CISN California Integrated Seismic Network
California's Partner to the ANSS Advanced National Seismic System
CGS USGS CalEMA Caltech UC Berkeley

CISN Shake/Alert:

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Three Years of Comparative Real-Time Earthquake Early Warning Testing in California

G. Cua[1], R. Allen[2], M. Boese[3], H. Brown[2], D. Given[5], M. Fischer[1], E. Hauksson[3], T. Heaton[3], M. Hellweg[2], M. Liukis[4], T. Jordan[4], O. Khainovski[2], P. Maechling[4], D. Neuhauser[2], D. Oppenheimer[5], K. Solanki[3], M. Caprio[1]

[1] Swiss Seismological Service-ETH Zurich, [2]UC Berkeley, [3]California Institute of Technology, [4]Southern California Earthquake Center, [5]US Geological Survey

contact: georgia.cua@sed.ethz.ch

I. Introduction

The California Integrated Seismic Network (CISN) recently concluded a three-year project (August 2006-July 2009) aimed at the implementation, real-time testing, and comparative performance evaluation of three participating earthquake early warning (EEW) algorithms: 1) the Tau-C/Pd OnSite algorithm developed by Caltech, 2) the ElarmS algorithm developed by UC Berkeley, and 3) the Virtual Seismologist (VS) algorithm developed by the Swiss Seismological Serice at ETH Zurich. These three EEW algorithms were installed and continue to run in real-time at the Southern California Seismic Network (SCSN), the Berkeley Digital Seismic Network (BDSN), and the USGS Menlo Park network. Over the last three years, these EEW algorithms submitted real-time and automatic non-interactive offline event reports to the CISN EEW Testing Center, established by the Southern California Earthquake Center (SCEC) to independently evaluated algorithm performance relative to the ANSS earthquake catalogue.

II. California-wide Testing

During the three year study, all three algorithms successfully detected many earthquakes, and in some cases, predicted peak ground shaking before it occurred. Each algorithm, originally designed for a specific region of the state, was expanded to process data from throughout California, to run continuously in real-time, and to provide real-time alert messages. All three algorithms submitted event reports, consisting of magnitude and peak ground shaking estimates (and location estimates for VS and ElarmS) to the CISN EEW Testing Center, which compared the event reports to the ANSS earthquake catalogue. Algorithm performance was evaluated based on magnitude and location accuracy, as well as false and missed alerts. The CISN EEW Testing Center posted regularly updated performance summaries on its website (http://www.scec.org/eew).

All together, statewide testing made use of 382 stations with a total of 585 broadband and strong motion instruments from the AZ, BK, CI, NC, and NP subnetworks of the CISN, with processing facilities at Caltech/Pasadena, UC Berkeley, and USGS Menlo Park.

