Proposed Time Measurement Model for Earthquake Early Warning Systems

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Summary: This poster describes a method for evaluating the speed of operation for an EEW system. We define an EEW system as a system that can produce a **ground motion warnings (GMW)**. A GMW consists of two predictive parameters delivered to a site: (1) the duration until strong ground motions occur at the site, and (2) intensity of peak ground motions that will occur. We assume peak ground motions occur at S-wave arrival time. We define a **useful warning area** as all sites within 200km of an epicenter. Then, we define a GMW as **effective** for an earthquake if sites within the useful warning area can recieve the GMW before the S-wave arrives. We then define an EEW system's **Effectiveness** by calculating what percentage of sites within the useful warning area could have received an **effective GMW** for a specific event.The effectiveness of a given EEW system varies by event based on the hypocenter, station coverage, and processing times. Our timeline-based measurement model and our **Effectiveness** metric can be used to compare the speed of performance for alternative EEW algorithmic approaches and to compare the effects of system performance improvements such as greater station density and faster telemetry or processing.

1. Define the Purpose of the EEW System and Effective Ground Motion Warnings and System Effectiveness:

We define a ground motion warning (GMW) as two pieces of information delivered to a site: (1) a prediction of future peak ground motions, (2) the duration until the peak ground motions occurs. We will assume peak ground motions at a site occur at S-wave arrival time. We define a GMW as effective for a site if the site is within 200km of the epicenter and the site could receive the GMW before the S-wave arrives. The engineering goal of our EEW system is to produce effective GMW's for as many sites as possible for every earthquake. An EEW system that can produce effective GMW's for all sites within 200km of the epicenter will be considered 100% effective. A 100% effectiveness rating for an EEW is not possible due to the existence of warning blind zone.

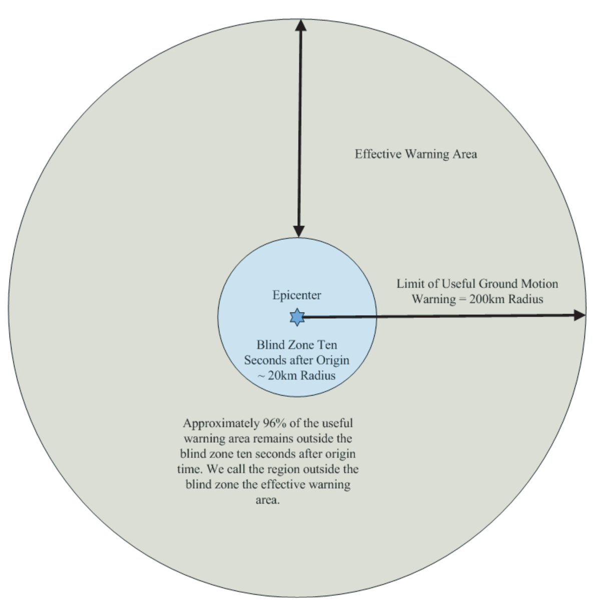

Figure 1: Useful Warning Area (Green) - Limit of S-wave propagation at Tw = 10 second (Blue). Sites located in the effective warning area can receive advance warning of strong ground motions.

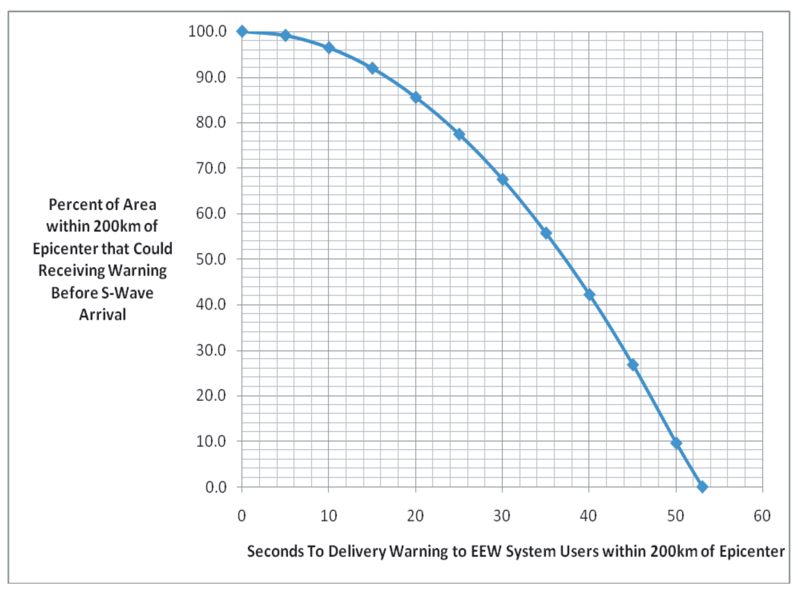

Figure 2: Using Vp=7km/sec and Vs=4km/sec and assuming that GMW can be delivered throughout the Useful Warning Area in constant time, then the Effectiveness of an EEW system depends only on Dw. Effectiveness falls below 50% if the EEW system takes more than 37 seconds to produce a warning.

