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Verification and Validation of Earthquake Ground Motion Simulation in the San Francisco Bay Area with SW4

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June 17, 2021



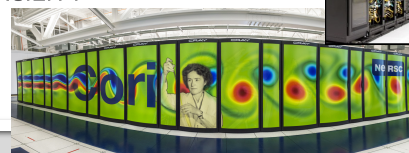
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Thanks to many coworkers over the years



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- Houjun Tang (LBNL)
- Norm Abrahamson (UCB & UCD)
- Albert Kottke (PG&E)
- Rob Graves, Brad Aagaard (USGS)
- **Computing Facilities**
 - Livermore Computing (LLNL)
 - OLCF (Oak Ridge Lab)
 - NERSC (LBNL)



3D Seismic wave propagation simulations are complex, require verification and validation

- Ground motions depend on several factors
 - simulations must all of these get correct
- V&V are crucial to demonstrating accuracy and confidence
 - Key to acceptance of simulated ground motions

Verification

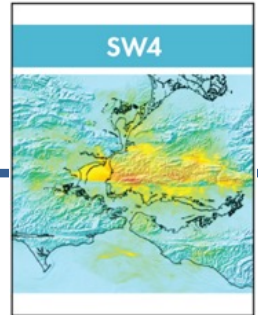
- Numerical method must be accurate
- Computer code must solve the algorithm correctly

Related topic: Performance benchmarking

Validation

- Inputs must be accurate and physically meaningful
 - Source, earthquake rupture
 - Earth model must represent true 3D structure
 - Path propagation effects: crustal, basin, topographic structure
 - Site effects: minimum shear wavespeed, linear and non-linear response

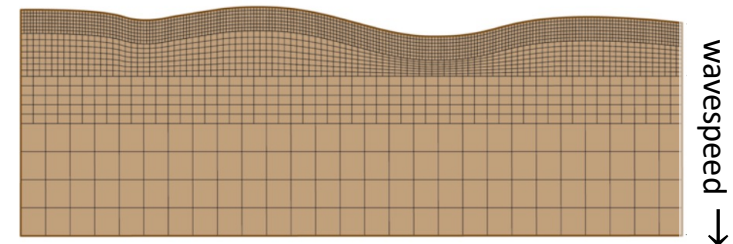
SW4: seismic wave propagation code based on the summation-by-parts FD method



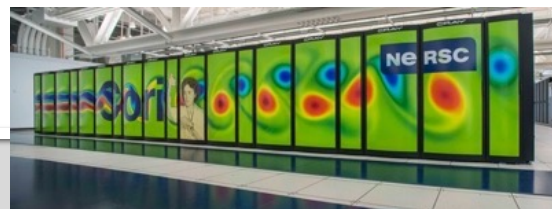
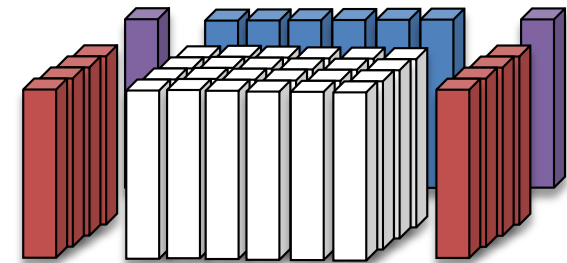
github.com/geodynamics/sw4

- Summation-by-parts FDTD
 - Node-centered, displacement formulation
 - Not velocity-stress staggered grid!
 - Accurate, provably stable & energy conserving
 - Super-grid boundary conditions
- SW4 is 4th order accurate (time & space)
 - Fully 3D material models (iso- and anisotropic)
 - Topography (curvilinear mesh)
 - Mesh refinement in Curv. & Cart. meshes
 - Accurate at boundaries & interfaces, w/ hanging nodes
- Optimized for the hardware
 - Many core CPU's (e.g. NERSC's Cori-II)
 - Hybrid MPI/OpenMP communications
 - GPU's (e.g. Sierra & Summit)
 - RAJA directs work on GPU's

Curvilinear mesh with refinements

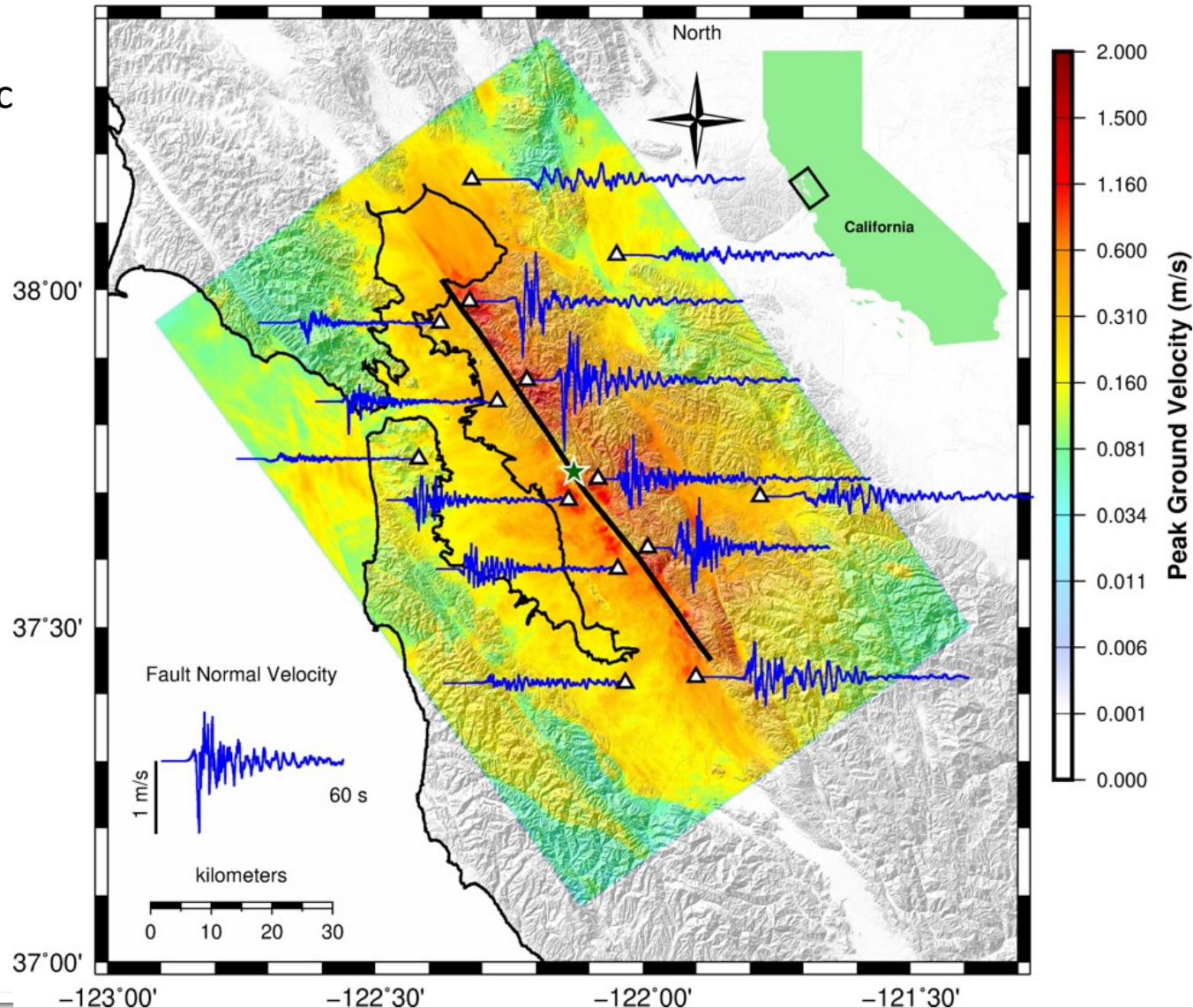
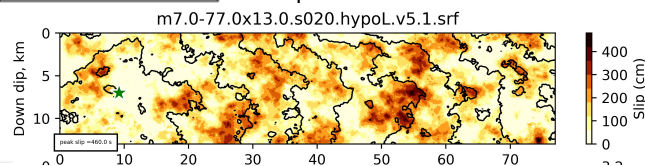
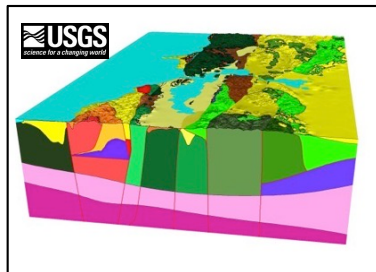
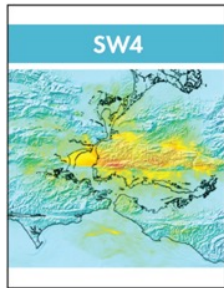


Cartesian mesh with refinements



Our demonstration problem: Hayward Fault M_w 7.0 scenario earthquake

- Regional-scale
- Broadband, fully deterministic
 - $f_{\max} = 10$ Hz @ 8 PPW
 - $h_{\min} = 6.25, 3.125$ m
 - $\lambda_{\min} = 50, 25$ m
 - $v_{S\min} = 500, 250$ m/s
- 3D USGS model (Jachens, Brocher, Aagaard & coworkers)
 - Surface topography
 - Anelasticity, Q
- Graves & Pitarka ruptures



FY20 EQSIM performance evaluation for a M7 Hayward fault SFBA simulation

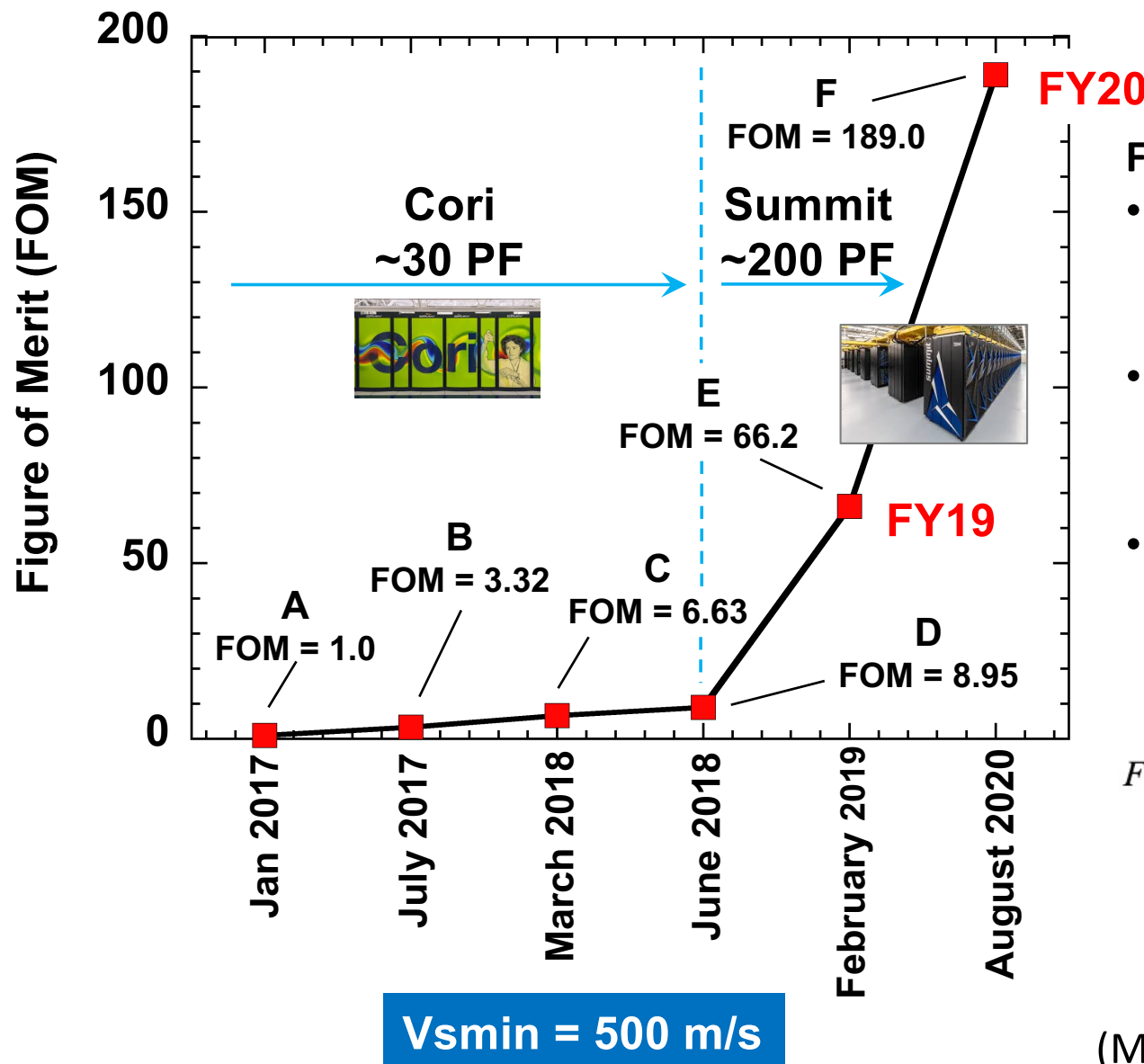


Figure of Merit (FOM)

