Non-ergodic Ground-Motion Models for California

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Traditional Approach to Ground Motion Models

- Ground Motion Prediction Equations (GMPEs) are Typically Global Averages (Ergodic Model)
  - Need to have enough large magnitude data at short distances to develop an empirical model
  - Group data from analogous tectonic regions
  - Site Response
    - Use VS30 and basin depth
  - Path (wave propagation)
    - Use closest distance
  - Source
    - Use Magnitude and depth

Ergodic GMPE

$$GMPE_{BASE}\left(M, R_{rup}, F, V_{S30}, Z_{TOR}, \ldots\right) =$$

$$\theta_0 + f(M) + \left(\theta_4 + \theta_5 M\right)\ln\left(\sqrt{R_{RUP}^2 + \theta_6^2}\right) + \theta_7 R_{RUP}$$

$$+ \theta_8 F + \theta_{10} Z_{TOR} + \theta_{11} \ln\left(V_{S30}\right)$$

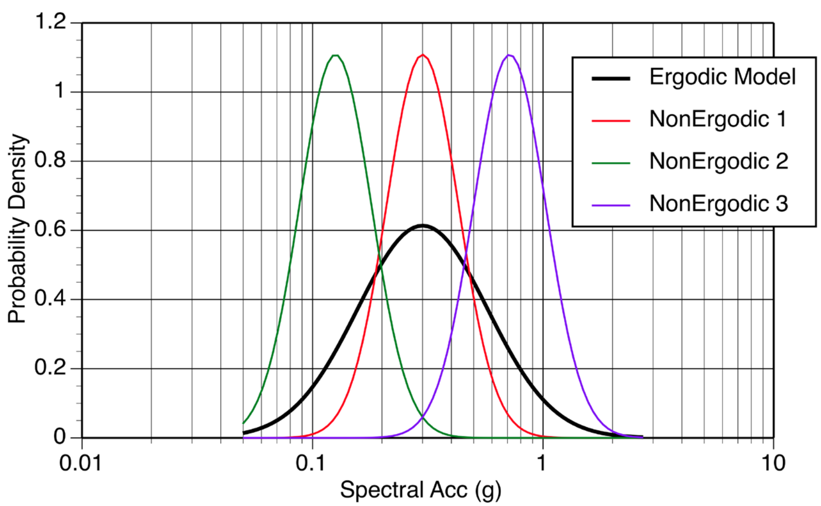
$$+ f_{HW}\left(M, R_{rup}, R_x, \ldots\right) + f_{NL-site}\left(V_{S30}, PSA_{1100}\right)$$

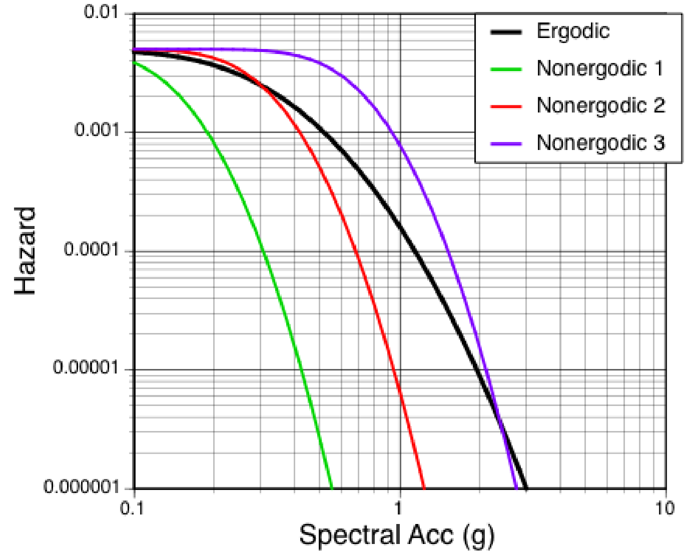
Good “Empirical” GMPEs

- Developing a good GMPE is a model building process, not statistical curve fitting
  - Key to constrain how the GMPE extrapolates to the case important for design, not how well it fits available data (often not important for design)
  - GMPE developers apply constraints to the extrapolation based on scaling from physics-based numerical simulations

Motivation for Moving to Nonergodic GMPEs

- About 60% of the aleatory variance in ergodic GMPEs is due to systematic effects (source, path, site).
  - For T=0.2 sec
    - Sigma ergodic = 0.70
    - Sigma non-ergodic = 0.40
- The path is the largest contributor





Move to Non-Ergodic GM models

Global models (NGA-W1, 2008)	Average Mag and distance scaling around the world. Gives enough data from large mag at close distances to constrain the scaling
Single-station sigma (2006-2011)	Removes the systematic site terms from the aleatory variability.
Broad Regionalization (NGA-W2, 2014)	Account for systematic differences in the large distance (linear R), VS30, Z1.0, Z2.5 and constant terms for broad regions. Also average regional differences in source (median stress-drop)
Broad Regionalization (NGA-SUB, 2018)	Regional differences in linear R, VS30, Z1.0, Z2.5, and constant terms

What is Next in Regionalization?

Continuous spatial regionalization (2016)	Zoneless regionalization. - Regionalized GMPE terms vary based on the location of the site and location of the source - Path effects are isotropic
Site/Source-specific path effects (2018)	Allows the distance scaling to vary for each site and for each source (non-isotropic) - Begins to mimic the approach in 3-D simulations

Empirical Nonergodic GMPE

$$LN(PSA) = GMPE_{BASE}\left(M, R_{rup}, F, V_{S30}, Z_{TOR}\right)$$

$$+ \delta\theta_4(\vec{x}_{Rrup}) \ln\left(\sqrt{R_{RUP}^2 + \theta_6^2}\right)$$

