Derivation of structural models

from ambient vibration array recordings

- How to measure?
- How to process?
- How to interpret dispersion curve results?
- How to invert?

→ Optimum deployment and processing strategy / tools ?

Assessing the reliability of DC estimates

Dispersion curve (DC) properties are related to :

- ❖ **structure (predominantly shear wave velocity)**

DC (narrowband phase velocity) estimation is related to :

- ➢ **Recording - measurement conditions, experiment design**
- ➢ **Processing – applied method and underlying assumptions**
- ➢ **Nature of ambient vibration wave field (wave types?/energy?)**
  - ❖ **ambient vibration sources – excitation, distribution**
  - ❖ **structure – wave propagation effects**

Assessing the reliability of DC estimates

DC (narrowband phase velocity) estimation is related to :

- **Recording - measurement conditions, experiment design**
- **Processing – applied method and underlying assumptions**
- **Nature of ambient vibration wave field (wave types?/energy?)**
  - **ambient vibration sources – excitation, distribution**
  - **structure – wave propagation effects**

Assessing the reliability of DC estimates

DC (narrowband phase velocity) estimation is related to :

- **Recording - measur ent design**

maybe under control

- **Processing – applie ssumptions**
- **Nature of ambient vibration wave field (wave types?/energy?)**
  - **ambient vibration sources – excitation, distribution**
  - **structure – wave propagation effects**

Assessing the reliability of DC estimates

DC (narrowband phase velocity) estimation is related to :

- **Recording - measurement conditions, experiment design**
- **Processing – applied method and underlying assumptions**
- **Nature of ambient vibration wave field (wave types?/energy?)**
  - **ambient vibration sources – excitation, distribution**
  - **structure – wave propagation effects**

maybe under control

not under control!

Assessing the reliability of DC estimates

DC (narrowband phase velocity) estimation is related to :

- Recording - measurement conditions, experiment design
- Processing – applied method and underlying assumptions
- Nature of ambient vibration wave field (wave types?/energy?)
  - ambient vibration sources – excitation, distribution
  - structure – wave propagation effects

maybe under control

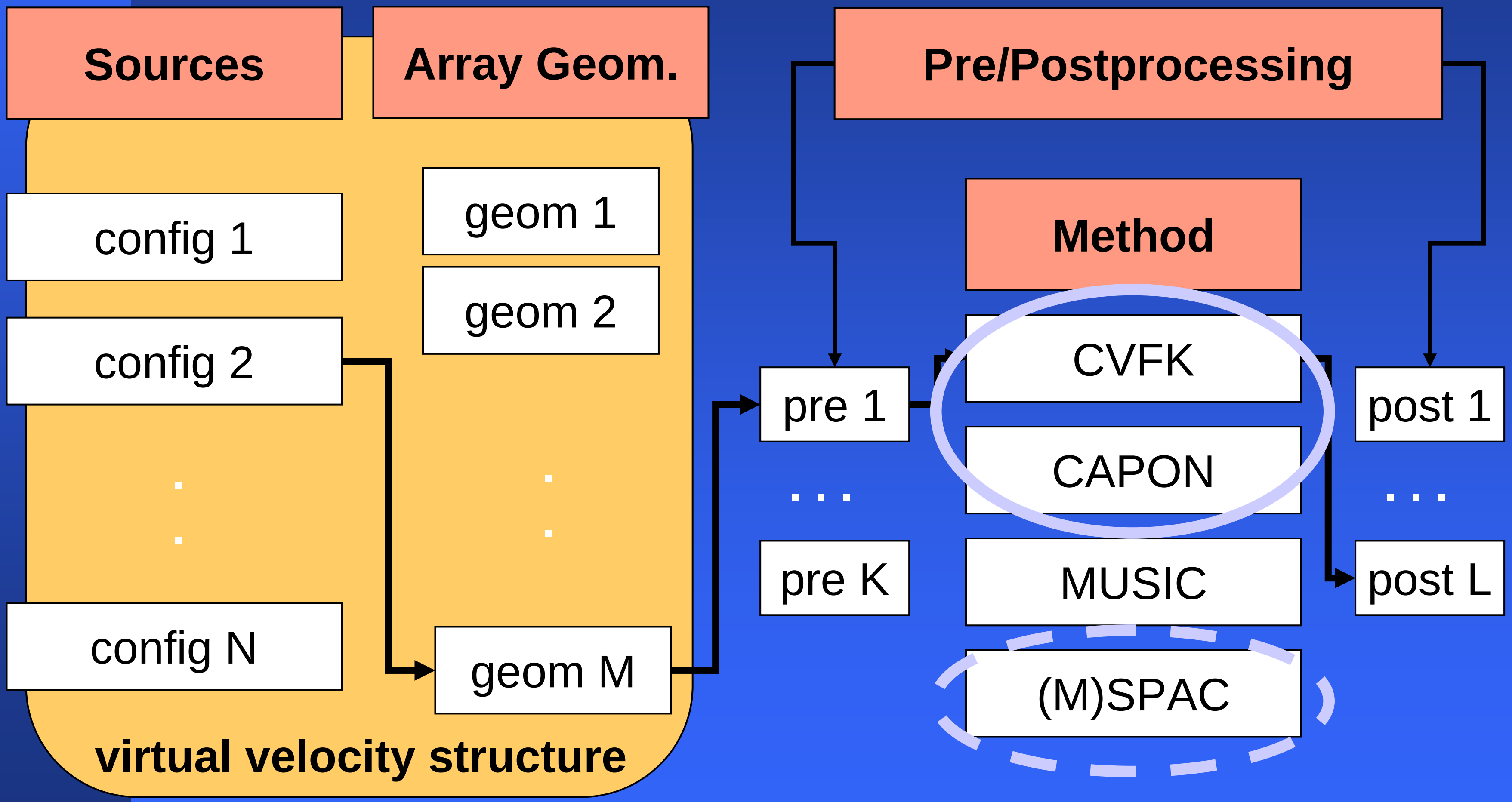
not under control!

Separation of effects on DC estimation by tests in controlable virtual environments

Using Ambient Vibration Array Techniques for Site Characterisation

Forward modelling of ambient wave field

Analysis of virtual wave field



Sources

Array Geom.

Pre/Postprocessing

config 1

config 2

.
.

config N

geom 1

geom 2

.
.

geom M

virtual velocity structure

pre 1

. . .

pre K

Method

CVFK

CAPON

MUSIC

(M)SPAC

post 1

. . .

post L

Virtual site structure I: Liege (model derived from amb. vibration data)

Layer	Thickness [m]	VP [m/s]	VS [m/s]	RHO [g/cm^3]	QP low / mod / high	QS low / mod / high
1	7.8	310	193	2.0	20 / 100 / 250	5 / 25 / 100
2	20.0	1112	694	2.0	50 / 100 / 250	15 / 25 / 100
HS	--	2961	2086	2.0	100 / 100 / 500	25 / 25 / 200

Source configuration	Number of source locations	Number of excitations	Source-distances(km)	Modal summation seismograms
random	5000	7500	0.-5.	32768 pts @ 50 Hz
1src-0500	1	1000	0.5	32768 pts @ 50 Hz
1src-1000	1	1000	1.0	32768 pts @ 50 Hz
1src-4000	1	1000	4.0	32768 pts @ 50 Hz

only impulsive point sources at the surface are considered

Virtual site I: Liege – receiver configurations

Receiver configuration	Number of virtual sensors	Shape	Aperture [m]	min. interstation Distance [m]
geom10-Z	6	hexagonal	4	2
geom11-Z	6	hexagonal	10	5
geom12-Z	6	hexagonal	30	15
geom13-Z	6	hexagonal	50	25
geom14-Z	6	hexagonal	100	50
geom15-Z	6	hexagonal	200	100
P001-P030-Z	30	hexagonal	100	2

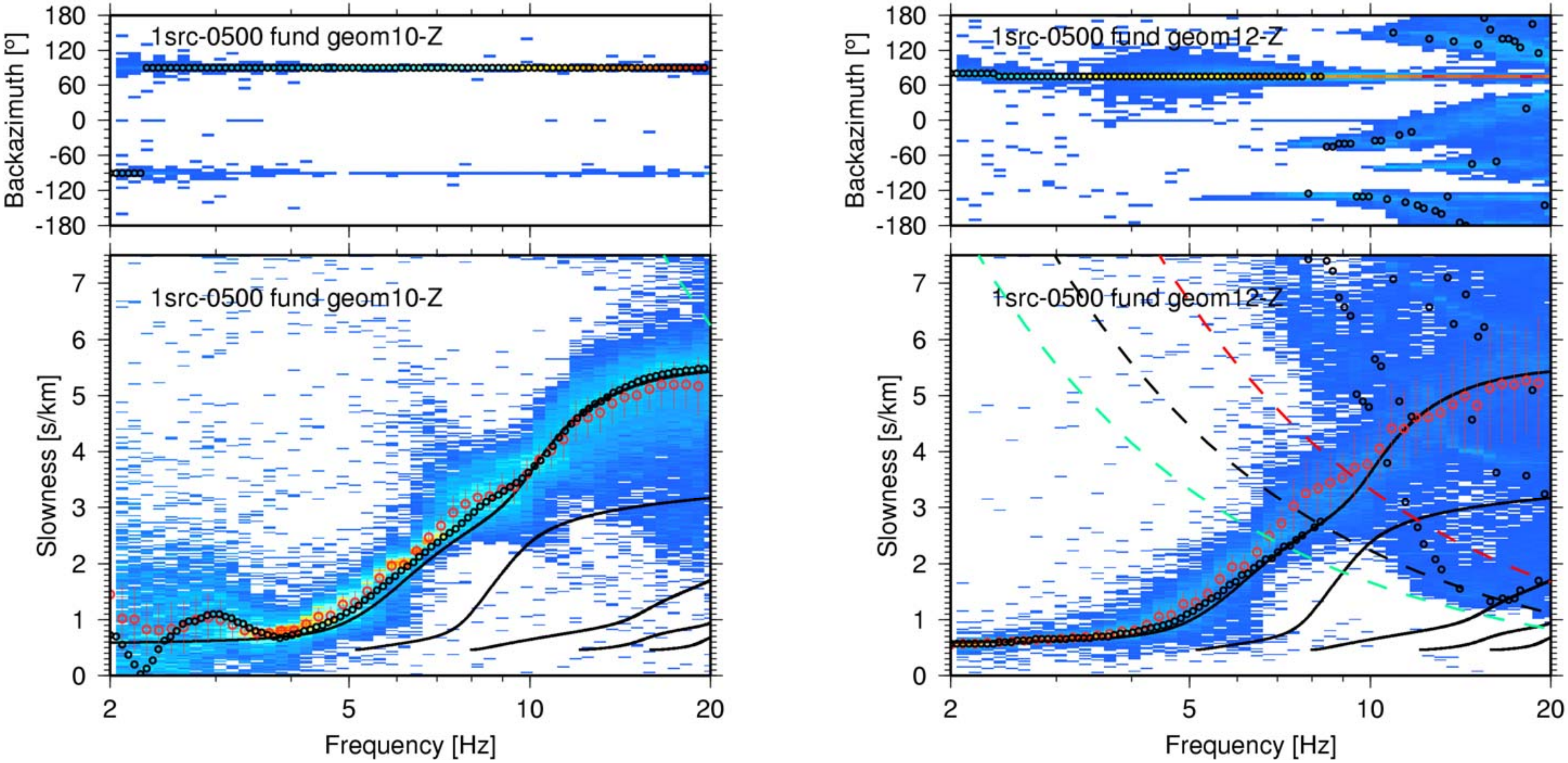
Virtual site: waveform simulation approach

Waveform computation by modal summation code of B. Herrmann (1996)

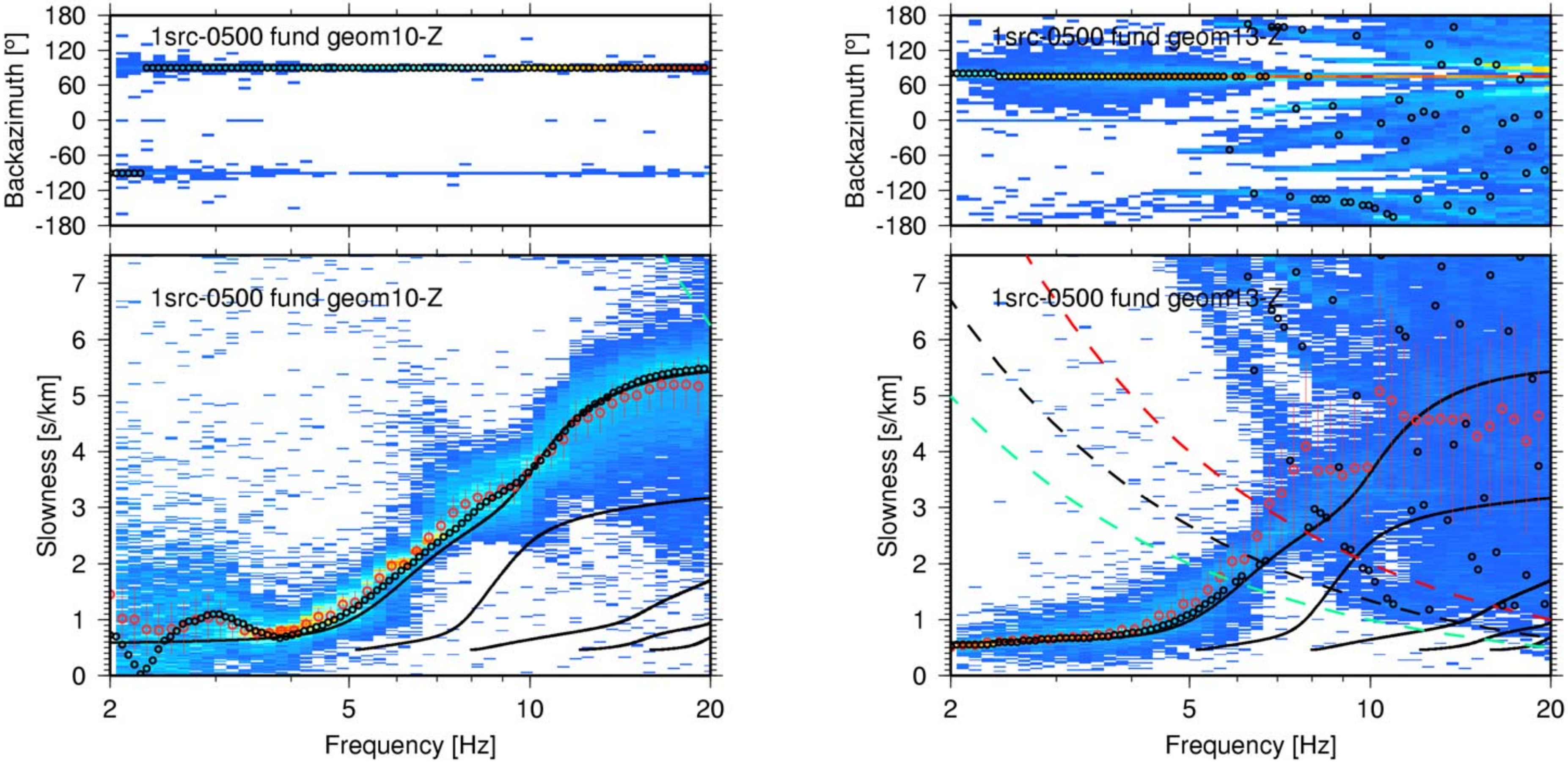
→ For each source distribution two alternative data sets