- Measure of computational efficiency for our demonstration problem
- Normalized to performance at the beginning of the project (2017)
- Maximum resolved frequency, $Freq$, increasing

$$FOM = \frac{(Freq)^4}{(Wall\ Clock\ Time \times 7.6)} \left(\frac{500}{V_{smin}} \right)^4$$

Verification: the accuracy of mathematics and computation of numerical simulations

- Comparison of computed solutions (time-series) against analytic solutions or other computed solutions
- Goal: to obtain accurate and reliable simulations of seismic response and build confidence in solutions
- Criteria for comparing waveforms
 - Pointwise differences with analytic or 1D semi-analytic solution (e.g. reflectivity)
 - Anderson (2004) Goodness-of-fit score of waveform measurements
 - Kristekova et al. (2006) time-frequency phase and envelope misfit
 - wavelet-based decomposition
- A few notable examples:
 - S. M. Day, J. Bielak, D. Dreger, S. Larsen, R. Graves, A. Pitarka, and K. B. Olsen (2003). Test of 3D elastodynamic codes: Lifelines program task 1A02. Technical report, PEER & SCEC.
 - Moczo et al. (2006). Comparison of Numerical Methods for Seismic Wave Propagation and Source Dynamics - the SPICE Code Validation, ESG2006, Grenoble, France
 - Bielak et al. (GJI, 2010) Compares 3 SCEC ShakeOut simulations
 - Chaljub et al. (GJI, 2015) Mygdonian Basin, Greece: stringent methods

SW4 uses the method of manufactured solutions for accuracy & convergence: “twilight mode”

Elastodynamic equations of motion in 3D

$$\begin{aligned}\rho \mathbf{u}_{tt} &= \nabla \cdot \mathcal{T} + \mathbf{F}(\mathbf{x}, t), & \mathbf{x} \text{ in } \Omega, & 0 \leq t \leq T, \\ \mathbf{u}(\mathbf{x}, 0) &= 0, \quad \mathbf{u}_t(\mathbf{x}, 0) = 0, & \mathbf{x} \text{ in } \Omega.\end{aligned}$$

A.1 Method of manufactured solutions

The method of manufactured solutions provides a general way of testing the accuracy of numerical solutions of partial differential equations, including effects of heterogeneous material properties and various boundary conditions on complex geometries. The test scripts can be found in the directory

.../sw4/examples/twilight

In these tests, we take the material properties to be

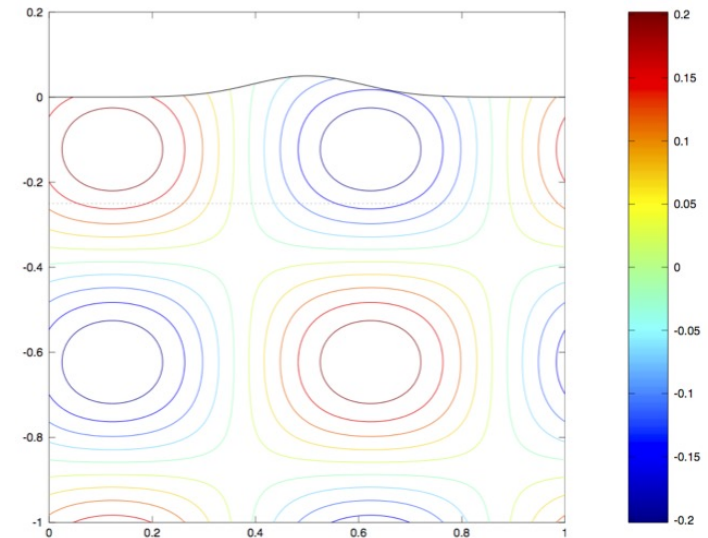
$$\left. \begin{aligned}\rho(x, y, z) &= A_\rho (2 + \sin(\omega_m x + \theta_m) \cos(\omega_m y + \theta_m) \sin(\omega_m z + \theta_m)), \\ \mu(x, y, z) &= A_\mu (3 + \cos(\omega_m x + \theta_m) \sin(\omega_m y + \theta_m) \sin(\omega_m z + \theta_m)), \\ \lambda(x, y, z) &= A_\lambda (2 + \sin(\omega_m x + \theta_m) \sin(\omega_m y + \theta_m) \cos(\omega_m z + \theta_m)).\end{aligned} \right\} \begin{array}{l} \text{3D} \\ \text{Earth} \\ \text{model} \end{array}$$

The internal forcing, boundary forcing and initial conditions are chosen such that the exact (manufactured) solution becomes¹

$$\begin{aligned}u_e(x, y, z, t) &= \sin(\omega(x - c_e t)) \sin(\omega y + \theta) \sin(\omega z + \theta), \\ v_e(x, y, z, t) &= \sin(\omega x + \theta) \sin(\omega(y - c_e t)) \sin(\omega z + \theta), \\ w_e(x, y, z, t) &= \sin(\omega x + \theta) \sin(\omega y + \theta) \sin(\omega(z - c_e t)).\end{aligned}$$

The values of the material parameters $(\omega_m, \theta_m, A_\rho, A_\lambda, A_\mu)$ and the solution parameters (ω, θ, c_e) , can be modified in the input script. Since the exact solution is known, it is possible to evaluate the error in the numerical solution. By repeating the same test on several grid sizes, it is possible to establish the convergence rate of the numerical method.

Computed response



- Compare computed and analytic solutions
- Compute norm for different grid spacing
- Measure convergence

Chosen response

From SW4 User Guide, Petersson & Sjogreen, 2021

Recent porting of SW4 to GPU/CPU platforms requires verification of code: 0-5 Hz HF M7

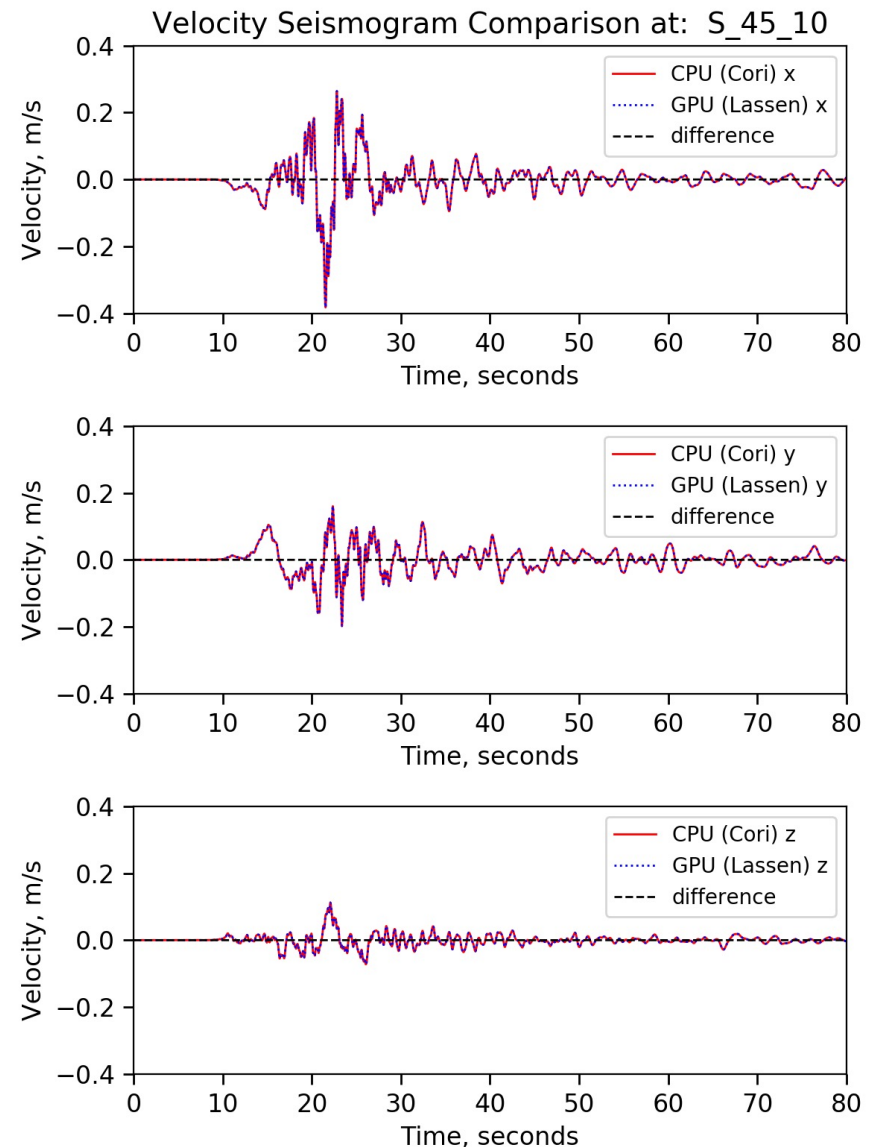
SW4 uses RAJA C++ package to manage work on GPU

SW4-RAJA uses the same source code as SW4 and a machine-specific profile to know how to offload compute intensive loops to GPU

