Continuous waveform data stream analysis: Detection and location of the L'Aquila earthquake sequence

Michelini A.[1], Maggi, A.[2]

[1].Istituto Nazionale di Geofisica e Vulcanologia, via di vigna murata, 605, 00143 Roma, Italy, (alberto.michelini@ingv.it)

[2]. Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, France (alessia@unistra.fr)

Abstract

We present a continuous waveform earthquake location technique which does not rely on wave onset phase picking or on event phase association. The technique adopts and further develops a methodology introduced by Withers et al. (1999) based on the cross-correlation between "Green's functions" within a predefined distance range, and stream-like, continuously recorded data. At each time step, earthquake occurrence is tested through the sum of the cross-correlation values on a grid of potential location points. In real time processing and in absence of station latencies, the technique, when applied at regional and local scales, can provide locations within 10-30 seconds from origin time depending on the pre-assigned distance of the Green's functions and station coverage. In addition the technique can be used off-line to analyse previously recorded data. The methodology is applied to data recorded by the permanent Italian National Seismic Network operated by INGV. The resulting epicentral locations are generally found to match closely those determined using manual picks and standard location programs. In addition we detect a number of events that were missed by the standard manual location procedure. The technique shows potential for unattended and rapid seismic source detection/location in seismic monitoring centers.

Data

The waveform data used in this study were recorded by the stations of the Italian National Seismic Network (international network code IV) and MedNet (MN). Twenty-five permanent stations are situated within a radius of 100 km from the city of L'Aquila (Fig. 5a). We have selected vertical component data (HHZ), from 00:00 UTC on April 6, 2009, to 23:59 UTC on April 30, 2009, for a total of 25 days. The data were decimated to 10 Hz after low-pass filtering at 2.5 Hz in order to avoid possible aliasing, then were arranged in 35-minute time-windows, with an overlap of 5 minutes every half hour. Given that most of the stations rely on satellite telemetry, gaps are present in some of the data. In order to avoid data-gaps, we have only considered stations that recorded and transmitted successfully all the data samples within a given data window. Therefore, the station coverage we use varies between different time-windows. For the 25 days covered by this study, the median value of the number of stations used for a single time-window is 22, and 99\% of the windows contain complete data recorded by more than 10 stations.

Method

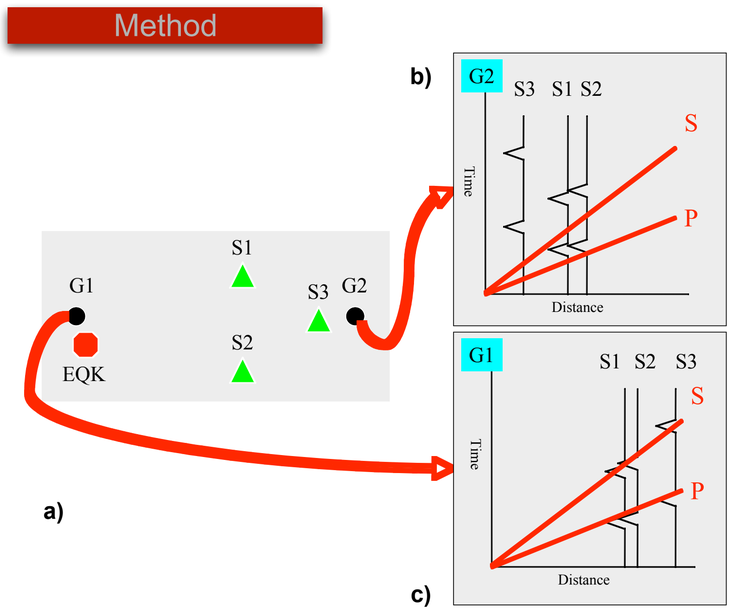

Figure 1. The cartoon, shows a simplified acquisition geometry, consisting of three stations (S1, S2 and S3), the true seismic source location (E1), and two potential seismic source location points (G1 and G2). WaveLoc tests both the potential source locations, in order to decide which one is closer to the true one. The data are correlated with the appropriate GFs for the distances between the stations and the potential earthquake sources b) and c). In this example, the GFs are simply box-cars centered at the appropriate P- and S-wave arrival times. We see that when the source G2 is chosen, the data are not aligned correctly with the GFs, with the exception of the S-wave recorded at S2 aligning with the theoretical P-wave arrival time. Conversely, when the source G1 is chosen, the data are aligned correctly with the GFs. Therefore, the WaveLoc algorithm will prefer G1 over G2.