- **fundamental mode Rayleigh wave only**
- **all Rayleigh wave modes**

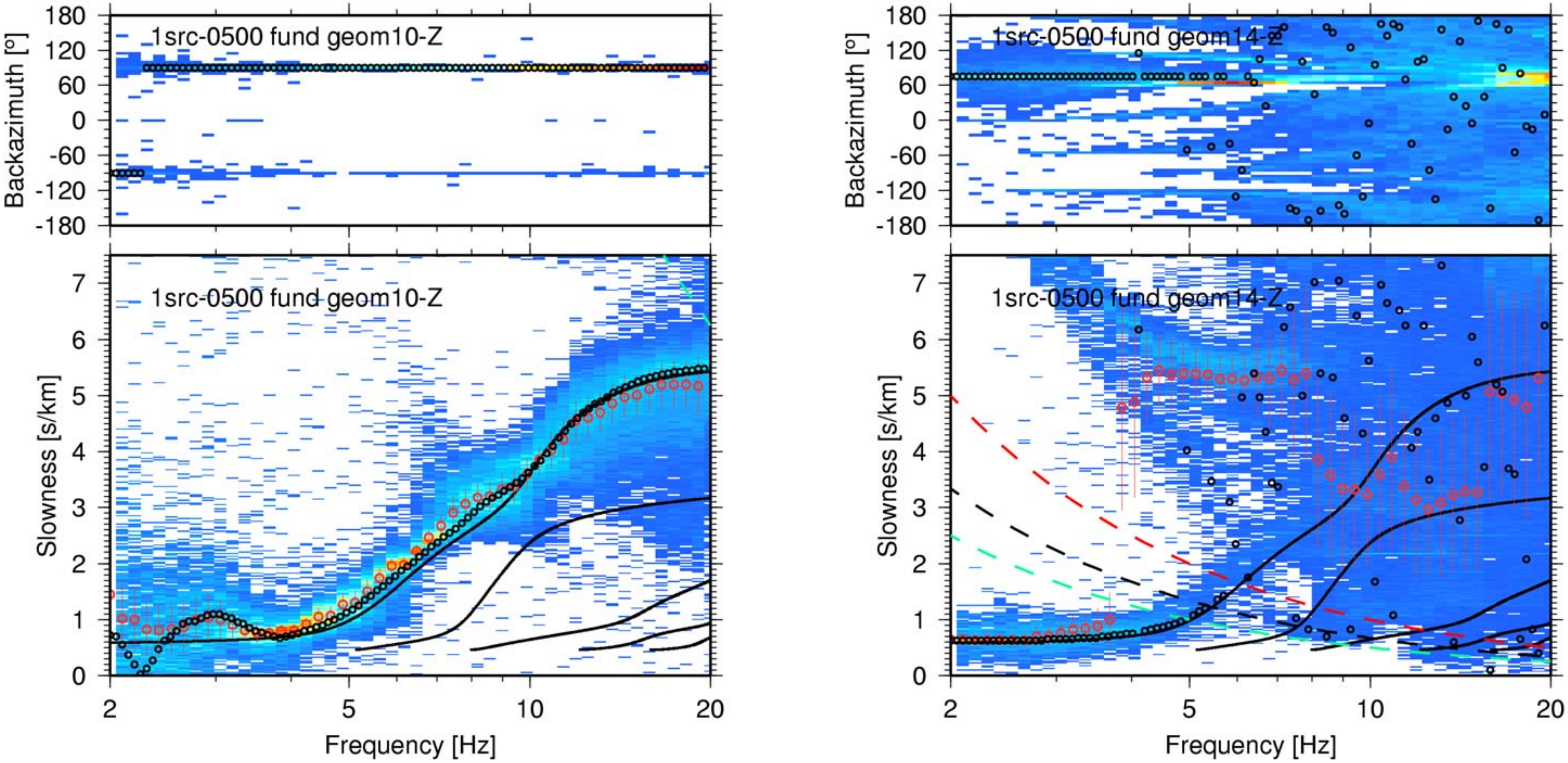
Influence of array aperture on DC estimates



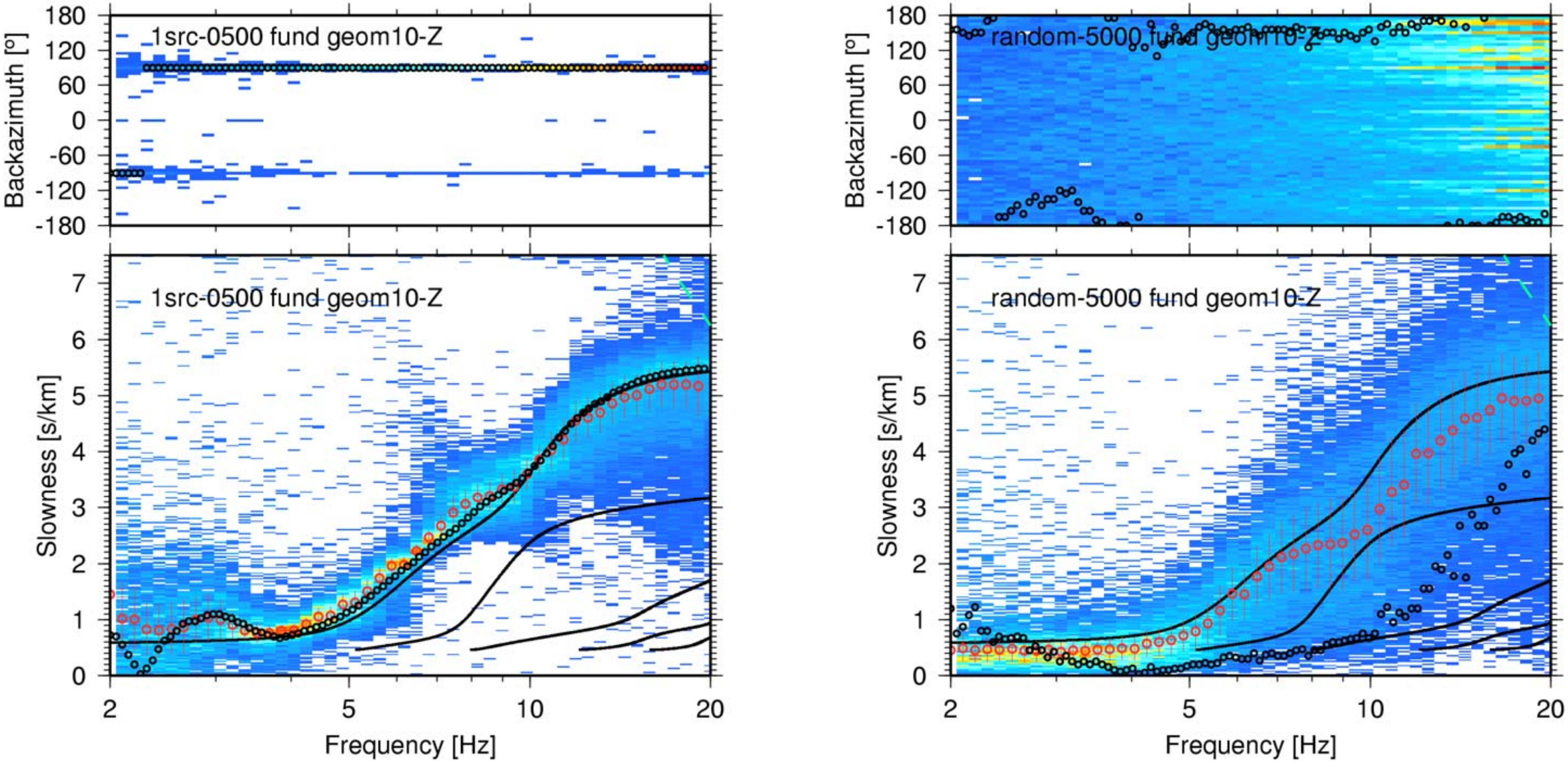
Influence of array aperture on DC estimates