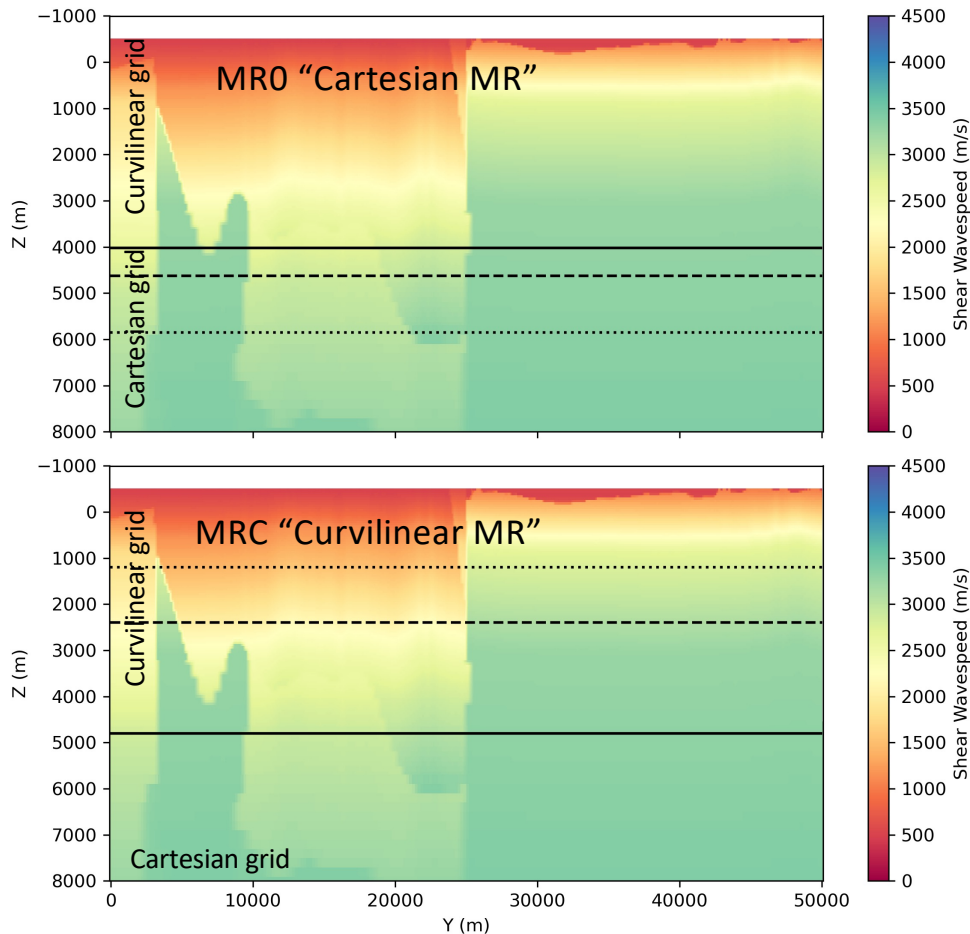
Hayward Fault, M_w 7.0, resolved 0-5 Hz

Use point-wise differences

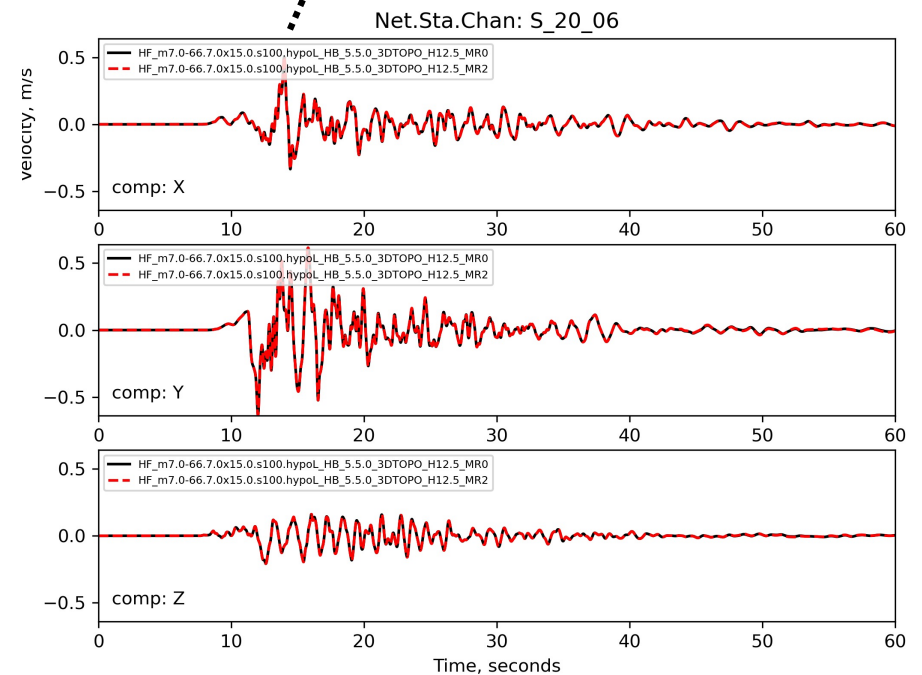
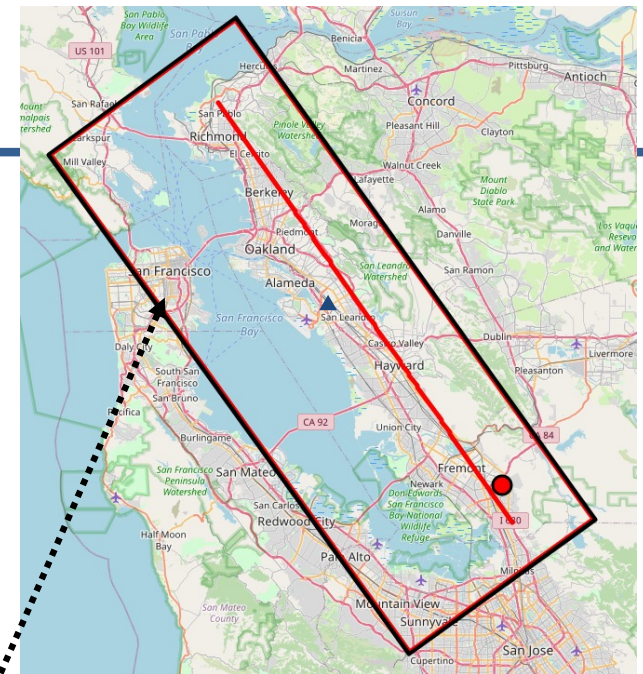
- We get excellent agreement
- Waveforms agree to 10^{-7}
- 3-component waveforms at 2301 sites



Verification of mesh refinement cases



Run	MR Type	Npoints ratio	Run time ratio
MR0	Cart	1.0	1.0
MRC	Curv	0.386	0.44

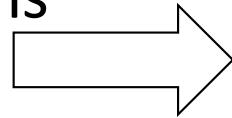


Validation: the evaluation of the physical accuracy of numerical simulation

- Comparison of computed solutions against empirical data
 - Tests inputs: source and Earth model with a verified code
- Goal: to ensure that simulation predictions are realistic and consistent with empirical observations, to build confidence
- Moderate (M_w 3-5) earthquakes provide data sets for testing 3D Earth models in California
 - A few examples:
 - Rodgers et al., (BSSA, 2008) SFBA moderate events, waveforms
 - Kim et al. (BSSA, 2021) SFBA moderate events, intensities
 - Olsen & Mayhew (SRL, 2010) 2008 Chino Hills GOF
 - Taborda & Bielak (BSSA, 2013) 2008 Chino Hills
 - Hirakawa and Aagaard (SSA, 2021) update(s) of USGS SFBA model
- Large scenario events without empirical data
 - Compare with ground motion models (GMM's, GMPE's) or data from similar events

Earlier evaluation of the USGS 3D model using moderate events & long-periods (33-4 sec.)

Events, BB (BK) Stations
& Paths



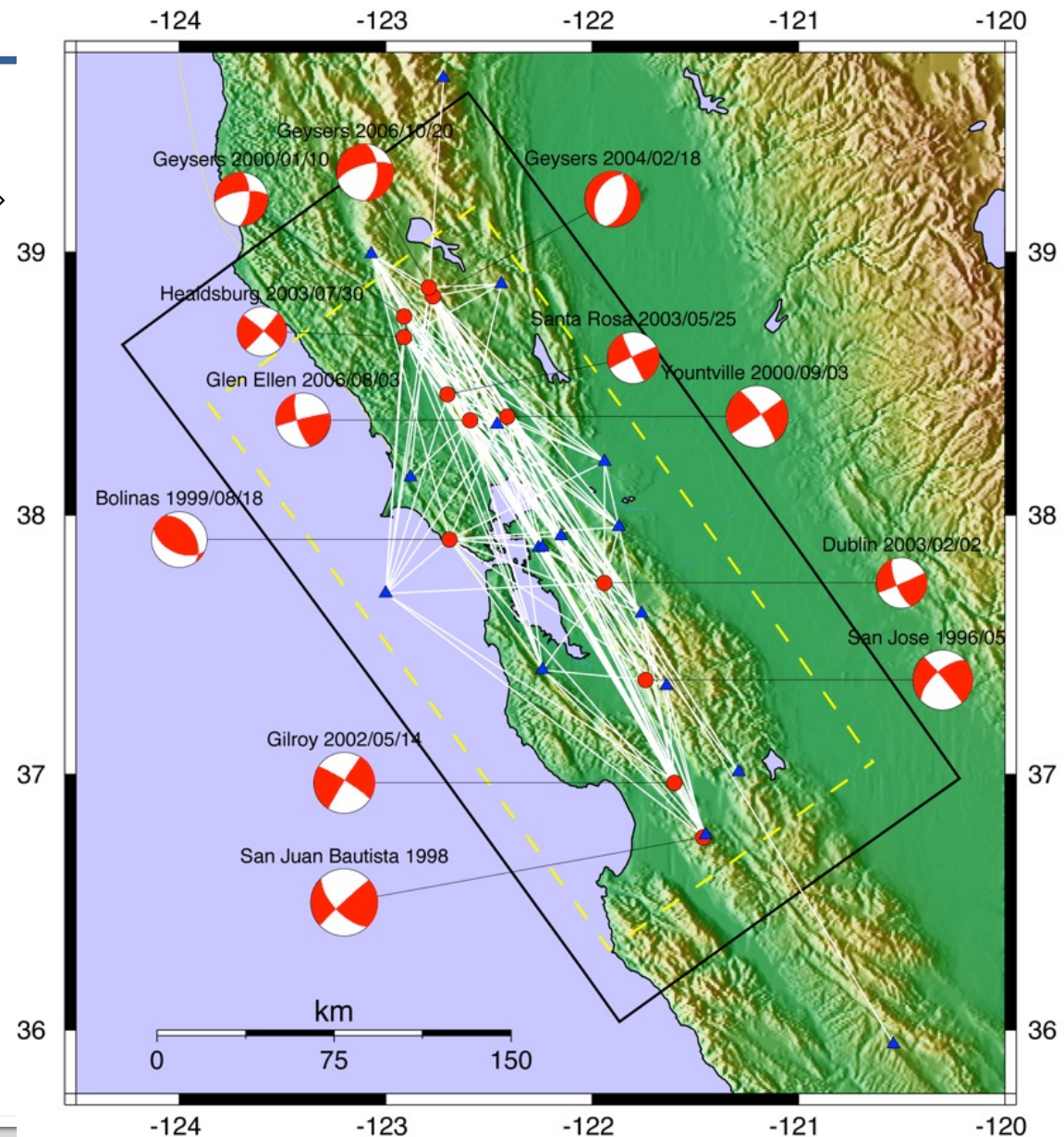
Moderate (M_W 4-5)

12 events (circles)

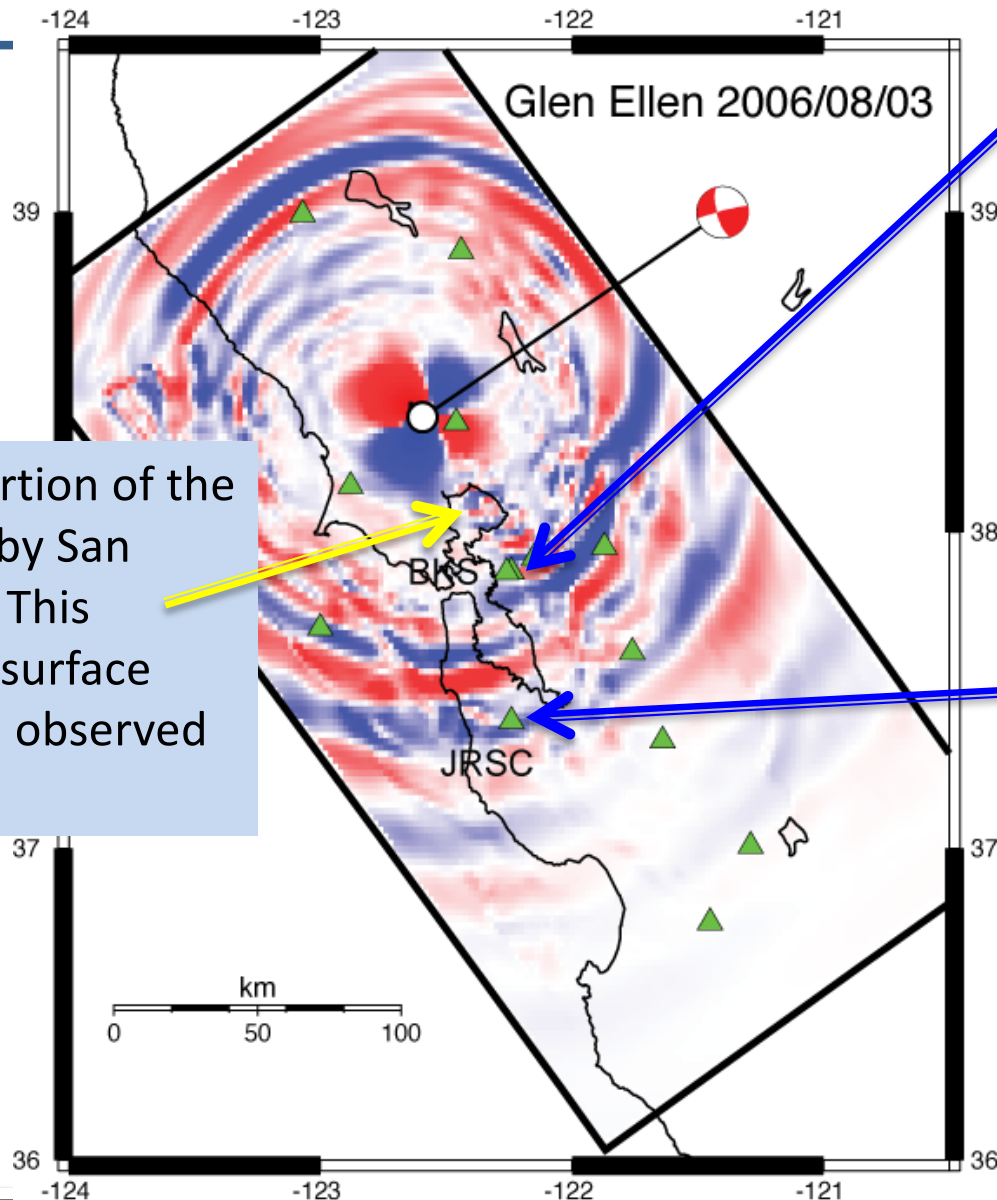
15 stations (triangles)

Coverage uneven, many
paths along Hayward Fault

Rodgers et al. (BSSA, 2008)

