Unconventional and Optimized Surface-Wave Acquitision and Analysis

giancarlo dal moro
gdm@winmasw.com

Keywords:
Seismic data, data acquisition, MASW, multi-component MASW, *Full Velocity Spectrum* (FVS) analysis, HVSR, ESAC (Extended Spatial AutoCorrelation), ReMi (Refraction Microtremors), seismic data inversion, joint analysis, joint inversion, *Miniature Array Analysis of Microtremors* (MAAM), *winMASW*, *HoliSurface* (HS), *Multiple Filter Analysis* (MFA), body waves, surface waves, Rayleigh waves, Love waves, Scholte waves, refraction, seismology, vibrational analyses, building resonance.

Tutti gli argomenti presenti in questo documento sono trattati nel seguente volume edito dalla Elsevier (molto più aggiornato rispetto il volume della Flaccovio e con numerosi nuovi casi studio).

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SURFACE WAVE ANALYSIS FOR NEAR SURFACE APPLICATIONS

Giancarlo Dal Moro

Surface Wave Analysis for Near Surface Applications presents the foundational tools and techniques necessary to properly analyze surface-wave propagation nowadays performed for a number of applications.

In the last decades, surface-wave analysis has in fact become critical to near-surface geophysics both for geotechnical goals, seismic-hazard assessment, and environmental studies. This book presents both the theoretical background and the applications which the author has assembled while considering different possible approaches selected from the latest developments in research, with a special emphasis of the joint analysis of the different components that can be conveniently considered.

The book aims at building a bridge between academic research and field practice and at illustrating a number of possible pitfalls often made while analyzing surface waves also suggesting the way to overcome them via joint analyses.

Authored by a geophysicist with nearly 20 years of experience in research, consulting, and geophysical software development.

- Nearly 100 figures, photographs, and examples aid in the understanding of fundamental concepts and techniques.
- Presents the latest research in surface wave analysis while considering both active and passive techniques (MASW, MFA, ESAC, ReMi, HVSR etc.) and different inversion strategies.
- A number of real world case studies—14 in all—bring the book's key principles to life.

A unique blend of theory and practice, the book's concepts are based on exhaustive field research conducted over the past decades.

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SURFACE WAVE ANALYSIS FOR NEAR SURFACE APPLICATIONS

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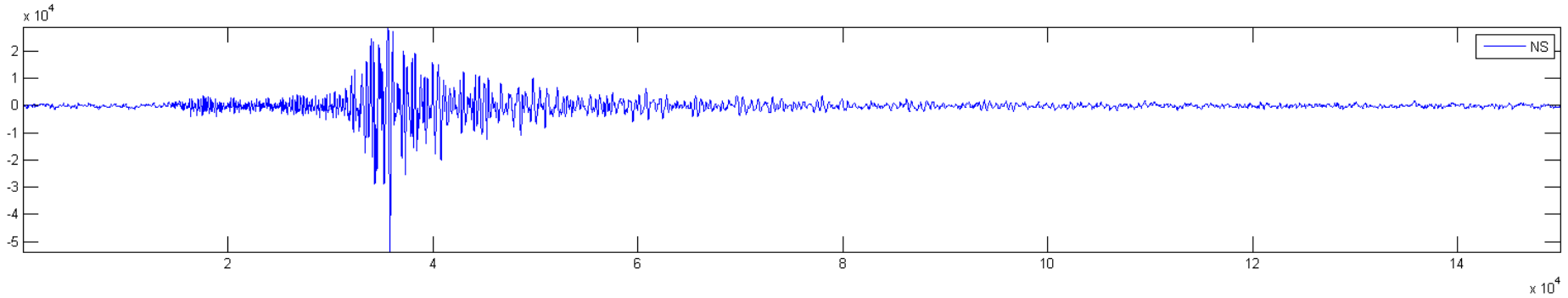
Some Garage Seismology

Definiamo la struttura crostale media dell'Adriatico in modo rapido e economico.



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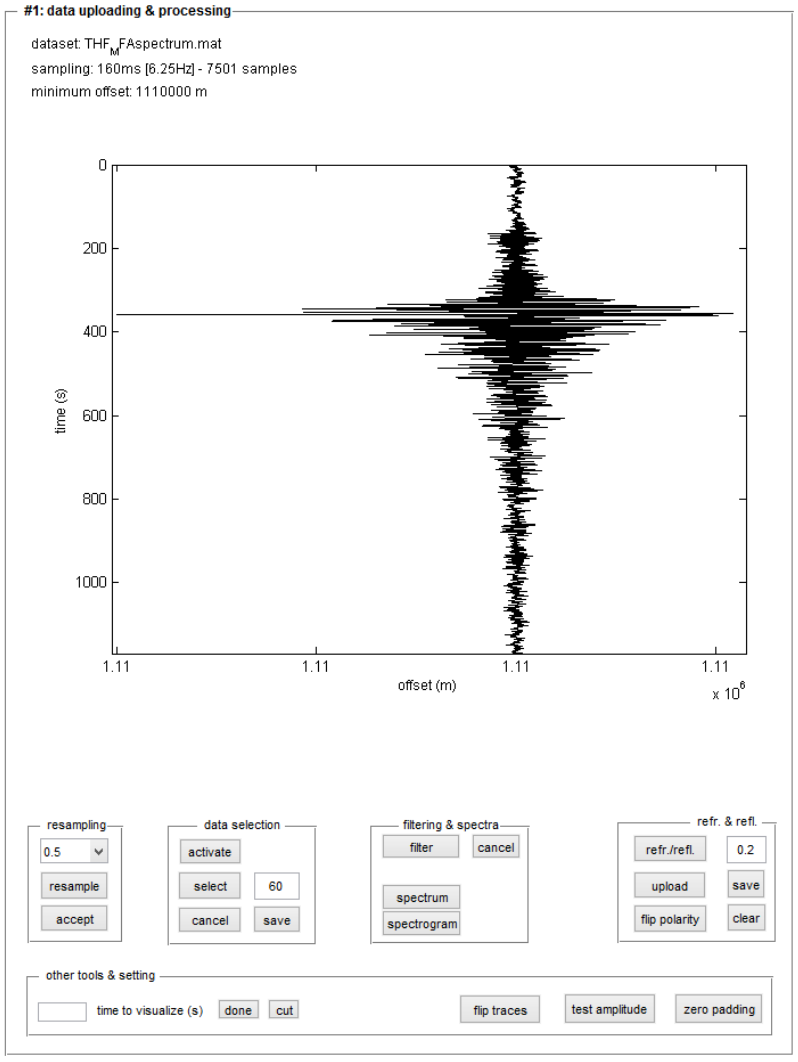

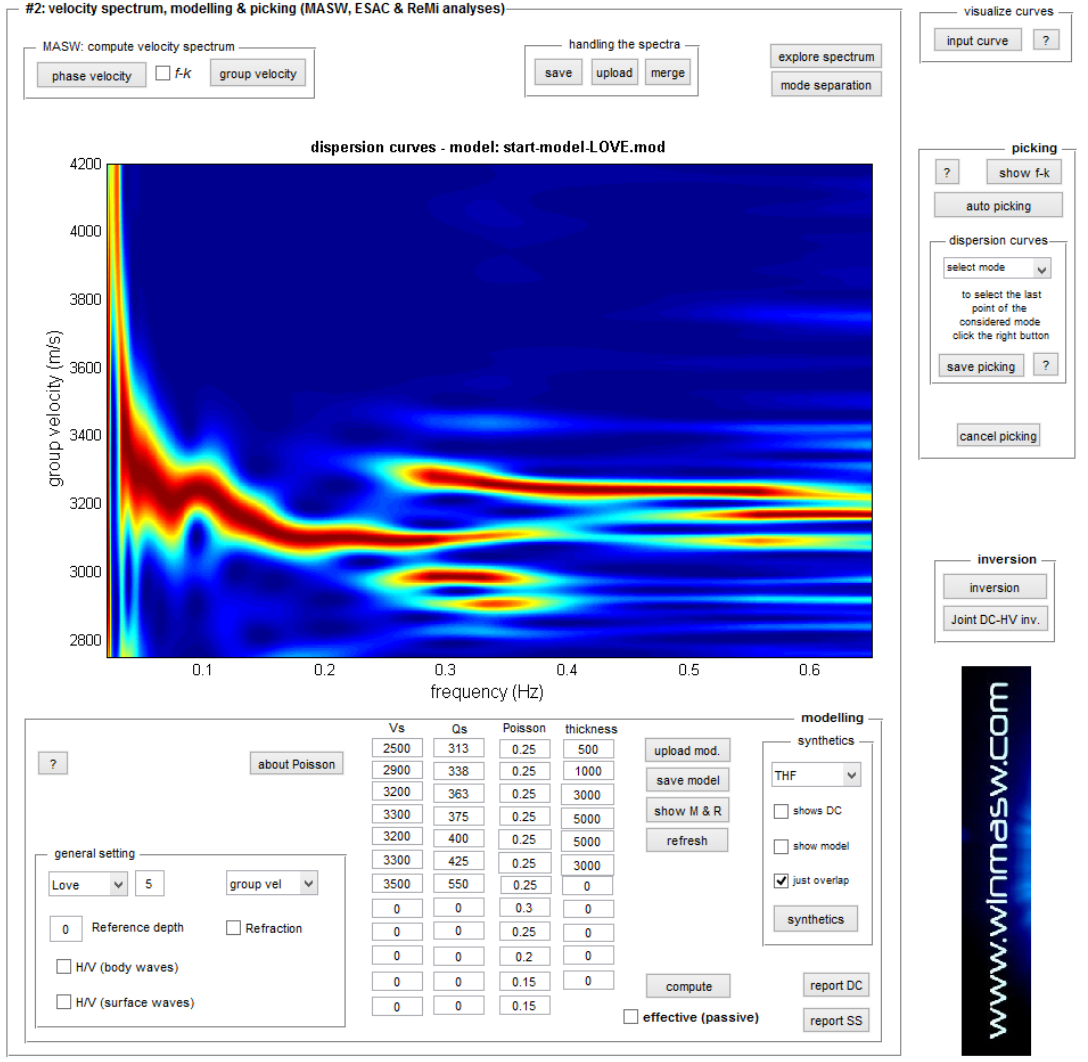

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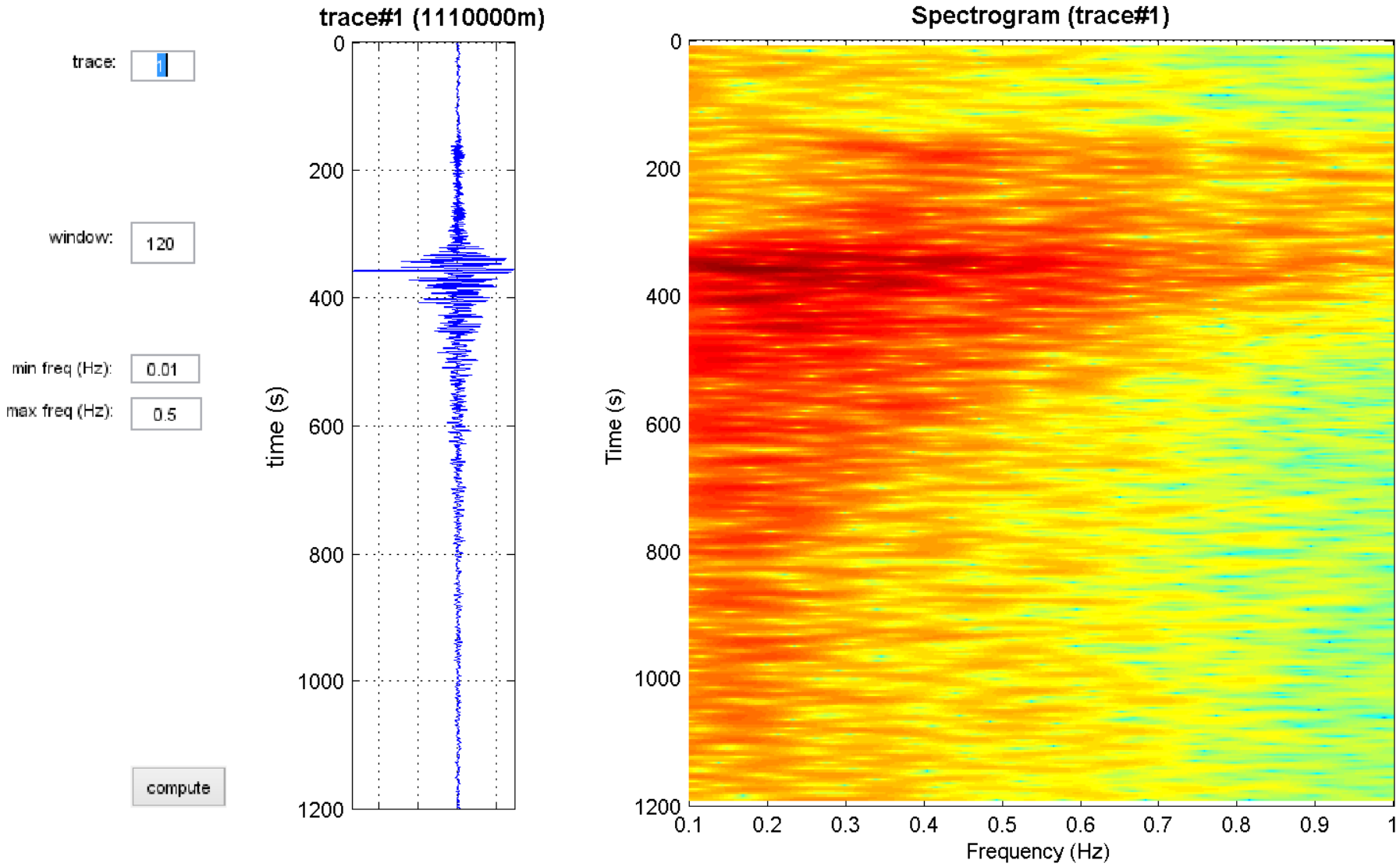

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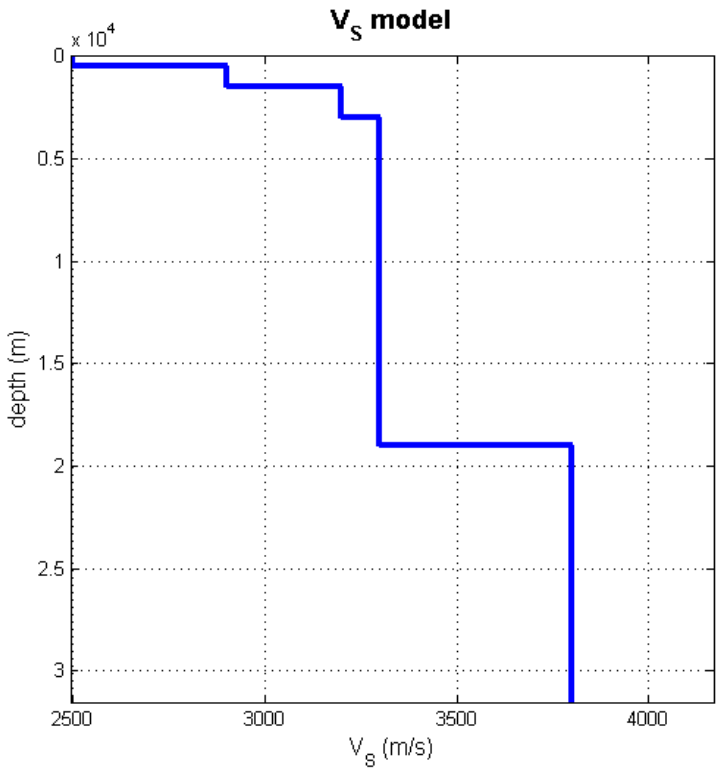

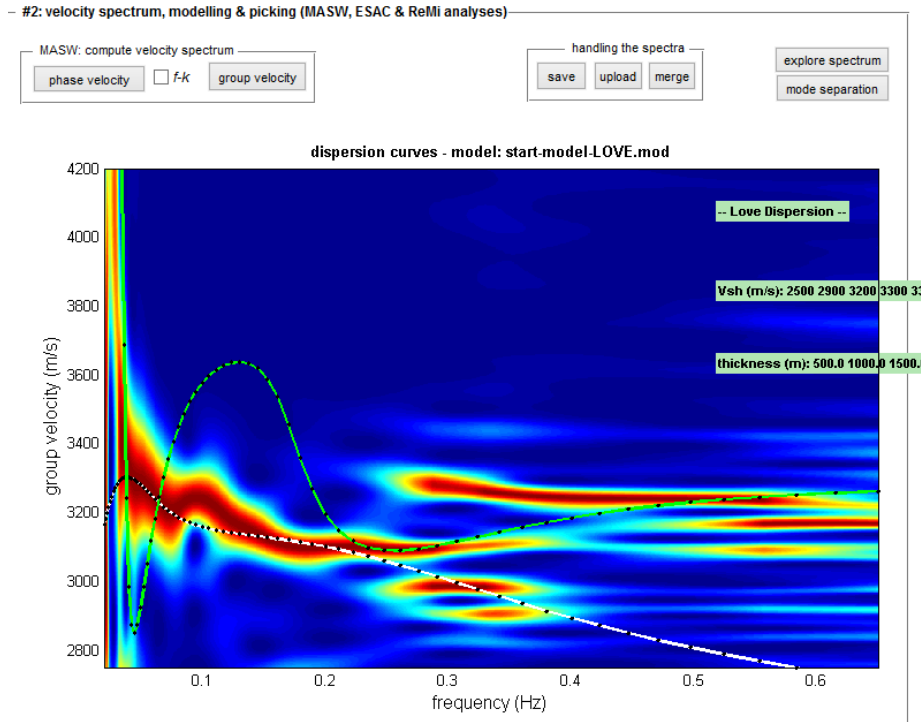

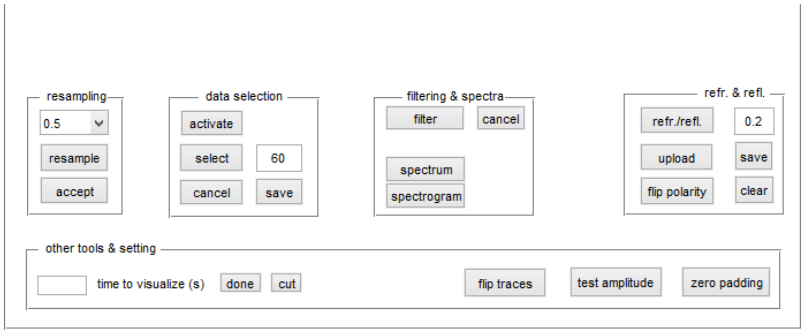

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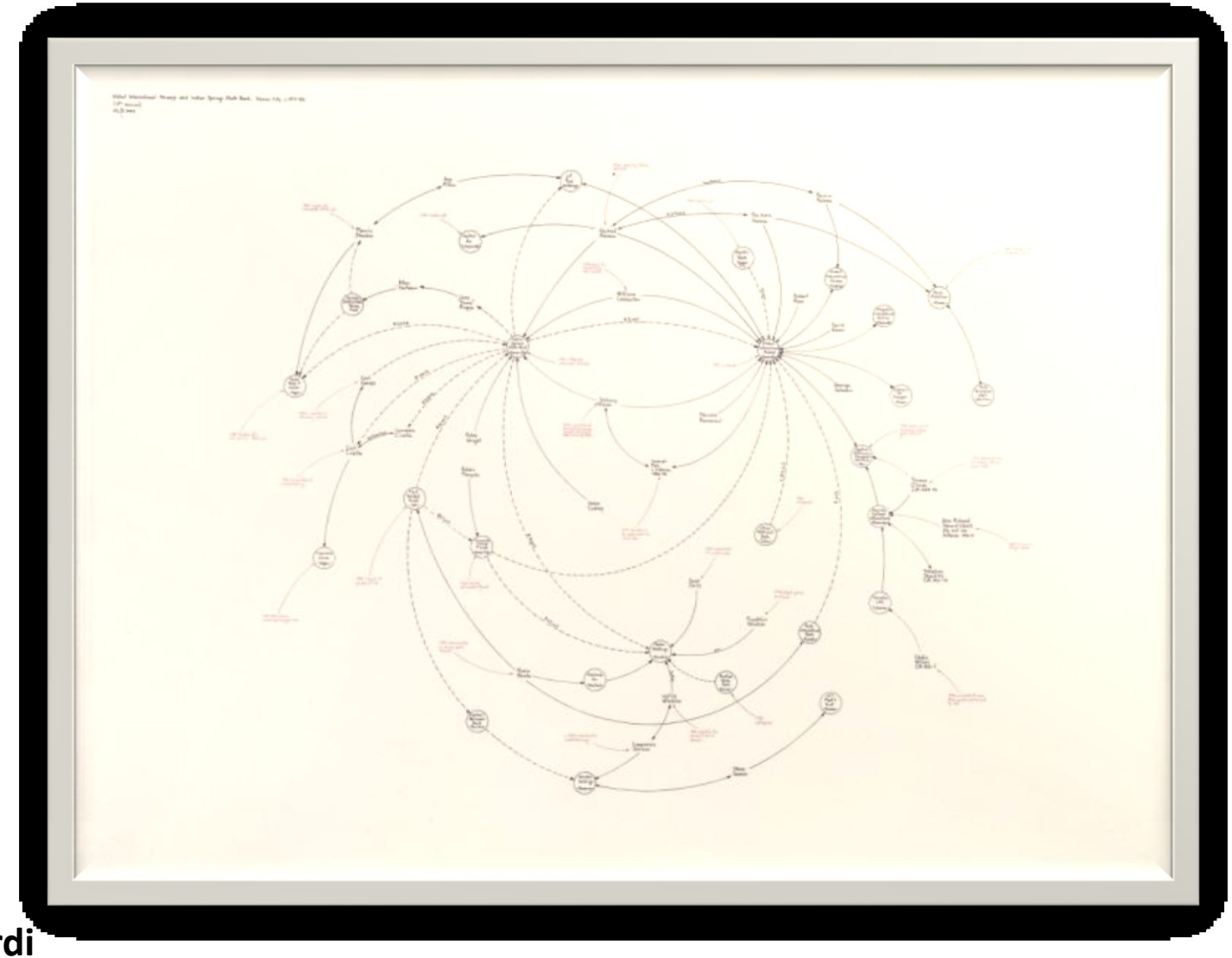
Tutoring

It's not what you look at that matters, it's what you see.

