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geophysical software and services

winMASW ® 2024

JOINT ANALYSIS OF SEISMIC DATA

February 7, 2024

draft version of the 2024 release (work-in-progress)

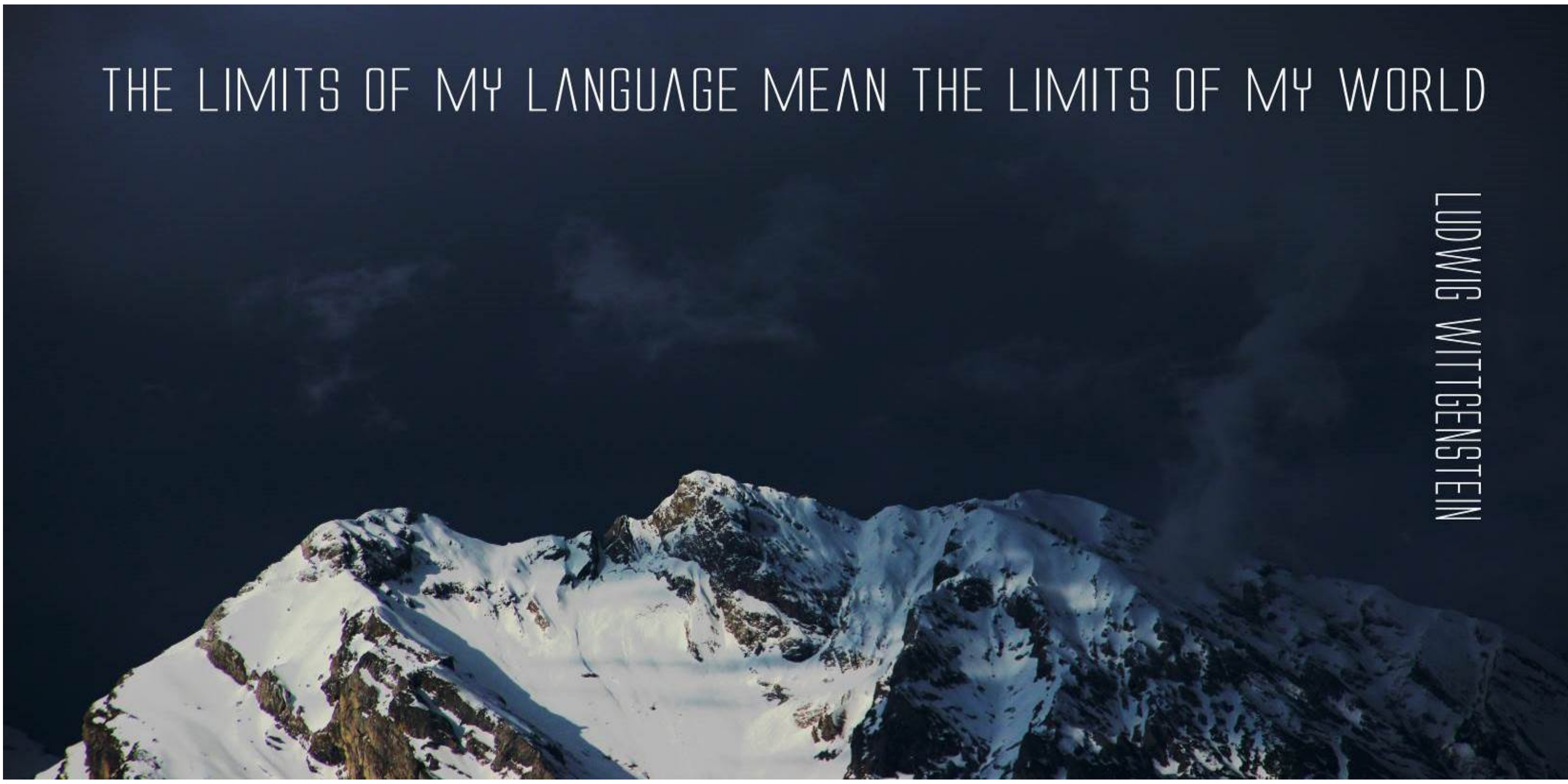
www.winmasw.com

winMASW®

Surface Waves & Beyond

JOINT ANALYSIS OF SEISMIC DATA

- Software for the joint analysis of Surface Waves: **multi-component active and passive data: MASW, MFA and RPM; HVSR, ReMi, ESAC/SPAC, multi-component passive data for the reconstruction of 2D V_S sections [PS-MuCAA & 2D-SuPPSALA], interferometry etc.**
- Analysis of **non-equally spaced data** (both for active and passive data)
- Synthetic seismograms and **Full Velocity Spectra (FVS) inversion** (no interpretation of the velocity spectra) + computation of the *modal* and *effective* dispersion curves
- **PS-MuCAA (Passive Seismic – MUlti Component Amplitude Analysis):** multi-component analysis of passive data for a robust V_S profile and the identification of possible lateral variations
- **2D-SuPPSALA (SUbsurface Profiling via Passive Surface wave data Analysis from Linear Array)**: a powerful tool for the 2D profiling from multi-component passive data
- Effective **management of geo-referenced photos** from, for instance, your smartphone for the site localization and/or the exploration of large areas
- Analysis of Rayleigh–wave attenuation
- Effective management of **geo-referenced photos** from your smartphone also for the exploration of large areas
- **Batch (automatic) processing of several HVSR files** (also for the reconstruction of 2D HVSR sections)
- Analysis (and joint inversion together with the dispersion data) of the RPM (Rayleigh-wave Particle Motion) frequency-offset surface
- **Back-scattering analysis** (helping in the identification of possible cavities).
- Tool for the **site response analysis**
- Several new and improved **tools for editing, assessing the quality and analyzing your active and passive data**



Seismic techniques and main abbreviations

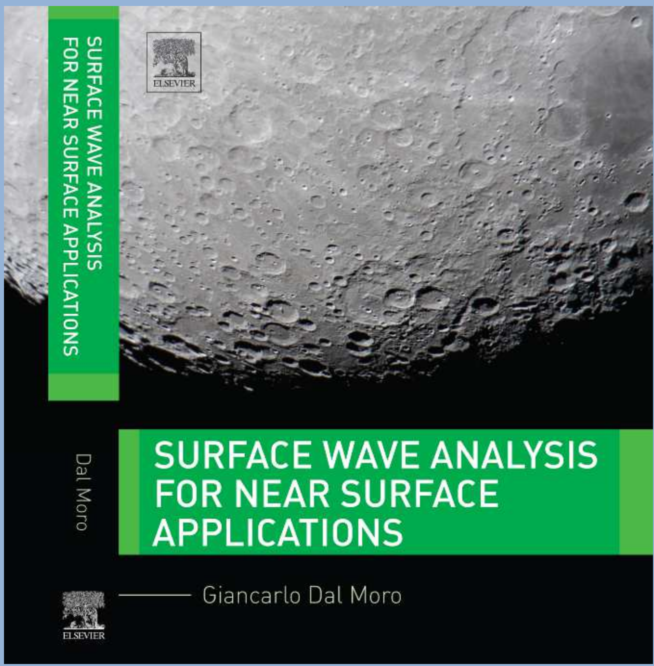
	definition	notes
MASW	Multi-channel Analysis of Surface Waves	Methodology for the determination of the phase velocity spectrum from multi-offset active data. Mathematics can have a series of possible variants: *fk* analysis, τ-p or *phase shift* (this latter is surely the best one). In order to solve the inevitable non-uniqueness issues, it is recommended to analyse multi-component data
MFA / FTAN	Multiple Filter Analysis / Frequency-Time ANalysis	Methodology for the determination of the group-velocity spectrum from the analysis of one single trace [MFA and FTAN are equivalent]
FVS	Full Velocity Spectrum	Methodology for the dispersion analysis carried out *not* through the interpretation of the modal dispersion curves but through the inversion / modelling of the entire (full) velocity spectrum (hence the entire velocity-frequency matrix). In this way it is not necessary to give any *interpretation* of the velocity spectra. Possible both for phase-velocity spectra [multi-offset approach] and group-velocity spectra [single-offset approach]; both for single-component data and multi-component data [joint analysis].
HS	HoliSurface [Holistic Analysis of Surface Waves]	Improved MFA/FTAN methodology that considers multi-component data (recorded at one single offset from the source) and analysed together with the RPM and/or RVSR curves [dispersion is analyses according to the FVS [*Full Velocity Spectrum*] approach. See our *HoliSurface®* application software
RPM	Rayleigh-wave Particle Motion	Curve that represents the retrograde-prograde motion due to the Rayleigh wave as a function of the frequency (useful to better constrain the subsurface model).
RVSR	Radial-to-Vertical Spectral Ratio	Spectral ratio of the radial and vertical components from active data (Rayleigh-wave ellipticity). Useful, especially in the low-frequency range in the joint analysis of dispersion data

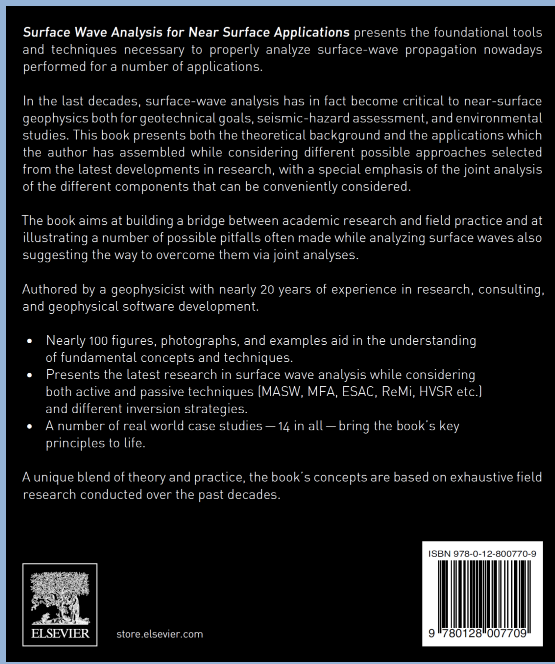
HVSR	Horizontal-to-Vertical Spectral Ratio	Ratio of the horizontal components with respect to the vertical one from passive (microtremor) data. It depends on the amount of Rayleigh and Love waves in the microtremor field (α factor)
ReMi	Refraction Microtremors	Determination of the dispersive properties from passive data using a mathematics pretty similar to the one usually used from active (MASW-style) data.
SPAC	SPatial AutoCorrelation	Methodology for the determination of the dispersive properties of passive data recorded according to a circular geometry. Less flexible compared to ESAC (this latter is preferable cause provides better results and works with any geometry)
ESAC	Extendend SPatial AutoCorrelation	Methodology for the determination of the dispersive properties of passive data recorded according to *any* geometry (included linear arrays – which we often recommend [see the winMASW® manual]). It's the "generalization" of the SPAC approach (*E* stands for *Extended*)
PS-MuCAA	Passive Seismics – Multi-Component Amplitude Analysis	Joint analysis of multi-component passive data used to define dispersive properties for all the considered components and the HVSR at each point (so to possibly define 2D V_S sections)
2D-SuPPSALA	Subsurface Profiling via Passive Surface wave data Analysis from Linear Array	Methodology useful to obtain 2D V_S section from multi-component passive data
MAAM	Miniature Array Analysis of Microtremors	Determination of the phase velocities [*effective* dispersion curve] from passive data recorded considering a circular geometry [e.g. equilateral triangle] with a particularly-limited radius (miniature array). The mathematics is different compared to the ESAC & SPAC approaches and the radius necessary to investigate a similar frequency range is considerably smaller (see our *HoliSurface®* application software)
SSR	Standard Spectral Ratio	Spectral Ratio (SR) of the amplitude spectra obtained at one site with respect to the amplitude spectra at a *reference* (rocky) site considering the data recorded during one or more earthquake(s). It is the actual site amplification (with respect to the rocky reference site).
SSRn	Standard Spectral Ratio - *noise*	As for the SSR but considering microtremor data (*n* stands for *noise*)
GHM	Gaussian-filtered Horizontal Motion	Methodology for the determination of the eigen-frequencies of a structure and the respective mode (flexural, torsional or mixed) from vibration (microtremor) data recorded at two (or more) points of the structure itself. See our *HoliSurface®* application software

Refraction seismics

The need (or usefulness) of the various techniques depends on the goals and on the technical characteristics (pro and cons) of the methodologies although, unfortunately, inertia and bad habits often dominate. **When do we "need" to use refraction seismics?** When we need to try to reconstruct the 2D structure of the most superficial layers in case significant lateral variations occur. On the field this can be easily and quickly verified by comparing the HVSR curves at 2 or 3 points along the section we need to investigate [see also our **HS-QC software**]. If, in the pertinent frequency range, they are different then refraction can be useful otherwise not. Remember that refraction has **limited penetration depth**: in the lucky cases, you can reconstruct the velocity profile down to almost 1/3 of the length of the array (and just in the central part of it).

When needed, using less than 16/24 channels is not recommended because you would not collect the data needed for that objective. **P or SH waves?** If you are working on soft sediments with the presence of water (even far from saturation conditions) P waves are not recommended because you risk seeing just the water table.




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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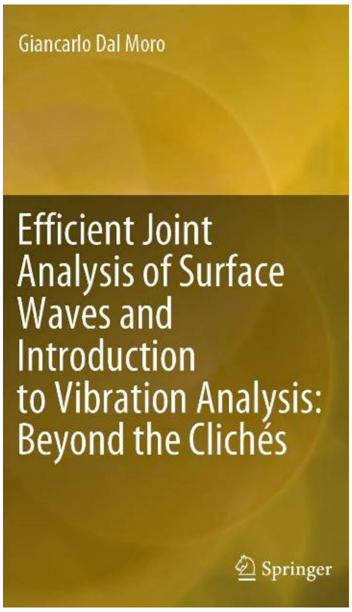
Efficient Joint Analysis of Surface Waves and Introduction to Vibration Analysis: Beyond the Clichés



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What is a *beta* version?

A development status given to a program or application that contains most of the major features, but is not yet complete. Sometimes these versions are released only to a select group of people, or to the general public. The testers are usually expected to report any bugs they encounter or any changes they'd like to see before the final release. This is the second major stage of development following the alpha version, and comes before the release candidate (from *Wikipedia*)

In order to receive *news* and *case studies* please, subscribe to our newsletter

https://www.winmasw.com/_uk/contatti

WORKSHOPS AND TRAINING

Eliosoft is available to organize workshops and meetings about all the practical and theoretical aspects related to MASW (Rayleigh + Love), MFA, HoliSurface, ESAC/SPAC, MAAM (Miniature Array Analysis of Microtremors), ReMi, HVSR, SSR/SSRn, vibration data analysis and so forth.

Please, consider that *winMASW® Academy* is a highly-sophisticated software which is absolutely impossible to fully and properly exploit without attending our workshops or studying our books and articles.

Some of the news in the recent *releases* of *winMASW®*

✓ Compatible with Windows 11

✓ User manual highly improved with more and more information and case studies

✓ In the **ESAC panel**:
- **Interferometry** analysis (of multi-component data)
- various Spectral Ratios tools for the estimation of **lateral variations [PS-MuCAA]** together with the dispersion analysis of **passive multi-component data** (i.e. Z, R and T components) via **2D-SuPPSALA (reconstruction of 2D V_S sections)**

✓ Significantly improved the ReMi panel (validity limits, tools etc.)

✓ Among the appendices of the manual we are now also reporting a small collection of things you can do with *winMASW®*

✓ Highly improved the tool for the creation of the **2D sections** [see utilities]

✓ *winMASW® Academy* & *HoliSurface®*: **the speaking software**. Now a series of warnings and suggestions are provided also as vocal messages!