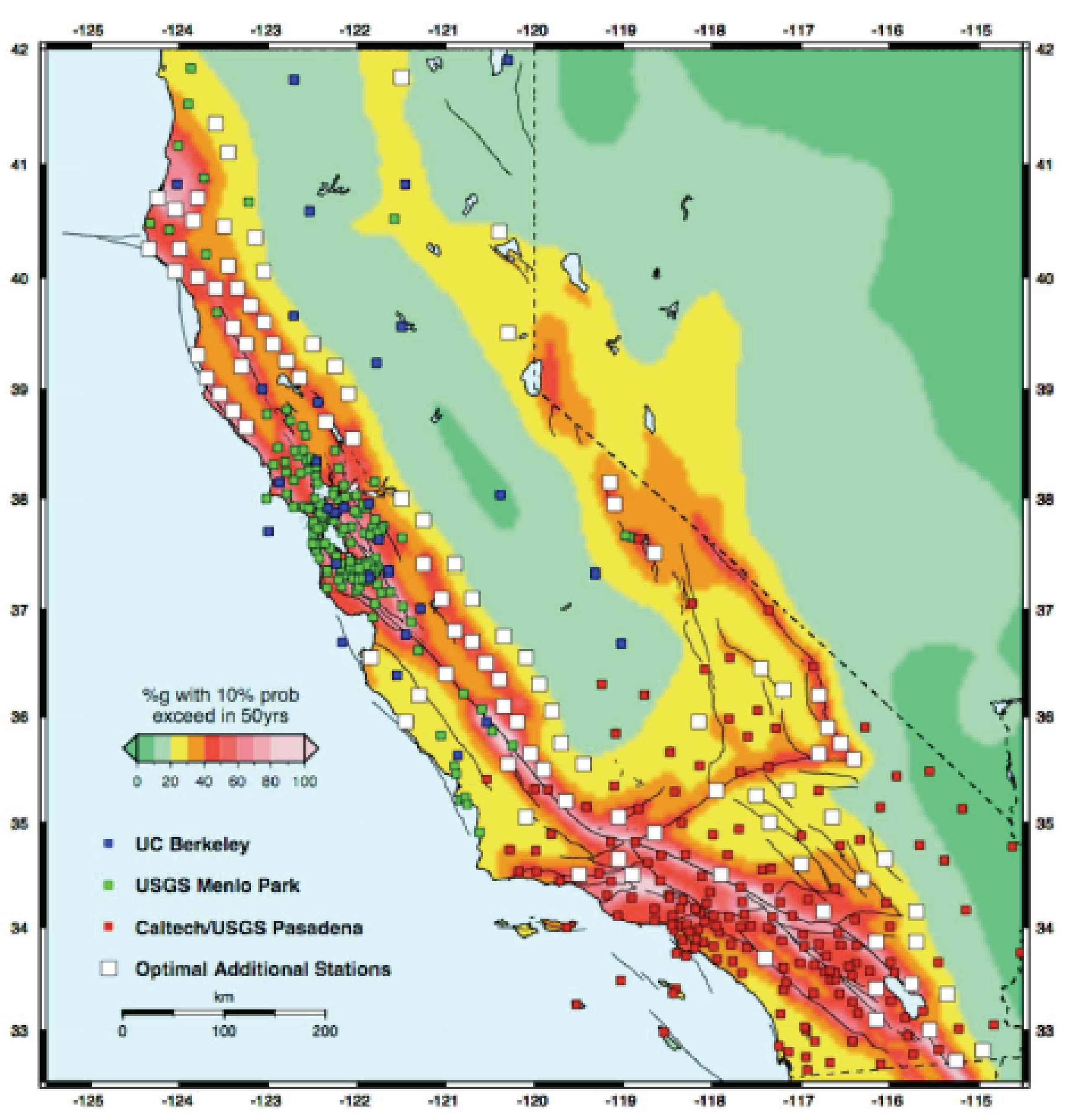

Figure 1: EEW algorithm performance is strongly tied to station density. All three EEW algorithms performed extremely well (95-100% detection capability at M>=3.0 level) in regions with ~20 km interstation spacing.In general, performance degraded with decreasing station density. Above is a map of the real-time seismic stations used in EEW testing (blue, green, red squares), overlaid on a seismic hazard map. White squares are ~100 additional stations needed to have 20 km station spacing for high hazard regions and 40 km station spacing along the San Andreas fault.

III. OnSite Algorithm Highlights

The OnSite algorithm being implemented by Caltech uses the frequency content and amplitude information of the first few seconds of the observed P-wave at a given site to estimate magnitude and peak ground motion at the same site. Over the last 3 years, the OnSite algorithm detected ~140 local earthquakes in California and Baja Mexico in the magnitude range 3.5 ≤ Mw ≤ 5.4. Most reporting delays ranged between 9 and 16 seconds and has recently been reduced to 4 to 11 seconds due to software design improvements.