Influence of array aperture on DC estimates

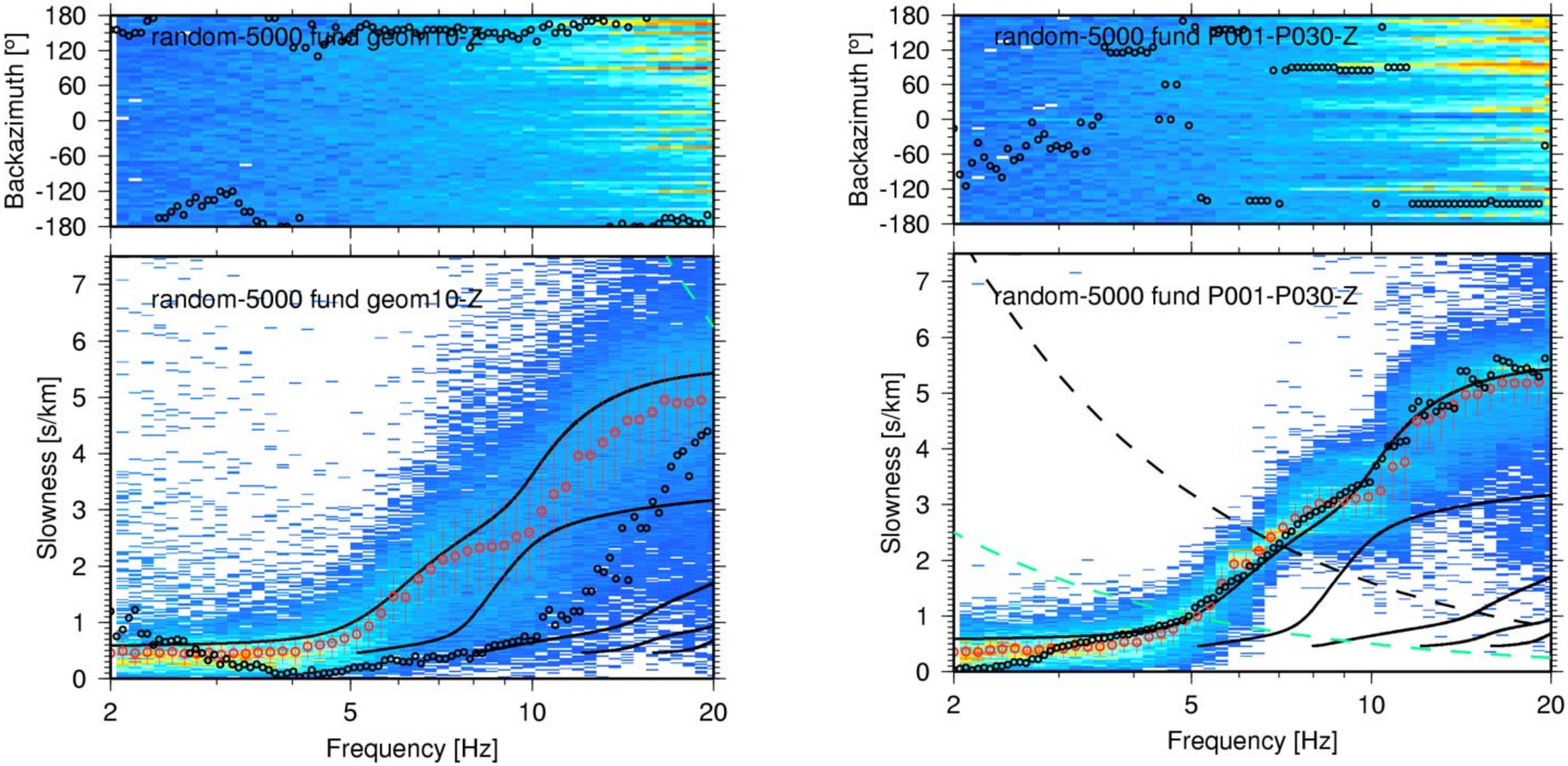


Influence of source distribution on DC estimates

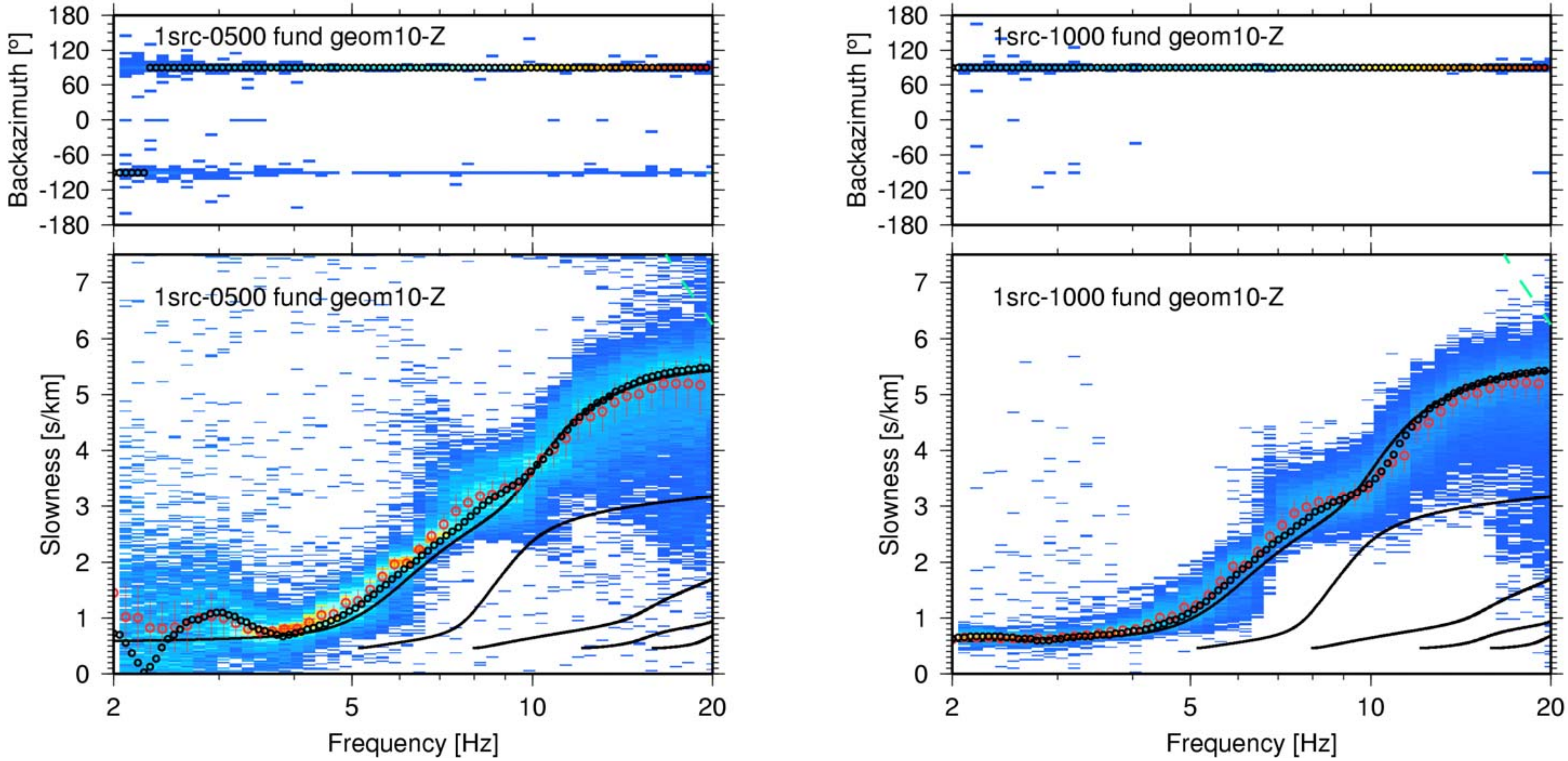


Influence of number of sensors on DC estimates

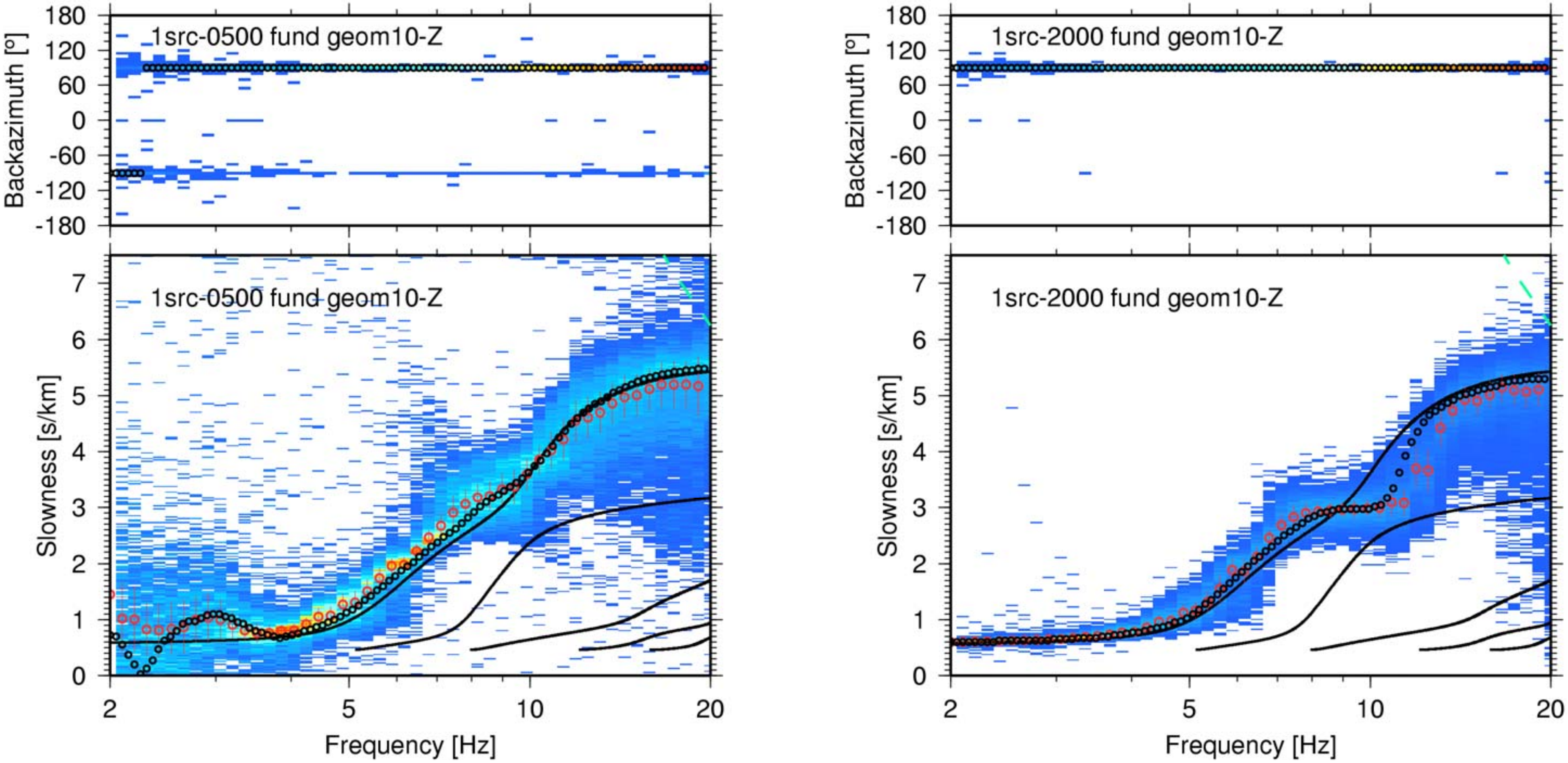
6 Stations vs. 30 stations



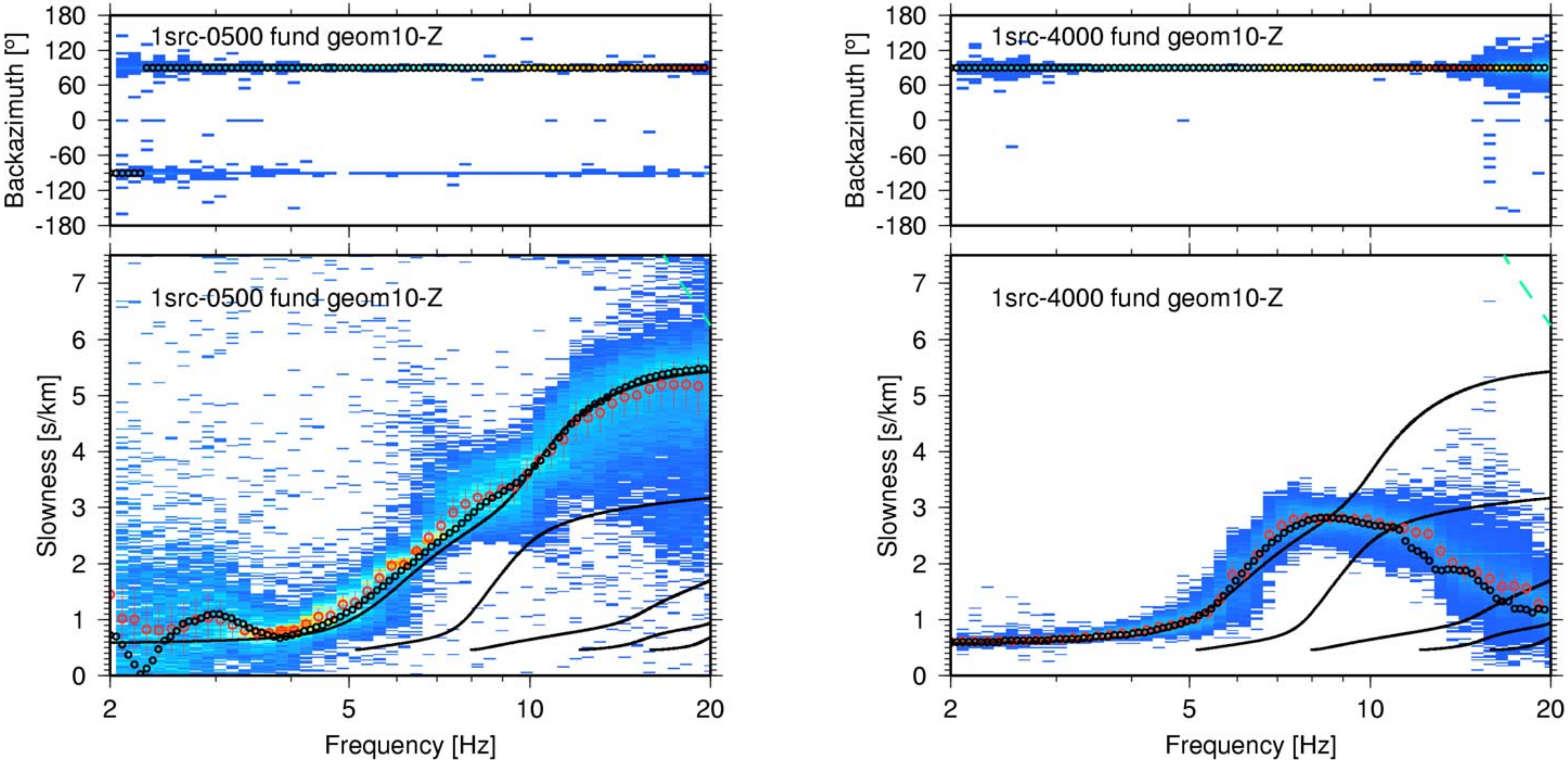
Influence of source distance on DC estimates I – high Q structure



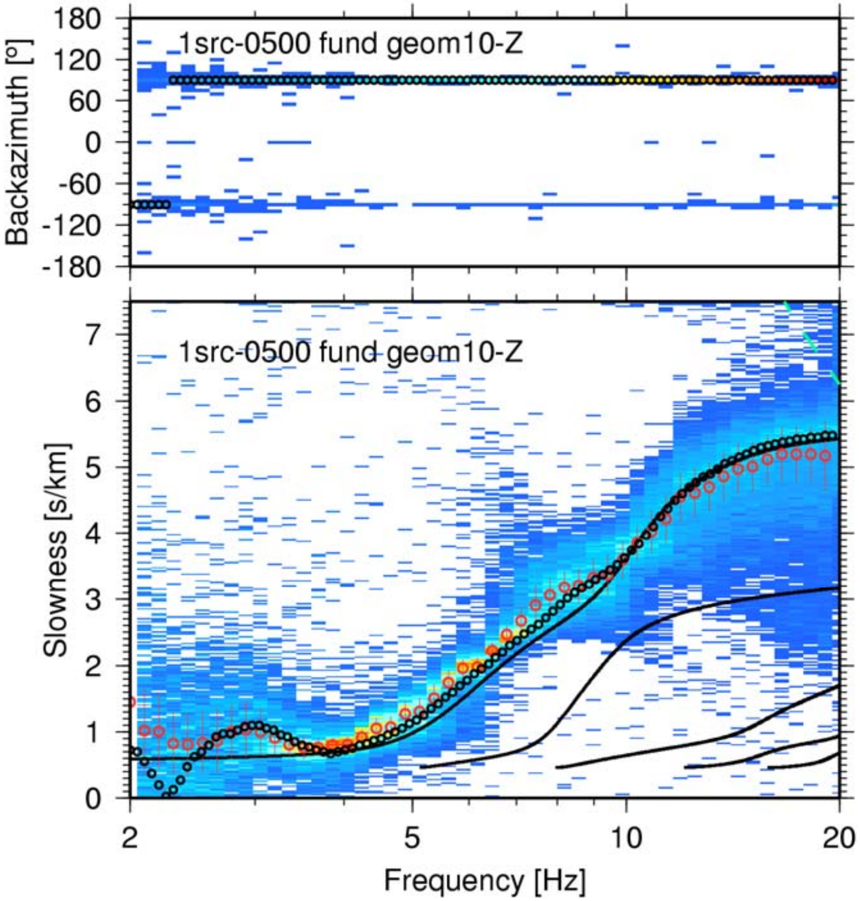
Influence of source distance on DC estimates I – high Q structure

