Novel Algorithms Enabling Rapid, Real-Time Earthquake Monitoring and Tsunami Early Warning Worldwide

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Introduction

We have introduced new methods to determine rapidly on a regional to global scale the tsunami potential and magnitude of large earthquakes (e.g., Lomax and Michelini, 2009ab, 2011, 2012). To validate these methods we have tested them on 120 large earthquakes (6.4 ≤ Mw ≤ 9.1) and implemented them along with other new algorithms within the *Early-est earthquake monitor* at INGV-Rome: **http://early-est.rm.ingv.it**, **http://early-est.alomax.net**. Early-est is a lightweight software package for real-time earthquake monitoring (including phase picking, phase association and event detection, location, magnitudes, first-motion mechanisms, ...), and for tsunami early warning (based on the Td·T0 and Td·T50Ex discriminants for earthquake tsunami potential). In a simulation using archived broadband seismograms 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-thrusting mechanism within 8 min. Real-time monitoring with Early-est gives similar results for most large earthquakes using currently available, real-time seismogram data.

Here we present key algorithms within Early-est that enable rapid, real-time earthquake monitoring and tsunami early warning worldwide, and we show Early-est analysis results for the 2010 Mentawai tsunami earthquake.

FilterPicker - a broad-band picker

FilterPicker is a general purpose, broad-band, phase detector and picker which is applicable to real-time seismic monitoring and earthquake early-warning. FilterPicker uses an efficient algorithm which operates stably on continuous, real-time, broadband signals, avoids excessive picking during large events, and produces onset timing, realistic timing uncertainty, onset polarity and amplitude information. FilterPicker operates on a set of band-passed time-series with different center frequencies. Characteristic functions are determined for each frequency band and a pick is declared if and when, within a specified time window, the integral of the maximum of the characteristic functions exceeds a pre-defined threshold.

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**

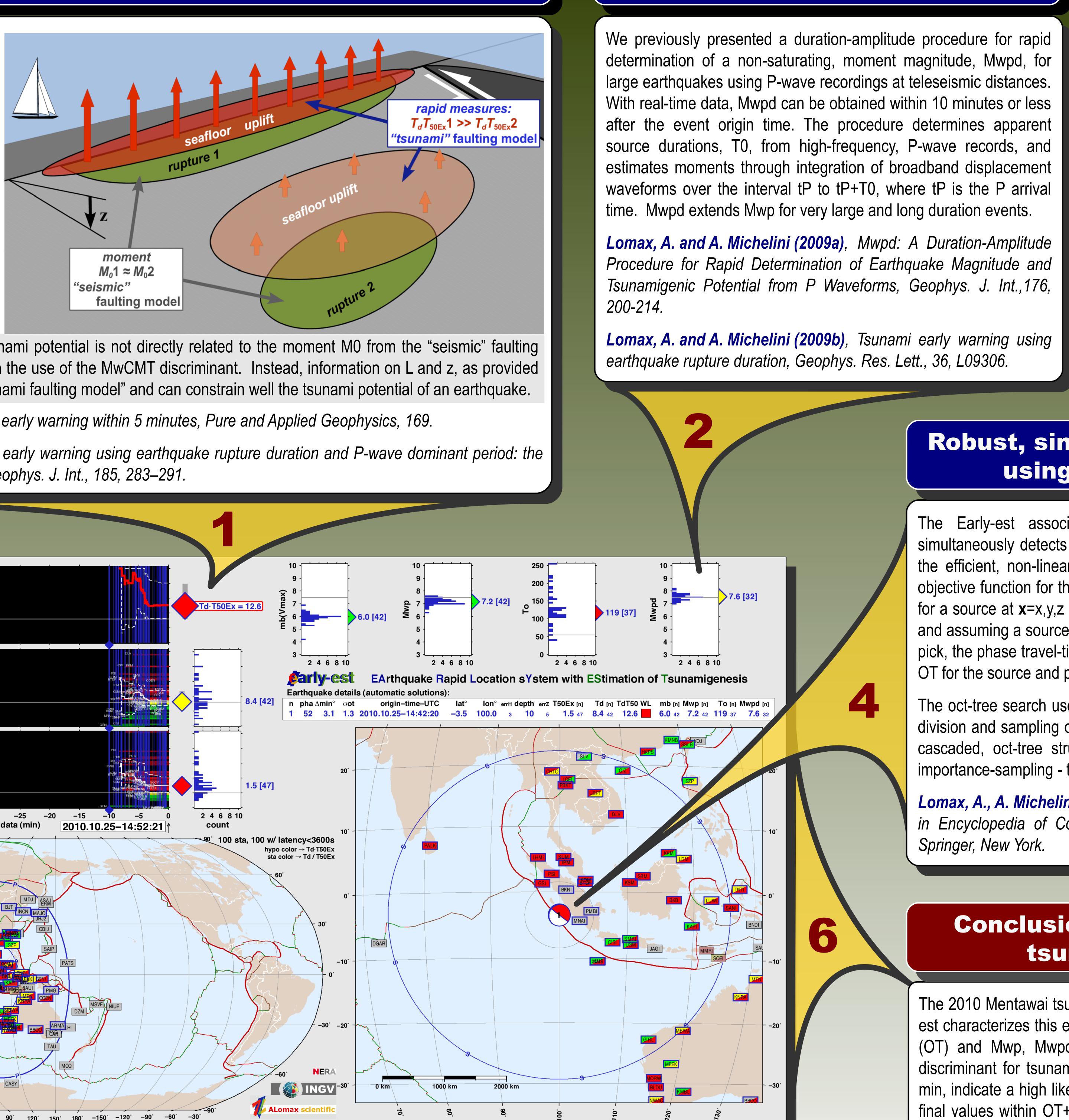## P polarity on broad-band waveforms; first-motion focal mechanisms

