Coherency Models

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Coherency

- Measure of the similarity of shapes of two time series
- Scale factor differences have no effect on the coherency

Measures of Coherency

- Lagged Coherency
  - Similarity of two time series after applying a time lag that is optimized for each frequency band and station pair
- Unlagged Coherency
  - Similarity of two time series without a time lag (vertical wave propagation case)
- Plane-Wave Coherency
  - Similarity of two time series after applying a time lag based on a single plane wave for all frequencies and station pairs (inclined plane-wave case)

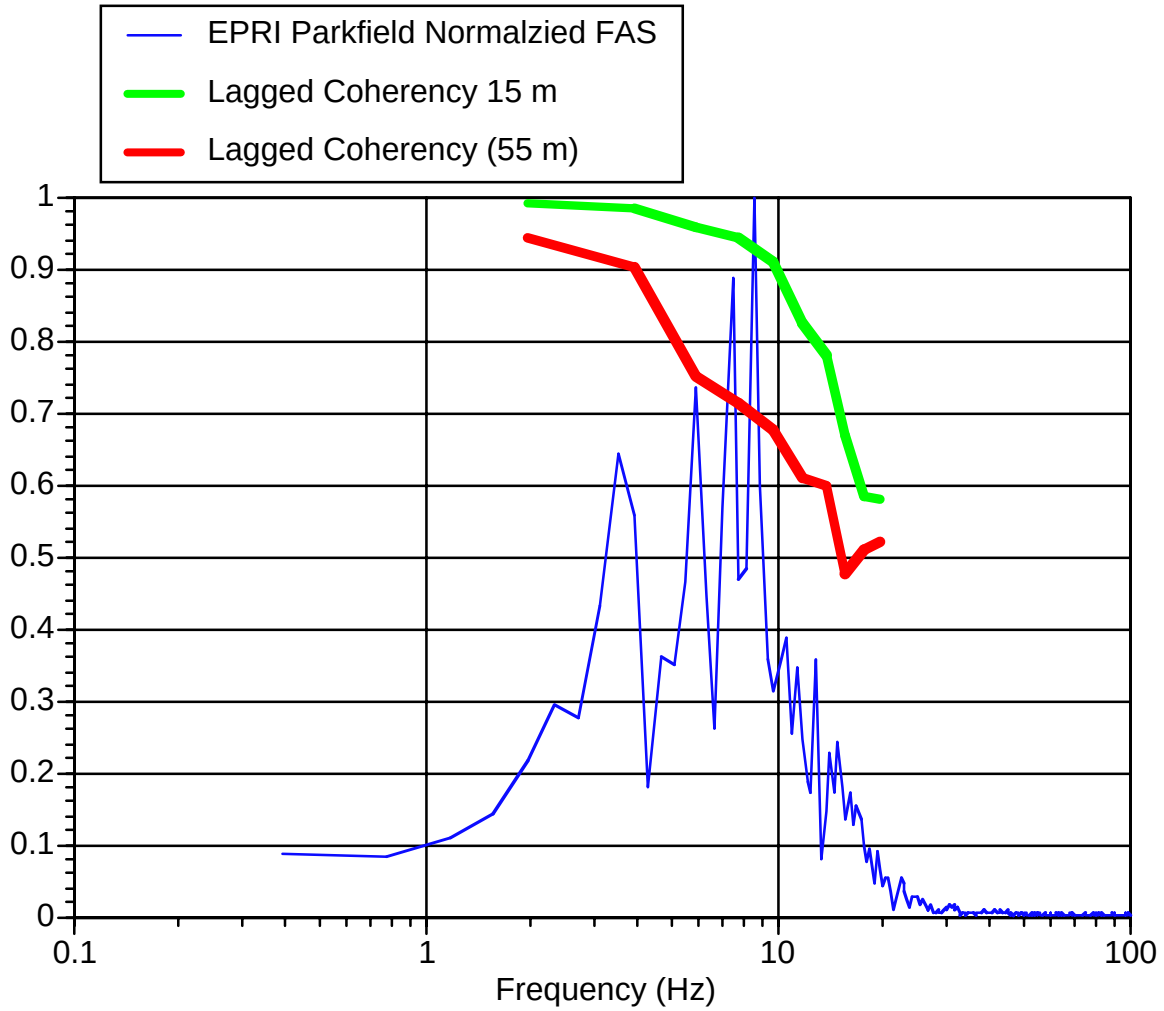
Understanding Coherency

- Time Domain
  - Cross-correlation vs coherency
- Frequency Domain
  - Range of phase differences in the complex plane

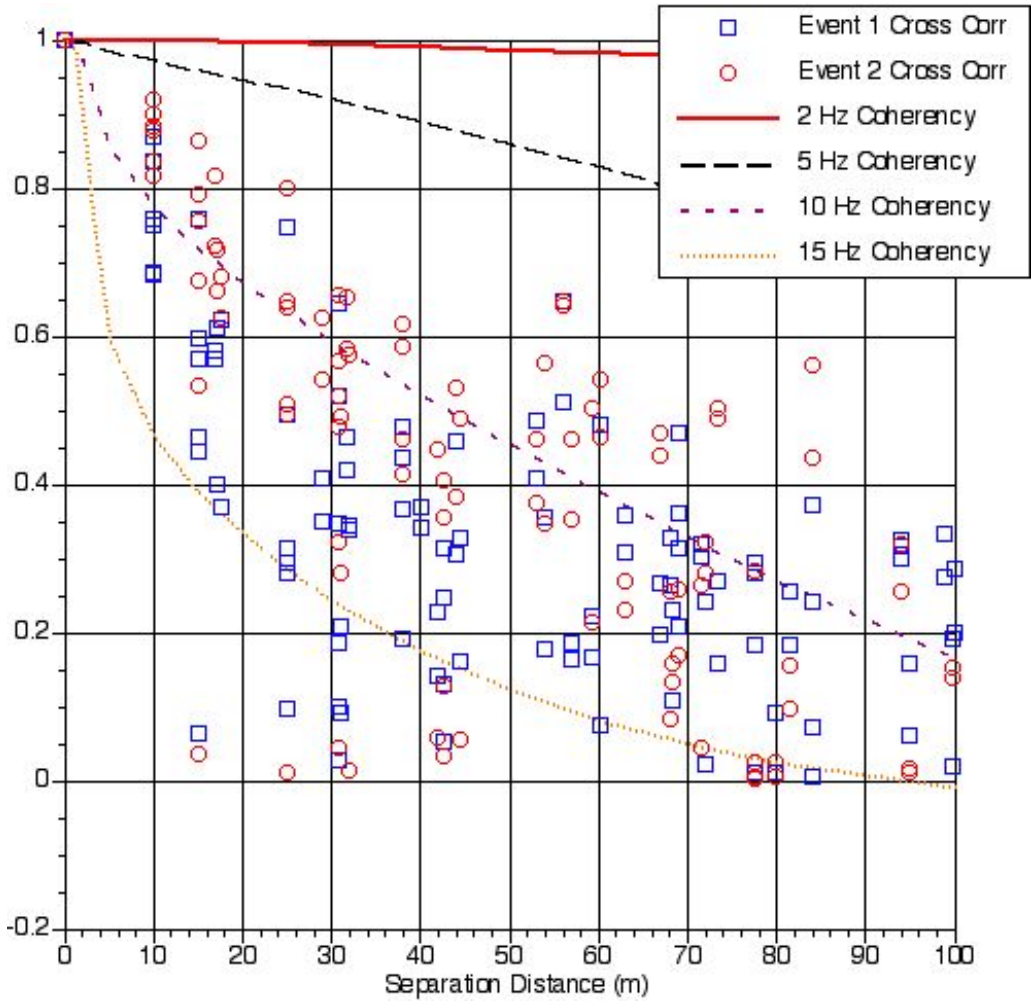
Cross-Correlation

- Measures similarity of two ground motions over all periods
  - Frequencies with the largest spectrum will dominate the cross-correlation
- Maximum cross-correlation is similar to the lagged coherency
- Cross-correlation at time zero (no shift) is similar to the unlagged coherency

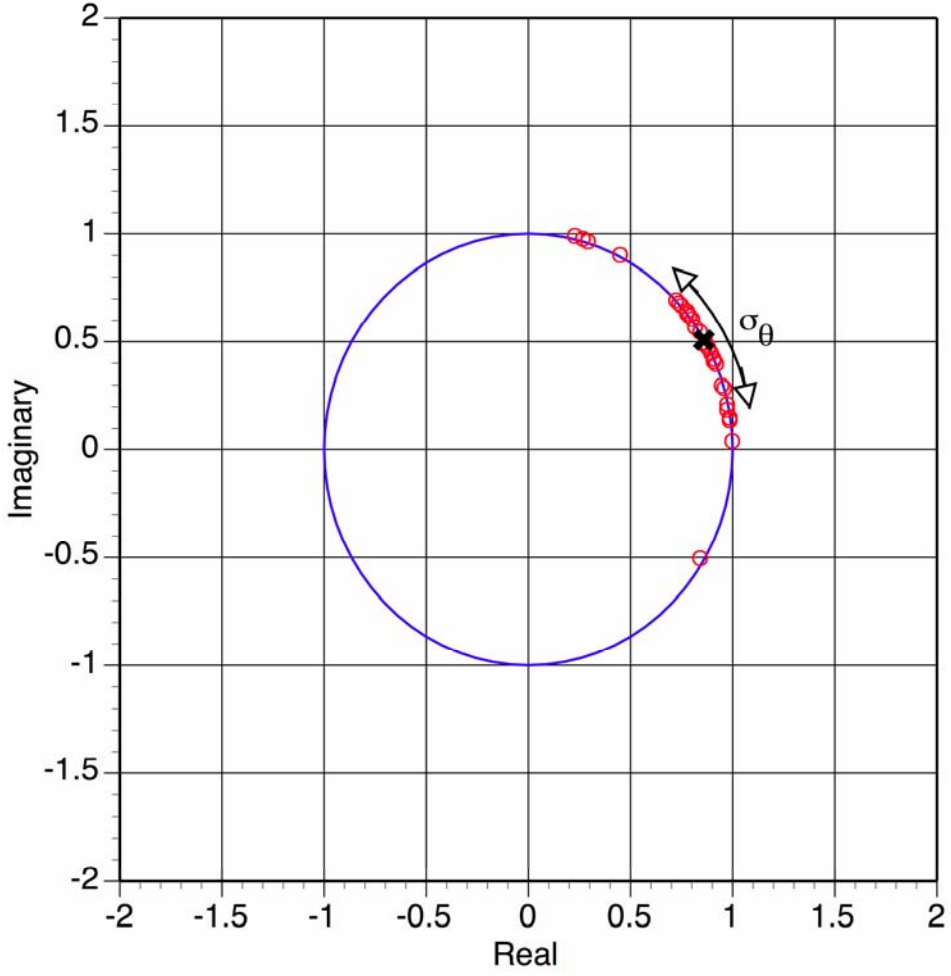
Example: ERPI Parkfield Array



Cross-Correlation



Variability of Phase Differences (Normalized Amplitude)



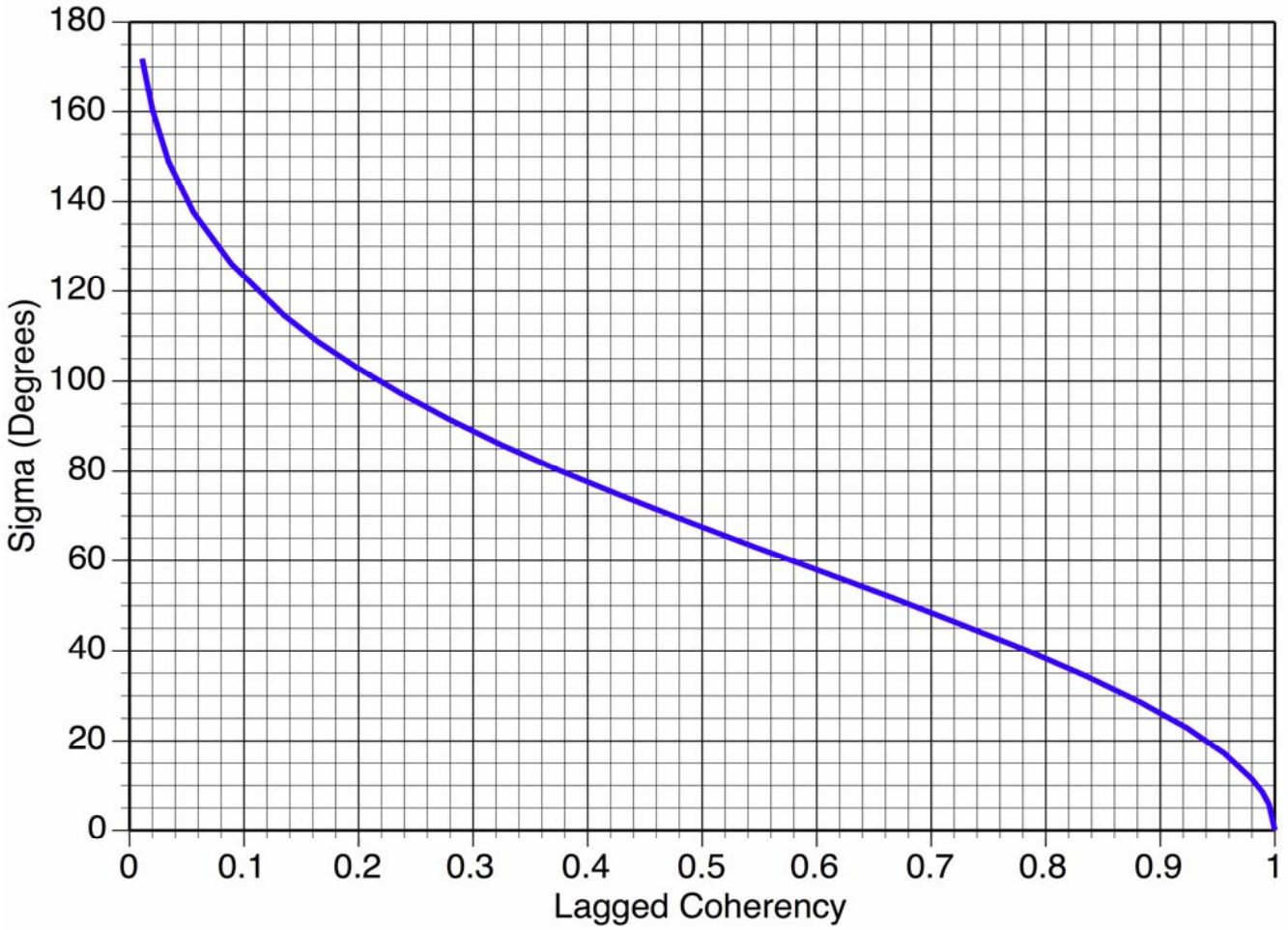
Example:

Mean = 30 degrees

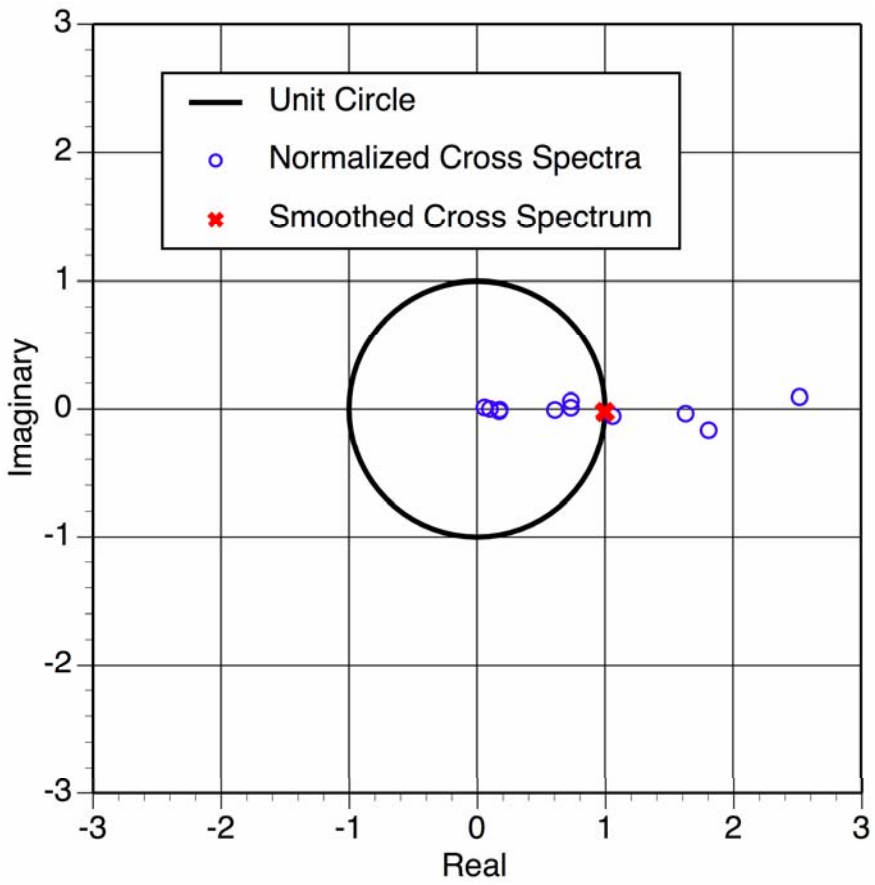
Sigma = 20 degrees

Lagged Coher = 0.94

Phase Difference Variability and Coherency

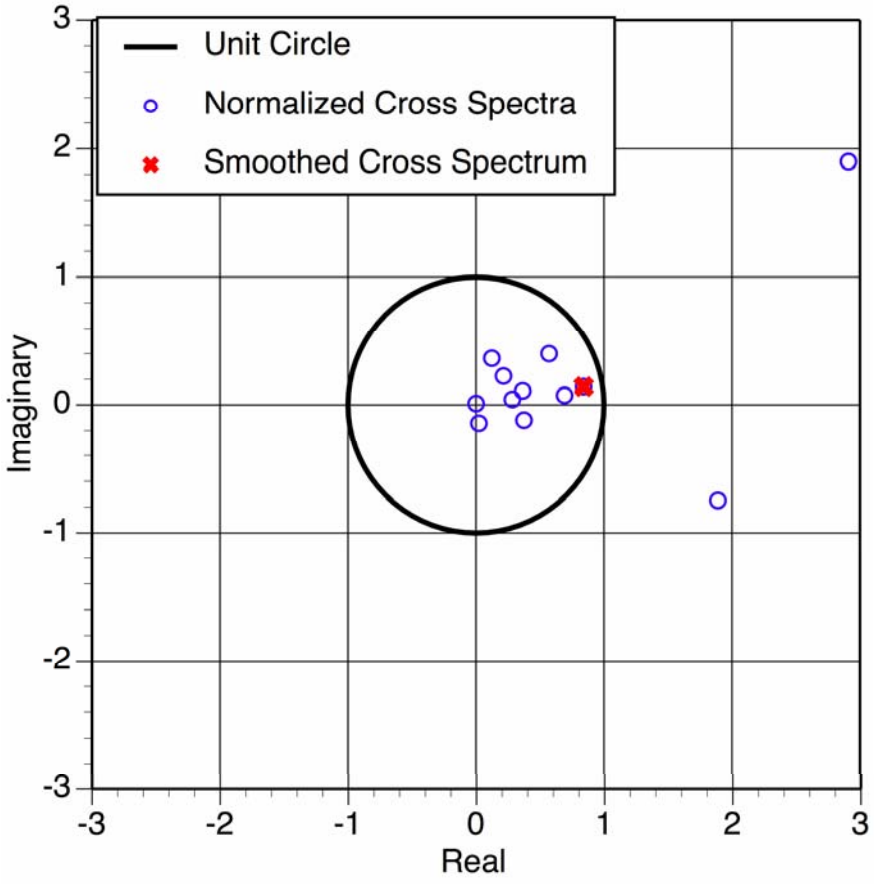


Separation = 18 m
Frequency = 2 Hz



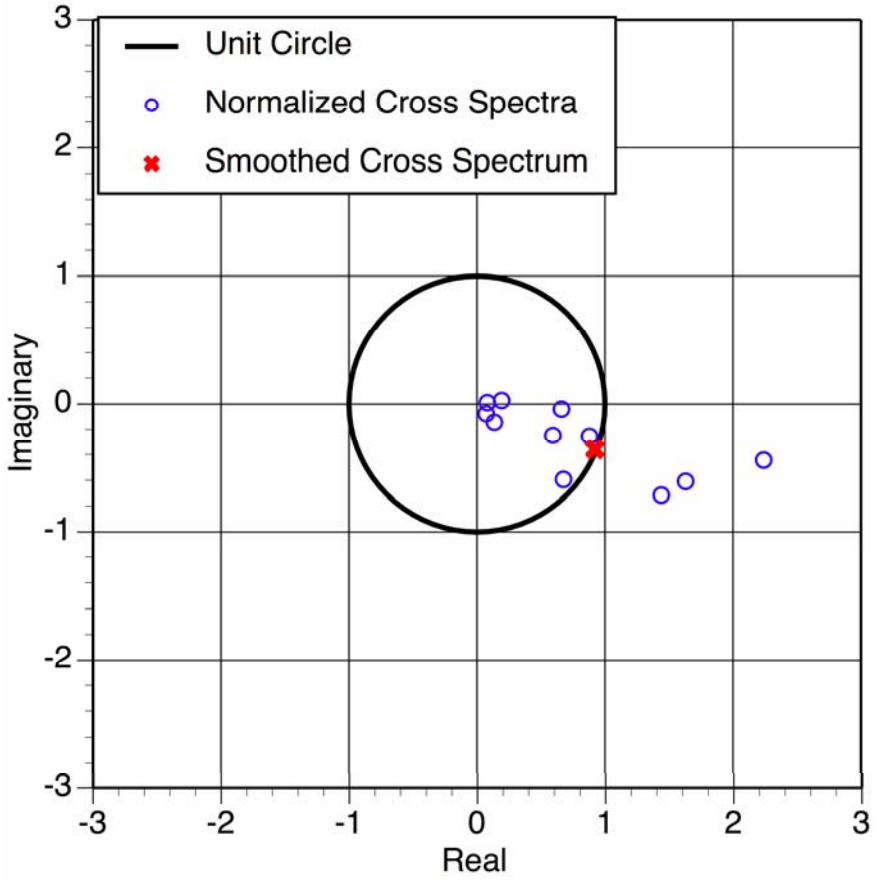
Lagged Coh = 1.00
Unlagged Coh = 1.00

Separation = 18 m
Frequency = 15 Hz



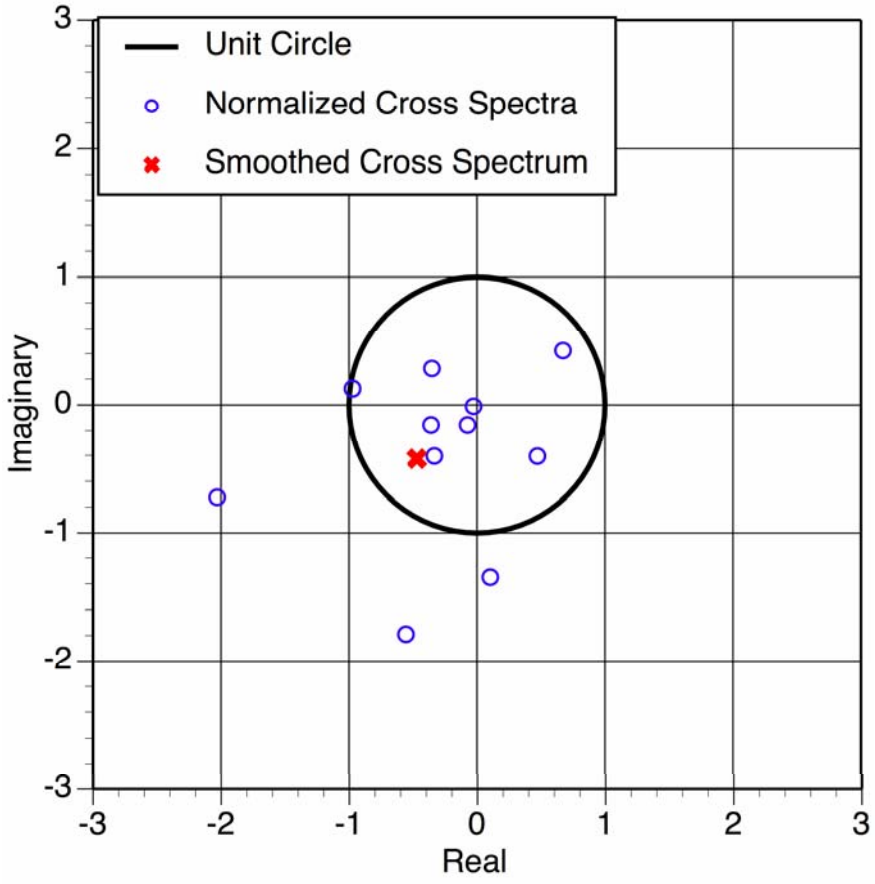
Lagged Coh = 0.85
Unlagged Coh = 0.84

Separation = 128 m
Frequency = 2 Hz



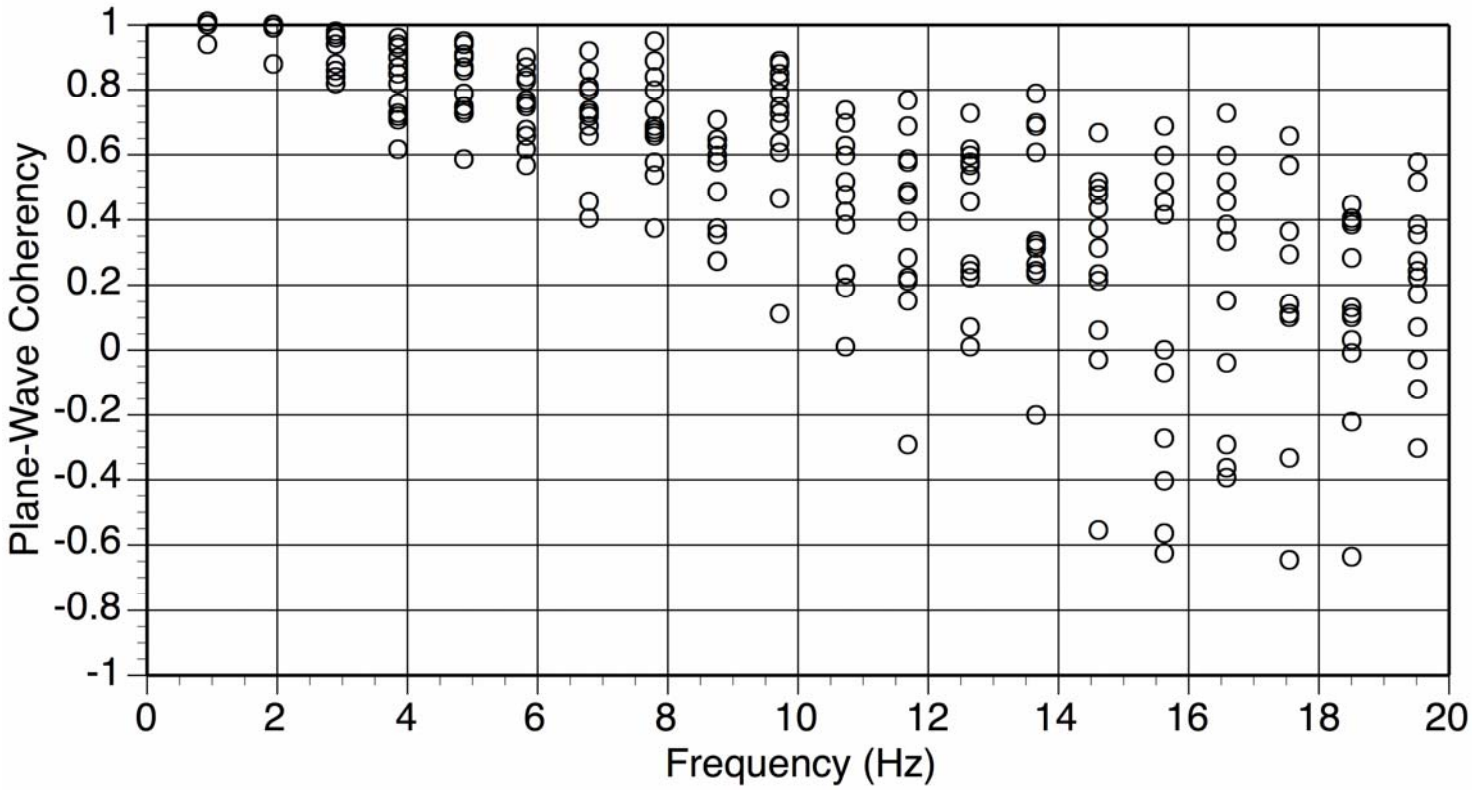
Lagged Coh = 0.99
Unlagged Coh = 0.92

Separation = 128 m
Frequency = 15 Hz

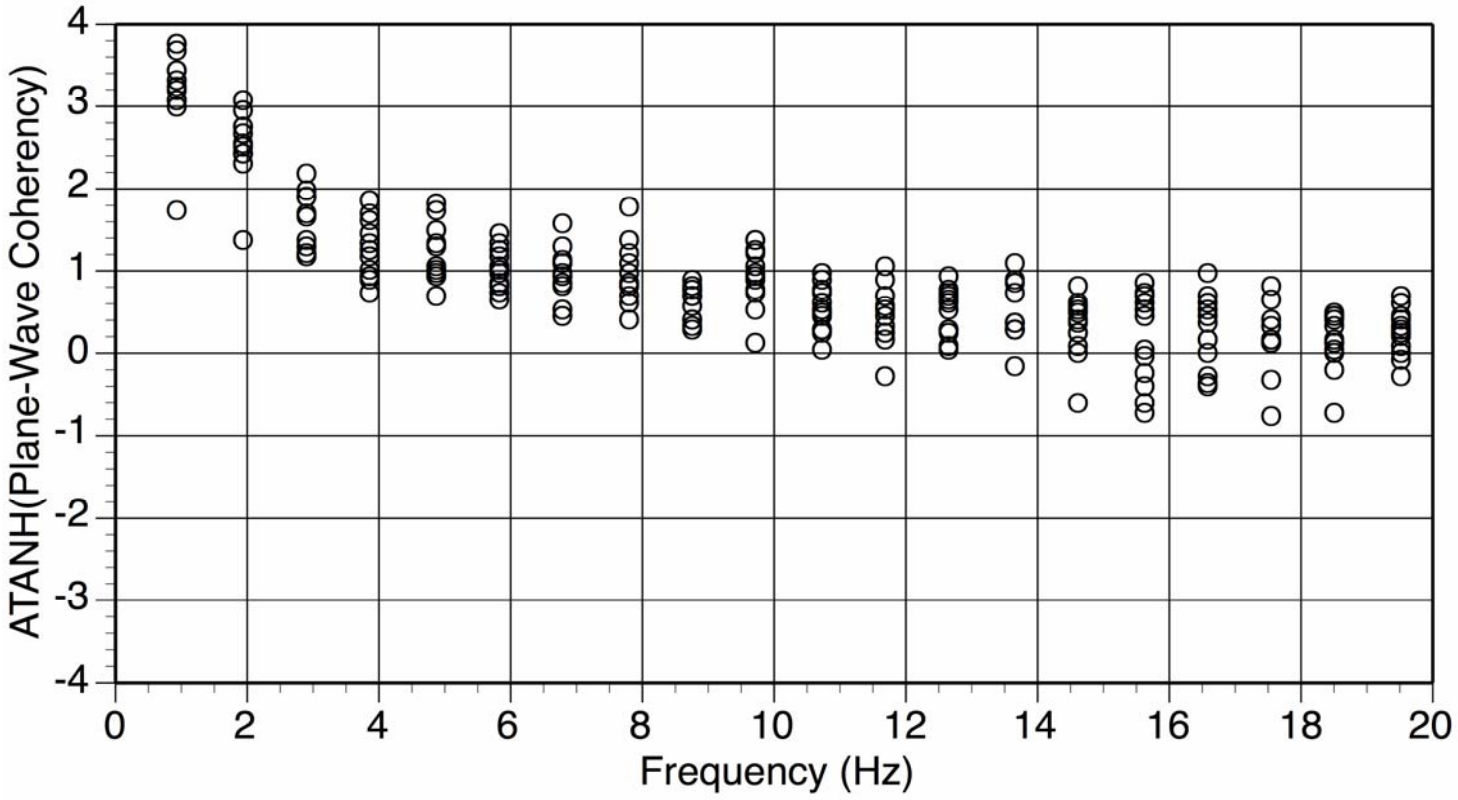


Lagged Coh = 0.63
Unlagged Coh = -0.47

Coherency is not normally distributed



ATANH Transformation



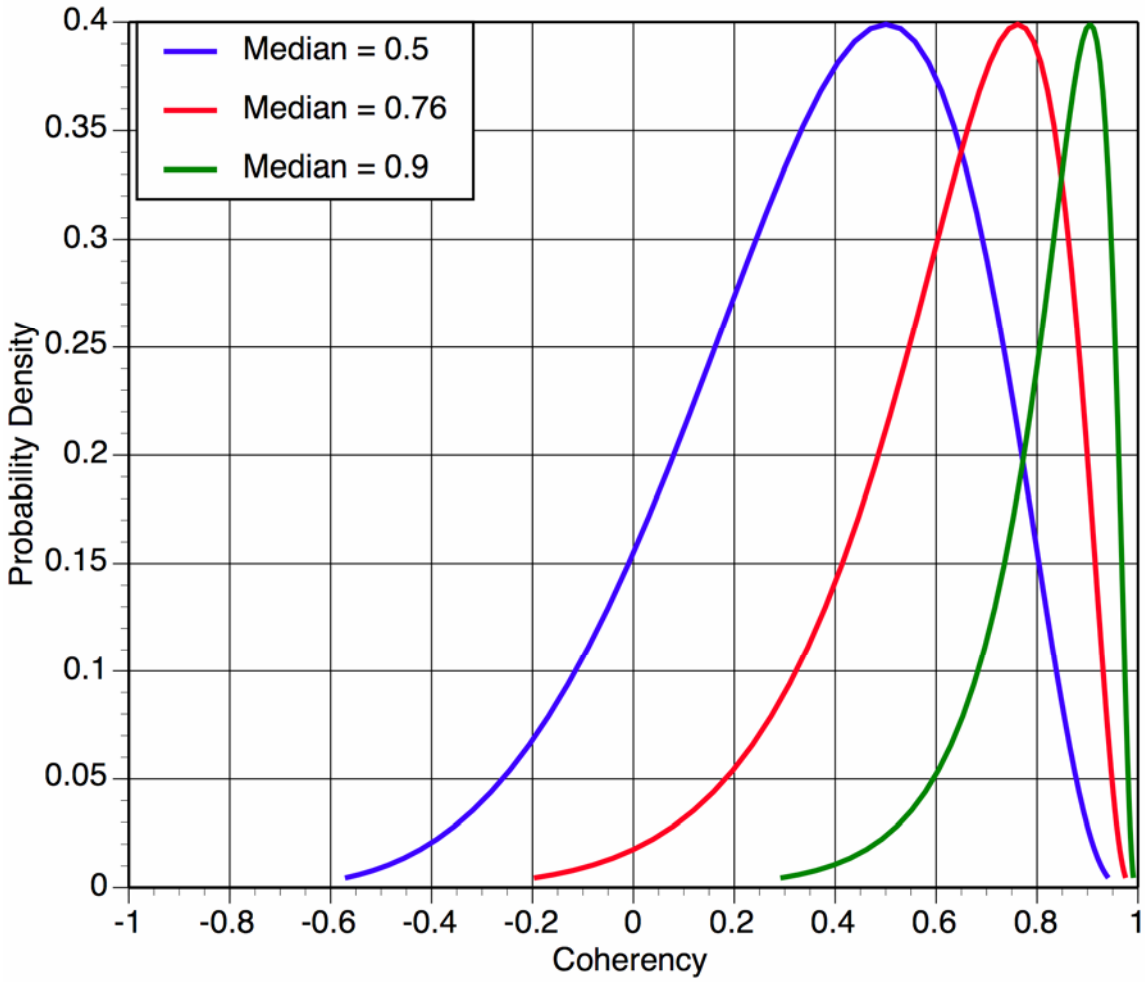
Development of Coherency Models

- Curve fitting is applied to ATANH coherency
  - Allows use of least-squares
- Model is converted back to coherency units for ease of application
  - Allows constraint: coherency to be unity at zero distance and zero frequency

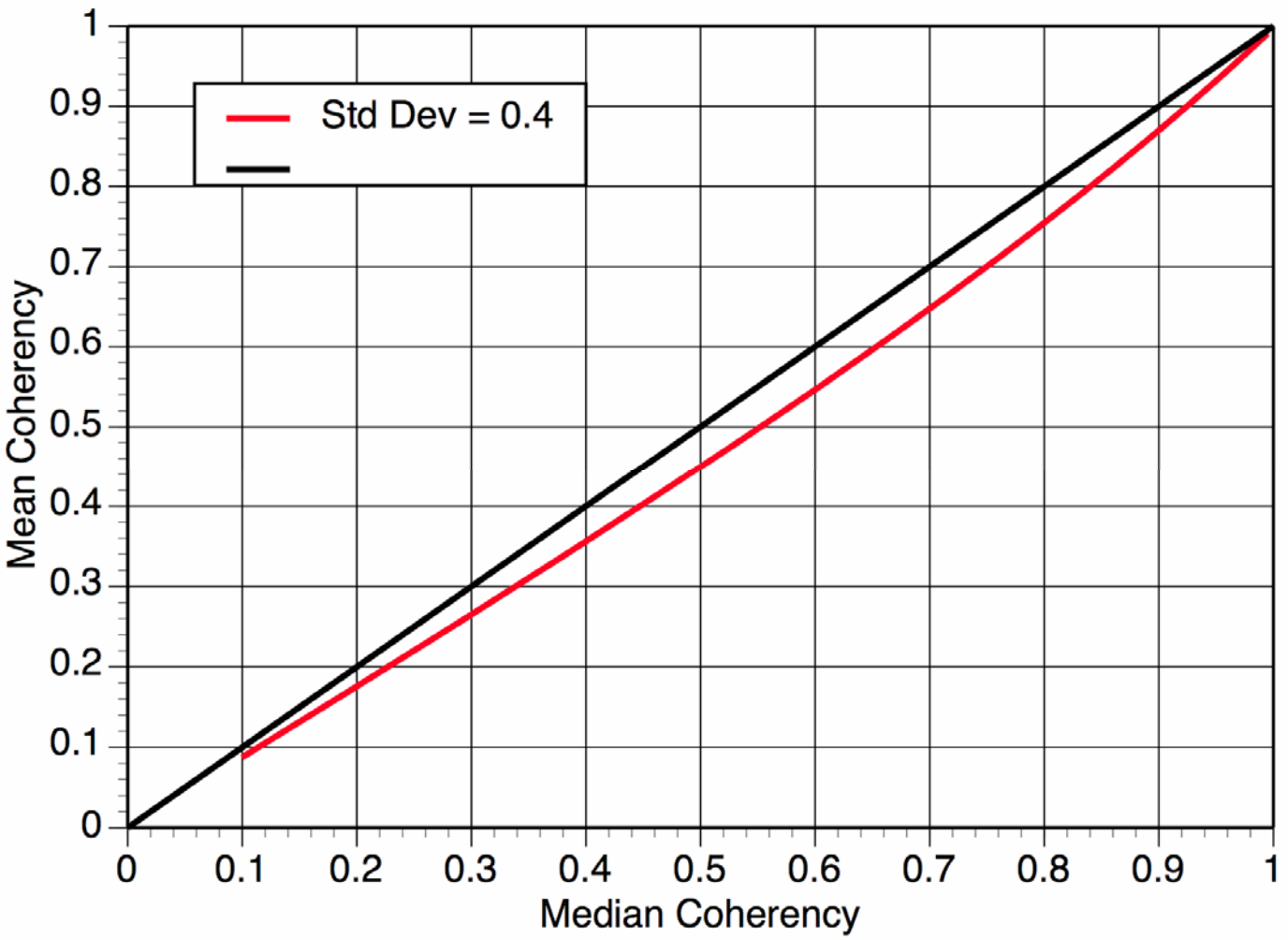
Mean Coherency

- Models developed for the ATANH(coherency) since this is normally distributed
- Equations give the median coherency