Henry David Thoreau

Le due alternative:
comprendere tutto o *non capire nulla*



L’opera di Mark Lombardi

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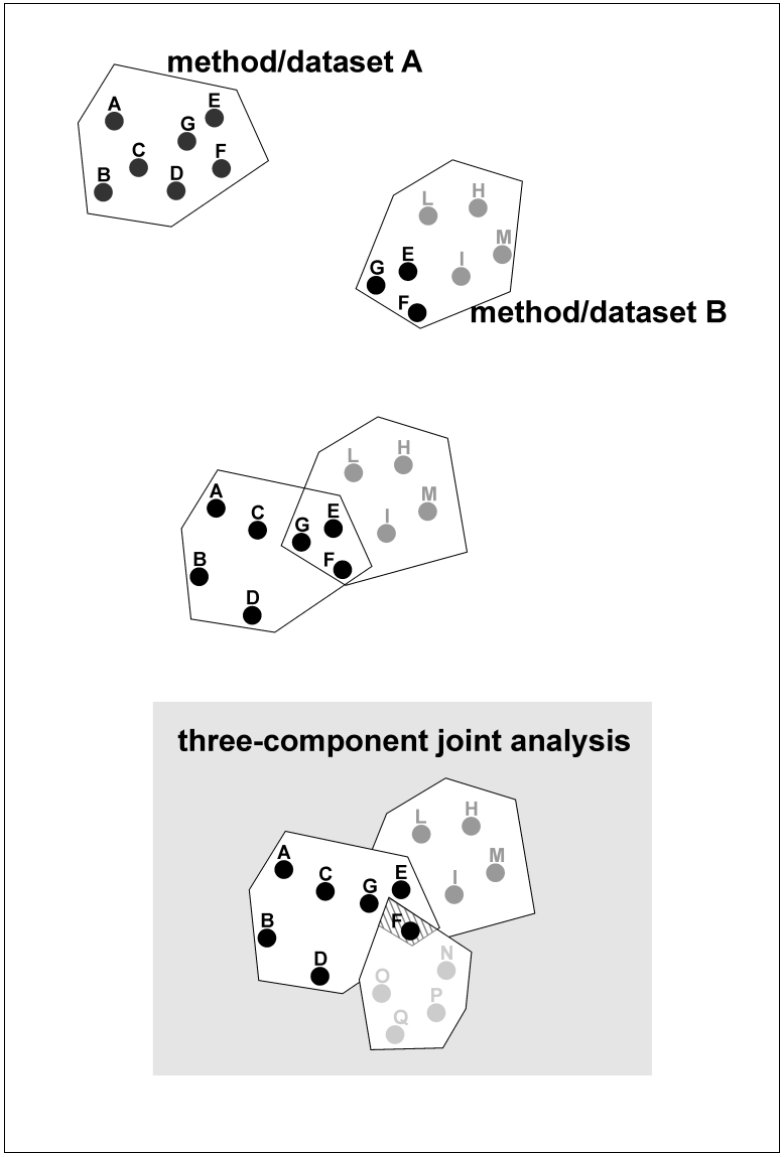
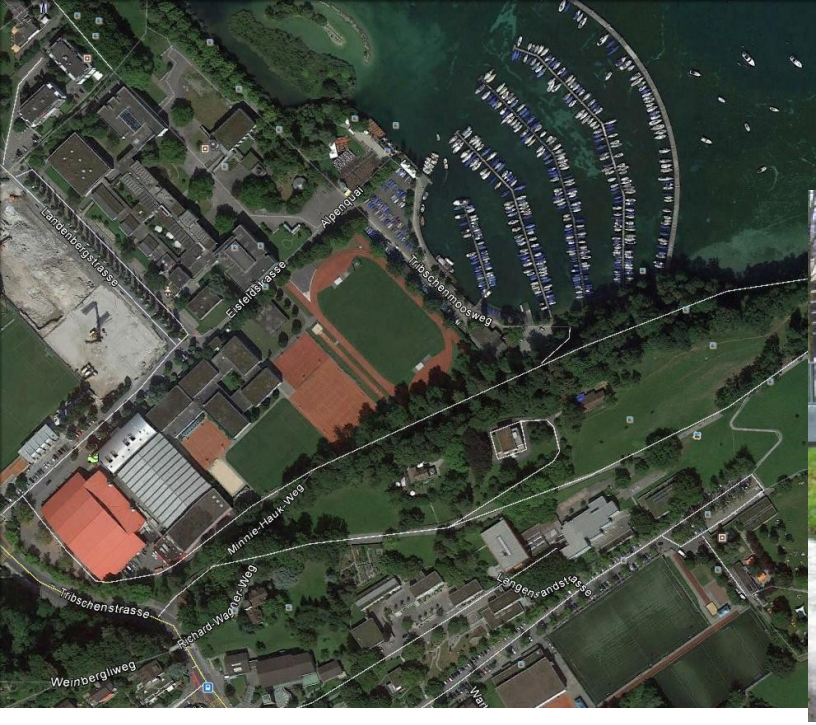
Two R&D lines

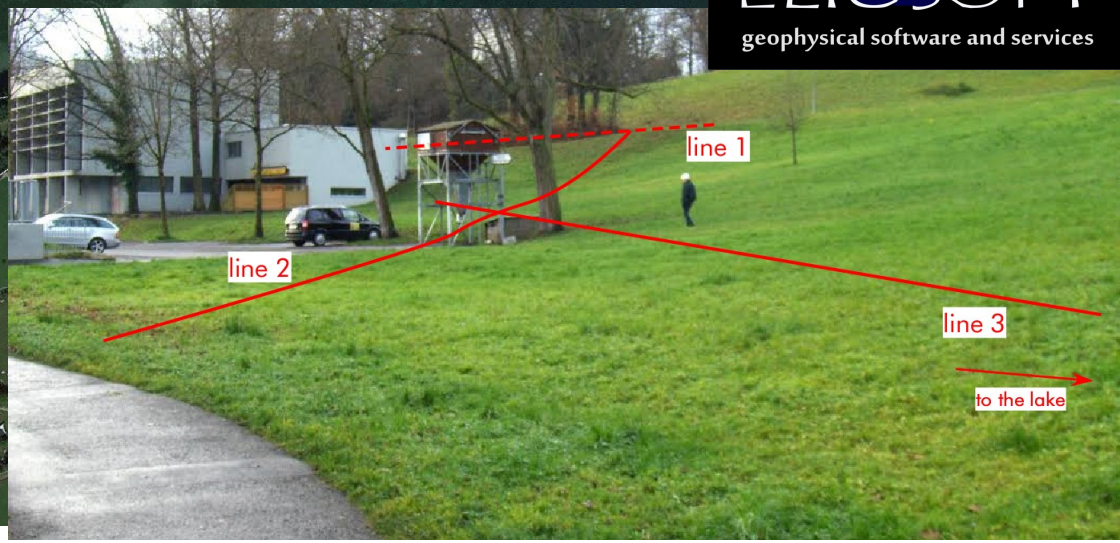
Classical (improved) methodologies:
e.g., multi-component MASW analyses according to FVS

Unconventional (particularly effective) methodologies: *HoliSurface* & MAAM

Non-uniqueness of the solution







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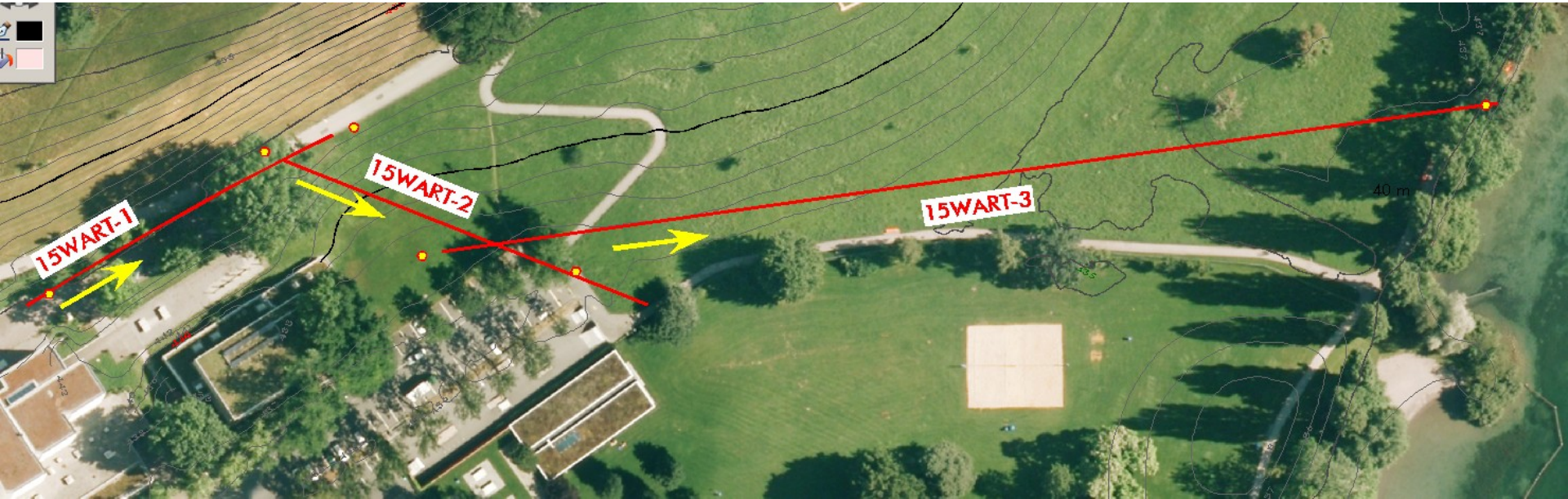
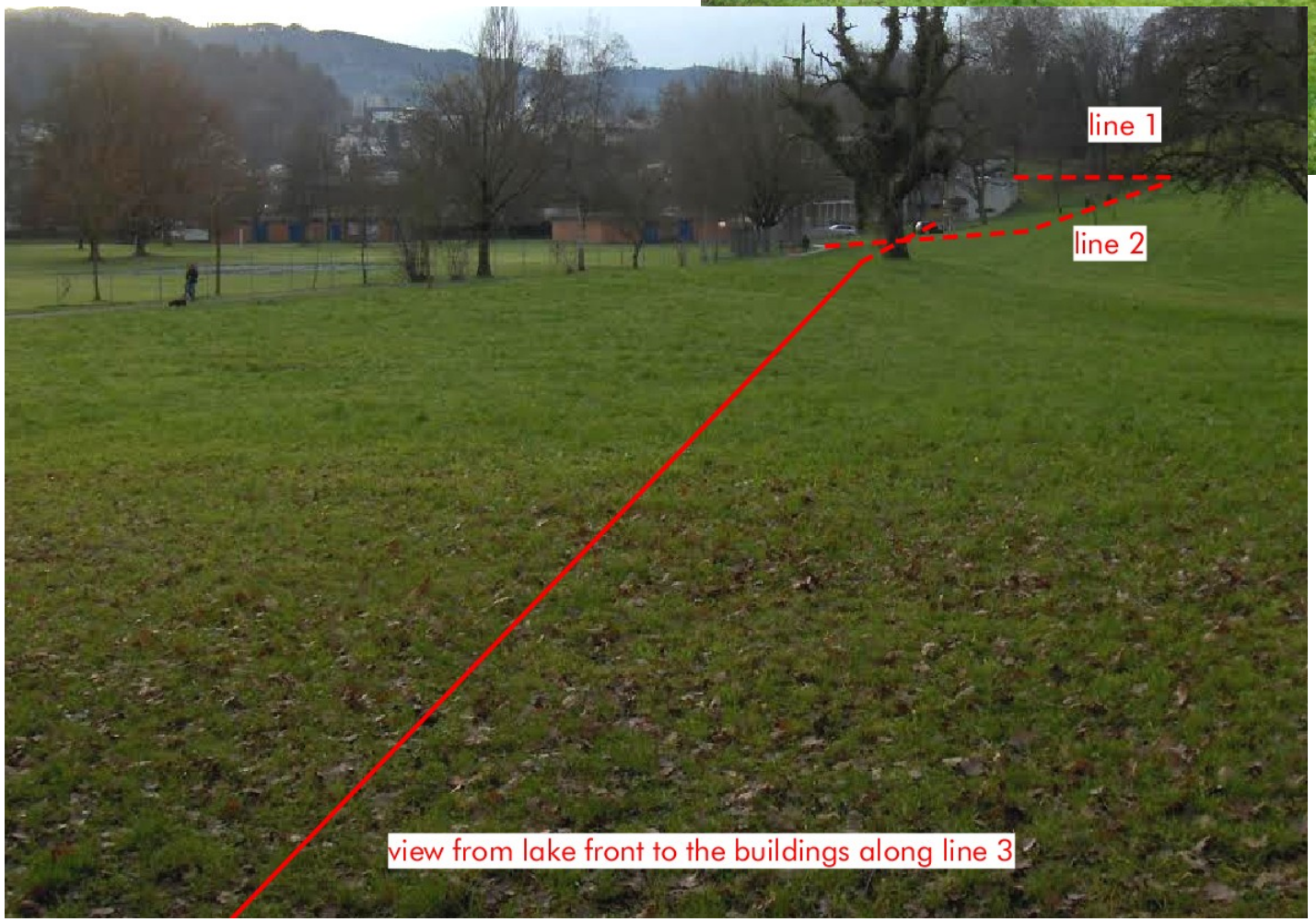
Esempio di efficienza: “Vierwaldstättersee” survey



Vierwaldstättersee survey



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ADAM-2D

Apparent-**D**ispersion **A**nalysis of **M**ulticomponent Data – **2D**

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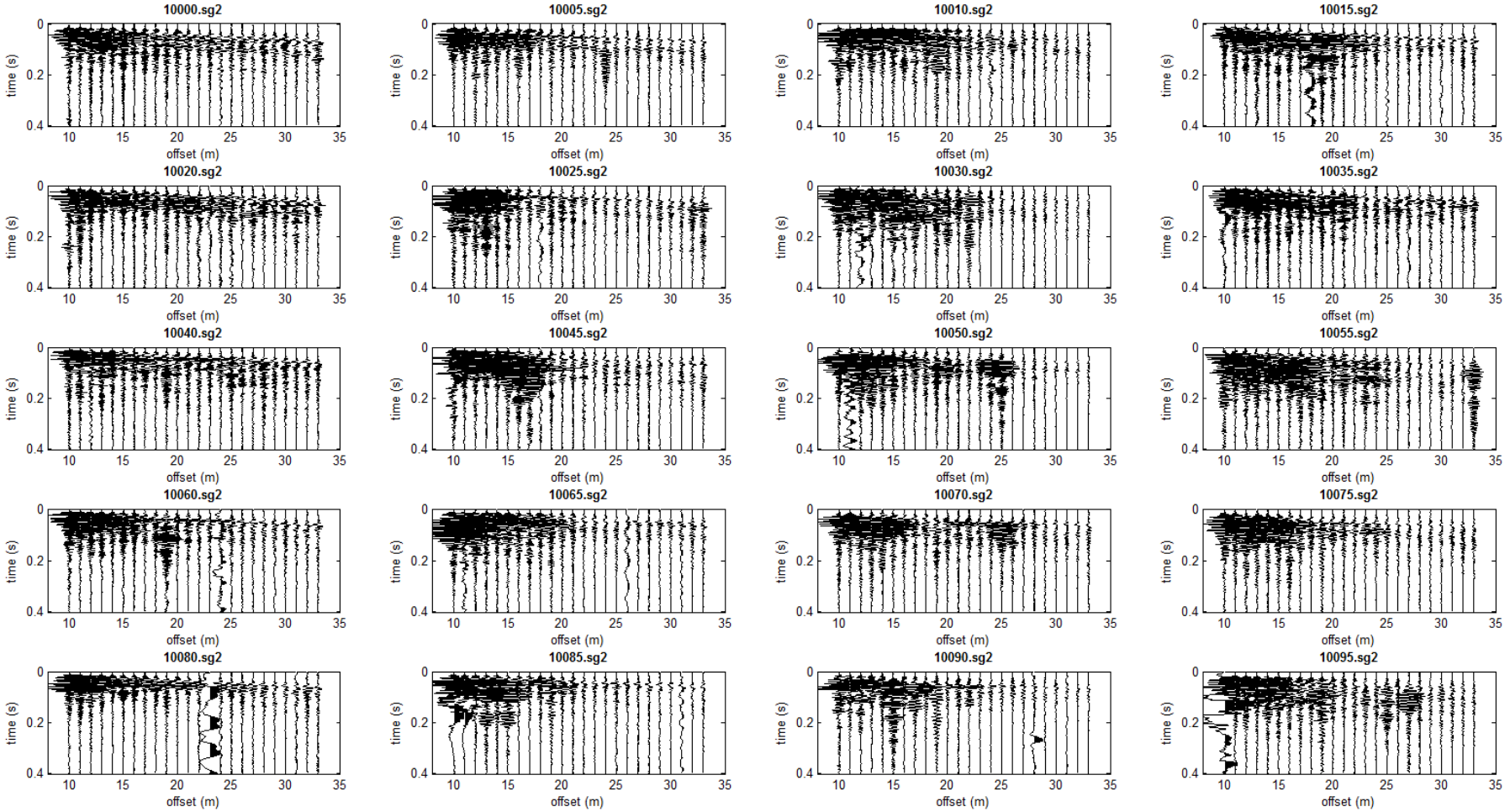
Apparent-**D**ispersion **A**nalysis of **M**ulticomponent Data – **2D**

Qatar survey

Automatic upload and pre-processing of the data

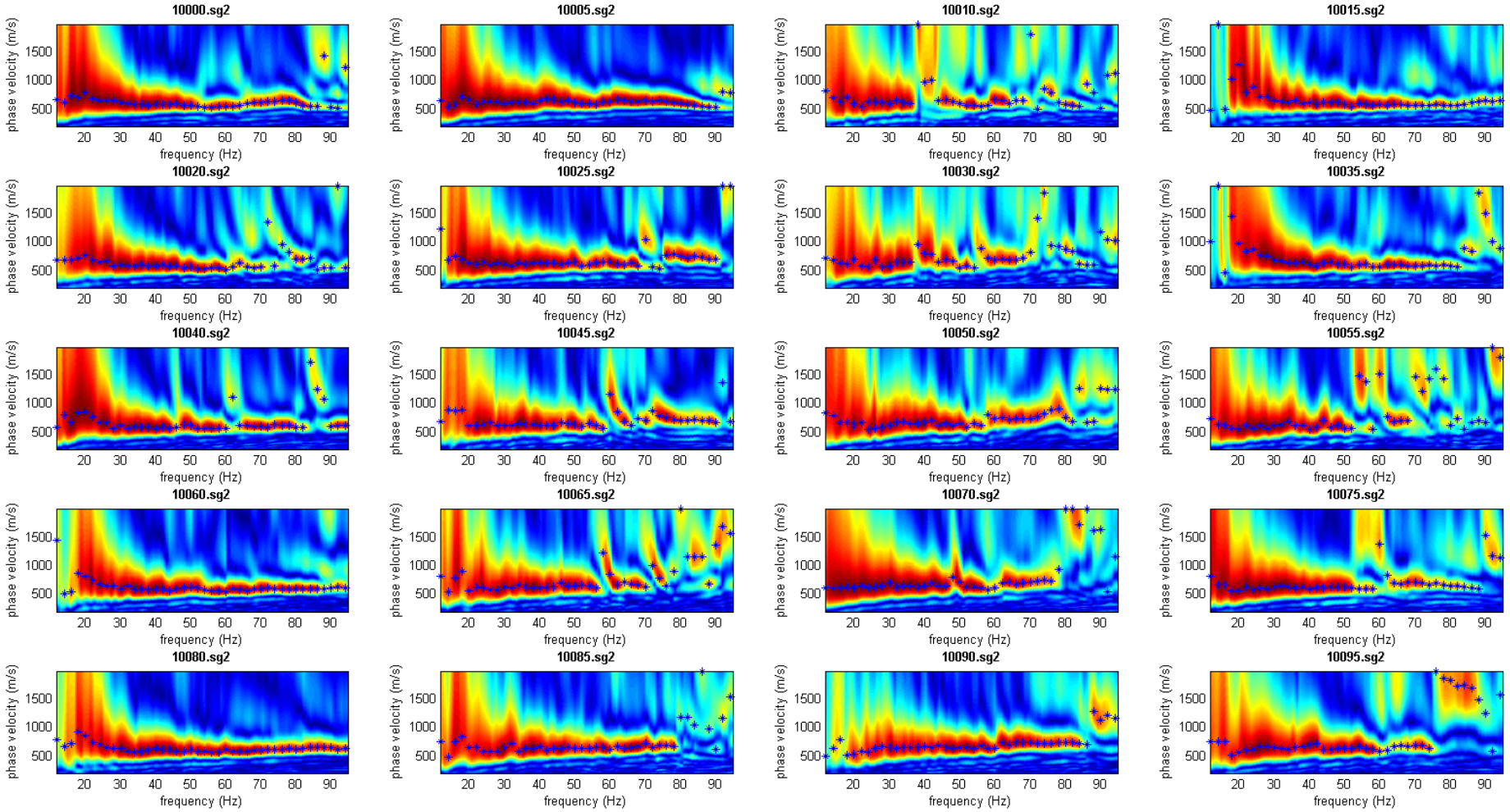


ADAM-2D

Apparent-**D**ispersion **A**nalysis of **M**ulticomponent Data – **2D**

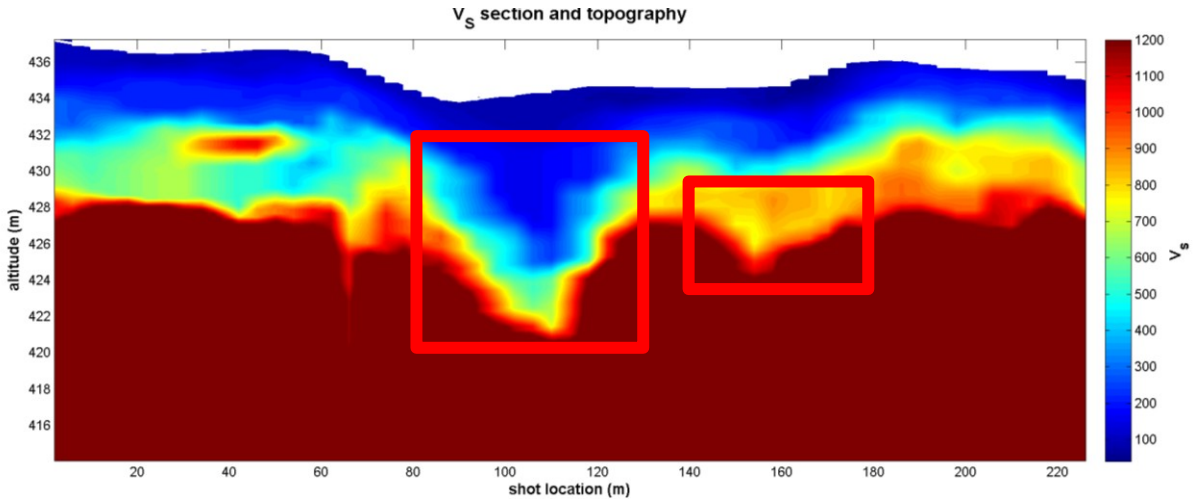
Qatar survey

Automatic computation of velocity spectra and <u>apparent dispersion curves for multi-component data</u>



ADAM-2D

Vs


V_S section and topography
altitude (m)
436
434
432
430
428
426
424
422
420
418
416
20
40
60
80
100
120
140
160
180
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220
shot location (m)
1200
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700
600
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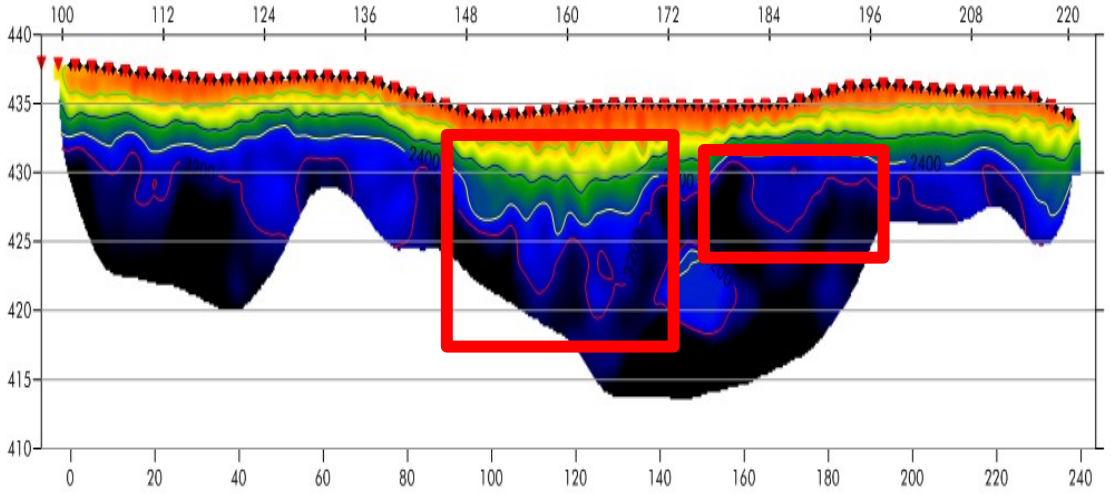
300
200
100
V_s

Vp


100
112
124
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148
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172
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208
220
440
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2400

Oberflächengebundene Bestimmung eines robusten Vs-Modells als Eingangsparameter zu bodendynamischen Berechnungen an einer historischen Klosterkirche

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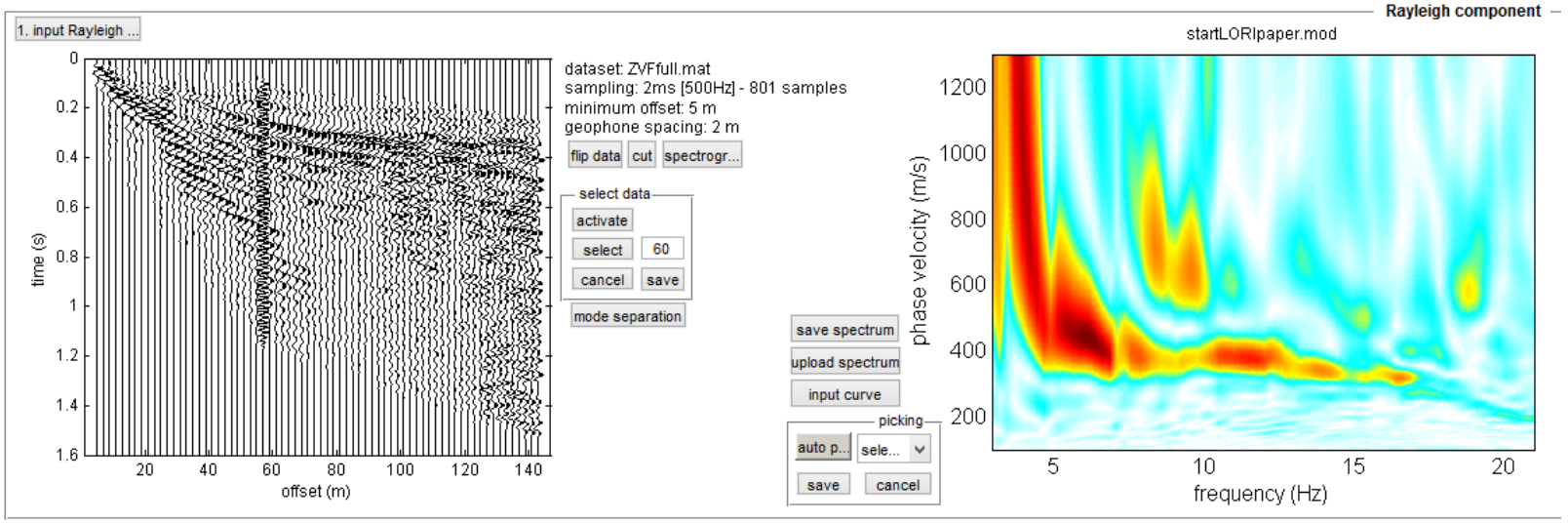
([3]) Résonance Ingénieurs-Conseils SA, dynamic engineering, Carouge (Switzerland)

Oberflächengebundene Bestimmung eines robusten Vs-Modells als Eingangsparameter zu bodendynamischen Berechnungen an einer historischen Klosterkirche

The “ordinary” multi-channel approach



Oberflächengebundene Bestimmung eines robusten Vs-Modells als Eingangsparameter zu bodendynamischen Berechnungen an einer historischen Klosterkirche

