Engineering Characterization of Spatially Variable Ground Motion

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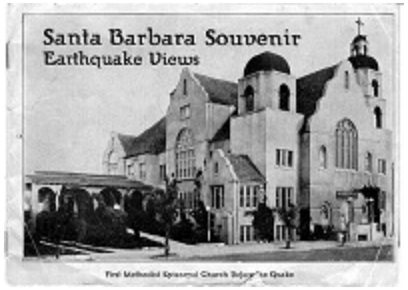

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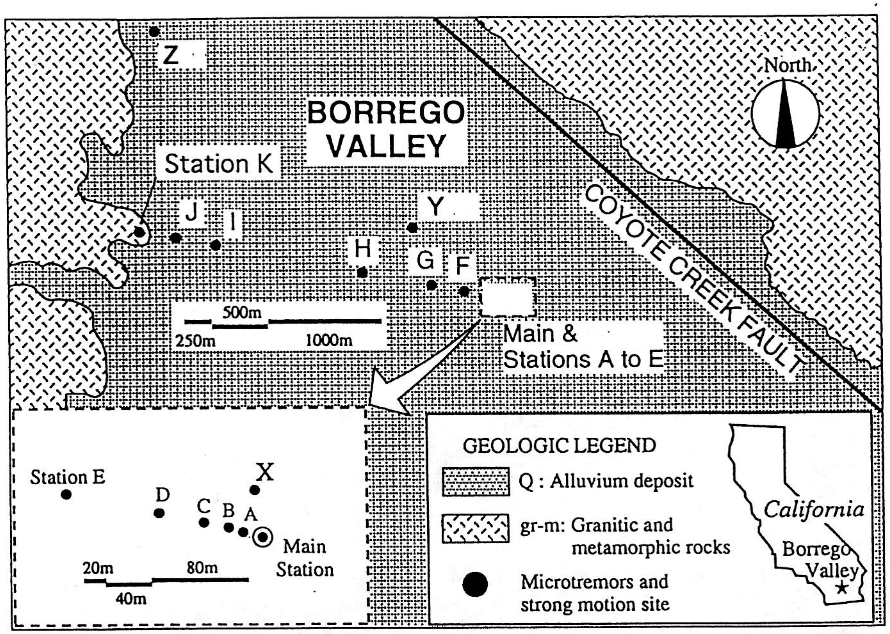
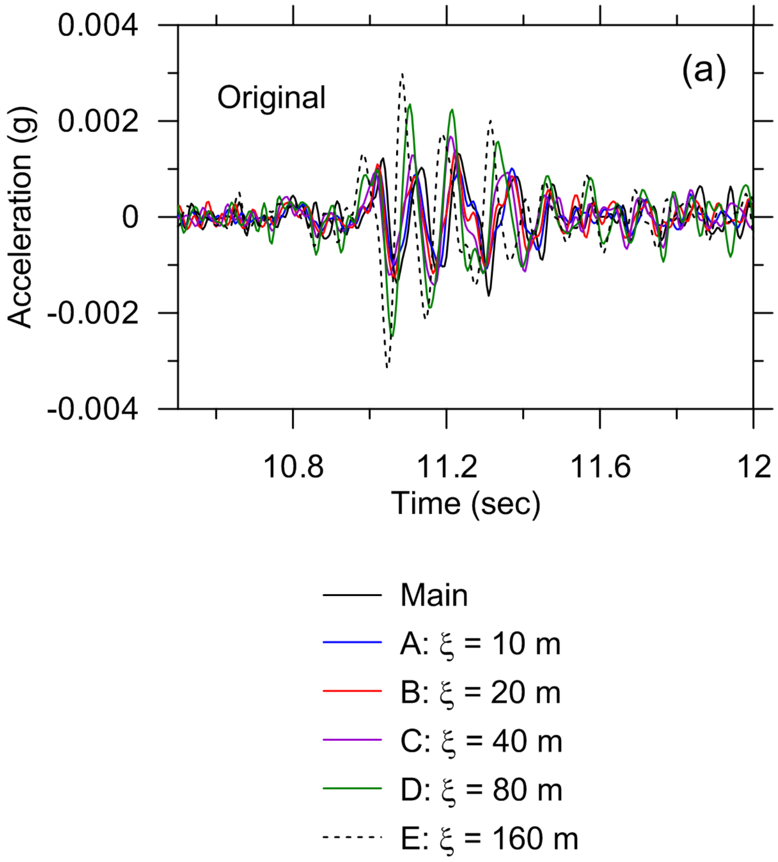
Outline

- Motivation
- Metrics of spatial variability in ground motions (SVGM)
- Simulation procedure for generating SVGMs
- Investigation of seismic ground strains
- Conclusions

Motivation



Kato et al., 1998



Example applications

Seismic demands on buried structures (pipelines, tunnels)

e.g., Hashash et al., 2001
O'Rourke and Deyoe, 2004

Example applications

Seismic demands on buried structures (pipelines, tunnels)

Multi-support excitation for extended structures (bridges)

e.g., Der Kiureghian & Neuenhofer, 2004

Example applications

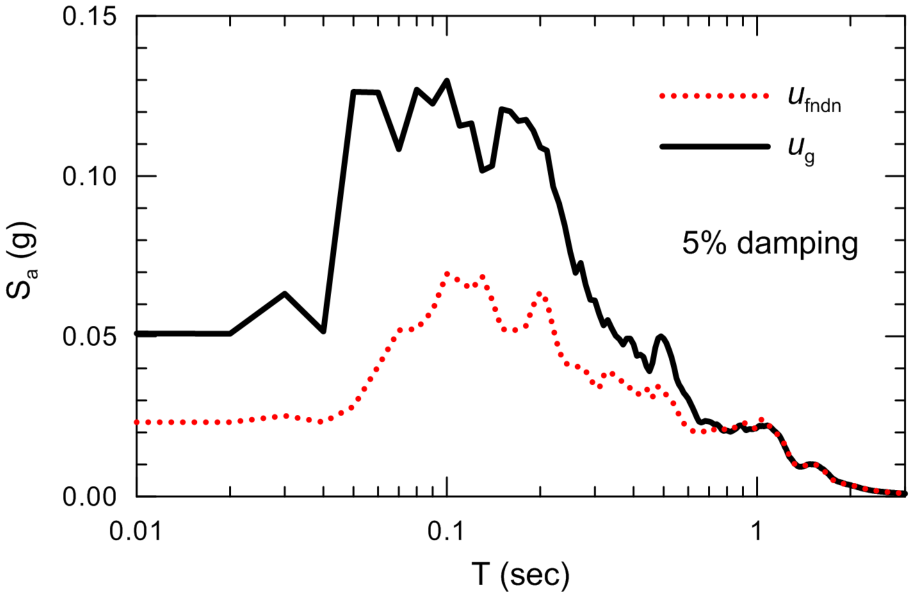
Seismic demands on buried structures (pipelines, tunnels)

Multi-support excitation for extended structures (bridges)

Foundation – level ground motion reduction from kinematic soil-structure interaction

e.g., ASCE-41

Rancho Cucamonga Law & Justice Center
1987 Whittier Earthquake



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- Motivation
- **Metrics of spatial variability in ground motions (SVGM)**
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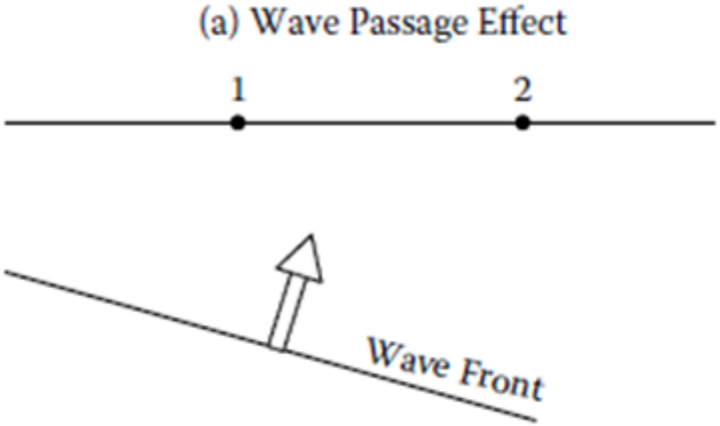
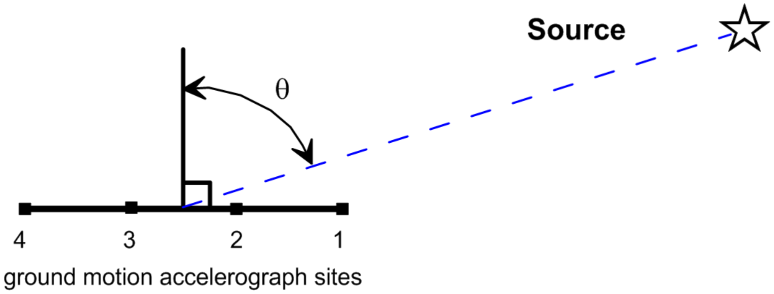
Metrics of SVGM

