

5. CMPCC and CMPSPAC

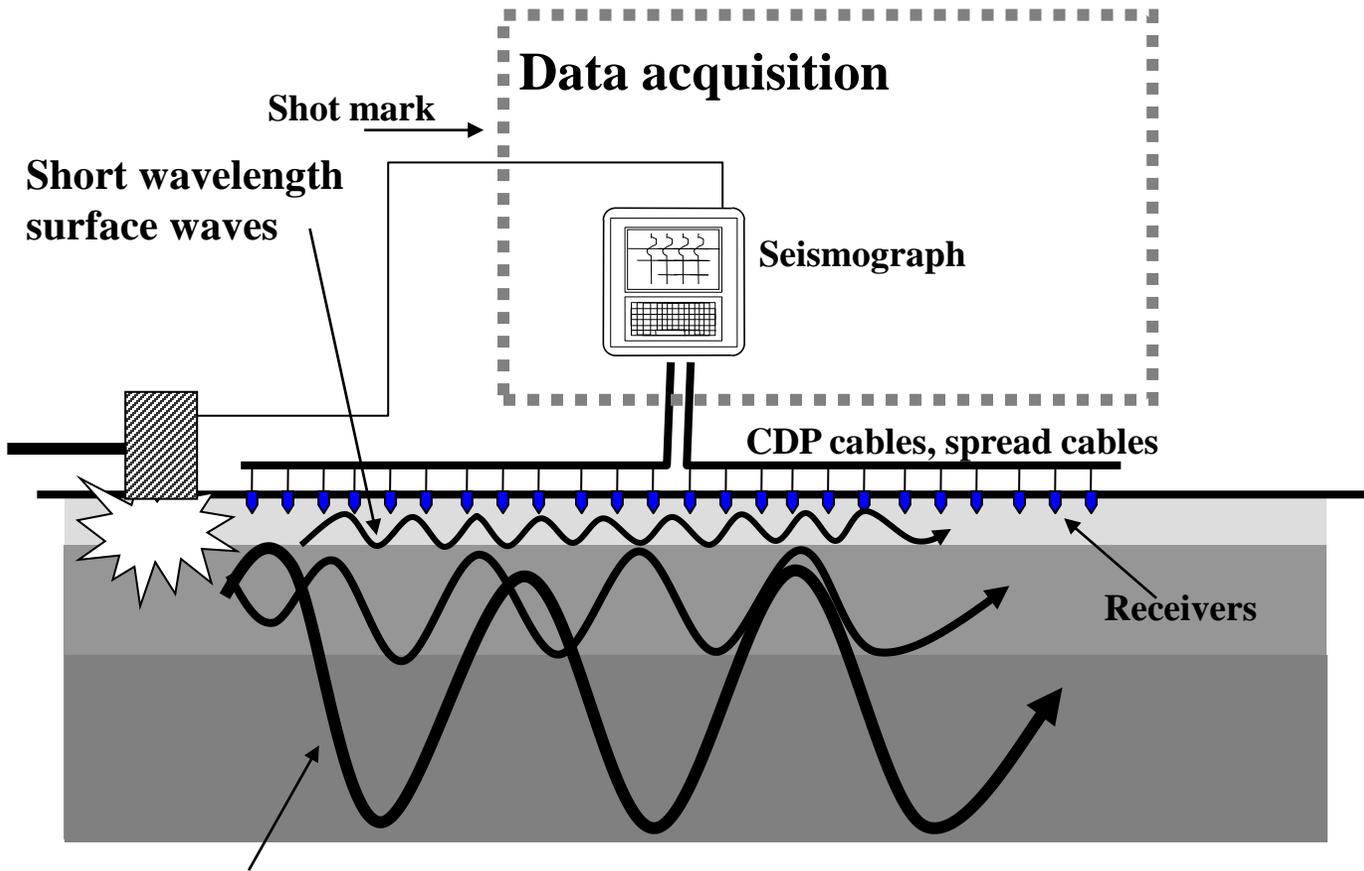
From 1D to 2D and 3D !

- 1D active surface wave method
- 2D active surface wave method
- Common Midpoint Cross-correlation (CMP-CC) analysis
- 3D passive surface wave method and Common Midpoint Spatial Autocorrelation (CMP-SPAC) analysis

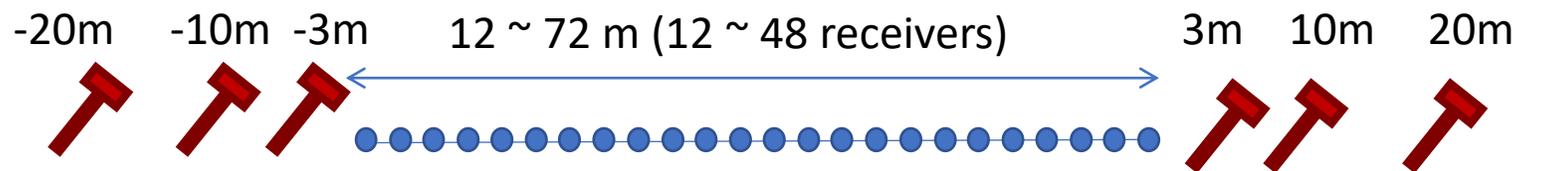
5. CMPCC and CMPSPAC

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1D active data acquisition



Long wavelength surface wave



Data example

Typical setting:

Sampling rate : 1msec

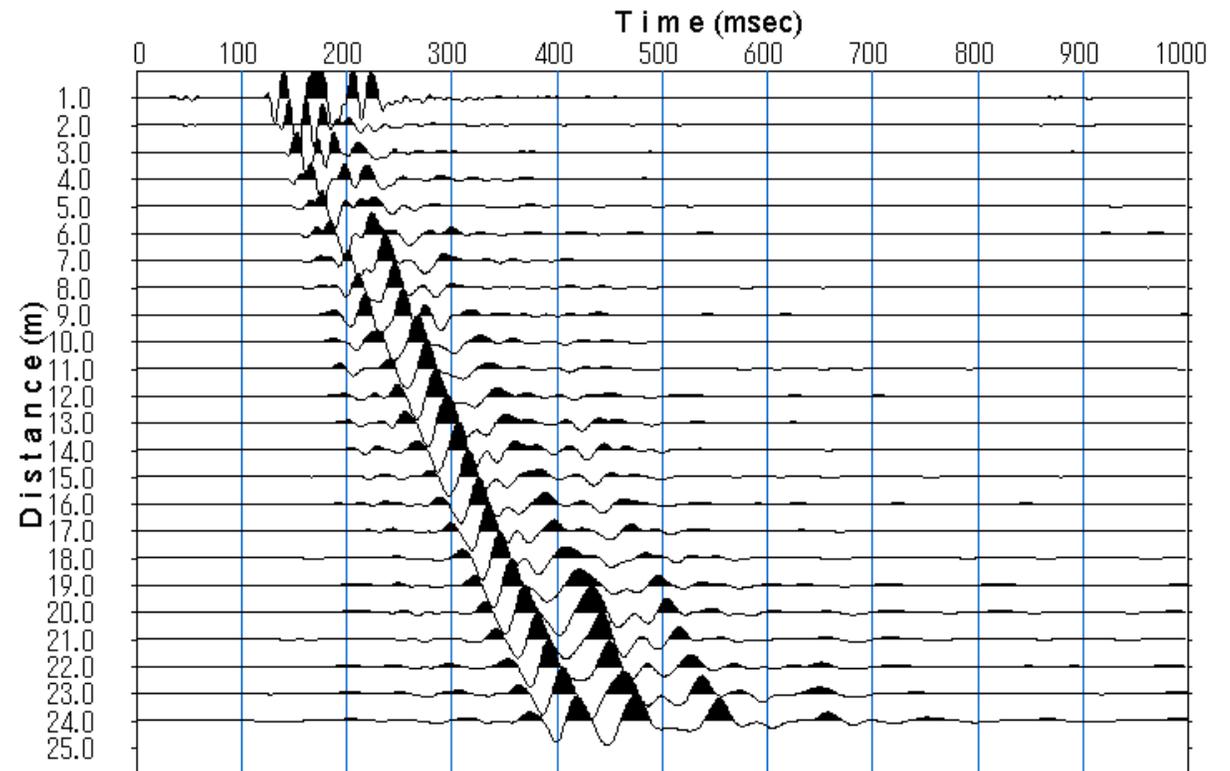
Data length : 2048 (2.048 sec)

Receiver spacing : 1 ~ 3 m

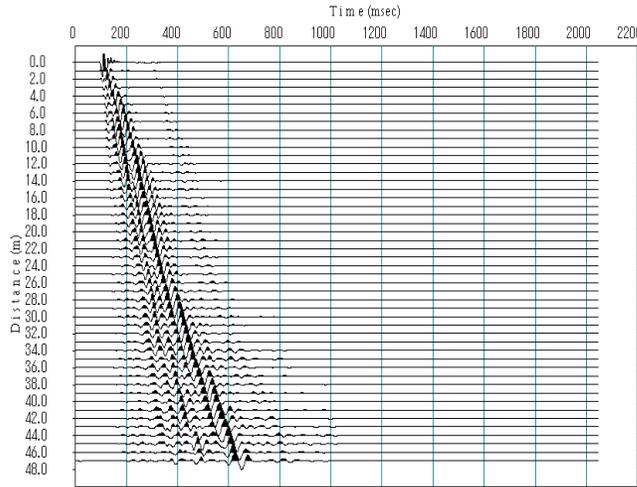
Number of receiver : 12 ~48

Spread length : 24 ~ 72 m

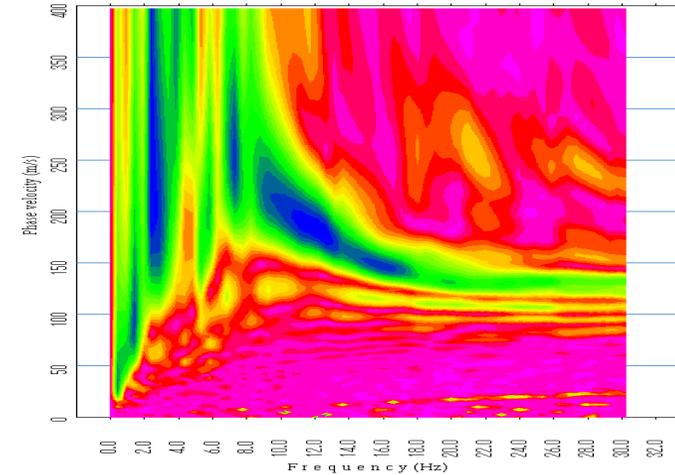
Do not saturate !
Keep all waveforms !



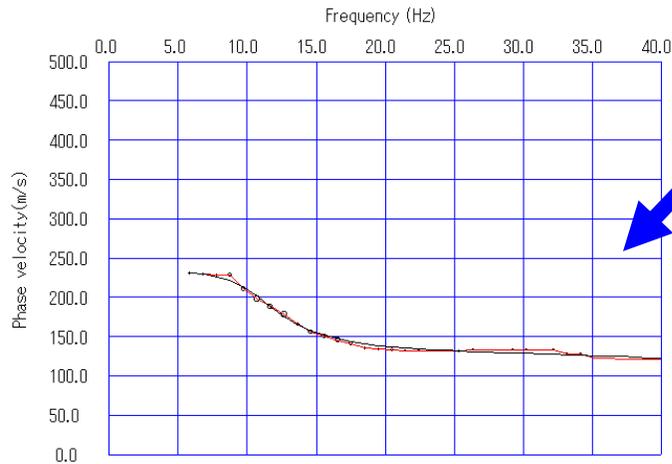
Dispersion curve and its analysis



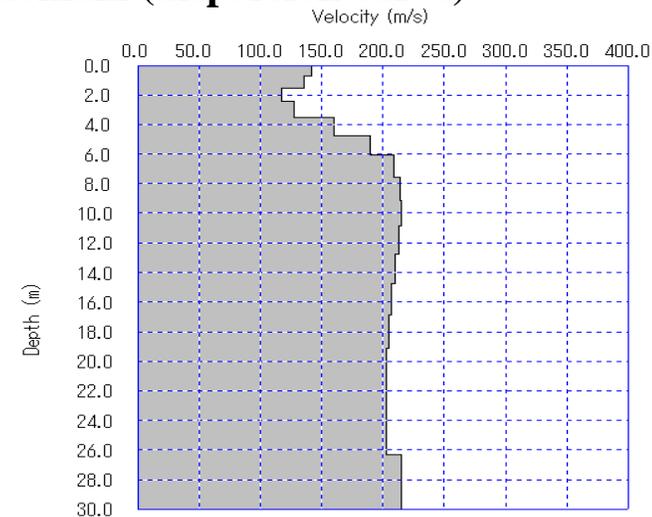
Common shot gather



Phase-velocity image in frequency domain (dispersion curve)

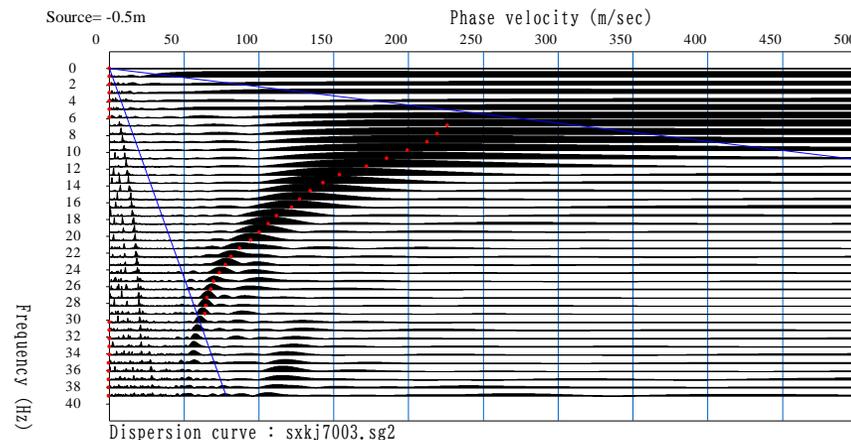
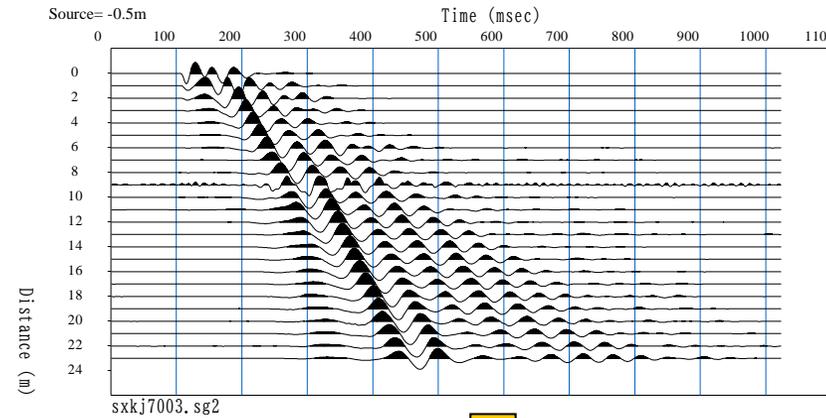


Dispersion curve inversion



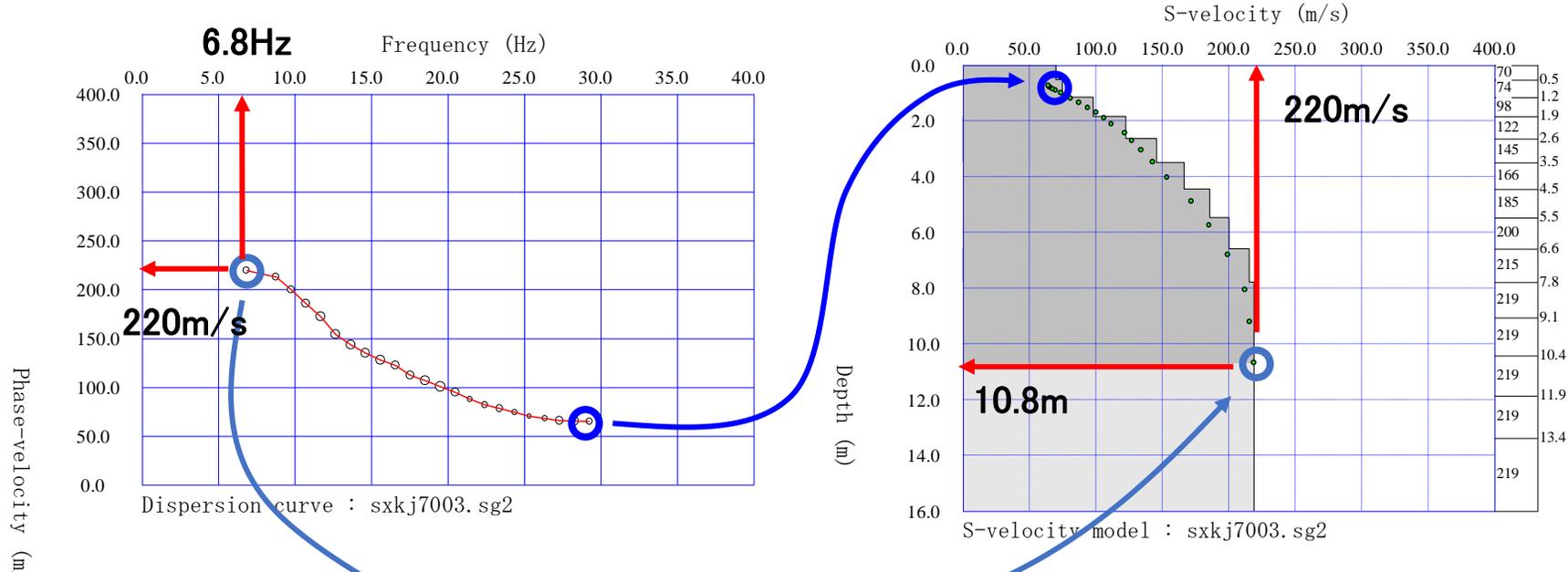
1D S-wave velocity model

Estimating an initial velocity model in terms of 1/3 wave-length theory



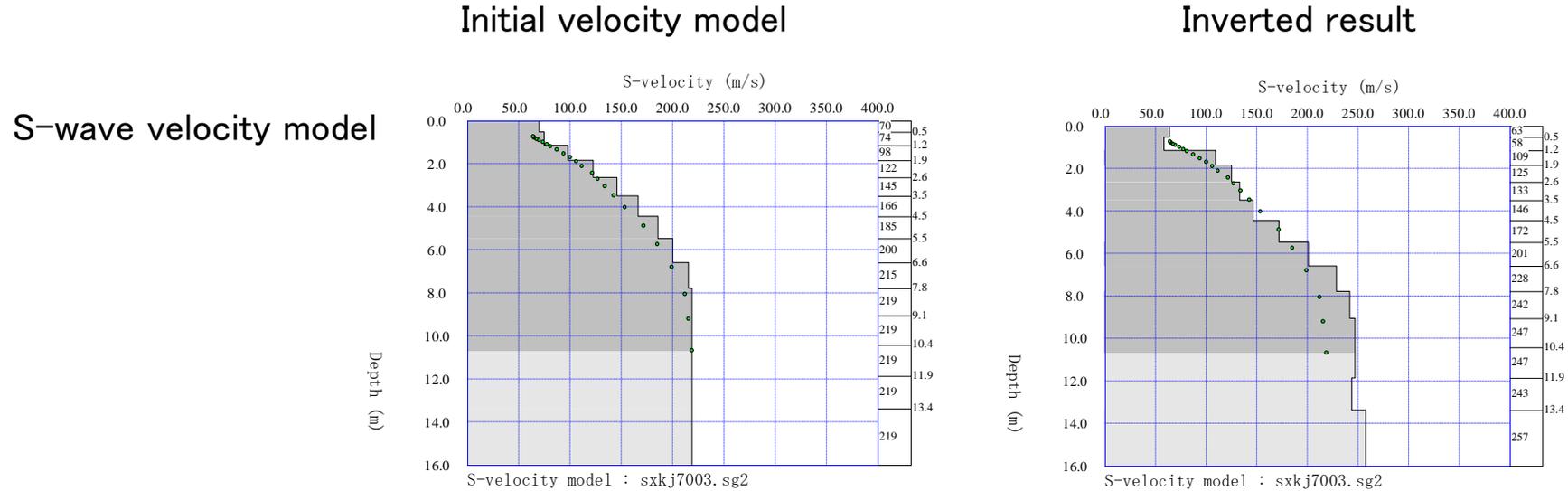
Estimating an initial velocity model in terms of 1/3 wave-length theory

$$\text{Depth} = \text{Phase-velocity} / \text{Frequency} / 3$$

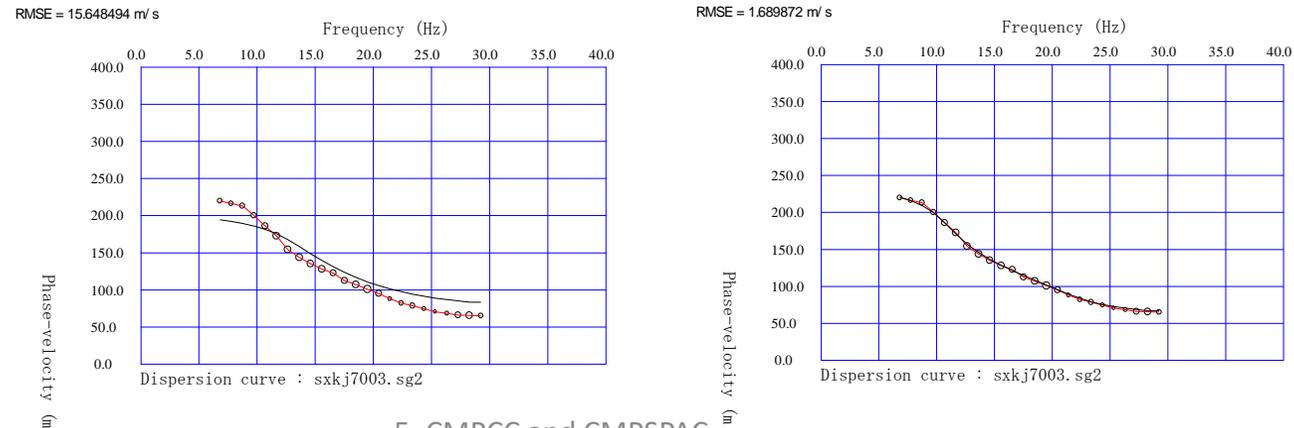


$$\text{Depth} = 10.8 = 220 / 6.8 / 3 = \text{Phase-velocity} / \text{Frequency} / 3$$

Estimating an initial velocity model in terms of 1/3 wave-length theory

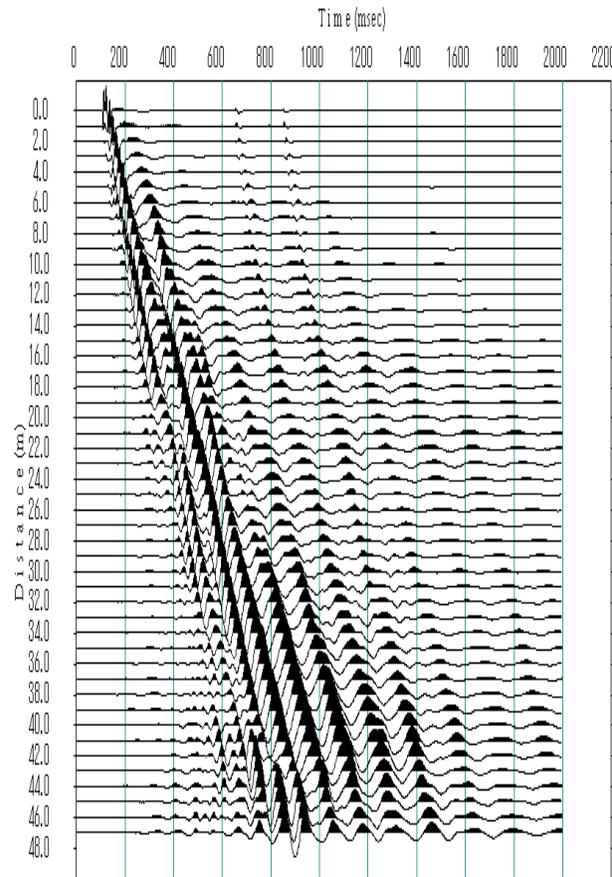


Comparison of theoretical and observed dispersion curves

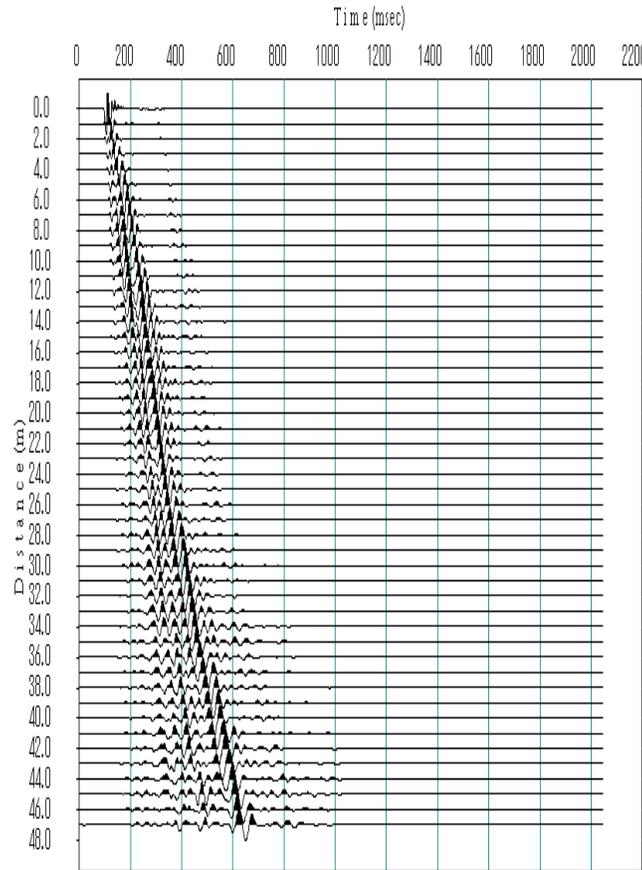


Comparison of the original waveforms

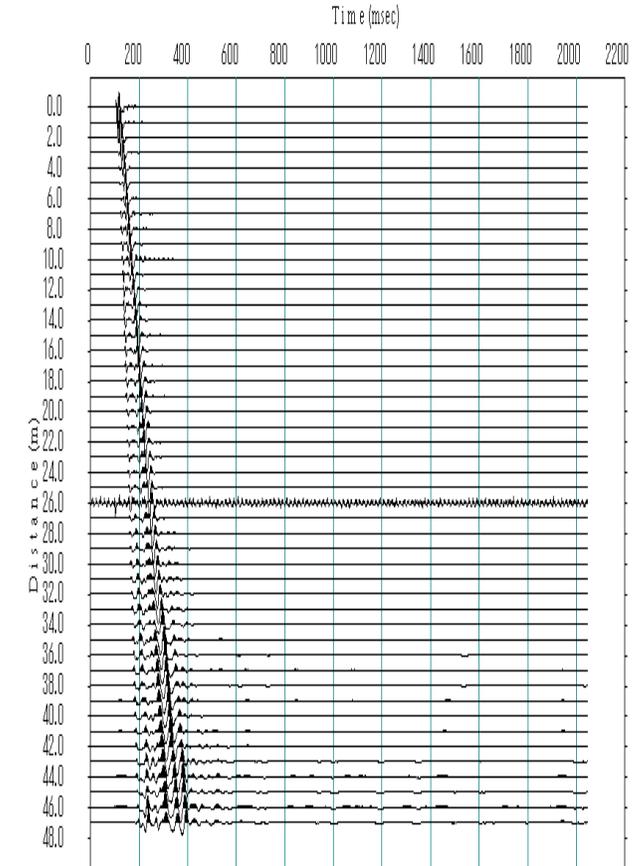
Alluvium
(soft)



Terrace
(middle)



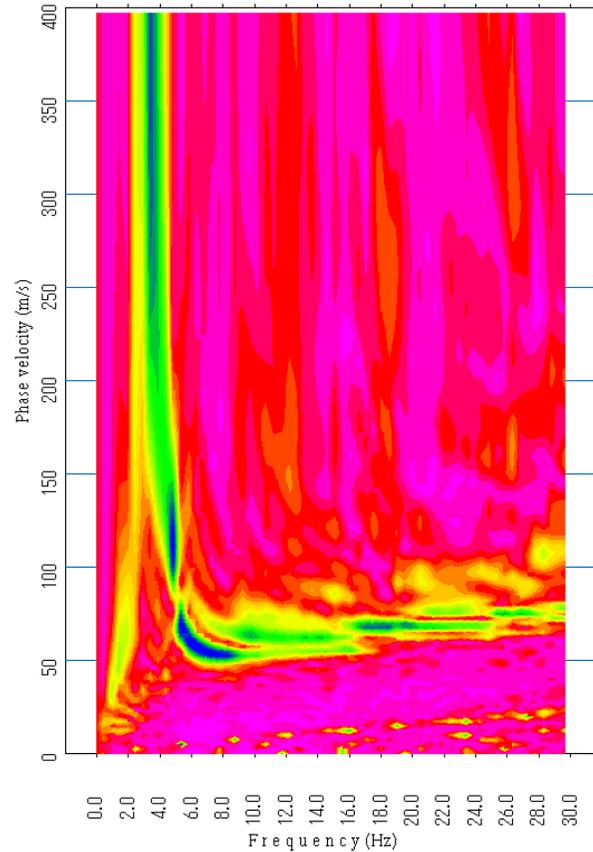
Compacted gravel
(stiff)



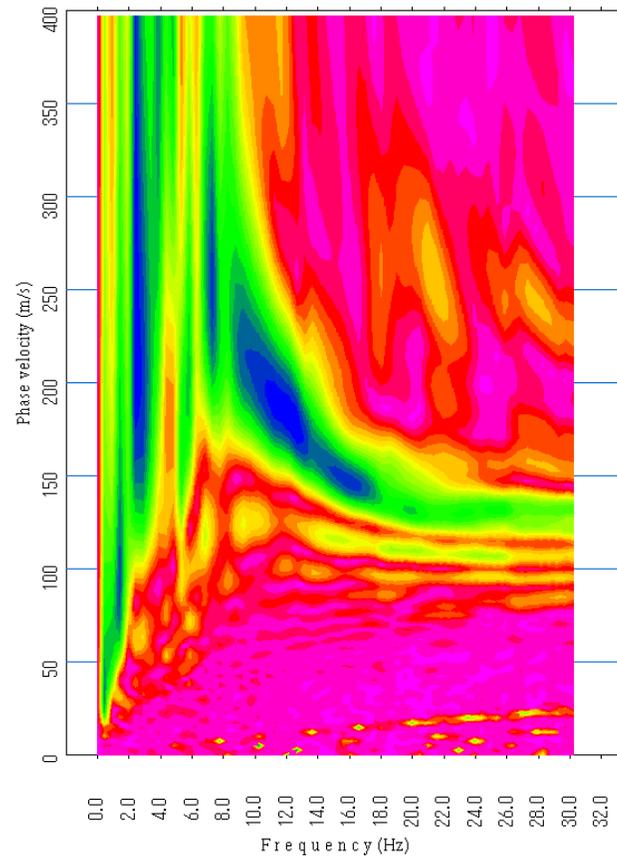
Source : Sledge hammer, Geophone : 4.5Hz, Receivers : 1m spacing x 48 points

Comparison of the dispersion curves

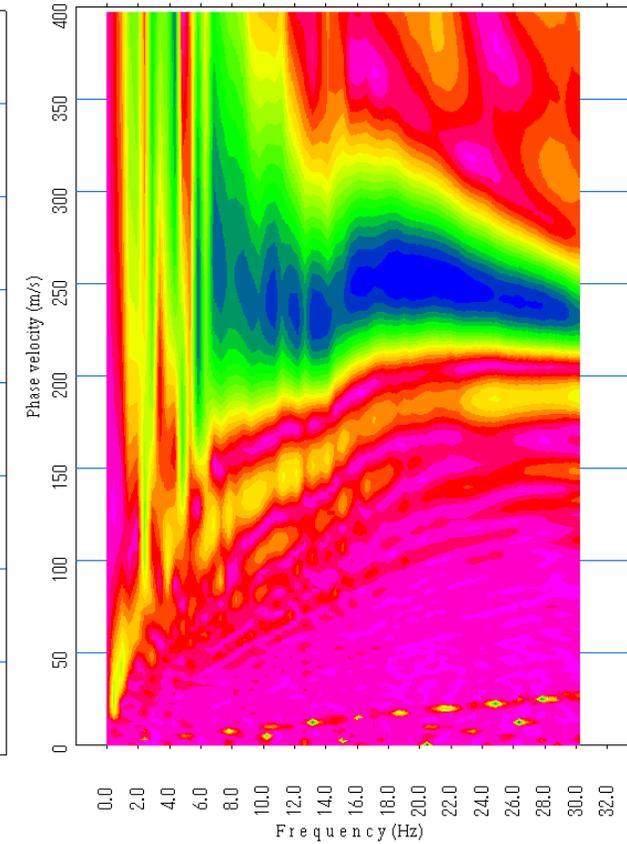
Alluvium
(soft)



Terrace
(middle)