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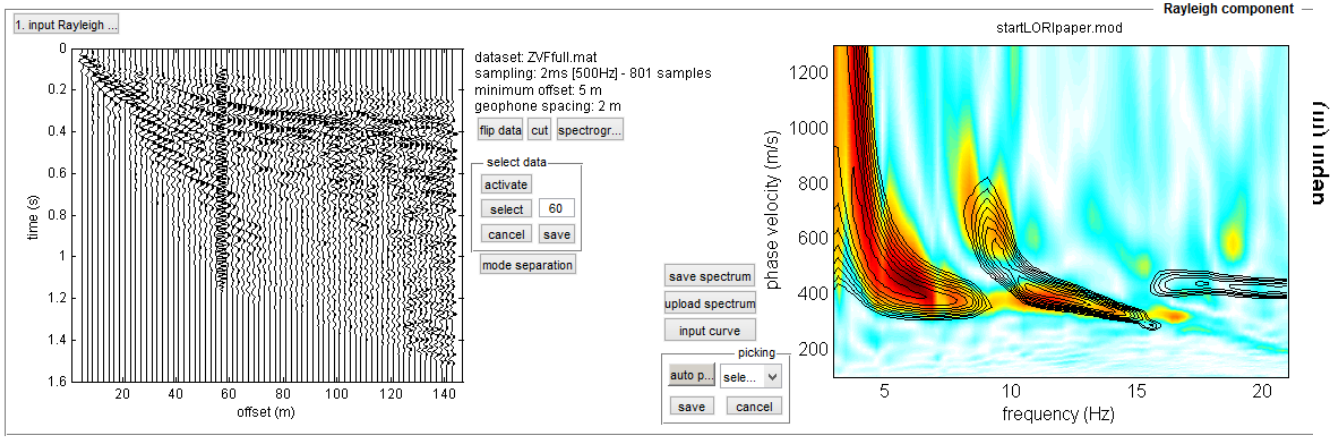
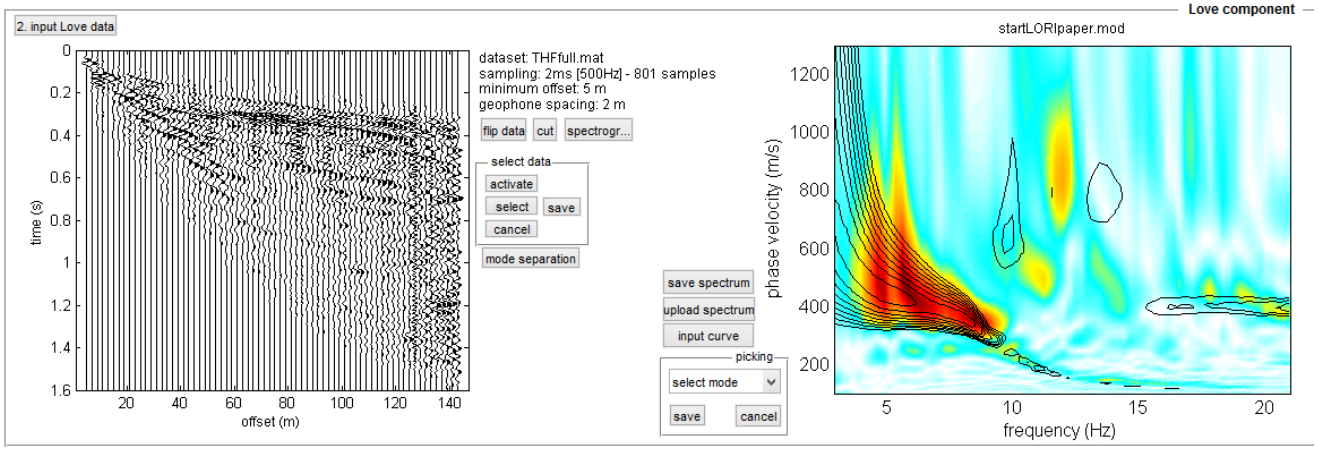
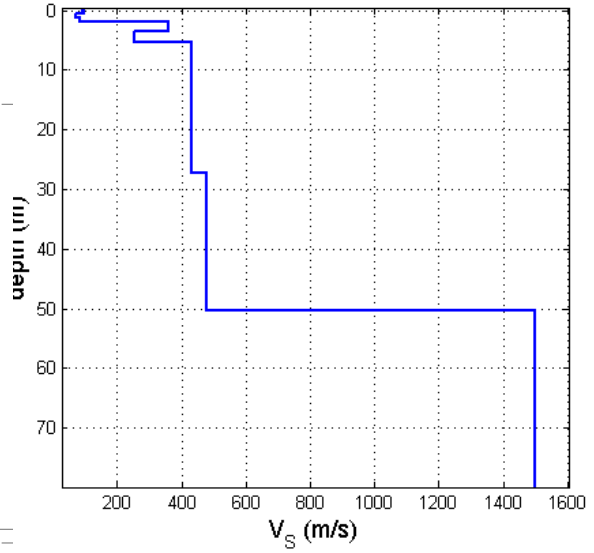
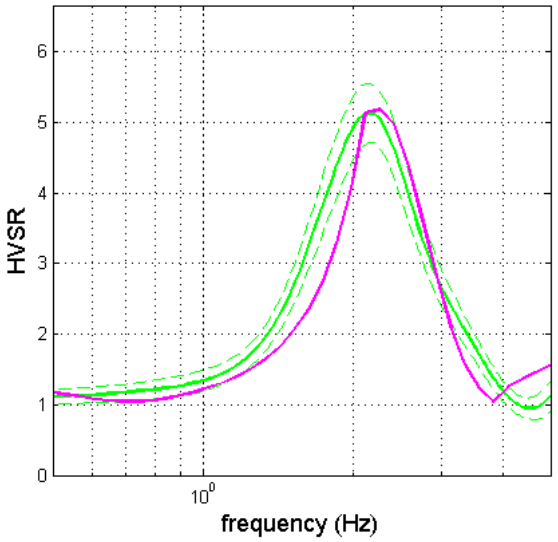






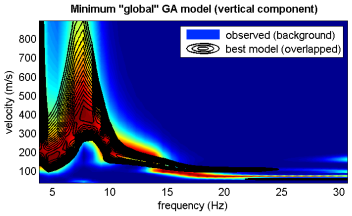


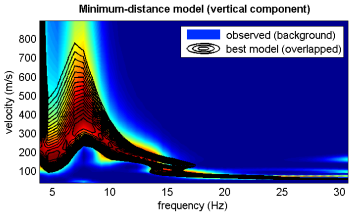
the unordinary approaches

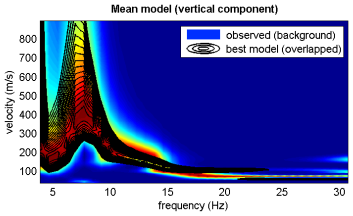
The more you know,
the less you need.

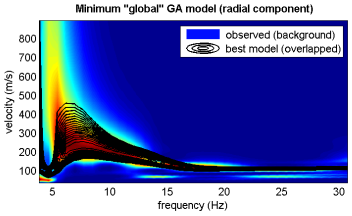
Yvon Chouinard

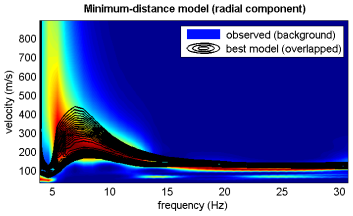
Oberflächengebundene Bestimmung eines robusten Vs-Modells als Eingangsparameter zu bodendynamischen Berechnungen an einer historischen Klosterkirche

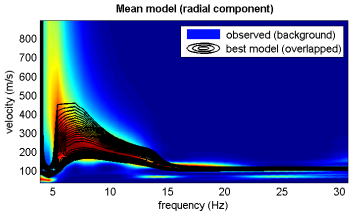


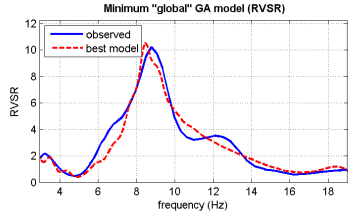


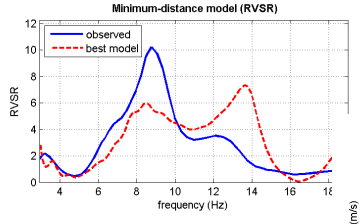


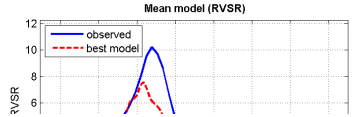


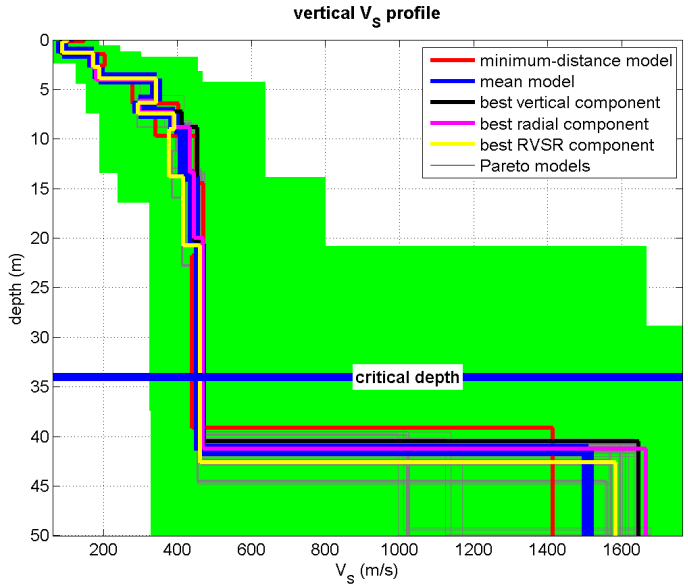


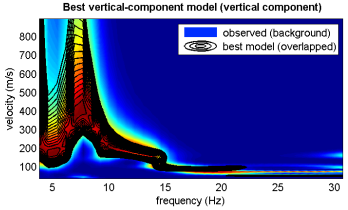


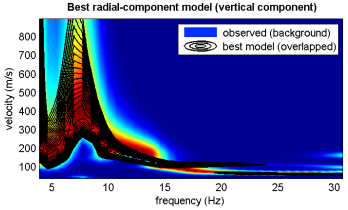


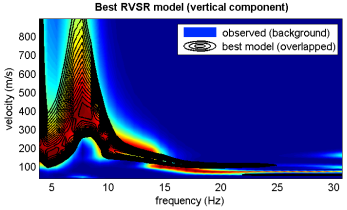


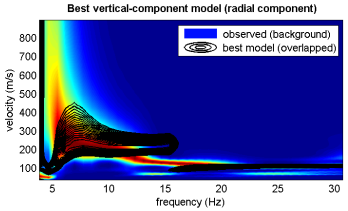


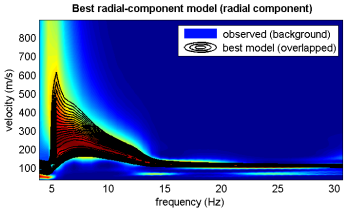


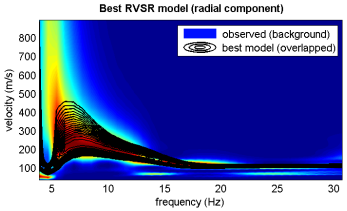


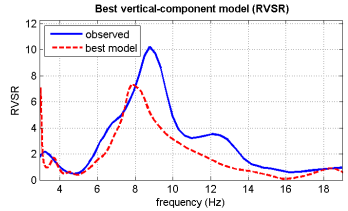


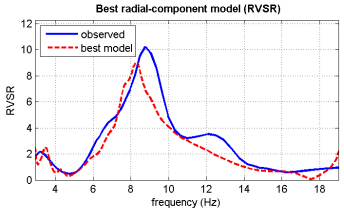


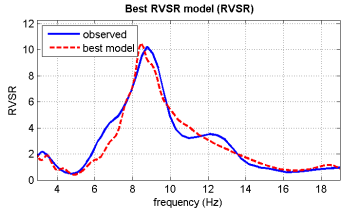






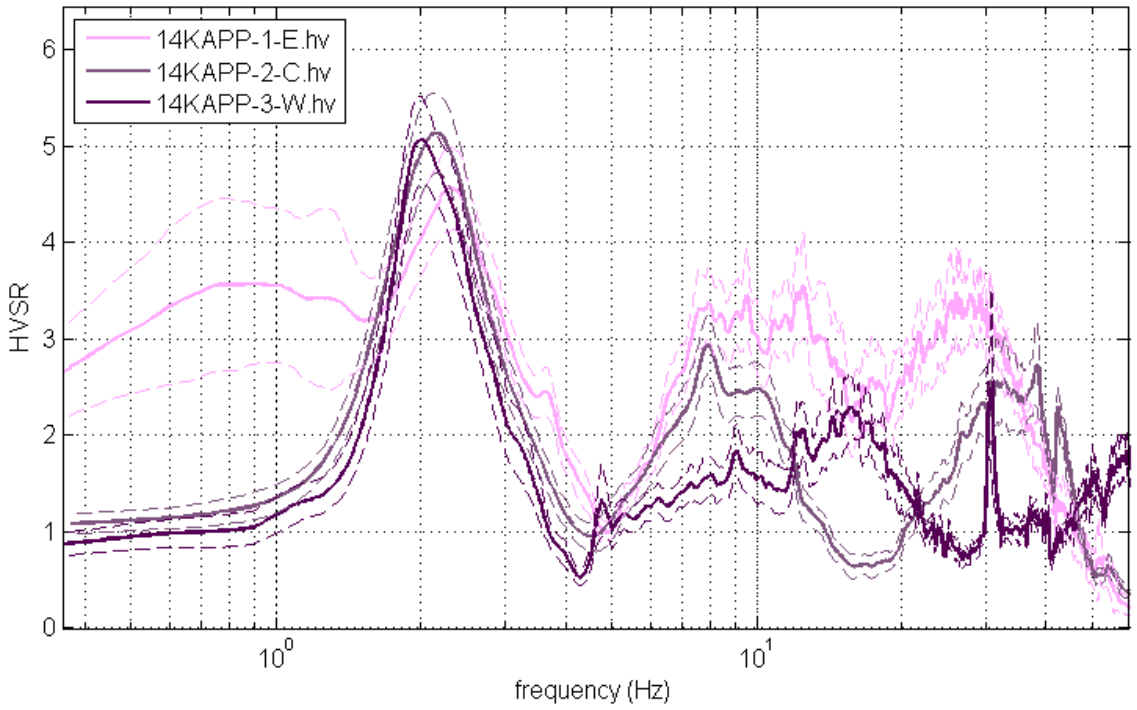




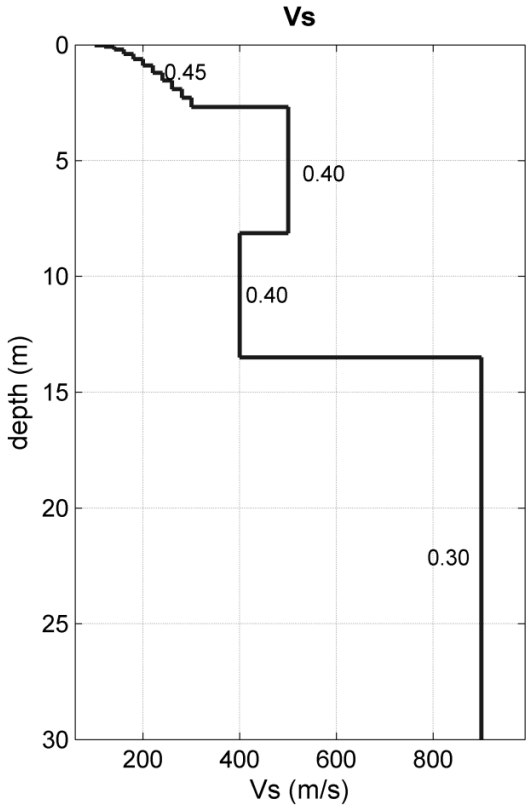


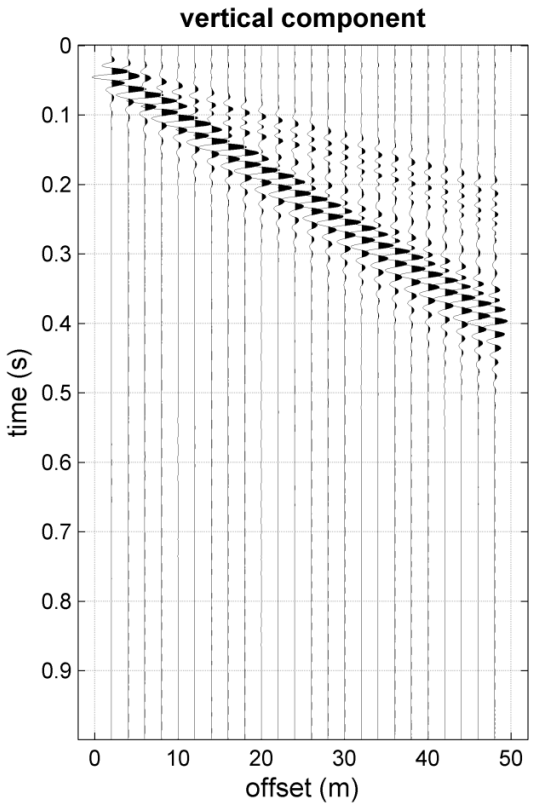
Pure *HoliSurface*

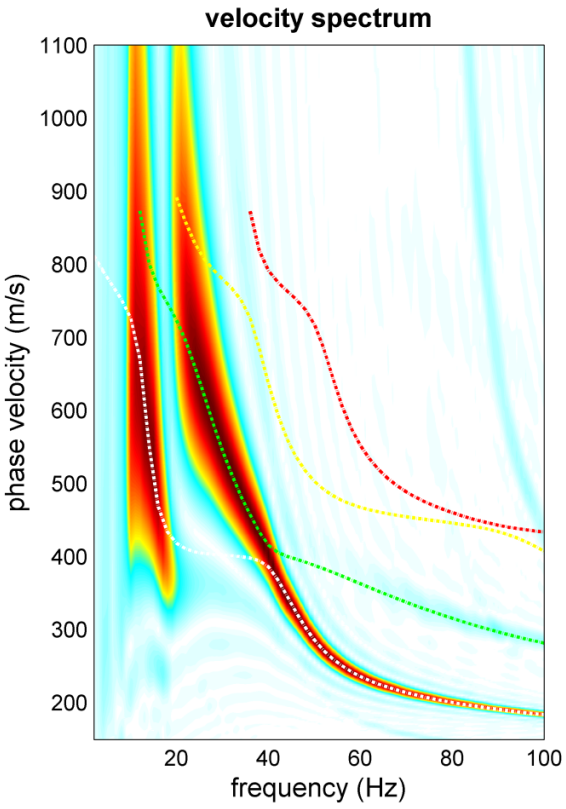
Oberflächengebundene Bestimmung eines robusten Vs-Modells als Eingangsparameter zu bodendynamischen Berechnungen an einer historischen Klosterkirche



Modal and effective dispersion curves: problems and solutions



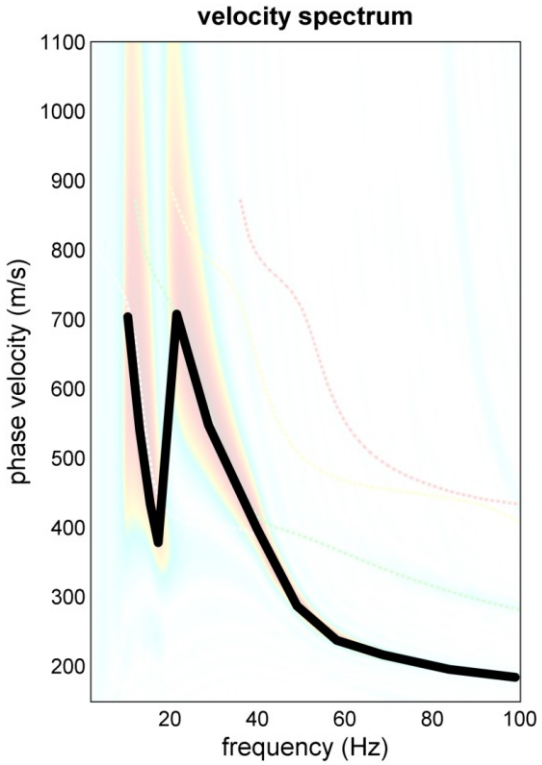




Onde di Rayleigh:
La continuità di un segnale non significa che quel segnale appartiene ad un unico/singolo modo.

<u>Soluzione</u>: analisi congiunte con le onde di Love!

Modal and effective dispersion curves: problems and solutions



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<u>Soluzione</u>: analisi congiunte con le onde di Love!

Modal and effective dispersion curves: problems and solutions

From (11) and (12), the relative powers of the vertical and horizontal motions of mth mode can be expressed as $A_m^2 c_m$ and $(A_m[\dot{u}/\dot{w}]_m)^2 c_m$, respectively. Hence, by knowing A_m, c_m, and $[\dot{u}/\dot{w}]_m$ of each mode for a frequency f, the apparent phase velocities of vertical and horizontal motions for a given sensor distance can be determined as

$$c_{sv} = \frac{2\pi f D}{\cos^{-1}\left[\dfrac{\sum_{m=1}^{M} A_m^2 c_m \cos\left(\dfrac{2\pi f D}{c_m}\right)}{\sum_{m=1}^{M} A_m^2 c_m}\right]} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

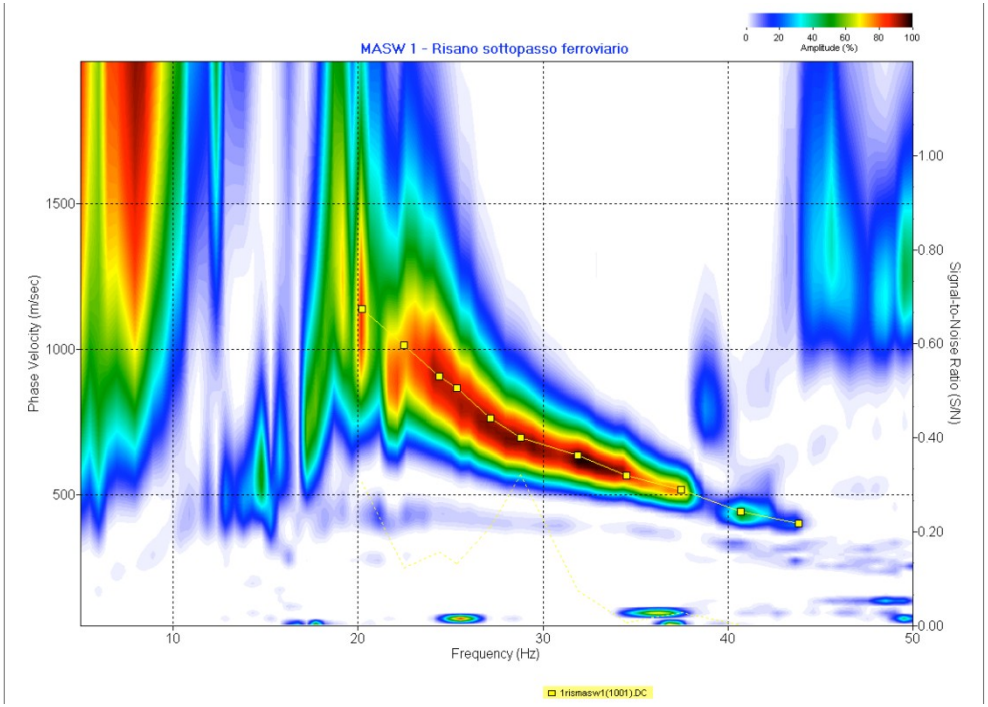
$$c_{sh} = \frac{2\pi f D}{\cos^{-1}\left[\dfrac{\sum_{m=1}^{M} \left(A_m \left[\dfrac{\dot{u}}{\dot{w}}\right]_m\right)^2 c_m \cos\left(\dfrac{2\pi f D}{c_m}\right)}{\sum_{m=1}^{M} \left(A_m \left[\dfrac{\dot{u}}{\dot{w}}\right]_m\right)^2 c_m}\right]} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

Modal and effective dispersion curves: problems and solutions

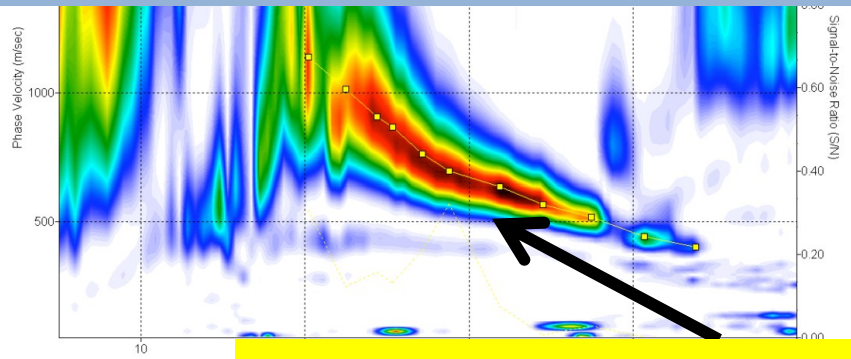
“MASW”

Downhole

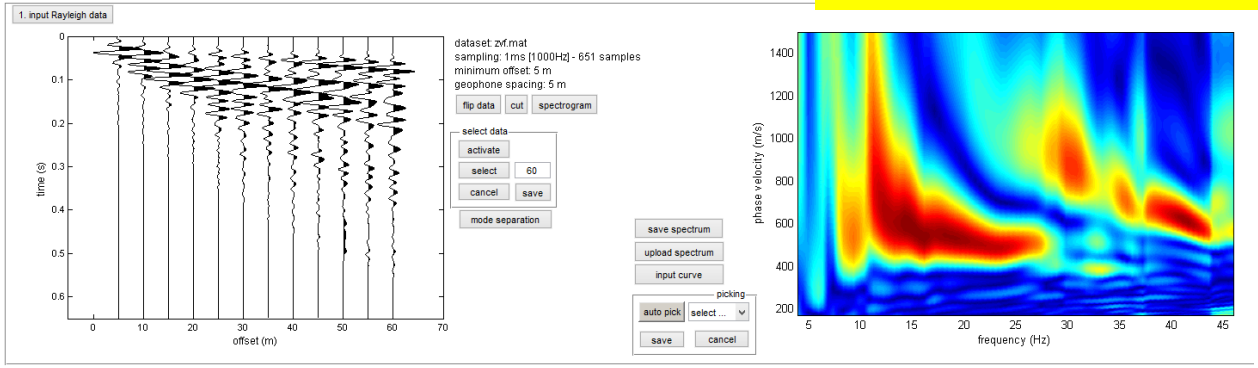
P-wave refraction

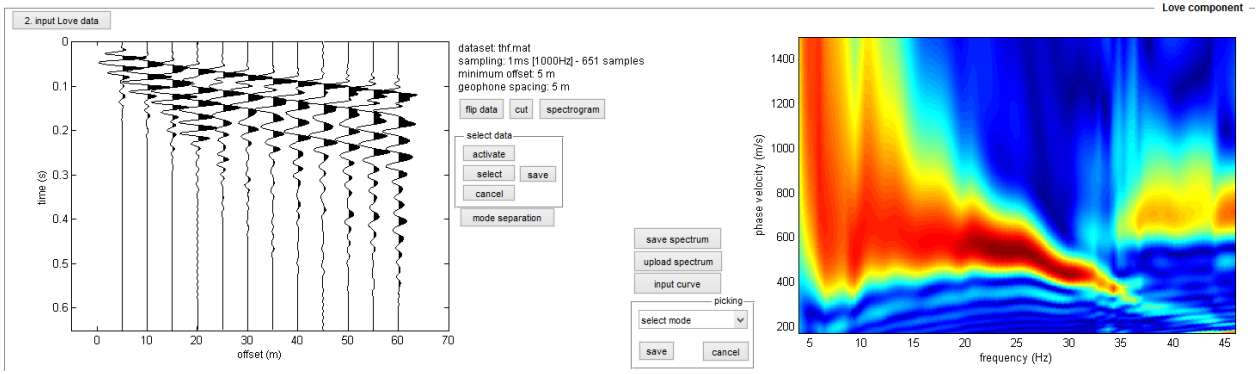


Modal and effective dispersion curves: problems and solutions

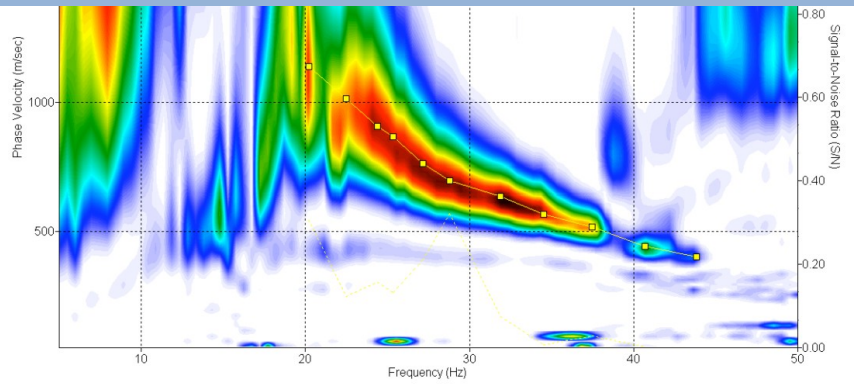


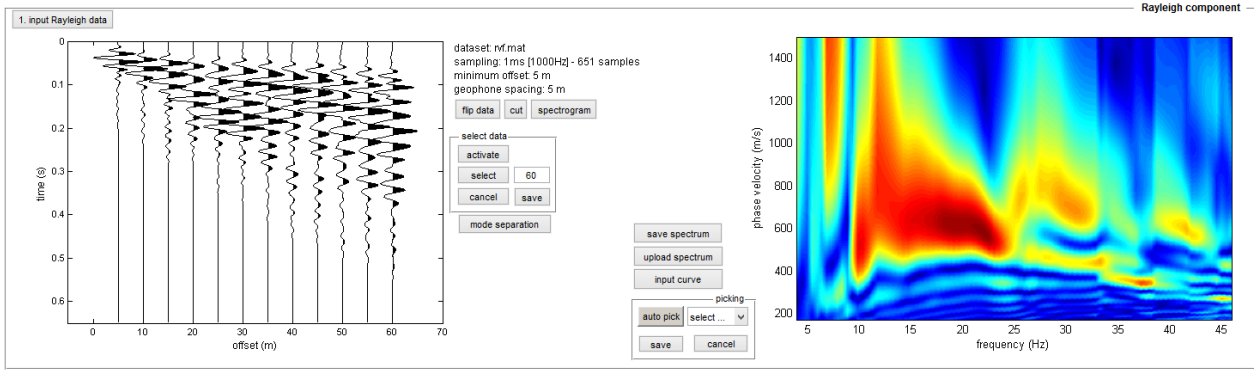
Dies ist nicht der Fundamentalmodus!

