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Lehrgang zur Verarbeitung von Oberflächenwellen

16. prosince 2025, Albertov 6, Praha 2 a online

16. Dezember 2025, Albertov 6, Prag 2 und online

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Evropskou unií

FACULTY OF SCIENCE
Charles University

SURFACE WAVES FOR NEAR-SURFACE CHARACTERIZATION

basic analysis

Martin Mazanec

Jan Valenta

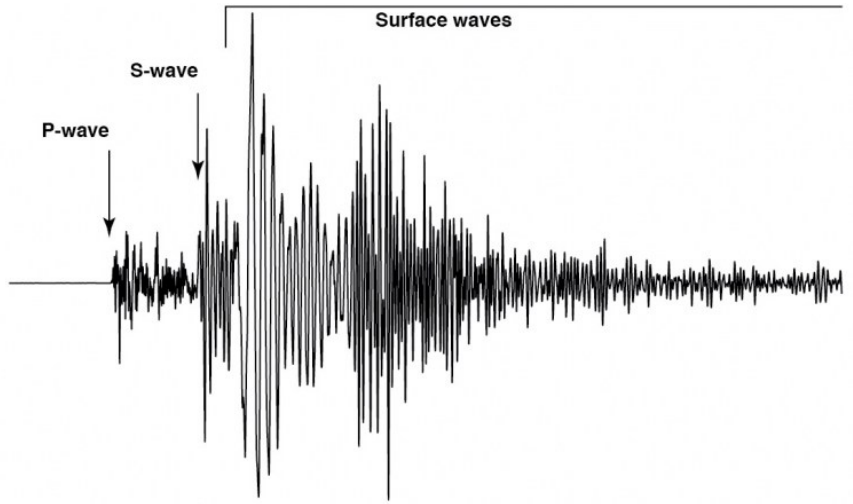
MOTIVATION

Surface waves

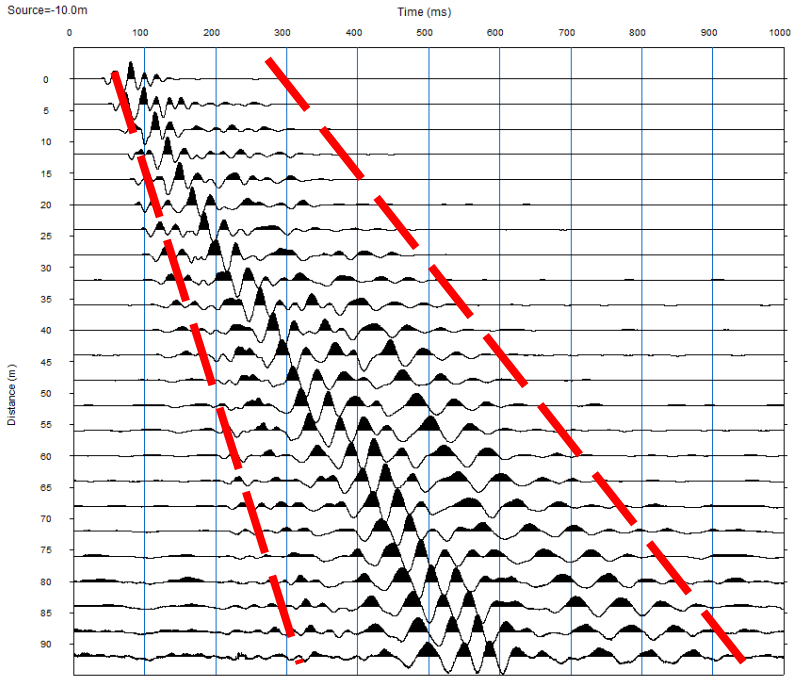
- Dominant part of the seismic record
- Miller and Pursey (1955):
  - Surface waves 67%
  - P-waves 7%
  - S-waves 26%
- Surface wave vel. (V_{SW}) closely related to shear-wave vel. (V_S)

$$V_{SW} \approx 0.87–0.95 \cdot V_S$$

- Can be estimated from refraction data



(geo.mtu.edu)



MOTIVATION

Shear-wave velocity

- V_S directly related to the shear modulus of the soil skeleton

-> more sensitive to changes in rock mass disturbance than P-wave velocit (V_P)

-> extend the potential of conventional near-surface geophysics

Why S-Velocity (Vs)?

— Because of Shear (μ) and Young's (E) Moduli —

$$\mu = \rho V_s^2 \qquad (\rho = \text{density})$$

(Shear modulus heavily depending on V_s)

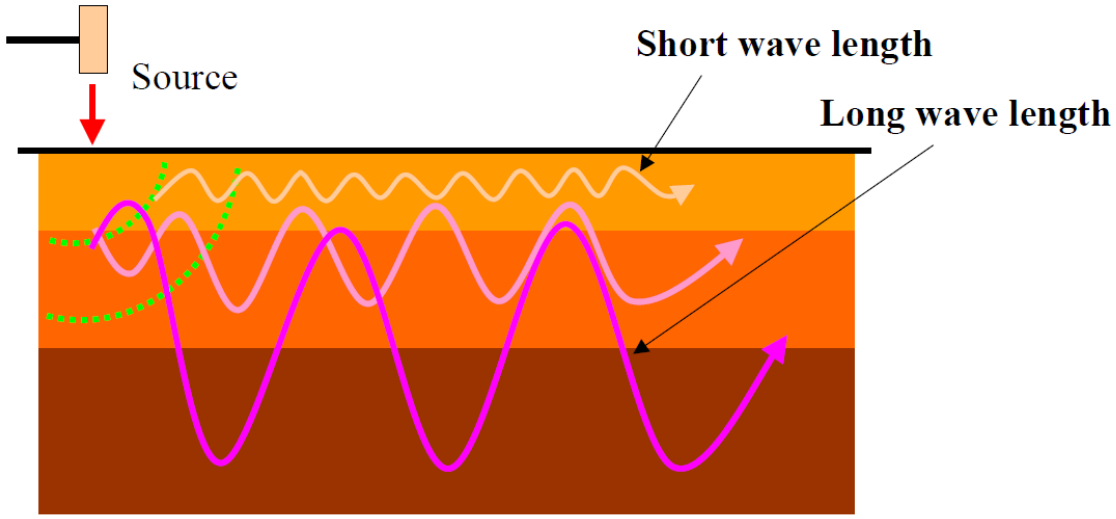
$$E = \rho V_s^2 \frac{3\left(\frac{V_p}{V_s}\right)^2 - 4}{\left(\frac{V_p}{V_s}\right)^2 - 1}$$

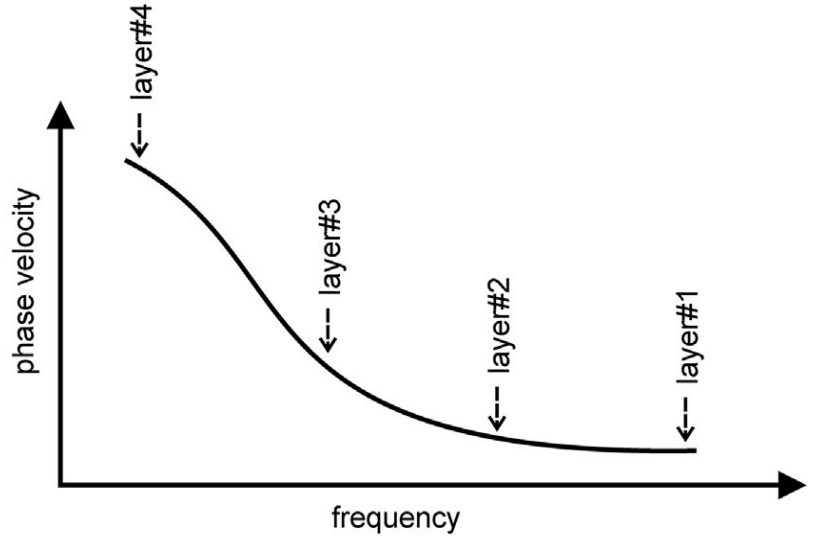
(Young's modulus heavily depending on V_s, and almost neutral to V_p/V_s or Poisson's Ratio, σ)

(From Suto, 2007)

SURFACE WAVES

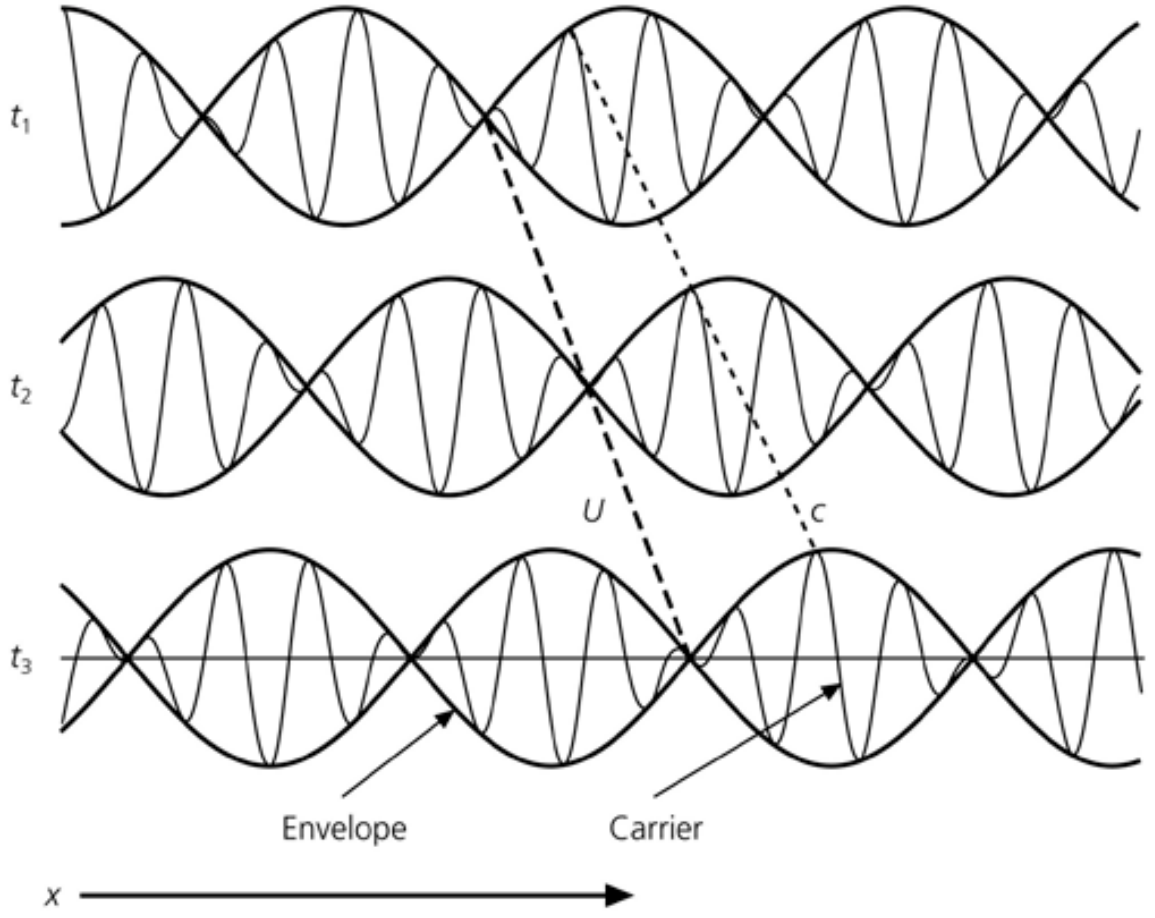
- resulting from the complex interaction between body waves and the mechanical boundary condition imposed by the surface
- Rayleigh waves
  - Retrograde elliptical particle motion
  - Vertical + radial components
- Love waves
  - Horizontally polarized SH motion
- Dispersive = velocities are a function of frequency
- Amplitude decays exponentially with depth





SURFACE WAVES ANALYSIS

- *Phase Velocity - velocity of a constant phase of the wave (e.g. a wave crest):*
- *Group Velocity – velocity of the the wave packet envelope propagation:*
    - *thus represents the velocity of energy and information transfer.*



