EEW – Algorithm Testing Document

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Contributions from:

Maren Boese, Egill Hauksson, Phil Meachling, Georgia Cua, Richard Allen, and Peggy Hellweg

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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_{origin}: timepoint (absolute time), at which the earthquake rupture initiates as specified in the eq. catalogues

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

algorithm time $T_{algorithm}$: timepoint, at which an estimated parameter (e.g. magnitude) could be theoretically available, if $D_{telemetry}$=0 and $D_{processing}$= 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_{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; $T_{alert} = T_{algorithm} + D_{telemetry} + D_{processing}$

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

zero-delay alert interval I_{zd}: $I_{zd} = T_{algorithm} - T_{origin}$

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 up-dated with time

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

ElarmS AL: zero-delay mode of ElarmS, i.e. *time* = *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 up-dated with time

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

VS AL: zero-delay mode of VS, i.e. *time* = *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 <u>not</u> up-dated with time

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

Tauc-Pd AL: zero-delay mode of the Tauc-Pd Algorithm, i.e. *time* = *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-min = 3.0
max. epicentral distance for assessment: Dist-max = 200 km

Caltech

Tauc-Pd RT/AL:

- For each triggered station ≤ Dist-max, send one alert of:
  - M-est with T_{alert} and $T_{algorithm}$
  - PGV-est with T_{alert} and $T_{algorithm}$
    PGV-obs if M ≥ M-min
- For each M ≥ M-min, send one alert of:
  - Number of reporting and non-reporting stations ≤ Dist-max as a function of T_{alert} and $T_{algorithm}$

UC Berkeley

ElarmS RT:

- For each triggered event, send one alert of:
  - M-est as a function of T_{alert}
  - Loc-est as a function of T_{alert}
  - PGA-est at each station ≤ Dist-max without S-wave arrival as a function of T_{alert}
    PGA-obs at each station≤ Dist-max if M ≥ M-min
  - PGV-est at each station ≤ Dist-max without S-wave arrival as a function of T_{alert}
    PGV-obs at each station≤ Dist-max if M ≥ M-min
  - Number of reporting and non- reporting stations ≤ Dist-max as a function of T_{alert}

ElarmS AL:

- For each triggered event, send one alert of:
  - M-est as a function of $T_{algorithm}$
  - Loc-est as a function of $T_{algorithm}$
  - PGA-est at each station ≤ Dist-max without S-wave arrival

as a function of $T_{algorithm}$
PGA-obs at each station≤ Dist-max if M ≥ M-min
- PGV-est at each station ≤ Dist-max without S-wave arrival as a function of $T_{algorithm}$
  PGV-obs at each station≤ Dist-max if M ≥ M-min
- Number of reporting and non- reporting stations ≤ Dist-max as a function of $T_{algorithm}$

ETH Zurich

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

VS AL:
- For each trigger, send one alert of:
  - M-est as a function of $T_{algorithm}$
  - Loc-est as a function of $T_{algorithm}$
  - PGA-est at each station ≤ Dist-max without S-wave arrival as a function of $T_{algorithm}$
    PGA-obs at each station ≤ Dist-max if M ≥ M-min
  - PGV-est at each station ≤ Dist-max without S-wave arrival as a function of $T_{algorithm}$
    PGV-obs at each station ≤ Dist-max if M ≥ M-min
  - Number of reporting and non- reporting stations ≤ Dist-max as a function of $T_{algorithm}$

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 ≥ M-min:

Summary Reports for each M ≥ M-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	$I_{alert} = T_{alert} - T_{origin}$
ElarmS AL:	zero-delay alert interval	$I_{zd} = T_{algorithm} - T_{origin}$
VS RT:	alert interval	$I_{alert} = T_{alert} - T_{origin}$
VS AL:	zero-delay alert interval	$I_{zd} = T_{algorithm} - T_{origin}$
Tauc-Pd RT:	alert interval	$I_{alert} = T_{alert} - T_{origin}$
Tauc-Pd AL:	zero-delay alert interval	$I_{zd} = T_{algorithm} - T_{origin}$

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

t_1= 1.0 sec
t_2= 3.0 sec
t_3= 6.0 sec
t_4=10.0 sec
t_5=15.0 sec
t_6=20.0 sec
t_7=25.0 sec

A proposed scheme for the evaluation of predicted ground motions GM is given in the Appendix.

