Performance analysis of the Early-Est software within the tsunami early warning system installed at the INGV

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Abstract

Fast, accurate and reliable earthquake source parameters are crucial for seismologically based tsunami early warning procedures. These parameters should be obtained within a few minutes after event origin time when coastlines in the near-field of the seismic source are potentially threatened. Thus there is no time for a detailed analysis and accurate revision of the automatic solution, and only a quick validation/rejection of the results may be performed in most of the cases by a seismologist. Within this context it is important to have a reliable estimate of the uncertainties of the earthquake epicenter location, depth and magnitude. Early-Est (EE) is a software currently installed at the recently established Centro Allerta Tsunami (CAT), the operational segment of the Italian National Tsunami Warning Centre (It-NTWC), in the seismic monitoring centre of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome (Italy). EE operates on continuous-realtime seismic waveform data to perform trace processing and picking, phase association, event detection, hypocenter location, and event characterization. This characterization includes mb and Mwp magnitudes, and the determination of duration, T0, large earthquake magnitude, Mwpd, and assessment of tsunamigenic potential using Td and T50Ex. In order to test the performance of the fully automatic EE solutions for tsunami early warning, we first compare the hypocenters and magnitudes provided at global scale by different agencies (NEIC, GFZ, CSEM) for events with magnitude Mw ≥ 5.5. We then compare the empirical uncertainties we obtain in this way with EE solution and with the differences between the EE system and the reference catalogues. Our analysis shows that EE is suitable for the purpose of the CAT since it generally provides fully automatic reliable locations and magnitudes within the uncertainties expected from statistical analysis of the manually revised reference catalogs. We also analyze the performances of EE for several offshore earthquakes occurred in the last two years in the Mediterranean and analyze the warning messages that would have been issued for each of the events considered.

Empirical uncertainty of epicenter location and magnitude

The Early-Est (EE) software is running at INGV continuously since begin of march 2012. Early-Est is a software for global automatic location and assessment of tsunamigenic potential (Lomax and Michelini 2009a, 2009b, 2011). Once EE has first located an earthquake, continuously re-locate the event by adding new phases and re-computing the magnitudes (mb, Mwp and Mwpd). Relocation is updated every minute during the hour after event origin time.

In this work we evaluated the empirical uncertainties of epicenter location and magnitude for earthquakes with magnitude larger than M ≥ 5.5 at global scale provided by EE. The epicenter locations and magnitude differences between the GFZ, the EMSC and the NEIC catalogues are used to set empirical uncertainties. Magnitudes values and magnitudes types may vary; for this reason we set the threshold for the minimum magnitude for the data request at M≥5.0. Using this threshold level, we ensure to have selected all earthquakes with magnitude M≥ 5.5.The time windows for data selection starts for the NEIC at begin 2004, for the EMSC at October 2004 and for GFZ at august 2006. The time window ends at end 2013 for all catalogs. The derived empirical uncertainties are then used to set the reliability of the fully automatic locations and magnitude estimations provided by EE.

EE runs fully automatic and no revision is performed on the derived earthquake parameters. The three reference catalogs are manually revised.

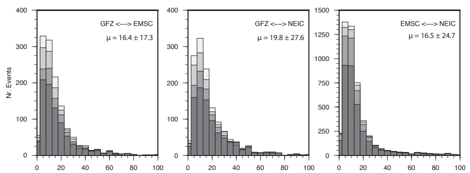


Figure 1

Comparison of the epicenter location differences in km for magnitudes ranges (see table at the bottom of this box for color ranges) between the three reference catalogs.
The mean μ and the standard deviation are computed for the entire magnitude range dataset.

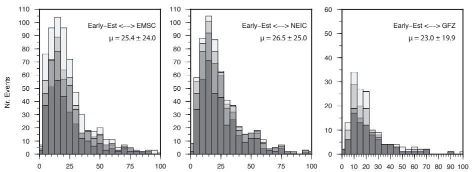
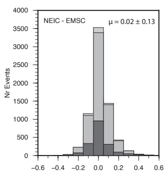


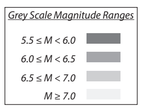
Figure 2

Comparison of the epicenter location differences in km for magnitudes ranges between the three reference catalogs and EE. The distribution is wider and the mean difference is about 10 km larger than in figure 1. Such differences are generally not relevant for offshore tsunamigenic large events.

Figure 3

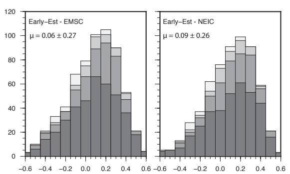
The GFZ catalog did not provided the magnitude type. Thus we compared only EMSC with NEIC magnitudes.