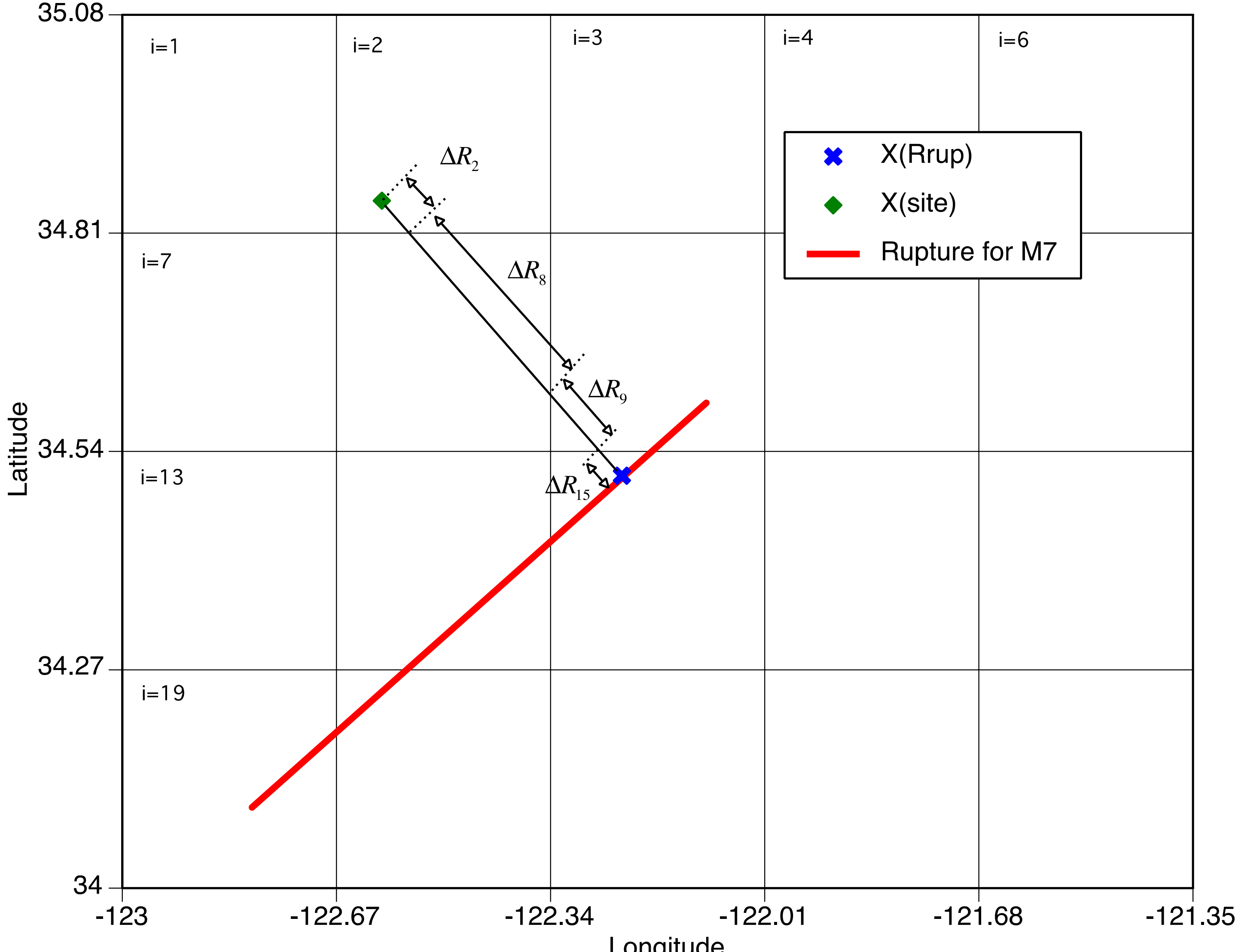
$$+ \delta\theta_{0A}(\vec{x}_{site}) + \delta\theta_{11}(\vec{x}_{site}) \ln\left(V_{S30}\right)$$

$$+ \delta\theta_{0B}(\vec{x}_{Rrup})$$

$$+ \sum_{i=1}^{nCell} \Delta R_i(\vec{x}_{site}, \vec{x}_{Rrup})\, \delta\theta_{7\_i}$$

Empirical Path effects

Path defined from closest point on the rupture

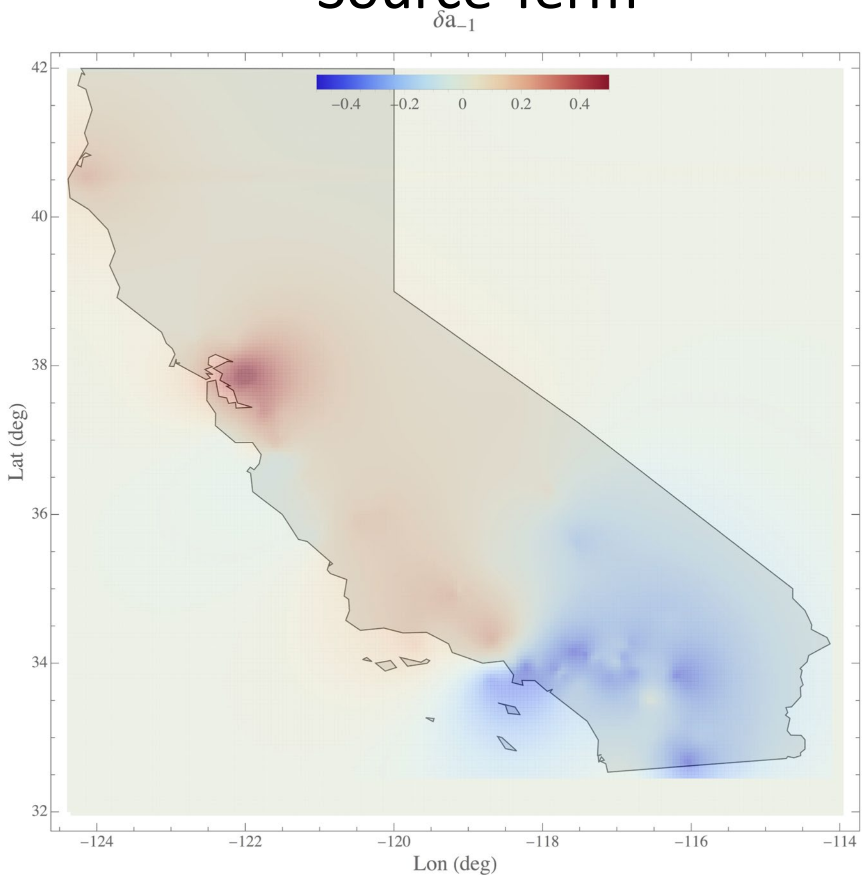


Scale of Regionalization

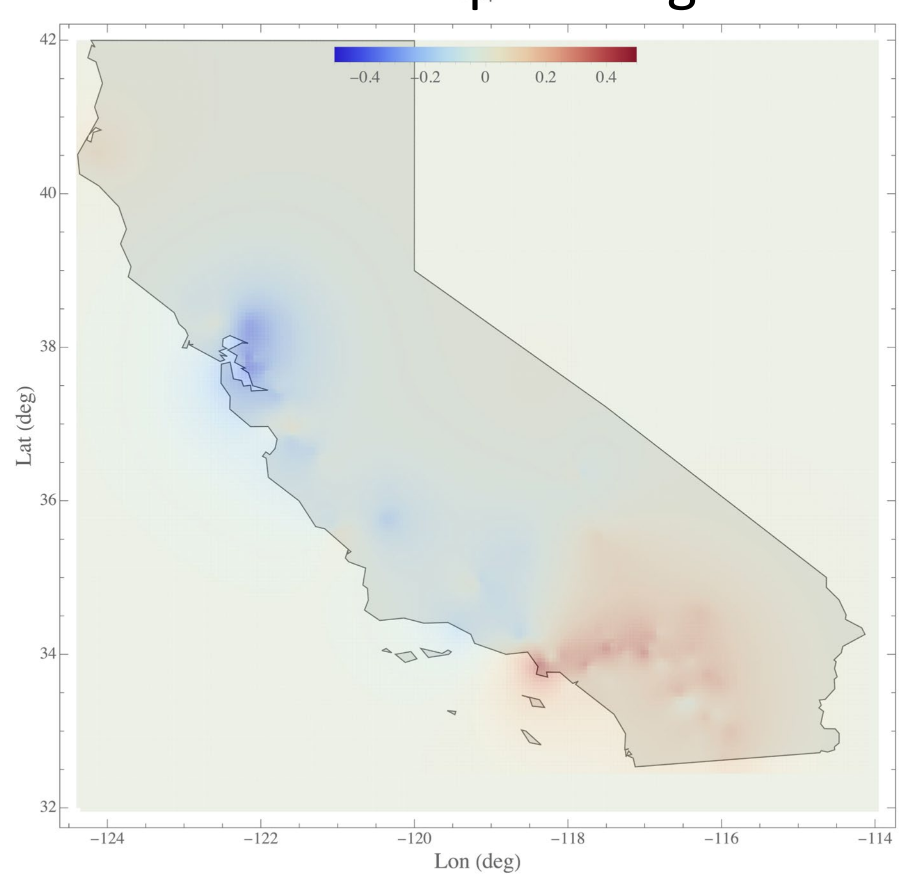
- How fine should we make the regionalization?
  - Do we need to subdivide the broad regions?
- Example of finer regionalization
  - Site-specific median basin effects based on 3-D simulations
    - Systematic differences in median basin term over a few km

