Early warning development and testing in California

with a focus on

www.ElarmS.org
Earthquake Alarm Systems

Richard Allen, Holly Brown, Peggy Hellweg,
Oleg Khainovski, Peter Lombard, Doug Neuhauser

University of California Berkeley Seismological Laboratory

Maren Böse, Georgia Cua, Doug Given,
Egill Hauksson, Tom Heaton, Tom Jordan,
Hiroo Kanamori, Phil Maechling,
David Oppenheimer, Kalpesh Solanki,
Michael Zeleznik

U.S. Geological Survey

Caltech

SCEC
USC

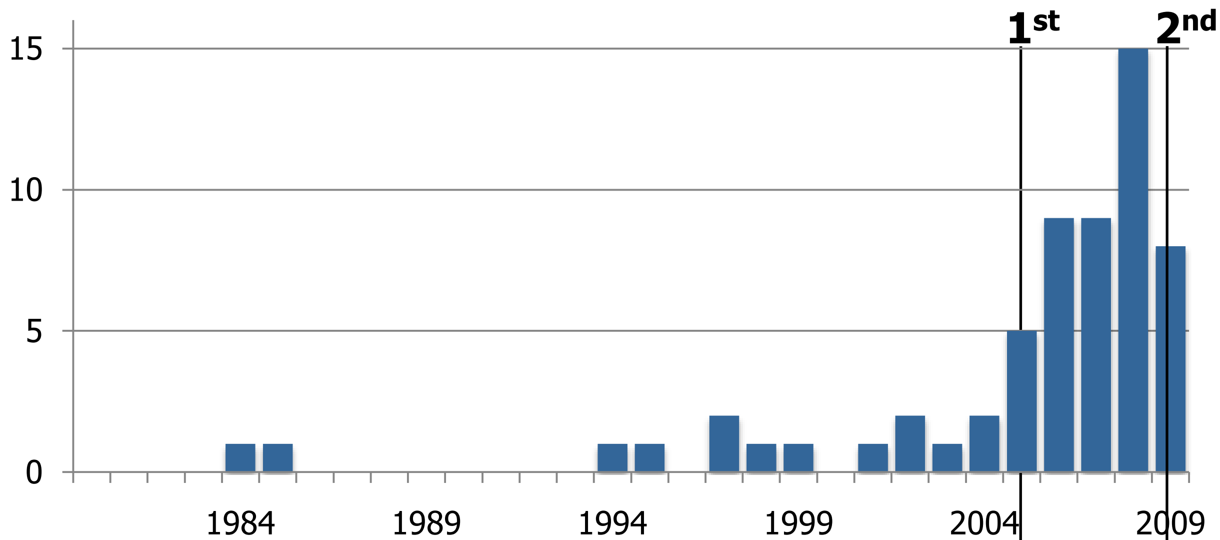
Swiss Seismological Service

CISN
California Integrated Seismic Network
ANSS

Funded by USGS
science for a changing world

Accelerating early warning development

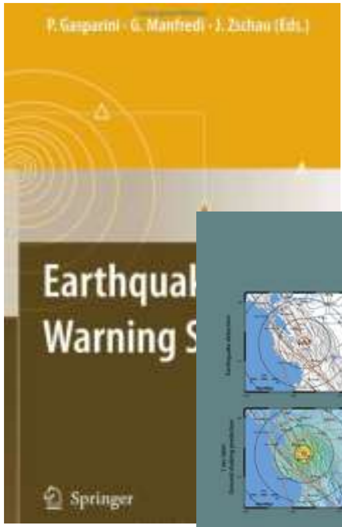
Number of early warning publications per year



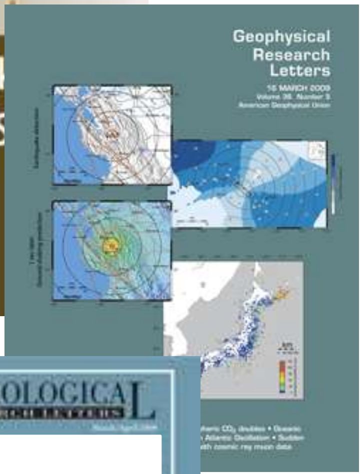
2005: 1st International EEW conference, Caltech

2009: 2nd International EEW conference, Kyoto

2007 Springer



2009 Geophys Res Lett

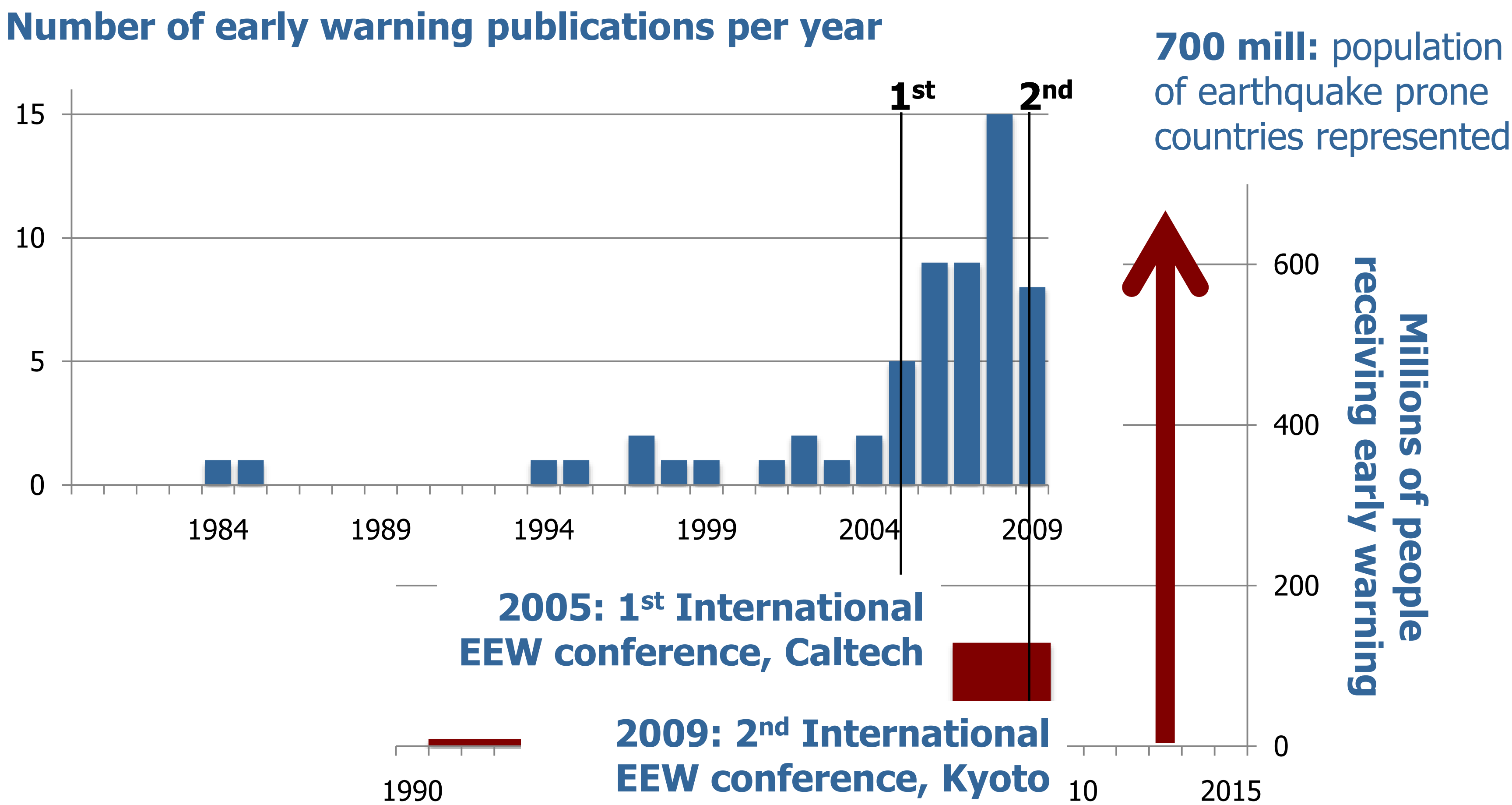


2009 Sep/Oct **Seismo Res Lett**

Development projects

California: CISN statewide testing
Europe: SAFER project
Japan: Implementation of public warning

Accelerating early warning development



Goal for the next meeting: implementation

Implementation in California?

April 9, 2009 – State Legislation (AB 298):
Statewide Alert System Integrated with High Speed Rail

Allocates funding from High Speed Rail bond funds to determine the economic loss and loss of life that could be prevented by an earthquake Early Warning System linked to the rail system.

April 15, 2009
U.S. Interior Secretary Ken Salazar
$29.4 mill to improve national and international earthquake monitoring system

To upgrade instrumentation and reduce telemetry delays

Goal for the next meeting: implementation


?

Earthquake early warning

warning *before* ground shaking

Statewide testing of three methodologies

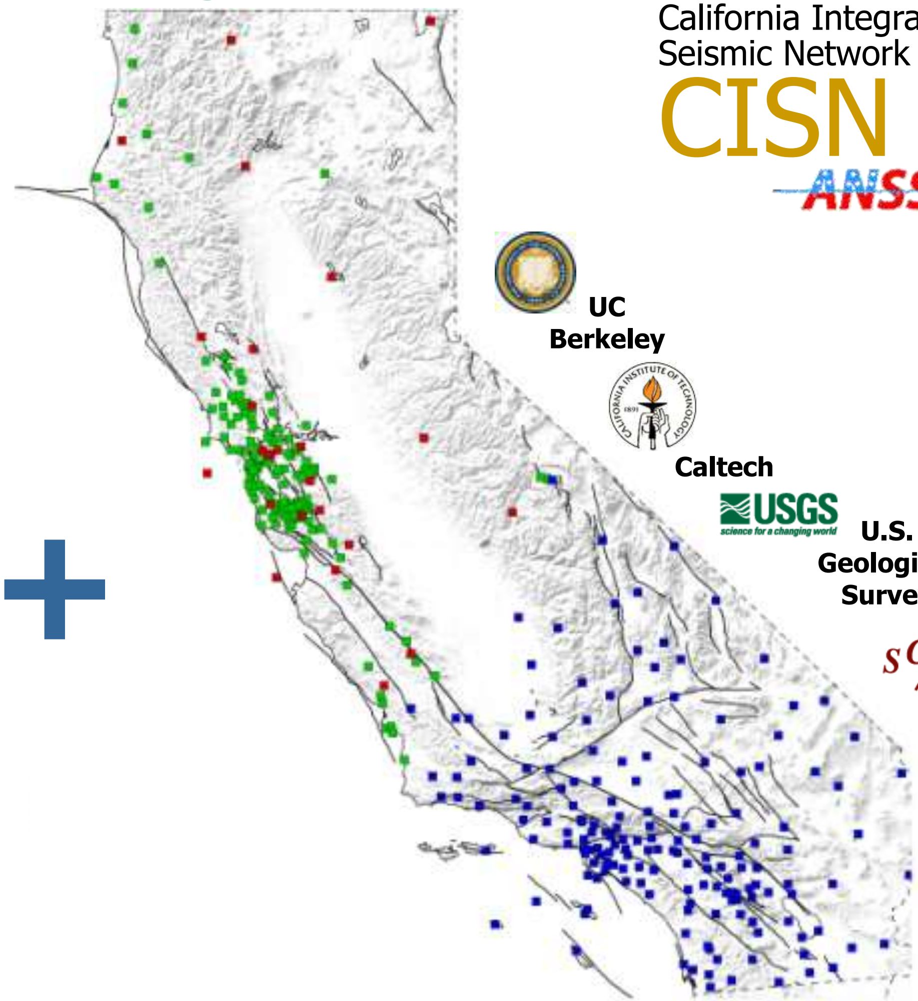
ElarmS (UC Berkeley)

Virtual Seismologist (Caltech/ETH)

Onsite warning (Caltech/National Taiwan University)

funded by USGS science for a changing world

+



California Integrated Seismic Network

CISN

ANSS

UC Berkeley

Caltech

USGS science for a changing world U.S. Geological Survey

SCEC

SCEC/USC

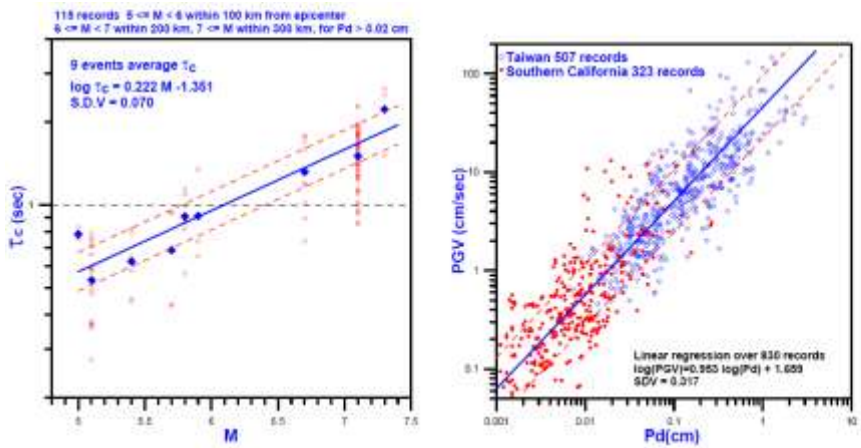
=

Real-time earthquake early warning test

Onsite method

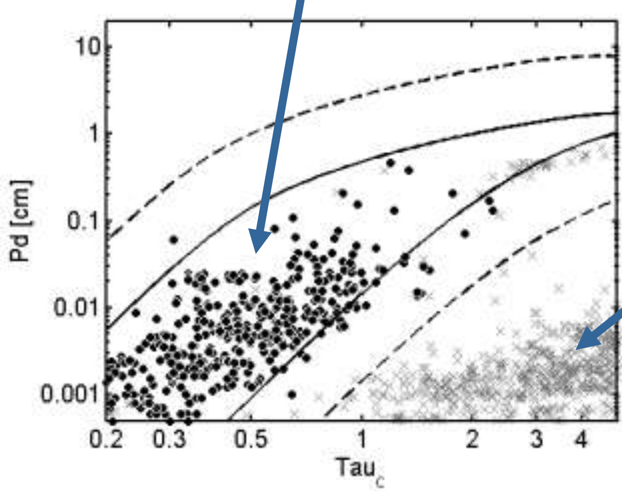
Caltech/National Taiwan University

- **Single station approach**
- Triggers on **P-waves**
- Alarms when both amplitude and period suggest large magnitude earthquake