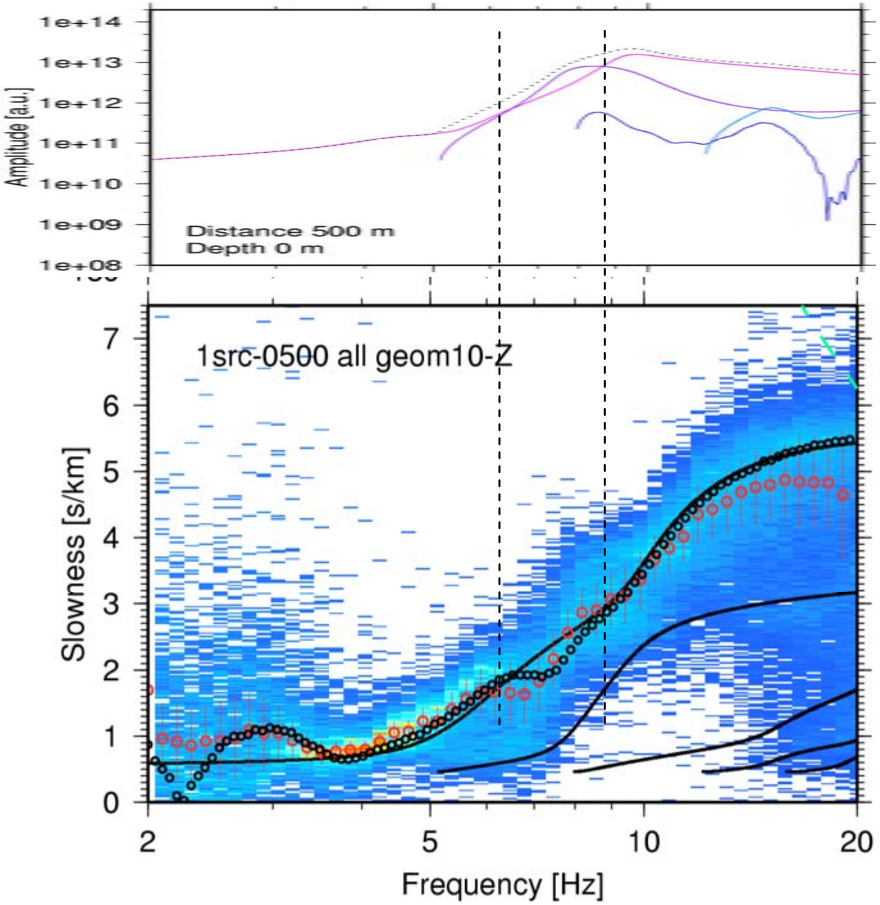


Influence of source distance on DC estimates I – high Q structure

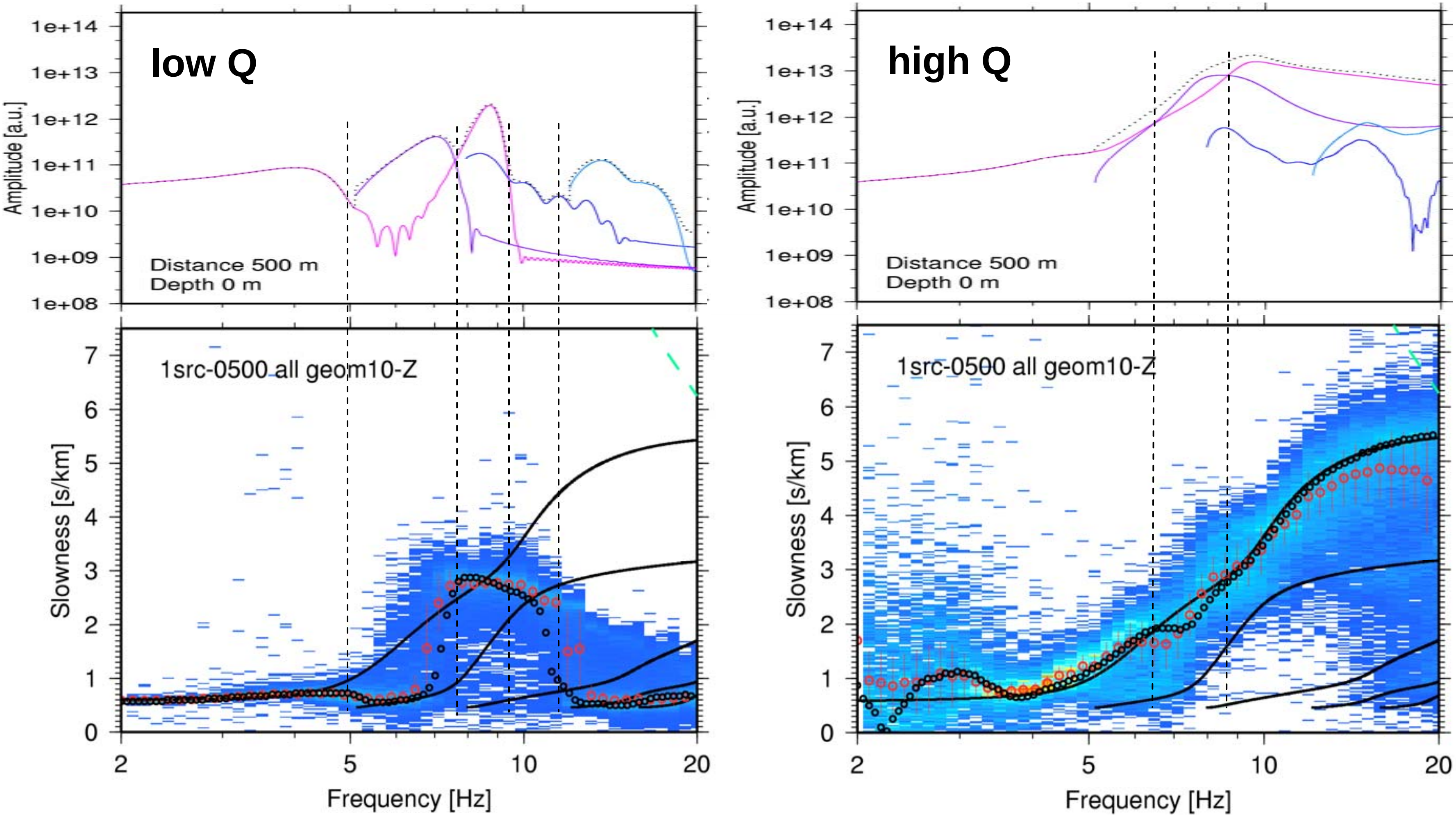


Influence of higher modes – high Q structure



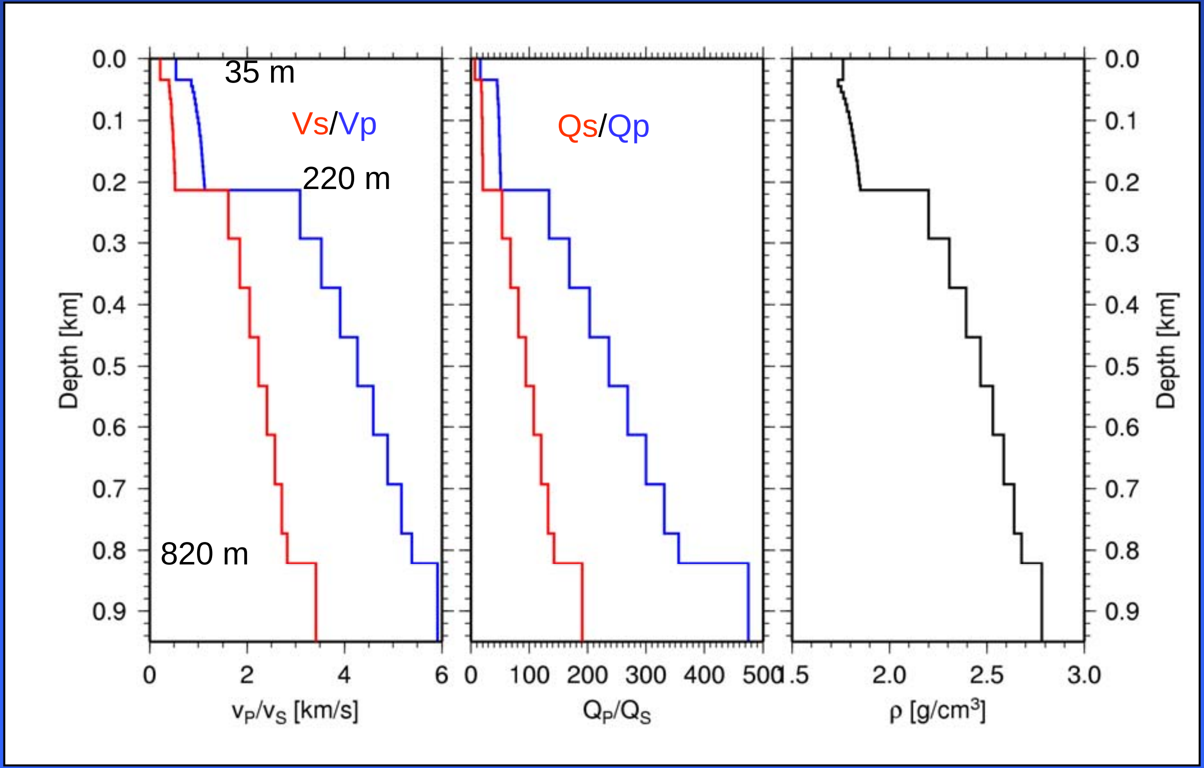


Dominating higher modes – a matter of Q structure?



Virtual site strucure II: Lower Rhine Embayment / Pulheim

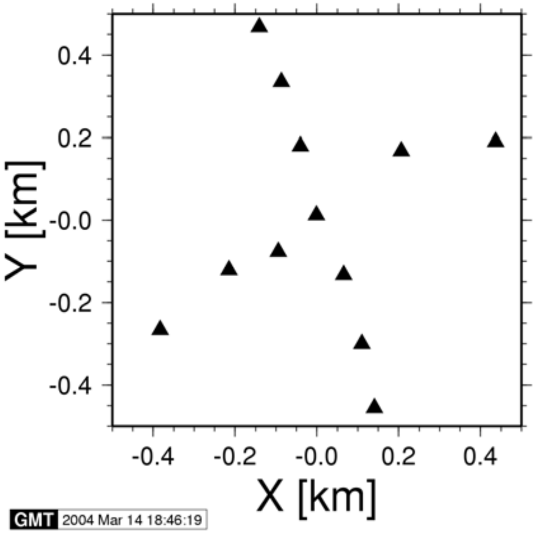
Generic deep sedimentary basin model (GBC, (Brüstle and Stange, 1999) with modifications of shallowest part / Q (Budny, 1984)