Spatially Varying Coefficients (T=0.2)

Source Term

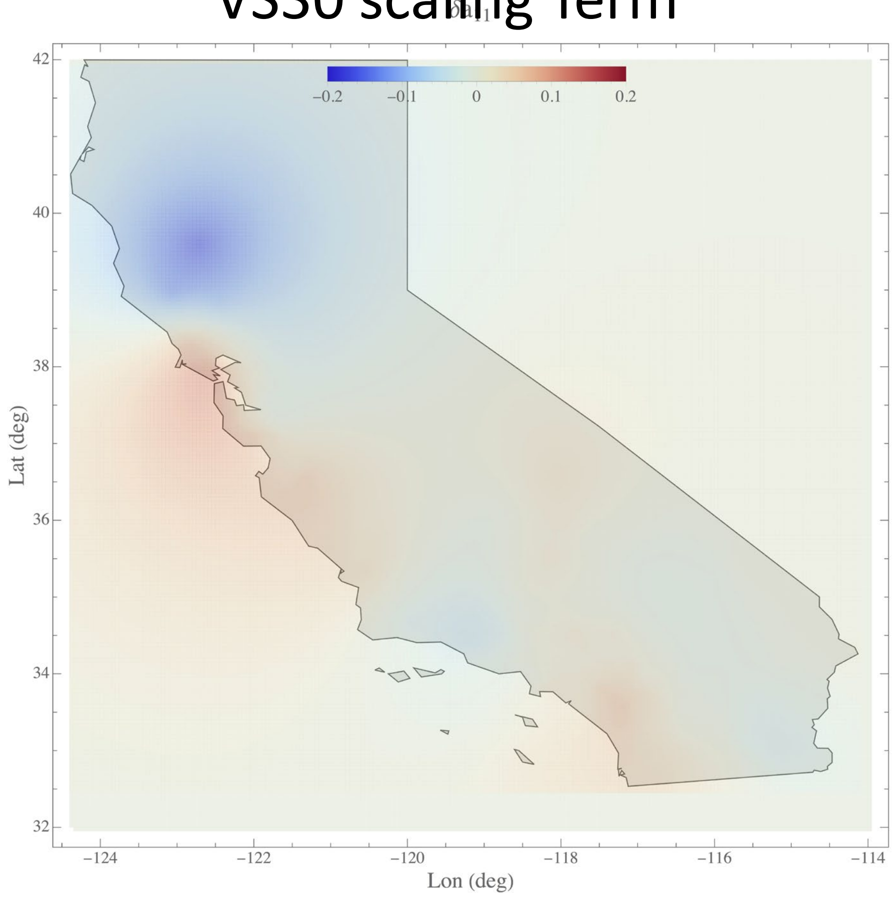


Geometrical Spreading Term

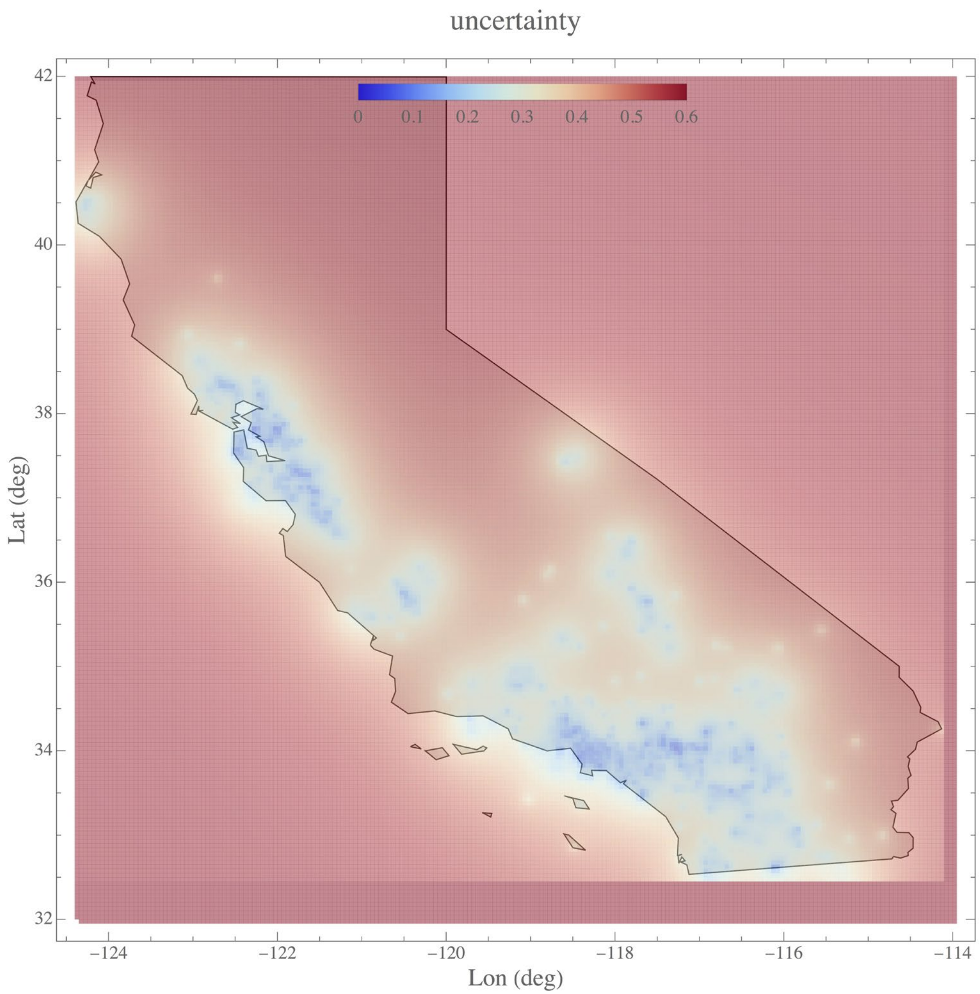


Spatially Varying Coefficients (T=0.2)