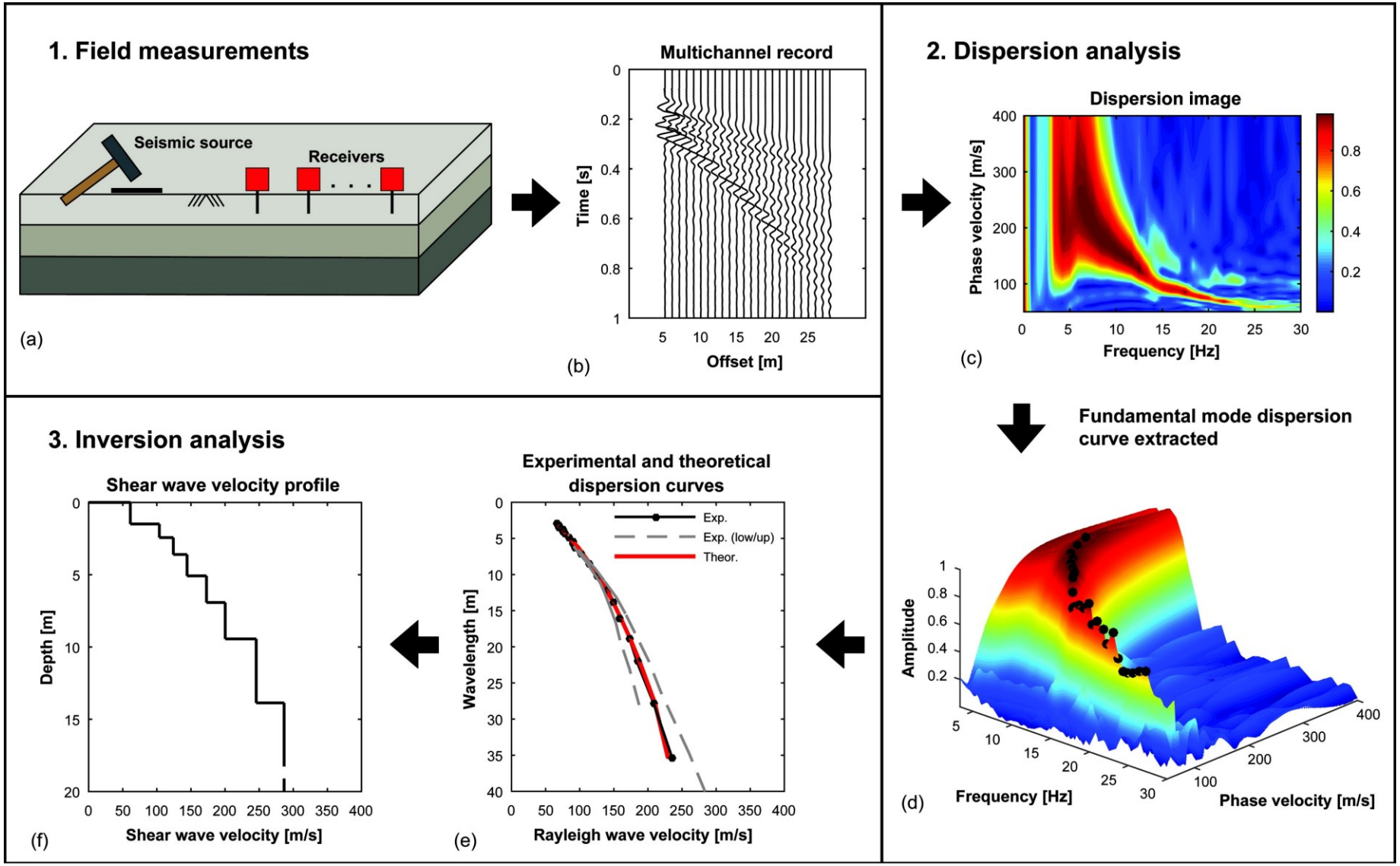
METHODS

PASSIVE

	Technique	Pros	Cons	Notes
Active	Standard MASW (vertical-component of Rayleigh waves and modal dispersion analysis)	Pretty popular	Velocity spectra can be highly ambiguous (and, consequently, the picking erroneous) Solution is non-unique (see Sect. 1.3)	Dispersion can be analyzed considering the dispersion curves or according to the FVS approach (more detailed with respect to the standard approach based on the modal dispersion curves—see Chap. 2)
	Multi-component MASW	Requires the acquisition of at least 2 components (see Figs. 1.6 and 1.7)	It solves the ambiguities of the velocity spectra It strongly reduces the non-uniqueness of the solution	
	HS (*HoliSurface—Holistic analysis of Surface waves*)	Very simple acquisition setting (just one 3-component geophone)	Currently still not very popular	
	SH-wave refraction	Reconstruction of 2D sections	Complex field operations Limited investigated depth The presence of shallow stiff layers prevents from the correct identification of the deeper velocities (i.e. the identification of velocity inversions is problematic)	–
Passive	ReMi	–	Ambiguities in the determination of the *effective* dispersion curve (due to the linearity of the array which, in passive seismics, does not allow to handle the directivity of the signals)	Dispersion must be modelled according to the *effective* dispersion curve and **not** to the fundamental mode (details in Chaps. 3 and 4)
	ESAC (Extended Spatial AutoCorrelation)/ SPAC (SPatial AutoCorrelation)	Obtained *effective* dispersion curve does not suffer from the ambiguities typical of the ReMi approach	Complex field operations (necessary large *bidimensional* arrays—SPAC requires circular geometries)	
	MAAM (*Miniature Array Analysis of Microtremors*)	It requires just 4 or 6 (high-quality) vertical geophones and limited room (for near surface applications about 2–5 m—see Chap. 4)	Very sensitive to the quality of the equipment and to the accuracy of the acquisition procedures (see Dal Moro 2019b and Chap. 4 of this book)	
	HVSR (*Horizontal-to-Vertical Spectral Ratio*)	Simple acquisition procedures	Highly non-unique	Recommended to be used only together with dispersion data (see other methods)

(Dal Moro, 2020)

Multichannel analysis of surface waves (MASW)



(Olafsdottir, 2016)

Multichannel analysis of surface waves (MASW)

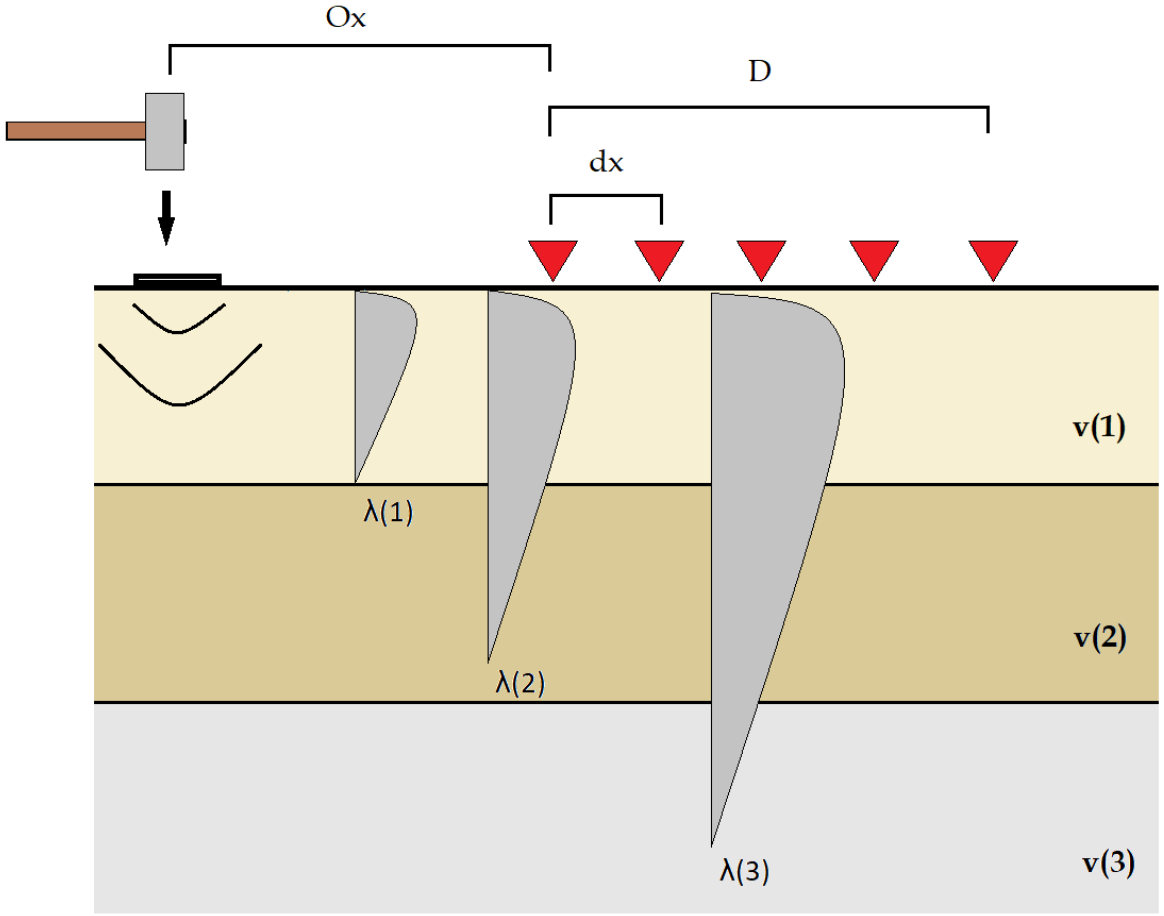
Assumptions

- Approximate lateral homogeneity along the profile
- Predominantly 1D vertical layering
- Sufficient contrast in shear-wave velocity with depth
- Dominance of surface waves in recorded data
- Coherent wavefield across the array
- Adequate frequency content for the target depth
- Correct and accurate array geometry
- Limited influence of near-field effects

1. DATA ACQUISITION

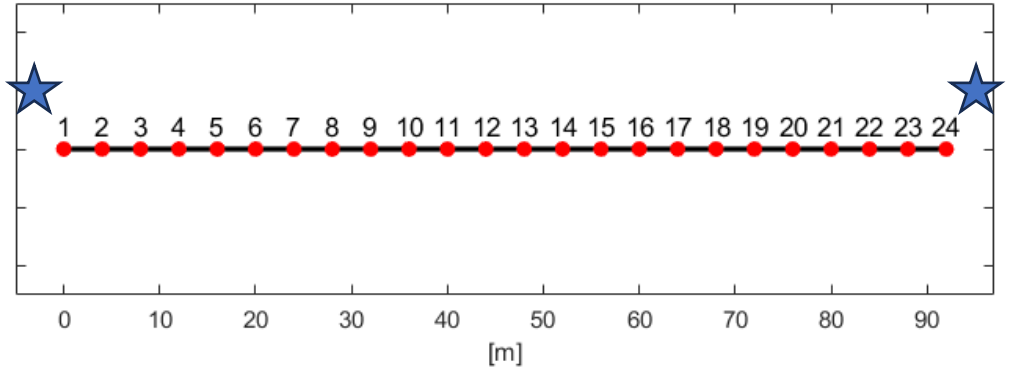
Active data - parameters

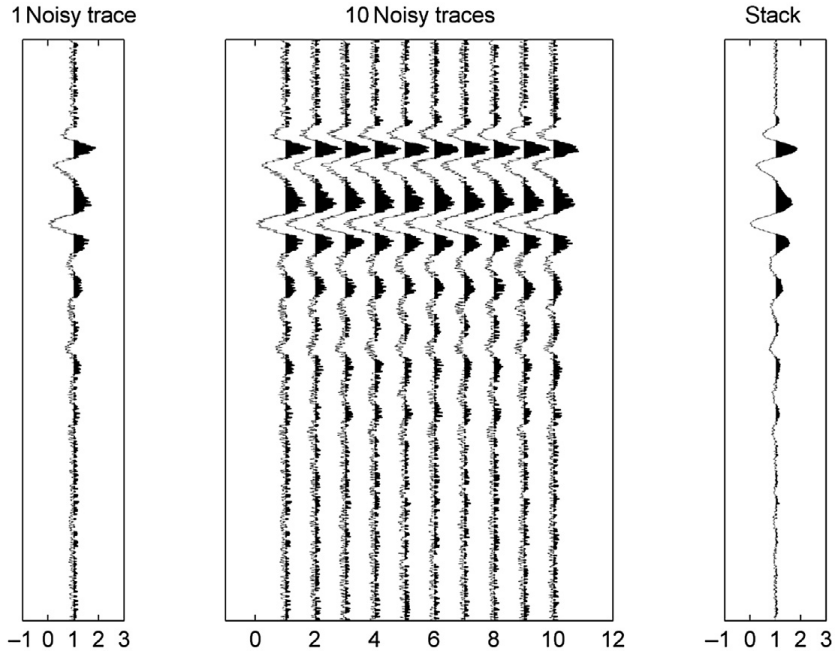
- Minimum shot offset: 5-20 m
- Geophone spacing (d_x): 3-5 m
- Z_{max} = array length = *0.3-0.5* λ_{max}
- $Z_{min} = kd_x$ (0.3≤ k≤ 1.0)
- Recording time: 1-2 s
- Sampling frequency: 1000 Hz
- Multiple shots -> stacking



