EEW – Algorithm Testing Document

Version 01b

3 March 2008

Up-dated July 2010 (eq. 3.1 to 3.3)

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Definitions

Times
We distinguish three types of times:

- **timepoint** $T$ – a point in time
- **duration** $D$ – a length of time or a certain number of clock ticks
- **interval** $I$ – the period between two points in time

**origin time** $T_{\text{origin}}$: timepoint (absolute time), at which the earthquake rupture initiates as specified in the eq. catalogues

**telemetry duration** $D_{\text{telemetry}}$: measurement (or estimate) of the length of time needed to transfer the data from the field to the site where the EEW algorithm runs

**processing duration** $D_{\text{processing}}$: measurement (or estimate) of the length of time needed by a processing system to calculate a warning from seismograms

**algorithm time** $T_{\text{algorithm}}$: timepoint, at which an estimated parameter (e.g. magnitude) could be theoretically available, if $D_{\text{telemetry}}=0$ and $D_{\text{processing}}=0$. This timepoint is the largest timestamp on any of the data used to estimate the parameter; also called **zero-delay alert time**

**alert time** $T_{\text{alert}}$: timepoint, at which an estimated parameter (e.g. magnitude) is available for distribution to EEW users. This can be measured by the EEW algorithm by calling an accurate clock when a warning is available. It can also be calculated from other system measures; $T_{\text{alert}} = T_{\text{algorithm}} + D_{\text{telemetry}} + D_{\text{processing}}$

**alert interval** $I_{\text{alert}}$: interval between the alert time and the origin time: $I_{\text{alert}} = T_{\text{alert}} - T_{\text{origin}}$

**zero-delay alert interval** $I_{zd}$: $I_{zd} = T_{\text{algorithm}} - T_{\text{origin}}$
Ground Motion Parameters

**PGA:**
peak ground acceleration; refers to the largest value of all 3 components; PGA-obs is the observed, PGA-est the estimated PGA value at a given site; the values include site effects

**PGV:**
peak ground velocity; refers to the largest values of all 3 components; PGV-obs is the observed, PGV-est the estimated PGV value at a given site; the values include site effects

**I:**
seismic intensity on the MMI scale; can be estimated from PGV or PGA using empirical relationships proposed by Wald et al. (1999) – see Appendix; I-obs is determined from PGA-obs or PGV-obs; I-est is determined from PGA-est or PGV-est

**ΔI:**
intensity increment = I-obs – I-est; can be used for the evaluation and comparison of predicted ground motion amplitudes PGA and PGV (see Appendix)

Source Parameters

**Loc:**
geographical coordinates of the earthquake source (= epicenter); Loc-obs is the observed (as in the eq. catalogues), Loc-est is the estimated source location

**M:**
M-obs is the observed magnitude (as in the eq. catalogues). As with alerted CISN magnitudes M_w is preferred over M_L which is preferred over M_d as the reference magnitude; M-est is the estimated magnitude
Algorithms

**ElarmS:** regional warning approach based on sensor network; capable to estimate M, Loc, PGA and PGV (within 200 km around epicenter); estimates are updated with time

**ElarmS RT:** real-time mode of ElarmS, i.e. \( \text{time} = \text{alert time} \) (as would be available in an operational EEW system)

**ElarmS AL:** zero-delay mode of ElarmS, i.e. \( \text{time} = \text{algorithm time} \) (i.e. assuming telemetry and processing delay = 0 sec)

**Virtual Seismologist (VS):** regional warning approach based on sensor network; capable to estimate M, Loc, PGA and PGV (within 200 km around epicenter); estimates are updated with time

**VS RT:** real-time mode of VS, i.e. \( \text{time} = \text{alert time} \) (as would be available in an operational EEW system)

**VS AL:** zero-delay mode of VS, i.e. \( \text{time} = \text{algorithm time} \) (i.e. assuming telemetry and processing delay = 0 sec)

**Tauc-Pd Algorithm:** = “amplitude and period monitor”; on-site warning approach based on a single sensor; capable to estimate M and PGV (at the site of observation) from initial 3 sec waveform data; estimates are not updated with time

**Tauc-Pd RT:** real-time mode of the Tauc-Pd Algorithm, i.e. \( \text{time} = \text{alert time} \) (as would be available in an operational EEW system)

**Tauc-Pd AL:** zero-delay mode of the Tauc-Pd Algorithm, i.e. \( \text{time} = \text{algorithm time} \) (i.e. assuming telemetry and processing delay = 0 sec)
I. Algorithm Testing/Website