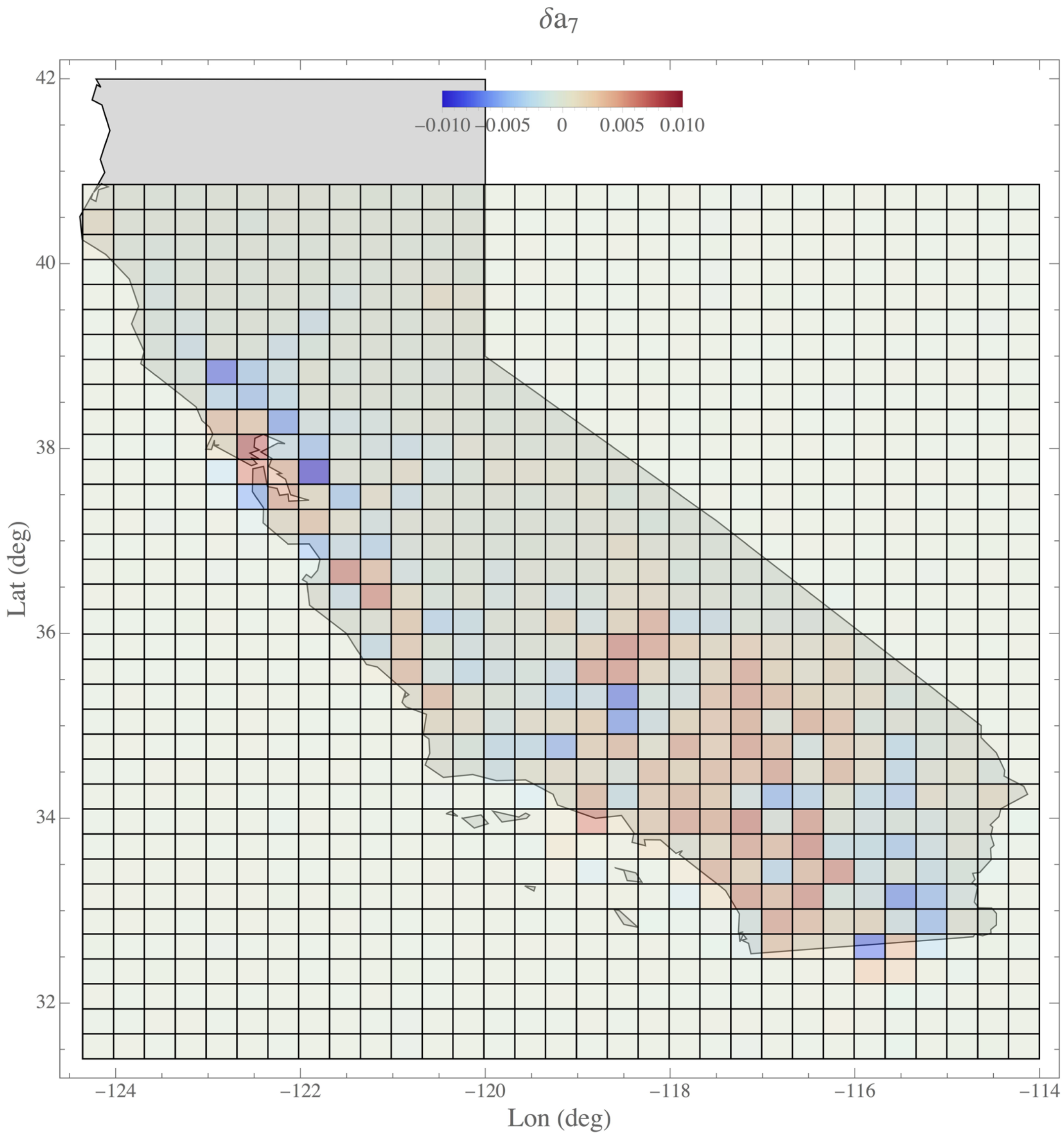
VS30 scaling Term



Epistemic uncertainty in PSA (T=0.2) due to non-ergodic terms



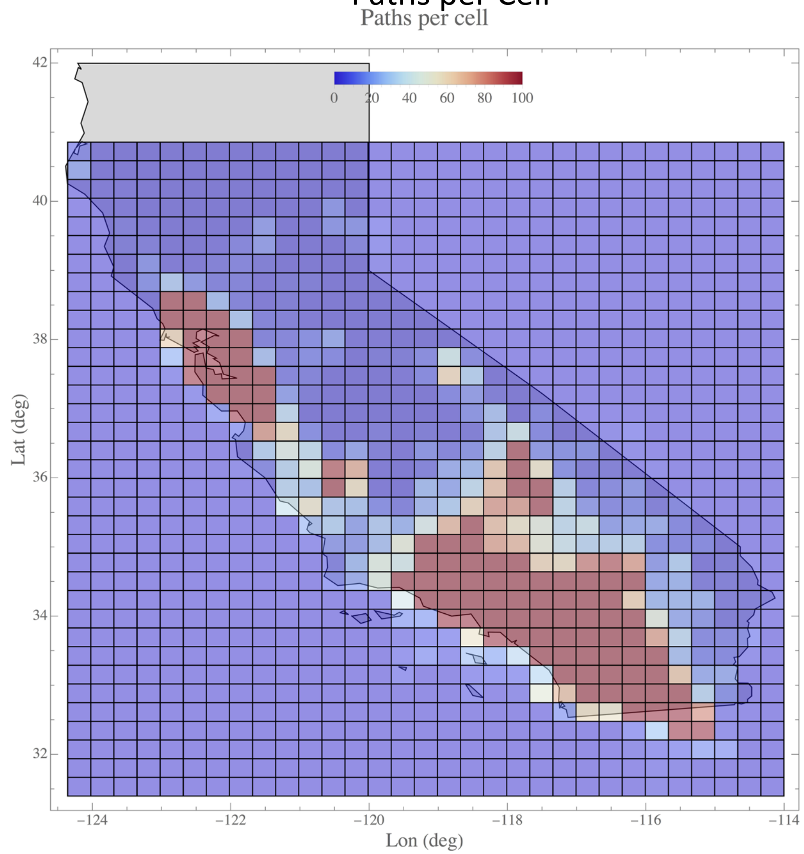
Delta Theta7 by cell (T=0.2)



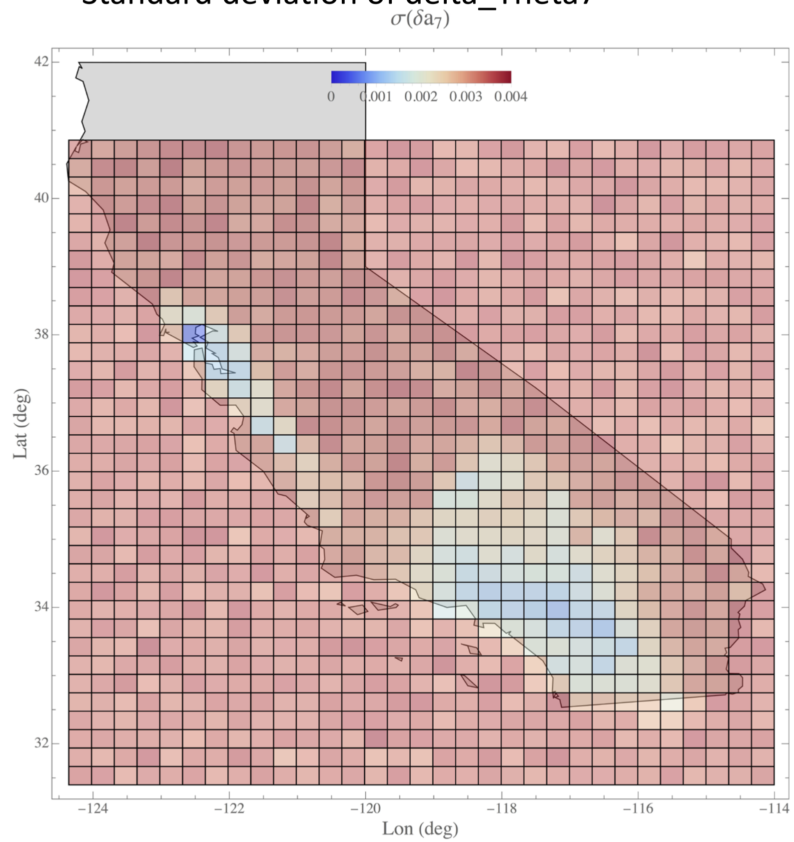
From Abrahamson et al (2018)