In addition to FilterPicker P first-motion polarities, Early-est estimates P polarity on broadband displacement waveforms. The P polarity is given by the sign of the mean displacement after the P onset within a window proportional to the Mwp pulse duration. Either the broadband, waveform polarity or the FilterPicker polarity is used for mechanism determination, depending on the quality of the polarity measures and signal-to-noise ratios. First-motion focal mechanisms are obtained with the HASH program (Hardebeck and Shearer, 2002) which determines a set of acceptable mechanisms and associated probabilistic uncertainties. For larger events, a focal mechanism is usually available in Early-est a few minutes after OT.
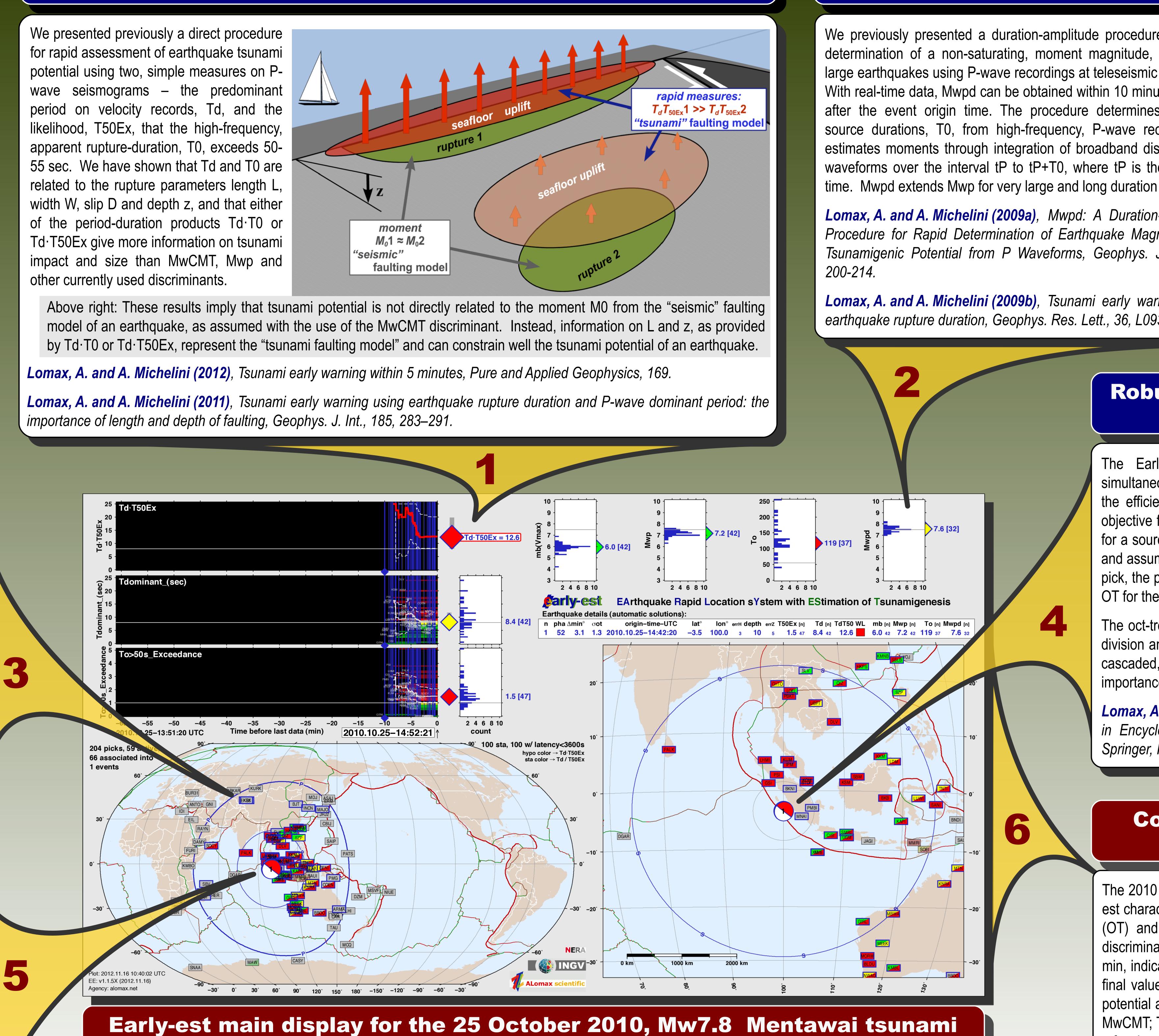
Hardebeck, J. L. and P. M. Shearer, (2002). A new method for determining first-motion focal mechanisms, Bull. Seism. Soc. Am., 92, 2264-2276.