1. DATA ACQUISITION

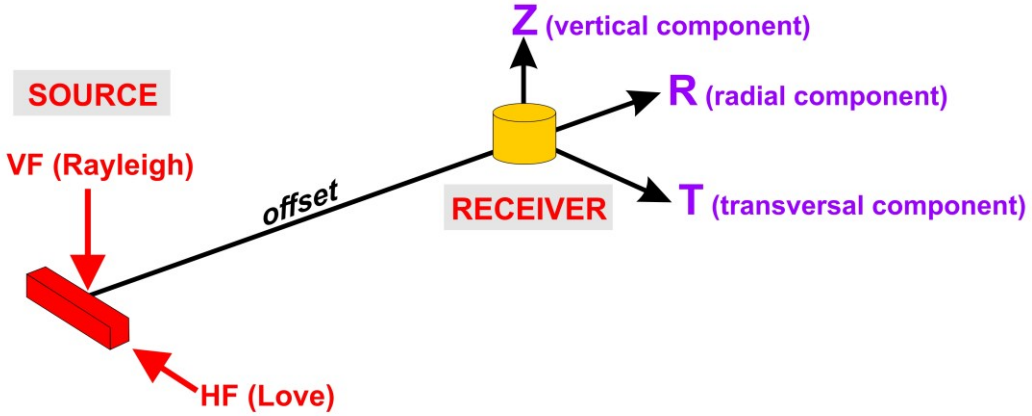
Active data - array

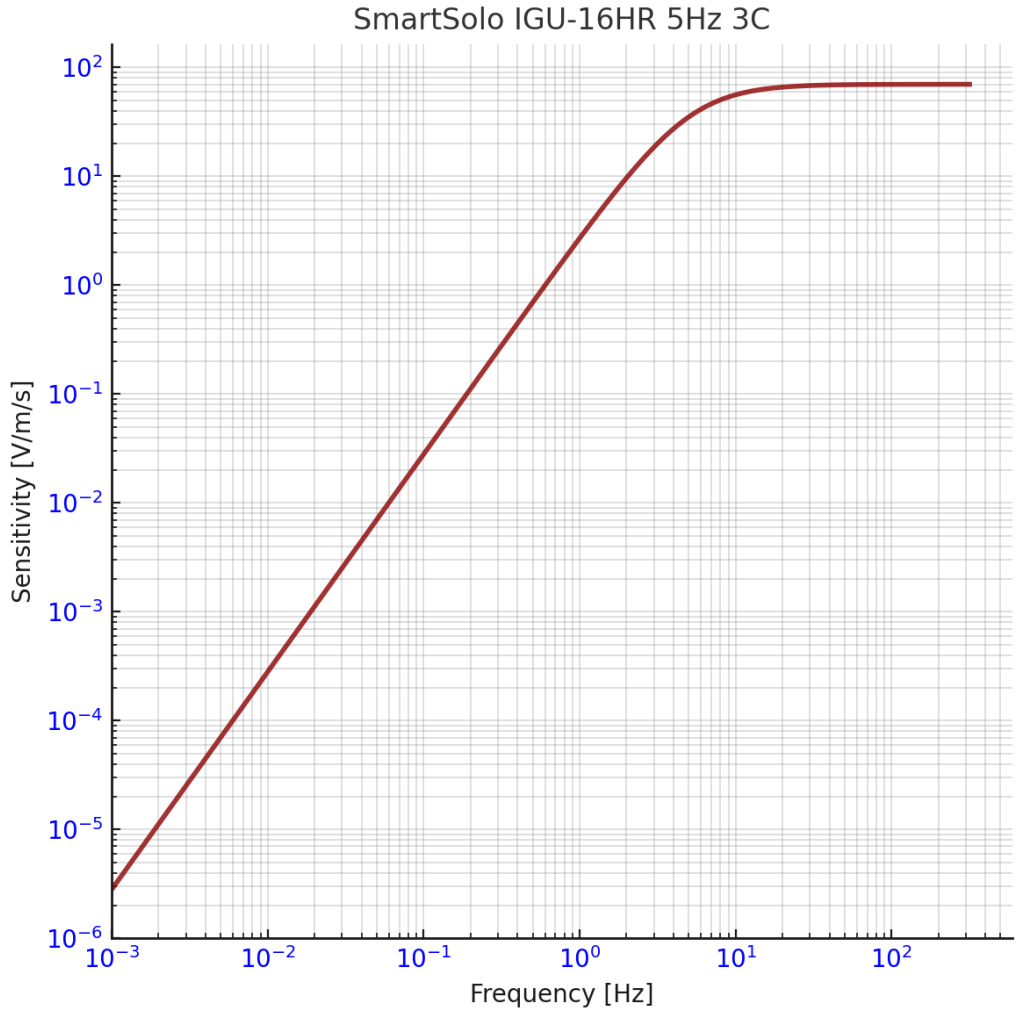




1. DATA ACQUISITION

Active data - recievers

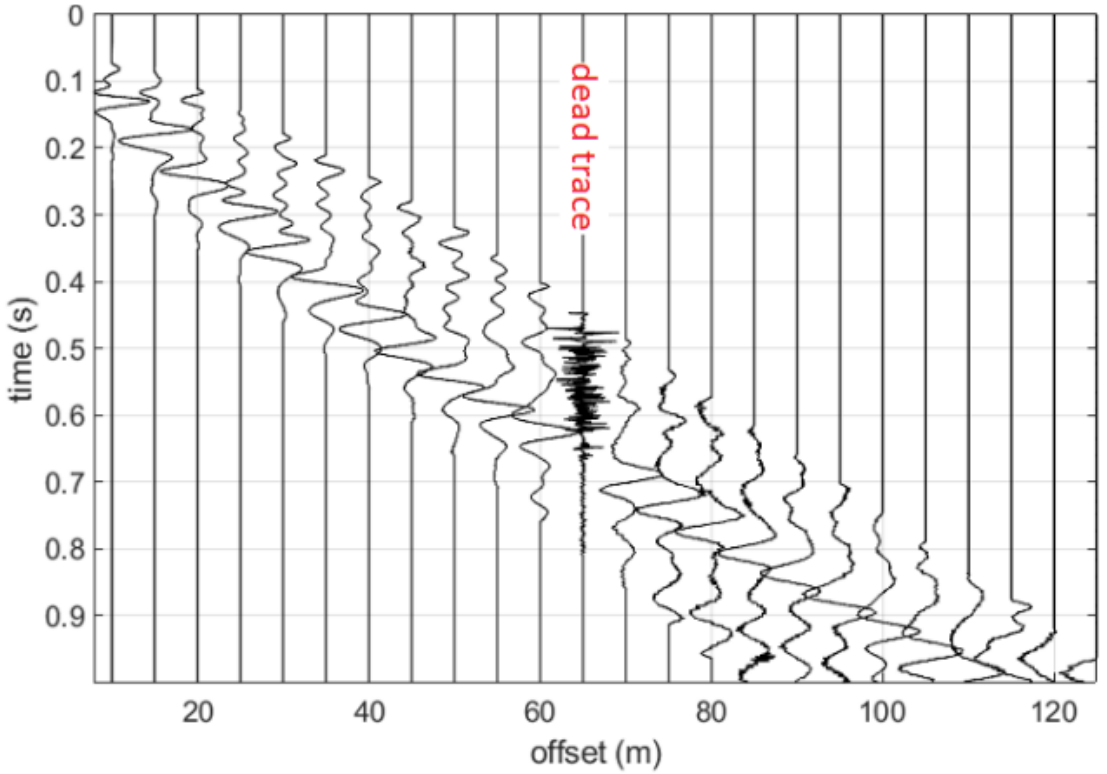




2. MULTICHANNEL DATA PROCESSING

Data quality control

- Geophone coupling
- Raw data inspection
- Signal-to-noise considerations
- Frequency range actually usable for dispersion
- Penetration depth estimation



2. MULTICHANNEL DATA PROCESSING

Dispersion analysis

Table 2
List of methods adopted for the processing of surface wave data.

Label	Method	Data	References
FK	Frequency-wavenumber transform	active	[29]
PF	Slowness-frequency transformation method	active	[30]
PS	Phase-shift transform, a special case of PF transform	active	[31]
FDBF	Frequency domain beamformer	passive	[29,68]
HFK	High resolution frequency-wave-number transform	passive	[27]
SPAC	Spatial Autocorrelation Coefficient method	passive	[26]
MSPAC	Modified SPAC	passive	[69]
3C+WD	Three component high-resolution f-k analysis and wave field decomposition	passive	[66,70]
SPAC_directFit[a]	SPAC spectra computed from smoothed coherency-frequency spectra	passive	[62]
FB[a]	Fourier-Bessel expansion coefficients	active	[63]
Ellipticity[a]	Ellipiticity of Rayleigh waves from the noise recordings	passive	[65]

[a] The experimental dispersion curve is not explicitly considered in the approach.

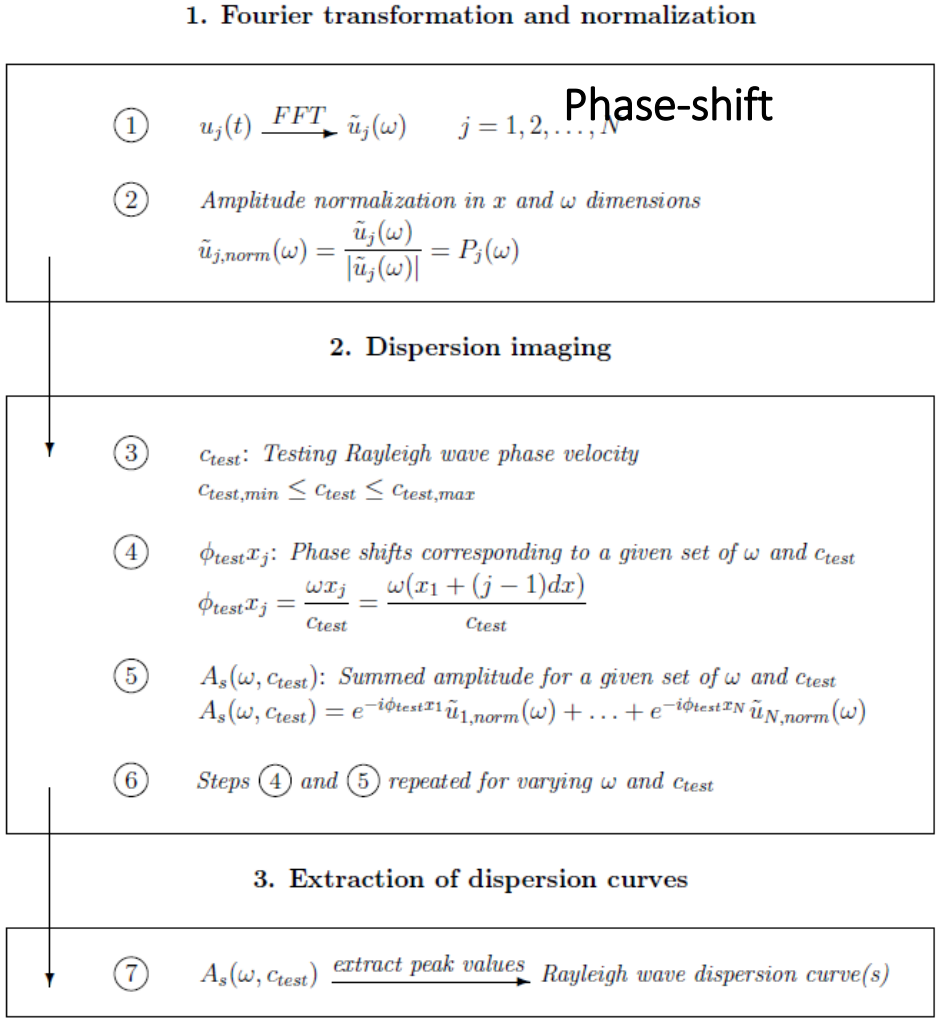
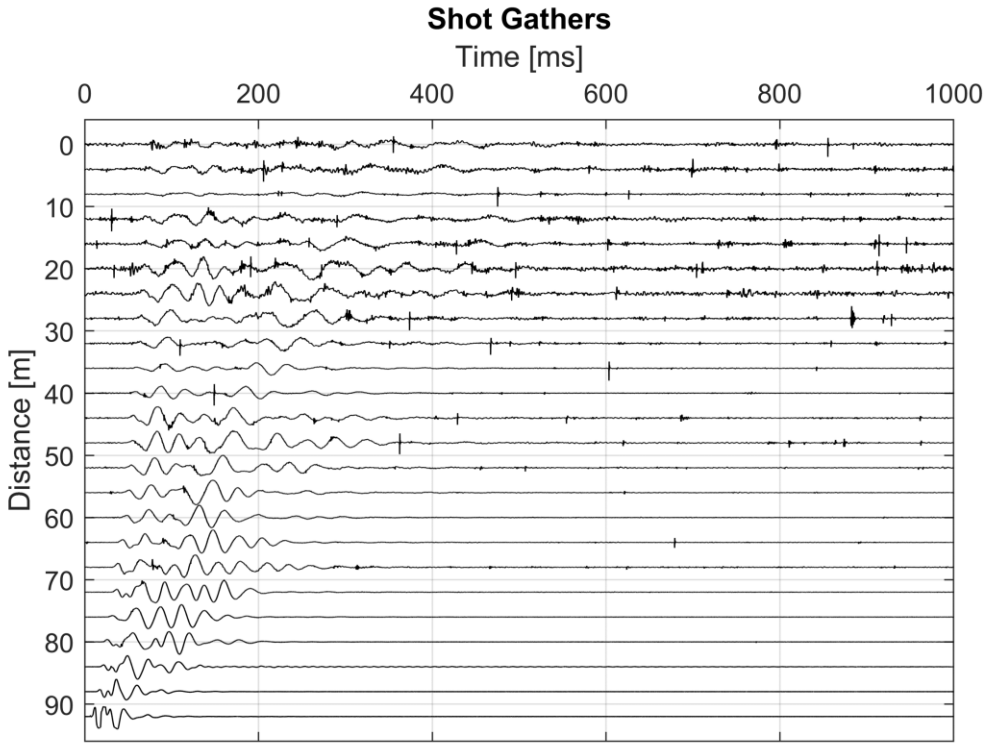


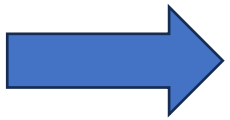
Figure 6.7: Overview of the phase shift method.

