Schweizerischer Erdbebendienst
Swiss Seismological Service

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Real-Time Performance of the Virtual Seismologist Earthquake Early Warning Algorithm in Southern California

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Outline

- Description of VS algorithm (Bayes' theorem in EEW)
- Implementation of likelihood function
- Challenges of operating in real-time (with noise)
- Some performance statistics (13 July 2008 - 9 April 2009)
- Conclusions and Outlook

Virtual Seismologist EEW algorithm (Cua and Heaton)

- regional, network-based Bayesian approach to EEW
- quantifying “back of the envelope” methods of human seismologists
- implemented by ETH through SAFER
- real-time testing and performance evaluation through CISN EEW project
- real-time in Southern California since 13 July 2008
- coming soon to Northern California and Switzerland

Bayes’ Theorem in EEW

Given the available set of observations (picks and amplitudes), the most probable source characterization is given by

$$prob(M, lat, lon \mid obs) \propto prob(obs \mid M, lat, lon) \cdot prob(M, lat, lon)$$

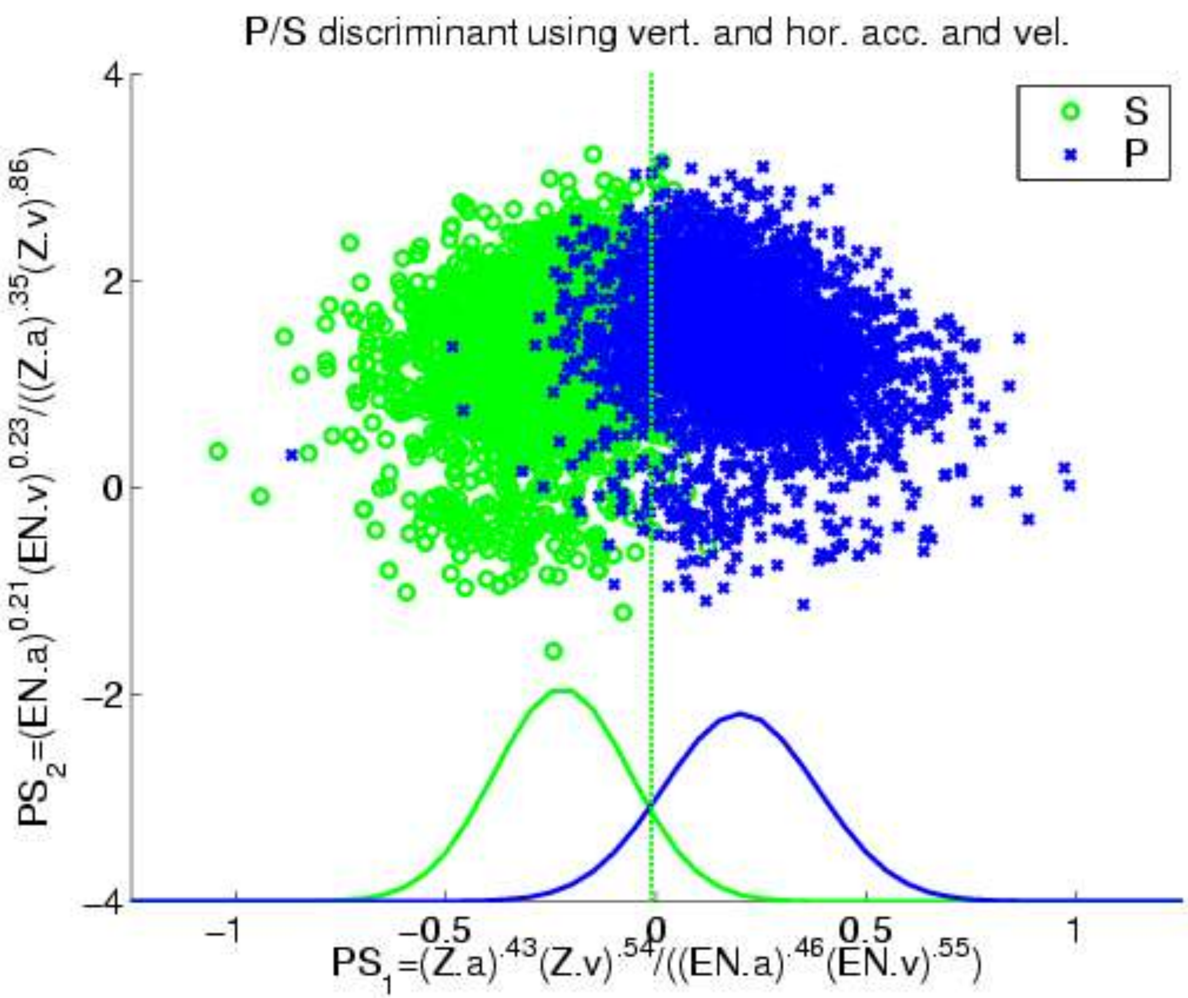
Posterior (“answer”) Likelihood (“data”) Prior (“other” information)

Virtual Seismologist (VS) EEW algorithm (Cua and Heaton)

- Regional, networ-based Bayesian approach to EEW for regions with distributed seismic hazard/risk
- Modeled on “back of the envelope” methods of human seismologists for examining waveform data
  - Shape of envelopes, relative frequency content
- Capacity to assimilate different types of information
  - Previously observed seismicity
  - State of health of seismic network
  - Known fault locations
  - Gutenberg-Richter recurrence relationship

VS likelihood function

- **P-S discriminant**
- Estimating M from ground motion ratio
- Envelope attenuation relationships