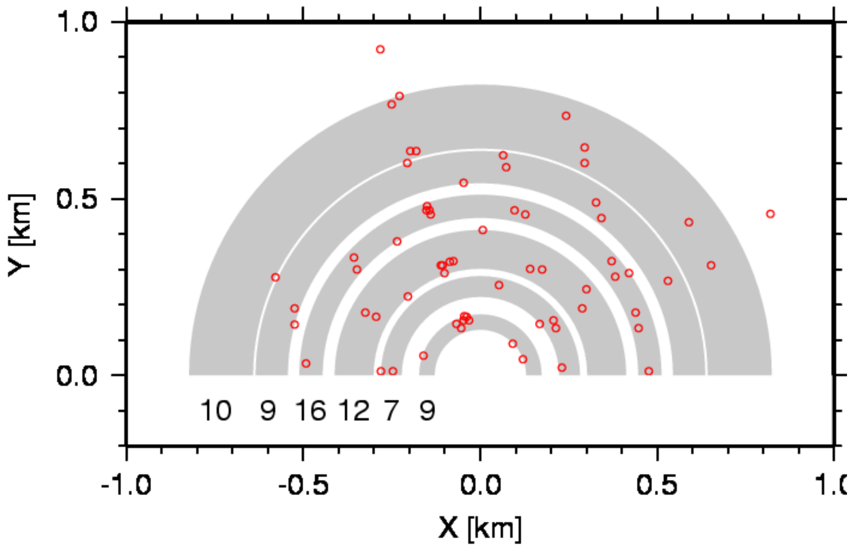


Virtual site I: Pulheim – source configuration

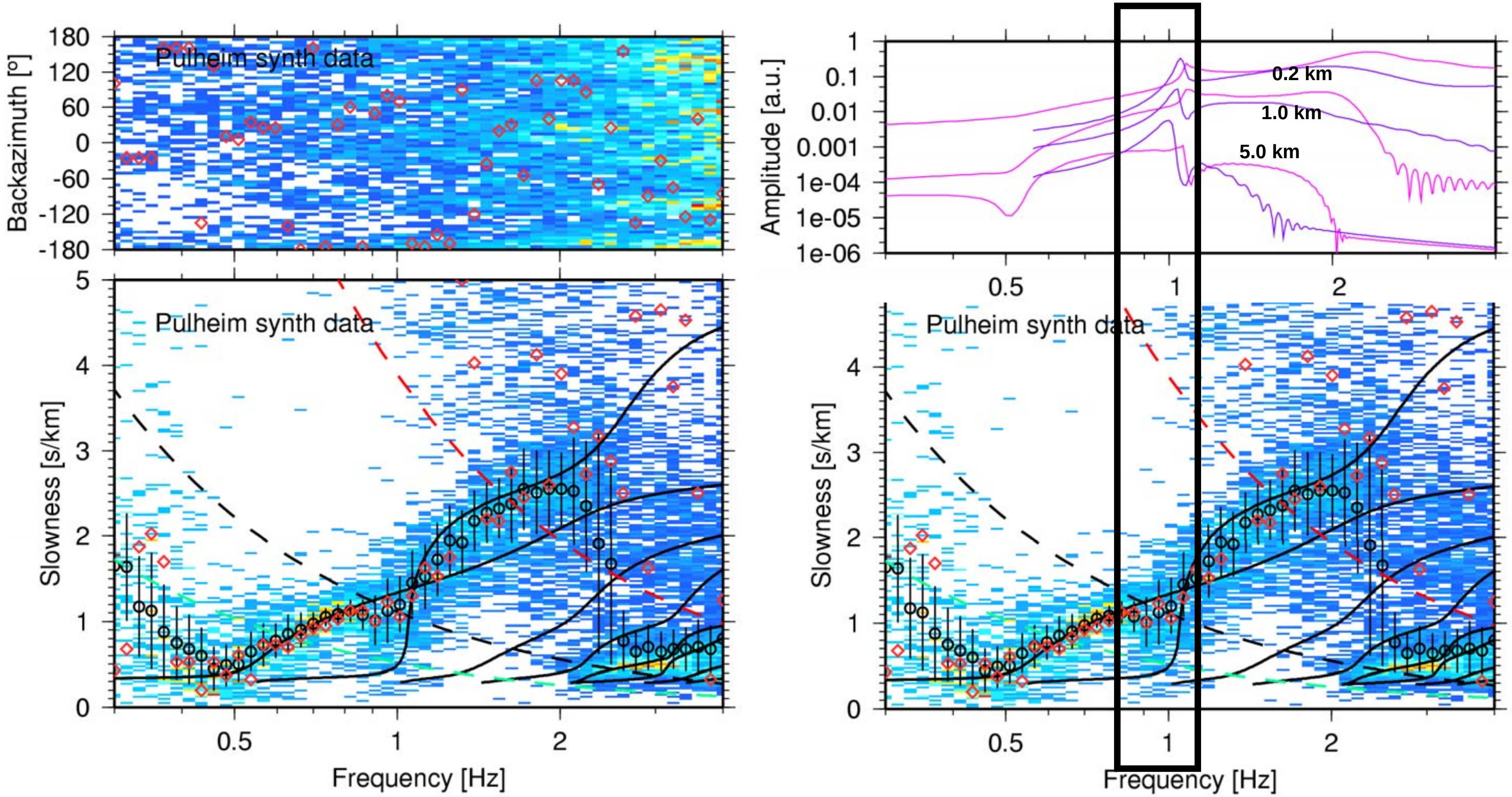
Source configuration	**Number of source locations**	**Number of excitations**	**Sources-array distances(km)**	**Modal summation seismograms**
random	2000	6000	0-5	32768 pts @ 50 Hz

Virtual site I: Pulheim – receiver configuration

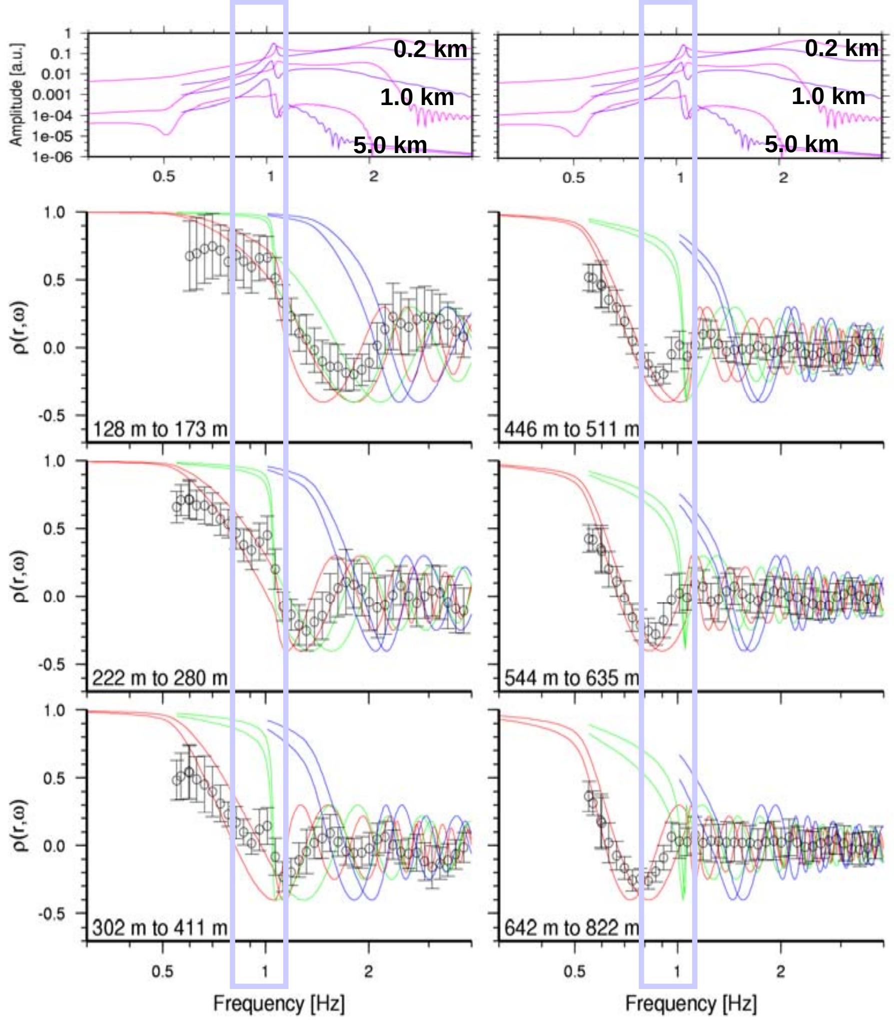



Co-array and ring selection for MSPAC

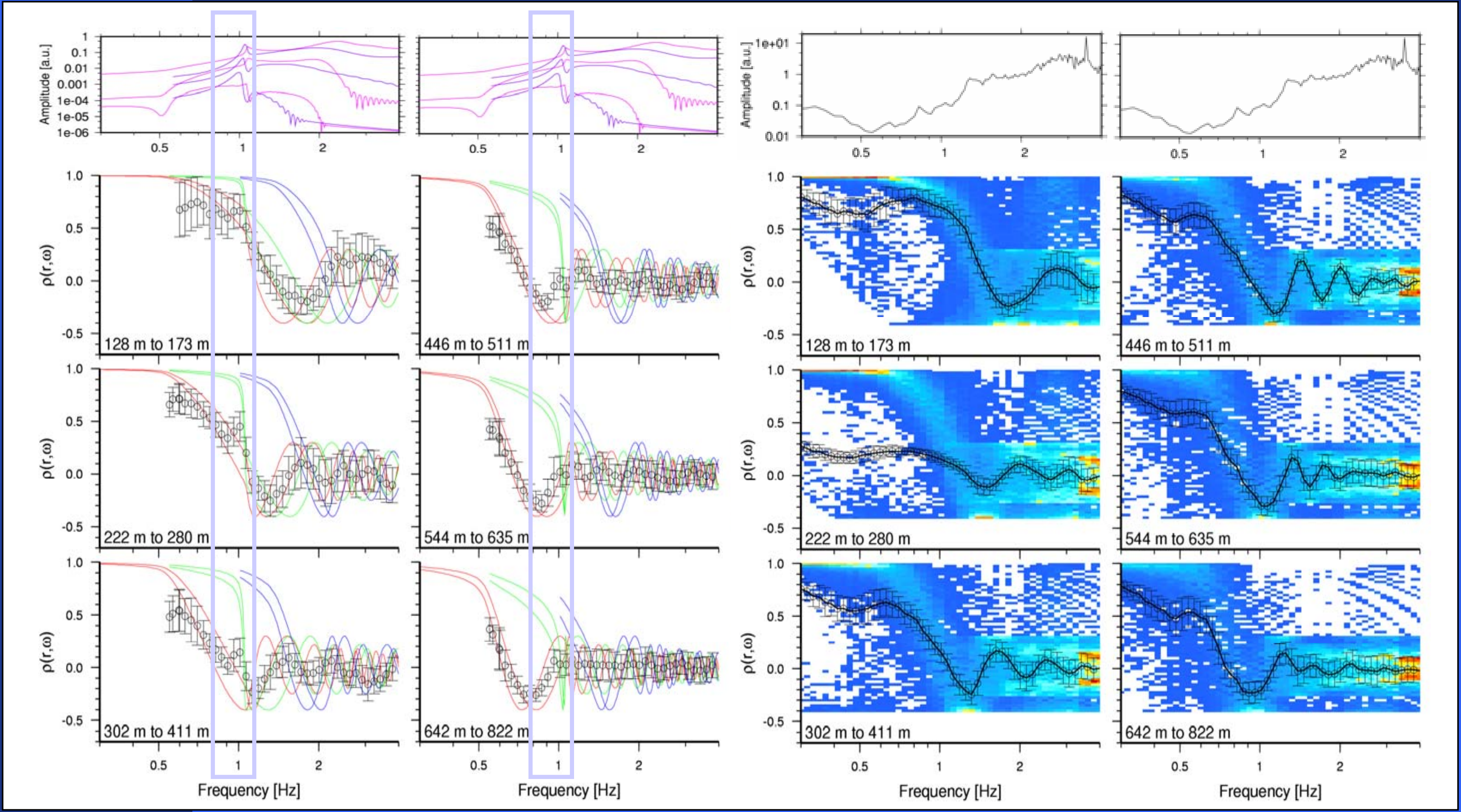
Pulheim synth FK analysis: higher modes detectable



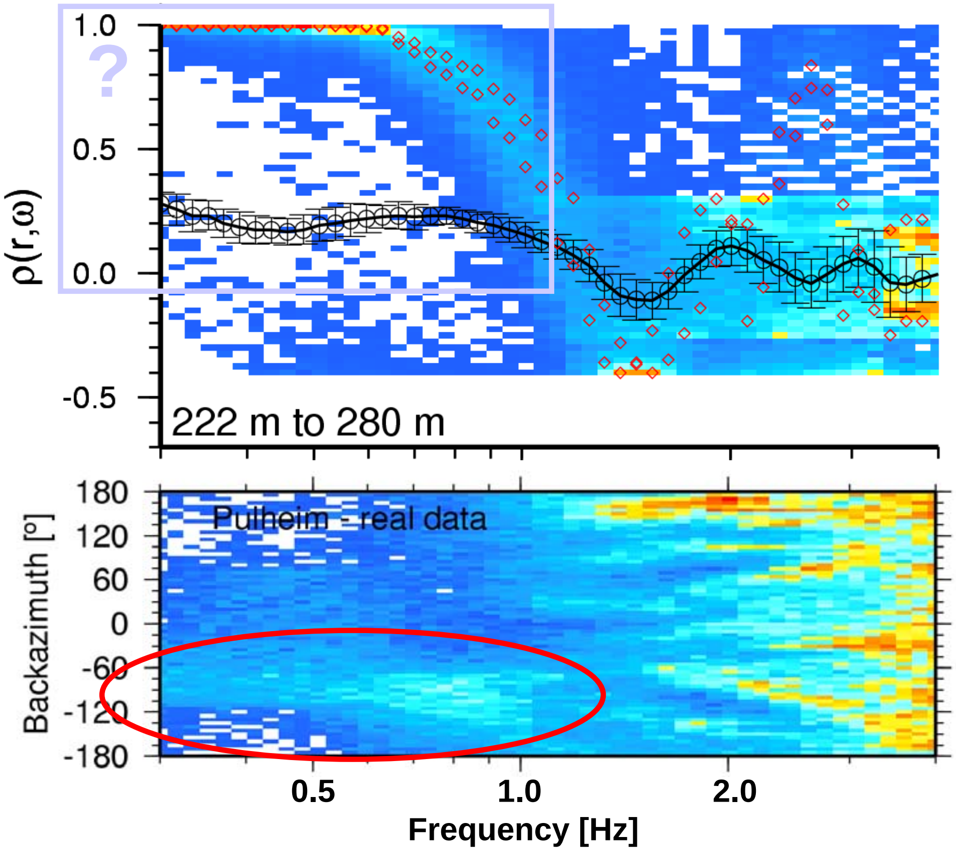
Pulheim MSPAC analysis: higher modes detectable