- Mean coherency will be different from the median

Distribution of ATANH



Mean vs Median



Mean vs Median

- ATANH distribution is skewed to smaller values
- Mean coherency will be slightly less than the median
  - Some conservatism (for translational response) by using the median in place of the mean

Selection of Data Sets

- Short separations relevant to foundations of NPP
  - Min separation distances < 70 m
- Avoid strong topography variations
  - Select near flat arrays
- Include small and large magnitudes
  - Scattering similar for large and small earthquakes
- Relative timing needed
  - Plane-wave coherency requires relative timing

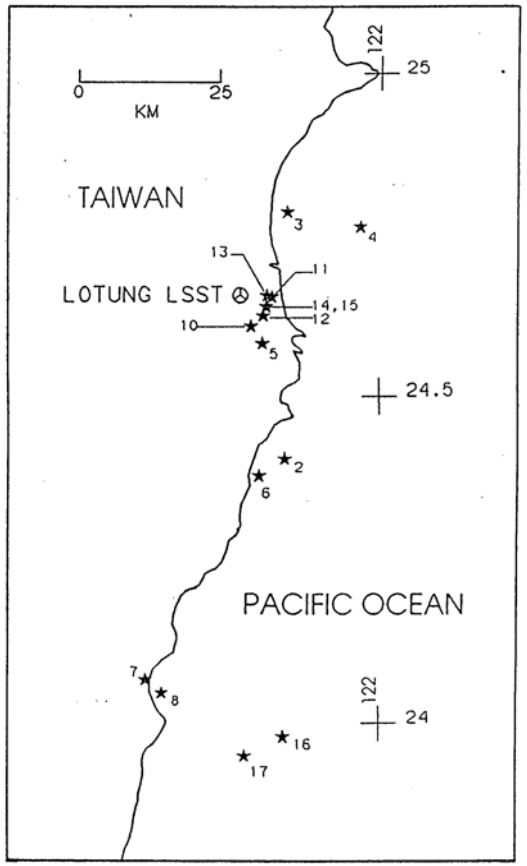
Dense Arrays Selected

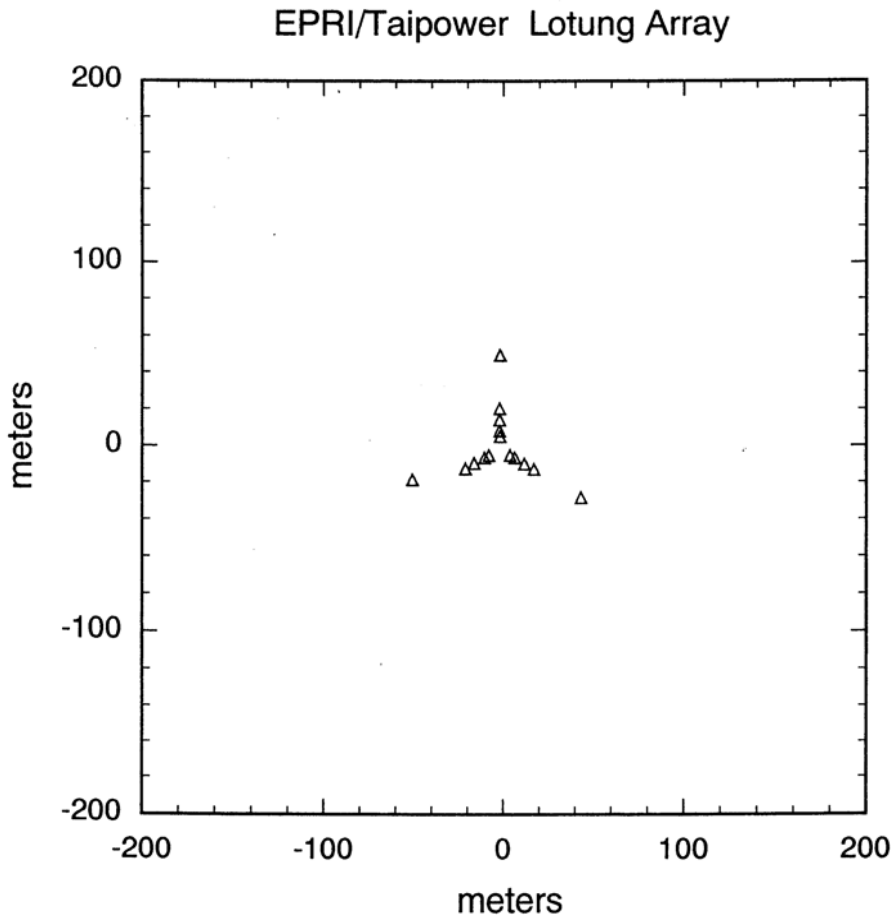
Array	Location	Site	Sta Sep (m)
EPRI LSST	Taiwan	Soil	3-85
Chiba	Japan	Soil	5-319
Hollister	CA	Soil	61-256
IV Diff	CA	Soil	18-213
EPRI Park	CA	Soft-rock	10-191
Coalinga	CA	Soft-rock	48-313
Pinyon Flat	CA	Hard-rock	7-340

Earthquakes

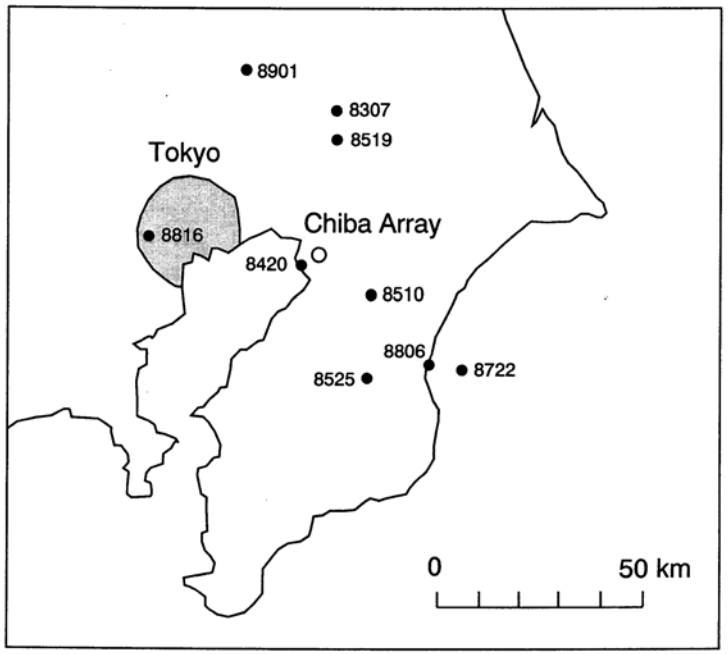
Array	Number of eqk	Magnitude	Epicentral Dist (km)
EPRI LSST	13	3.0-7.8	5-113
Chiba	9	4.8-6.7	61-105
Hollister	1	5.3	17
IV Diff	2	5.1-6.5	9-24
EPRI Park	2	3.0-3.9	13-15
Coalinga	4	3.2-5.2	1-5
Pinyon Flat	78	1.0 - 3.6	7-107