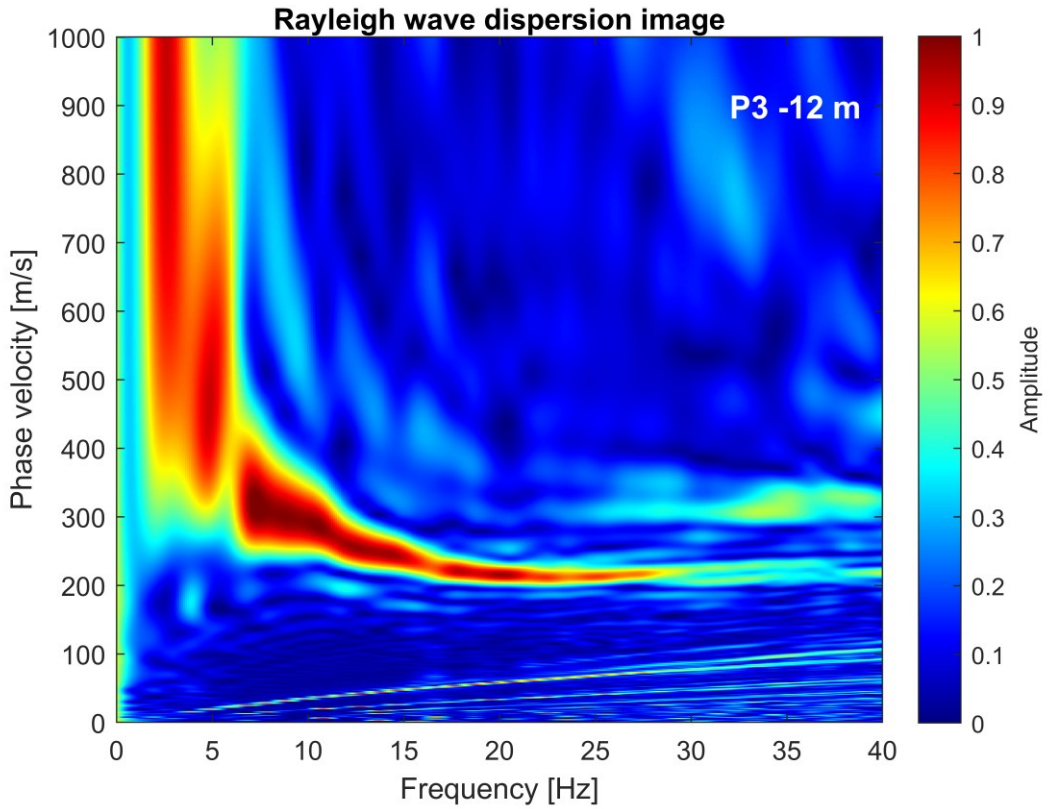
(Olafsdottir, 2016)

2. MULTICHANNEL DATA PROCESSING

Dispersion analysis





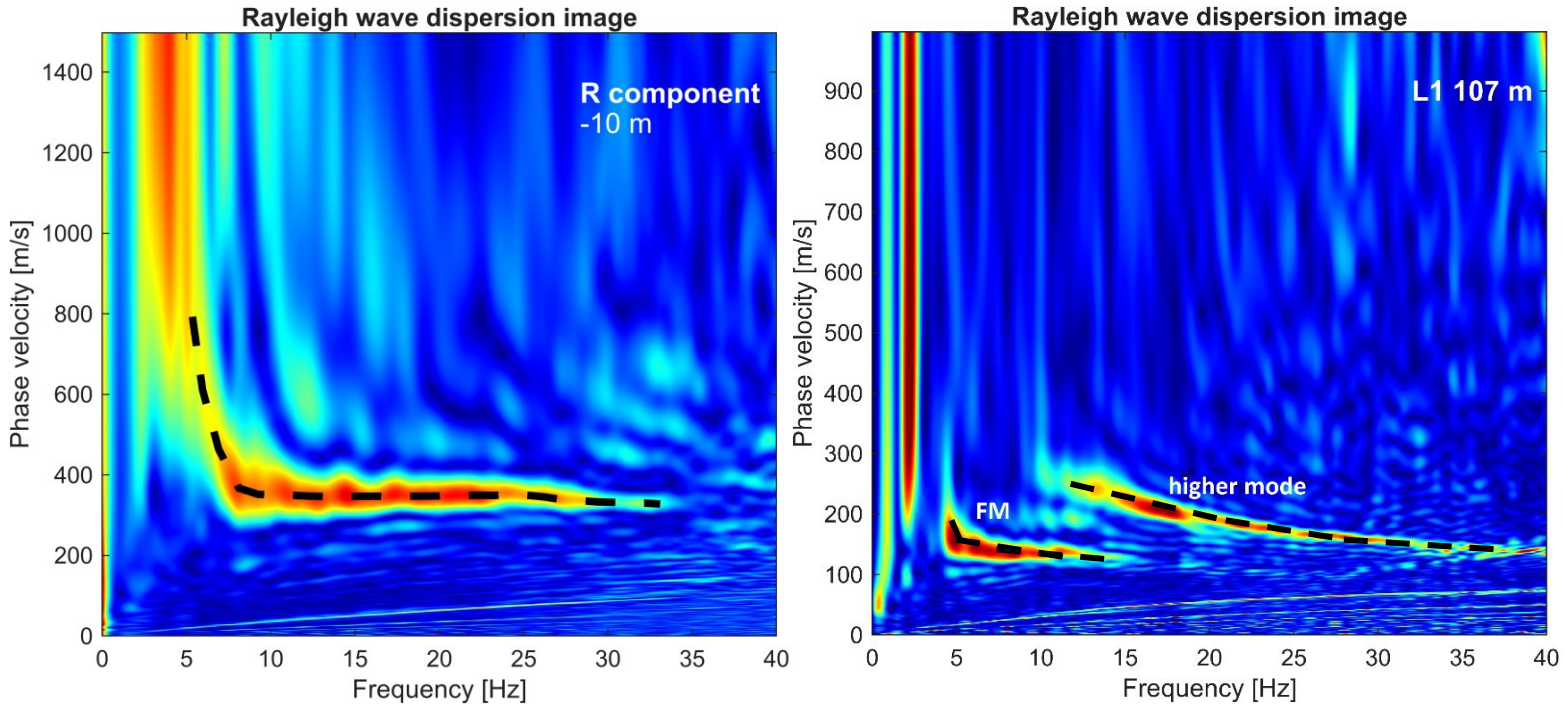


2. MULTICHANNEL DATA PROCESSING

Dispersion analysis

Dispersion curve picking

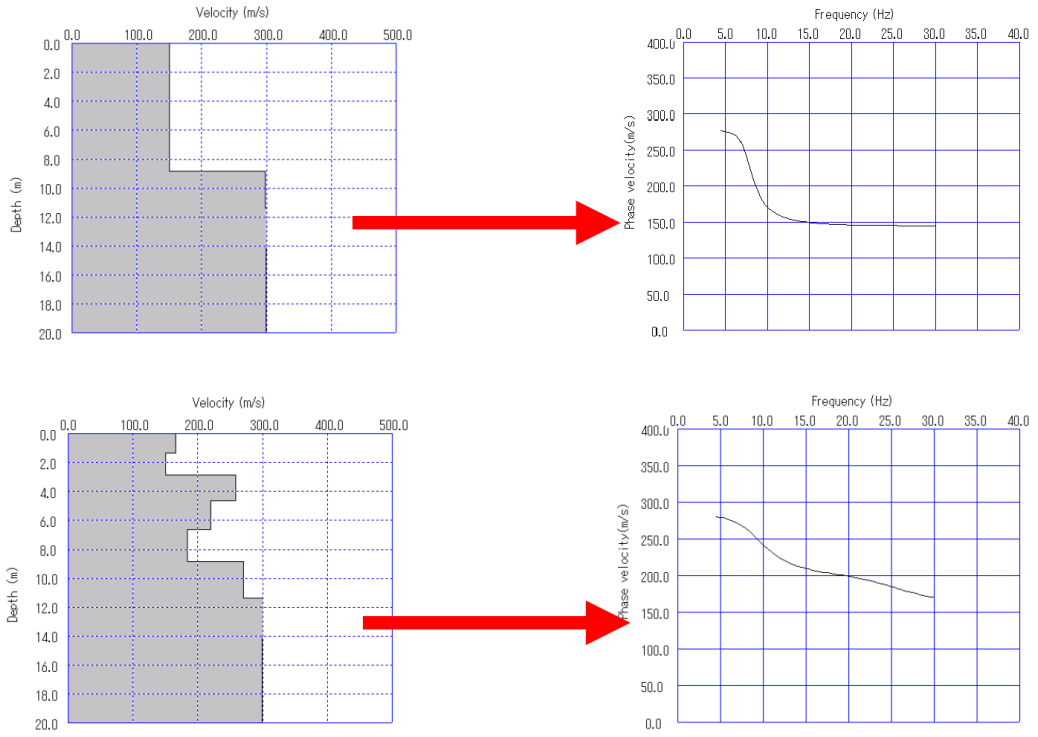
- Fundamental mode
- Multi-modal
- Effective
- Full Velocity Spectra



2. MULTICHANNEL DATA PROCESSING
Dispersion analysis

Characteristics of dispersion curves

- Phase-velocity curve is to be a smooth curved line, or a straight line
- Phase-velocity curve reflects the averaged velocity model beneath receiver array
- Higher modes exist
- The frequency range is to be fixed by the minimum/maximum receiver spacing



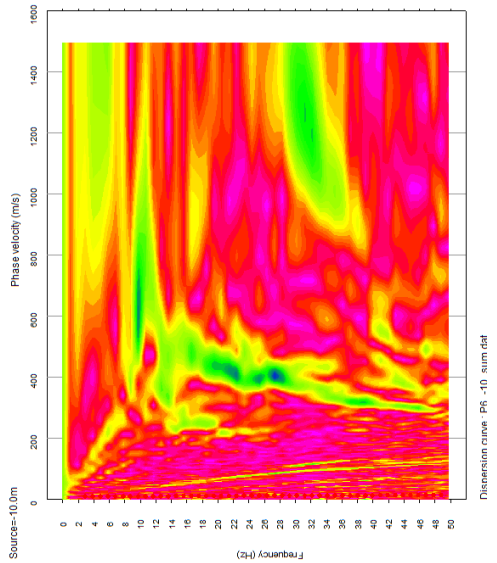
2. MULTICHANNEL DATA PROCESSING
Dispersion analysis

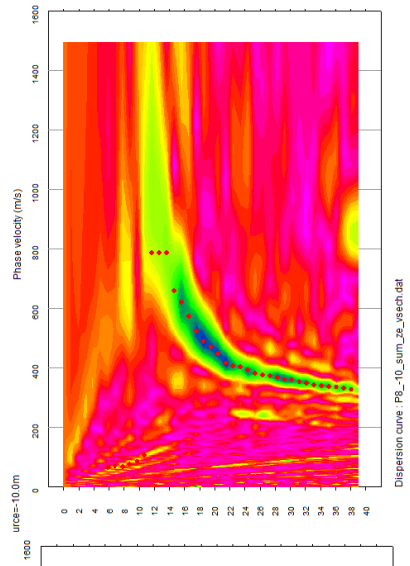
Dispersion curves pitfalls

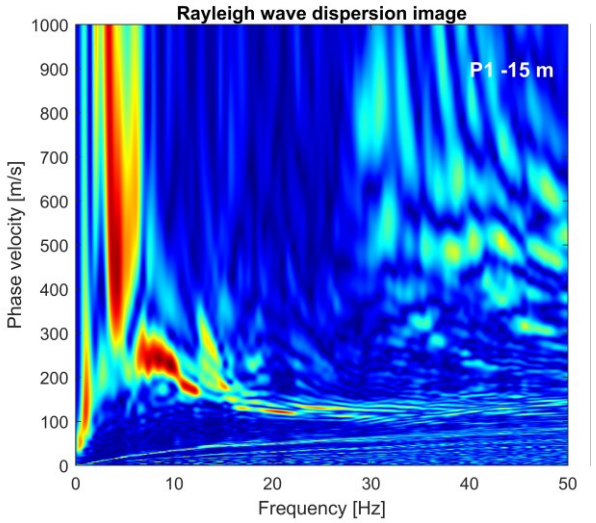
- Subjective operator influence
  - Overconfidence in poorly constrained frequency ranges
  - Inconsistent picking across frequency ranges
- Mode misidentification (fundamental vs. higher modes)
  - Bias toward the strongest amplitude rather than the correct mode
- Limited frequency bandwidth of reliable picks

