Exit Seminar:

Inter-period correlations of Fourier amplitude spectra of ground-motions: modeling, calibration of earthquake simulations, and significance in seismic risk

Jeff Bayless

Advisor: Dr. Norman Abrahamson

UC Davis

Acknowledgement

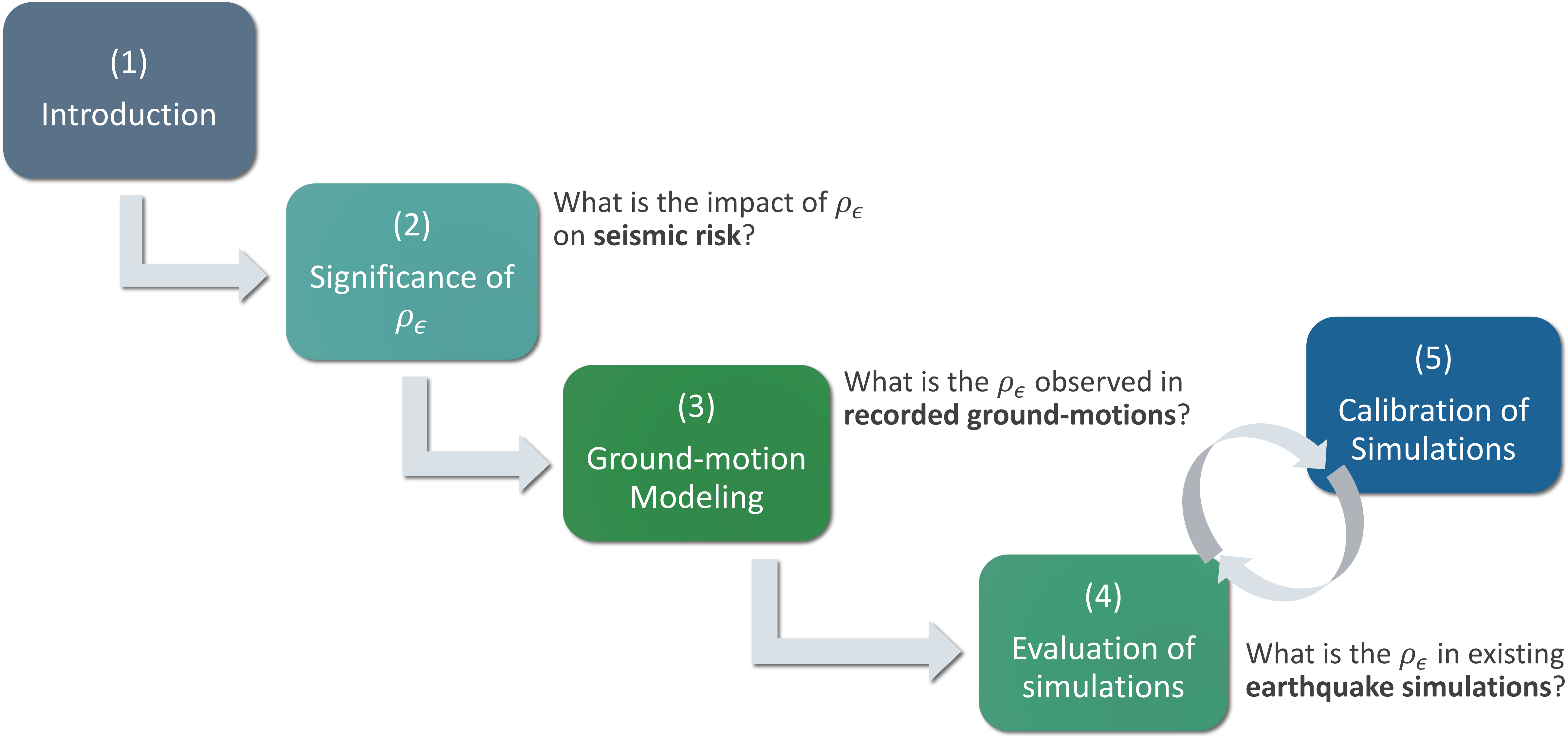
Thanks to my advisor, Norm Abrahamson.

2-sentence summary

The aim of this research is to **improve ground-motion simulations**, precisely with respect to their **inter-period correlation**.

The purpose of this research is:

- to illustrate that the inter-period correlation is a critical feature of ground-motions that influences variability of structural response and which should be considered as a validation parameter,
- to develop an avenue for improving the correlation in the simulations, and
- to provide an example application which can help guide future calibrations.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What is the impact of ρ_ϵ on **seismic risk**?
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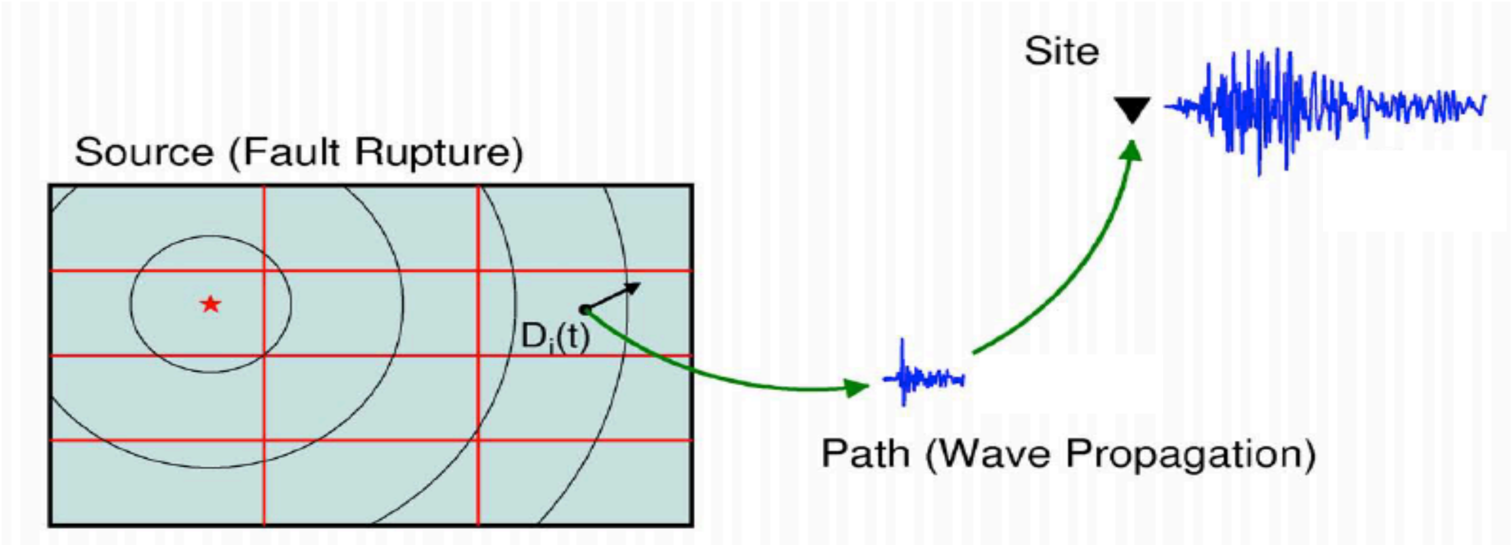
What is the ρ_ϵ in existing **earthquake simulations**?
(5)
Calibration of Simulations

(1) Introduction

- "Physics-based" earthquake ground-motion simulations:
  - the prediction of the ground-motion generated by earthquakes by means of numerical methods/models that incorporate the physics of the earthquake source and the resulting propagation of seismic waves (Taborda and Roten, 2014)
  - Kinematic vs Dynamic source, 3D FEM and FD vs 1D Green's Functions, stochastic, point source vs finite fault, etc.

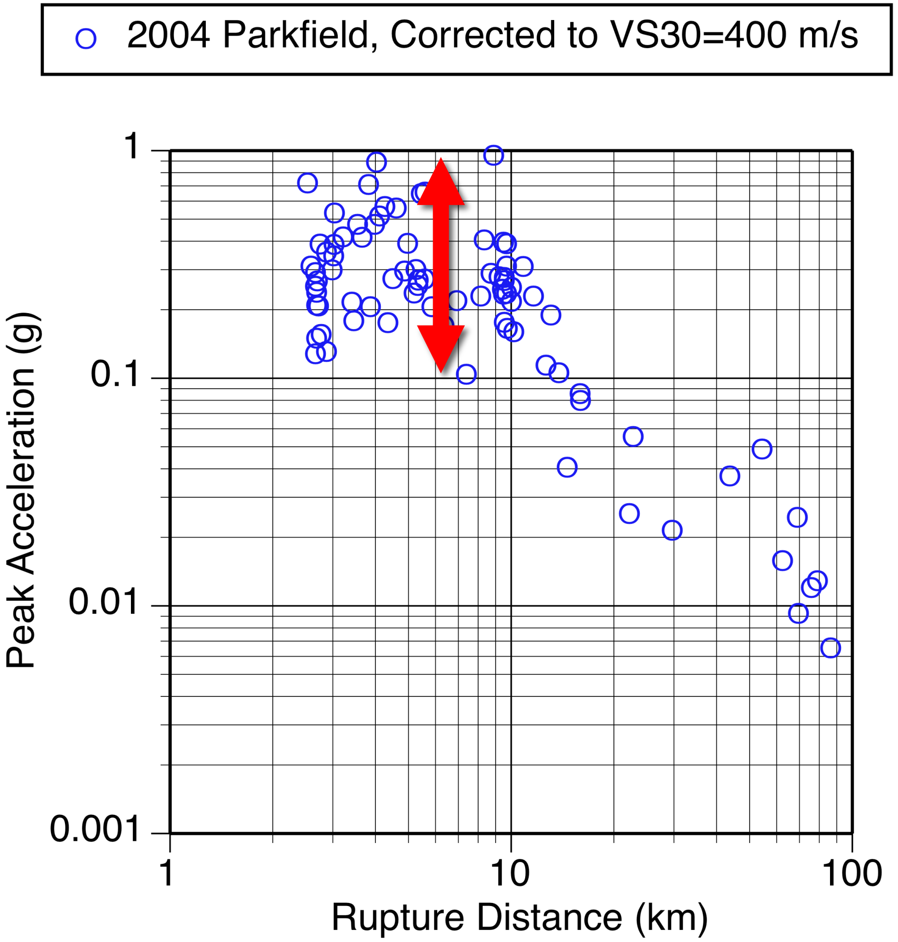


(image from Graves 2014)

- In practice, simulations will be used by engineers increasingly in the next decade.
- To use them, we need to **validate** that they contain the ground-motion properties found in recordings.

(1) Introduction

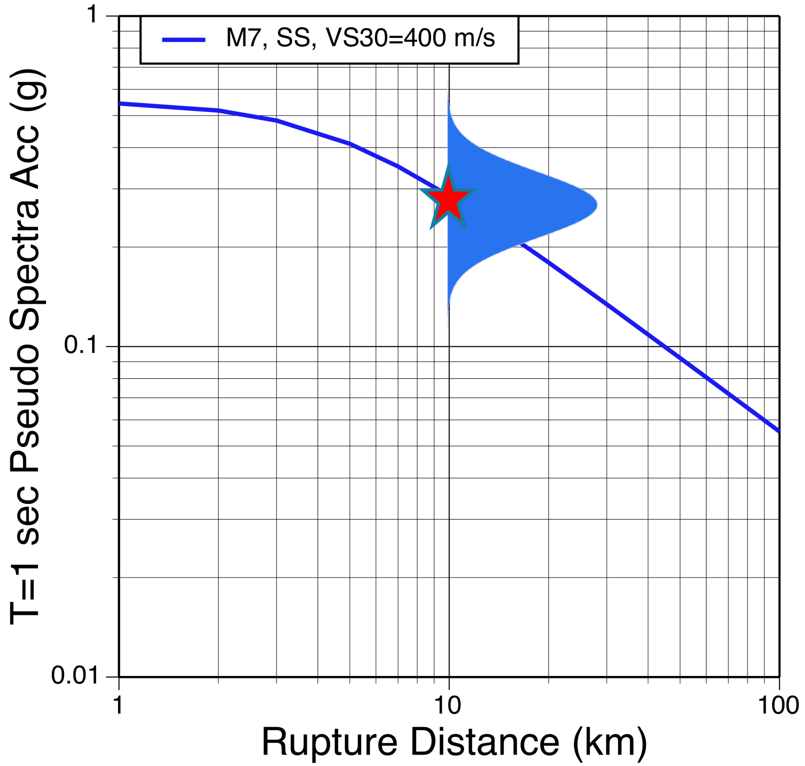
- There is large variability in observed ground motions (GMs)



(image from Abrahamson 2016)

(1) Introduction

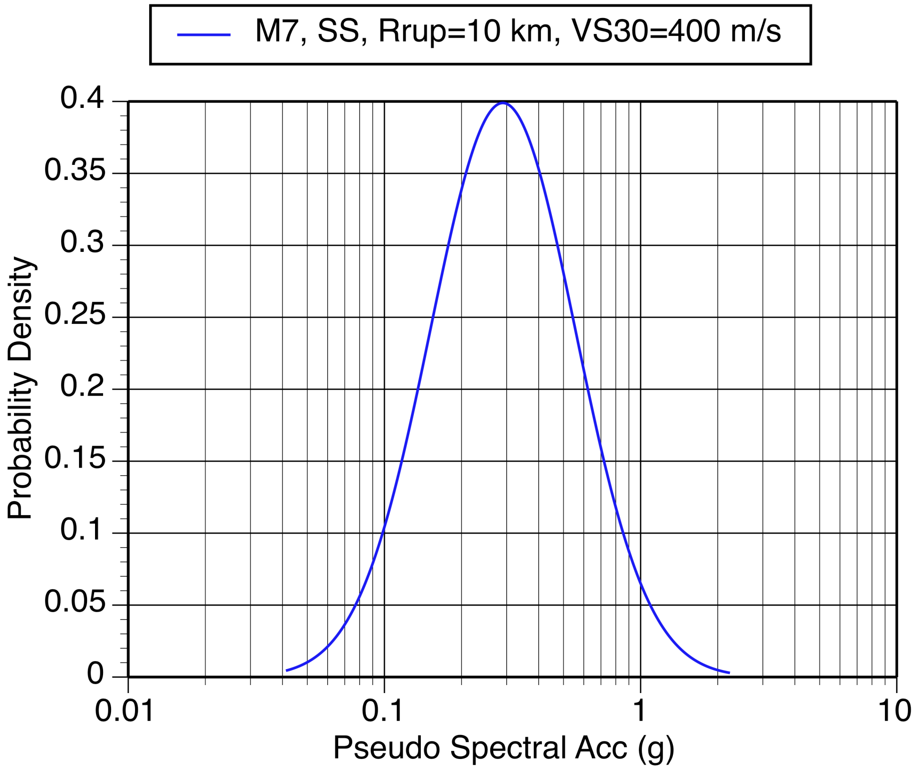
GM Model (median)



GM Model distribution

Standard deviation, σ = 0.65 ln units

$e^{0.65} \approx 2$, so median +/- 1σ is nearly a factor of four!



