Alternative Hybrid Empirical Ground-Motion Model for Central and Eastern North America using Hybrid Simulations and NGA-West2 Models (Summary of SP16 GMM)

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MARCH 7, 2018

USGS WORKSHOP[

Overview

- The hybrid empirical method.
  - Pezeshk, Zandieh, Campbell, and Tavakoli (2015) - hybrid empirical method for Central and Eastern North America. **[NGA-EAST Report]**
  - Pezeshk, Zandieh, Campbell, and Tavakoli (2018) - hybrid empirical method for Central and Eastern North America. **[BSSA]**
  - Shahjouei and Pezeshk (2015) - Alternative Hybrid Empirical Ground-Motion Model for Central and Eastern North America using Hybrid Simulations - **[NGA-EAST Report]**
  - Shahjouei and Pezeshk (2016) - Alternative Hybrid Empirical Ground-Motion Model for Central and Eastern North America using Hybrid Simulations - **[BSSA]**

Hybrid Empirical Model (HEM)

- The hybrid empirical method (Campbell, 1981) is a procedure to develop ground-motion prediction equations (GMPEs) or ground-motion models (GMMs) in areas with sparse ground motions (target region)
- Incorporates the empirically developed GMPEs from an area with well recorded earthquakes (host region)
- Apply the regional modification factors between two regions
- Requires earthquake simulations for both regions to calculate the modification factors

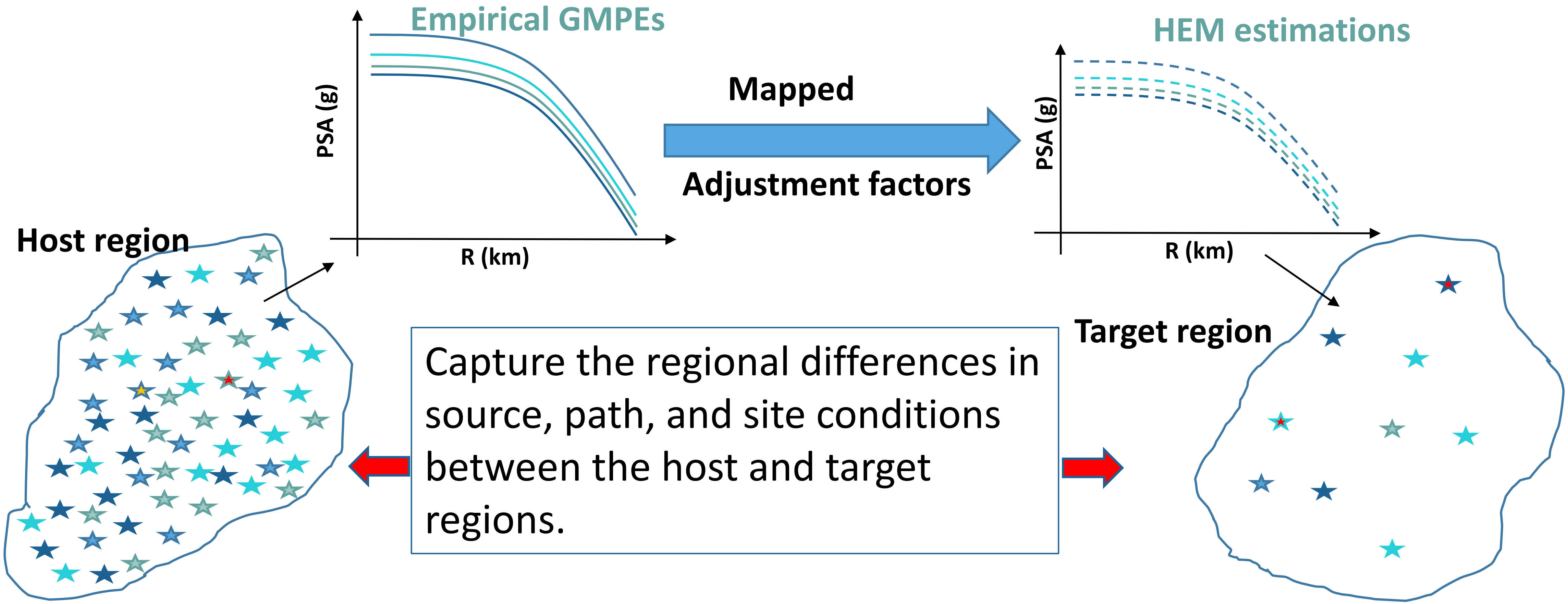
$$\frac{Y_{CENA}}{Y_{WNA\_empirical}} = \frac{Y_{CENA\_HBBsynthetics}}{Y_{WNA\_HBBsynthetics}}$$

Synthetics developed for the target

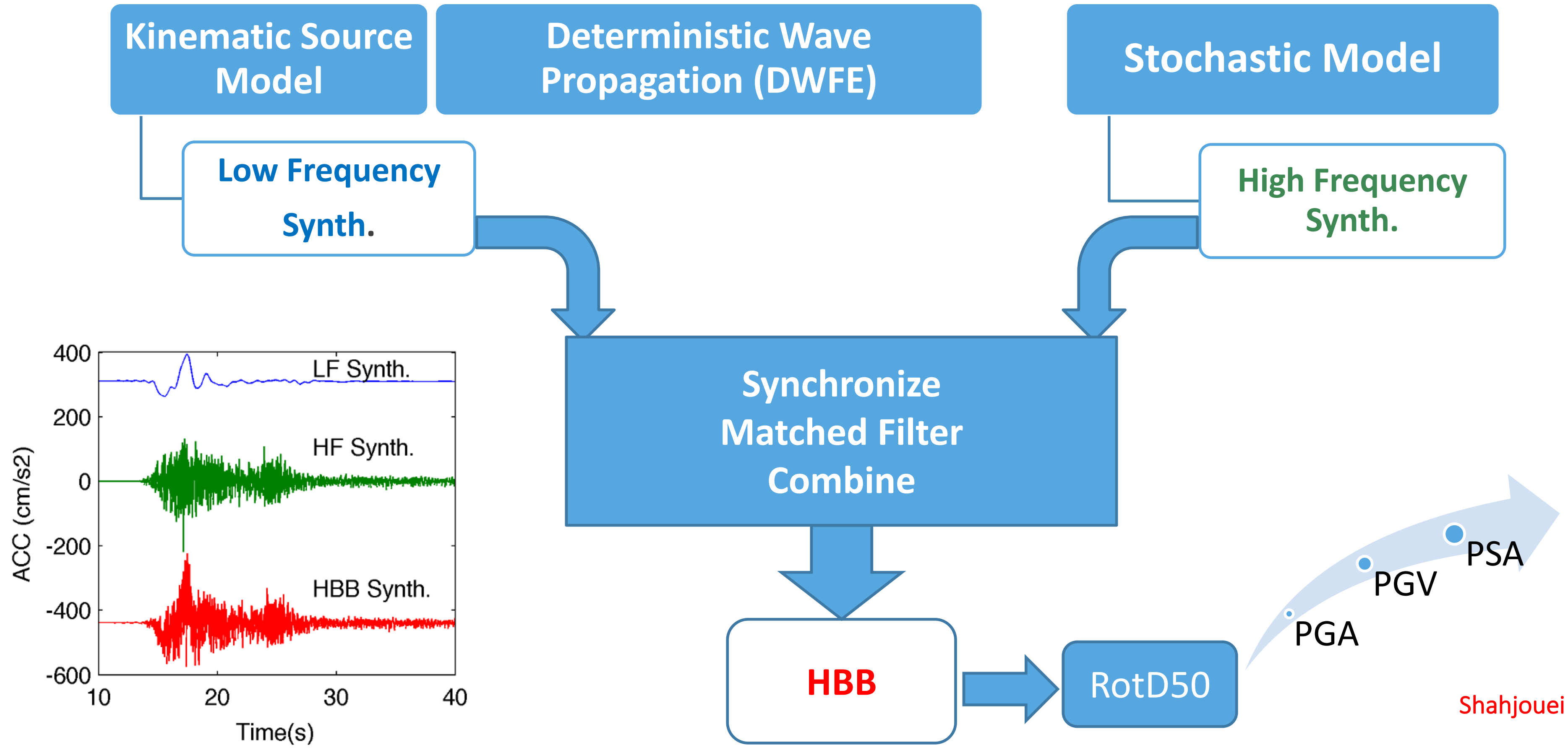
Empirical GMPEs from the host

Synthetics developed for the host

Hybrid Empirical Model (HEM)