Wu, Kanamori, and others

California earthquake
$4.2 \leq M \leq 7.3$



Noise,
Distant earthquakes
Low S/N

Böse et al., sub. BSSA

Tuned tau-c-Pd Trigger Criterion

Started testing 2008

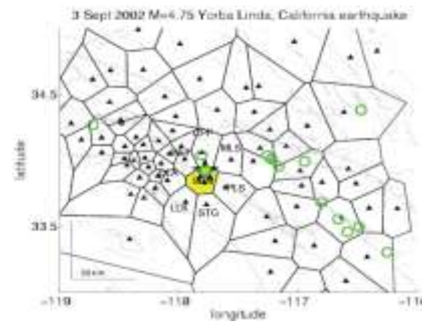
- M_w 5.4 July 29, 2008 successfully detected
- few false triggers

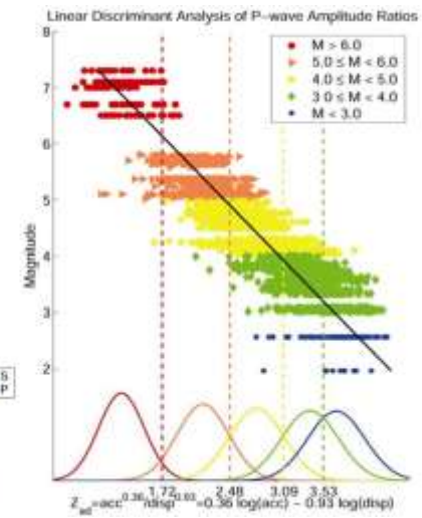
CISN California Integrated Seismic Network EEW

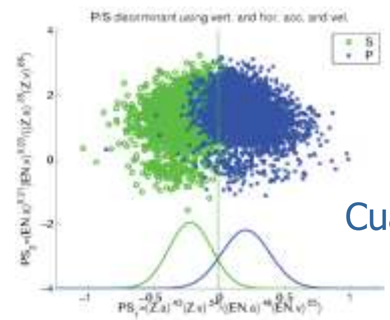
Virtual seismologist

ETH/Caltech

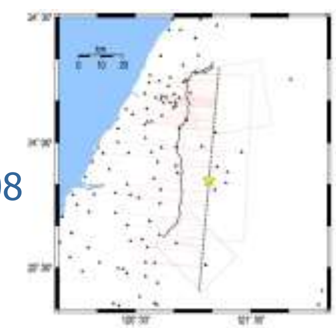
- **Regional network approach**
- **Bayesian approach:** Include likelihood of earthquake given past observations
  e.g. Gutenberg-Richter relation and distribution of previous seismicity
- Triggers on **P-waves**
- Uses envelope functions of waveforms
- Magnitude derived from 3 sec of the P-wave
- Predicts the distribution of ground shaking
- Finite fault discriminate



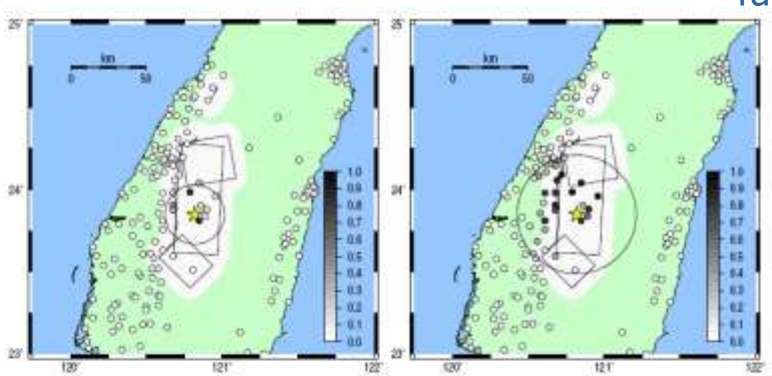


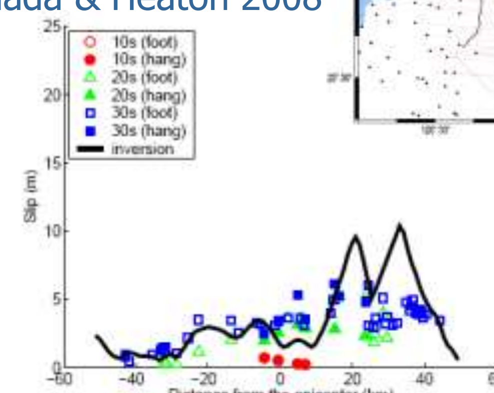


Cua & Heaton 2007



Yamada & Heaton 2008



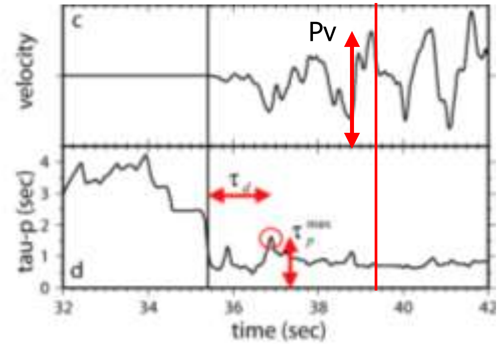


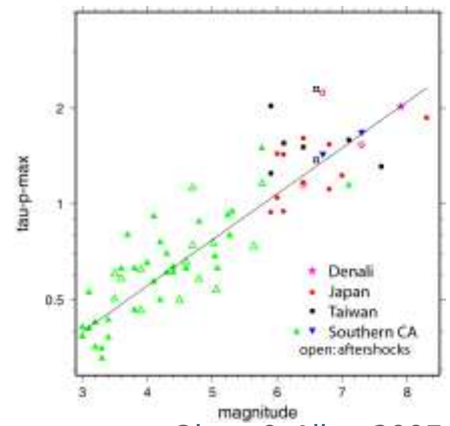
CISN California Integrated Seismic Network EEW

ElarmS **UC Berkeley**

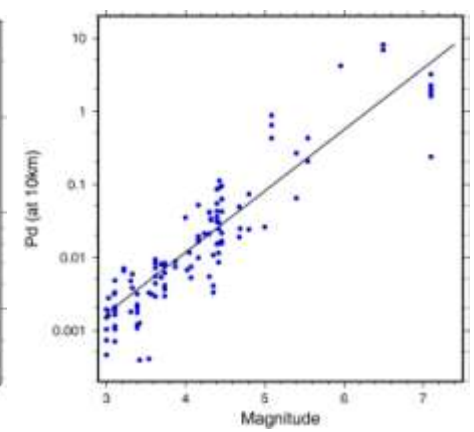
- **Regional network approach**
- Triggers on **P-waves**
- Uses arrival times, frequency and amplitude of P-wave. Uses PGA and PGV as they become available.
- Magnitude initially estimated 1 sec after P-wave trigger and updated
- Predicts the distribution of ground shaking using ShakeMap approach

➔ **AlertMaps**





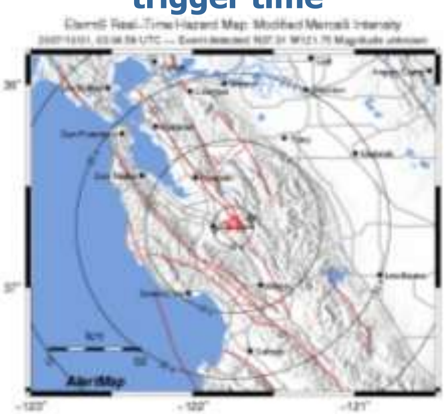
Olson & Allen 2005



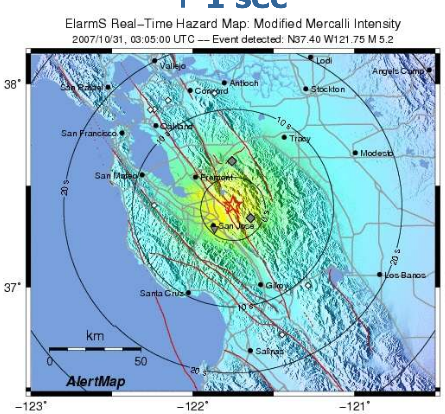
Wurman et al 2007

AlertMaps – *ElarmS*-**RT** – M_W5.4 October 30, 2007

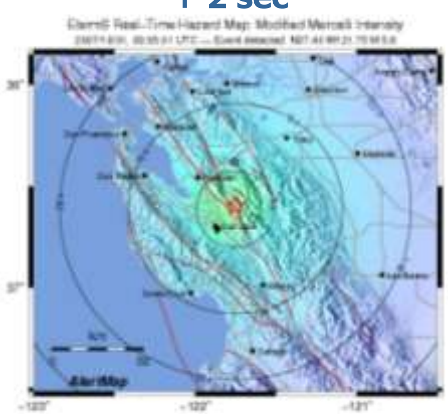
trigger time



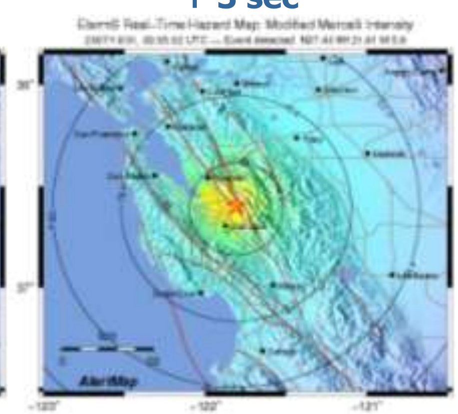
+ 1 sec



+ 2 sec



+ 3 sec



CISN California Integrated Seismic Network EEW

Testing center

USC/SCEC

CISN EEW algorithm performance site: http://www.scec.org/eew

- Archives processing results
- Generates performance summaries
  - location, magnitude, shaking accuracy; timeliness

	For all rows	ORIGIN TIMES - Observed vs. Forecast						MAGNITUDES - Observed vs. Forecast						Trigger Status rows Time Diffs Origin minus		Source Info	
	ANSS Event rows		Obs	Observed Origin	Valid range				Obs	Mag	Valid range					Net	Event ID
	Trigger Status rows		Obs	Observed Origin	Fcst	Forecast Origin	Diff		Obs	Mag	Fcst	Mag	Diff	Alert	Algo	Trigger Source	
1	ANSS Event	*Times*	Obs	2008-11-15 17:50:41		[-10 to +30]		*Mags*	Obs	3.90		[-1.0 to +1.0]		Alert	Algo	NC	51211277
1	**Correct Trigger**	*Times*	Obs	2008-11-15 17:50:41	Fcst	2008-11-15 17:50:43	**2**	*Mags*	Obs	3.90	Fcst	3.04	**-0.86**	--	11	UCB-Elarms-NI	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 17:50:41	Fcst	2008-11-15 17:50:45	**4**	*Mags*	Obs	3.90	Fcst	3.16	**-0.74**	--	15	UCB-Elarms-NI	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 17:50:41	Fcst	2008-11-15 17:50:45	**4**	*Mags*	Obs	3.90	Fcst	3.16	**-0.74**	--	20	UCB-Elarms-NI	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 17:50:41	Fcst	2008-11-15 17:50:44	**3**	*Mags*	Obs	3.90	Fcst	3.16	**-0.74**	--	25	UCB-Elarms-NI	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 17:50:41	Fcst	2008-11-15 17:50:44	**3**	*Mags*	Obs	3.90	Fcst	3.16	**-0.74**	--	30	UCB-Elarms-NI	
1	ANSS Event	*Times*	Obs	2008-11-15 17:12:55		[-10 to +30]		*Mags*	Obs	2.21		[-1.0 to +1.0]		Alert	Algo	NC	51211273
1	ANSS Event	*Times*	Obs	2008-11-15 16:44:57		[-10 to +30]		*Mags*	Obs	2.35		[-1.0 to +1.0]		Alert	Algo	NC	51211270
1	ANSS Event	*Times*	Obs	2008-11-15 13:20:52		[-10 to +30]		*Mags*	Obs	2.42		[-1.0 to +1.0]		Alert	Algo	CI	14403424
1	ANSS Event	*Times*	Obs	2008-11-15 12:36:28		[-10 to +30]		*Mags*	Obs	2.86		[-1.0 to +1.0]		Alert	Algo	NC	51211265
1	ANSS Event	*Times*	Obs	2008-11-15 09:52:51		[-10 to +30]		*Mags*	Obs	3.53		[-1.0 to +1.0]		Alert	Algo	CI	14403392
1	**Correct Trigger**	*Times*	Obs	2008-11-15 09:52:51	Fcst	2008-11-15 09:52:59	**8**	*Mags*	Obs	3.53	Fcst	4.19	**0.66**	16	8	CIT-OnSite	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 09:52:51	Fcst	2008-11-15 09:53:00	**9**	*Mags*	Obs	3.53	Fcst	3.49	**-0.04**	18	9	CIT-OnSite	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 09:52:51	Fcst	2008-11-15 09:53:10	**19**	*Mags*	Obs	3.53	Fcst	3.23	**-0.30**	26	19	CIT-OnSite	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 09:52:51	Fcst	2008-11-15 09:52:52	**1**	*Mags*	Obs	3.53	Fcst	3.58	**0.05**	21	--	ETH-VS-RT	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 09:52:51	Fcst	2008-11-15 09:52:51	**0**	*Mags*	Obs	3.53	Fcst	3.62	**0.09**	23	--	ETH-VS-RT	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 09:52:51	Fcst	2008-11-15 09:52:51	**0**	*Mags*	Obs	3.53	Fcst	3.63	**0.10**	26	--	ETH-VS-RT	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 09:52:51	Fcst	2008-11-15 09:52:51	**0**	*Mags*	Obs	3.53	Fcst	3.64	**0.11**	30	--	ETH-VS-RT	
1	**Correct Trigger**	*Times*	Obs	2008-11-15 09:52:51	Fcst	2008-11-15 09:52:52	**1**	*Mags*	Obs	3.53	Fcst	3.63	**0.10**	35	--	ETH-VS-RT	

magnitude accuracy

warning delay with current CISN network

theoretical warning delay with no telemetry or processing delays

Approaching 3 years of testing

Phase I: Development and testing of realtime algorithms

Parallel testing of multiple methodologies

Talks

Maren Böes – EEW development at Caltech (including Onsite)