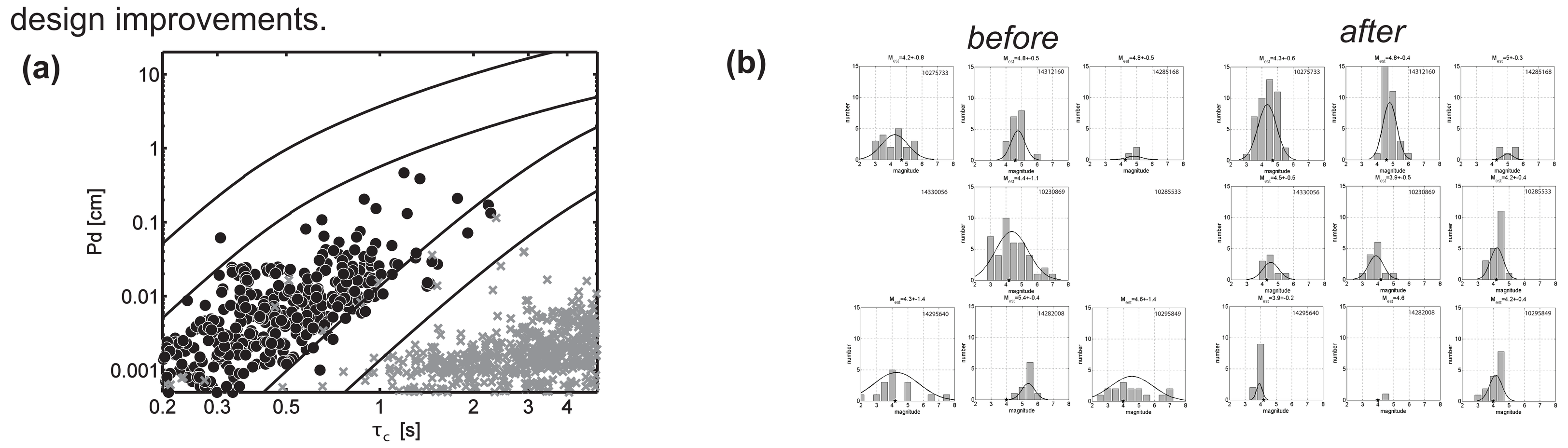

Figure 2: The Tau-C / Pd trigger criteria was developed to improve real-time performance of the OnSite algorithm. **(a)** This criteria uses Tau-C (and hence magnitude)-dependent thresholds for Pd, takes into account empirical ground motion attenuation characteristics in Southern California, and sucessfully removed 97% of previous false triggers on broadband stations. **(b)** The criteria also reduced the scatter in magnitudes estimates for small earthquakes.