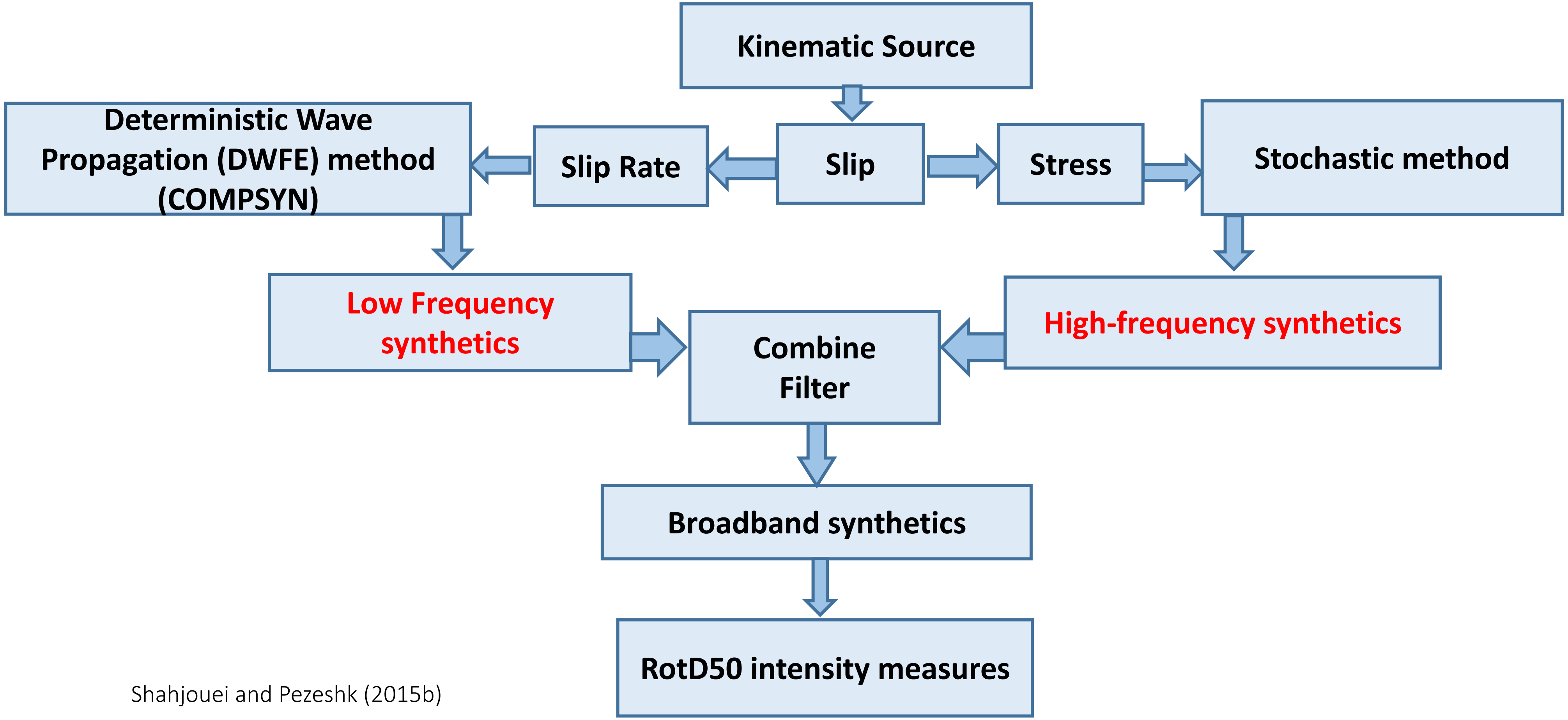


The Hybrid Broadband (HBB) Earthquake Simulation Package



Shahjouei and Pezeshk (2015b)

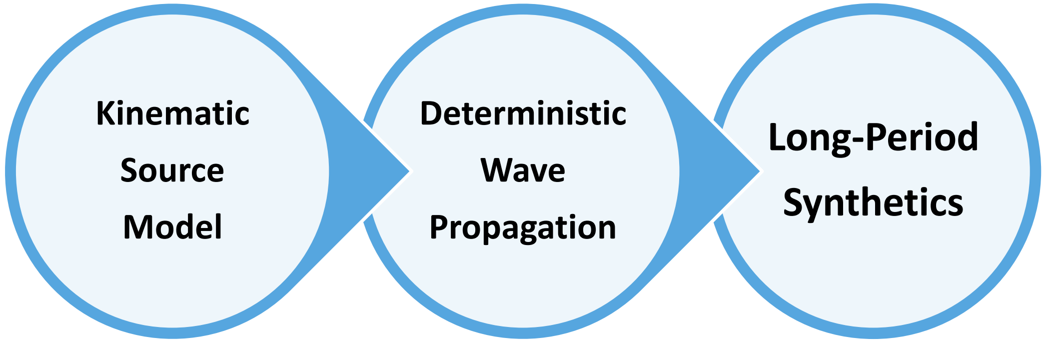
HBB Simulation
Flowchart



Shahjouei and Pezeshk (2015b)