(image from Abrahamson 2016)

(1) Introduction

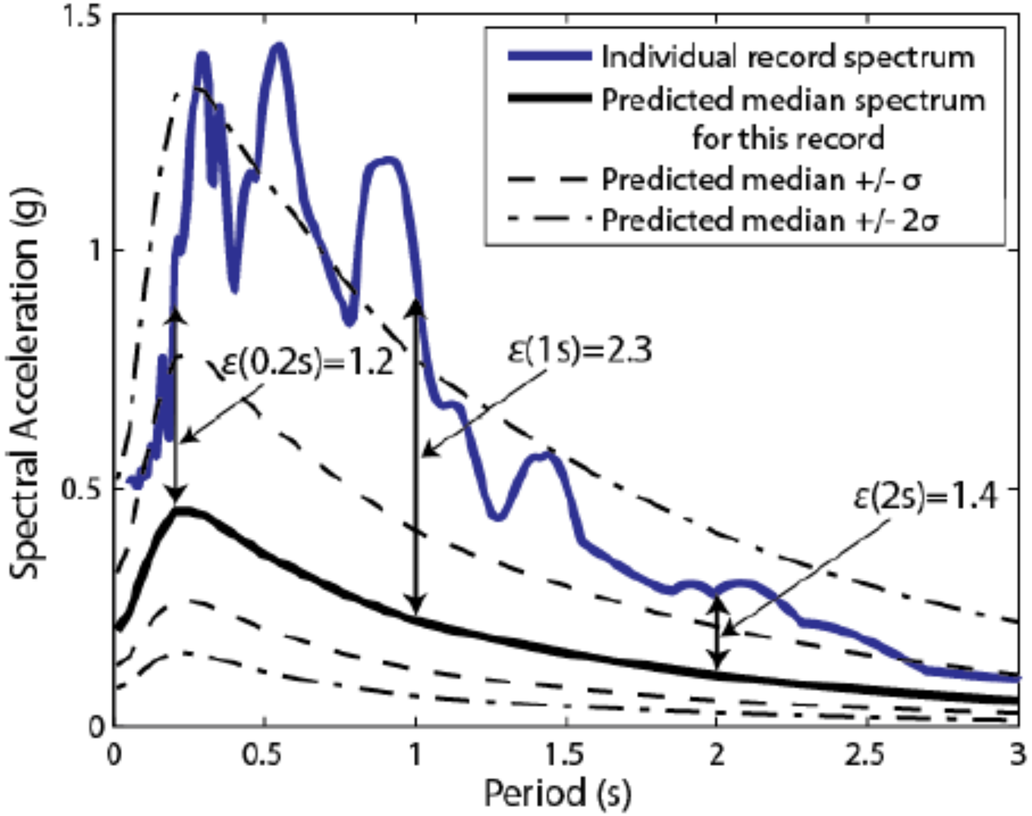
Epsilon (ϵ) is the number of standard deviations difference between the observed GM and the median model prediction (ln units)

data model median

$$\varepsilon(T) = \frac{\ln Sa(T) - \mu_{\ln Sa}(M,R,T)}{\sigma_{\ln Sa(T)}}$$

model sigma

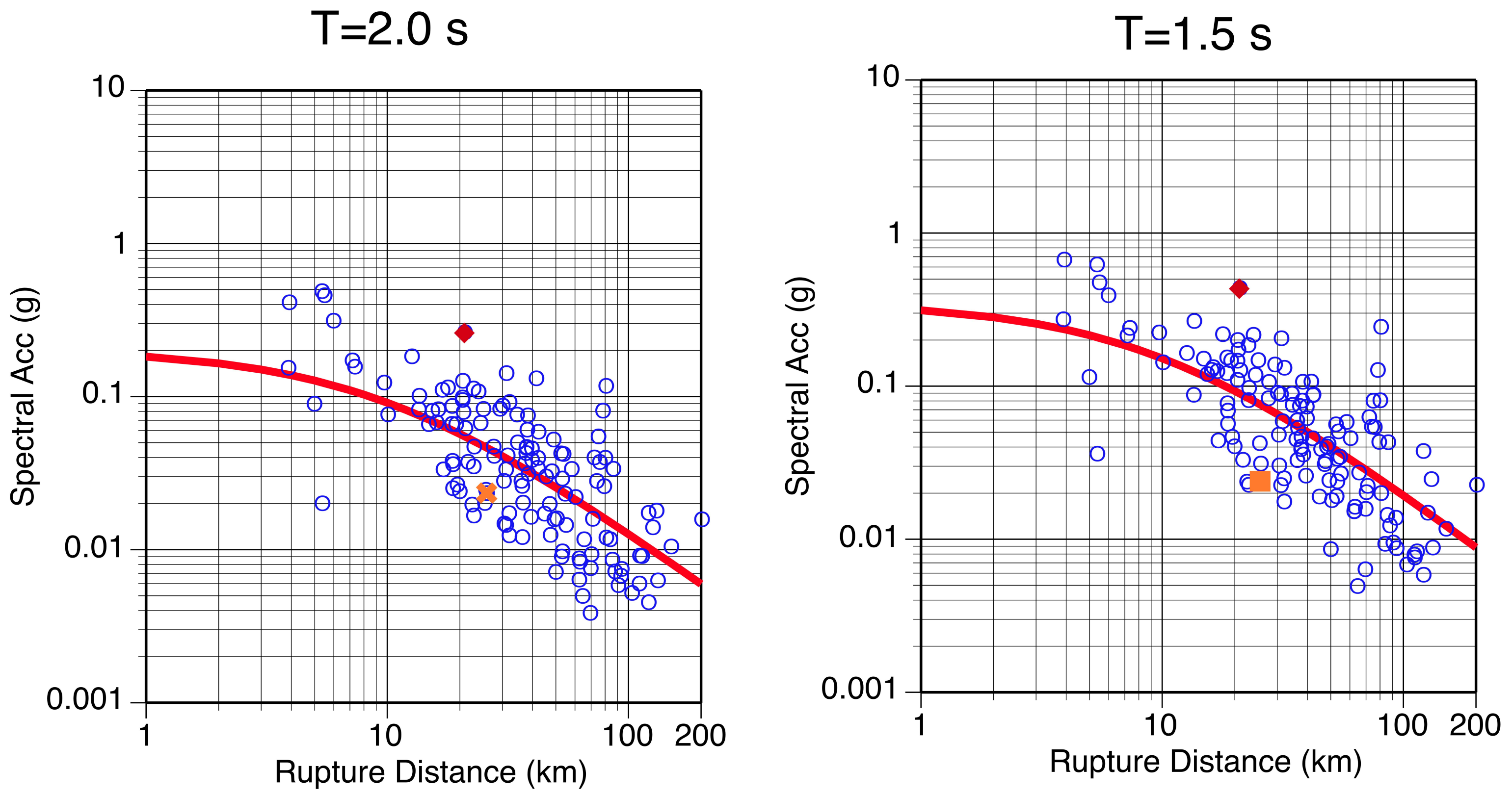
- ϵ is a “normalized residual”
- ϵ is **correlated** between spectral periods



(image from Baker 2010)

(1) Introduction

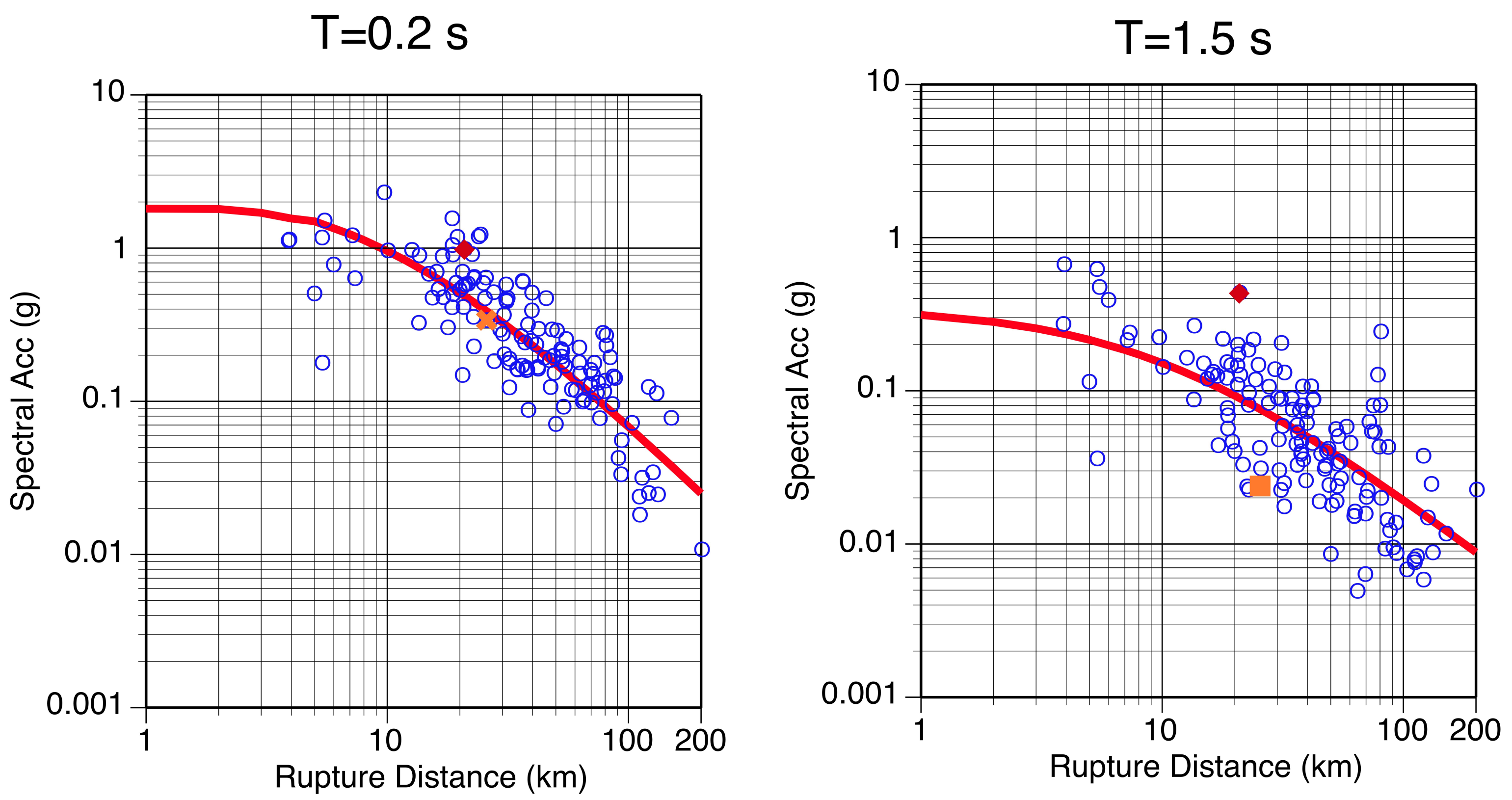
- **Closely spaced** spectral periods:



(image from Abrahamson 2016)

(1) Introduction

- **Widely spaced** spectral periods:



(image from Abrahamson 2016)

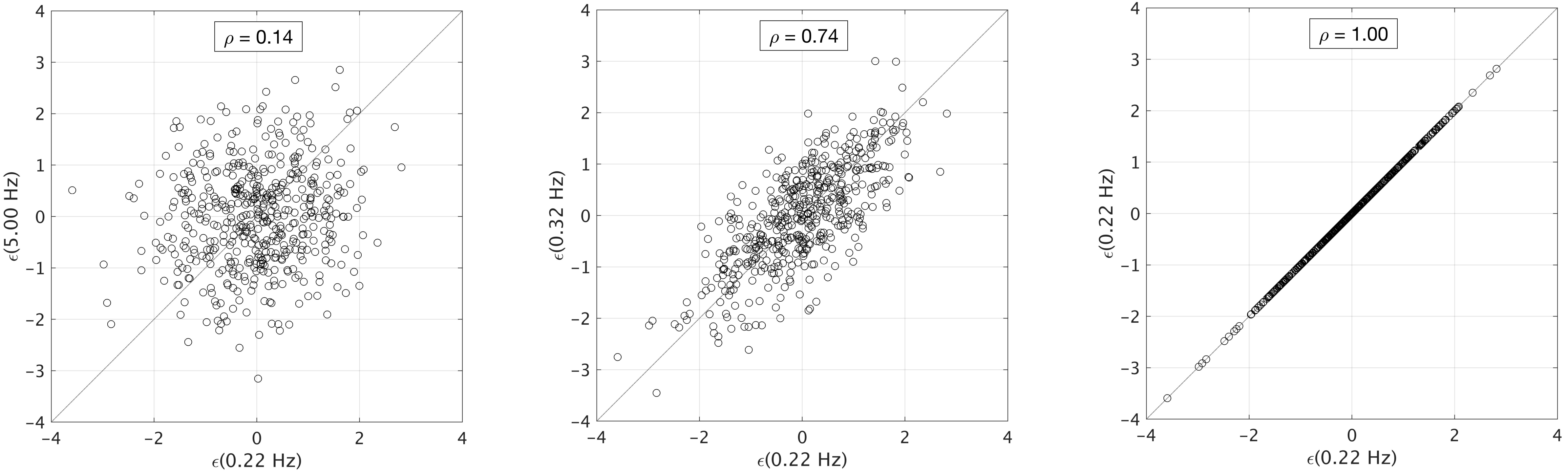
(1) Introduction

For an entire database:

$F_1 = 0.2$ Hz, $F_2 = 5$ Hz
$\rho = 0.14$

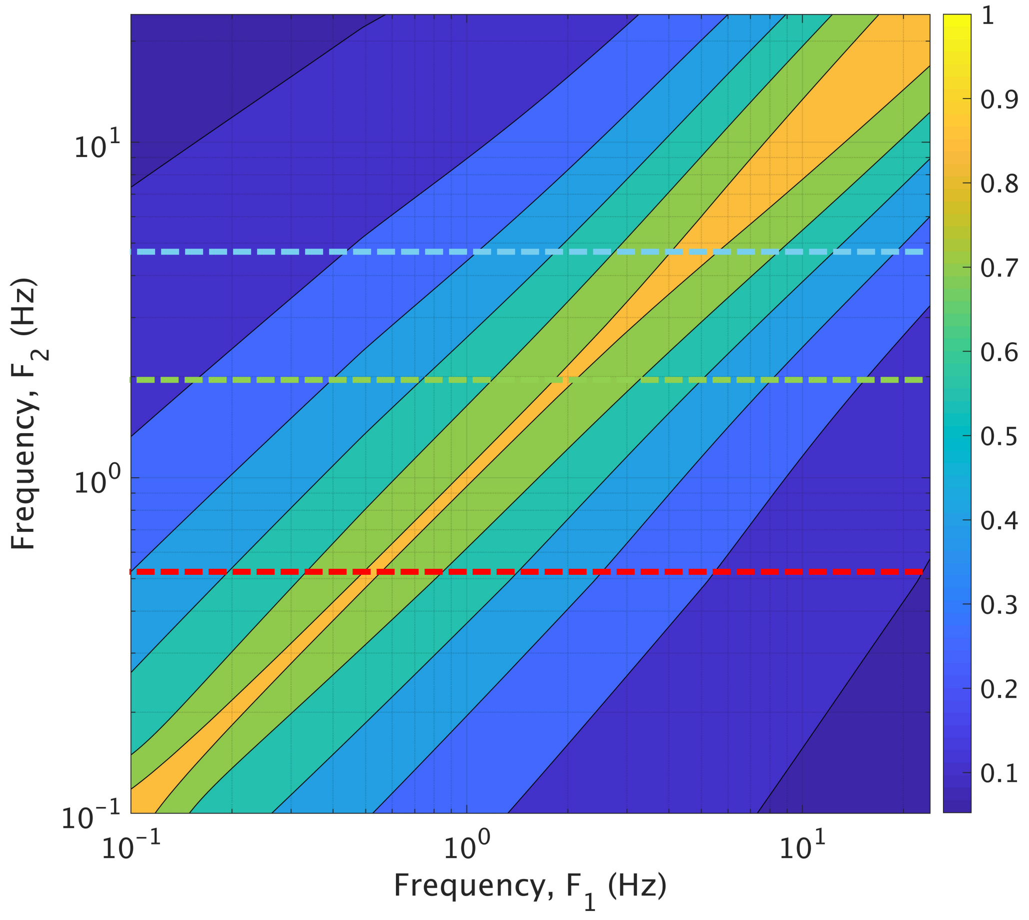
$F_1 = 0.2$ Hz, $F_2 = 0.3$ Hz
$\rho = 0.74$

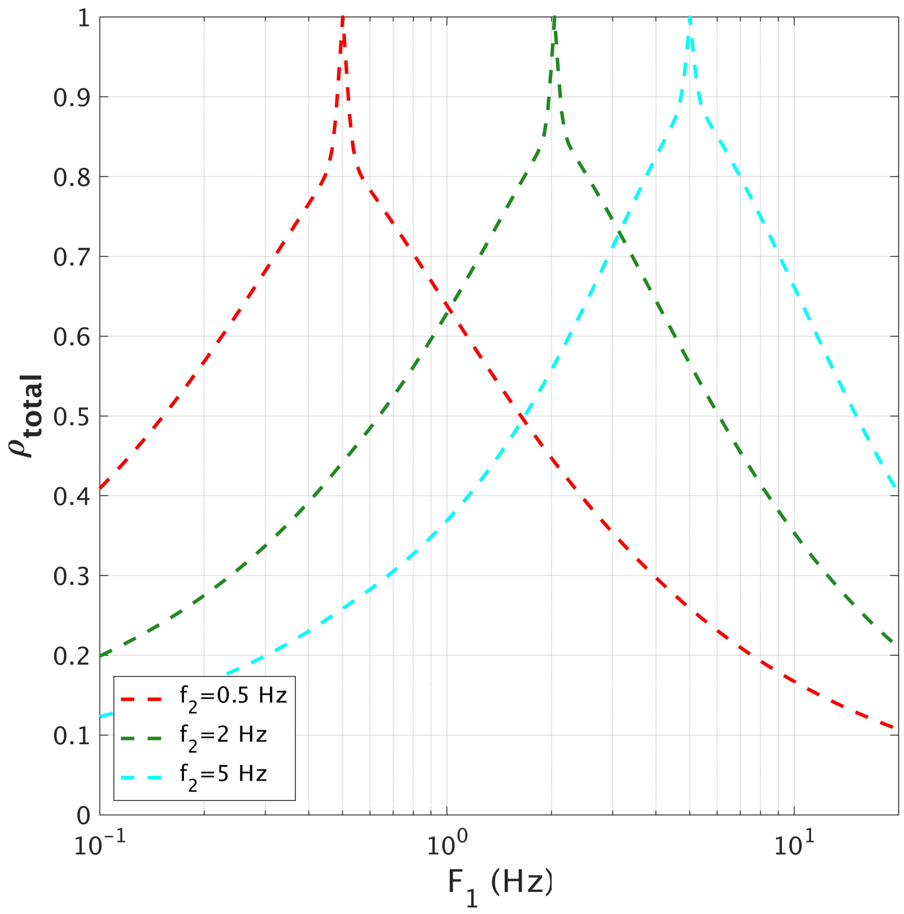
$F_1 = 0.2$ Hz, $F_2 = 0.2$ Hz
$\rho = 1.0$

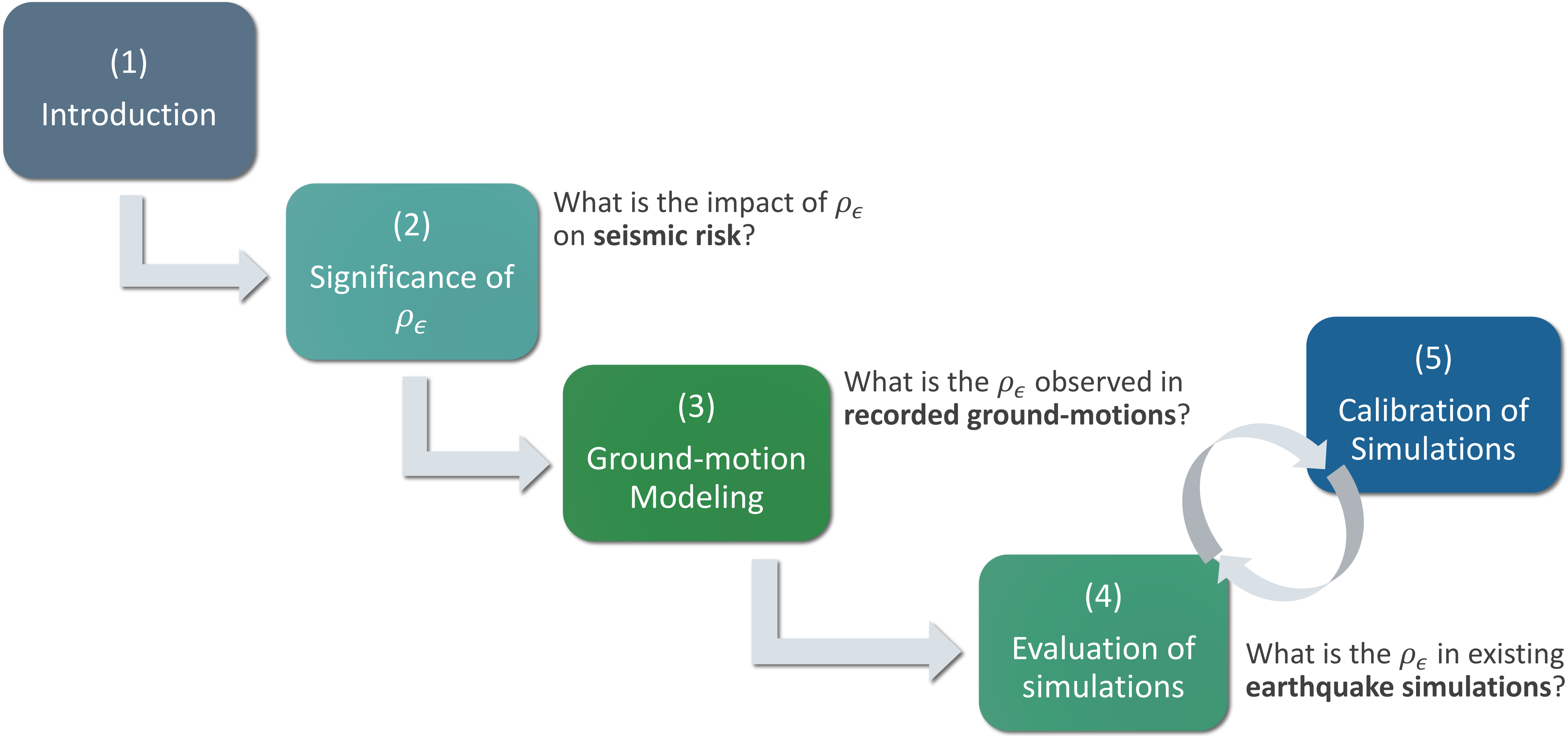


(1) Introduction

Repeat this calculation of ρ for each period (or frequency) pair of interest.



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Calibration of Simulations

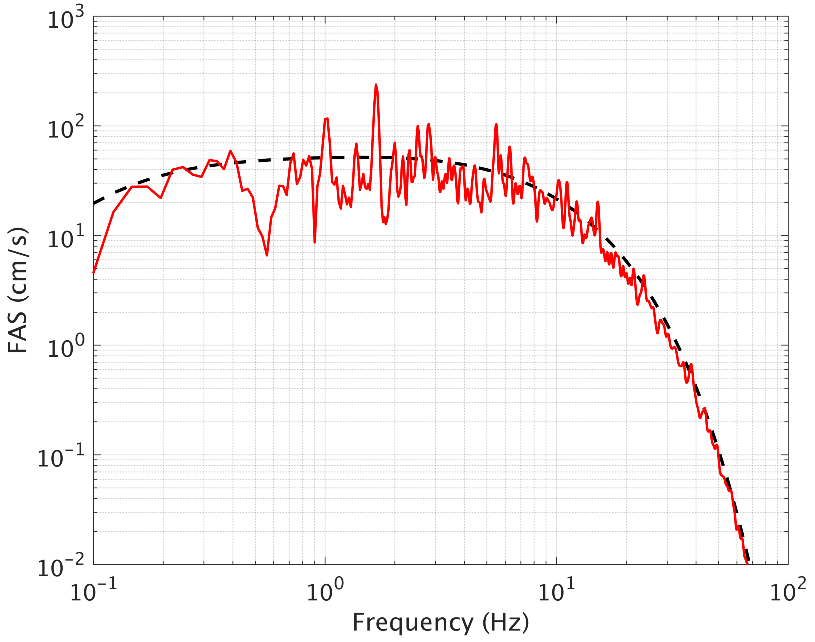
(2) Significance

Why does the **inter-period correlation of ϵ** (ρ_ϵ) matter?

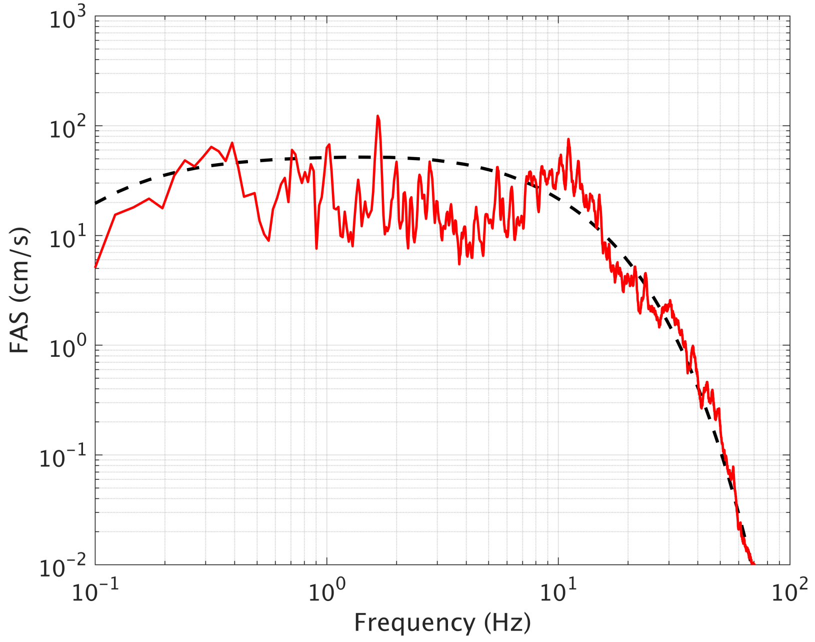
- ρ_ϵ quantifies the relationship of ϵ values between periods for a given recording
- ϵ is an indicator of the local peaks and troughs at a given frequency in a spectrum
- therefore ρ_ϵ characterizes the relative width of these extrema.

