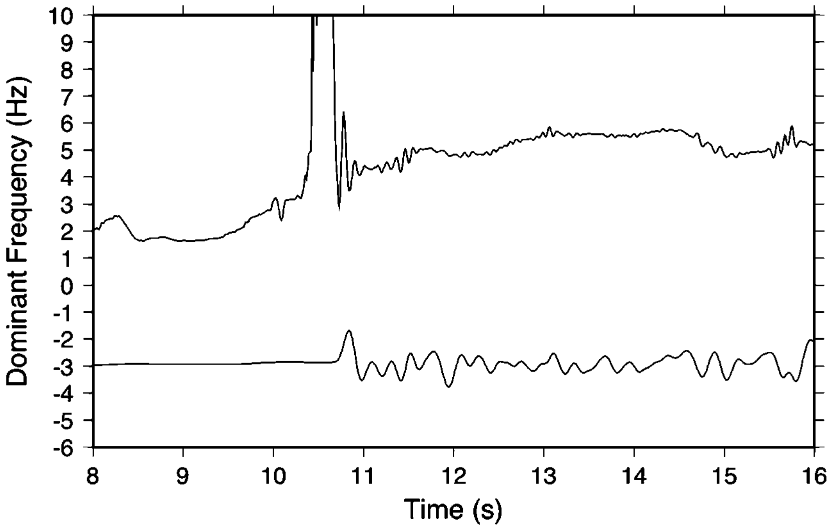
and (3)

$$M_L = 3.91 + 4.28 \log(T_P) \quad \text{for } 3.5 < M_L < 6.0$$

Discussion and Conclusions

These two new linear relations can be the starting point for implementing an EEW system in Italy that will enhance the capability of providing quick and robust estimates of the earthquake parameters. The deployment of new stations in the network by the INGV will increase the density of broadband sensors transmitting their data on-line to INGV. This will make it possible to calculate the T_P function for both filters continuously and in real time for many places in Italy. As shown from Figure 5a, the dominant period saturates for large magnitudes and this is caused by the filter used. In the real automatic processing the magnitude will be *a priori* unknown; this means that there is no way to discriminate between the two relations. But, if the estimated magnitude is larger than about 3.5, we know that this estimate can be "saturated" and we should use the result from the process filtered for larger events that has been extrapolated for events with magnitude between 3.5 and 6.0.

Kanamori and Allen (2003) are correct in pointing out the need of averaging over several different T_P observations



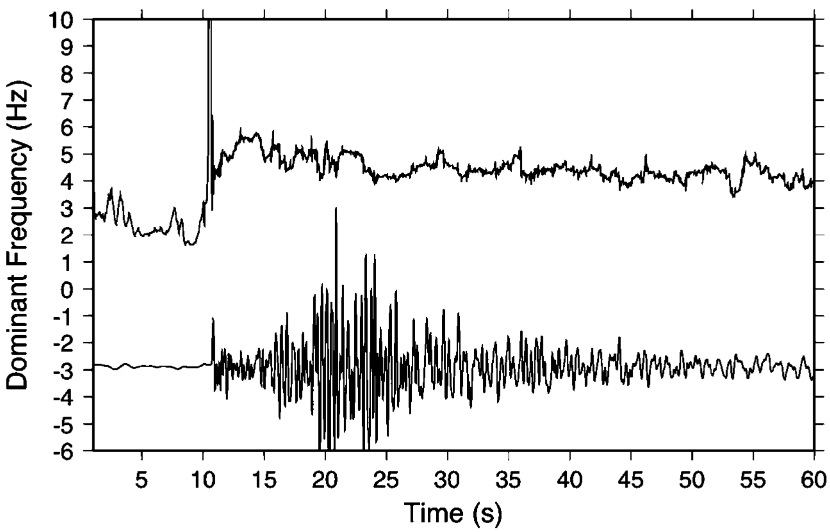


Figure 3. Example of an M_L 3.5 event as recorded at station AIO on 21 February 2002. (Bottom) The whole trace superimposed with the dominant frequency function. (Top) Enlarged view of the first 5 sec of the signal.

for the same event to obtain a robust relation between magnitude and dominant period and with a reasonable error bar of about 0.5. This will help to better understand the errors associated with the single observations that, as pointed out by Wolfe (2006), can be due to different but not neglectable reasons. In our case, where the database is made by single event-station observations, the existence of a linear relation is clear but the data are too scattered to address these results as a rule for magnitude estimates in the Italian region. The proposed magnitude versus dominant period relation will be the starting point for a detailed study based on the Broadband Italian Seismic Network. This network will consist of about 200 stations, most of them equipped with 40-sec sensors and some with 5-sec sensors. The data recorded by both kinds of stations will be suitable for such a quick magnitude estimate because the low-pass filter for the large event processing will have a corner at 2.5 Hz. This means that, on average, the *P*-wave onset will reach the station about 4 sec after the origin time and the first magnitude estimate will be available about 2–3 sec later. Moreover, about 5 sec later, data from about four additional stations will contribute with their magnitude estimate, and a robust magnitude estimate will be ready for release about 10 sec after the occurrence of the earthquake.