- Wave passage
- Lagged coherency
- Amplitude variability
- Correlations

Wave passage

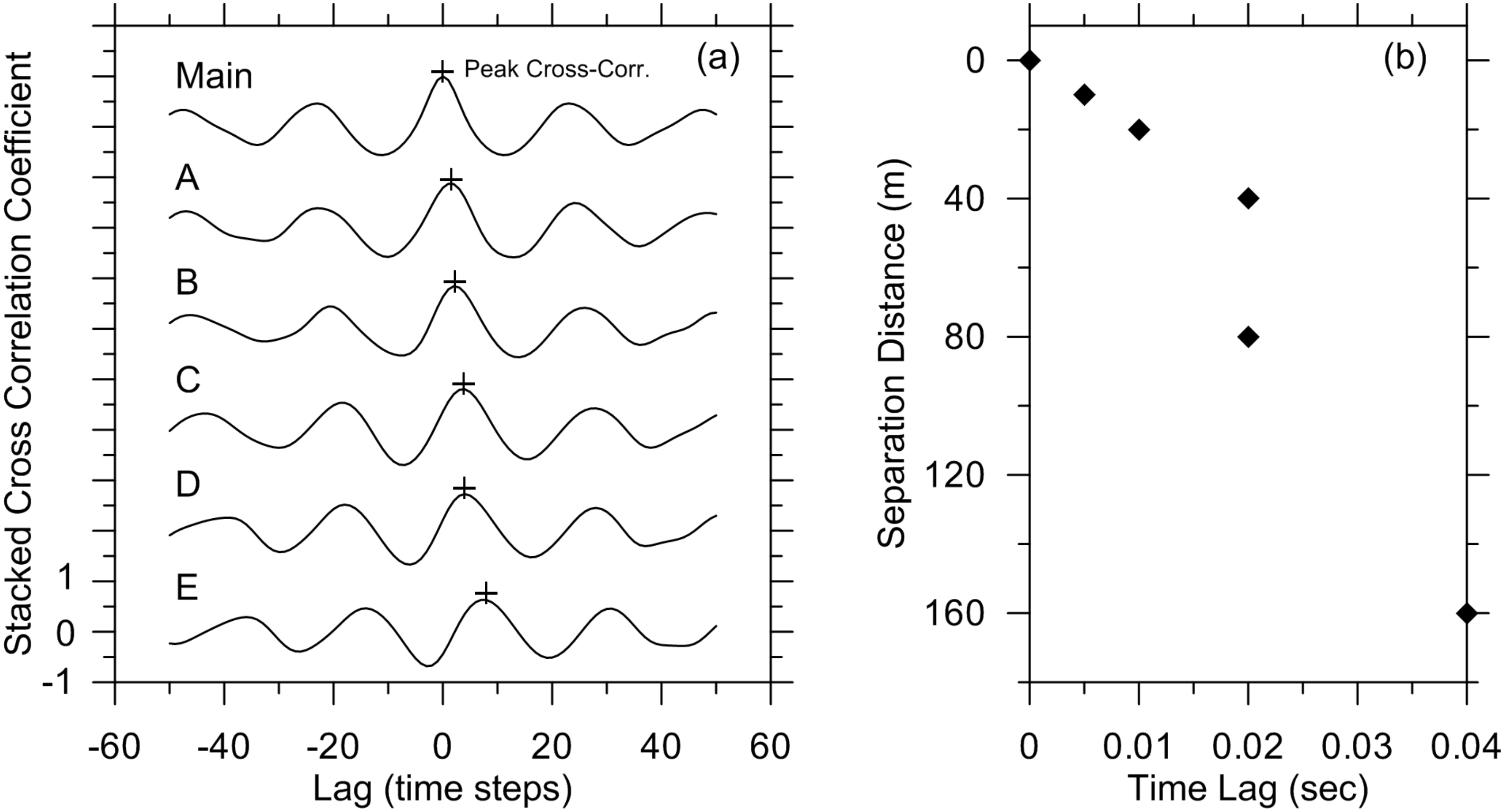


Zerva, 2009

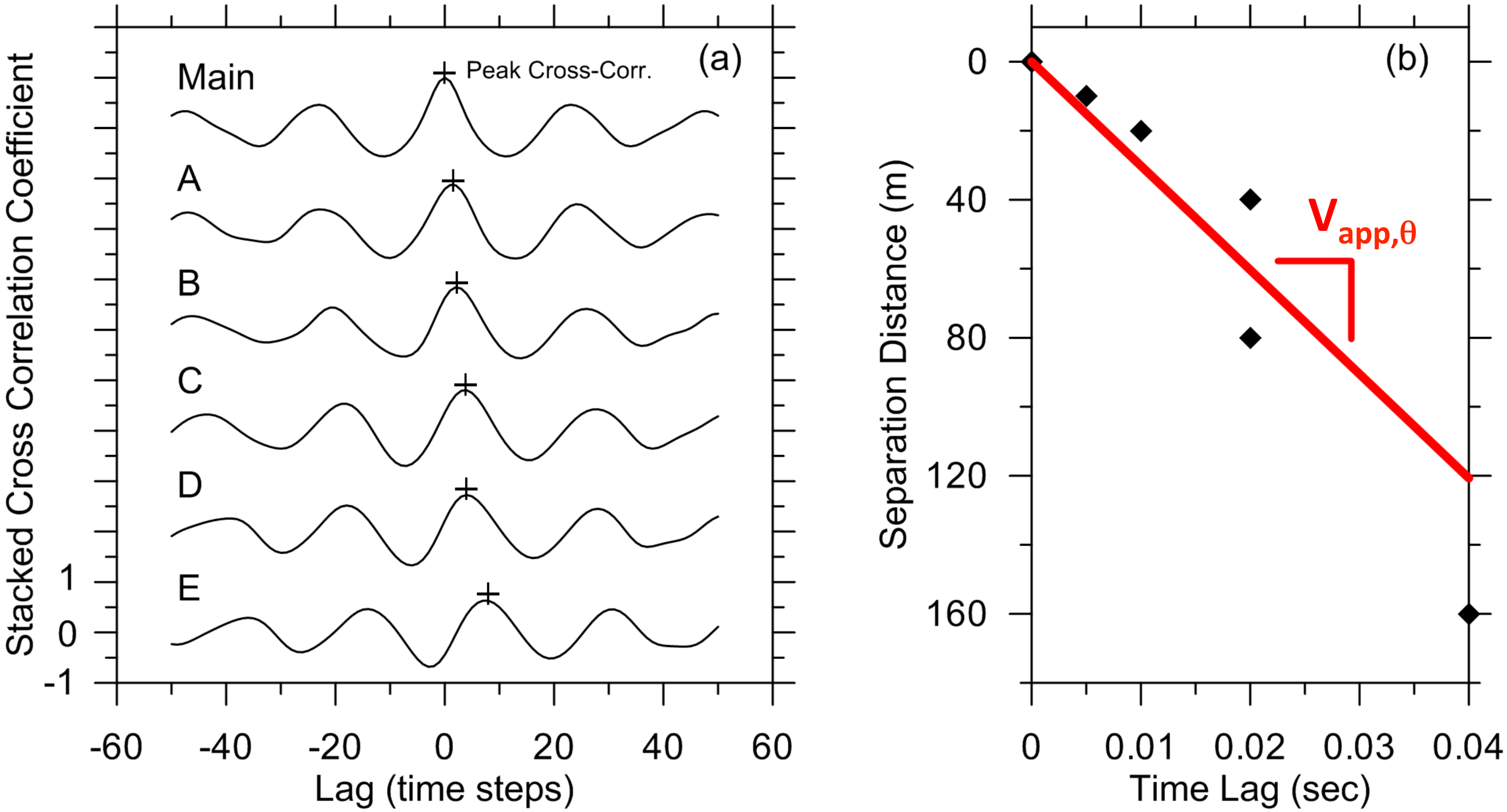


$$V_{app,\theta} = \frac{V_{app}}{\sin\theta}$$

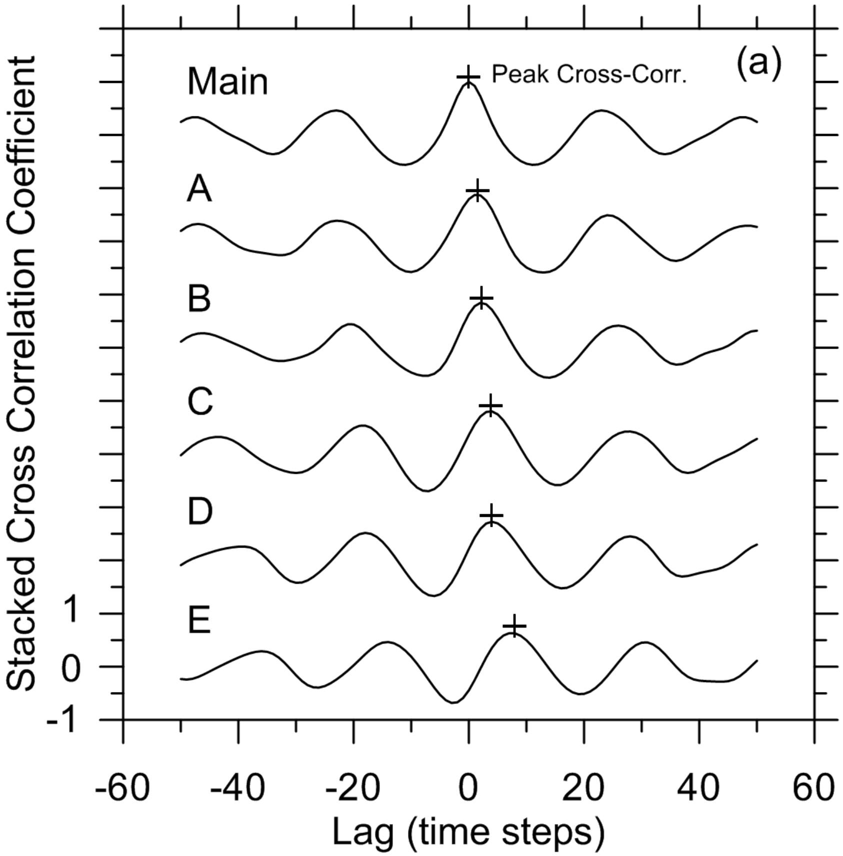
Wave passage

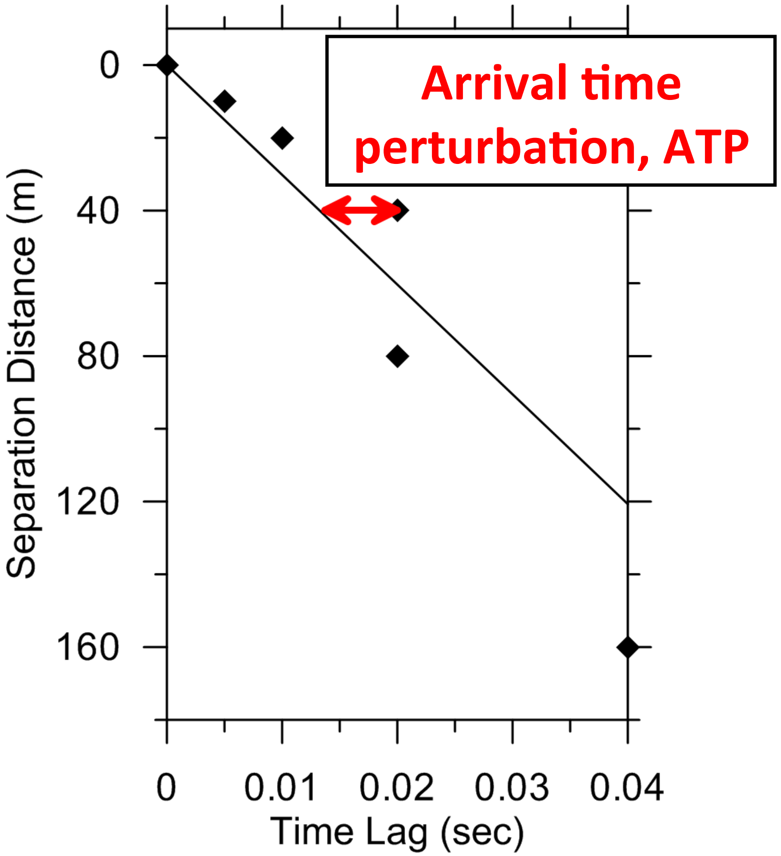


Wave passage



Wave passage





Arrival time perturbation, ATP

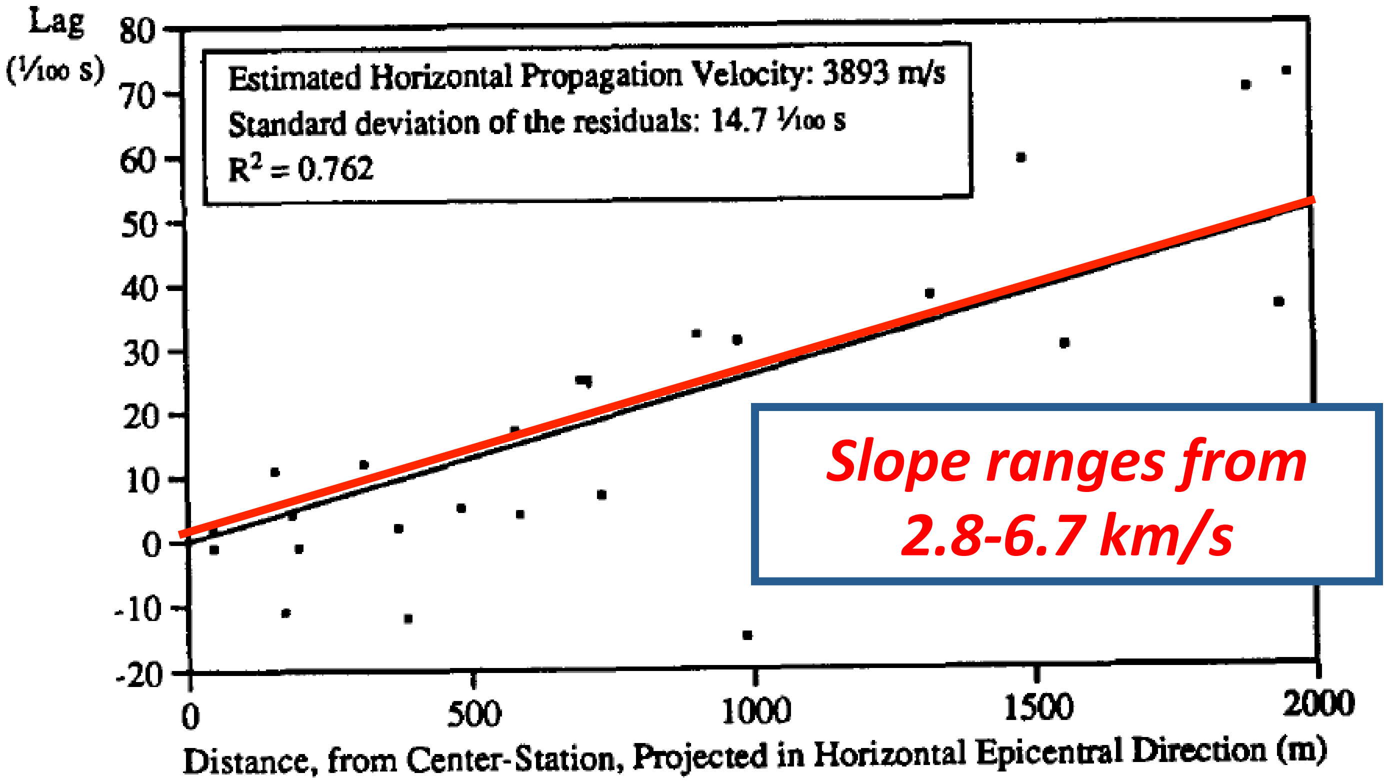
Wave passage

Sensitive to waveform duration – full signal or S-window

Can have poor results if varying site conditions

Wave passage

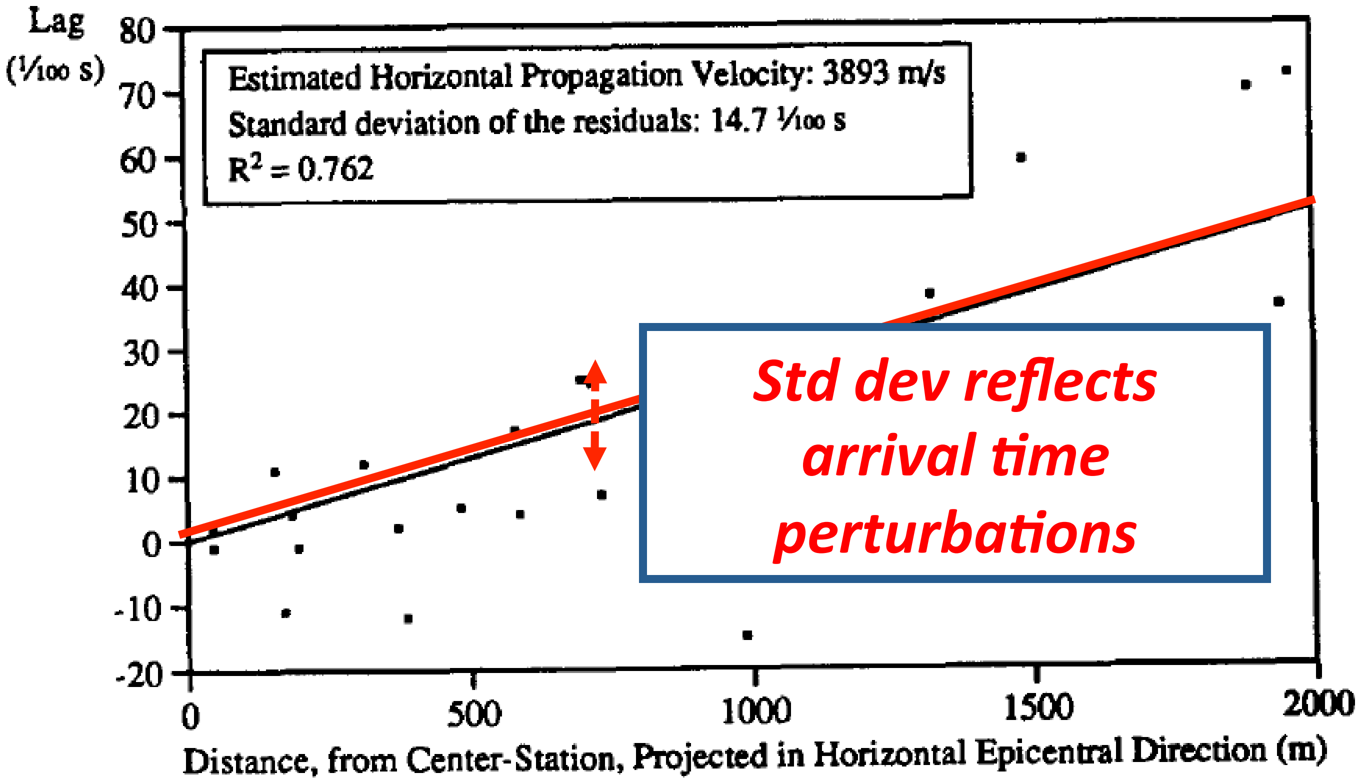
Lotung SMART 1 data: Boissieres and Vanmarcke (1995)



Slope ranges from 2.8-6.7 km/s

Wave passage

Lotung SMART 1 data: Boissieres and Vanmarcke (1995)



Std dev reflects arrival time perturbations

Wave passage

BVDA and LSST Data (this study)

BVDA Event	**θ (deg.)**	**$V_{app,\theta}$ (m/sec)**	**V_{app} (m/sec)**
2	7	12048	1468
3	7	12270	1495
4	7	11834	1442
5	72	3527	3355
6	63	2959	2636
8	89	3017	3016
9	31	4902	2525
10	2	na	na
11	82	3914	3876
13	2	na	na
14	58	8734	7407
16	31	2999	1544
	$\sigma_{\ln V}$=	**0.62**	**0.54**
	Med.=	**4408**	**2580**