Example Fourier Amplitude Spectra (FAS):

Lower ρ_ϵ



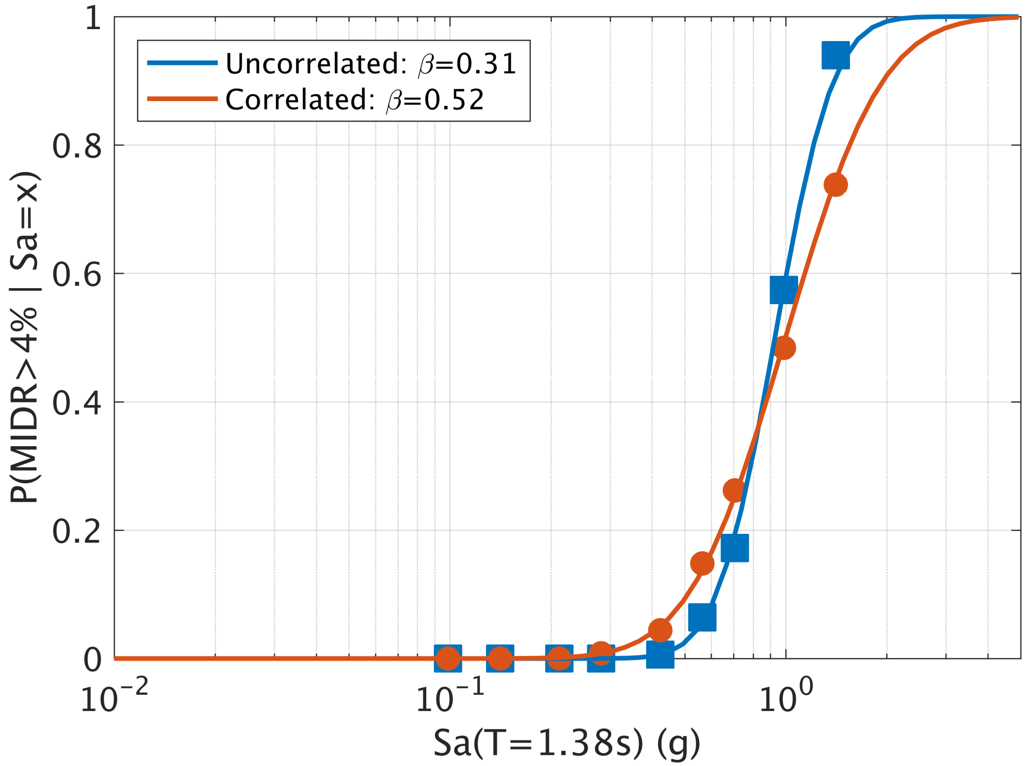
Higher ρ_ϵ

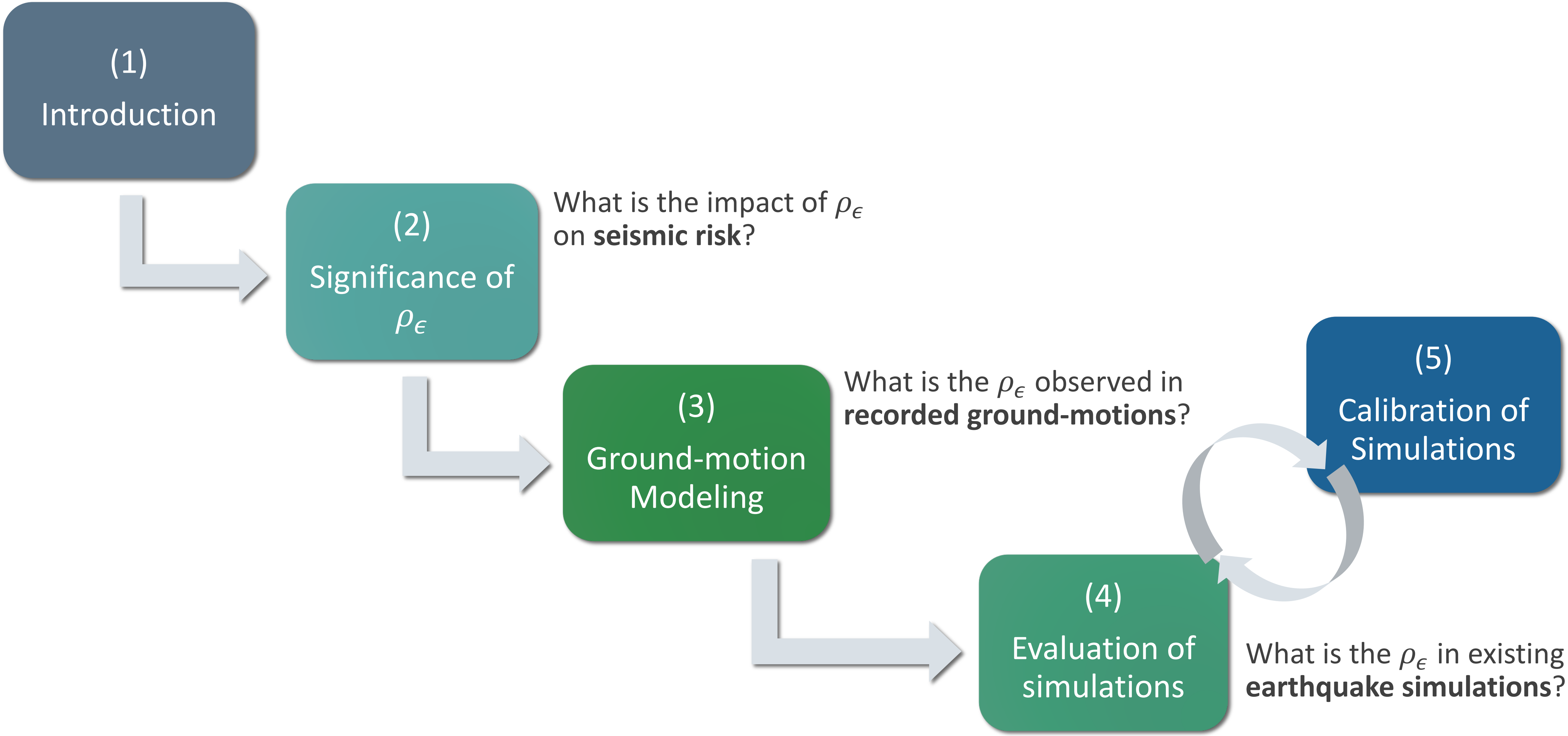


(2) Significance

- As a measure of the width of spectral peaks, is relevant in dynamic structural response
  - Structures are sensitive to a range of frequencies about the fundamental one, especially for nonlinear response
  - Breadth of spectral peaks influences variability of the response
  - This leads to flatter fragility curves
  - Therefore influences seismic risk

- An important metric for **validation** of simulations





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(3) Ground-motion modeling

Purpose: to develop a model for ρ_ϵ using Fourier Amplitude Spectra (FAS)

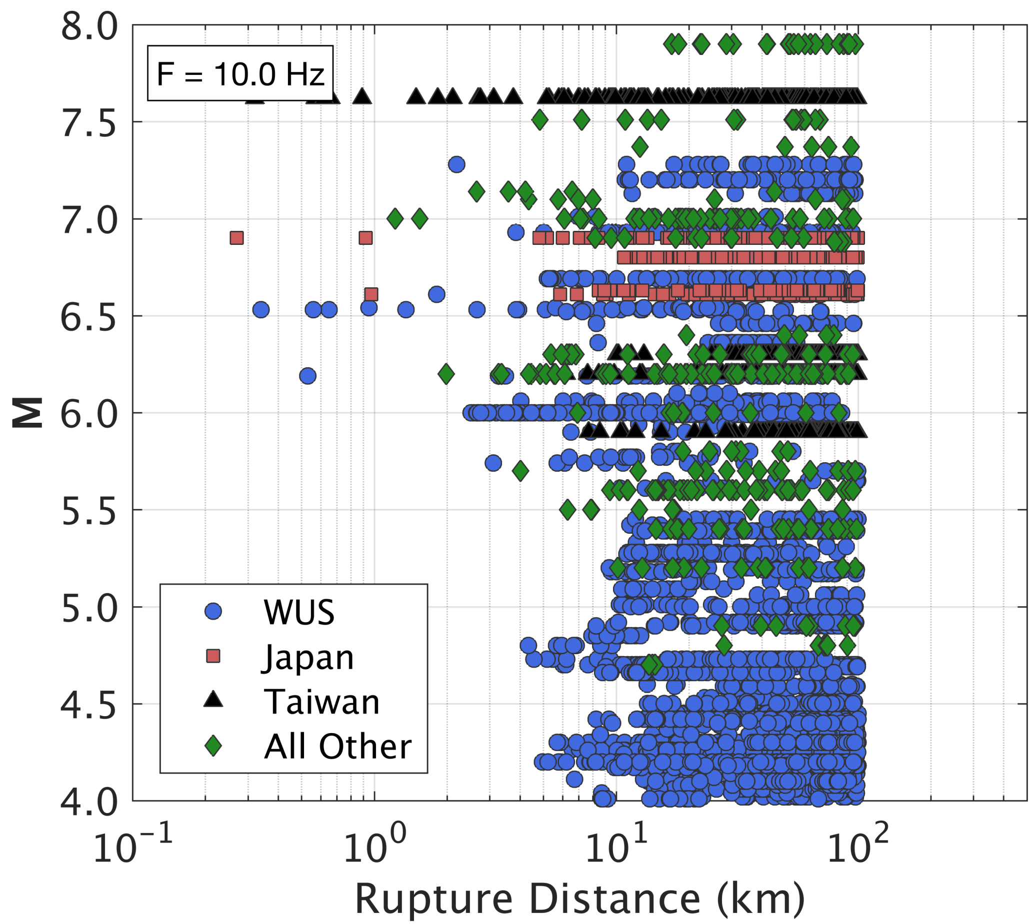
1. Model for the FAS
2. Model for ρ_ϵ (requires FAS residuals)

Why FAS and not response spectra (PSA)?

- The FAS is a more direct representation of the GM than PSA
- FAS scaling is easier to explain using seismological theory
- For calibrating simulations, is more closely related to the physics and better understood by seismologists

(3) Ground-motion modeling

1. Model for the FAS



$$EAS(f) = \sqrt{\frac{1}{2}\left[FAS_{HC1}(f)^2 + FAS_{HC2}(f)^2\right]}$$

Smoothed in log-space

(3) Ground-motion modeling

1. Model for the FAS

$$ln\ EAS = ln\ EAS_{med} + \epsilon\sigma$$

$$ln\ EAS_{med} = f_M + f_P + f_S + f_{Ztor} + f_{NM} + f_{Z1}$$

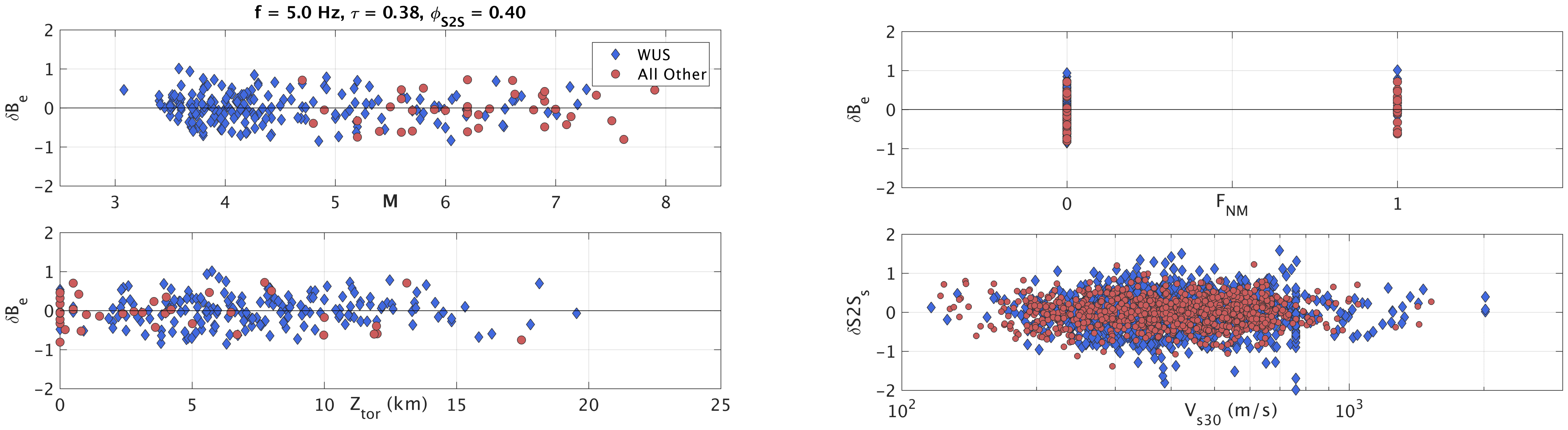
$$\sigma = \sqrt{\tau^2 + \phi_{S2S}^2 + \phi_{SS}^2}$$

- For the smoothed EAS
- Non-linear mixed effects regression at each frequency independently
- Performed in a series of regression steps
  - to prevent trade-off of correlated model coefficients and to constrain different components of the model using the data relevant to each piece
- Emphasis is placed on model scaling and extrapolation outside ranges well constrained by data
- Uses finite-fault simulations to constrain near-fault saturation