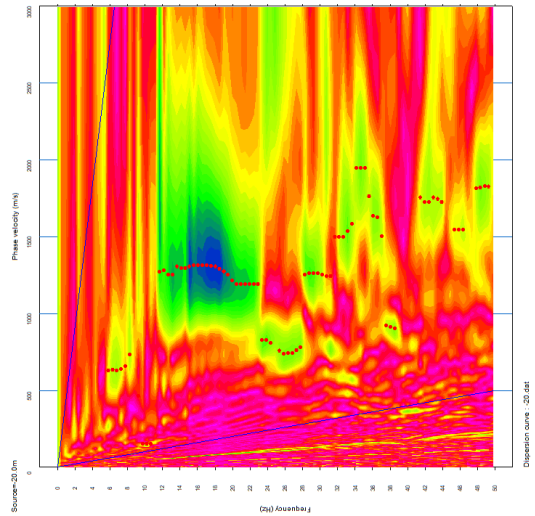
2. MULTICHANNEL DATA PROCESSING

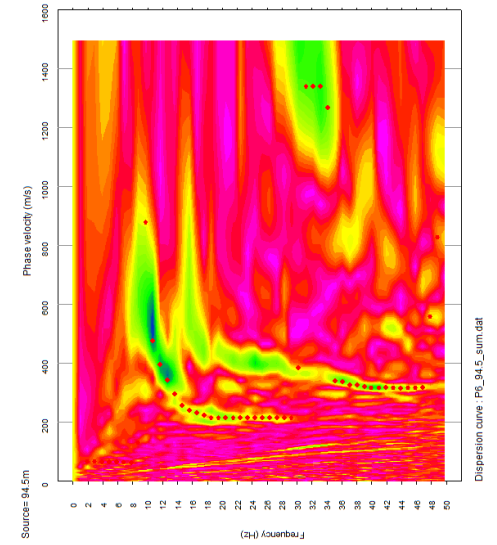
Dispersion analysis

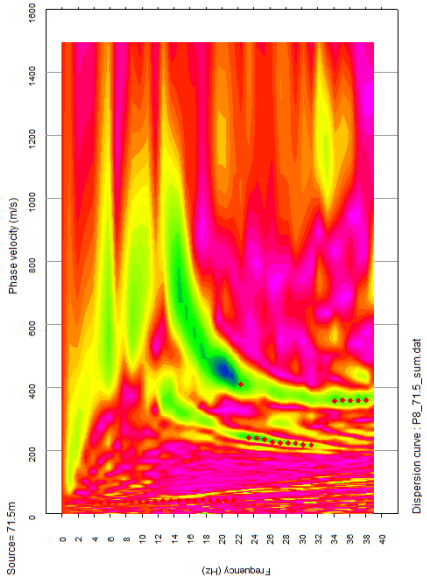


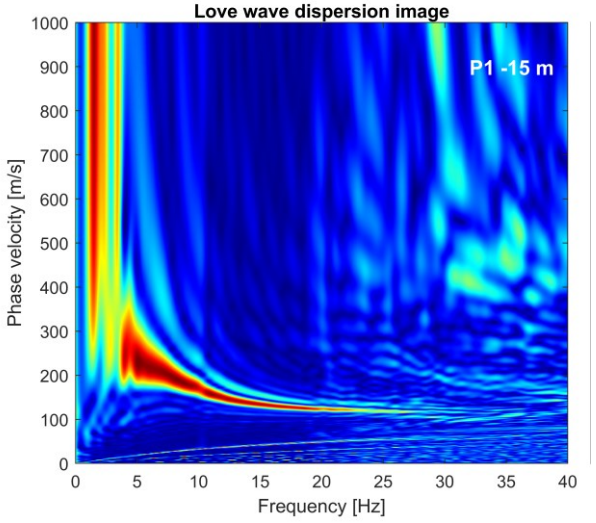


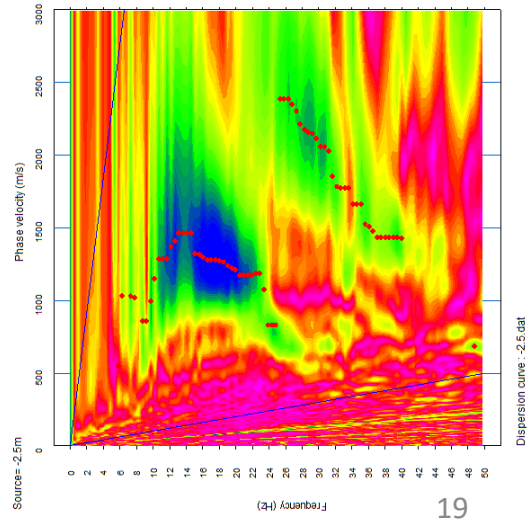








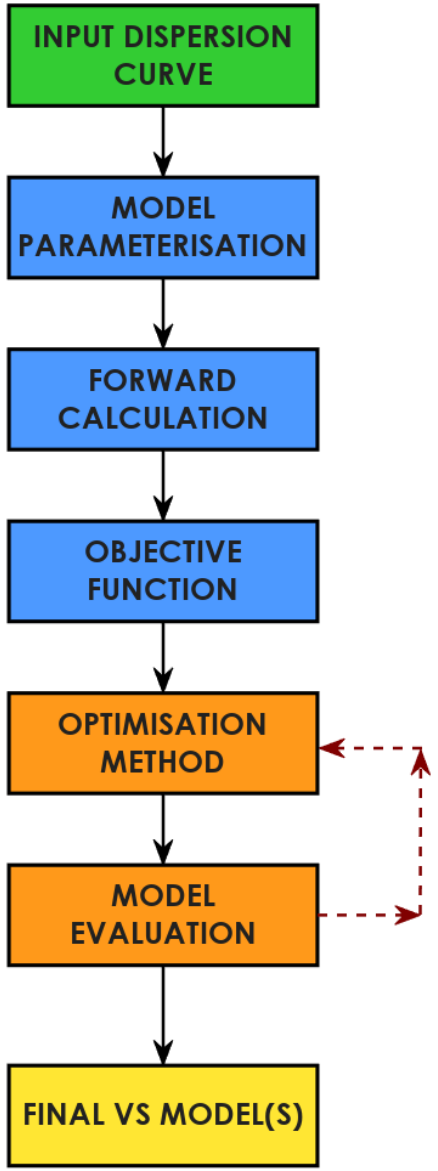




3. MULTICHANNEL DATA PROCESSING

Inversion analysis

- Inversion converts dispersion curves into a 1D Vs model
- The solution is non-unique
- Results depend on starting model and constraints
- Phase velocity is fitted, depth is inferred
- Resolution decreases with depth
- Aim for a realistic Vs profile



List of algorithm adopted to solve the inverse problem.

Label	Algorithm	References
NA	Neighborhood Algorithm	[38]
MC	Monte Carlo method	[37,39]
GA	Genetic Algorithm	[90,34]
SA-GA	Simulated Annealing and genetic algorithm in an hybrid heuristic search method	[91]
NLS	Non-linearized least-squares algorithm	[92]
LLS_EYE	Linearized Least Square and trial and error procedure	[62,40,76]
EYE	Trial and error procedure	

3. MULTICHANNEL DATA PROCESSING
Inversion analysis

Model input parameters (what we invert for):

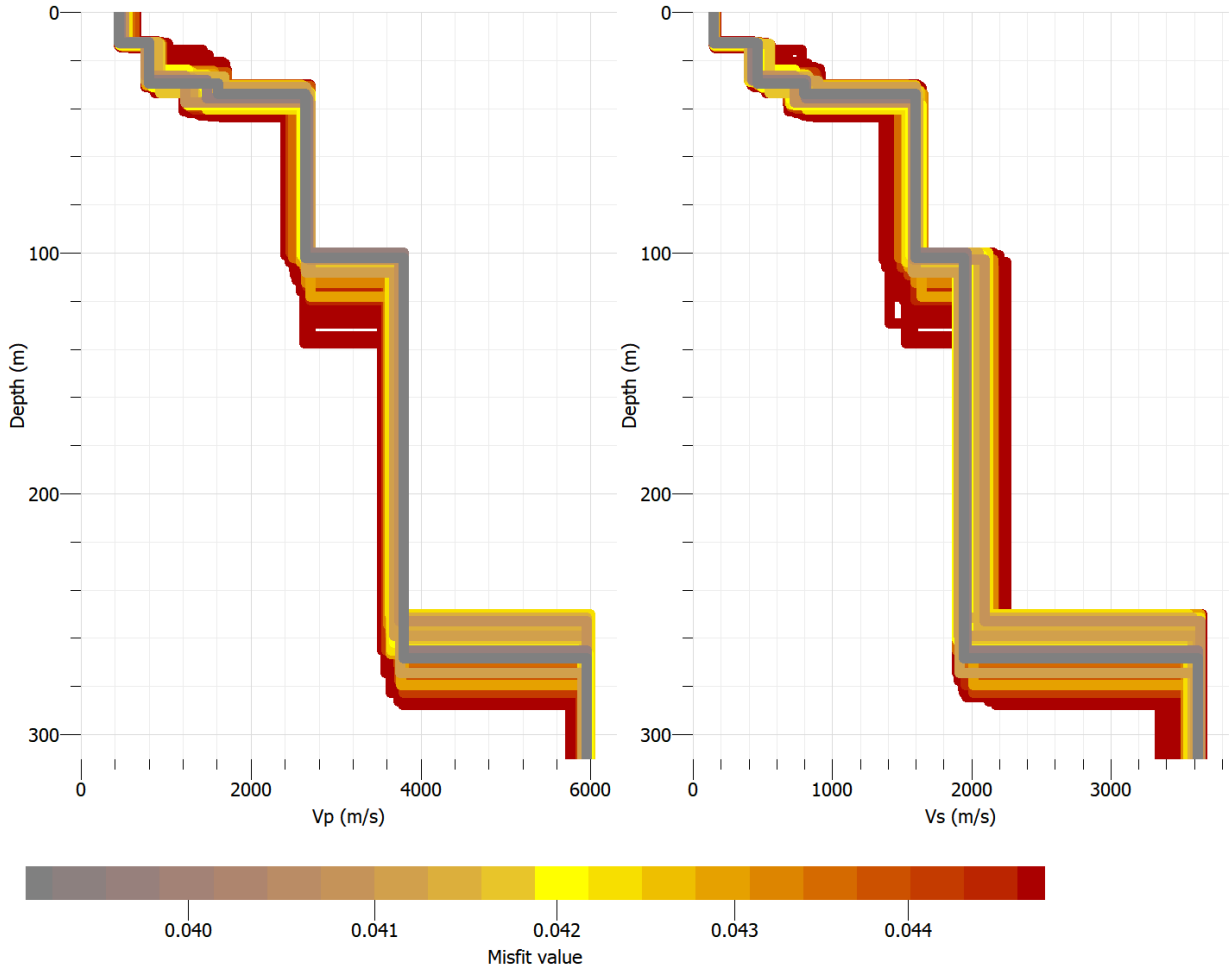
- Number of layers
- Layer thicknesses (fixed or variable)
- Vs of each layer
- Vp/Vs ratio or Poisson's ratio
- Density (fixed or linked)
- Half-space properties