EE provids three type of magnitudes: mb, Mwp and Mwpd. The magnitude mb is always computed, while Mwp and Mwpd only for the larger events. Only the magnitude type, which compares with the one listed into the two reference catalogs is used to produce the following histograms and to compute the mean and the standard deviation.

Figure 4



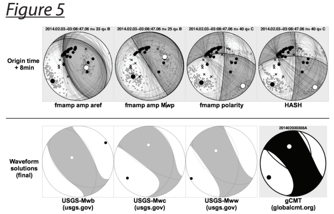
Rapid focal mechanism determination

The use of P first-motion data is critical in Ealry-est for determining focal mechanisms in the first 5- 10min after an event, since waveform mechanisms are only available 10-20min or later after origin time. The program *fmamp* is a probabilistic, global-search, focal mechanism code using first-motion polarities (*fmamp* polarity), or high-frequency average P amplitudes (*fmamp amp* aref; Early-est "aref" amplitude measure), or displacement amplitudes derived from the Early-est Mwp magnitude (*fmamp* amp Mwp). The sign of the amplitude is set from first-motion polarities or a waveform polarity based on the Early-est Mwp measure (Lomax and Michelini, 2012). Predicted radiation amplitudes are calculated using Aki and Richards, 1980, eqs. 4.84–4.86.
Global-search: *fmamp* uses an oct-tree search (Lomax et al., 2009), which provide a smoother and more complete search and set of "acceptable" solutions than regular grid searches; the set of "acceptable" solutions indicates the uncertainty and quality of the determined mechanisms.
Misfit functions: The *fmamp* polarity misfit uses a count of agreement between observed and predicted first-motion polarities for each tested fault-plane solution. This misfit function is similar to that of standard first-motioncodes, suchas HASH (Hardebeck and Shearer,2002). The *fmamp amp* misfit uses the quality of fit of observed versus predicted P amplitudes to a line through the origin with fixed slope A_obs_mean/A_pred_mean - the expected relation between perfect data and predicted amplitudes. The mean amplitude ratio A_obs_mean/A_pred_mean is related to the event size; this ratio is calculated directly from the observed and predicted data. The amplitude misfit function uses an L1 norm for robustness with regards to amplitude anomalies errors.

Example: Figure 5 shows *fmamp* and HASH mechanisms for data available at 8 min after origin time for a recent, large Mediterranean earthquake. The *fmamp* polarity and HASH results are based on the same polarity data and similar misfit function and thus are directly comparable. Note the generally better constraint (less scatter in acceptable P and T axes, and fault planes) and same or higher quality solutions (A, B, C, ...) for the *fmamp* results relative to HASH. The *fmamp amp* results, despite having the fewest data, show better agreement with waveform solutions than the other algorithms.

In general, the *fmamp* polarity and HASH results are often similar, except for quality levels, while the *fmamp* amplitude solutions, when available, often show higher constraint and quality than the polarity methods. We will investigate using in Early-est: 1) *fmamp* polarity, giving a small gain in constraint and quality of mechanisms, along with 2) *fmamp amp* Mwp to provide additional information and better constrained, higher quality mechanisms for moderate and larger events.

Figure 5



Comparison of the focal mechanism solutions obtained for the Mw=6.2 Greece earthquake obtained automatically 8 minutes after origin time, using *fmamp* and *HASH* compared with the USGS and the global CMT solutions.

Early-Est real time performances

Figure 6

EE can provide a first automatic location 2 minutes after event origin time. Few events are first located 7-8 minutes after event origin time; most of these earthquakes occur offshore and faraway from the seismic stations, which provide real time data.

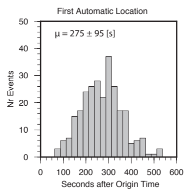
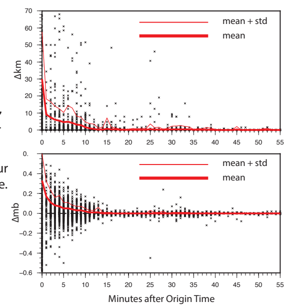


Figure 7

EE continuously adds new phases each minute in the hour following the event origin time. These new phases better constrain the location and the magnitude. Generally the source parameters stabilize within a few run after the first location.



Top: difference in km between the epicenters obtained after each run. The location stabilizes very quickly within a range of 10 km uncertainty.
Bottom: Difference between the magnitudes mb obtained after each run. The mean and the standard deviation are computed from the absolute values of the mb differences. The mb stabilizes very quickly within a range of 0.1 uncertainty.