(3) Ground-motion modeling

1. Model for the FAS

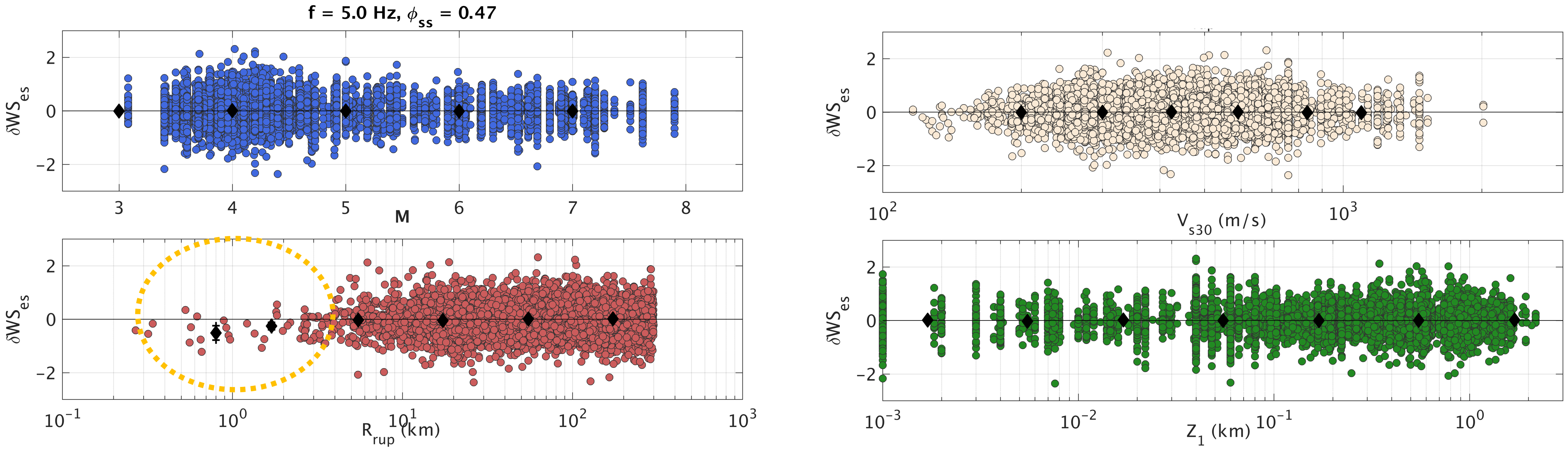
Example Residuals



(3) Ground-motion modeling

1. Model for the FAS

Example Residuals

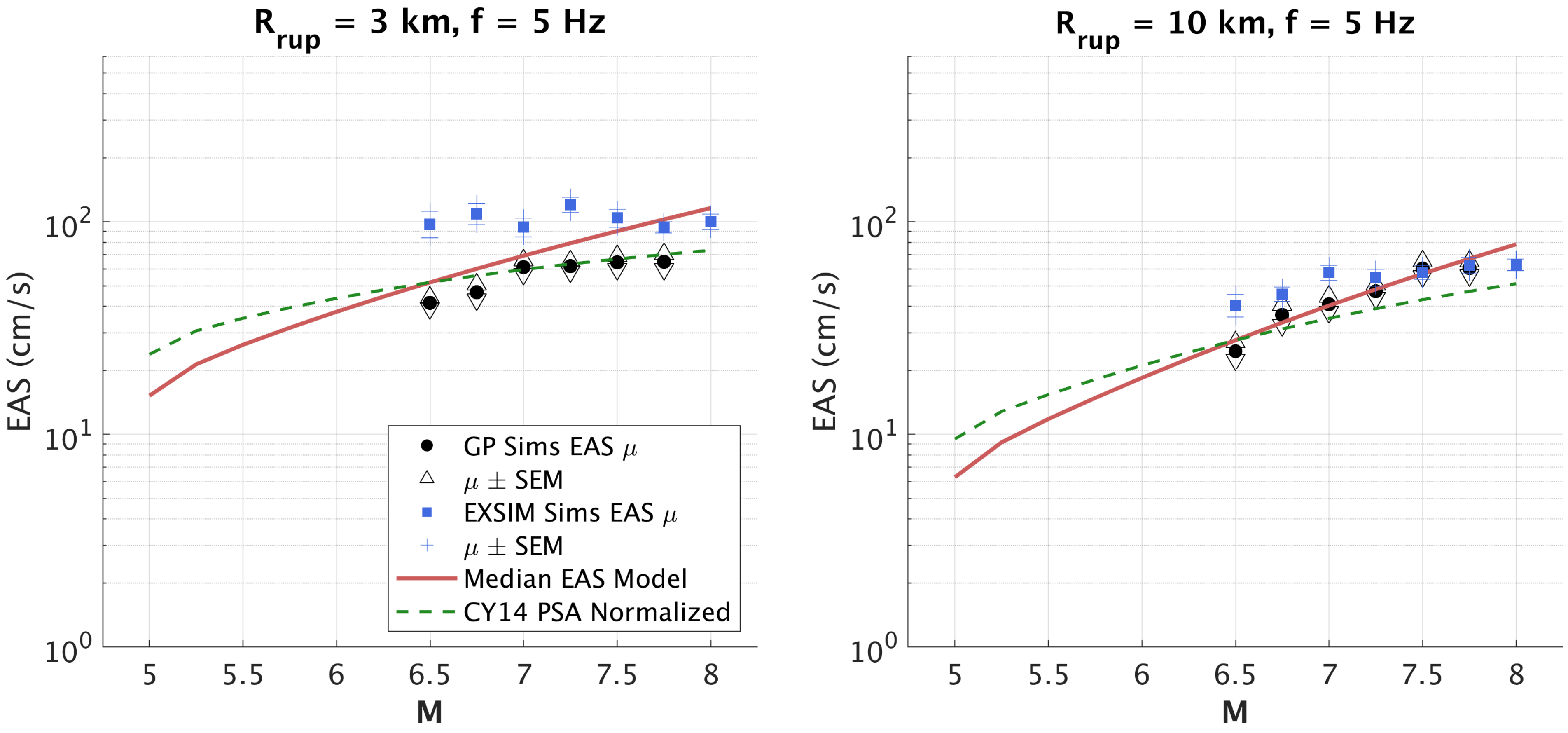


Near-fault saturation in the model is not as strong as implied by the data; doesn't allow over-saturation (intentional)

(3) Ground-motion modeling

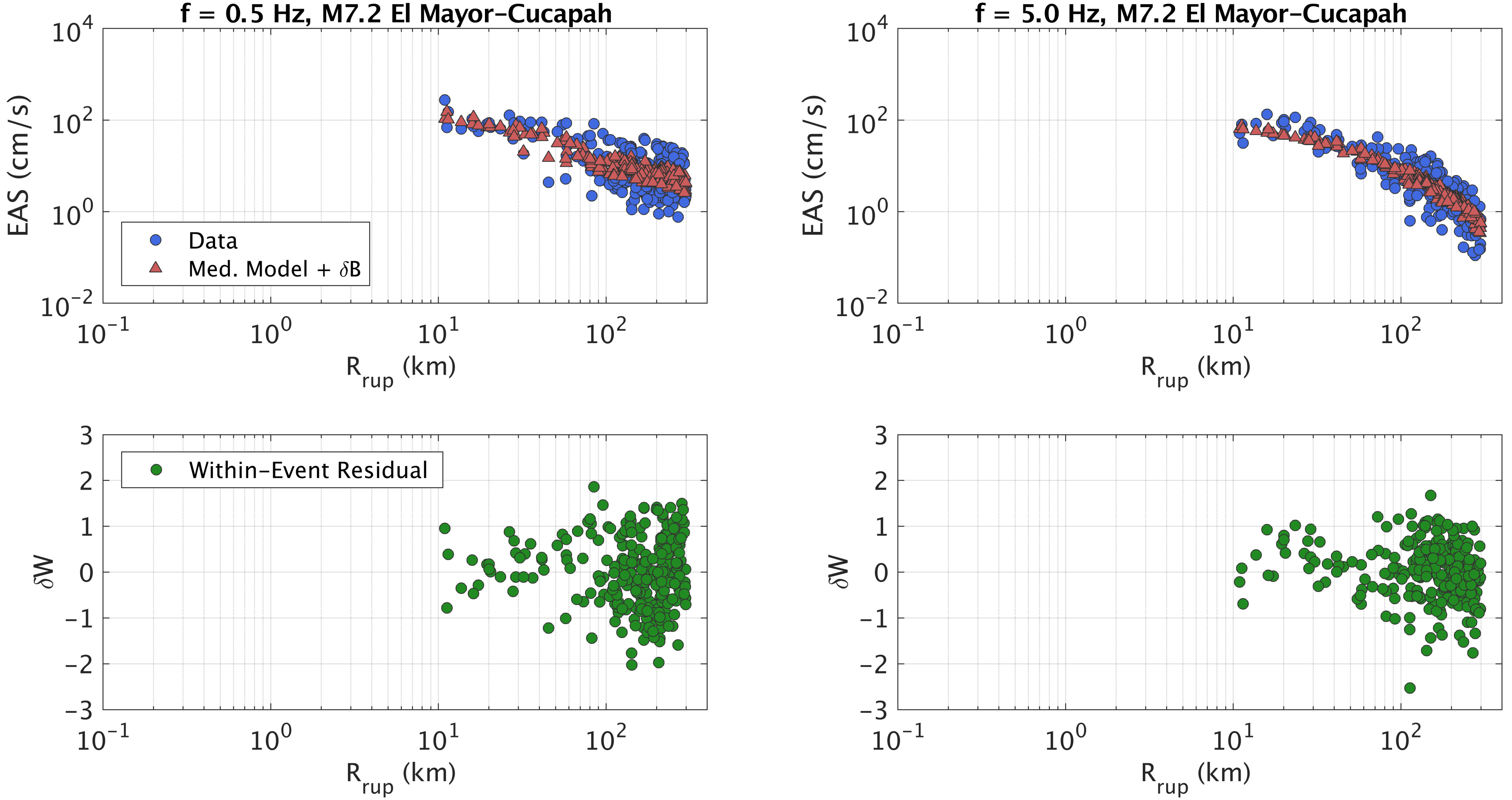
1. Model for the FAS

M-scaling Saturation



(3) Ground-motion modeling

1. Model for the FAS

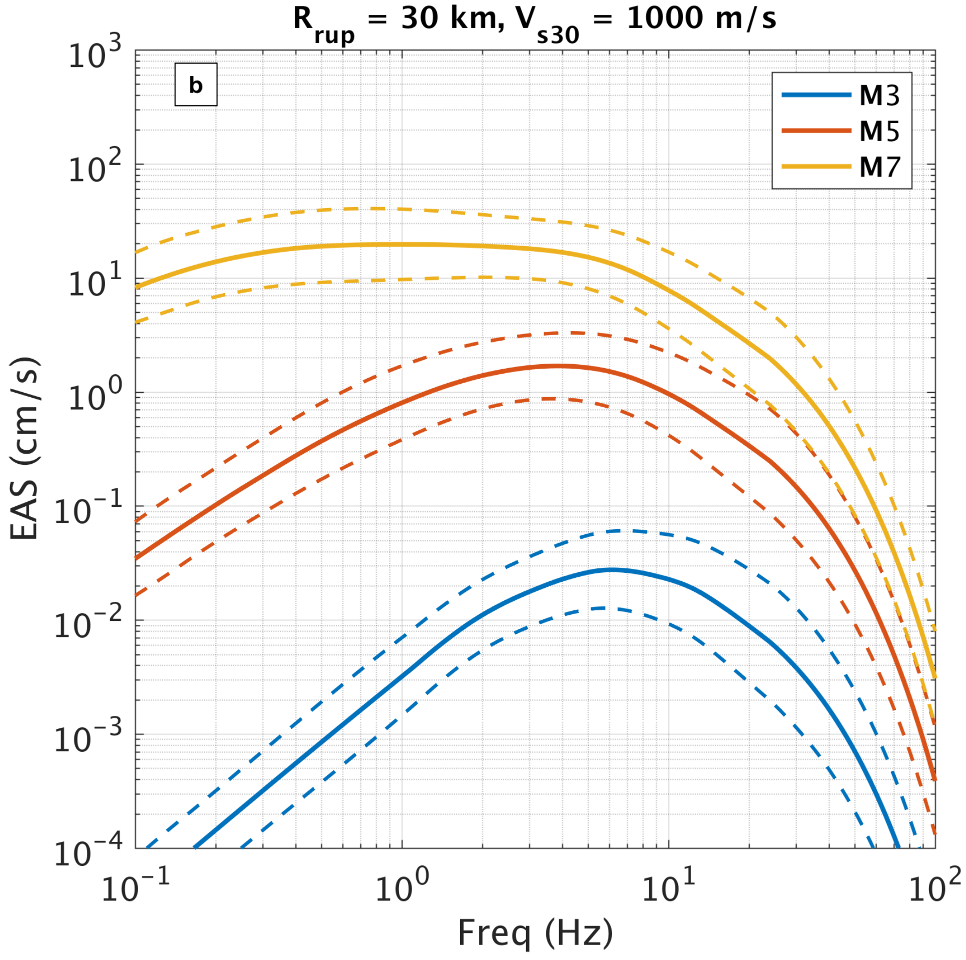


(3) Ground-motion modeling

1. Model for the FAS

Range of Applicability

- Frequency range: 0.1 – 100 Hz; kappa-based extrapolation beyond 24 Hz
- Regionalized for CA/Nevada (but uses data worldwide to constrain the magnitude scaling and geometric spreading)
- Rupture Distances 0 – 300 km
- **M** 3-8
- Vs30 from 180 – 1500 m/s



(3) Ground-motion modeling

2. Model for ρ_ϵ

$$\rho_{\epsilon,total,Model}(f_1, f_2) = tan\,h[\,A(f_m)e^{B(f_m)*f_r} + \;C(f_m)e^{D(f_m)*f_r}]$$

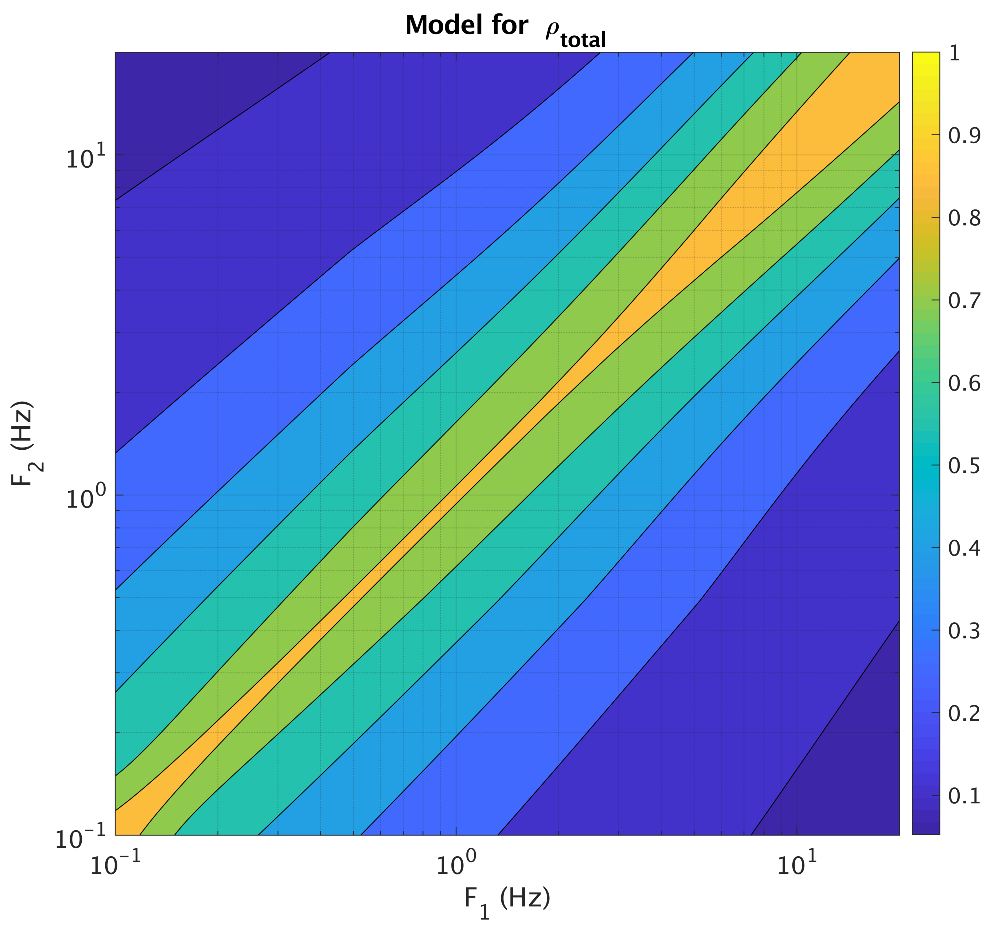
$$f_r = \left|ln\left(\frac{f_1}{f_2}\right)\right|$$