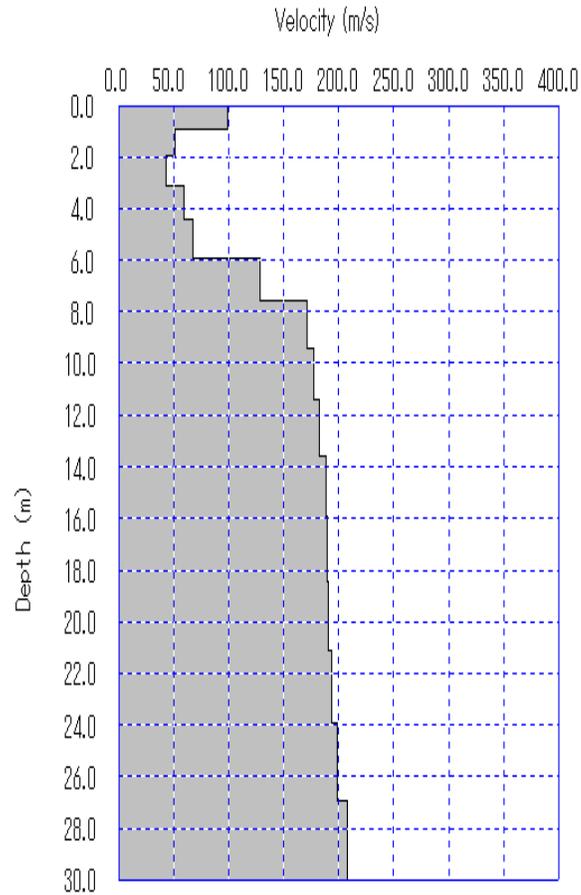


Compacted gravel
(stiff)

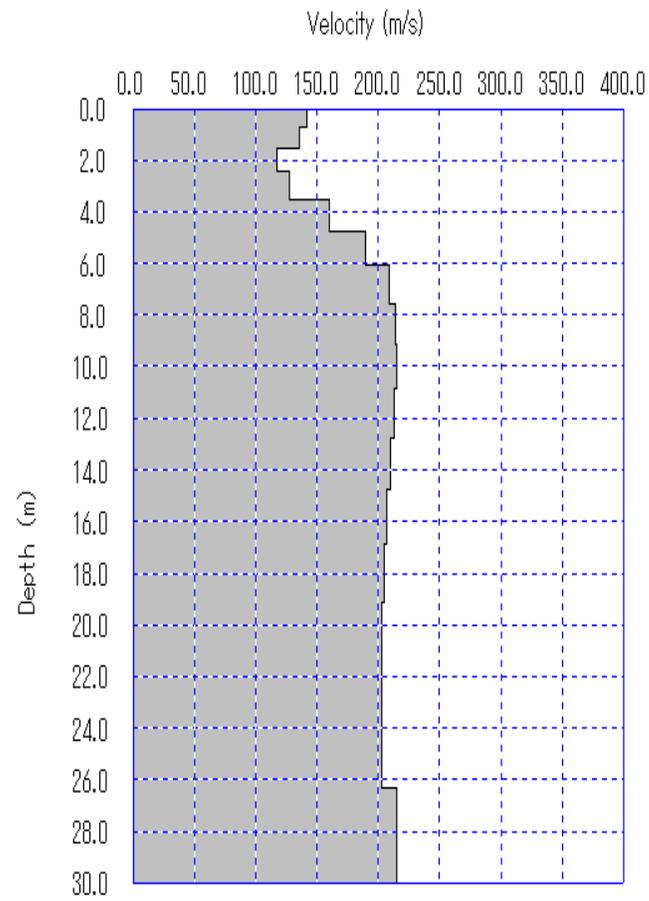


Comparison of the S-wave velocity structures

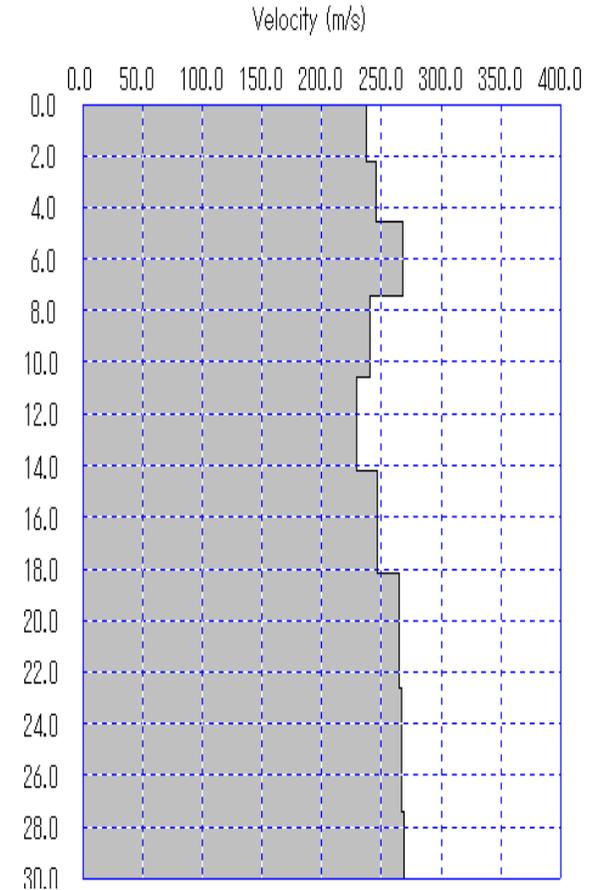
Alluvium
(soft)



Terrace
(middle)



Compacted gravel
(stiff)



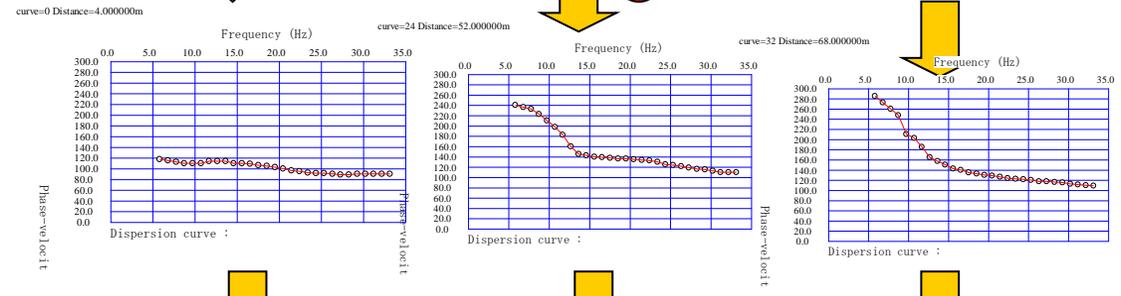
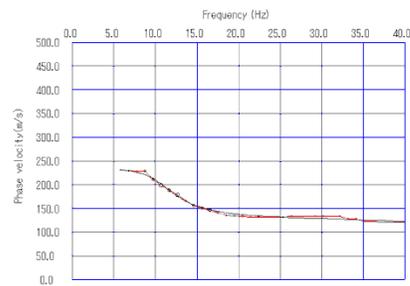
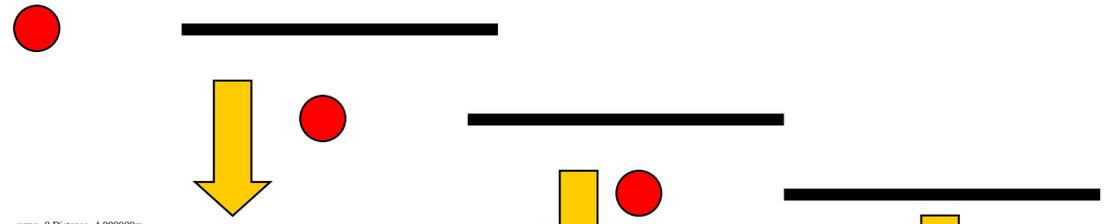
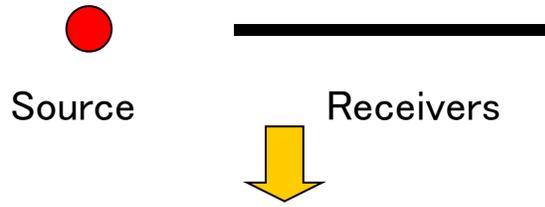
5. CMPCC and CMPSPAC

- 1D active surface wave method
- 2D active surface wave method
- Common Midpoint Cross-correlation (CMP-CC) analysis
- 3D passive surface wave method and Common Midpoint Spatial Autocorrelation (CMP-SPAC) analysis

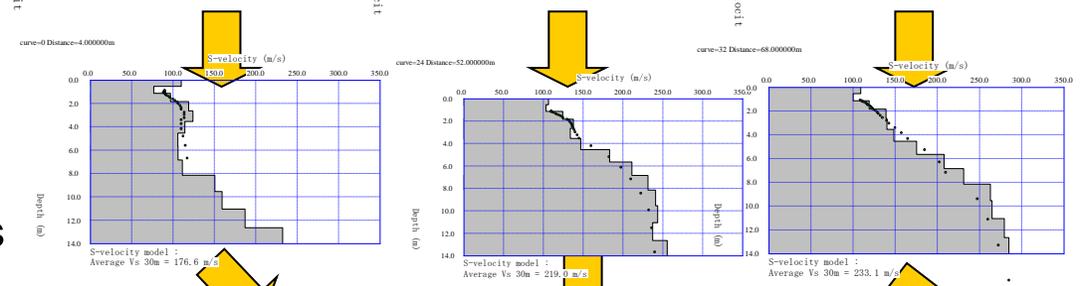
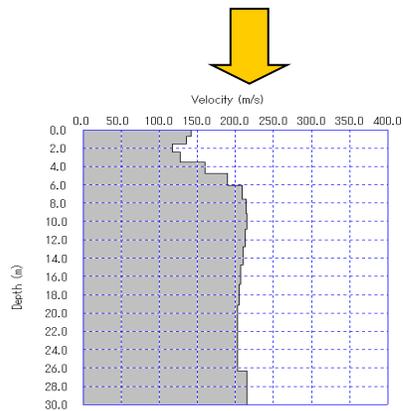
2D active data acquisition

1D survey

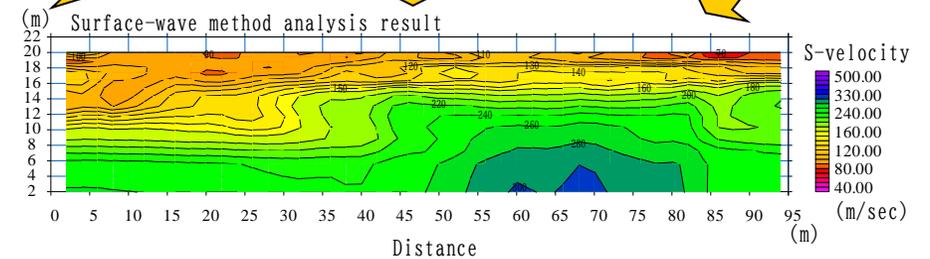
2D survey



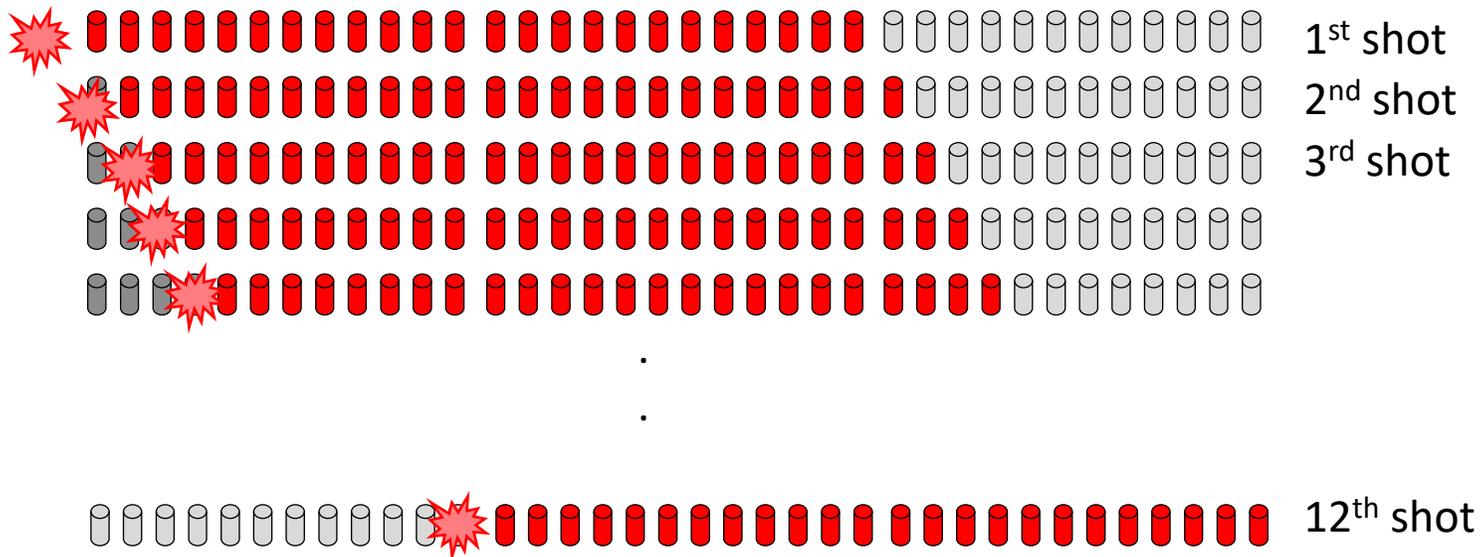
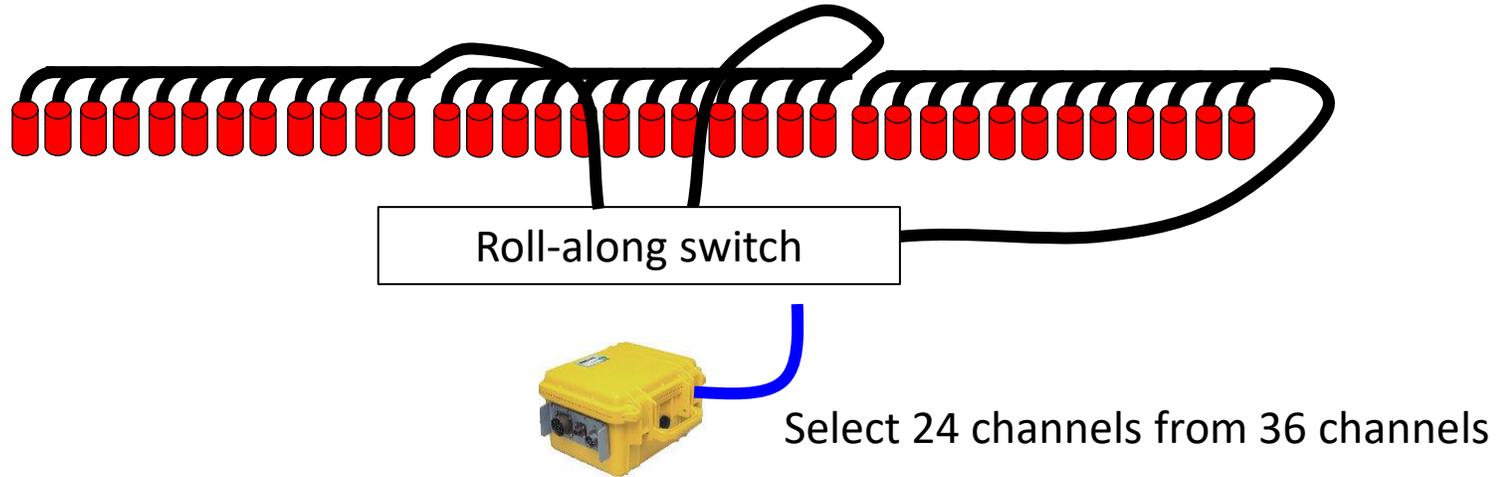
Dispersion curves



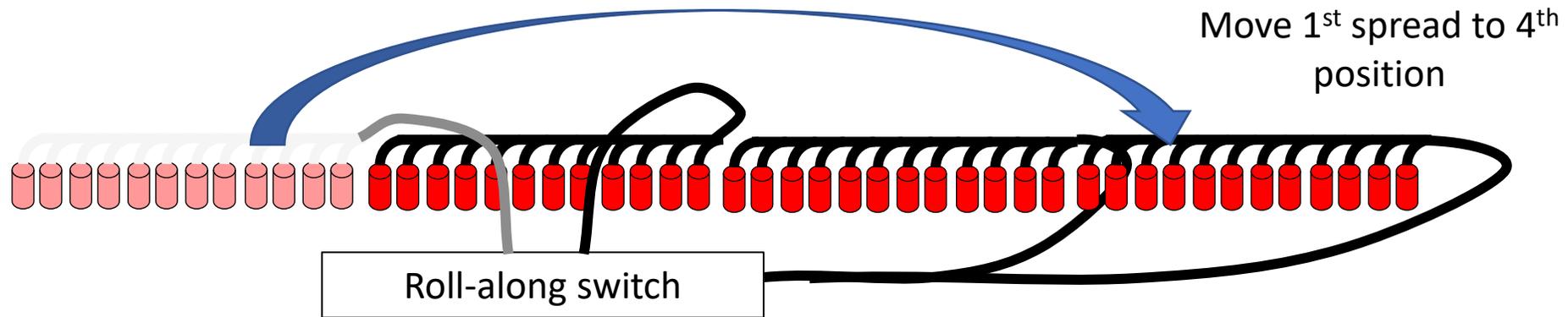
S-wave velocity profiles



2D active surface wave methods using a roll-along switch (1)



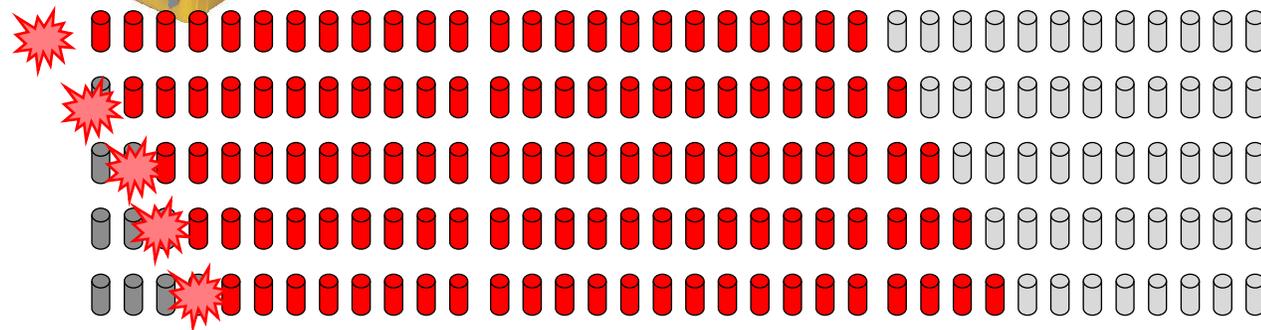
2D active surface wave methods using a roll-along switch (2)



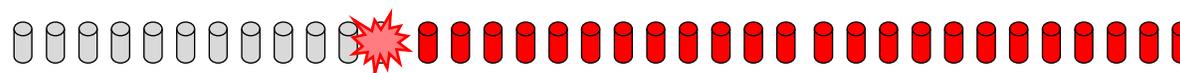
13th shot

14th shot

15th shot

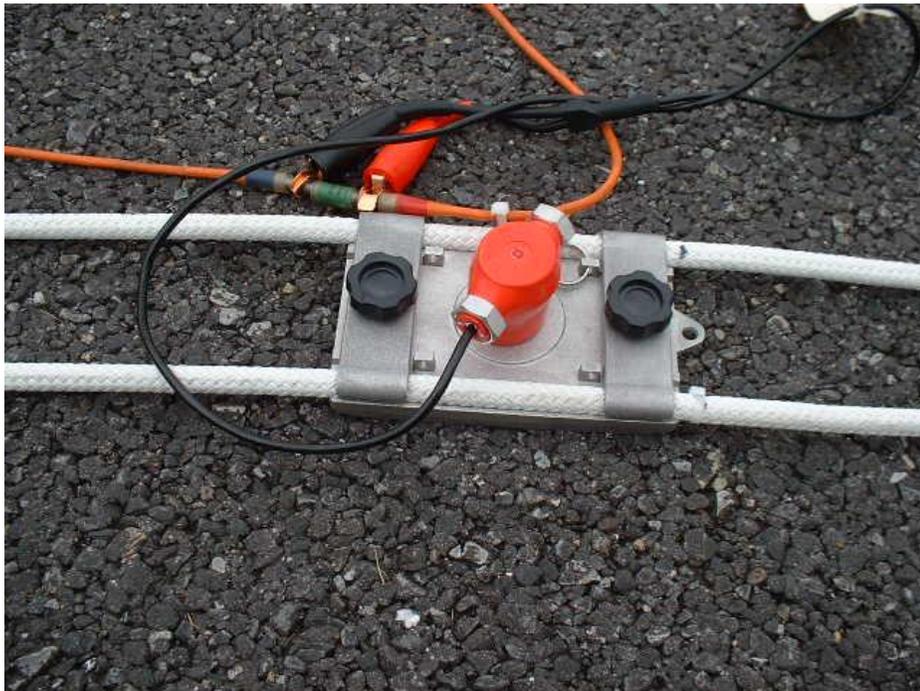


24th shot

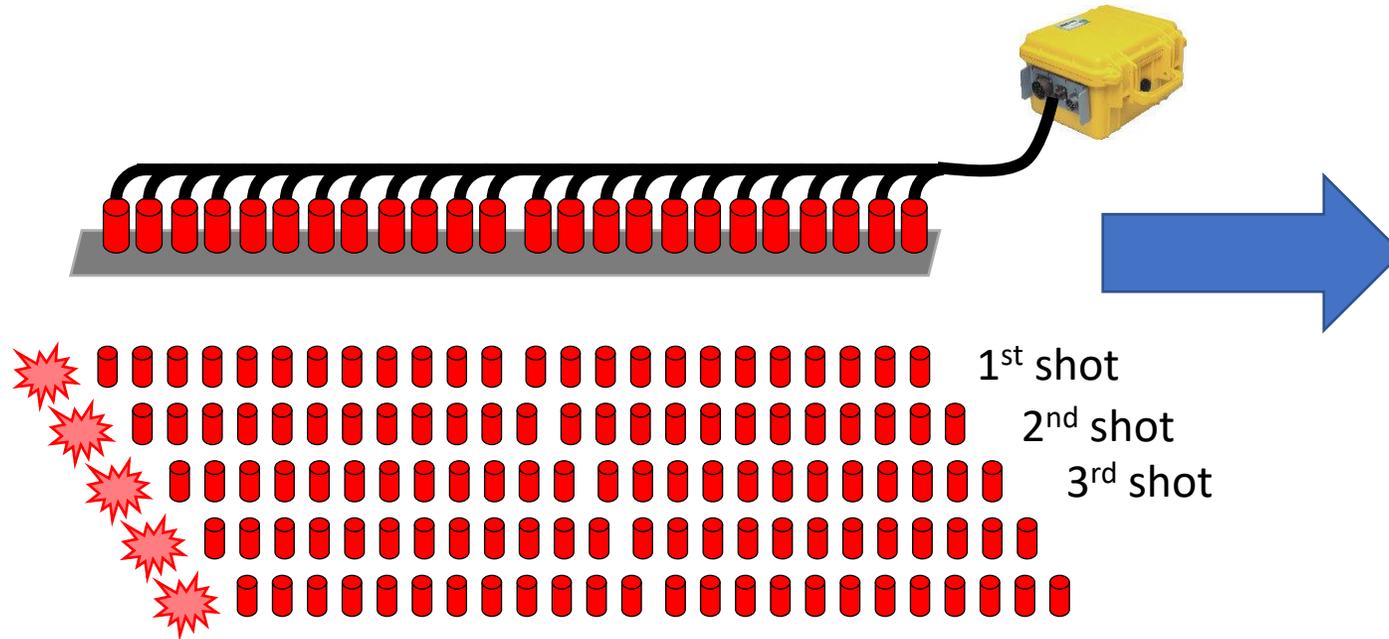


2D active surface wave methods using a land streamer

In the land streamer, the geophones are not stuck on ground surface and can be moved quickly.



2D active surface wave methods using a land streamer

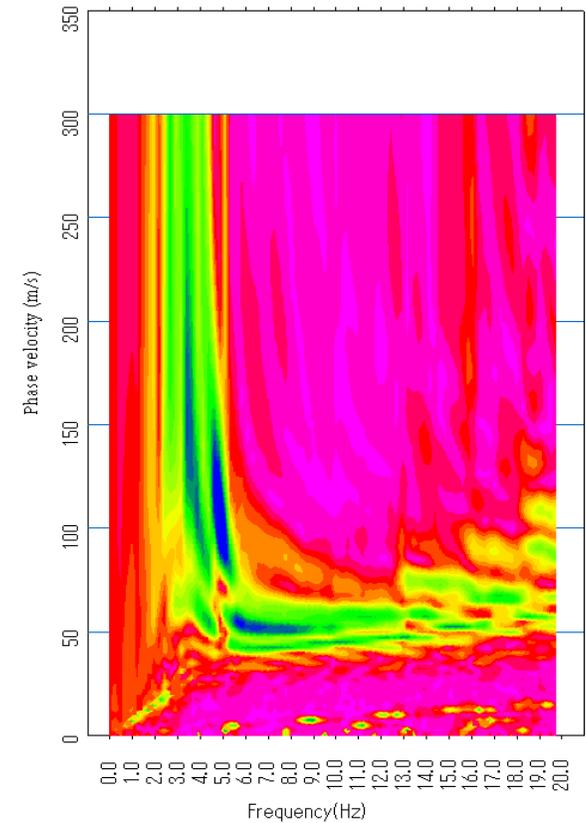
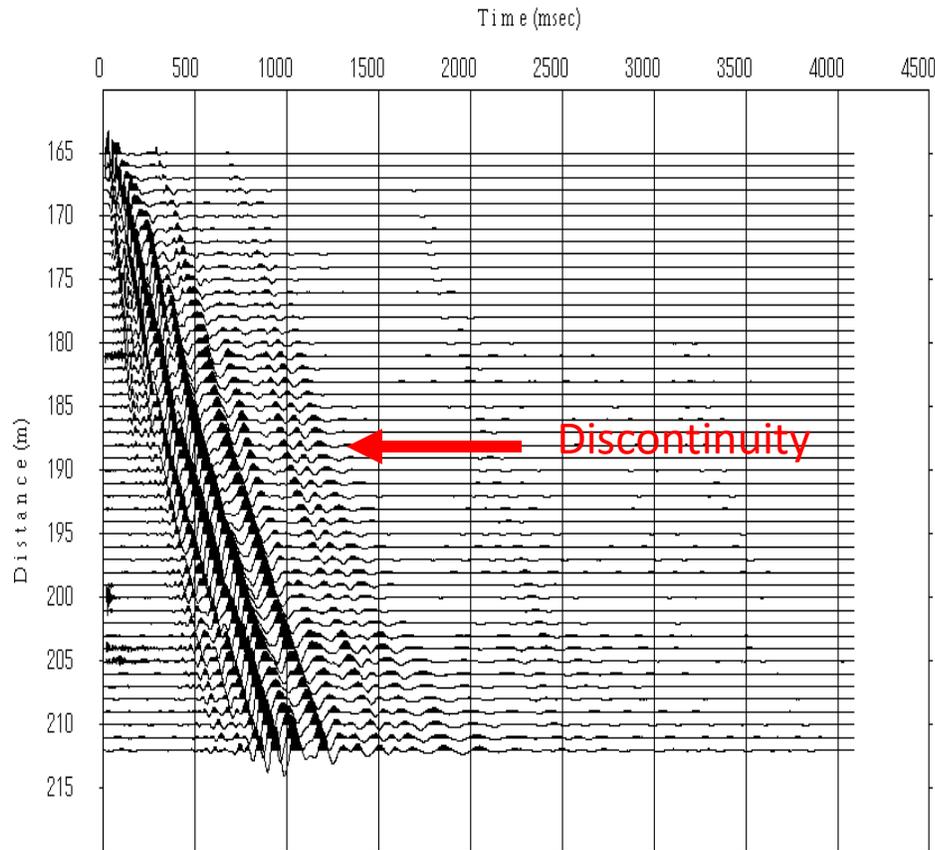


5. CMPCC and CMPSPAC

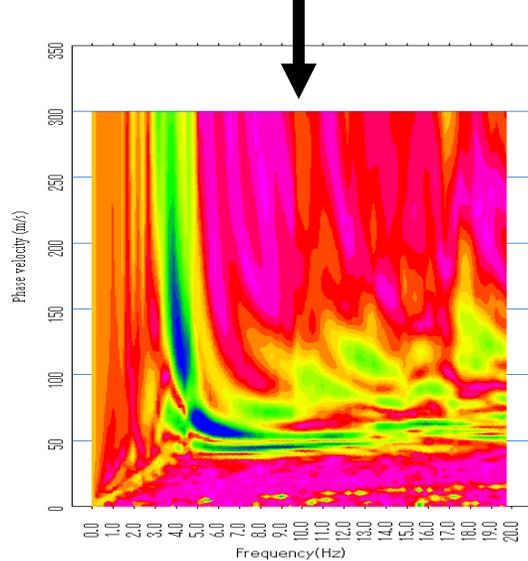
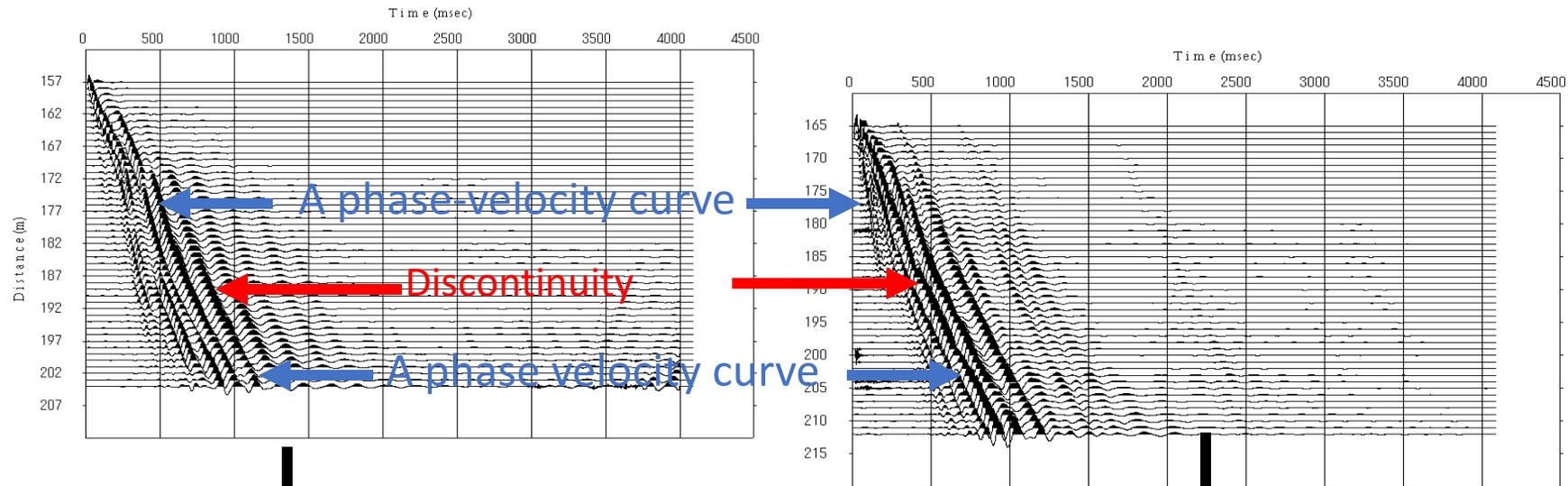
- 1D active surface wave method
- 2D active surface wave method
- **Common Midpoint Cross-correlation (CMP-CC) analysis**
- 3D passive surface wave method and Common Midpoint Spatial Autocorrelation (CMP-SPAC) analysis

Problem in conventional 2D processing

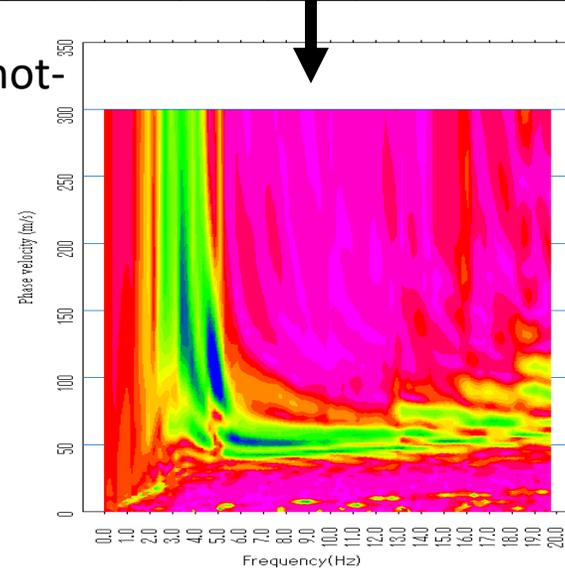
Phase-velocity curves cannot be determined correctly if the velocity structure changes horizontal direction in a shot gather