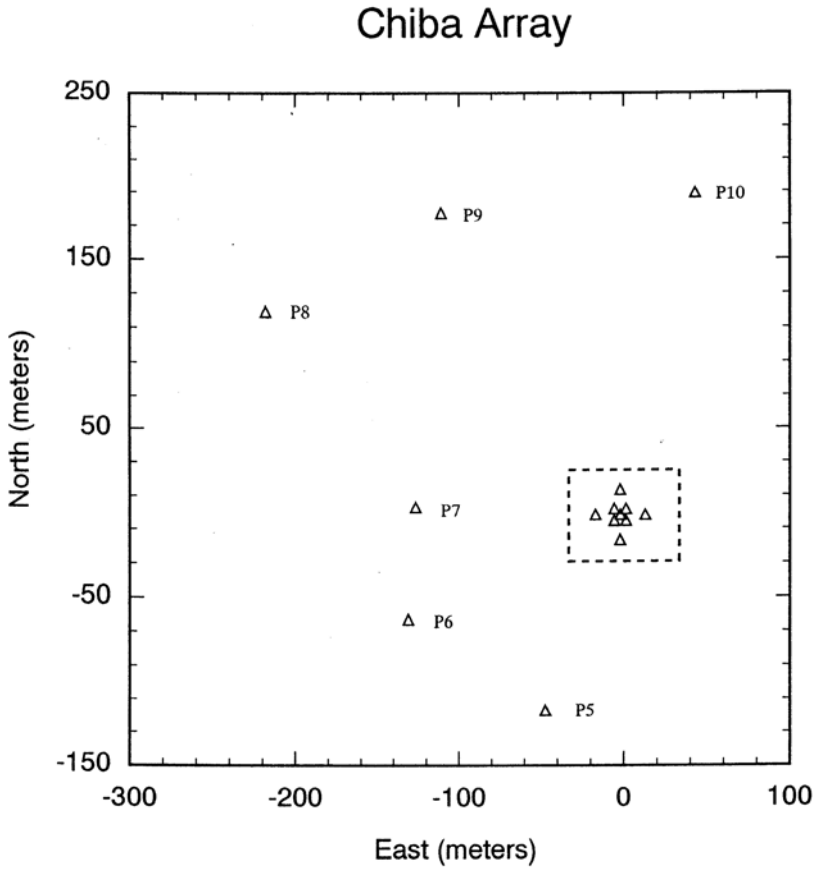
LSST Array


0
25
KM
122
25
TAIWAN
3
4
13
11
LOTUNG LSST
14,15
12
10
5
24.5
2
6
PACIFIC OCEAN
7
8
122
24
16
17

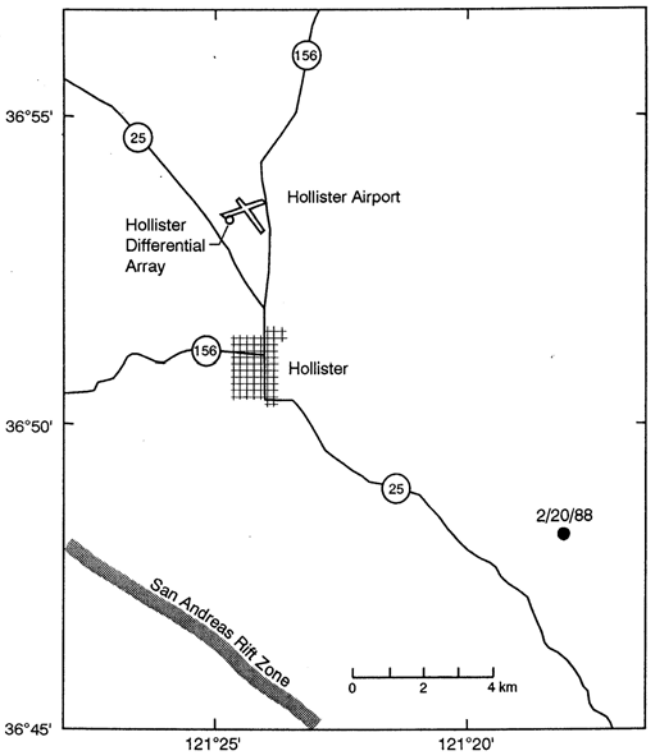

EPRI/Taipower Lotung Array
200
100
0
-100
-200
meters
-200
-100
0
100
200
meters

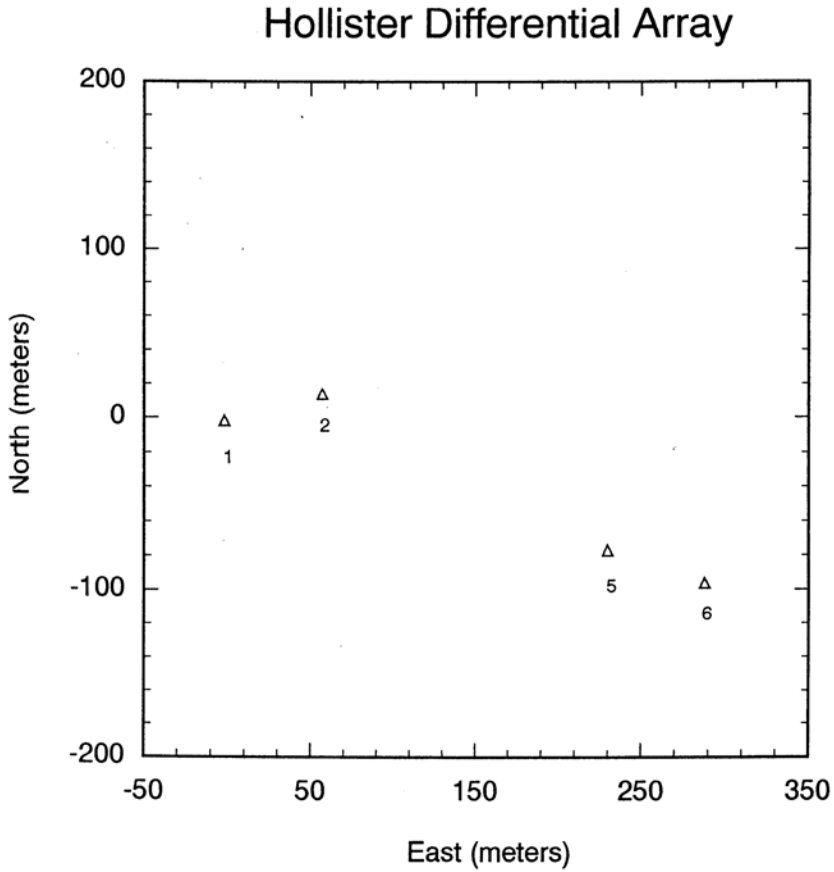
Chiba Array


8901
8307
8519
Tokyo
8816
Chiba Array
8420
8510
8806
8722
8525
0
50 km

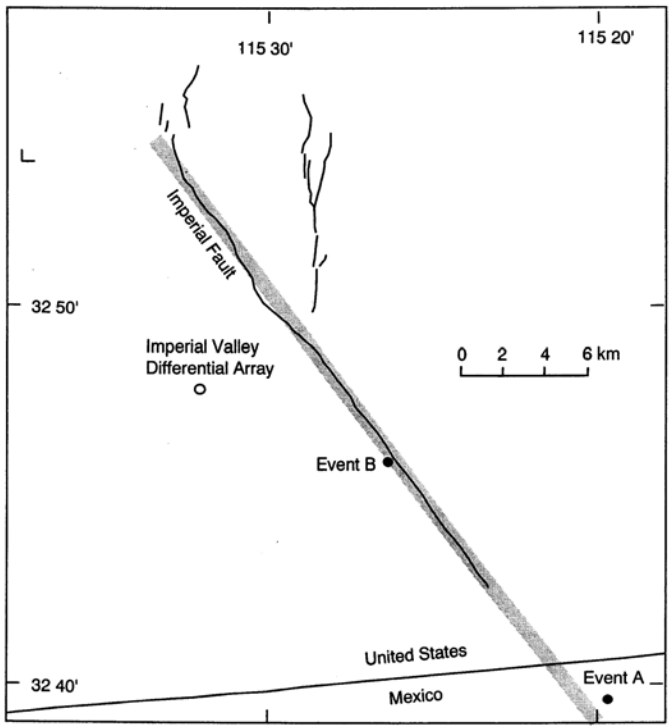

Chiba Array
250
150
50
-50
-150
North (meters)
-300
-200
-100
0
100
East (meters)
P10
P9
P8
P7
P6
P5

