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Rapid and robust characterization of the earthquake source for tsunami early-warning

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Introduction

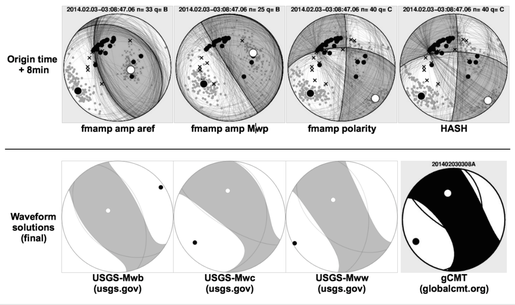
Effective tsunami early-warning after an earthquake is difficult when the distances and tsunami travel-times between earthquake/tsunami source regions and coast lines at risk are small, especially since the density of seismic and other monitoring stations is very low in most regions of risk. For tsunami warning worldwide, seismic monitoring and analysis currently provide the majority of information available within the first tens of minutes after an earthquake. This information is used for direct tsunami hazard assessment, and as basic input to real-time, tsunami hazard modeling. It is thus crucial that key earthquake parameters are determined as rapidly and reliably as possible, in a probabilistic, time-evolving manner, along with full uncertainties.

Early-est (EArthquake Rapid Location sYstem with EStimation of Tsunamigenesis) is the module for 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. In a simulation for the devastating M9, 2011 Tohoku earthquake and tsunami, Early-est determines: the epicenter within 3 min after the event origin time (OT), discriminants showing very high tsunami potential within 5-7 min, and magnitude Mwpd(RT) 9.0–9.2 and a correct, shallow-thrust mechanism within 8 min. Real-time monitoring with Early-est gives similar results for most large earthquakes using currently available, real-time seismogram data.

We discuss key algorithms in Early-est that produce fully automatic, robust results and their uncertainties in the shortest possible time using sparse observations. We show how Early-est may be used within time-evolving, decision and modeling systems for tsunami early warning, along with Early-est analysis results for the 2010 Mentawai tsunami earthquake.

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 and waveform polarities based on the Early-est Mwp measure (fmamp polarity), or high-frequency average P amplitudes (fmamp amp aref), or displacement amplitudes derived from the Early-est Mwp magnitude (fmamp amp Mwp). For larger events, a focal mechanism is usually available in Early-est a few minutes after OT.



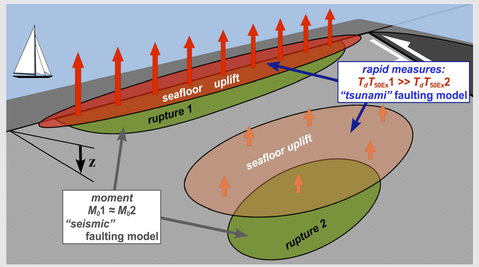
2014.02.03-03:08 Mw6.1 Greece: Polarity, amplitude & waveform mechanisms.

HASH - Hardebeck, J. L. and P. M. Shearer, (2002, Bull. Seism. Soc. Am., 92, 2264-2276.

Period-duration discriminants TdT0 and TdT50Ex for tsunami potential; available within 5-10 min after OT

We presented previously a direct procedure for rapid assessment of earthquake tsunami potential using two, simple measures on P-wave seismograms – the predominant period on velocity records, Td, and the likelihood, T50Ex, that the high-frequency, apparent rupture-duration, T0, exceeds 50-55 sec. We have shown that Td and T0 are related to the rupture parameters length L, width W, slip D and depth z, and that either of the period-duration products Td·T0 or Td·T50Ex give more information on tsunami impact and size than MwCMT, Mwp and other currently used discriminants.

Right: These results imply that tsunami potential is not directly related to the moment M0 from the "seismic" faulting model of an earthquake, as assumed with the use of the MwCMT discriminant. Instead, information on L and z, as provided by Td·T0 or Td·T50Ex, represent the "tsunami faulting model" and can constrain well the tsunami potential of an earthquake.



Lomax, A. and A. Michelini (2012), Tsunami early warning within 5 minutes, Pure and App. Geophys., 169.

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., 185, 283–291.

Mwpd: large earthquake magnitude within 10 min

We previously presented a duration-amplitude procedure for rapid determination of a non-saturating, moment magnitude, Mwpd, for large earthquakes using P-wave recordings at teleseismic distances. With real-time data, Mwpd can be obtained within 10 minutes or less after the event origin time. The procedure determines apparent source durations, T0, from high-frequency, P-wave records, and estimates moments through integration of broadband displacement waveforms over the interval tP to tP+T0, where tP is the P arrival time. Mwpd extends Mwp for very large and long duration events.

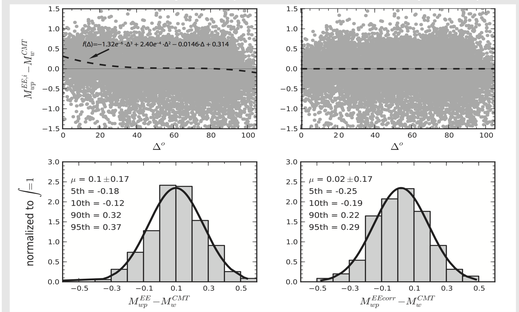
Lomax, A. and A. Michelini (2009a), Mwpd: A Duration-Amplitude Procedure for Rapid Determination of Earthquake Magnitude and Tsunamigenic Potential from P Waveforms, Geophys. J. Int.,176, 200-214.