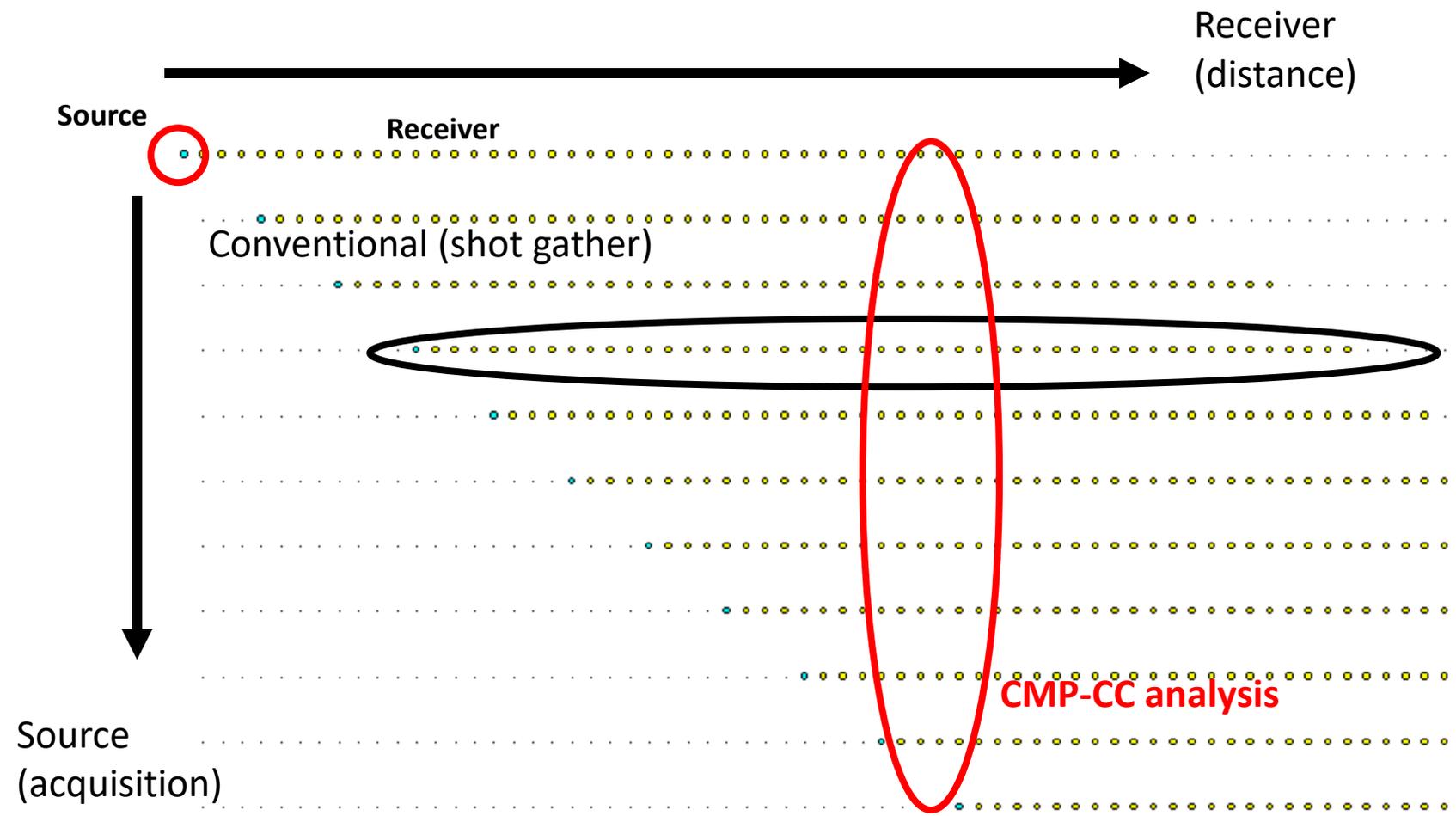
Calculating a phase-velocity curve from multi-shot gathers



A phase-velocity image calculated from each shot-gather



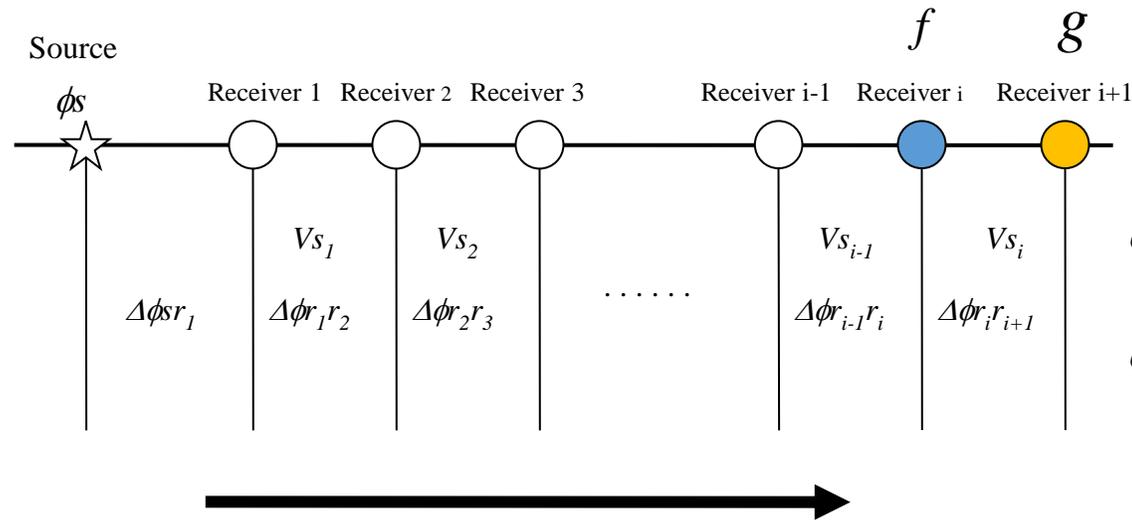
Concept of Common Midpoint Cross-correlation (CMP-CC)



Comparison between reflection and 2D active surface-wave method

	Single channel	Shot gather	CDP gather
Reflection			
	Conventional method (SASW)	Multi-channel analysis (MASW)	CMP-CC analysis
Surface-wave method			

Concept of CMP-CC analysis



Surface waves travel with horizontal direction

$$\phi_f(\omega) = \phi_s(\omega) + \Delta\phi_{sr_1}(\omega) + \Delta\phi_{r_1r_2}(\omega) + \Delta\phi_{r_2r_3}(\omega) + \dots + \Delta\phi_{r_{i-1}r_i}(\omega)$$

$$\phi_g(\omega) = \phi_s(\omega) + \Delta\phi_{sr_1}(\omega) + \Delta\phi_{r_1r_2}(\omega) + \Delta\phi_{r_2r_3}(\omega) + \dots + \Delta\phi_{r_{i-1}r_i}(\omega) + \Delta\phi_{r_i r_{i+1}}(\omega)$$

ϕ_s : Phase associated with source wavelet.

$\Delta\phi_{sr_1}$: Phase difference between source and receiver 1.

$\Delta\phi_{r_1r_2}$: Phase difference between receiver 1 and 2.

$\Delta\phi_{r_2r_3}$: Phase difference between receiver 2 and 3.

$\Delta\phi_{r_{i-1}r_i}$: Phase difference between receiver i-1 and i.

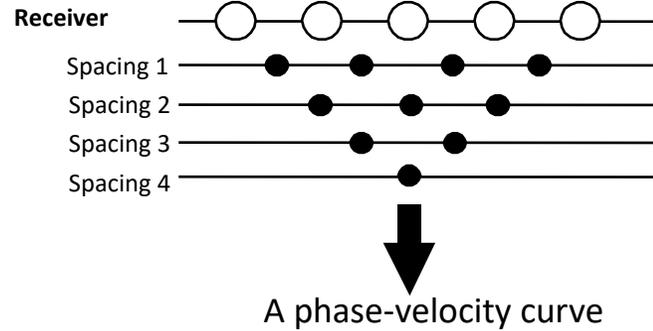
$\Delta\phi_{r_i r_{i+1}}$: Phase difference between receiver i and i+1.

$$\Delta\phi_{fg}(\omega) = \phi_g(\omega) - \phi_f(\omega) = \Delta\phi_{r_i r_{i+1}}(\omega)$$

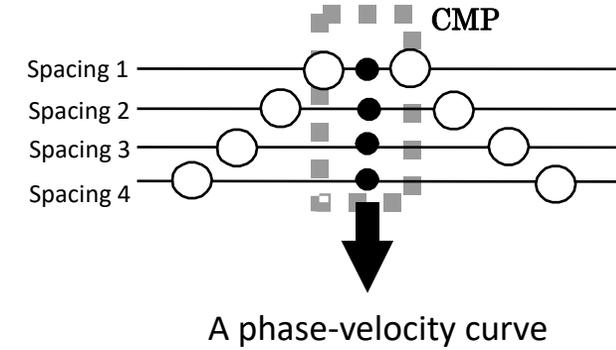
Concept of CMP-CC analysis

●:Center of cross-correlation ○:Receivers

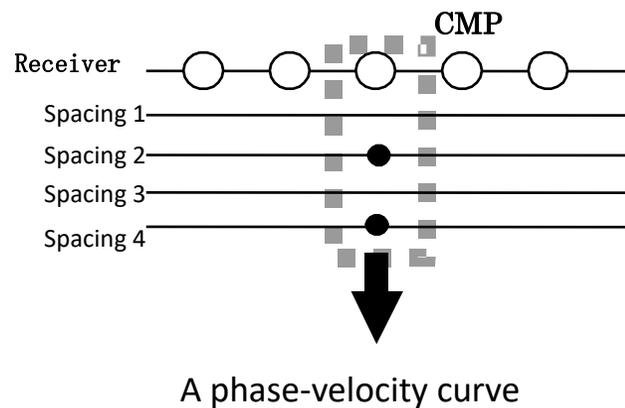
a) Conventional multi-channel analysis



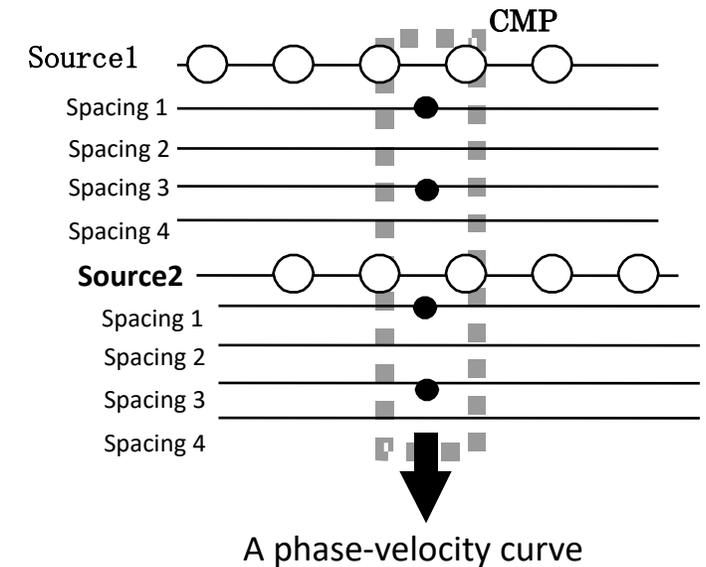
b) Ideal CMP analysis



c) CMP cross-correlations from one shot gather



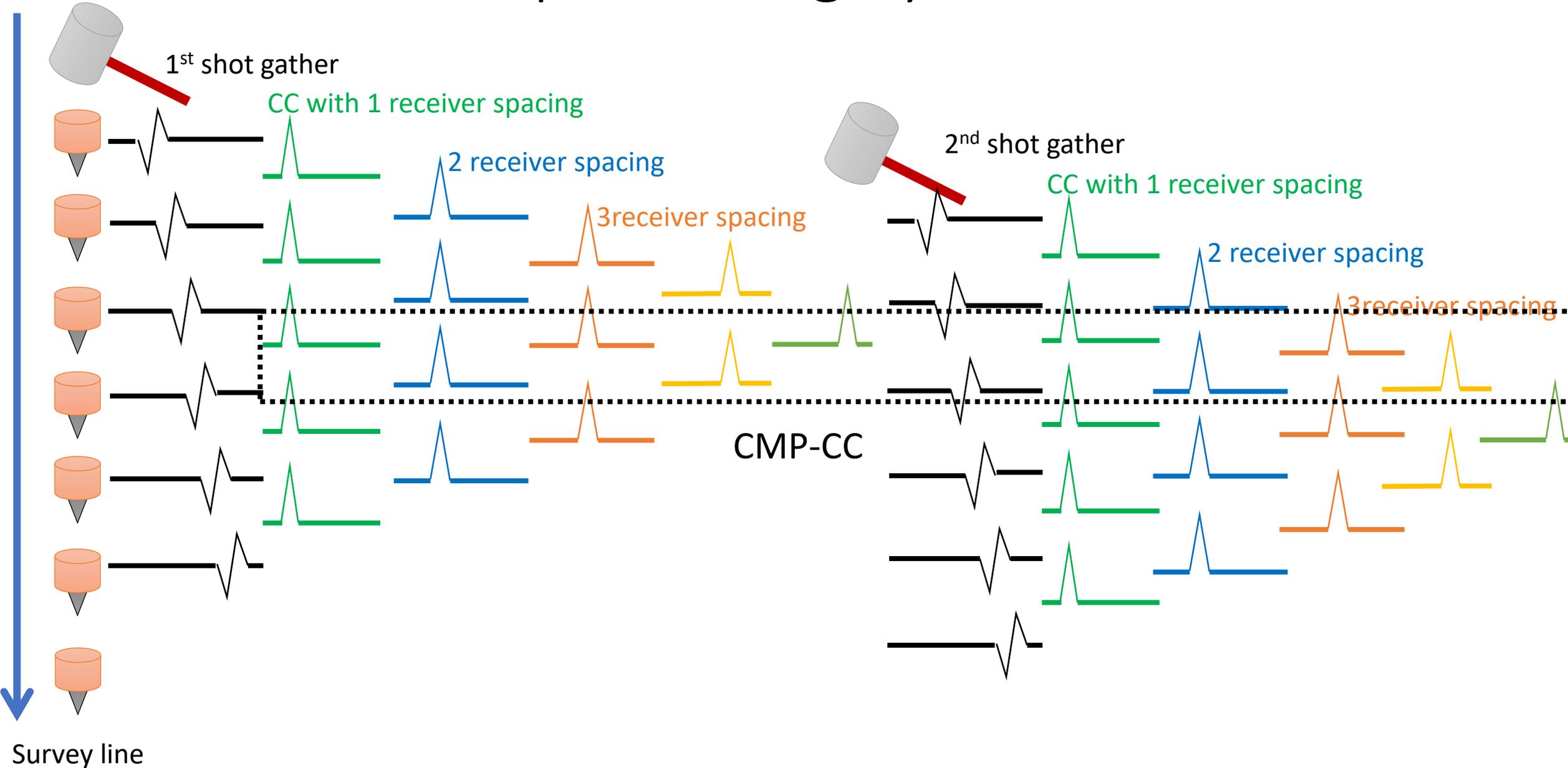
d) CMP cross correlations from multi-shot gathers



Calculating a phase-velocity curve from multi-shot gathers

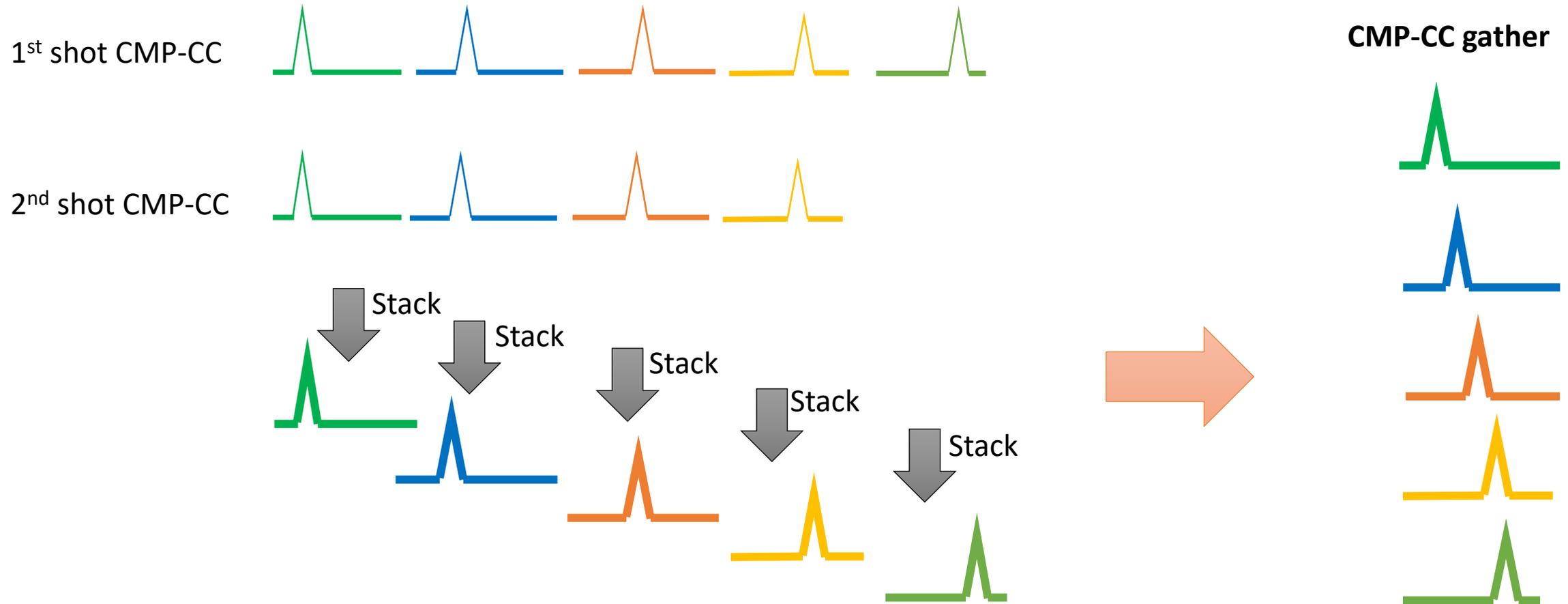
- Stacking on time-domain
⇒ × (cannot remove phase-difference between shots)
- Stacking as phase-differences
⇒ × (cannot remove phase wraparound or spatial aliasing)
- Stacking as cross-correlation
⇒ ○

2D active data processing by CMP-CC

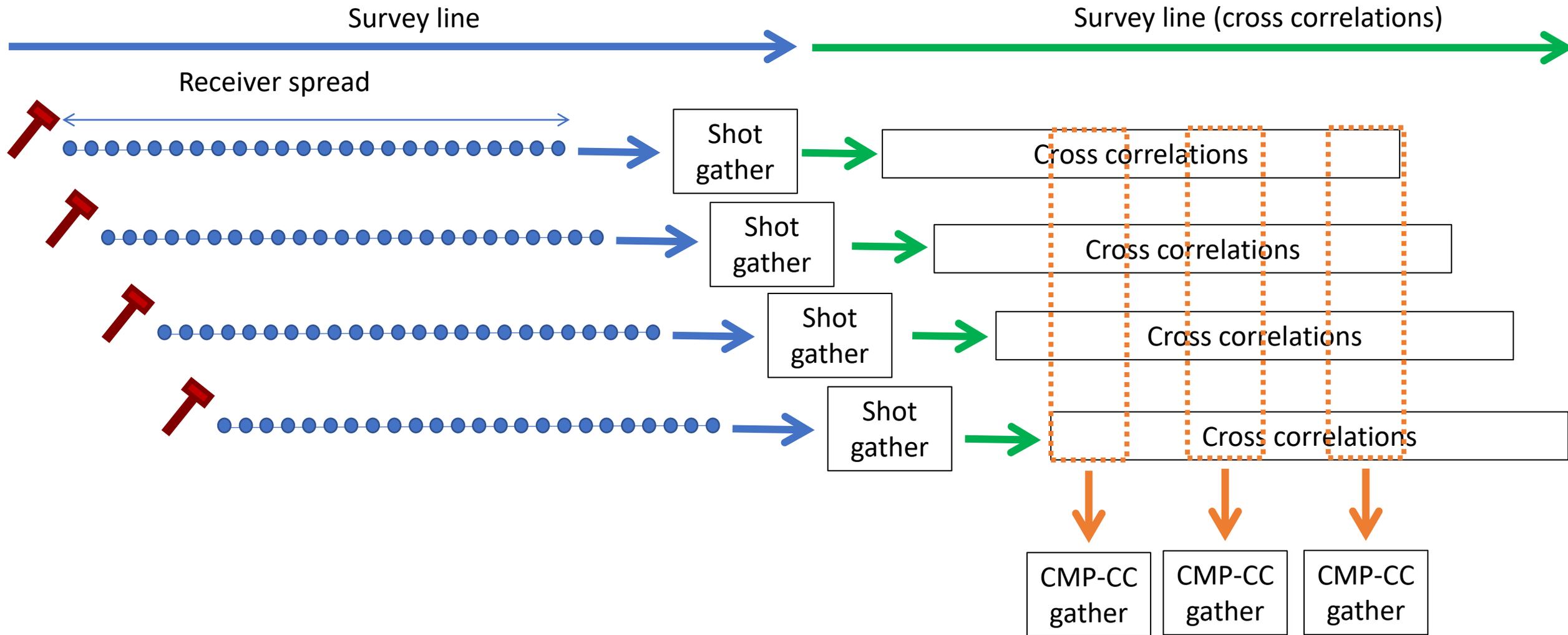


2D active data processing by CMP-CC

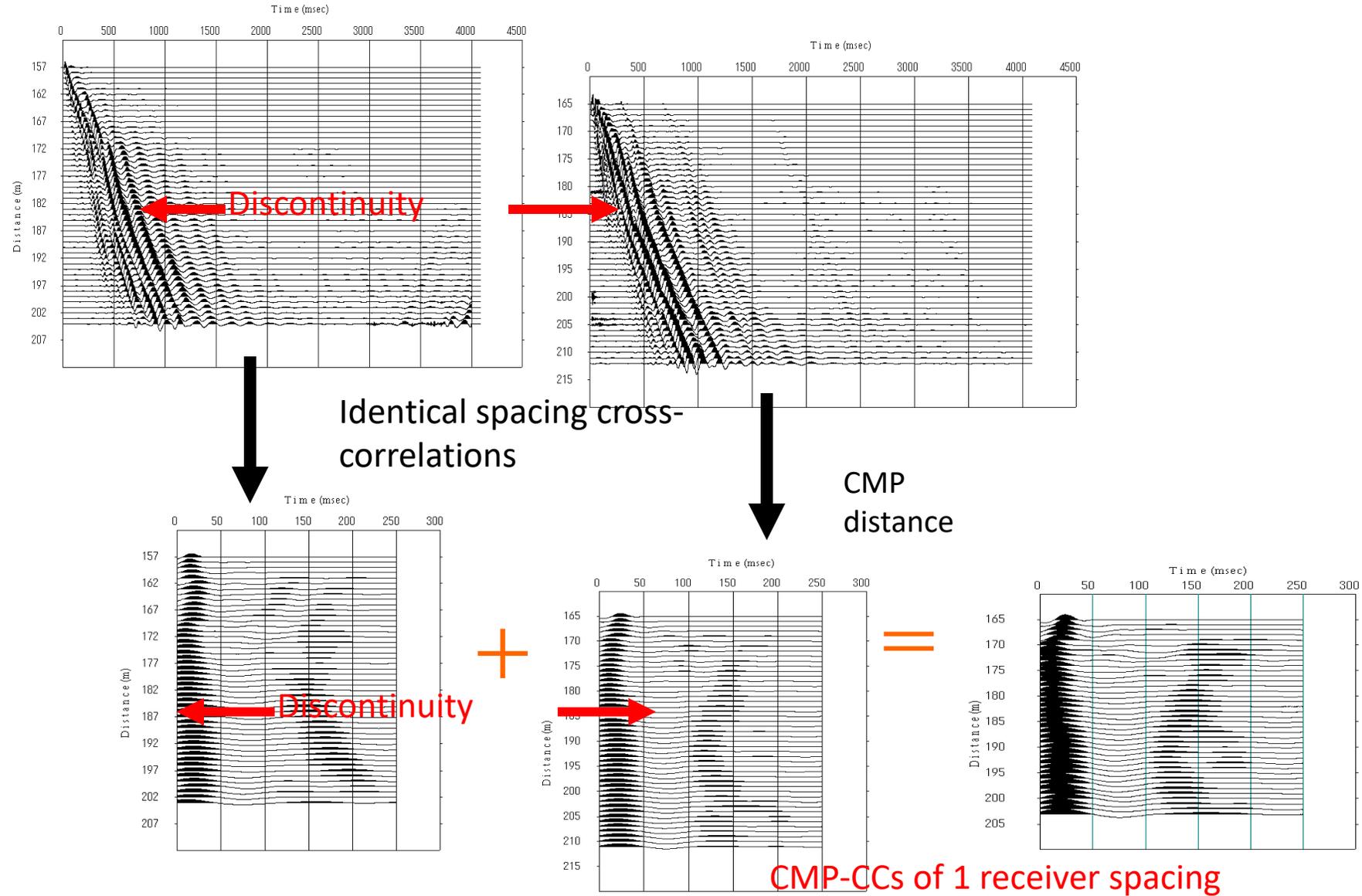
CC with 1 receiver spacing 2 receiver spacing 3 receiver spacing



2D active data processing by CMP-CC

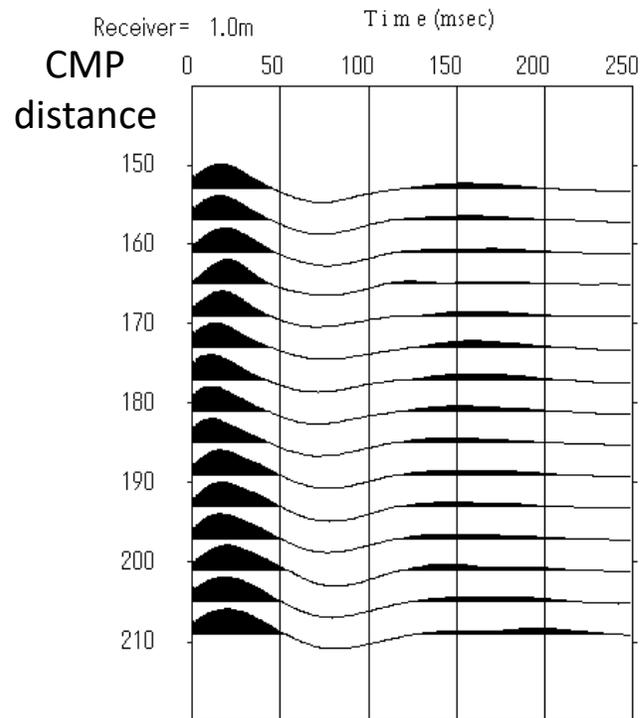


Real data example

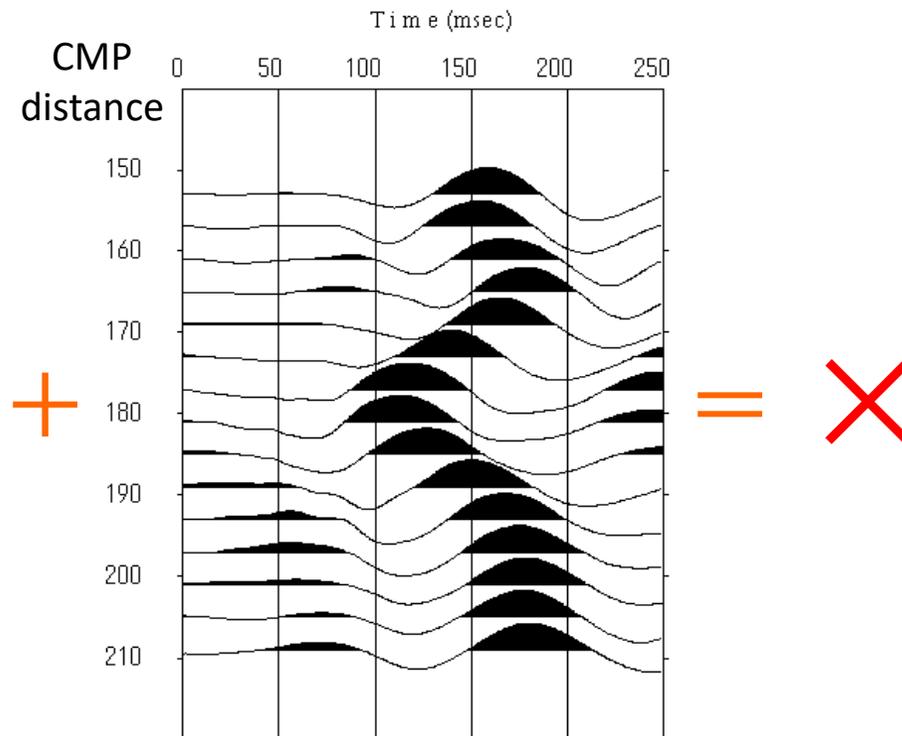


Calculating a phase-velocity curve from different spacing cross-correlations

1m spacing CMP cross-correlations

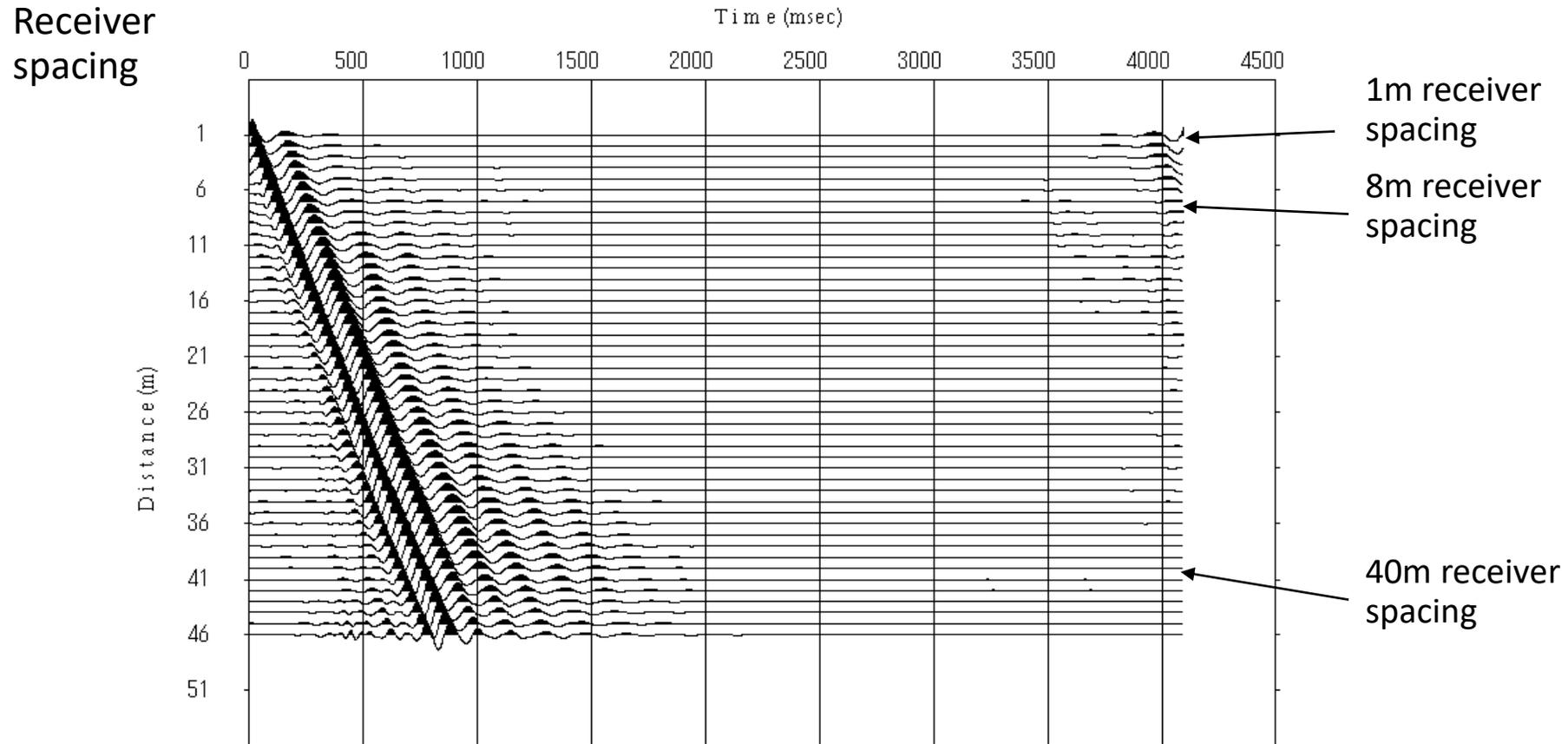


8m spacing CMP cross-correlations



Try to order with respect to their receiver spacing!

CMP cross-correlations ordered with respect to receiver spacing

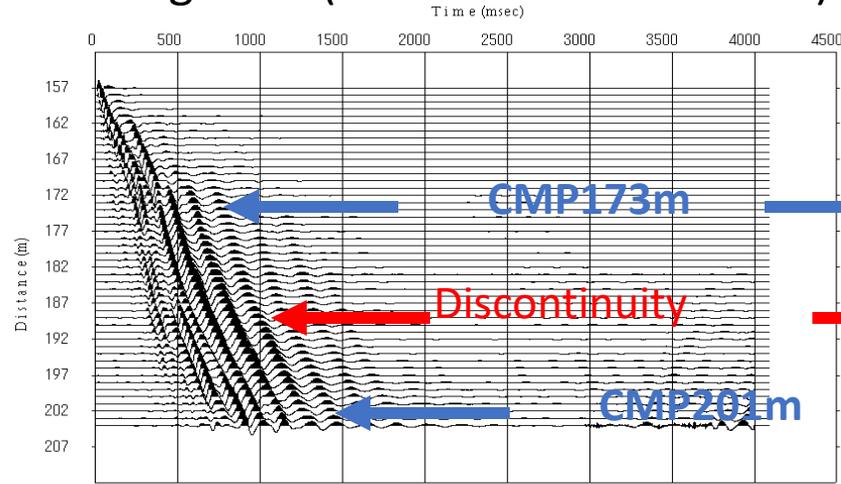


CMP Cross-correlation Gather !