Simulation Methodology

Low-Frequency Simulations

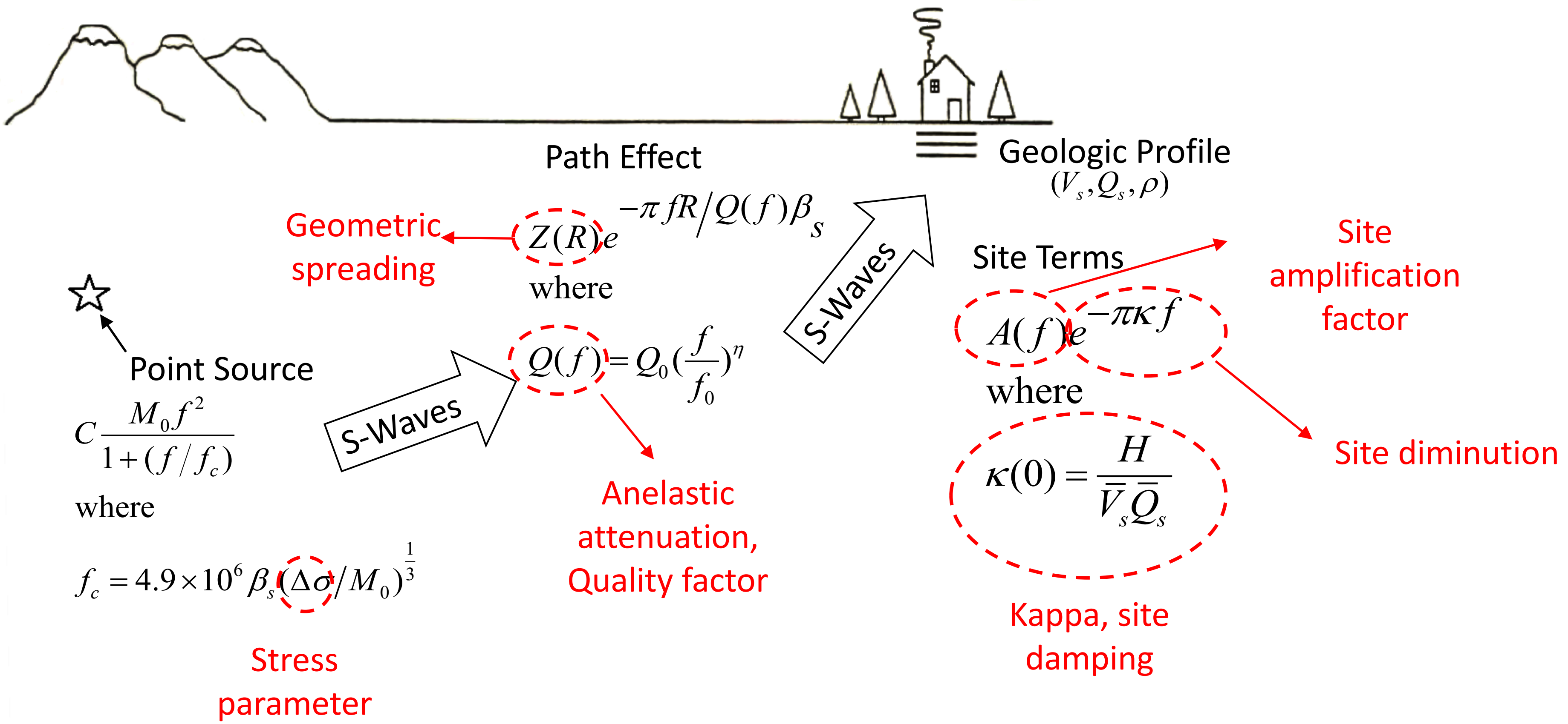


- Kinematic Source Model:
  - Define Shaking Scenarios
  - Consider Variability of Parameters
- Deterministic Wave Propagation:
  - Green's function are calculated in discrete wavenumber/finite element method

Stochastic Method

$$Y(M_0, R, f) = E(M_0, f)\, Z(R) \exp\left[-\pi f R / Q(f) \beta_s\right] A(f) \exp(-\pi \kappa f)$$

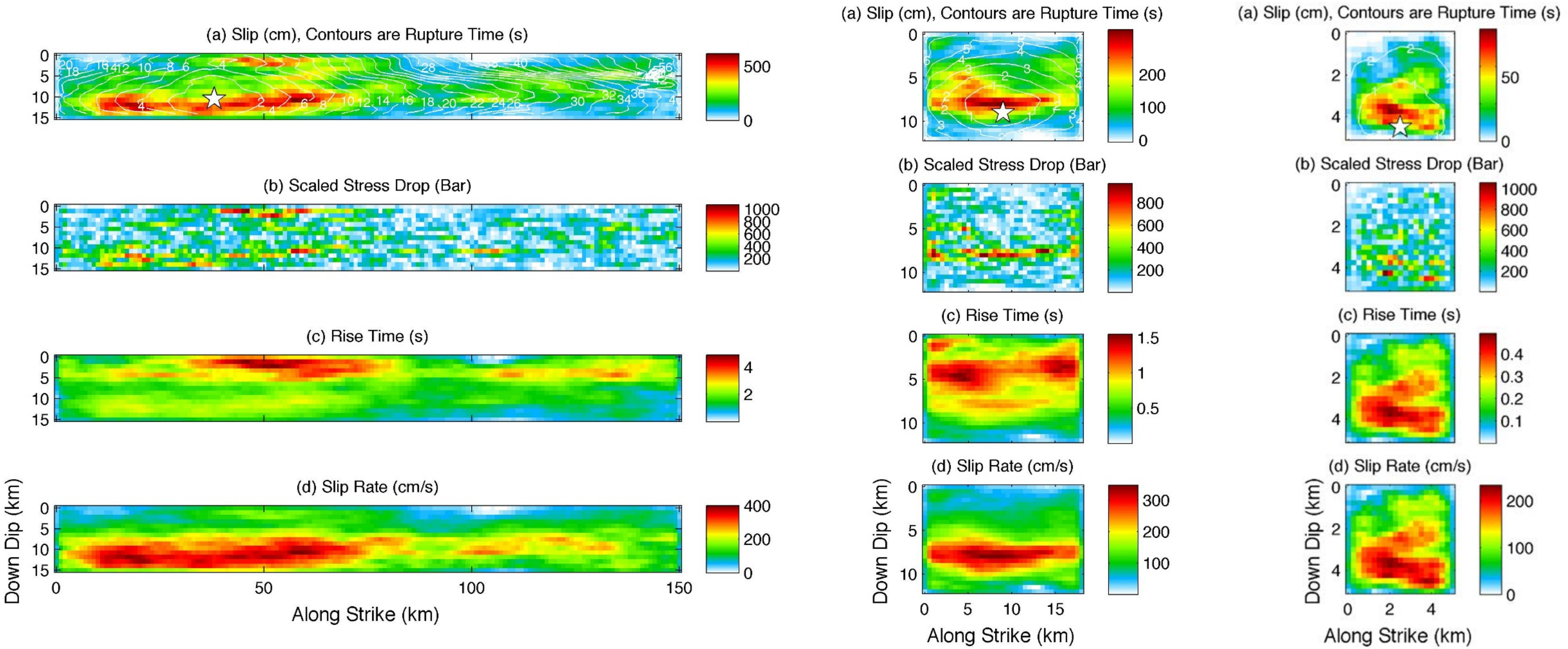
↓ FAS of Disp. ↓ Source Spec. ↓ Path Effect ↓ Site Response Term



Examples of Earthquake Source characterization

M 7.5, 6.5, and 5.5

Shahjouei and Pezeshk (2015b)



Simulation Parameters (SP16)

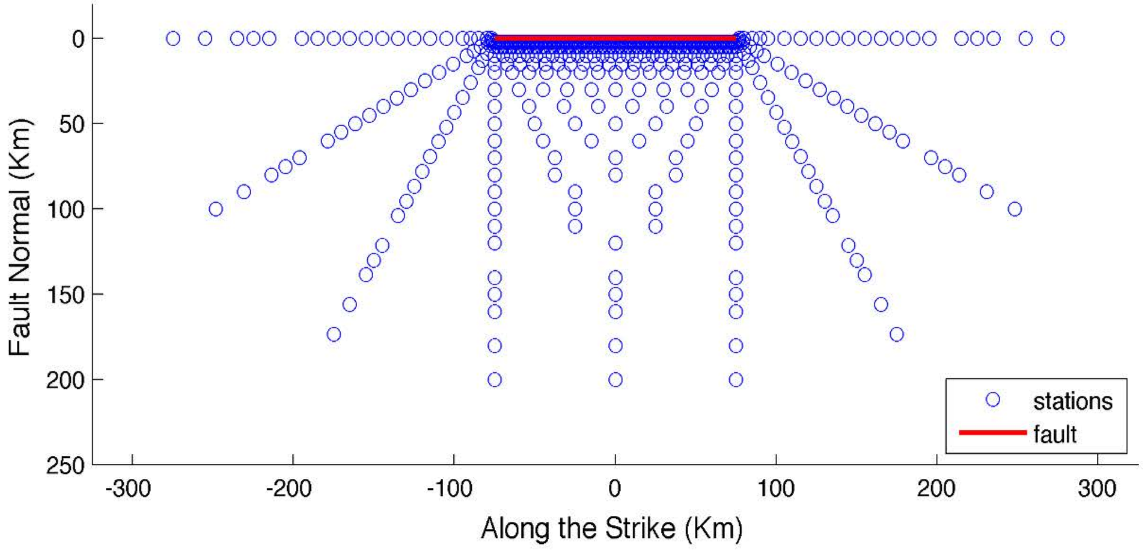
Low-Frequency Synthetics

M	CENA (km)				WNA (km)			
	L	W	Z_{TOR}	Z_{Hypo}	L	W	Z_{TOR}	Z_{hypo}
5.0	2	3	3–5	6.5±1.5	3.0	4	3–4	6.0±1.0
5.5	5	5	3–5	7.5±2.0	4.5	4.5	3–4	6.5±1.0
6.0	8	6	3–5	8.0±1.5	12	7	3–4	8.5±1.0
6.5	18	12	2–4	11.0±1.5	18	12	2–3	12±1.5
7.0	23	12	2–4	11.0±1.5	50	13	2–3	12±1.5
7.5	150	15	2–3	12.0±2.0	150	15	1–2	13.5±2
8.0	150	22	2–3	17.0±2.0	180	25	1–2	18±2