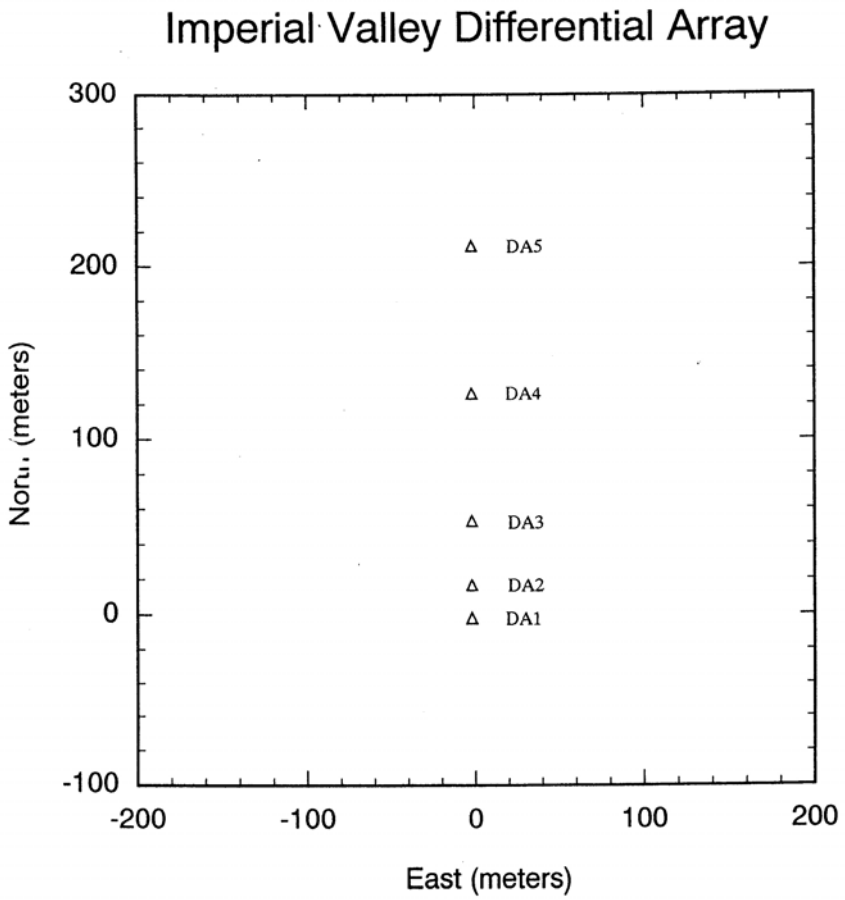
Hollister Differential Array



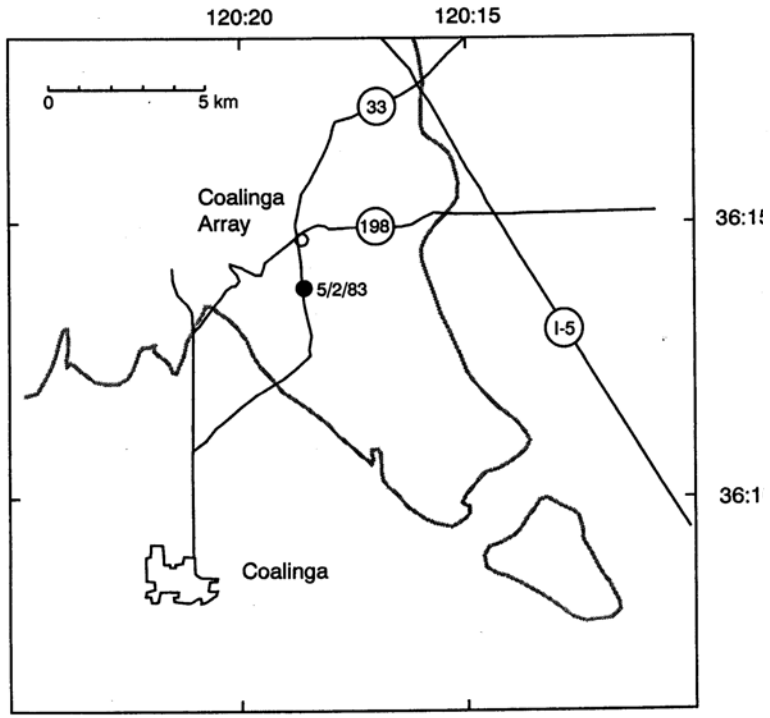


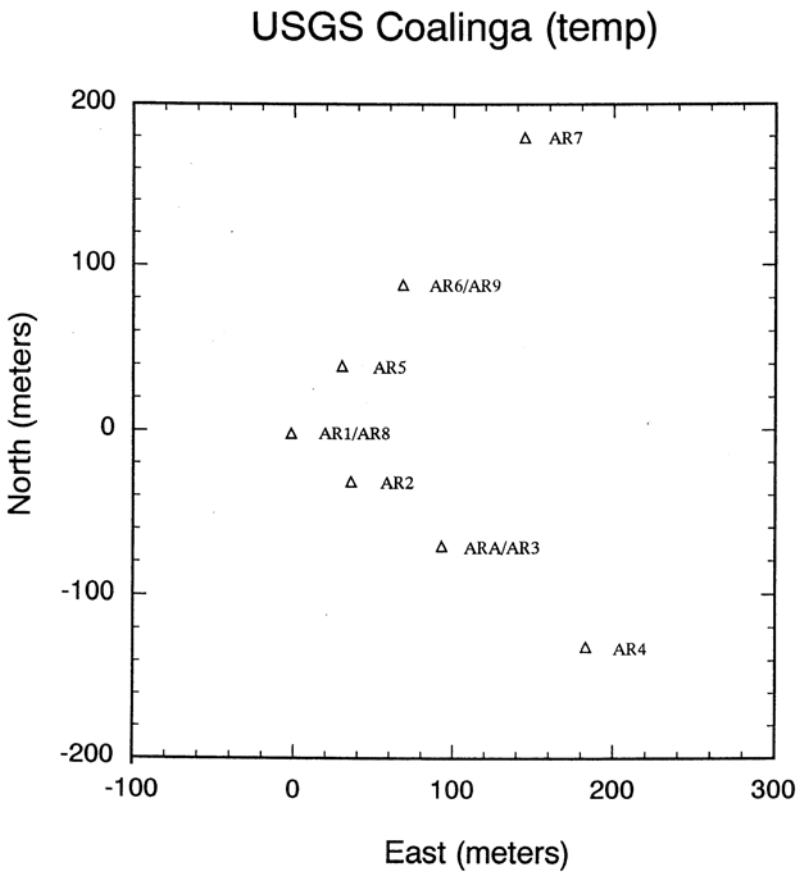
Imperial Valley Differential Array



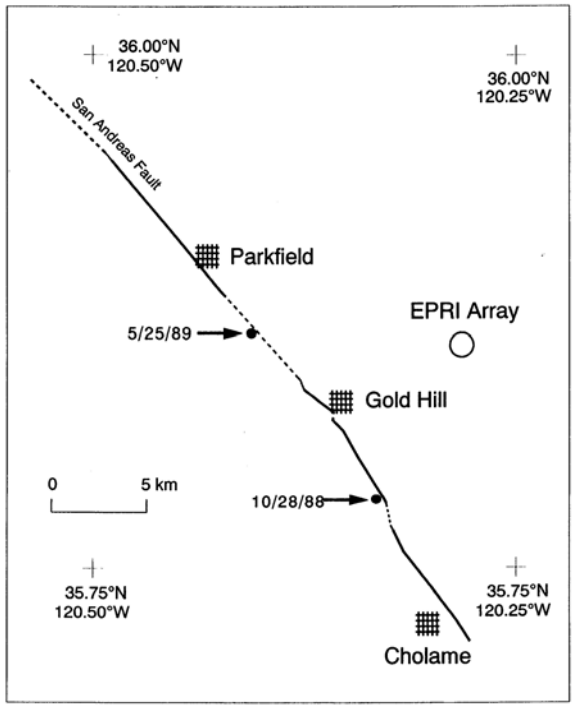


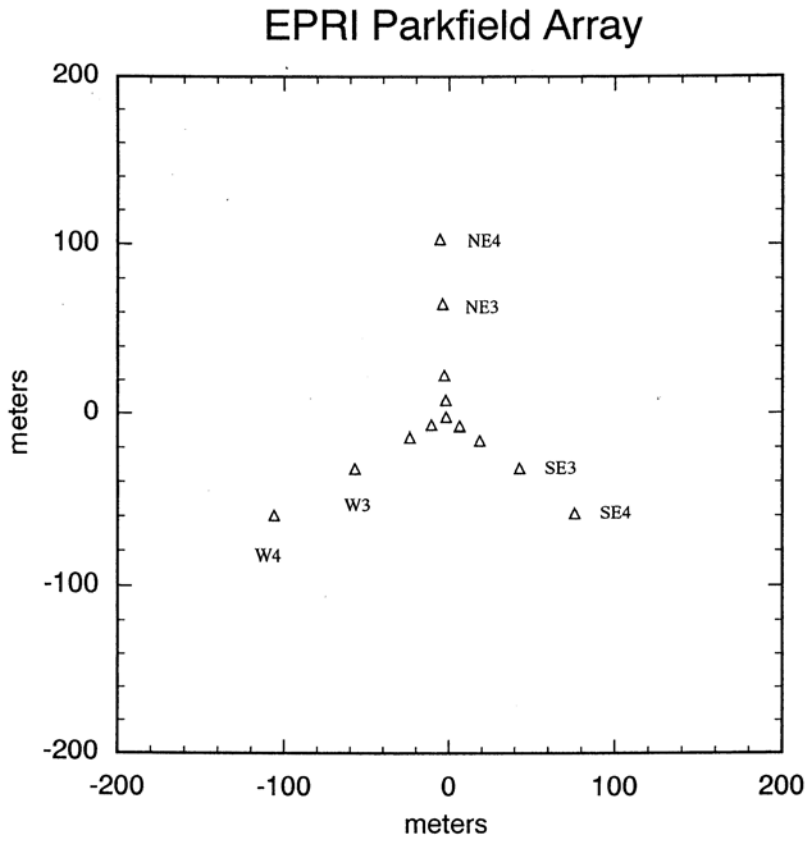
Coalinga Array



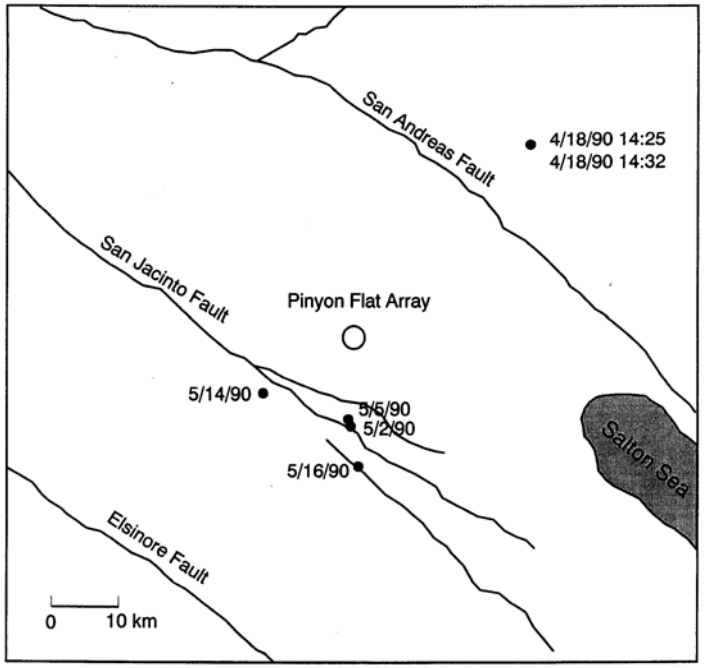


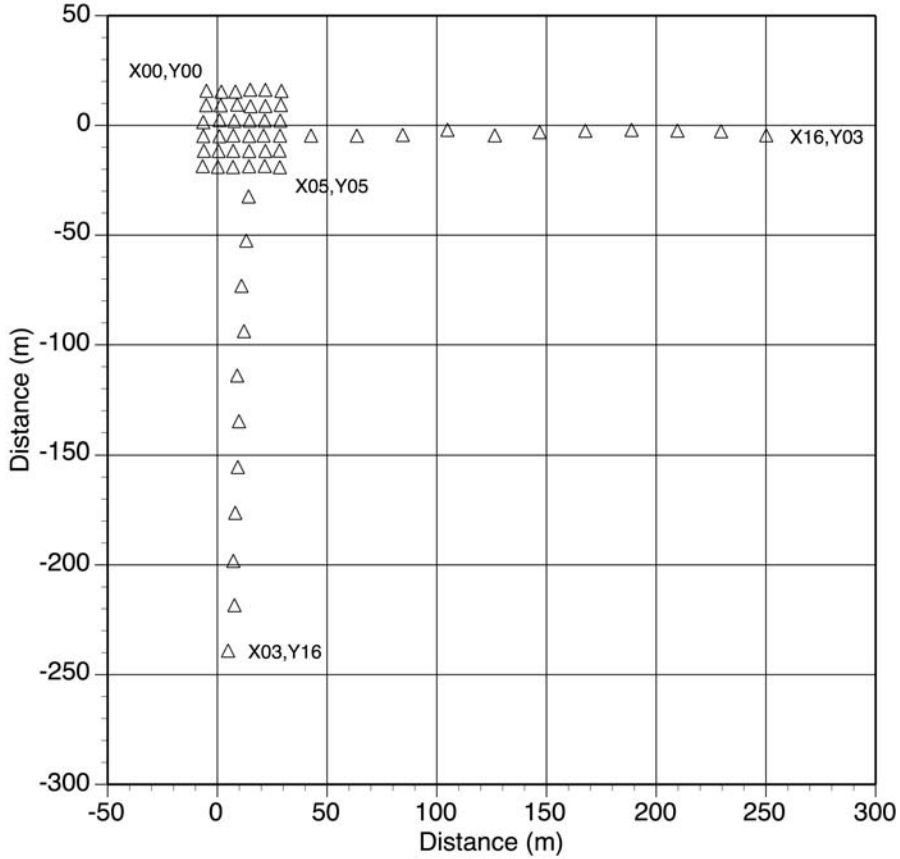
EPRI Parkfield Array





Pinyon Flat Array

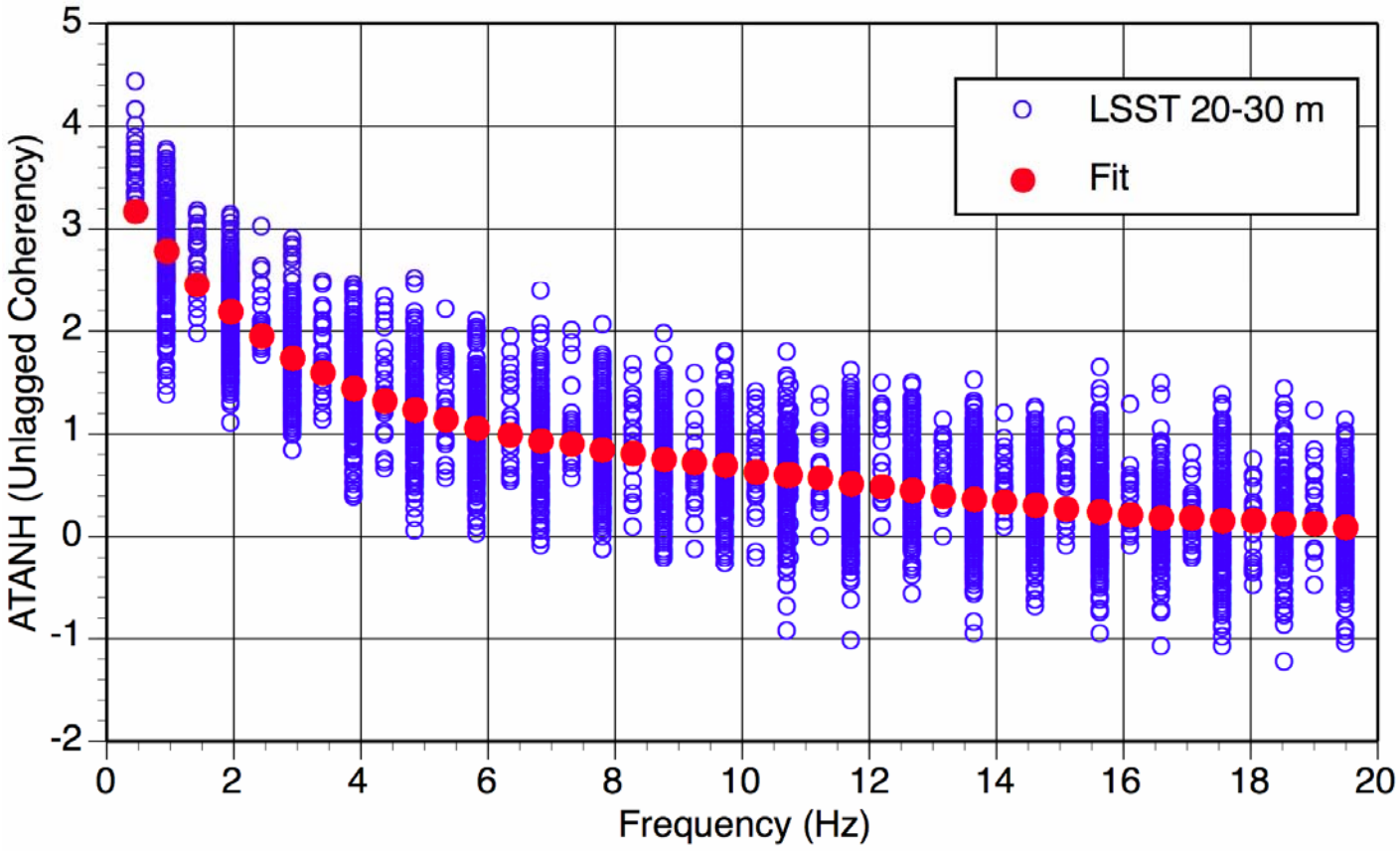




Factor That May Affect Coherency

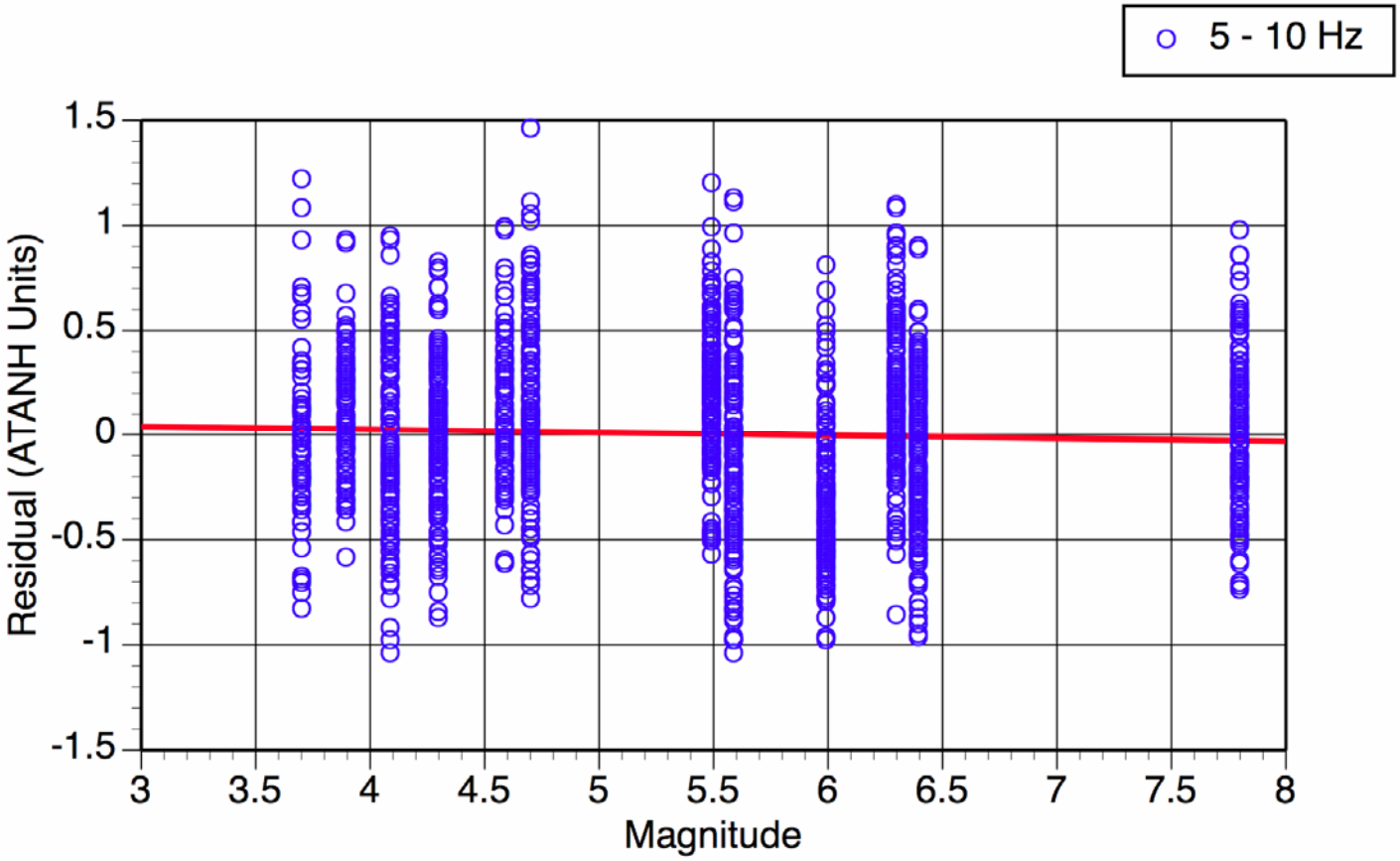
- Magnitude
  - For a point source, the earthquake magnitude should not affect the coherency (scattering is linear)
  - Large magnitudes at short distance could lead to a reduction in coherency due to different wave paths from different parts of the rupture
- Distance
  - For a point source, distance should not affect the coherency
- Site Condition
  - Just changing the 1-D VS profile would not affect coherency
  - If lateral variability of the VS structure is related to VS, then site condition will have an effect on coherency
  - Topography differences will lead to reduced coherency (more scattering and changes in the travel times)

LSST Array
20-30 m Separation



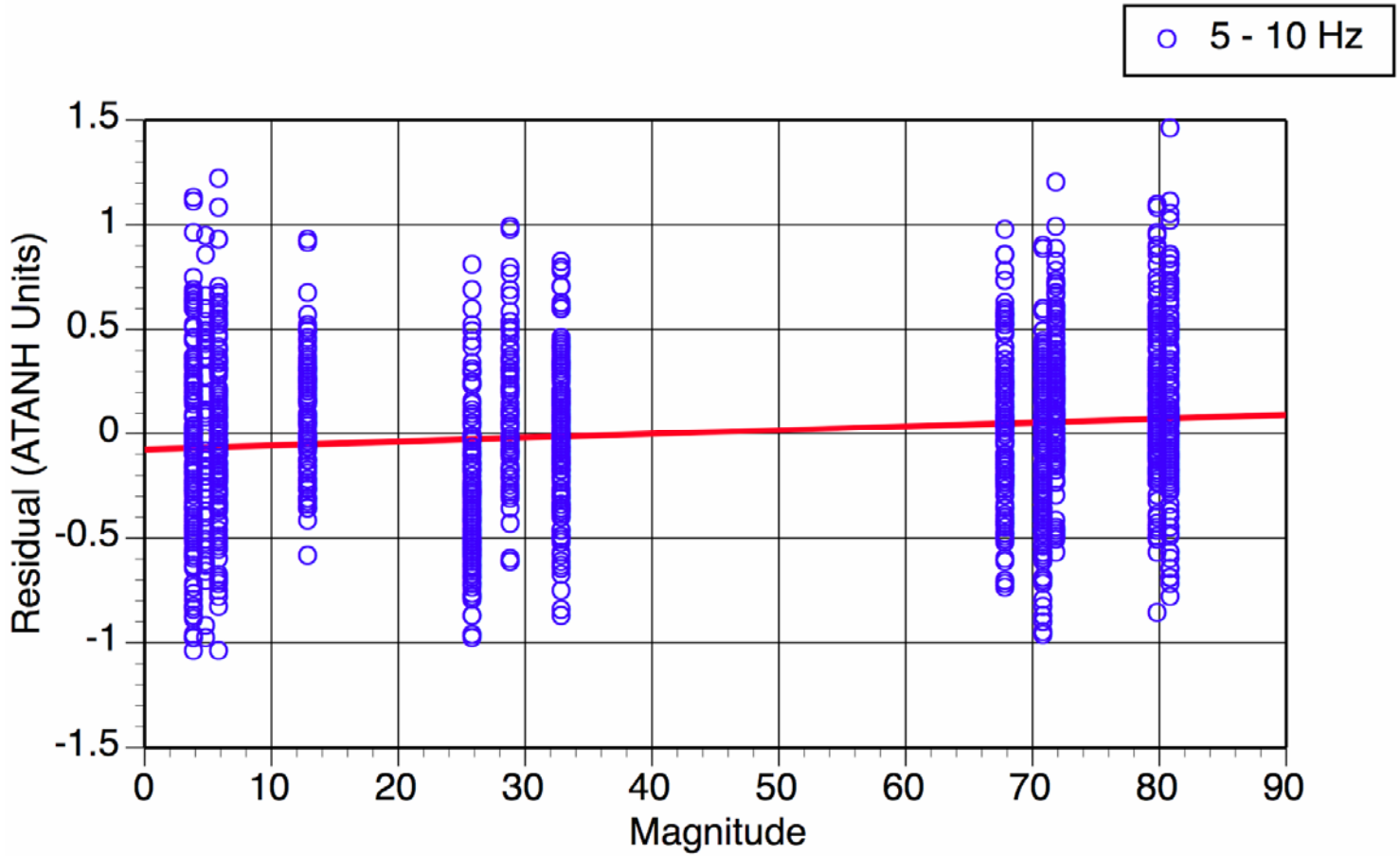
Magnitude Dependence

(5-10 Hz, 20-30 m, from LSST Array)