✓ **Back-scattering** tool (*winMASW® Academy*)

✓ Easy management of the **GPS information** extracted from the photos taken from common smart phones (as well as from Drones or Action cameras)

✓ <u>HVSR panel</u>:
1) improved automatic identification and removal of industrial signals
2) batch (automatic) processing of a several microtremor (HVSR) data
3) you can read/upload seg2 data (without having to transform them as SAF file)
4) new tools for the automatic removal of transient events (in the time domain) and outlier HVSR curves (in the frequency domain)

✓ Several improvements in the **Site Response** (*Response Spectra*) tool

✓ Possibility to handle non-equally spaced MASW data (*winMASW® Academy*).

✓ Tool for the computation of pure synthetics (synthetic seismograms and HVSR): possibility to add certain amount of noise (so to make the traces more realistic). Useful for educational purposes as well as in the design of important acquisition campaigns

✓ Improved the tool for the *seg2SAF conversion* (from *seg* to *SAF*): now you can specify the units (mm/s or counts) and indicate a multiplicative factor (seg data are multiplied by this factor and then saved in the SAF file).

✓ Implementation of the *RPM (Rayleigh-wave Particle Motion) frequency-offset surface* analysis and joint inversion with the velocity spectra (see "Analysis of Rayleigh-Wave Particle Motion from Active Seismics" - Dal Moro et al., 2017) and *RVSR* (*Radial-to-Vertical Spectral Ratio*) for all the offsets

✓ Implementation of apparent/effective dispersion curves (e.g. Tokimatsu et al., 1992) for both Rayleigh (radial and vertical components) and Love waves. **Use them for passive data (ESAC/SPAC or ReMi).**

✓ HVSR modelling considering both Rayleigh and Love waves also considering attenuation and the *α* factor (see our two books [Elsevier & Springer])

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Main facts for the different versions

	Lite	HVSR	Standard	3C	Pro	Academy
2D Vs sections via joint analysis of multi-component passive data: tools **PS-MUCAA** *and* **2D-SuPPSALA** **NEW**						X
Smart and full management of GPS information from field photos (from smartphones, GoPro and Drones) **NEW**						X
HVSR: automatic identification and removal of industrial components/signals **NEW**						X
Back-scattering analysis **NEW**						X
Tool for visualizing and handle RayFract results [.GRD files] **NEW**						X
Non-equally-spaced MASW analyses **NEW**						X
ESAC panel highly improved (conversion of geographical coordinates, spectral ratios computations etc.) **NEW**						X
MASW analyses considering both Rayleigh and Love waves (and their joint inversion)	Rayleigh Waves only		Rayleigh Waves only	X	X	X
Vs30 and VsE (Vs equivalent) computation	X	X	X	X	X	X
Band- Low- High-pass filters	X		X	X	X	X
Analysis of Rayleigh-wave attenuation					X	X
ReMi analyses (passive seismics – linear arrays) [also for non-equally spaced datasets - **NEW**]			X		X	X [also for non-equally spaced data]
Group-velocity Analysis (*Multiple Filter Analysis*) for group-velocity determination (both for Rayleigh & Love)						X
RPM frequency-offset surface (computation and joint inversion with dispersion data) + RVSR						X
Computation and modelling of the HVSR (Nakamura's method) to estimate the resonance frequency etc.		X		X	X	X
Spectral analyses: computation of amplitude and phase spectra and spectrograms (frequency content over time)			X		X	X
1D modelling of *refraction* travel times (also considering low-velocity layers)				only for P waves	X	X
1D modelling of *reflections* (also considering low-velocity layers)	X			X		X
Tool to combine two active shots and simulate a dataset with a double number of channels (you record 2 active 12-channel datasets and got one with 24 channels)			X	X	X	X
Elastic moduli tool			X		X	X
Joint inversion of dispersion curve & *HVSR*						X
Synthetic seismograms both for Rayleigh & Love waves						X
Full Velocity Spectra (FVS) analysis via synthetic seismogram computation (recommended for complex velocity spectra from active acquisitions - see manual)						X
Computation of the *apparent* (or *effective*) dispersion curve (recommended for passive ESAC/SPAC and ReMi data)						X
Tool for the *vertical stacking*						X
Tool for creating 2D sections						X
Tool for putting in evidence specific (even "hidden") modes						X
ESAC and FK analyses (bi-dimensional arrays)					linear *arrays*	X (2D)
Tool **TCEMCD** (*Three-Component Extraction from Multi-Channel Data*) for efficient passive joint ESAC/MAAM + HVSR acquisitions (see TCEMCD Appendix).					X	X
Tool for combining several traces acquired by a single 3-component geophone @ different offsets and obtaining datasets useful for MASW analysis considering both Rayleigh (radial and vertical component) + Love waves.				X	X	X
Site Response (Response Spectra) panel						X
Pure Synthetics (see related section of the manual)						X

WARNING

Buy and use horizontal geophones and jointly analyze Rayleigh (radial component) and Love waves!
Please, acquire the data strictly following our guidelines and download and read the papers, books and case studies listed in our web sites

If you are not completely sure about the best type of equipment to buy (type and number of geophones and type of 3-component geophone for HVSR measurements) for analyzing surface waves, please write us (winmasw@winmasw.com) and we will give you our recommendations.

REGISTRATION

Do not forget to register your purchase: please provide the name of the reseller, the date of your purchase and the version (*Lite*, *Standard, 3C, Professional* or *Academy*). This way you will receive our *newsletter* with recommendations, news and case studies.

To register send an email to: winmasw@winmasw.com

VIDEO TUTORIALS

Updates of the present manual can be downloaded from our web site. In addition, it is also possible to download a series of *video tutorials* aimed at properly using the main *winMASW* features.
The tutorials are focused on specific kinds of analyses: standard MASW analysis (Rayleigh waves), joint analysis of Rayleigh & Love dispersion, joint analysis of phase & group velocities, ReMi and ESAC analyses; HVSR analyses etc.

Several **helps** are displayed just pointing the cursor on the button: a notice on yellow background will display providing basic information.
Some of the figures in the manual might refer to former versions of the software. All upgrades keep their same features, adding new functions.

The key point of *winMASW®* is anyway represented by the possibility of joint analysis of several datasets/components acquired according the guidelines briefly reported in this manual, in the *Elsevier* and *Springer* books and all the papers mentioned in the *References*.

Remember that a software is just a *tool*.

Accuracy of results always and necessarily depends on the users' skills and experience.
We highly recommend to attend our workshops.

“***One of the great challenges in this world is knowing enough about a subject to think you're wright, but not enough about the subject to know you're wrong.***”

Neil deGrasse Tyson (astrophysicist)

Introduction: the *winMASW*® holistic perspective

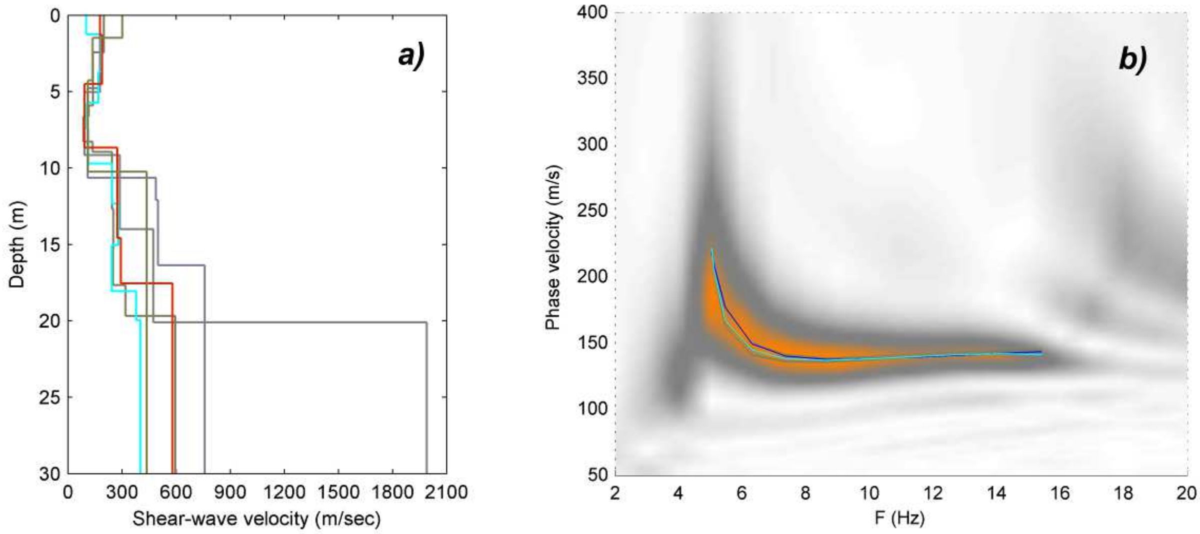
Generalities

The ***winMASW®*** software allows to analyze seismic data in order to achieve the vertical profile V_S (shear-wave velocity) using the following methods:

- multi-component MASW analysis (Rayleigh & Love waves, also jointly and also considering non-equally spaced data): please, carefully read this introductory section in order to understand why we strongly recommend to use (also) Love waves
- MFA/FTAN for the determination of the group velocities
- ReMi and ESAC/SPAC analyses (we highly recommend multi-component ESAC)
- PS-MuCAA: amplitude analysis of multi-component passive data for the improved joint analysis aimed at defining a very robust V_S profile and the identification of lateral variations
- 2D-SuPPSALA: 2D **Su**bsurface **P**rofiling via **P**assive **S**urface wave data **A**nalysis from **L**inear **A**rray
- HVSR (*Horizontal-to-Vertical Spectral Ratio*) (also jointly with dispersion data)
- 1D (P and SH waves) refraction travel time modelling
- generation of synthetic seismograms via *modal summation,* consequently: inversion of the *Full Velocity Spectra* (FVS) with no need of picking/mode interpretation (pay attention since this anyway requires a good knowledge of several theoretical aspects and a state-of-the-art PC)
- Rayleigh-wave attenuation analyses (for estimating Q_S quality factors)
- Site response tool

The *winMASW®* software application is designed considering all the problems related to the data ambiguity and the non-uniqueness of the solution (for an overview on these topics, please see our *Elsevier* and *Springer* books).

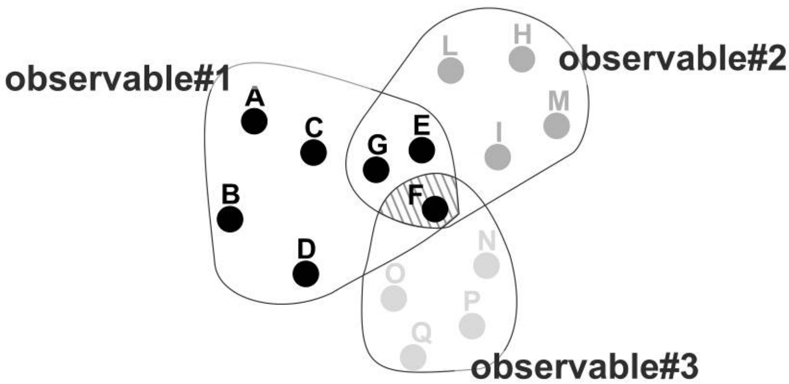
In order to illustrate such a problem, in the following figure we report six V_S models and, overlapped with a phase-velocity spectrum obtained from a real-world dataset, their respective dispersion curves (fundamental mode) in the 4.5-16 Hz frequency range.
As you can see even if the six models are pretty different, the dispersion curves are quite similar and compatible with the field velocity spectrum (in the background).
This means that the analysis of just one component and the modal dispersion curves cannot solve the intrinsic ambiguity of the data/analyses.



Our software applications are designed in order to solve this problem. This is accomplished though the joint analysis of several components/observables, so to obtain a final model (the V_S profile) free from major ambiguities (otherwise inevitable).

A simple **conceptual scheme** will clarify this crucial point (for details and synthetic and real-world example see our books published by *Elsevier* and *Springer*).

Let us imagine we are considering three different observables (e.g. the Rayleigh-wave velocity spectrum, the Love-wave velocity spectrum and the HVSR curve).



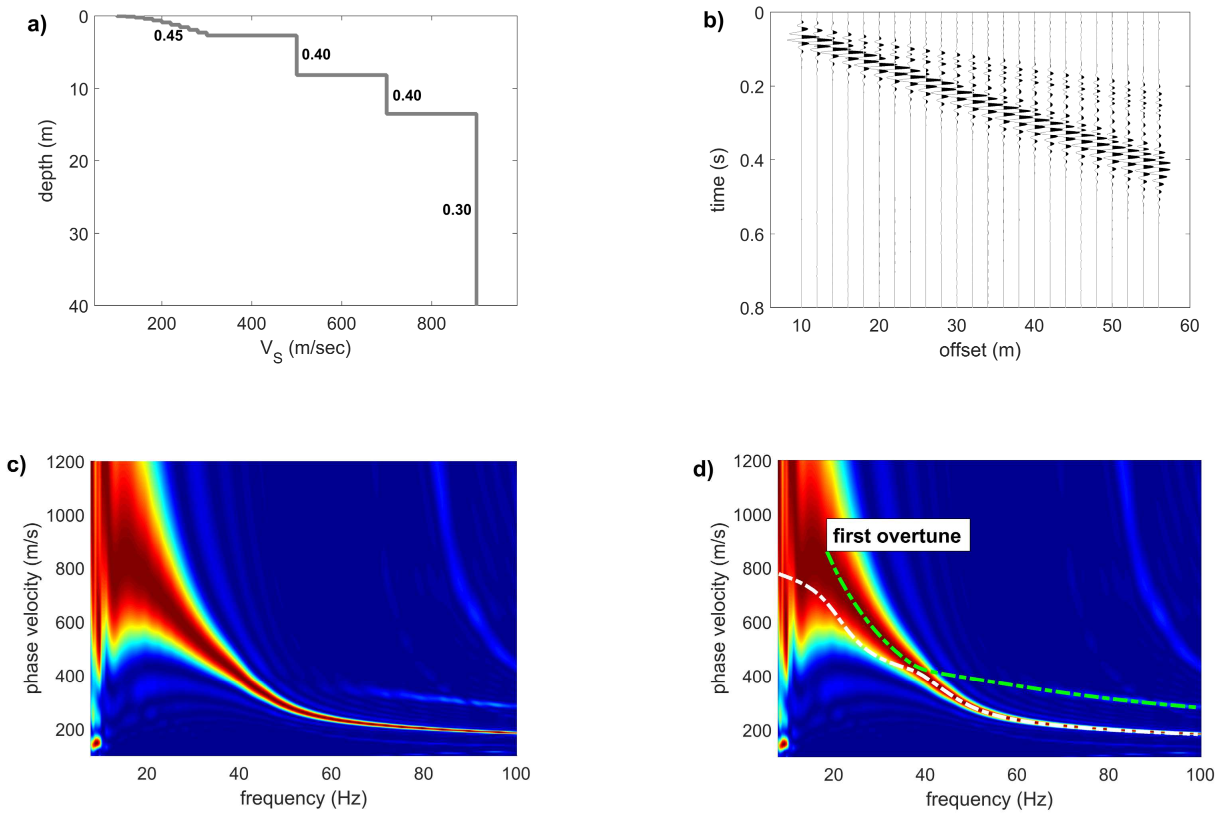
In case we would use <u>only the method/dataset A</u> (e.g. the Rayleigh-wave velocity spectrum), the possible solutions would be the A, B, C, D, E, F and G models.
In case we would use <u>only the method/dataset B</u> (e.g. the Love-wave velocity spectrum), the possible solutions would be the G, E, F, L, I, M and H models.
In case we would use <u>only the method/dataset C</u> (e.g. the HVSR curve), the possible solutions would be the F, O, N, Q and P models.

It is clear that the only model which is consistent with all the three considered methods/datasets is the model F.