M	$\log_{10}(M_0)$	f_{cross}	CENA		WNA	
	(N. m)	(Hz)	Ave. Slip (m)	Ave. Rise Time (s)	Ave. Slip (m)	Ave. Rise Time (s)
5.0	16.550	3.0	0.18	0.21	0.10	0.12
5.5	17.301	3.0	0.25	0.38	0.25	0.20
6.0	18.041	2.6	0.71	0.67	0.40	0.36
6.5	18.799	2.4	0.90	1.20	0.88	0.64
7.0	19.550	1.6	2.56	2.12	1.65	1.13
7.5	20.300	0.8	2.70	3.75	2.68	2.02
8.0	21.050	0.8	10.3	6.72	7.56	3.58

Synthetic Simulations (SP15/SP16)

Station Map



M	R ≤ 200 km		R > 200 km	Total	
	CENA	WNA	Both Regions	CENA	WNA
5.0	346	342	140	486	482
5.5	384	384	140	524	384
6.0	380	363	140	520	363
6.5	438	438	140	578	438
7.0	404	355	140	544	355
7.5	459	459	140	599	459
8.0	520	459	140	660	459

Simulation Parameters (SP16)

Stochastic High-Frequency Finite-Fault Model

Parameter	WNA (100%)	CENA-Alternative 1 (50%)	CENA-Alternative 2 (50%)
Source spectrum model	Single corner frequency, ω^{-2}	Single corner frequency, ω^{-2}	Single corner frequency, ω^{-2}
Stress parameter, Δσ (bars)	135	600	400
Shear-wave velocity at source depth, β_s (km/s)	3.5	3.7	3.7
Density at source depth, ρ_s (gm/cc)	2.8	2.8	2.8
Geometric spreading, Z (R)	$\begin{cases} R^{-1.30} & R < 45km \\ R^{-0.96} & 45 \le R < 125km \\ R^{-0.5} & R \ge 125km \end{cases}$	$\begin{cases} R^{-1.3} & R < 50km \\ R^{-0.5} & R \ge 50km \end{cases}$	$\begin{cases} R^{-1.3} & R < 60km \\ R^{0} & 60 \le R < 120km \\ R^{-0.5} & R \ge 120km \end{cases}$
Quality factor, Q	$202 f^{0.54}$	$525 f^{0.45}$	$440 f^{0.47}$
Source duration, T_s (s)	$1/f_a$	$1/f_a$	$1/f_a$
Path duration, T_p (s)	Boore and Thompson (2015) Table 1	$\begin{cases} 0 & R \le 10km \\ +0.16R & 10 < R \le 70km \\ -0.03R & 70 < R \le 130km \\ +0.04R & R > 130km \end{cases}$	Boore and Thompson (2015) Table 2
Site amplification, A(f)	Atkinson and Boore (2006) - Table 4	Boore and Thompson (2015)-Table 4	Boore and Thompson (2015)-Table 4
Kappa, k_0 (s)	0.035	0.005	0.006

Hybrid Empirical Model (HEM)

PSA (g)

PGV (cm/s)

PGA (g)

$$\frac{Y_{CENA}}{Y_{WNA\_empirical}} = \frac{Y_{CENA\_HBBsynthetics}}{Y_{WNA\_HBBsynthetics}}$$

Synthetics developed for the target
Hybrid broadband Simulations
(Central and Eastern North America)

Synthetics developed for the host
Hybrid broadband Simulations
(Western North America)

5 Empirical NGA-West2 GMPES
Abrahamson et al. (2014) ~ ASK14
Boore et al. (2014) ~ BSSA14
Campbell & Bozorgnia (2014) ~ CB14
Chiou & Young (2014) ~ CY14
Idriss (2014) ~ I14

HEM

Synthetic Earthquake Simulations for WNA and CENA

- Methodology: HBB Platform (Shahjouei and Pezeshk, 2015b)
- Different regional parameters:
  - Source term effects
  - Path effects
  - Site conditions
- Magnitude range: M5–8
- Distance range: 2–1000 km
- Variability of Parameters (combination of kinematic and stochastic parameters)
  - WNA (9*1=9 alternative source models) & CENA (9*2=18 alternative source models) for each magnitude
- Numbers of stations: 486–660 (varies with magnitude) for each simulation
- Used HPC

Functional Form and the Coefficients

- The median GMPEs:

$$\log(\overline{Y}) = c_1 + c_2 M + c_3 M^2 + (c_4 + c_5 M) \times \min\{\log(R), \log(60)\}$$
$$+ (c_6 + c_7 M) \times \max[\min\{\log(R/60), \log(120/60\}, 0]$$
$$+ (c_8 + c_9 M) \times \min\{\log(R/120), 0\} + c_{10} R$$

$$R = \sqrt{R_{JB}^2 + c_{11}^2}$$

- GMPEs: PGA, PGV, and PSA (T)
- Coefficients: Nonlinear least squares regression analysis

Aleatory Variability and Epistemic Uncertainty

- **Aleatory Uncertainty:** characterize the inherent randomness in the predicted model as the results of unknown characteristics of the model
  - Standard deviation of geometric mean of 5 NGA-West2 GMPEs

$$\sigma_{\ln}(\bar{Y}) = \begin{cases} c_{12}M + c_{13} & M \leq 6.5 \\ \psi M + c_{14} & M > 6.5 \end{cases}$$

  - Standard deviation of regression analysis

$$\sigma^{T}_{\ln(\bar{Y})} = \sqrt{\sigma^{2}_{\ln(\bar{Y})} + \sigma^{2}_{\mathrm{Re}\,g}}$$

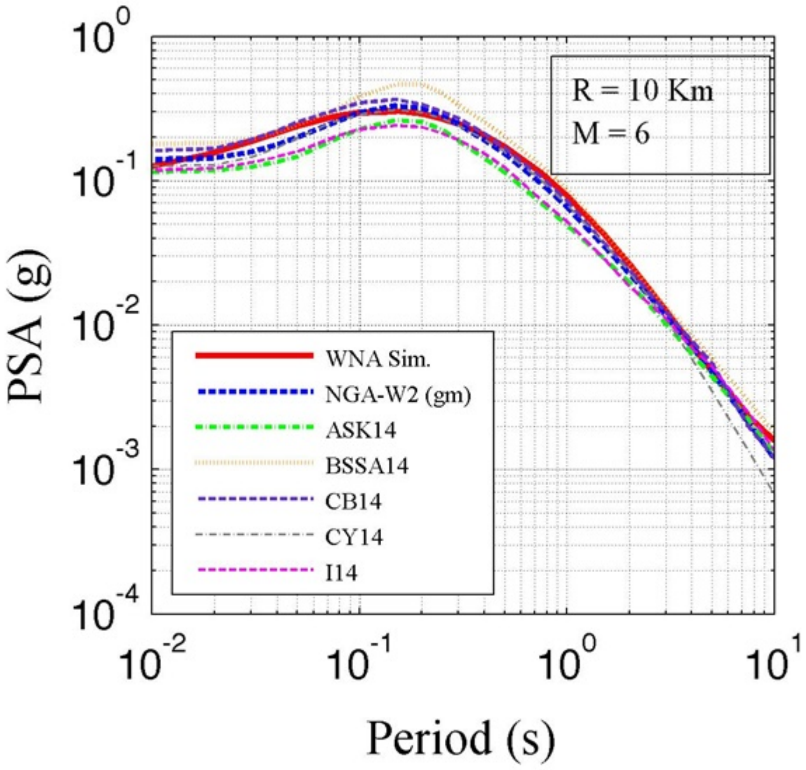
- **Epistemic Uncertainty:** A systematic uncertainty which is due to lack of knowledge
  - Parametric modeling
  - Epistemic in median estimation of NGA-West2 GMPEs