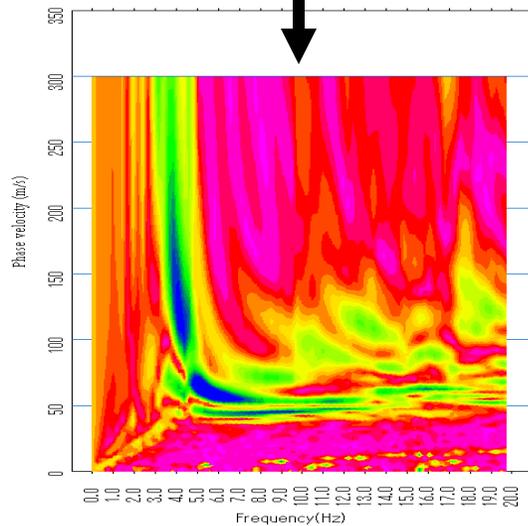
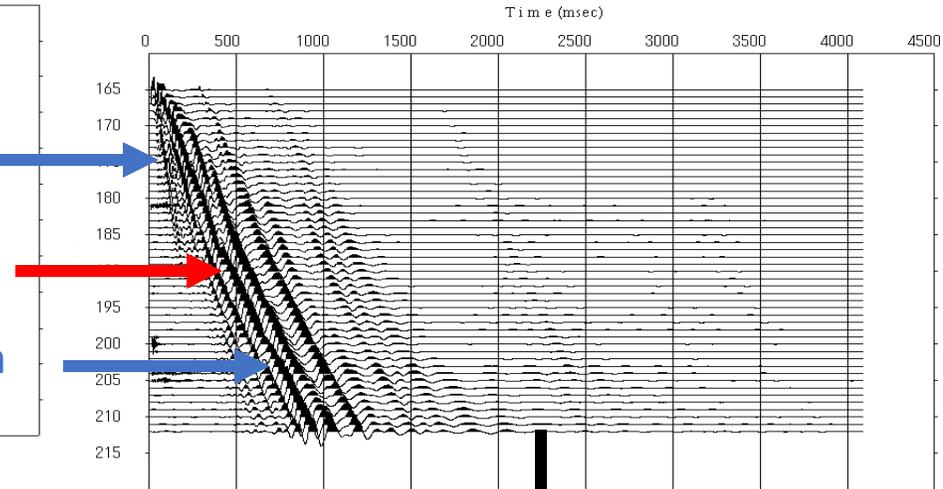
It can be considered as a pseudo-shot gather!
⇒ Multi-channel analysis can be applied

Example of CMP analysis

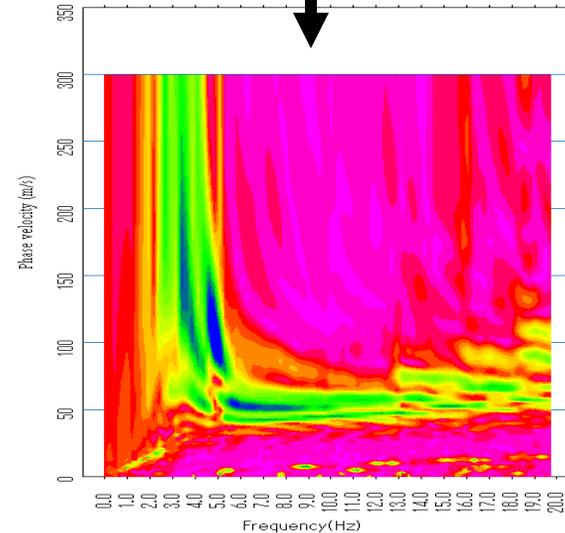
A shot gather (shot distance of 156m)



A shot gather (shot distance of 164m)

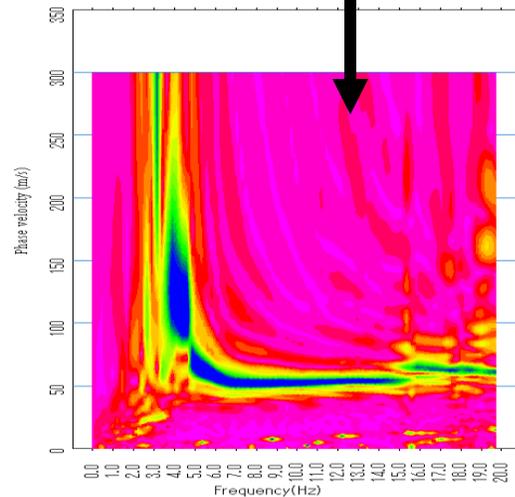
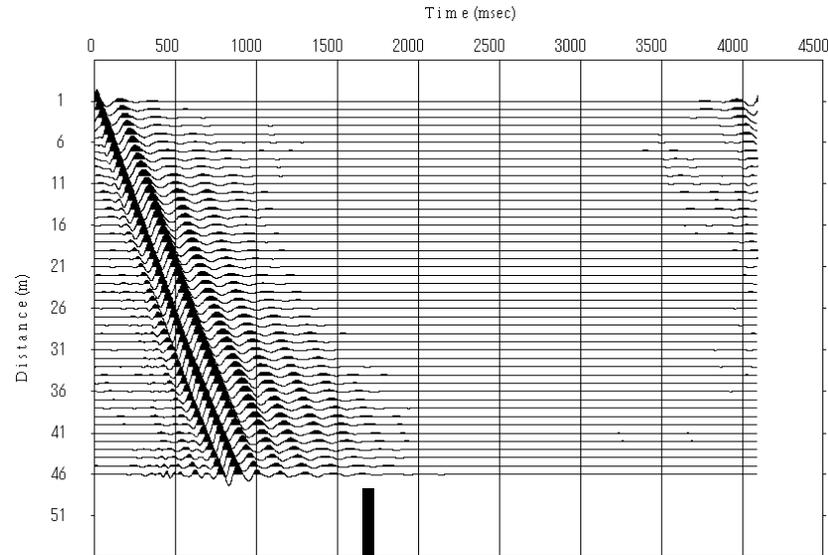


Phase-velocity imaged
calculated from shot
gathers



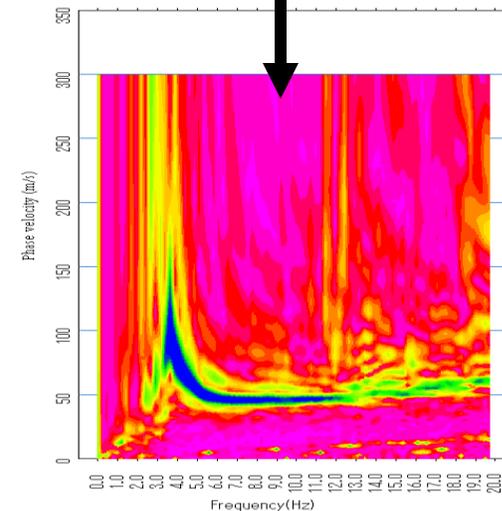
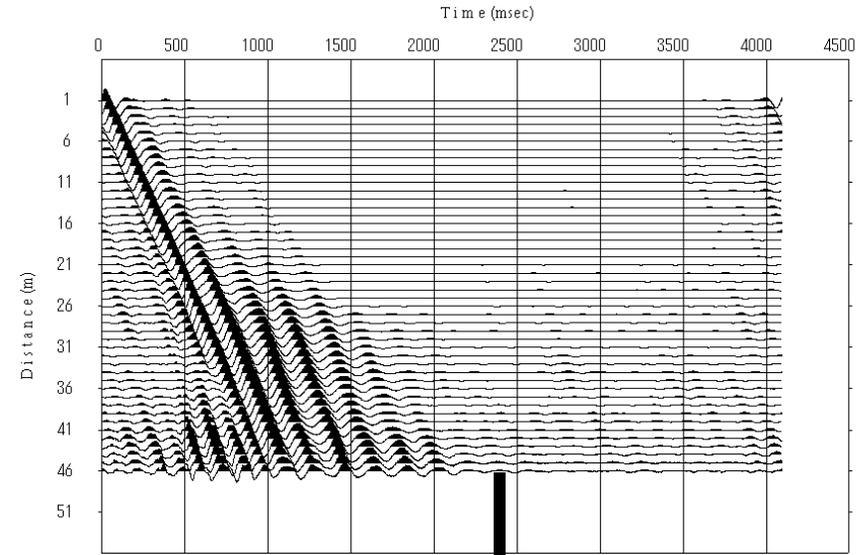
Example of CMP analysis

CMP cross-correlation gather at the CMP distance of 173m



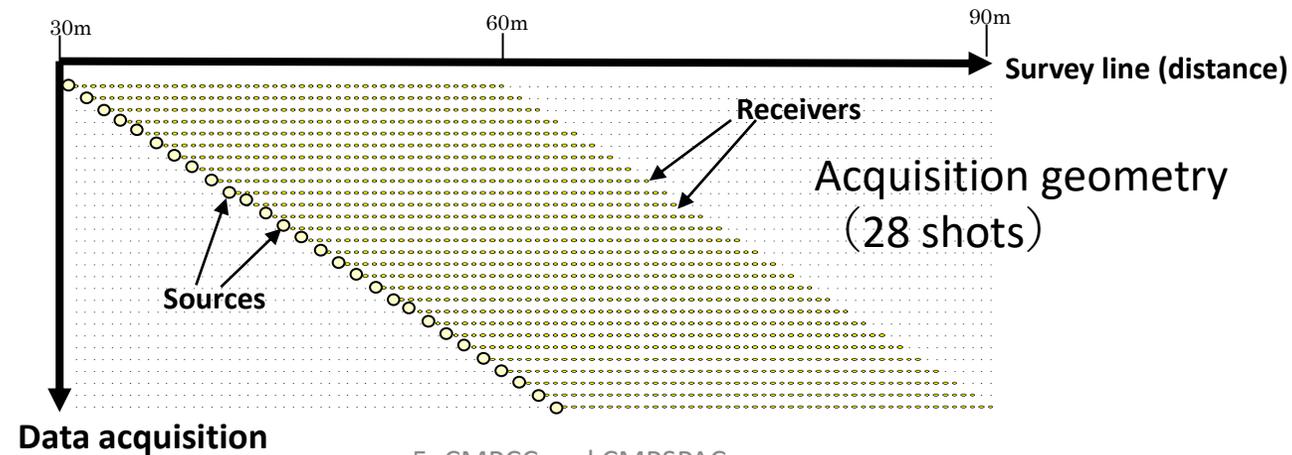
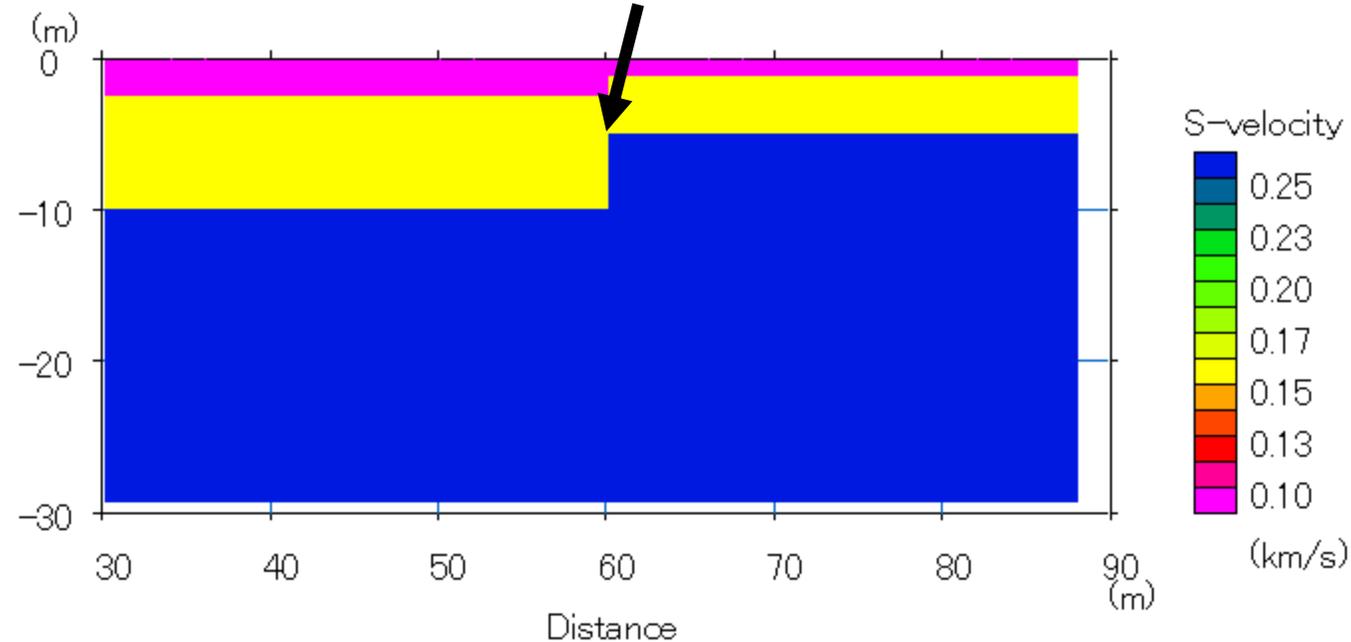
Phase-velocity image
calculated from CMP cross-
correlation gather

CMP cross-correlation gather at the CMP distance of 201m



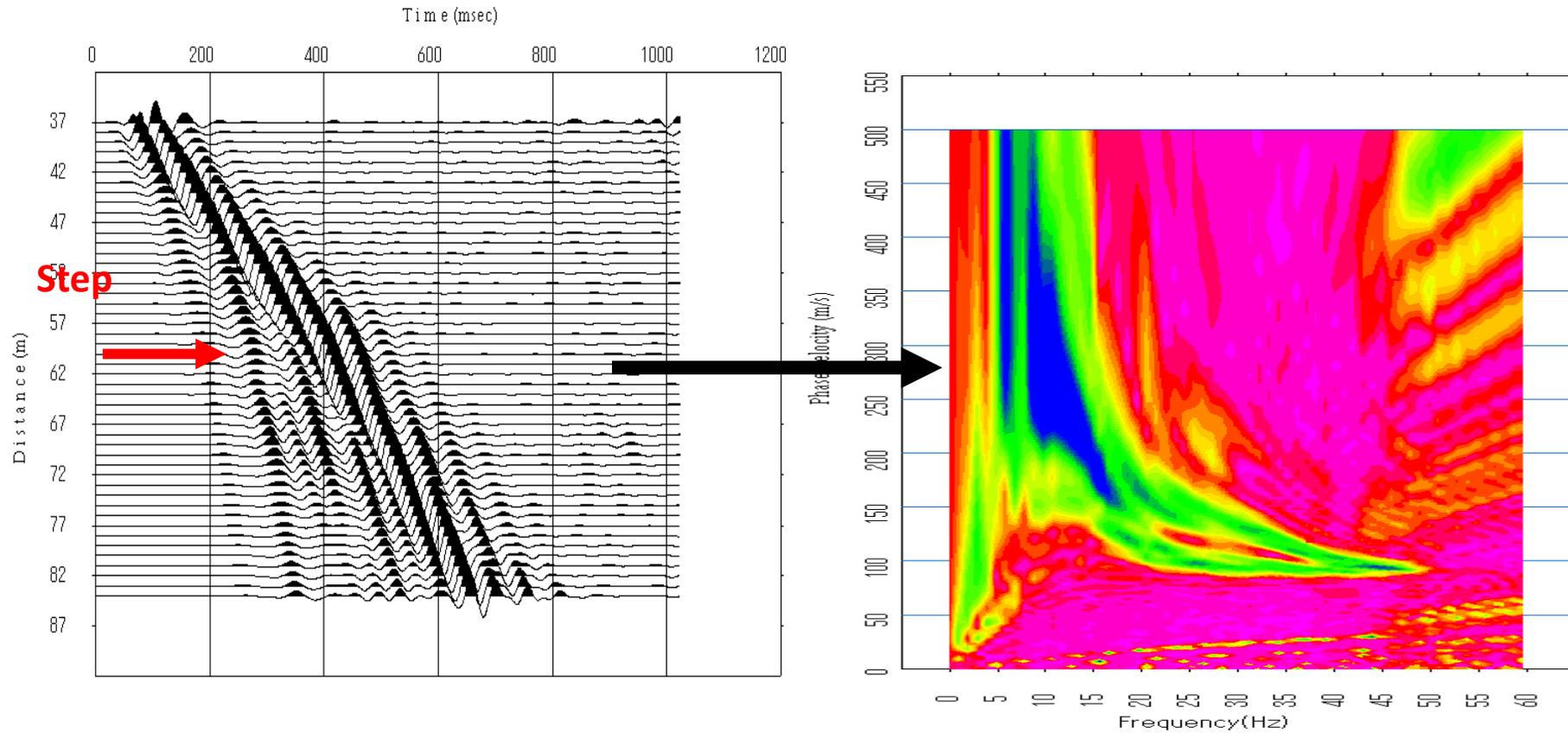
Numerical example

Step (at the distance of 60m)



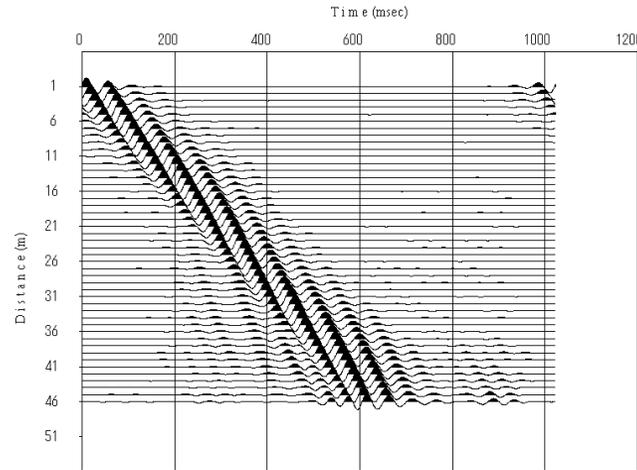
Example of a shot gather

The shot gather at the distance of 35.6m

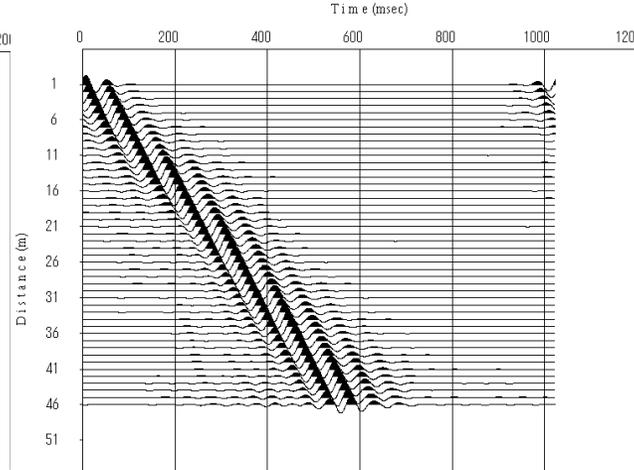


CMP cross-correlation gathers

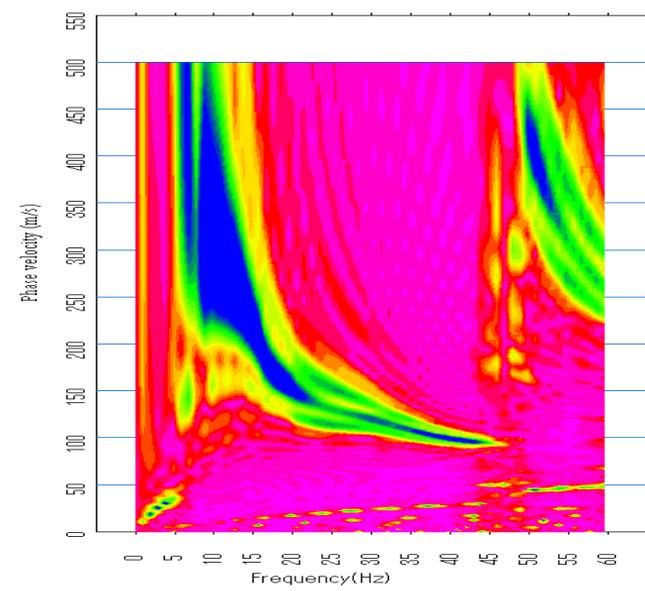
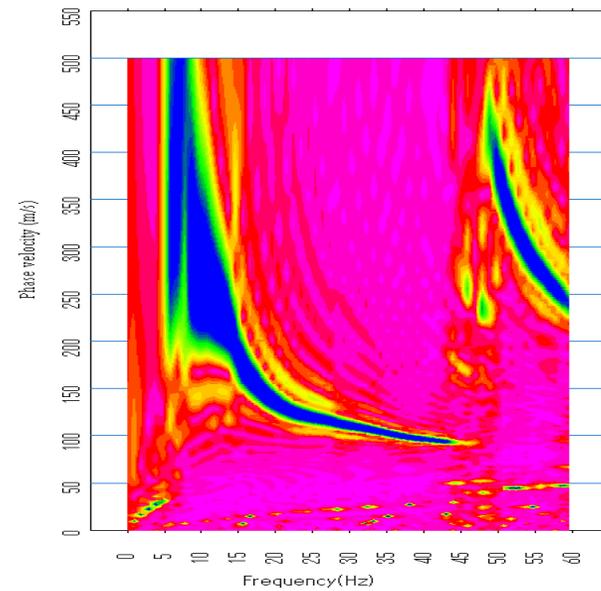
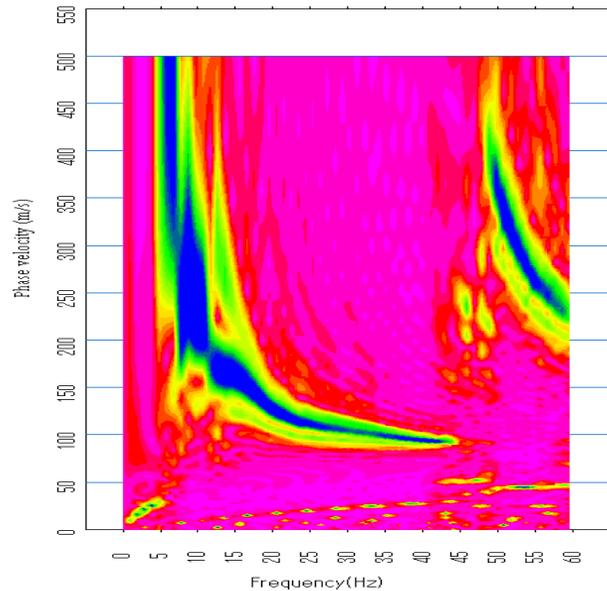
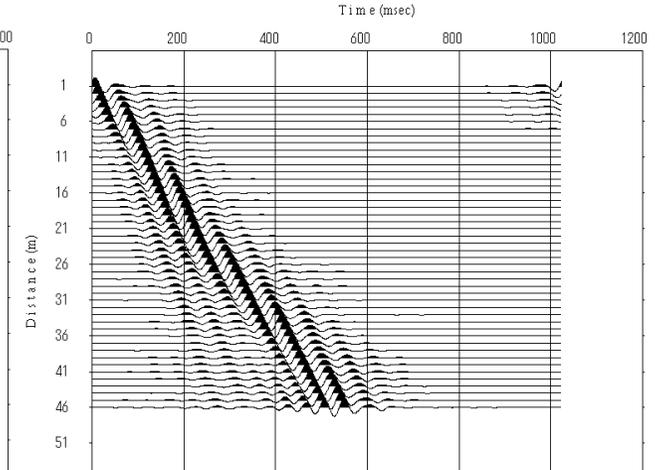
CMP 50.8m



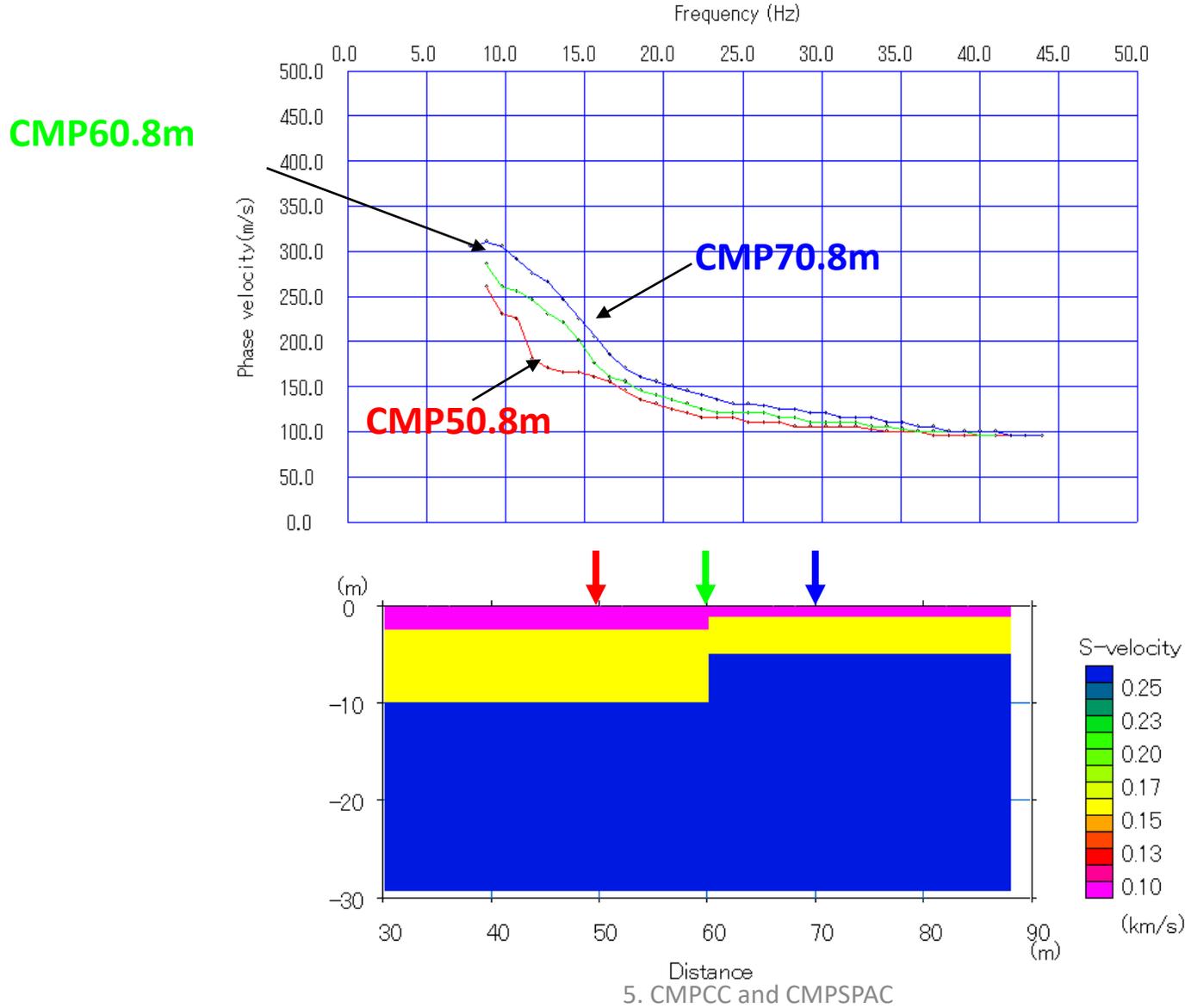
CMP 60.8m



CMP 70.8m

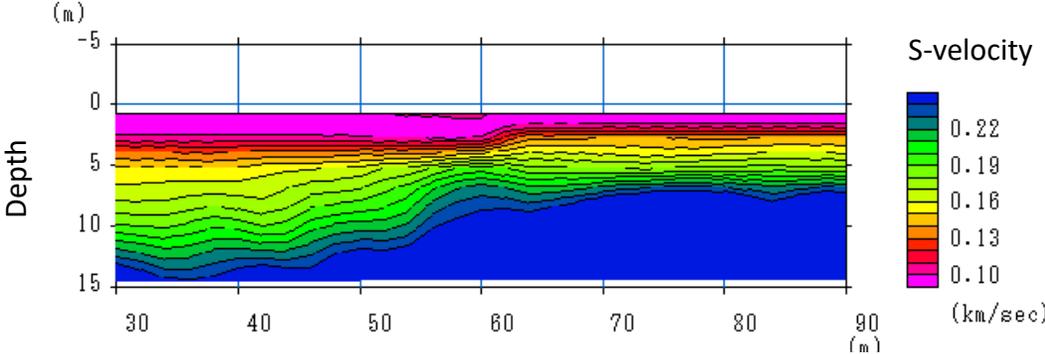


Phase-velocity curves obtained through CMP cross-correlation gathers

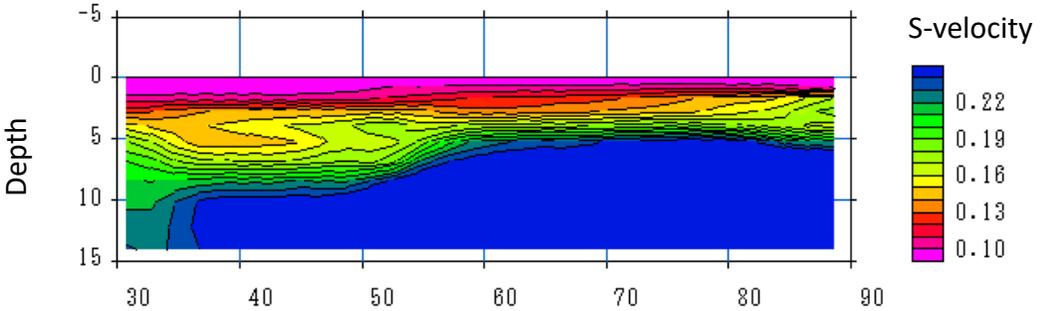


CMP analysis result (numerical example)

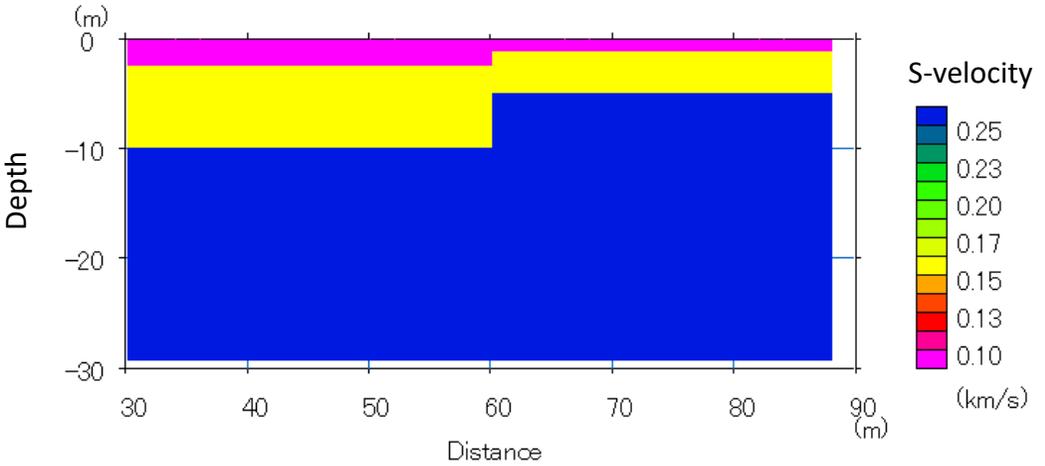
Shot gather analysis



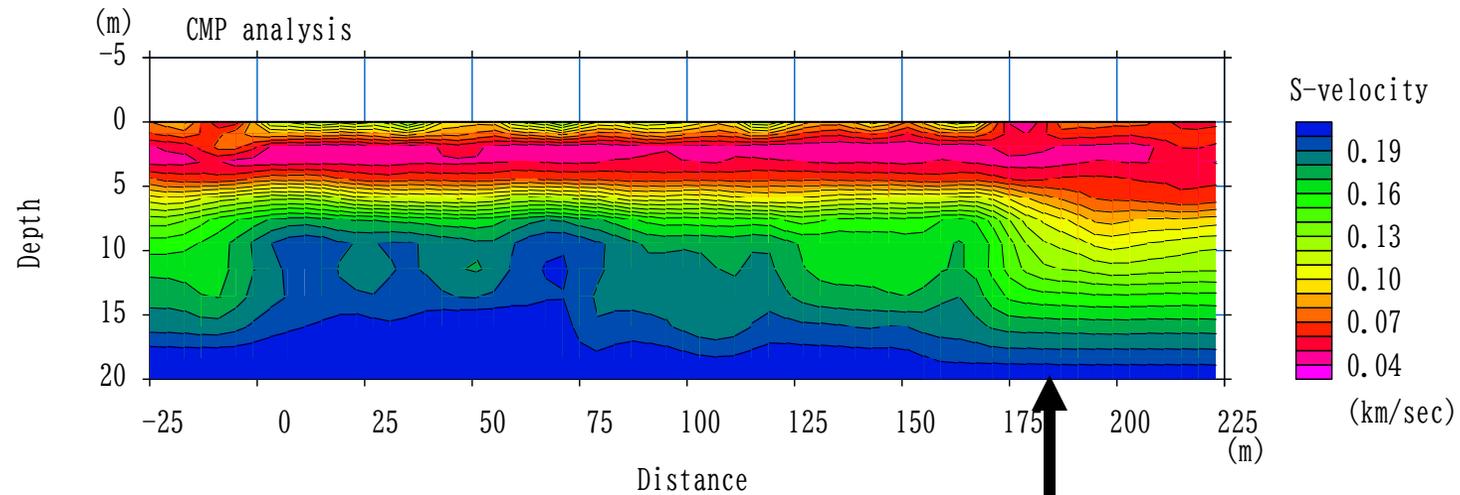
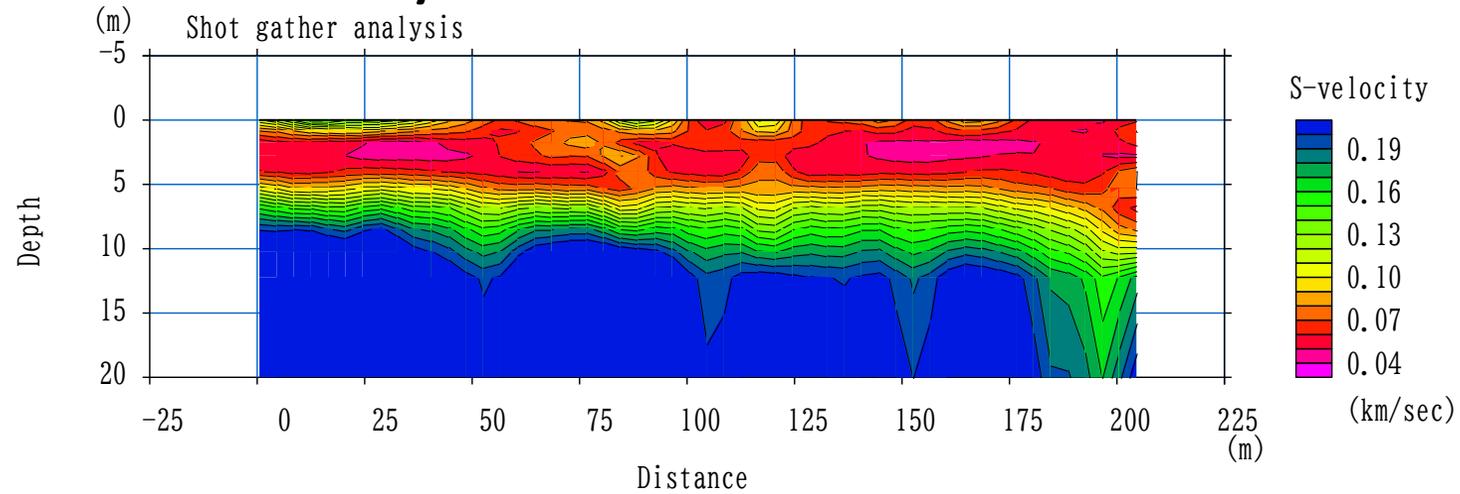
CMP analysis