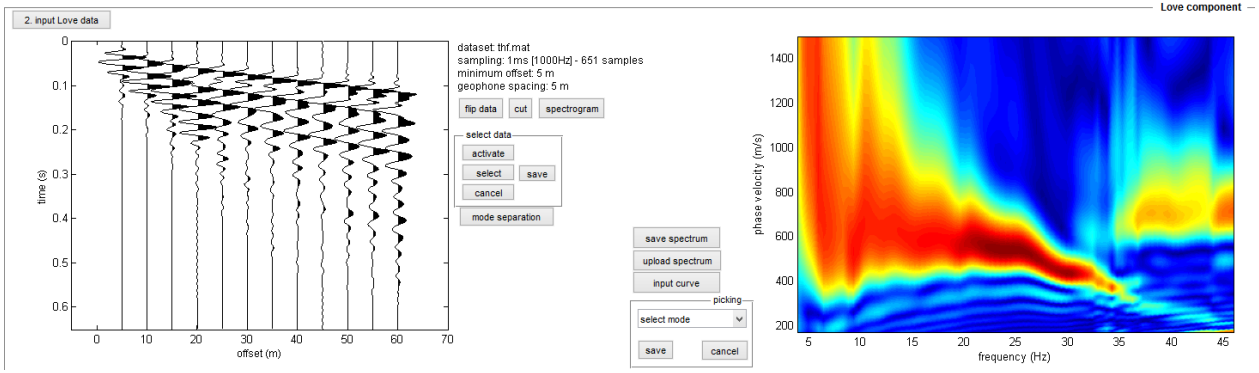




Modal and effective dispersion curves: problems and solutions

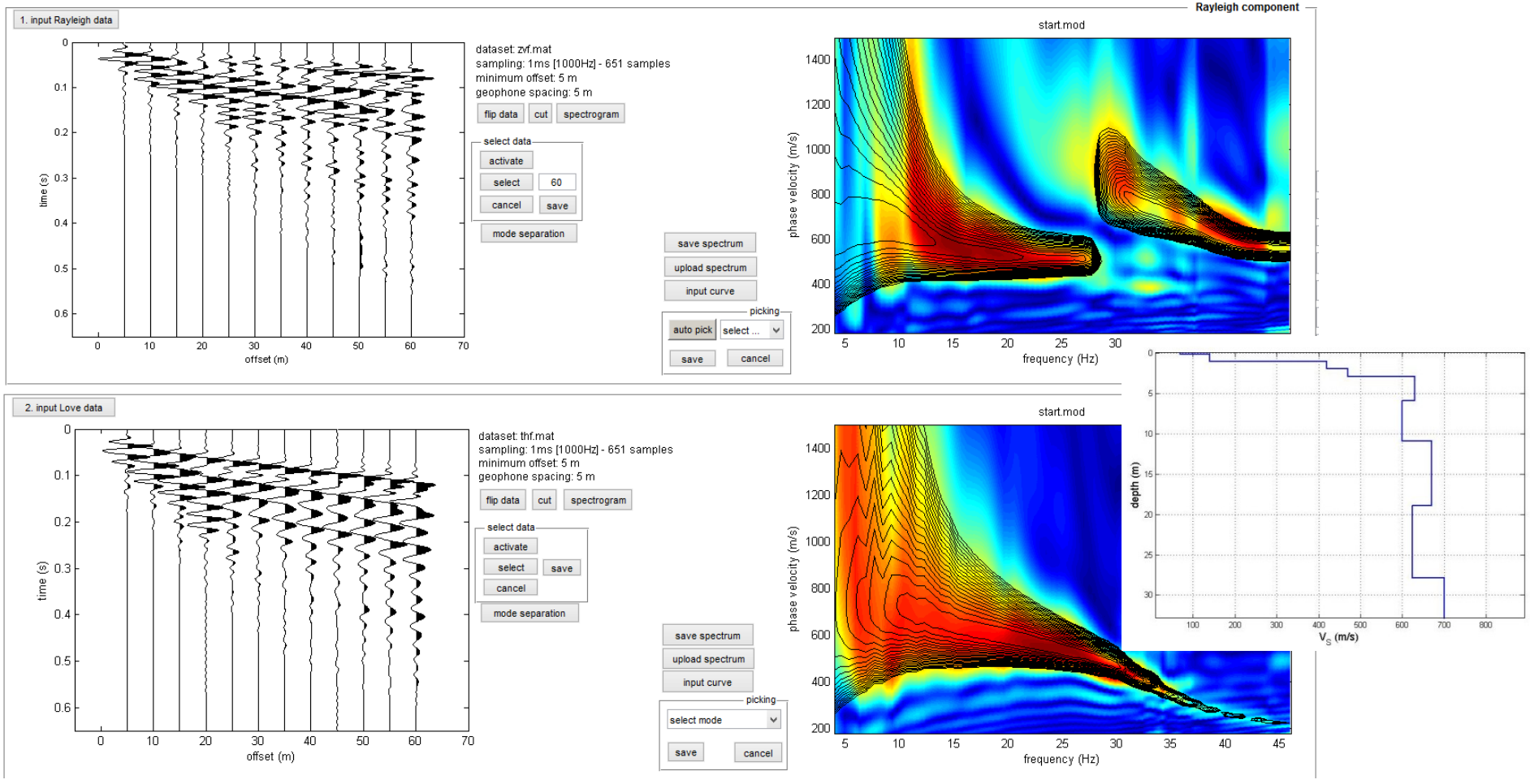






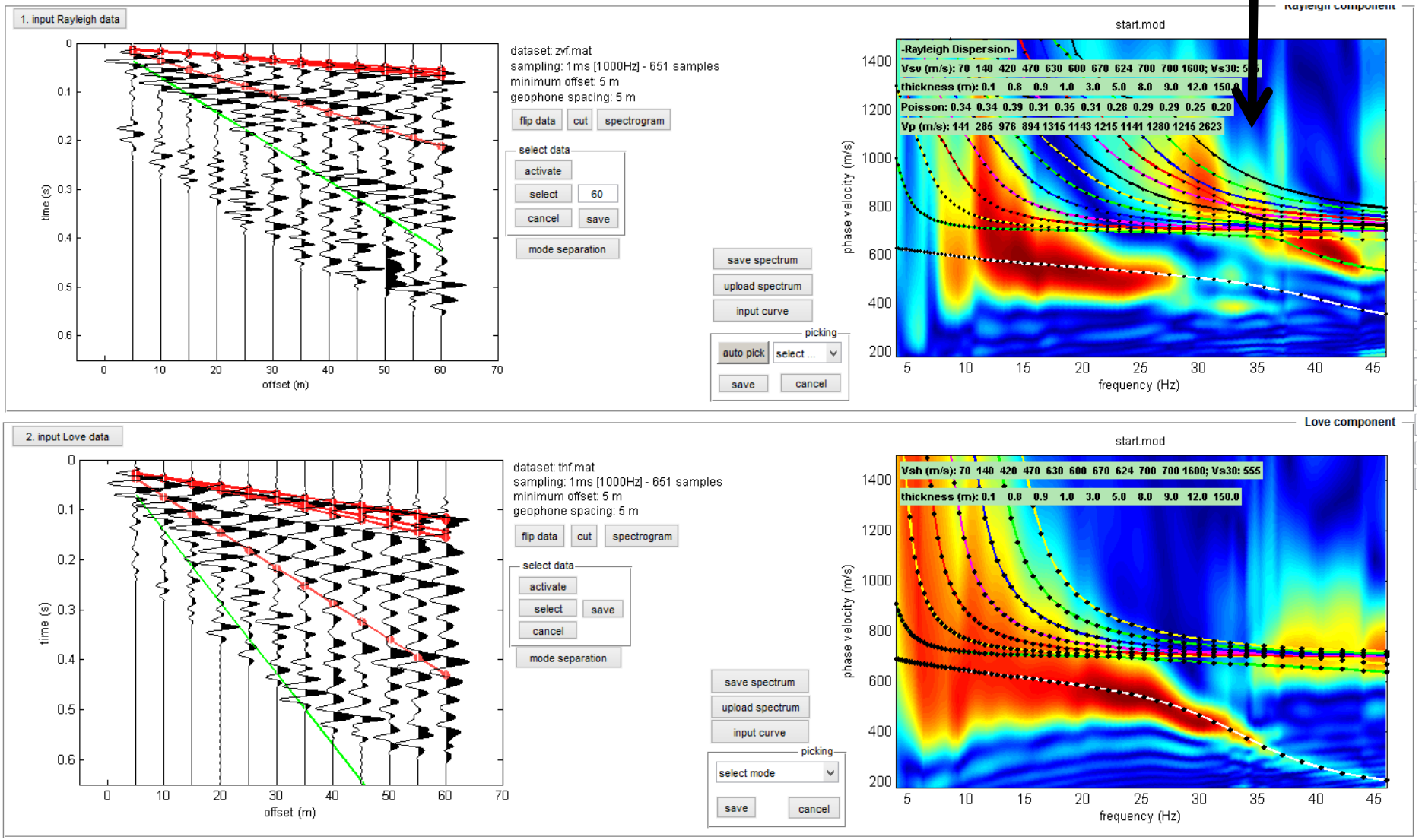
Modal and effective dispersion curves: problems and solutions

Our joint FVS solution: our synthetic velocity spectra perfectly overlap with the observed ones

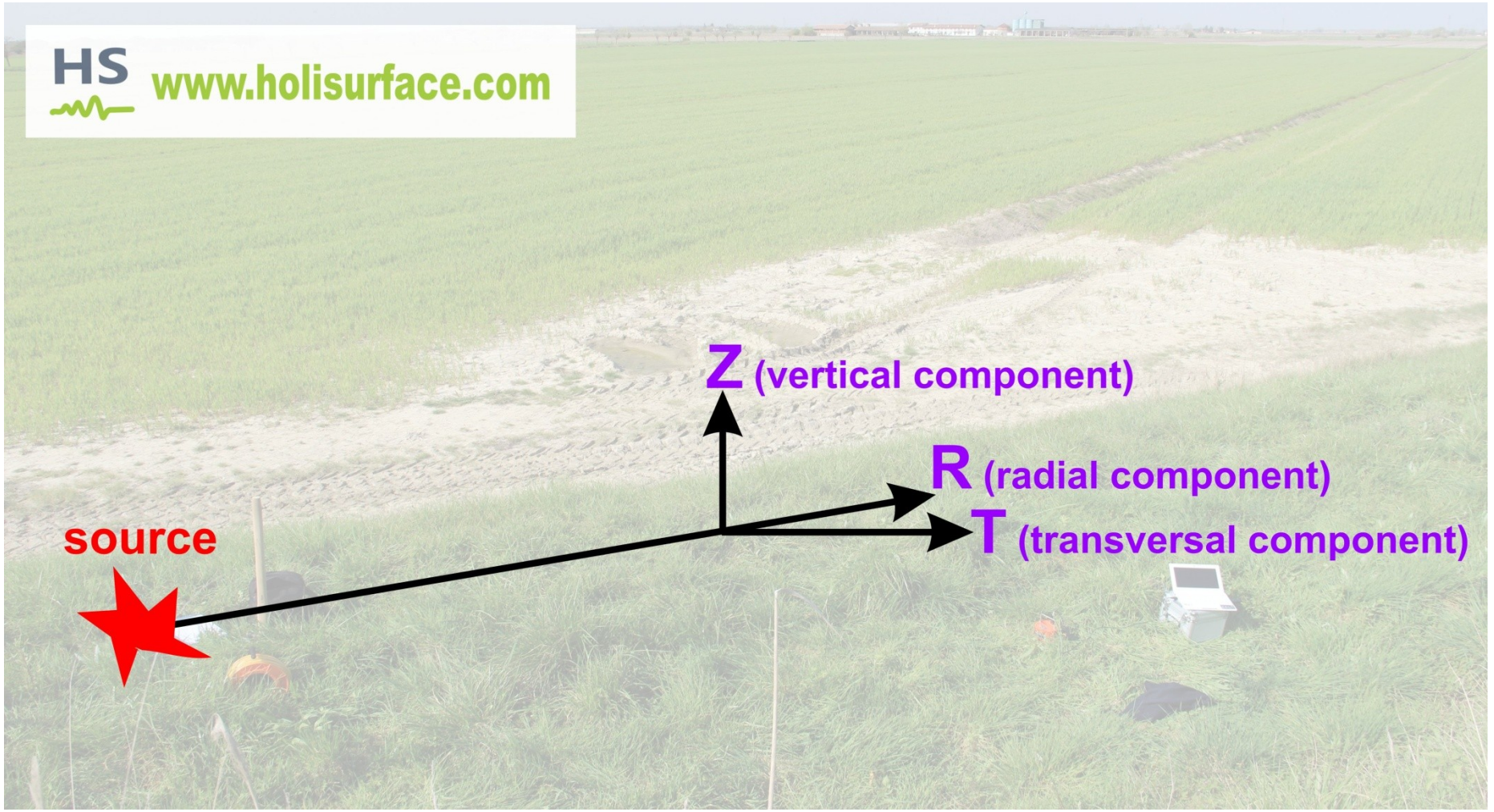


About modes (and refraction)

Dies ist nicht ein einziger Modus!



just recruiting


HS
www.holisurface.com
Z (vertical component)
R (radial component)
T (transversal component)
source

A circle, a line: they look good, they are abstract, they are common knowledge. They belong to everyone and equally to the past, the present and the future.

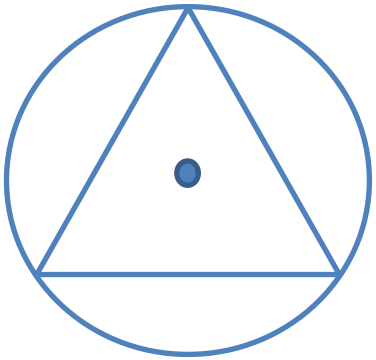
Richard Long

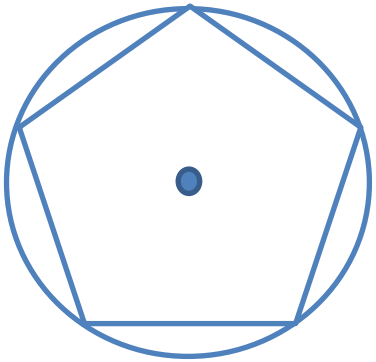
What's in common?

HS

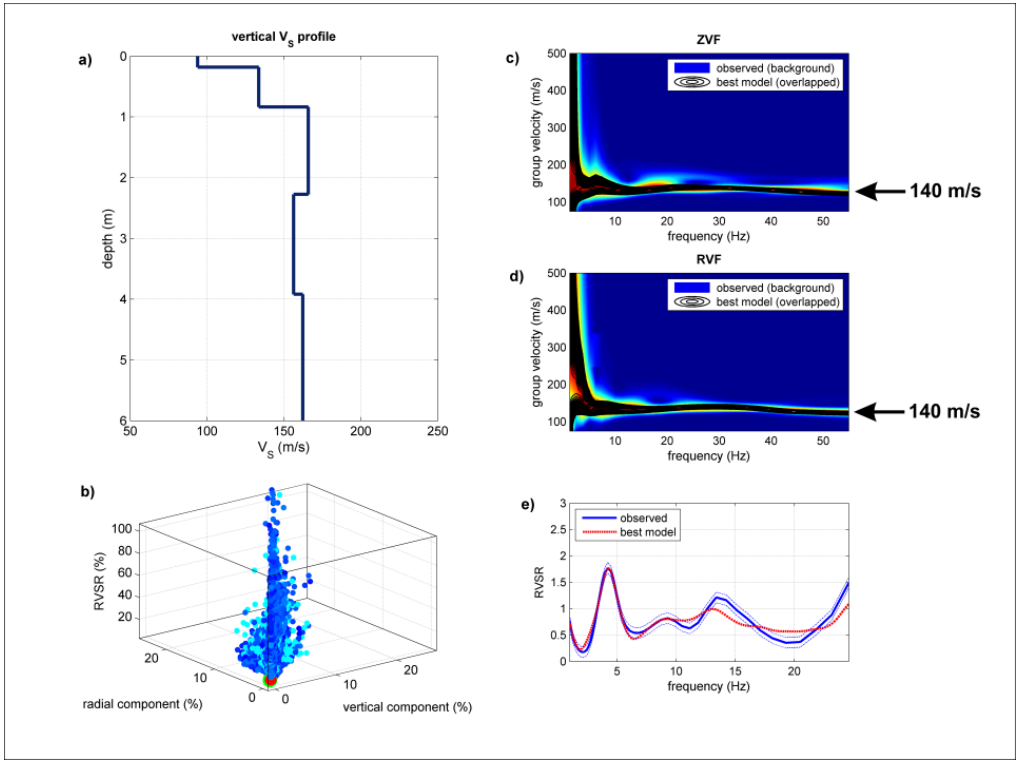
HVSR

MAAM

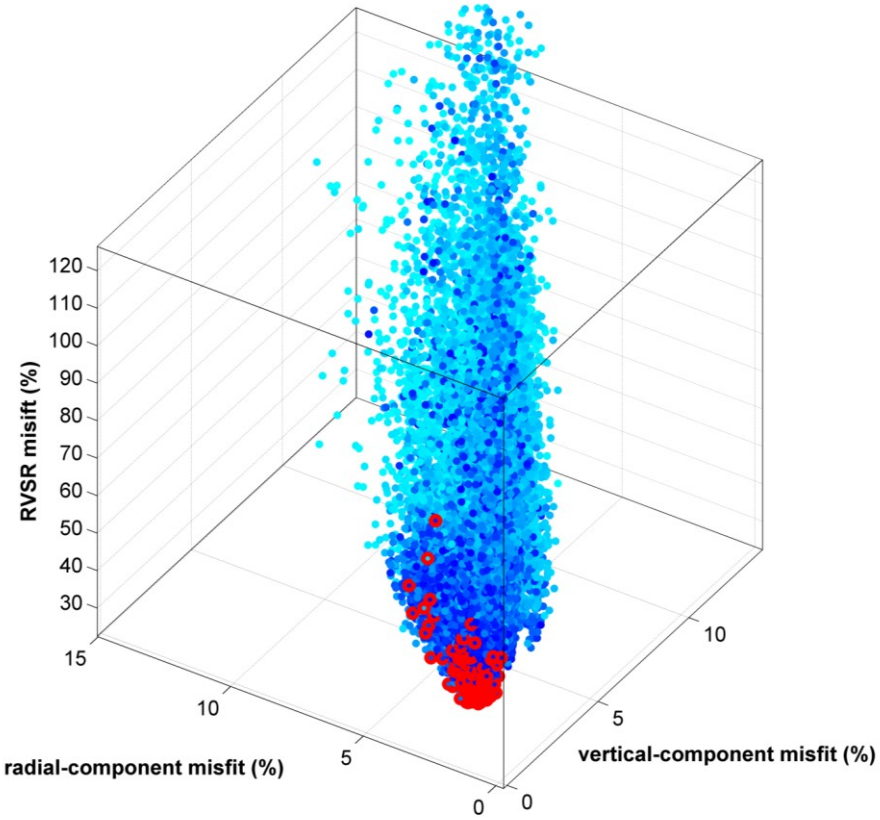


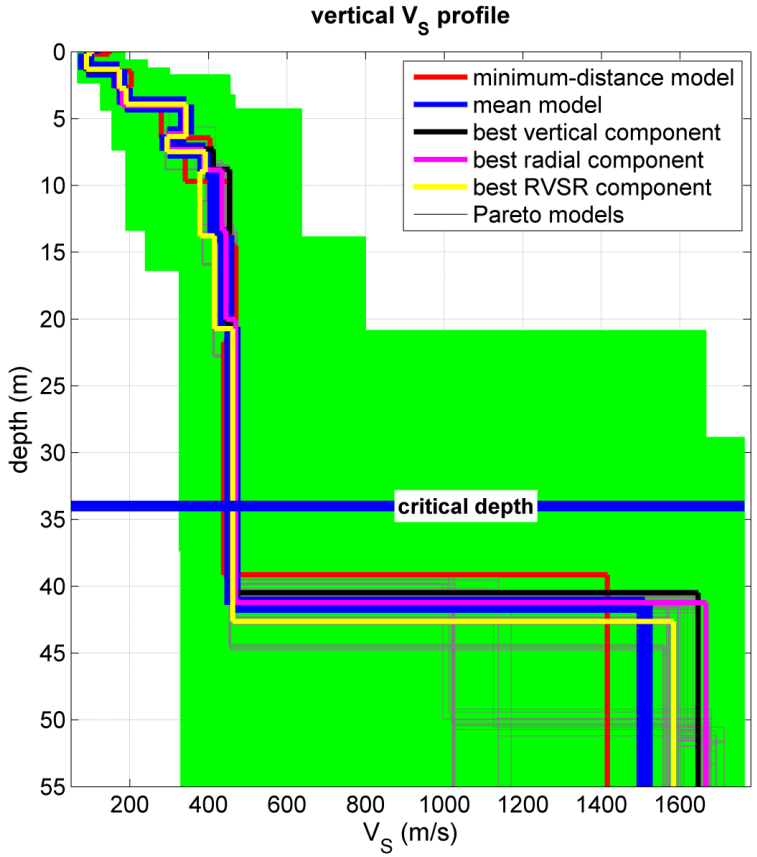


What's in common?