I.3.1 Summary Reports for each M ≥ M-min

Summary 1: Magnitude

- ElarmS/VS:
  - X-Y Plot: M-est as a function time, M-obs plotted as a line (because M-obs is constant with time)
  - Table: M-est at seven time steps
- Tauc-Pd Algorithm:
  - Table: M-est at each station with corresponding time, i.e., station1: time1 M-est; station2: time2 M-est;…. and M-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: ΔI=I-obs - I-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

<u>Summary for all stations ≤ Dist-max (without S-wave arrival):</u>
Use descriptive scales for the evaluation of estimated GM (Appendix)

- <u>ElarmS/VS</u>:
  - 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

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

<u>Summary 4: System performance</u>

Ratio of reporting and non-reporting stations (as a function of time)

I.3.2 Monthly Summary Reports

<u>Summary 5: False triggers</u>

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)

<u>Summary 6: Missed triggers</u>

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

APPENDIX

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 (PGA < 0.17 %g, PGV < 0.1 cm/s)
2. Weak shaking/no damage potential (0.17 %g ≤ PGA < 1.4 %g, 0.1 cm/s ≤ PGV < 1.1 cm/s)
3. Light shaking/do damage potential (1.40 %g ≤ PGA < 3.9 %g, 1.1 cm/s ≤ PGV < 3.4 cm/s)
4. Moderate shaking/very light damage (3.90 %g ≤ PGA < 9.2 %g, 3.4 cm/s ≤ PGV < 8.1 cm/s)
5. Strong shaking/light damage potential (9.20 %g ≤ PGA < 18. %g, 8.1 cm/s ≤ PGV < 16. cm/s)
6. Very strong shaking/moderate damage (18.0 %g ≤ PGA < 34. %g, 16. cm/s ≤ PGV < 31. cm/s)
7. Severe shaking/moderate to heavy d. (34.0 %g ≤ PGA < 65. %g, 31. cm/s ≤ PGV < 60. cm/s)
8. Violent shaking/heavy damage pot. (65.0 %g ≤ PGA < 124 %g, 60. cm/s ≤ PGV < 116 cm/s)
9. Extreme shaking/very heavy damage (124 %g ≤ PGA, 116 cm/s ≤ 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**.**

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1. Ground motion scale after Wald et al. (1999) used in ShakeMaps.

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*)

$I = 2.10\ log(PGV) + 3.40$ for *I*<V, and (1.1a)

$I = 3.47\ log(PGV) + 2.35$ for *I*>=V (1.1b)

and/or of peak ground acceleration (*PGA*)

$I = 2.20\ log(PGA) + 1.00$ for *I*<V, and (1.2a)

$I = 3.66\ log(PGA) - 1.66$ for *I*>=V. (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 *ΔI*. We obtain for PGV

$\Delta I = I_{est} - I_{obs} = 2.10\ log\left(\frac{PGV_{est}}{PGV_{obs}}\right)$ for *I*<V, and (2.1a)

$\Delta I = I_{est} - I_{obs} = 3.47\ log\left(\frac{PGV_{est}}{PGV_{obs}}\right)$ for *I*>=V, (2.1b)

and in the same manner for PGA

$\Delta I = I_{est} - I_{obs} = 2.20\ log\left(\frac{PGA_{est}}{PGA_{obs}}\right)$ for *I*<V, and (2.2a)

$\Delta I = I_{est} - I_{obs} = 3.66\ log\left(\frac{PGA_{est}}{PGA_{obs}}\right)$ for *I*>=V. (2.2b)

The relationships between amplitude ratios for PGV and PGA and intensity increments *ΔI* 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(*PGA*) + 1 (3.1)

if *I* > V, then *I* = 3.66 * log (*PGA*) - 1.66 (3.2)

if *I* > VII, then *I*=3.47 * log(*PGV*) + 2.35. (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 ΔI:

1. abs(ΔI) <=0.5 intensity units: "Very Good"
2. 0.5< abs(ΔI) <=1.0 intensity units: "Good"
3. 1.0< abs(ΔI) <=1.5 intensity units: "Moderate"
4. 1.5< abs(ΔI) <=2.0 intensity units: "Poor"
5. 2.0< abs(ΔI) 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.