Only through the joint analysis of several *observables* you can obtain the right model (in this case labelled as F), which is consistent with all the considered data/methods.
A concrete/simple example is the joint analysis of Rayleigh and Love waves (recorded by using just 12 horizontal geophones – see *Guidelines for the data acquisition*) jointly with the HVSR.

Why you should not use (only) the vertical geophones

Example of synthetic dataset (classical ZVF component) to put in evidence the intrinsic ambiguity of standard (single component) surface-wave data: **a)** considered V_S model (numbers report the Poisson ratios); **b)** synthetic traces; **c)** phase velocity spectrum computed from the synthetic traces (such a velocity spectrum is apparently simple [smooth and continuous without any weird feature] and thus suitable for the classical *picking*-and-*inversion* procedure); **d)** phase velocity spectrum with the theoretical modal dispersion curves of the first two modes.

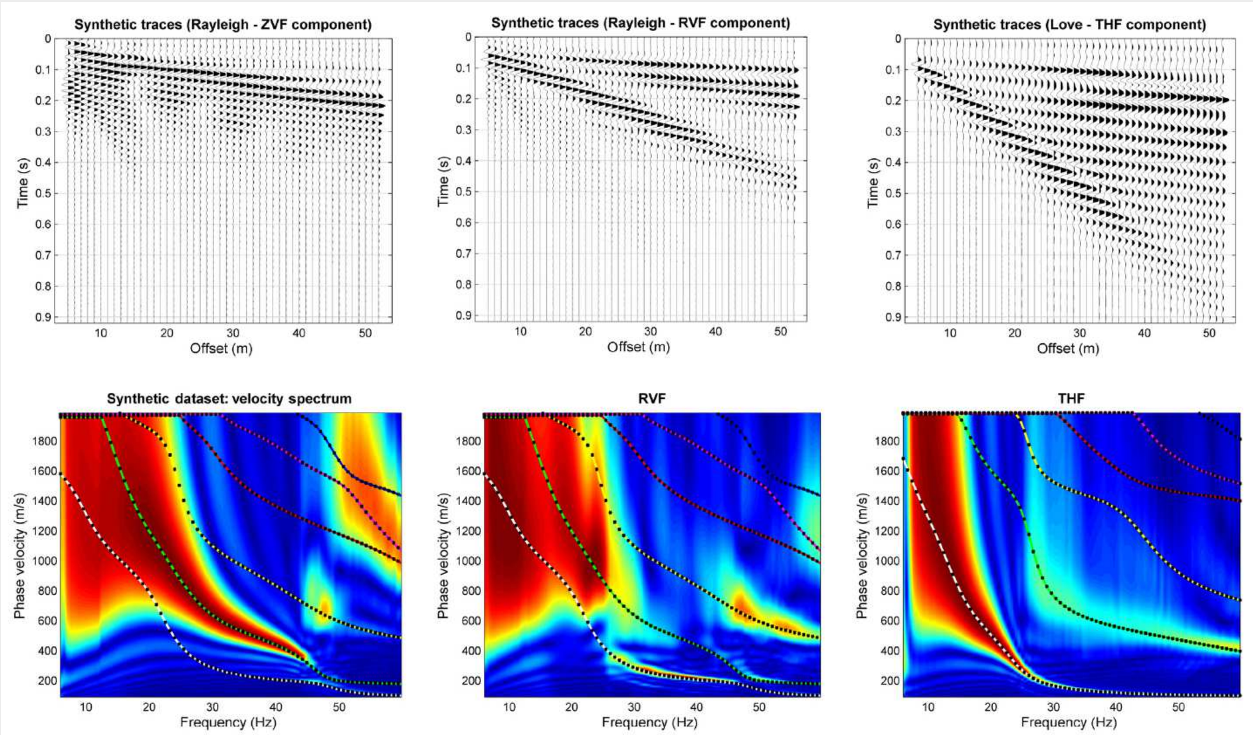


The problem is that, once we plot the modal dispersion curves of the first two modes (*d* plot), we realize that such continuous signal **does not belong to a single mode but is the combination of the fundamental mode (for frequencies higher than 40 Hz) and the first higher mode (for lower frequencies)**
It should be clear that, as a matter of fact, it is impossible to realize that the observed data (*c* plot) are actually composed of two distinct modes and, by following the ordinary approach, you would pick the dispersive signal in the *c* plot as the fundamental mode, thus eventually obtaining an erroneous V_S profile (with overestimated values).

It must be underlined that the inversion of the erroneously-picked dispersion curve would surely provide a seemingly-good misfit (any dispersion curve— right or wrong—can be associated to a subsurface model).
The practical consequence is that everything would seem simple and fine but, as a matter of fact, the obtained solution would be meaningless (over-estimated V_S values).

This kind of data are impossible to solve since the phase-velocity spectrum cannot be correctly interpreted in terms of modal dispersion curves.

In some cases, Rayleigh waves do not show *any* evidence of the fundamental mode (see Dal Moro et al. 2015, *Multi-component Joint Analysis of Surface Waves* or the *Elsevier* book). In the following figure are reported the phase velocity spectra of the vertical (Z) and radial (R) components of Rayleigh waves and Love waves with, overlaying, the modal dispersion curves.
Do you see that the vertical (Z) component of Rayleigh waves do not show any evidence of the fundamental mode? The stratigraphy excites just the higher mode(s).



Example of dataset/site where the vertical component of Rayleigh waves *do not* show any evidence of the fundamental mode. Only higher modes are excited (from Dal Moro et al., 2015).

This means that without the "support" of the Love waves you will inevitably interpret the higher mode(s) of the Rayleigh waves as fundamental mode and, consequently, significantly overestimate the shear-wave velocities. This is why you should not use (only) the vertical geophones (actually we rarely use them and for just very specific goals – see for instance the PS-MuCAA tools).

What is the *solution* to these problems? The joint acquisition and analysis of several components/observables (which is possible through several approaches implemented in our *winMASW®* and *HoliSurface®* software applications – see Appendix about *Surface-wave data acquisition*).

More examples and details in the *Elsevier* and *Springer* books as well as in several of the papers mentioned in the *References*.

In order to pursue such a goal it is crucial to implement a proper field equipment that allows you to record data suitable for this sort of analyses (which are the only way to avoid a long series of pitfalls widely described in the two above-mentioned books as well as I n several articles published in specialized journals – see References).

To keep it simple: **it is impossible to obtain a correct V_S profile if you try to analyse the data recorded using just vertical geophones and the modal dispersion curve (this is the standard approach that, unfortunately, several fellows still consider *the MASW method*).**

Also: as widely explained in our books and papers the acronym "MASW" is nowadays completely meaningless because by this acronym we can indicate a very wide series of different techniques having completely-different performances (ESAC, multi-component multi-offset MASW, *HoliSurface*, MFA, ReMi, FVS or modal analysis, modal or effective curves and so on and so on: they are all "MASW").

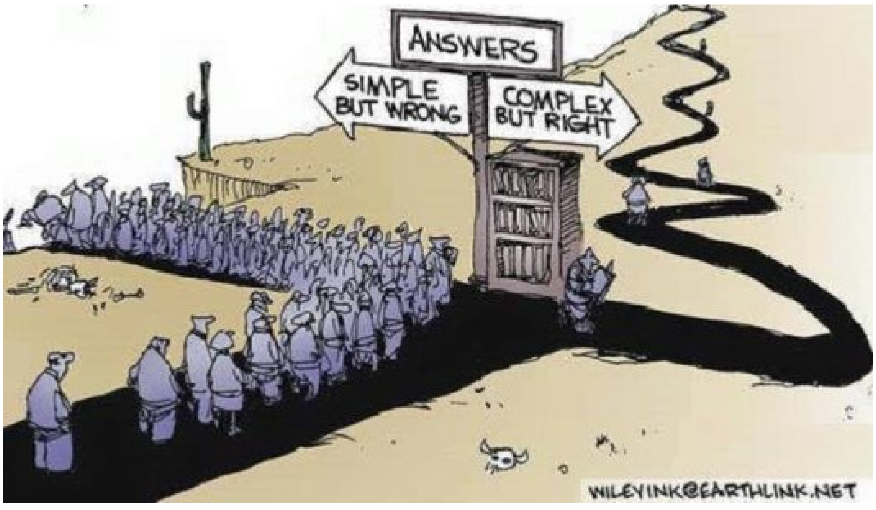
So, "MASW" no longer means anything.

Before buying your field equipment, please consider that "MASW" can (should be) be something different that deploying a set of vertical geophones and then trying to guess where the fundamental mode is (sometimes the fundamental mode does not show up at all).

Remember that your goal is NOT to perform a "MASW/ESAC/HVSR test" but to obtain the correct V_S profile.

In the section *References* we report a series of papers about all the "objects" (or, better, *observables*) that can be analyzed thanks to the methodologies implemented in *winMASW*® and *HoliSurface*® (multi-component MASW, MFA, FVS, ESAC/SPAC, ReMi, RPM, MAAM, HVSR, SSR and SSRn etc.).

In *winMASW*®, the automatic inversion is performed via *Genetic Algorithms*, but we would like to underline that forward (direct) modelling is often preferred.
Genetic algorithms represent an optimization procedure belonging to the classification of heuristic algorithms (or also *global-search methods* or *soft computing)*
Compared to the traditional linear inversion methods based on gradient methods (*Jacobian matrix*) these inversion techniques grant a very reliable result in terms of precision and completeness.



Refraction tomography. Please, consider that:

1) "It is now generally recognized that non-uniqueness is a fundamental reality with the inversion of virtually all sets of geophysical data (Oldenburg and Li, 2005; Treitel and Lines, 1988), including near-surface seismic refraction data (Ivanov et al, 2005a, 2005b). Nevertheless, there can still be considerable reluctance to address the issue with the inversion of near-surface seismic refraction data, often because of the implications for litigation with geotechnical applications." (*The Inverse Problem of Refraction Travel Times, Part I: Types of Geophysical Nonuniqueness Through Minimization* - Ivanov et al., 2005, *Pure and Applied Geophysics* 162(3):447-459; DOI: 10.1007/s00024-004-2615-1)

2) **"**The inversion of near-surface seismic refraction data for geotechnical and environmental investigations is fundamentally non-unique. It is possible to generate tomograms, which range from the geologically improbable to the very detailed, all of which satisfy the traveltime data to sufficient accuracy.**"**

&

"It is concluded that the major effect of tomography is largely cosmetic: refraction tomography rarely, if ever, improves resolution. Furthermore, a simplistic comparison of the misfit errors of tomography does not "prove" that a given result is either "correct" or even geologically reasonable. It is proposed that the three tomograms generated with detailed GRM time and velocity models for the optimum XY value and plus/minus half the station spacing, constitute a more useful measure of the uncertainties of refraction inversion." (*Are refraction attributes more useful than refraction tomography?* Derecke Palmer, 2010 - *First break*, *28*)

In simple terms: solution obtained from seismic refraction is also *non-unique* and tomographic processing does not solve the problem. In addition to this, the V_P values obtained considering the vertical component (vertical geophones) are necessarily heavily influenced by the saturation conditions of the subsurface materials (see *compressibility* parameter in the equation defining the V_P values), which do not seriously affect the V_S values (*compressibility* is not involved in the equations defining the V_S value). This means that if you perform a P-wave refraction survey, you will obtain one of the possible solutions (in terms of V_P) which is related to how much water there is in the soil (in alluvial plains with shallow water table, V_P refraction study will allow you to see the depth of the water table but *nothing* below it). On the other side the V_S values indicate the soils/materials in a more straightforward manner.

For the most common applications, it is therefore recommended to use a set of horizontal geophones for both SH-wave refraction and surface waves (Love and radial component of Rayleigh waves) (see *Appendix* on data acquisition).

In order to obtain 2D V_S sections, remember that you can use the SuPPSALA tool from winMASW® Academy.

Please remember that, in addition to software applications for the data analysis, we also provide hardware solutions (**seismographs**, **seismic cables**, **geophones etc.**) for the correct and efficient acquisition of the field data necessary to obtain an unambiguous and robust solution (i.e. the correct subsurface V_S profile).

V_S equivalent (VsE) [the mean Vs down to the bedrock depth]

The V_S equivalent (VsE or VsH) is defined according to the following equation:

$$V_{S,eq} = \frac{H}{\sum_{i=1}^{N} \frac{h_i}{V_{S,i}}}$$

where the depth H is the depth where V_S is equal or higher than 800 m/s (*seismic bedrock*).

In case the seismic bedrock is deeper than 30 m (from the foundation depth) VsE = Vs30.

Quality is never an accident; it is always the result of intelligent effort

John Ruskin

Active and passive seismics? A short note

Nowadays the expression "passive seismics" and "active seismics" are often used to indicate *very* different techniques. It is therefore, when we speak to somebody, to indicate exactly the technique/methodology we are interested in. Passive (or active) seismics, in fact, means nothing. We can refer to HVSR, SPAC, ESAC (single of multi-component?), ReMi (single or multi-component), MAAM, interferometry, microtremor correlation etcetera.
Similarly, we can deal with several kinds of active data (multi-offset MASW can be both single and multi-component), HoliSurface® and so on.
Please, have a look at the list of main abbreviations in the beginning of this manual.

So, do not be vague and clearly indicate the specific methodologies you are dealing with.

The seismic components

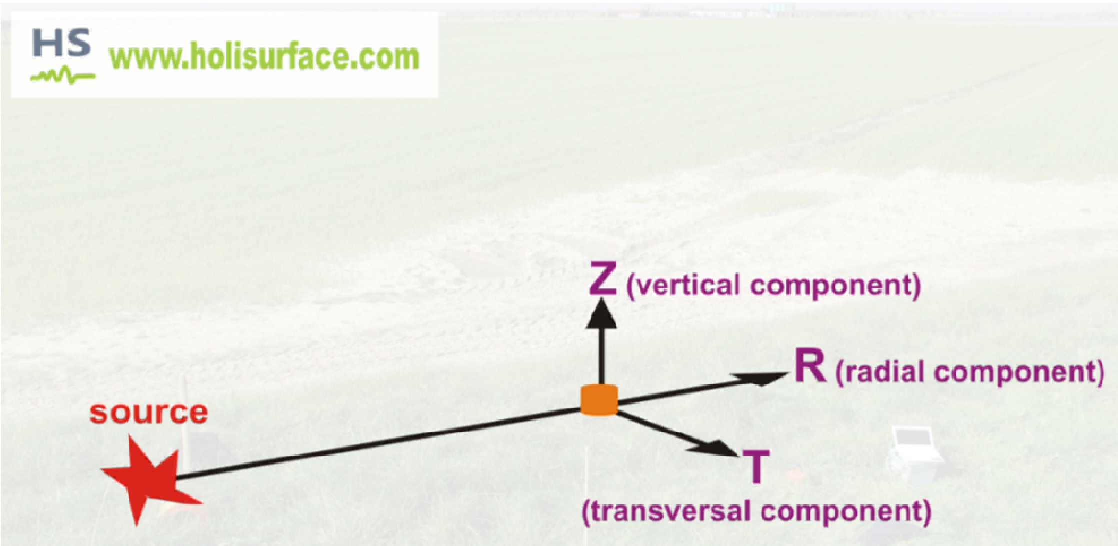
In simple terms, the *components* can be imagined as the *directions* along which we record the particle motion.

We can consider the picture here below:

- the Love waves move along the T (transversal) component, as well as the SH refracted waves;
- Rayleigh waves move along the vertical (Z) and radial (R) components [as well as the P-wave refracted waves]

By **multi-component analysis** we mean the joint analysis of the data recorded along two or more directions (this allows to consider several possible *objects* – see for instance the papers "*Improved Holistic Analysis of Rayleigh Waves for Single- and Multi-Offset Data: Joint Inversion of Rayleigh-Wave Particle Motion and Vertical- and Radial-Component Velocity Spectra*" and "*Effective Active and Passive Seismics for the Characterization of Urban and Remote Areas: Four Channels for Seven Objective Functions*").

winMASW® 3C, *Professional* and *Academy* aim at the joint analysis of different *observables* to define a well-constrained solution (i.e. a detailed and robust V_S profile).