Epistemic Uncertainty in Delta theta7

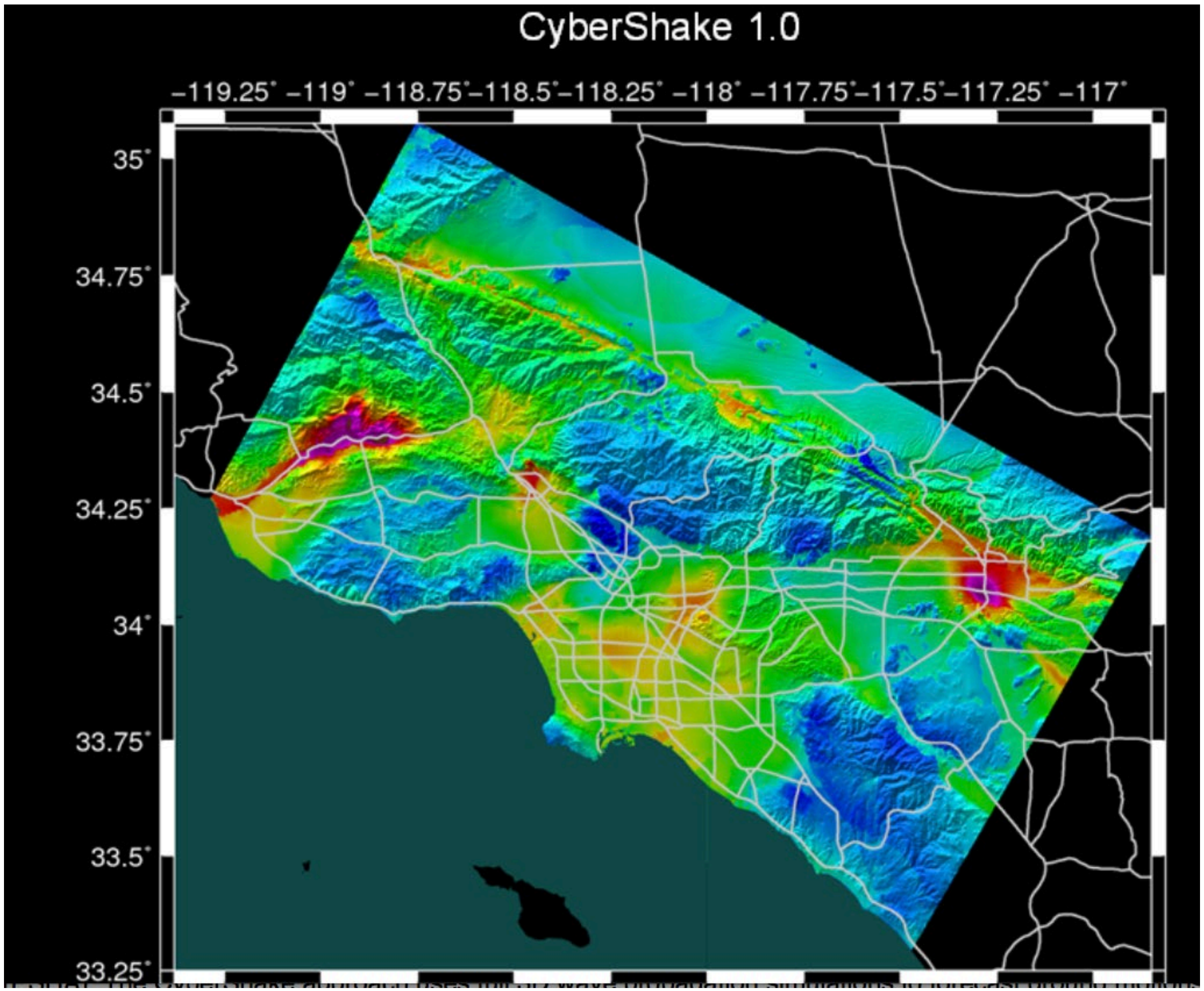
Paths per Cell



Standard deviation of delta_Theta7



Fine Regionalization in 3-D CyberShake in Los Angeles



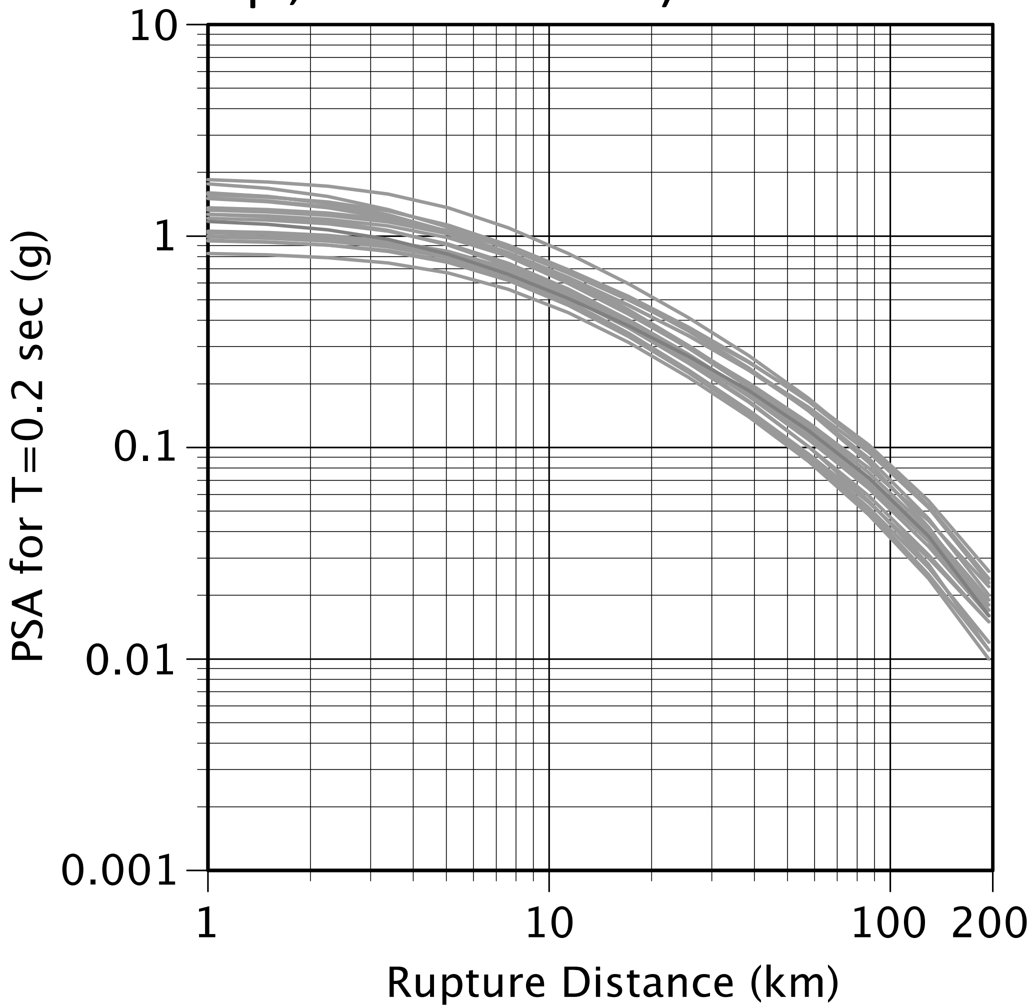
SCEC CyberShake 1.0

Empirical Nonergodic GMPEs for CA

- Variable Coefficient Model (VCM) by Landwehr et al (2016)
  - Used CA data set from ASK14
  - Estimated spatially varying coefficients