L'Aquila main shock

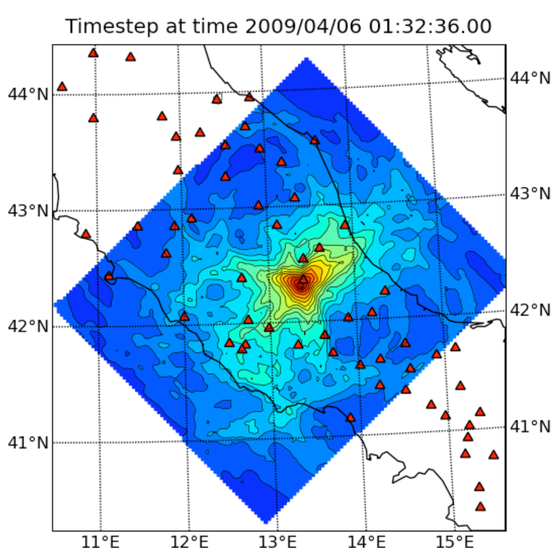

Figure 3. WaveLoc location of the L'Aquila main shock

L'Aquila sequence: Detected/Undetected

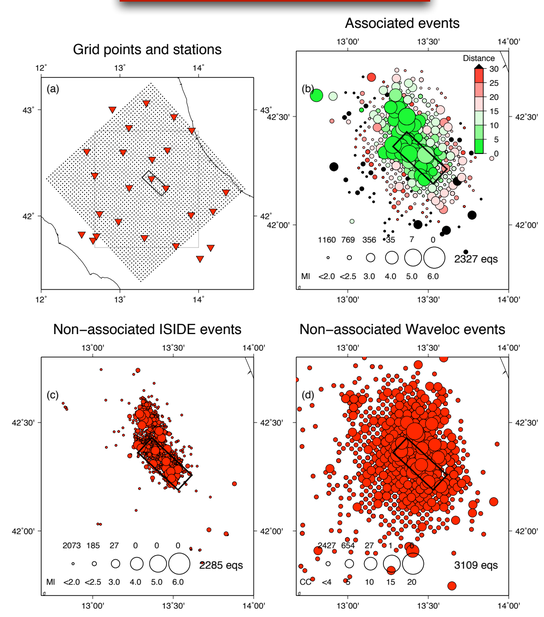

Figure 5. L'Aquila sequence plan view maps. Stations and grid configuration (a); WaveLoc events associated to the ISIDE catalogue (b); Events in ISIDE but undetected by WaveLoc (c); Events detected by WaveLoc but not listed in ISIDE (d).

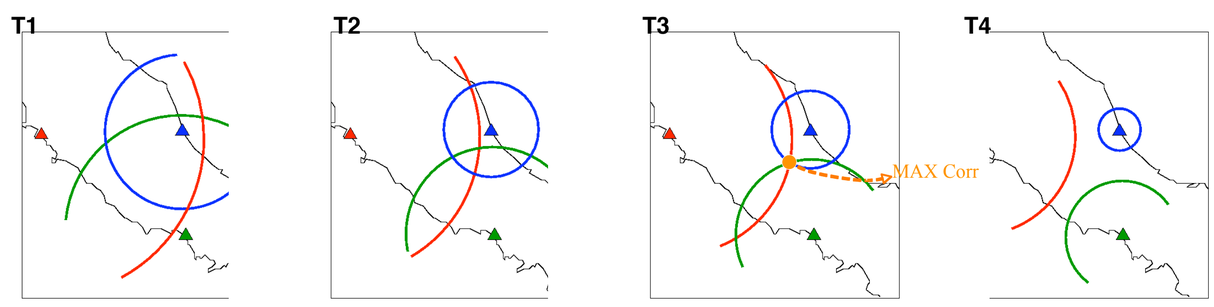

Figure 2. The cartoon, shows through time the insurgence of high levels of correlation for an hypothetical earthquake occurring near the "blue stations". At time T1, the three stations have all detected the first P-waves. The correlation level circles reduce their radius progressively as time proceeds (T1 -> T4). The optimal location is obtained when all the circles overlap and the level of maximum correlation attains its maximum value. Time T3 is thus the origin time of the earthquake and the location is that given by the maximum correlation level. In practice, this approach replicates what Richter (1958) describes as the strip method for determining earthquake location.