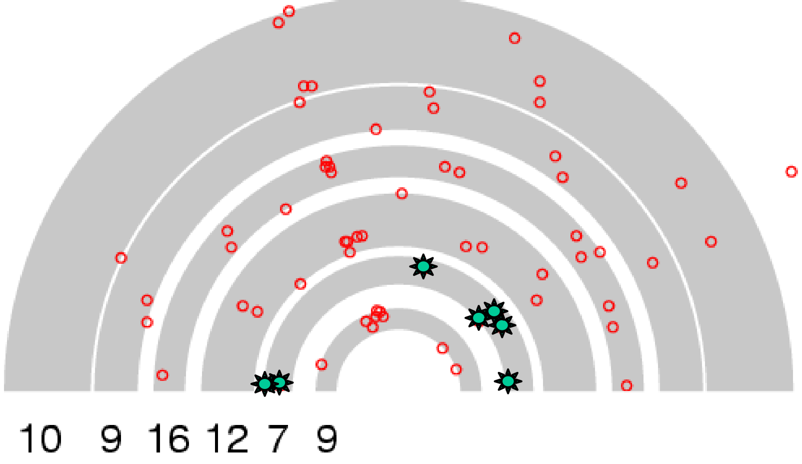


Comparison MSPAC analysis: simulated vs. real



Comparison: f-k <-> MSPAC





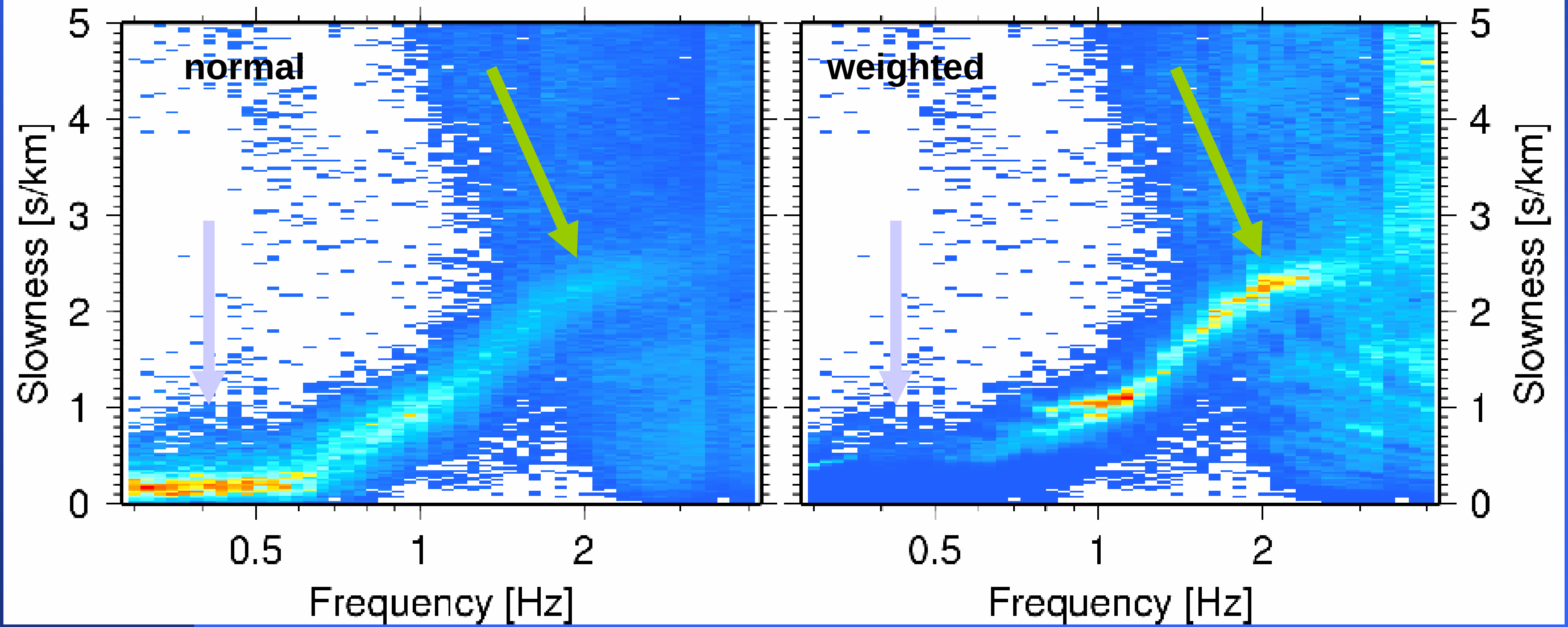
Interpretation:
Deviation between f-k and MSPAC is a result of insufficent azimuthal sampling (difference between direction of wave propagation and interstation distance)

→ combined interpretation

Combining F-K & MSPAC?

$$L(s_{fk}^{est}(f,t)) = \sum_{j=1}^{N} \left[\frac{1}{\sqrt{2\pi\sigma_{spac}^2(r_j,f)}} \exp\left(- \frac{(J_0(2\pi r_j s_{fk}^{est}(f,t)) - \overline{\rho}_{spac}(r_j,f))^2}{2\sigma_{spac}^2(r_j,f)} \right) \right]$$

Likelihood weighting of f-k histograms by MSPAC-curves



Conclusions

- The limits of the valid frequency band for the dispersion curve determination are connected to a) the array layout and b) the energy contribution of the wave field.

- For a limited number of sensors, it is in most cases not possible to obtain reliable DC estimates for the complete frequency band of interest.
However, it seems an appropriate choice to develop an adaptive measurement scheme in order to optimize the array geometry for certain wavelength ranges.

- The Q-structure has a signifanct influence on the partitioning of energy between the individual mode contributions of the wave field.
The question remains, whether any site with strong Q contrast between sediment and underlying bedrock exhibits a wave field with a dominant contribution of higher mode energy?

- A combination of analysis methods eases interpretation to detect certain wave field peculiarities (higher mode contributions, spectral holes)

Proposition of tentative measurement strategy (recording and processing)

Before going to the field:

(1) select adequate equipment for measurements ($f_{seis} << f_0$ site). Huddle test – verify calibration of instruments (estimate possible instrument related delay times).

(2) Collect a priori information about site (e.g. $f_{H/V}$, bedrock depth, shallow v_P, geological, geotechnical, etc.) ➔ Purpose: derive approximate wavelength range of interest.

Proposition of tentative measurement strategy (recording and processing)

Steps within a field measurement:

1) build very small array – AR00
suggestion: circle with N sensors (N = 6, ..., practical/financial limit),
radius of circle 2 m - 5 m

2) Estimate amplitude spectra and H/V ratios →
provides information of analyzable frequency bands!

3) Do broadband f-k analysis for data obtained at AR00

Proposition of measurement strategy ... continued.

(4) Derive approximate frequency band / slowness limits of wavefield from (2 + 3)

(5) Apply narrowband array analysis methods to frequency band which has been determined as appropriate (as in 4)

- CVFK
- CAPON
- (M)SPAC

(6) Derive frequency band which shows consistent phase velocity estimates for all methods

- derive first partial branch of dispersion curve
- derive corresponding wavelength range
- crosscheck results with capabilities/limitations of array geometry in terms of aliasing and resolution

Proposition of measurement strategy ... continued.

(7) Define next narrow target wavelength range which extends the previously analysed wavelength range to longer wavelengths and adjust array aperture to be optimal for the wavelengths to be analysed.

(8) Rearrange array geometry according to (7)

(9) Repeat steps (5) to (8) until a well estimated, consistent dispersion relation is obtained for the complete frequency band of interest (or better: which is needed for the inversion of DC to velocity models).

Arguments for proposed measurement steps – potential sources of error / uncertainty

Recall:

Time delays between stations (in particular between pairs of stations) are the base of our measurements.

Therefore we should ask ourselves:

- ❖ **what kind of effects do we have to consider that might have a non-neglible influence on the estimates of time delays between stations?**
- ❖ **What magnitude can we expect for those effects?**
- ❖ **Are the effects of random or systematic nature?**

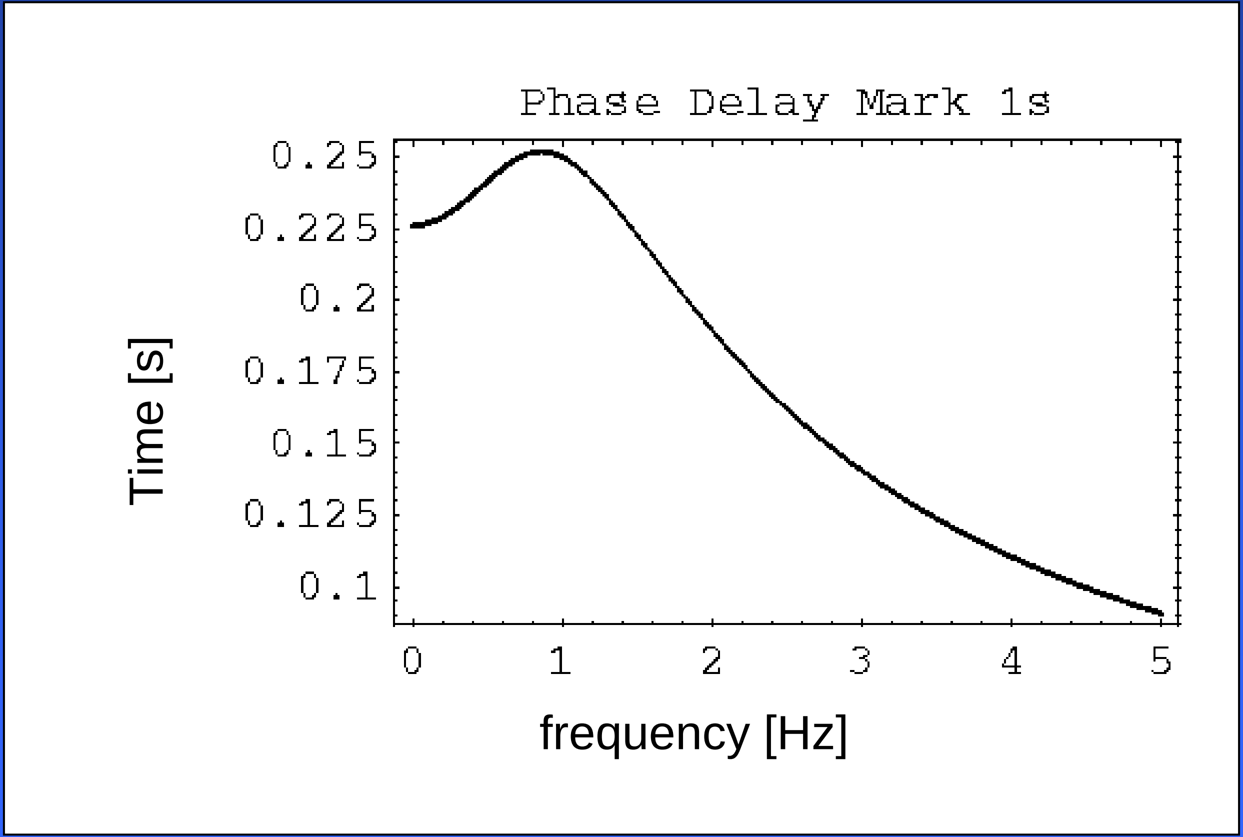
Arguments for proposed measurement steps

What kind of effects do we have to consider that might have a non-neglible influence on the estimates of time delays between stations?

- ❖ **Instrumental effects**
- ❖ **Source – receiver geometry**
- ❖ **Energetic content of wavefield**

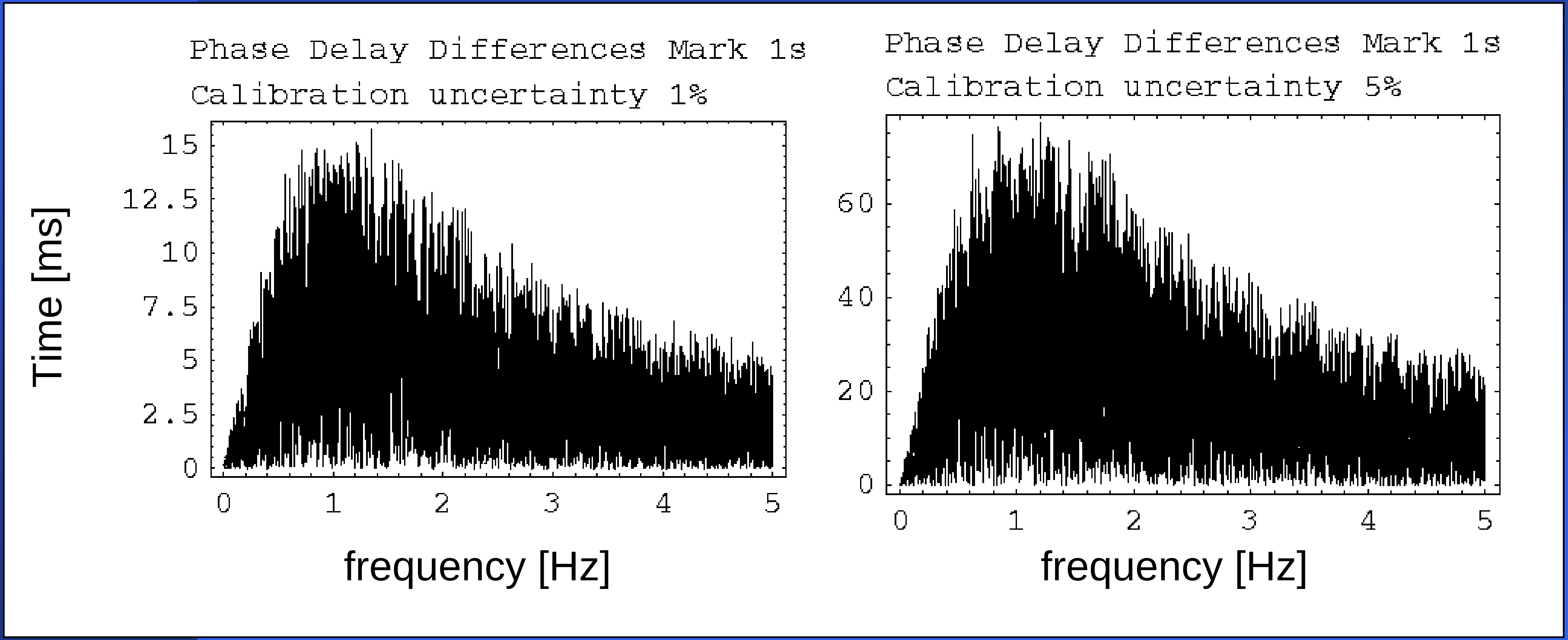
Arguments for proposed measurement steps – potential sources of error / uncertainty