- Path-dependent attenuation by Abrahamson et al (2018)
  - Added large distance (Q) nonergodic term to the Landwehr model (Similar to Dawood and Rodriguez-Marek, 2014), T=0.2 only
- PEER project will extend the non-ergodic GMPE to all periods (T=0.01 to T=10 sec)

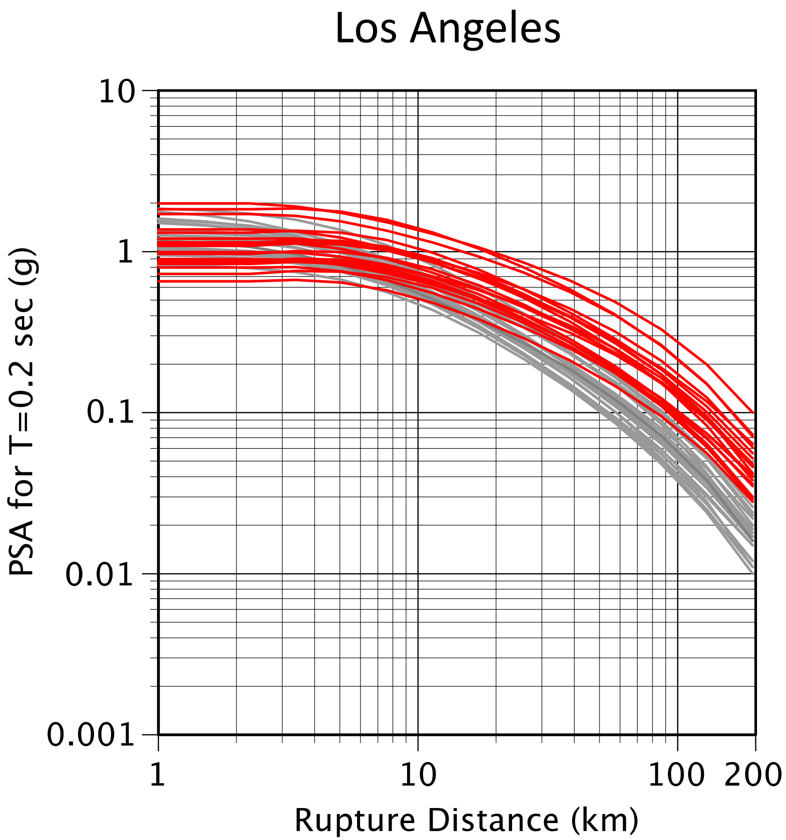
Example of Epistemic Uncertainy for Ergodic GMPEs for California

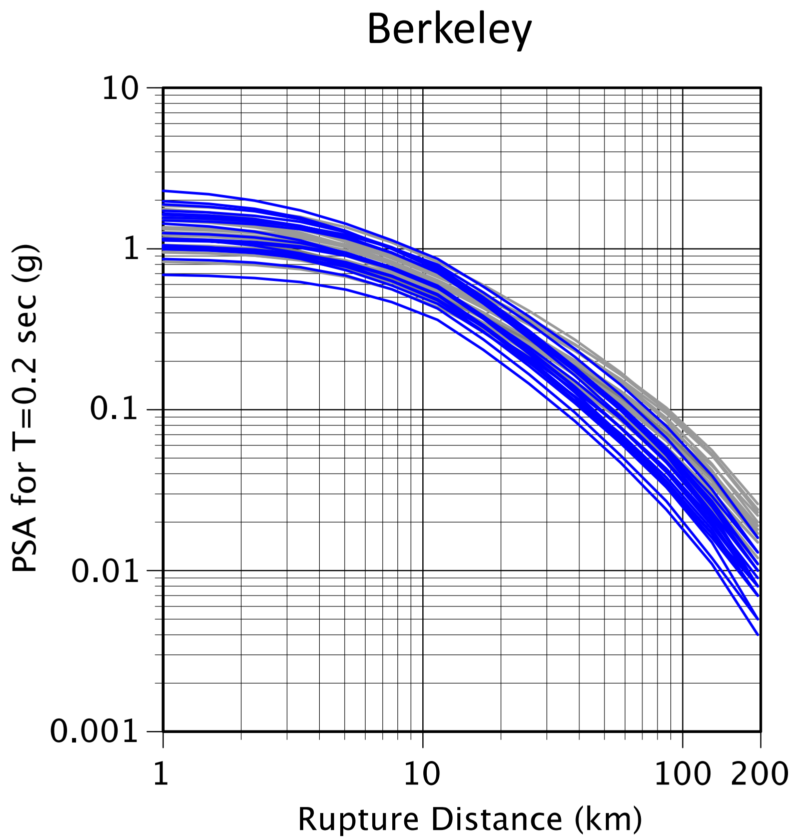
(M7, Strike-slip, VS30-760)