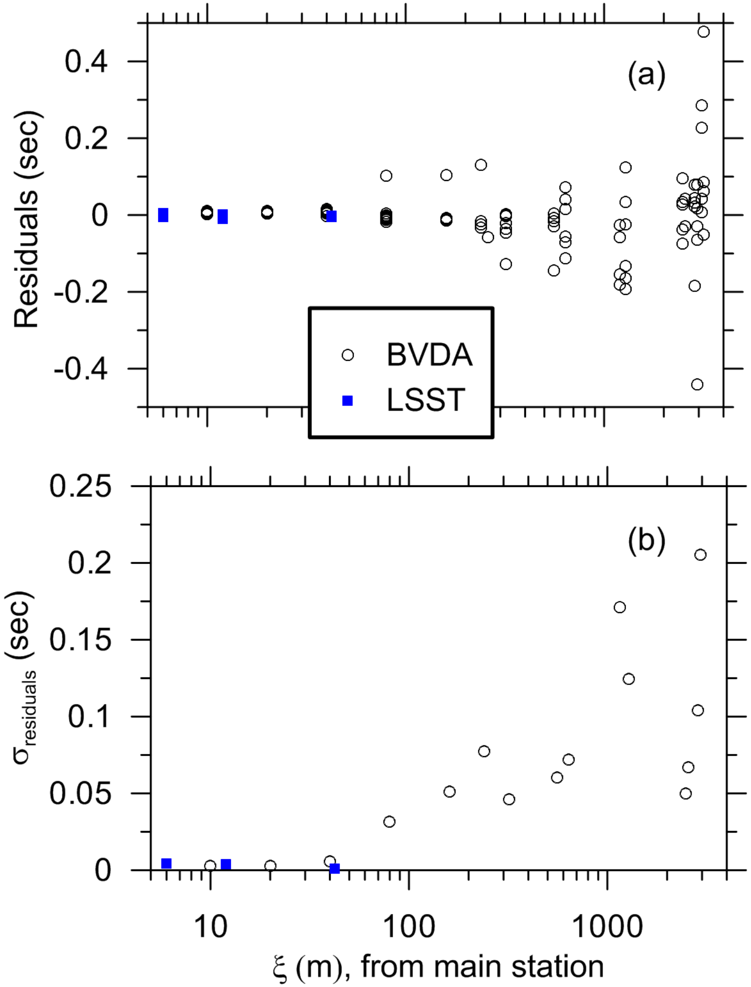
LSST Event	**θ (deg.)**	**$V_{app,\theta}$ (m/sec)**	**V_{app} (m/sec)**
4	29	11976	5806
5	-69	-2260	2110
6	-84	-1441	1433
7	-105	-2472	2388
16	-84	-1795	1785
	$\sigma_{\ln V}$=	**0.84**	**0.54**
	Med.=	**2260**	**2110**

Lower $\sigma_{\ln V}$ for V_{app} $\therefore$ preferred to $V_{app,\theta}$

V_{app} = 2.1-2.6 km/s

$\sigma_{\ln V}$ = 0.5-0.6

Wave passage

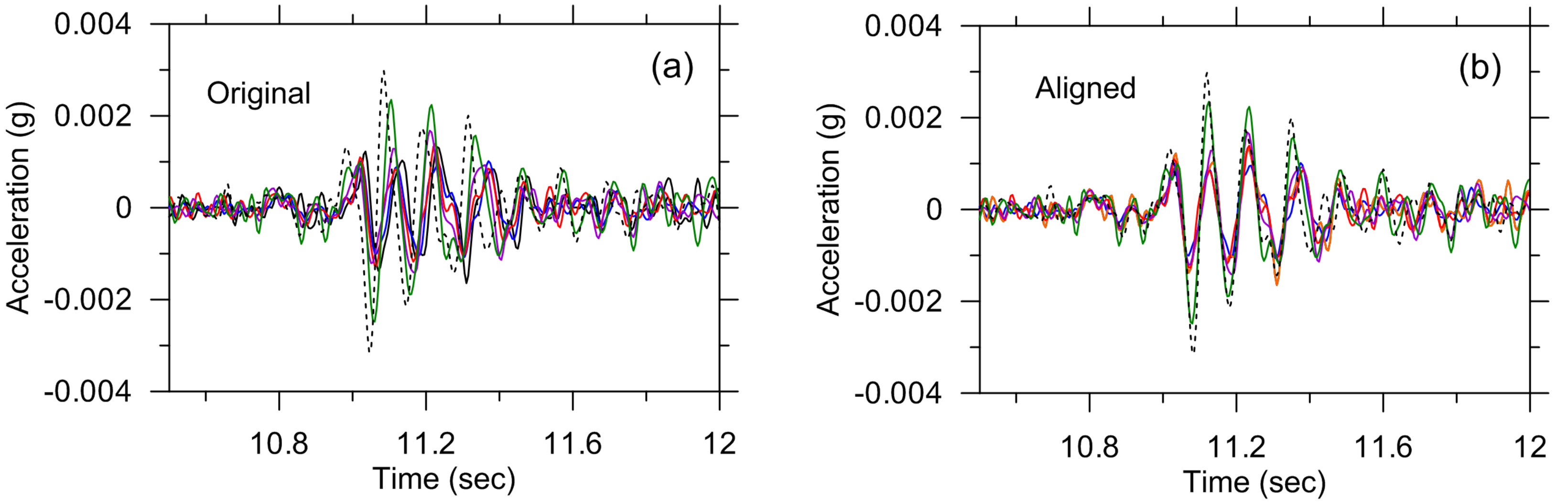


BVDA and LSST Residuals
(this study)

Negligible ATP for $\xi < 50$ m

Lagged Coherency

Reflects phase variability that remains after aligning stations (removing wave passage and ATP).



Lagged Coherency

Derived from smoothed power spectral density functions

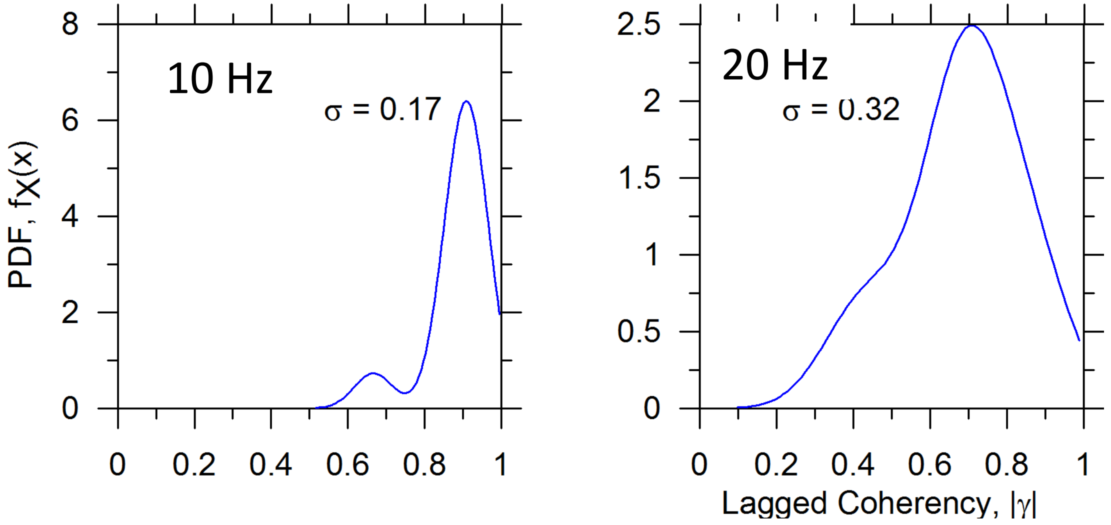
$$\gamma_{jk}\left(f\right)=\frac{S_{jk}\left(f\right)}{\left[S_{jj}\left(f\right)S_{kk}\left(f\right)\right]^{1/2}}$$

$$\gamma\left(\xi,f\right)_{jk}=\boxed{\left|\gamma\left(\xi,f\right)_{jk}\right|}\exp\left[i\theta\left(\xi,f\right)_{jk}\right]$$

Sensitive to level of smoothing, windowing procedures, etc.

Lagged Coherency

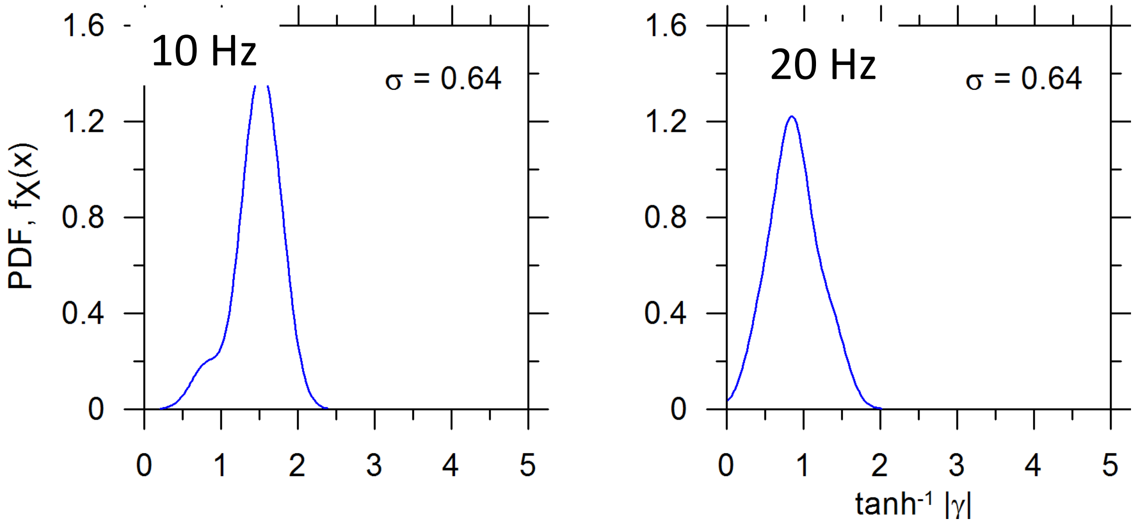
Complex statistical properties



Kernal density estimate of PDF

Lagged Coherency

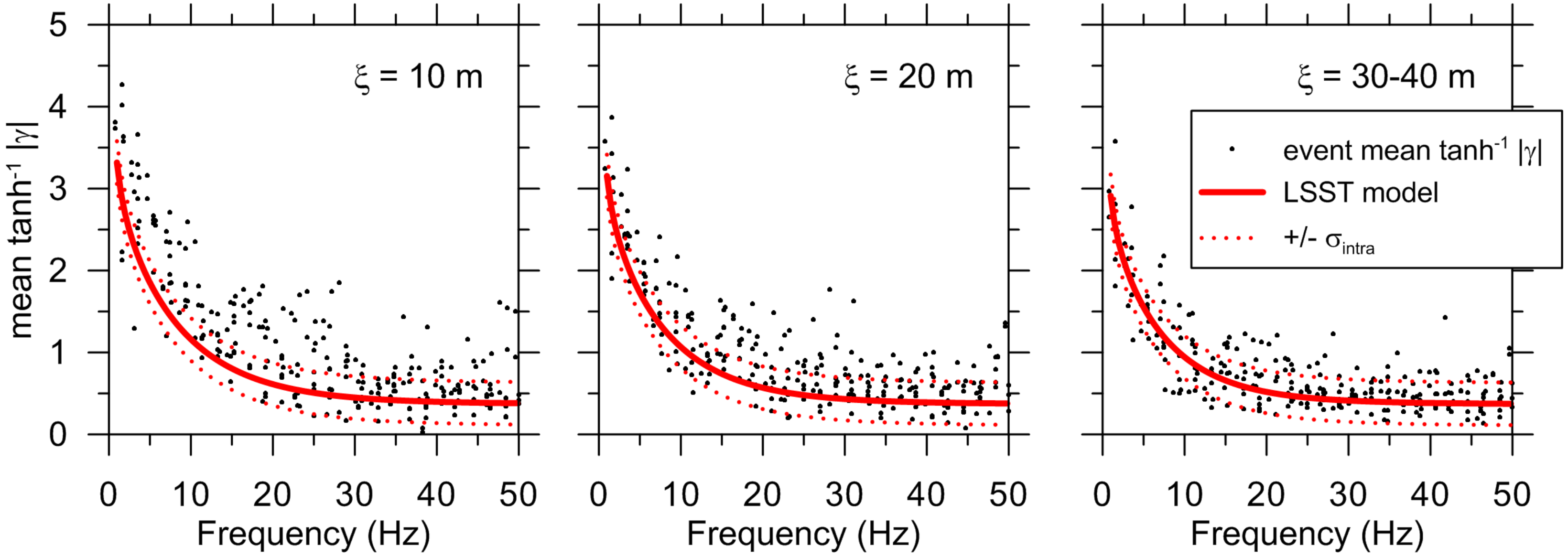
Complex statistical properties



Transformation using $\tanh^{-1}$ produces normal distribution

Lagged Coherency

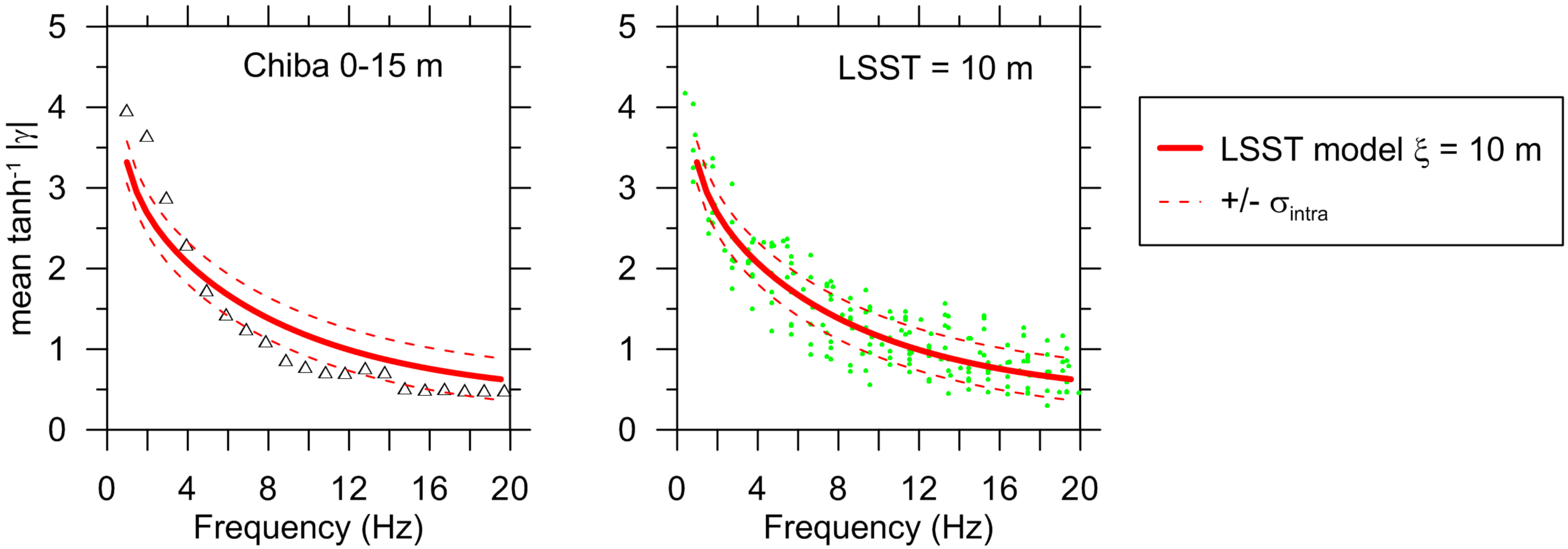
Trends with frequency and distance (BVDA data)