VS likelihood function

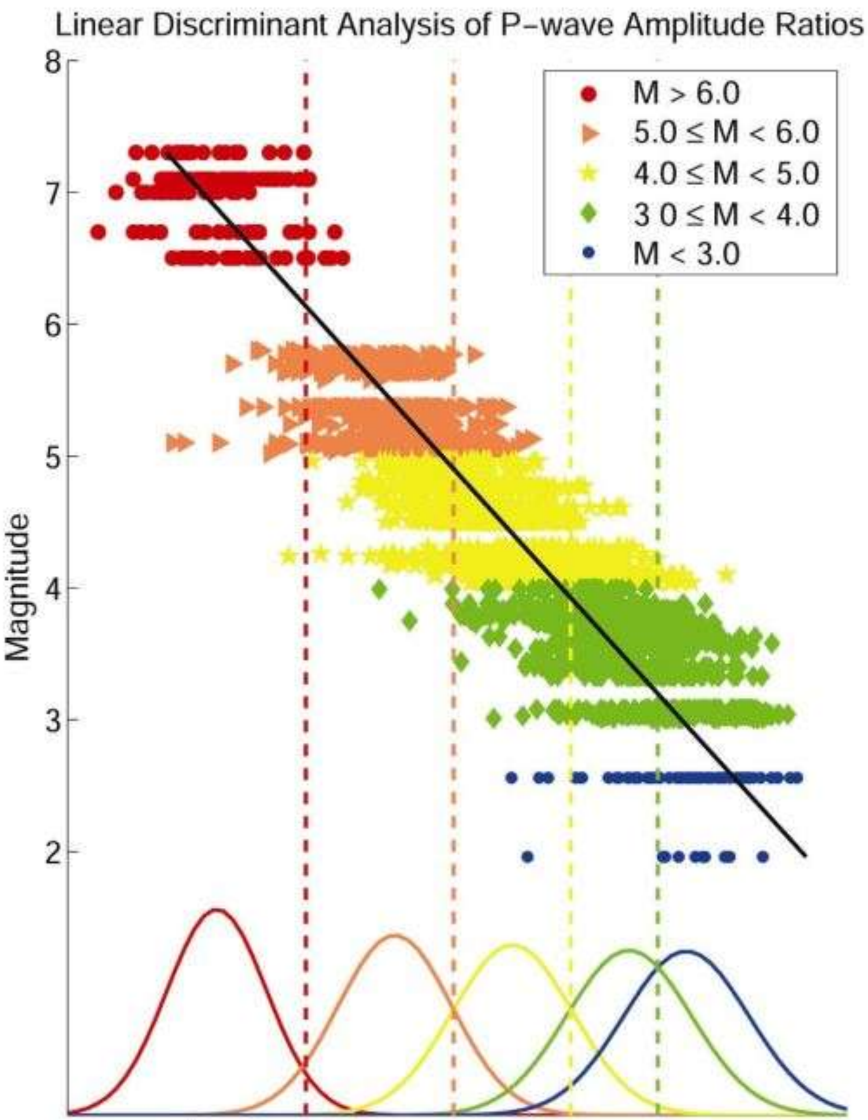
- P-S discriminant
- **Estimating M from ground motion ratio**
- Envelope attenuation relationships

P-wave frequency content scales with M (Nakamura, 1986; Allen and Kanamori,2003)

Single station magnitude estimate

$$M_P = -1.627 Z_{ad} + 8.94, \sigma_{M_P} = 0.45$$

$$M_S = -1.459 Z_{ad} + 8.05, \sigma_{M_S} = 0.41$$



$$Z_{obs} = \log\left(\frac{PVA^{0.36}}{PVD^{0.93}}\right) = 0.36\log(PVA) - 0.93\log(PVD)$$