I.1 What the Algorithm Developers will Change and Provide

**minimum magnitude for assessment:** $M_{\text{min}} = 3.0$

**max. epicentral distance for assessment:** $\text{Dist-max} = 200 \text{ km}$

**Caltech**

Tauc-Pd RT/AL:
- For each triggered station $\leq \text{Dist-max}$, send one alert of:
  - $M$-est with $T_{\text{alert}}$ and $T_{\text{algorithm}}$
  - PGV-est with $T_{\text{alert}}$ and $T_{\text{algorithm}}$
  - PGV-obs if $M \geq M_{\text{min}}$
- For each $M \geq M_{\text{min}}$, send one alert of:
  - Number of reporting and non-reporting stations $\leq \text{Dist-max}$ as a function of $T_{\text{alert}}$ and $T_{\text{algorithm}}$

**UC Berkeley**

ElarmS RT:
- For each triggered event, send one alert of:
  - $M$-est as a function of $T_{\text{alert}}$
  - Loc-est as a function of $T_{\text{alert}}$
  - PGA-est at each station $\leq \text{Dist-max}$ without S-wave arrival as a function of $T_{\text{alert}}$
  - PGA-obs at each station $\leq \text{Dist-max}$ if $M \geq M_{\text{min}}$
  - PGV-est at each station $\leq \text{Dist-max}$ without S-wave arrival as a function of $T_{\text{alert}}$
  - PGV-obs at each station $\leq \text{Dist-max}$ if $M \geq M_{\text{min}}$
- Number of reporting and non-reporting stations $\leq \text{Dist-max}$ as a function of $T_{\text{alert}}$

ElarmS AL:
- For each triggered event, send one alert of:
  - $M$-est as a function of $T_{\text{algorithm}}$
  - Loc-est as a function of $T_{\text{algorithm}}$
  - PGA-est at each station $\leq \text{Dist-max}$ without S-wave arrival
as a function of $T_{\text{algorithm}}$
PGA-obs at each station $\leq \text{Dist-max}$ if $M \geq M_{\text{min}}$
- PGV-est at each station $\leq \text{Dist-max}$ without S-wave arrival as a function of $T_{\text{algorithm}}$
  PGA-obs at each station $\leq \text{Dist-max}$ if $M \geq M_{\text{min}}$
- Number of reporting and non-reporting stations $\leq \text{Dist-max}$ as a function of $T_{\text{algorithm}}$

**ETH Zurich**

**VS RT:**
- For each trigger, send one alert of:
  - $M$-est as a function of $T_{\text{alert}}$
  - Loc-est as a function of $T_{\text{alert}}$
  - PGA-est at each station $\leq \text{Dist-max}$ without S-wave arrival as a function of $T_{\text{alert}}$
    PGA-obs at each station $\leq \text{Dist-max}$ if $M \geq M_{\text{min}}$
  - PGV-est at each station $\leq \text{Dist-max}$ without S-wave arrival as a function of $T_{\text{alert}}$
    PGV-obs at each station $\leq \text{Dist-max}$ if $M \geq M_{\text{min}}$
  - Number of reporting and non-reporting stations $\leq \text{Dist-max}$ as a function of $T_{\text{alert}}$

**VS AL:**
- For each trigger, send one alert of:
  - $M$-est as a function of $T_{\text{algorithm}}$
  - Loc-est as a function of $T_{\text{algorithm}}$
  - PGA-est at each station $\leq \text{Dist-max}$ without S-wave arrival as a function of $T_{\text{algorithm}}$
    PGA-obs at each station $\leq \text{Dist-max}$ if $M \geq M_{\text{min}}$
  - PGV-est at each station $\leq \text{Dist-max}$ without S-wave arrival as a function of $T_{\text{algorithm}}$
    PGV-obs at each station $\leq \text{Dist-max}$ if $M \geq M_{\text{min}}$
  - Number of reporting and non-reporting stations $\leq \text{Dist-max}$ as a function of $T_{\text{algorithm}}$
I.2 What the EEW Website will Provide and Calculate

1) Loc-obs, M-obs and origin times from QDDS and QDM/ web page to do associations
2) Calculate I-obs from PGA-obs or PGV-obs, and I-est from PGA-est or PGV-est (see Appendix)

I.3 Summary Reports to be issued by the EEW Website

Summary reports will be generated monthly and/or after every \( M \geq M\text{-min} \):

**Summary Reports for each \( M \geq M\text{-min} \):**
- Summary 1: Magnitude
- Summary 2: Location
- Summary 3: Ground Motion
- Summary 4: System Performance