Model bias for f < 10 Hz and ξ < 30 m

Lagged Coherency

Chiba and LSST array data

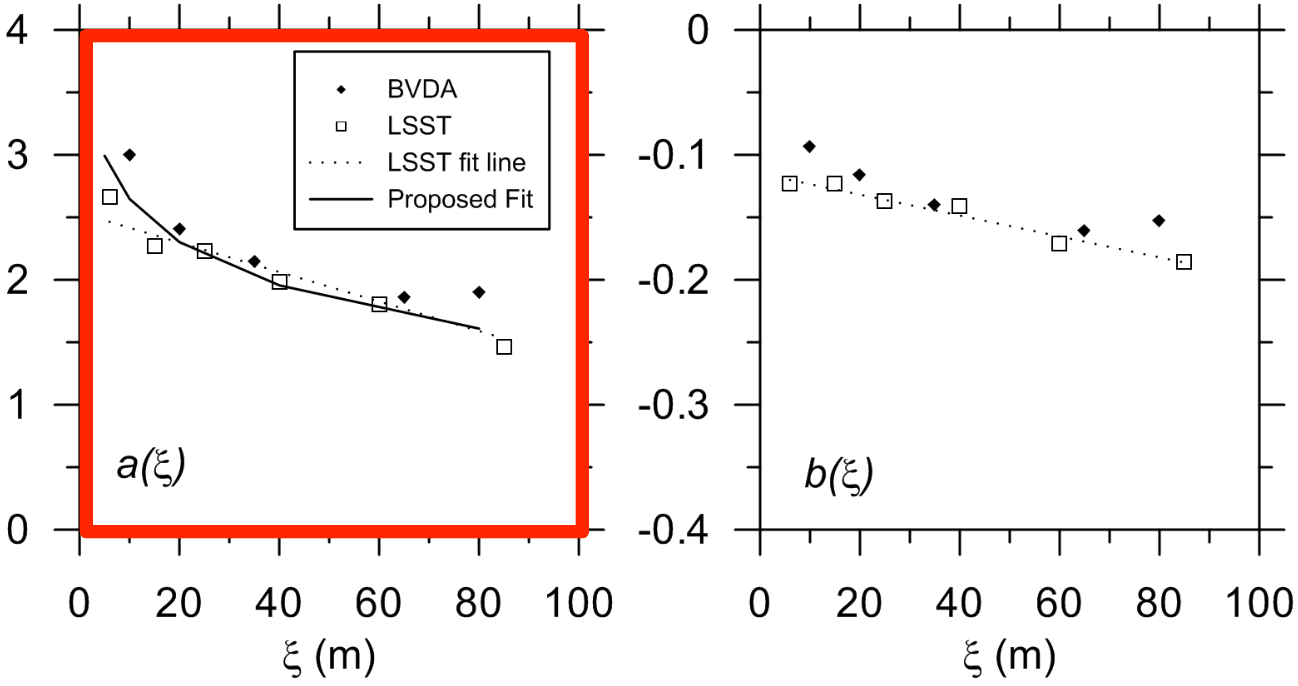


Bias for Chiba; no bias for LSST

Lagged Coherency

Model adjustment

$$\tanh^{-1}\left|\gamma\left(f,\xi\right)\right| = a\left(\xi\right)\exp\left\{b\left(\xi\right)f\right\} + d\left(\xi\right)f^{c(\xi)} + k$$

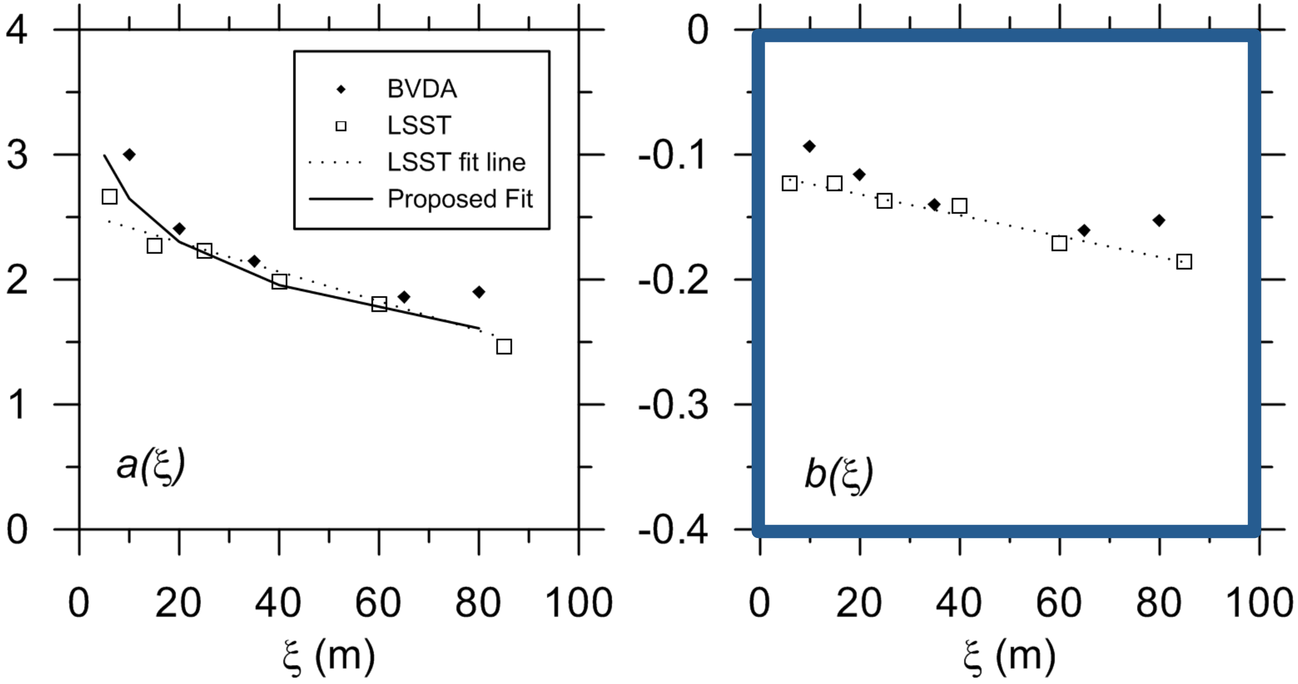


Lagged Coherency

Model adjustment

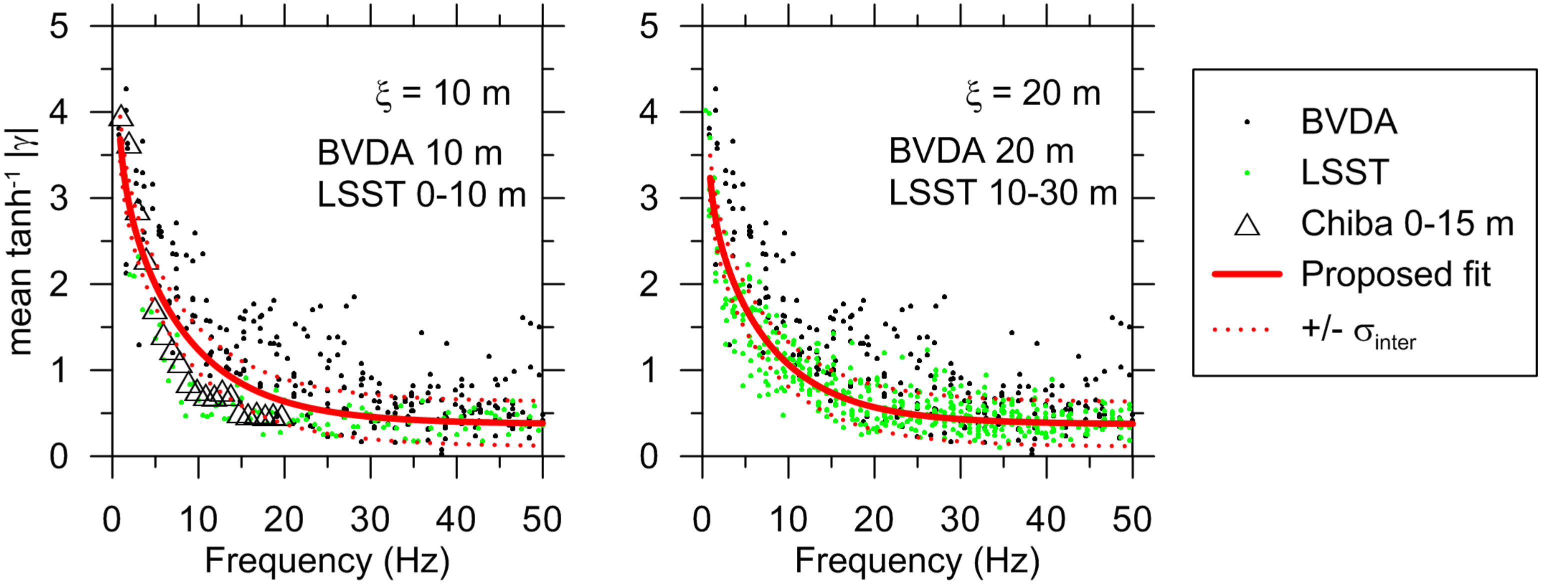
No change in b, c, d

$$\tanh^{-1}\left|\gamma\left(f,\xi\right)\right| = a\left(\xi\right)\exp\left\{b\left(\xi\right)f\right\} + d\left(\xi\right)f^{c(\xi)} + k$$