Example

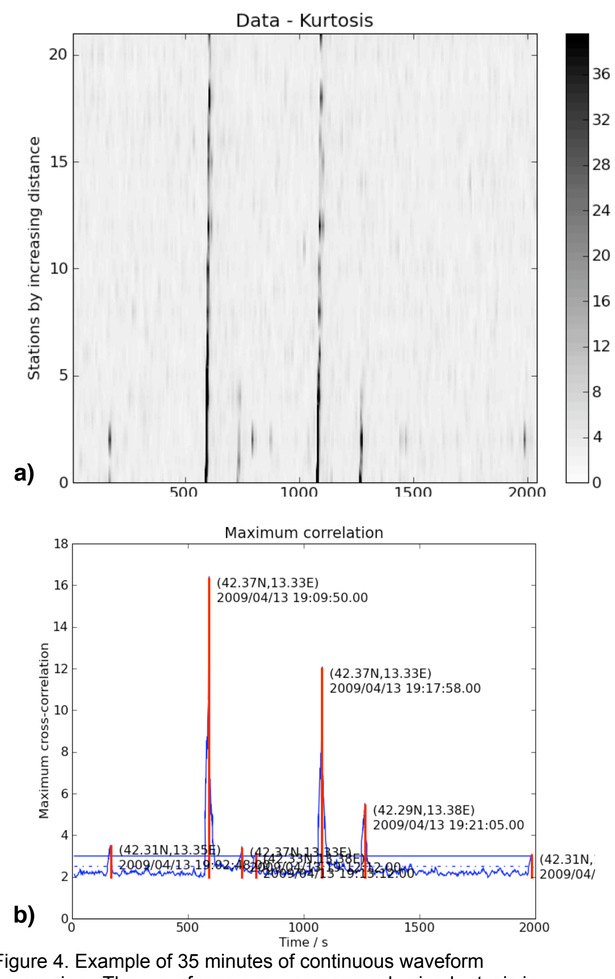

Figure 4. Example of 35 minutes of continuous waveform processing. The waveforms are preprocessed using kurtosis in order to enhance the first arrival times a). The result of the continuous correlation through time where the peaks correspond to the OTs of the earthquakes b).

Discussion and Coclusions

The methodology, originally proposed by Withers et al. (1999), has been coded and implemented introducing some new waveform pre-processing schemes such as skewness, envelope and kurtosis.

The results show that a total of 5590 seismic events were detected by WaveLoc in the 25-day time period from April 6 to April 30, 2009.

2327 earthquakes could be associated to events listed in the ISIDE catalogue (http://iside.rm.ingv.it) - the latter resulting from manual picks performed by analysts and improved station geometry.

Depending on the magnitude range, we have shown that more than 90% of the events listed ISIDE have been correctly identified and located in the range $2.5 \leq M_L < 3.0$ and nearly 100% for larger magnitudes. To this regard, careful manual revision has shown that the missed events belong either to the first half-hour after the main shock when the overall noise level is very hight owing to the multiple event scattering or to inconsistencies in the ISIDE OTs.

However, the large majority of the "missed" events that are catalogued in ISIDE feature local magnitudes less than 1.5. In contrast, we have found that WaveLoc detected many events not reported in ISIDE. Although many of these events are probably falses, we have found nevertheless several tens of events that feature large correlation values which have been probably missed by the INGV monitoring system.

WaveLoc can be adopted both on real-time data streams for quick identification and location of seismic events, and off-line for the analysis of large volumes of data without human intervention.

Although in its present stage of development the technique cannot substitute more standard algorithms based on manual picking and phase association, it can be found nevertheless effective for rapid determination of earthquake location in seismic monitoring centers and for the off-line analysis of large volumes of waveform data.