Oberflächengebundene Bestimmung eines robusten Vs-Modells als Eingangsparameter zu bodendynamischen Berechnungen an einer historischen Klosterkirche

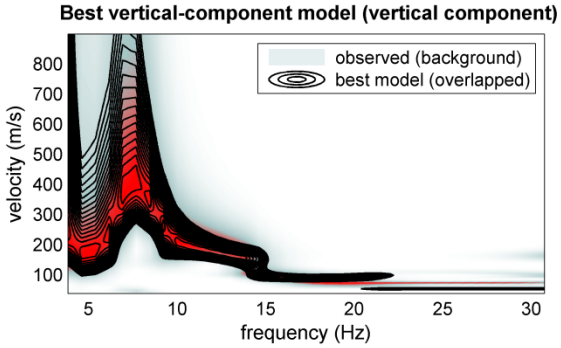


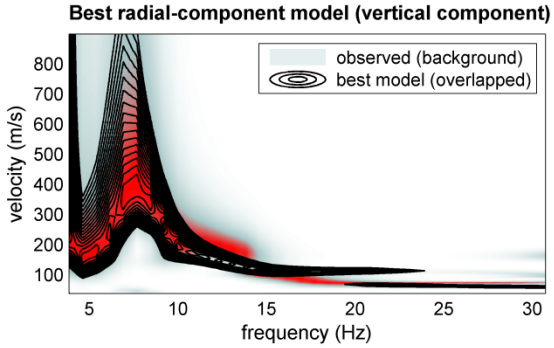


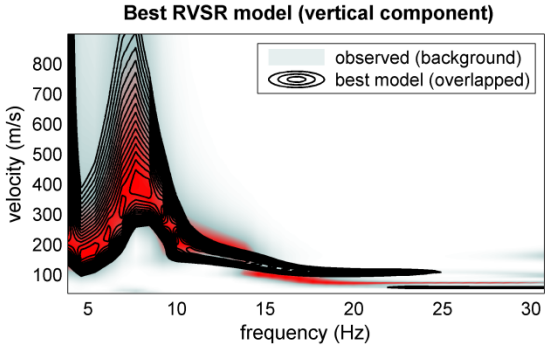
The unordinary *HoliSurface* approach

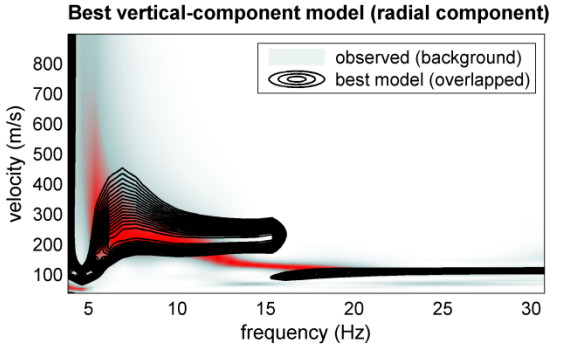
Oberflächengebundene Bestimmung eines robusten Vs-Modells als Eingangsparameter zu bodendynamischen Berechnungen an einer historischen Klosterkirche

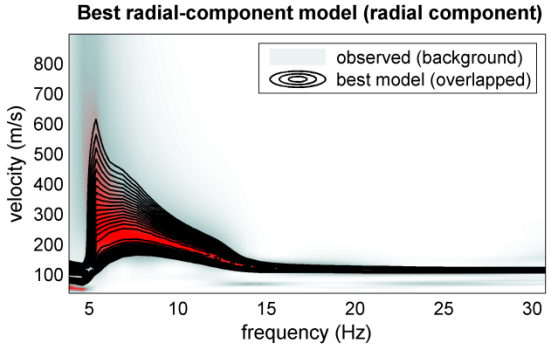
The unordinary *HoliSurface* approach

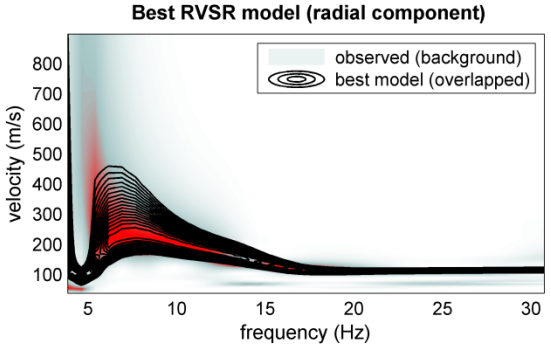


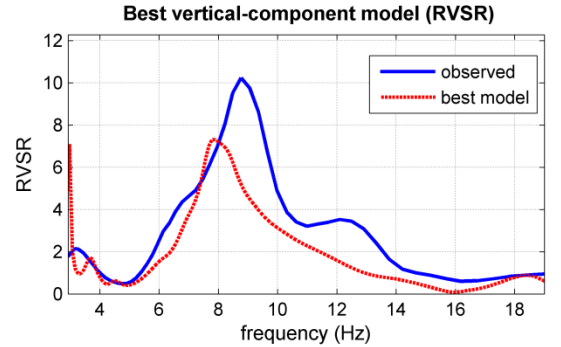


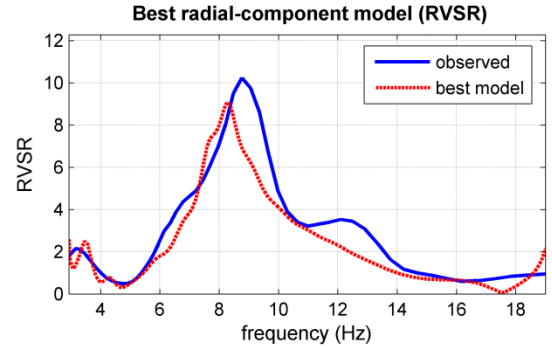


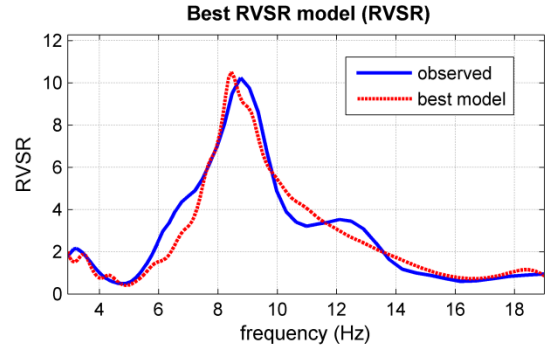






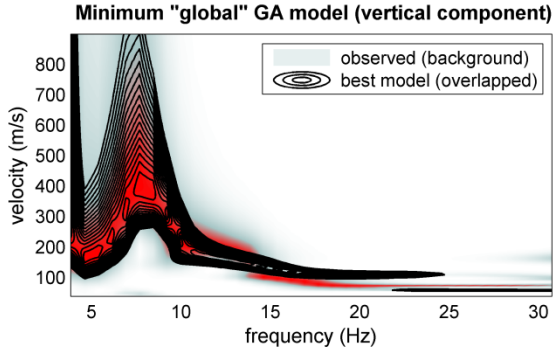


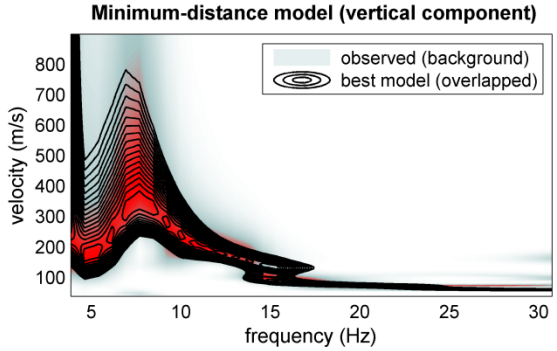


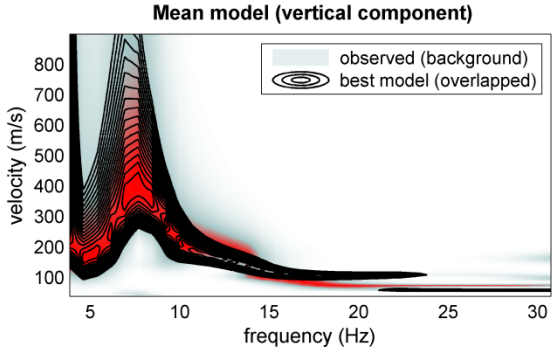


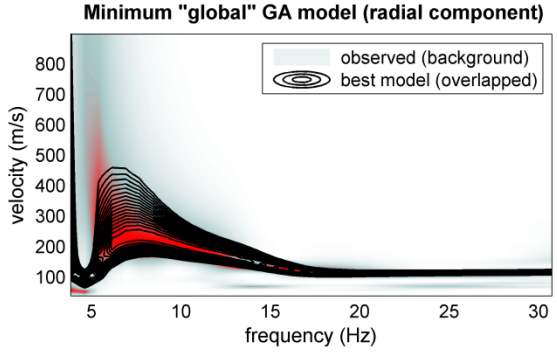
Oberflächengebundene Bestimmung eines robusten Vs-Modells als Eingangsparameter zu bodendynamischen Berechnungen an einer historischen Klosterkirche

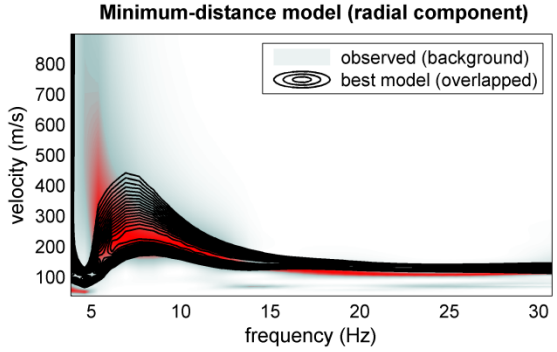
The unordinary *HoliSurface* approach

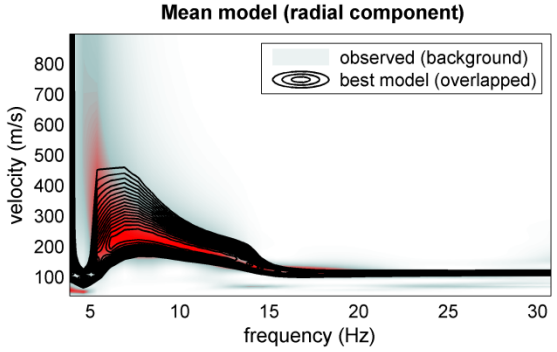


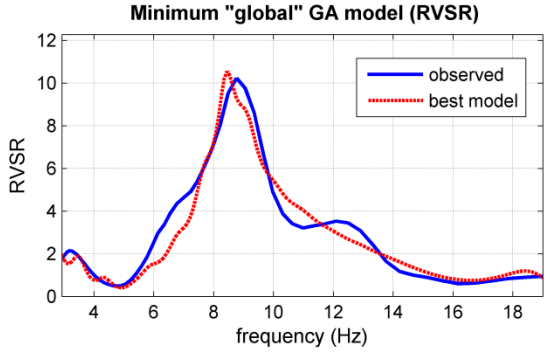


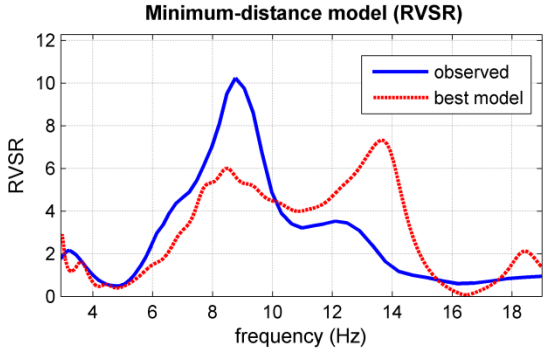


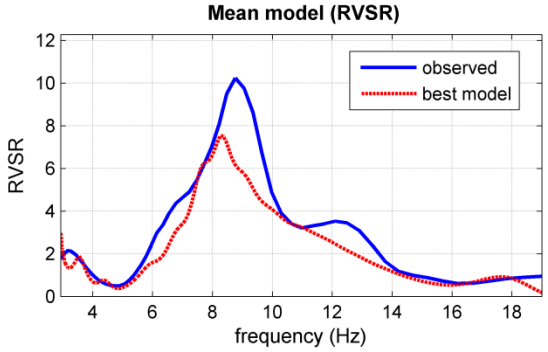












HoliSurface results compared to VSP (Vertical Seismic Profiling)

A Comprehensive Seismic Characterization via Multi-Component Analysis of Active and Passive Data (Dal Moro G., Keller L., Poggi V.), *First Break (September, 2015)*

first break volume 33, September 2015

technical article

A comprehensive seismic characterisation via multi-component analysis of active and passive data

G. Dal Moro[1*], L. Keller[2] and V. Poggi[3]

Abstract

A comprehensive seismic survey was conducted with the aim of characterising one of the *Swiss Digital Seismic Network* stations in Northern Switzerland. Both active (P- and S-wave refraction tomography, surface-wave analysis, vertical seismic profiling) and passive methodologies (wavelet decomposition, Horizontal-to-Vertical Spectral Ratio, three-component frequency-wavenumber analysis) were jointly considered in order to solve the intrinsic non-uniqueness of the solution and determine a consistent subsurface model free from ambiguities, eventually used for the assessment of the local site amplification.

HoliSurface results compared to VSP (Vertical Seismic Profiling)

A Comprehensive Seismic Characterization via Multi-Component Analysis of Active and Passive Data

(Dal Moro G., Keller L., Poggi V.), *First Break (September, 2015)*

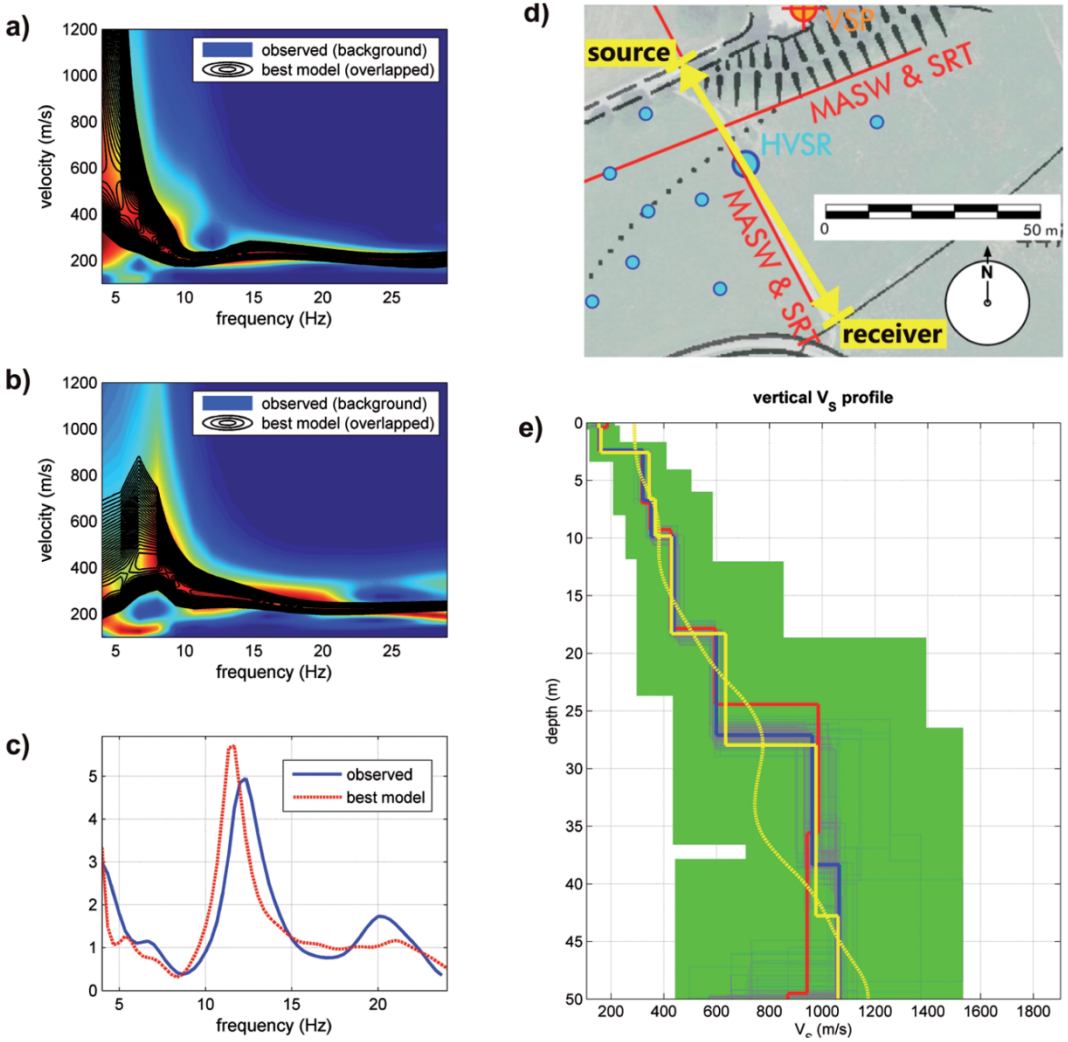


Figure 10 *Holistic analysis of the vertical and radial-component group-velocity spectra jointly with the Radial-to-Vertical Spectral Ratio (RVSR): a) and b) the observed velocity spectra (background colours) and, overlaying (black contour lines), the synthetic ones; c) observed and computed RVSRs; d) map reporting the position of the source (in this case a simple vertical-impact sledgehammer) and receiver (a single 3-component calibrated geophone – offset 70 m); e) the retrieved V_S profile and the one obtained by means of VSP analysis.*

Noise

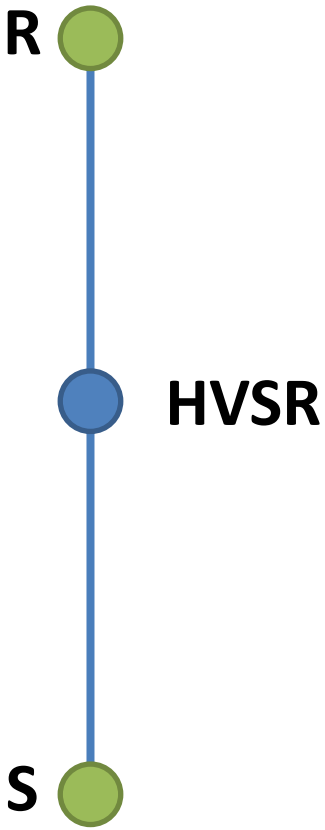
Two volunteers, please

HoliSurface®

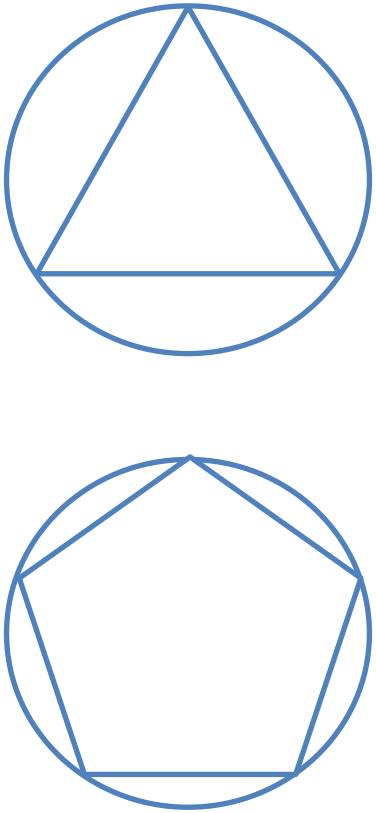
HoliSurface®

A circle, a line: they look good, they are abstract, they are common knowledge.
They belong to everyone and equally to the past, the present and the future.
Richard Long

HS

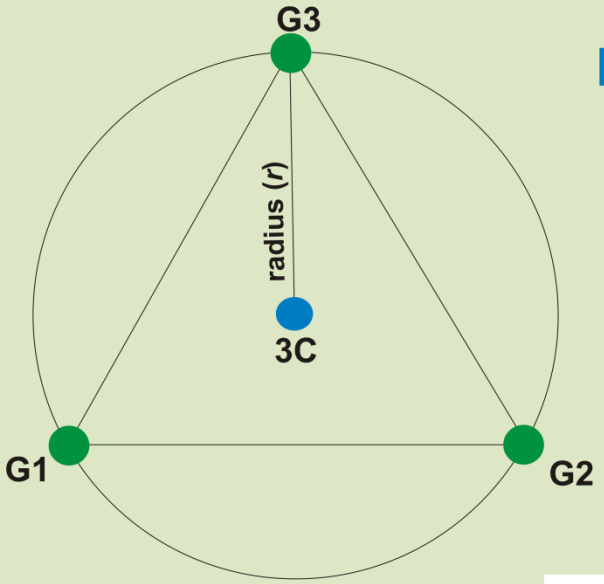


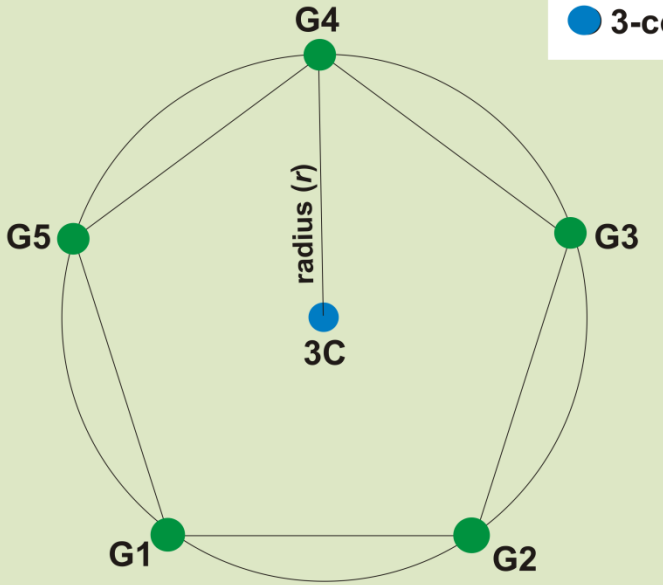
MAAM



An efficient urban palindrome

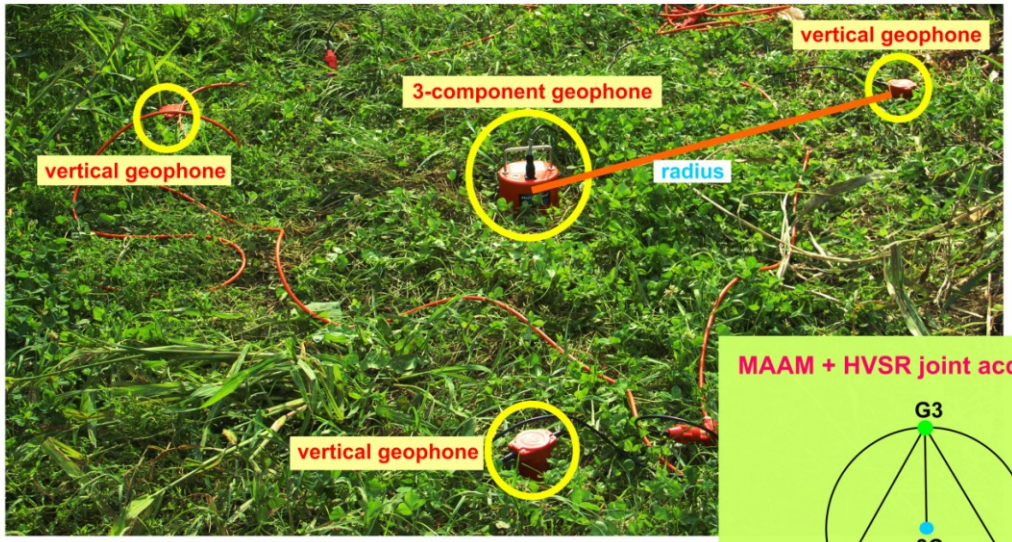
MAAM + HVSR joint acquisition

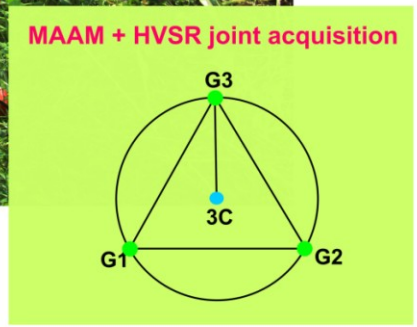




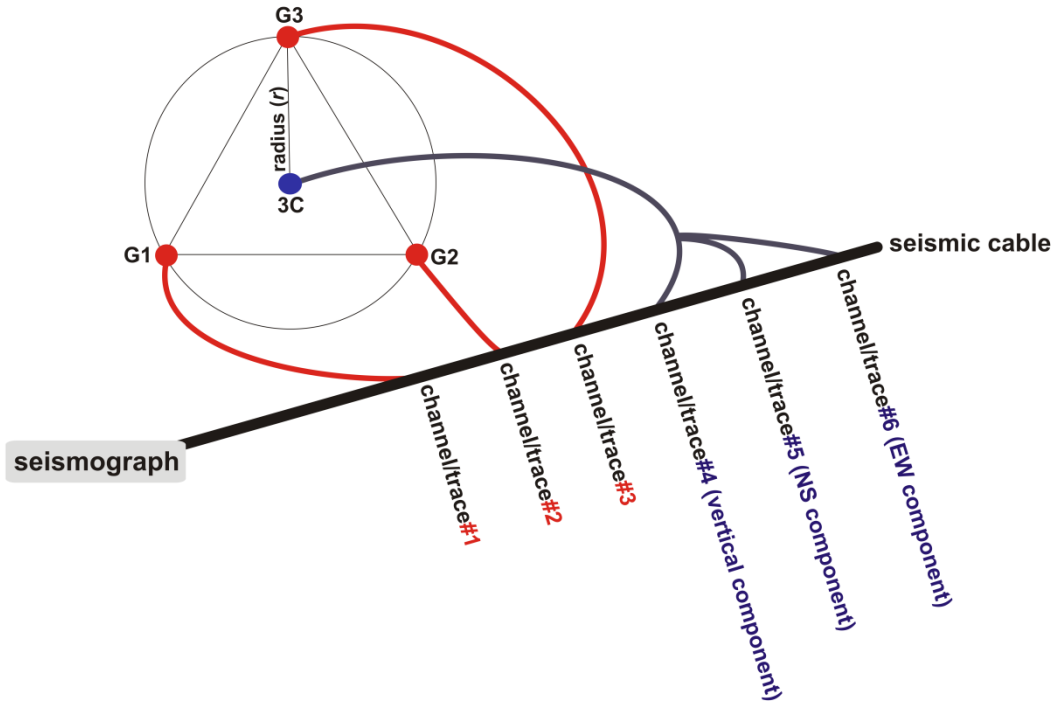
2Hz vertical geophone

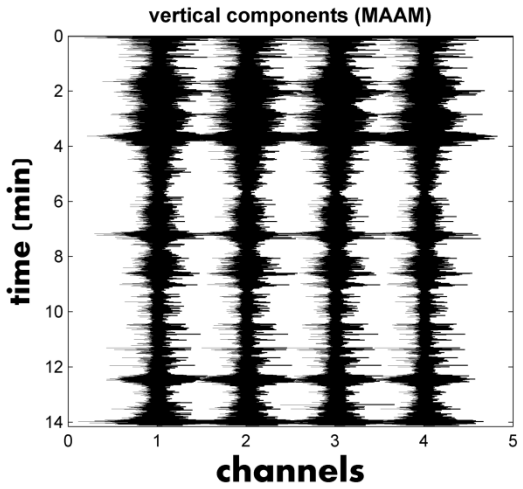
3-component geophone (for HVSR and MAAM)