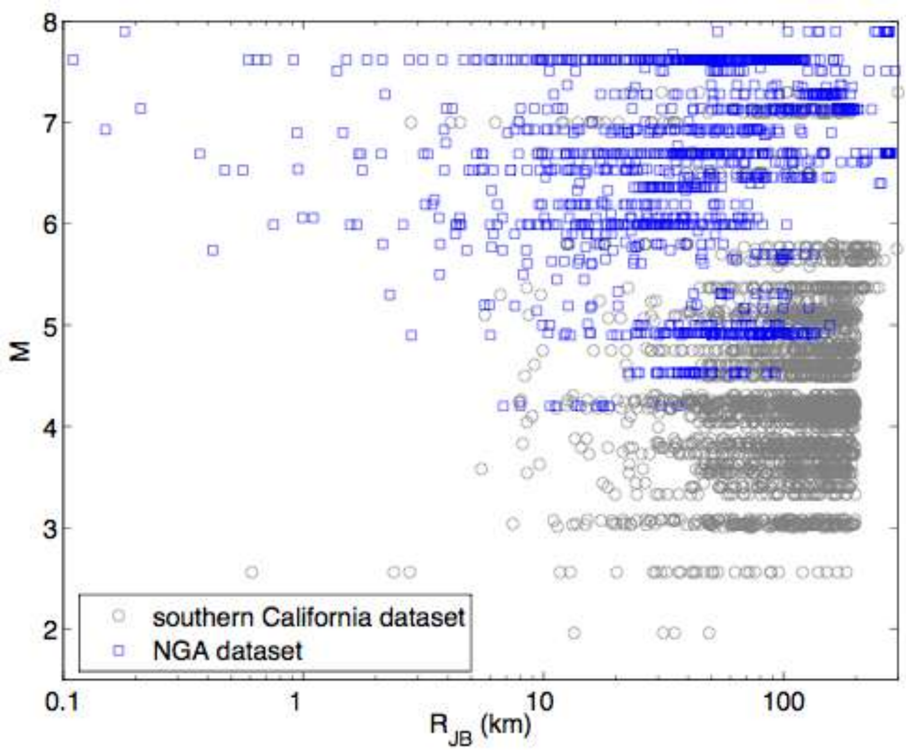
VS likelihood function

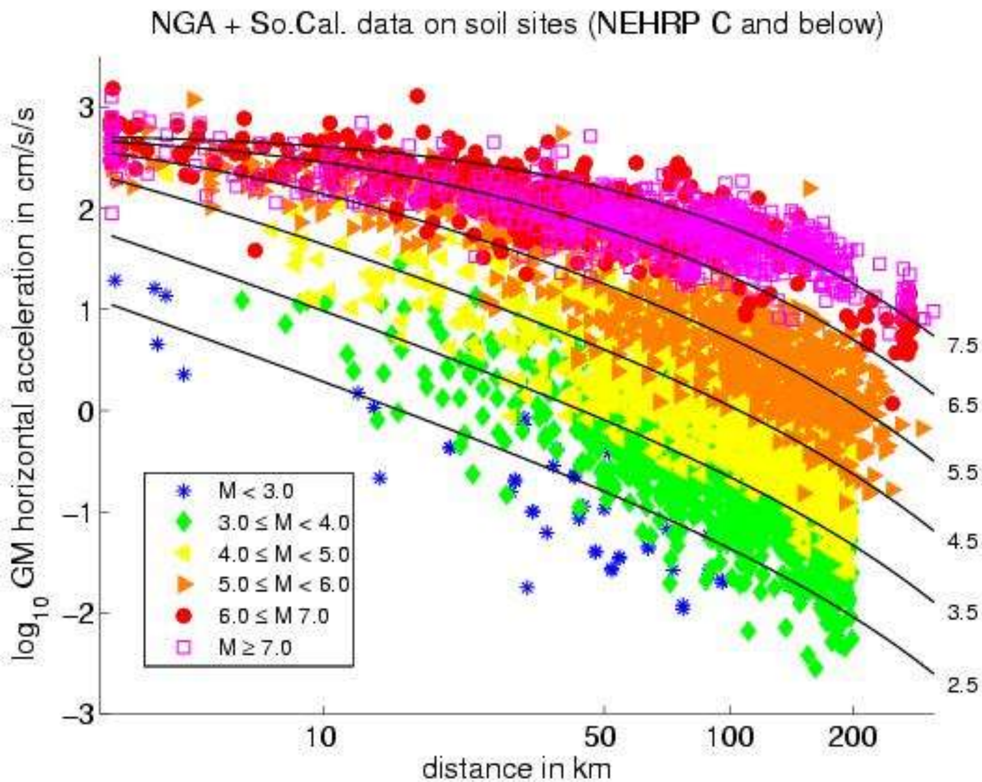
- P-S discriminant
- Estimating M from ground motion ratio
- **Envelope attenuation relationships**

$$\log Y = aM + b(R_1 + C(M)) + d\log(R_1 + C(M)) + e$$

$$R_1 = \sqrt{R^2 + 9}$$

$$C(M) = c_1(\arctan(M-5) + 1.4)\cdot\exp(c_2(M-5))$$





VS likelihood function

- P-S discriminant
- Estimating M from ground motion ratio
- Envelope attenuation relationships

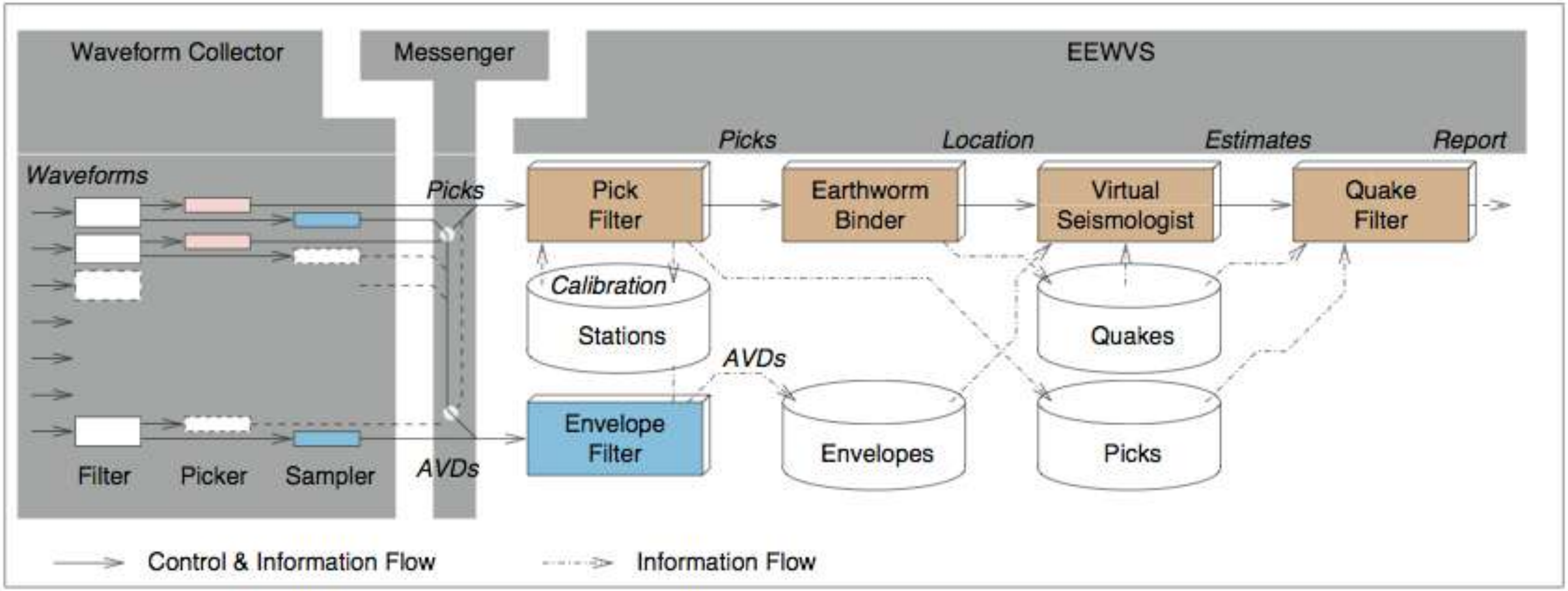
$$prob(M,lat,lon \mid obs) \propto prob(obs \mid M,lat,lon) \cdot prob(M,lat,lon)$$