We always suggest the multi-component acquisitions and analyses that strongly reduce the ambiguities in the data and analyses (see for instance the case studies in the Elsevier book as well as more recent published papers).

For common studies we recommend to use just twelve (12) horizontal geophones (so that you can analyze both the RVF and THF components), while for more important jobs you can go for instance for the ZVF+RVF+RPM analyses (see pertinent section).

Please, notice that if you use just the Z component (vertical geophones) several ambiguities will affect the solution (see introductory section of the manual).

Improve your equipment: our hardware & software solutions

ELIOSOFT provides fully-equipped **ACQUISITION SYSTEMS** (seismographs, seismic cables, geophones etc.) optimized for the efficient acquisition of multi-component holistic seismic data


- 4.5 Hz vertical and horizontal geophones (for MASW and ESAC acquisitions): remember that, for active MASW, Rayleigh (the radial component) and Love waves can be recorded using only horizontal geophones
- High-sensitivity vertical geophones (for ESAC and MAAM acquisitions - MAAM is a kind of mini-ESAC implemented in our *HoliSurface*® software application)
- 3-component geophones (which are equalized via software down to about 0.2 Hz) for HVSR and optimized joint acquisition of *HoliSurface*®, ESAC, ReMi, MAAM and vibration data.
- Double borehole geophones. Having a double borehole geophone allows you to halve the acquisition effort and our **ELIOVSP software application** is designed so to easily and efficiently manage also this sort of data (jointly with the HVSR curve, so to significantly increase the investigated depth).

3-component HOLI3C geophone
(passive geophone to connect to your seismograph)

Vertical and horizontal geophones and the metallic tripod for working on asphalt cover

Your clips: when you order your geophones, please remember to indicate whether your seismic cable accepts *Split Spring* or *Mueller*-type clips

Split Spring

Müller (or *Mueller*)

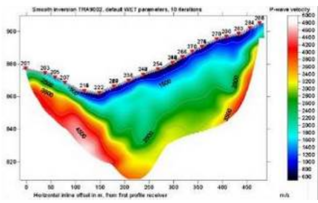
SOFTWARE APPLICATIONS

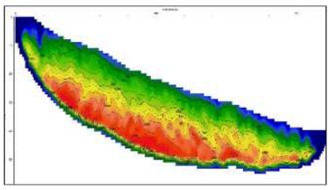
HoliSurface®
Holistic analysis of surface waves and vibration data

winMASW®
surface waves and beyond

VSP
ELIOSOFT
DownHole seismics

RayFract





ReflexW

DATA PROCESSING for your seismic data (see our ADAM2D service)

1. System requirements

The *winMASW®* software application works only on 64bit *Operating Systems* (OS).

It is important to frequently update your operating system ("windows update") in order to let *winMASW* properly use updated functionalities.

We recommend *Windows*11 (but *win8* is fine as well).

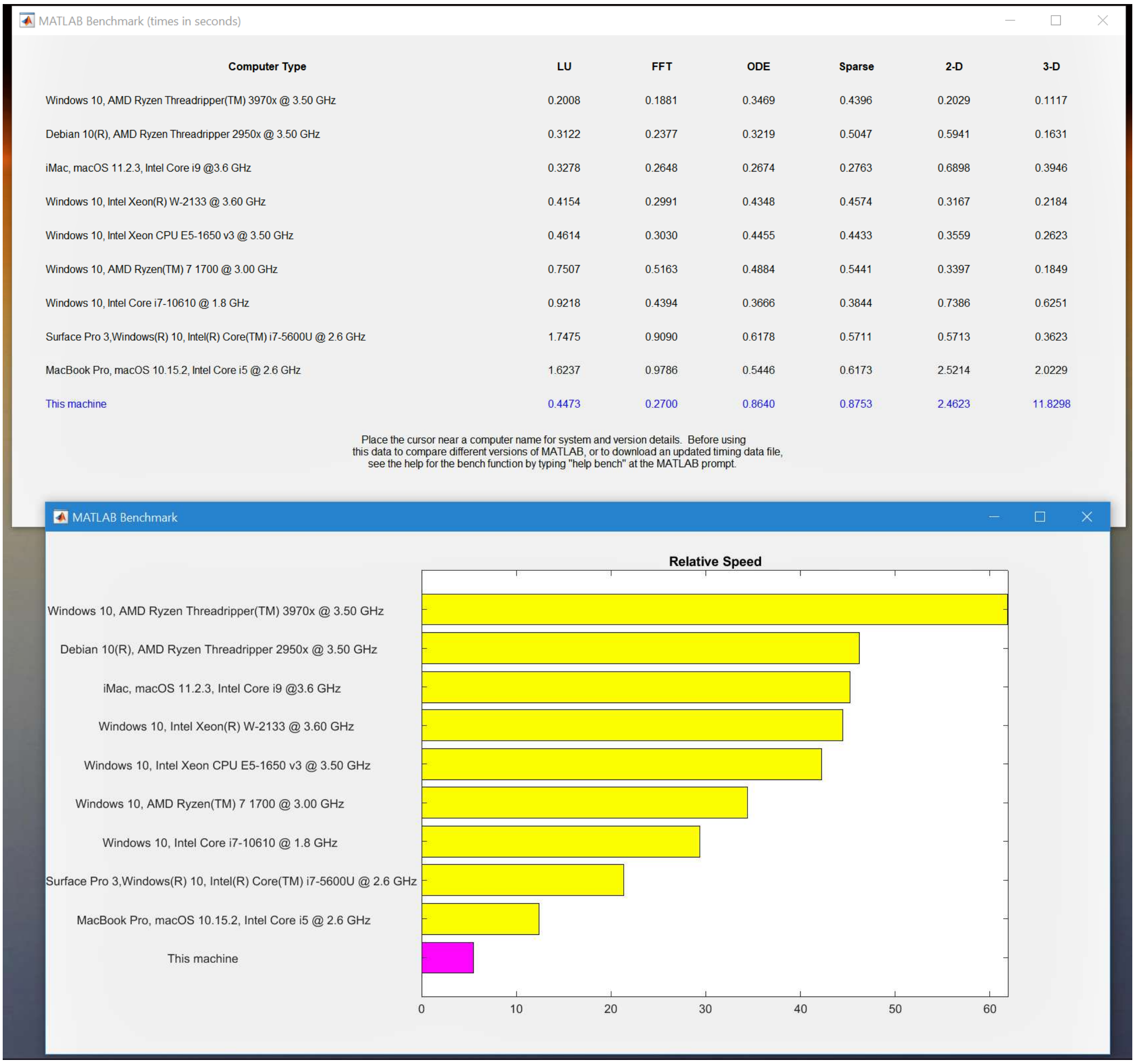
If you are using a Mac, there are several possibilities to run a windows software: https://www.howtogeek.com/187359/5-ways-to-run-windows-software-on-a-mac/

While for *winMASW® Lite*, *Standard*, *3C* and *Professional*, no special requirement is needed, for the *Academy* version (and *HoliSurface®*) and some of its most advanced features (e.g. the *Full Velocity Spectrum* (FVS) inversion, PS-MuCAA etc.), in order to fully exploit the potentiality of the software, we recommend to work with a computer with a good CPU.
We might for instance consider the *Intel i9-10900 K* (10 cores, 20 threads) or the AMD Ryzen 9 3950X (16 *cores*, 32 threads) CPUs. On the other side, if we plan to analyse (almost daily) a massive amount of data, you can set up a real *workstation* with a motherboard capable of handling **two Xeon CPUs** (with a sufficiently-large number of cores), thus doubling the number of cores.
In this case, if you buy the right **motherboard**, you can initially install just one (Xeon) CPU and, in case in future you decide to further increase the computational power of your ***workstation***, you can then install a second CPU.
This is the solution we recommend **in case you plan to analyze a large amount of data according to the more advanced procedures** possible in **winMASW® Academy** and/or **HoliSurface®** (so this is not necessary for "standard" MASW/ReMi/HVSR/ESAC analyses): buying a *workstation* with a motherboard capable of handling two CPUs. Initially you can install just one (not less than 8 physical cores) but you will be able to install a second CPU (in case your needs grow). The cost will be surely higher compared to an ordinary computer but your work will significantly benefit from it and your workstation will continue to be an excellent tool for many more years.

RAM: 16 GB (for *winMASW® Academy* and *HoliSurface®*)

Monitor resolution: 1920x1080 (or higher)

Thanks to the "**current releases & benchmarks**" button (from the main panel of the software), you can get an idea of the performance of your processor (the power of one single core) compared to a set of reference systems.
Here is an example for an old CPU composed or pretty slow cores which is nevertheless still quite powerful since the total number of cores is pretty large (in this case 36).



MATLAB Benchmark (times in seconds)

Computer Type	LU	FFT	ODE	Sparse	2-D	3-D
Windows 10, AMD Ryzen Threadripper(TM) 3970x @ 3.50 GHz	0.2008	0.1881	0.3469	0.4396	0.2029	0.1117
Debian 10(R), AMD Ryzen Threadripper 2950x @ 3.50 GHz	0.3122	0.2377	0.3219	0.5047	0.5941	0.1631
iMac, macOS 11.2.3, Intel Core i9 @3.6 GHz	0.3278	0.2648	0.2674	0.2763	0.6898	0.3946
Windows 10, Intel Xeon(R) W-2133 @ 3.60 GHz	0.4154	0.2991	0.4348	0.4574	0.3167	0.2184
Windows 10, Intel Xeon CPU E5-1650 v3 @ 3.50 GHz	0.4614	0.3030	0.4455	0.4433	0.3559	0.2623
Windows 10, AMD Ryzen(TM) 7 1700 @ 3.00 GHz	0.7507	0.5163	0.4884	0.5441	0.3397	0.1849
Windows 10, Intel Core i7-10610 @ 1.8 GHz	0.9218	0.4394	0.3666	0.3844	0.7386	0.6251
Surface Pro 3,Windows(R) 10, Intel(R) Core(TM) i7-5600U @ 2.6 GHz	1.7475	0.9090	0.6178	0.5711	0.5713	0.3623
MacBook Pro, macOS 10.15.2, Intel Core i5 @ 2.6 GHz	1.6237	0.9786	0.5446	0.6173	2.5214	2.0229
This machine	0.4473	0.2700	0.8640	0.8753	2.4623	11.8298

Place the cursor near a computer name for system and version details. Before using this data to compare different versions of MATLAB, or to download an updated timing data file, see the help for the bench function by typing "help bench" at the MATLAB prompt.

2. Installation

The software installation is pretty simple: just *click* as Administrator on the exe installation file (for details please read the README.PDF file in the *winMASW* DVD) and follow the simple an standard procedure/instructions.

PAY ATTENTION

According to some operative systems (Windows Vista in particular) the management of privileges and writing in some files is quite restrictive.
It was noticed that (especially with Vista) installing the software outside the "system folders" (*C:\Program Files*, *C:\Programmi* e *C:\Windows*), that meaning inside dedicated folders (as for instance *C:\winMASW* o *C:\geofisica\winMASW*) can help sorting that matter out, avoiding consequent problems.
Should you face any problem when launching *winMASW* (this usually happens with Windows Vista) first check the privilege details (by clicking the right key of the mouse on the winMASW icon on the desktop).
It is necessary that the *winMASW* user has a writing privilege on the folder "winMASW/output" (if you set up the software as "Administrator" and then launch it with a different user this might not happen).
If using *Windows Vista* it is strongly suggested to install the software in an external folder as "*C:\winMASW*".

Install the software as Administrator of the computer and run the installation executable using the right button of the mouse ("run as Administrator")

The winMASW application refers to *Matlab libraries*, simultaneously installed with the software (choose English as set up language):

Should the *Matlab* libraries already be installed in your Computer, in following window choose the option "modify"

During the set up of libraries a message as follows might display:

Just click on "Ok" , ignoring it!

Firewalls and parallel computing

If your firewall is particularly strict, it is possible that when you lunch the software a message like the following appears:

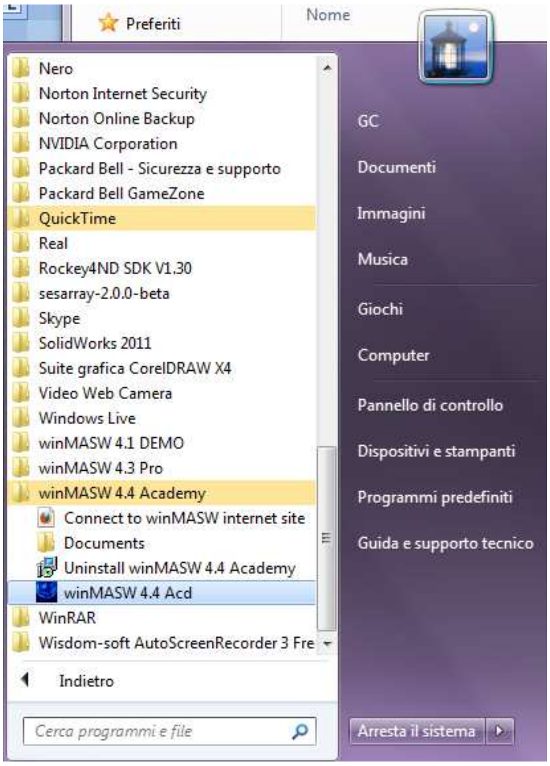
This happens cause, in order to exploit all the workers/cores of your machine, it is necessary to perform some operation that must be explicitly allowed. So do not worry and allow that.

Possible problems with some anti-virus systems

Some *anti-virus systems* might be unable to manage the software protection based on the *envelope* system that protects *winMASW*. In this case it is possible that your anti-virus will warn you about a *trojan* in the *winMASW*.exe binary application. In that case just tell the anti-virus to ignore the folder where you are installing *winMASW*. Smarter *anti-virus systems* (we might suggest the free and excellent **AVG**) do not have such a problem which so far occurred with **AVAST, AVIRA, Panda, Trend Micro Internet Security and Eset Nod32 (which we strongly advise against)**.

Once the installation is done the icon *winMASW* will display on the desktop (the usual double click will launch the application)

Also, a group *winMASW* is created on the Windows programs main menu (see snapshot):



3. User License, USB dongle and assistance

The *winMASW®* software works by means of a hardware key (USB dongle)

To know more about costs please ask the distributor or look up the web pages dedicated to *winMASW®* in the ELIOSOFT web site (www.winmasw.com)

In case the USB dongle gets damaged a new one only can be obtained after receipt of the damaged one and after the new dongle + its delivery expenses are settled.

ELIOSOFT (as well as any software distributor) can't be responsible for any improper use of the software due to misuse or misunderstanding or bad knowledge of the MASW/MFA/ESAC/ReMi methods.

Possible advices/alternative interpretations of the software (the purchase of the license actually gives the possibility to achieve two different interpretations) forwarded by users are allowed to be used by *ELIOSOFT* for further teaching and exemplification purposes.

Technical support is provided by e-mail (winmasw@winmasw.com) or on the phone (visit the website www.winmasw.com for updated information)

Free of charge upgrades are available within the first year of purchase (new software versions). That time expired, a fix quote is requested according to both the date of purchase and to the version (standard or professional).

The routine for the computation of the H/V spectral ratio from body waves (available in the *3C*, *Professional* and *Academy* versions, as well as in *HoliSurface®*) is provided to *ELIOSOFT* under license of Prof. Herak (University of Zagreb, Croatia).

Educational License

universities and scientific institutions can ask for an *Educational License* granted at special conditions.

https://www.winmasw.com/_uk/contatti

4. General procedures: fundamentals and recommendations

Active data acquisition: it is recommended to use file names with a clear and straightforward meaning (see our books published for Elsevier and Springer in 2014 and 2020, respectively).