True velocity model



CMP analysis result (real data)



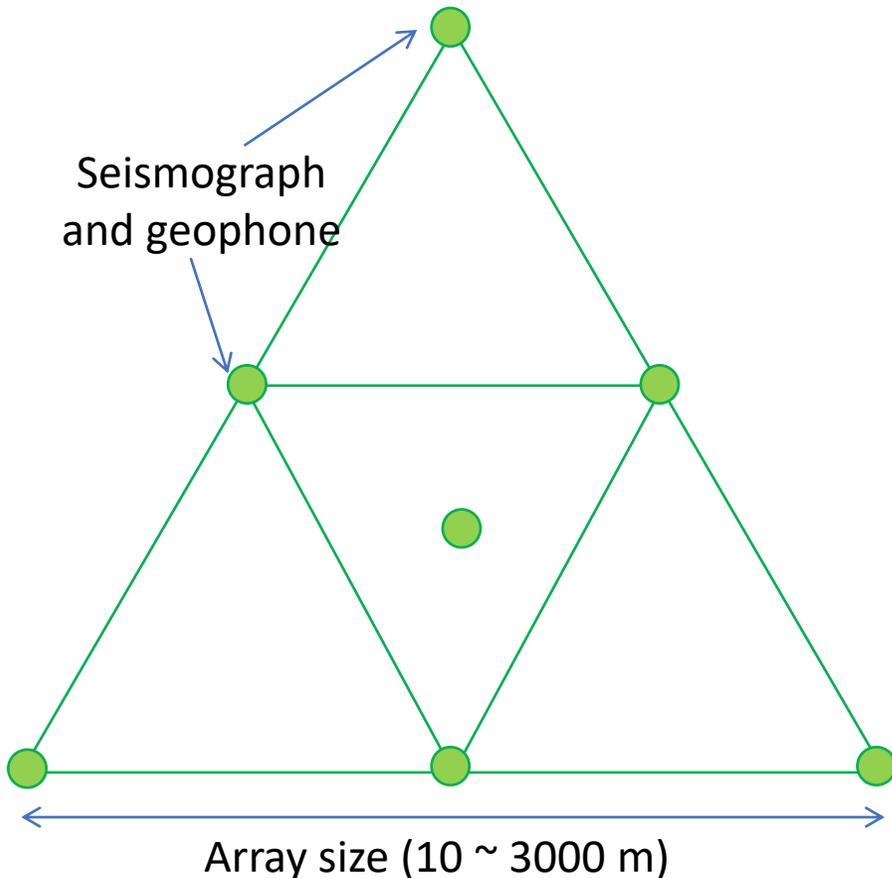
Discontinuity at 180m

5. CMPCC and CMPSPAC

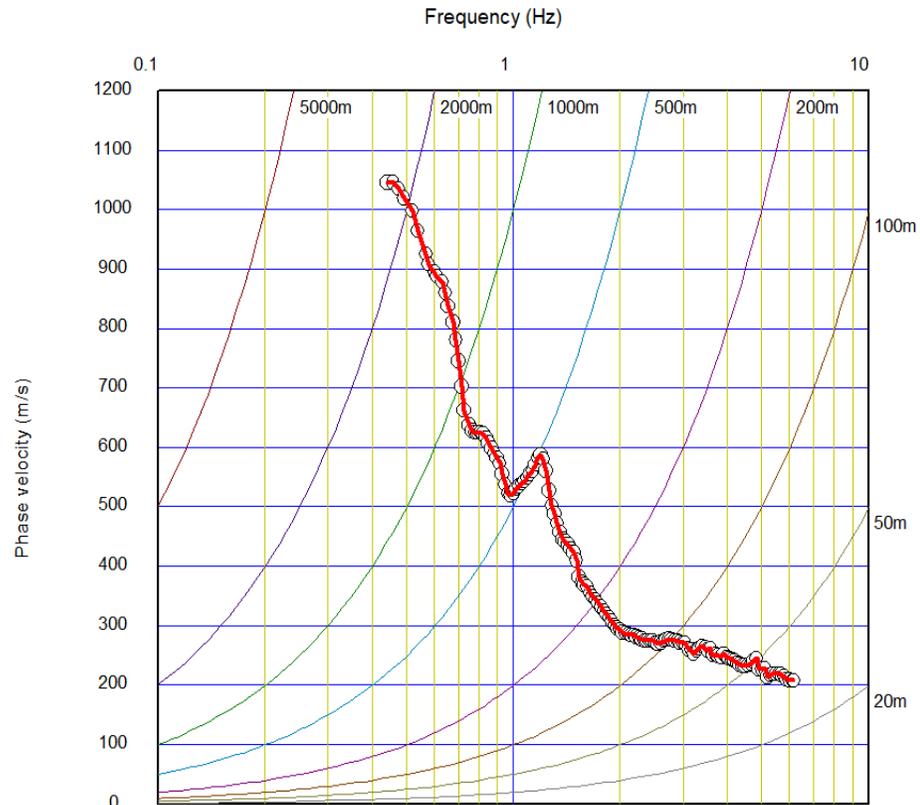
- 1D active surface wave method
- 2D active surface wave method
- Common Midpoint Cross-correlation (CMP-CC) analysis
- 3D passive surface wave method and common Midpoint Spatial Autocorrelation (CMP-SPAC) analysis
 - Concept of CMP-SPAC
 - Data acquisition
 - Numerical example
 - Real data example

Conventional spatial autocorrelation (SPAC) for 1D S-wave velocity investigation

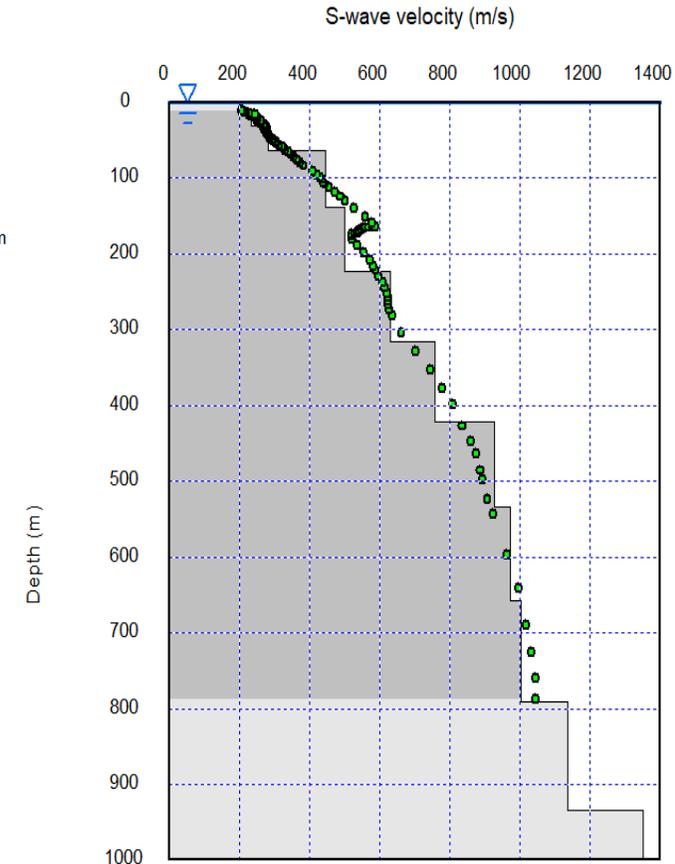
Data acquisition geometry



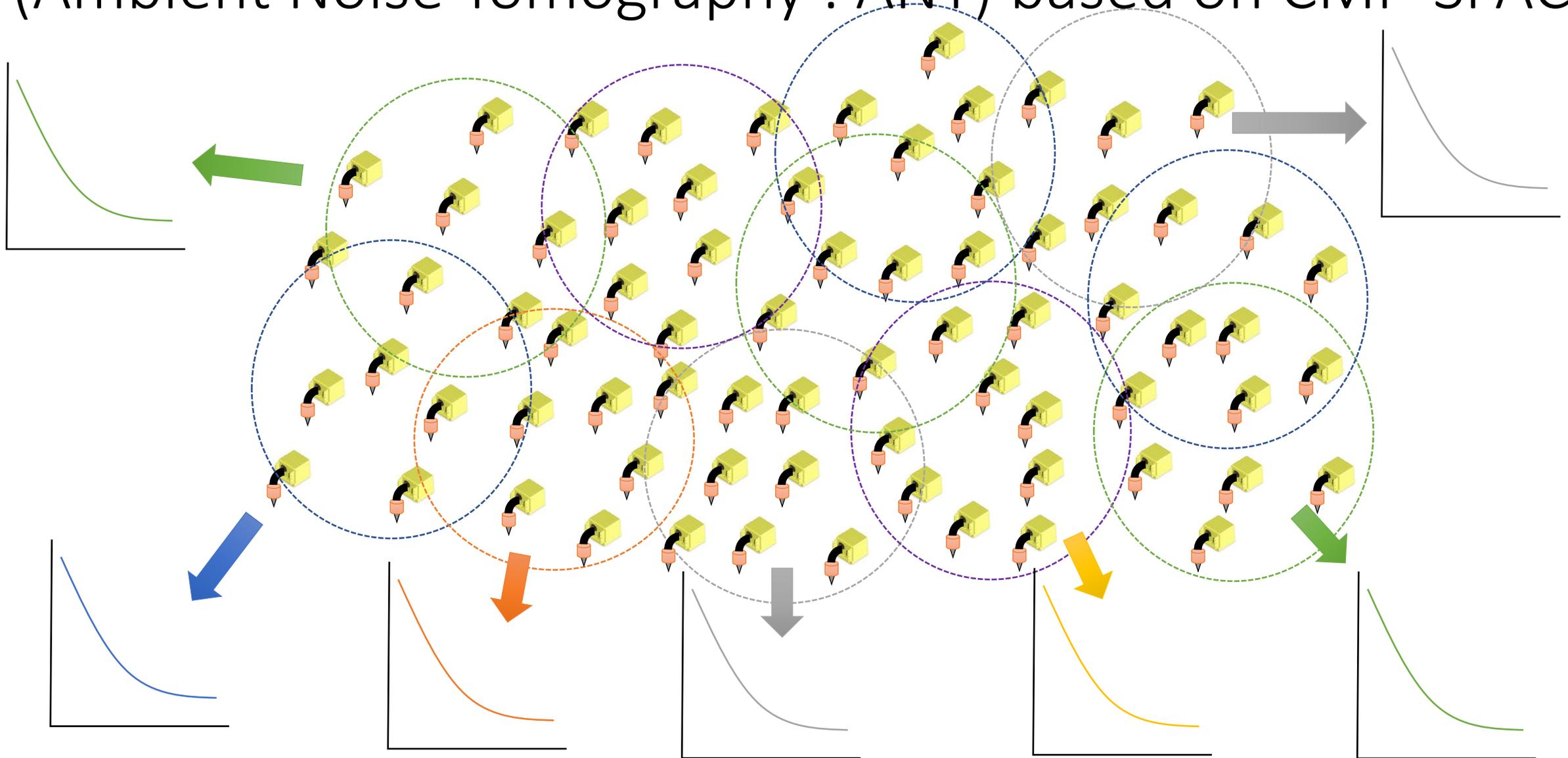
Dispersion (phase velocity) curve



1D S-wave velocity model



Concept of 3D passive surface wave method (Ambient Noise Tomography : ANT) based on CMP-SPAC



Processing of 2D/3D ambient noise tomography by Common Midpoint Spatial Autocorrelation (CMP-SPAC)

1. The recorded vertical component of ambient noise data is divided into several overlapping time blocks.
2. Coherencies are calculated for all time blocks and all receiver pairs.
3. The coherencies are averaged over all time blocks in the frequency domain.
4. Coherencies are sorted by CMP. The real part of coherencies at each CMP can be considered as spatial autocorrelation (SPAC), since coherencies were calculated from receiver pairs with many different directions and thus include directional averaging.
5. Dispersion curves are calculated from each CMP-SPAC gather by comparing observed SPAC traces and theoretical Bessel functions.
6. A pseudo 2D/3D V_s model is reconstructed through 1D non-linear least squares inversion of dispersion curves.

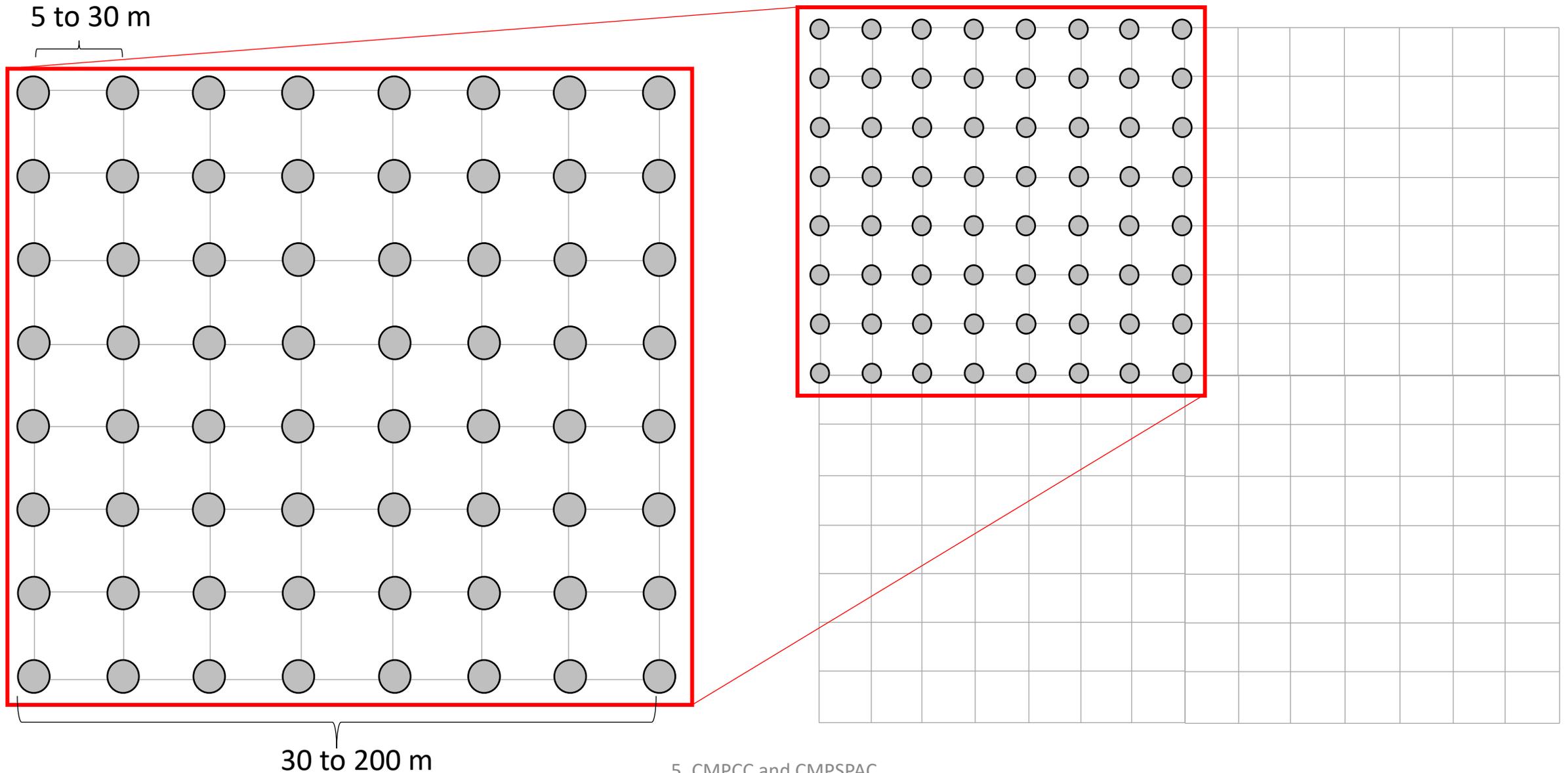
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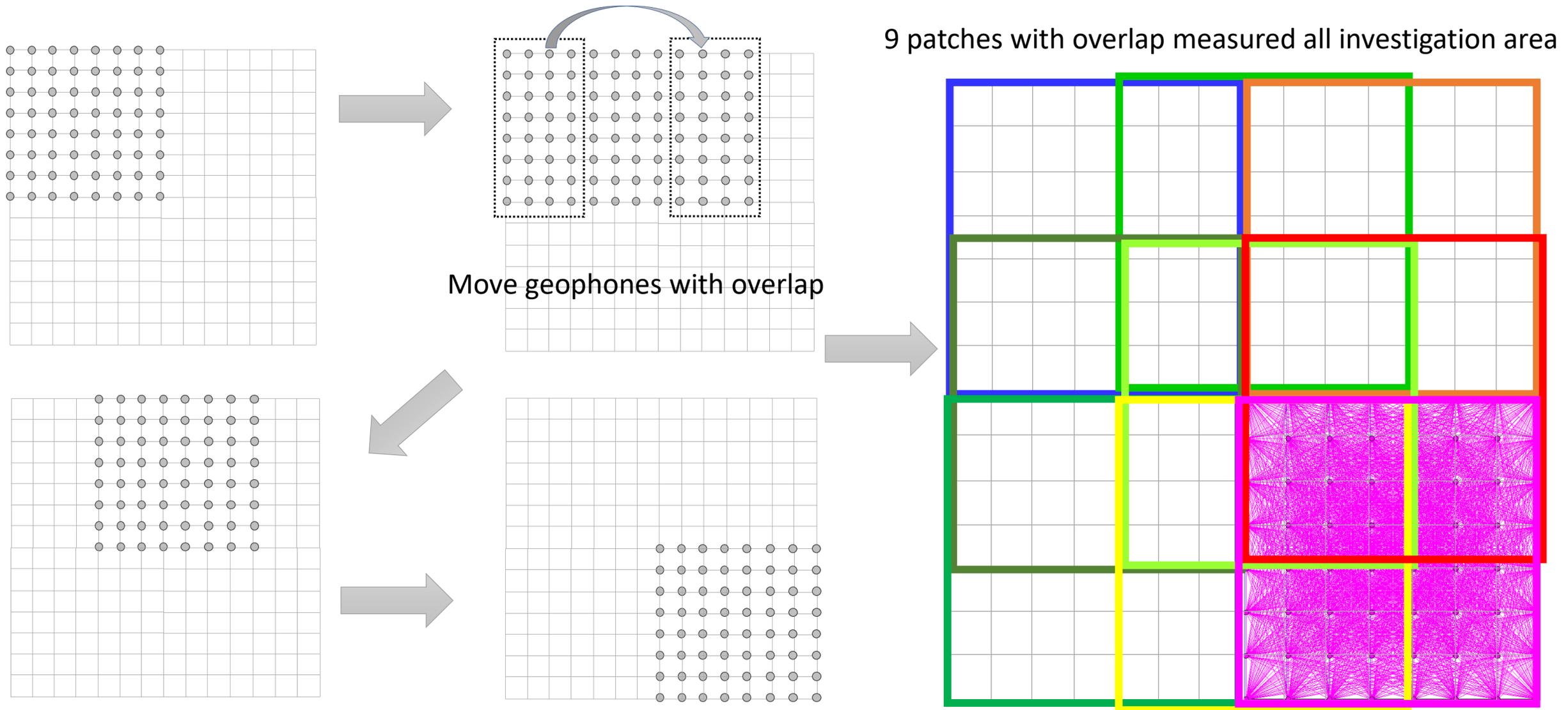
Data acquisition : cable free 3D measurements



3D ambient noise tomography : geometry example

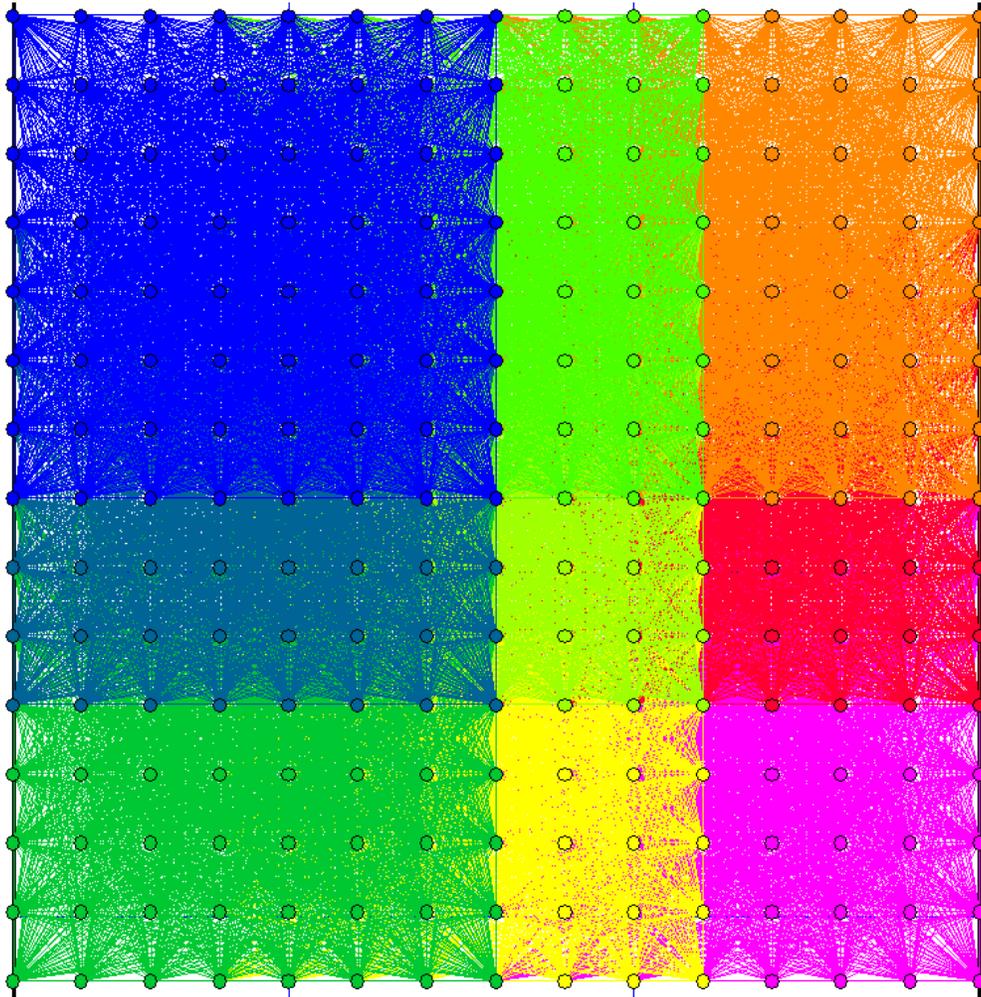


3D ambient noise tomography : geometry example

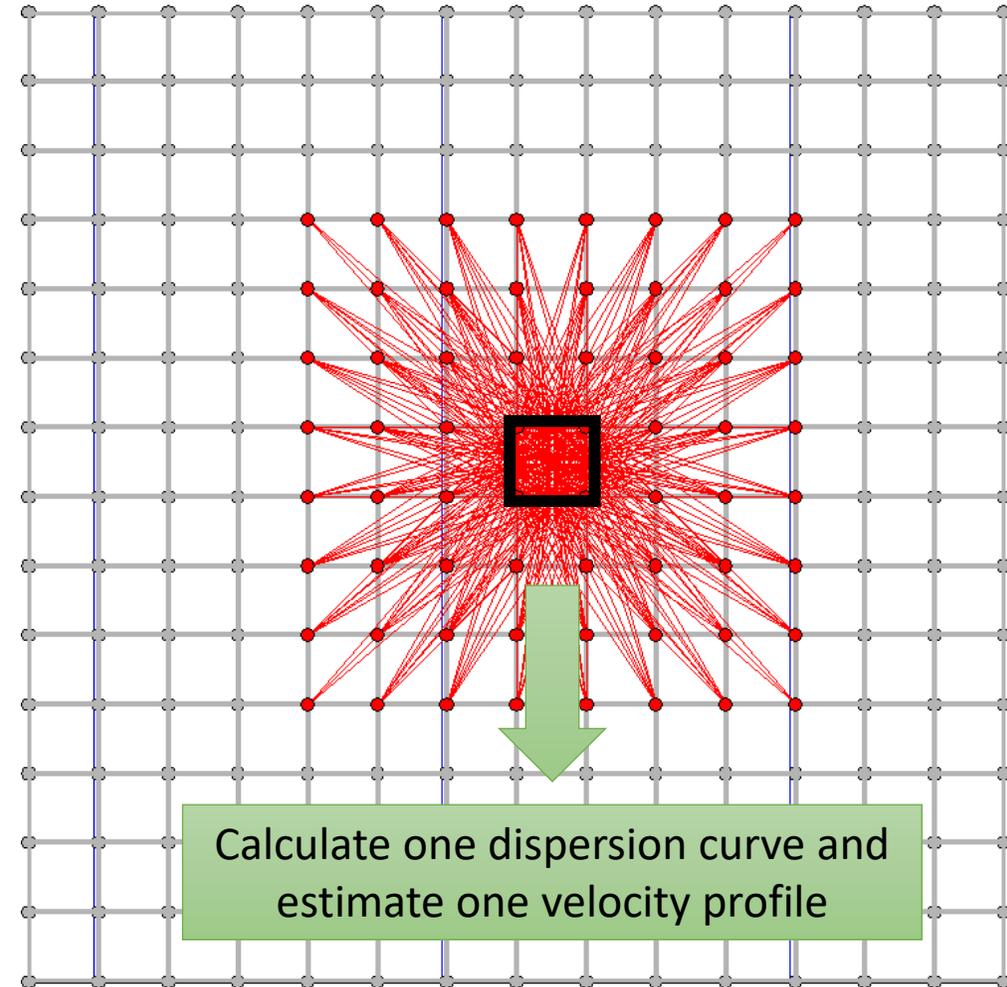


3D ambient noise tomography : geometry example

All possible receiver pairs



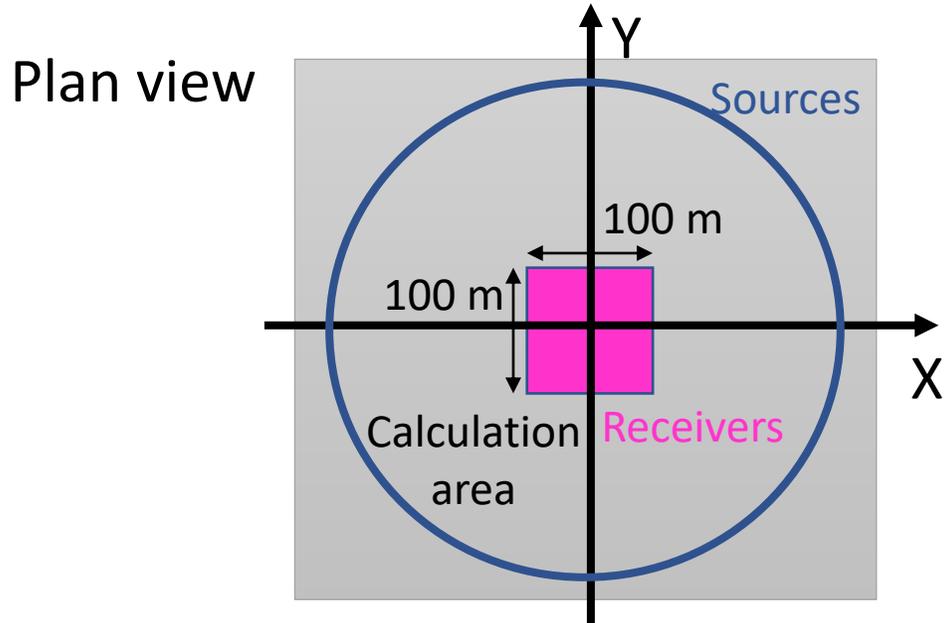
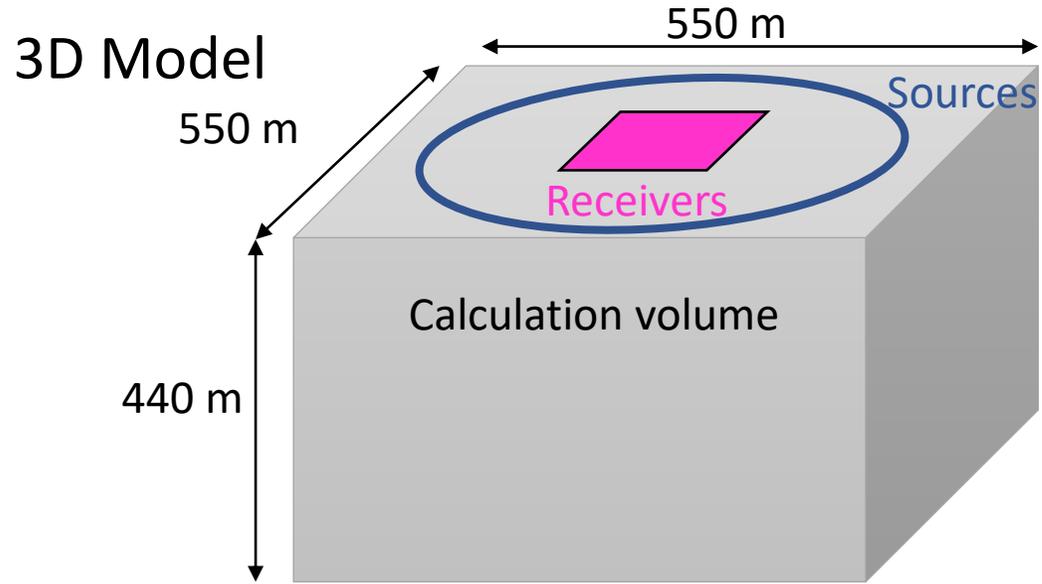
Receiver pairs in a CMP bin



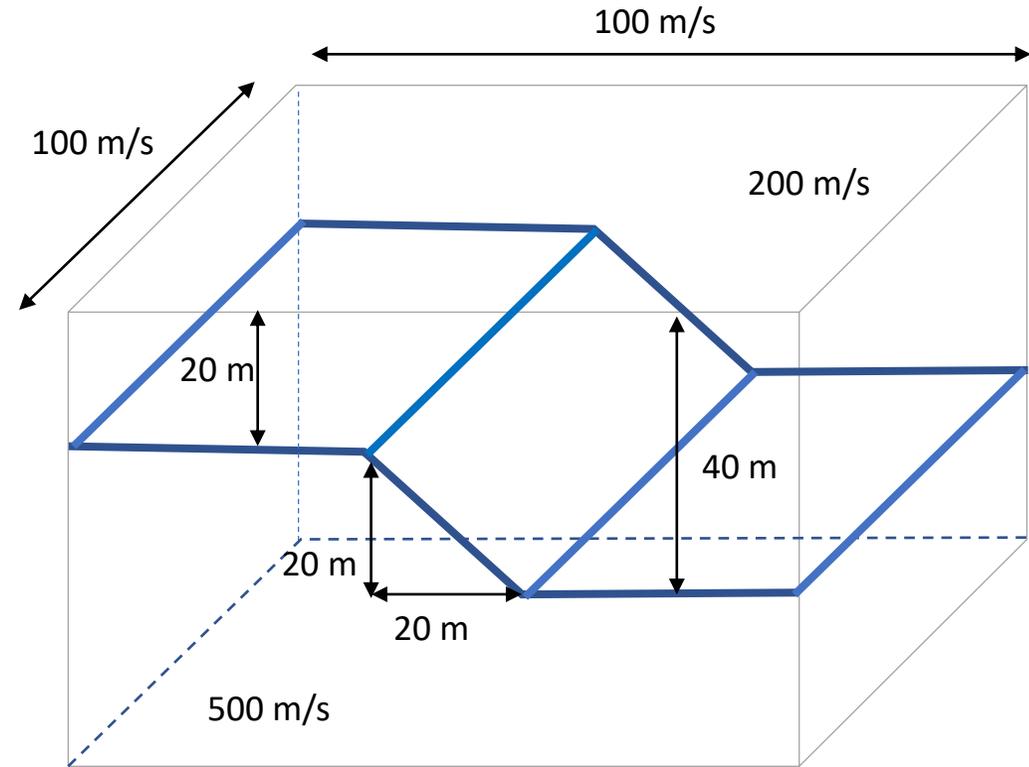
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3D Finite-difference simulation