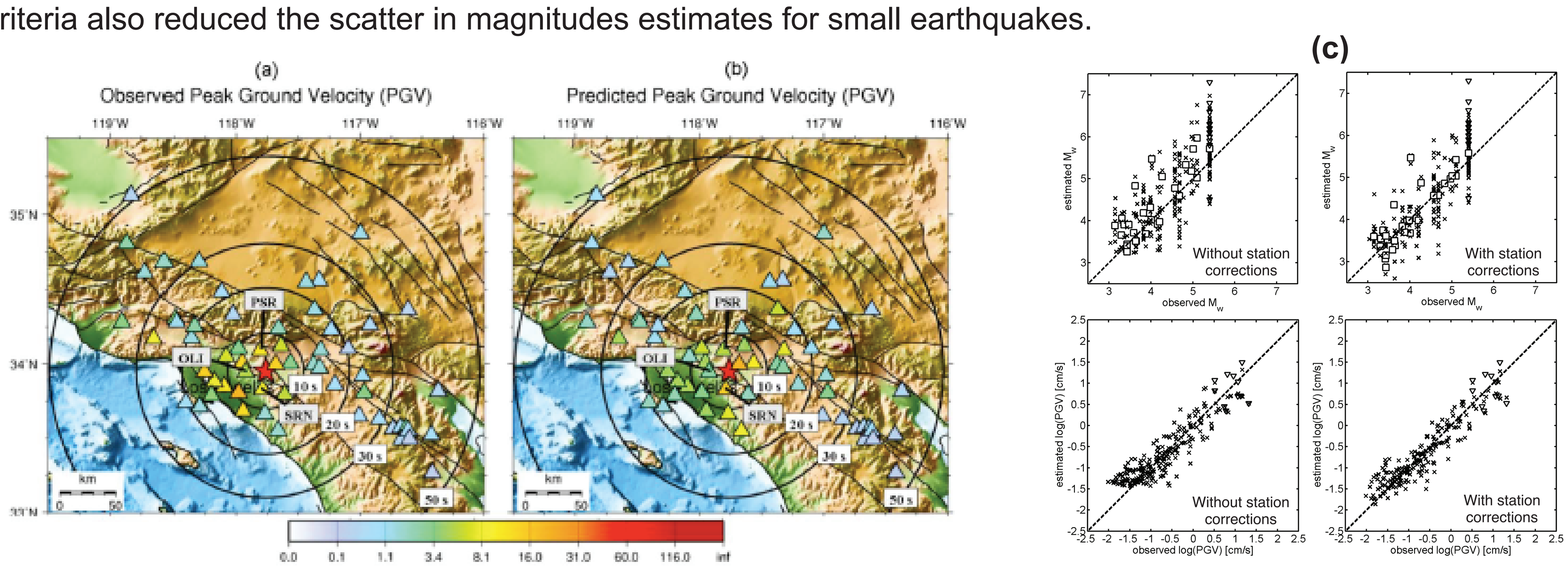

Figure 3: Distribution of (a) observed and (b) predicted values of PGV at 60 CISN stations that triggered the OnSite algorithm during the 29 July 2008 Mw5.4 Chino Hills earthquake. Each estimate in (b) would have been available within 3 seconds of the P-wave arrival. The Chino Hills event demonstrated that Tau-C and P-d are site-dependent parameters. (c) Taking into account station correctionis reduces the uncertainty in magnitude and peak ground motion estimates.

IV. ElarmS Algorithm Highlights

The ElarmS algorithm is a network-based algorithm being implemented by UC Berkeley. The algorithm detects P-wave arrivals at several stations around an event epicenter and uses arrival times, amplitudes, and frequency content of the P-wave to rapidly estimate the magnitude and location of the event. ElarmS then uses regional GMPEs to predict the expected peak ground shaking throughout a region in real-time.