Georgia Cua – Virtual Seismologist in California

Jim Goltz – Societal and public policy issues

Tom Heaton – Finite sources

Posters

Holly Brown – Testing ElarmS in Japan

Phil Maechling – Time measurement models for EEW

Kalpesh Solanki – EEW implementation at Caltech

and now…

Development and performance of ElarmS in California

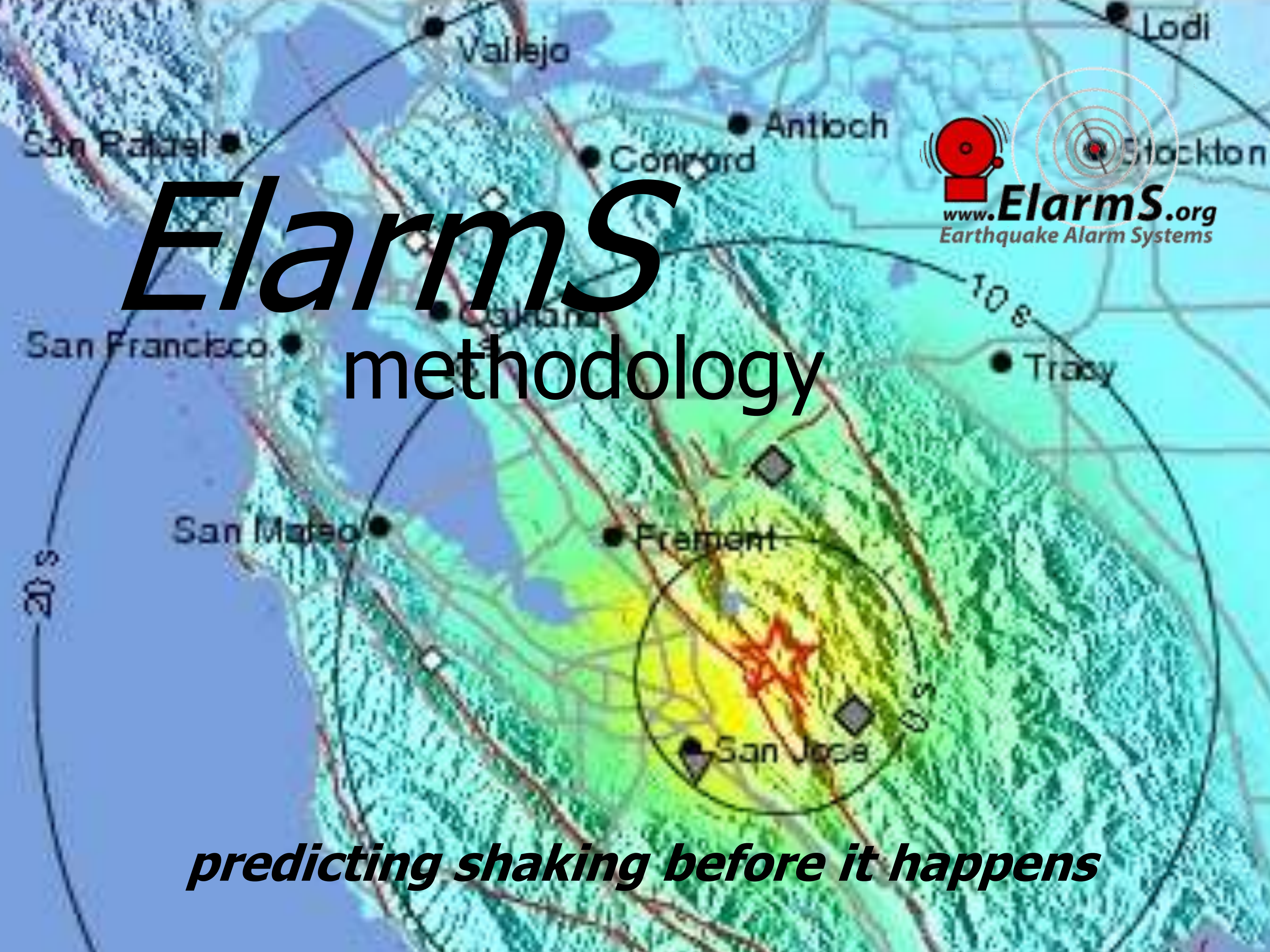
Phase II: Implementing a prototype warning system

A single CISN early earning output to a group of test users

ElarmS

methodology

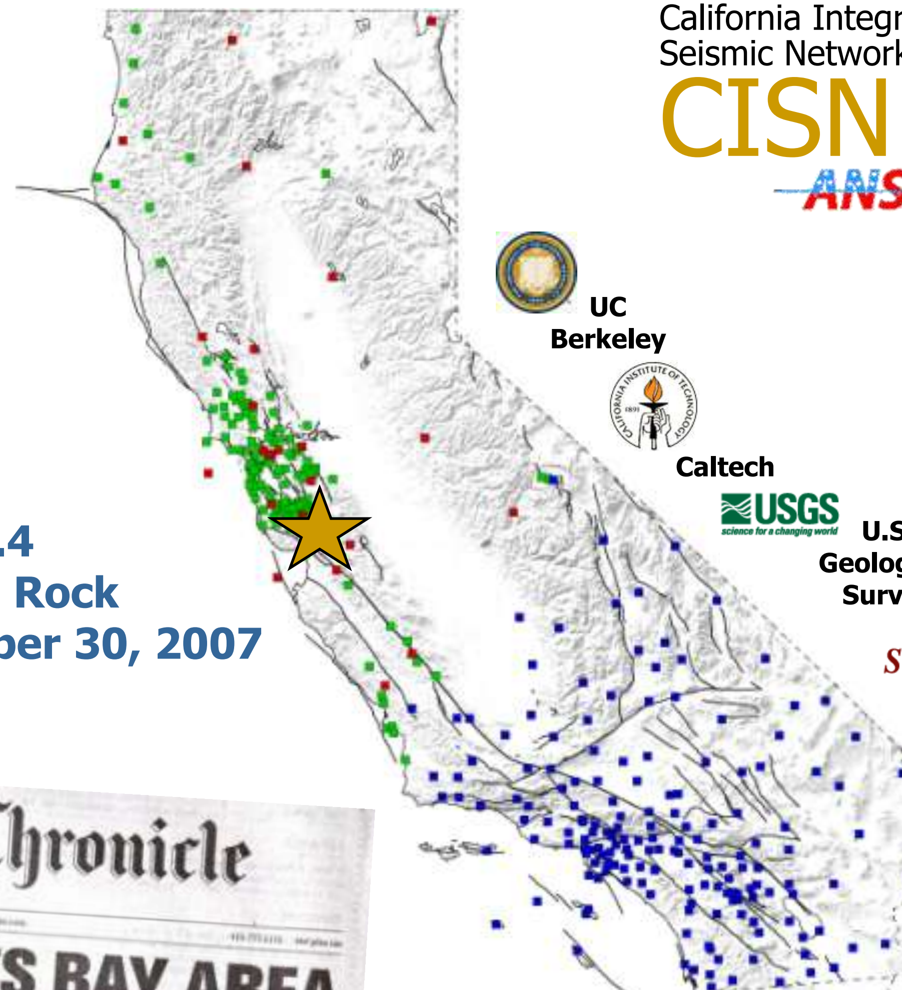
www.ElarmS.org
Earthquake Alarm Systems



predicting shaking before it happens

Alum Rock Earthquake

M_w 5.4
Alum Rock
October 30, 2007



California Integrated Seismic Network

CISN

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UC Berkeley

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U.S. Geological Survey

SCEC/USC

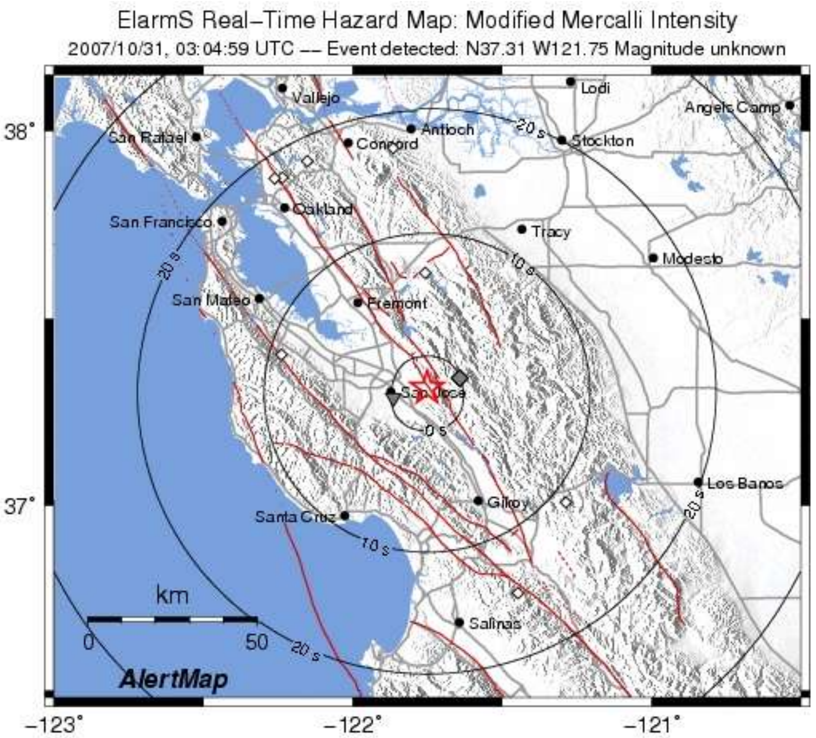
ElarmS methodology

Goal: predict peak ground shaking before onset

1. **Determine earthquake location**

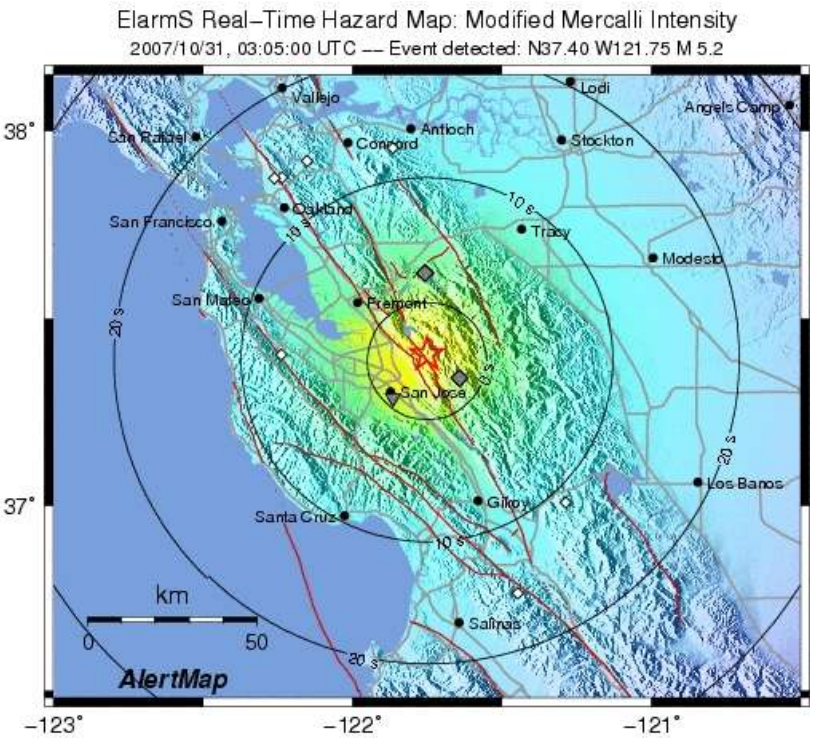
   Using P-wave arrival times

2-station location



detection

3-station location



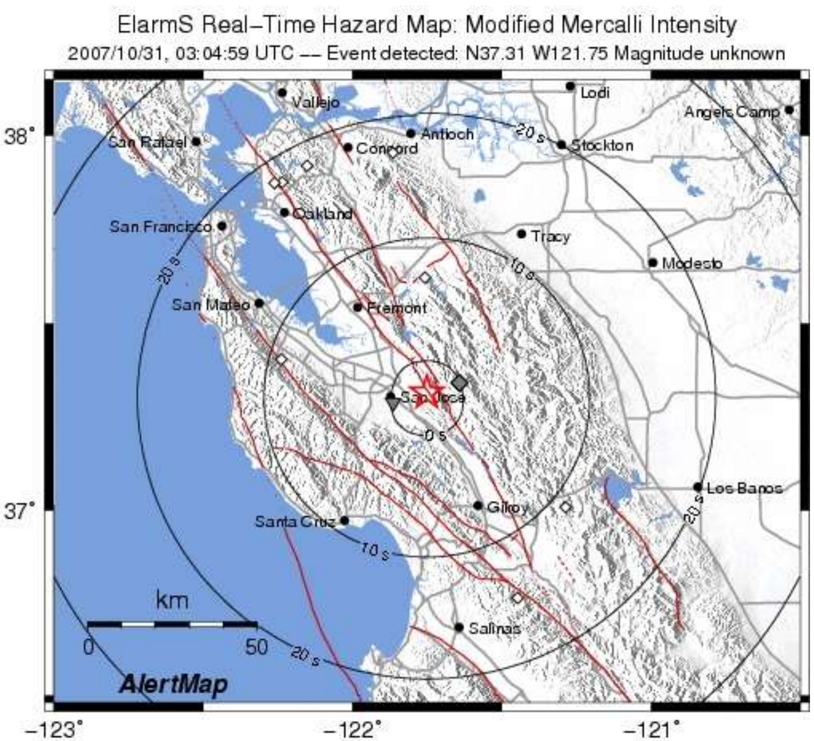
detection + 1 sec

ElarmS methodology

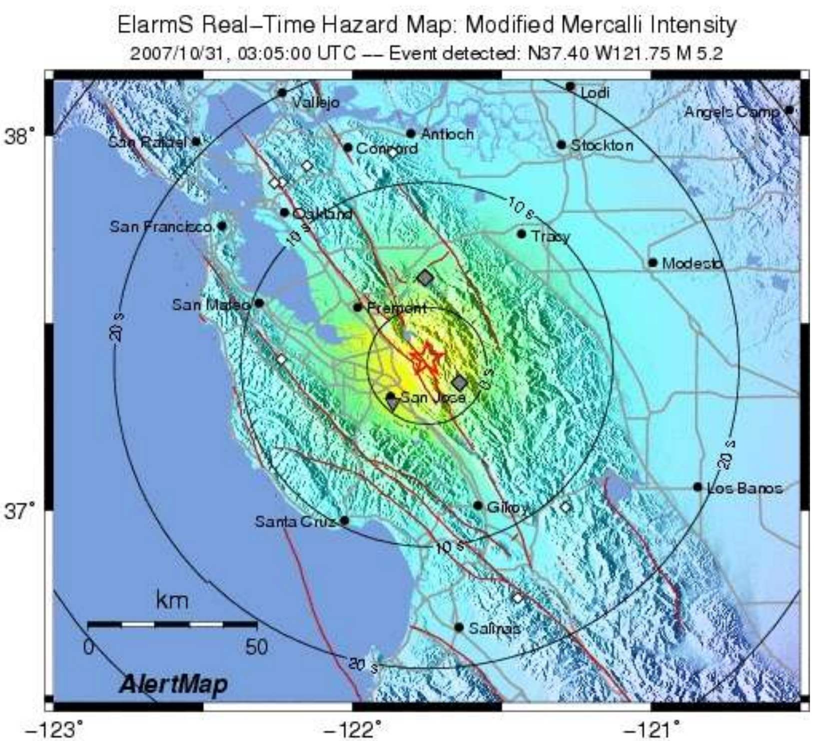
Goal: predict peak ground shaking before onset