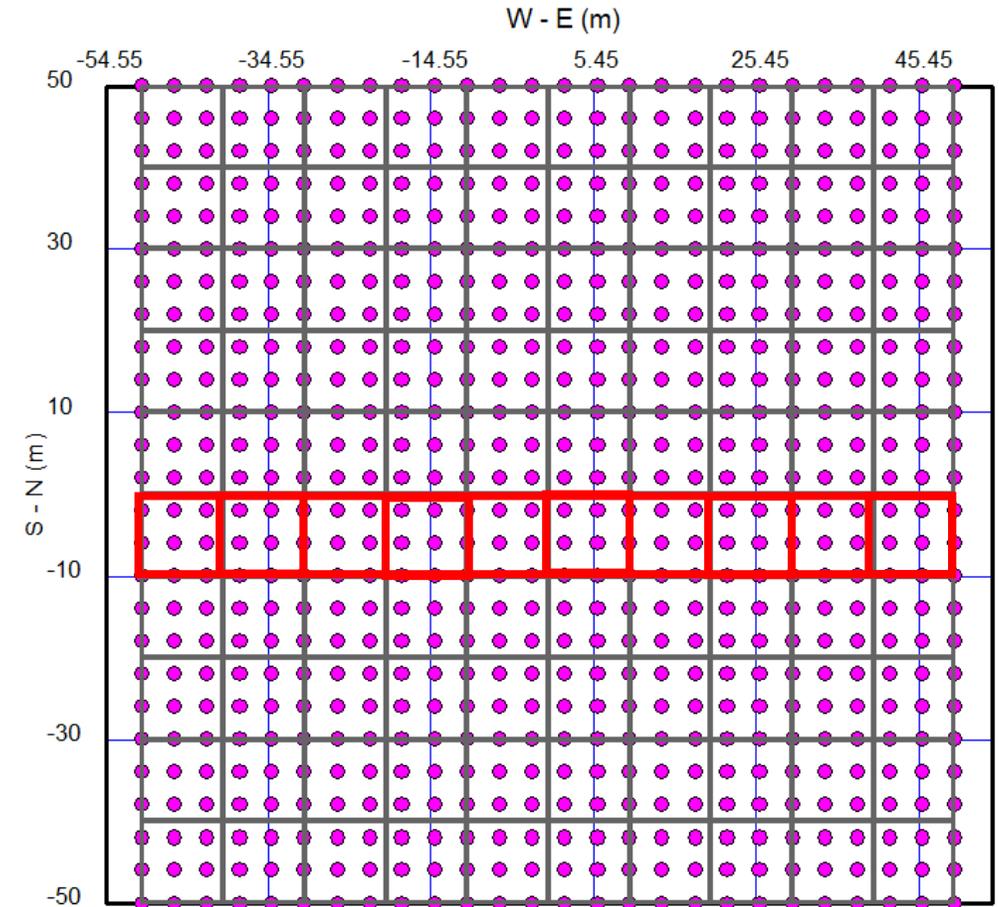
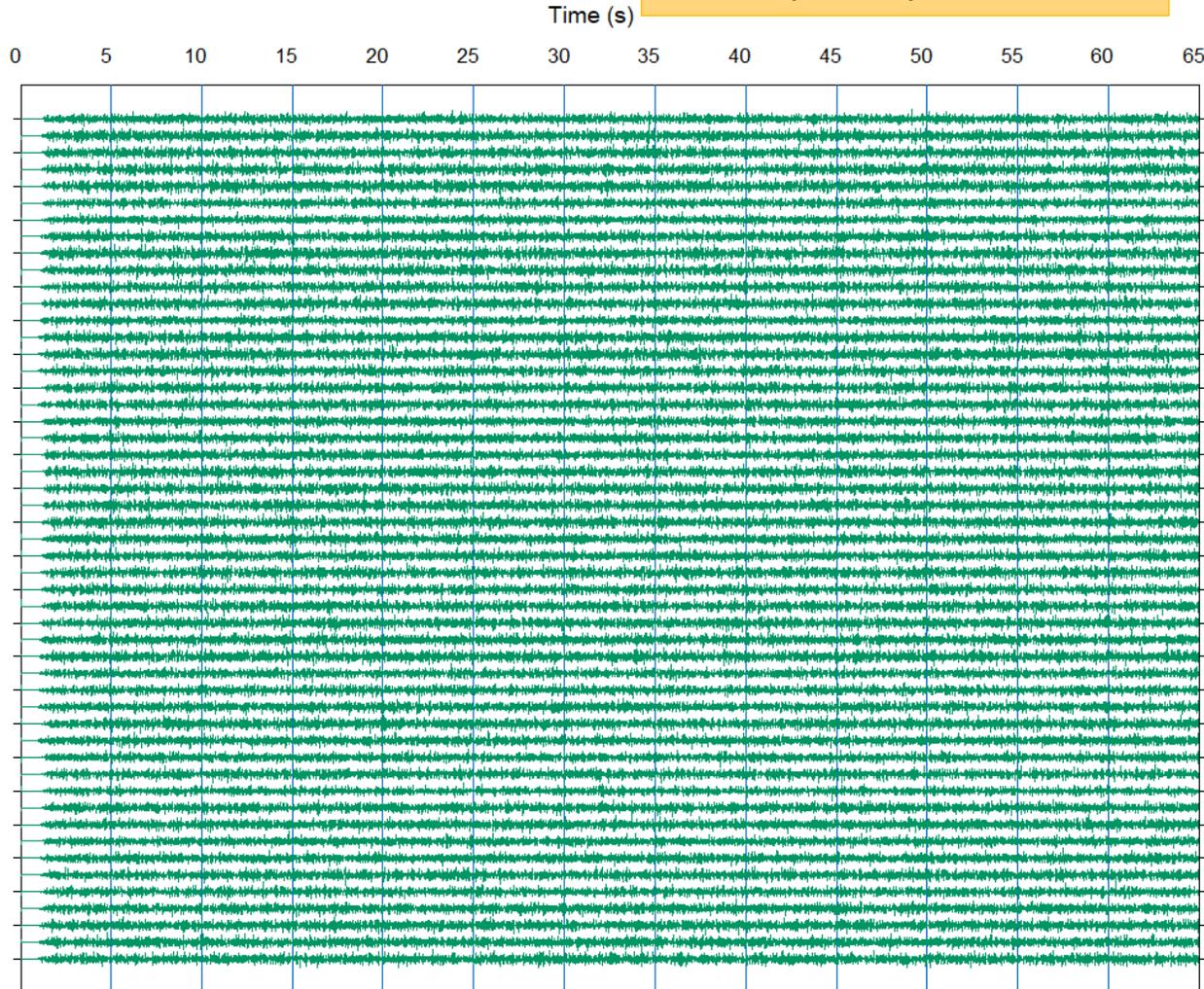
2 layer velocity model with a step



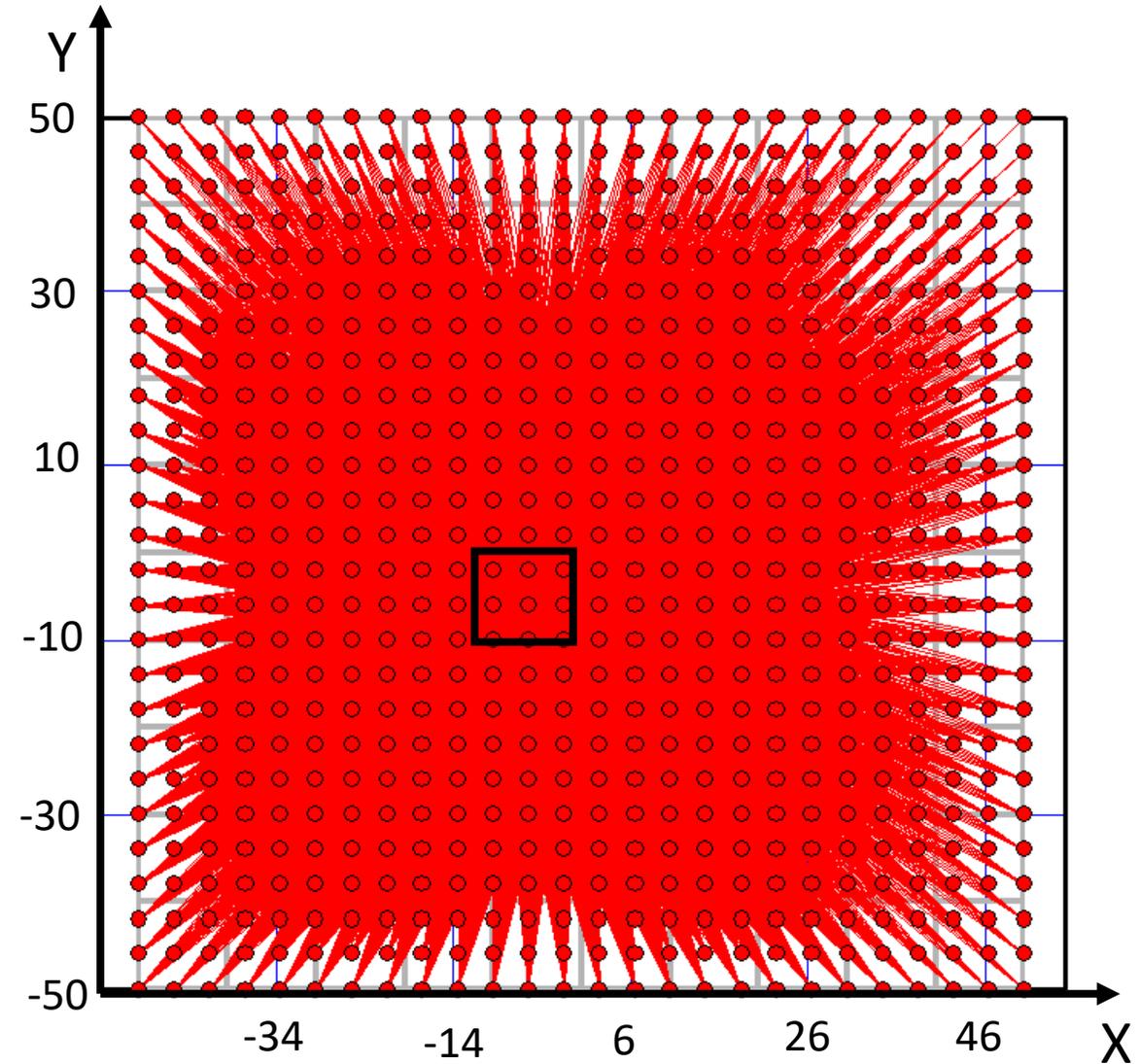
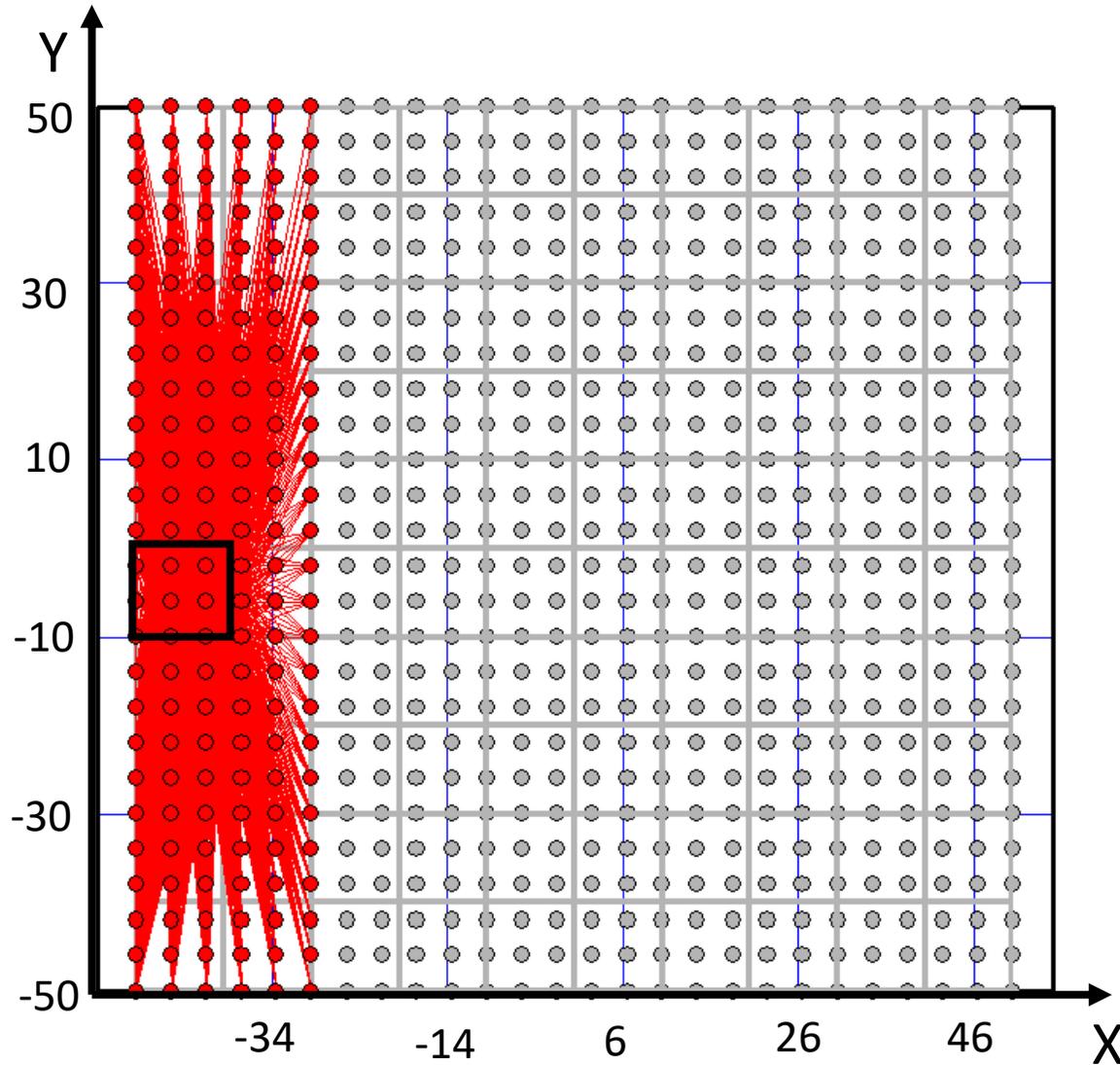
Example data and processing geometry

Example of waveform data

Average 10 records in
frequency domain

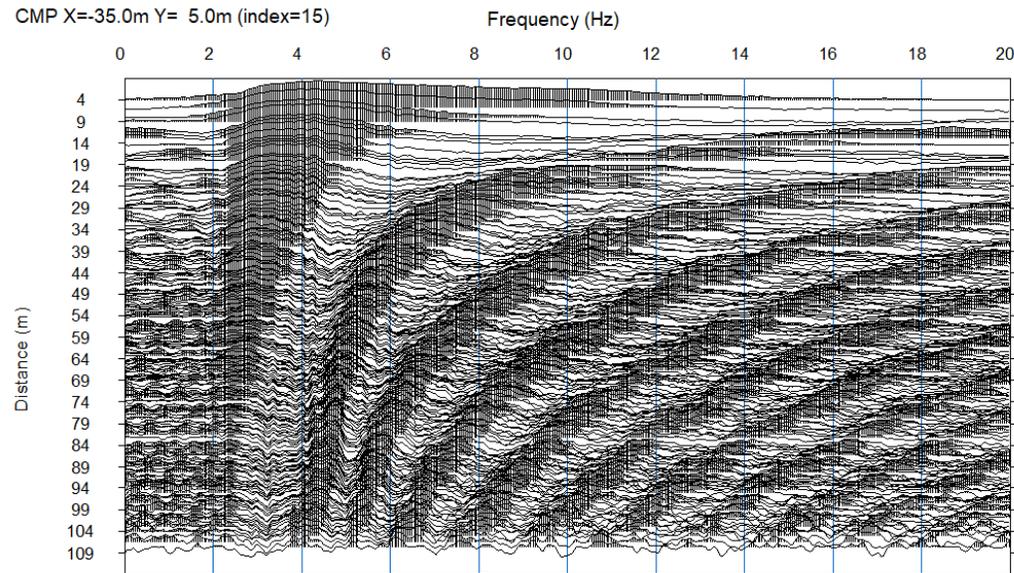


Examples of CMP-SPAC pairs in one cell (bin)



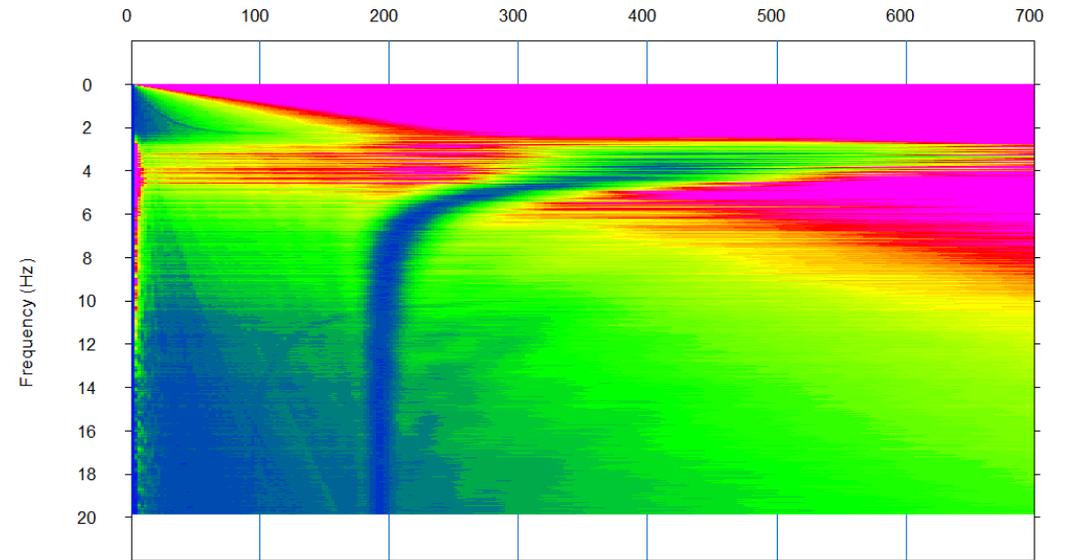
Examples of coherencies and phase velocity image

Shallow
bedrock

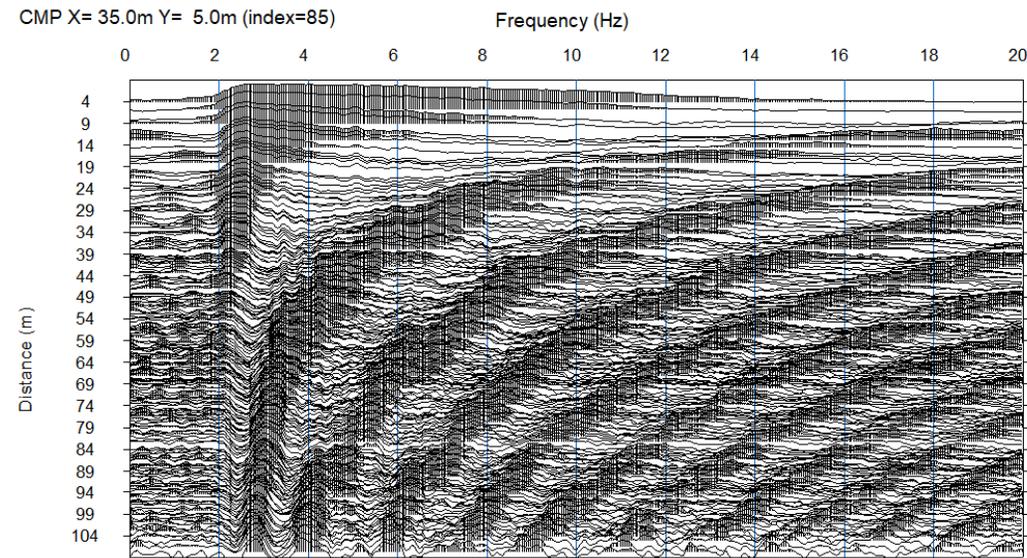


CMP X=-35.0m Y= 5.0m (index=15)

Phase velocity (m/s)

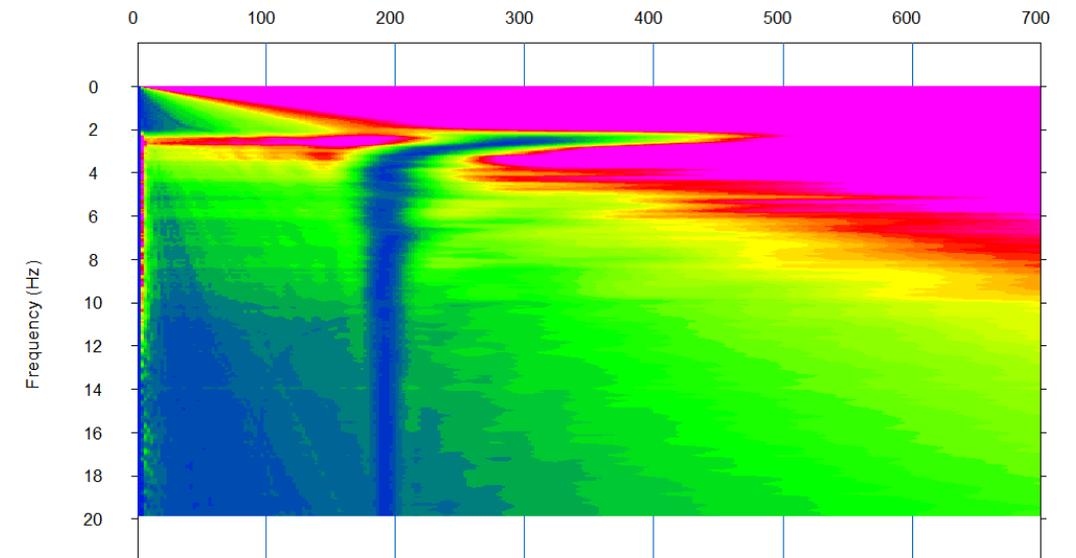


Deep
bedrock

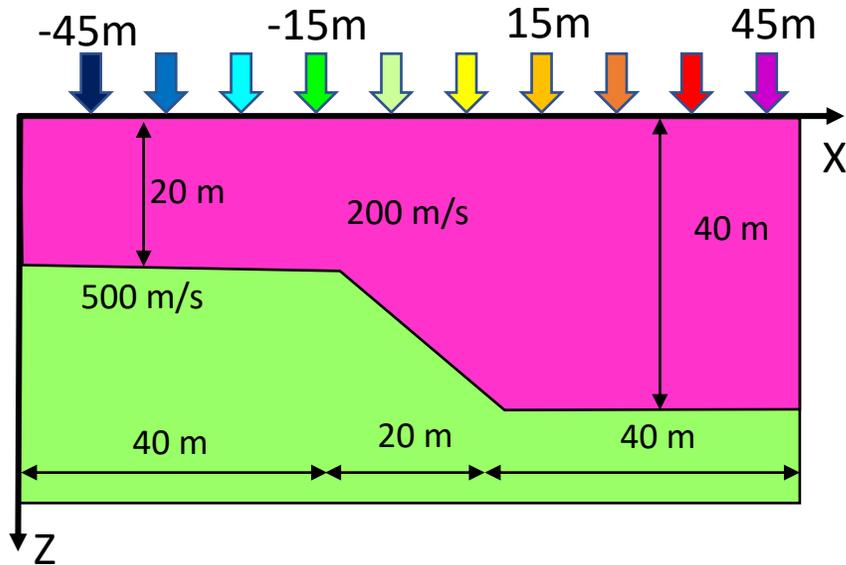


CMP X= 35.0m Y= 5.0m (index=85)

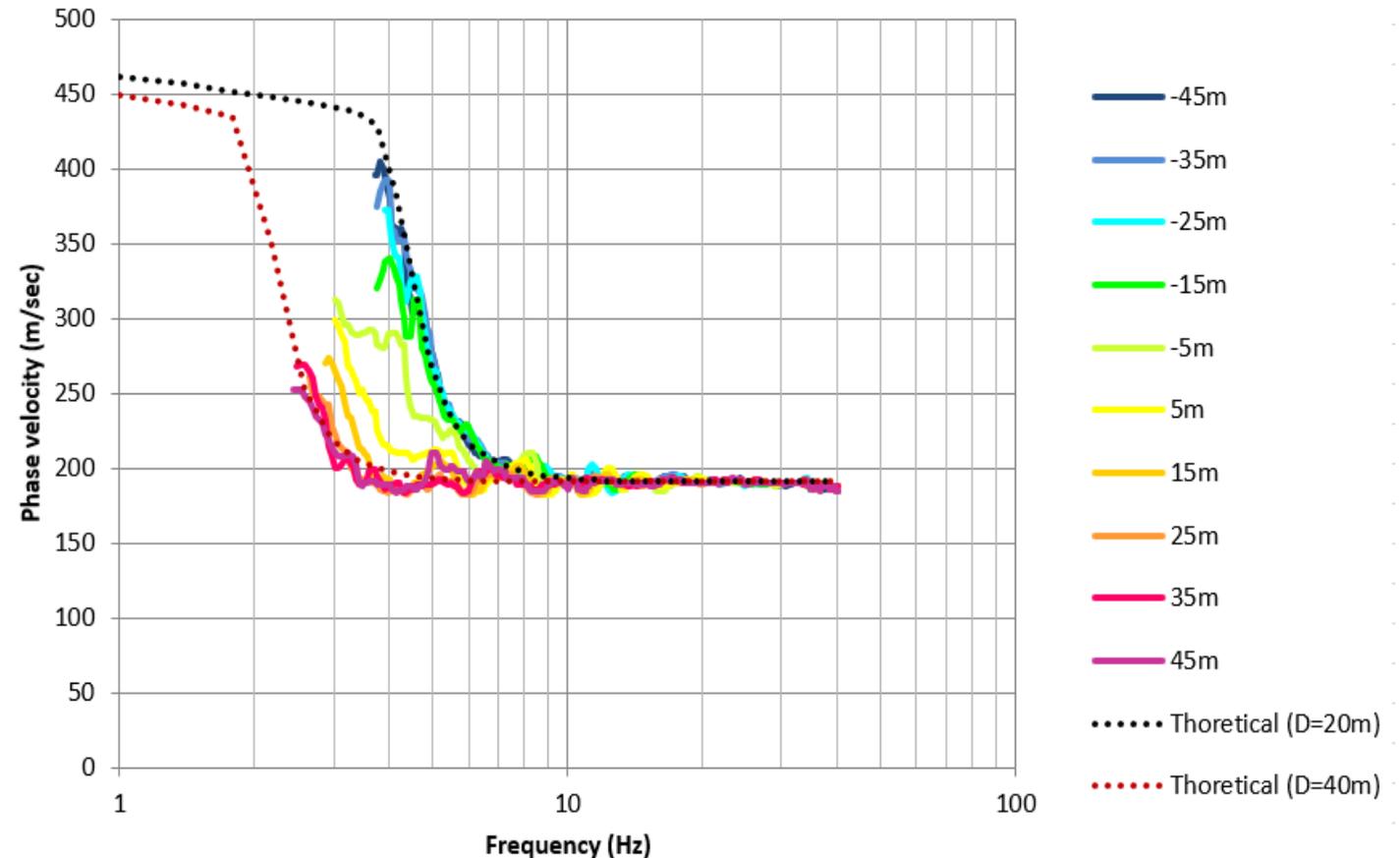
Phase velocity (m/s)