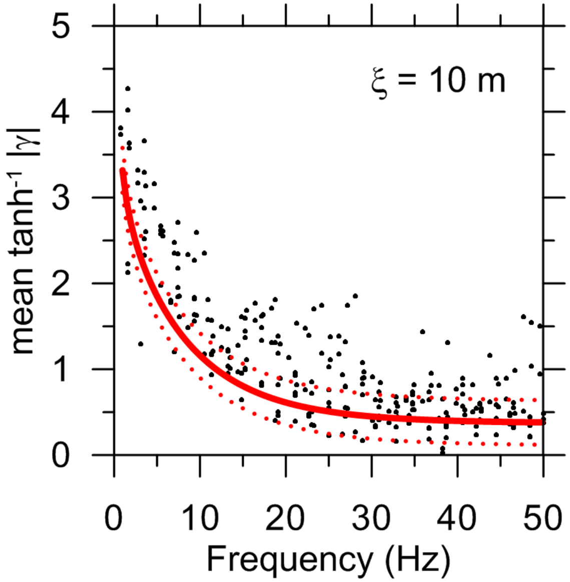
Lagged Coherency

Adjusted model compared to data



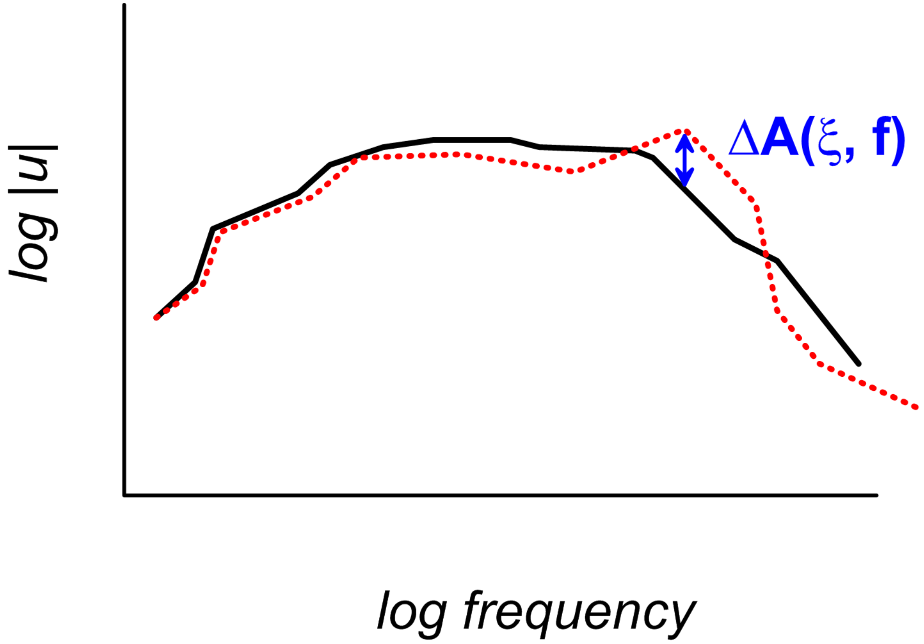
Lagged Coherency

Adjusted model compared to data



Amplitude Variability

Fourier amplitude variation in pair, $\Delta A(\xi , f)$



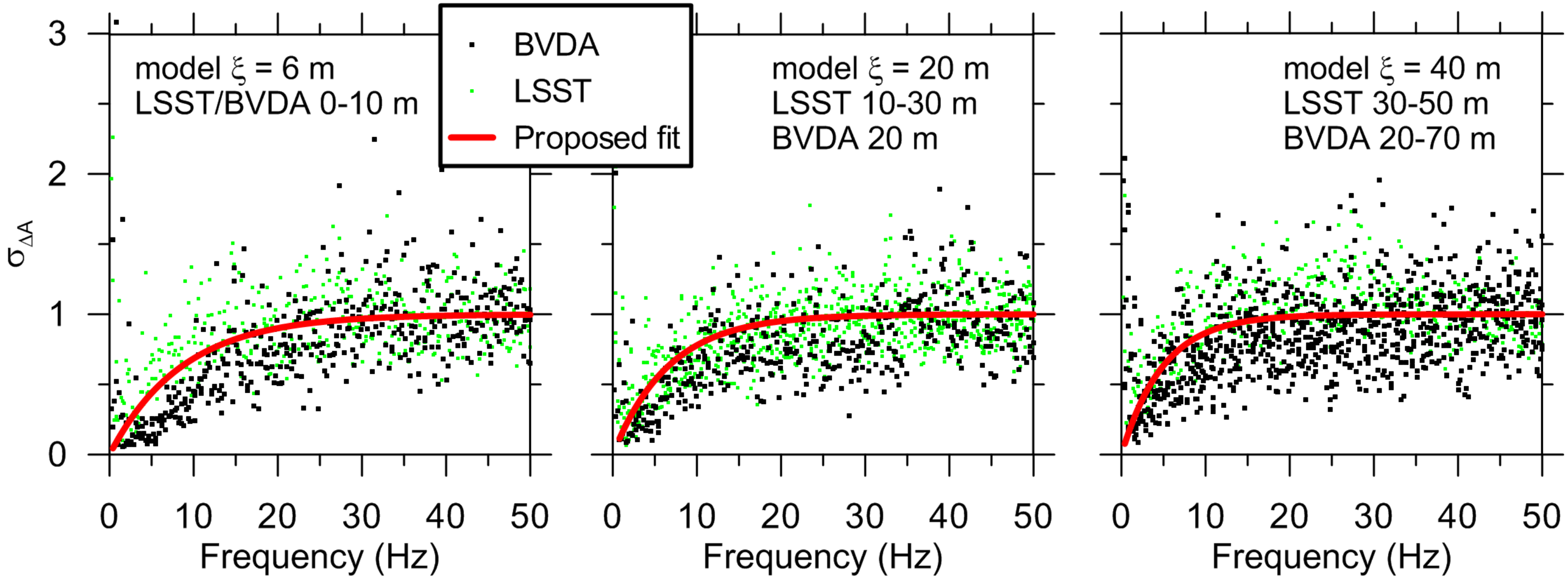
Amplitude Variability

Fourier amplitude variation in pair, $\Delta A(\xi, f)$

Distribution of $\Delta A(\xi, f)$ has mean zero and $\sigma_{\Delta A}$

Amplitude Variability

BVDA & LSST data



$$\sigma_{\Delta A}(f) = A\left(1 - e^{Bf}\right)$$

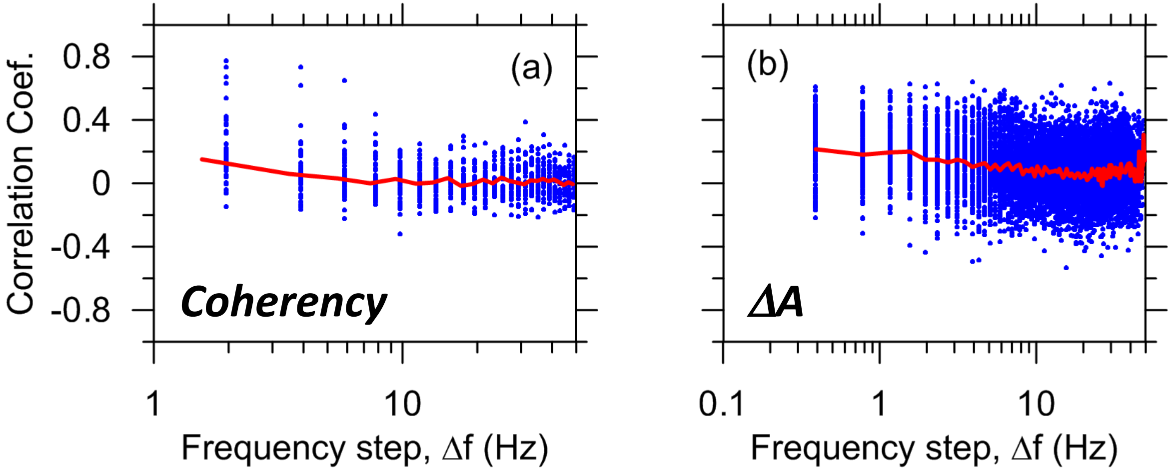
$$B = b_1 + b_2\xi$$

Correlations

Frequency-to-frequency correlations for coherency or amplitude variability

Calculated for frequency steps

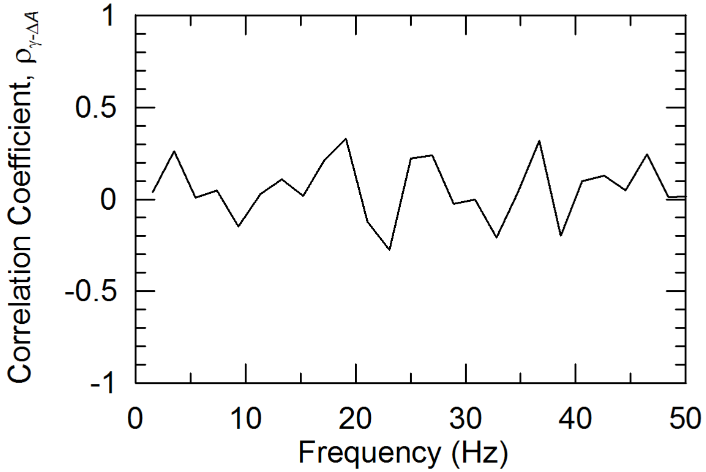
Weak correlation



Correlations

Frequency-to-frequency correlations for coherency or amplitude variability

Amplitude variability – coherency correlation



No apparent correlation

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SVGM Simulations

- Objective
- Phase modification
- Amplitude modification
- Frequency-dependent windowing

Objective

Given seed accelerogram, generate simulated motion compatible with $|\gamma|$ and ΔA models

Useful for response history analysis of structures

Useful for estimation of ground strains

Phase Modification

$$\phi_j(f,\xi) = \enclose{circle}{\phi_i(f)} + \varepsilon_{ij}^{n}(f,\xi) + 2\pi f \Delta t$$

Phase of seed record

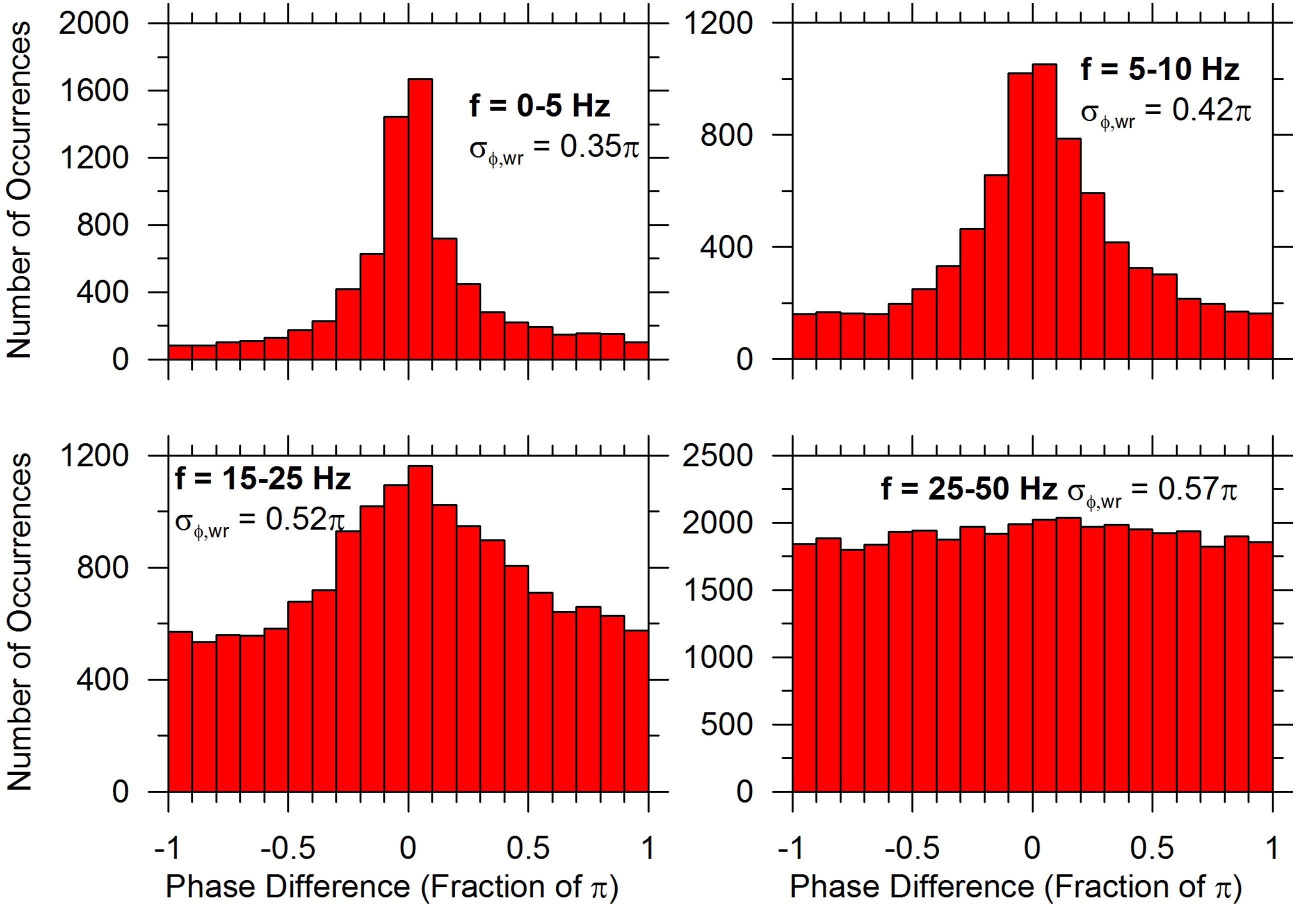
Phase Modification

$$\phi_j\left(f,\xi\right)=\phi_i\left(f\right)+\boxed{\varepsilon_{ij}^{n}\left(f,\xi\right)}+2\pi f\Delta t$$

Random phase change.

Zero Mean

Standard deviation σ_ϕ



Normal distribution

Appears uniform at high frequency due to wrapping

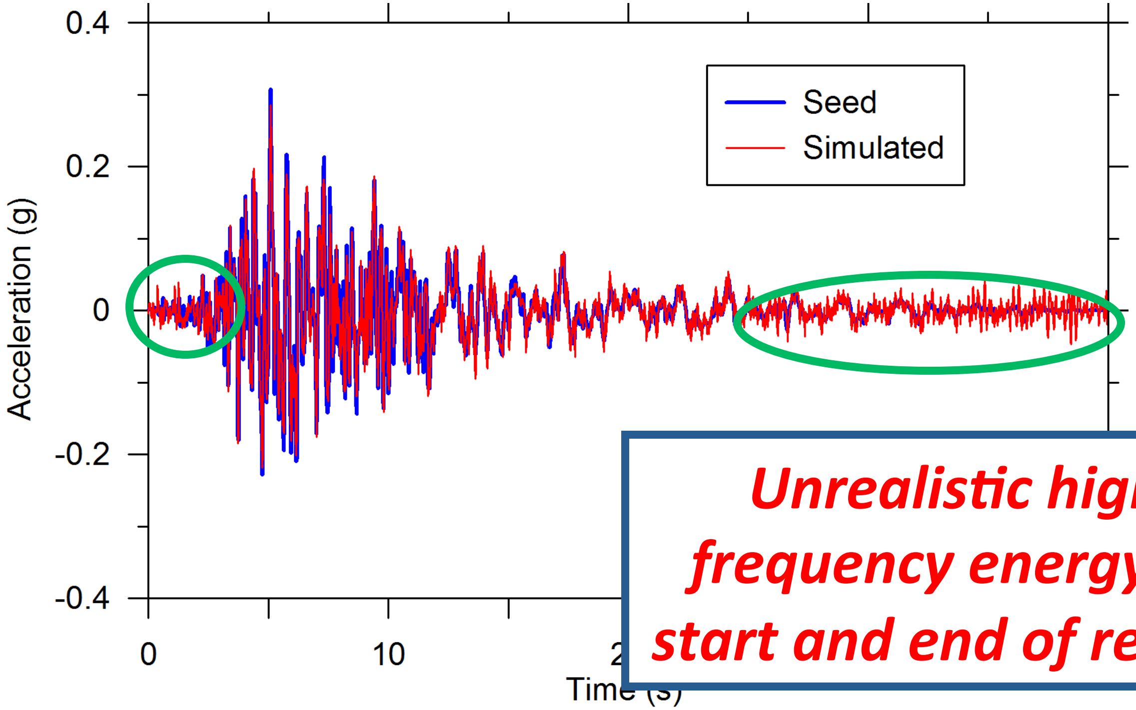
Phase Modification

$$\phi_j(f,\xi) = \phi_i(f) + \varepsilon_{ij}^{n}(f,\xi) + \boxed{2\pi f \Delta t}$$

Wave passage.
Δt from ξ and V$_{app,\theta}$

Phase Modification

Result of phase modification (full duration):



Unrealistic high frequency energy at start and end of record

Amplitude Modification

$$A_j(f) = \exp\left\{\ln\left[\boxed{A_i(f)}\right] + \varepsilon_{ij}^{A}(f) \cdot \frac{1}{\sqrt{2}}\sigma_{\Delta A}(f)\right\}$$

Amplitude of seed record

Amplitude Modification

$$A_j\left(f\right) = \exp\left\{\ln\left[A_i\left(f\right)\right] + \varepsilon_{ij}^{A}\left(f\right) g \frac{1}{\sqrt{2}} \sigma_{\Delta A}\left(f\right)\right\}$$

Gaussian random number.