1. **Determine earthquake location**
2. **Estimate warning time**

   Based on expected time of peak shaking



detection



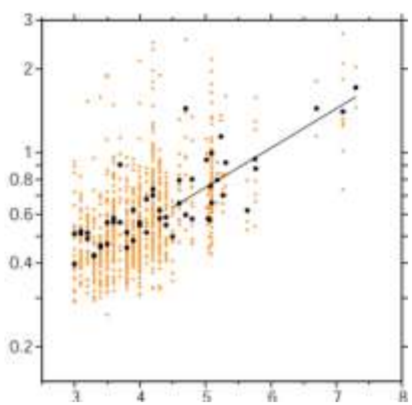
detection + 1 sec

ElarmS methodology

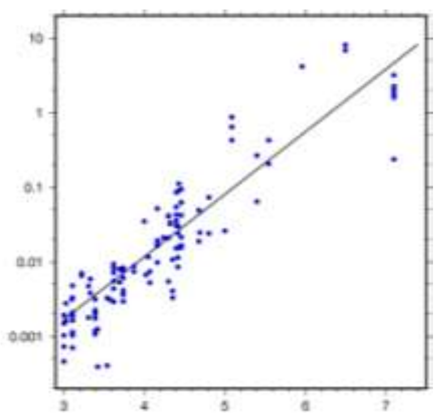
Goal: predict peak ground shaking before onset

1. **Determine earthquake location**
2. **Estimate warning time**
3. **Estimate magnitude**

   From the ***frequency content and amplitude*** of the P-wave



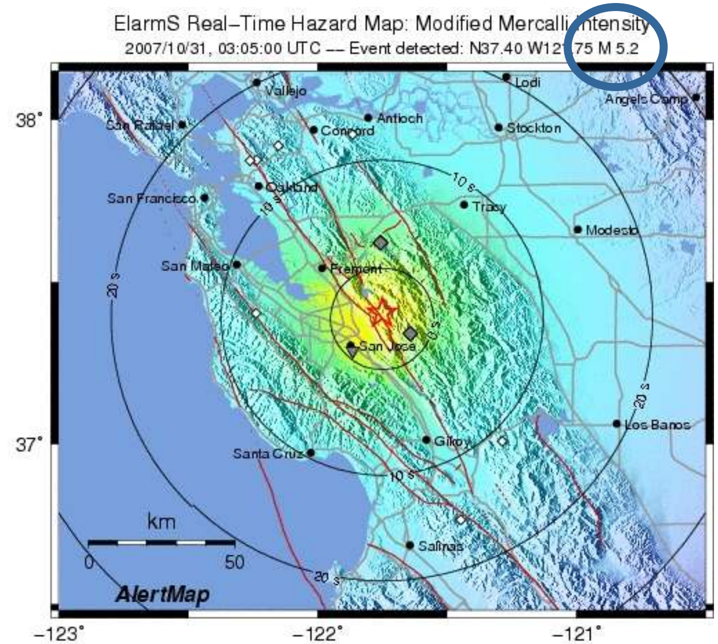
Predominant period
Nakamura, 1988



Peak displacement
Wu & Kanamori, 2005

CISN: M_w5.4

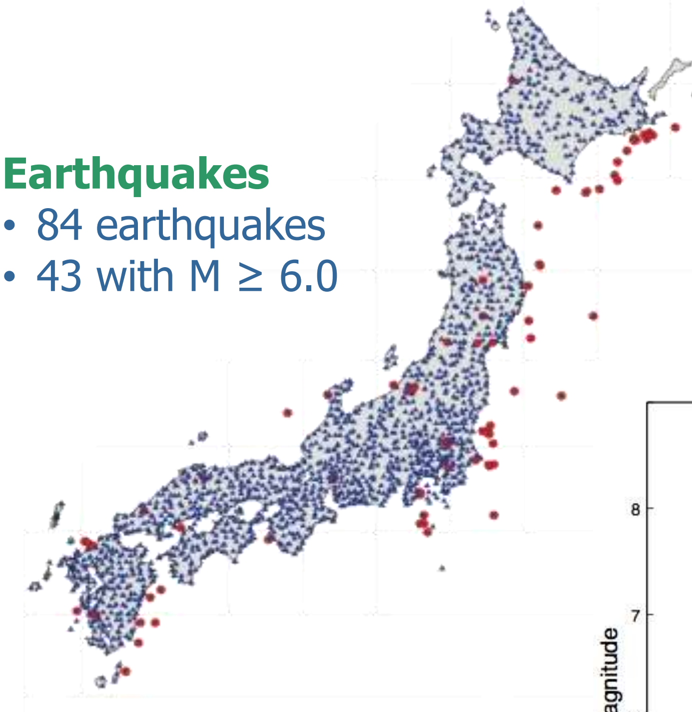
M5.2



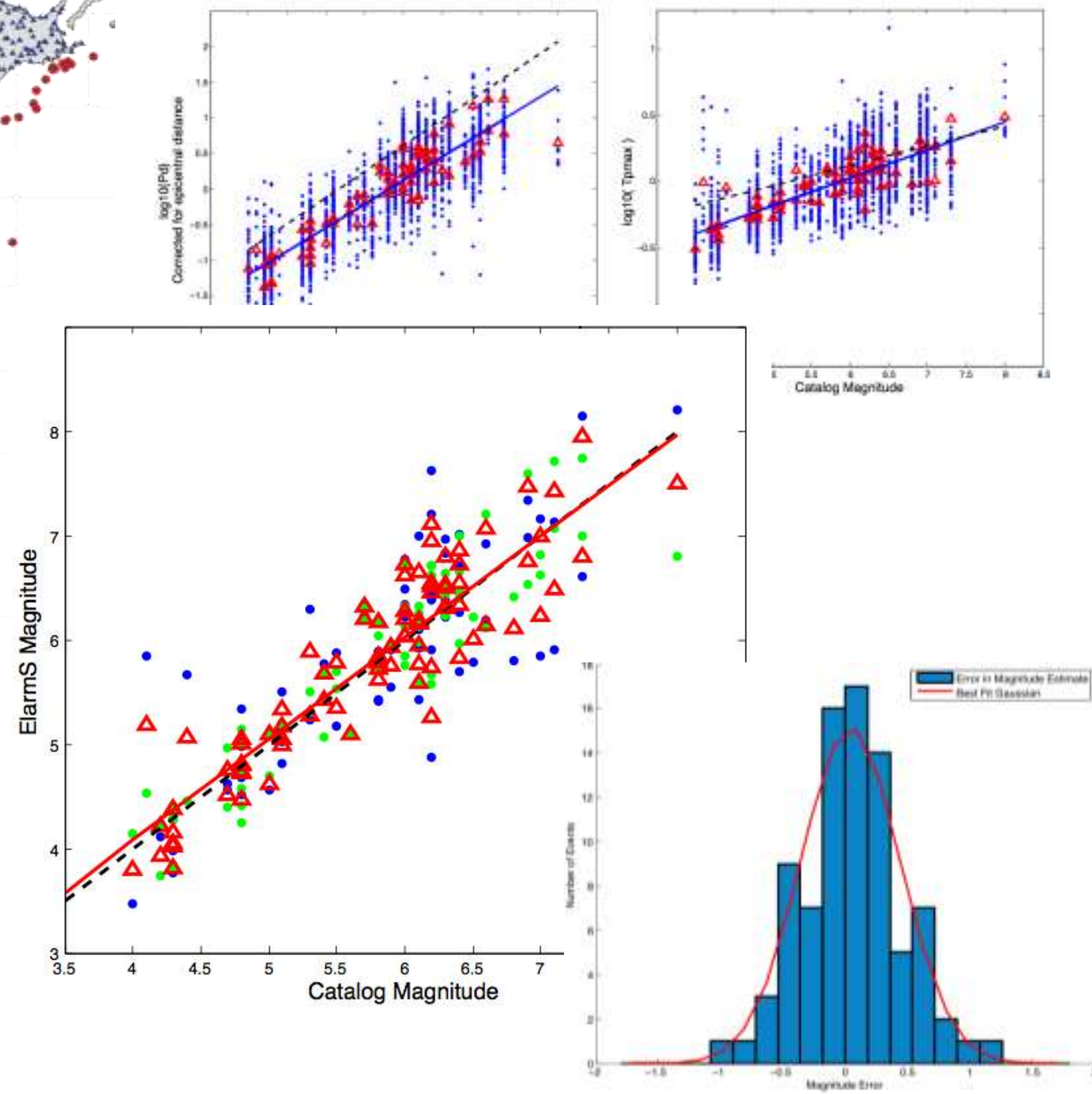
detection + 1 sec

ElarmS magnitude estimation for **large** earthquakes

…SEE HOLLY BROWN'S POSTER "ELARMS IN JAPAN"



Earthquakes
- 84 earthquakes
- 43 with M ≥ 6.0



Magnitude errors

All events 0.0 ± 0.4
M ≥ 6.0   0.0 ± 0.5
M ≥ 7.0   -0.2 ± 0.5

ElarmS methodology

Goal: predict peak ground shaking before onset

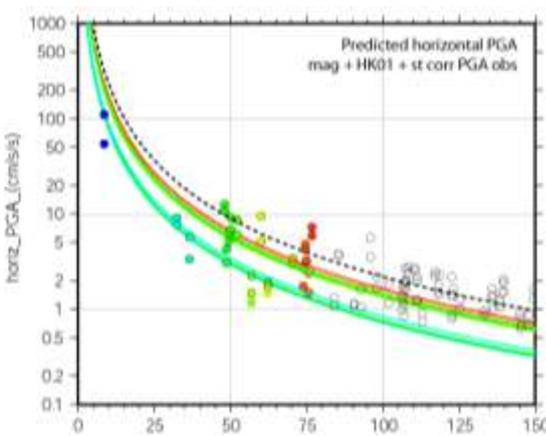
1. **Determine earthquake location**
2. **Estimate warning time**
3. **Estimate magnitude**
4. **Calculate shaking intensity**

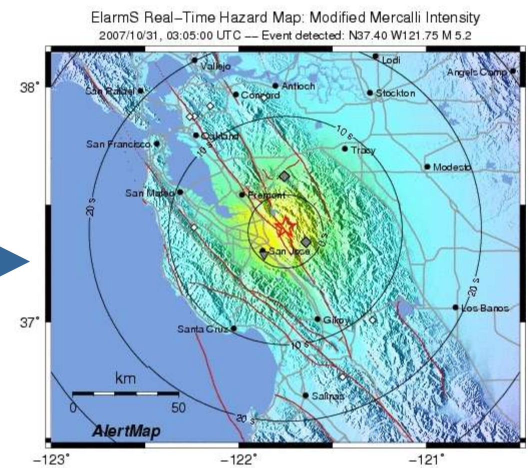
   Attenuation relations: Require magnitude, distance and site corrections

magnitude defines ground shaking as a function of distance

+ fit to peak shaking observations

+ correct for site effects





this is what ShakeMap does

developed by Dave Wald and many others

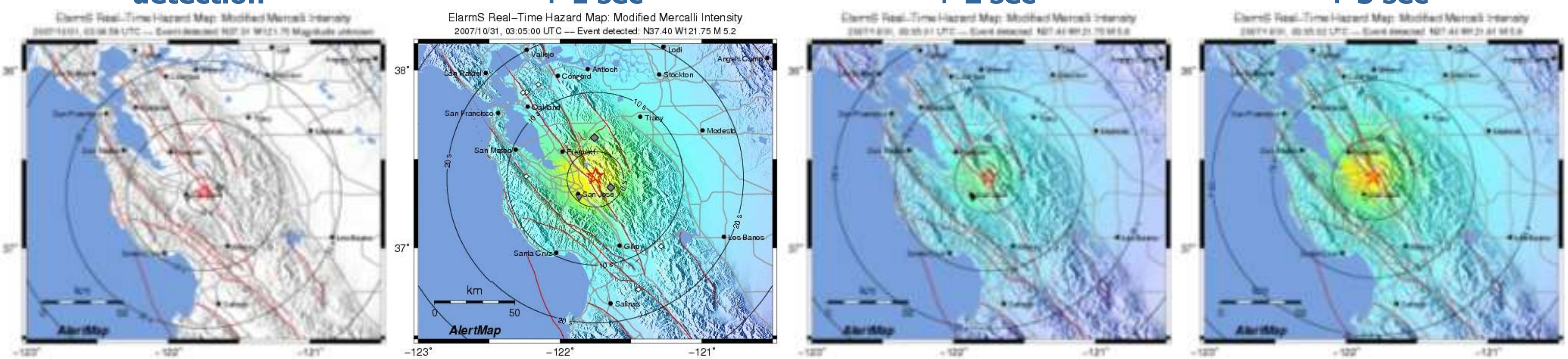
…use a modified version of ShakeMap to produce an AlertMap