**Monthly Summary Reports:**
- Summary 4: False Triggers
- Summary 5: Missed Triggers

*In the following, the term time shall mean (see Definitions):*

- **ElarmS RT:** alert interval \( I_{\text{alert}} = T_{\text{alert}} - T_{\text{origin}} \)
- **ElarmS AL:** zero-delay alert interval \( I_{\text{zd}} = T_{\text{algorithm}} - T_{\text{origin}} \)
- **VS RT:** alert interval \( I_{\text{alert}} = T_{\text{alert}} - T_{\text{origin}} \)
- **VS AL:** zero-delay alert interval \( I_{\text{zd}} = T_{\text{algorithm}} - T_{\text{origin}} \)
- **Tauc-Pd RT:** alert interval \( I_{\text{alert}} = T_{\text{alert}} - T_{\text{origin}} \)
- **Tauc-Pd AL:** zero-delay alert interval \( I_{\text{zd}} = T_{\text{algorithm}} - T_{\text{origin}} \)

*Proposed time steps (used in the tables):*

\[
\begin{align*}
t_1 &= 1.0 \text{ sec} \\
t_2 &= 3.0 \text{ sec} \\
t_3 &= 6.0 \text{ sec} \\
t_4 &= 10.0 \text{ sec} \\
t_5 &= 15.0 \text{ sec} \\
t_6 &= 20.0 \text{ sec} \\
t_7 &= 25.0 \text{ sec}
\end{align*}
\]

A proposed scheme for the evaluation of predicted ground motions GM is given in the Appendix.
I.3.1 Summary Reports for each $M \geq M_{\text{min}}$

**Summary 1: Magnitude**
- **ElarmS/VS:**
  - X-Y Plot: $M_{\text{est}}$ as a function of time, $M_{\text{obs}}$ plotted as a line (because $M_{\text{obs}}$ is constant with time)
  - Table: $M_{\text{est}}$ at seven time steps
- **Tauc-Pd Algorithm:**
  - Table: $M_{\text{est}}$ at each station with corresponding time, i.e., station1: time1 $M_{\text{est}}$; station2: time2 $M_{\text{est}}$; ... and $M_{\text{obs}}$

**Summary 2: Location**
- **ElarmS/VS:**
  - X-Y Plot: distance (in km) between Loc-est and Loc-obs as a function of time
  - Table: distance (in km) between Loc-est and Loc-obs at seven time steps
- **Tauc-Pd Algorithm:** -

**Summary 3: Ground motion GM**

**For each single station:**
- **ElarmS/VS:**
- **Tauc-Pd Algorithm:**
  - Table: $\Delta I = I_{\text{obs}} - I_{\text{est}}$ (see Appendix) with corresponding time

Use in addition descriptive scales (see Appendix) for
- the evaluation of estimated GM
- a description of the level of obs. and estimated GM
Summary for all stations ≤ Dist-max (without S-wave arrival):
Use descriptive scales for the evaluation of estimated GM (Appendix)
- ElarmS/VS:
  - X-Y Plot: ΔI vs. I-obs
  - Histogram: percentage of stations with “excellent”, “very good”,
    “good”, “moderate” and “poor” predictions of I as a function of time

- Tauc-Pd Algorithm:
  - Histogram: percentage of stations with “excellent”, “very good”,
    “good”, “moderate” and “poor” predictions of I

Summary 4: System performance
Ratio of reporting and non-reporting stations (as a function of time)

I.3.2 Monthly Summary Reports

Summary 5: False triggers
Provide a list of false triggers (=events that could not be associated
with a local earthquake in California with time diff.=5 sec and M ≥ M-
min)

Summary 6: Missed triggers
Provide a list of missed triggers (=events in California with M ≥ M-min
for which no EEW alert is available)
Algorithm Testing

Three algorithms for earthquake early warning (EEW) are currently tested in a real-time environment using the infrastructure of the California Integrated Seismic Network (CISN): (a) ElarmS (Allen and Kanamori, 2003; Allen et al., 2007), (b) the Virtual Seismologist (Cua and Heaton, 2007), and (c) the tauc-Pd algorithm (Kanamori, 2005). Aside from estimating seismic source parameters, such as magnitudes, all three algorithms are capable to predict the level of ground shaking. This occurs either in terms of peak ground velocity (PGV) and/or peak ground acceleration (PGA). Here we propose a scheme for the evaluation and comparison of the predicted ground motions.