Acquisition of HF data for the analysis of Love waves and SH-wave refraction (details in the Springer book)

Passive data acquisitions (for all the methodologies): it is recommended not to record exceedingly-large files (you may have problems managing them). Maximum **sampling frequency** can be fixed by considering the ***Nyquist-Shannon theorem*** (if you are interested in the frequencies up di x, you should use a 2x sampling frequency – consider that, usually, passive data are relevant only up to 30-50 Hz or so).
If, for some special need, you need to monitor a site for 12 hours, instead of a single 12h file sampled at 250 Hz, it is recommended to reduce the frequency sampling to 100 Hz and record, for instance, six 2-hour files (most of the up-to-date acquisition system can be easily programmed so to do it automatically).

Three ways to produce Love waves

The acquisition and analysis of Love waves in a ***crucial point*** in surface wave analysis (please see our Elsevier and Springer books and references therein mentioned).

You can produce SH (and therefore Love) waves by using a classical wooden beam as in the following photo:

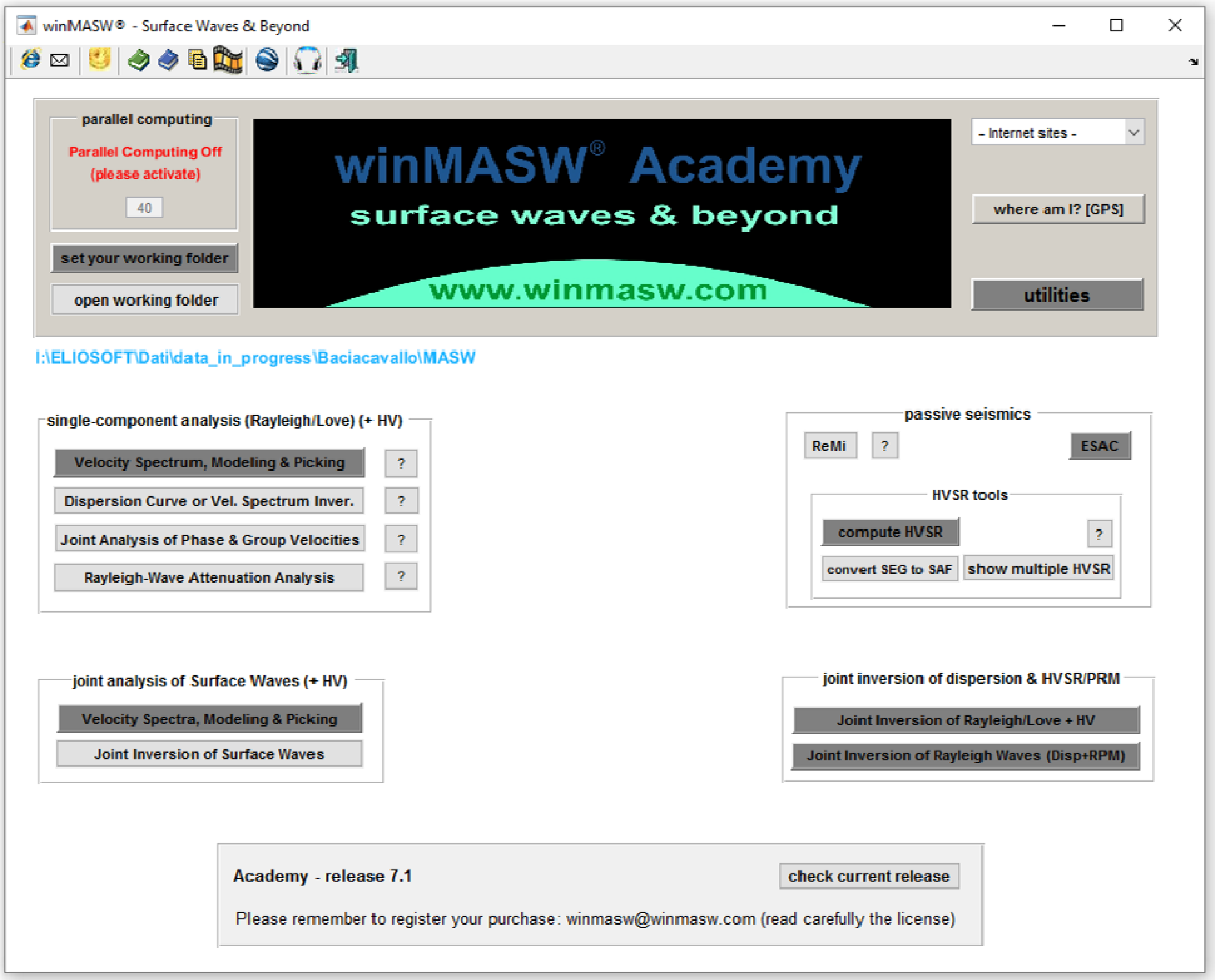
In order not to damage the wood, you can also cover the beam with the polyethylene plate used for the VF acquisitions:

Finally, when working on soft soils, you can dig a small hole in the soil and place the polyethylene plate (almost) vertically like in the following picture:

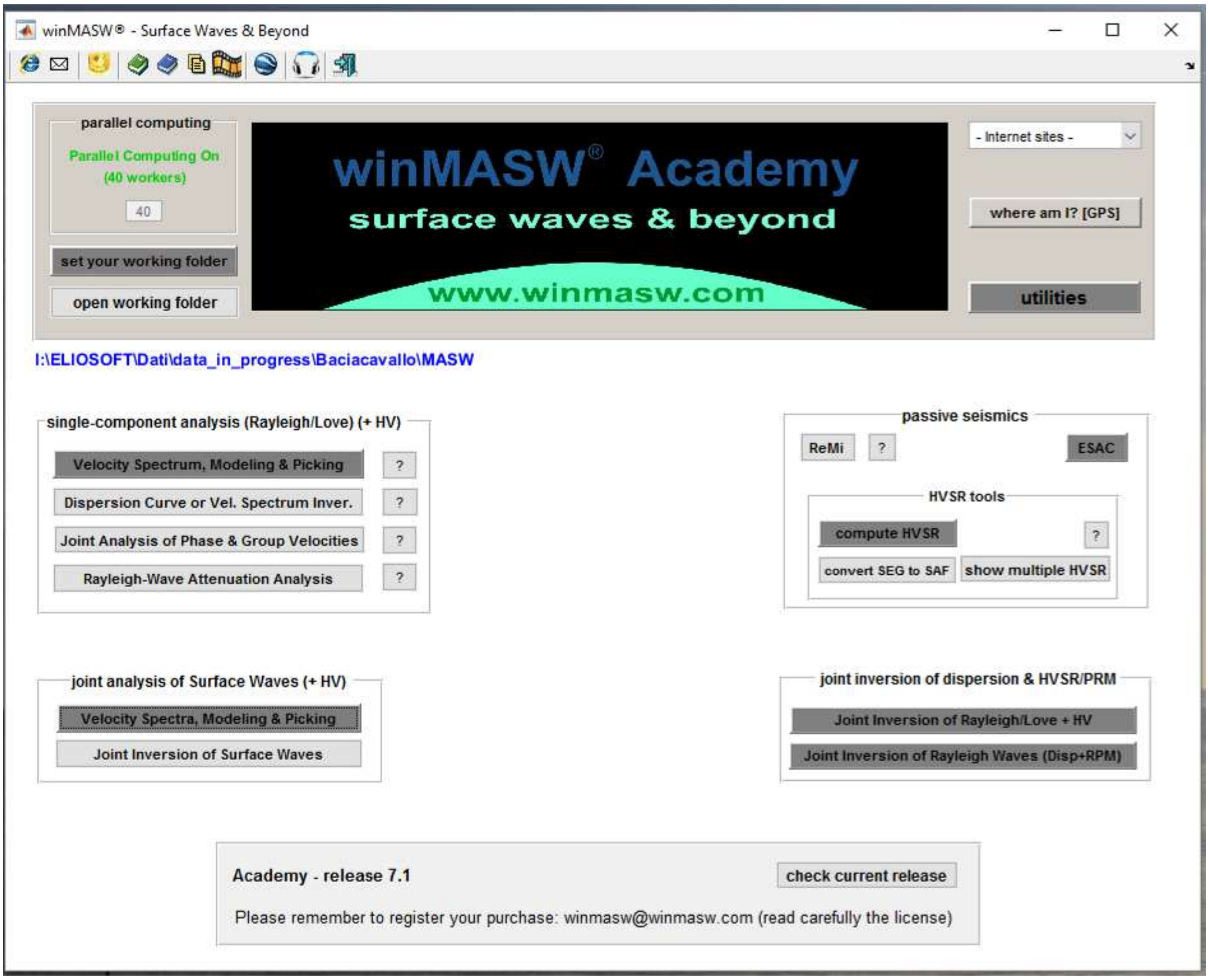

ELIOSOFT


ELIOSOFT
geophysical software and services
www.winmasw.com
everything for your seismic surveys
VSP
ELIOSOFT
8 and 10-kg sledgehammer and polyethylene plate
In the beginning...
using the plate to generate Love waves
... after some months of hammering
HS

When *winMASW®* is launched, together with the main panel, a black DOS window background appears, containing all information about analysis and warning/error messages.



<u>The very first thing to do</u> is the activation of the *Parallel Computing* (see upper right part of the main window). This will allow a full exploitation of multi-core CPUs thus reducing the computational times required by some operations (this is particularly important if you deal with the computation of synthetic seismograms and related procedures such as the full velocity spectrum inversion).



Please, notice that if you store your field datasets in a certain folder (e.g. “Desktop/Berlin”), the output folder will be automatically created within such a “working folder” (that you must set from the main or any other panel of *winMASW®*).

We suggest to download our *video tutorials* in the *winMASW/Documents/videos* folder (then accessible from any panel – icon).

Manuals are also accessible from any panel (icons – for the English & Italian version).

See *video tutorials* from **our YouTube channel** and in the winMASW® USB.

GPS data in our software applications (winMASW®, HoliSurface® & ELIOVSP®)

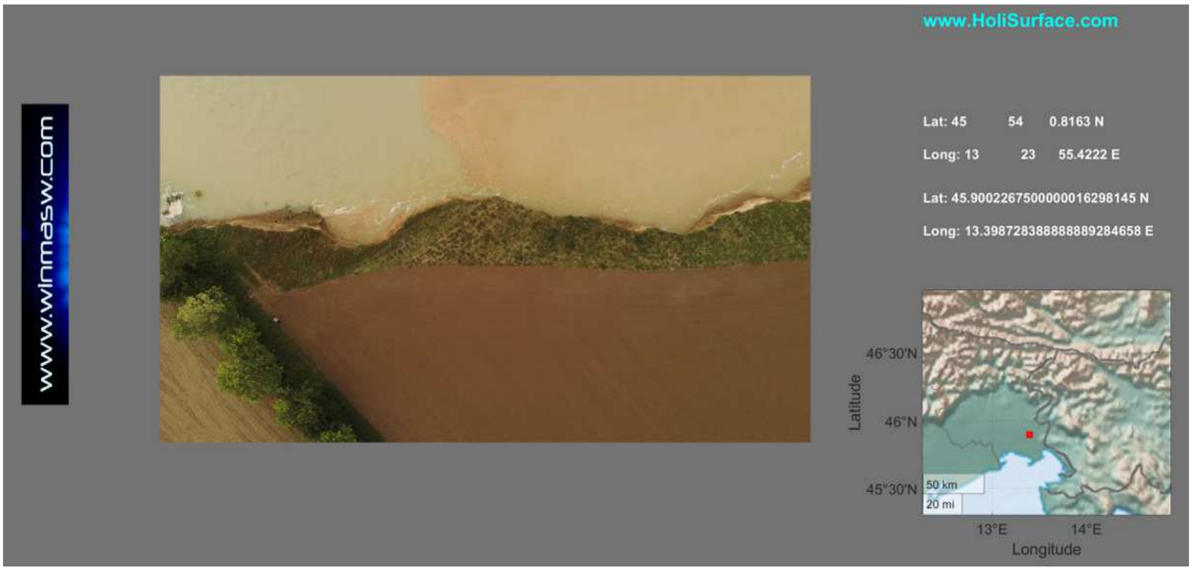
In most of the panels, it is possible to upload an image (to include in the report) and, in case such an image contains GPS information (several APPs of your mobile can do that [e.g. *MapCam* or *GPS Map Camera*] as well as all the Action Cameras [e.g. GoPro] and *drones*), **the GPS information (Latitude, Longitude, Altitude and number of satellites) will be reported and shown in the output report.**

See also the "managing multiple geo-referenced photos [exploration of large areas]" appendix.

Of course, it is possible to upload any photo you want to automatically insert in your report, even without the GPS information.

MapCam GPS Map Camera Action cameras

Drones



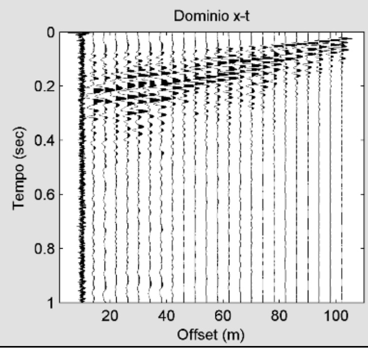
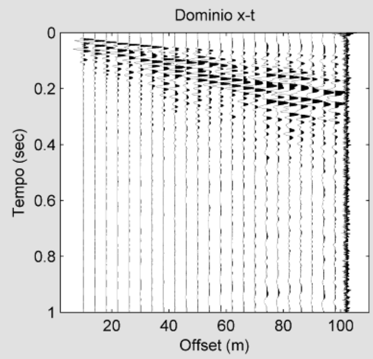
4.1 Single-component analysis: velocity spectra, picking, modelling (dispersion, refraction and HVSR)

MASW, *ESAC,* ReMi, ESAC & MFA *analyses (phase and group velocities)*

4.1.1 MASW Analysis

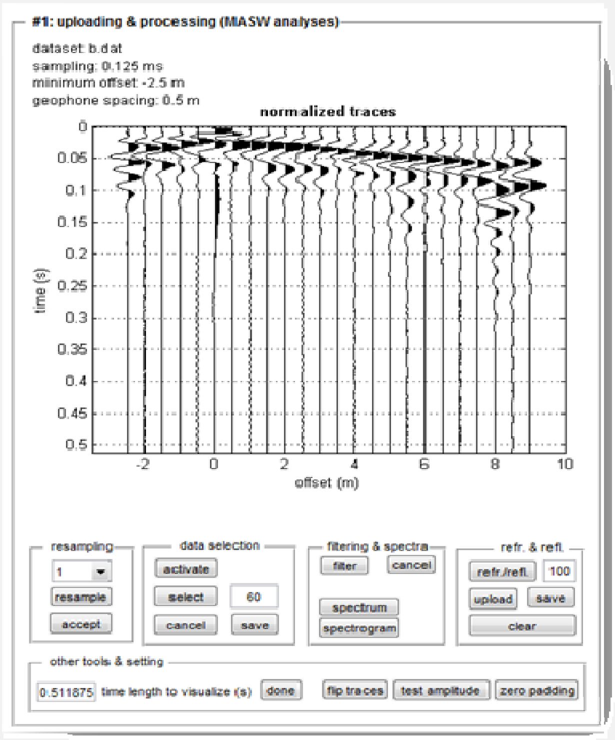
First upload the *common-shot gather*. Execute it clicking on the icon top left, allowing to open the needed file (see the box regarding the supported format). Due to frequent and possible common shots mistakes, the user always need to verify that the input data (min offset, distances between traces, and so on) are correct and if necessary, correct them.
According to the execution mode (order of the traces) it can be possible that the dataset be "inverted". In this case you only need to click on "rotate traces" (see box "Rotate traces") giving consequently an order to the data.
Once the data are uploaded the next step is the calculation of the Velocity Spectrum, through the relevant homonymous button. The user has to input velocity and max and min frequencies (in other words, the limits of the velocity spectrum) (see figure 1a)
The result will be similar to what you can see in figure 1b.
In the case you are not happy with the spectrum window (frequency-velocity interval) and you prefer to have a better vision of the area where the signal of interest is actually concentrated (the dispersion curve(s) related to surface-wave propagation), you can recalculate the velocity spectrum with new parameters, by clicking again on "phase velocity" (for MASW analyses) or "group velocity" (for MFA analyses).
Since the input data here also will be considered for the spectrum as shown in the results window (see figure 7a). We suggest to use such limits that can give a clear visualization without need to zoom in.