ElarmS methodology

Goal: predict peak ground shaking before onset

1. **Determine earthquake location**
2. **Estimate warning time**
3. **Estimate magnitude**
4. **Calculate shaking intensity**
5. **System updates prediction every second**

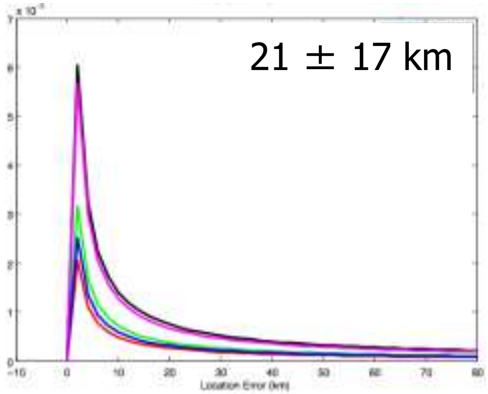
detection | **+ 1 sec** | **+ 2 sec** | **+ 3 sec**



with time the AlertMap evolves into a ShakeMap

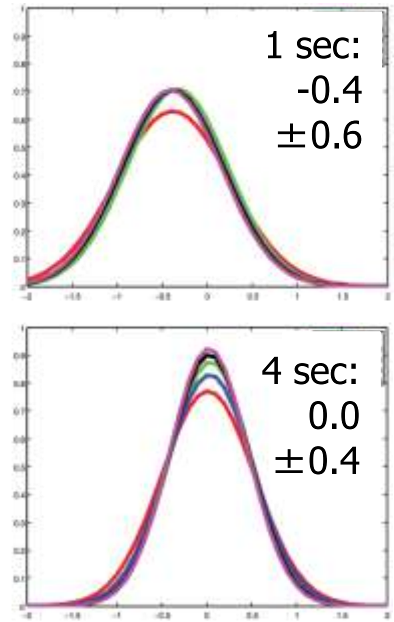
ElarmS error estimation

…SEE
HOLLY BROWN'S POSTER
"ELARMS IN JAPAN"



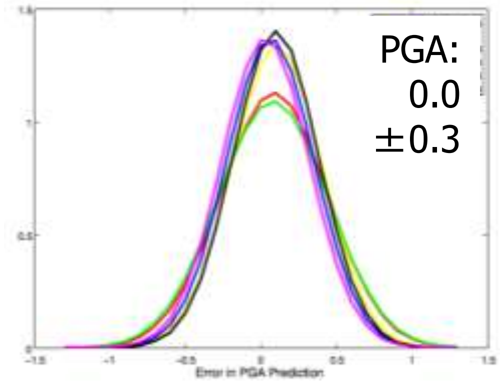
Location error
function of number of trigger times

+



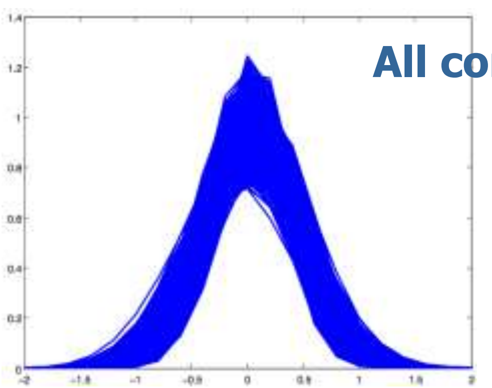
Magnitude error
function of number of trigger and time

+



Attenuation relation
function of number of PGA, PGV observations

=

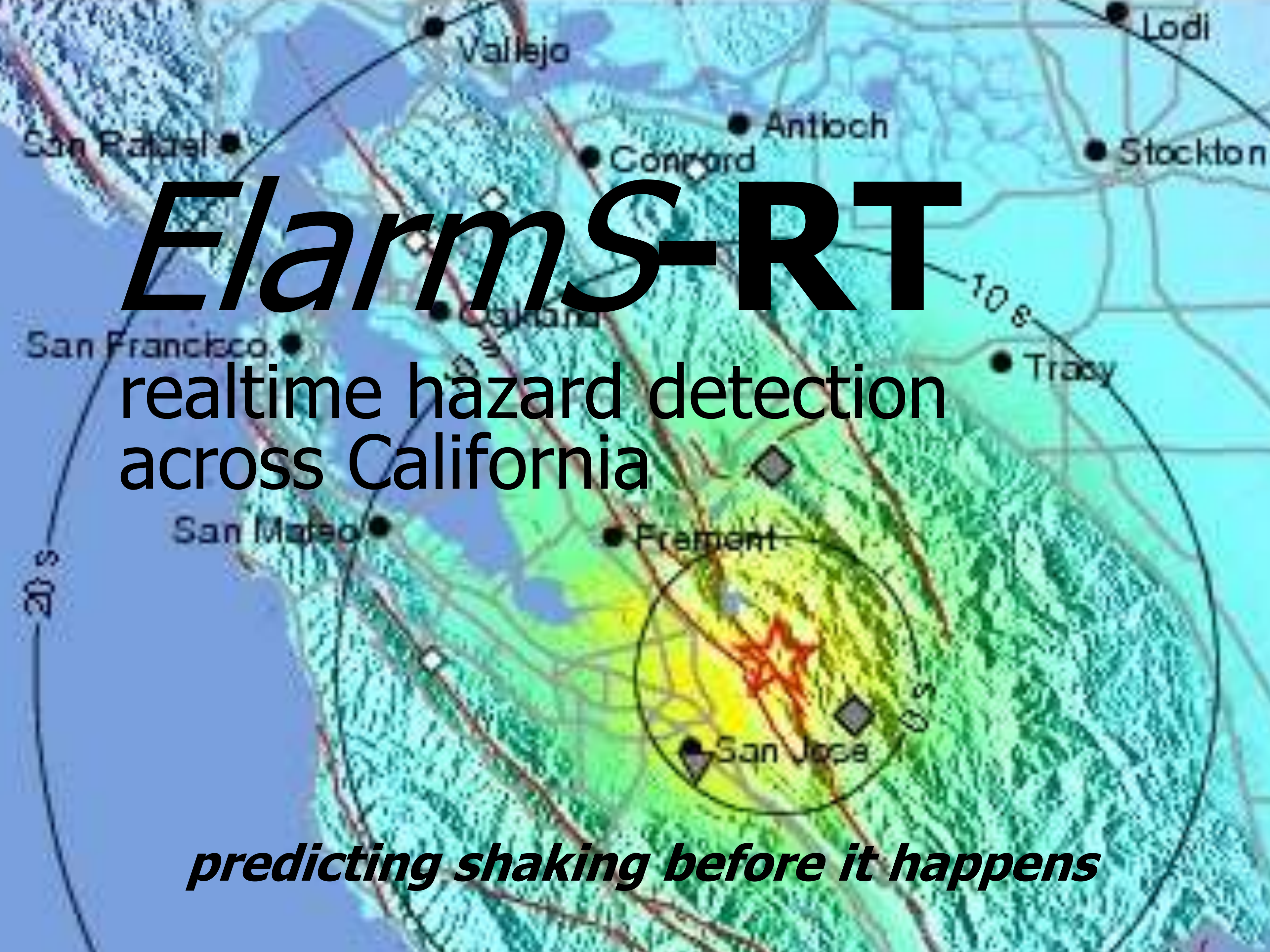


factor of 2 error = 0.7

All combinations: numbers of triggers, magnitudes, peak ground shaking observations (up to five).

mean -0.2 to 0.2, st dev 0.3 to 0.6

no mag error: mean 0.0 to 0.2, st dev 0.3 to 0.5
no loc error: mean -0.1 to 0.2, st dev 0.3 to 0.5
no att error: mean -0.3 to 0.3, st dev 0.2 to 0.4