Lomax, A. and A. Michelini (2009b), Tsunami early warning using earthquake rupture duration, Geophys. Res. Lett., 36, L09306.

Mwp at distances Δ < 30° for earlier magnitudes

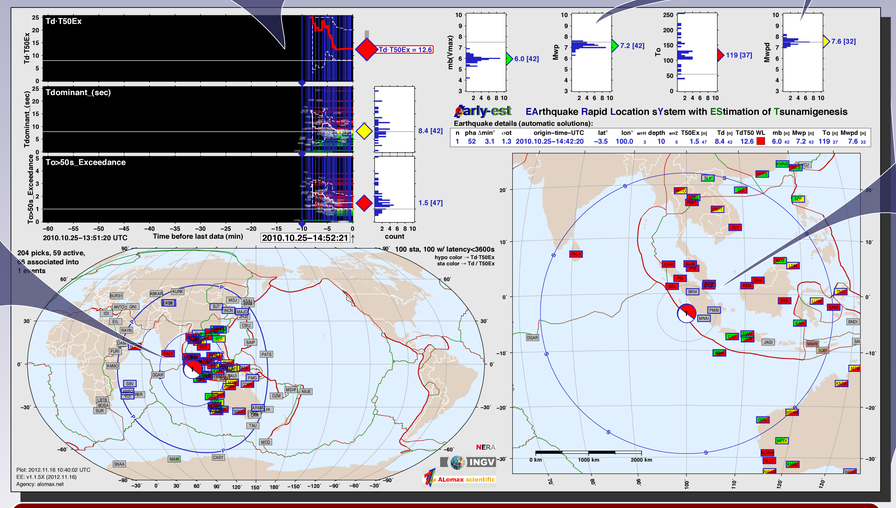
Mwp uses a far-field approximation to the P-wave displacement (Tsuboi et al., 1995*), thus Mwp in the near-field may be biased. Indeed, the distance dependency of Mwp at each station (upper left) overestimates MwCMT at Δ < 30°. Since Early-est must provide magnitudes within a few minutes after OT, obtaining accurate Mwp from closer stations is critical.

A regression line computed from the residuals (upper left) is used to correct (right) the distance dependency of the Mwp values. Re-computing the M_{wp} magnitudes for each event using the corrected station values, we removes the overestimation of MwCMT by Mwp at Δ < 30° (bottom right).



Differences between Early-Est Mwp and MwCMT for earthquakes shallower 100km (2012-2014)

** Tsuboi, S., Abe, K., Takano, K., and Yamanaka, Y. (1995), Bull. Seism. Soc. Am., 85, 606-613.*



Early-est main display for the 25 October 2010, Mw7.8 Mentawai tsunami earthquake at origin time + 10min (off-line simulation)

Robust, simultaneous association and location using a probabilistic, global-search

The Early-est associate/locate module efficiently and robustly associates picks, and detects and locates seismic events over the whole Earth to 700km depth using the non-linearized, oct-tree importance-sampling search (Lomax et al., 2009). The objective function for the oct-tree search is a likelihood based on stacking of implicit origin-times for a source at **x**=x,y,z for each pick: given a velocity model, a pick time Tp at a seismic station, and assuming a source point **x** in the model and seismic phase type that may have produced the pick, the phase travel-time from source to station Tx can be calculated and an implicit origin-time OT for the source and phase can be determined by back projection (e.g., OT=Tp–Tx).

Lomax, A., A. Michelini, A. Curtis (2009). Earthquake Location, Direct, Global-SearchMethods, in Encyclopedia of Complexity and Systems Science, Part 5, 2449-2473, ed. Meyers, A., Springer, New York.

Picking is done with FilterPicker is a general purpose, broad-band, phase detector and picker which is applicable to real-time seismic monitoring and earthquake early-warning. *Lomax, A., C. Satriano and M. Vassallo (2012), Automatic picker developments and optimization: FilterPicker - a robust, broadband picker for real-time seismic monitoring and earthquake early-warning, Seism. Res. Lett. , 83, 531-540.* **http://alomax.net/FilterPicker**

Time evolution of Early-est event characterization : The 2010, Mw7.8 Mentawai tsunami earthquake

The 2010 Mentawai tsunami earthquake generated a large, destructive, local tsunami. Early-est characterizes this event with an epicenter constrained in the first minutes after the origin time (OT) and Mwp, Mwpd(RT) and Td·T50Ex measures available at OT+3→4 min. All three discriminant for tsunami potential, Td·T50Ex at OT+3→4 min, and T0 and Td·T0 at OT+5→6 min, indicate a high likelihood that a tsunami was generated. All measures stabilize to near their final values within OT+7→8 min. For this event, in addition to early indication of high tsunami potential at OT+3→6 min, Early-est gives: at OT+6→9 min Mwpd(RT) 7.6-7.7 that matches final MwCMT; T0≈120s and mb-log10(Td·T0)≈3.0, suggesting this event is a tsunami earthquake; and a focal mechanism corresponding to an interplate thrust event. (see **mpeg animation** for time-evolution of event characterization)

Lomax, A. and A. Michelini (2012), Tsunami early warning within 5 minutes, Pure and Applied Geophysics, 169.

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