L'Aquila sequence: some simple statistics

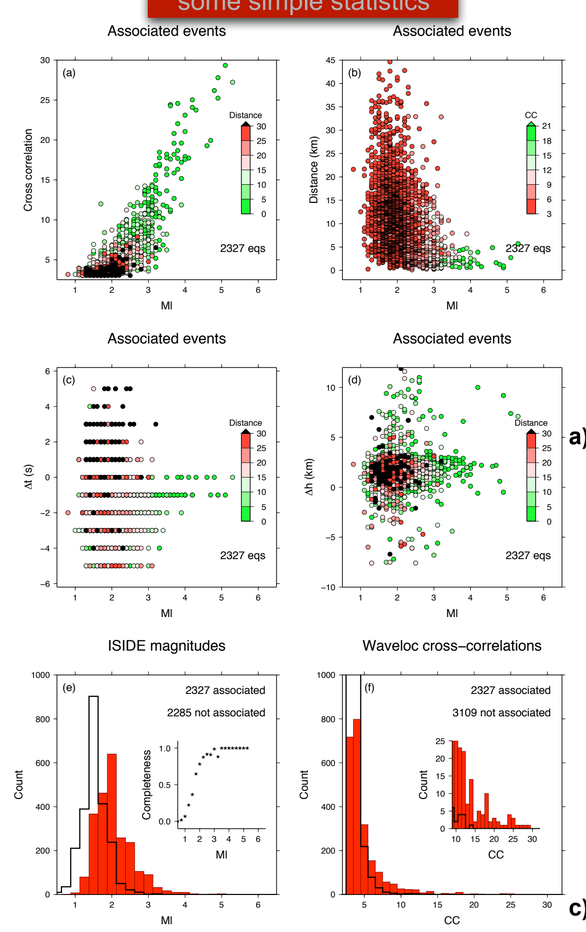

Figure 6. L'Aquila sequence statistics for events detected by associated to ISIDE. Correlation between correlation value and M_L (a); WaveLoc location accuracy vs M_L (b); WaveLoc origin time accuracy vs M_L (c); WaveLoc dependency upon depth vs M_L (d); Histograms of WaveLoc events associated to ISIDE vs M_L (*red*) and unassociated (*white*) (e); Histograms of WaveLoc events associated to ISIDE vs correlation value (*red*) and unassociated (*white*) (f).

L'Aquila sequence: examples of missed events

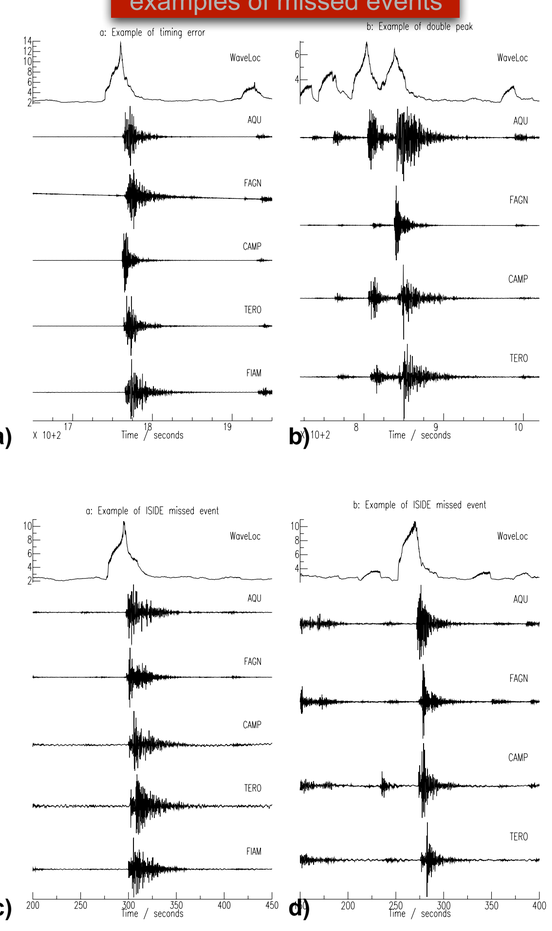

Figure 7. Examples of missed events for the L'Aquila sequence. Case of WaveLoc missed event due to timing error in ISIDE (a); Event missed by WaveLoc because of correlation peak detection criteria (b); Event missing in ISIDE but detected by WaveLoc (c) and (d).

Acknowledgements

We would like to thank the CNT-Analisi Dati Sismici Group for the providing the data.

Bibliography

Richter, C. F., Elementary Seismology, W. H. Freeman and Co, 1958.

Withers, M.; Aster, R. & Young, C. (1999), 'An automated local and regional seismic event detection and location system using waveform correlation', Bulletin of the Seismological Society of America 89(3), 657--669