ElarmS-**RT**

realtime hazard detection across California

predicting shaking before it happens

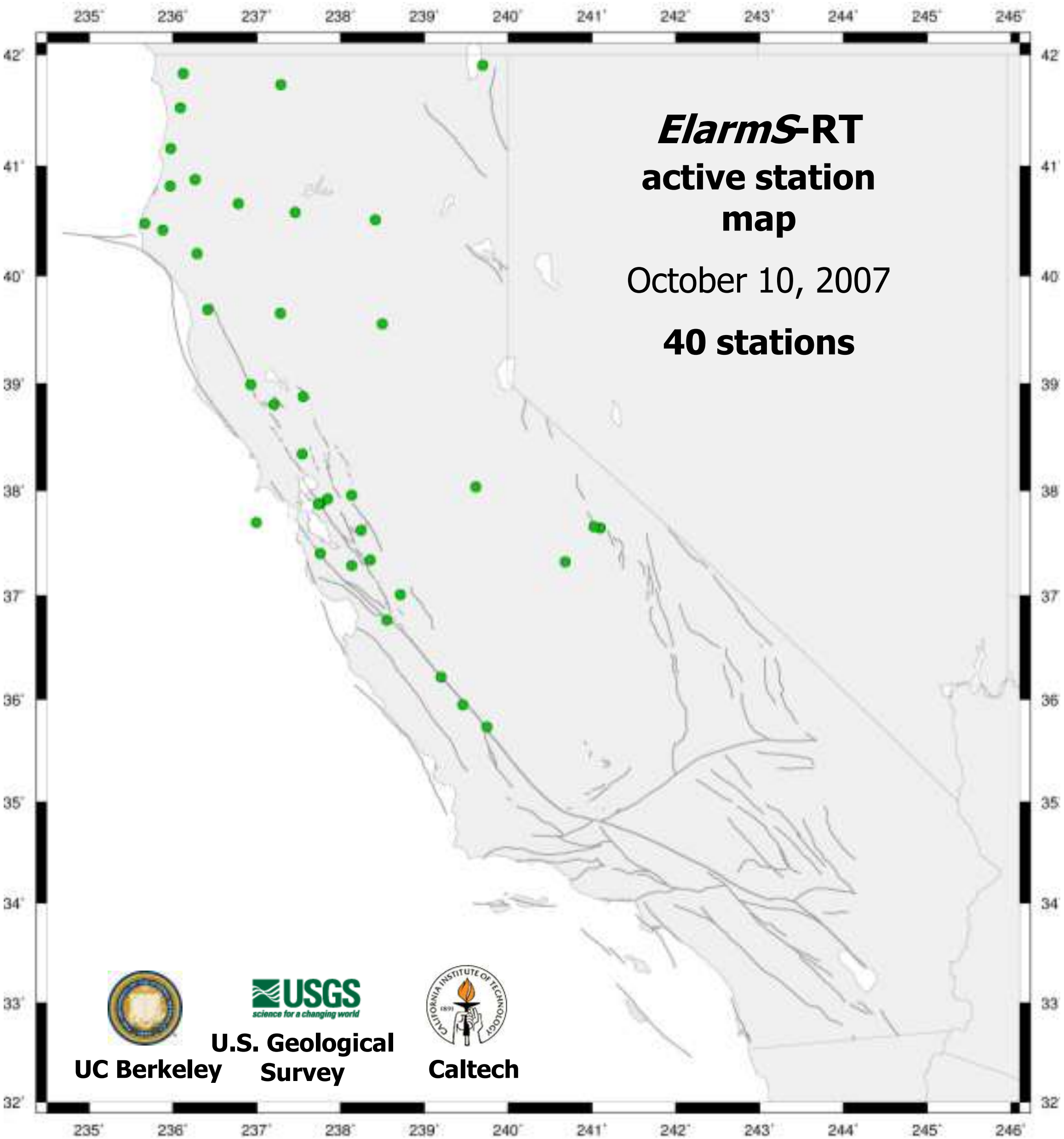
ElarmS-RT
Realtime processing

Adding networks to the *ElarmS* data flow

October 10, 2007

started realtime testing

BK + some NC



ElarmS-RT
Realtime processing

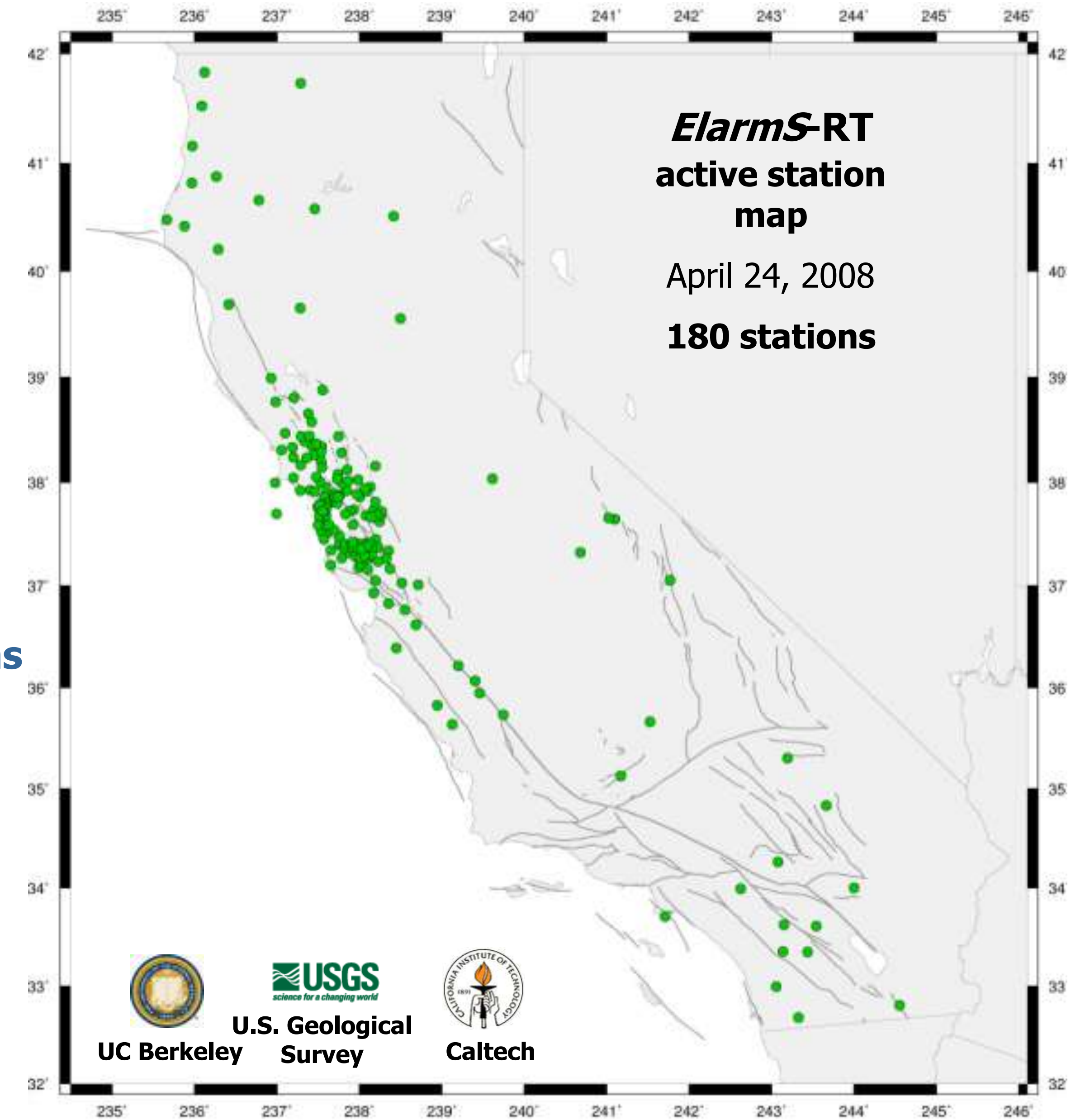
Adding networks to the *ElarmS* data flow

October 10, 2007

- **started realtime testing**
  BK + some NC

April 24, 2008

- **all northern CA stations**
- **few southern CA stations**
  BK + NC + NP + some CI



ElarmS-RT
Realtime processing

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started realtime testing

BK + some NC

April 24, 2008

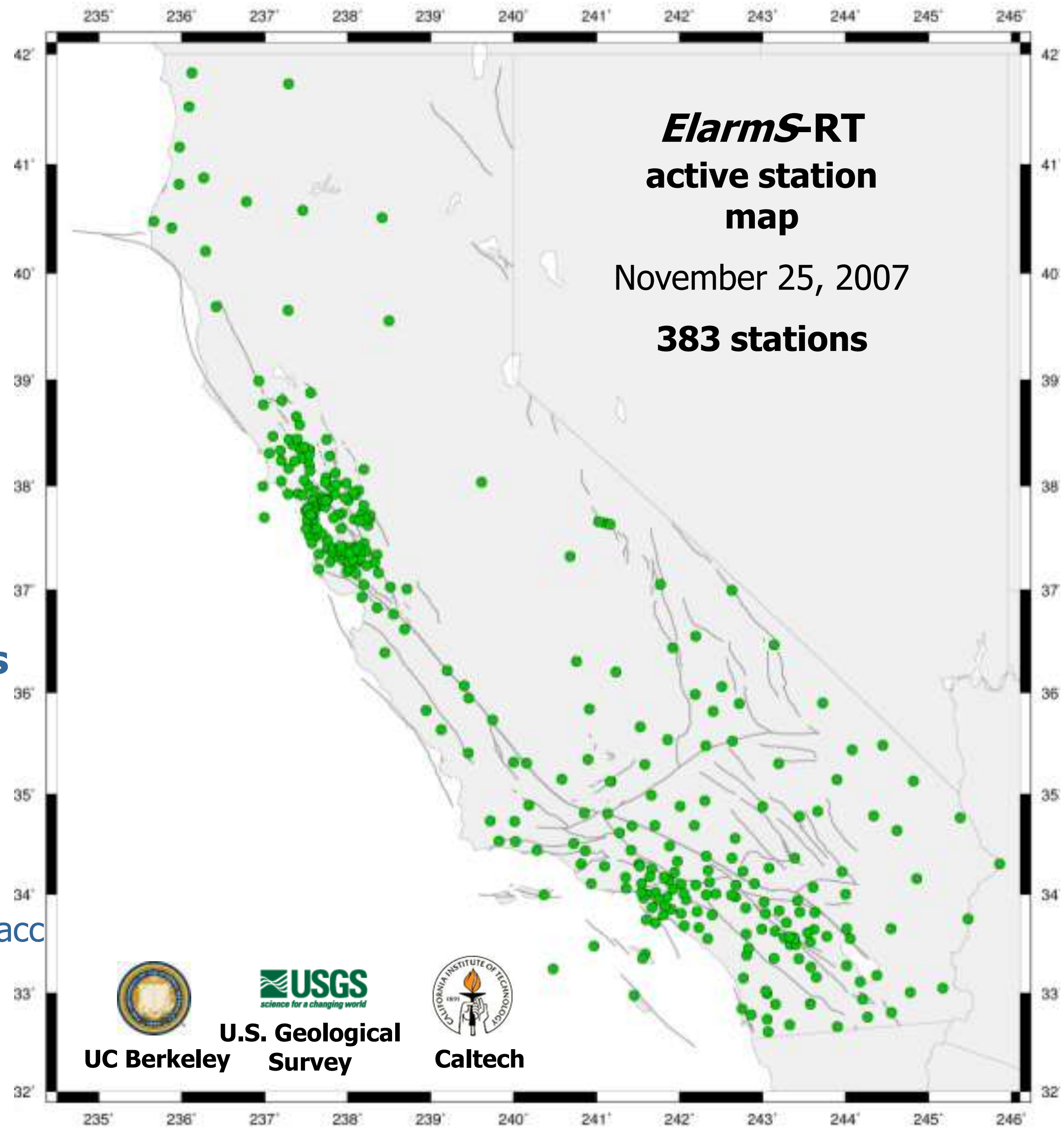
all northern CA stations
few southern CA stations