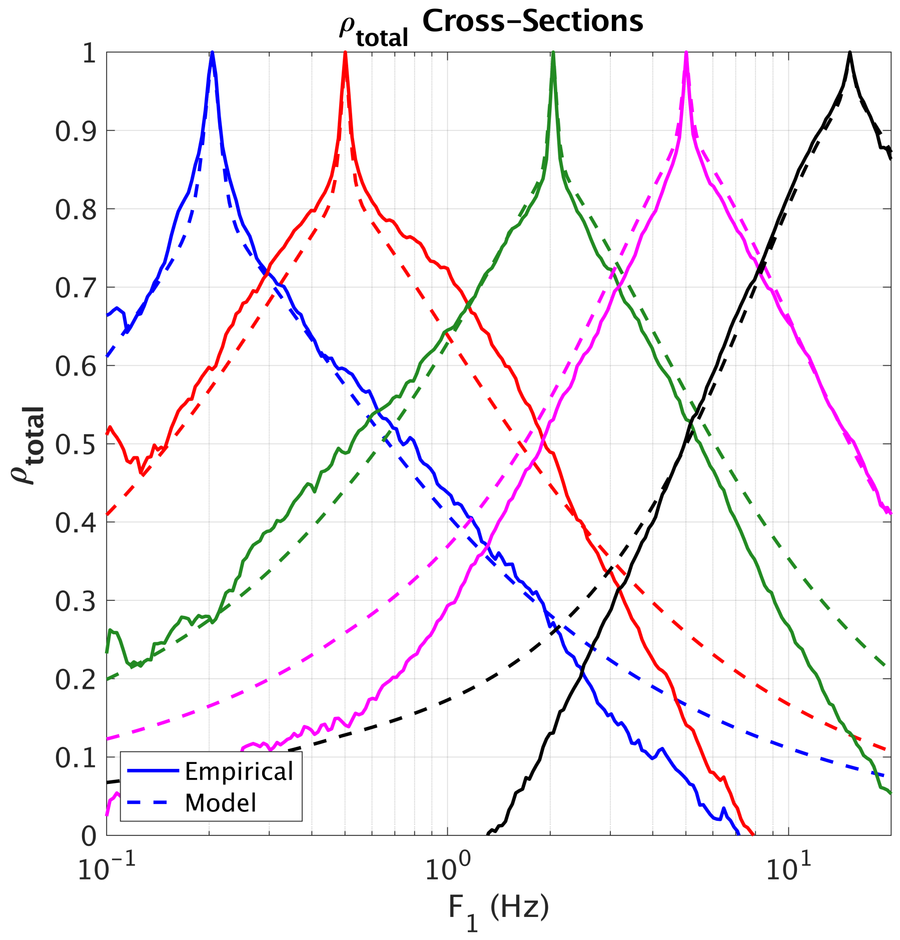
$$f_m = min(f_1, f_2)$$

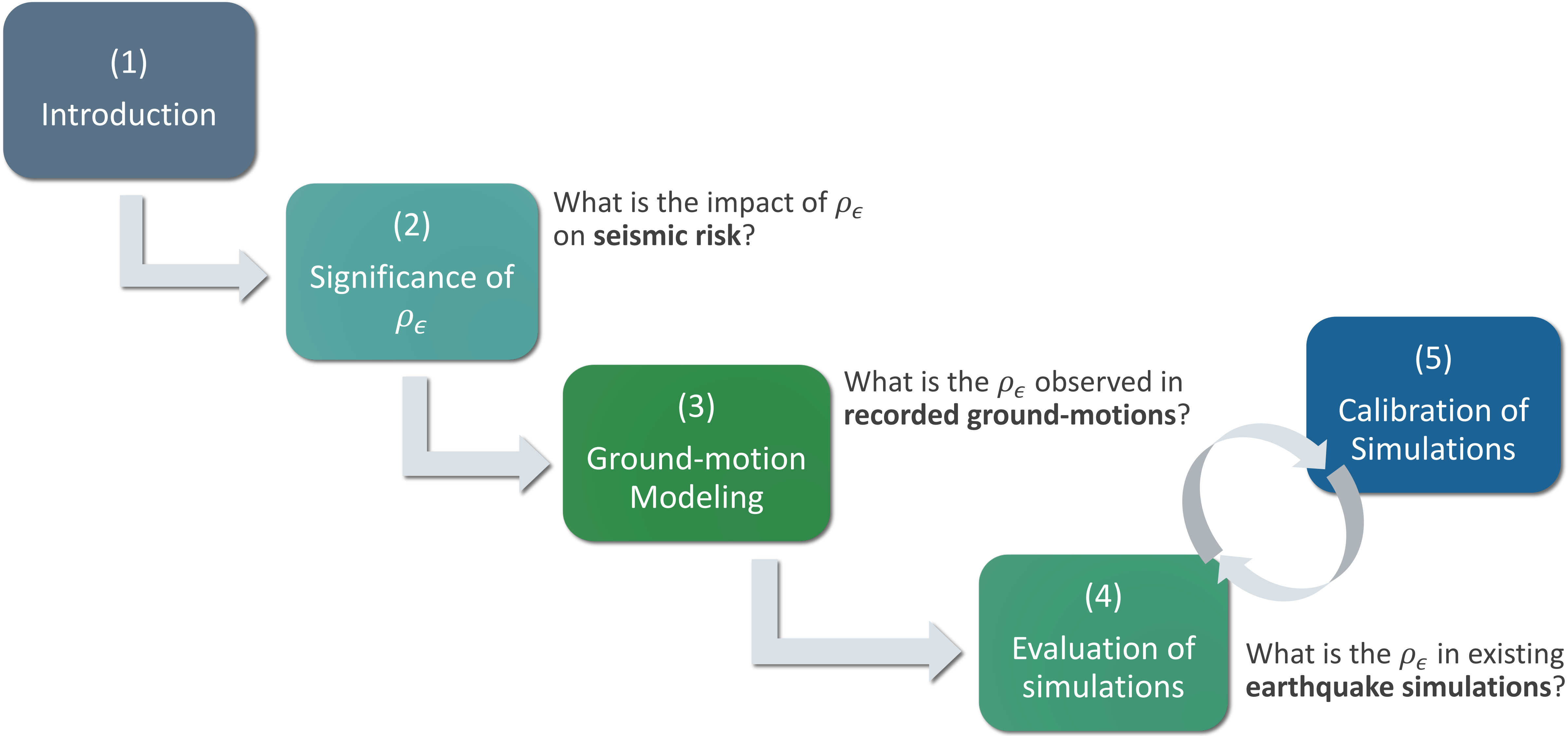
- Uses residuals from the EAS model
- Model is developed for the total correlation (a combination of the contribution from different residual components)
- Is two-term exponential decay with the natural logarithm of frequency, on Fisher VST values
- Applicable to shallow crustal earthquakes in active tectonic regions
- Is independent of magnitude, distance, and Vs30

(3) Ground-motion modeling

2. Model for ρ_{ϵ}



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(4) Evaluation of ground-motion simulations

Purpose: to compare ρ_ϵ in the data with that of several established simulation methods

Simulation Methods Evaluated:

EXSIM (Atkinson and Assatourians, 2015)
GP (Graves and Pitarka, 2015)
SDSU (Olsen and Takedatsu, 2015)
UCSB (Crempien and Archuleta, 2015)
SONG (Song, 2016)
LLNL (Rodgers et al., 2018)

- The first 5 use 1-D (plane-layered) earth models with no site effects on the SCEC BBP. 4 of these have been validated for their median PSA
- Simulations of 9 crustal earthquakes, each with 50 alternate source realizations
- LLNL simulations are a M7.0 Hayward fault scenario, with 3-D earth model, f<5 Hz, one realization

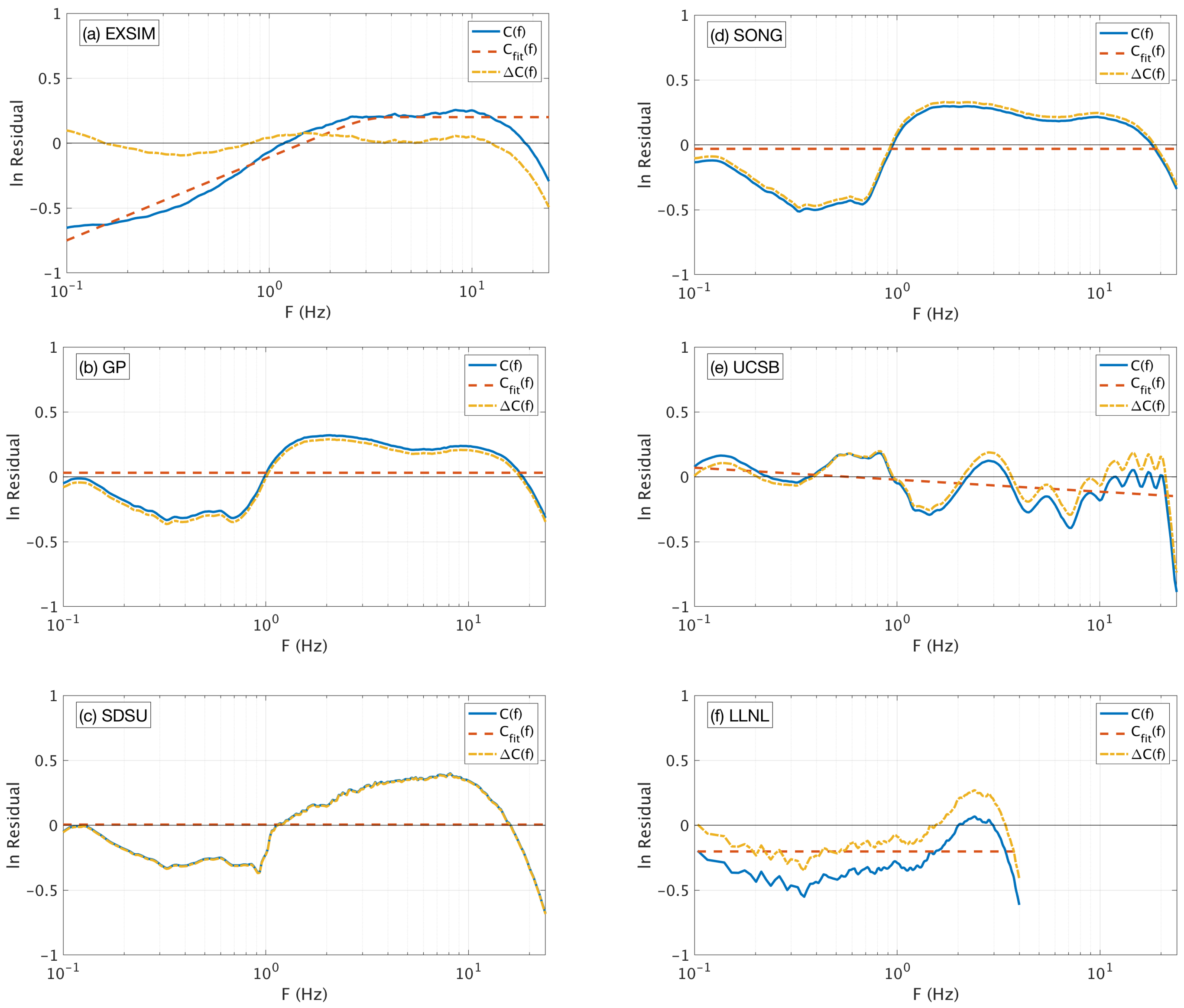
(4) Evaluation of ground-motion simulations

Evaluation Procedure

- Calculate residuals from the simulations relative to the FAS model
- Partition the residuals into components: mean bias, between-event, ~~between-site~~, within-site
- Calculate ρ_ϵ for each residual component and the total ρ_ϵ