1. Levels of Perceived Shaking and Damage Potential

In order to make observed and predicted levels of ground shaking, PGV_{obs} (PGA_{obs}) and PGV_{est} (PGA_{est}), easily understandable (also for unskilled persons), these levels need to be associated with a qualitative description (in words) of the (a) perceived shaking and the (b) potential damage, which are characteristic for the corresponding shaking level. These descriptions should be in agreement with the ShakeMaps (Wald et al., 1999) and consider nine levels (Figure 1):

1. Not felt/no damage potential \((\text{PGA} < 0.17 \text{ %g}, \text{PGV} < 0.1 \text{ cm/s})\)
2. Weak shaking/no damage potential \((0.17 \text{ %g} \leq \text{PGA} < 1.4 \text{ %g}, 0.1 \text{ cm/s} \leq \text{PGV} < 1.1 \text{ cm/s})\)
3. Light shaking/very light damage \((1.40 \text{ %g} \leq \text{PGA} < 3.9 \text{ %g}, 1.1 \text{ cm/s} \leq \text{PGV} < 3.4 \text{ cm/s})\)
4. Moderate shaking/very light damage \((3.90 \text{ %g} \leq \text{PGA} < 9.2 \text{ %g}, 3.4 \text{ cm/s} \leq \text{PGV} < 8.1 \text{ cm/s})\)
5. Strong shaking/light damage potential \((9.20 \text{ %g} \leq \text{PGA} < 18. \text{ %g}, 8.1 \text{ cm/s} \leq \text{PGV} < 16. \text{ cm/s})\)
6. Very strong shaking/moderate damage \((18.0 \text{ %g} \leq \text{PGA} < 34. \text{ %g}, 16. \text{ cm/s} \leq \text{PGV} < 31. \text{ cm/s})\)
7. Severe shaking/moderate to heavy damage \((34.0 \text{ %g} \leq \text{PGA} < 65. \text{ %g}, 31. \text{ cm/s} \leq \text{PGV} < 60. \text{ cm/s})\)
8. Violent shaking/heavy damage potential \((65.0 \text{ %g} \leq \text{PGA} < 124 \text{ %g}, 60. \text{ cm/s} \leq \text{PGV} < 116 \text{ cm/s})\)
9. Extreme shaking/very heavy damage \((124 \text{ %g} \leq \text{PGA}, 116 \text{ cm/s} \leq \text{PGV})\)

By usage of an additional color-code (i.e., Not felt/no damage potential to Extreme shaking/very heavy damage potential), these descriptions might become even more comprehensible.

![Figure 1. Ground motion scale after Wald et al. (1999) used in ShakeMaps.](image)
2. Evaluation of Errors in Ground Motion Predictions

II.1 Empirical Relationships between PGV and PGA and Seismic Intensity

The evaluation of predicted ground motions is based on empirical relationships between ground motion amplitudes (PGV and PGA) and seismic intensity $I$. Wald et al. (1999) propose the following relationships for peak ground velocity (PGV)

\[
I = 2.10 \log(\text{PGV}) + 3.40 \quad \text{for } I < V, \quad \text{(1.1a)} \\
I = 3.47 \log(\text{PGV}) + 2.35 \quad \text{for } I \geq V, \quad \text{(1.1b)}
\]

and/or of peak ground acceleration (PGA)

\[
I = 2.20 \log(\text{PGA}) + 1.00 \quad \text{for } I < V, \quad \text{(1.2a)} \\
I = 3.66 \log(\text{PGA}) - 1.66 \quad \text{for } I \geq V. \quad \text{(1.2b)}
\]

II.2 Transform Errors in PGV and PGA into Intensity Increments

Using eq.(1.1a) to (1.2b) we can transform the ratios of estimated and observed peak amplitudes (PGV and/or PGA) into much more meaningful intensity increments $\Delta I$. We obtain for PGV

\[
\Delta I = I_{est} - I_{obs} = 2.10 \log \left( \frac{\text{PGV}_{est}}{\text{PGV}_{obs}} \right) \quad \text{for } I < V, \quad \text{(2.1a)} \\
\Delta I = I_{est} - I_{obs} = 3.47 \log \left( \frac{\text{PGV}_{est}}{\text{PGV}_{obs}} \right) \quad \text{for } I \geq V, \quad \text{(2.1b)}
\]

and in the same manner for PGA

\[
\Delta I = I_{est} - I_{obs} = 2.20 \log \left( \frac{\text{PGA}_{est}}{\text{PGA}_{obs}} \right) \quad \text{for } I < V, \quad \text{(2.2a)} \\
\Delta I = I_{est} - I_{obs} = 3.66 \log \left( \frac{\text{PGA}_{est}}{\text{PGA}_{obs}} \right) \quad \text{for } I \geq V. \quad \text{(2.2b)}
\]

The relationships between amplitude ratios for PGV and PGA and intensity increments $\Delta I$ are visualized in Figure 2.