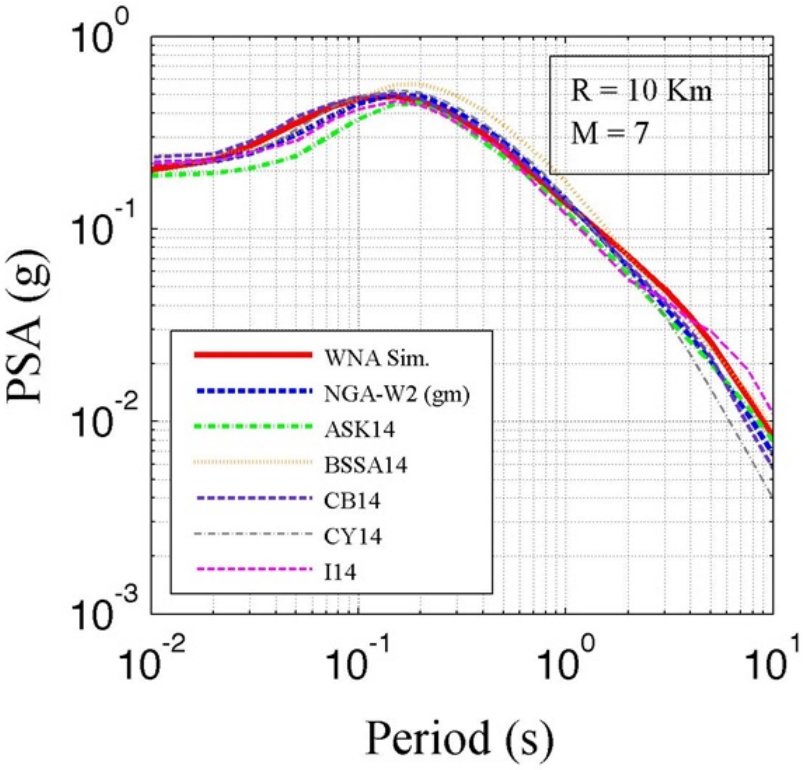
$$\eta^{Sub}_{\ln(\bar{Y})} = \sqrt{{\sigma_{\mu\ln(psa)-eps1}}^{2} + {\sigma_{Par}}^{2}}$$

- **Total variability and uncertainty**

$$\sigma^{Combined}_{\ln(\bar{Y})} = \sqrt{{\sigma^{T}_{\ln(\bar{Y})}}^{2} + {n^{Sub}_{\ln(\bar{Y})}}^{2}}$$

Model Validation and Comparison
Validation - NGA-West2 GMPEs

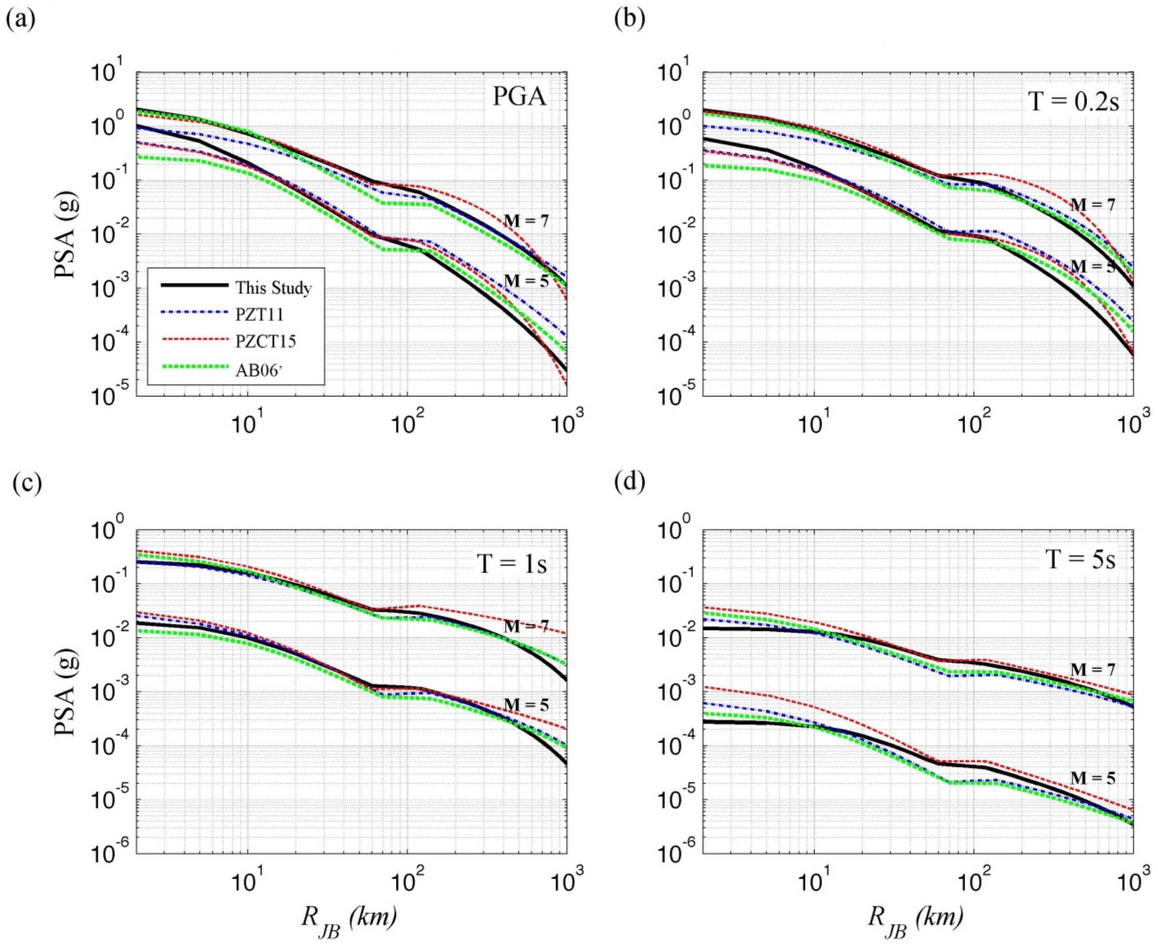




Shahjouei and Pezeshk (2016)

Results

Comparison with the previous GMMs in CENA



Shahjouei and Pezeshk (2016)