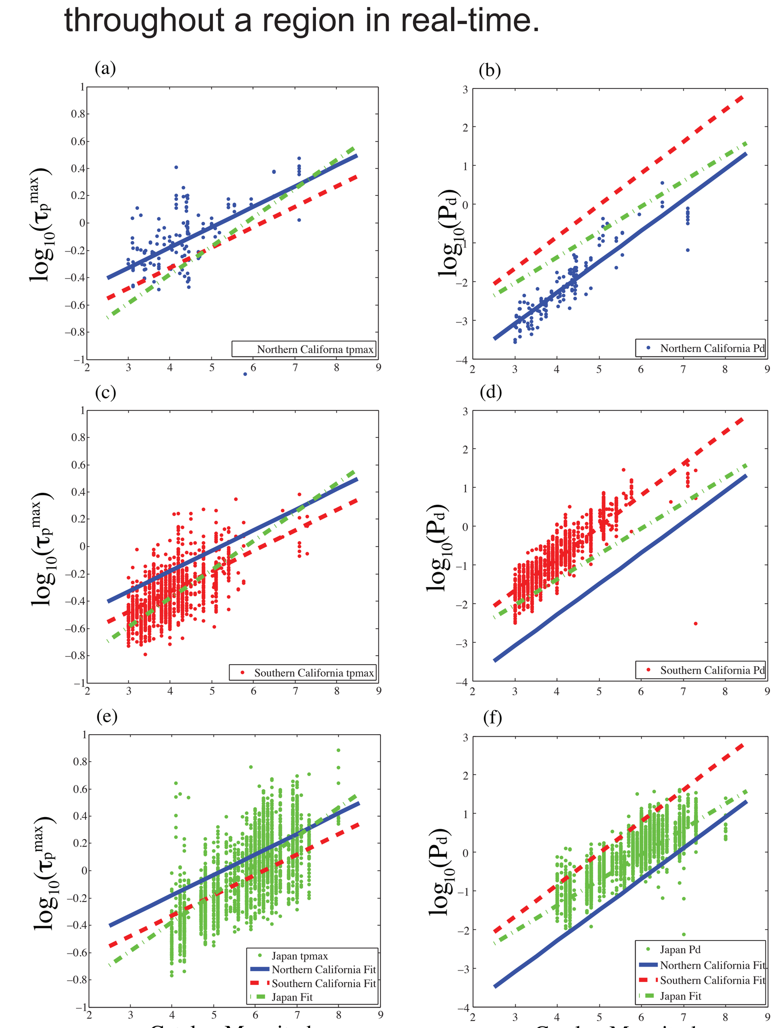

Figure 4: Region-dependent scaling relations for Tau-P and P-d were developed for Northern California (a,b), Southern California (c,d), and Japan (e,f).

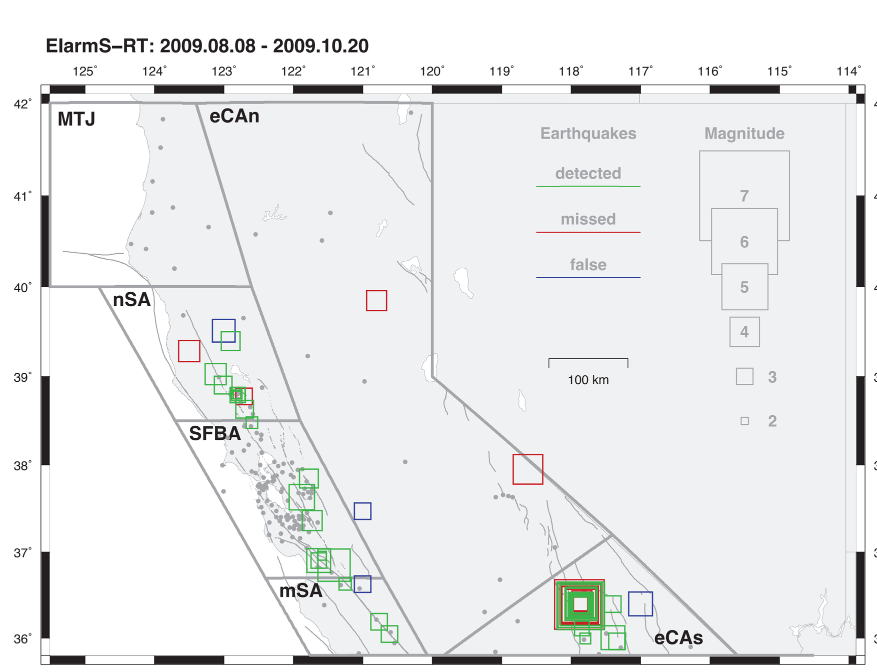

Figure 5: Map showing all ElarmS detected M>3.0 events, false and missed alerts during from 8 August through 20 October 2009. There were 63 M>3.0 events in Northern California during this testing period. ElarmS detected 45 events, missed 18 events, and sent 4 false alerts. ElarmS alert criteria is region-dependent, based on station density.

	0 stations	1 station	2 stations	3 stations	4 stations	5 stations
Mag, 1 sec	-	-0.38 ± 0.63	-0.33 ± 0.56	-0.37 ± 0.57	-0.39 ± 0.56	-0.41 ± 0.56
Mag, 2 sec	-	-0.2 ± 0.57	-0.15 ± 0.5	-0.18 ± 0.54	-0.21 ± 0.52	-0.22 ± 0.50
Mag, 3 sec	-	-0.09 ± 0.53	-0.05 ± 0.48	-0.08 ± 0.52	-0.10 ± 0.49	-0.10 ± 0.47
Mag, 4 sec	-	0.01 ± 0.52	0.04 ± 0.46	0.03 ± 0.48	0.03 ± 0.44	0.02 ± 0.43
Mag, 5 sec	-	0.04 ± 0.50	0.07 ± 0.45	0.07 ± 0.48	0.07 ± 0.43	0.06 ± 0.42
Location	-	33.6 ± 17.9	32.1 ± 21.4	32.5 ± 18.7	18.8 ± 13.6	21.1 ± 16.8
PGA	0.11 ± 0.30	0.09 ± 0.35	0.08 ± 0.37	0.06 ± 0.29	0.10 ± 0.28	0.03 ± 0.30