Mean zero

Standard deviation of unity

Amplitude Modification

$$A_j(f) = \exp\left\{\ln\left[A_i(f)\right] + \varepsilon_{ij}^{A}(f) \cdot \frac{1}{\sqrt{2}} \boxed{\sigma_{\Delta A}(f)}\right\}$$

From amplitude variability model

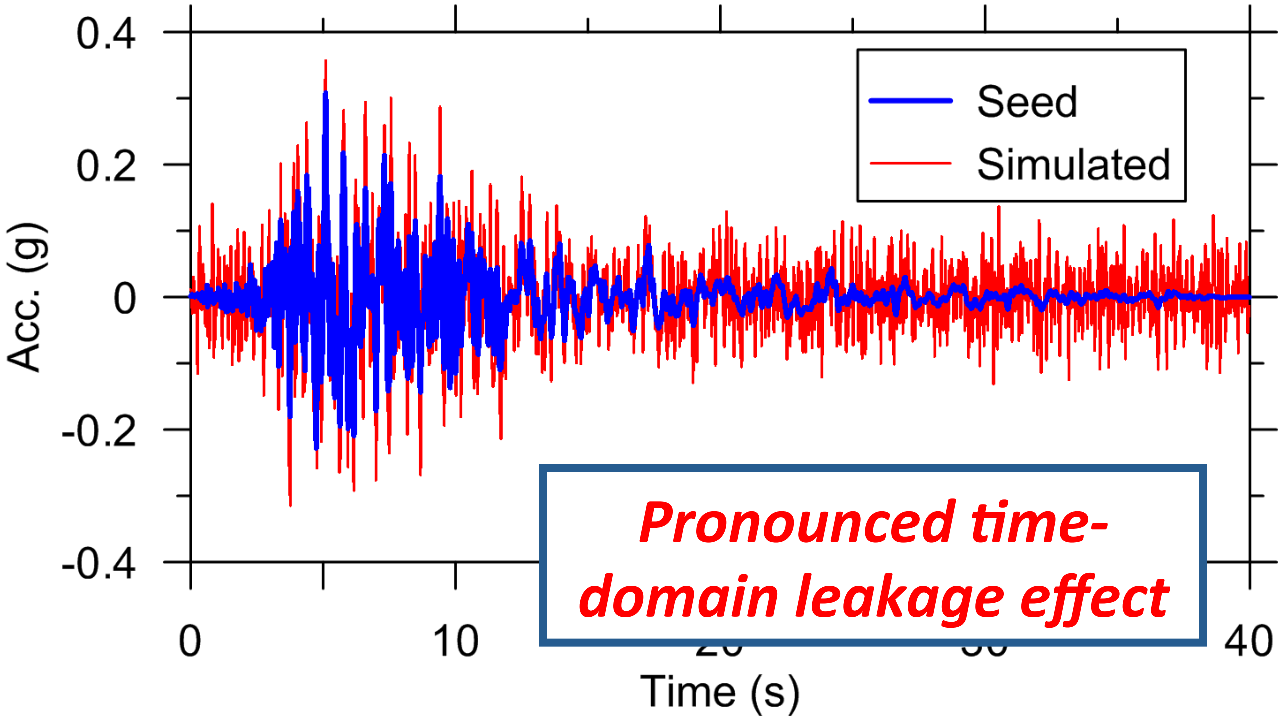
Amplitude Modification

$$A_j\left(f\right) = \exp\left\{\ln\left[A_i\left(f\right)\right] + \varepsilon_{ij}^{A}\left(f\right)\mathrm{g}\boxed{\frac{1}{\sqrt{2}}}\sigma_{\Delta A}\left(f\right)\right\}$$

To represent single station amplitude variability

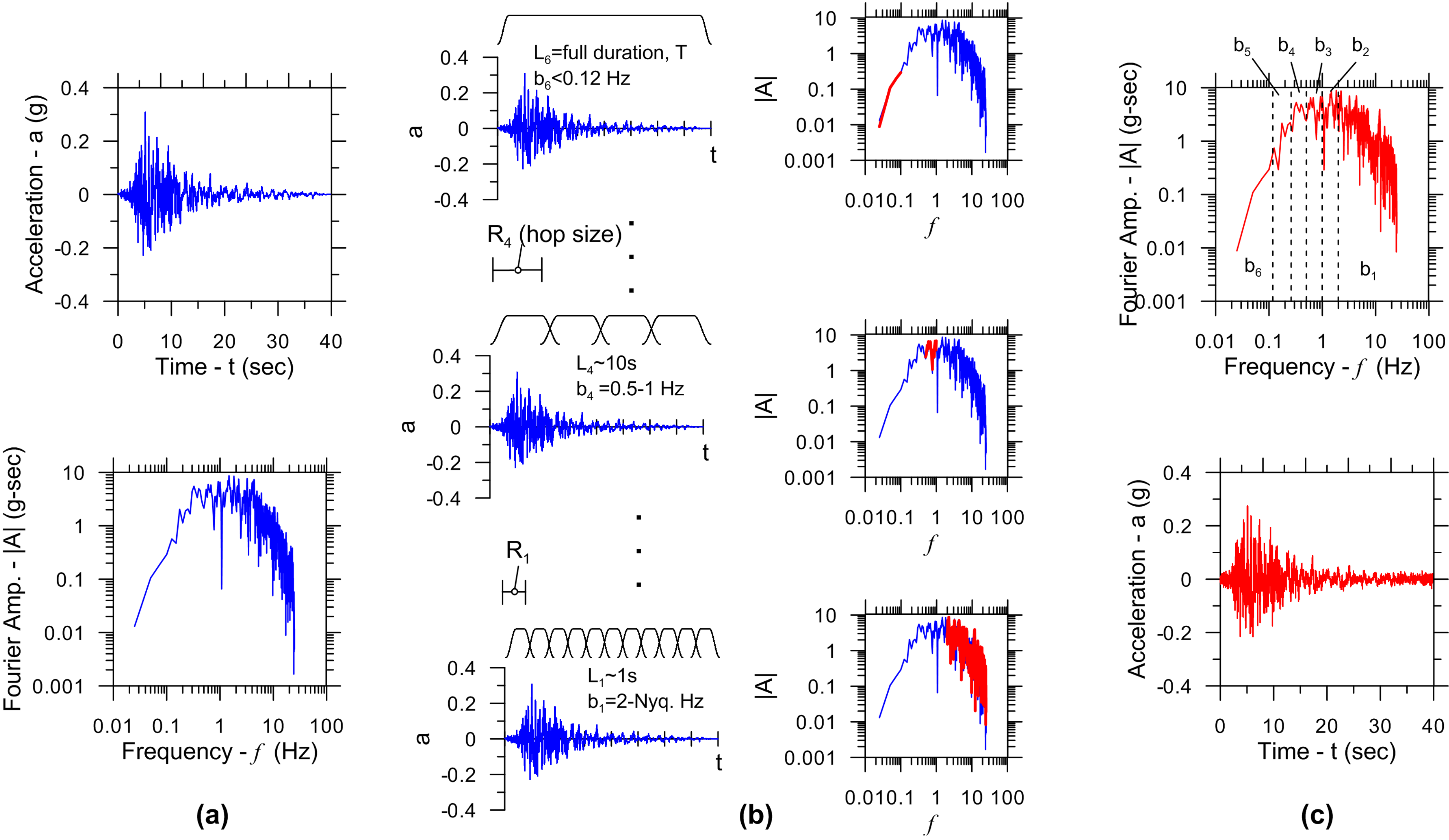
Amplitude Modification

Result of amplitude modification (full duration):



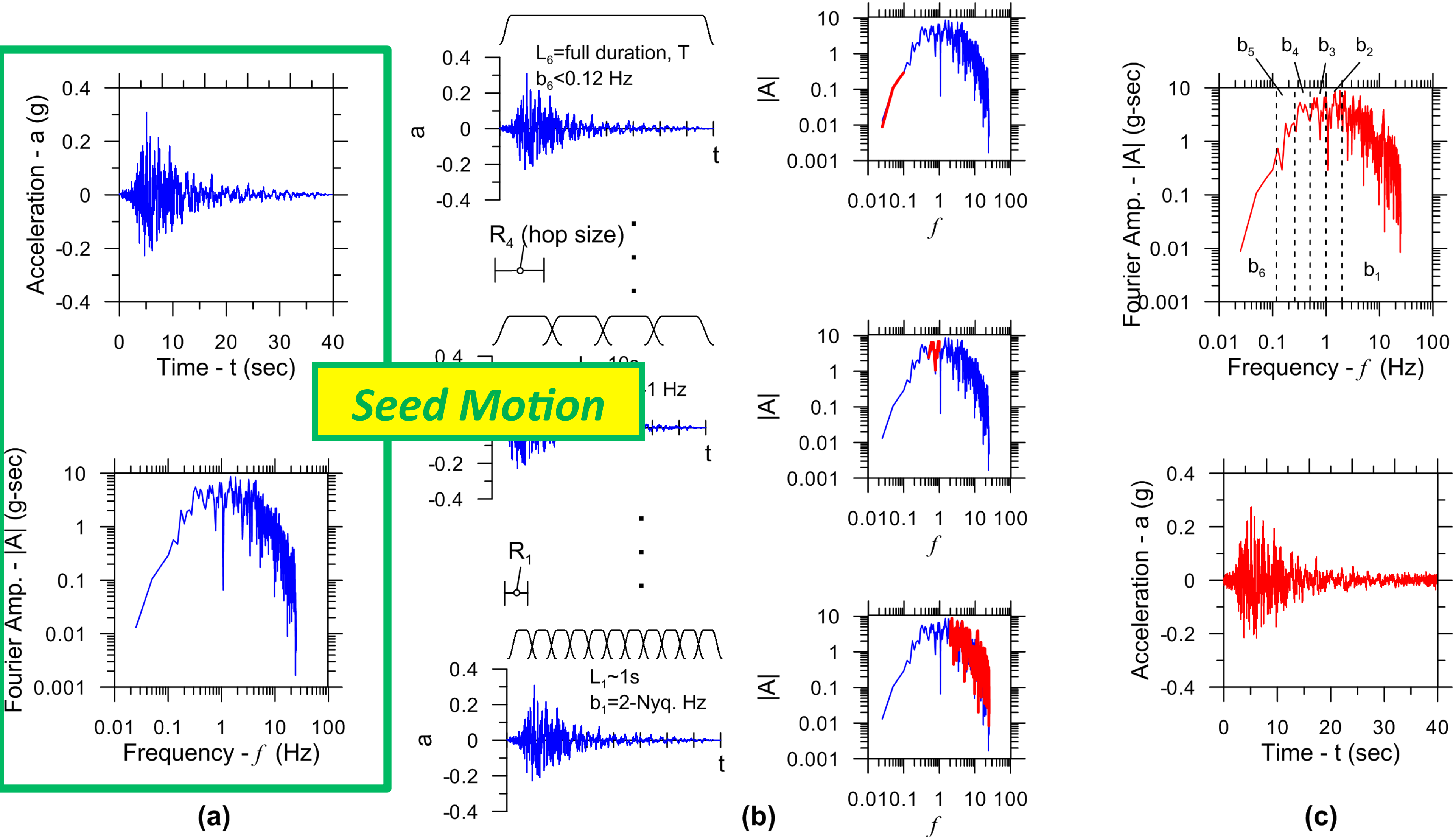
Pronounced time-domain leakage effect

Frequency Dependent Windowing



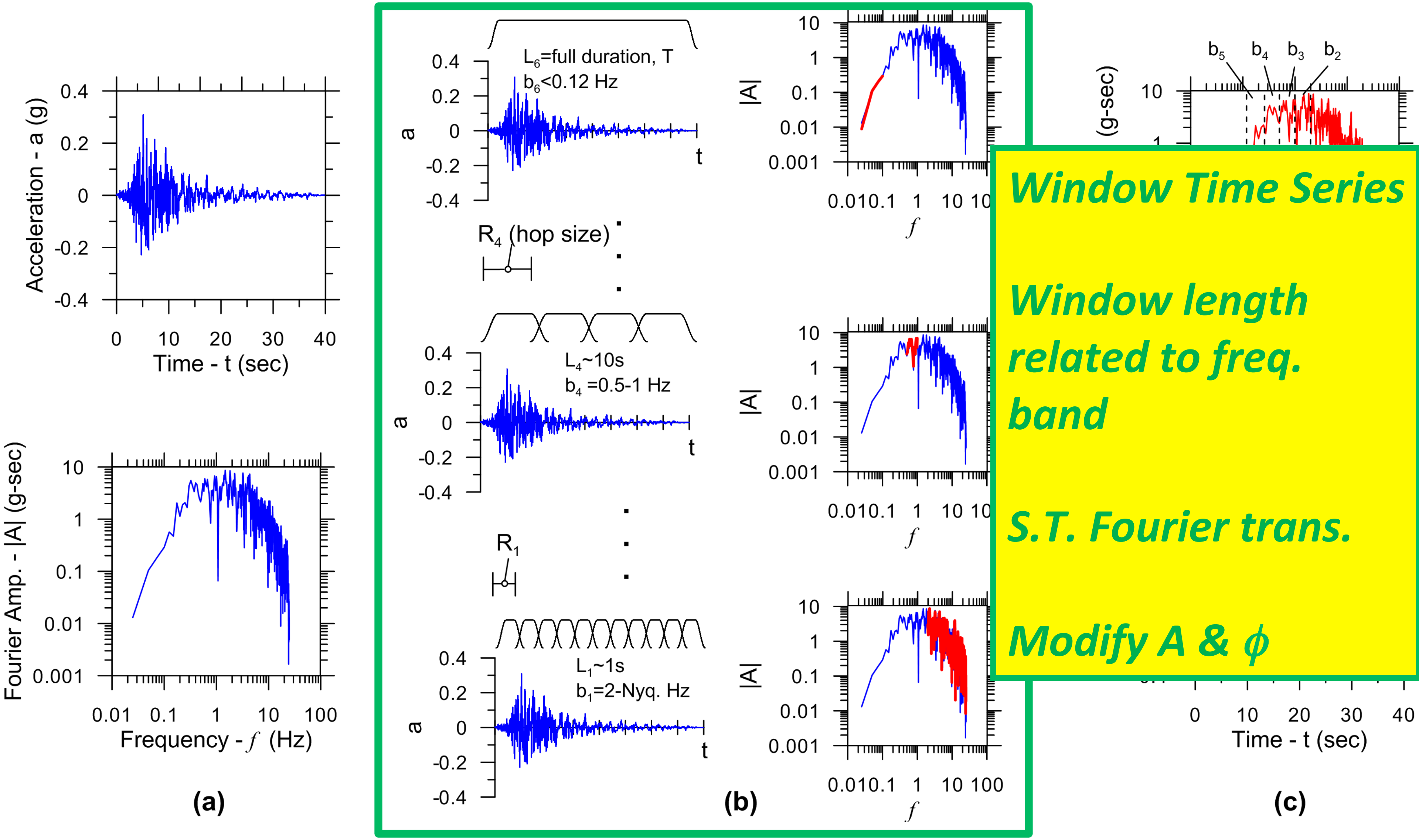
(a) **(b)** **(c)**

Frequency Dependent Windowing



Seed Motion

Frequency Dependent Windowing



(a)

(b)

(c)