Results

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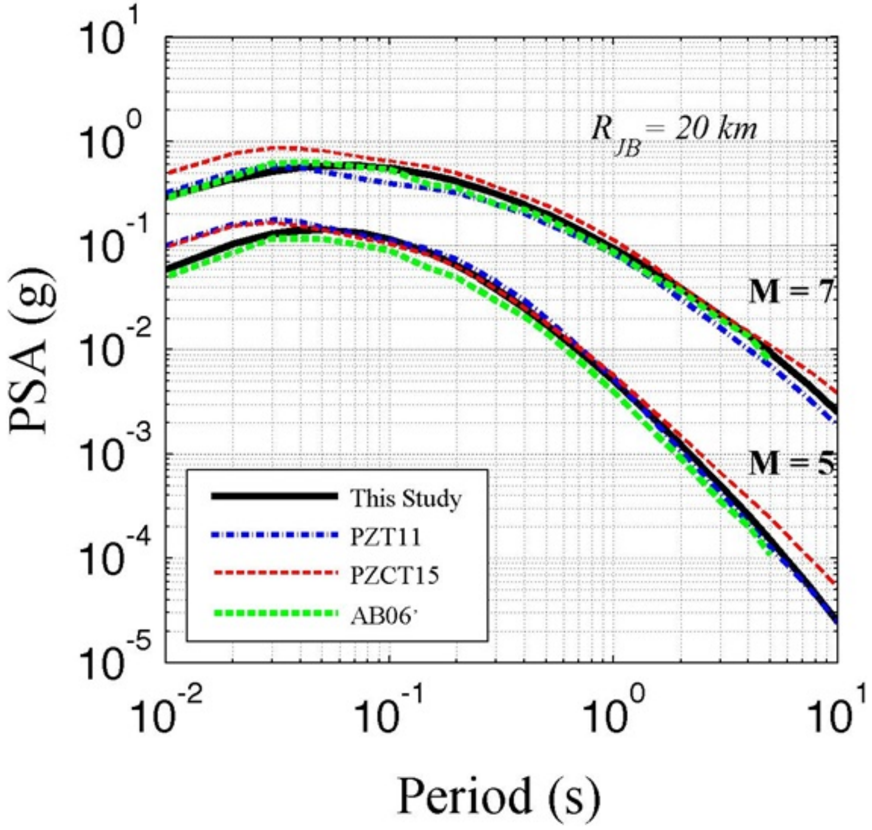
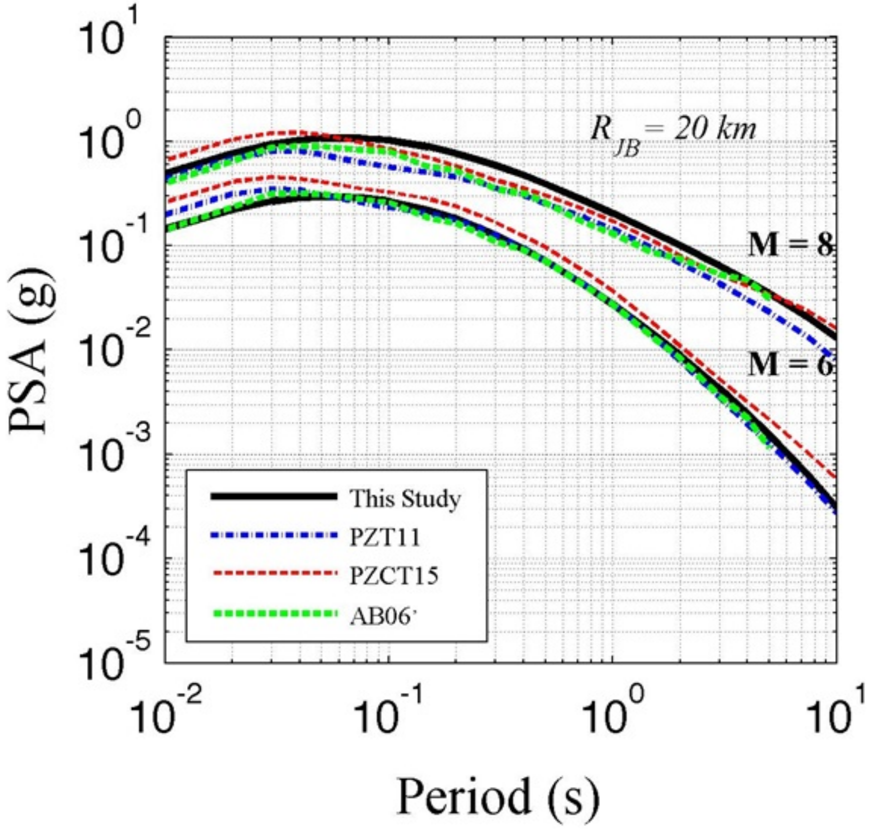


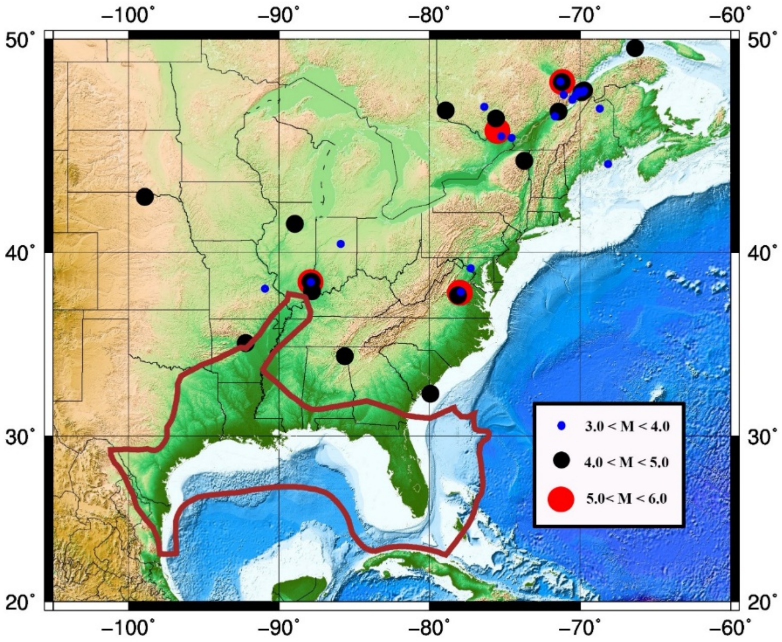


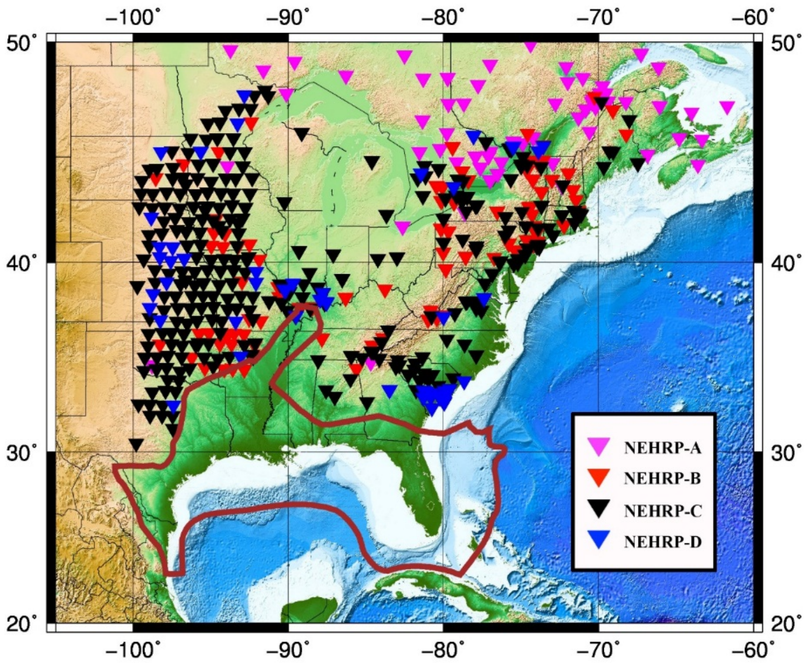
Shahjouei and Pezeshk (2016)