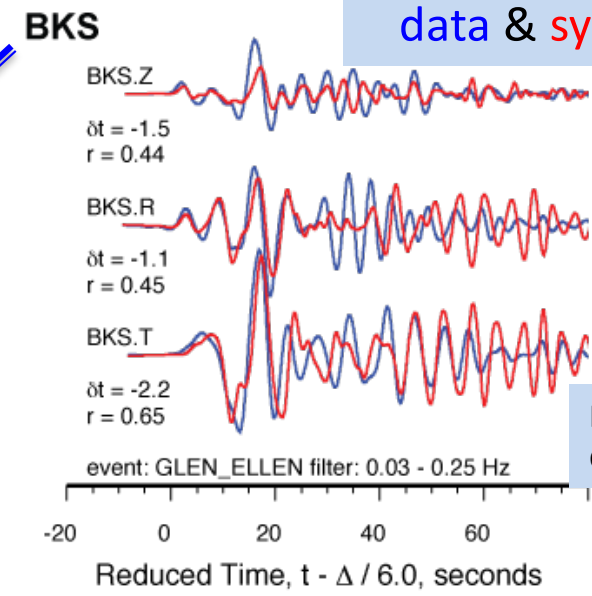


Long-period waveform comparisons for August 3 2006, Glen Ellen Earthquake

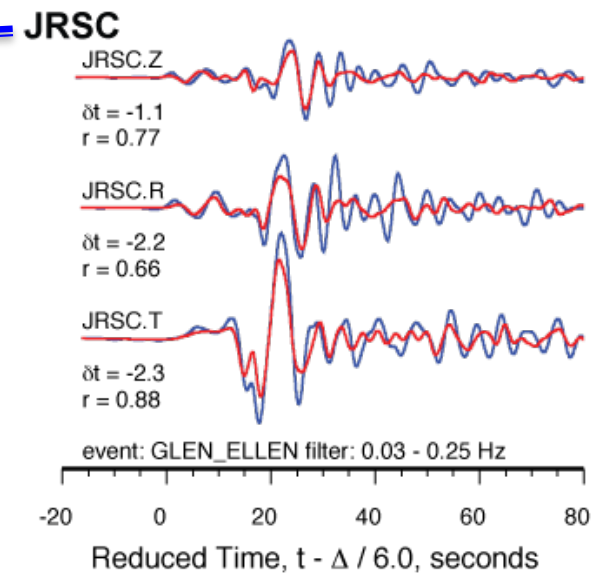


Note distortion of the wavefield by San Pablo Bay. This generates surface wave coda observed at BKS.

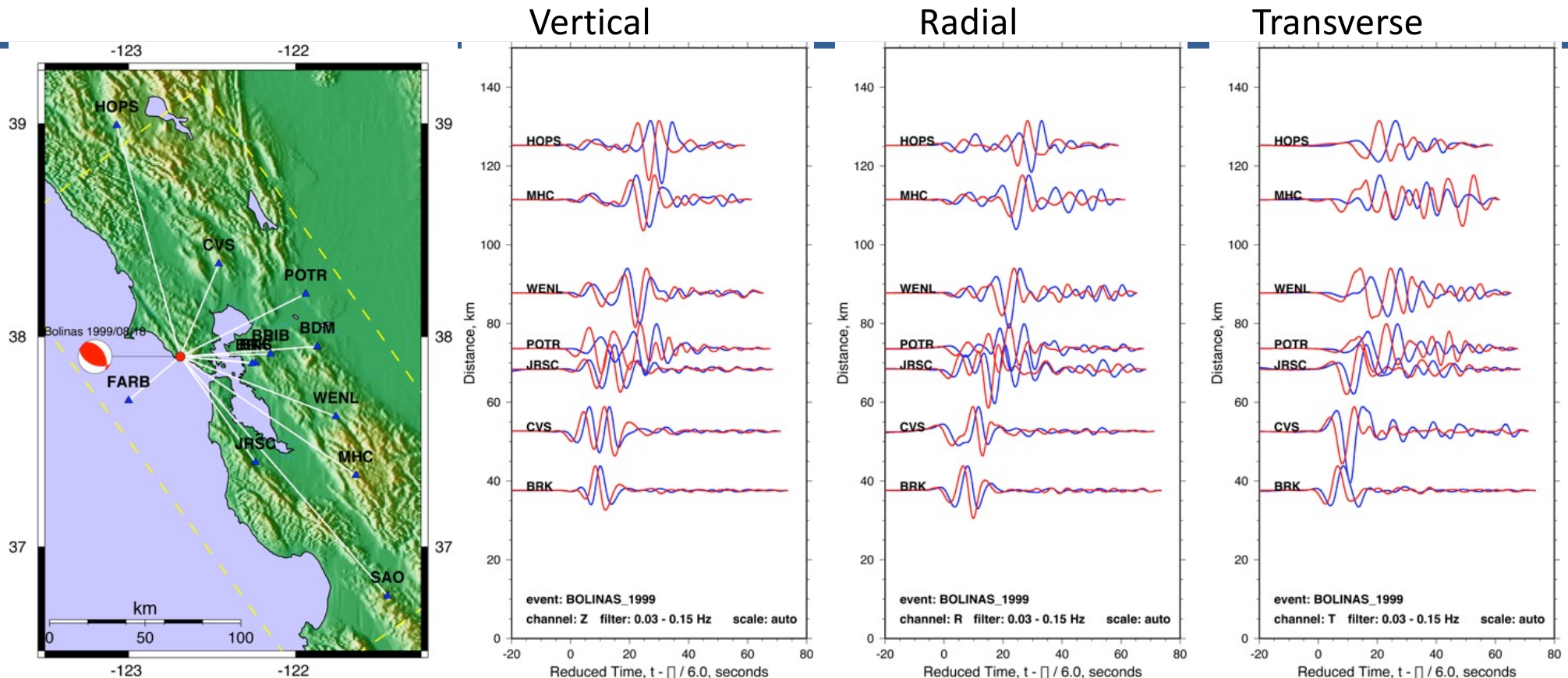
Shifted and aligned
data & **synthetic**



Note long duration



Long-period waveform comparisons for Aug. 18 1999, Bolinas Earthquake



Frequencies = 0.03-0.15 Hz
Periods = 7-33 seconds

Delays increase with distance, suggests systematic bias
Note amplitudes are well matched
- see Kim, Dreger & Larsen, BSSA (2010)
Data such these are useful for waveform tomography

More recent effort
looking at shorter
periods: 1-32 sec.

8 events
 M_W 4.4-5.5
1998-present

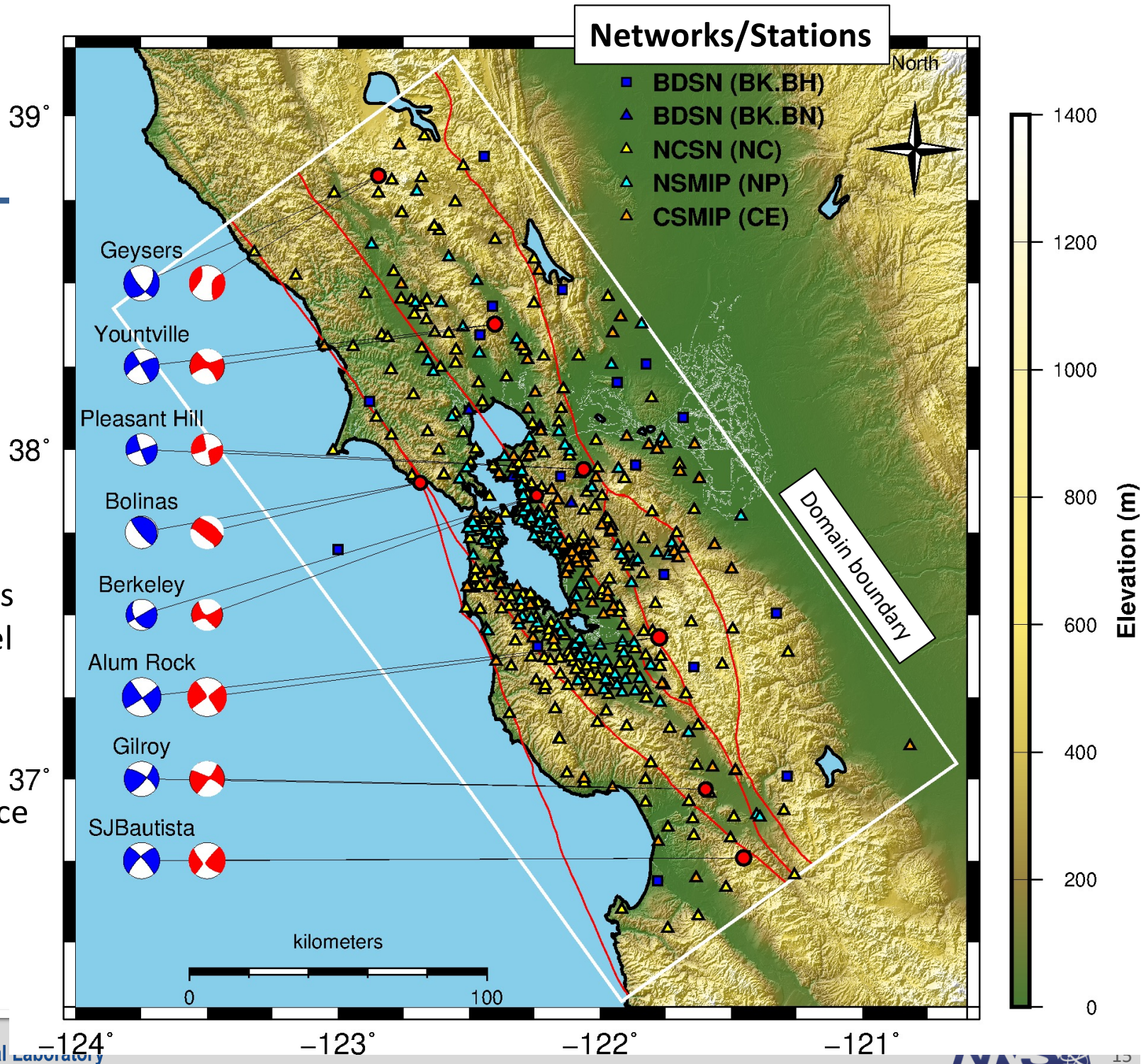
With strong-motion
sites

SW4 domain same as
USGS Detailed model

Earth models:

- 3D + topography
- 1D flat free-surface

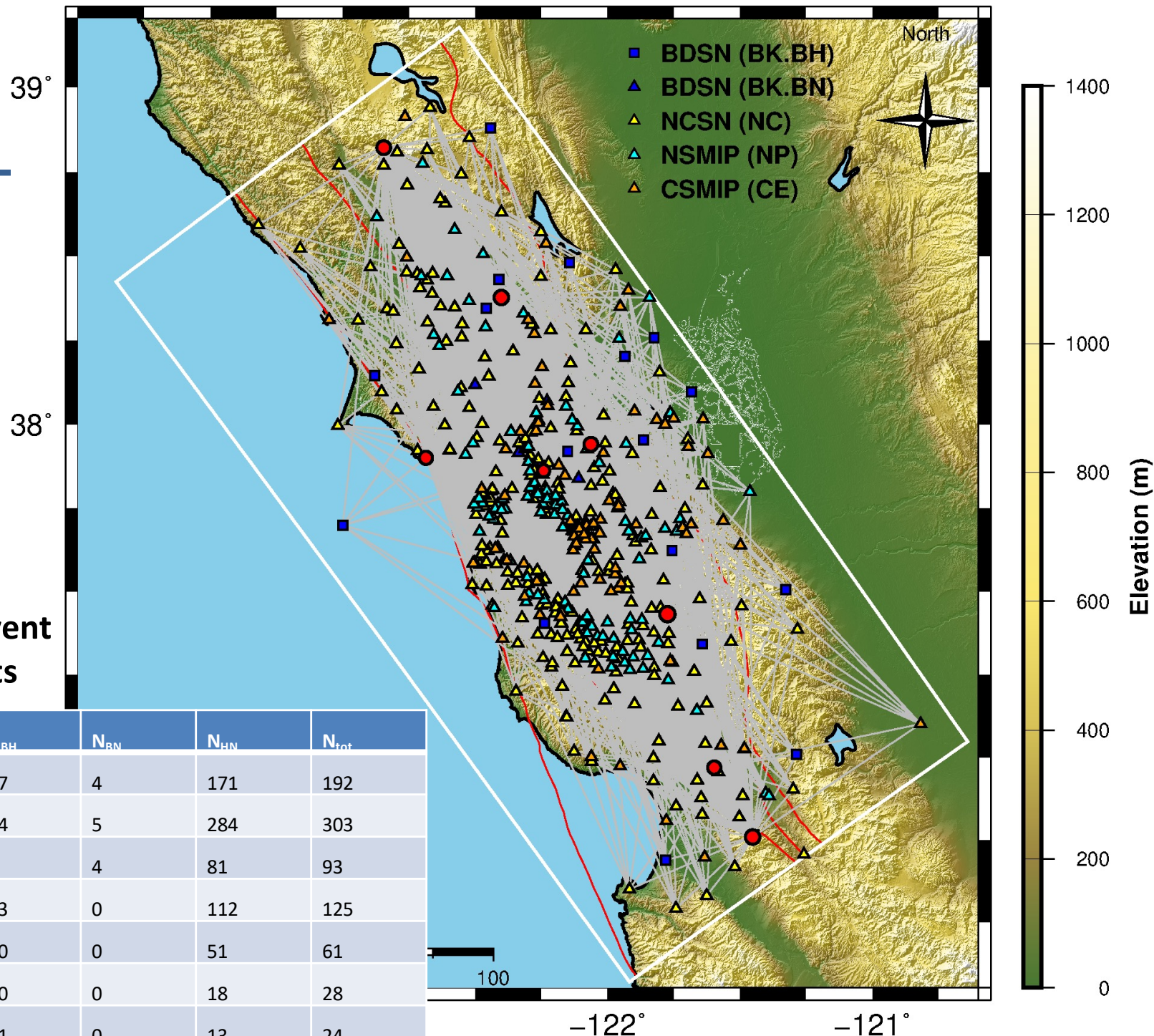
DC and MT focal
mechanisms



Path Map

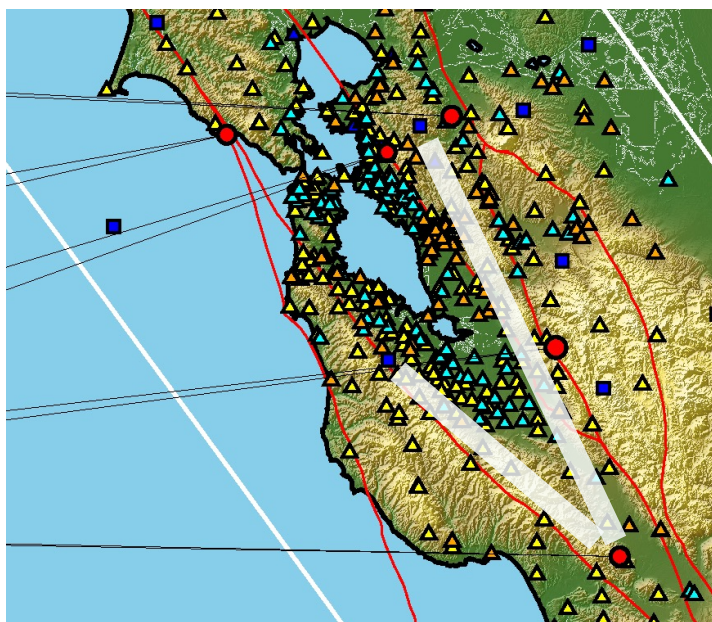
Number of paths/event
839 total for 8 events

Event	Event ID	N _{BH}	N _{BN}	N _{HN}	N _{tot}
Pleasant Hill	73291880	17	4	171	192
Berkeley	72948801	14	5	284	303
Geysers	72737985	8	4	81	93
Alum Rock	40204628	13	0	112	125
Gilroy	21254601	10	0	51	61
Yountville	21123384	10	0	18	28
Bolinas	21044694	11	0	13	24

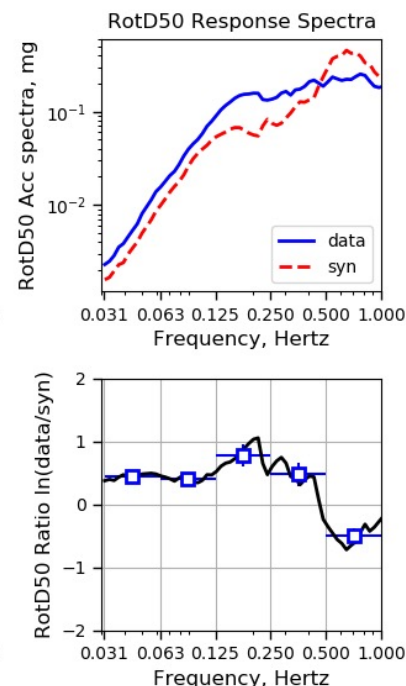
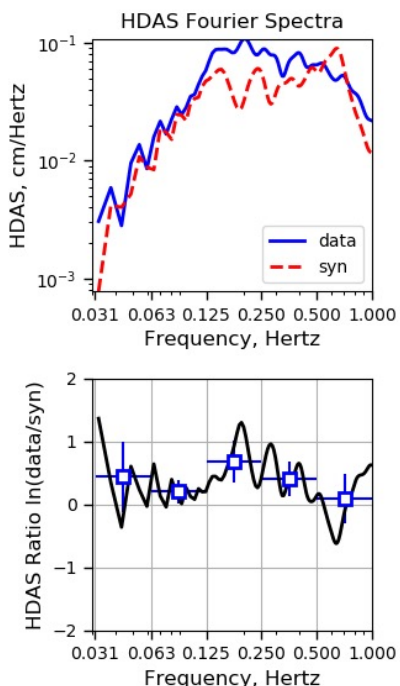
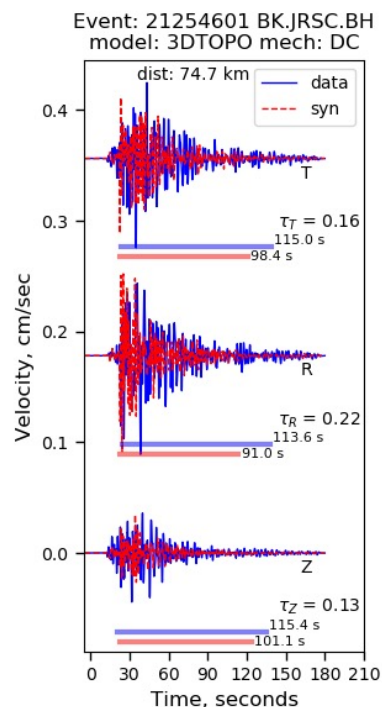
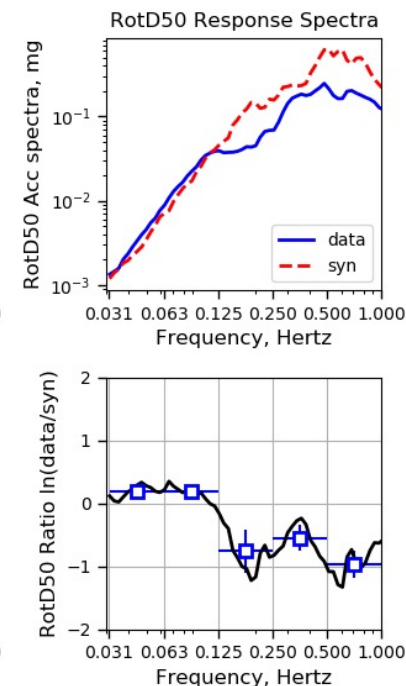
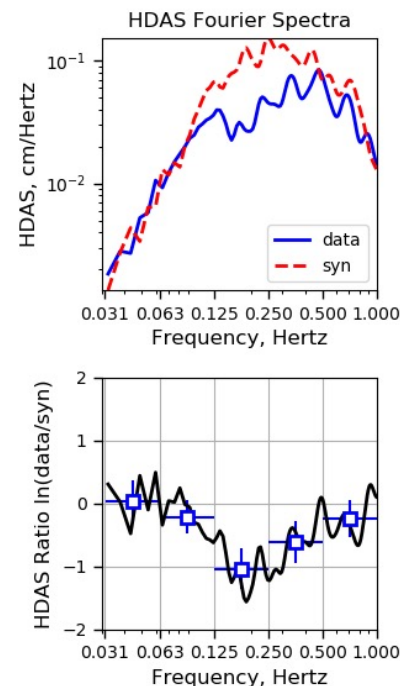
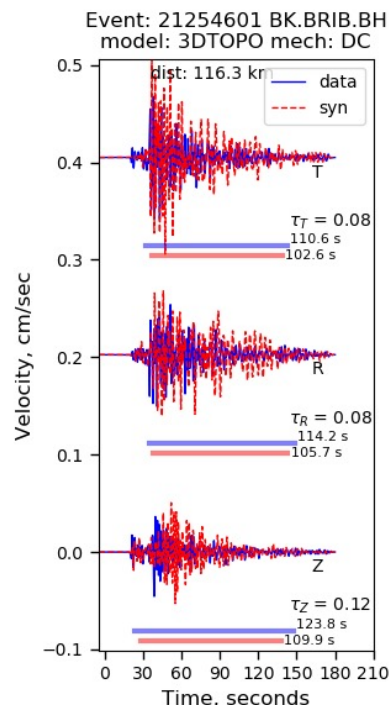


Gilroy 2002-05-14 Mw 4.9 to BDSN broadband stations

Path through East Bay Hills:
USGS 3D model produces higher
amplitudes than observed

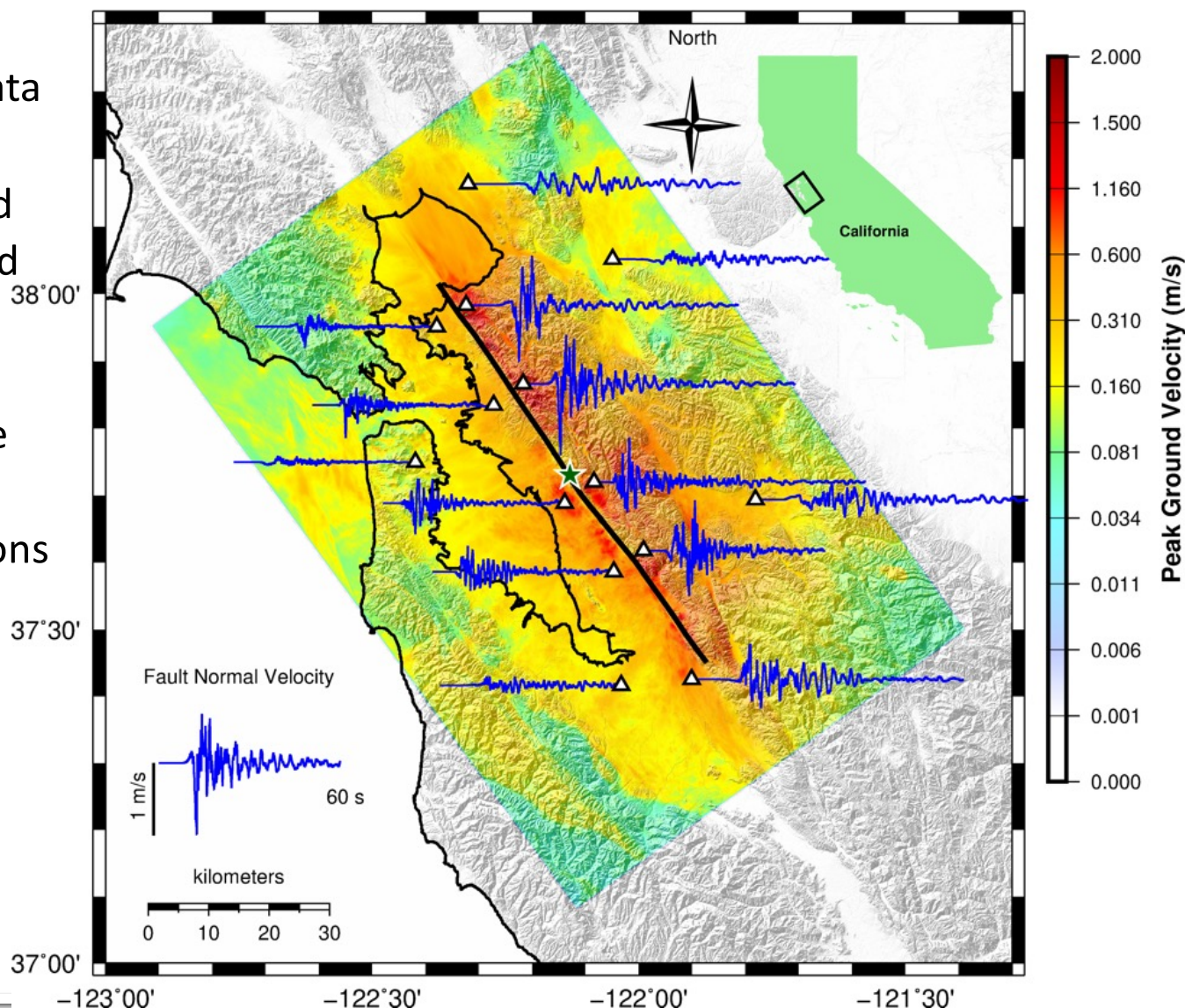


Path through Santa Cruz Mtns:
USGS 3D model produces
relatively unbiased amplitudes