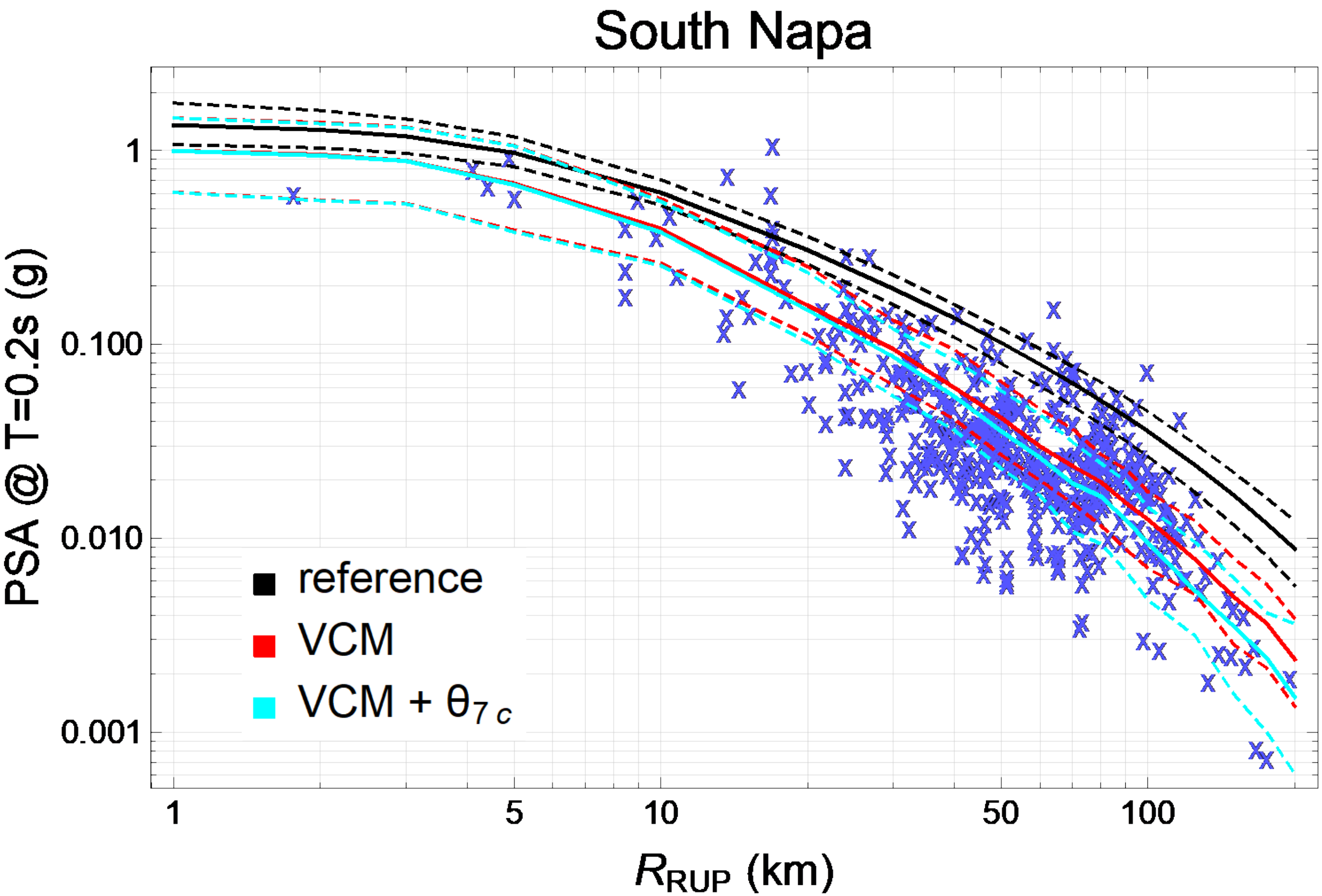
Example of SVC GMPEs in Regions with Data

(M7, Strike-slip, VS30-760)





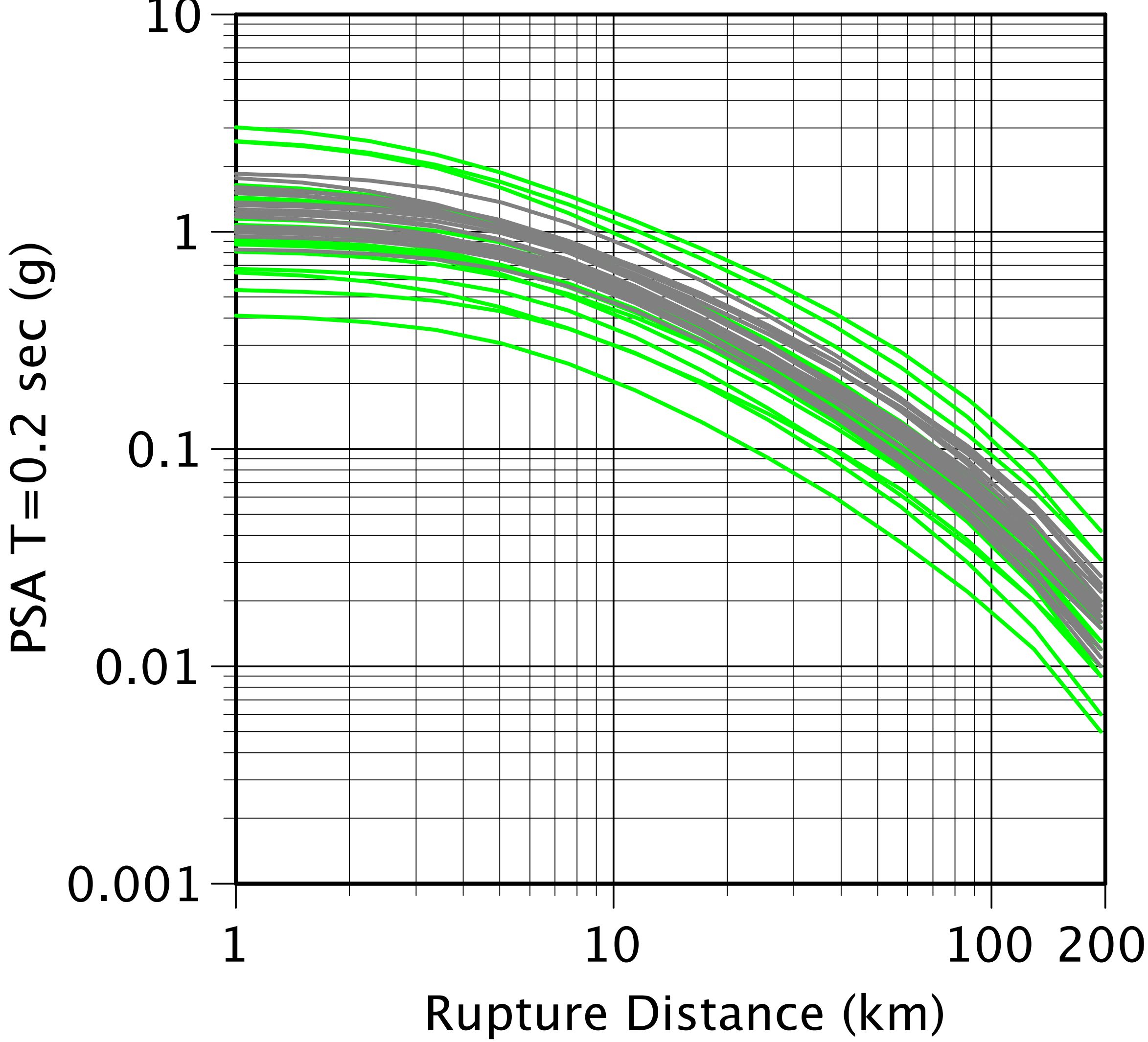
Comparison with Napa Earthquake (Data not used in the SVC model)



What if you don’t GM data in your region to use?