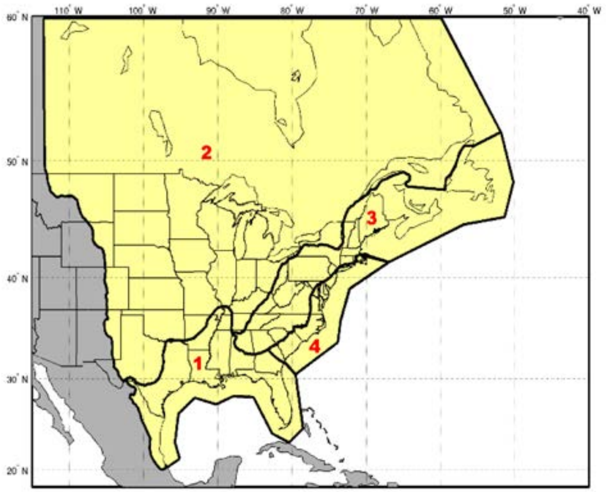
Model Validation

Comparison with the recorded earthquakes in CENA

- Stations and earthquakes used in the residual analysis



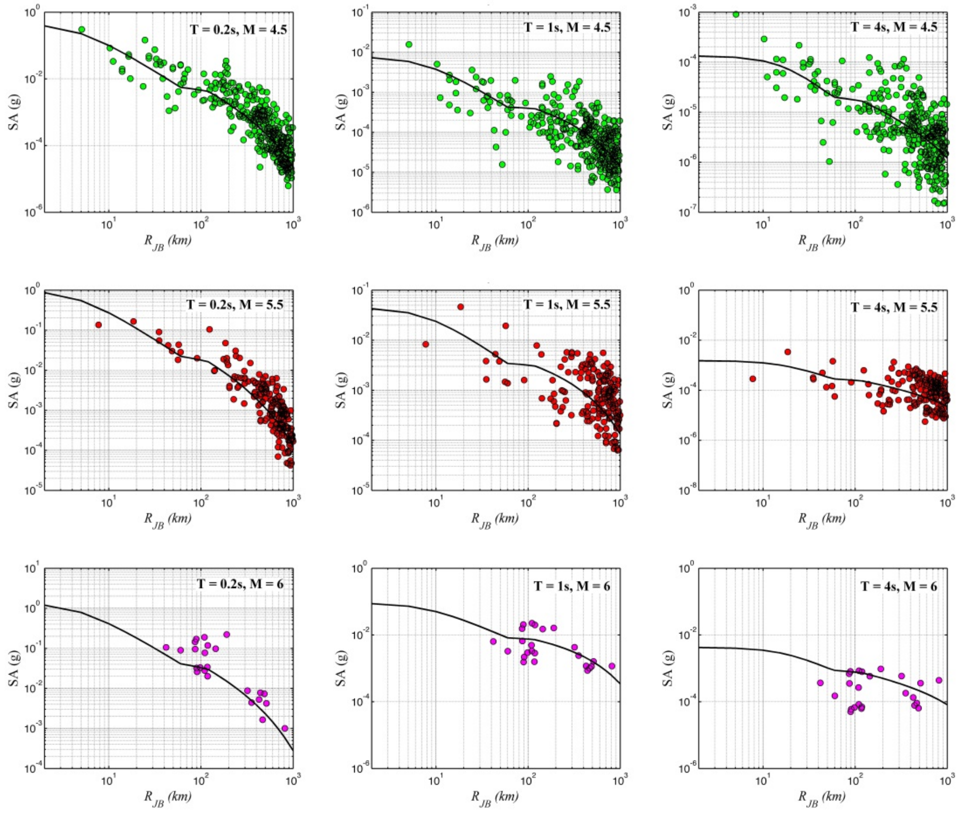




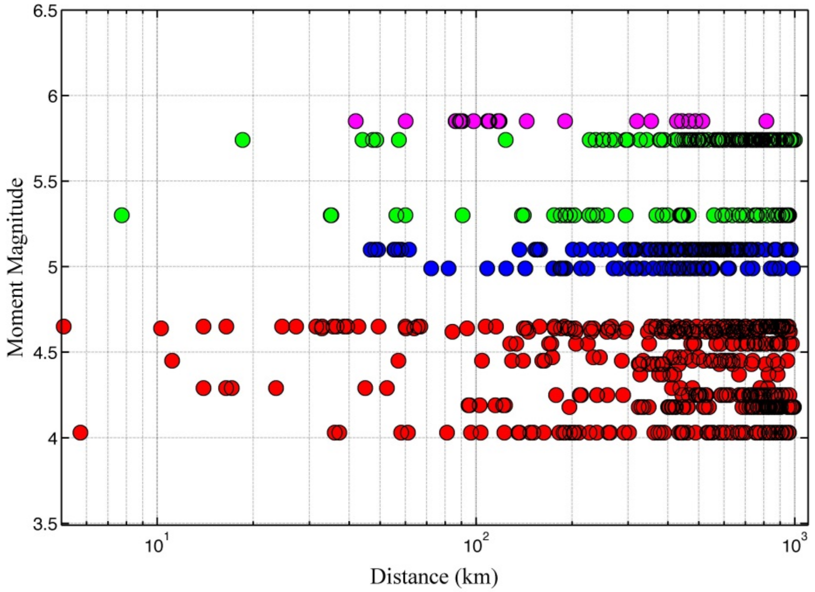
Goulet and Bozorgnia (2015)