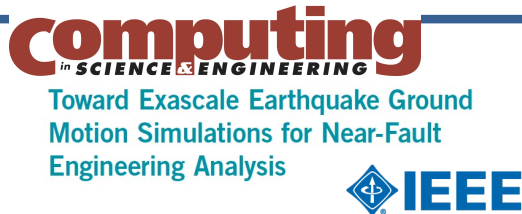


Our demonstration problem: Hayward Fault M_w 7.0 scenario earthquake

- In the absence of empirical data for scenario earthquakes,
- we compare simulated ground motion intensities with ground motion models
- Recall that we are pushing the limits of fully deterministic scenario earthquake simulations to $f_{\max} = 10$ Hz
- This potentially exposes shortcomings of our:
 - source model
 - $v_{\text{Smin}} = 500$ m/s
 - linear wave propagation



Several recent papers focus on simulations of M7 Hayward Fault scenario earthquakes



Hans Johansen | Lawrence Berkeley National Laboratory
Arthur Rodgers and N. Anders Petersson | Lawrence Livermore National Laboratory
David McCallen | Lawrence Berkeley National Laboratory
Bjorn Sjogreen | Lawrence Livermore National Laboratory
Mamun Miah | Lawrence Berkeley National Laboratory

Application modernization for massively parallel time-domain simulations of earthquake ground motion in 3D models is increasing application resolution and providing ground motion estimates for critical infrastructure risk evaluations. Improvements to the geophysics application code SW4 algorithms, developed while porting the code to systems at Lawrence Berkeley National Laboratory, revealed that reorganizing operation order can improve performance for massive problems.

Broadband (0–5 Hz) Fully Deterministic 3D Ground-Motion Simulations of a Magnitude 7.0 Hayward Fault Earthquake: Comparison with Empirical Ground-Motion Models and 3D Path and Site Effects from Source Normalized Intensities

by Arthur J. Rodgers, N. Anders Petersson, Arben Pitarka, David B. McCallen, Bjorn Sjogreen, and Norman Abrahamson

ABSTRACT

We report on high-performance computing (HPC) fully deterministic simulation of ground motions for a moment magnitude (M_w) 7.0 scenario earthquake on the Hayward fault resolved to 5 Hz using the SW4 finite-difference code. We computed motions obeying physics-based 3D wave propagation at a regional scale with an M_w 7.0 kinematic rupture model generated following Graves and Pitarka (2016). Both plane-layered (1D) and 3D Earth models were considered, with 3D subsurface material properties and topography interpolated from a model of the U.S. Geological Survey (USGS). The resulting ground-motion intensities cover a broader frequency range than typically considered in regional-scale simulations, including higher frequencies relevant for engineering analysis of structures. Median intensities for sites across the domain are within the reported between-event uncertainties (σ) of ground-motion models (GMMs) across spectral periods 0.2–10 s (frequencies 0.1–5 Hz). The within-event standard deviation ϕ of ground-motion intensity measurement residuals range 0.2–0.5 natural log units with values consistently larger for the 3D model. Source-normalized ratios of intensities (3D/1D) reveal patterns of path and site effects that are correlated with known geologic structure. These results demonstrate that earthquake simulations with fully deterministic wave propagation in 3D Earth models on HPC platforms produce broadband ground motions with median and within-event aleatory variability consistent with empirical models. Systematic intensity variations for the 3D model caused by path and site effects suggest that these epistemic effects can be estimated and removed to reduce variation in site-specific hazard estimates.

This study motivates future work to evaluate the validity of the USGS 3D model and investigate the development of path and site corrections by running more scenarios.

Supplemental Content: Animation of ground motions from the 3D subsurface model with topography.

INTRODUCTION

The Hayward fault (HF) dominates seismic hazard in the eastern San Francisco Bay area (SFBA), also referred to as the “East Bay.” Currently, the HF and its northern extension, the Rodgers Creek fault, represent the most likely fault in the SFBA to rupture with a moment magnitude (M_w) 6.7 or greater in the next 30 yrs according to the Uniform California Earthquake Rupture Forecast, Version 3 (Field and 2014 Working Group on California Earthquake Probabilities, 2015). Figure 1 shows the area of interest for this study. The HF is capable of earthquakes up to M_w 7.0 and presents significant ground-motion hazard to the heavily populated East Bay cities, including Oakland, Berkeley, Hayward, and Fremont. The last major HF rupture occurred on 21 October 1868 with an M_w 6.8–7.0 event (Toppo et al., 1981, 2002; Rubin, 1999). Instrumental observations of this earthquake are not available; however, historical triangulation data inform the moment magnitude and fault length (7.0 and 52 km, respectively; Yu and Siegel, 1996). Reported intensities were used to create a ShakeMap for the 1868 event (Boatwright and Bando, 2008). Modified Mercalli intensities of VII–IX



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Key Points:
• Efficient high-performance computing accelerates greatly increase ground motion frequencies of a Hayward Fault earthquake
• Path effects result in higher motions on the eastern side of the fault compared to the western side
• Simulated intensities are consistent with Ground Motion Prediction Equations, but path and site effects for the 3D model lead to greater scatter

Supporting Information:
• Supporting Information S1

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Broadband (0–4 Hz) Ground Motions for a Magnitude 7.0 Hayward Fault Earthquake With Three-Dimensional Structure and Topography

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Abstract We performed fully deterministic broadband (0–4 Hz) high-performance computing ground motion simulations of a magnitude 7.0 scenario earthquake on the Hayward fault (HF) in the San Francisco Bay Area of Northern California. Simulations consider average one-dimensional (1-D) and three-dimensional (3-D) anelastic structure with flat and topographic free surfaces. Ground motion intensity measures (GMMs) for the 3-D model display dramatic differences across the HF due to geologic heterogeneity, with low wave speeds east of the HF amplifying motions. The median GMMs agree well with Ground Motion Prediction Equations (GMPEs); however, the 3-D model generates more scatter than the 1-D model. Ratios of 3-D/1-D GMMs from the same source allow isolation of path and site effects for the 3-D model. These ratios show remarkably similar trends as site-specific factors for the GMPE predictions, suggesting that wave propagation effects in our 3-D simulations are on average consistent with empirical data.

Plain Language Summary With the use of powerful supercomputers and an efficient numerical method, modeling of ground shaking for a magnitude 7.0 earthquake on the Hayward fault results in more realistic motions than previously achieved. The model includes the current best representation of the Earth topology and surface topography to compute seismic wave ground shaking throughout the region. Shaking intensity shows differences across the Hayward fault that arise from rocks of different geologic origin. On average, results are consistent with models based on actual recorded earthquake motions from around the world. This study shows that powerful supercomputing can be used to calculate earthquake shaking with more realism than previously obtained.

Regional-Scale 3D Ground-Motion Simulations of M_w 7 Earthquakes on the Hayward Fault, Northern California Resolving Frequencies 0–10 Hz and Including Site-Response Corrections

Arthur J. Rodgers^{1,2}, Arben Pitarka³, Ramesh Pankajakishan⁴, Bjorn Sjogreen⁵, and N. Anders Petersson⁶

ABSTRACT

Large earthquake ground-motion simulations in 3D Earth models provide constraints on site-specific shaking intensities but have suffered from limited frequency resolution and ignored site response in soft soils. We report new regional-scale 3D simulations for moment magnitude 7.0 scenario earthquakes on the Hayward fault, northern California with SW4. Simulations resolved significantly broader band frequencies (0–10 Hz) than previous studies and represent the highest resolution simulations for any such earthquake to date. Seismic waves were excited by a kinematic rupture following Graves and Pitarka (2016) and obeyed wave propagation in a 3D Earth model with topography from the U.S. Geological Survey (USGS) assuming a minimum shear wave speed, $V_{s,min}$, of 500 m/s. We corrected motions for linear and nonlinear site response for the shear wave speed, V_s , from the USGS 3D model, using a recently developed ground-motion model (GMM) for Fourier amplitude spectra (Bozdogan and Abrahamson, 2016, 2018). At soft soil locations subjected to strong shaking, the site-corrected intensities reflect the competing effects of linear amplification by low V_s material, reduction of stiffness during nonlinear deformation, and damping of high frequencies. Sites with near-surface V_s of 500 m/s or greater require no linear site correction but can experience amplitude reduction due to nonlinear response. Averaged over all sites, we obtained reasonable agreement with empirical ergodic median GMMs currently used for seismic hazard and design ground motions (less than 1), with marked improvement at soft sedimentary sites. At specific locations, the simulated shaking intensities show systematic differences from the GMMs that reveal path and site effects not captured in these ergodic models. Results suggest how next generation regional-scale earthquake simulations can provide higher spatial and frequency resolution while including effects of soft soils that are commonly ignored in scenario earthquake ground-motion simulations.

KEY POINTS

- Advanced methods and computing enable high-resolution regional-scale 3D earthquake ground-motion simulations.
- Average site-corrected intensities for M_w 7 Hayward fault ruptures are in agreement with ergodic models.
- Site-specific intensities reveal variations related to wave propagation in the 3D Earth (path and site effects).

Supplemental Material:

INTRODUCTION

Seismic hazard analyses typically rely on ground-motion models (GMMs) based on empirical data and constraints from analytical seismological and geotechnical (site-response) models.

For example, GMMs from the Pacific Earthquake Engineering Research Center Next Generation Attenuation-West (NGA-West2) Project (Abrahamson et al., 2014; Boore et al., 2014).

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Research Paper



Earthquake Spectra

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EQSIM—A multidisciplinary framework for fault-to-structure earthquake simulations on exascale computers part I: Computational models and workflow

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Research Paper



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EQSIM—A multidisciplinary framework for fault-to-structure earthquake simulations on exascale computers, part II: Regional simulations of building response

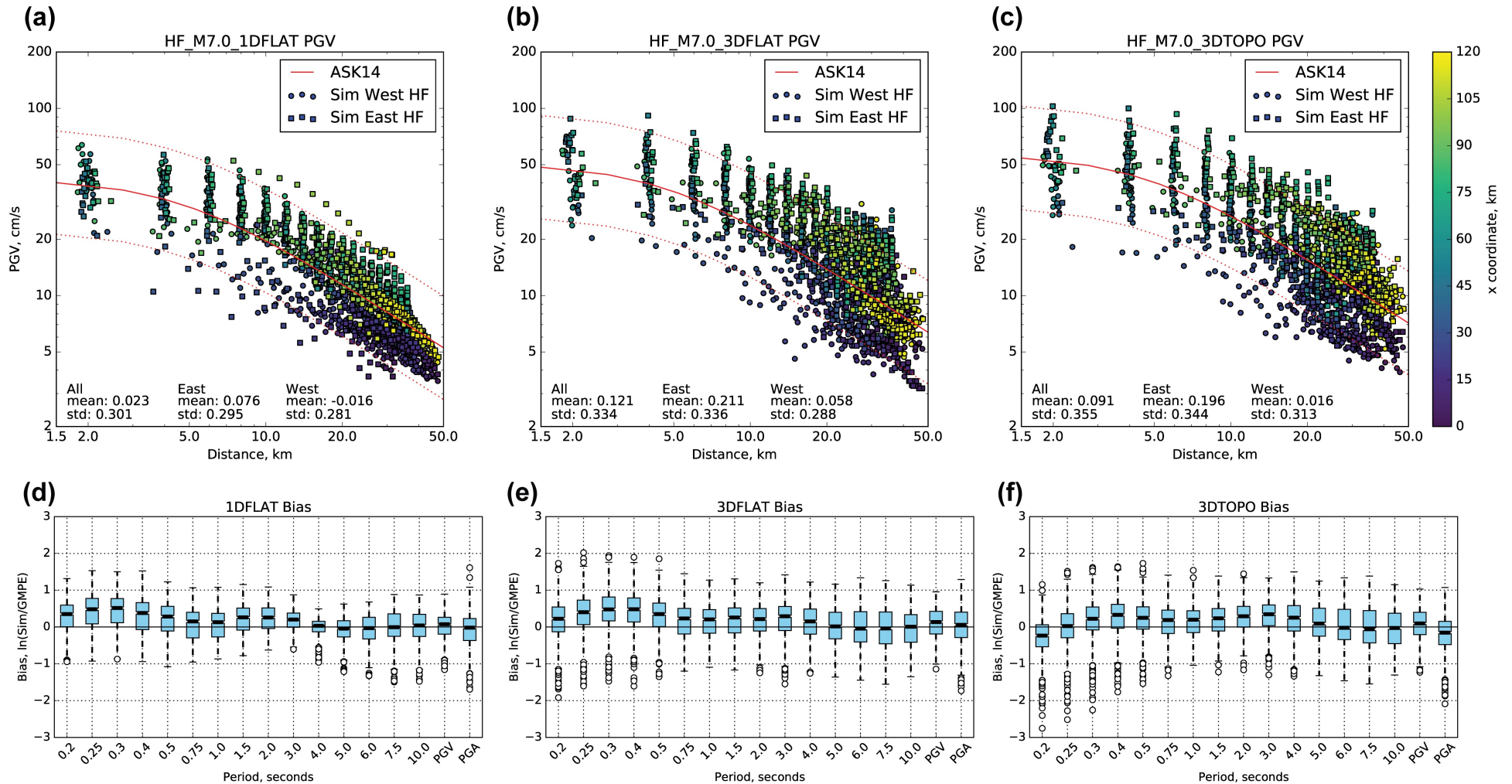
David McCallen, M. EERI^{1,2}, Floriana Petrone, M. EERI^{1,2}, Mamun Miah², Arben Pitarka³, Arthur Rodgers³, and Norman Abrahamson⁴