Implementation

If both PGA and PGV estimates are available, intensity can be estimated from (Wald et al., 1999)

\[
I = 2.20 \log(\text{PGA}) + 1 \quad \text{(3.1)}
\]

if $I > V$, then $I = 3.66 \log(\text{PGA}) - 1.66 \quad \text{(3.2)}$

if $I > VII$, then $I=3.47 \log(\text{PGV}) + 2.35$. \quad \text{(3.3)}
II.3 Evaluation of Prediction Errors

We propose the following descriptive scale for the evaluation of predicted ground motion amplitudes PGV and PGA and their corresponding intensity increments \( \Delta I \):

1. \( \text{abs}(\Delta I) \leq 0.5 \) intensity units: “Very Good”
2. \( 0.5 < \text{abs}(\Delta I) \leq 1.0 \) intensity units: “Good”
3. \( 1.0 < \text{abs}(\Delta I) \leq 1.5 \) intensity units: “Moderate”
4. \( 1.5 < \text{abs}(\Delta I) \leq 2.0 \) intensity units: “Poor”
5. \( 2.0 < \text{abs}(\Delta I) \) intensity units: “Very poor”

The advantage of the proposed scheme is that the predictions of PGV and PGA can be directly compared with each other on the same scale (intensity scale). Prediction errors for large amplitudes become assigned a higher weight.

Example 14312160

The following table shows the results of the Tauc-Pd algorithm for event \#14312160 with an evaluation of ground motion predictions (here PGV) using the described evaluation scheme.

<table>
<thead>
<tr>
<th>Station</th>
<th>Time</th>
<th>PGVobs</th>
<th>PGVest</th>
<th>abs((\Delta I))</th>
<th>observed GM</th>
<th>predicted GM</th>
<th>prediction (based on abs((\Delta I)))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALP.</td>
<td>07:58:58</td>
<td>0.204</td>
<td>0.557</td>
<td>0.9161</td>
<td>Not felt/no damage potential</td>
<td>Not felt/no damage potential</td>
<td>good</td>
</tr>
<tr>
<td>BRE.</td>
<td>07:59:04</td>
<td>0.064</td>
<td>0.056</td>
<td>0.1218</td>
<td>Not felt/no damage potential</td>
<td>Not felt/no damage potential</td>
<td>very good</td>
</tr>
<tr>
<td>DJJ.</td>
<td>07:59:54</td>
<td>0.329</td>
<td>0.289</td>
<td>0.1182</td>
<td>Not felt/no damage potential</td>
<td>Not felt/no damage potential</td>
<td>very good</td>
</tr>
<tr>
<td>DLA.</td>
<td>07:59:02</td>
<td>0.098</td>
<td>0.037</td>
<td>0.8884</td>
<td>Not felt/no damage potential</td>
<td>Not felt/no damage potential</td>
<td>good</td>
</tr>
<tr>
<td>Location</td>
<td>Time</td>
<td>P</td>
<td>S</td>
<td>GM</td>
<td>Comment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>-----</td>
<td>-----</td>
<td>------</td>
<td>-------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCG</td>
<td>07:58:57</td>
<td>0.267</td>
<td>0.167</td>
<td>0.4280</td>
<td>Not felt/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LFP</td>
<td>07:58:52</td>
<td>2.740</td>
<td>1.110</td>
<td>0.8241</td>
<td>weak/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOP</td>
<td>07:58:54</td>
<td>1.633</td>
<td>0.548</td>
<td>0.9958</td>
<td>weak/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RIN</td>
<td>07:58:52</td>
<td>1.014</td>
<td>0.905</td>
<td>0.1037</td>
<td>Not felt/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RIO</td>
<td>07:59:00</td>
<td>0.066</td>
<td>0.099</td>
<td>0.3698</td>
<td>Not felt/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMB</td>
<td>07:58:56</td>
<td>1.025</td>
<td>0.669</td>
<td>0.3891</td>
<td>Not felt/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STC</td>
<td>07:58:58</td>
<td>0.400</td>
<td>0.333</td>
<td>0.1672</td>
<td>Not felt/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STS</td>
<td>07:59:03</td>
<td>0.086</td>
<td>0.155</td>
<td>0.5372</td>
<td>Not felt/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VCS</td>
<td>07:58:58</td>
<td>0.160</td>
<td>0.176</td>
<td>0.0869</td>
<td>Not felt/no damage potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WSS</td>
<td>07:58:52</td>
<td>1.271</td>
<td>3.356</td>
<td>0.8855</td>
<td>weak/no damage potential</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Summary (of GM prediction):**

- **Very good**: 57.1%
- **Good**: 42.9%