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.

Above 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 Applied Geophysics, 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 magnitude for very large earthquakes 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.

Also: SeisGramWeb – a portable-device ready seismogram viewer

SeisGramWeb is an interactive, browser based viewer for seismograms obtained from time-series web services. SeisGramWeb runs within a browser on any platform, including portable devices, since it uses standard HTML and JavaScript. More information: **http://alomax.net/webtools/sgweb/info.html**

Early-est includes extensive graphics / HTML / web output, including SeisGramWeb for one-click viewing of seismograms from monitored and picked stations in real-time.

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

The Early-est associate/locate module efficiently and robustly associates picks, and simultaneously detects and locates seismic events over the whole Earth to 700km depth using the efficient, 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).

The oct-tree search uses an initial, coarse, regular grid-search followed by recursive, octal sub-division and sampling of cells in three-dimensional, latitude/longitude/depth space to generate a cascaded, oct-tree structure of sampled cells. The oct-tree search produces approximate importance-sampling - the spatial density of sampled cells follows the objective function P.

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.

Conclusion: The 2010, Mw7.8 Mentawai tsunami earthquake in Early-est

The 2010 Mentawai tsunami earthquake generated a large and 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. (**mpeg animation**)
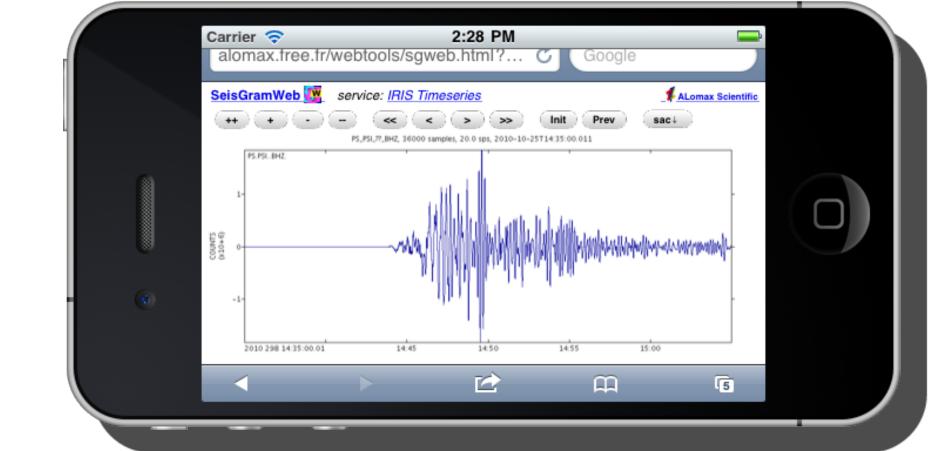
Lomax, A. and A. Michelini (2012), Tsunami early warning within 5 minutes, Pure and Applied Geophysics, 169.

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

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