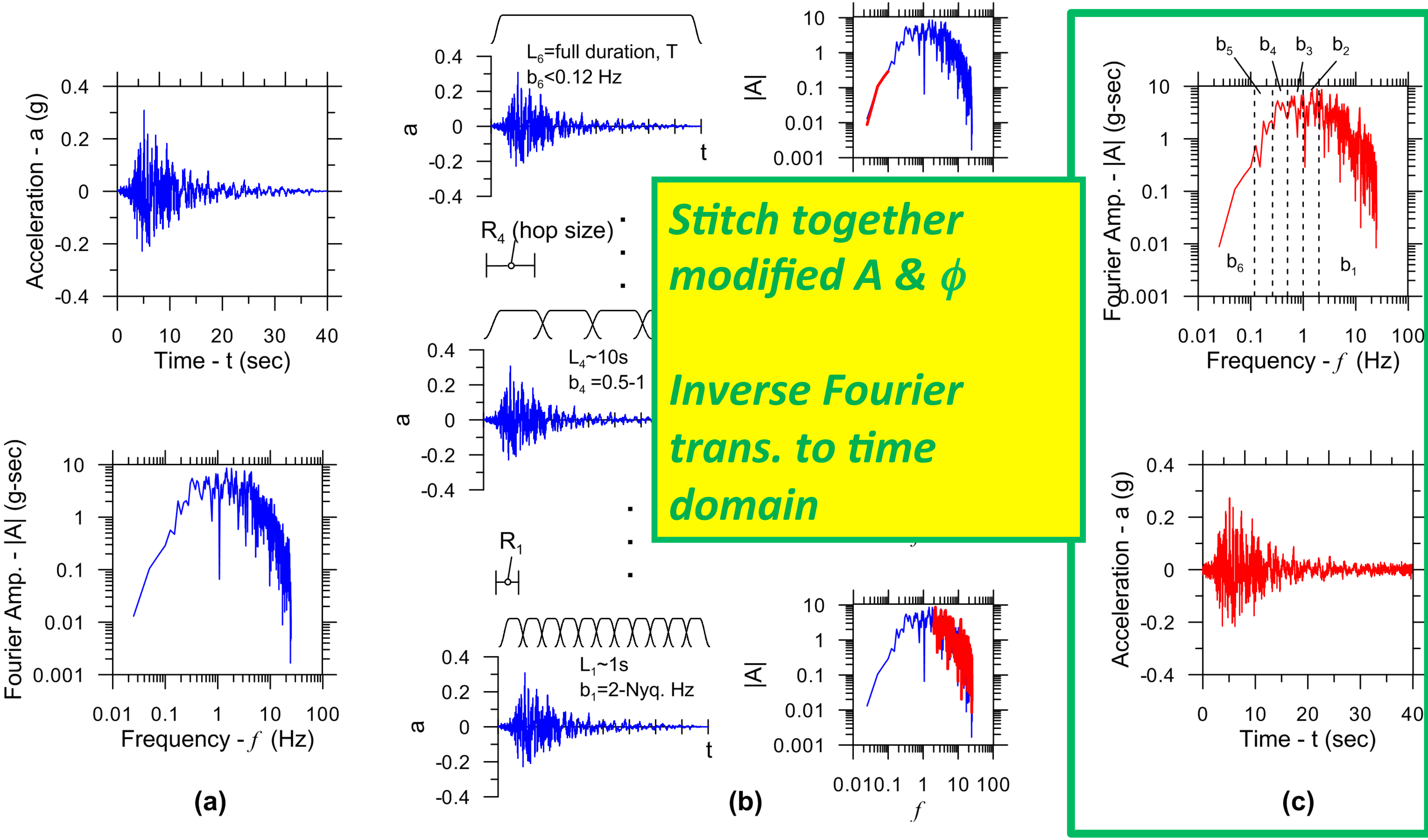
Window Time Series

Window length related to freq. band

S.T. Fourier trans.

Modify A & ϕ

Frequency Dependent Windowing



Stitch together modified A & ϕ

Inverse Fourier trans. to time domain

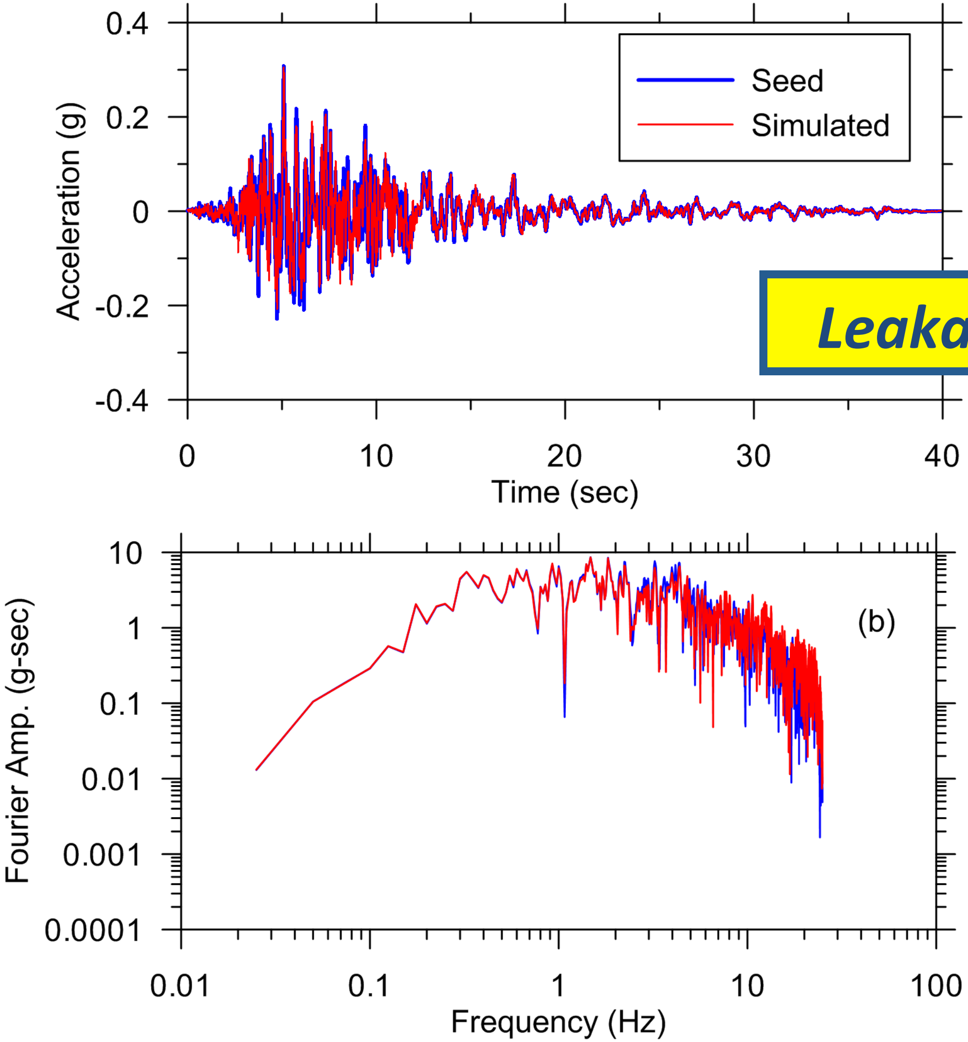
Frequency Dependent Windowing

Critical details:

- Windowing procedure
- Recombination procedure

Details in Ancheta et al. (2011, Earthquake Spectra, in review)

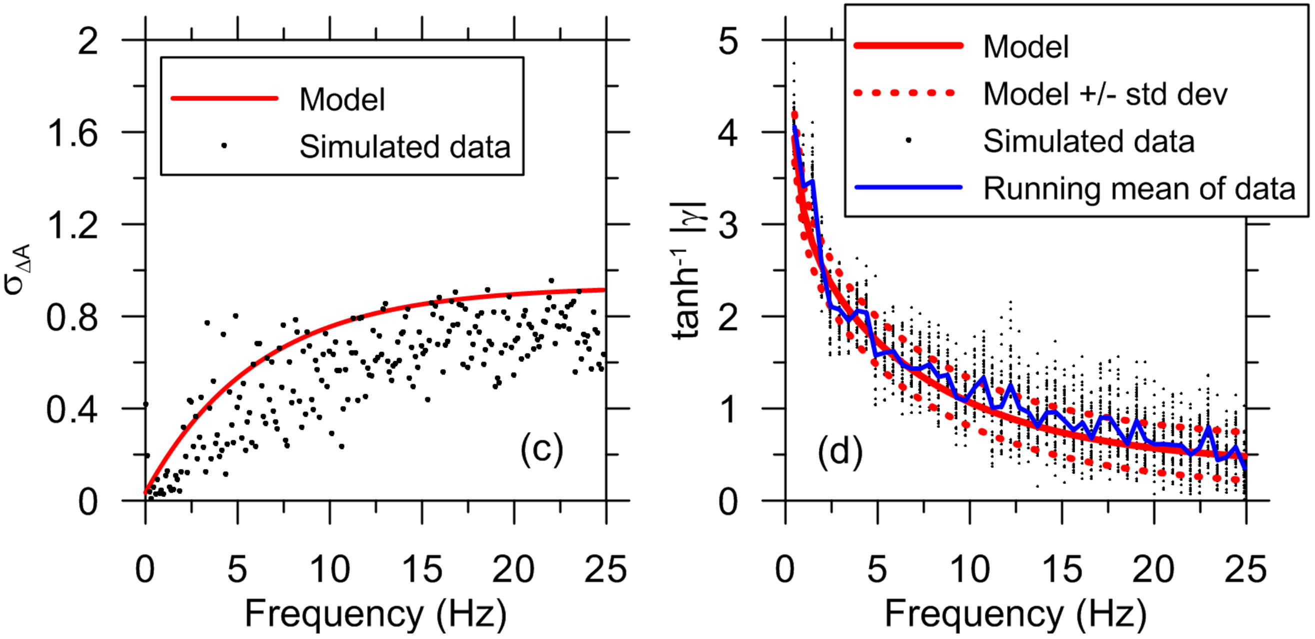
Frequency Dependent Windowing



Leakage removed

Frequency Dependent Windowing

Compare simulations to underlying models



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Seismic Ground Strains

- Previous work
- Procedure for simulation-based strain estimation
- Simulation results & prediction equations
- Verification using array data

Previous Work

Strains from wave passage

$$PGS = A\frac{PGV}{V_{app}}$$

Newmark, 1967
Yeh (1974)
St. John and Zahrah (1987)
Trifunac and Lee (1996)
Hashash et al. (2001)

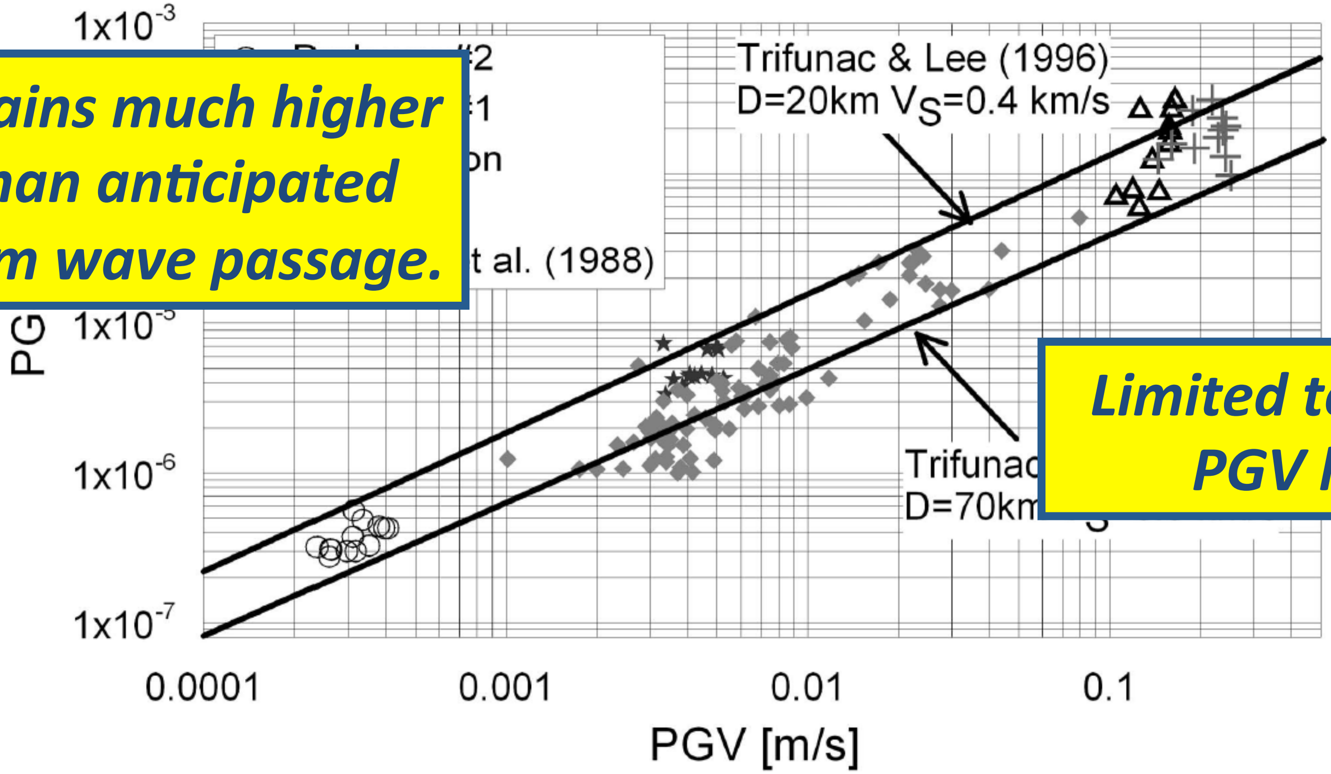
Previous Work

Strains from wave passage

Inference of strains from arrays using geodetic approach

O'Rourke et al. (1984)
Bodin et al. (1997)
Gomberg et al. (1999)
Paolucci and Smerzini (2008)

Previous Work



Strains much higher than anticipated from wave passage.

Limited to modest PGV levels

Paolucci and Smerzini (2008)

Strain Estimation from Simulations

1. N_i seed motions selected for j=1..N_e events
2. For each seed motion, simulate N_s motions for suites of separation distances (ξ = 6, 10, 20, 40, 80 m) and apparent velocities (V_{app}).
3. Each seed-simulated motion integrated twice to displacement & normalized by ξ to calculate strain history. Peak is *PGS*.