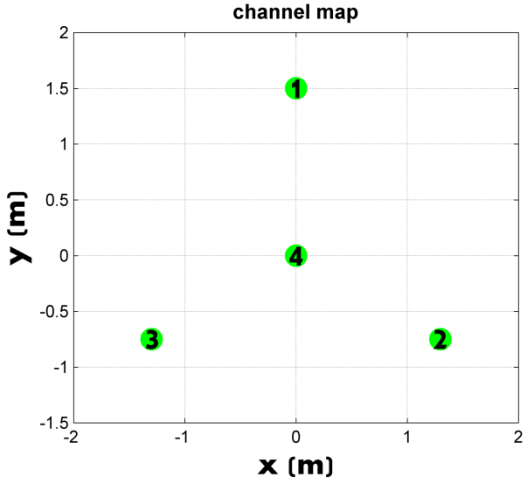




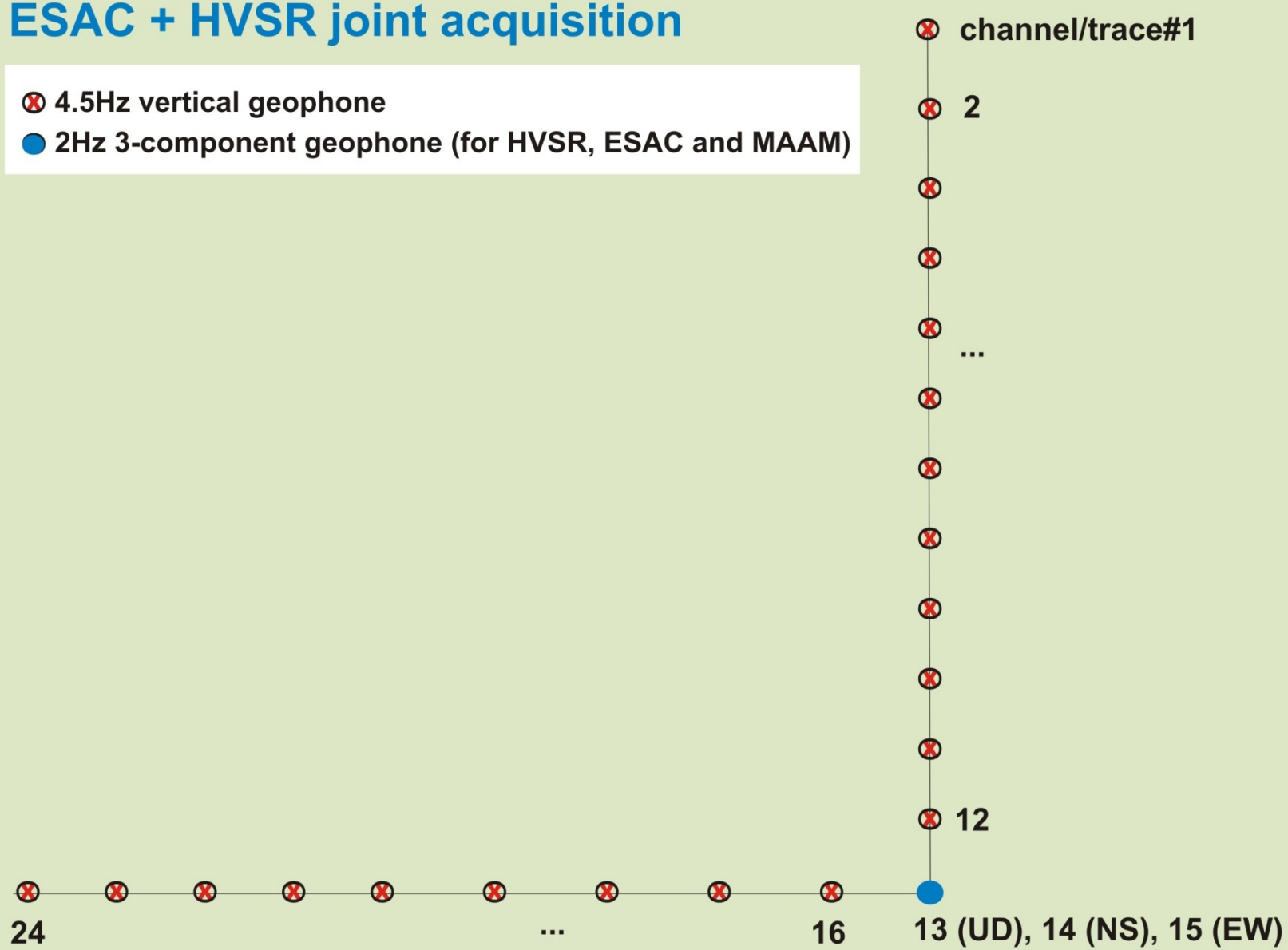
HoliSurface®





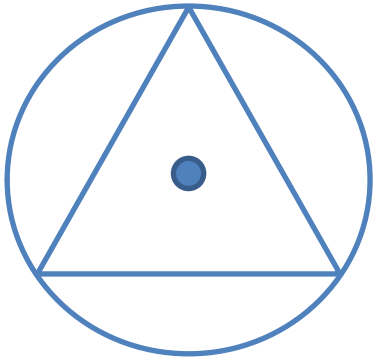


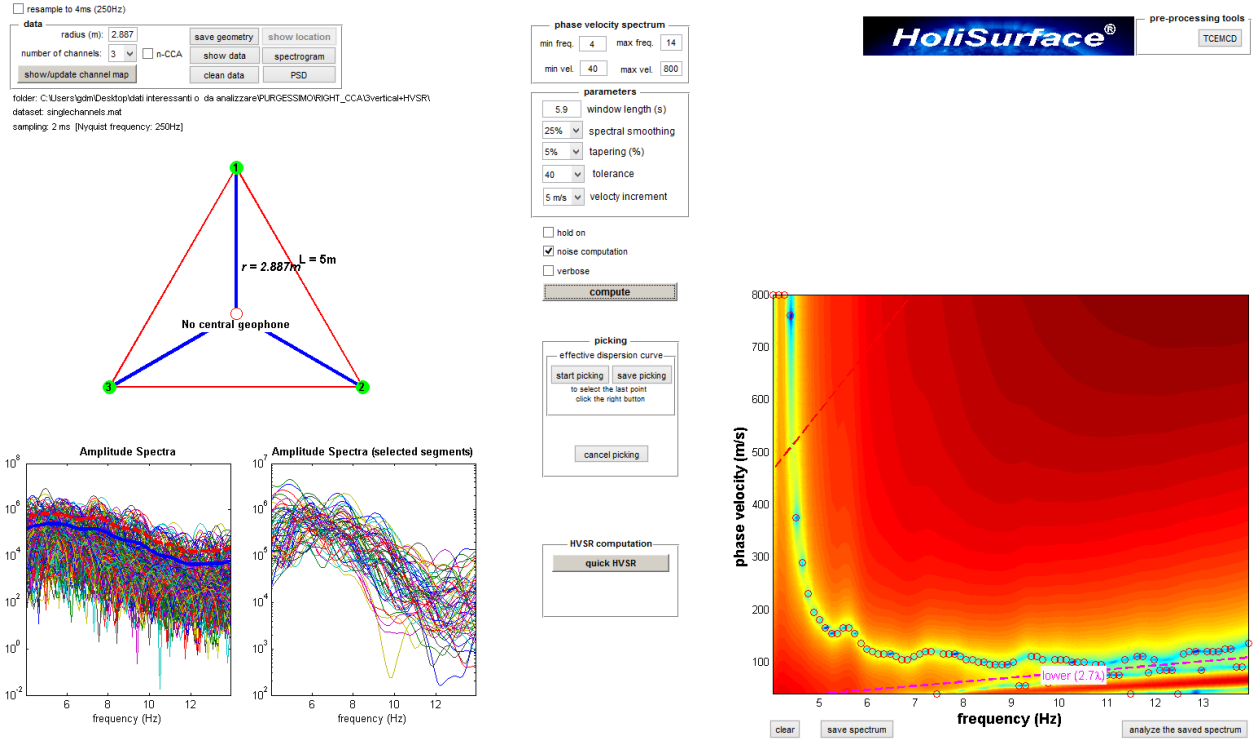
ESAC + HVSR joint acquisition



HoliSurface®

MAAM

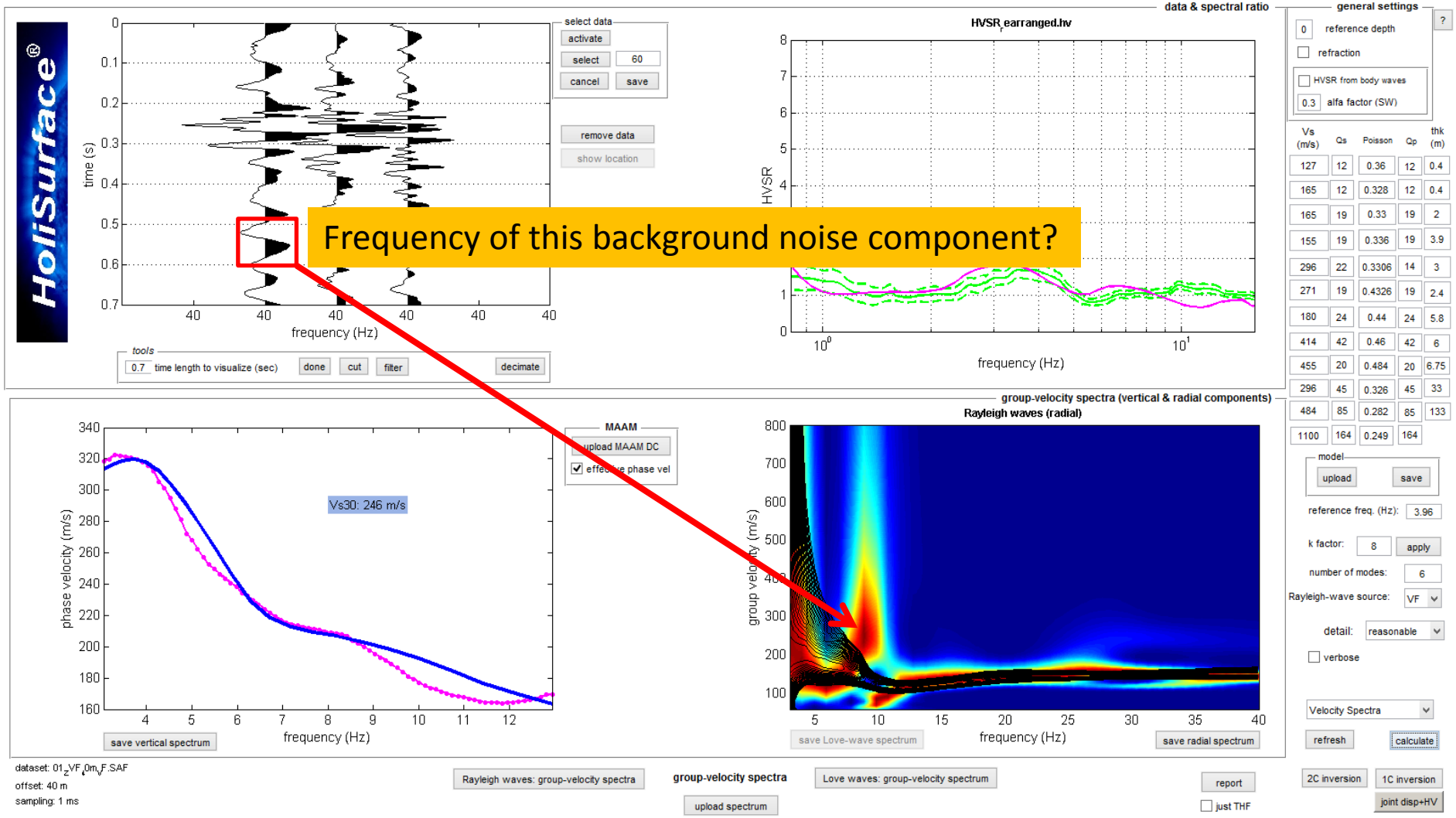




A circle, a line: they look good, they are abstract, they are common knowledge. They belong to everyone and equally to the past, the present and the future.

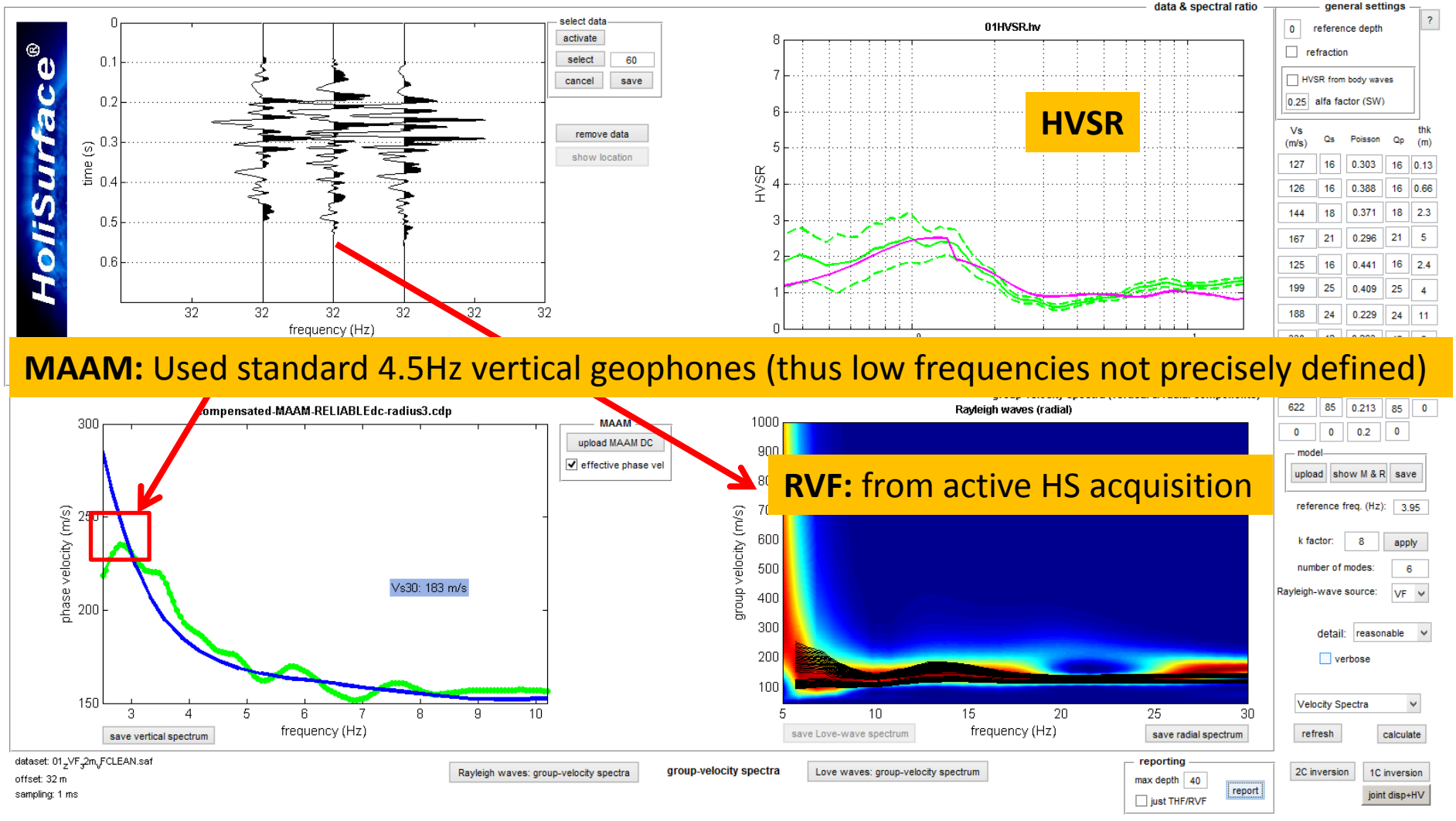
Richard Long

A “noisy” desperate case

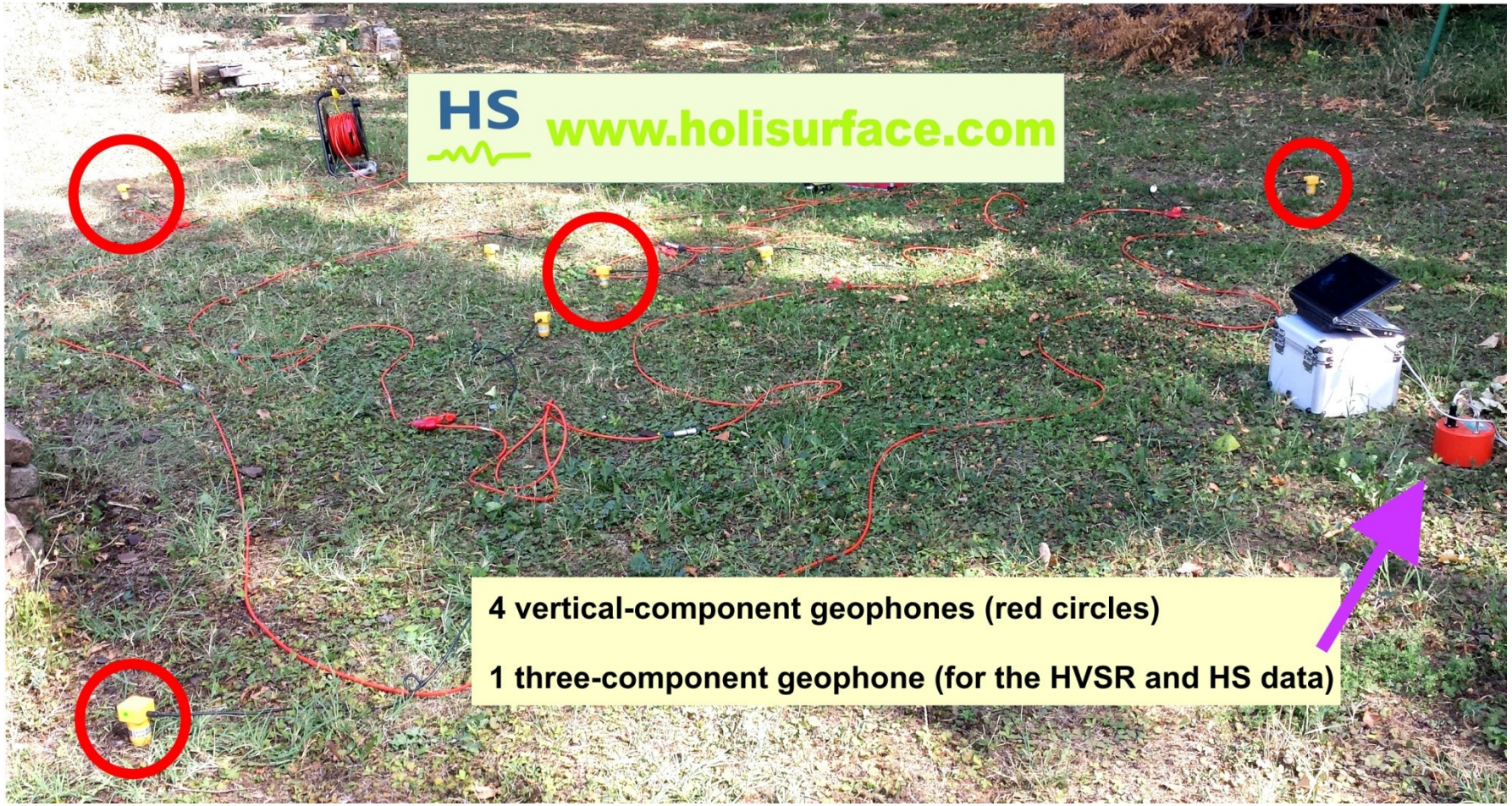


HoliSurface®

A further problematic case (little room available and noisy active data)

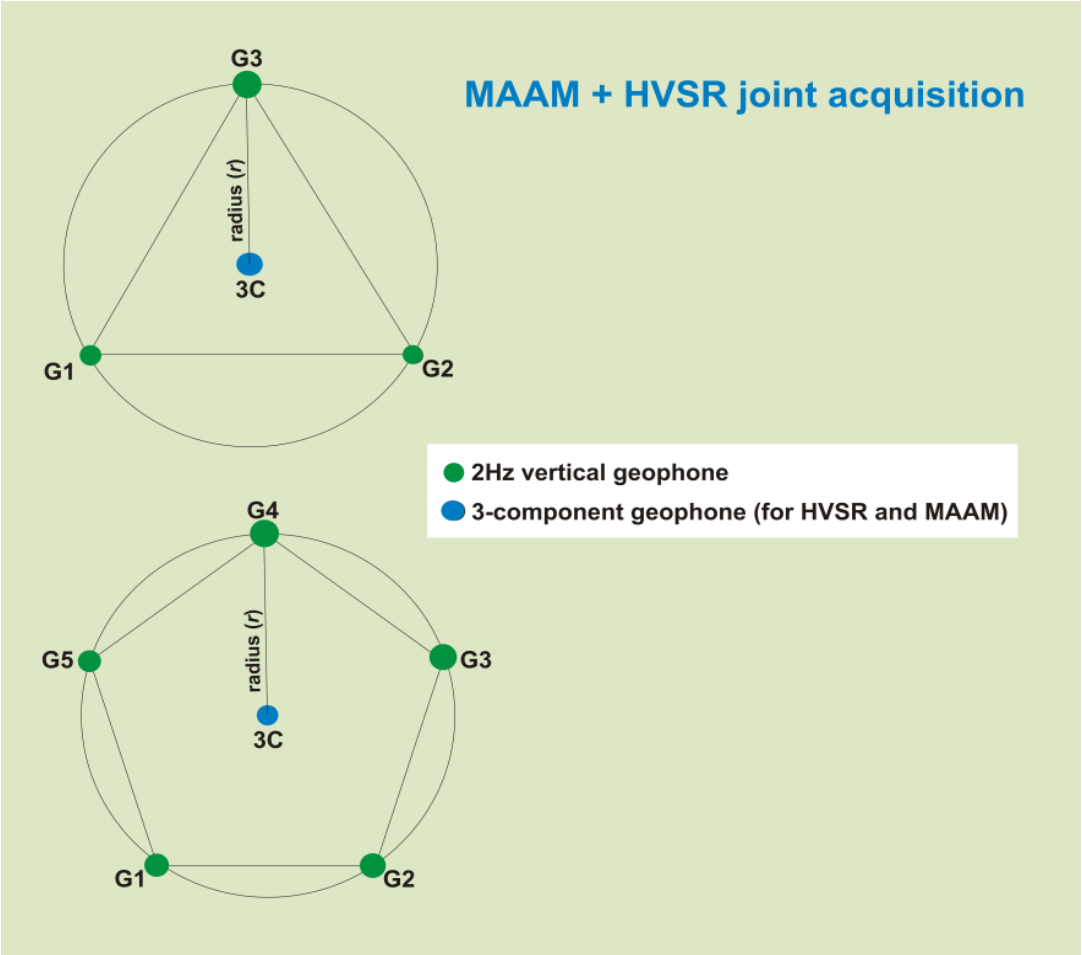


A further problematic case (little room available and noisy active data): the acquisition procedures



HoliSurface®

MAAM (Miniature Array Analysis of Microtremors)



MAAM

Preliminary equipment test

N+1 identical geophones (2 or 4.5Hz?)

radius/radii

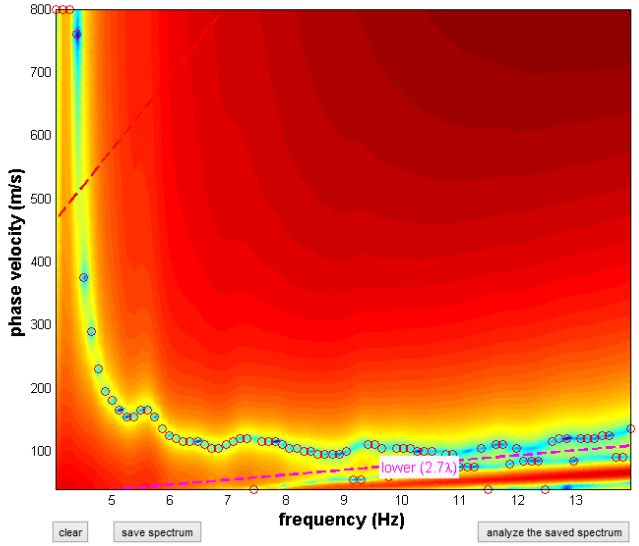
Tolerance & smoothing

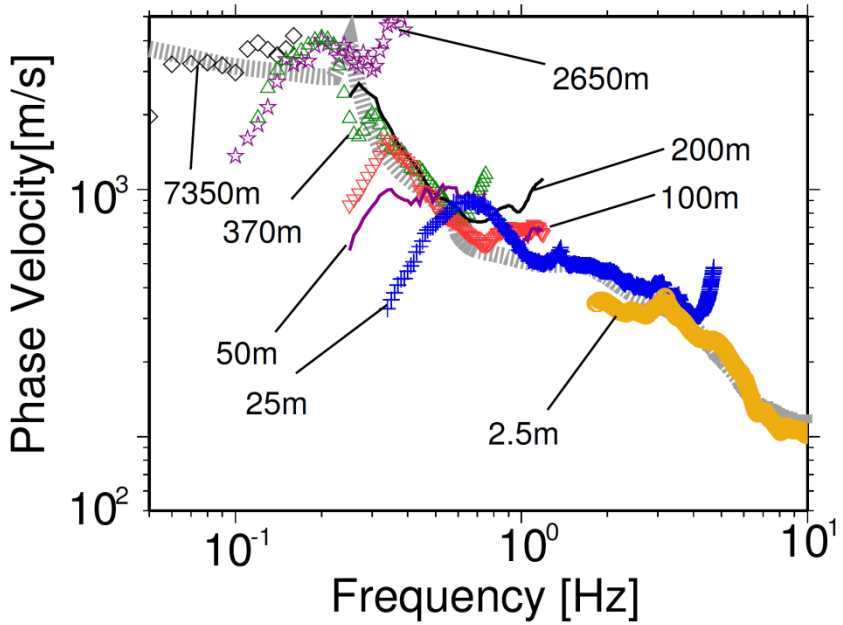
window length

data cleaning

MAAM

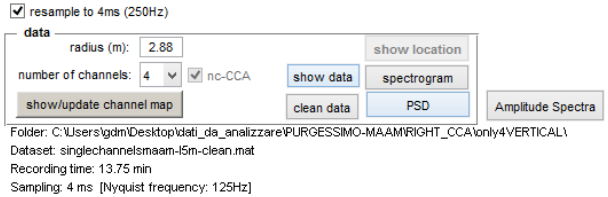
MAAM

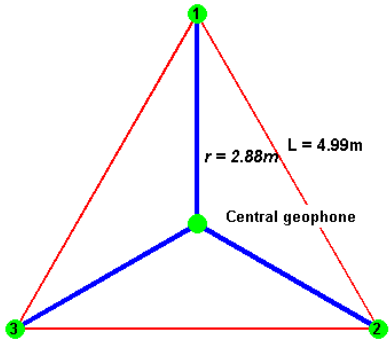

phase velocity (m/s)
frequency (Hz)
lower (2.7λ)
clear
save spectrum
analyze the saved spectrum