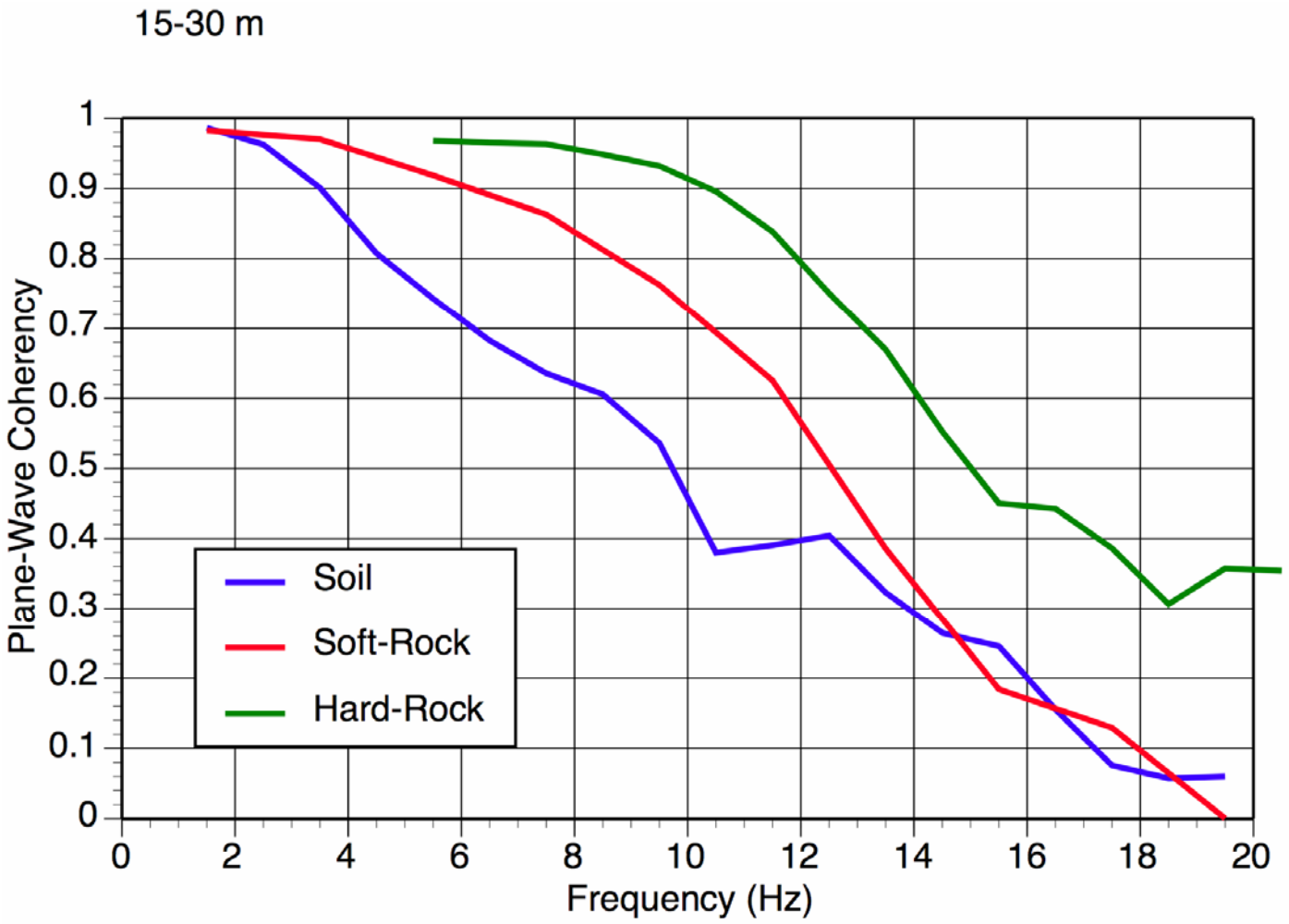


Distance Dependence

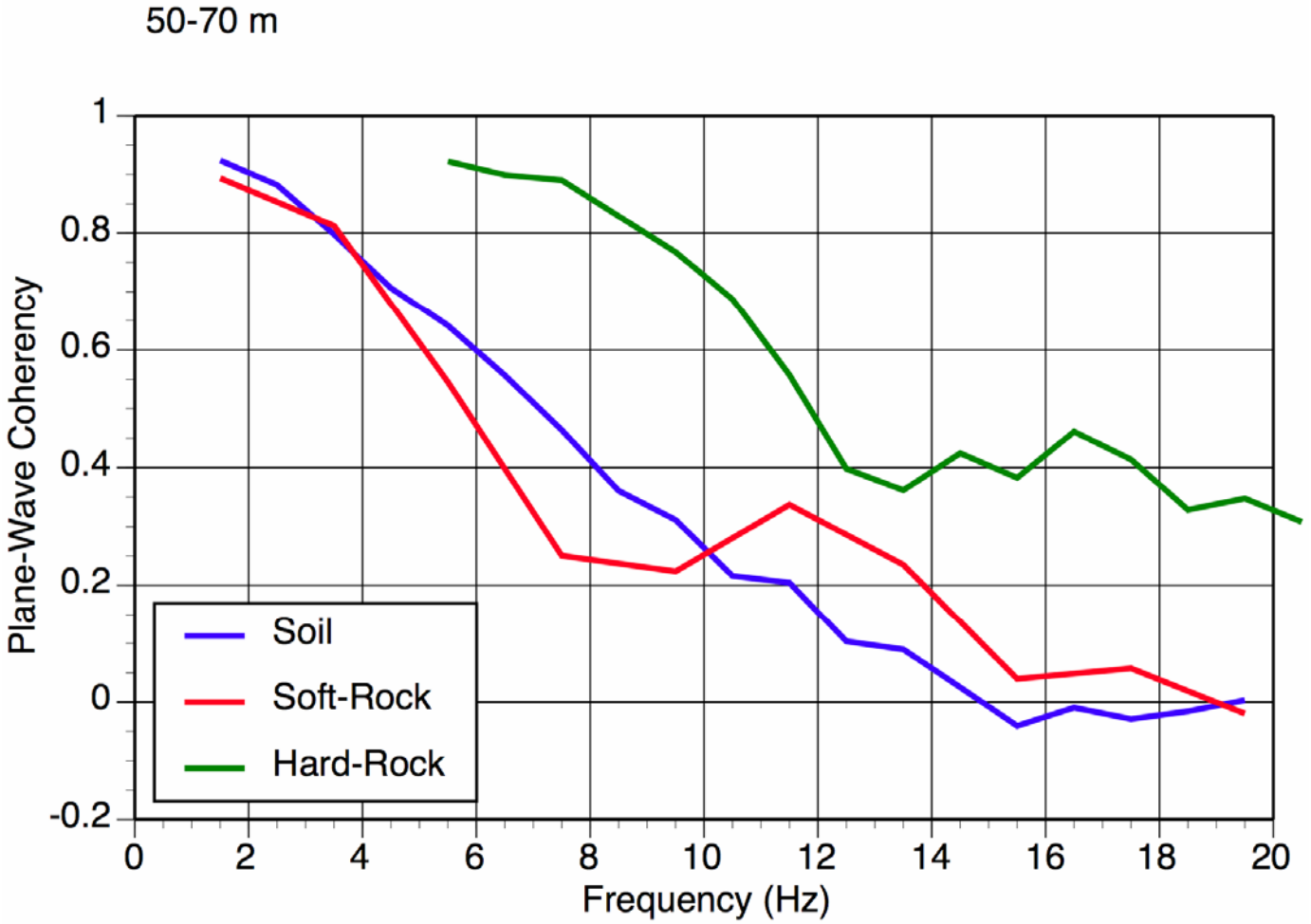
(5-10 Hz, 20-30 m, from LSST Array)



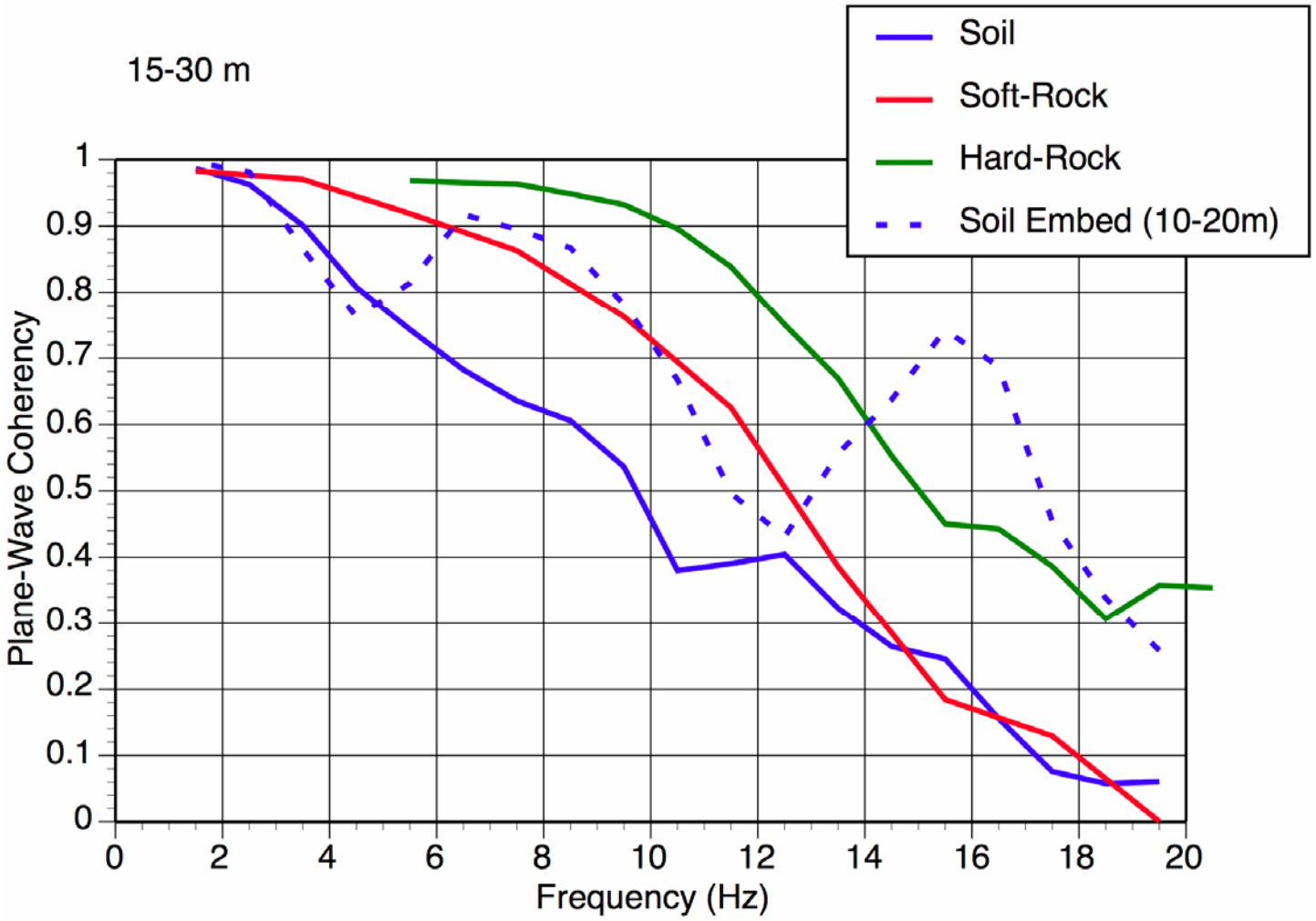
Site Dependence (15-30 m)



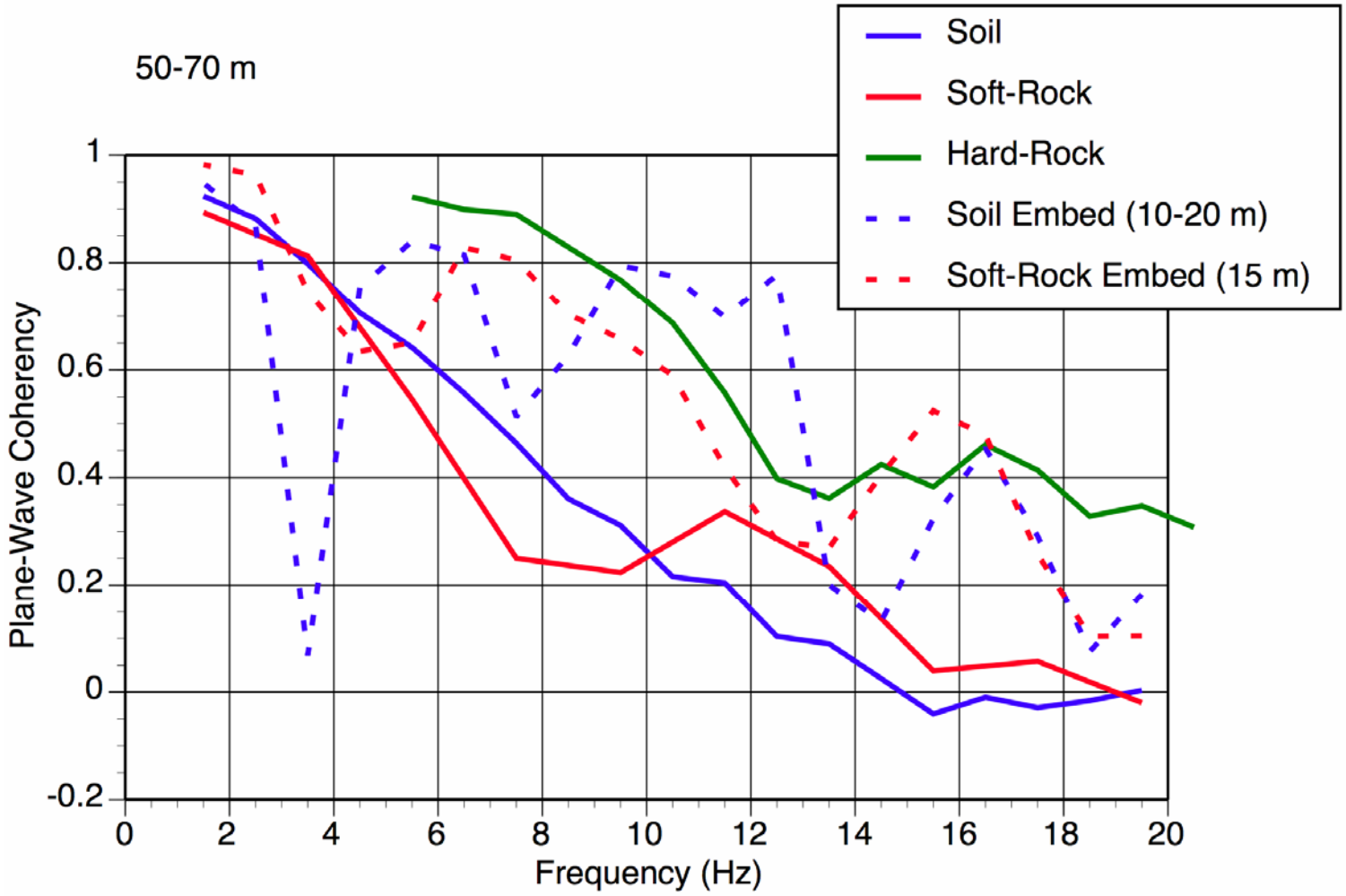
Site Dependence (50-70 m)



Site Dependence & Embedment (15-30 m)



Site Dependence & Embedment (50-70 m)