Button "flip traces"

	**Wrong lay out** An erroneous disposition of the channels can give following *common-shot gather* (arrival times decrease as the offset increases). Click on the button "flip traces" to obtain below lay out.
	**Right lay out** Right layout of traces (offset increasing rightwards)

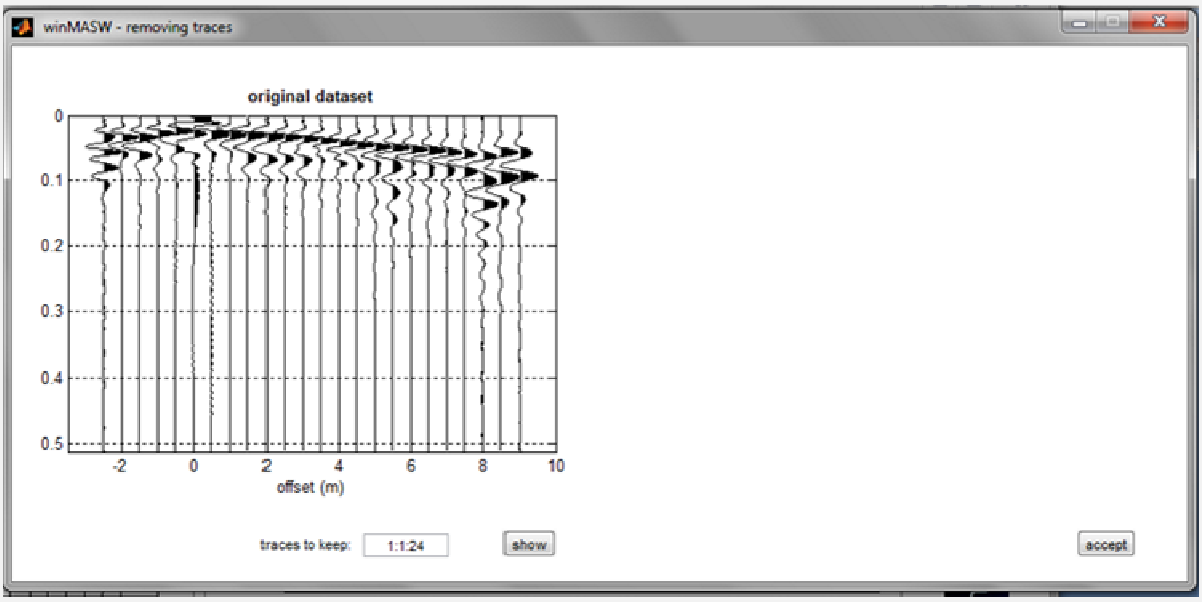
Tool for removing traces from the uploaded dataset (*Academy* version)

Upload a dataset:



In this example the shot is "internal" to the geophone array (minimum offset -2.5)

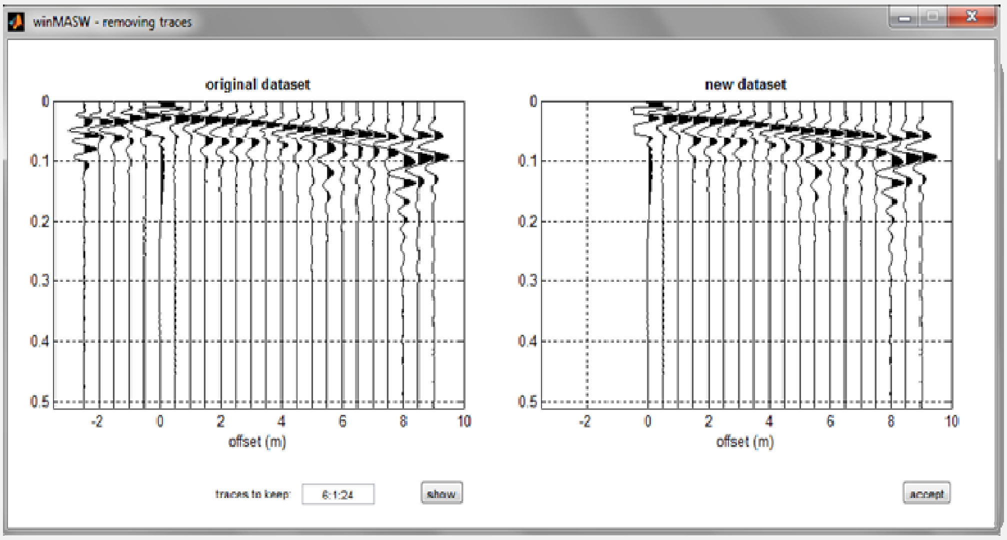
By clicking on the ✂ icon in the *toolbar* you will get the following panel:



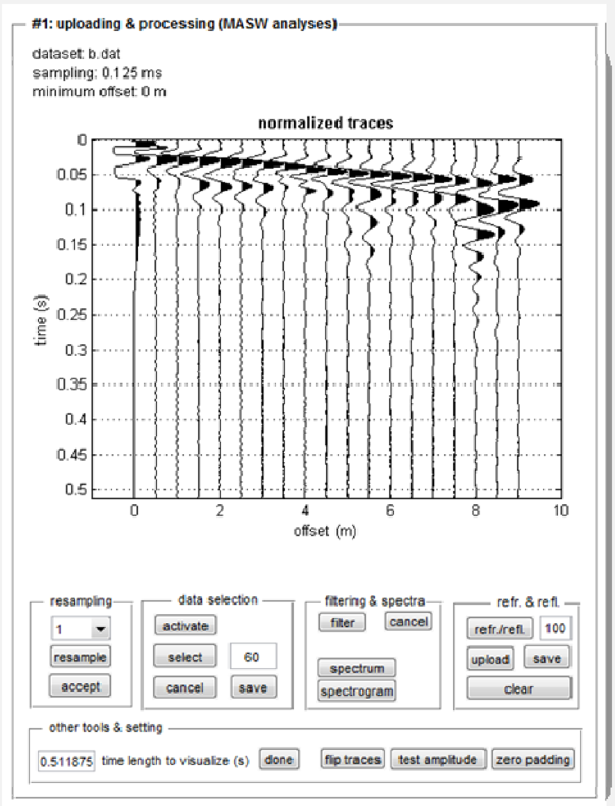
In the "traces to keep" box the user must insert the traces to keep by adopting the following syntax:

first trace to keep : step : last trace to keep

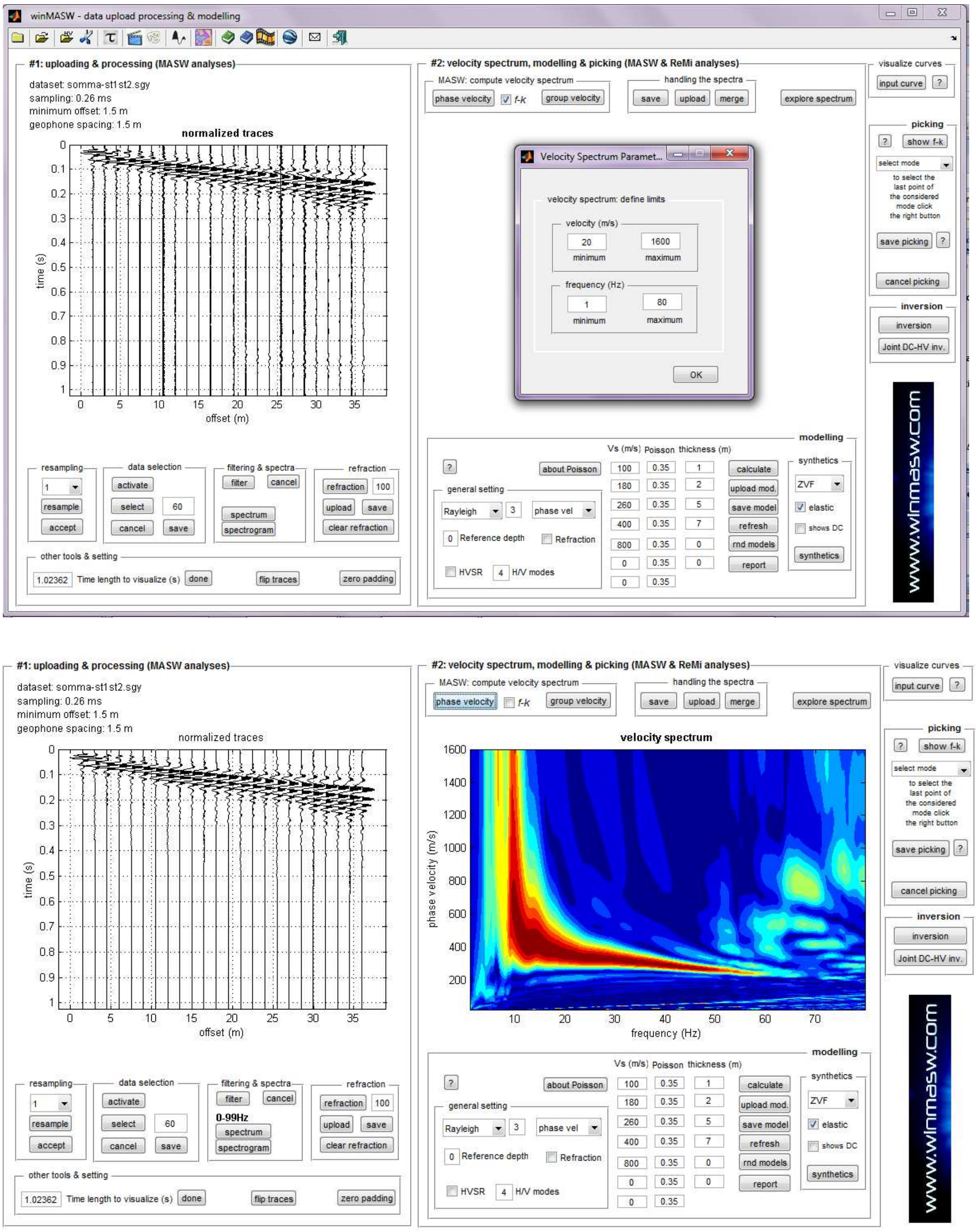
In the following example we keep all the traces from 6 to 24 (all of them, since the step is 1) (please notice that by writing for instance “6:2:14” we would keep the following traces: 6 8 10 12 and 14)



We first click on “show” to see whether the parameters we inserted are the right ones and once we are satisfied with the (new) dataset we just click “accept”. This way we get back to the main panel:



Now the user can continue with the analysis (it is not necessary to save the new dataset in a new file, but it can be done using the “save” button in the “data selection” group.



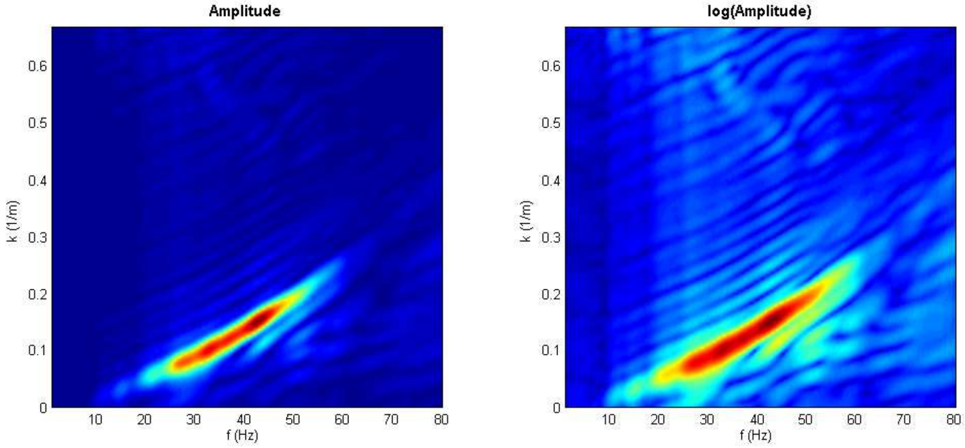
a)

b)

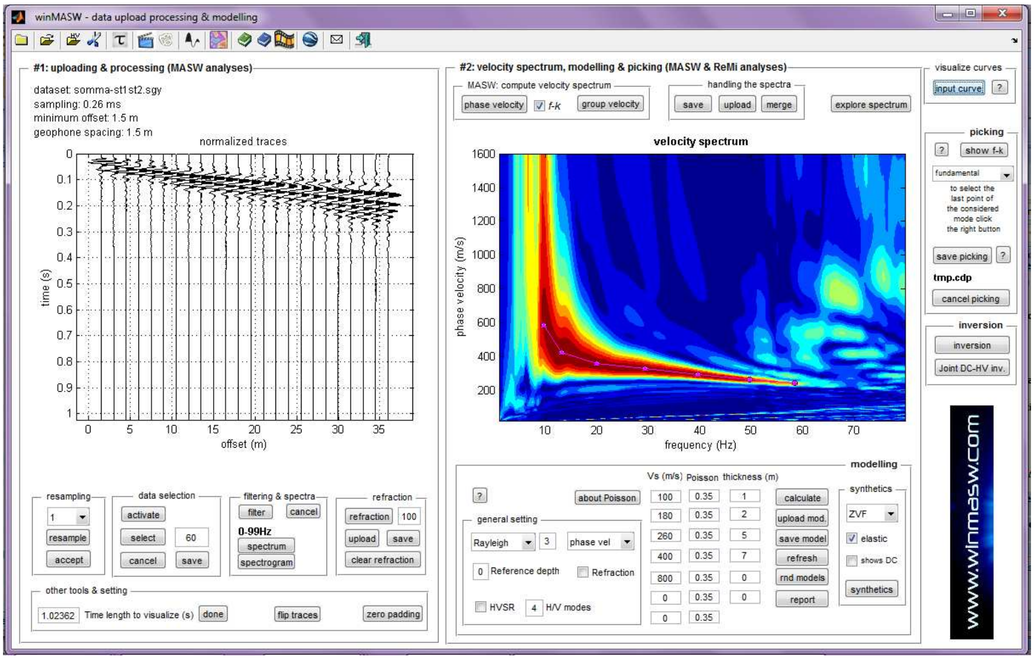
Figure 1. Calculation of the velocity Spectrum. The limits of the window need to be entered: frequencies and velocities (min and max).