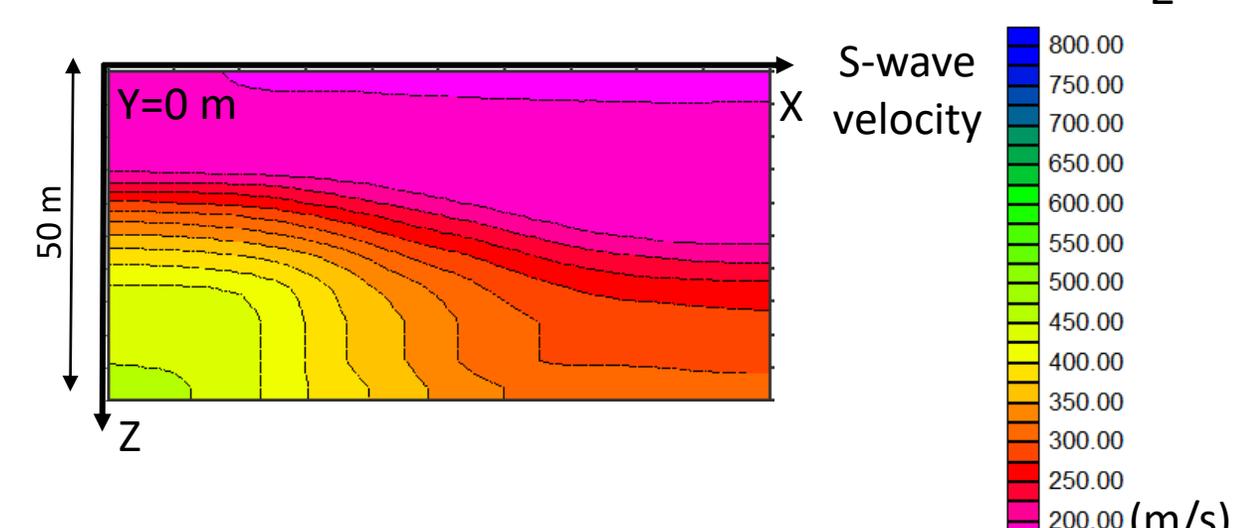
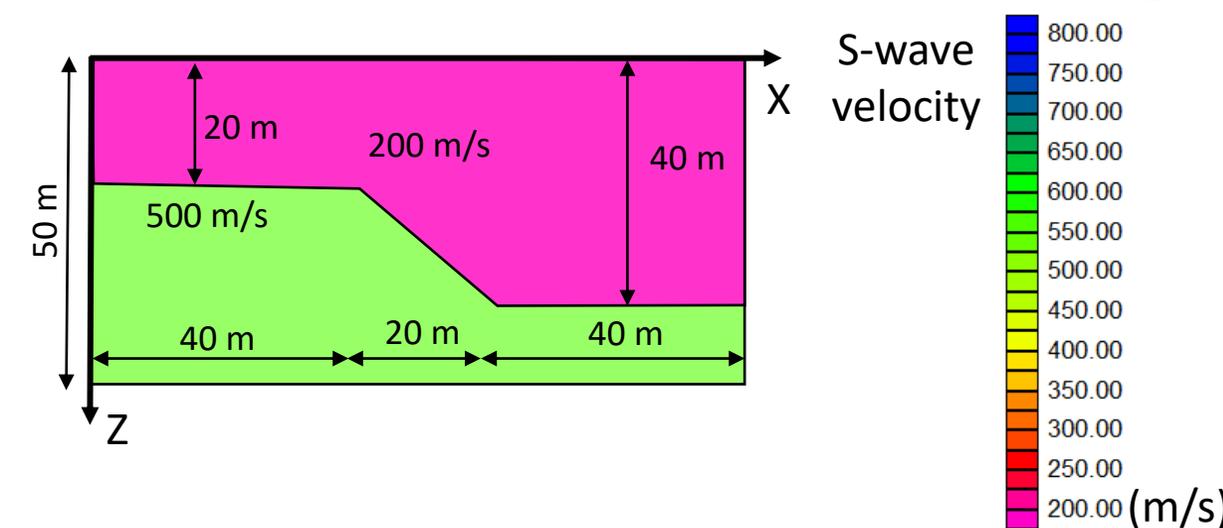
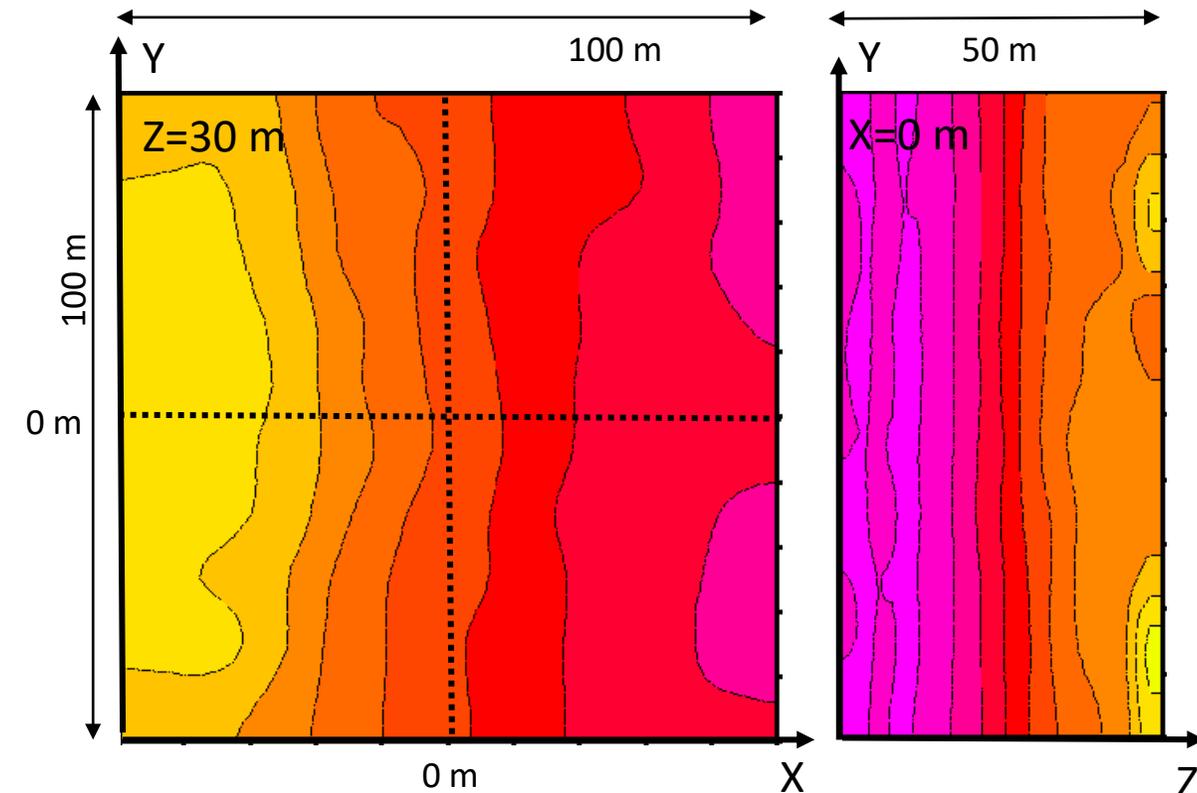
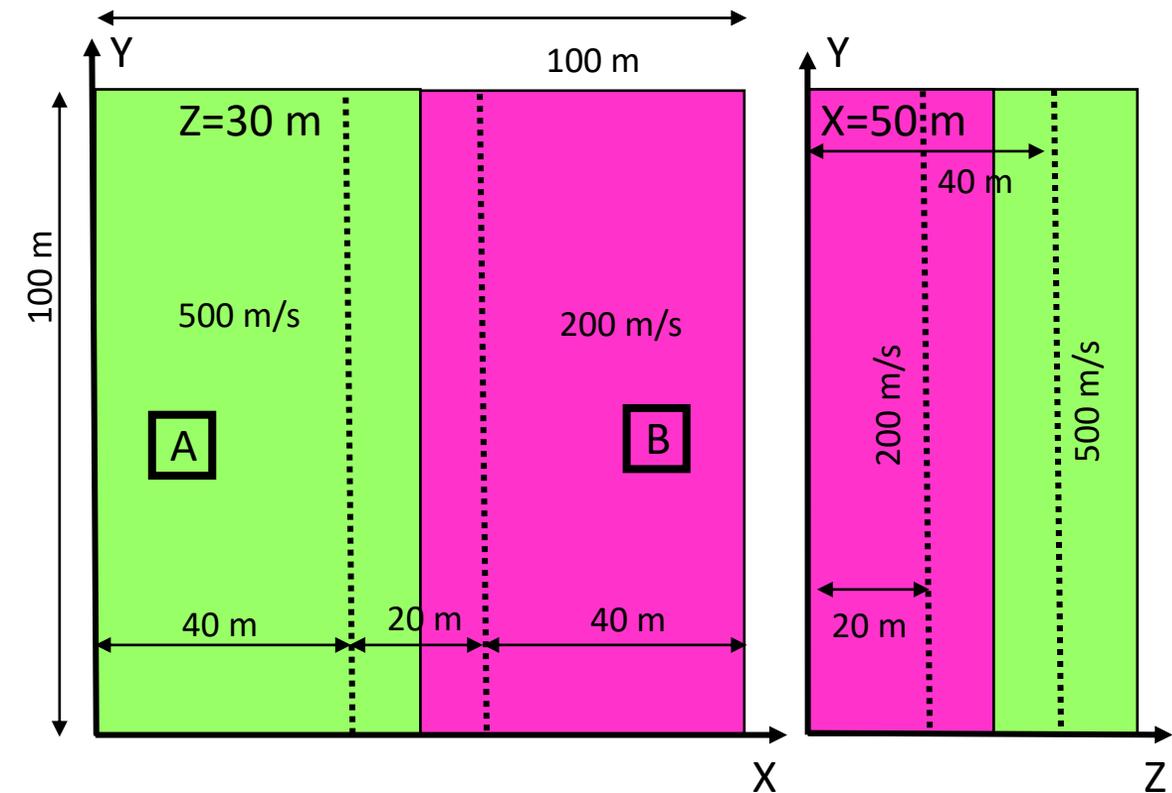


Comparison of dispersion curves cross the step

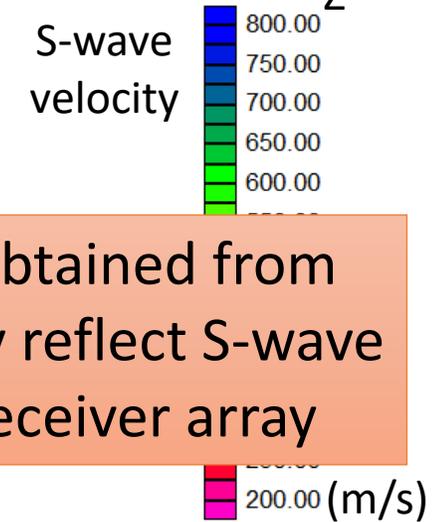
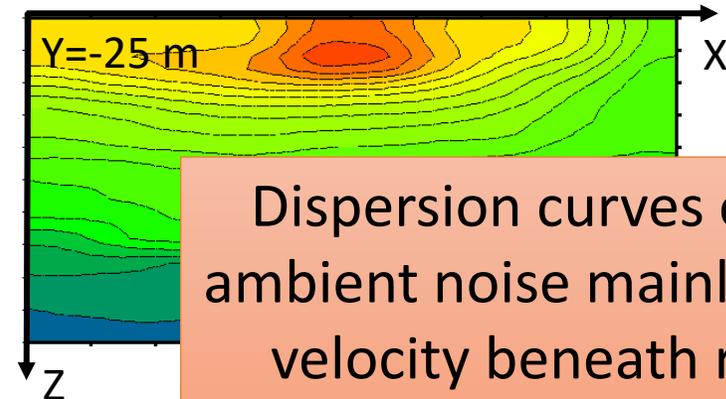
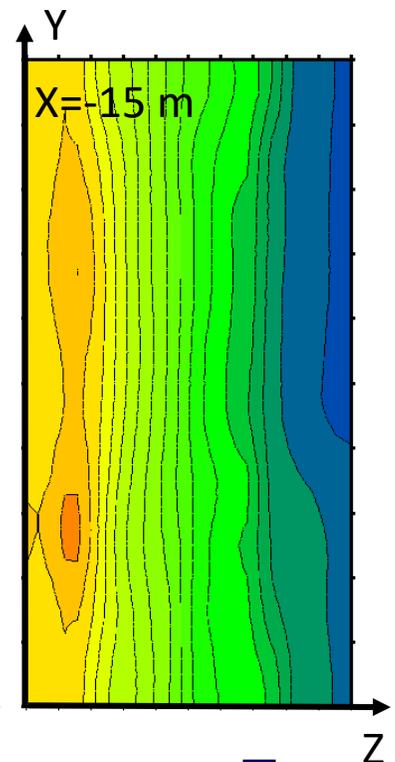
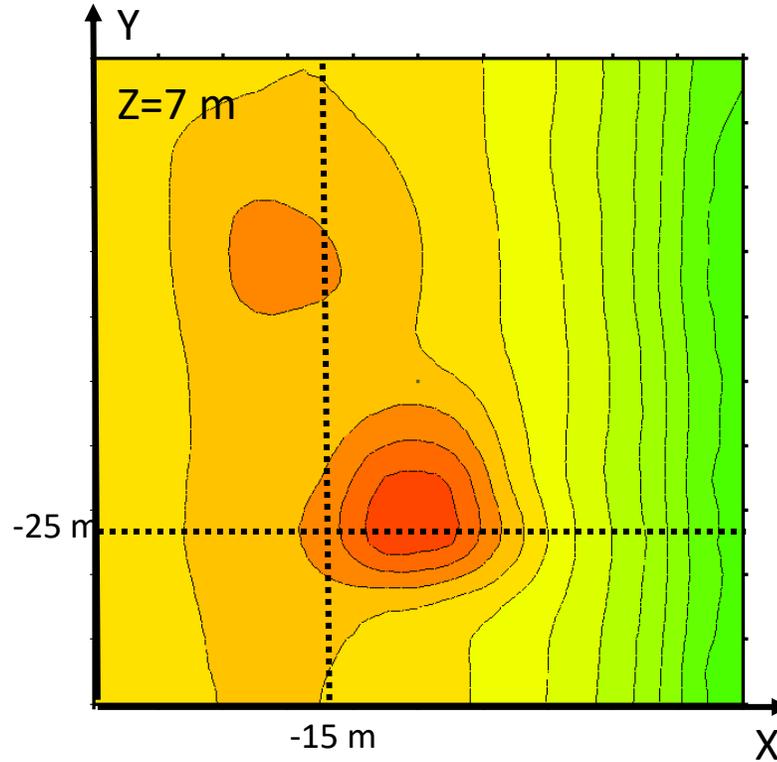
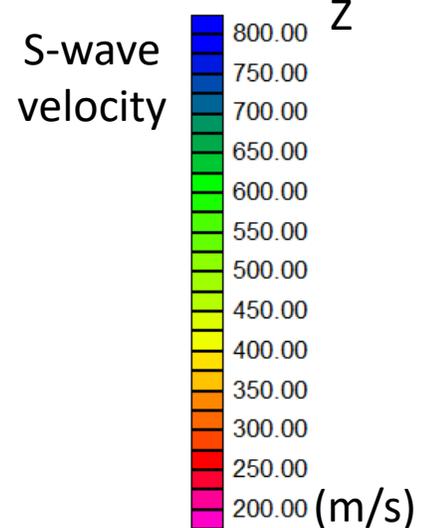
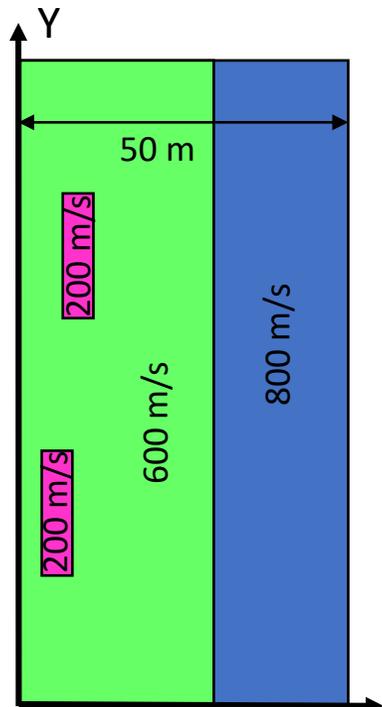
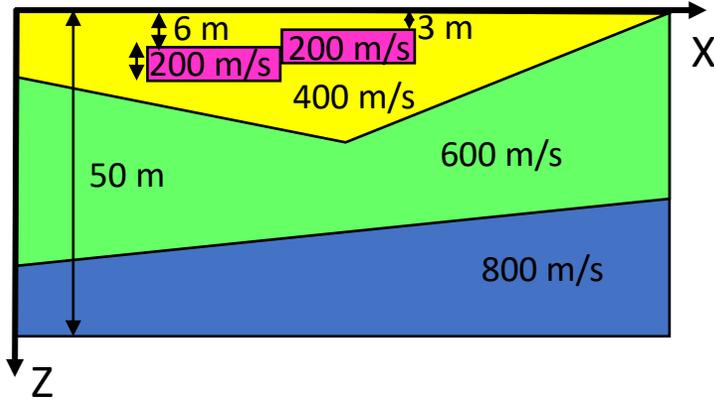
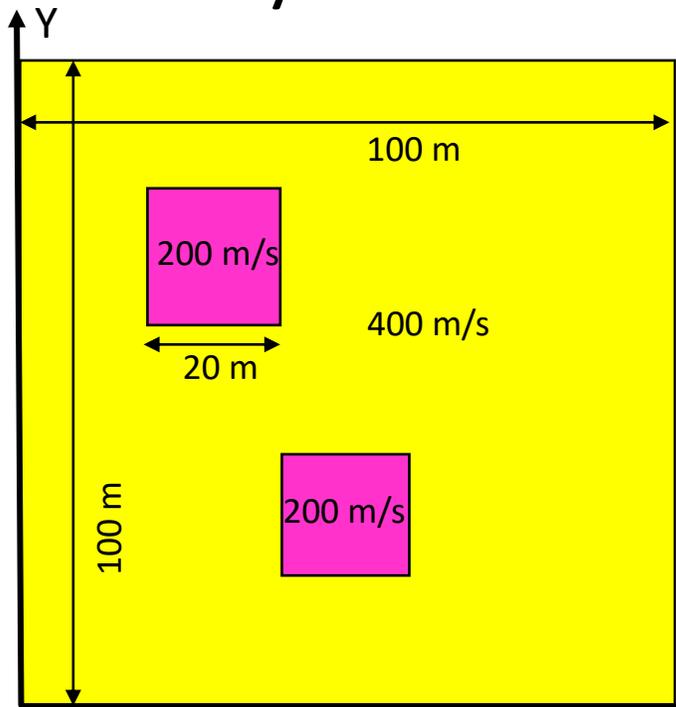


Dispersion curves obtained from ambient noise mainly reflect S-wave velocity beneath receiver array





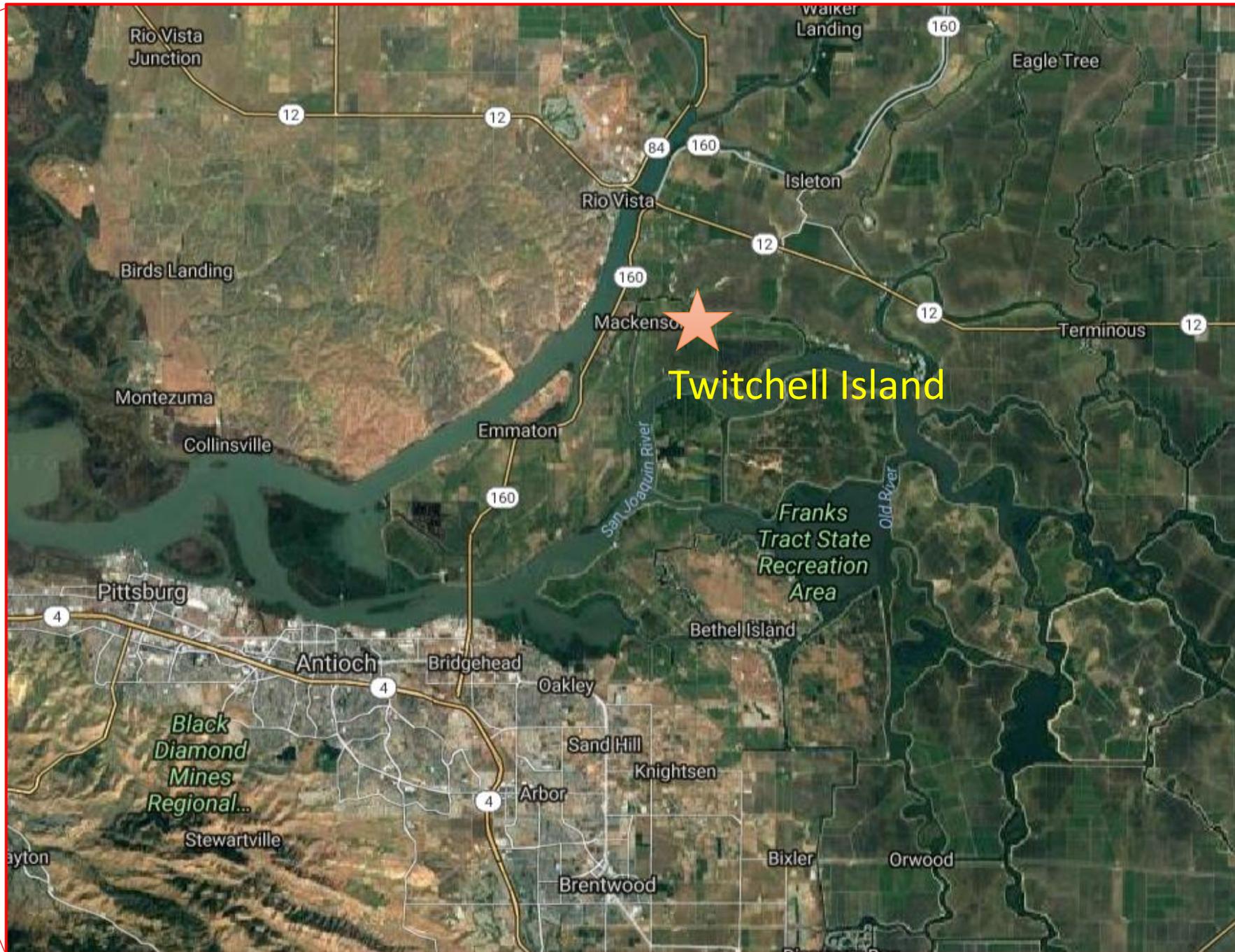
3 layer Model



Dispersion curves obtained from ambient noise mainly reflect S-wave velocity beneath receiver array

5. CMPCC and CMPSPAC

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 - Real data example

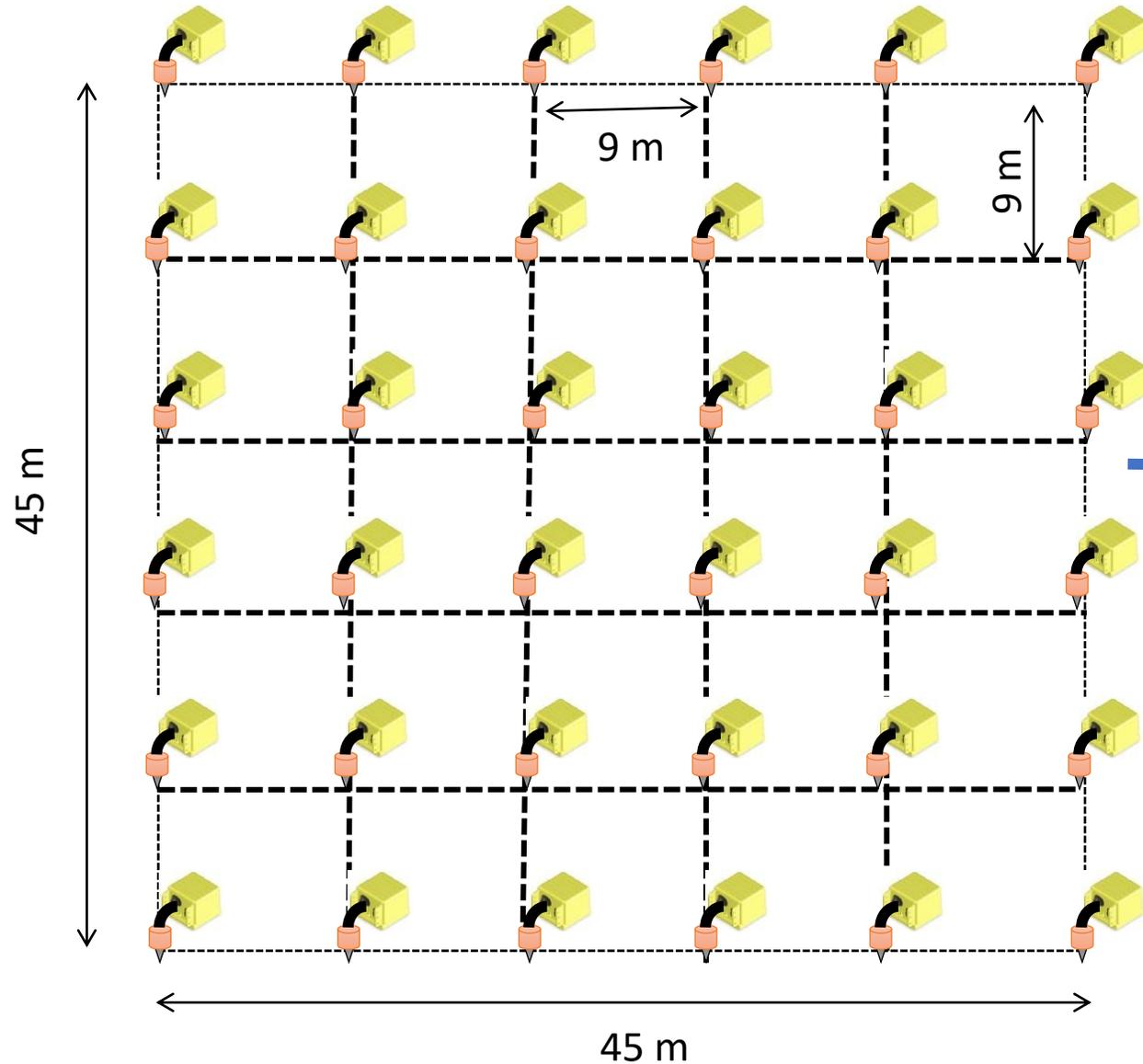


3D measurements at 2 Islands

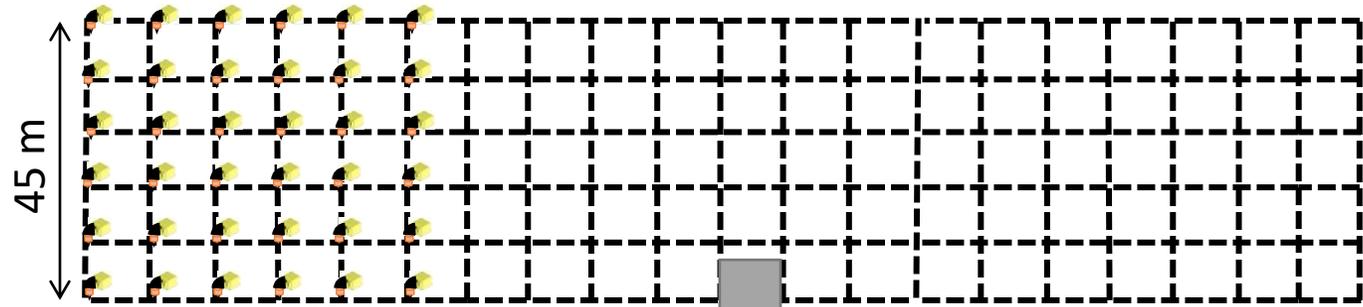
36 Atoms



One measurements (36 Atom AUs)

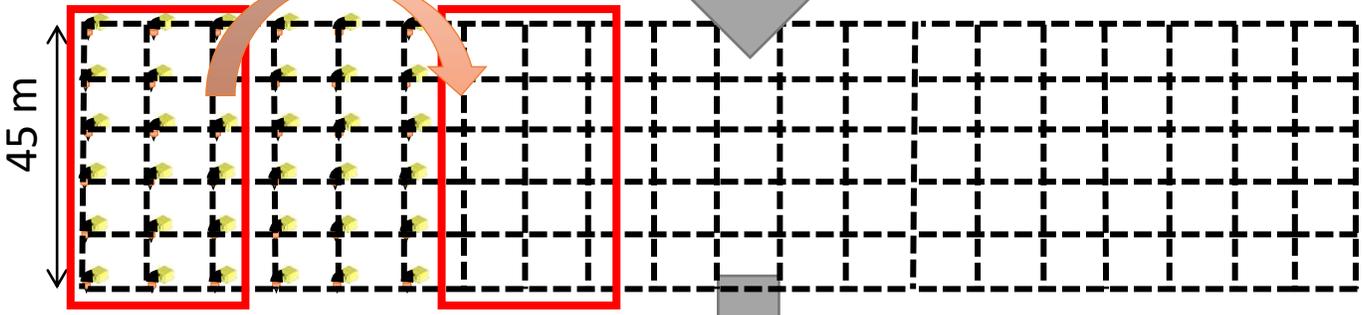


1)



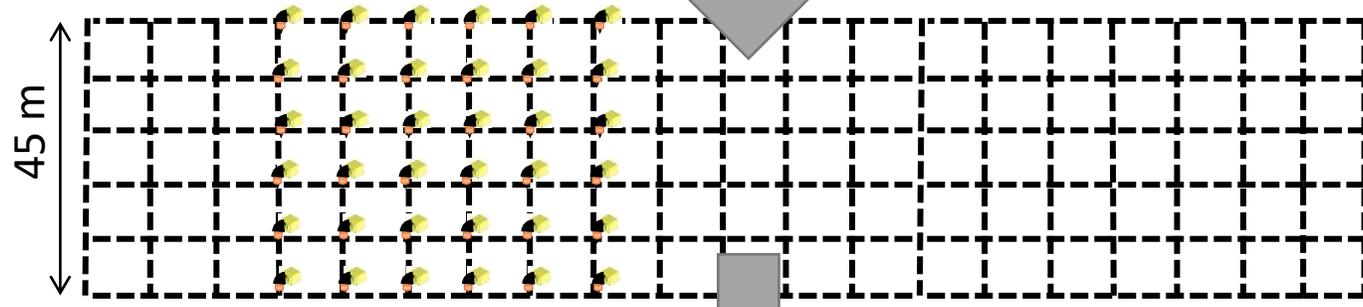
1st measurement.
Recording 15 to 20 min.
ambient noise.

2)



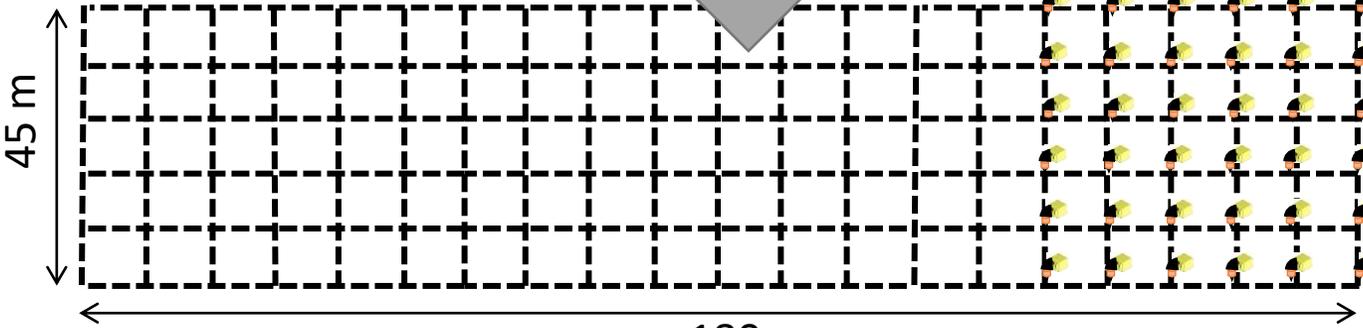
Total data acquisition took half
a day with several people.

3)



2nd measurement.
Recording 15 to 20 min.
ambient noise.

4)

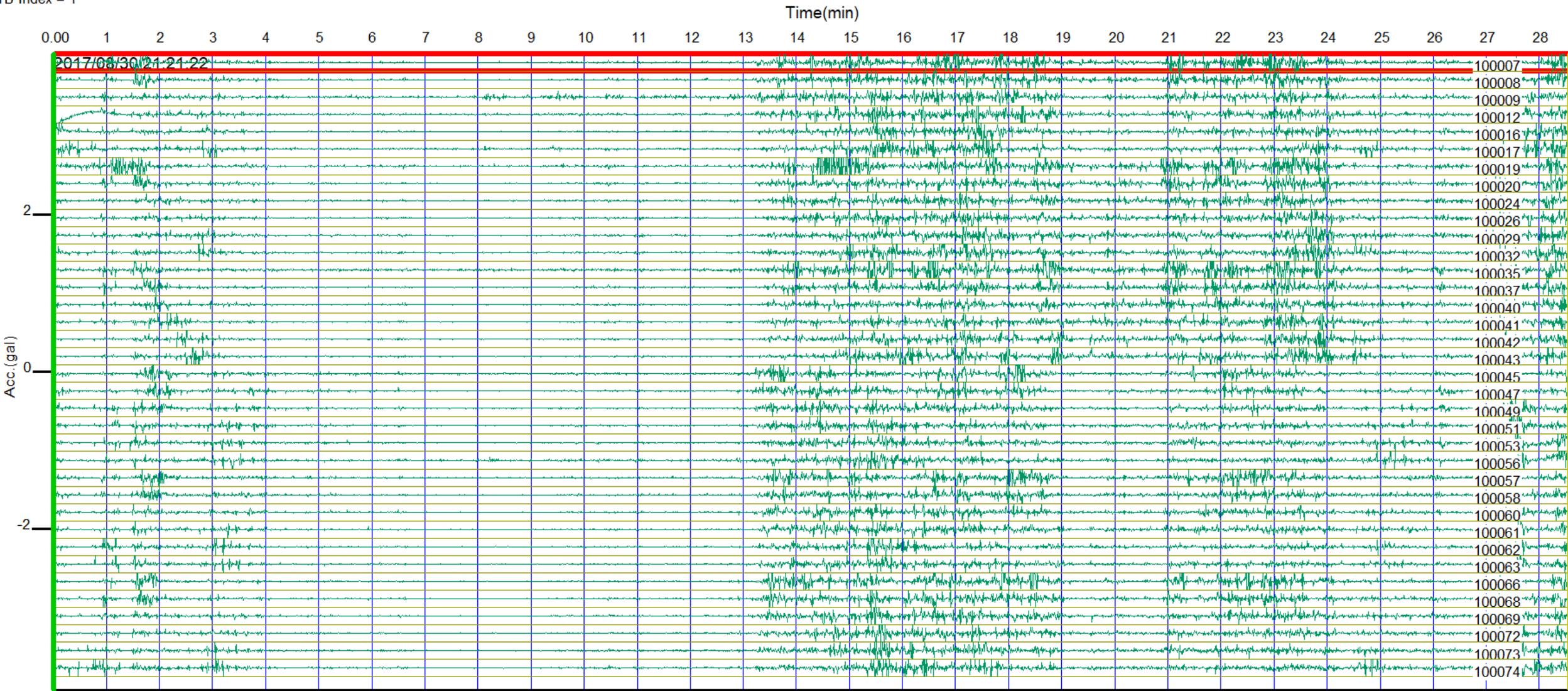


6th measurements.

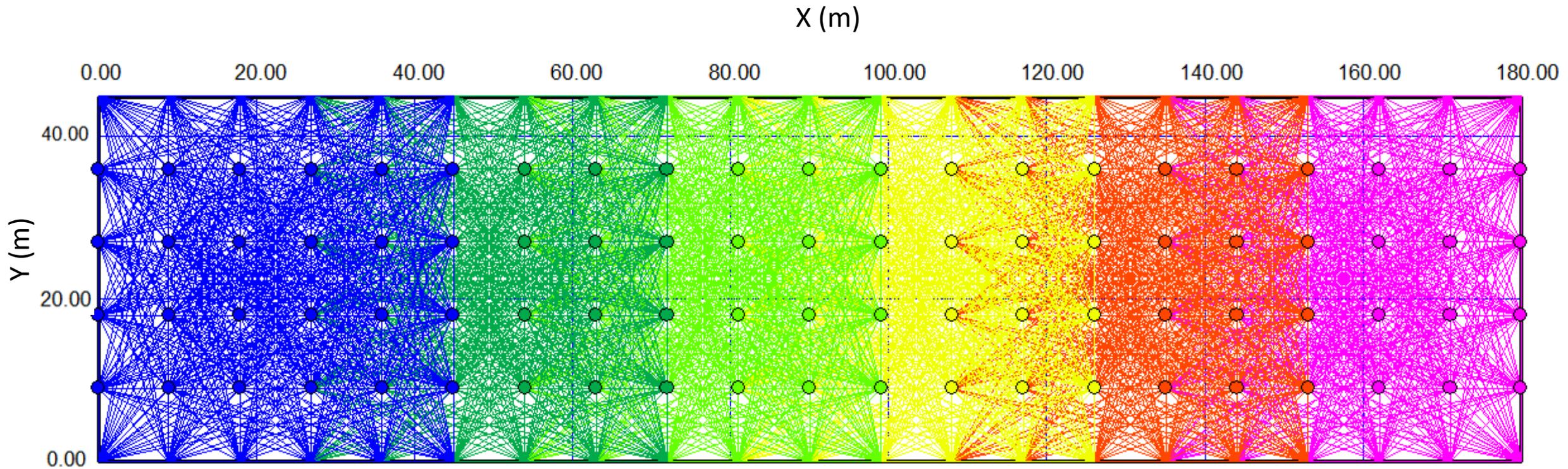
Sensors.