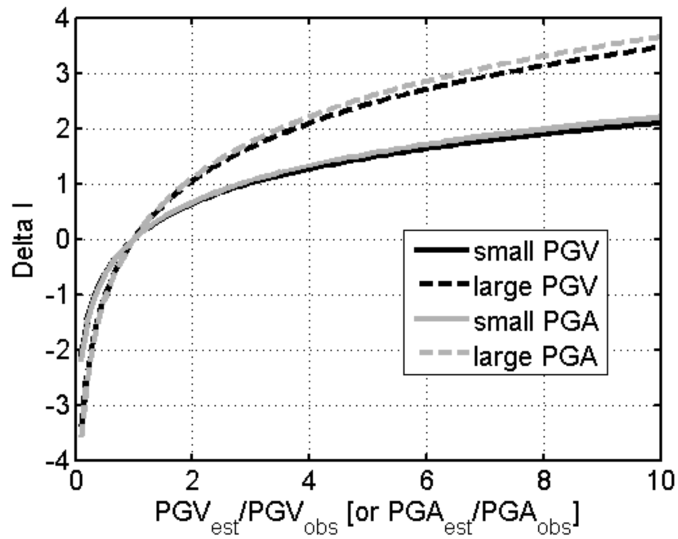

Figure 2. Relationships between amplitude ratios (PGV and PGA, relative to the observed levels) and intensity increments ΔI for small and large amplitudes.

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.

Magnitude : 4.57
Origin Time : 2007/08/09 07:58:49
Lat : 34.30
Lon : -118.62
Z : 7.58

Station	time	PGVobs	PGVest	abs(ΔI)	observed GM	predicted GM	prediction (based on abs(ΔI))
ALP.	07:58:58	0.204	0.557	**0.9161**	Not felt/no damage potential	Not felt/no damage potential	good
BRE.	07:59:04	0.064	0.056	**0.1218**	Not felt/no damage potential	Not felt/no damage potential	very good
DJJ.	07:58:54	0.329	0.289	**0.1182**	Not felt/no damage potential	Not felt/no damage potential	very good
DLA.	07:59:02	0.098	0.037	**0.8884**	Not felt/no damage potential	Not felt/no damage potential	good

LCG.	07:58:57	0.267	0.167	**0.4280**	Not felt/no damage potential	Not felt/no damage potential	**very good**
LFP.	07:58:52	2.740	1.110	**0.8241**	**weak/no damage potential**	**weak/no damage potential**	**good**
MOP.	07:58:54	1.633	0.548	**0.9958**	**weak/no damage potential**	Not felt/no damage	**good**
RIN.	07:58:52	1.014	0.905	**0.1037**	Not felt/no damage potential	Not felt/no damage potential	**very good**
RIO.	07:59:00	0.066	0.099	**0.3698**	Not felt/no damage potential	Not felt/no damage potential	**very good**
SMS.	07:58:56	1.025	0.669	**0.3891**	Not felt/no damage potential	Not felt/no damage potential	**very good**
STC.	07:58:58	0.400	0.333	**0.1672**	Not felt/no damage potential	Not felt/no damage potential	**very good**
STS.	07:59:03	0.086	0.155	**0.5372**	Not felt/no damage potential	Not felt/no damage potential	**good**
VCS.	07:58:58	0.160	0.176	**0.0869**	Not felt/no damage potential	Not felt/no damage potential	**very good**
WSS.	07:58:52	1.271	3.356	**0.8855**	**weak/no damage potential**	**weak/no damage potential**	**good**

Summary (of GM prediction):

very good 57.1 %
good 42.9 %