The Use of Preliminary First-Motion Mechanisms and Later Moment Tensor Solutions for Rapid Tsunami Early-Warning Scenario Forecasting

Science Against Barriers
Build Bridges not Walls

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Abstract

Following the ICG/NEAMTWS guidelines, the first tsunami warning messages for events with magnitude M ≥ 5.5 are based only on seismic information, i.e., epicenter location, hypocenter depth, and magnitude. However, in order to provide more informative, real-time tsunami scenario forecasting, reliable faulting mechanism information is needed. Full-waveform, moment tensor solutions (MT) are typically available in 3-15 *min* after event origin time for local/near-regional events and in 15-20 *min* for regional/teleseismic events. Classic, P first-motion focal-mechanisms can be available within 3 min for local/near-regional events and in 5-10 *min* for regional/teleseismic monitoring, depending on station coverage.
We present first a robust, probabilistic, adaptive grid-search, first-motion inversion (pFM) which, combined with fast magnitude estimates such as M_{wp}, forms a preliminary mechanism estimate and proxy for MT solutions. This MT proxy allows rapid event characterization and analysis, such as estimation of shaking distribution and initial modeling of tsunami waves, before a definitive, waveform MT is available. Secondly, we present a near real-time MT inversion using waveforms band-pass filtered from 0.01 – 0.02*Hz* band and a minimum of 6 min of signal after the event origin time for events in the Mediterranean area. The solution is then updated every minute by adding 1 min of signal and using the epicenter parameters available in real time from the automatic localization provided by the Early-Est rapid earthquake location system. Tests on events since 2000 in the Mediterranean area indicate that reliable solutions are available within 7-15 minutes after event origin time. Implementing both methodologies in our system allows the use of pFM mechanisms for rapid, preliminary tsunami forecasting within a few minutes after the earthquake occurrence, and the use of a definitive MT solution a few minutes later for further forecasting updates.

1. Rapid, Robust, Probabilistic First-Motion Mechanisms

The classic, P first-motion focal-mechanism (e.g. Byerly, 1955) combined with fast moment magnitudes such as M_{wp}, provide a preliminary faulting mechanism, enabling early tsunami scenario forecasting before a first MT solution is available. Our rapid, robust, probabilistic focal-mechanism inversion procedure includes:

- *First-motion polarity obtained from broad-band pick first-motion (Lomax et al., 2012), or from P waveform polarity if signal-to-noise ratio is high.*
- *Weighting of each polarity observation based on 1) quality of polarity determination, and 2) distribution of all observations on the focal-sphere.*
- *Misfit/likelihood function for strike, rake and dip based on sum of weights of incorrect polarities, and allows for fixed proportion of outliers.*
- *Rapid, thorough, probabilistic, global search for solution probability density function (PDF) performed using adaptive, oct-tree importance sampling (Lomax and Curtis, 2001, Lomax et al., 2009).*
- *Realistic solution uncertainty derived from scatter of P and T axes for samples drawn from PDF.*
- *Optimal and acceptable solutions, uncertainty and quality information output parametrically and graphically.*

This fully automatic procedure requires minor computing resources and CPU time; pFM mechanisms can be obtained within a few minutes after the earthquake occurrence (e.g. within 3min for local/near-regional events and in 5-10 min for regional/teleseismic monitoring). This delay depends on the distances of close stations, station coverage and first motion polarity quality, the latter two improve rapidly with increasing event magnitude.This thorough, probabilistic inversion is robust: it determines an optimal mechanism that usually matches the final CMT solution, while avoiding alternative, locally optimal but incorrect solutions, even with few polarity observations.

pFM Quality

The quality measure is based on the spread in degrees of the P- and T-axes of the accepted solution scatter sample (eq. 1 and Table 1); the set of P- and T-axes are plotted on each focal mechanism, as the optimal P- and T-axes (Figure 1).

$$Q_{pFM} = \sqrt{\left(\overline{\Delta_P}\right)^2 + \left(\overline{\Delta_T}\right)^2} \quad \text{eq. 1}$$

Table 1

Quality A	*Quality B*	*Quality C*	*Quality D*
$Q_{pFM} \le 20$	$Q_{pFM} \le 35^{\circ}$	$Q_{pFM} \le 50^{\circ}$	$Q_{pFM} > 50^{\circ}$