2. Time Measurement Conventions:

In this analysis, we will specify the types of our time measurements. Valid time measurement types include time points, durations, and intervals consistent with the ISO 8601 standard.In our current analysis, we use mostly time points, and durations. Many of our speed of processing calculations produce intervals as answers. However, intervals can be expressed as a time point and a duration. Usually, in our system performance work, we will use only the duration value of the interval. We will typically deal with durations, and we will make a special note if both the time point and duration parts of interval measures are important.

3. Timeline-based EEW System Performance Model:

We use a timeline-base EEW system performance model to measure whether an EEW system produces a useful ground motion warning for a site. We define the time it takes to produce a ground motion warning in terms that map to seismic network and EEW engineering features that we might optimize.In our formulation, we include end-to-end processing of GMWs including delays delivering GMW to users. Warning Times are site specific time points which we define as:

To |—Dp—|—Da—|—Dt—|—Dc—|—Dd—|—Dn—| Tw

Tw = To + Dp +Da + Dt + Dc + Dd + Dn

Where the following terms are used:
To – Origin time of earthquake
Dp – Duration of P-wave propagation time to sensors
Da – Duration of data after P-wave arrival needed by algorithm
Dt – Duration of transmission (packaging and telemetry) delay
Dc – Duration of computation time on EEW processing system
Dd – Duration to deliver data to users warning device
Dn – Duration of time to produce user notification
Tw – Time point warning notification is available to user

If we make a few assumptions about our system, we can then use these terms to define the size of the blind zone for this system for this event. If we assume that the terms Dd (duration to deliver GMW to user) and Dn (duration to set off alarm at user site) are equal for all users in the useful warning zone, then we can define the warning duration as:

Dw = Tw – To

Dw identifies the S-wave propagation time we will use in our effectiveness rating. This duration defines the extent of the blind zone for this system and this event.

4. Multi-channel EEW GMW Formula:

For multi-station, or multi-channel, EEW algorithms, the Tw formulation must be changed to include multiple channels of data used to produce the warning. The limiting term in the formula becomes the data channel used by the EEW algorithm that takes the longest to arrive at the EEW algorithm processing system. So for multi-channel algorithms, we restate:

Tw = To + Max(Dpi + Dai + Dti) + Dc + Dd + Dn

In this expression, Max(Dpi + Dai + Dti) represent the maximum delay of any channel used in the warning to get to the algorithm processing system. Note Dp, Da, and Dt are all for the same channel i.

5. System Performance Measurements for CISN:

We have designed our effective GMW formulation around system delay measurements of interest. Currently, within the CISN system, the real-time algorithms contribute speed of operations information to the CISN EEW Testing Center as time measurements we call Alert time and Algorithm time. Here is how the measurements compare to the time-line-based formulation we have just defined:

Origin Time	Ptt to sensor	Algorithm	Transmission	Computation	Delivery	Notification
To	Dp	Da	Dt	Dc	Dd	Dn
To	Alert Duration				0	0
To	Algorithm Duration		0	0	0	0

6. Effectiveness of CISN Algorithms Under Test:

We can use this system to calculate the effectiveness of the CISN algorithms for several Mw4.0+ events in California over the last few months. These are preliminary results. All three EEW algorithms are still under development and their performance continues to be enhanced. As CISN upgrades station dataloggers and other equipment in the future, the performance of the algorithms are likely to improve significantly.

Assume Vp=7km/sec and Vs=4km/sec throughout the region and assume that the CISN EEW systems can deliver a GMW to any site within the useful warning zone with zero delay. For algorithms that report only Algorithm time, assume Dt and Dc are zero. We assume GMWs based on TauC-PD trigger-based algorithm can determine a distance to the event using trigger reports from 3 stations, so we use time measurements from the third TauC-PD trigger in these results.