(4) Evaluation of ground-motion simulations

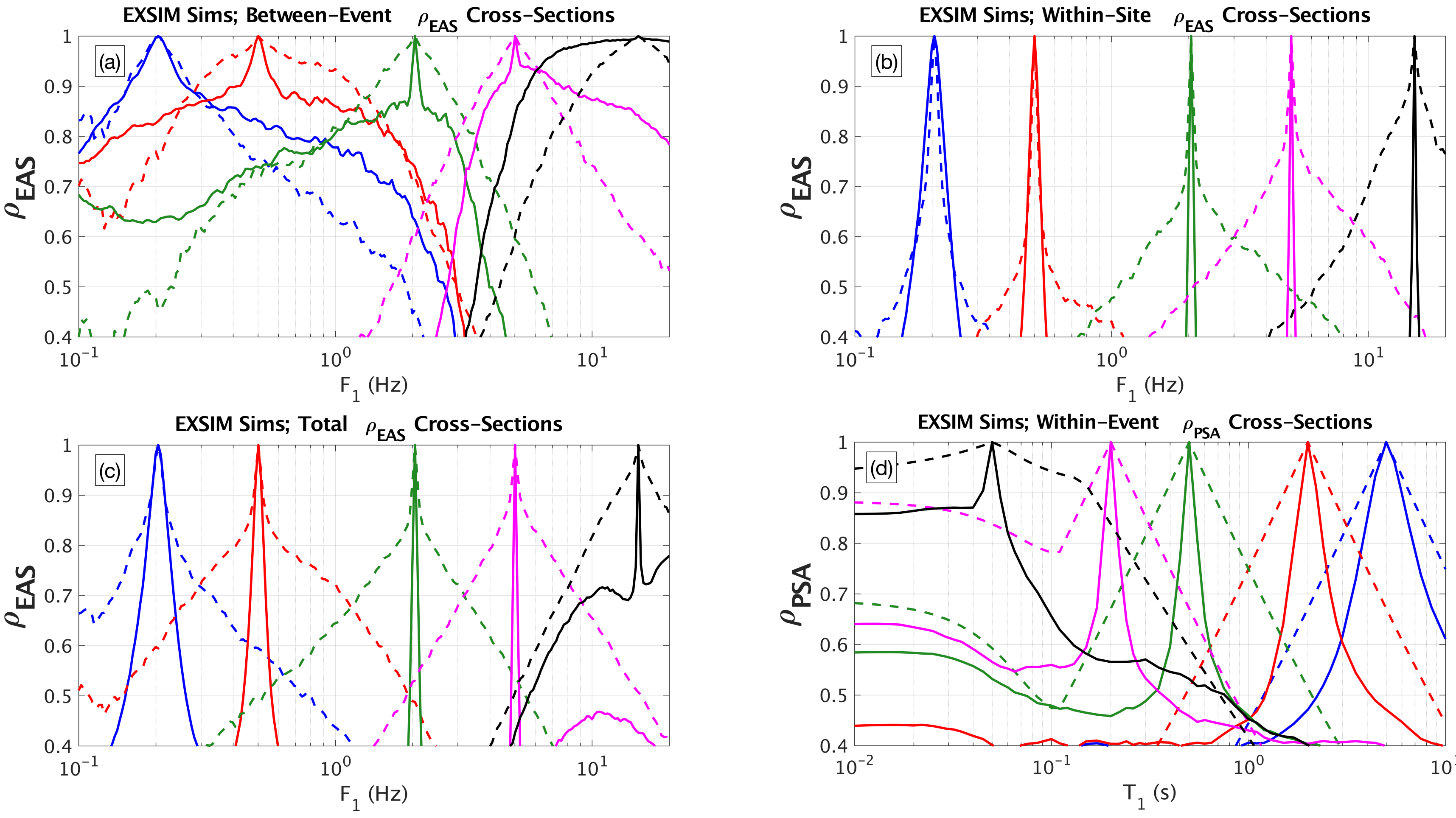
Mean Bias



(4) Evaluation of ground-motion simulations

EXSIM

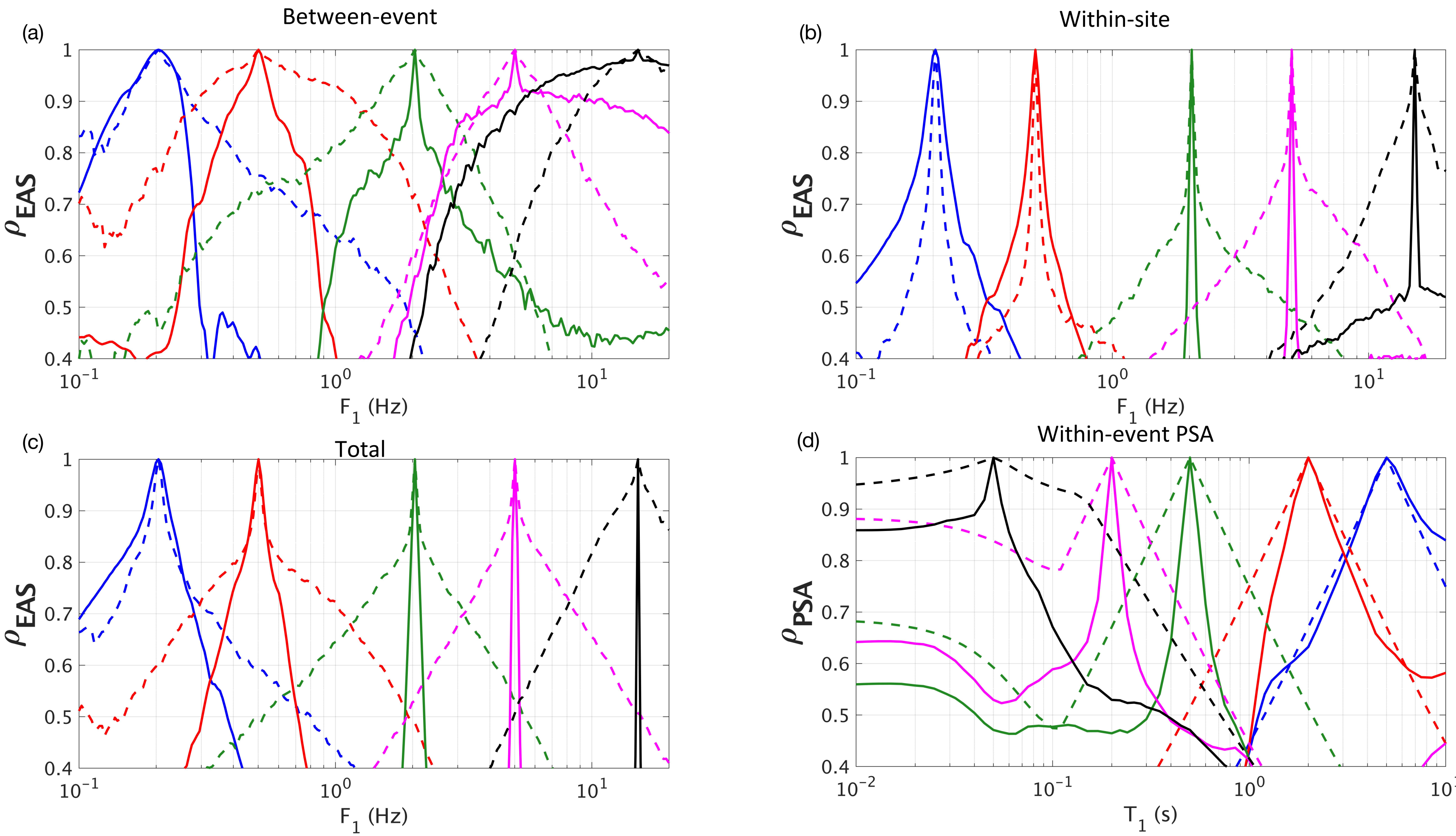
(no between-event term)

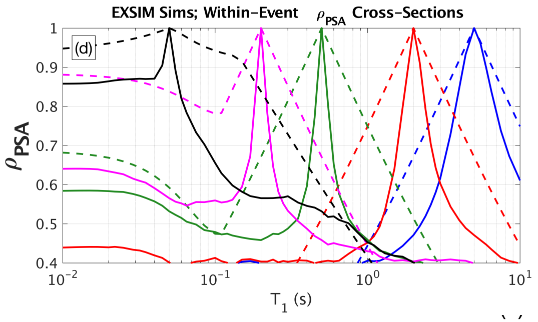


(4) Evaluation of ground-motion simulations

GP

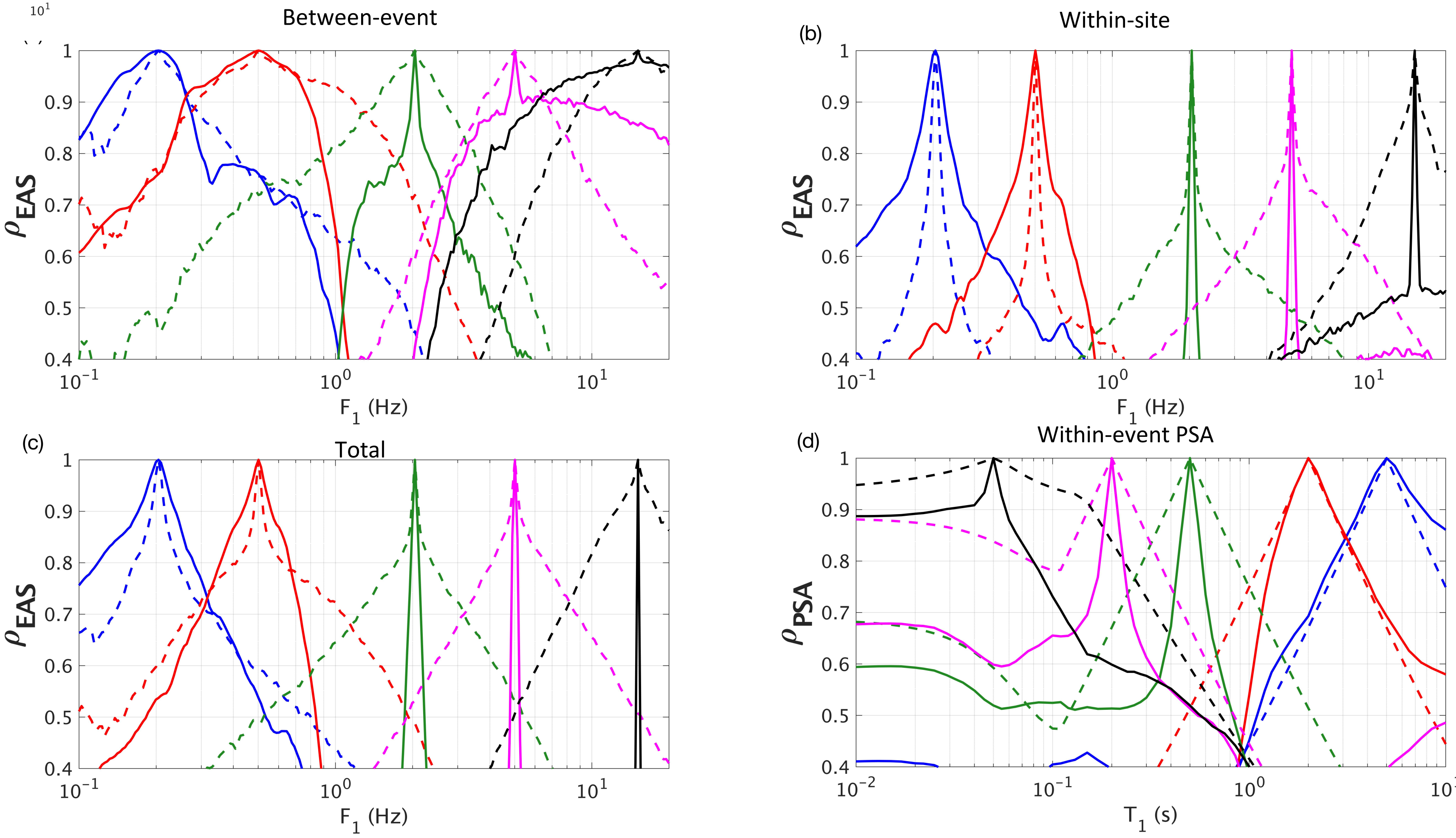
(no between-event term)





...tion of ground-motion simulations

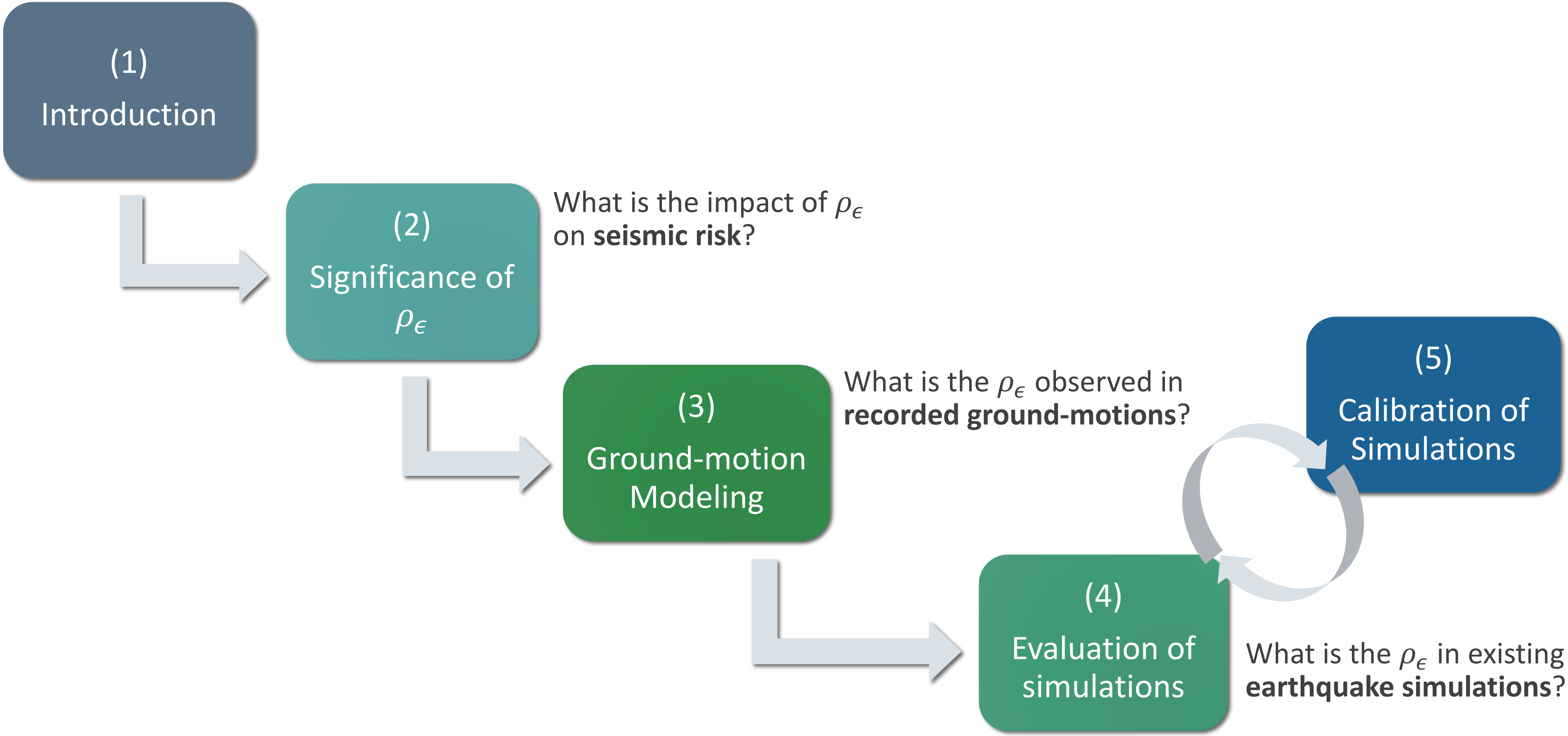
(no between-event term)



(4) Evaluation of ground-motion simulations

Conclusions

- None of the six finite-fault simulation methods tested adequately capture ρ_ϵ over the entire frequency range evaluated
- Several show promise, especially at low frequencies.
- changes to the rupture generator may be the most promising approach to modifying the long period ρ_ϵ
- Using the correlation of the EAS provides the developers of the simulation methods better feedback in terms of how they can modify their methods that is not clear when using PSA
- More calibration is required…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(5) Calibration of ground-motion simulations