Lawrence Livermore National Laboratory
LLNL-PRES-823639



HF M7 0-4 Hz compared to ASK (2014) GMM



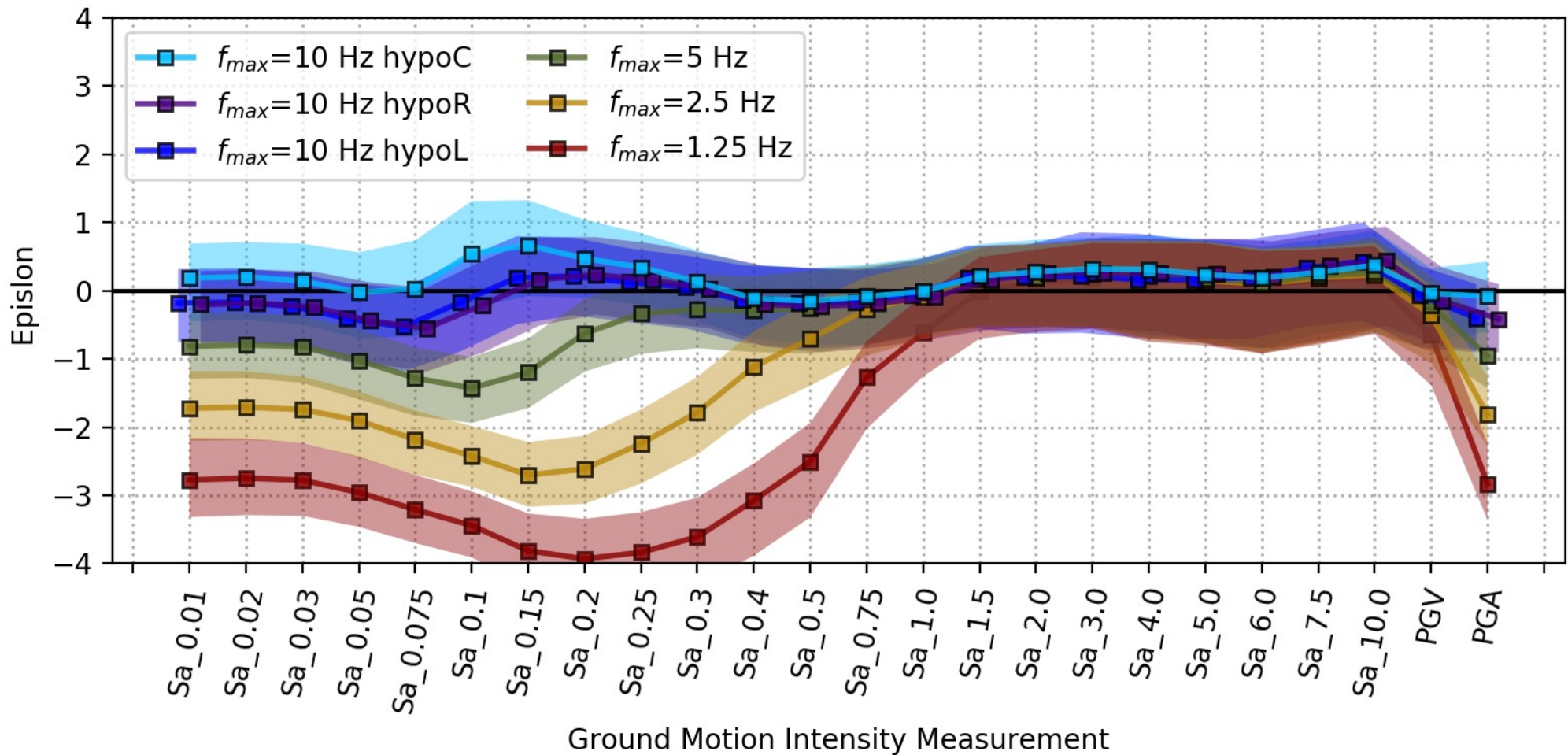
Median bias are near zero, within one σ of GMM

Variations $\sigma_{1D} < \sigma_{3DFLAT} < \sigma_{3DTOPO} < \sigma_{GMM}$

Rodgers et al. (GRL, 2018)

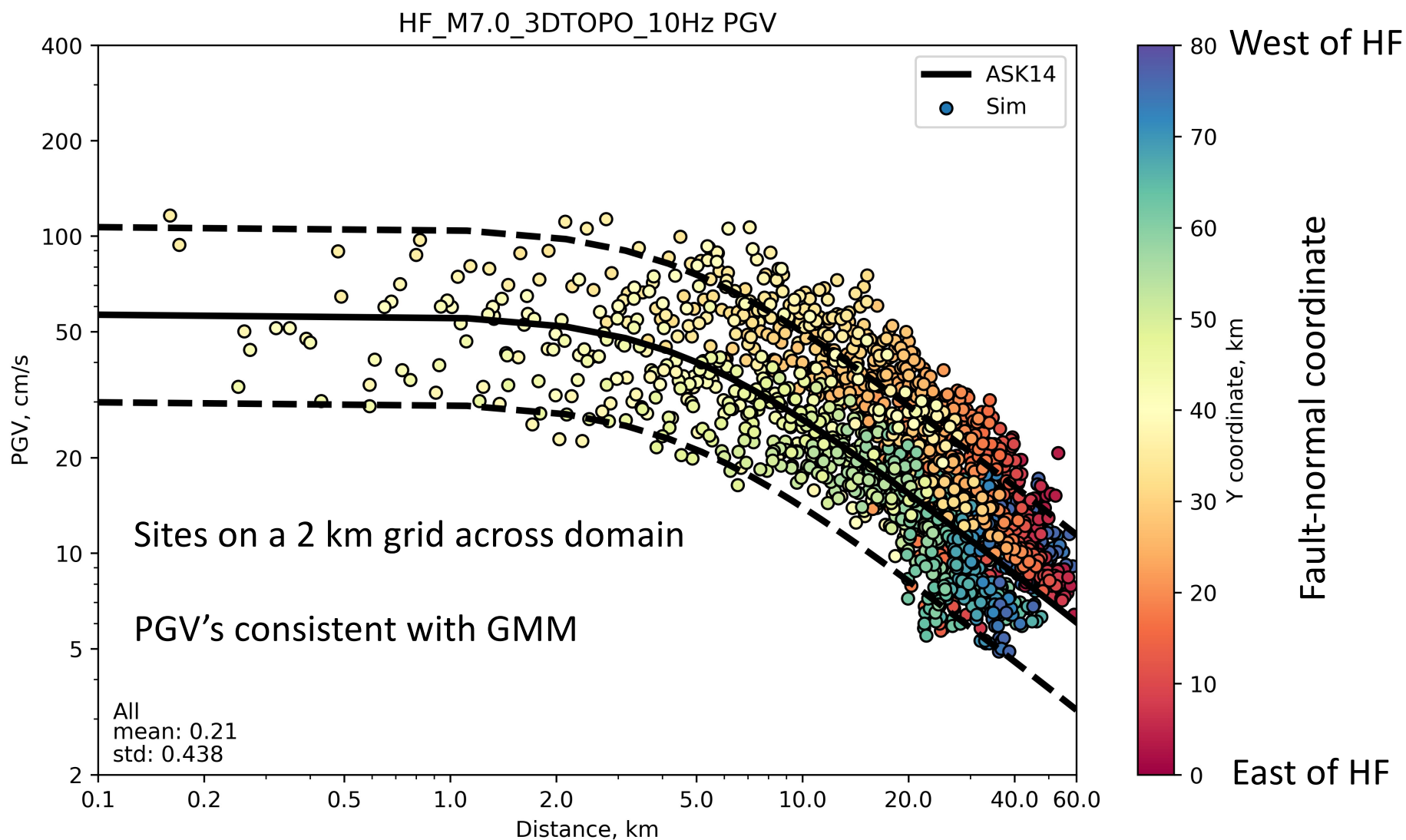
Epsilon for all sites, 3D model, $f_{\max} = 1.25 - 10$ Hz

Colored bands show 50% of data, interquartile range



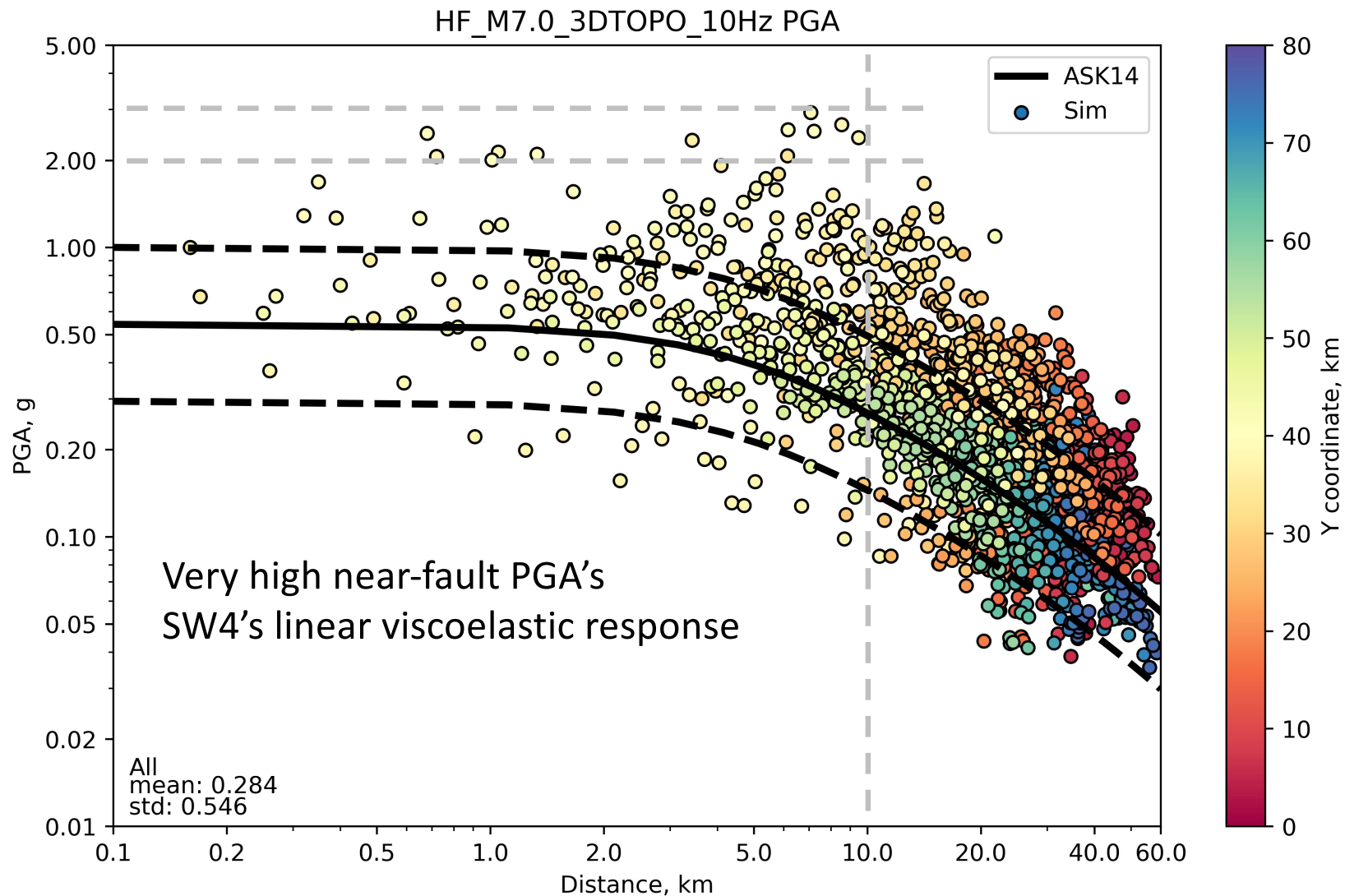
SW4 (viscoelastic) PGV versus distance compared with ASK (2014) GMM