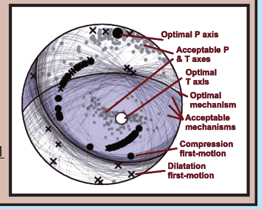

Figure 1
pFM output with symbols

2. Rapid, Regional, Full Waveform Moment Tensor Inversion

The automatic procedure to compute the moment tensor solutions is designed to solve events with magnitude M_w ≥ 5.5.The procedure to compute the moment tensor solutions uses broadband seismic data recorded at stations with epicentral distance between 200 and 1000 kilometers (regional distance). The inversion is perfromed in time domain using all 3 components (the horizontal components are rotated to radial and trasversal) and deconvolved from the isntrument response. Synthetics and observed are bandpassed in a frequancy range between 0.007-0.02 *Hz*. The Green's are computed using the PREM Earth-model, which genearlly woks fine for events of that size occurred in the Mediterranean region (Bernardi et al., 2004).

The procedure is triggered by an automatic location of the Early-Est System (Bernardi et al. 2015). The first inversion is perfromed using 240 seconds of waveform from event origin time using the closer stations. The procedure remove the traces with low signal-to-noise ratio and iteratively remove the stations with lower variance and higher phase shift realigning values, till a robust solution is obtained or alla traces are removed. The solution is updated each minute adding 60 seconds of waveform and the more distant stations. Last inversion is performed 15 minutes after event origin time.

An automatic quality estimation indicates if the full MT (Quality A) or only the seismic moment Mo (Quality B) is reliable. Quality C solution are unreliable. The automatic quality is set by the number of station used to determine the MT solution.

Dataset for the MT assessment

The data set used to calibrate the automatic procedure and the automatic quality assessment includes 100 events with M_w ≥ 5.5 occurred in the European and Mediterranean region between January 2002 and December 2015 (Figure 2).

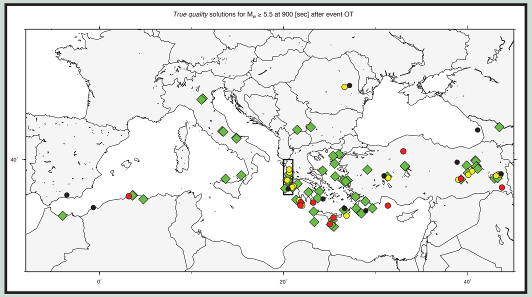

Figure 2

Events used to calibrate the procedure. The colors indicates the *true quality* of the MT solutions obtained using 15 minutes of time width after event origin time. The green diamonds indicate *true quality* A; the yellow dots the *true quality* B; the red dots the *true quality* C; the small black dots any solution. The events occurred in the area indicated by the small rectangular shape are inverted using longer bandpass filter and station closer with respect to the events occurred outside small rectangular shape.

MT Quality assessment

The *true quality* assessment is performed comparing all MT solutions with the gCMT catalog. We distinguish three quality levels: A well-resolved mechanisms and M_w; B well-resolved M_w; C is unreliable. The table 2 summarize the rules to define the *true quality* (Bernardi et al. 2004).

Table 2

True Quality A	*True Quality B*	*True Quality C*
$\lvert\Delta M_w\rvert \le 0.2$ $\lvert\Delta Ax\rvert \le 30^{\circ}$	$\lvert\Delta M_w\rvert \le 0.2$	All others

|ΔAx| is defined as the average of the differences in principal axes' orientation

The automatic *assigned quality* assessment is based on the number of stations and components used to obtain the MT solutions. Figure 3 shows the vales of $|\Delta M_w|$ and |ΔAx| for all MT solutions with respect the number of stations used to obtain the solution. Table 3 summarize the rules used to define the automatic *assigned quality* of the MT solutions.

Table 3

Assigned Quality A	*Assigned Quality B*	*Assigned Quality C*
M_w < 6.0; NrSta ≥ 4 M_w ≥ 6.0; NrSta ≥ 3	M_w < 6.0; NrSta = 3 M_w ≥ 6.0; NrSta = 2	All others

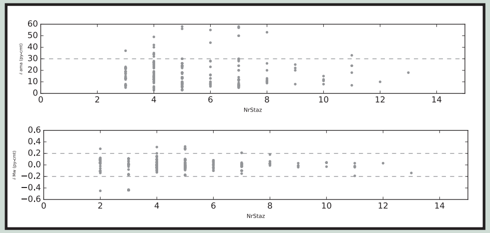

Figure 3 Values of |ΔAx| and $|\Delta M_w|$ for each solution with respect the number of station. Top: points below the dashed line may be *true quality* A. Bottom: points within the dashed lines may be *true quality* A or B.