Table 1: Statistical error distributions for ElarmS magnitude, location, and peak ground motion estimates (derived from Japanese data)

V. Virtual Seismologist (VS) Algorithm Highlights

The VS algorithm is a Bayesian network-based algorithm being implemented by the Swiss Seismological Service at ETH Zurich. The VS algorithm began real-time processing at the SCSN in July 2008. VS has also been installed more recently (Feb 2009) at BDSN and Menlo Park. Like ElarmS, VS uses picks and amplitude information to rapidly estimate the magnitude and location of an event. Regional GMPEs are then used to predict the distribution of peak ground shaking throughout a region in real-time. Based on the CISN EEW Testing Center definitions of triggers, VS has a false trigger rate of 5.5% at the M>4.0 level based on data from the last 6 months.

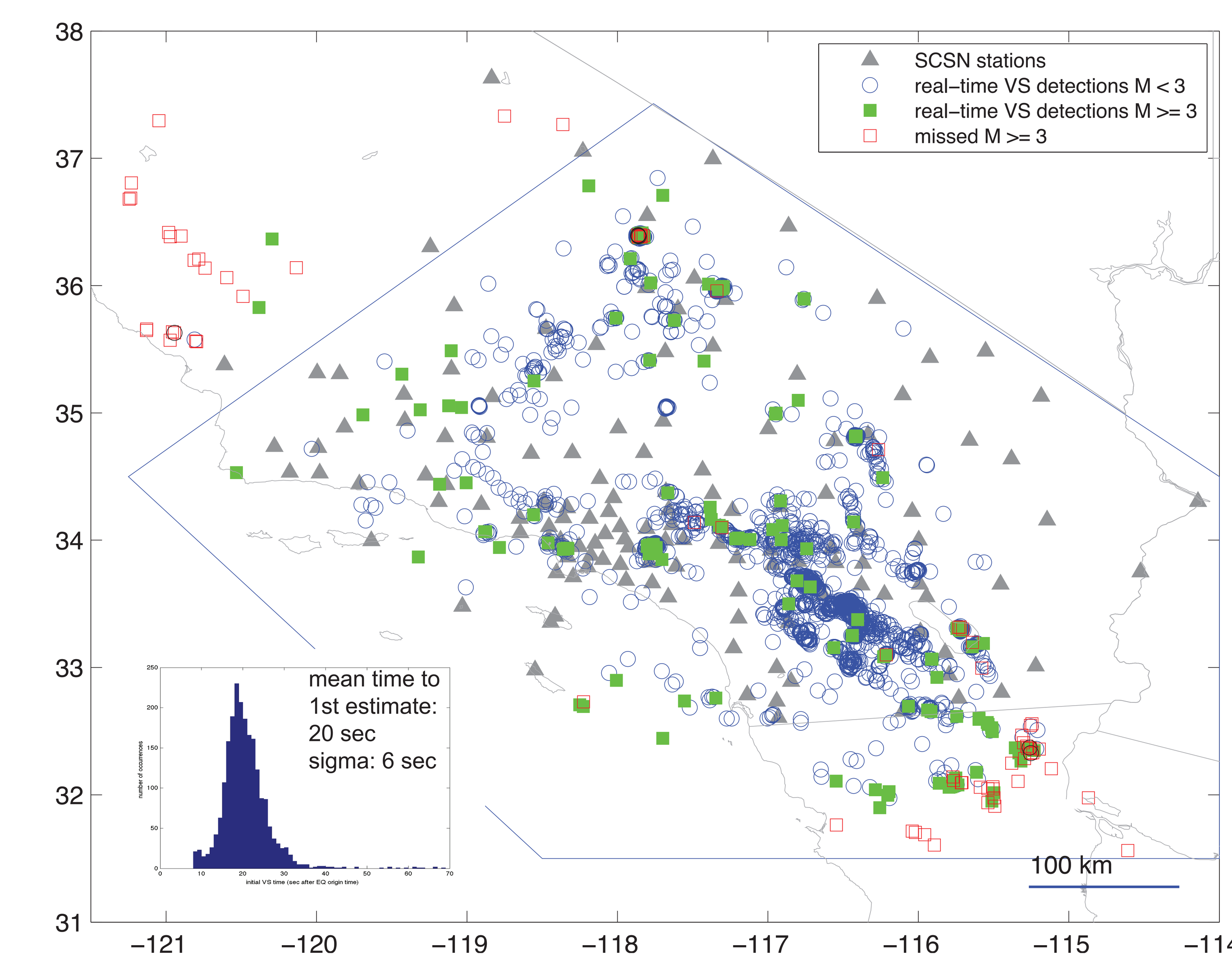

Figure 6 (left): VS real-time performance in Southern California from July 2008-Oct 2009. VS correctly detected 1970 M<3.0 events and 182 M>3.0 events during the 15-month testing period. There are concentrations of missed events at the edges and outside of the network. Over