Raw data example

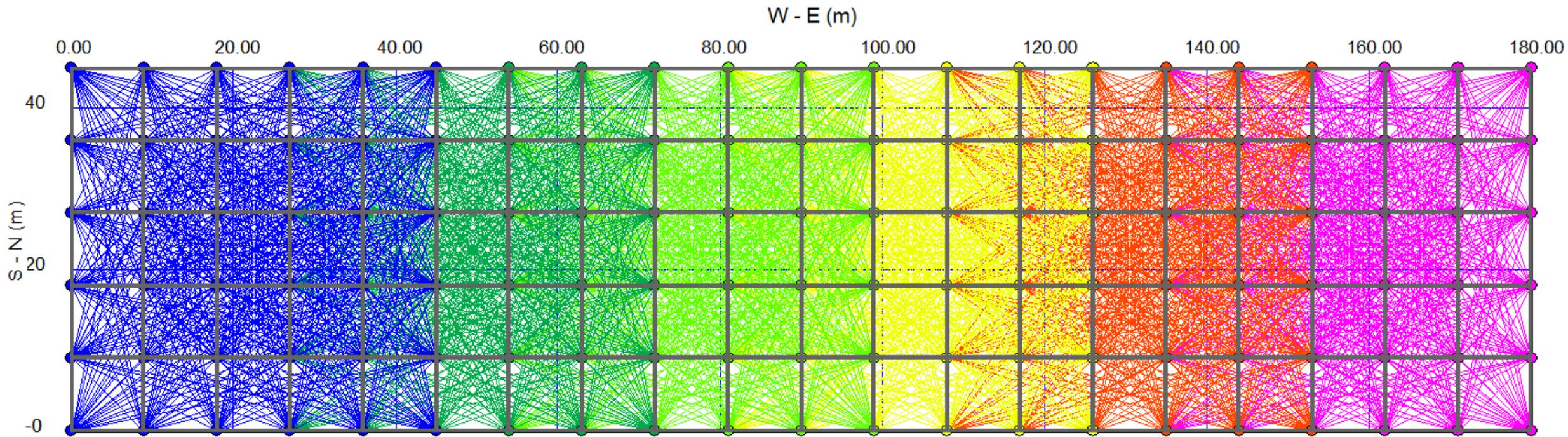
CTB Index = 1



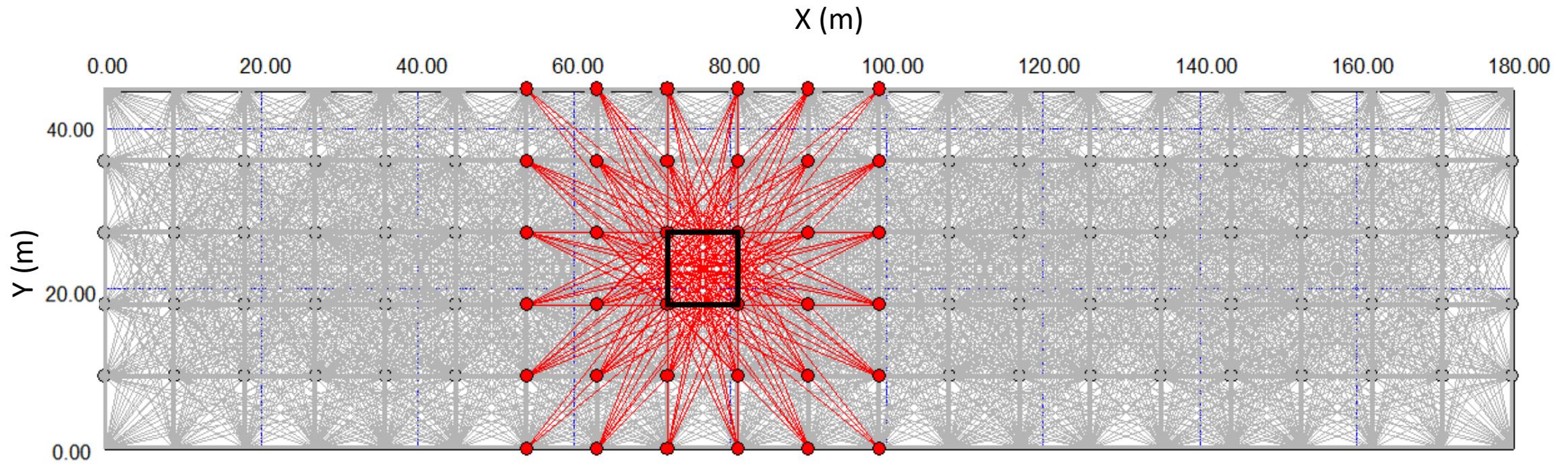
Coherencies are calculated
for all time blocks and all receiver pairs



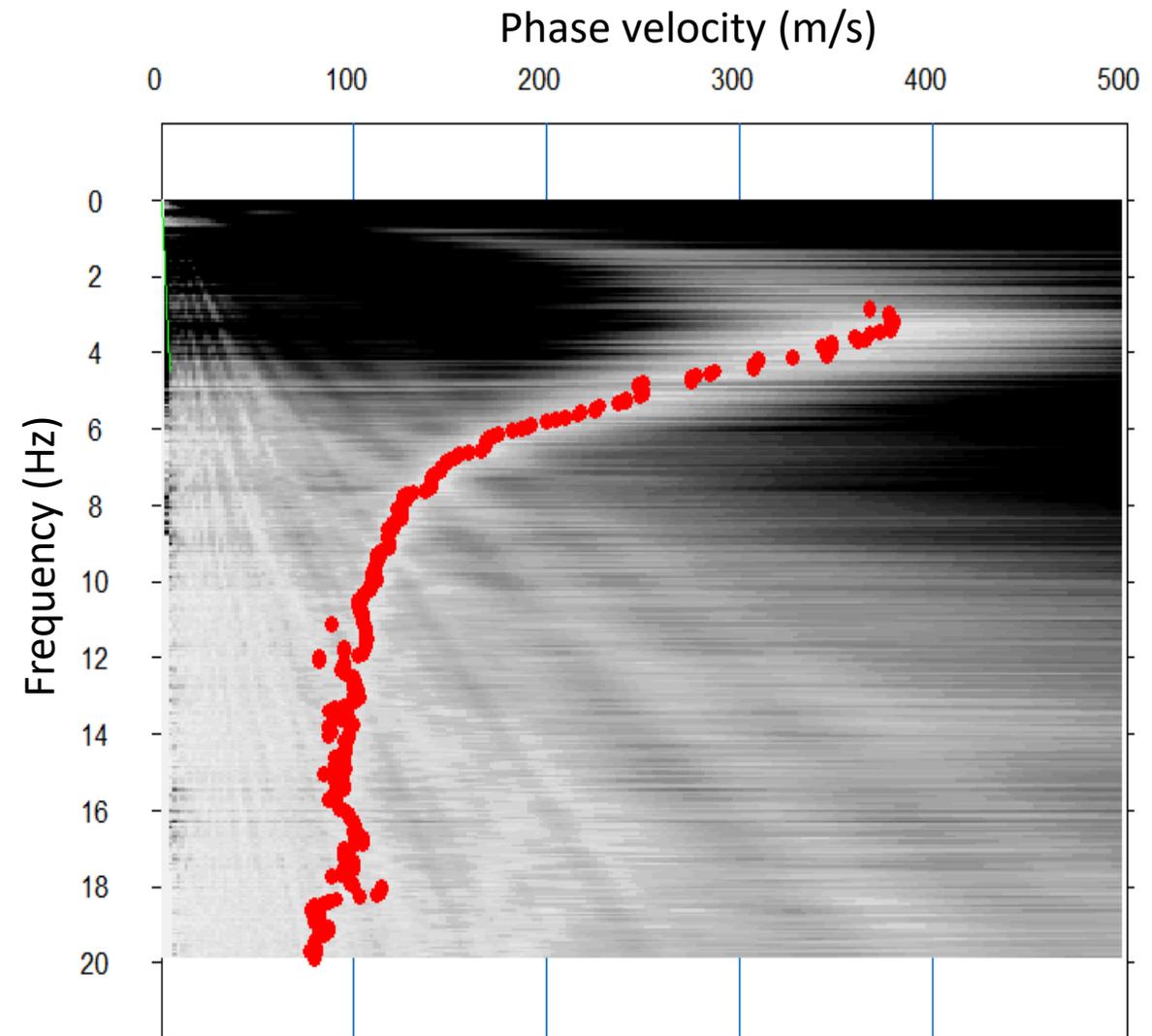
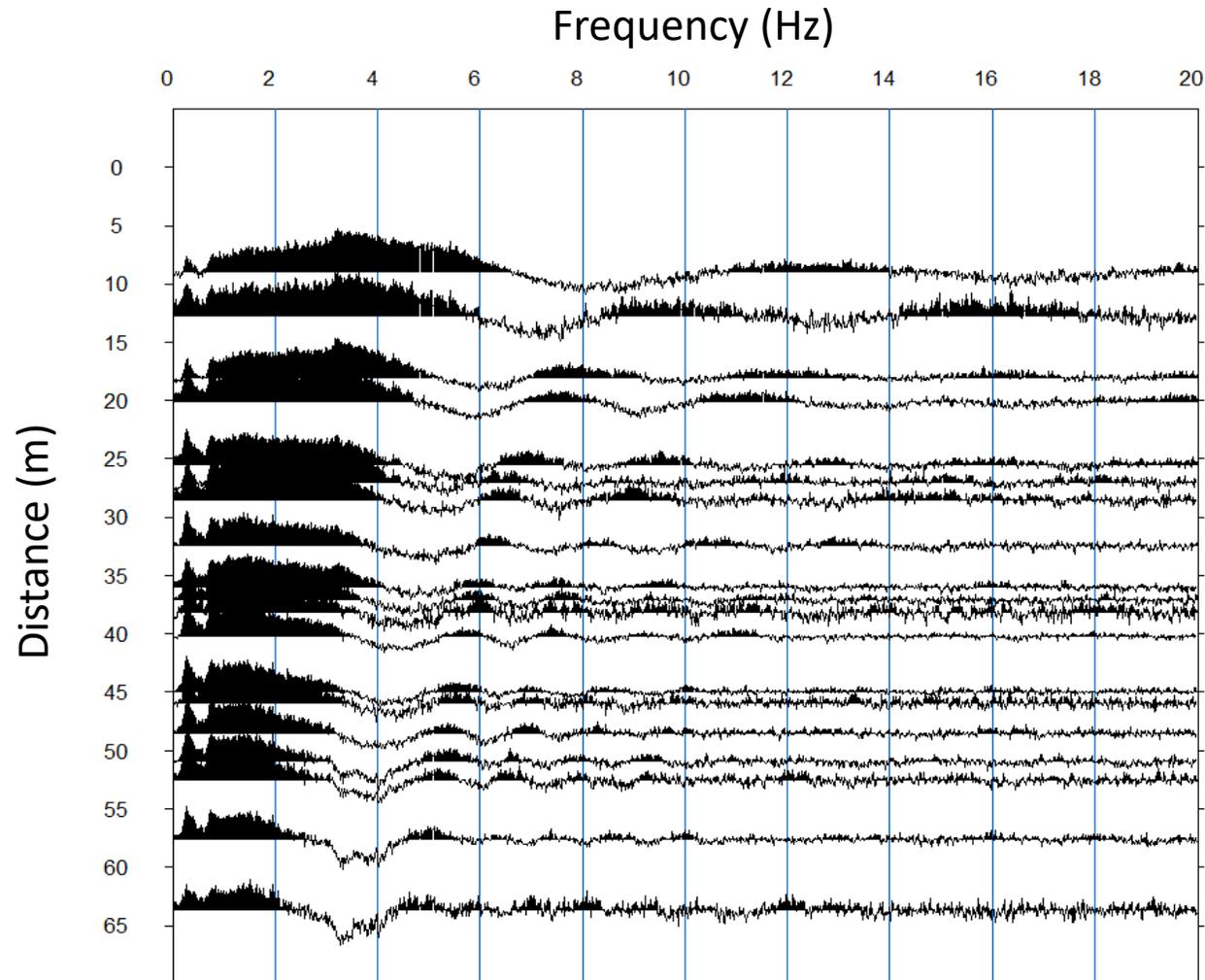
Coherencies are sorted by CMP.



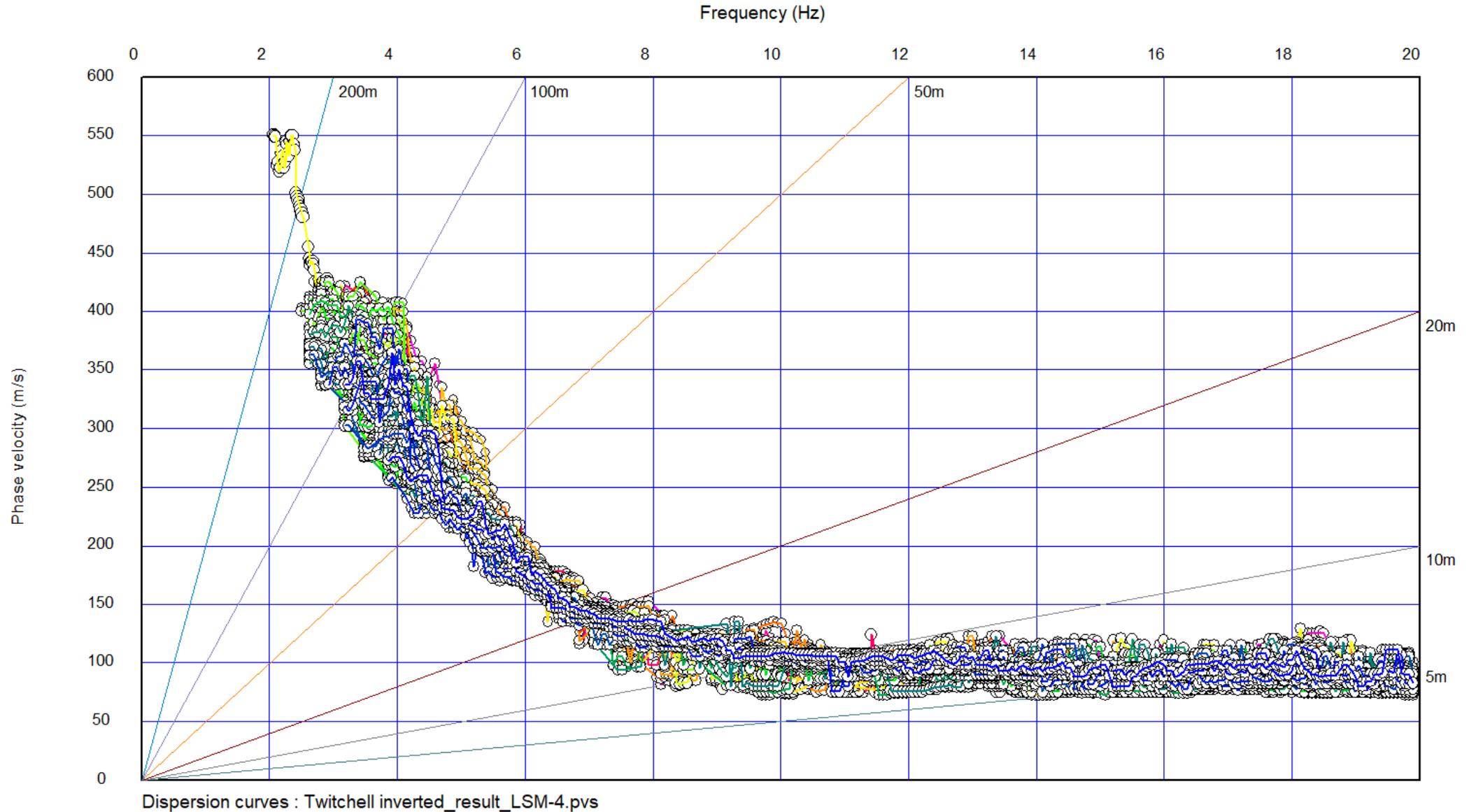
The real part of coherencies at each CMP can be considered as spatial autocorrelation (SPAC), since coherencies were calculated from receiver pairs with many different directions and thus include directional averaging



Dispersion curves are calculated from each CMP-SPAC gather by comparing observed SPAC traces and theoretical Bessel functions

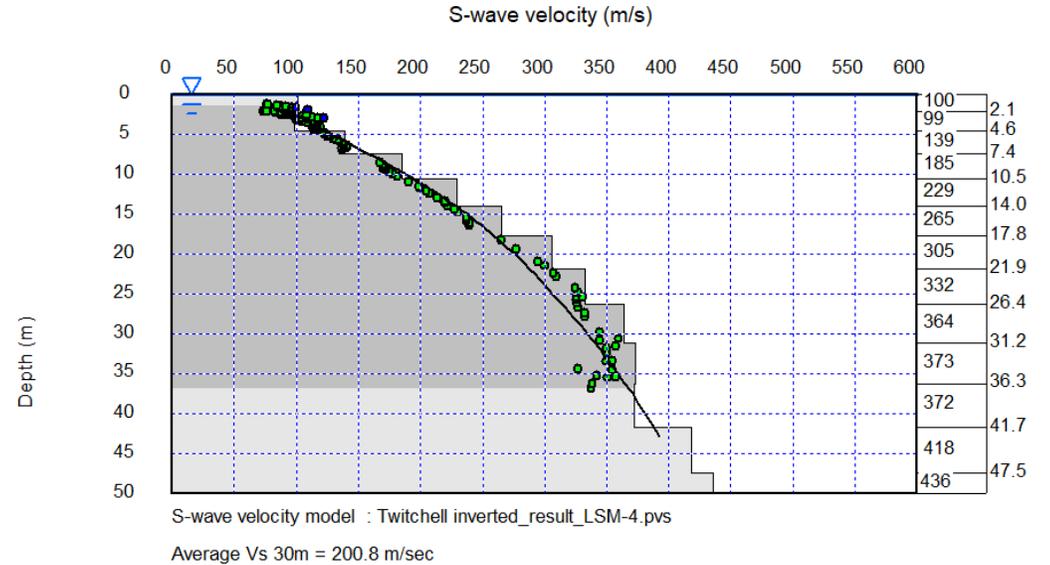
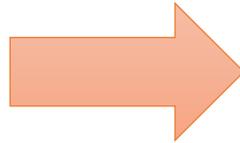
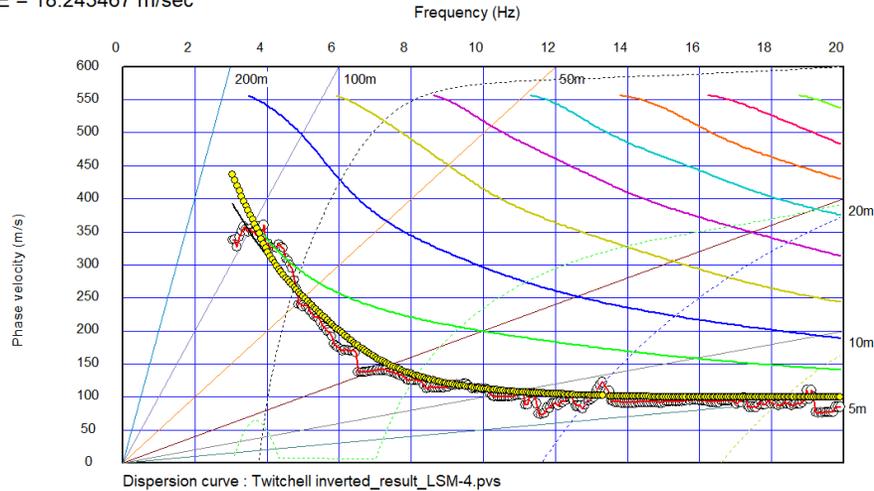


Dispersion curves calculated from all CMP-SPACs

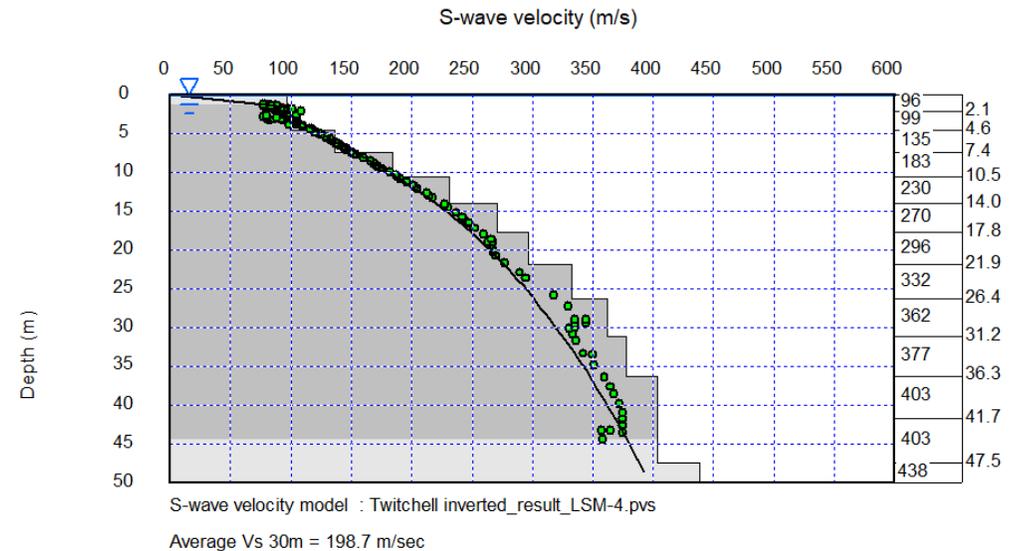
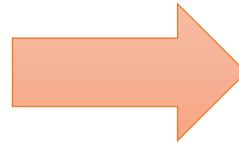
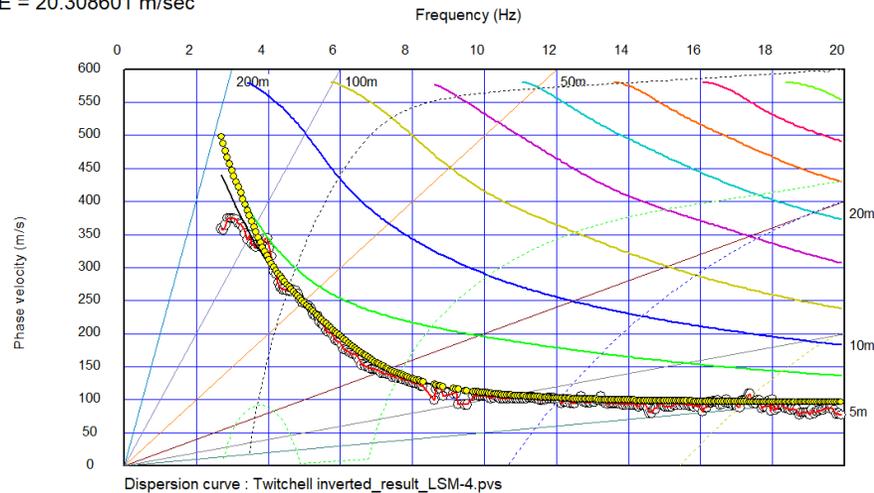


1D inversion estimates V_s profiles from each dispersion curves

Index=21 Station name = CMP 21 (X=40.500000m Y=13.500000m)
 RMSE = 18.243467 m/sec

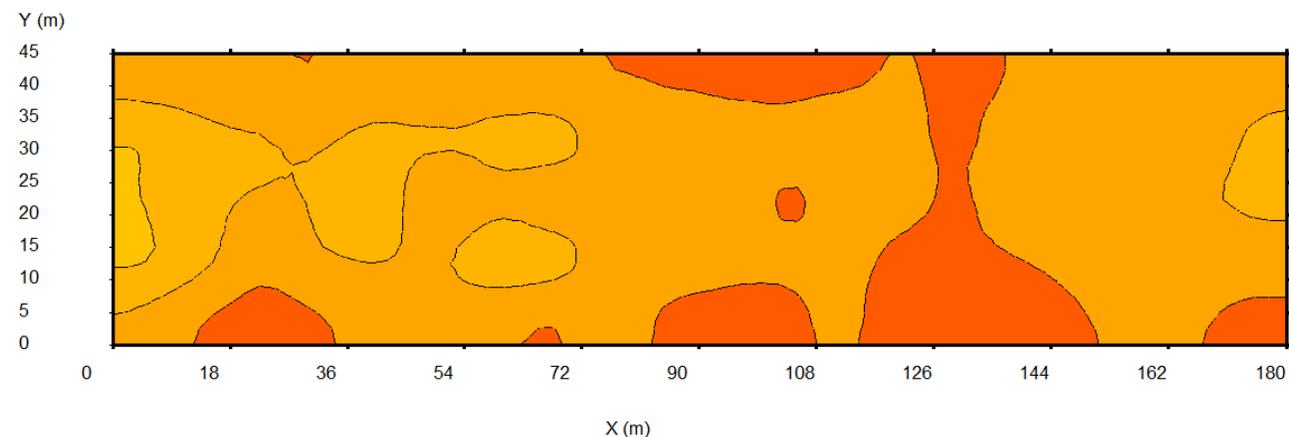


Index=42 Station name = CMP 42 (X=76.500000m Y=22.500000m)
 RMSE = 20.308601 m/sec

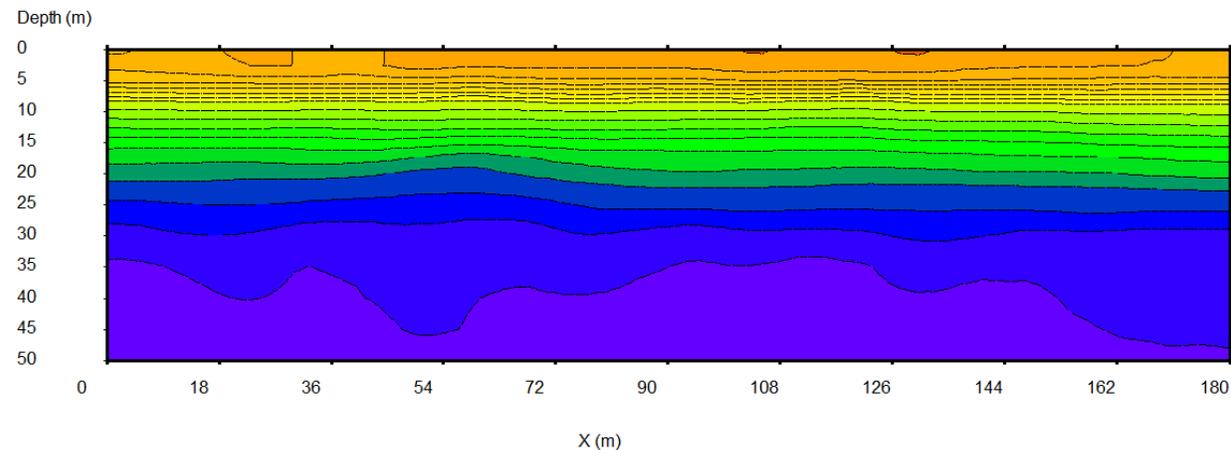


Twitchell Island : S-wave velocity model

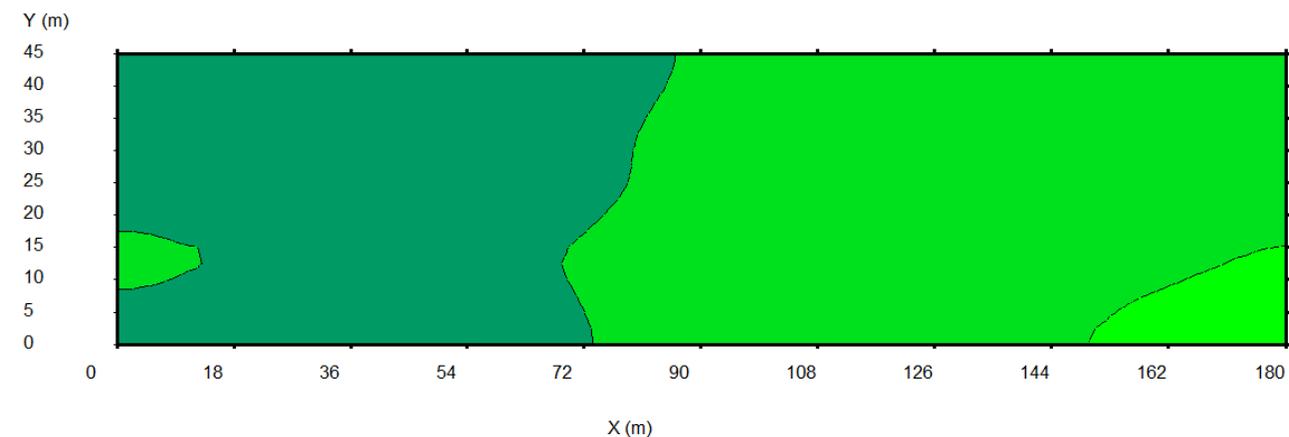
Depth slice (Z=0~2.5 m)



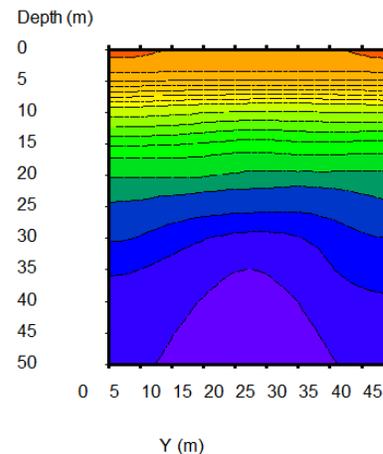
Cross section (Y=20.0~22.5 m)



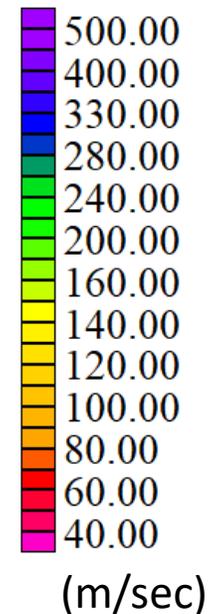
Depth slice (Z=17.5~20.0 m)



Cross section (X=100.0~102.5 m)

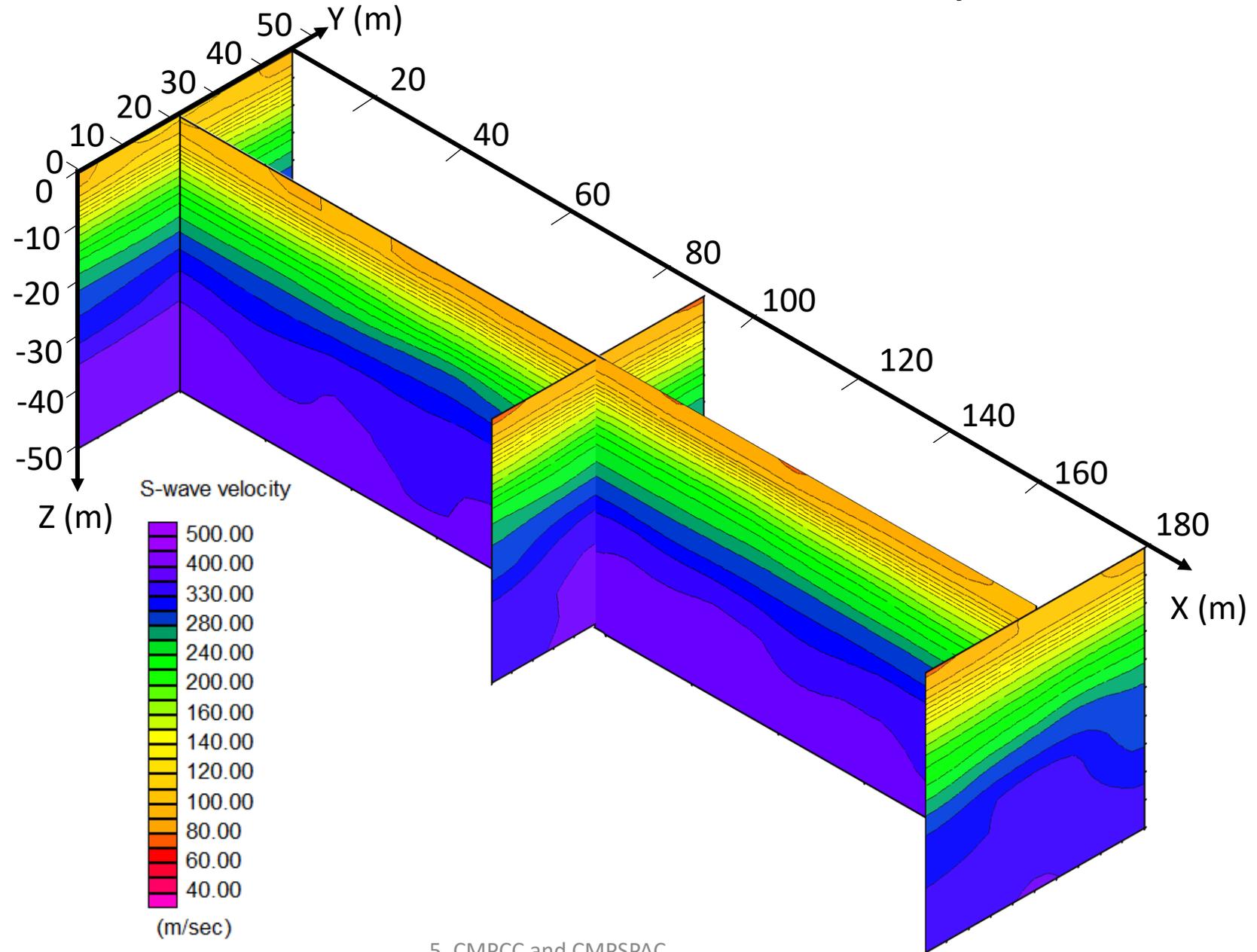


S-wave velocity



Investigation depth is 40 m

Twitchell Island : S-wave velocity model



Questions ?