Posterior ("answer") Likelihood ("data") Prior ("other" information)

$$L(M,lat,lon) = \sum_{i=1}^{stations} \sum_{j=1}^{P,S} L(M,lat,lon)_{ij}$$

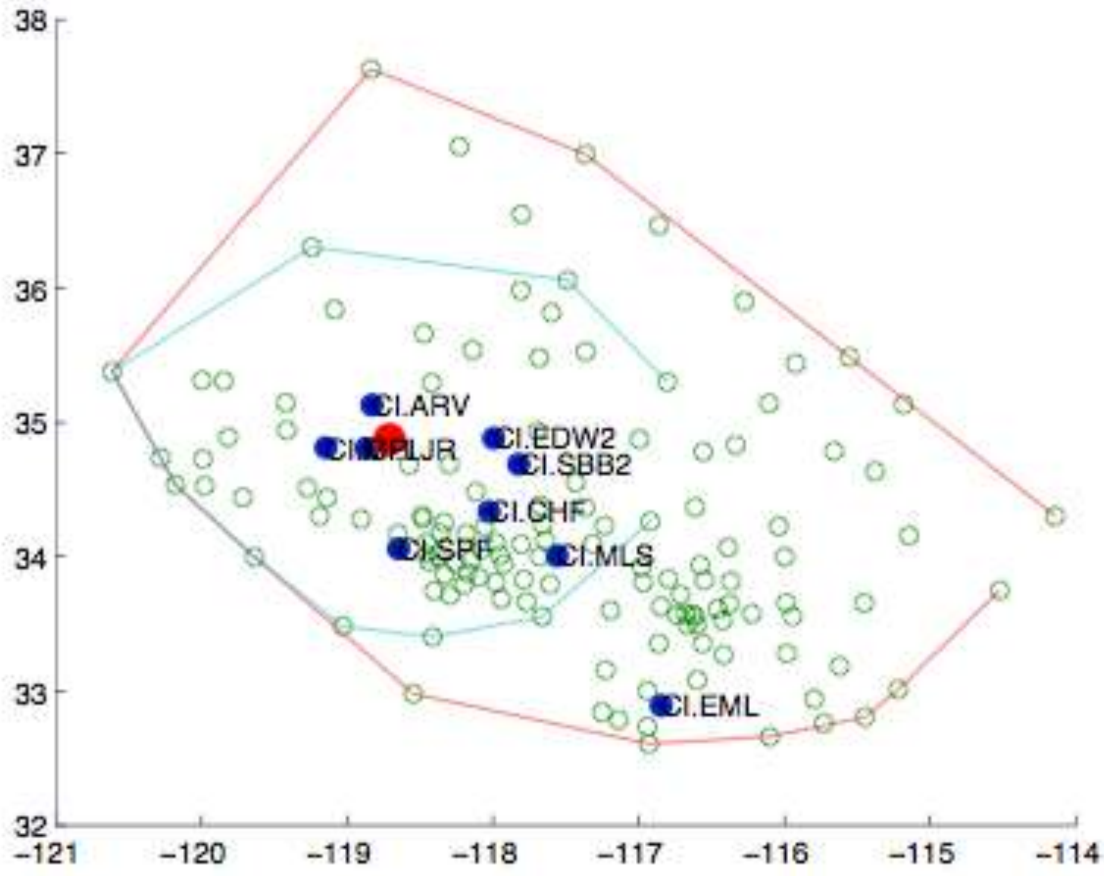
$$L(M,lat,lon)_{ij} = \frac{(ZAD_{ij} - \bar{Z}_j(M))^2}{2\sigma^2_{ZAD_j}} + \sum_{k=1}^{4} \frac{Y_{obs,ijk} - \bar{Y}_{ijk}(M,lat,lon)}{2\sigma^2_{ijk}}$$

System architecture of VS real-time codes



- Binder (earthworm phase associator)
- Virtual Seismologist module = VS likelihood function
- GIGO (“garbage in, garbage out”)
- Quake Filter (quantifying some rules of thumb)
- Processing time ~ 1 - 3 seconds (dependent on system load)

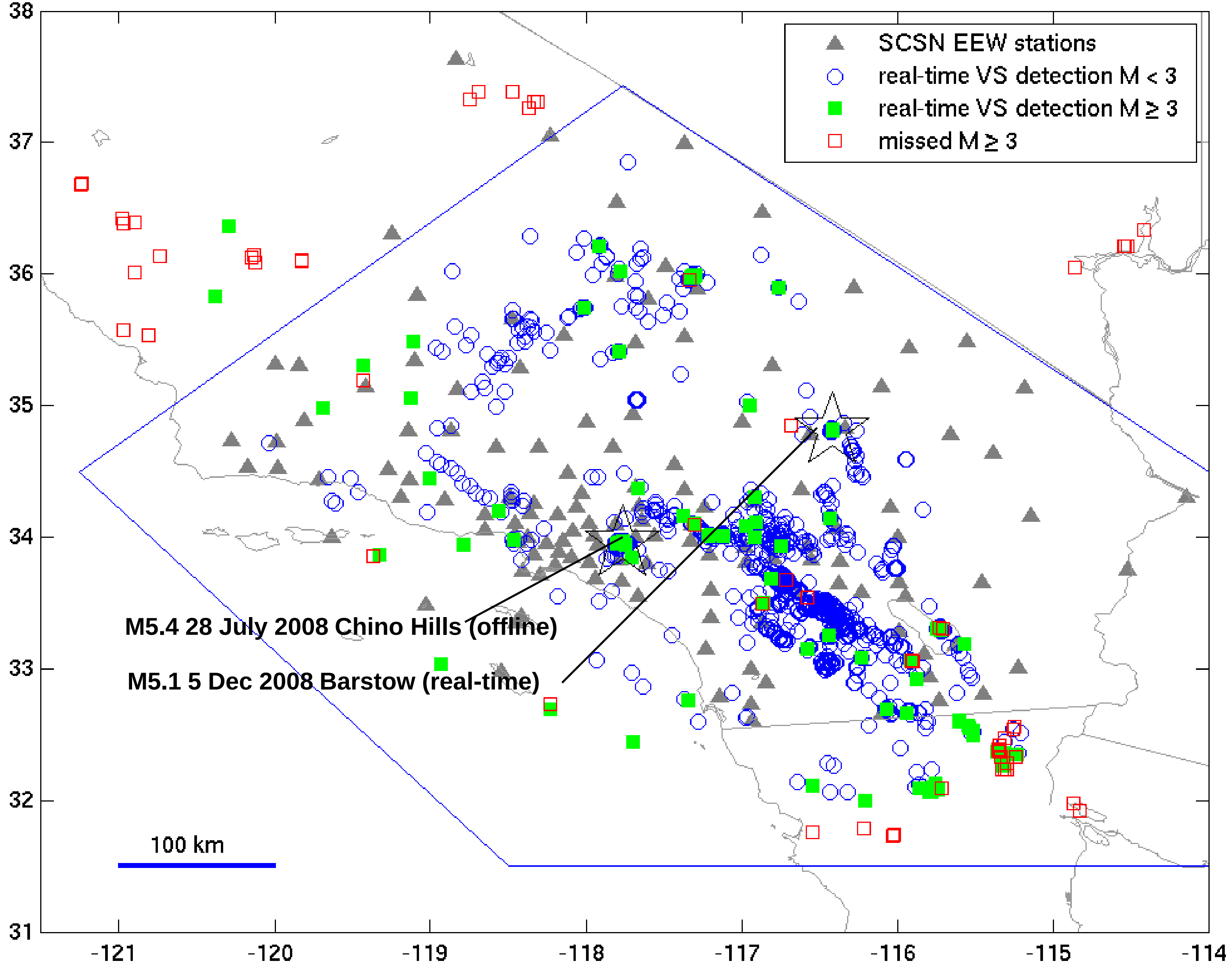
Illustrating Quake Filtering with teleseismic event