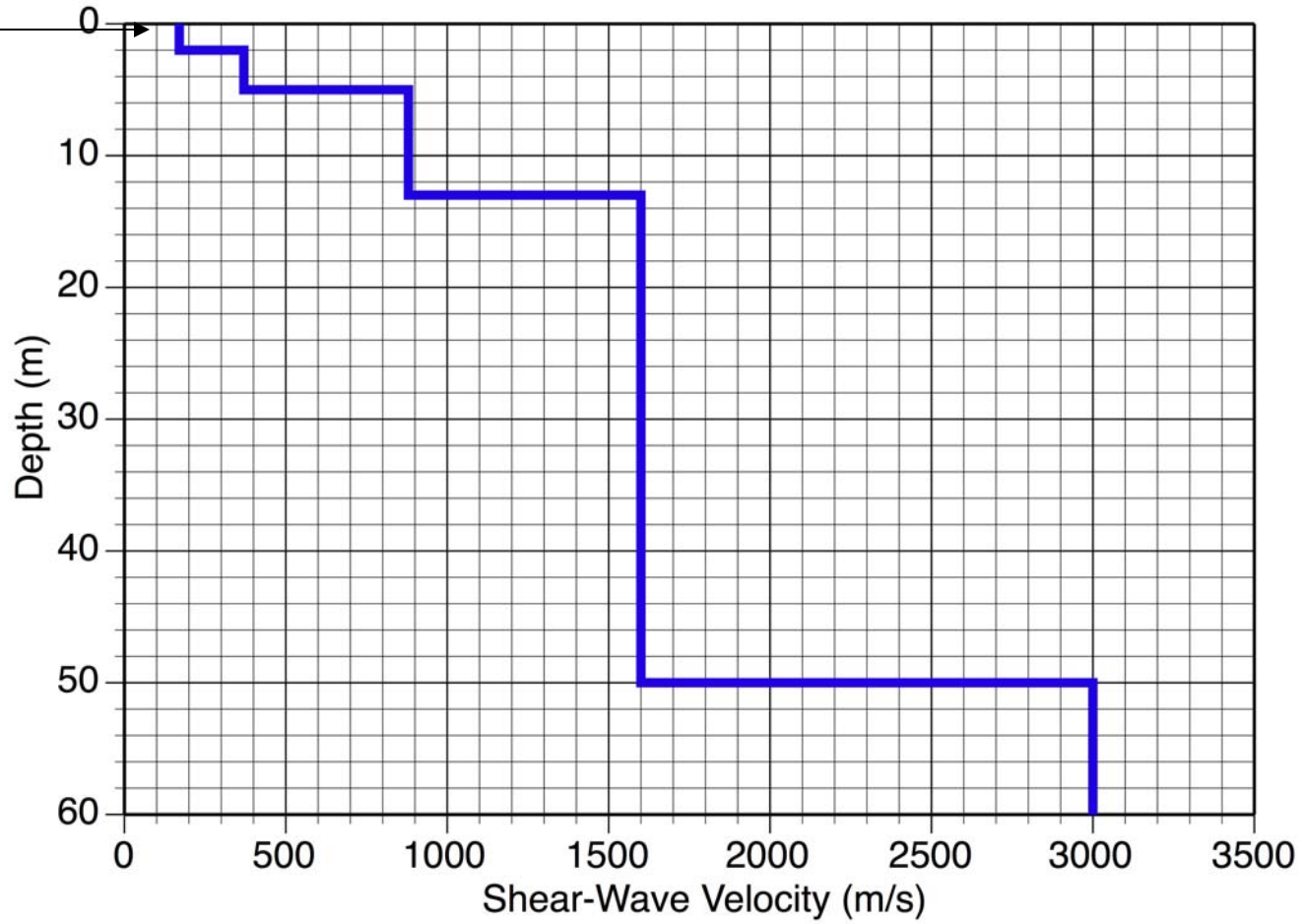


Hard-Rock Coherency Model

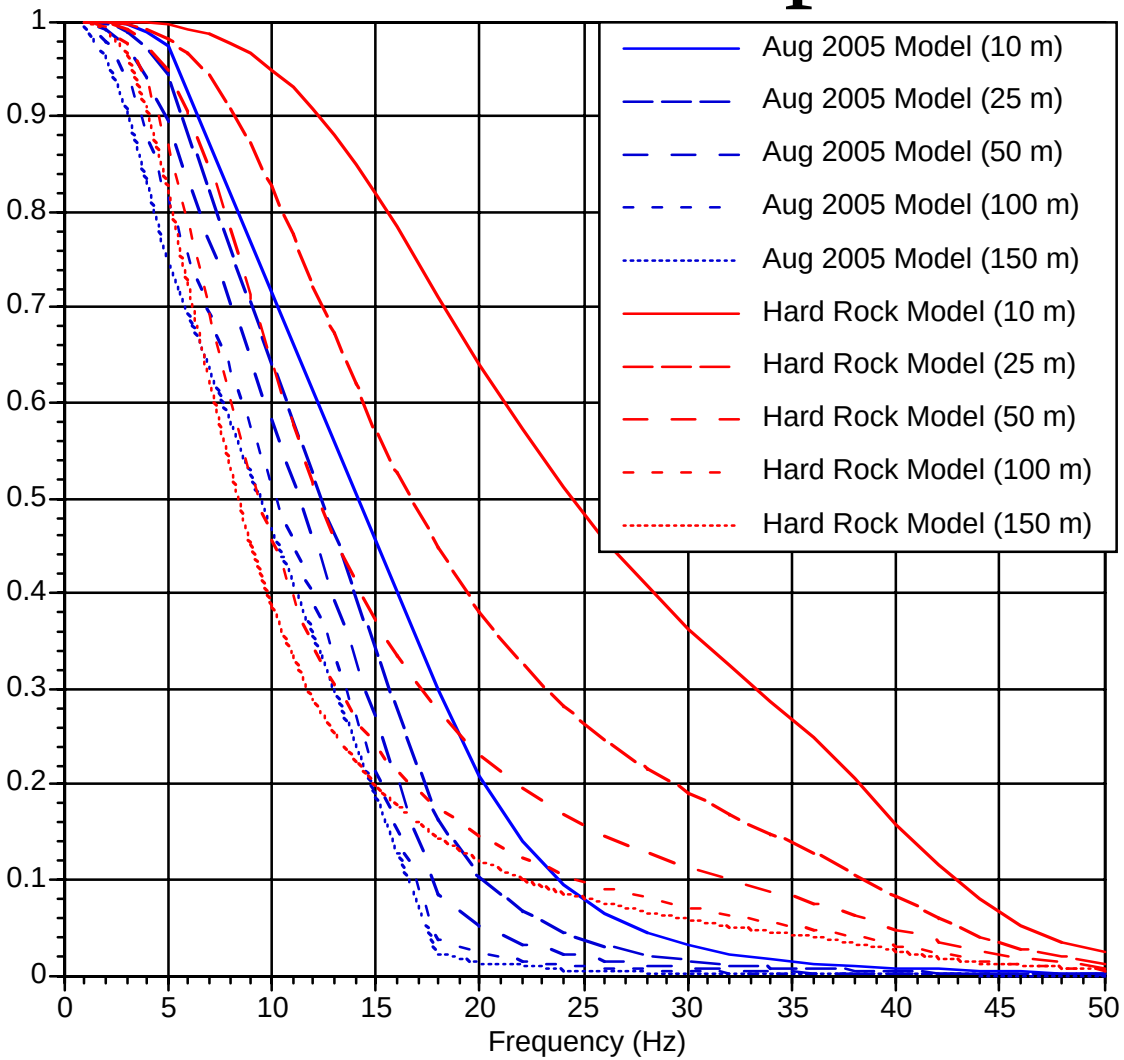
- Based on Pinyon Flat Array Only
  - 78 earthquakes
  - Small magnitudes (M1-M4)

Pinyon Flat

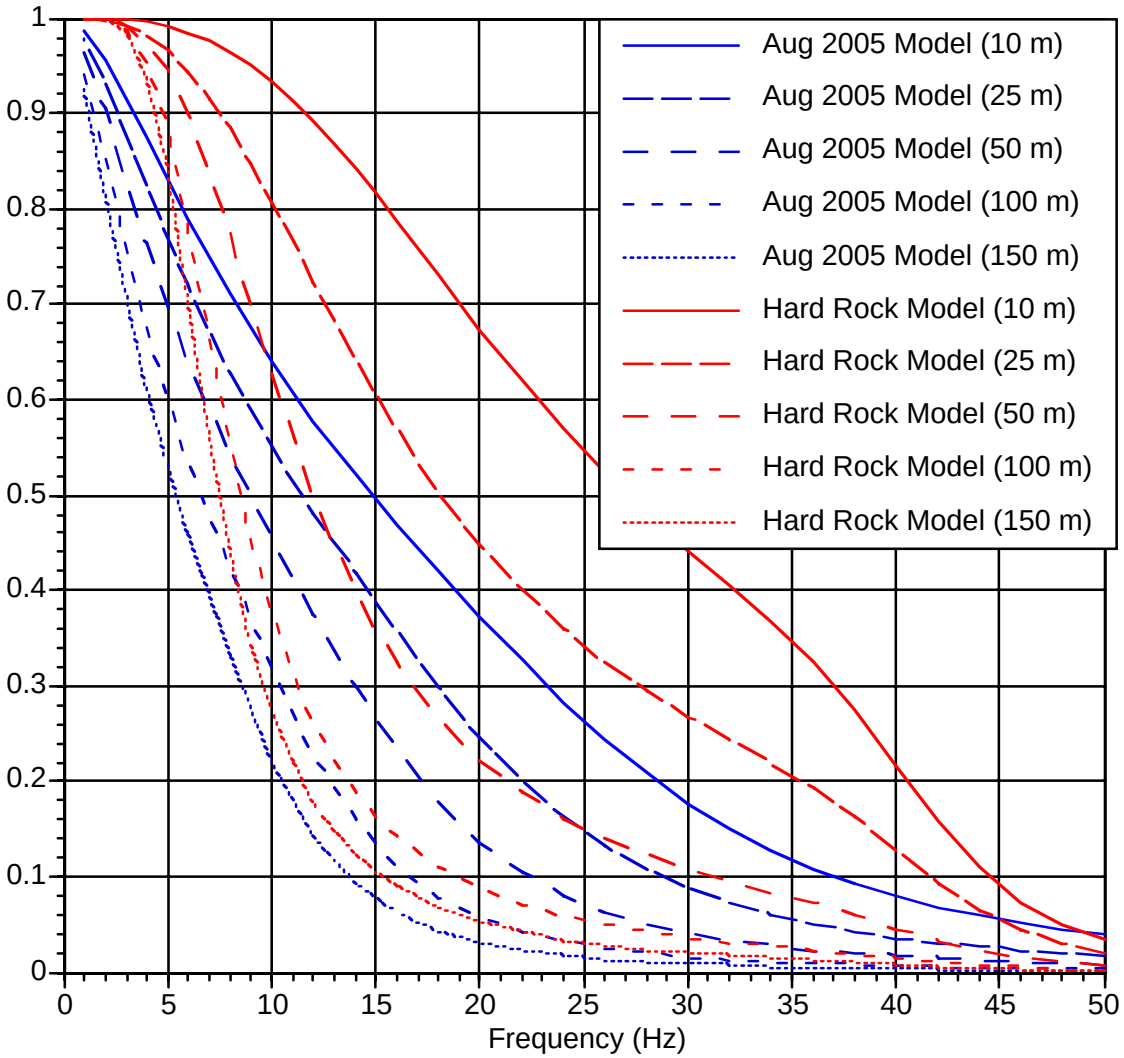
Top 2 m removed



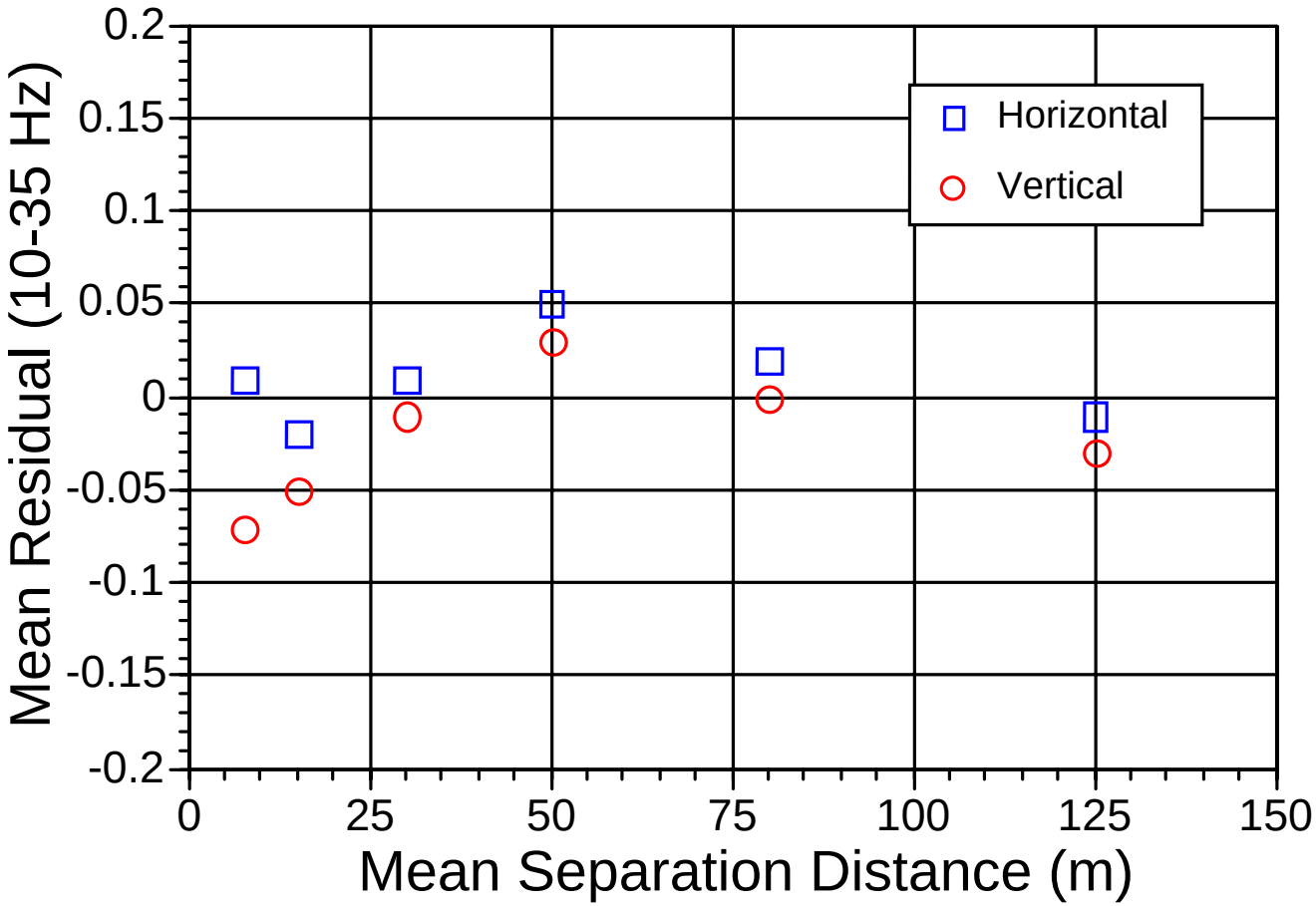
Hard-Rock Coherency for the Horizontal Component



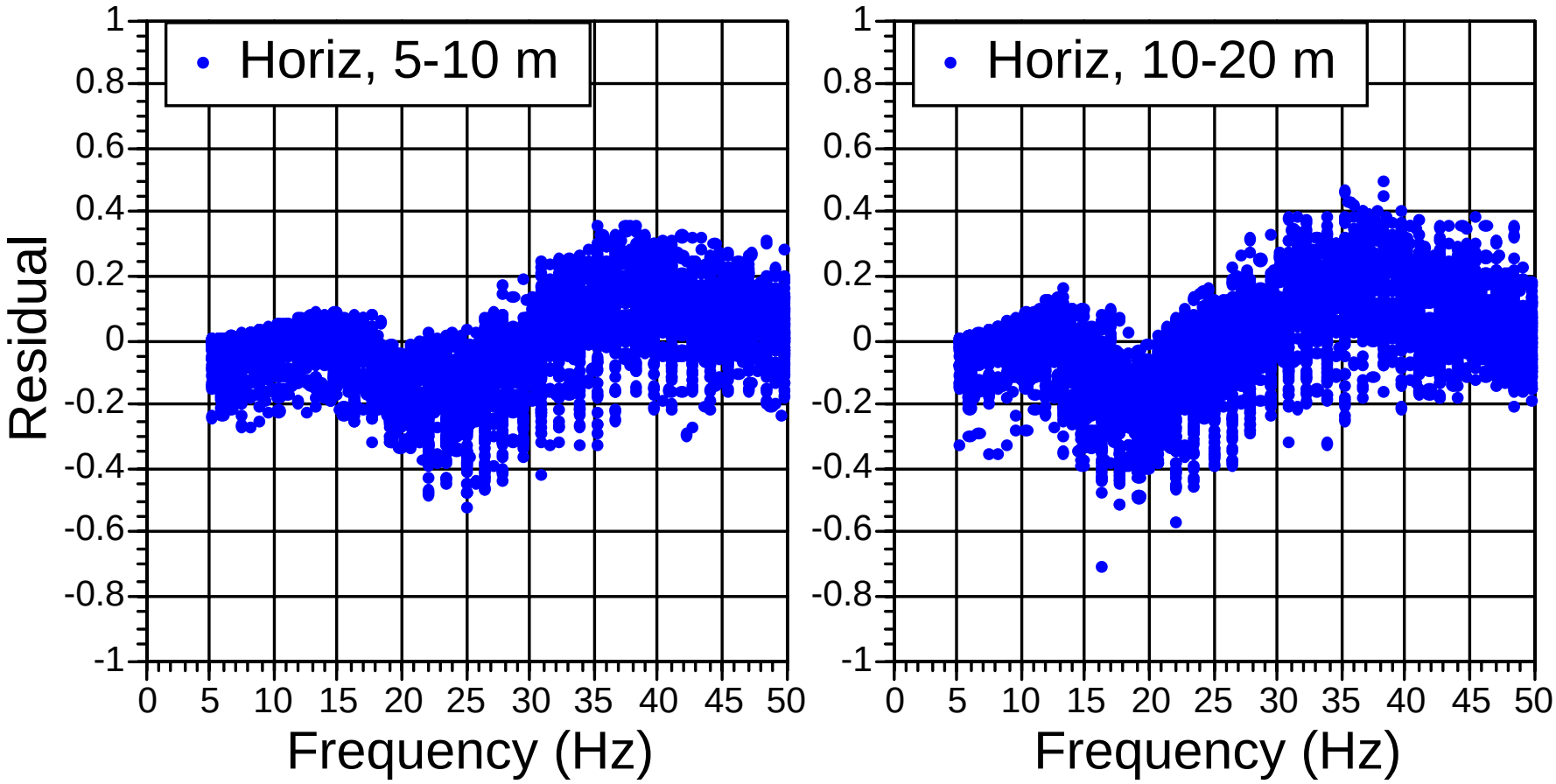
Hard-Rock Coherency for the Vertical Component