		Event ID	Lat	Lon	Mag	Algo	Alert	BZ Radius (km)	BZ Area (km2)	System Effectiveness for Event
TC	CI	14433456	33.32	-115.73	4.77	10	17	68	14526.71	88.44
TC	CI	14418600	35.41	-117.79	4.39	27	37	148	68813.39	45.24
TC	CI	10368325	32.57	-115.54	4.52	15	22	88	24328.47	80.64
TC	CI	14408052	34.81	-116.42	5.06	12	22	88	24328.47	80.64
TC	CI	14407020	35.97	-117.32	4.03	11	18	72	16286.00	87.04
ENI	NC	200812262043	39.96	-120.87	4.5	20	-	80	20106.18	84.0
ENI	NC	51213534	36.67	-121.3	4	5	-	20	1256.64	99.00
ENI	NC	51211307	40.31	-124.6	4.6	19	-	76	18145.82	85.56
VS	CI	14433456	33.32	-115.73	4.77		18	72	16286.00	87.04
VS	CI	14418600	35.41	-117.79	4.39		20	80	20106.18	84.00
VS	CI	10374021	32.69	-118.23	4.19		28	112	39408.10	68.64
VS	CI	10370141	34.11	-117.3	4.45		18	72	16286.00	87.04
VS	CI	10368325	32.57	-115.54	4.52		29	116	42273.24	66.36
VS	CI	14408052	34.81	-116.42	5.06		24	96	28952.89	76.96

7. Evaluate Impact of Improved Telemetry on EEW System Effectiveness:

To evaluate the impact EEW engineering speed of performance improvement, consider how our systems effectiveness if we speed up the telemetry and processing aspects of our current EEW system. In our timeline-based formulation, we can see that Dalert – Dalgorithm = Dt + Dc. The difference between the algorithm and alert times tells us how long it took our system to transmit the data and compute the ground motion warning. If we identify the minimum value for the Dt + Dc, then assume that telemetry improvements we could achieve this level of performance for all channels in the system. We can then recalculate our system effectiveness assuming we were able to obtain this speed of performance for the entire seismic network.

	Event ID	Mag	Orig Dw (= Alert)	Improved Dw (due to telemetry improvemt)	Orig BZ Radius (km)	Improved telemetry BZ Radius (km2)	Orig. System Effectiveness for Event	Improved System Effectiveness for Event
CI	14433456	4.77	17	14	68	56	88.44	92.16
CI	14418600	4.39	37	24	148	96	45.24	76.96
CI	10368325	4.52	22	19	88	76	80.64	85.56
CI	14408052	5.06	22	16	88	64	80.64	89.76
CI	14407020	4.03	18	15	72	60	87.04	91.00

8. Evaluate Effectiveness of Standalone EEW Systems :

We can use this technique to investigate the effectiveness of standalone EEW systems. Assume a standalone EEW system was developed that could produce GMWs from a single three component sensor. Such a system is similar to a p-wave detector but is able to predict both parameter in a GMW. We assume these standalone installations include ground motion sensors, a computer to run EEW algorithms, and an alarm device. We apply our EEW effectiveness rating to determine what percentage of the useful warning zone could benefit from such a standalone EEW system.

Make some simplifying assumptions in our first order analysis. Assume that a standalone EEW system has fixed values for some of our delay terms. Assume that we use an algorithm that requires 4 seconds of data after the p wave arrival and that it can turn on an alarm within 4 seconds. In this case : Tw = To + Dp + 8

We find the size of the blind zone for such a system by calculating the distance from the epicenter where the S-wave arrives at time Tw or later. The blind zone radius for a a device that has this speed of performance is approximately 77 km.

Dist Event to Self Generating GMW system (km)	P wave prop (Dp)	Other delay terms (Da + Dt + Dc + Dd + Dn)	Duration of delay before ground motion alarm (Dw)	S-travel dist in Dw (km) BZ Radius	Effectiveness for Self Generating EEW ground Motion Alarms
77.0	11	8	19	76	85.5

Assuming current CISN TauC-PD triggers produced GMW data, 1 out of 49 triggers in last four months would have produced an effective standalone GMW at current speed of operation : Event: CI 14408052 - Location: 34.81 -116.42 5.06 - Station: CIT CI NSS2 - Distance Site to Epicenter: 146.4km - Tw: To + 35 seconds - S-wave Distance at Tw: 140 km