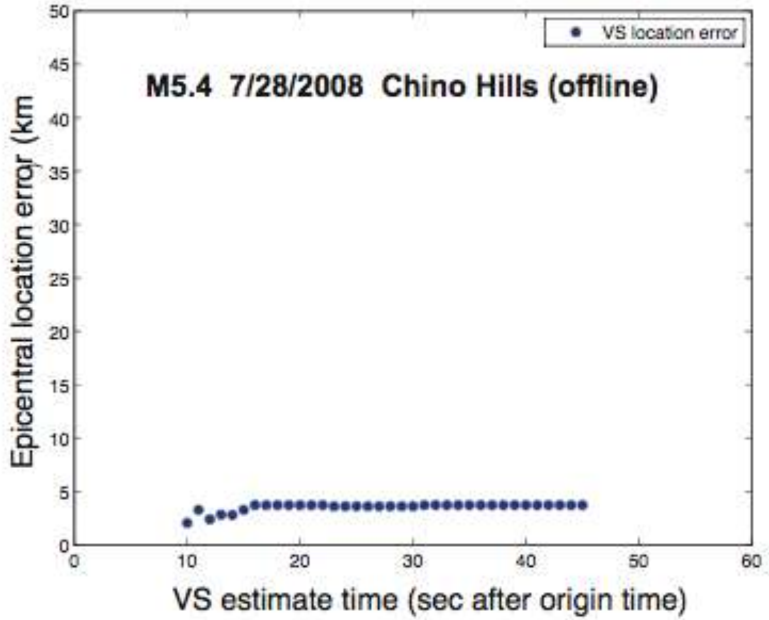


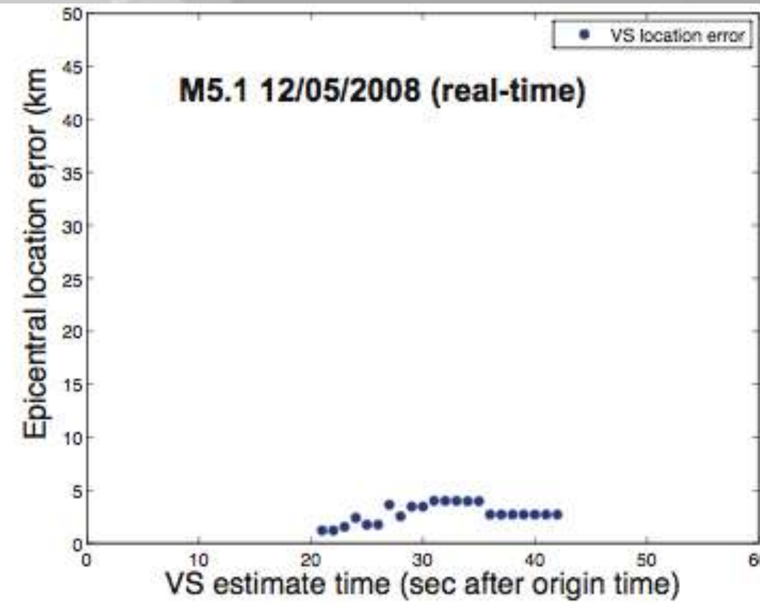
$$d_{thresh} = \frac{R_{\max} + \bar{R}}{2}$$

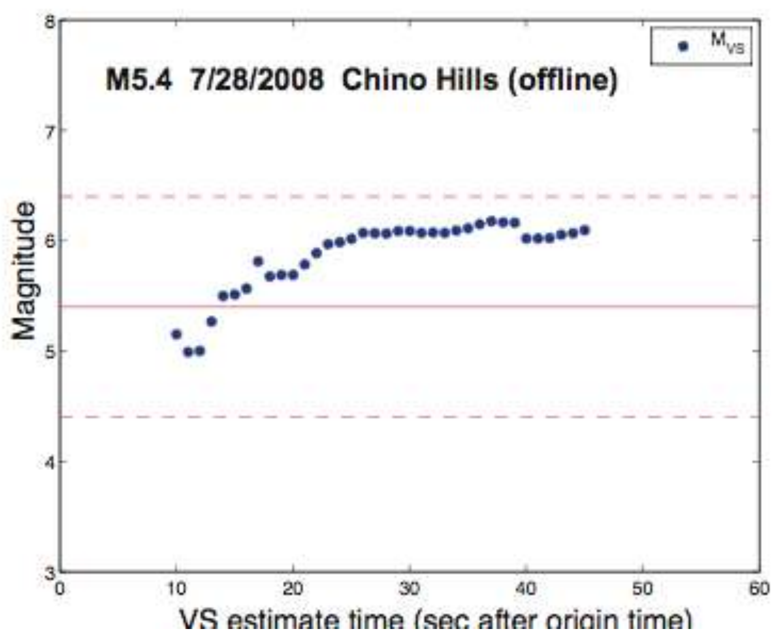
$$\left| M_{ZAD,ave} - M_{VS} \right| \leq 1.5$$