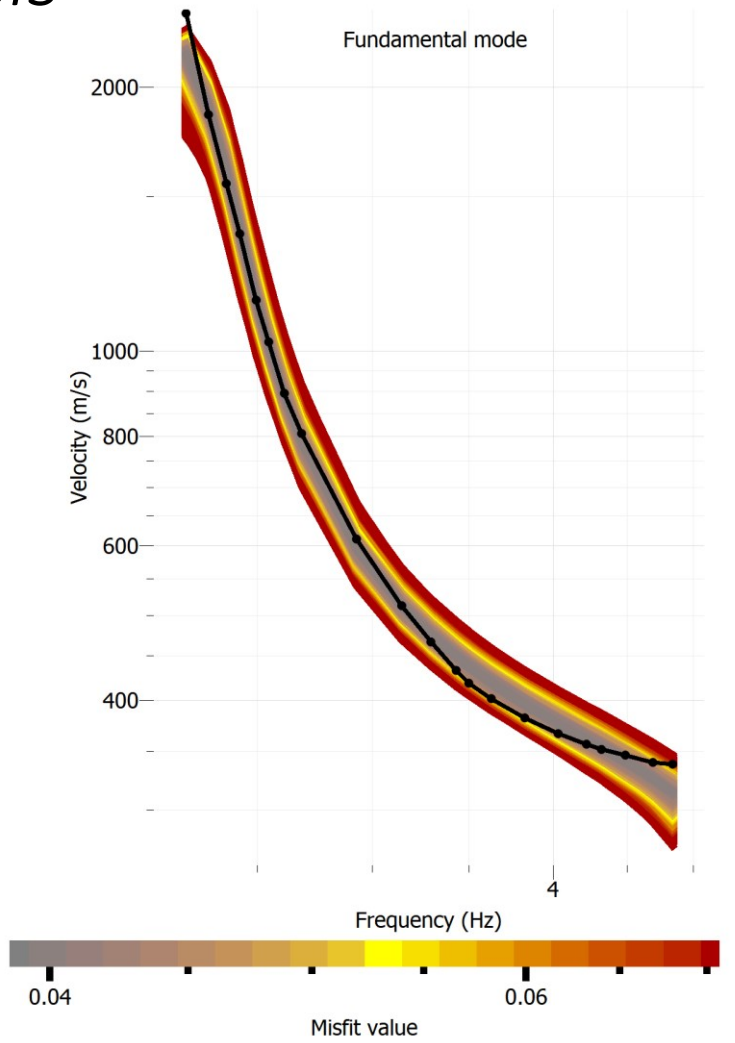
Inversion control parameters (how the search works):

- Initial/reference model
- Parameter bounds and constraints
- Misfit definition and weighting
- Number of iterations/models tested
- Step size or mutation range
- Stopping criteria

3. MULTICHANNEL DATA PROCESSING

Inversion analysis

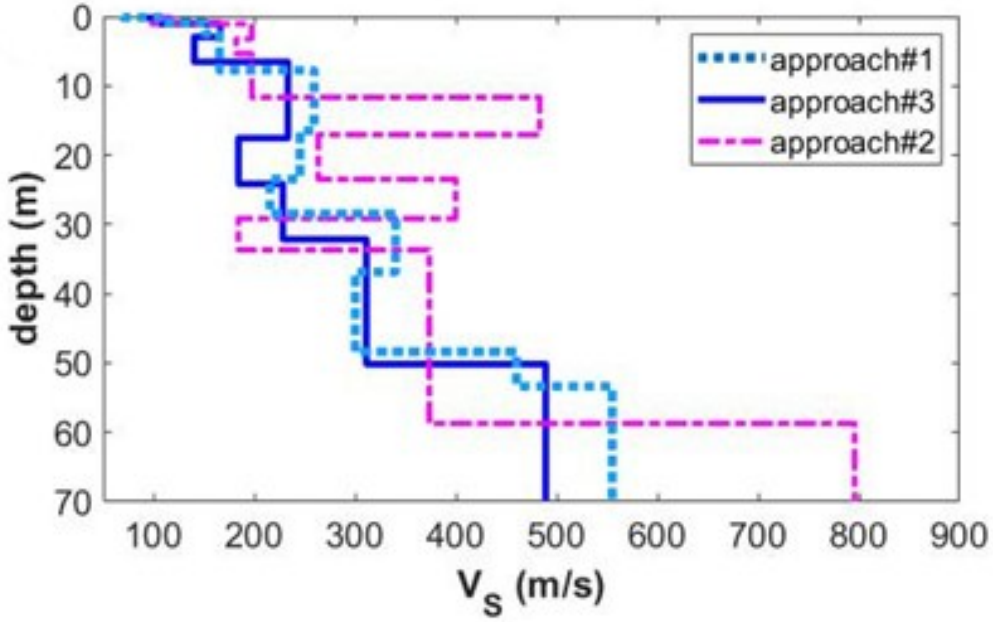




3. MULTICHANNEL DATA PROCESSING
Inversion analysis

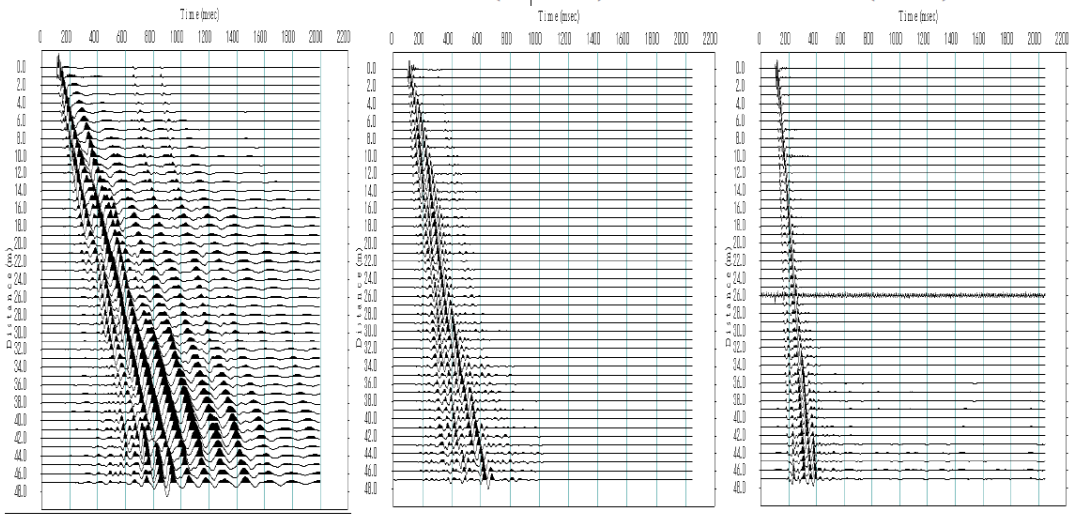
Inversion pitfalls

- Non-uniqueness of the inverted Vs model
- Misleading apparent resolution at depth
- Artificial layering caused by over-parameterization
- Strong dependence on initial model and constraints
- Propagation of picking errors into the final model
- Ignoring lateral heterogeneity in a 1D inversion
- Over-interpretation beyond data sensitivity



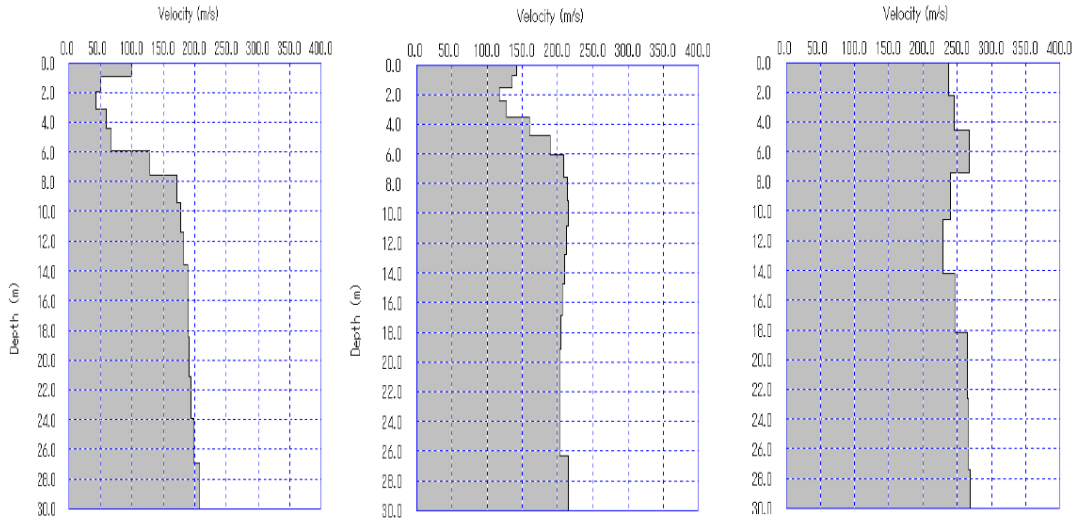
Comparison of the original waveforms

River bottom (Soft) | Diluvial plateau (Middle) | High embankment (Hard)



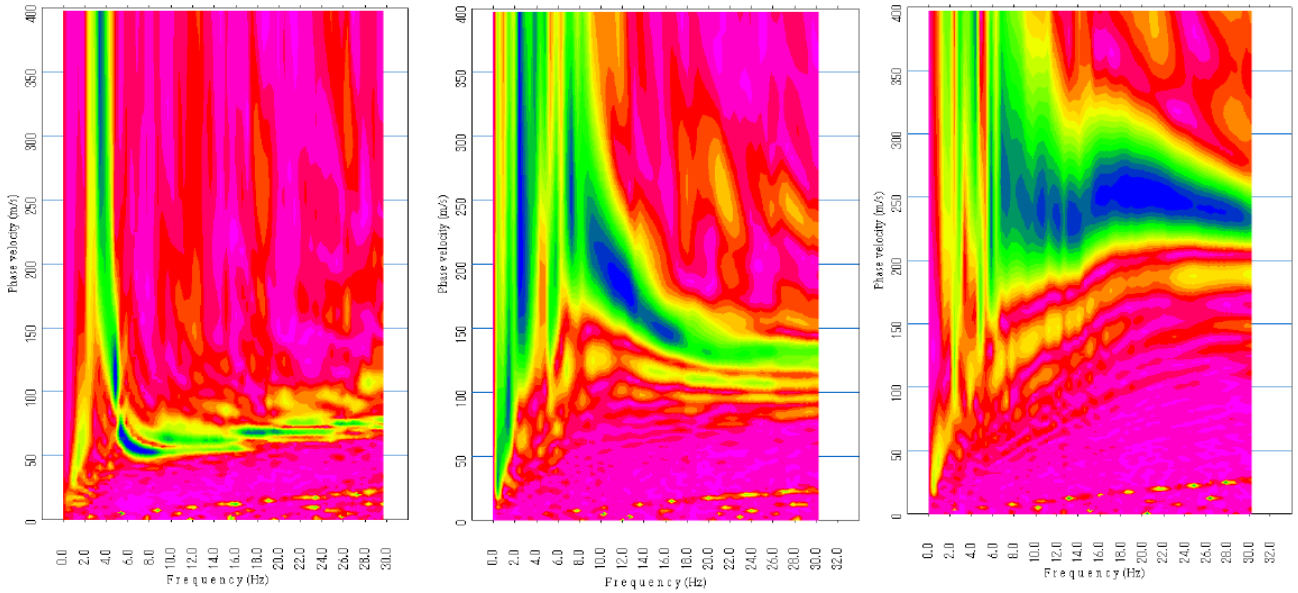
Comparison of the S-wave velocity structures

Riverbank (Soft) | Diluvial plateau (Middle) | High embankment (Hard)



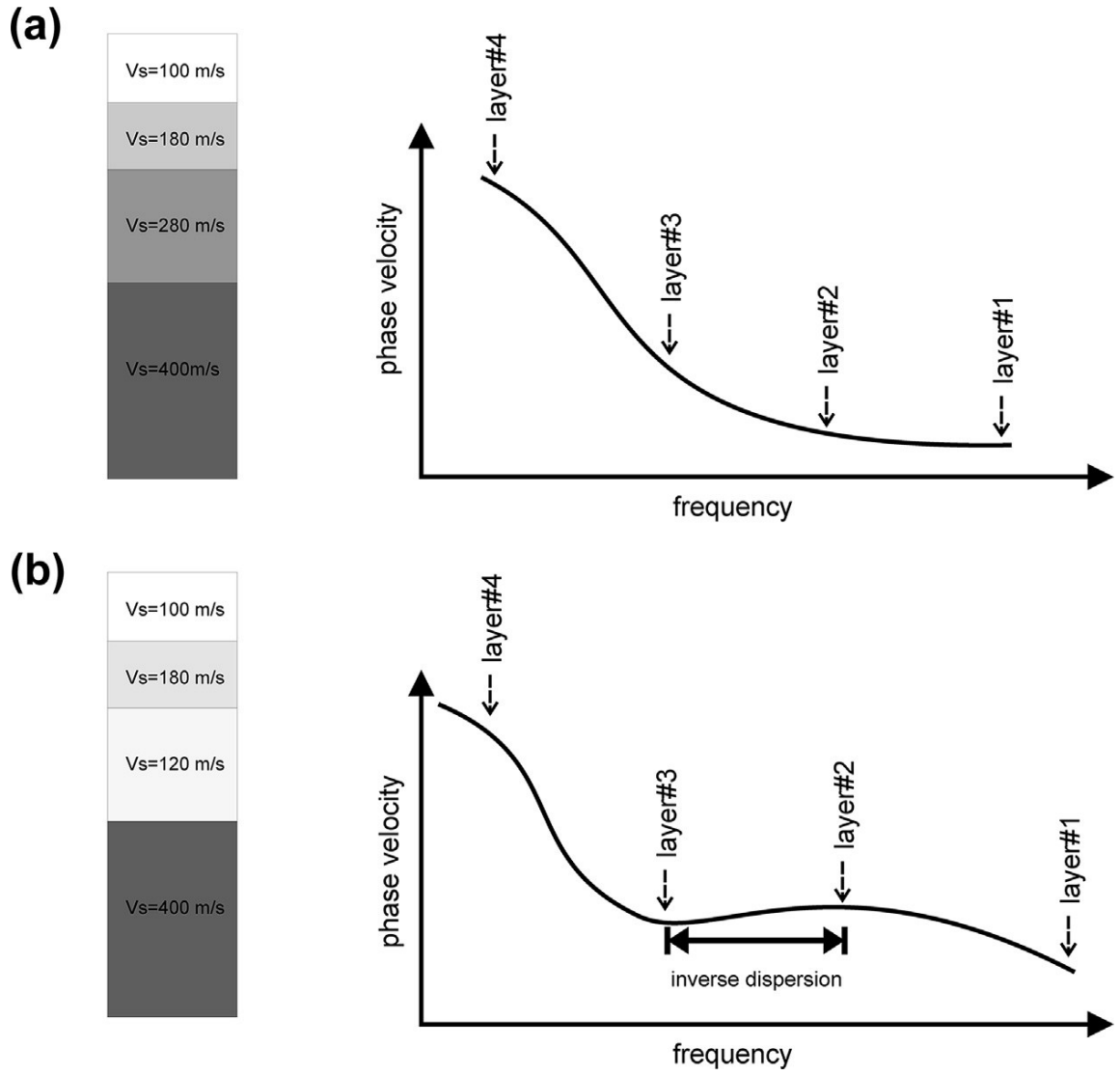
Comparison of the dispersion curves

River bottom (Soft) | Diluvial plateau (Middle) | High embankment (Hard)