the last 6 months, VS correctly detected 15 M>4.0 events, and had 3 M>4.0 false events that did not match an entry in the ANSS catalogue. This averages to 1 false M>4.0 event every 2 months. To date, VS has had no M>5.0 false events.

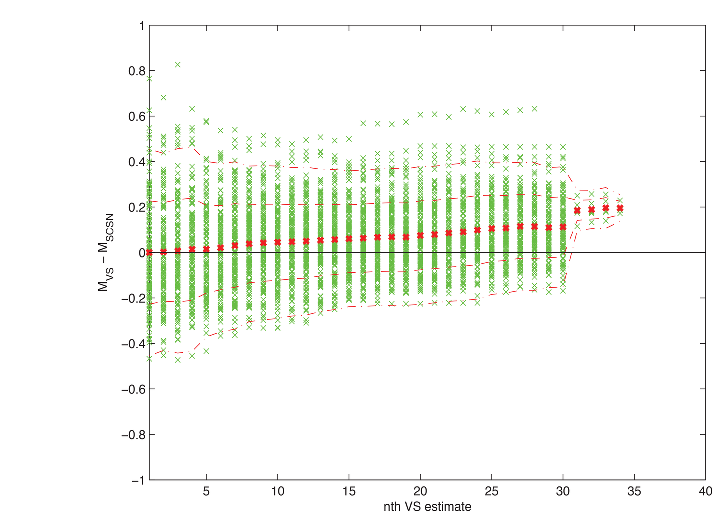

Figure 7 (above): VS magnitude error as a function of nth VS estimate for M>3.0 events in adequately instrumented regions where we expect reasonable VS performance. The red crosses denote the mean magnitude error of the nth VS estimate. The dashed lines denote the ±1 and ±2 sigma levels.

VI. CISN EEW Testing Center (SCEC) Highlights

The CISN EEW Testing Center was established by SCEC to provide an independent EEW algorithm performace evaluation system. Development of a common testing environment helped algorithm developers standardize on important issues such the definition of the testing region, time stamps, output parameters, data formats, and the type of performance summaries that are now produced on a regular basis.The CISN EEW Testing is designed to perform prospective testing and encourage "apples-to-apples" comparisons of EEW algorithm performance.