BK + NC + NP + some CI

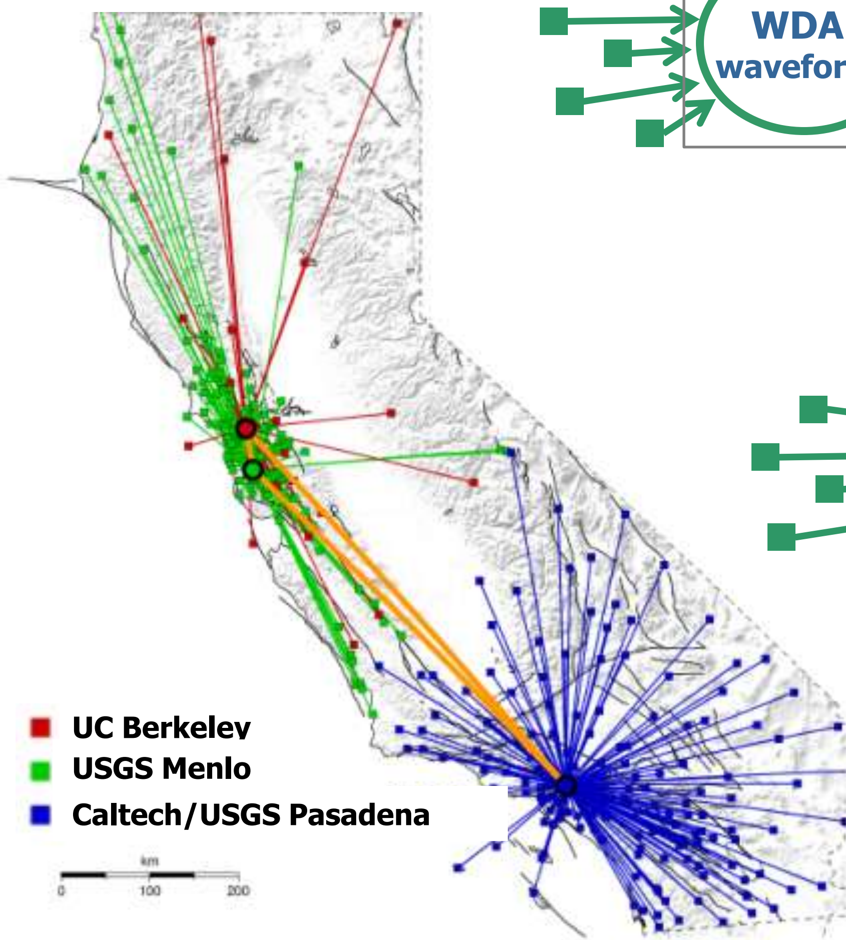
November 25, 2008

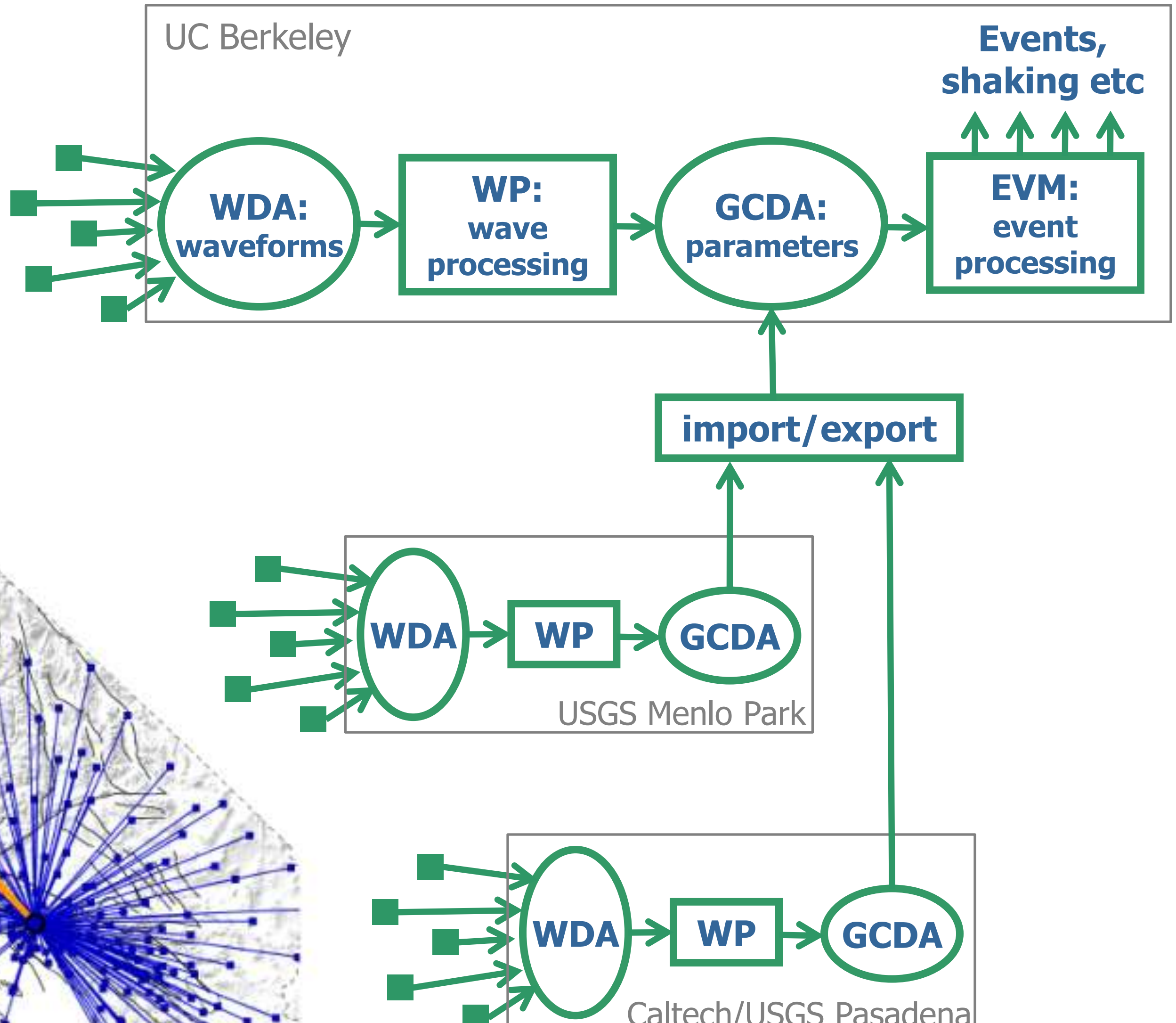
all CA stations

BK + NC + NP + CI + some AZ
all continuous broadband vel + acc



ElarmS statewide realtime
Data processing

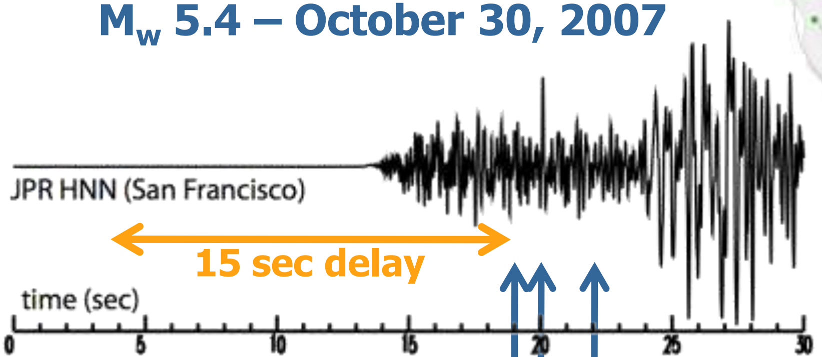


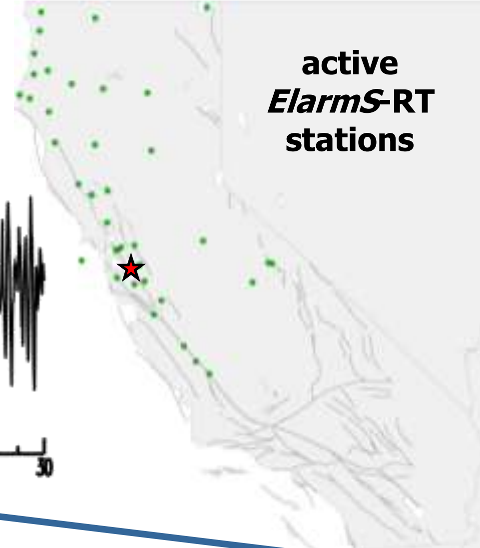


ElarmS-RT

Alum Rock

M_w 5.4 – October 30, 2007

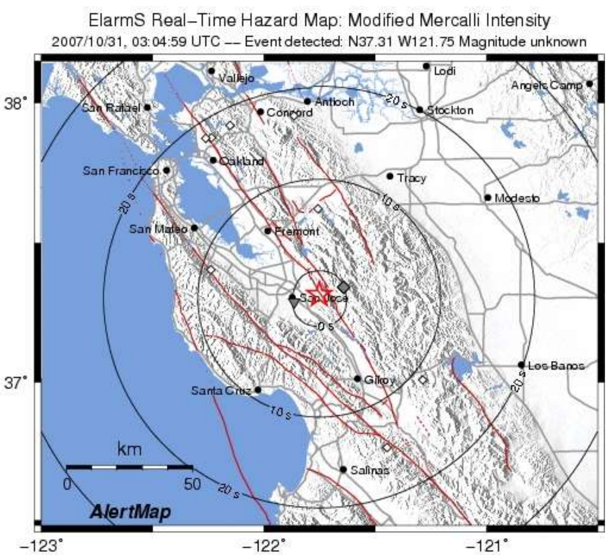


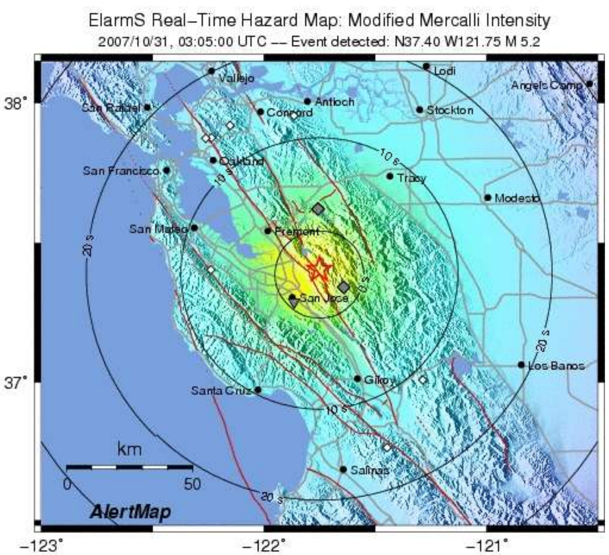


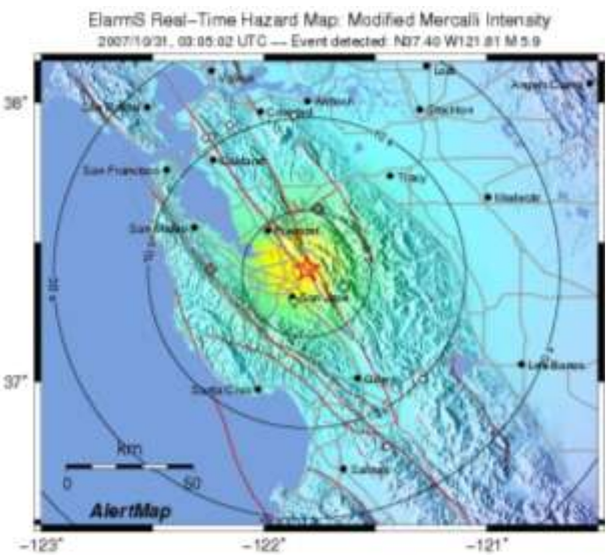
First detection (2 stations)
origin + **19 sec**
magnitude: **n/a**
loc error: **13 km**

3rd station detection
origin + **20 sec**
magnitude: **5.2**
loc error: **4 km**

4th station detection
origin + **22 sec**
magnitude: **5.9**
loc error: **4 km**

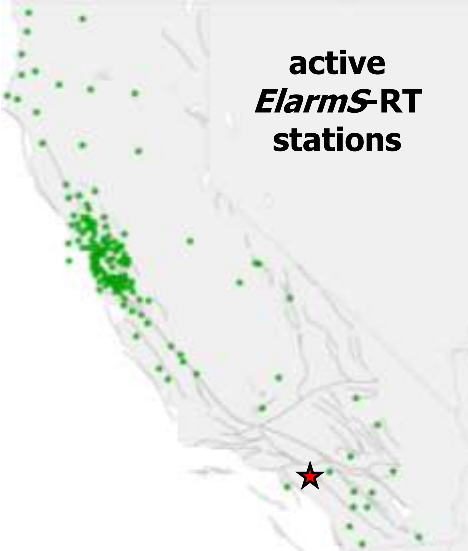






ElarmS-RT
Chino Hills
M_w 5.4 – July 29, 2008

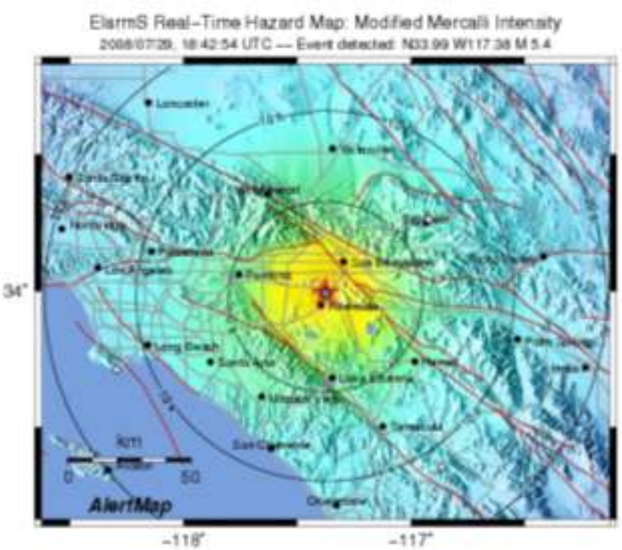
- Only 15 stations in southern CA, 3 within 100 km
- Communication bug introduced a 23 sec delay
- [Inserted 15 sec processing delay]

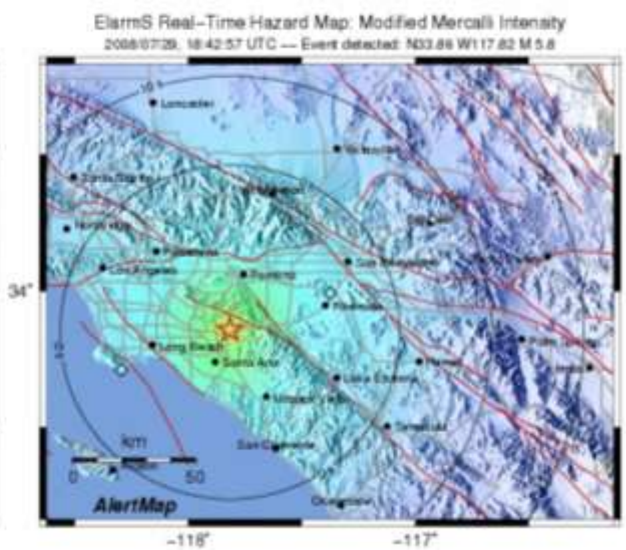


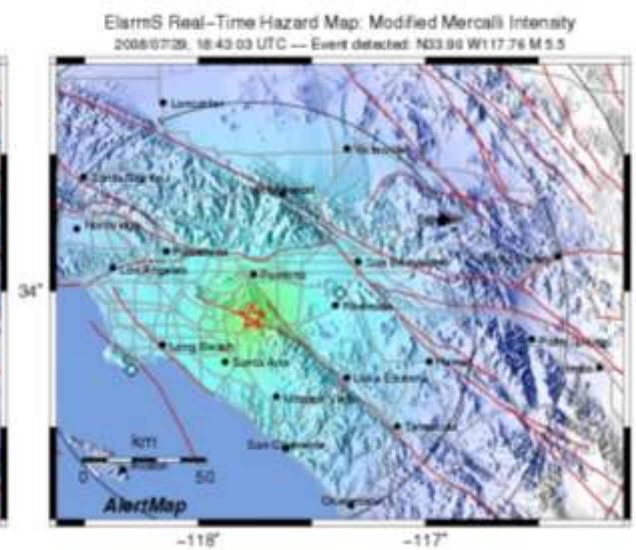
First detection
origin + **31 sec**
magnitude: **5.4**
loc error: **36 km**

2nd station detection
origin + **34 sec**
magnitude: **5.8**
loc error: **12 km**

3rd station detection
origin + **40 sec**
magnitude: **5.5**
loc error: **6 km**

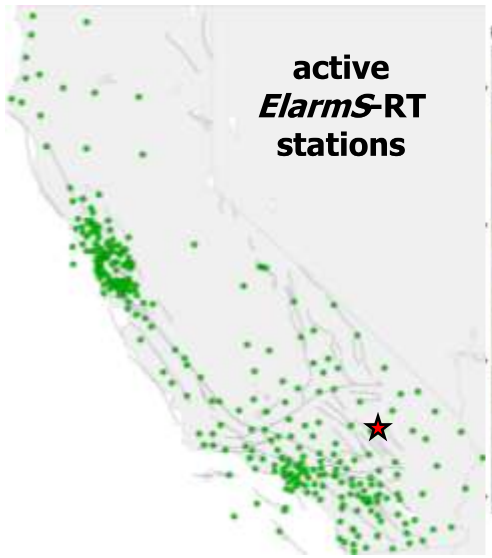


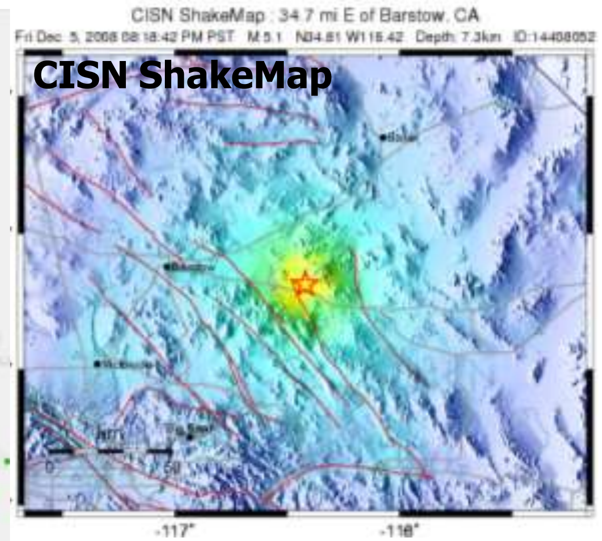




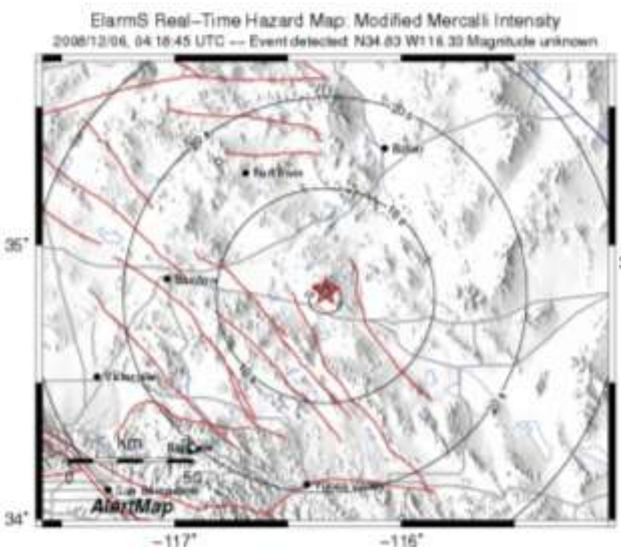
ElarmS-RT
Ludlow
M_w 5.1 – December 6, 2008

- Southern CA stations operational for 11 days
- Units error: cm/s vs. m/s!
- Inserted 15 sec processing delay

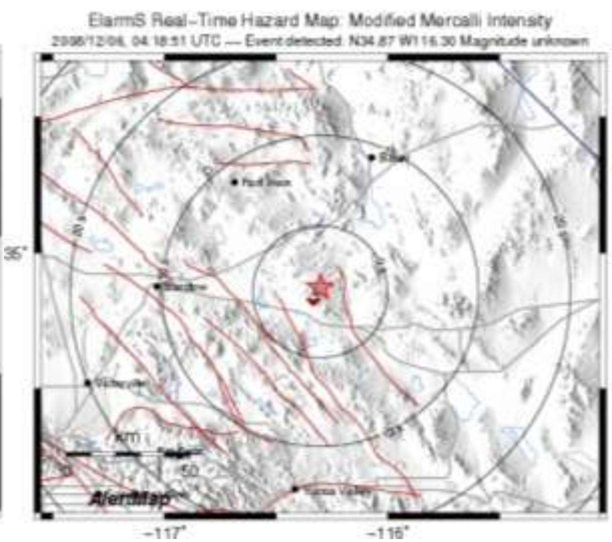




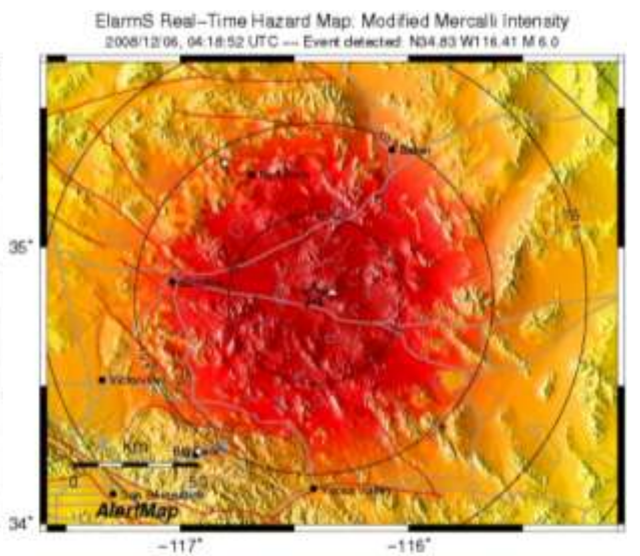
First detection
origin + **18 sec**
magnitude: **n/a**