From Koichi Hayashi, SAAGEEP 2003

VELOCITY INVERSION



An elemental and rudimentary representation: two different subsurface models, two different phase-velocity dispersion curves showing

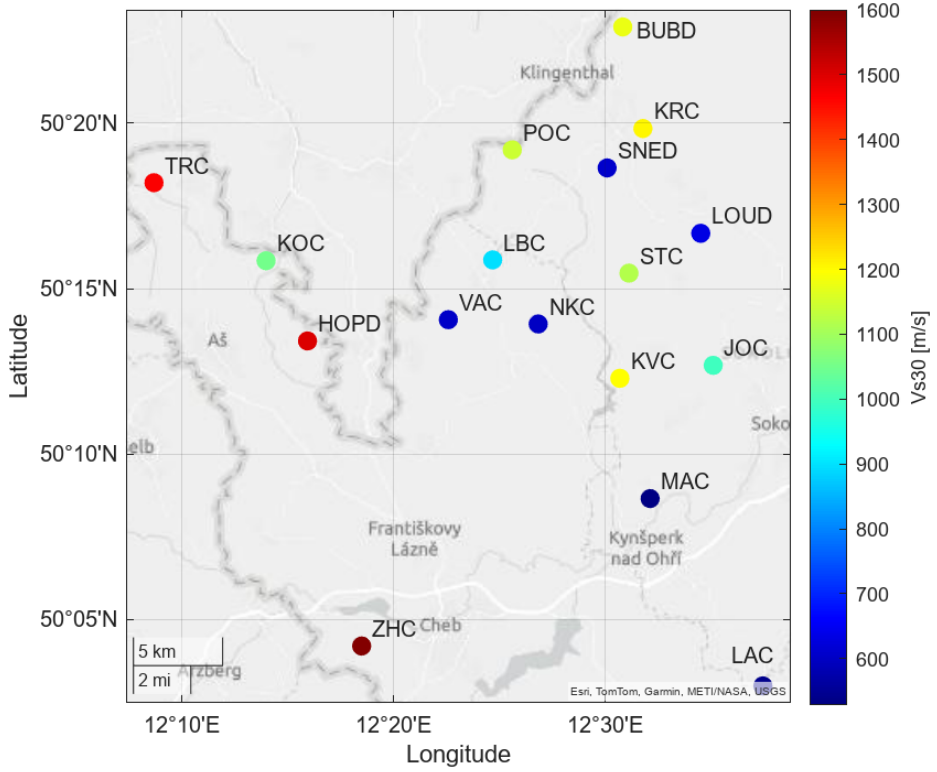
(a) normal and (b) inverse dispersion.

Limits and challenges

- Assumption of lateral homogeneity and 1D layering
- Limited depth resolution and decreasing sensitivity with depth
- Non-uniqueness of dispersion curve inversion
- Strong dependence on data quality and acquisition geometry
- Sensitivity to mode misidentification
- Difficulty in strongly heterogeneous or complex geological settings
- Results represent an averaged response over the array length

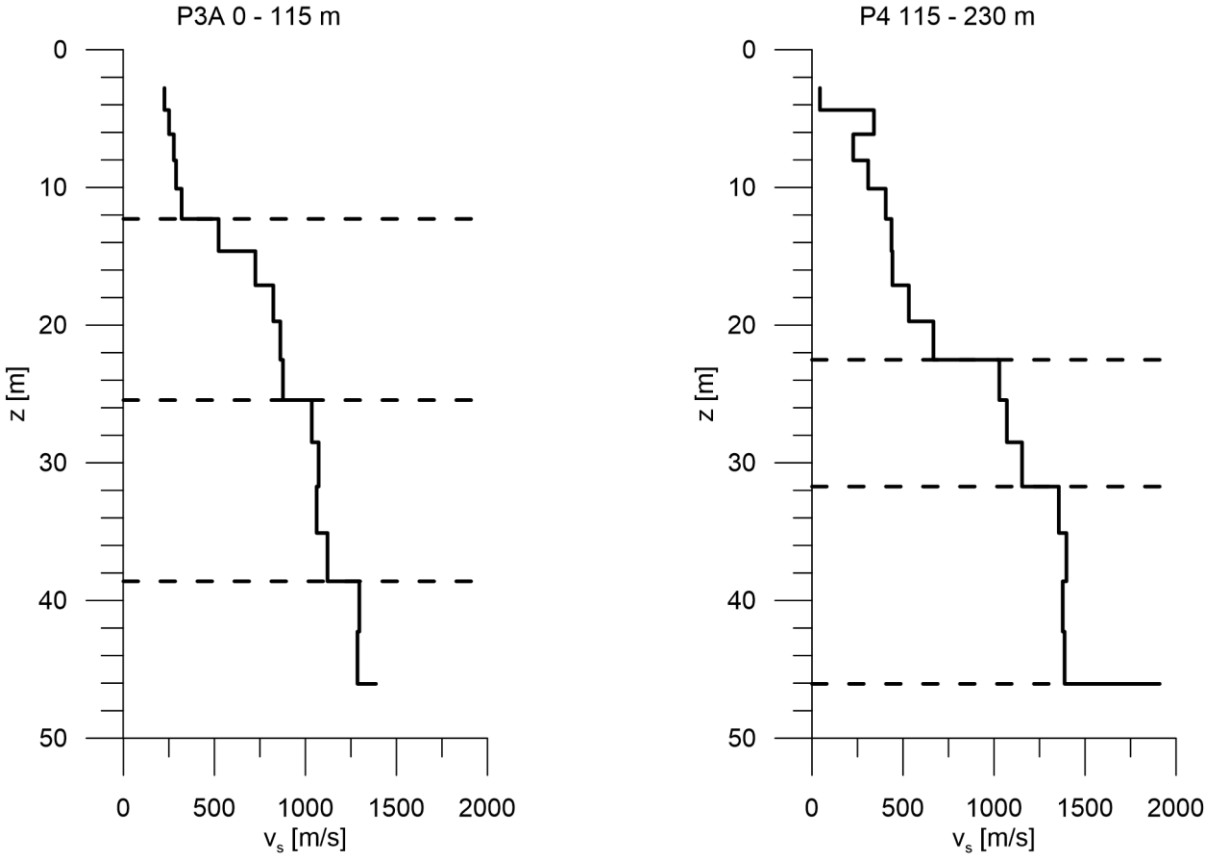
MULTICHANNEL SURFACE WAVES APPLICATIONS

- Shear-wave velocity profiling
- Bedrock mapping (Miller et al. 1999; Park 2016)
- Marine environments investigation (Kaufmann et al., 2005)
- Detection of low-velocity layers and velocity inversions
- Hydrogeological studies (Suto, 2019)
- Landslides (Strelec et al., 2017)
- Vs30 and site classification – seismic hazard

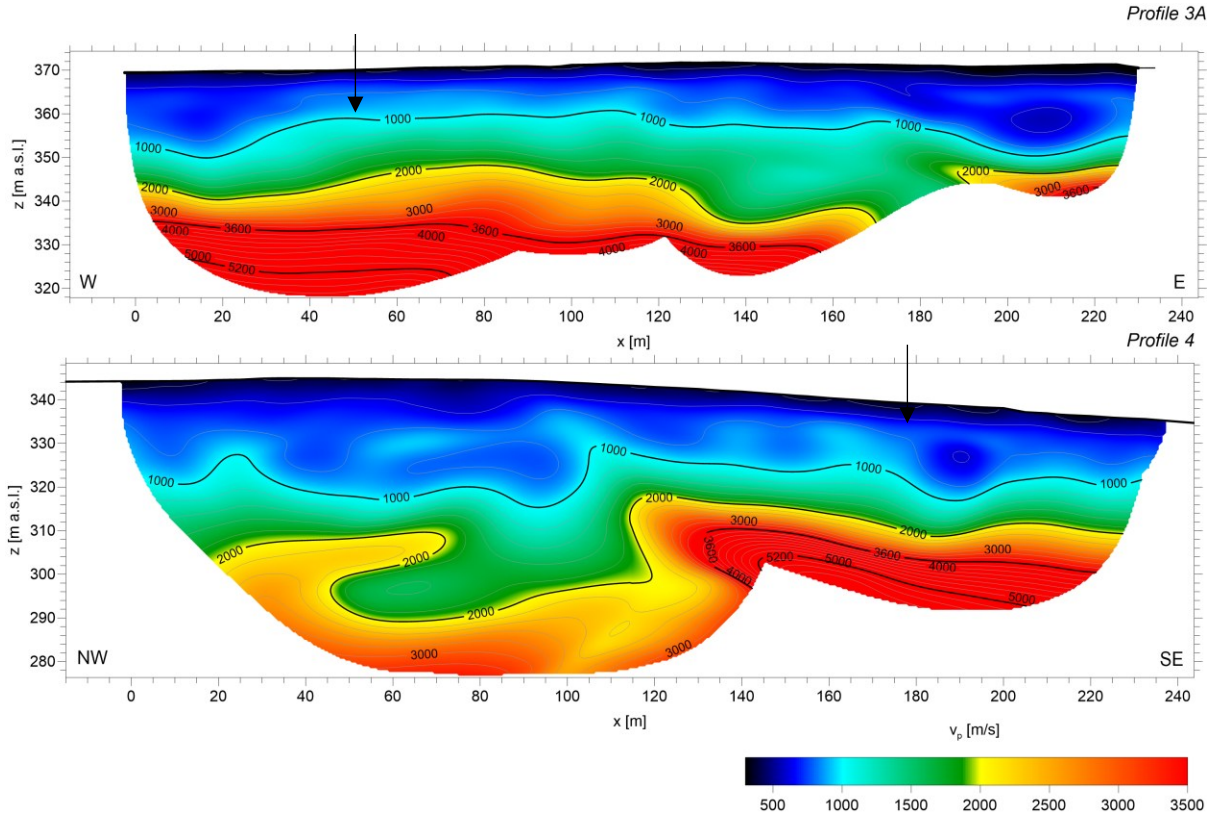


- Geotechnical site characterization (Penumadu and Park 2005; Park 2013; Abudeif et al. 2019)

Case study #1: Benešov - weathered zones definition



S-wave velocity profiles determined from Rayleigh waves for selected parts of the tomography profiles. The horizontal broken lines mark distinct velocity interfaces.



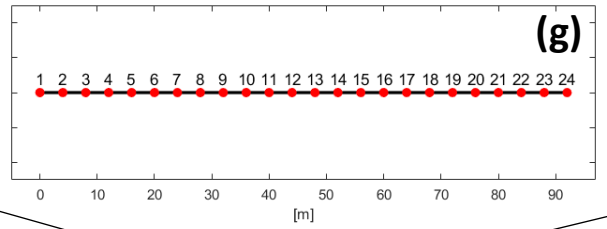
Travel time tomography at two profiles at the Benešov town site. Note the smooth velocity change making it difficult to determine the depth of weathering interface. The heavy lines of velocity contour lines (1000, 2000, 3600 and 5200 m/s) approximate interfaces determined from S-wave velocity profiles. Black arrow shows 1D Vs model positions.