HF M_w 7.0 10.0 Hz - PGV



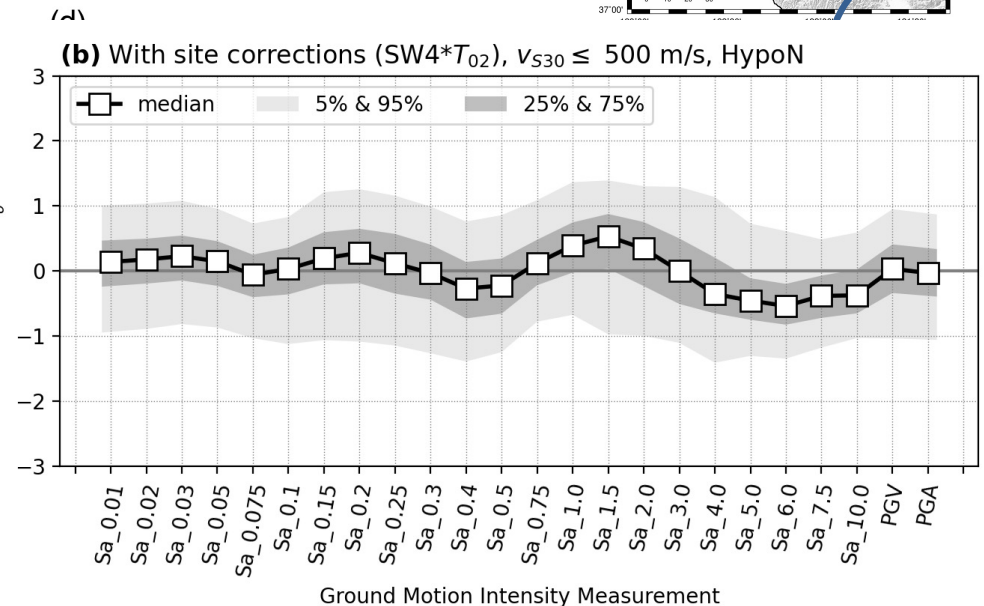
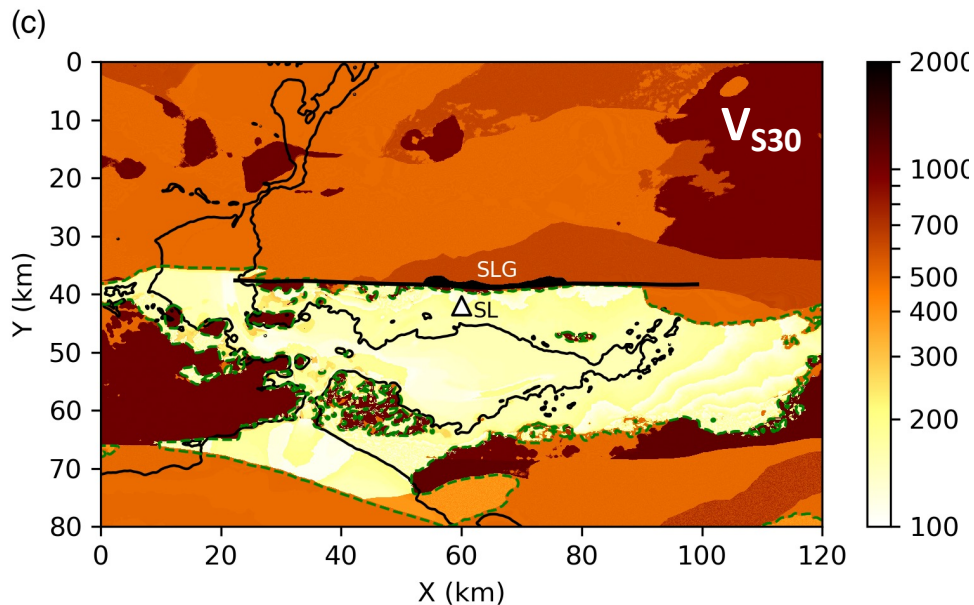
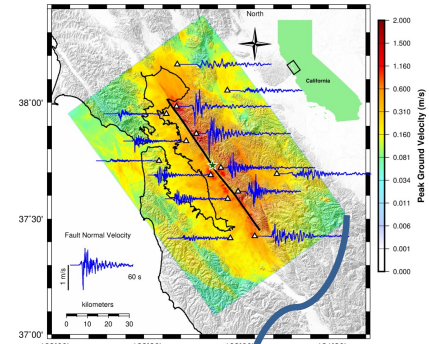
SW4 (viscoelastic) PGA versus distance compared with ASK (2014) GMM

HF M_w 7.0 10.0 Hz - PGA



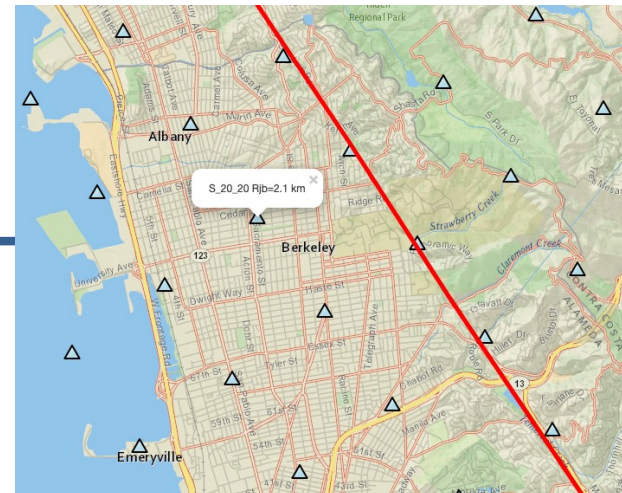
High PGA values indicate shortcomings in our simulations: linear viscoelasticity & assumed v_{Smin}

- Assumed $v_{Smin} = 500$ m/s does not honor weak near-surface soils
- These can respond with competing effects:
 - Amplify long-period weak motion
 - Dampen short-period strong motion



Site correction method reduces bias
At low V_{S30} sites Rodgers et al. (BSSA 2020)

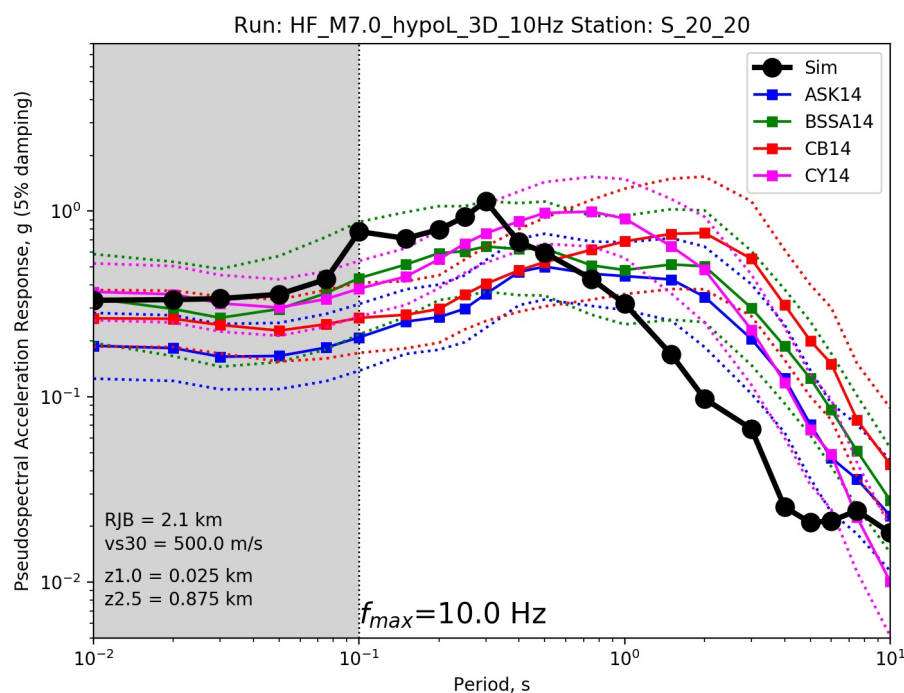
Ground motions without and with site response corrections: Berkeley



SW4 output, linear

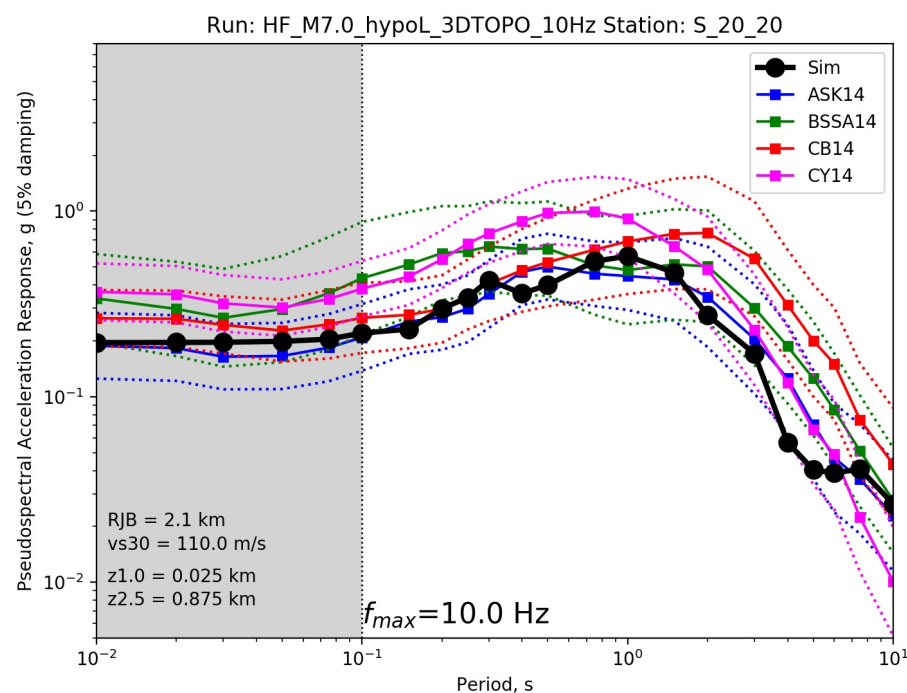
$v_{Smin} = 500 \text{ m/s}$

$v_{S30} = 500 \text{ m/s}$



SW4 with site response correction

$v_{S30} = 110 \text{ m/s}$

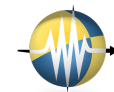


Conclusions

- Verification must be an essential and ongoing task for seismic simulation codes undergoing continuous development
- Validation is needed for both source and 3D Earth structure models
- Validation of path propagation in 3D Earth models with moderate events is important
 - We must learn as much as possible from smaller events
 - Basin effects, crustal structure, waveform tomography
 - We are awaiting update of the SFBA model from USGS (Hirakawa, Aagaard)
- Validation of large event ruptures is more complex due to:
 - Lack available empirical data
 - Dependence of intensities on source, path and site effects
 - *Simulated data may be consistent with GMM's, but is the Earth model correct?*
 - Additional criteria must be considered such as
 - Median epsilon
 - Within-event and between-event variability
 - Spectra correlation
 - Duration
 - Building response, engineering demand

Recommendations for community-based V&V

- Encourage FAIR (Findable, Accessible, Interoperable & Reusable) best-practices
 - Version control on data sets, synthetics and 3D models
- Standardization of waveform and event parameter data used in simulations for validation
 - Assembly with Python, ObsPy, Jupyter notebooks
 - Storage as ASDF (single HDF5 file per event)
- Standardization of simulated event data and metadata
 - Simulation metadata, e.g. input file(s) so others can reproduce
 - Storage as ASDF (single file per event)
 - Source and site parameters used in GMM's
- Standardize metrics for comparison
 - Waveform and intensity measurements



ObsPy
A Python Framework for Seismology



<https://seismic-data.org/>