Towards the pre-operational phase of INGV as candidate Tsunami Watch Provider (cTWP) for the NEAM region

(see also poster B227, this session)

Between march 2012 and end of december 2013 EE located 5 offshore earthquake with M ≥ 5.5 in the Mediterranean area (Table 1). Based on the location, magnitude and the NEAM decision matrix (Figure 8), the Centro Allerta Tsunami (CAT) at the INGV compiled test tsunami warning messages and tsunami travel times were calculated. Figure 9 and 10 are examples of the message and of the respective tsunami travel time map. The message and the map are automatically generated.These messages are not reviewed by a seismologist and they are not yet disseminated.

Nr	date	time	lat	lon	Z	mb	mwp	mwpd	lat	lon	Z	mb	mwp	mwpd	sec	lat	lon	Z	Mw
1	2012-06-10	12:44:15	36.36	28.93	19.7	5.7	6.1	6.9	36.33	29.01	19.7	6.3	6.2	6.5	167	36.36	28.93	30	5.9
2	2012-09-12	03:27:43	34.77	24.08	10.0	5.7	5.4	6.2	35.06	24.00	10.0	5.8	5.6	5.9	201	34.74	24.03	30	5.4
3	2013-01-08	14:16:09	39.62	25.49	10.1	5.7	5.7	6.8	39.64	25.59	19.8	6.1	6.0	0.0	174	39.66	25.54	10	5.7
4	2013-10-12	13:11:51	35.52	23.30	11.5	6.3	6.6	6.8	35.39	23.20	85.4	6.3	6.6	7.2	194	35.56	23.31	47	6.4
5	2013-12-28	15:21:06	36.04	31.30	56.8	6.0	6.0	6.1	36.06	31.45	34.2	5.8	5.9	6.4	358	35.96	31.29	64	5.9

Table 1

List of the 5 offshore events occurred in the NEAM region with M ≥ 5.5 between the beginning of 2012 and the end 2013. For each event are listed the epicentral coordinates, depth and magnitudes of the last EE iteration (sub table left); the same values corresponding to the first stable solution and the seconds after origin time when these parameters were available (sub table center); and the reference values listed into the EMSC catalog (sub table right).

Figure 8

Decision matrix (ICG-NEAMTWS, 2011) used to evaluate and compose the tsunami warning message, based on epicentral location, depth and magnitude. These rules apply only to events which occur into the Mediterranean basin.

Depth	Epicenter Location	Mw	Tsunami Potential	Type of Bulletin		
< 100 km	Offshore or close to the coast (≤ **40 km** inland)	5.5 to 6.0	weak potential of local tsunami	Local Tsunami Advidory	Information Bulletin	Information Bulletin
		6.0 to 6.5	Potential of destructive local tsunami < 100 km	Local Tsunami Watch	Regional Tsunami Advidory	Information Bulletin
	Offshore or close to the coast (≤ **100 km** inland)	6.5 to 7.0	Potential of destructive regional tsunami < 400 km	Local Tsunami Watch	Regional Tsunami Watch	Basin-wide Tsunami Advisory
		> 7.0	Potential of destructive tsunami in the whole basin > 400 km	Local Tsunami Watch	Regional Tsunami Watch	Basin-wide Tsunami Watch
> 100 km	Offshore or inland (≤ 100 km)	> 5.5	Nil	Information Bulletin	Information Bulletin	Information Bulletin

No message if the earthquake is localized inland beyond 100 km distance

Example of tsunami warning message automatically generated for the december 2013 earthquake (nr. 5 in table 1).

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TSUNAMI MESSAGE NUMBER 001
NEAM INGV IT-CAT NTWC
ISSUED AT 1527Z 28 DEC 2013

... TSUNAMI ADVISORY ...
THIS ALERT APPLIES TO CYPRUS
... TSUNAMI INFORMATION ...
THIS ALERT APPLIES TO ISRAEL  GREECE  EGYPT  ITALY  MALTA  FRANCE  SPAIN

THIS MESSAGE IS ISSUED AS ADVICE TO GOVERNMENT AGENCIES. ONLY
NATIONAL AND LOCAL GOVERNMENT AGENCIES HAVE THE AUTHORITY TO MAKE
DECISIONS REGARDING THE OFFICIAL STATE OF ALERT IN THEIR AREA AND ANY
ACTIONS TO BE TAKEN IN RESPONSE.