Instrumental effects → Sensor stability / calibration

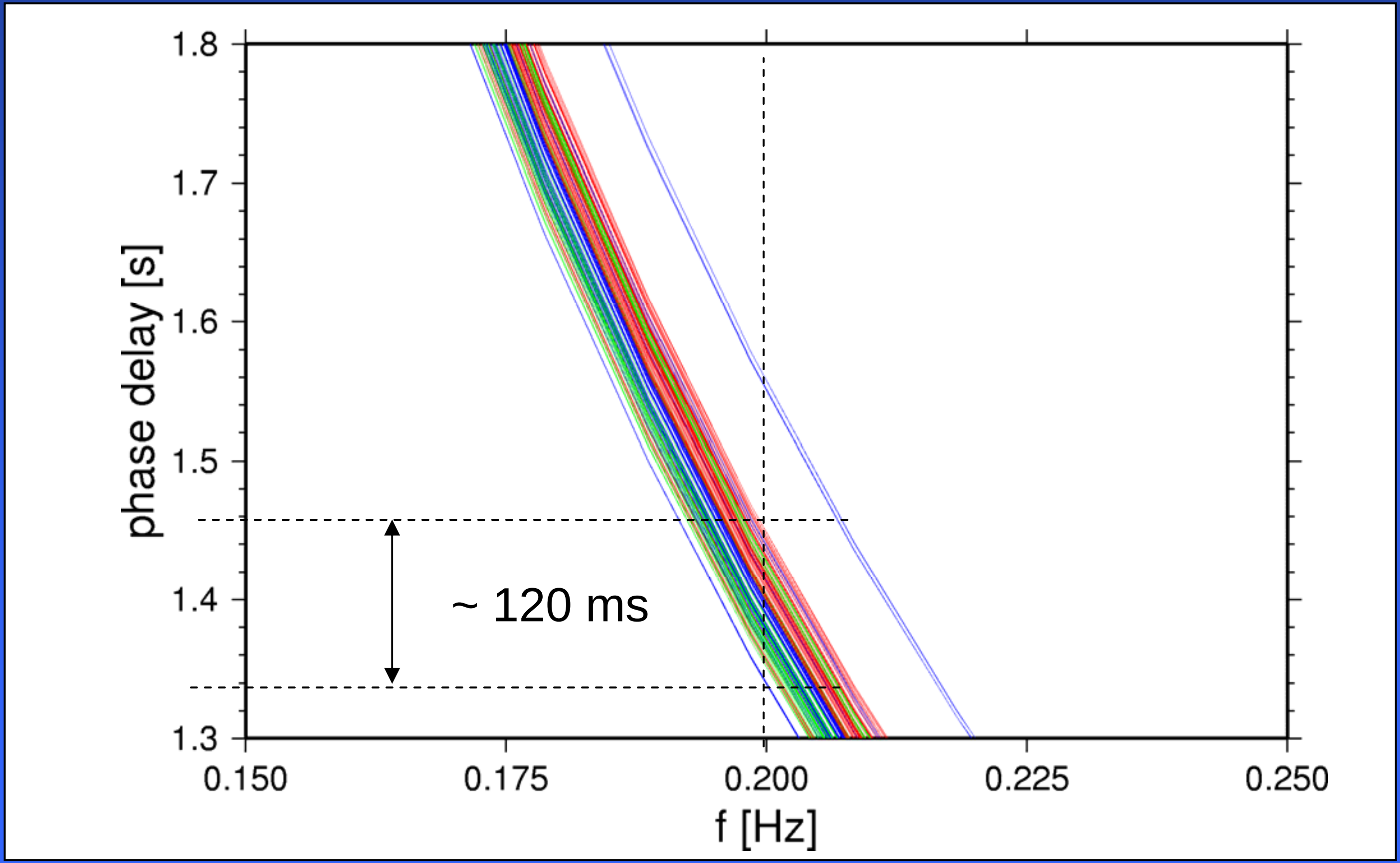


Arguments for proposed measurement steps – potential sources of error / uncertainty

Instrumental effects → Sensor stability / calibration



Laboratory huddle test Le3D-5s for relative calibration - D07.05



Consequences of systematic or random time delays within an array configuration

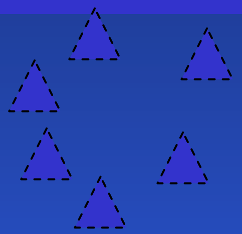
- Systematic time delays at single stations can be caused by:
  - Phase delay of instrument (up to several tens of ms)
  - Positioning error (wavespeed dependent – e.g. 250m/s, 1m ~ 4 ms)

- Random time shifts can be caused by:
  - time-jitter (unstable timing – unlocked GPS – seldomly locked GPS)
  - spectral estimate (phase!) of signals with low SNR

BUT: some systematic time delays turn to random ones for varying source propagation directions (positioning error)

NOTE: consequences on slowness estimates are function of time delays and wavefield properties and array geometry!

Effect of random time delays on slowness estimates: a simple numerical bootstrap test



For a fixed array geometry, repeat XXX times:

1) compute arrival times of a single plane wave arrival at the array sensors (randomly selected source azimuth)

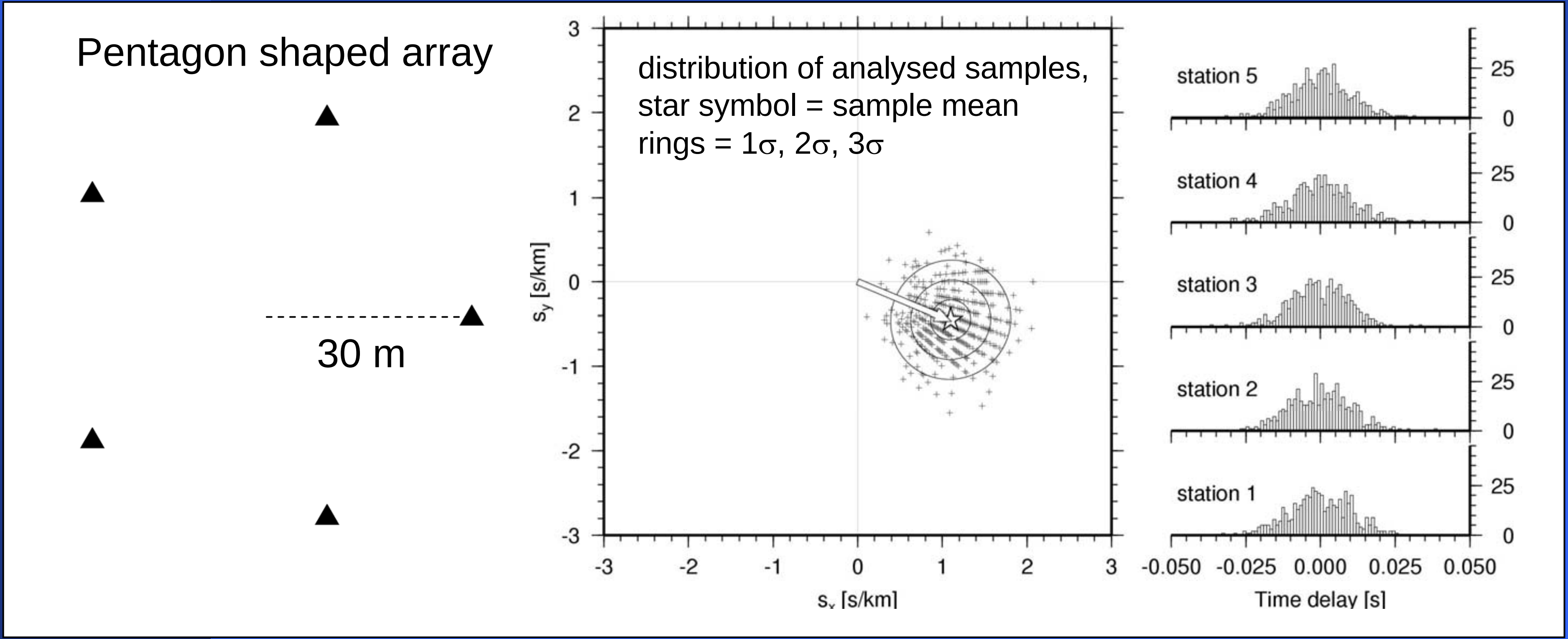
2) add random time delay for each sensor in array taken from a normal distribution with predefined mean and variance.

3) analyse perturbed wave arrival (distorted wave front) by FK

After XXX runs of 1)-3), derive mean and variance from obtained slowness vector distributions.

Quantification of random time delays on slowness estimates: a simple numerical bootstrap test

Example for 5 station array (pentagon shape) for array radius 30 m, Random time delays superimposed with μ=0 and σ=10 ms, 500 samples.

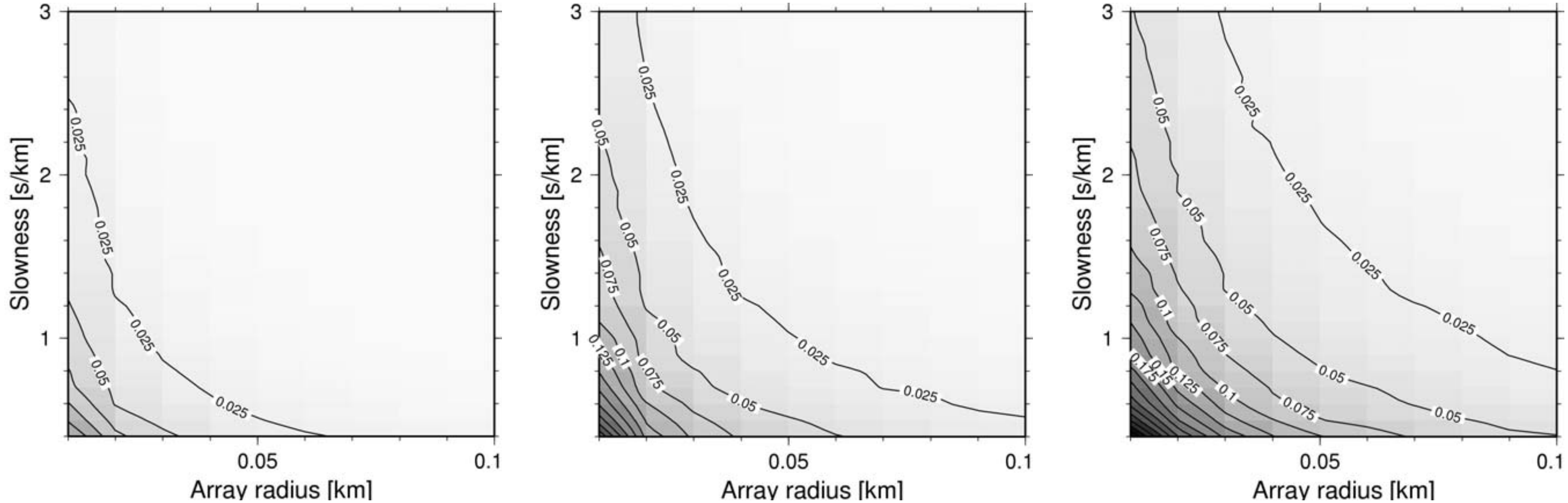


Pentagon shaped array

distribution of analysed samples,
star symbol = sample mean
rings = 1σ, 2σ, 3σ

Quantification of random time delays on slowness estimates: a simple numerical bootstrap test

Example for 5 station array (pentagon shape) for different array radii, plane wave slownesses and variance of random time delays. Distribution for all stations: zero.mean, variance indicated by isolines.



σ = 15 ms

σ = 30 ms

σ = 50 ms

Quantification of random time delays on slowness estimates: a simple numerical bootstrap test

Findings from bootstrap experiment

+ no bias of average slowness estimate for random time delays
--> correct estimate should be obtained from mean of distribution

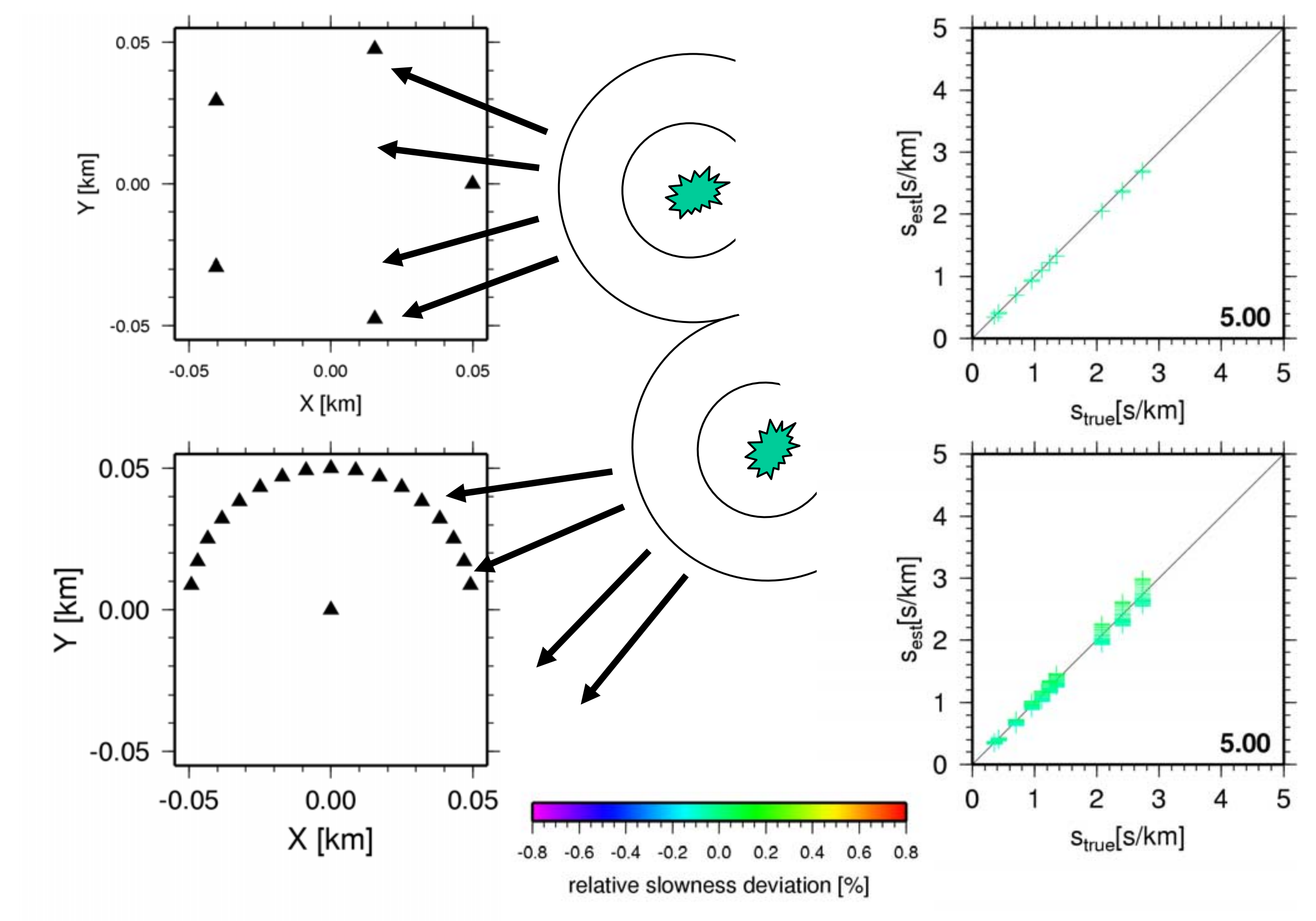
- amount of uncertainty depends on slowness and array size

- individual estimates can deviate extremely!