We did not attempt a regionalization of the M_L relationship because this would require a larger data set, and especially more, well-recorded larger events. What is now clear from our data is that earthquakes from northeastern Italy recorded at the station TRI do not follow our derived relations (see the magenta dots in Fig. 5). A rough analysis of these observations shows strong site effects that perturb the vertical component recordings. We can hypothesize that this may be related to coupling with the big vault (Grotta Gigante, a karstic cave 380 meters long, 65 meters wide, and 107 meters high), in which the STS-1 sensors of this station are located. For this reason, data recorded at TRI were re-

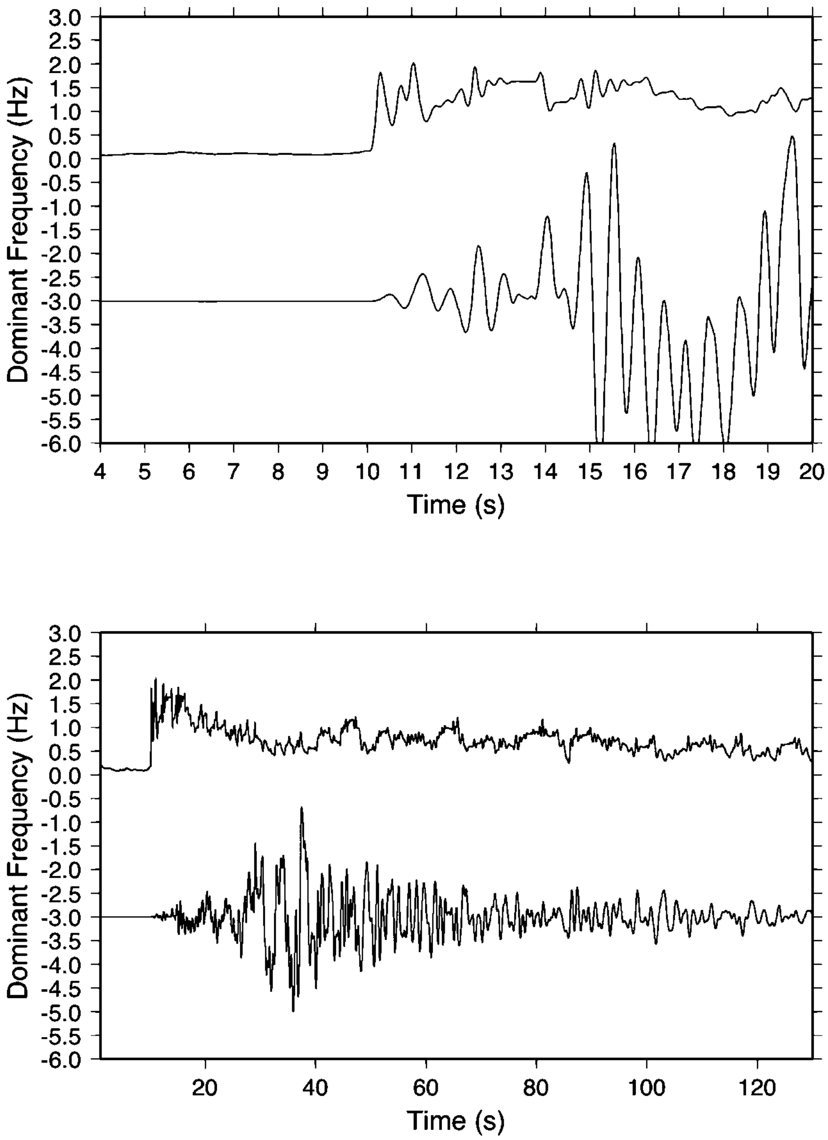


Figure 4. Same as in Figure 3, for the mainshock of the Umbria Marche earthquake sequence (26 September 1997, M_L 5.9) as recorded at AQU.

moved from the data set before the inversion for the M_L versus T_P relation and they will be object of a special study in the future.

At present, this new way for computing rapid magnitude estimates seems just a small step into the future, but its potential to prevent damage and to reduce the impact of relevant earthquakes is obvious. This approach should also be explored more in other tectonic regions in order to be applicable whenever high-risk infrastructures need such information to react in a few seconds after destructive earthquakes.

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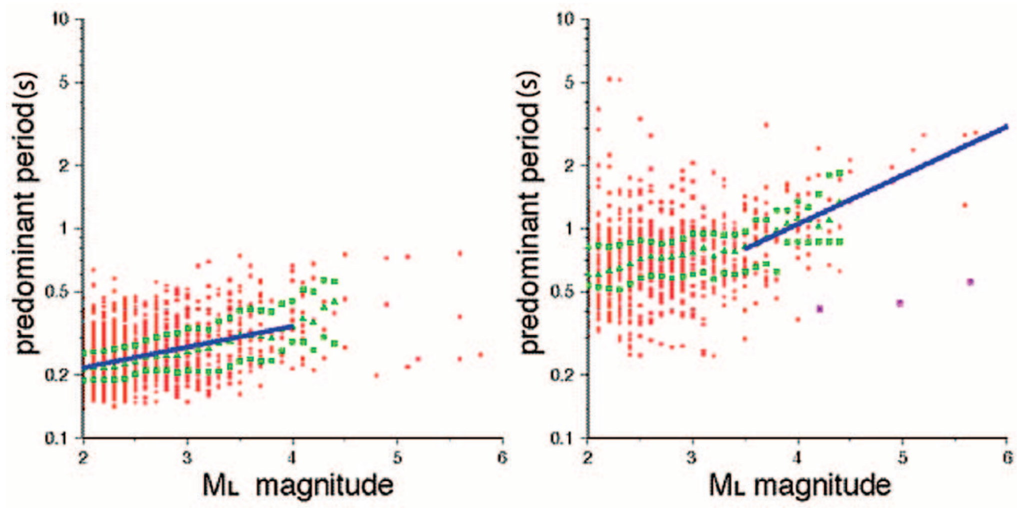

Figure 5. Predominant period observations for differently filtered data plotted versus local magnitudes (M_L). On the left, the application of the small-magnitude filter (high-pass 1 Hz) and on the right, the application of the high-magnitude filter (low-pass 2.5 Hz) is shown. The red dots are maximum TP values for single events observed at different stations. The green triangles represent the median and the 25 percentile from the median. The blue lines are the best fitting regression result.

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