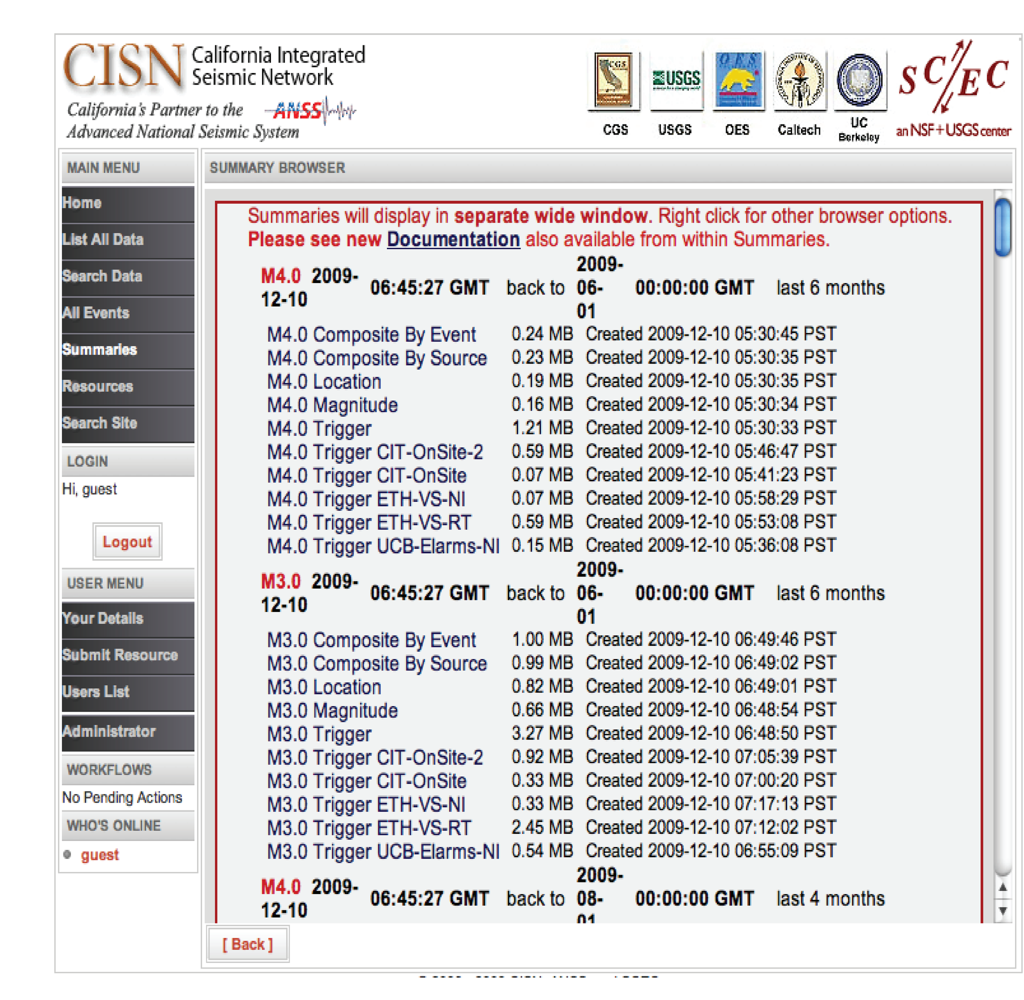

Figure 8 (left): A screen shot of the CISN EEW Testing Center website showing the various types of summary reports being created. On a nightly basis, the Testing Center software retrieves ANSS catalogue information for California, and compares triggers from the 3 algorithms against events in the catalogue. The ANSS catalogue is used as the reference data set. The CISN EEW Testing Center software framework is derived from an open source framework created at SCEC for the Collaboratory for the Study of Earthquake Predictabilty (CSEP). Use of the CSEP software has reduced the software development needed to support the Testing Center.

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VII. Outlook and Conclusions

In August 2009, a second three-year study was initiated to integrate the three test algorithms into CISN ShakeAlert, a single prototype EEW system that will provide real-time warning information to a small group of test users by the end of the study in 2012.

Over the next 2 years, stimulus funding will be used to upgrade many of the older, slower dataloggers throughout the CISN. This will reduce the median station data latency from 5.2 seconds to 2-3 seconds.

The algorithm testing efforts clearly illustrate the benefits of dense station spacing to reduce false and missed alerts, as well as to improve the speed of alert delivery. Enhancing the networks to provide ~20 km inter-station spacing (as is found in Japan, San Francisco Bay Area, and Los Angeles, where EEW works relatively well) throughout the source region of the San Andreas Fault system will require ~100 additional stations.