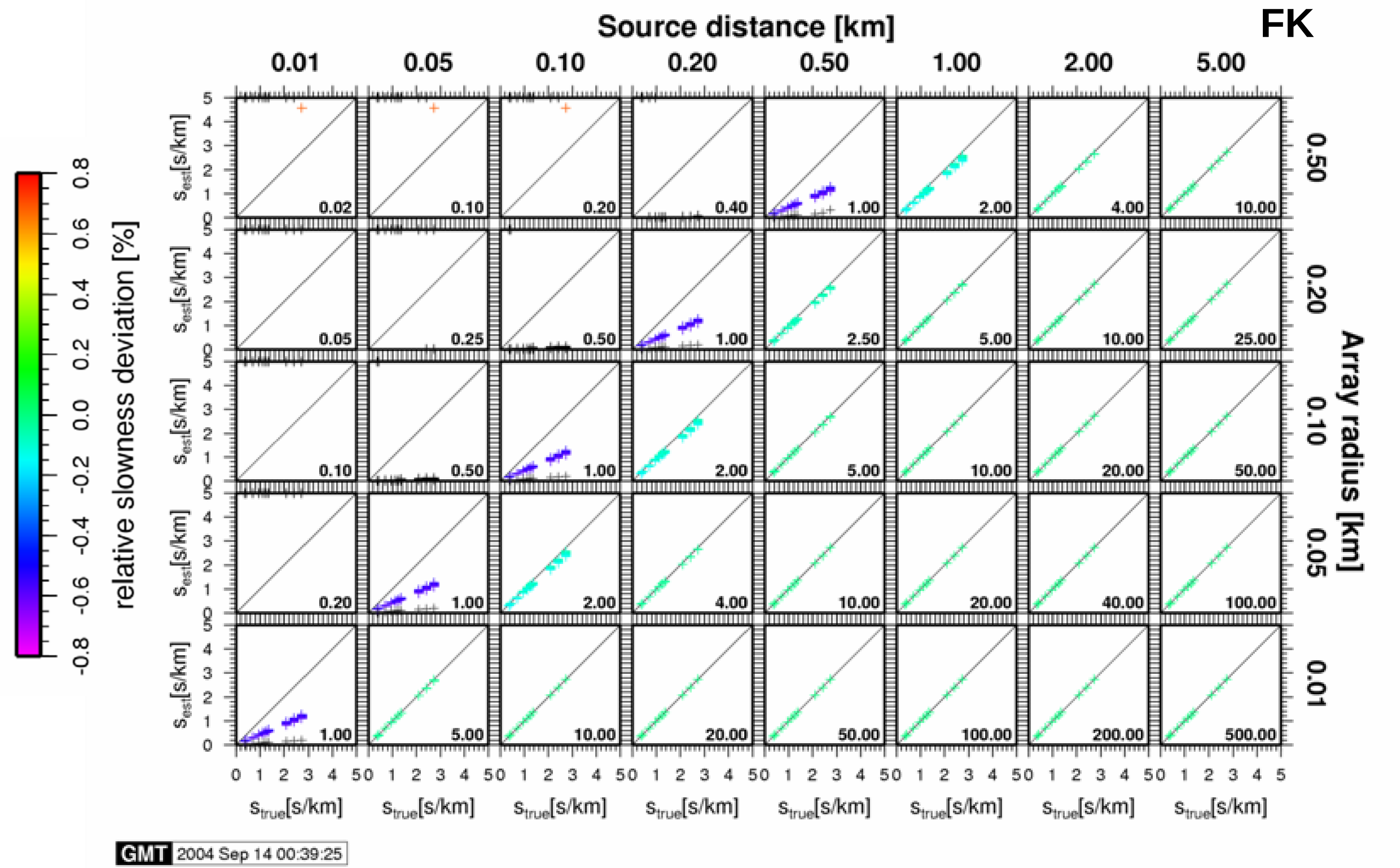
Conclusion:

- **We should look on the distribution of slowness estimates ,**
- **individual time windows can be heavily biased**
- **for a good estimate we need a large number of time windows**
- **work on short time series should be discarded**

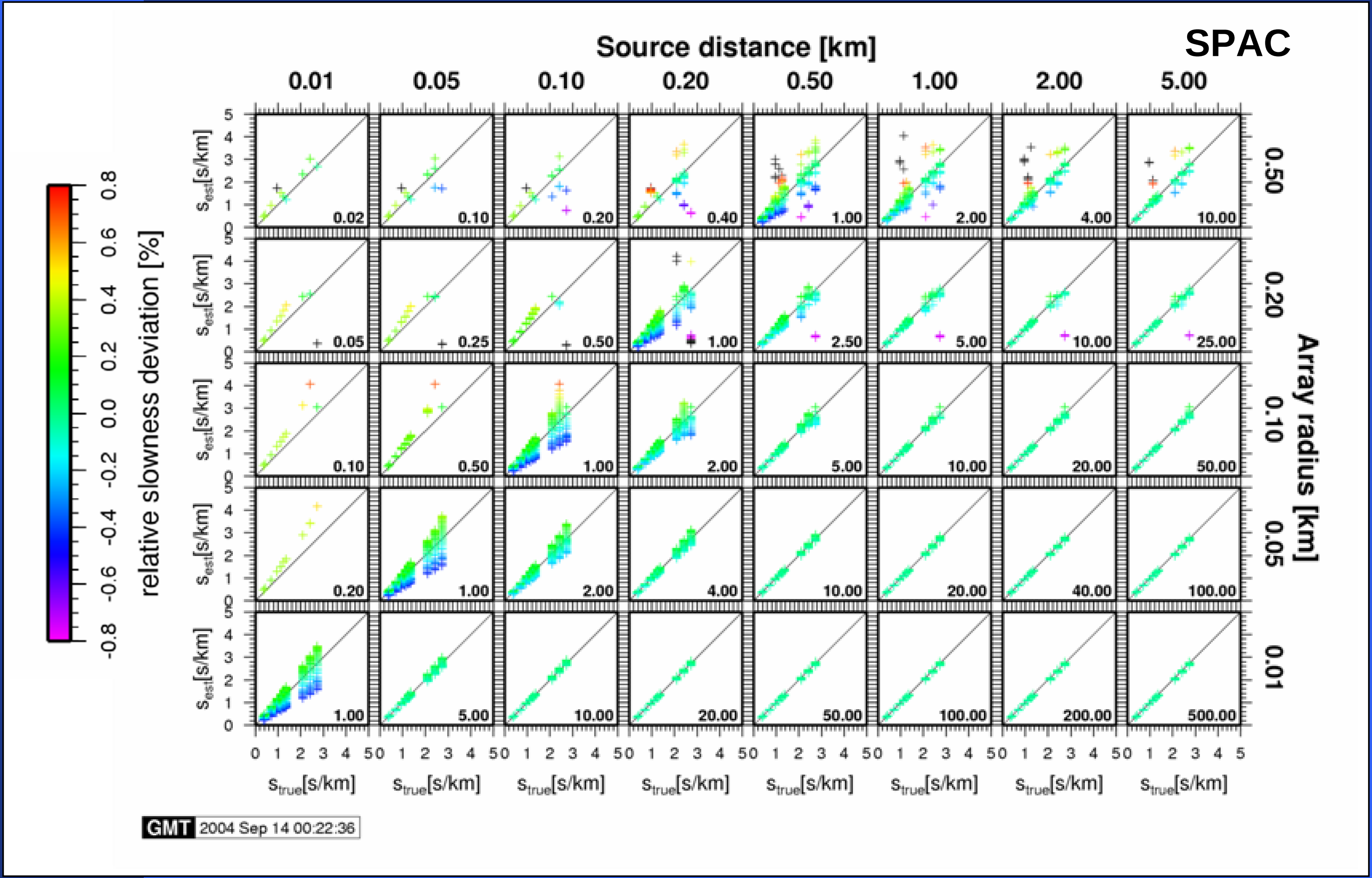
Another type of unexpected phase delays of wavearrivals – curved wavefronts –



Violating the plane wave assumption …
what are the effects on the dispersion curve estimates?



Violating the plane wave assumption …
what are the effects on the dispersion curve estimates?



Proposition of tentative measurement strategy (recording and processing)

- build very small array – AR00
  suggestion: circle with N sensors (N = 4, ..., 8, ...),
  radius of circle 2 m - 5 m

- Estimate amplitude spectra and H/V ratios → provides information of analyzable frequency bands!

- Do broadband f-k analysis for data obtained at AR00

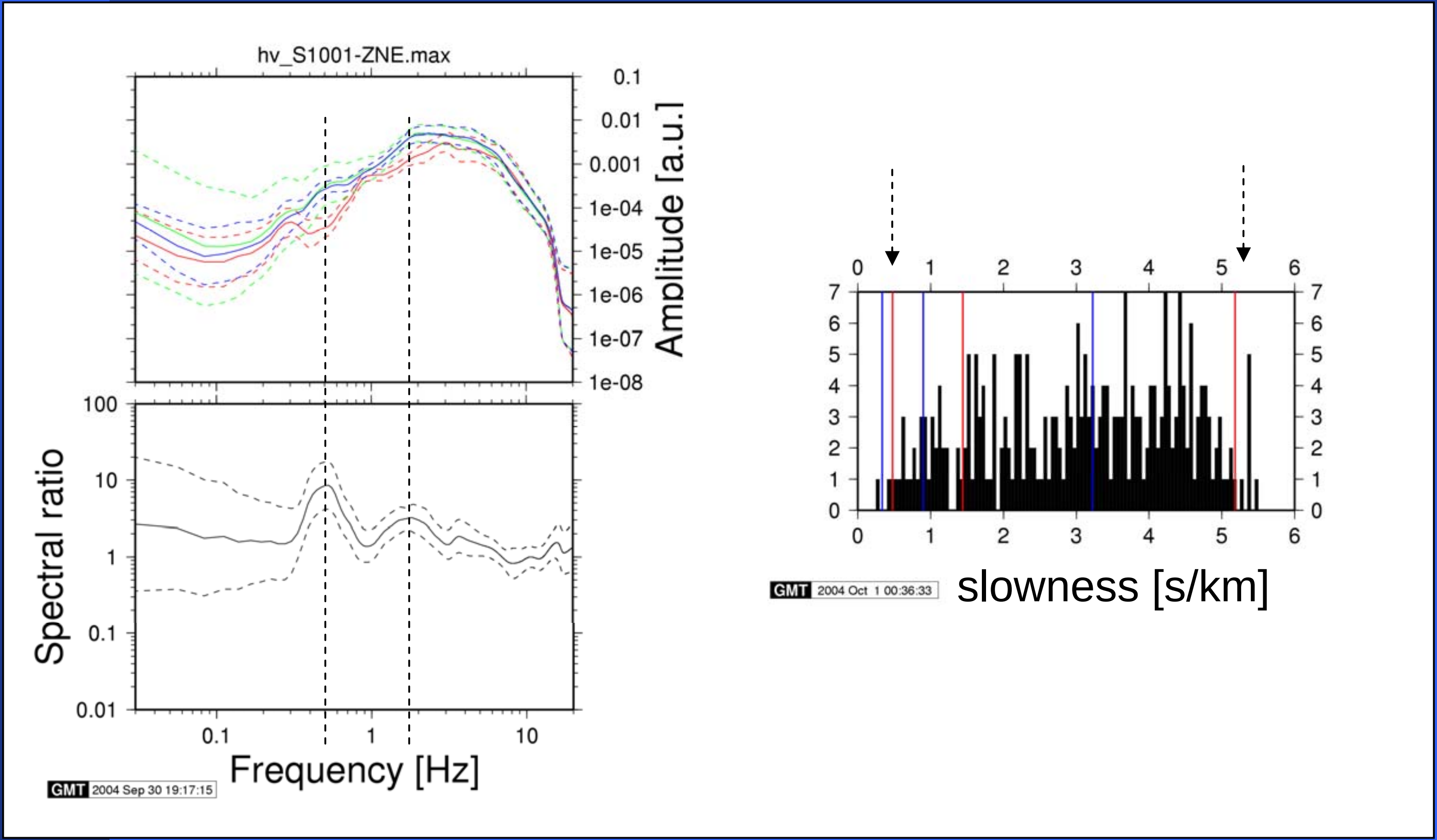
Proposition of tentative measurement strategy (recording and processing)

- **build very small array – AR00**
  suggestion: circle with N sensors (N = 4, ..., 8, ...),
  radius of circle 2 m - 5 m

- **Estimate amplitude spectra and H/V ratios → provides information of analyzable frequency bands!**

- **Do broadband f-k analysis for data obtained at AR00**

Approximate determination of frequency and slowness (wavenumber) ranges



Proposition of measurement strategy ... continued.

(4) Derive approximate slowness limits of wavefield from (3)

(5) Apply narrowband array analysis methods to complete frequency band which has been determined as appropriate (3)

- CVFK
- CAPON
- (M)SPAC

... Loop of deployment and immediate processing for guided adaptive strategy

What array geometry? - Shape issues

as source azimuths are unknown and most probably variable through time, we can define the following requirements:

- should have similar aliasing properties in all directions
- should have sharp 2D aliasing criteria rather than smooth increase of amount of aliasing in order to avoid misinterpretations

What array geometry? - size / resolution / depth penetration

as small as possible (aliasing, curved wavefronts)

as large as necessary (resolution, variance reduction of slowness estimates)

depth: $hmax \sim \lambda_{effective} / 3$

relevance factors for estimation of dispersion curve