AN EARTHQUAKE HAS OCCURRED WITH THESE PRELIMINARY PARAMETERS
ORIGIN TIME - 1521Z 28 DEC 2013
COORDINATES - 36.06 NORTH 31.45 EAST
DEPTH - 34 KM
LOCATION - CYPRUS_REGION
MAGNITUDE - 6.4

ALERT LEVEL IS ASSIGNED ACCORDING TO THE ABOVE ESTIMATIONS OF
EARTHQUAKE PARAMETERS AND BASING ON ICG/NEAMTWS DECISION MATRIX

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Disclaimer section, not reported in this picture
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ESTIMATED INITIAL TSUNAMI WAVE ARRIVAL TIMES AT FORECAST POINTS WITHIN
THE WATCH AREA ARE GIVEN BELOW. ACTUAL ARRIVAL TIMES MAY DIFFER AND
THE INITIAL WAVE MAY NOT BE THE LARGEST. A TSUNAMI IS A SERIES OF WAVES
AND THE TIME BETWEEN SUCCESSIVE WAVES CAN BE FIVE MINUTES TO ONE HOUR.
LOCATION, FORECAST POINT COORDINATES, ARRIVAL TIME, ALERT LEVEL
(ADVISORY, WATCH)
------------------------------- ----------- -----------
CYPRUS - PAPHOS 34.76N 32.41E 1543Z 28 DEC ADVISORY
CYPRUS - ZYGI 34.73N 33.34E 1558Z 28 DEC ADVISORY
CYPRUS - LARNACA 34.92N 33.64E 1607Z 28 DEC ADVISORY
CYPRUS - PARALIMNI 35.04N 34.04E 1611Z 28 DEC ADVISORY


SUPPLEMENT MESSAGES WILL BE ISSUED AS SOON AS NEW DATA AND
EVALUATION ALLOWS.
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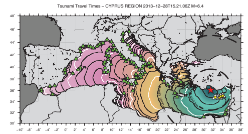
Figure 9



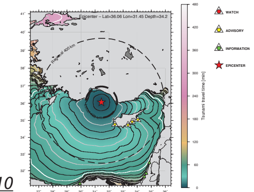


Figure 10

Tsunami travel times computed for the December 2013 earthquake (Table 1). Triangles with dots are 'virtual' forecast points for which the estimated tsunami arrival times are listed into the alert message (figure 9). Actual forecast points will be used in the pre-operational phase when IOC Member States will subscribe the cTWP services.

Conclusions

We compared global earthquake catalogs to set empirical uncertainties for the epicenter location and magnitude. For earthquakes with M >= 5.5 the location uncertainty is less than 20 km with a standard deviation smaller than 30 km. Magnitudes between EMSC and NEIC catalogs are coherent and show a standard deviation of 0.1 magnitude; generally differences do not exceed 0.2 magnitude.

Early-Est is running since two year providing automatic earthquake locations at global scale. Our analysis shows that the automatic locations of EE for earthquakes with M >= 5.5 is reliable.

Magnitude estimations compared with the reference catalogs show a mean over estimation of less than 0.1 magnitude with a standard deviation smaller than 0.3 magnitude; differences are decrease for events with M >= 6.0.

Early-Est provides stable and reliable epicenter locations and magnitude estimations, generally within 3-6 minutes after event origin time.

*We will further test fast and automatic focal mechanism estimation using **fmamp** polarity and **fmamp amp** Mwp. The performed test indicates that reliable focal mechanism solutions can be obtained within 8 minutes from event origin time.*

References:

Hardebeck, J.L. and Shearer P.M. (2002) , A New Method for Determining First-Motion Focal Mechanisms, Bulletin of the Seismological Society of America, Vol. 92, No. 6, pp. 2264–2276,
ICG-NEAMTWS, Interim Operational Users Guide for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and Connected Seas, (2011), Santander
Lomax, A., A. Michelini, A. Curtis (2009), Earthquake Location, Direct, Global-Search Methods, in Encyclopedia of Complexity and System Science, Part 5, Meyers, R. A. (ed.), Springer, New York, pp. 2449-2473
Lomax, A., and Michelini, A. (2009a). Mwpd : a duration-amplitude procedure for rapid determination of earthquake magnitude and tsunamigenic potential from P waveforms, Geophys. J. Int. 176, 200-214
Lomax, A., and Michelini, A. (2009b). Tsunami early warning using earthquake rupture duration, Geophys. Res. Lett. 36, L09306
Lomax, A., and A. Michelini (2011), Tsunami early warning using earthquake rupture duration and P-wave dominant period: the importance of length and depth of faulting, Geophys. J. Int, (2011) 185, 283–291
Lomax, A. and A. Michelini (2012), Novel Algorithms Enabling Rapid, Real-Time Earthquake Monitoring and Tsunami Early Warning Worldwide, AGU, December 2012, San Francisco, Eos Trans. AGU, NN(NN), Abstract S53B-2495