Model Validation

Comparison with the recorded earthquakes in CENA



- Small to moderate magnitude earthquakes in NGA-East database

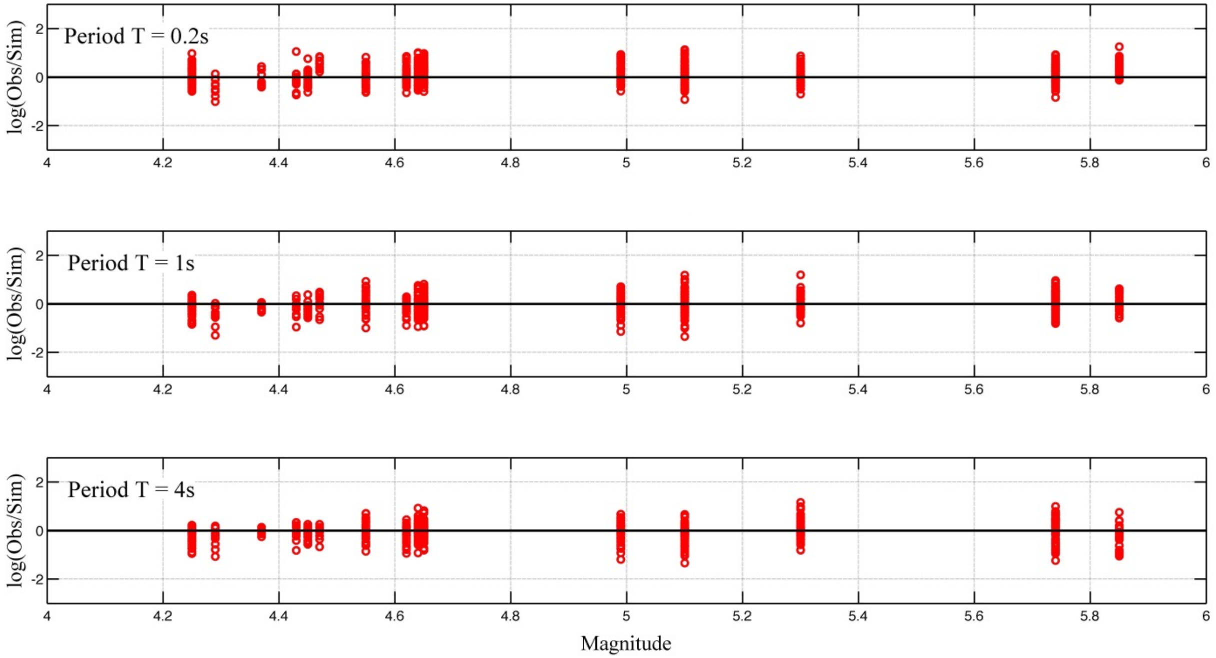


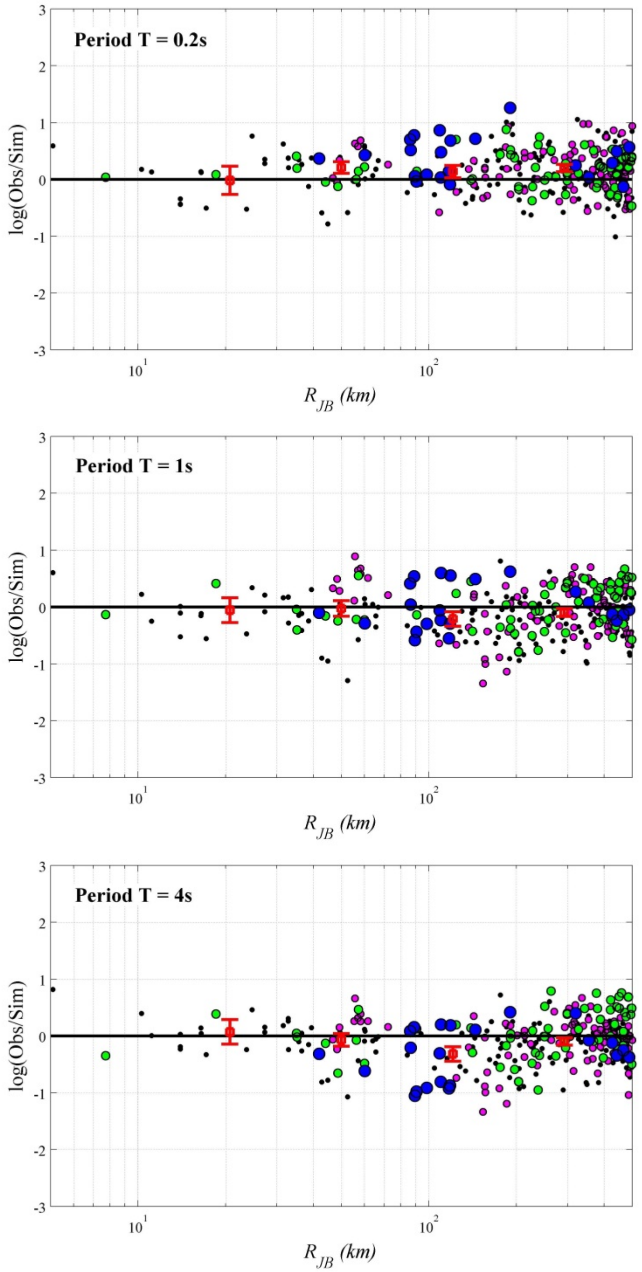
Shahjouei and Pezeshk (2016)

Residual Analysis

- With respect to the distance
  - Periods of T = 0.2, 1.0, and 4.0 seconds

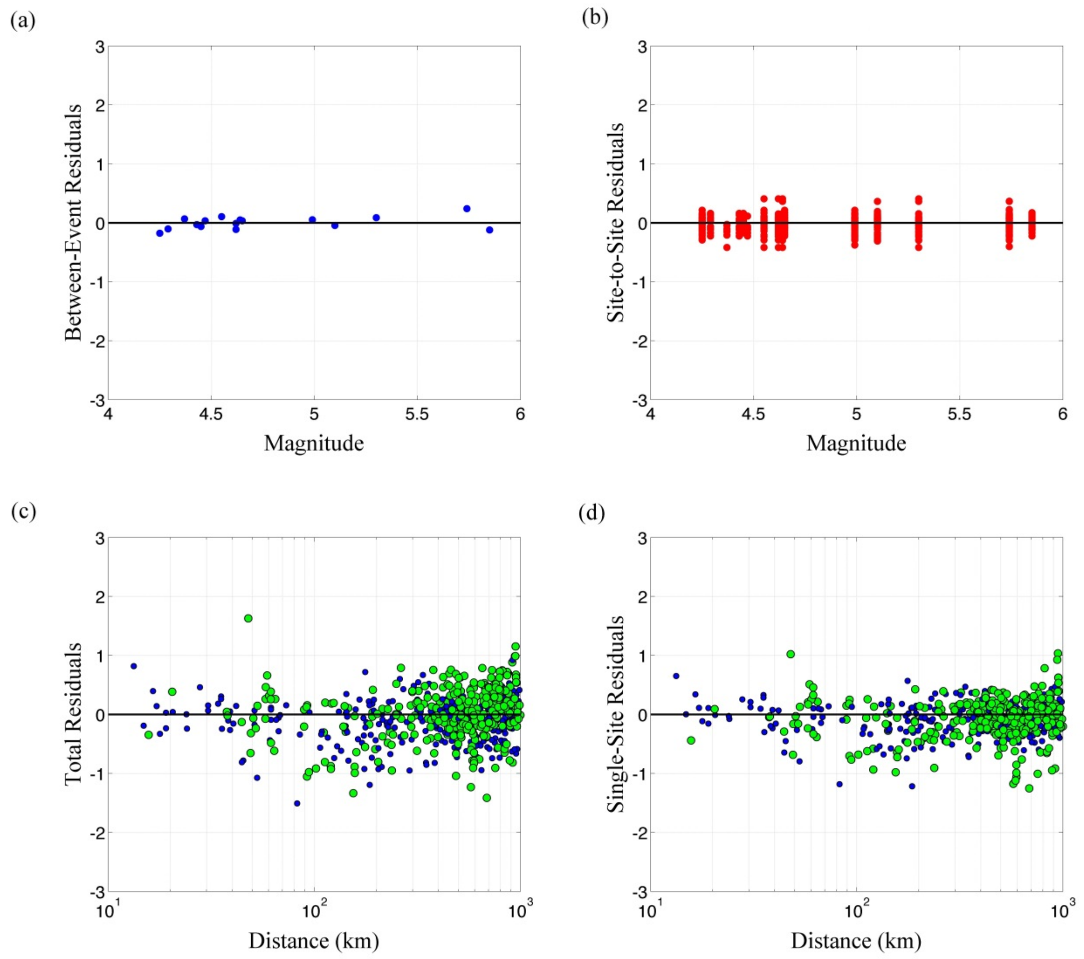
Shahjouei and Pezeshk (2016)





Residual Analysis
Classifications

- **With respect to the magnitude**
  - Inter-event (between-event) residuals (a)
  - Intra-event (within-event) residuals (b)
- **With respect to the distance**
  - Total residuals (c)
  - Single-site residuals (d)



Shahjouei and Pezeshk (2016)

Summary

- Alternative GMPE for CENA is developed using Hybrid Empirical Approach
- Model is developed for
  - 2 < R < 1000 km
  - 5.0 < **M** < 8.0
  - Reference rock site condition: V_{S30}=3 km/s for CENA
- A new proposed Hybrid Broadband simulation technique is incorporated in the earthquake simulations
  - Used HPC
- The empirical NGA-West2 GMPEs are employed
- Comparison with other GMMs.
- Comprehensive residual analysis is accomplished using the NGA-East database

SP16 vs. SP15

SP15 (NGA-East report) … SP16 (BSSA)

Similarities-Both models:

- Both models use Hybrid Empirical Approach for GMM development
- Both models uses Hybrid Broadband Simulation Technique (proposed by Shahjouei and Pezeshk, 2015b) for synthetic earthquake simulations in WNA and CENA

- **Differences:**
  - SP16 is an update to the SP15
  - SP16 uses different combinations of stochastic set parameters and more weighted to the most recent ones:
    - SP16: Equally weighted 2 sets of parameters for CENA and one set for WNA
    - SP15: Equally weighted 3 sets of parameters for CENA and two sets for WNA
  - SP16 incorporates additional earthquake simulations using the most recent seismological parameter.

- Both SP15 and SP16 models are originally developed for $5 \leq Mw \leq 8$; however based on the feedback from NGA-East TI team, new calibration is applied for lower magnitudes (for extrapolation to smaller magnitude events, M4-5)
- SP16 proposed a refined median GMMs as well as aleatory variability and epistemic uncertainty model

Acknowledgements

- Pacific Earthquake Engineering Research Institute (PEER)
- Dr. Paul Spudich (U.S. Geological Survey)
- Dr. Martin Mai (Computational Earthquake Seismology Center- King Abdullah University of Science and Technology)
- Drs. Giovanna Cultrera, Kenneth Campbell, Hiroshi Kawase, Christine Goulet, Kiran K. Thingbaijam and Hugo C. Jimenez.

Thank you for your attention