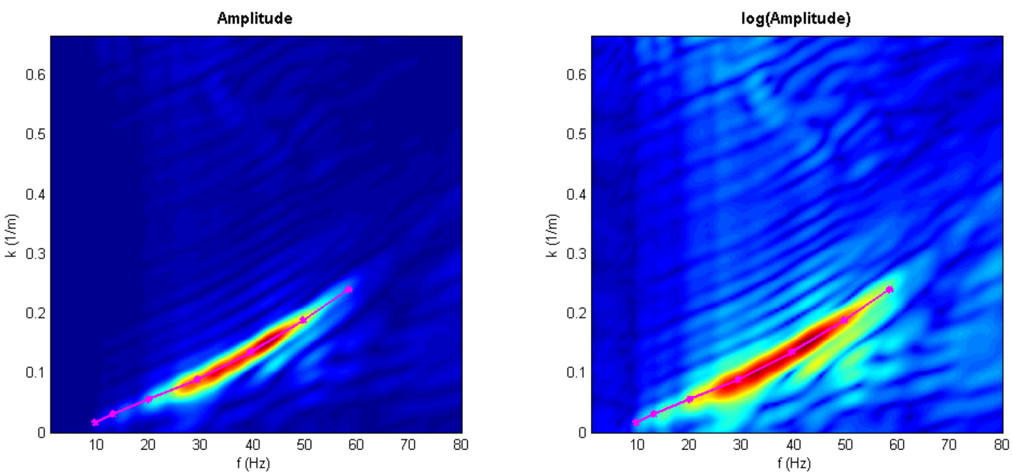
f-k spectrum

In case the f-k option is activated the f-k spectrum will also be shown:



So in case of picking/modelling, you can see the curve in both the domains (*f-k* and f-v):





Important: just *model*, do not invert!

Techniques based on the analysis of surface waves propagation are more and more common, but some aspects related to their generation and propagation impose to proceed with caution, as it means determination of velocity spectra and picking of the dispersion curve we want to invert.

This topic is considered for instance in the following papers:

Dal Moro G. and Ferigo F., 2011, *Joint Inversion of Rayleigh and Love Wave Dispersion Curves for Near-Surface Studies: Criteria and Improvements*, *J. Appl. Geophysics, 75, 573-589*

Dal Moro G., 2011, *Some Aspects about Surface Wave and HVSR Analyses: a Short Overview and a Case Study*, BGTA (Bollettino di Geofisica Teorica e Applicata), *invited paper*, 52, 241-259

Please also regularly visit the www.winmasw.com site (section "publications").

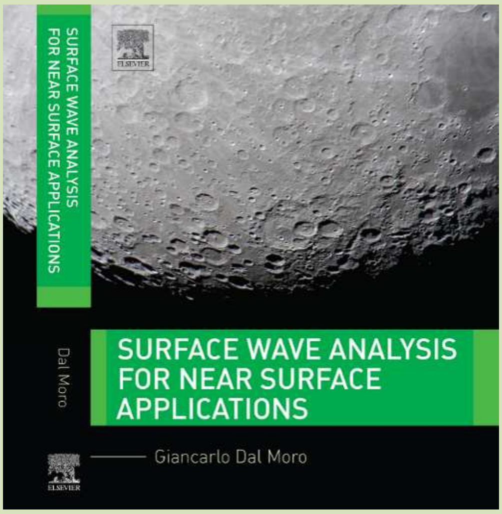
From a practical point of view please consider the following:

1. It is absolutely untrue that the maximum energy related to the surface waves is necessarily associated to the propagation of the fundamental mode: many modes can coexist in a same dataset

2. It is absolutely untrue that higher modes only appear at high frequencies. They can instead exist at low frequencies as well and several "mode jumps" can take place.

As a consequence, it is often advisable to replace the picking->inversion procedure with the "direct modelling" (see relevant section): searching the more logic coherence between energy distribution in the velocity spectrum (so far the only objective data) and theory dispersion curves from a model which the user tests and modifies, starting from prior stratigraphic knowledge and data (through the direct modelling procedures).

Recommended book:



Seismic data format

winMASW can currently read the following formats:

1. segy format (.segy or.sgy). This is a standard format suggested by the *Society of Exploration Geophysicists* (SEG).

2. seg2 (.dat or .sg2). This is a well known “common gathering” format. Many of the current available seismometers use this data writing format (typically in the integer 32 bits or Floating Point 32 bits formats). From the 3.0 version the software can automatically recognize the format but, in order to correct possible mistakes of the seismometer, the user is allowed to “force” the format

3. SU format (seismic Unix). Traditional format (although not frequently used)

4. ORG format (.org): traditionally used by many OYO seismographs (integer 32 bits traditional format)

5. ASCII format (.txt or .asc formats). Some devices and software use the ASCII format (that can be read with any text editor) where the columns represent the different traces (in other words this is a *m* x *n* matrix, being *m* the number of data and *n* the number of traces).
Please, notice that the format is
first line: *dt* (sampling rate in seconds),
second line: *offsets* (in meters) - <u>don’t have to be equally spaced</u>

Example (*dt* 1millisecond, minimum offset 6m):

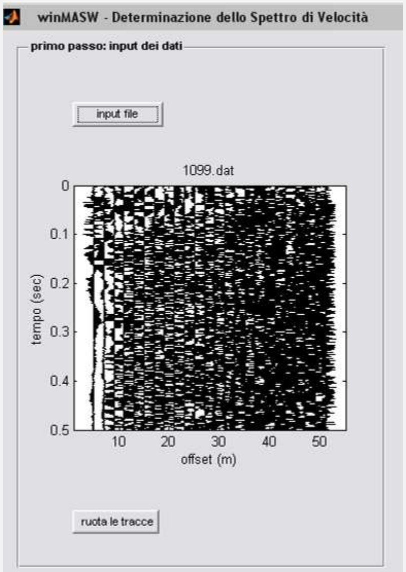
```
 0.001
6   10   14   18   22   26   30   34   48   52
 2.89   -40.07   125.33   27.35   76.92   -29.89   26.04   -55.37   117.62   -66.34
92.11   -86.07   -16.67   135.35   62.92   93.11   119.04   38.63   -124.38   57.66
90.11   93.93   130.33   161.35   94.92   170.11   111.04   127.63   -24.38   35.66
 2.11   -151.07   99.33   8.35   178.92   -8.89   72.04   -93.37   22.62   -21.34
-36.89   56.93   -77.67   121.35   33.92   171.11   14.04   63.63   -33.38   50.66
10.11   15.93   126.33   43.35   159.92   43.11   127.04   -0.37   95.62   -37.34
51.11   -118.07   9.33   43.35   157.92   44.11   -29.96   -116.37   13.62   1.66
91.11   57.93   100.33   228.35   78.92   214.11   146.04   139.63   28.62   66.66
53.11   -91.07   43.33   -30.65   139.92   -28.89   41.04   -56.37   75.62   -59.34
 4.11   10.93   -94.67   124.35   -54.08   190.11   -3.96   -22.37   -95.38   74.66
42.11   -1.07   11.33   -24.65   1.92   37.11   117.04   -71.37   92.62   -40.34
…
```

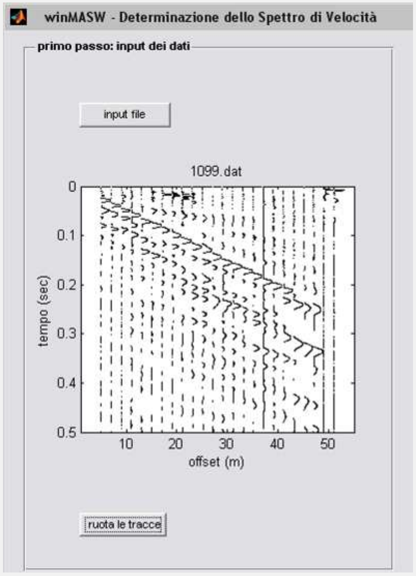
6. *Matlab* format (.mat). Actually very similar to the former one, but written according to the Matlab protocol. It deals with a simple matrix and the user has to input relevant data to the sampling interval, the min offset and the geophone distance.

7. SAC format (big endian): a common format for seismological data (used for 1-channel dataset).

Numerical data format

When uploading data it is very important the format be correct (chose from a scroll menu like "*Floating-point 32 bits*", "*Integer 16 bits*" etc.).
If the format is not correct the visualization will be different from what you see in figure 1 for instance, where the seismic trace correctly displays according to the so called "wiggle" modus

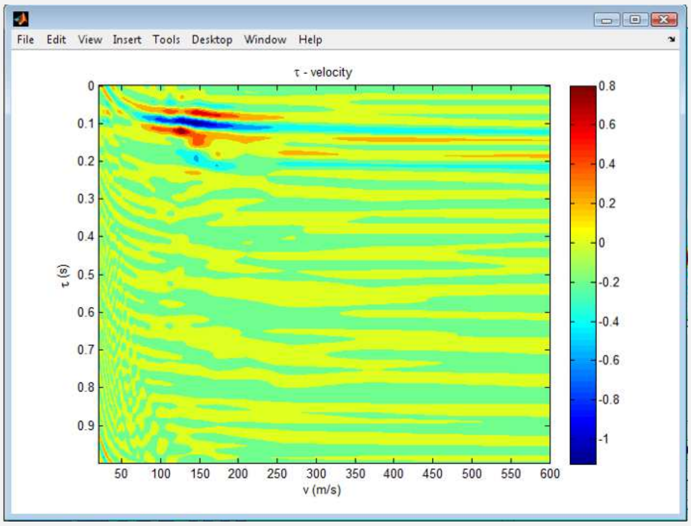




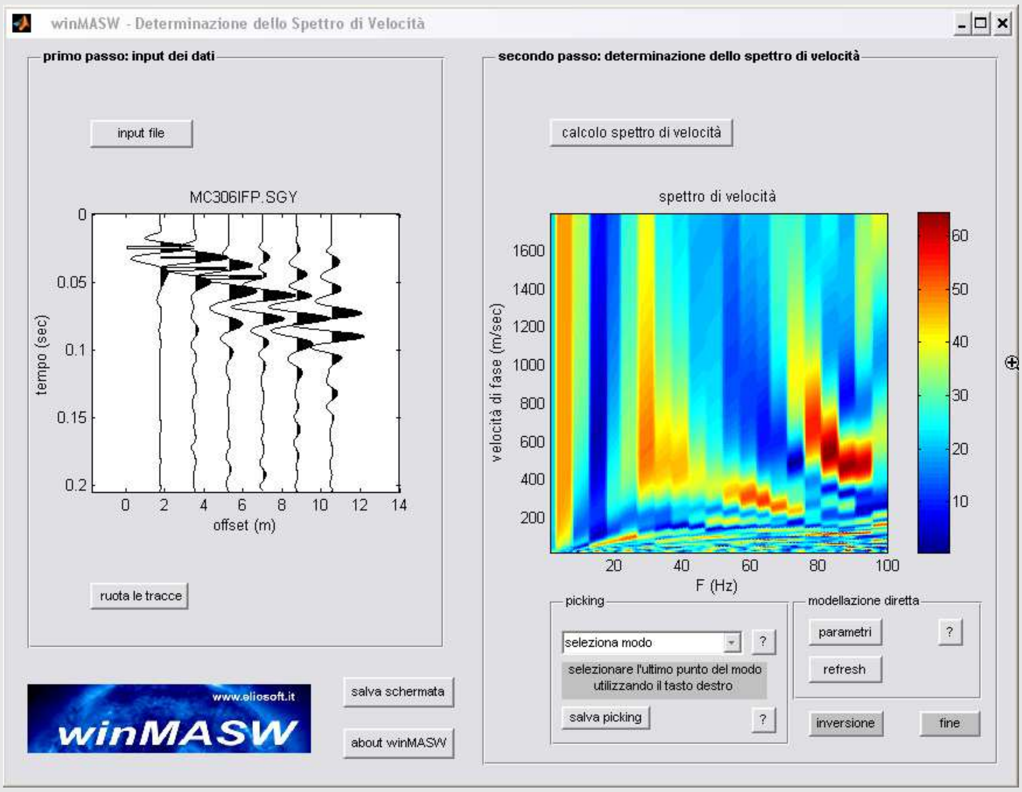
Herewith two more examples of the evidently wrong reading format are provided.
winMASW automatically identifies the data format for a .seg2.
By the way, there's always the possibility to force the reading according to different formats, should the seismograph mistake on writing

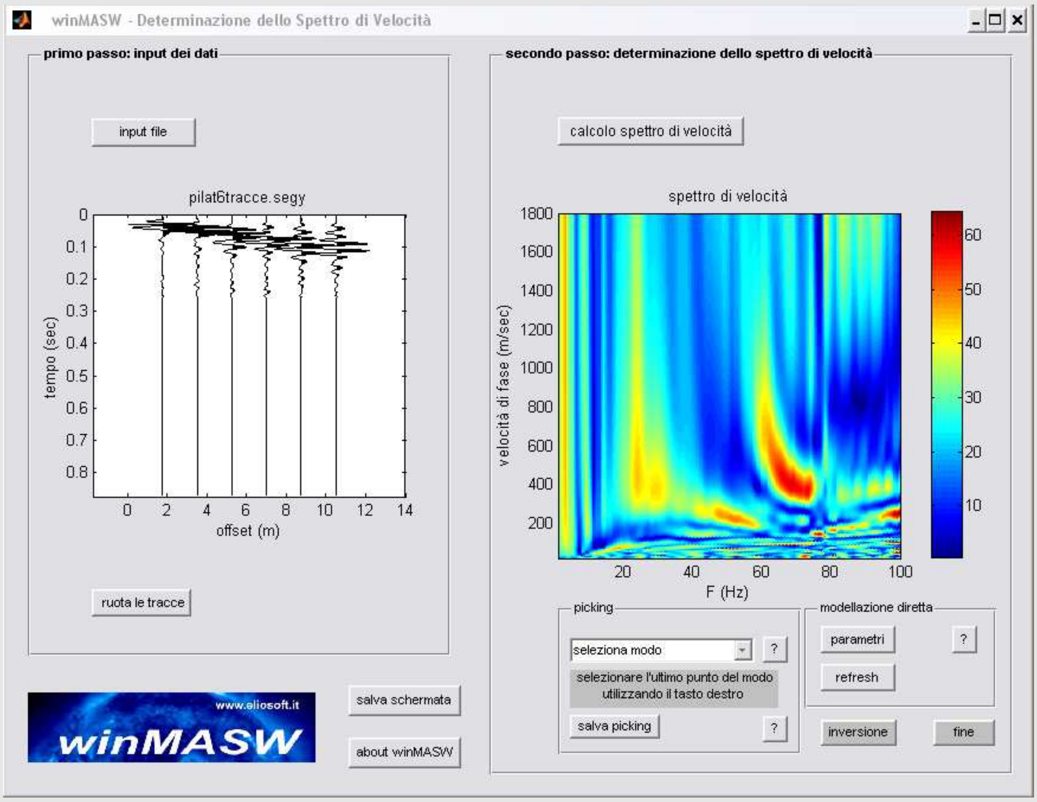
The τ- velocity domain

When calculating the velocity spectrum the data can also be represented in the domain τ-velocity (just activate the option *"Tau-v"* on the toolbar). The parameter τ is the intercepted time on the time axis and the operation is made by linear Radon transform.
For very-expert users the representation of data in this domain can be useful for more considerations, even for teaching purposes. For more details we refer back to future versions of *winMASW*.