Purpose: to test methods for calibrating ρ_ϵ of the simulations

Calibration Approach

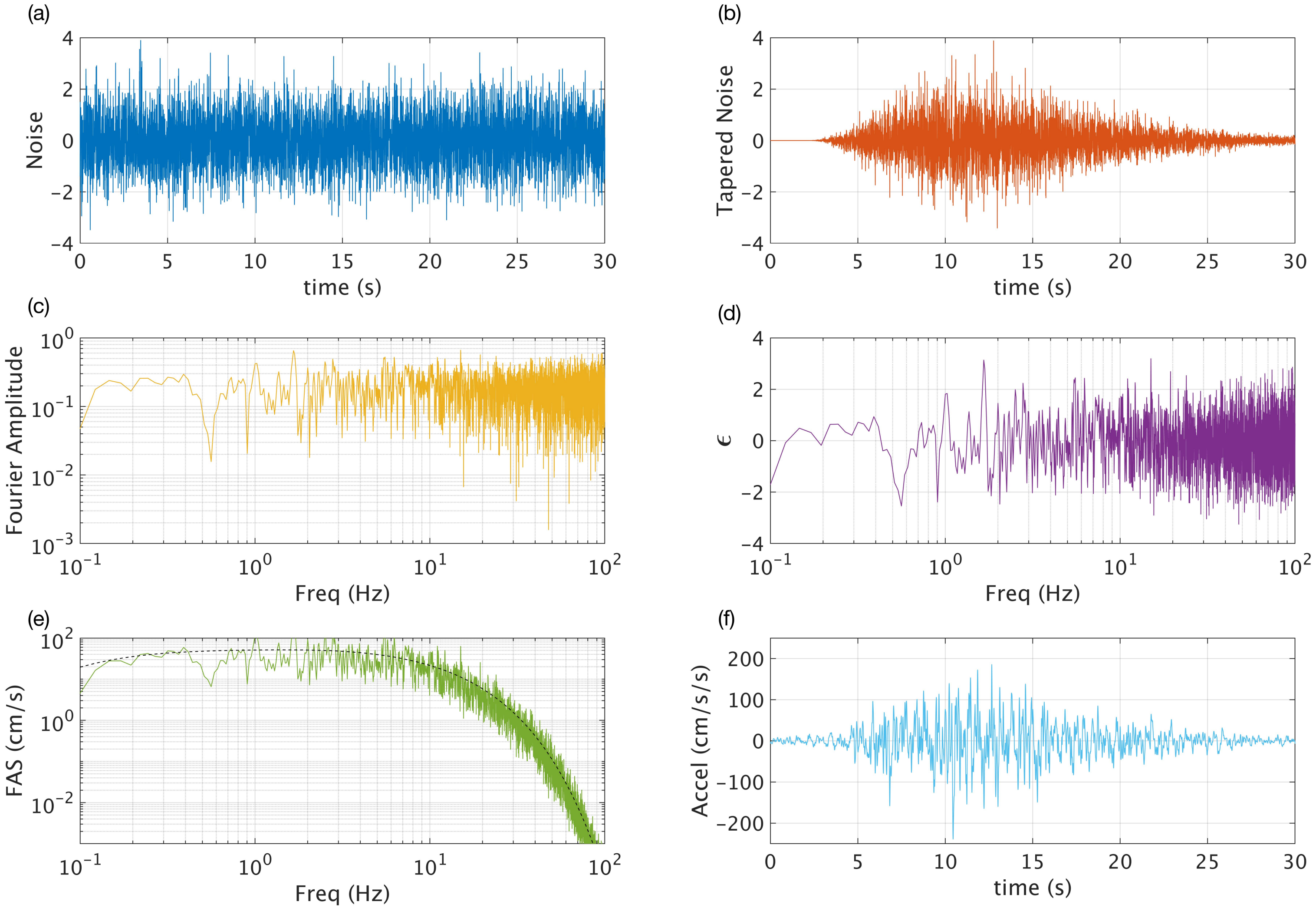
- Start with the simplest simulation method available: SMSIM
- build up to EXSIM
- GP is similar to EXSIM at high frequencies

(5) Calibration of ground-motion simulations

SMSIM Procedure
for generating simulated ground-motions

AKA the point-source stochastic method

This method has zero ρ_ϵ

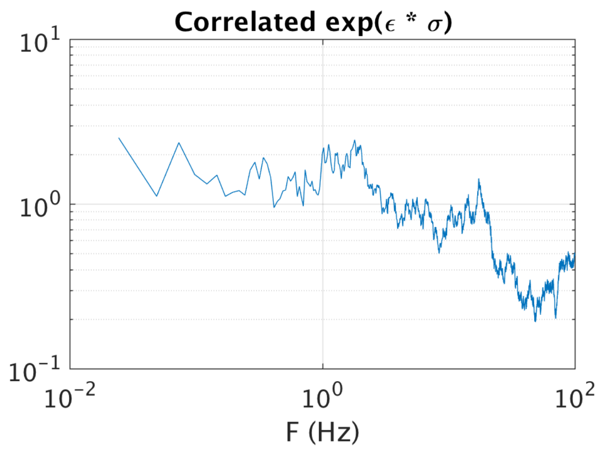


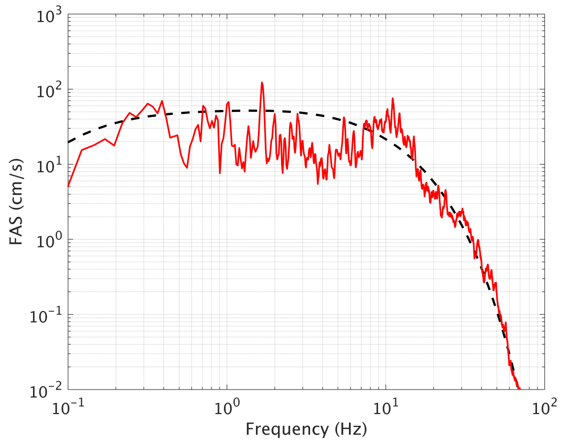
(5) Calibration of ground-motion simulations

Modifying the SMSIM Procedure

- Replace the uncorrelated epsilon values from step d with correlated ones using the model for ρ_{ϵ}
- Shape these to the scenario spectrum
- Proceed with the inverse Fourier transformation

- This method works well - results in time series with correlation and can be repeated quickly





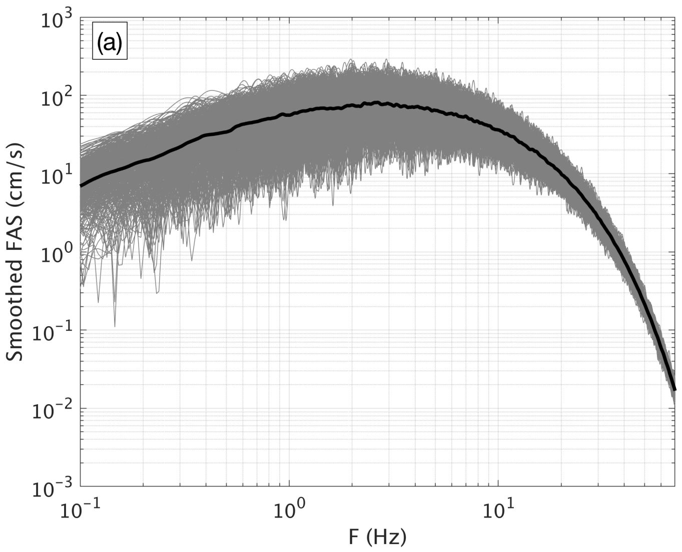
(5) Calibration of ground-motion simulations

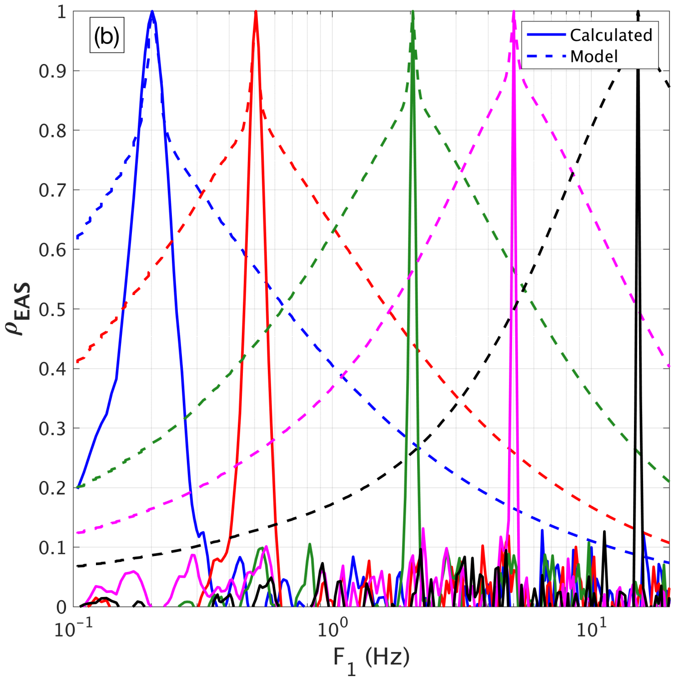
Calibrating EXSIM

EXSIM is the finite-fault extension of SMSIM; it divides a finite-fault rupture into sub-sources with each sub-source modeled as a point source using the point-source stochastic method.

The acceleration time series resulting from each sub-source is summed in the time domain after applying appropriate time delays for propagation of the rupture front

Unmodified EXSIM





(5) Calibration of ground-motion simulations

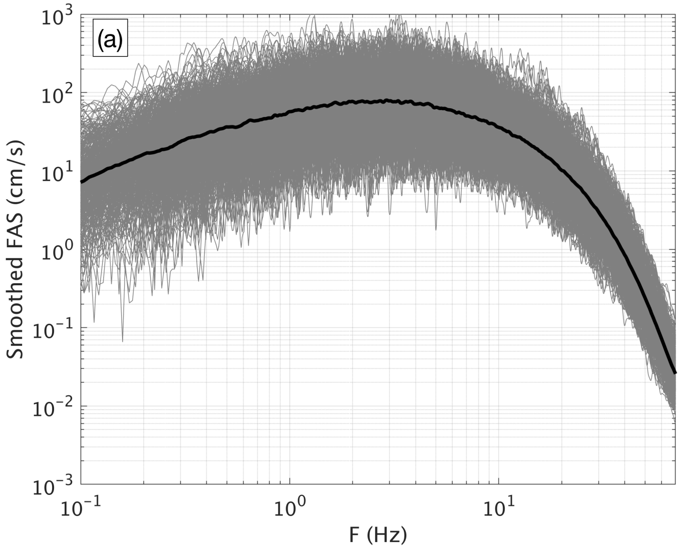
Calibrating EXSIM

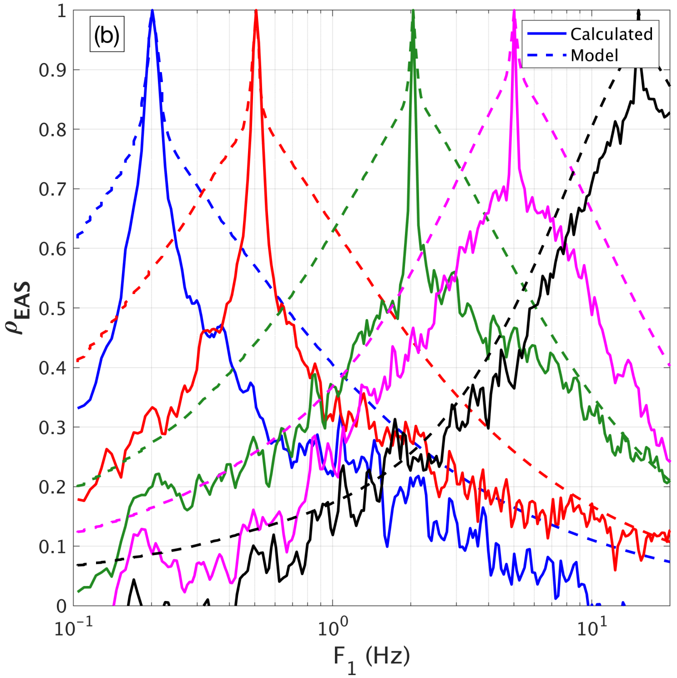
Method 1: different realization of epsilon each sub-source

Method 2: same realization

Both methods resulted in ground-motions with weaker ρ_ϵ than prescribed to each sub-source. This means there is destructive interference of the correlation between sub-sources

Method 2
Modified EXSIM





(5) Calibration of ground-motion simulations

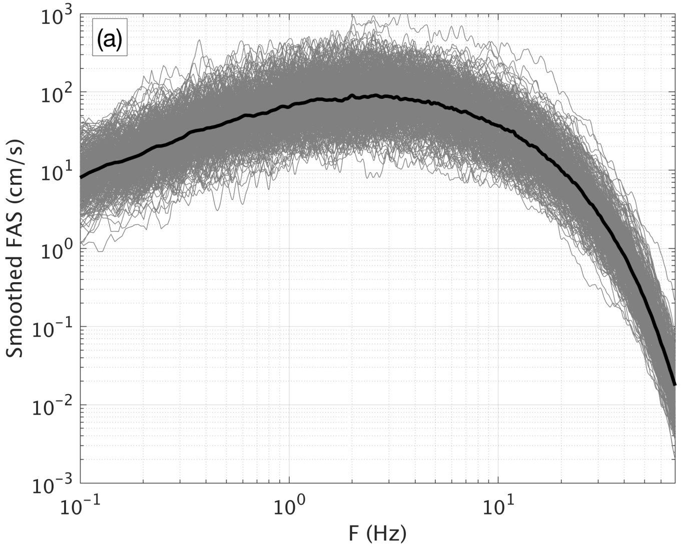
Calibrating EXSIM

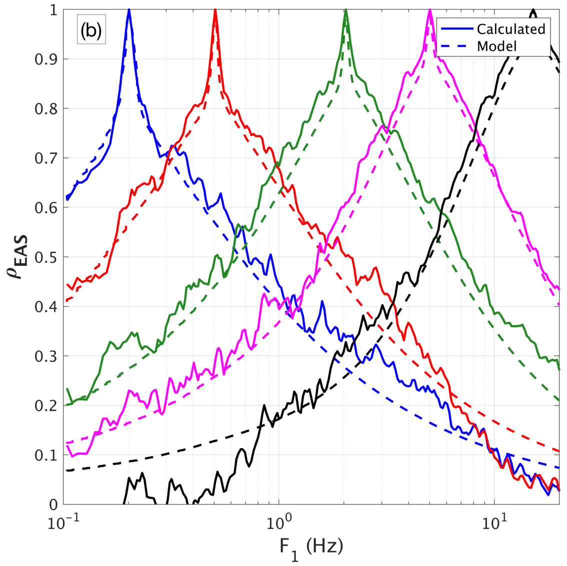
Post-processing method:

- Run the unmodified EXSIM algorithm n times.
- Calculate the geometric mean FAS of the n simulated time series.
- Using the mean spectrum as the target (in place of the point source spectrum), shape the sample of correlated ϵ to the target spectrum.
- use the phase angles from the tapered time domain noise from any of the i^{th} simulation realizations.

This method has been implemented and tested on the SCEC BBP

Drawback: the physical process built into the finite-fault simulations is ignored





(6) Summary and Future Work

Ground-Motion Models

- FAS and ρ_ϵ models for crustal earthquakes
- Future work:

  Regionalized FAS models for areas besides CA, increase FAS model complexity (HW, Directivity), re-evaluate regional dependence of ρ_ϵ with increased data.

Importance of $\boldsymbol{\rho_\epsilon}$ as a validation parameter

- Low FAS ρ_ϵ in simulations under-estimates the variability in structural response.
- This leads to structural fragilities which are too steep (under-estimated dispersion parameter β) and to non-conservative estimates of seismic risk.
- Future work:

  Ensure that future validation efforts focus on this important parameter

(6) Summary and Future Work

Evaluation of Simulations

- None of the methods evaluated are adequate for the full frequency range evaluated; some are acceptable at low f.
- Future work:

  Identifying causal features of the correlation in the simulations, evaluation of more 3-D methods, re-evaluation of the LLNL simulations using multiple source realizations

Calibration of Simulations

- Approaches tested to incorporate the observed ρ_{ϵ} into the finite-fault simulation algorithm EXSIM. The short-term post-processing solution is presented.
- Future work:

  Calibrating the EXSIM sub-source implementation, calibrating other BBP finite-fault simulation methods, upon successful calibration, performing validations of the correlation, mean, and variability, to ensure the calibration did not introduce adverse affects

Thank you

jrbayless@ucdavis.edu