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Real-time performance of probabilistic, first-motion earthquake mechanisms to improve tsunami early-warning

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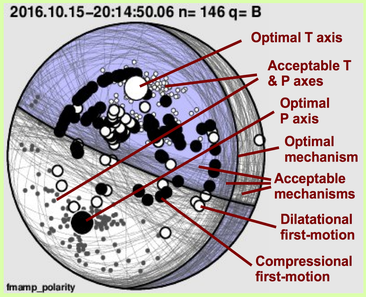
The first tsunami warning messages are typically based on simple earthquake parameters: epicenter location, hypocenter depth, and magnitude. The addition of early information on the faulting mechanism can enable more reliable estimates of seafloor uplift, tsunami excitation, tsunami potential and impact, and earlier, real-time tsunami scenario forecasting. Full-waveform, centroid moment tensor solutions (CMT) are typically available in 3-15min for local/near-regional earthquakes and in 10-30min for regional/teleseismic distances. In contrast, classic, P first-motion (FM) focal-mechanisms can be available within 3min for local/near-regional events and in 5-10 min for regional/teleseismic distances.

Here we present FMAMP, a procedure for robust, probabilistic, adaptive grid-search, FM mechanism determination which generates a comprehensive set of "acceptable" FM mechanisms and related uncertainties. This FM solution, combined with fast magnitude estimates such as Mwp, forms a CMT proxy for rapid source characterization and analysis before a definitive, waveform CMT is available.

FMAMP runs in realtime in Early-est (rapid earthquake detection, location and analysis) at the INGV tsunami alert center (CAT, "Centro di Allerta Tsunami"), part of the Italian candidate Tsunami Watch Provider (Bernardi et al 2015).

The FMAMP inversion procedure

- 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 weighted sum of incorrect polarities; 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 & Curtis 2001; Lomax et al 2009).
- Realistic solution uncertainty derived from scatter of P and T axes for samples drawn from PDF.
- Optimal solution, uncertainty and quality information output parametrically and graphically.



This procedure requires minor computing resources and CPU time. FM 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). The delay depends on the distance of close stations, station coverage and first motion polarity quality, the latter two improve rapidly with increasing event magnitude.

Real-time performance of FMAMP

The thorough, probabilistic inversion in FMAMP is robust: it defines a smooth set of "acceptable" mechanisms that usually match final CMT solutions, while minimizing alternative, locally optimal and scattered solutions, even with few polarity observations.

Below, real-time, Early-est results from FMAMP and a modern, grid-search FM algorithm HASH (Hardebeck & Shearer 2002) compared with final CMT mechanisms from GFZ and USGS, for events with relatively sparse, clustered and noisy FM polarity data.

HASH / standard grid search: multiple clustered and scattered solutions; early and final solutions can differ; ► **difficulty with noisy, clustered data**

FMAMP: gives smoothly distributed set of probabilistic, acceptable solutions; early and final solutions are stable, similar and well constrained (A or B quality); ► **robust results with clustered, noisy data**

event	CMT (~10-30min) USGS	CMT (~10-30min) GFZ	First Motion (early) HASH	First Motion (early) FMAMP	notes	First Motion (20min) FMAMP	First Motion (20min) HASH
Ecuador 2016.04.16 23:58 depth 20km Mw7.8					*early* = OT+9min Early-est Mwp7.4		
Greece – Albania 2016.10.15 20:14 depth 18km Mw5.5					*early* = OT+6min Early-est Mwp5.6		
Solomon Islands 2017.01.22 04:30 depth 135km Mw7.9					*early* = OT+7min Early-est Mwp7.9		
Crete, Greece 2017.01.25 18:50 depth 65km Mw5.2					*early* = OT+6min Early-est Mwp5.1		
Northern Sumatra 2017.03.14 13:13 depth 54km Mw5.2					*early* = OT+10min Early-est Mwp5.3		
Samar, Philippines 2017.04.10 00:43 depth 10km Mw5.6					*early* = OT+8min Early-est Mwp6.0		

These results show that the early (6-10min) FMAMP solutions combined with Mwp provide a CMT proxy which represents well the final (10-30min) CMT results, even for very large earthquakes.

Future developments and improvements

- Improve determination on waveforms of first-motions and their weights.
- Improve ray take-off angles with better 1D and 3D velocity models.
- Obtain earlier solutions by using prior information of previous faulting mechanisms near hypocenter.

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