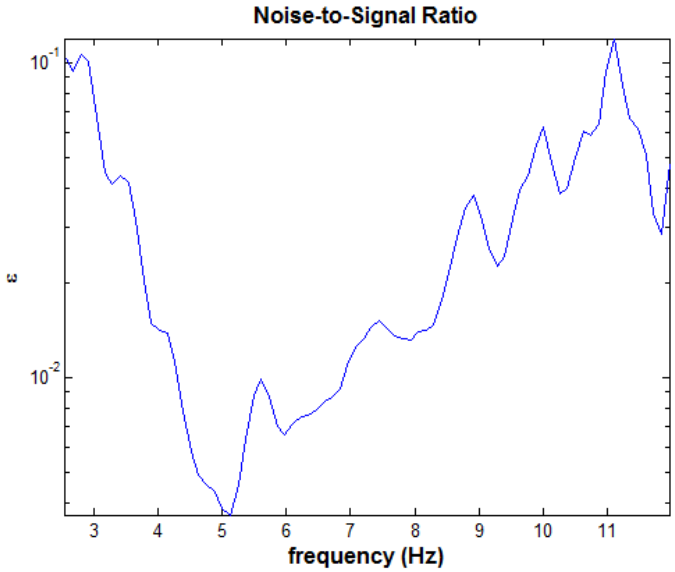

Phase Velocity[m/s]
Frequency [Hz]
2650m
7350m
370m
200m
100m
50m
25m
2.5m

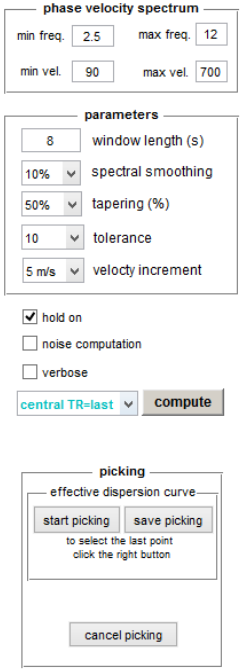
MAAM Comparing MASW-ZVF

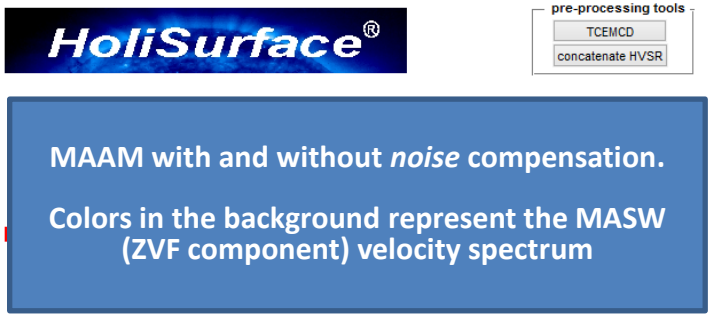
1. Purgessimo

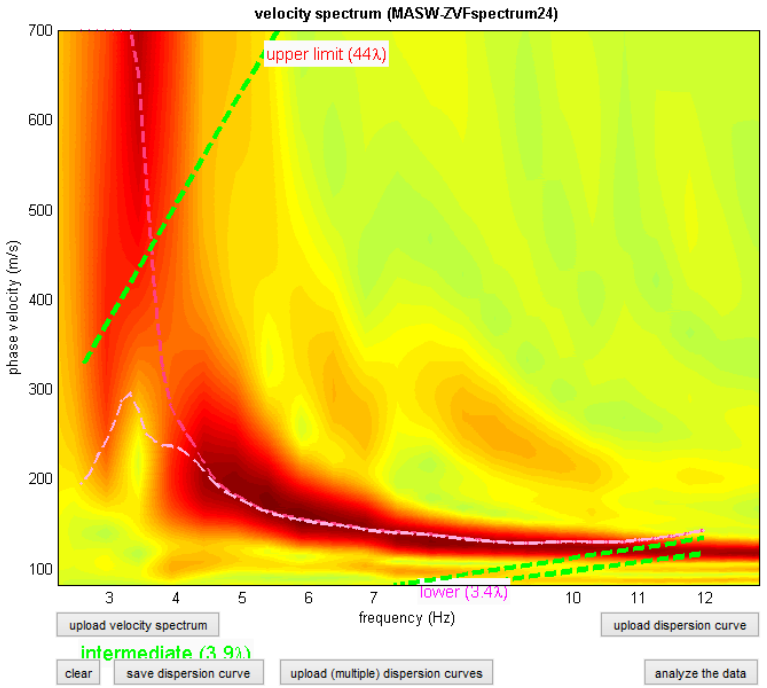












MAAM

Comparing ESAC

Equipment quality (N/S ratio)

6. Muscoli

Two radii (2 and 0.5m)

resample to 4ms (250Hz)

data

radius (m): 0.5 — show location

number of channels: 4 — nc-CCA — show data — spectrogram

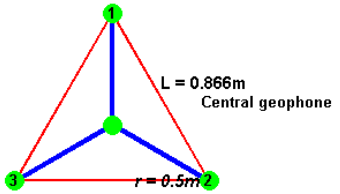
show/update channel map — clean data — PSD — Amplitude Spectra

Folder: C:\Users\gdm\Desktop\dati_da_analizzare\Muscoli-Cimitero\MAAM\radius50cm\

Dataset: MAAM-data-clean.mat

Recording time: 14.49 min

Sampling: 4 ms [Nyquist frequency: 125Hz]



phase velocity spectrum

min freq. 3 — max freq. 33

min vel. 100 — max vel. 700

parameters

9 — window length (s)

15% — spectral smoothing

50% — tapering (%)

5 — tolerance

5 m/s — velocty increment

hold on

noise computation

verbose

central TR=last — compute

picking

effective dispersion curve

start picking — save picking

to select the last point click the right button

cancel picking

HoliSurface®

pre-processing tools

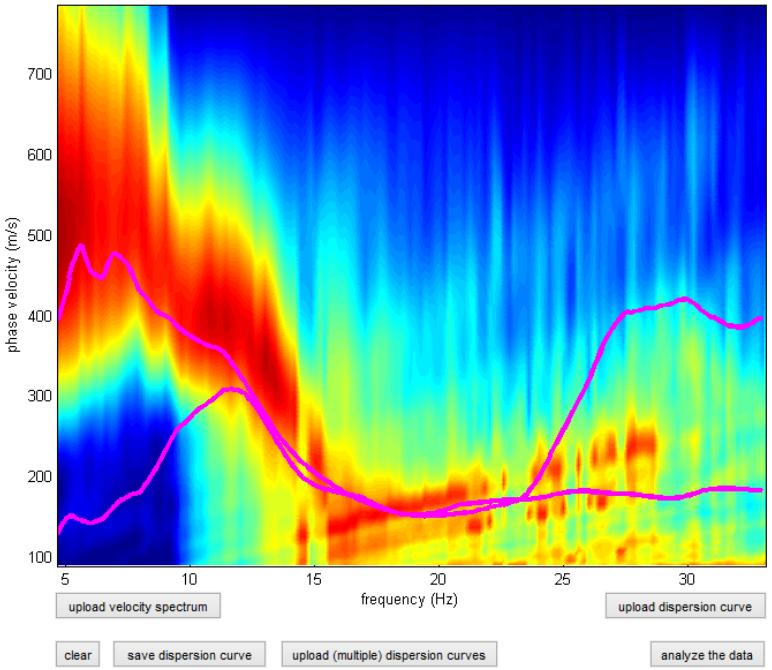
TCEMCD

concatenate HVSR

N

olors in the background are the ESAC velocity spectrum! (from large 2D arrays)

velocity spectrum (ESACpsvelspe)

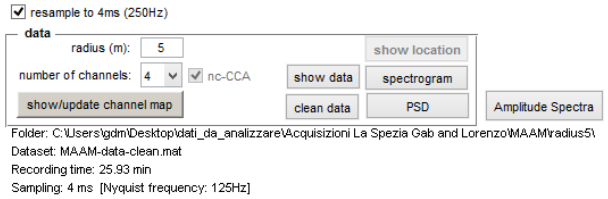


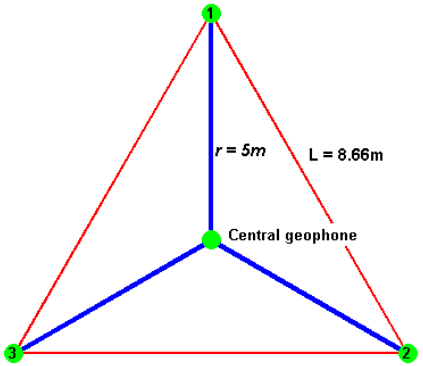
upload velocity spectrum — upload dispersion curve

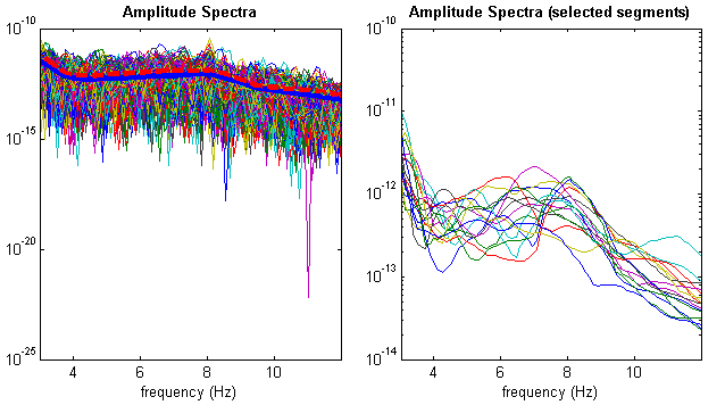
clear — save dispersion curve — upload (multiple) dispersion curves — analyze the data

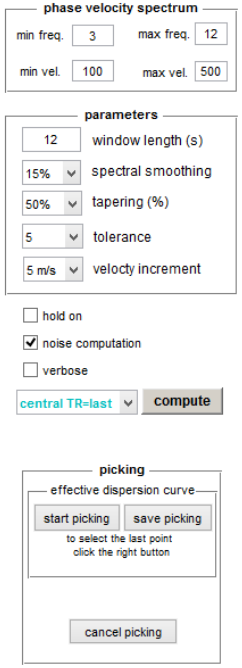
MAAM Comparing ESAC

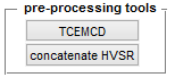
7. La Spezia



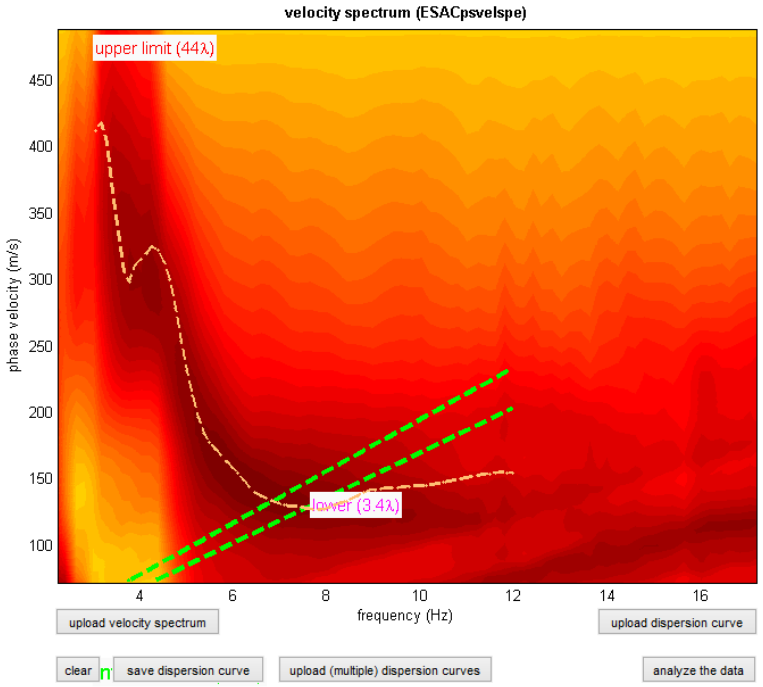








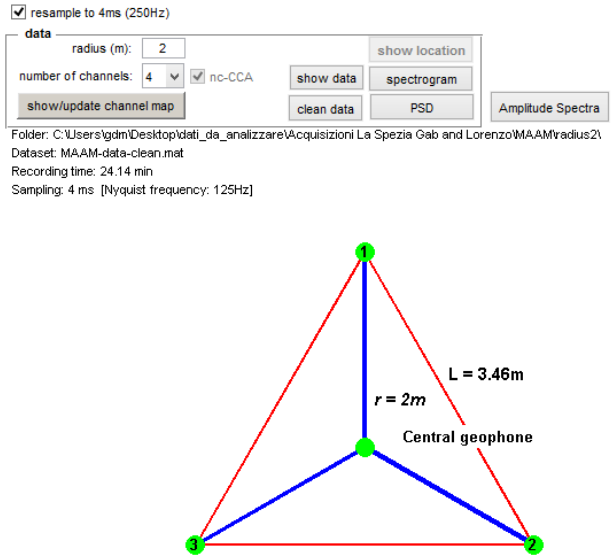
olors in the background are the ESAC velocity spectrum! (from large 2D arrays)

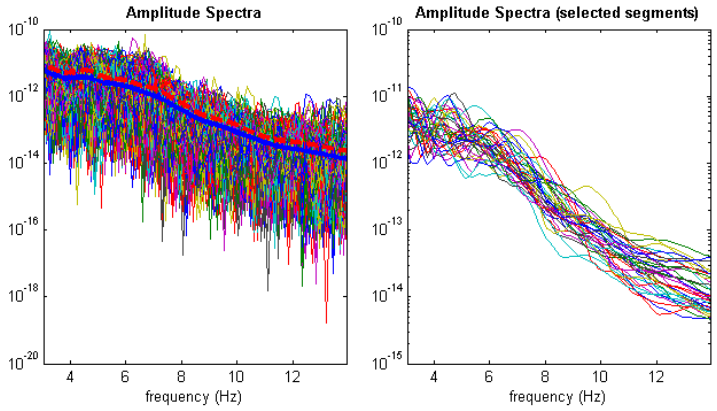


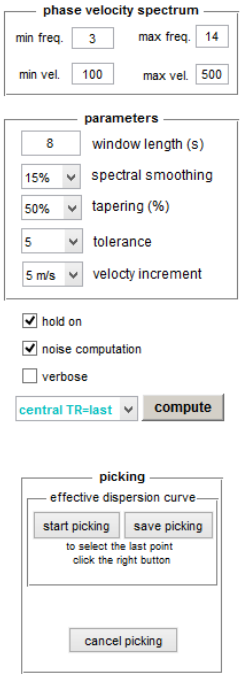
MAAM Comparing ESAC

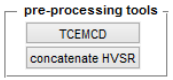
7. La Spezia

Two radii (5 and 2m)

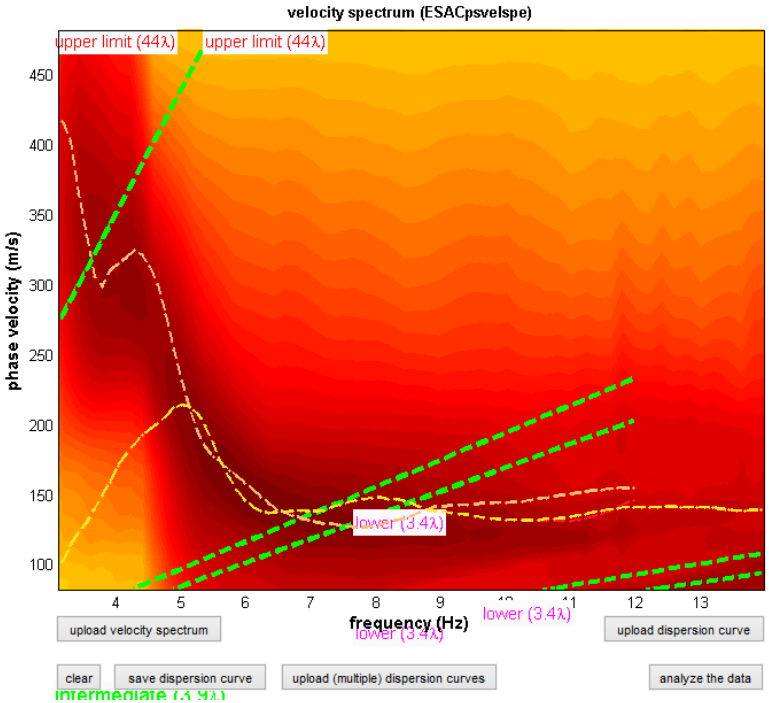








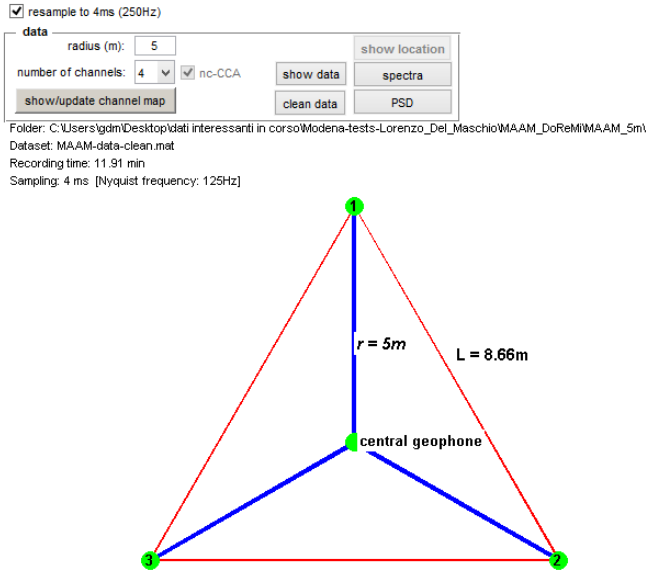
olors in the background are the ESAC velocity spectrum! (from large 2D arrays)

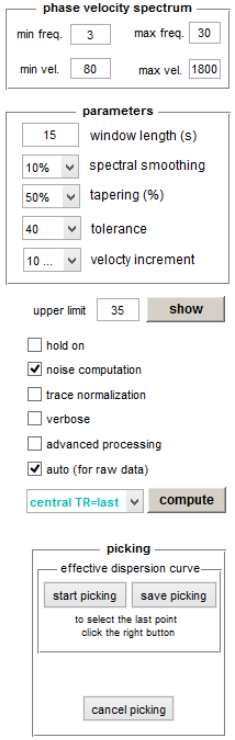


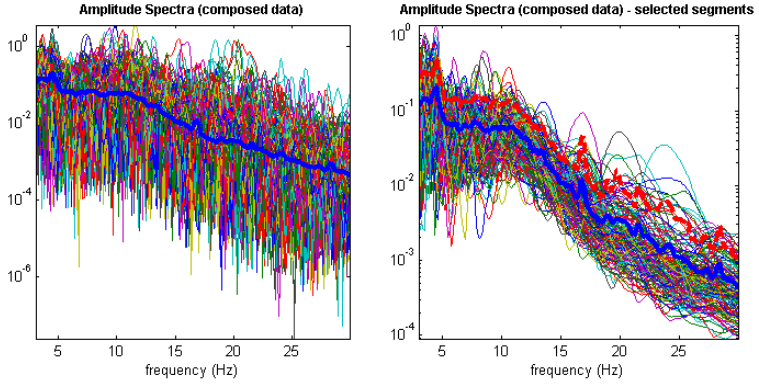
MAAM Comparing ESAC

8. Modena

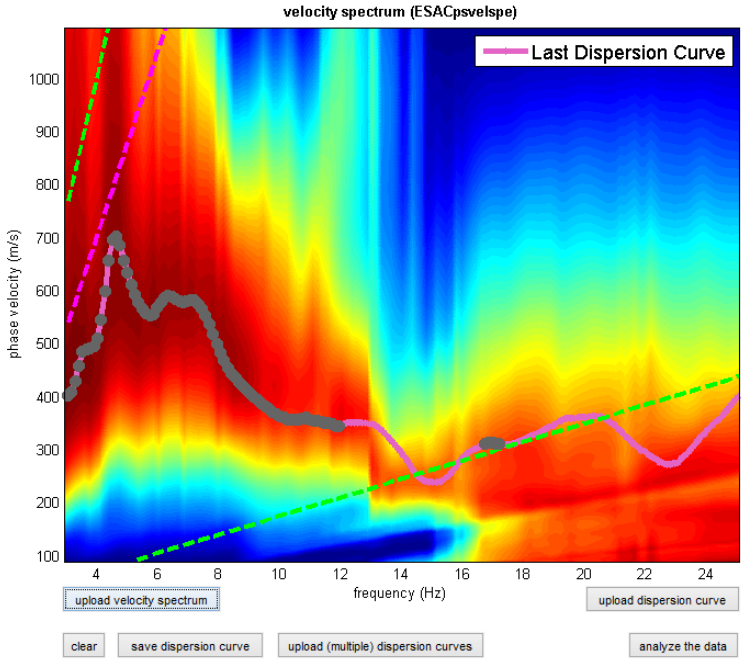
Radius (5m)
Colors in the background are the ESAC velocity spectrum! (from large 2D arrays)







Noise (epsilon) computed [dispersion compensated]



Love-wave contribution to the observed HVSR

$$\text{HVSR} = \sqrt{\frac{\alpha H_L(f) + H_R(f)}{V_R(f)}}$$

L = contributo delle onde di Love
R = contributo delle onde di Rayleigh

I microtremori sono essenzialmente costituiti da onde di Rayleigh e Love. La quantità di onde di Love (incognita e sintetizzabile con il "parametro alfa") è essenziale .

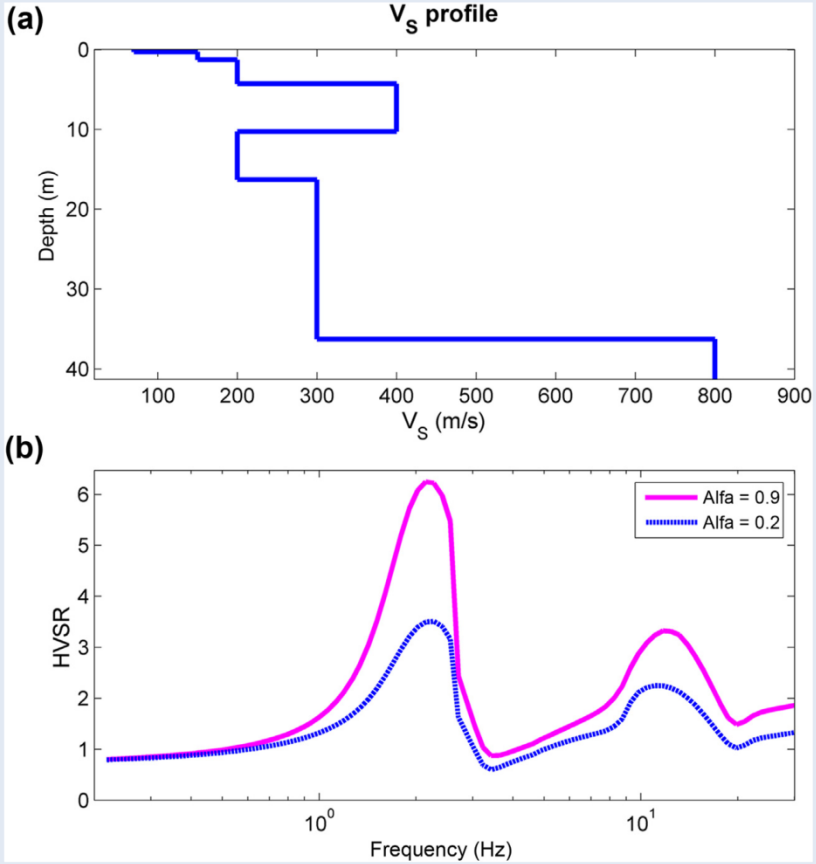


Figure 4.14 Effects of Love waves on the HVSR: (a) considered V_S profile; (b) the HVSR curves obtained while considering a different amount of Love waves (the α factor) in the microtremor field. In both cases Q_S values are fixed according to a simple rule of thumb ($Q_S = V_S/8$).

Two consequences are straightforward:

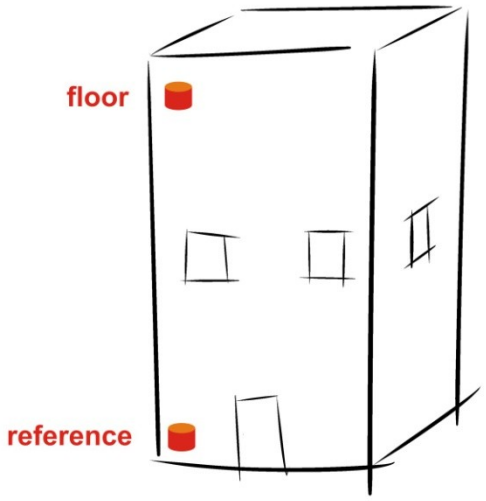
1. The amount of Love waves (synthetically expressed by the α factor) should be considered as a further variable in the inversion process aimed at determining the V_S profile (experience teaches that its value typically ranges from 0.3 to 0.6).
2. The HVSR curve alone is insufficient to properly and precisely define a V_S profile even when geological/stratigraphical information are available and, consequently, the only viable approach is represented by the joint inversion with further geophysical data (typically the dispersion curves of Rayleigh or Love waves).