2nd station detection
origin + **24 sec**
magnitude: **n/a**



3rd station detection
origin + **25 sec**
magnitude: **6.0**

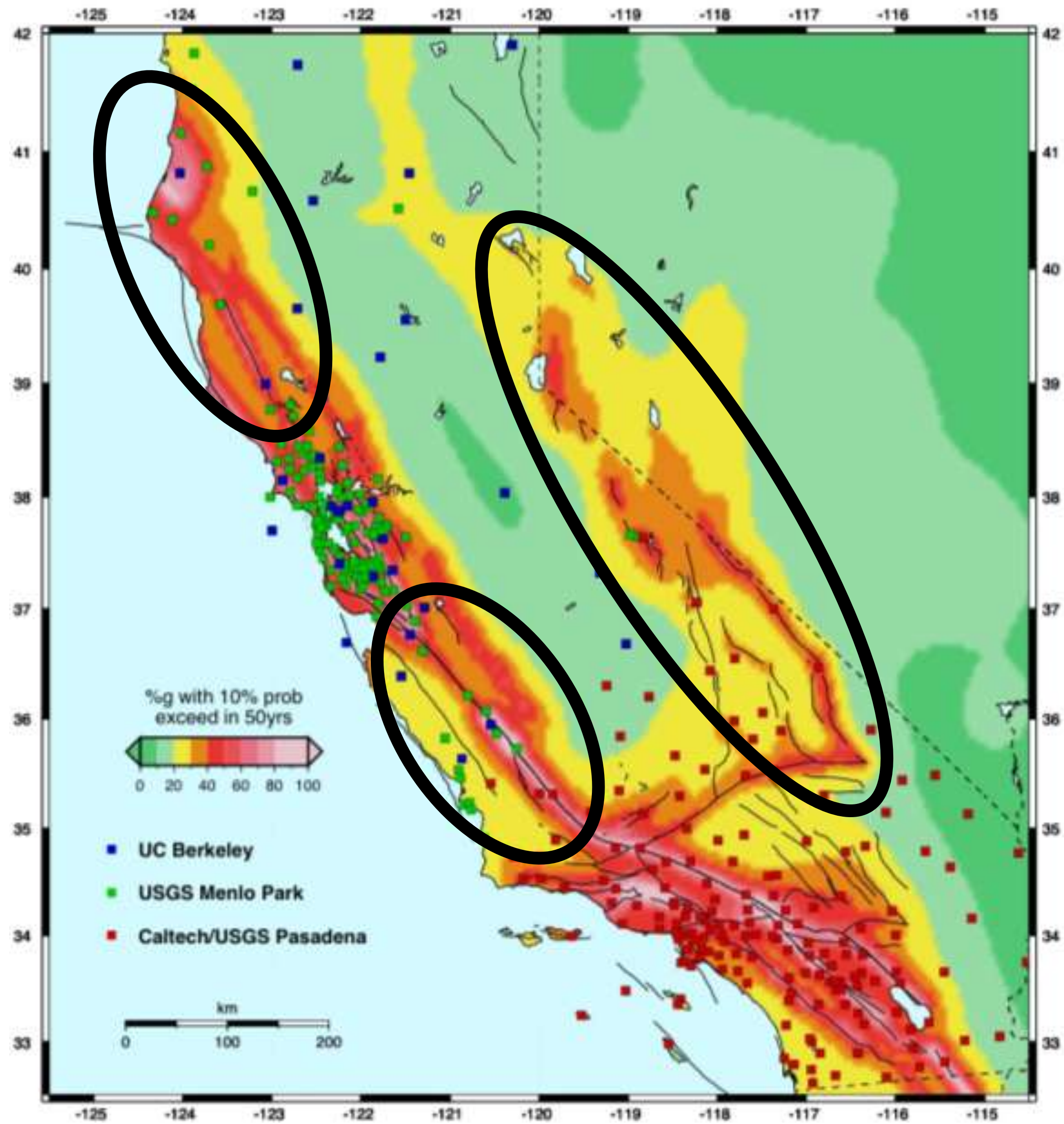


ElarmS-**RT**

Station distribution

384 station sites
603 sensors
222 velocity
381 accelerometers

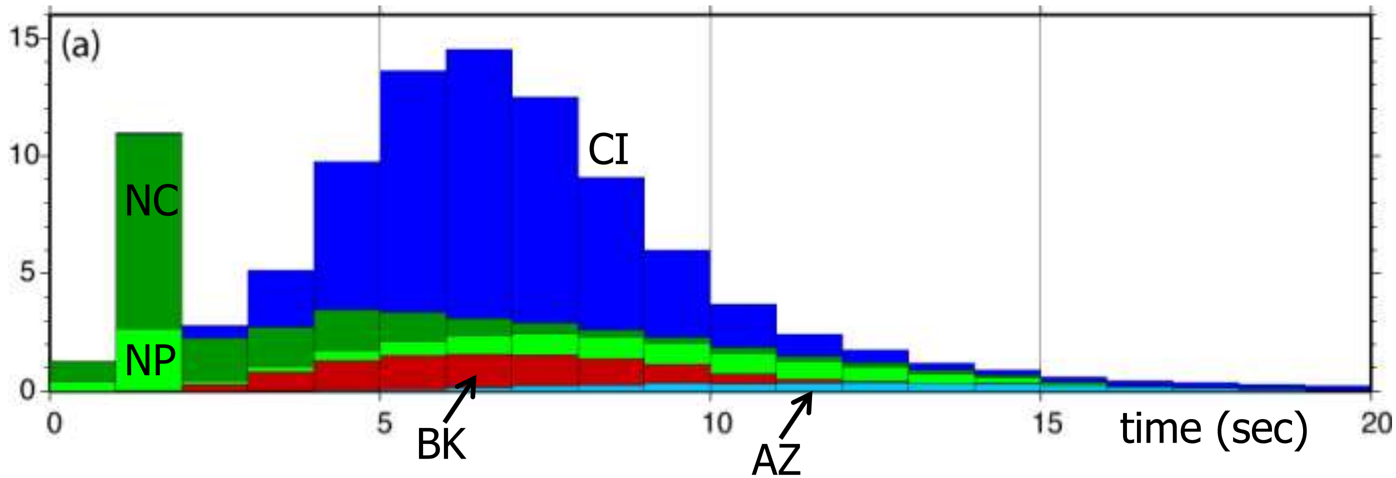
Big
Instrumentation
Gaps



ElarmS-**RT**
System latency

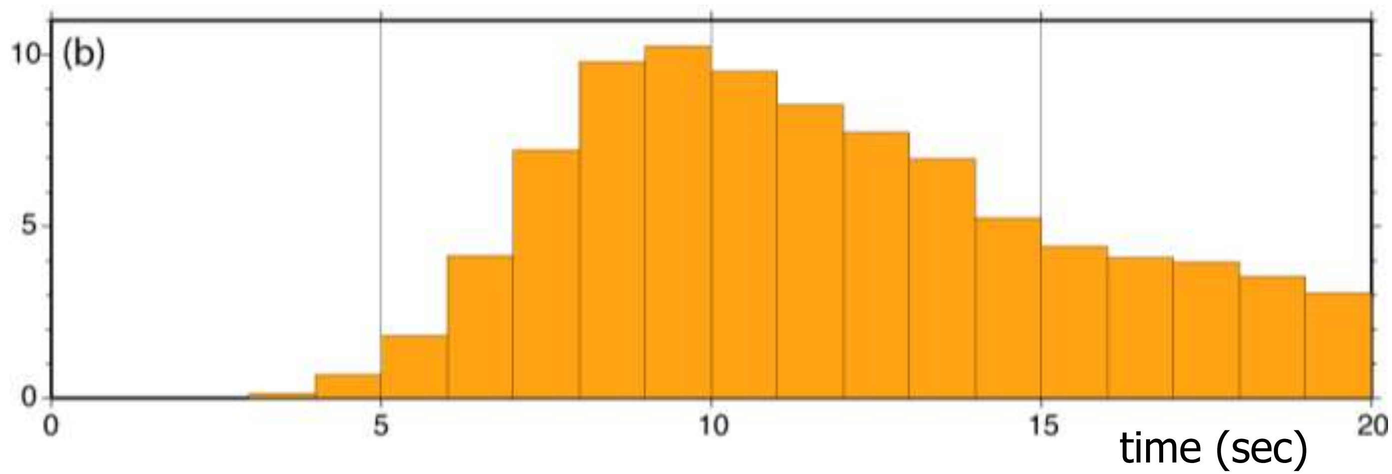
Data packetization and telemetry

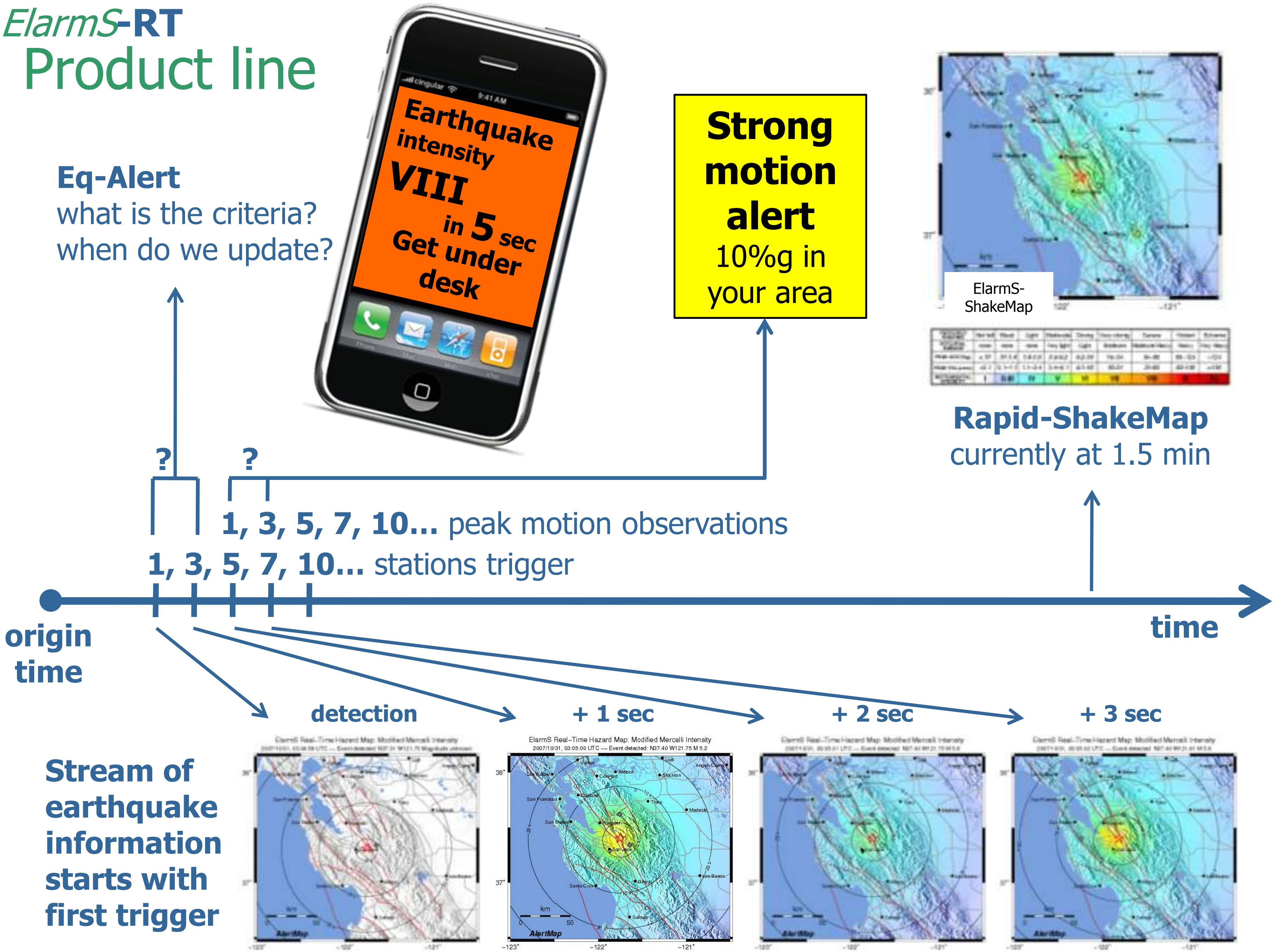
median:
6.5 sec



***ElarmS*-RT latency:** Seismometer to warning (on ElarmS computers)

median:
11.8 sec





ElarmS-RT
Product line
Earthquake intensity VIII in 5 sec Get under desk
Strong motion alert
10%g in your area
ElarmS-ShakeMap
Eq-Alert
what is the criteria?
when do we update?
Rapid-ShakeMap
currently at 1.5 min
?
?
1, 3, 5, 7, 10… peak motion observations
1, 3, 5, 7, 10… stations trigger
origin time
time
detection
+ 1 sec
+ 2 sec
+ 3 sec
ElarmS Real–Time Hazard Map: Modified Mercalli Intensity
2007/10/31, 03:05:00 UTC –– Event detected: N37.40 W121.75 M 5.2
AlertMap
Stream of earthquake information starts with first trigger

Summary

***ElarmS*-RT operational statewide in California**

– 600 sensors from 5 networks, 3 processing centers

Accurately detecting earthquakes
where there is good station coverage

– Alum Rock: prediction before ground shaking in San Francisco
– Chino Hills: accurate but slow (3 station within 100 km)

System latency currently 15 sec

– reduced to ~12 sec with current software/infrastructure
– reduced to ~7 sec with software upgrade
– reduced to 2-3 sec with infrastructure upgrade

Challenges/Questions for this workshop

What are the criteria to issue an alarm?

How do we do a better job for finite faults?

What are the appropriate steps toward implementation?