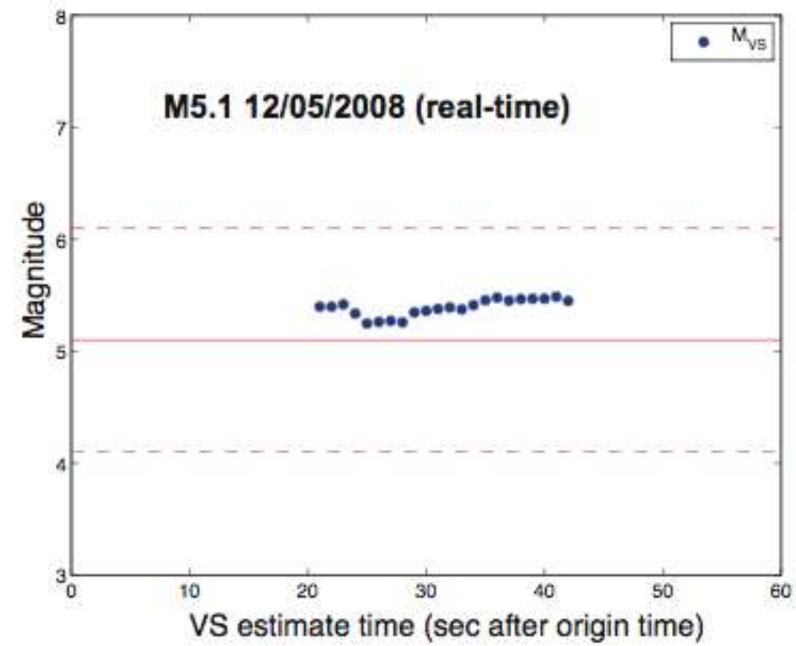
VS Performance 13 July 2008 - 9 April 2009



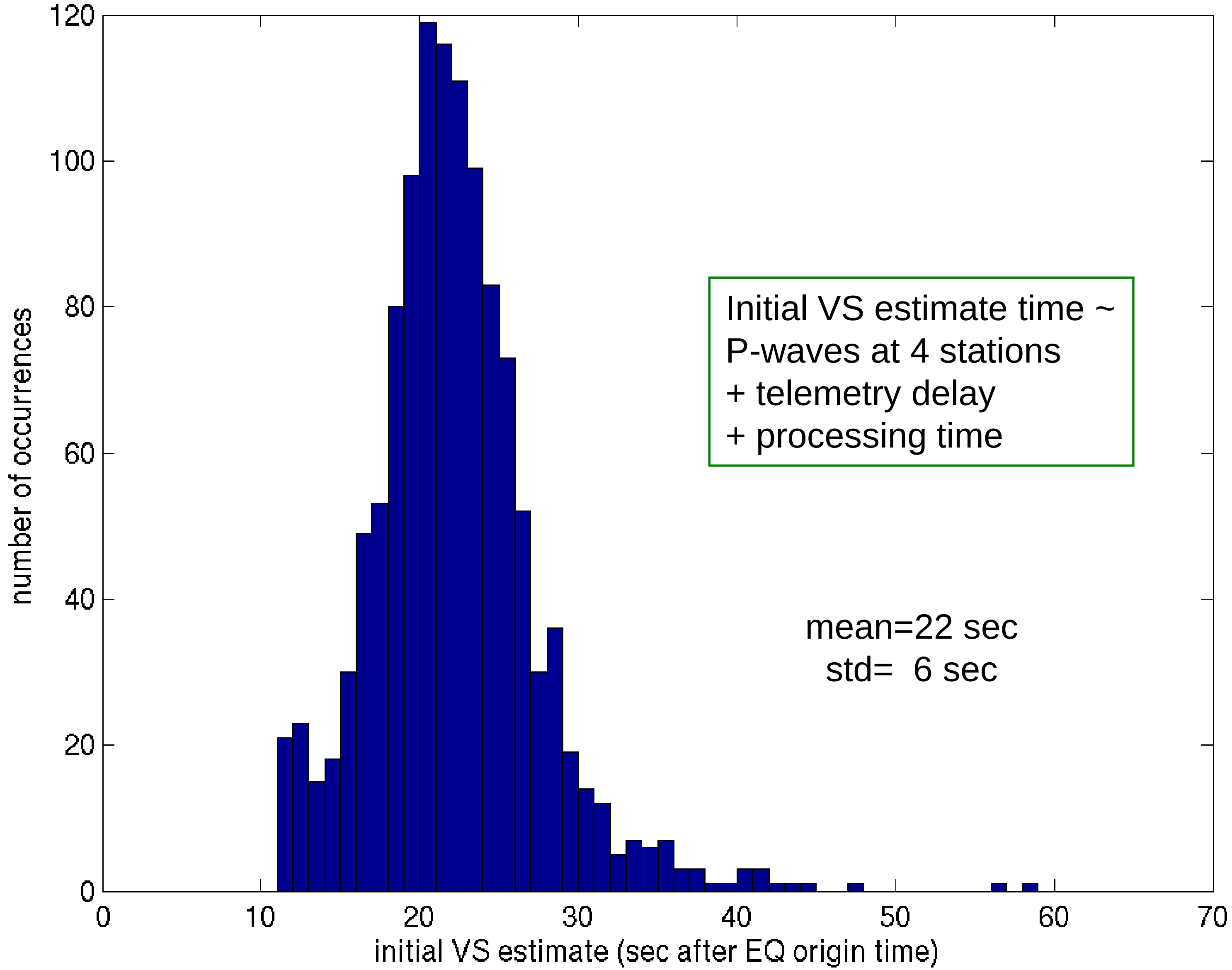

M5.4 7/28/2008 Chino Hills (offline)
VS location error
Epicentral location error (km
VS estimate time (sec after origin time)


M5.1 12/05/2008 (real-time)
VS location error
Epicentral location error (km
VS estimate time (sec after origin time)