- Lack of data means large uncertainty
  - Lack of data does not mean that the an ergodic GMPE applies to the region
  - It will still be nonergodic, but with large epistemic uncertainties
- May use variance and spatial correlation lengths from regions with adequate data

NE California: Site with Sparse Data



Approaches To Incorporate 3-D Simulations

- Replace GMPEs with 3D Simulations:
  - ISSUE: inadequate epistemic uncertainty in current models
    - Single model with no epistemic uncertainty in scaling and velocity profile
    - Only one rupture generator describing the source is used

- Adjust GMPEs based on 3D Simulations
  - ISSUE: centering the simulations on the GMPE
  - Use a ratio of 3D/1D simulations (given that the 1D simulations are consistent with the average of the ergodic GMPEs)
  - For application, correlated spatially-variable coefficients are applied as adjustment factors (Landwehr et al., 2016)

From Wooddell and Abrahamson (2018)

Centering Simulations on a GMPE

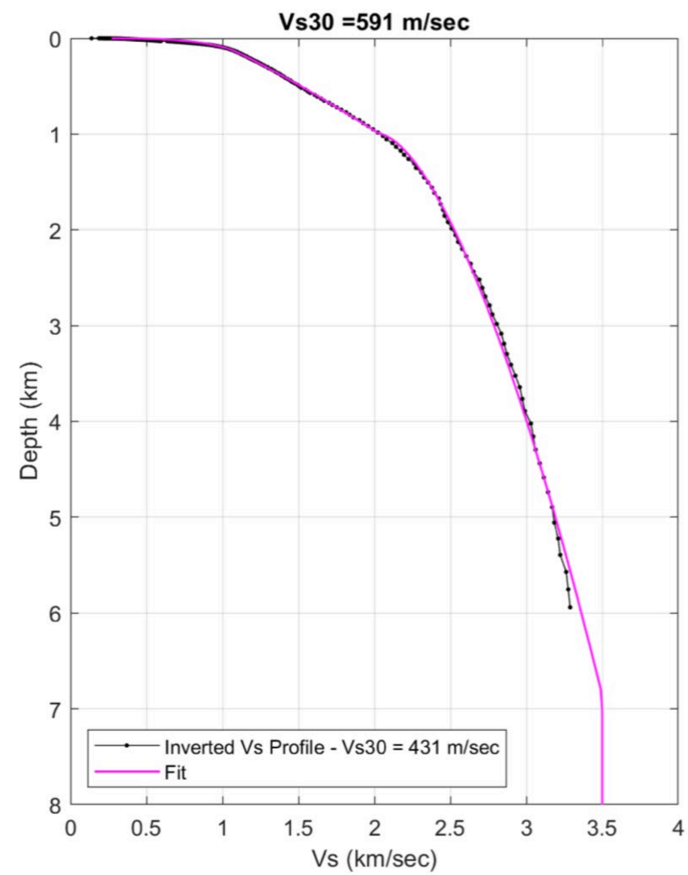
- Two Main Parts:
  1. Use a GMPE specific 1D velocity profile to ensure that the resulting 1D simulations are centered on the ergodic GMPE
  2. Cancel out the source scaling from the simulations by using 3D/1D ratios

- Requirements:
  - 3D Simulation Set:
    - Seismic source described by a kinematic rupture generator
    - Full 3D velocity model
  - 1D Simulation Set:
    - Seismic source described by a kinematic rupture generator (same as 3D case)
    - Average 1D velocity model representative of the average scaling in the GMPE

From Wooddell and Abrahamson (2018)

VS profile Consistent with the ASK14 GMPE

- Used FAS GMPE based on the data in ASK14 (Bayless 2018)
- Inverted the VS30 scaling in the FAS for a smooth VS profile
- This is not a realistic 1-D profile for the region
  - It is a 1-D profile that is consistent with the VS30 scaling in the GMPE



From AL-Atik, Abrahamson, and Wooddell (2018)

Centering Simulations on a GMPE

Non-Ergodic GMPE

$$LN(PSA) = ASK14(M, R_{RUP}, F, V_{S30}, Z_{TOR}) + \delta\theta_4(\vec{x}_{src}, \vec{x}_{site}) ln\left(\sqrt{R_{RUP}^2 + \theta_6^2}\right) + \delta\theta_{0A}(\vec{x}_{site}) + \delta\theta_{11}(\vec{x}_{site}) ln(V_{S30}) + \delta\theta_{0B}(\vec{x}_{src}) + \sum_{i=1}^{nCell} \Delta R_i\left(\vec{x}_{site}, \vec{x}_{R_{RUP}}\right) \delta\theta_{7\_i}$$

Isolating Non-Ergodic Path Terms Centered on ASK14

$$LN(SIM_{3D}) - LN\left(SIM_{ASK14\_1D}\right)$$
$$= \delta\theta_4(\vec{x}_{src}, \vec{x}_{site}) ln\left(\sqrt{R_{RUP}^2 + \theta_6^2}\right) + \delta\theta_{0A}(\vec{x}_{site}) + \sum_{i=1}^{nCell} \Delta R_i(\vec{x}_{site}, \vec{x}_{src}) \delta\theta_{7\_i}$$

From Wooddell and Abrahamson (2018)

Next Steps - Move to FAS GMPEs

- Improve feedback during validation of finite-fault simulation methods
  - Much easier to understand effects of the parameters for simulations using Fourier spectra than using response spectra
- Improve integration of GMPEs and 3-D simulations in the non-ergodic framework
- Allow use of data from smaller magnitude earthquakes (M3) to constrain the linear path effects without the complications of the response spectral scaling (depends on spectral shape)

Extend Ergodic GMPEs to small Magnitudes

- Reference ergodic GMPEs for FAS should be applicable down to M3 (or M2 if data are reliable)
  - This allows use of small magnitude data to constrain path effects

Benefits of the Nonergodic Framework for Using 3-D Simulations

- Allows incorporation of results from limited sets of 3-D simulations to be included in the GMPE
- CVM approach plus azimuthally dependent attenuation
  - Avoids issues of defining region boundaries and ray paths crossing between regions
- Regions without data (empirical or simulations) use the regionalized ergodic model as the central estimate with large epistemic uncertainties
  - Smooth transition from regions with data to regions without data to constrain the nonergodic GMPE terms

PSHA calculations with epistemic uncertainty for non-ergodic GMPE

- Non-ergodic models require capturing the epistemic uncertainty in all of the coefficients (alternative maps of non-ergodic terms)
- Need about 100 branches on the GMPE logic tree
- Need an alternative approach to PSHA calculation
  - Analytical methods can be used to estimate the effects of the epistemic uncertainty in the median GMPE on the hazard without having to run 100 branches.
  - Analytical Methodology developed by Lacour and Abrahamson (2019) in SIGMA 2

Phased Approach to Use of 3-D Simulations into PSHA

- Phase 1
  - Use the non-ergodic GMPE (with epistemic uncertainty) as a baseline
- Phase 2
  - Use 3-D simulations for medians for specific key scenarios
    - Update the nonergodic terms
    - May need to extrapolate to other scenarios
  - Use empirical model for the aleatory variability
- Phase 3
  - Use 3-D simulations for median and variability
    - Update the nonergodic terms
    - Update the aleatory variability

Conclusions

- We now know how far off our ergodic GM models can be
  - 60 of the aleatory variance in ergodic GMPEs is from systematic source, path, and site effects
- New GMPEs will continue to add region-dependent terms
  - Ultimate scale of the regionalization is on the order of 10s of km
  - As 3-D simulations start to be incorporated, the non-ergodic GMPE framework provides a smooth transition from regions with 3-D simulations to regions without 3-D simulations
- As nonergodic models begin to be applied in the next 5 years, expect large changes in hazard estimates