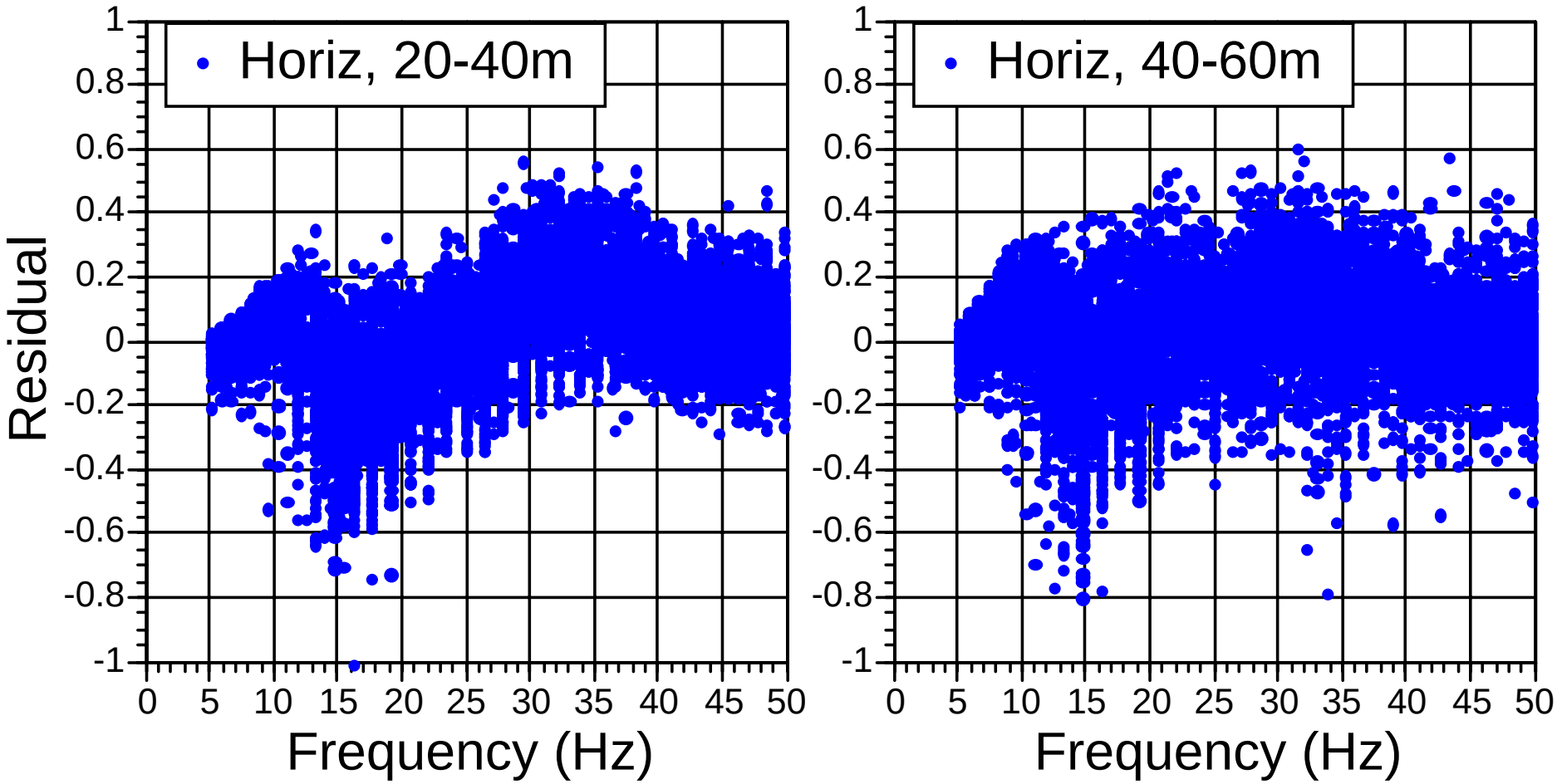
Mean Residuals
10-35 Hz



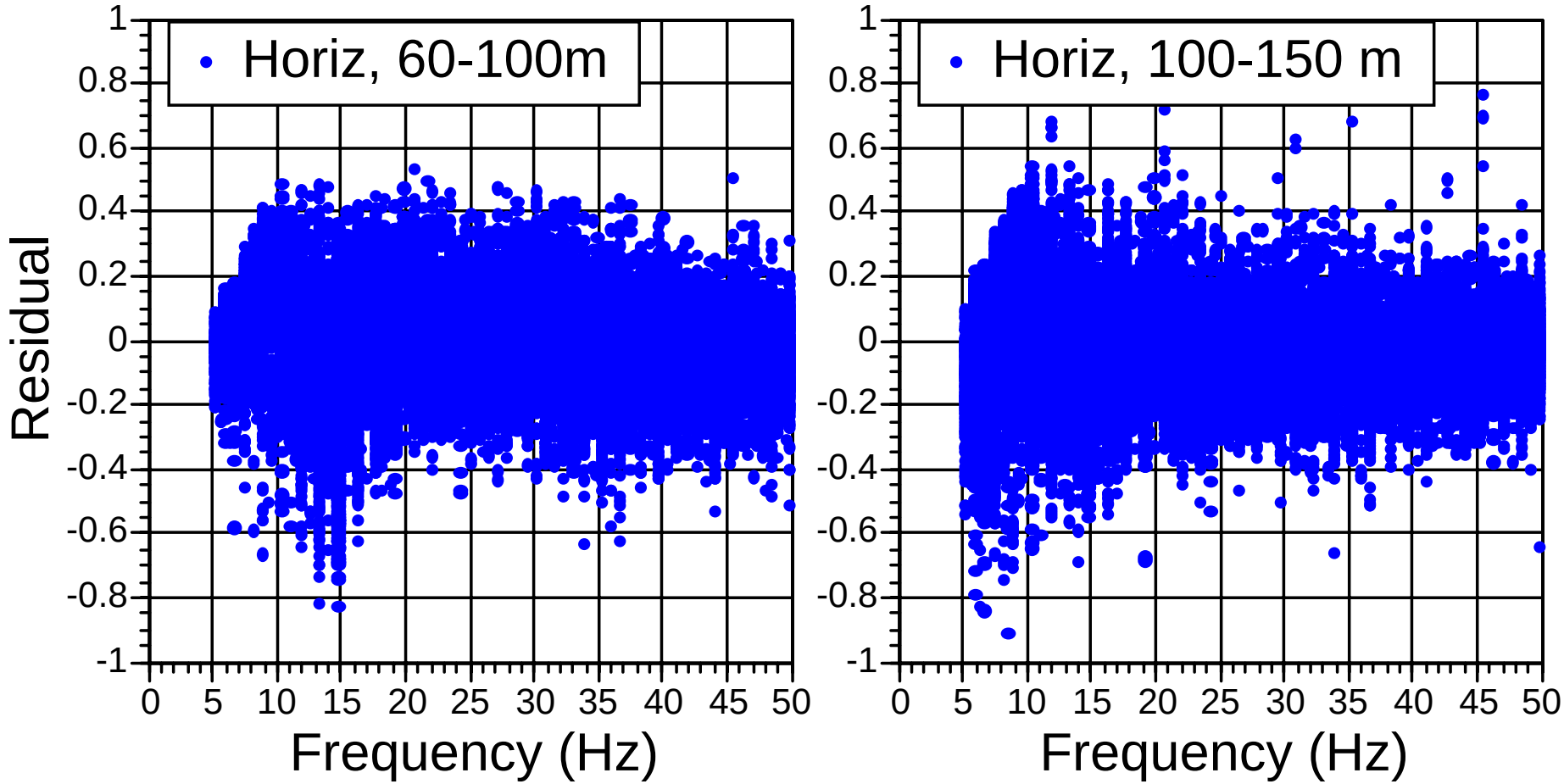
Residuals: Horizontal Comp



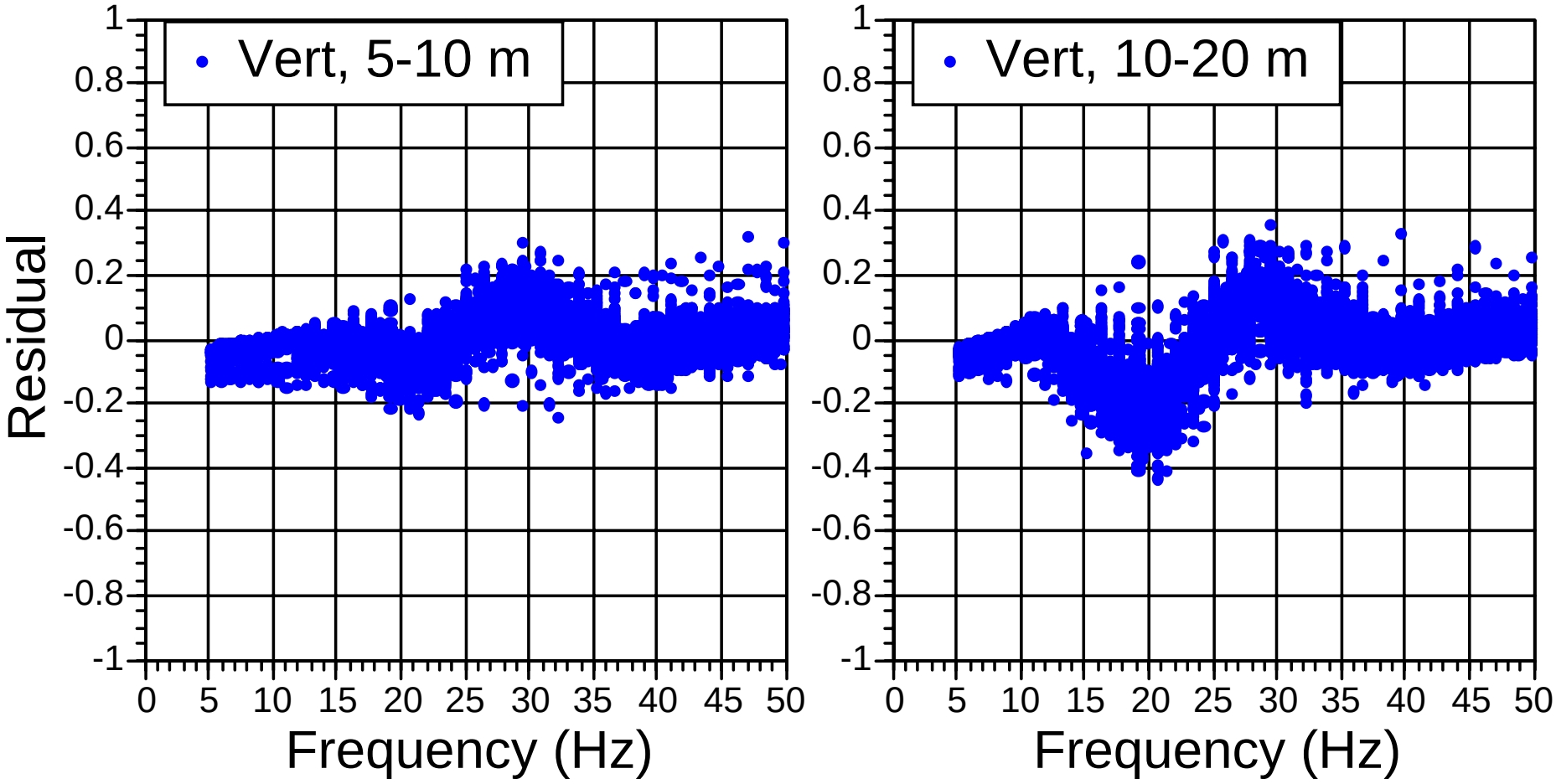
Residuals: Horizontal Comp



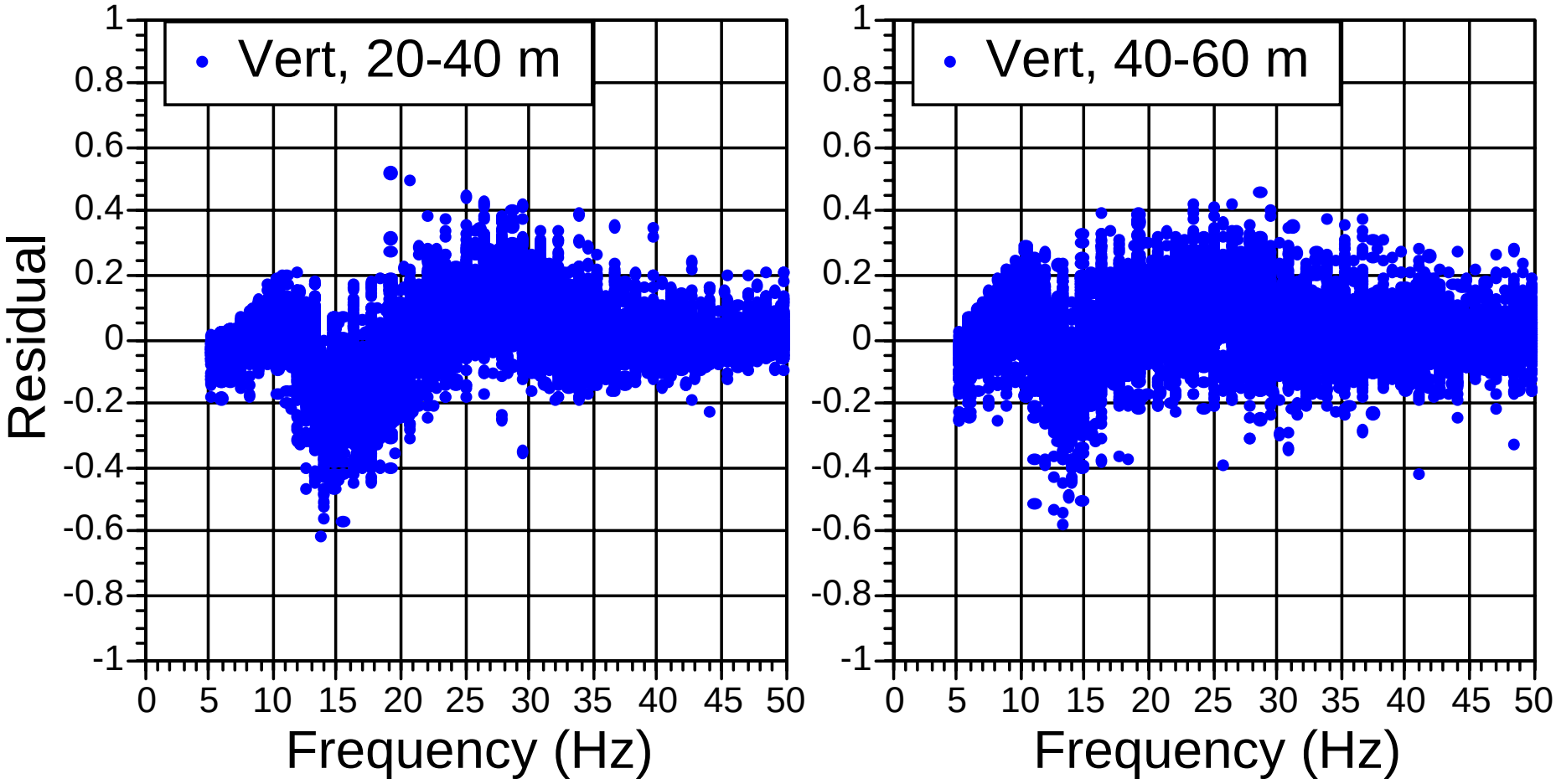
Residuals: Horizontal Comp



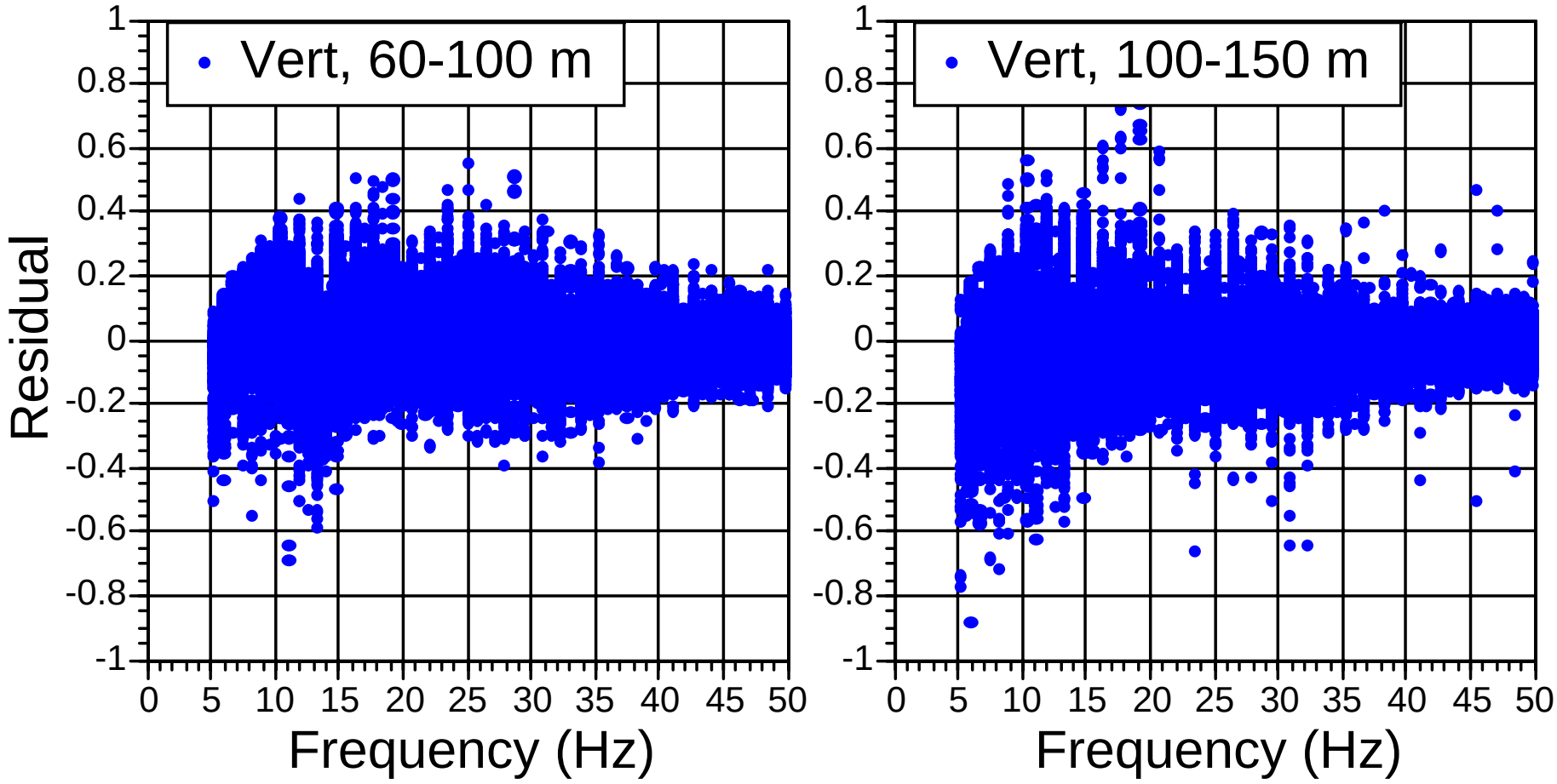
Residuals: Vertical Comp



Residuals: Vertical Comp



Residuals: Vertical Comp



Recommendations for Coherency Models

- Use the hard-rock model for all site conditions and for surface and embedded
  - Considered conservative
  - Coherency is not as important for soil sites since the soil will damp out much of the high frequencies
  - Allow sites to use a lower site-specific coherency if the model can be justified
- Use the median coherency as an estimate of the mean
  - Difference is small