Generally, the automatic procedure applied to the entire dataset, gives at 10 min after event origin time about 62% *true quality* A MT solutions and about 15% *true quality* B solutions. Considering only events with M_w ≥ 6.0 the *true quality* B solutions are about 20% of the entire dataset. Similar percentages are obtained at 15 min after origin.
Applying the rules to determine the automatic *assigned quality*, we obtain that the 91.9% of the *assigned quality* A solutions effectively correspond to *true quality* A solutions, with a mean axes difference |ΔAx| = 17.6° ≥ 11.1°.

3. Combining pFM and MT inversion algorithms. Examples for 2 events in the Northern Italy and in Greece

We show the results of the Rapid Probabilistic First-Motion Mechanisms and of the Rapid Full Waveform Moment Tensor Inversion, for two events occurred in the Mediterranean area. The first event (Figure 4, top) occurred in the Northern Italy in an area with very dense station coverage. The dense station coverage and the small epicentral distances of the stations gives reliable focal mechanism solutions with the pFM algorithm already within the first minute after event origin time; and a stable moment tensor solution 4 *min* after event origin time.
The second event (Figure 4, bottom) occurred in Greece offshore . Despite a less dense station coverage and larger epicentral distances than for the Northern Italy event, a stable First-Motion focal mechanism is obtained within 2 min after origin time, and a stable Moment Tensor solution 4 min after event origin time..

The Probabilistic First-Motion Mechanism algorithm, with the robust Mwp estimation from Early-Est (Lomax et. al 2009, Bernardi et al 2015), combined with the Rapid Full Waveform Moment Tensor Inversion, gives reliable information about the source mechanism and size for earthquakes with M_w ≥ 5.5 within the very first minutes after event origin time. This information is critical for initial tsunami forecasting and tsunami wave modelling in order to disseminate accurate alert messages to the civil authorities.

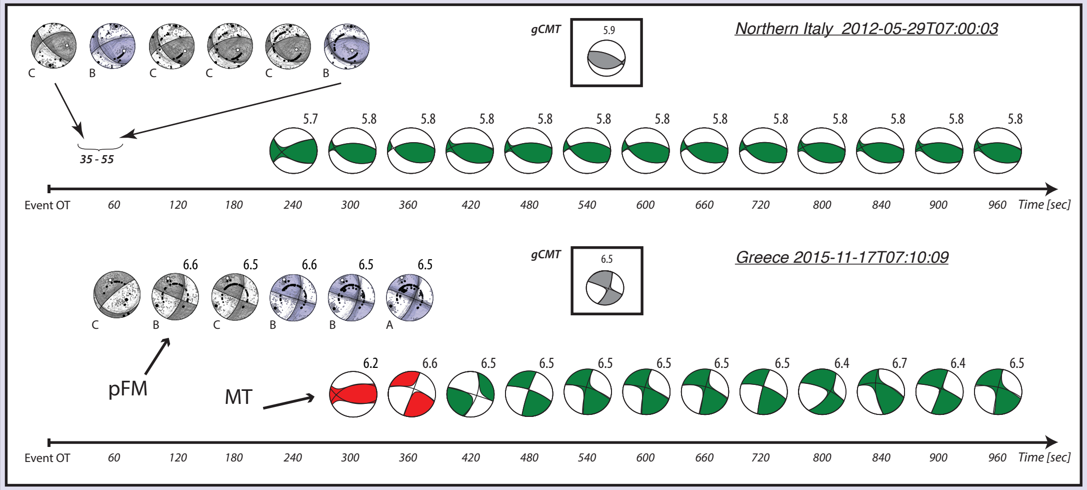

Figure 4

Timeline of the combined pFM and MT inversion algorithm for two events in the Mediterranean area. The box on the shows the gCMT focal mechanism and M_w. For The horizontal axes represent the time after event origin time in seconds. For both events we plot the focal mechanisms computed using the i) pFM; M_{wp} above; The quality on the bottom left of each. ii) the MT inversion; M_w; red mechanisms represent assigned quality C solution (unreliable) and green mechanisms represent assigned quality A solutions (reliable M_w and focal mechanism).

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