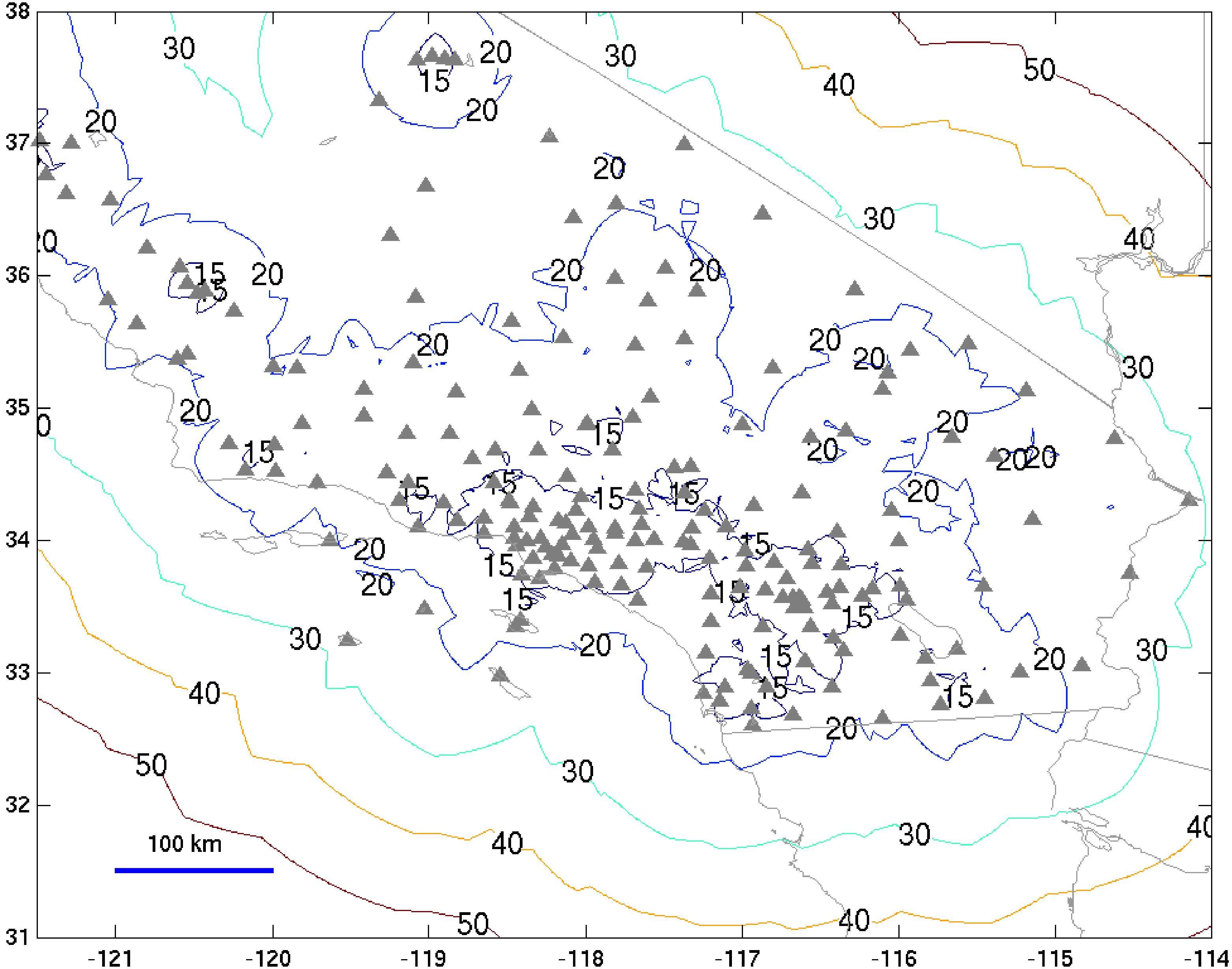

M5.4 7/28/2008 Chino Hills (offline)
M_{VS}
Magnitude
VS estimate time (sec after origin time)


M5.1 12/05/2008 (real-time)
M_{VS}
Magnitude
VS estimate time (sec after origin time)