Strain Estimation from Simulations

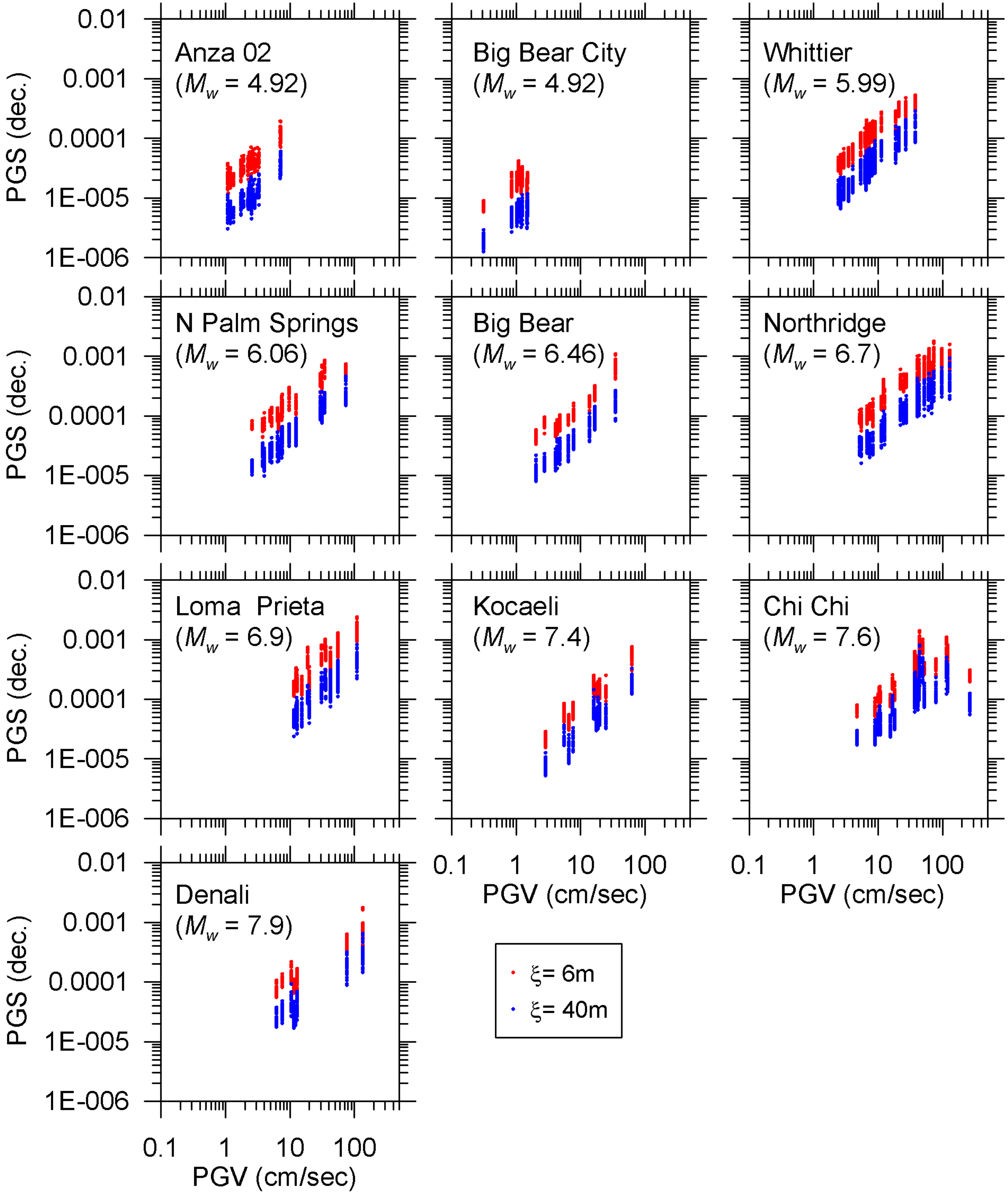
Events

M 4.9	Anza, CA
M 4.9	Big Bear City, CA
M 6.0	Whittier, CA
M 6.1	North Palm Springs, CA
M 6.5	Big Bear City, CA
M 6.7	Northridge, CA
M 6.9	Loma Prieta, CA
M 7.5	Kocaeli, Turkey
M 7.6	Chi Chi, Taiwan
M 7.9	Denali, AL

Soil sites selected

135 motions

Results of Simulations

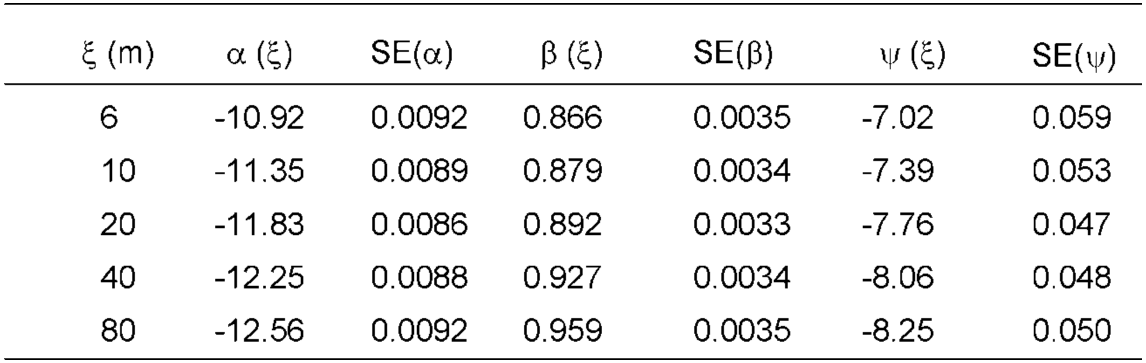


Affected by ξ

Saturation effect for PGV > ~ 80 cm/s

Fitting of Model

$$\ln PGS_{ijk} \mid \xi = \begin{cases} \alpha + \beta \ln PGV_{ijk} + \varepsilon_{ijk} & \text{for } PGV < PGV_L \\ \psi & \text{otherwise} \end{cases}$$

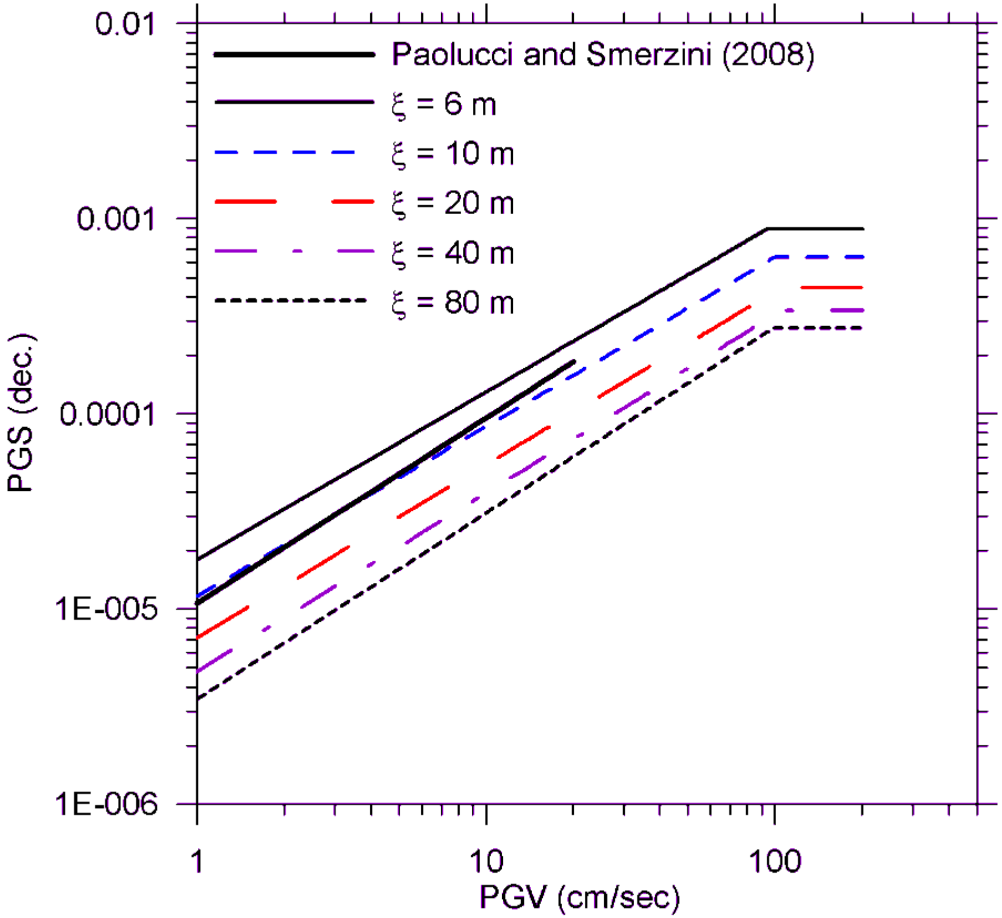


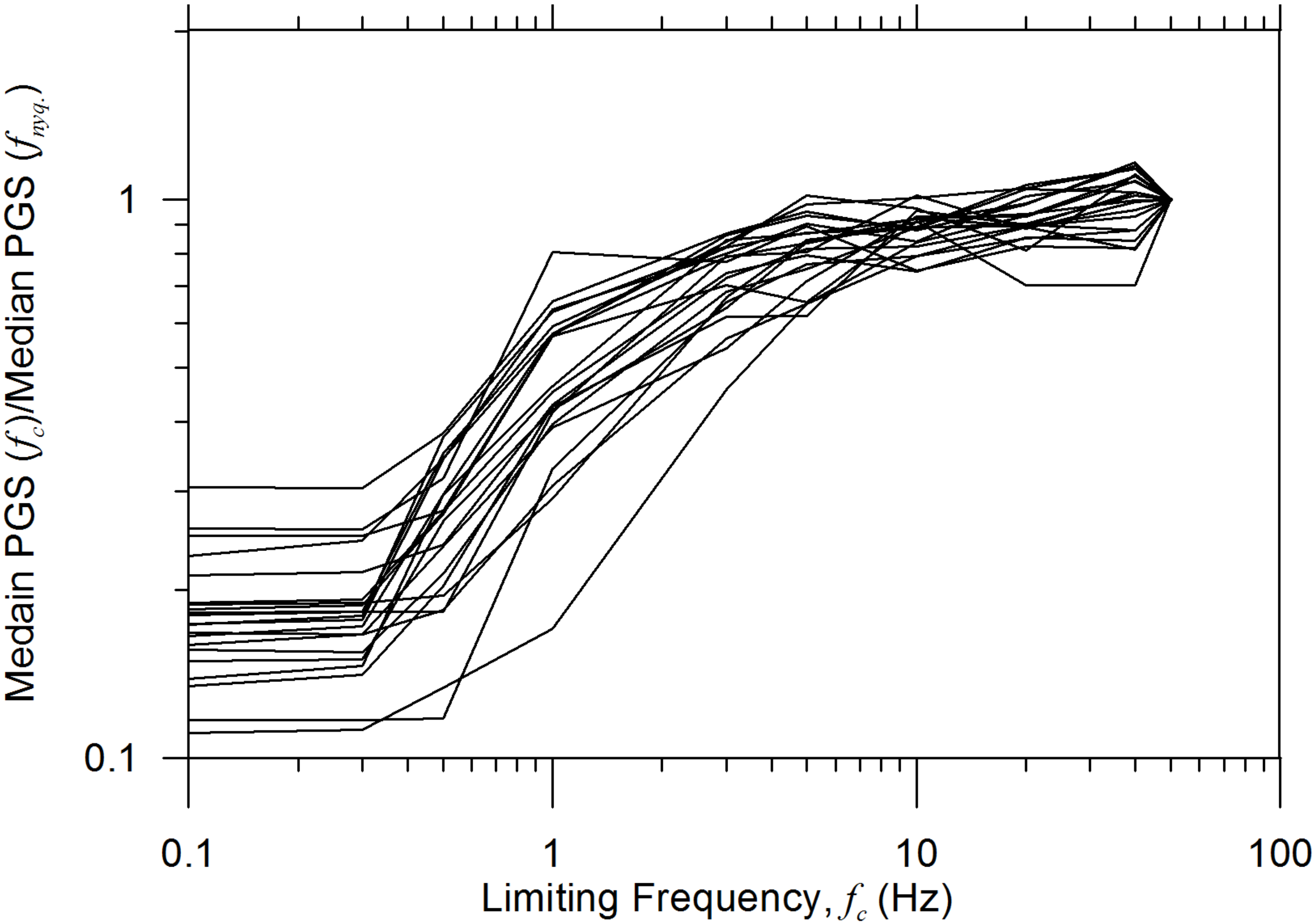
ξ (m)	α (ξ)	SE(α)	β (ξ)	SE(β)	ψ (ξ)	SE(ψ)
6	-10.92	0.0092	0.866	0.0035	-7.02	0.059
10	-11.35	0.0089	0.879	0.0034	-7.39	0.053
20	-11.83	0.0086	0.892	0.0033	-7.76	0.047
40	-12.25	0.0088	0.927	0.0034	-8.06	0.048
80	-12.56	0.0092	0.959	0.0035	-8.25	0.050

Final coefficients from random effects analysis.

FOSM used to represent range of V_{app} in data set.

Fitting of Model



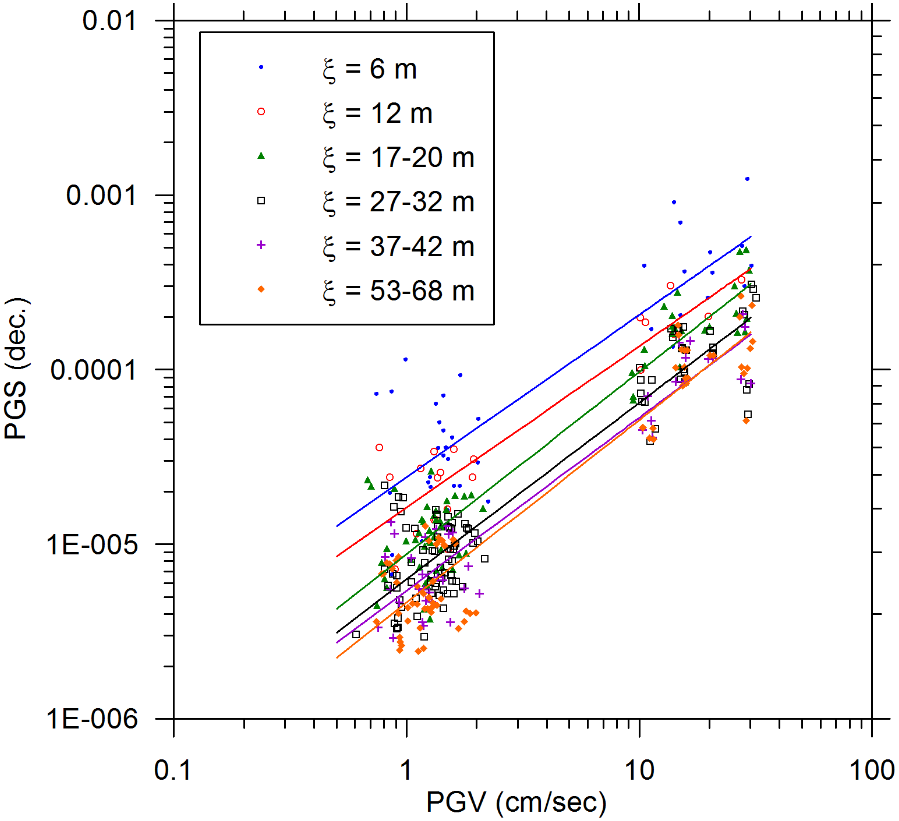

Medain PGS (f_c)/Median PGS ($f_{nyq.}$)
1
0.1
0.1
1
10
100
Limiting Frequency, f_c (Hz)

Verification of ξ-Dependence

LSST data

Calculate differential displacement from pairs & normalize by ξ.

Statistically significant difference for low ξ; not for $\xi > 20$ m.



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Summary of Key Results

- Three key metrics of SVGM.
  - Wave passage: Recommendations on V_{app}, σ_{lnV}, and importance of ATP
  - Modest adjustment of previous $|\gamma|$ model
  - Model for amplitude variability
- Simulation procedure provides realistic spatially variable waveforms including amplitude variability.
- New insights on ground strain:
  - Separation distance dependence
  - Saturation at large PGV

More Information

- Metrics of SVGM: this conference
- SVGM simulations: Ancheta et al., Earthquake Spectra, in review
- Ground strains: Ancheta (2010) dissertation; soon in PEER report