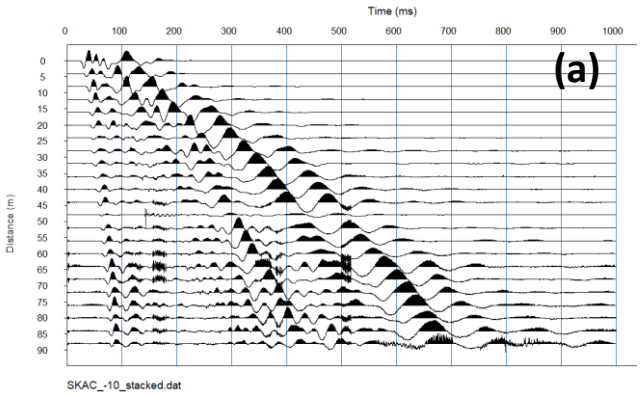
Case study #2: joint analysis

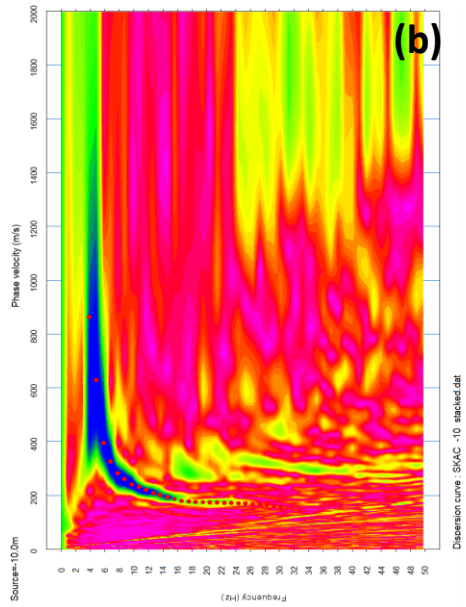
MASW
active

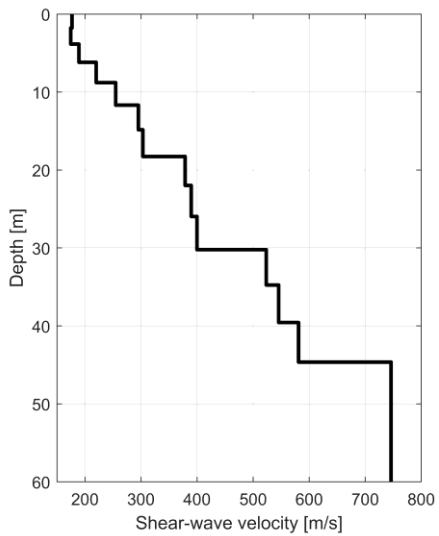
MAM
ambient

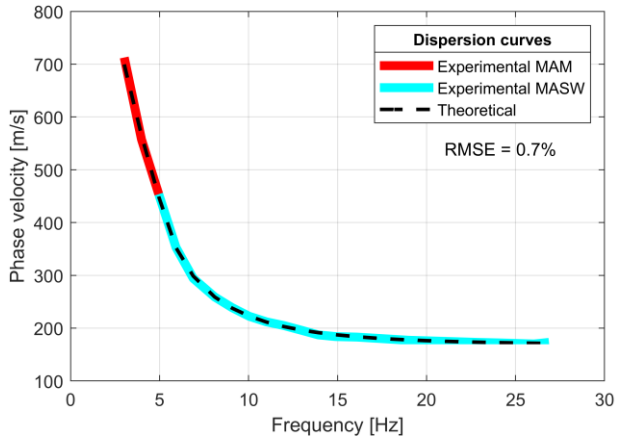
Joint
analysis

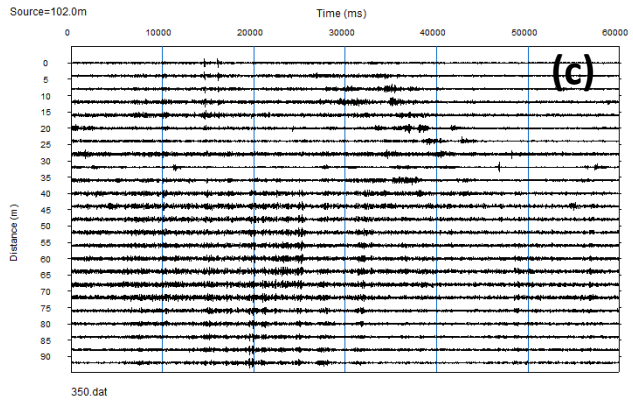


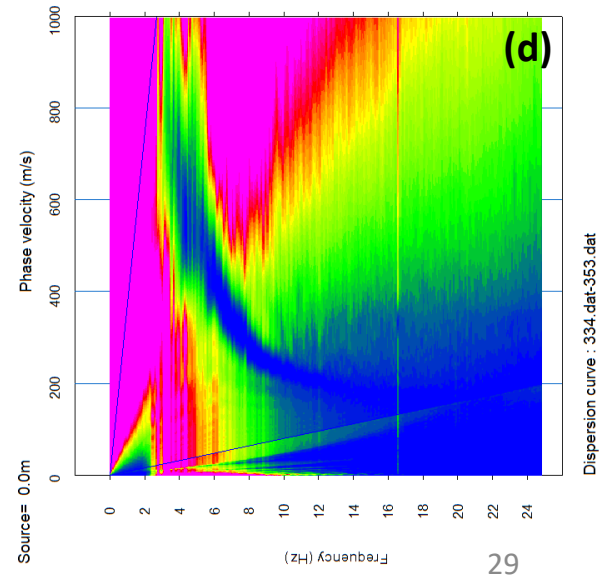












Joint analysis of active MASW and ambient MAM seismics. MASW: (a) example of seismic traces; (b) phase velocity spectrum. MAM: (c) acquired microtremors; (d) phase velocity spectrum. Joint analysis: (e) resulting Vs model and (f) joint dispersin curve from MAM (red) and MASW (blue). (g) acquisition geometry consited of 24 4.5 Hz vertical geophones with 4 m spacing.

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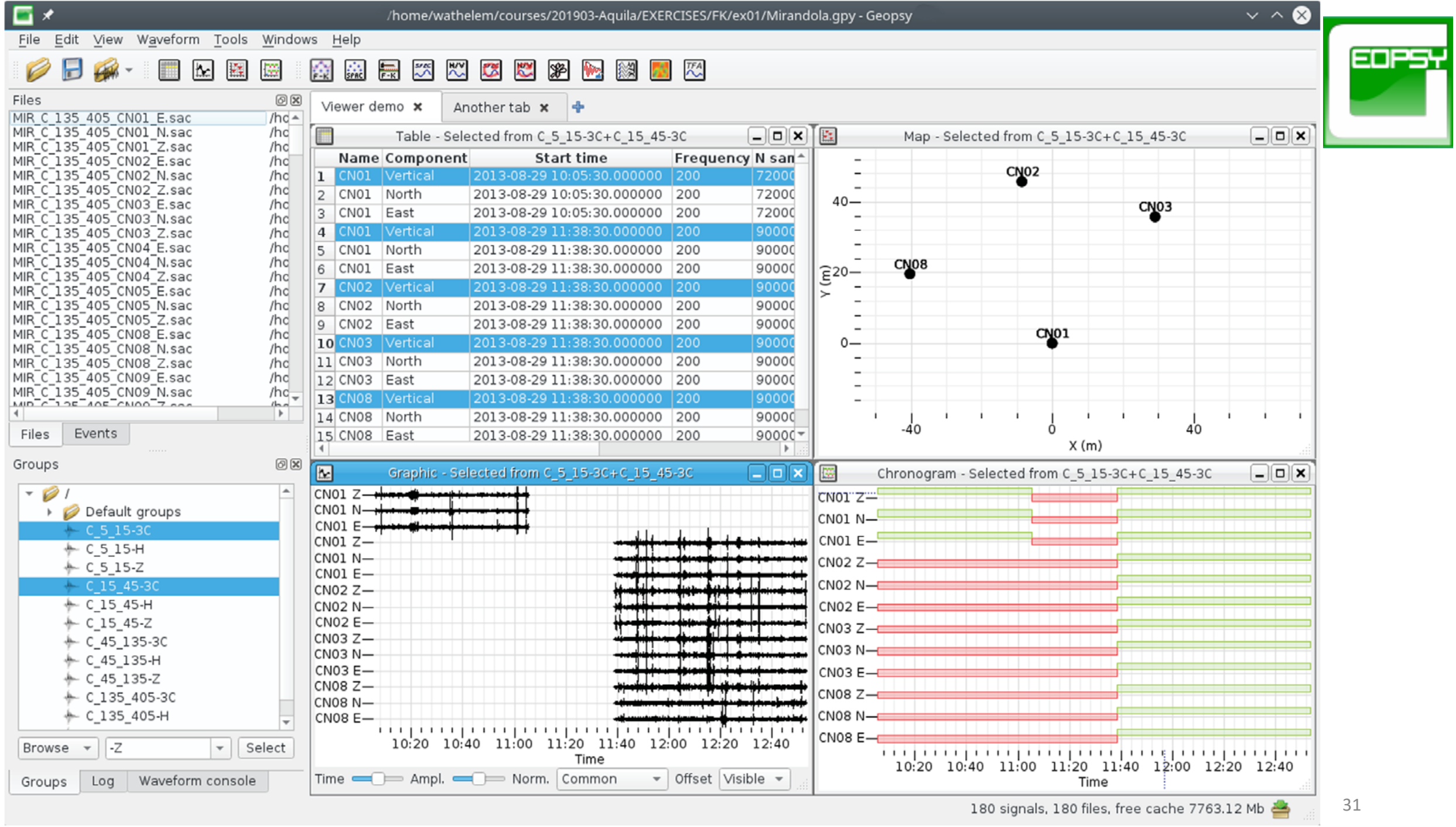
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File Edit View Waveform Tools Windows Help
Files
MIR_C_135_405_CN01_E.sac
MIR_C_135_405_CN01_N.sac
MIR_C_135_405_CN01_Z.sac
MIR_C_135_405_CN02_E.sac
MIR_C_135_405_CN02_N.sac
MIR_C_135_405_CN02_Z.sac
MIR_C_135_405_CN03_E.sac
MIR_C_135_405_CN03_N.sac
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MIR_C_135_405_CN04_E.sac
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MIR_C_135_405_CN08_N.sac
MIR_C_135_405_CN08_Z.sac
MIR_C_135_405_CN09_E.sac
MIR_C_135_405_CN09_N.sac
Files Events
Groups
/
Default groups
C_5_15-3C
C_5_15-H
C_5_15-Z
C_15_45-3C
C_15_45-H
C_15_45-Z
C_45_135-3C
C_45_135-H
C_45_135-Z
C_135_405-3C
C_135_405-H
Browse -Z Select
Groups Log Waveform console
Viewer demo
Another tab
Table - Selected from C_5_15-3C+C_15_45-3C
Name Component Start time Frequency N san
1 CN01 Vertical 2013-08-29 10:05:30.000000 200 72000
2 CN01 North 2013-08-29 10:05:30.000000 200 72000
3 CN01 East 2013-08-29 10:05:30.000000 200 72000
4 CN01 Vertical 2013-08-29 11:38:30.000000 200 90000
5 CN01 North 2013-08-29 11:38:30.000000 200 90000
6 CN01 East 2013-08-29 11:38:30.000000 200 90000
7 CN02 Vertical 2013-08-29 11:38:30.000000 200 90000
8 CN02 North 2013-08-29 11:38:30.000000 200 90000
9 CN02 East 2013-08-29 11:38:30.000000 200 90000
10 CN03 Vertical 2013-08-29 11:38:30.000000 200 90000
11 CN03 North 2013-08-29 11:38:30.000000 200 90000
12 CN03 East 2013-08-29 11:38:30.000000 200 90000
13 CN08 Vertical 2013-08-29 11:38:30.000000 200 90000
14 CN08 North 2013-08-29 11:38:30.000000 200 90000
15 CN08 East 2013-08-29 11:38:30.000000 200 90000
Map - Selected from C_5_15-3C+C_15_45-3C
CN02
CN03
CN08
CN01
40
20
0
Y (m)
-40
0
40
X (m)
Graphic - Selected from C_5_15-3C+C_15_45-3C
CN01 Z
CN01 N
CN01 E
CN01 Z
CN01 N
CN01 E
CN02 Z
CN02 N
CN02 E
CN03 Z
CN03 N
CN03 E
CN08 Z
CN08 N
CN08 E
10:20 10:40 11:00 11:20 11:40 12:00 12:20 12:40
Time
Time Ampl. Norm. Common Offset Visible
Chronogram - Selected from C_5_15-3C+C_15_45-3C
CN01 Z
CN01 N
CN01 E
CN02 Z
CN02 N
CN02 E
CN03 Z
CN03 N
CN03 E
CN08 Z
CN08 N
CN08 E
10:20 10:40 11:00 11:20 11:40 12:00 12:20 12:40
Time
180 signals, 180 files, free cache 7763.12 Mb

Thank you for your attention