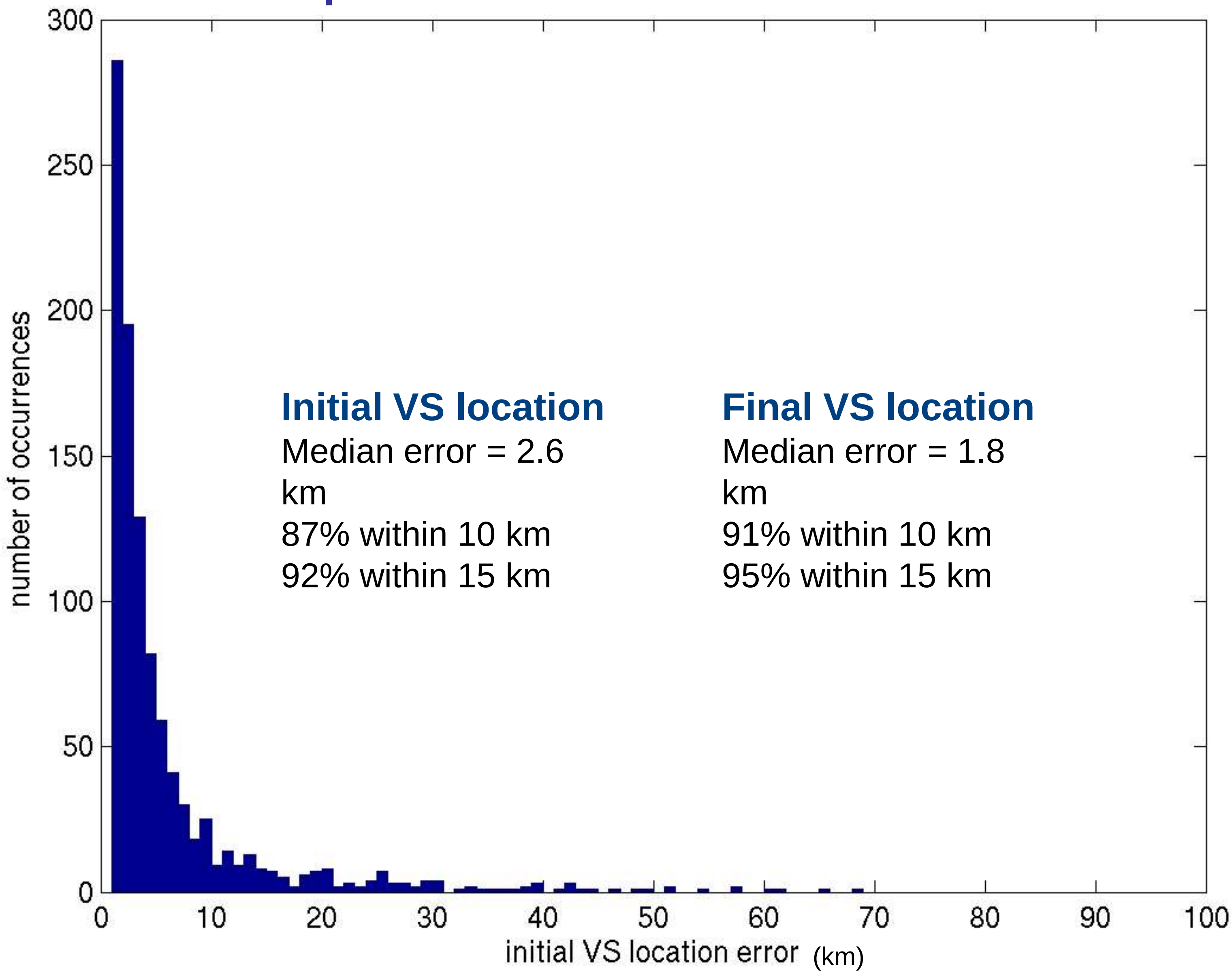
Availability of initial VS estimate



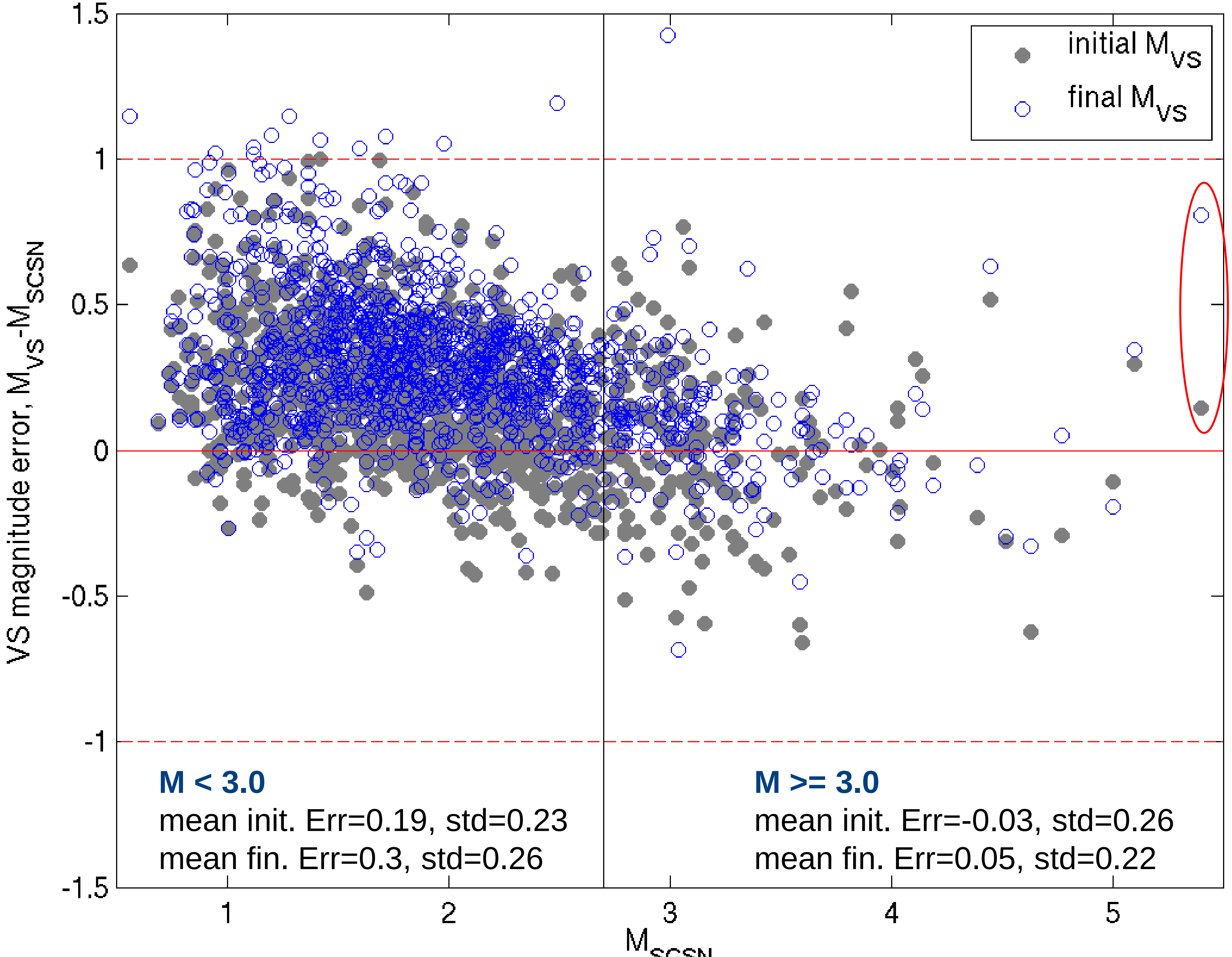
Contours of initial VS estimate time



Epicenter location estimation



Magnitude estimation



Conclusions and Outlook

- Real-time VS installation in Southern California is relatively stable, but needs to be faster for EEW
- Use of prior information and improved pick quality indicators (is a pick from an EQ or not) will allow for faster EEW information
- Accounting for site conditions, implementing Bayes prior will be part of future work

Thank you