Vibrational analyses

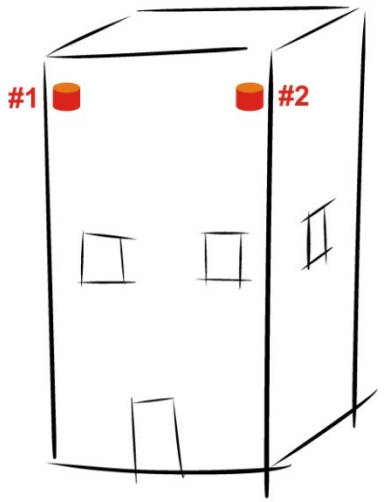
Allo scopo di analizzare in modo rigoroso le vibrazioni di un edificio, è fondamentale eseguire acquisizioni sincrone sia verticalmente che orizzontalmente (due terne che lavorano perfettamente sincornizzate).

Per un esempio clicca sul seguente link: https://www.youtube.com/watch?v=6O0SSil1MTo

synchronized (vertically)
2 sensors at 2 different floors (simultaneously)



synchronized (horizontally)
2 sensors at the same floor (simultaneously)



The Camerino Data and Analyses

Let's compare the analysis of classical multichannel data (performed according to the FVS approach) and the results obtained via HS (*HoliSurface* – a patented methodology based on the analysis of just a single 3-component geophone) . We will see that the results are practically identical.

The Camerino Data and Analyses

The idea of *HoliSurface®*.
From: A Comprehensive Seismic Characterization via Multi-Component Analysis of Active and Passive Data (Dal Moro G., Keller L., Poggi V.), *First Break* (September, 2015)

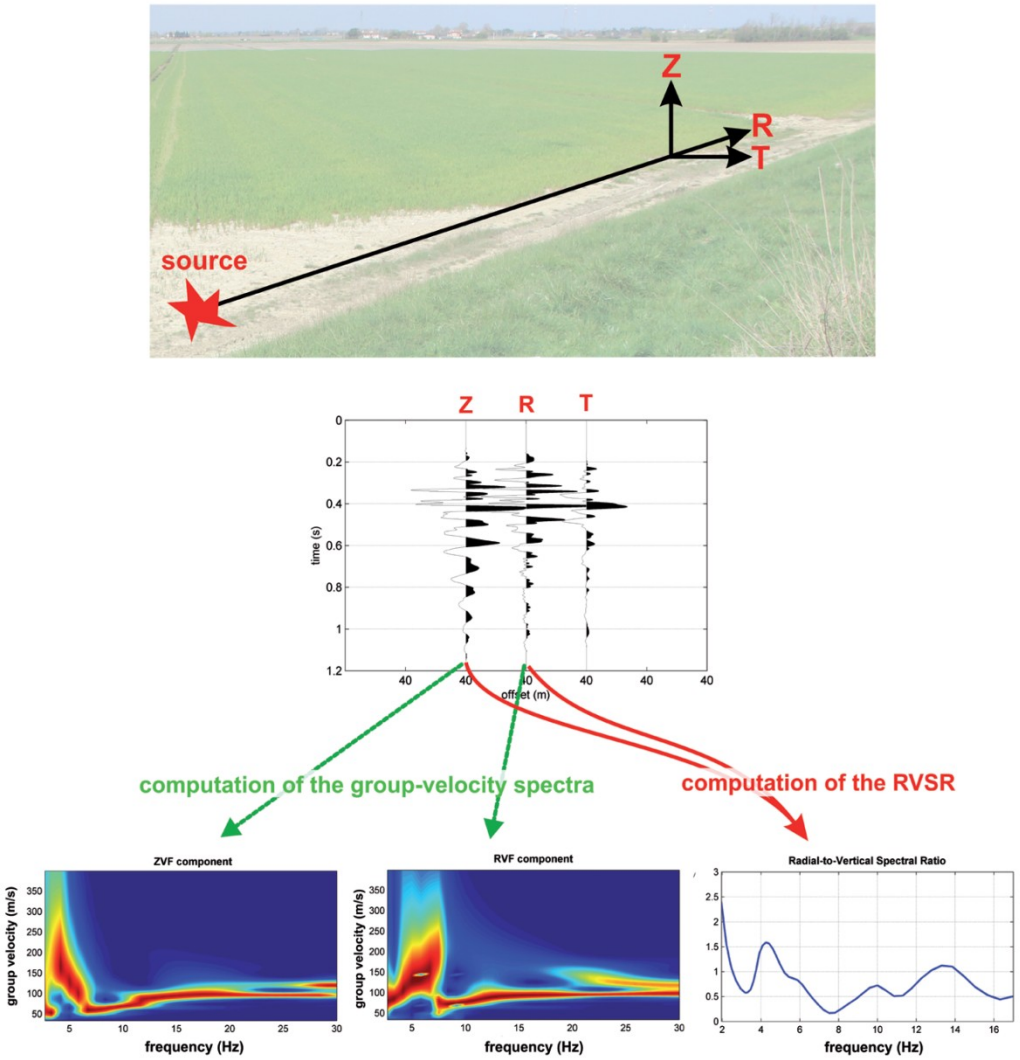
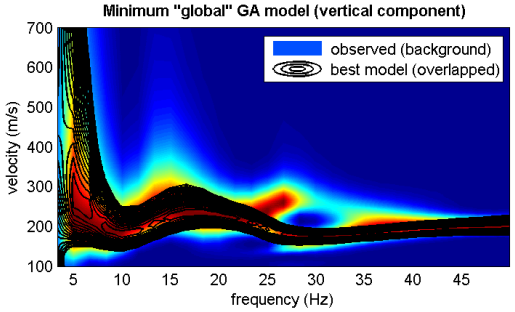
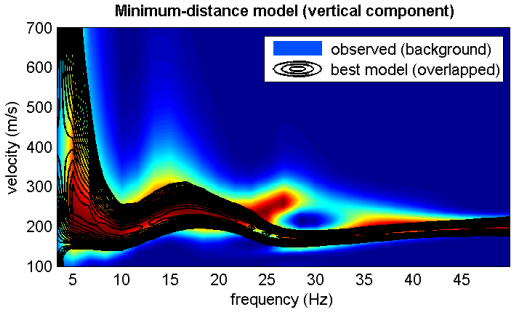


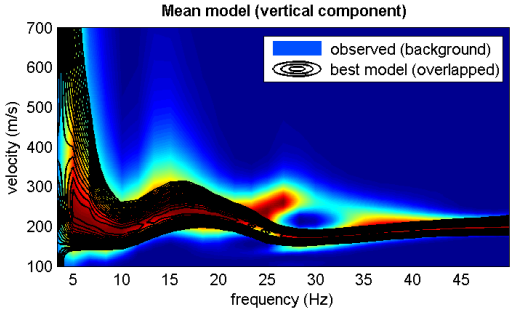
Figure 9 *Data acquisition for the holistic analysis of Rayleigh-wave propagation by means of a single (at least) 2-component geophone recording the vertical and radial components then used to determine the two group velocity spectra and the Radial-to-Vertical Spectral Ratio (RVSR).*

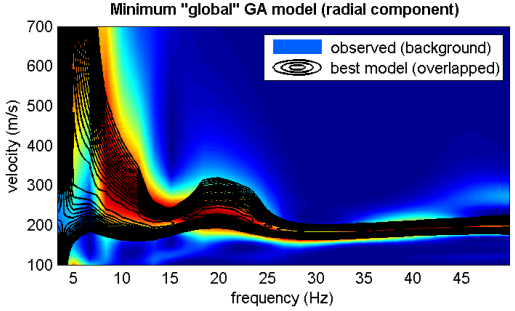
The Camerino Data and Analyses

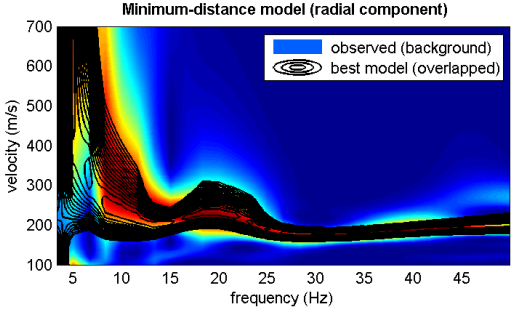
HoliSurface®

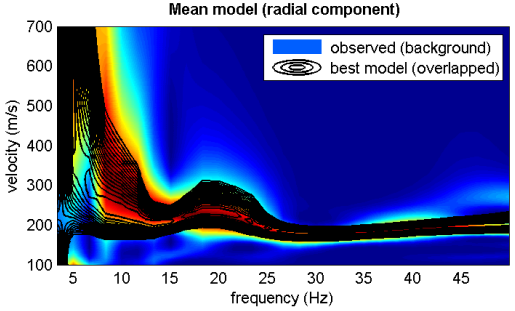


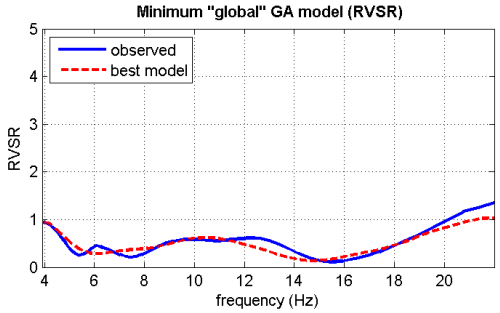


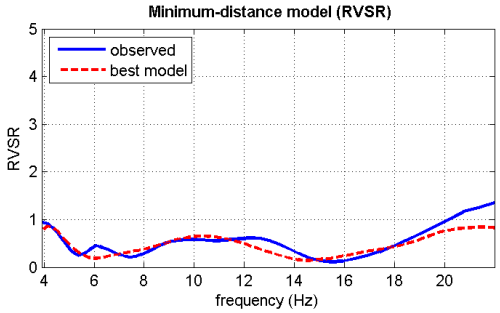


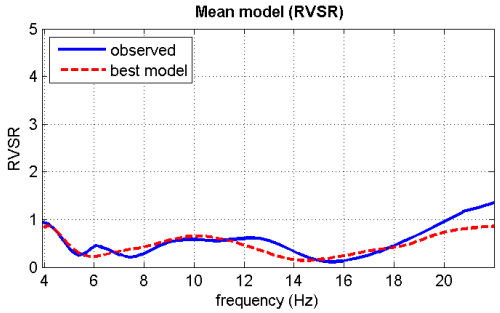








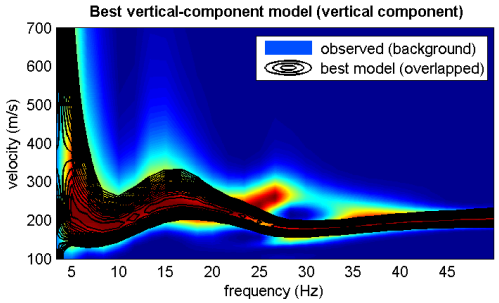


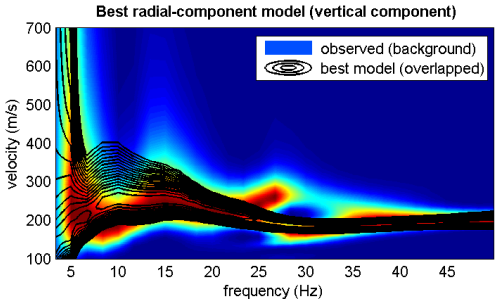


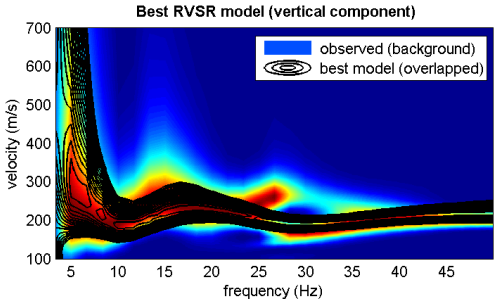
Global models

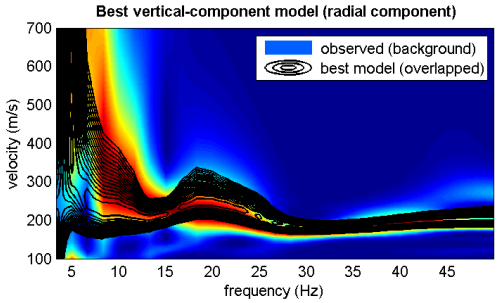
The Camerino Data and Analyses

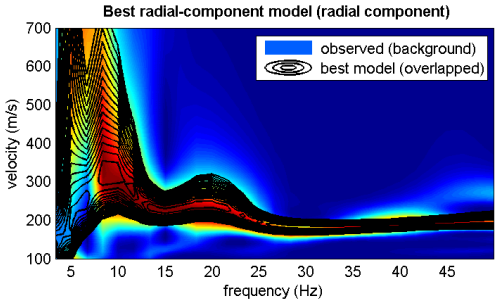
HoliSurface®

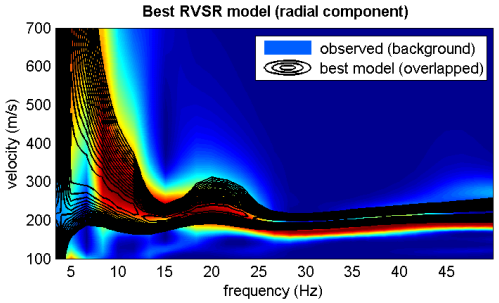


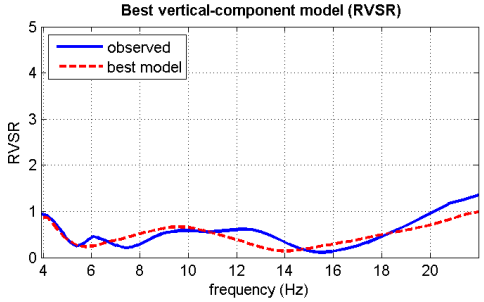


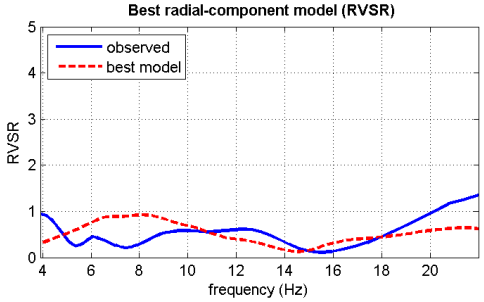


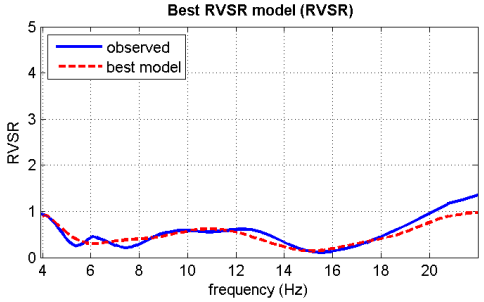








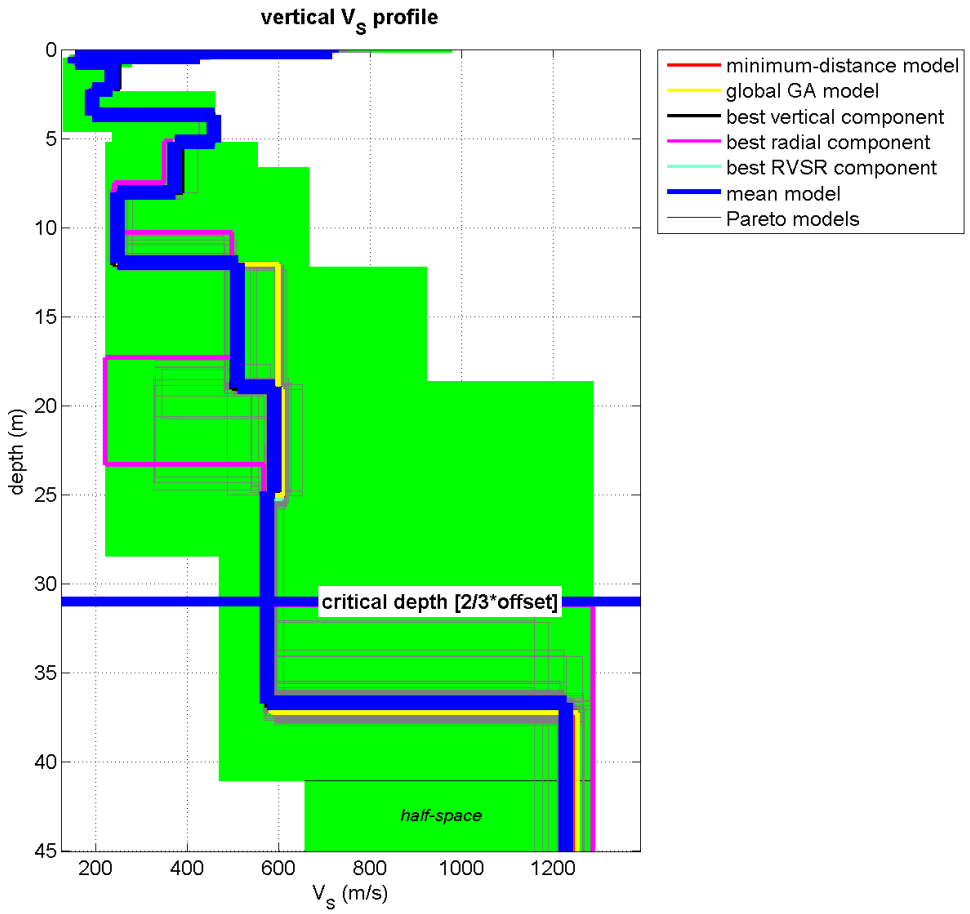




Best single-component models

The Camerino Data and Analyses

HoliSurface®

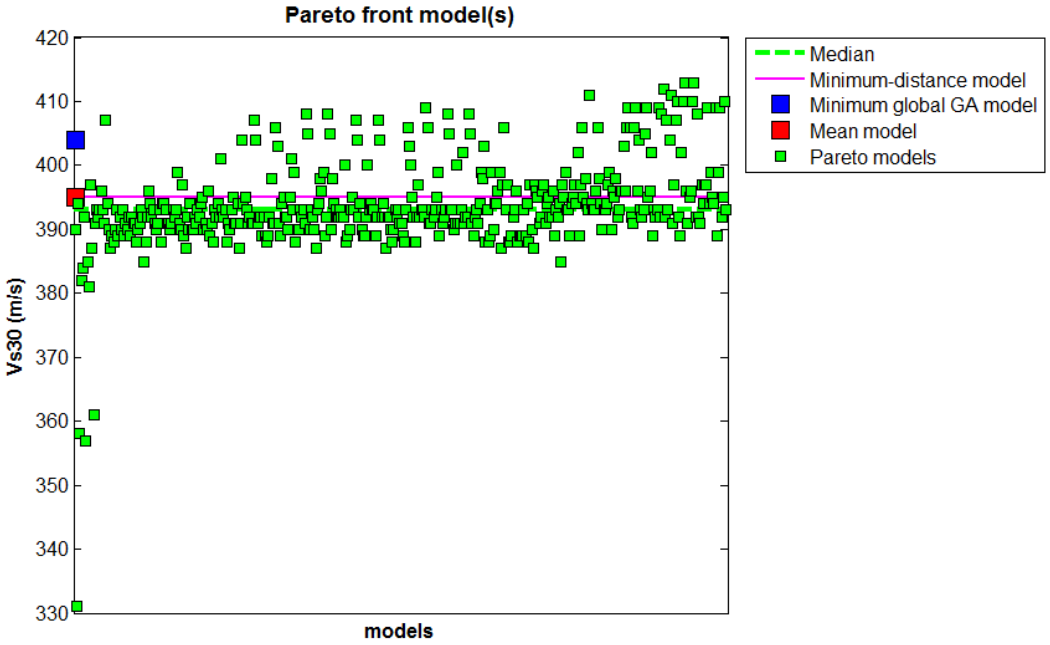


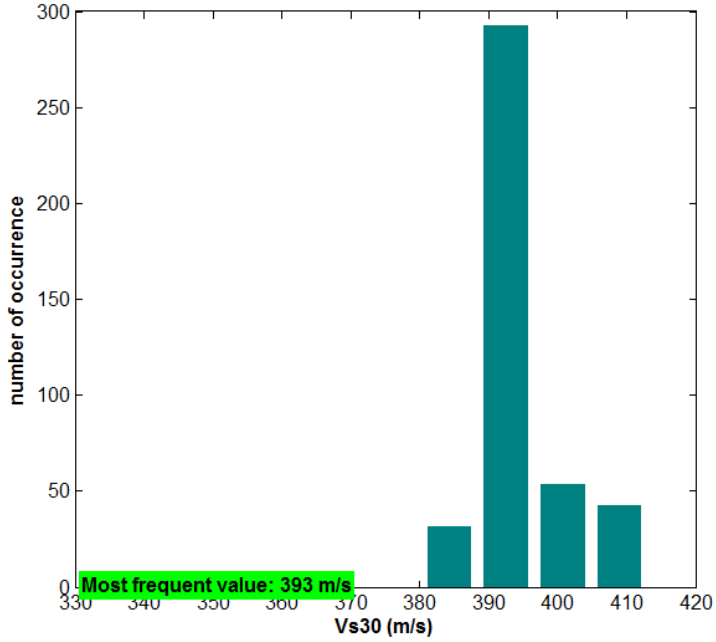
The best RVF model should be not considered (as too far from the rest of the models – which are instead extremely consistent)

The Camerino Data and Analyses

HoliSurface®

Statistics:
Vs30 values for the Pareto front models (extremely consistent distribution)

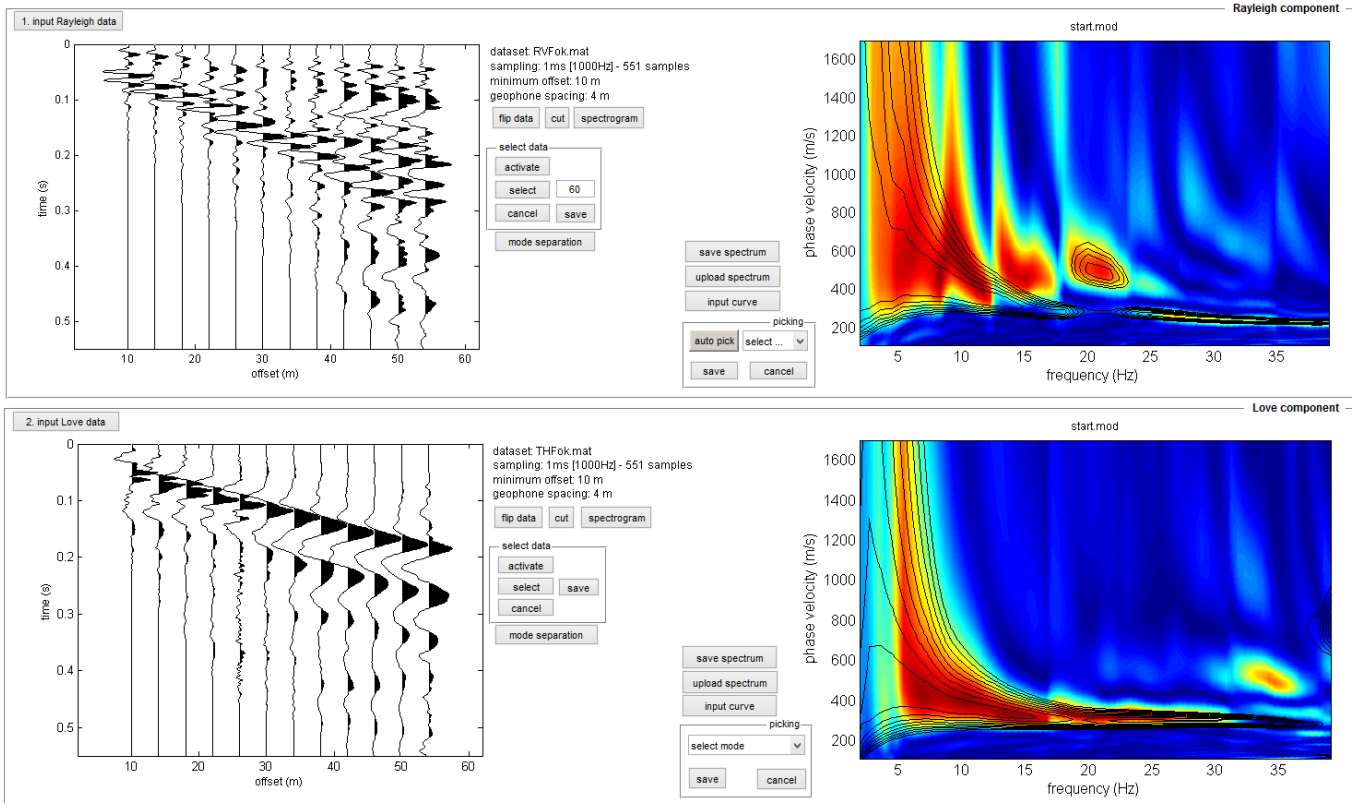




The Camerino Data and Analyses

The classical multi-channel approach: FVS joint analysis of Rayleigh & Love waves

Now we take the "best model" from the *HoliSurface* analysis and this is what we obtain:



An extremely good agreement for both the Rayleigh and Love waves, which clearly means that the HS analyses provided extremely good results, which can be considered "equivalent" to the performances possible with the standard multi-channel data.

RVF (radial component of Rayleigh waves) + THF (Love waves) *Full Velocity Spectrum* (FVS) joint analysis. Background color the field phase-velocity spectra, overlaying contour lines the synthetic velocity spectra of the considered Vs model.