Possible effects of “short” datasets

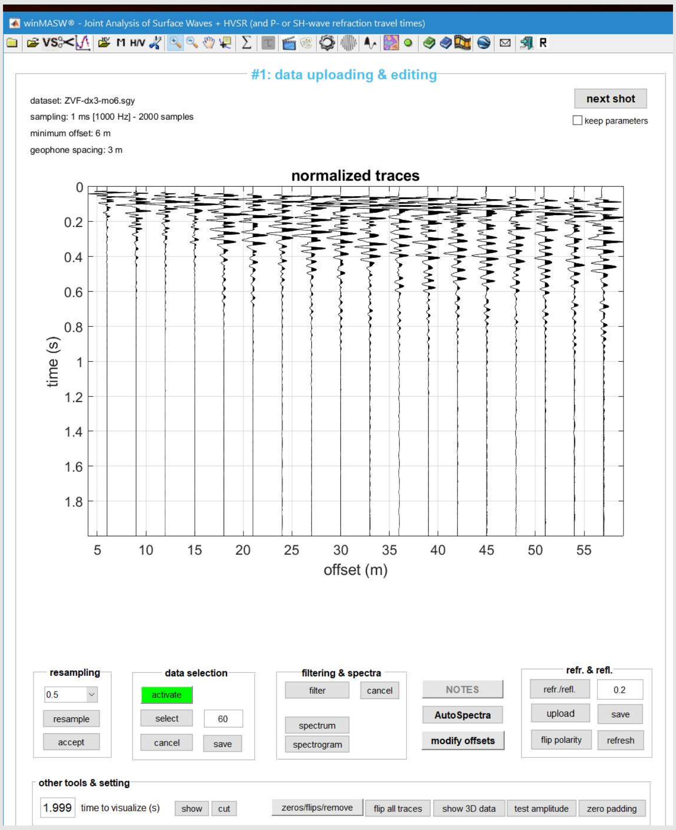




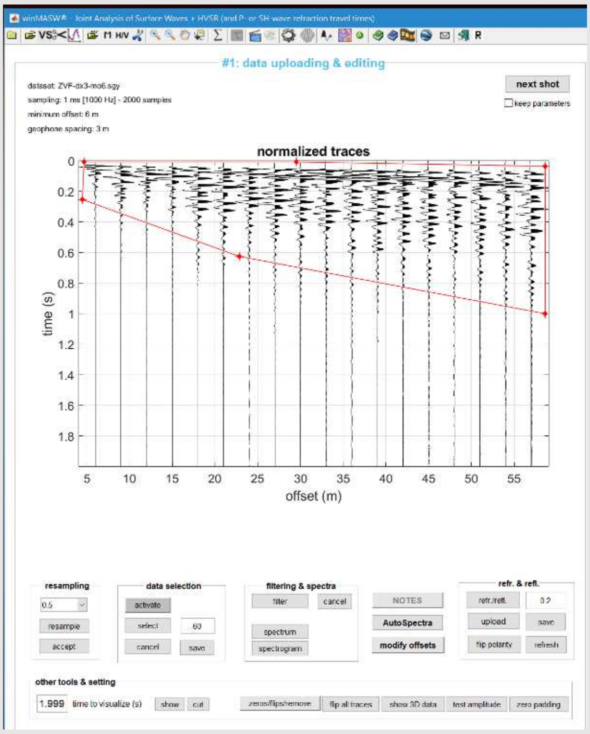
Problems related to a short acquisition time: in the figure the dataset it is limited to the first 0,2 seconds, while the data below has been “zero padded” (zeros were added to the traces) in order to better determine the spectrum.
In brief: gathering the whole trend of surface waves is not enough. Numerical factors impose long enough datasets.

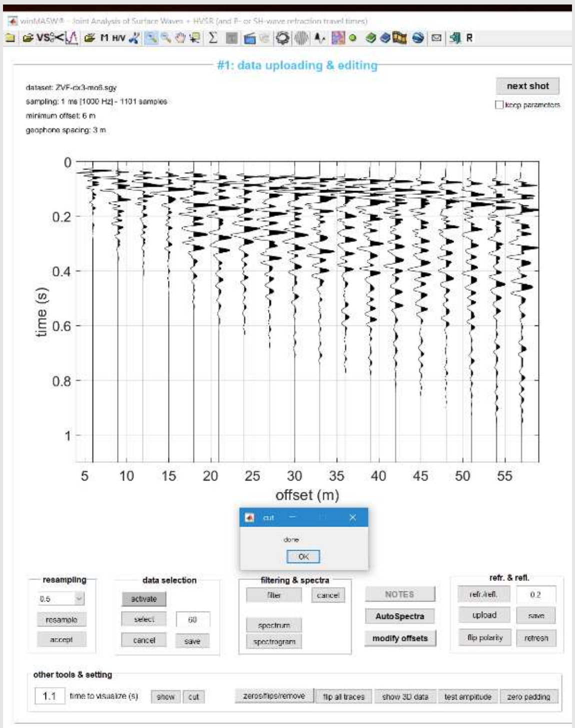
"select data" tools

This section allows you to clean the seismic traces in the time-offset domain.
Consider the buttons in the **"data selection" group**.



1) Click on the "**activate**" button and a polygon will appear. Moving the angles you'll select a specific area.
2) One you are satisfied with your polygon, click the "**select**" button so to cut the data outside the chosen polygon.





The number at the right side of the “select” button is the number of samples of the ramp considered to cut the data (this is done so to apply a soft transition between the data inside and outside the polygon).

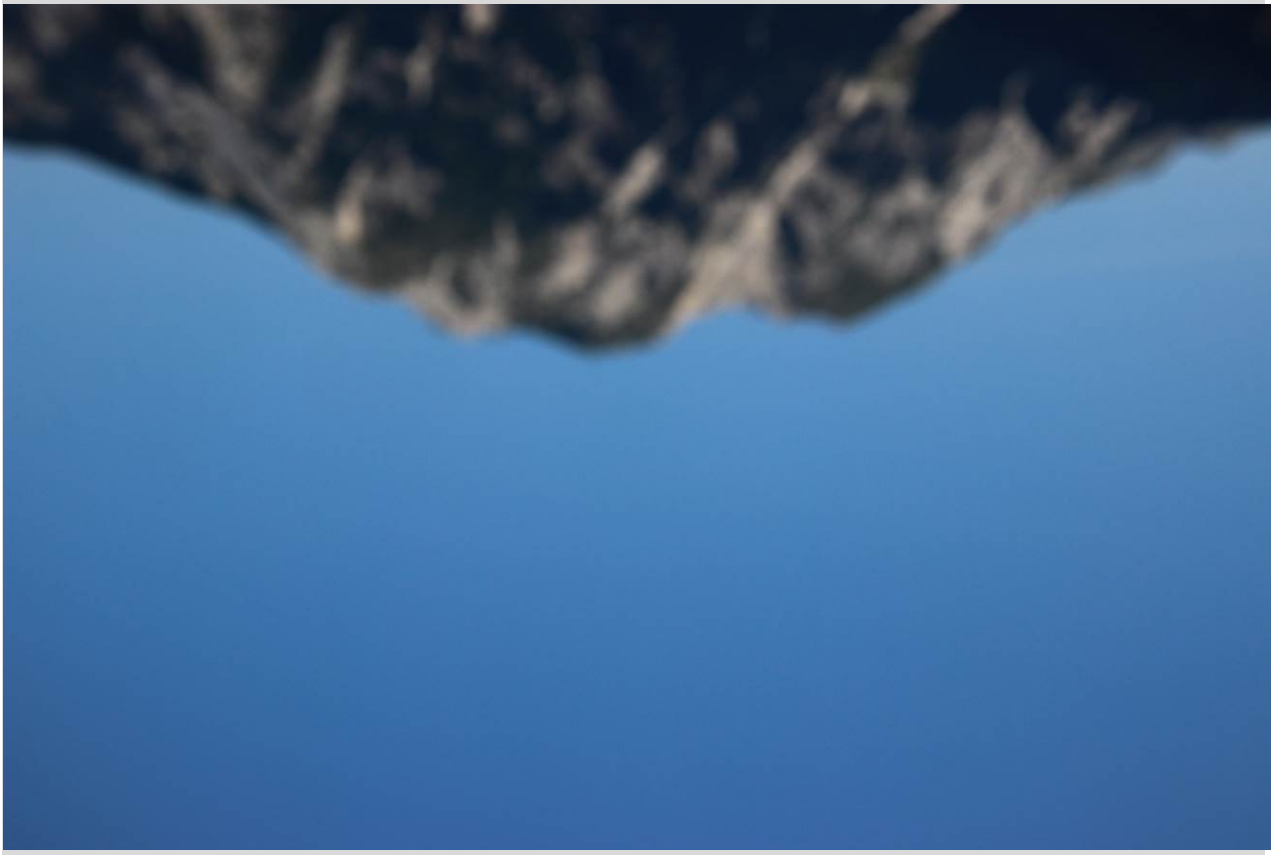
Once you clean/select the data you can then also remove the “surplus data” with the “cut” button, in the “other tools & setting” group: in the shown dataset, the we recorded 2 seconds but eventually cut the data to 1.1 seconds.

To proceed with the analysis (velocity spectra computation and forward modelling), the new dataset does not need to be saved but you can do it using the “save” button.

The same tools are available also in the panels for the analysis of multi-component data and in the panel for the joint analysis of phase and group velocities.

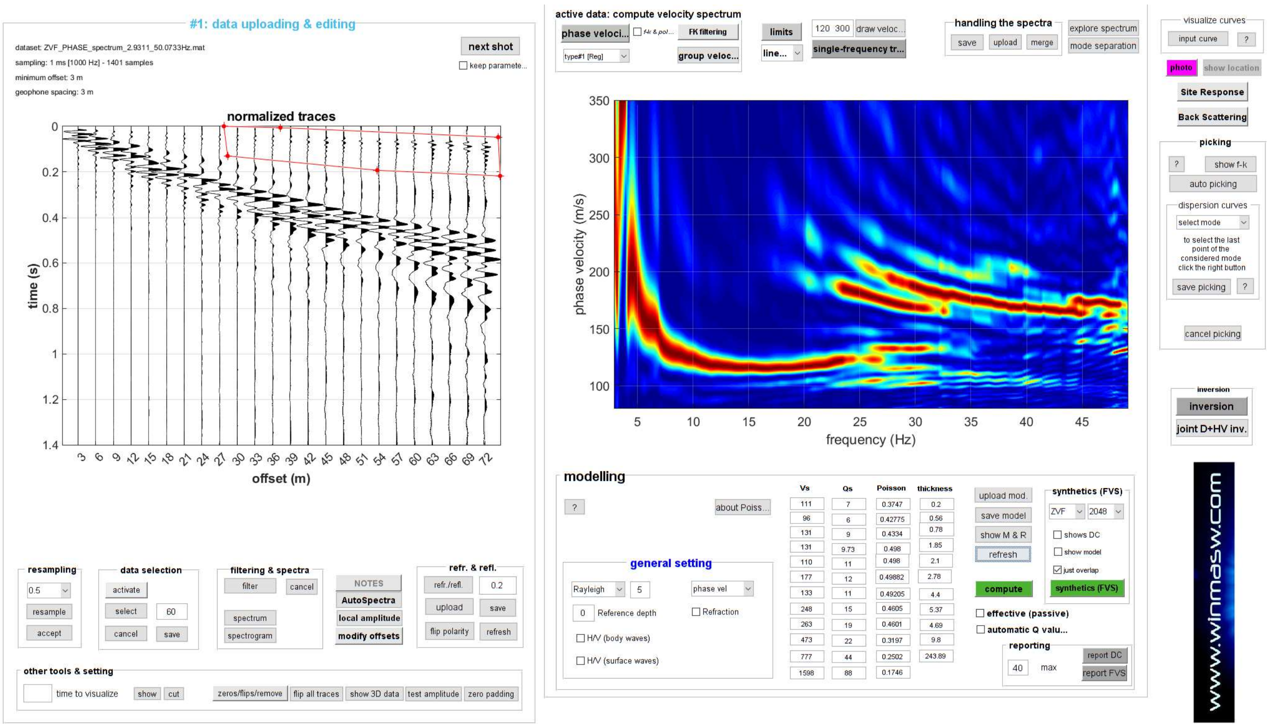
Please, see the video tutorials from our **youtube** channel.

JOINT ANALYSIS OF SEISMIC DATA

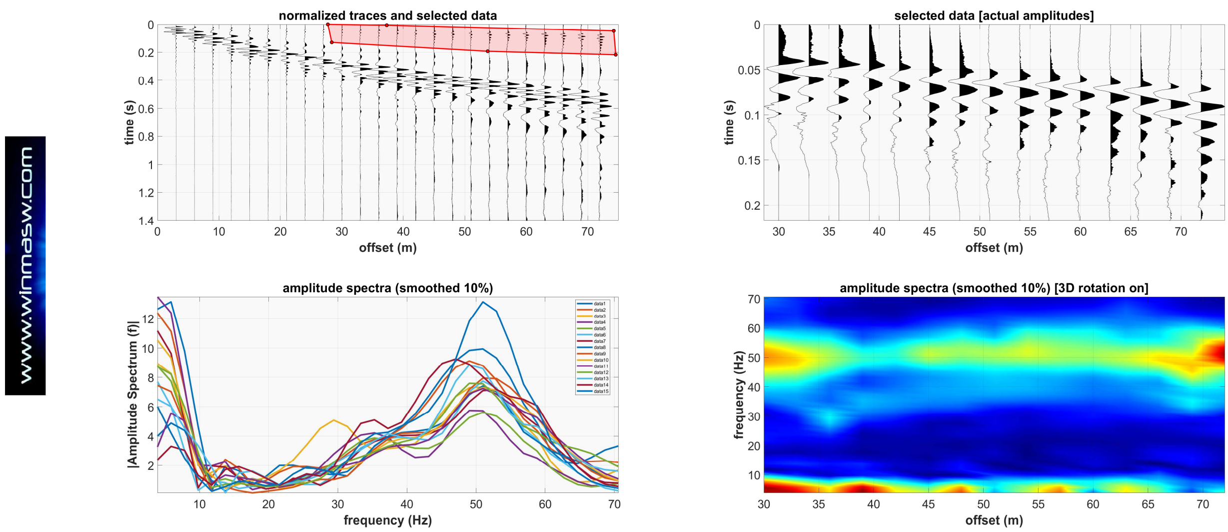


4.1.2 Local amplitude: a new tool for the computation of the amplitude spectra in a specified "data region" (winMASW® Academy)

The "local amplitude" button allows you to access to a tool aimed at revealing the spectral content of specific portions of the uploaded dataset. You first need to select the data region you are interested in using the "activate" button in the "data selection" group (see snapshot here below).

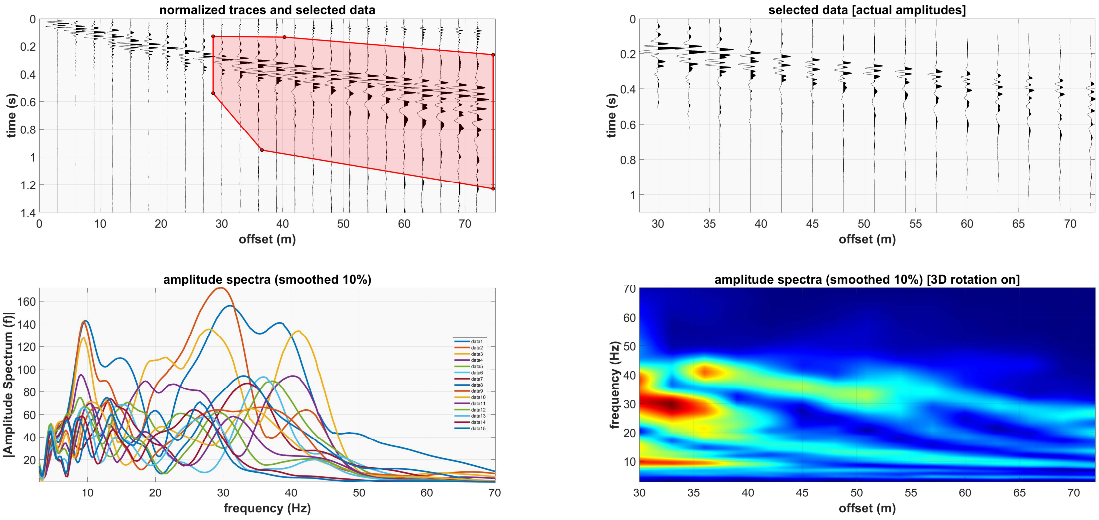


Once you have defined the region you are interested in, you simply need to click the "local amplitude" button. In the example considered in the snapshot below (obtained from the dataset shown above), we are considering the vertical (Z) component. The selected data clearly refer to the P-wave refraction (first arrivals) and the frequency content is clearly relatively high (this dataset is widely presented and commented in the Elsevier book "Surface wave analysis for near surface applications" – Dal Moro 2014).



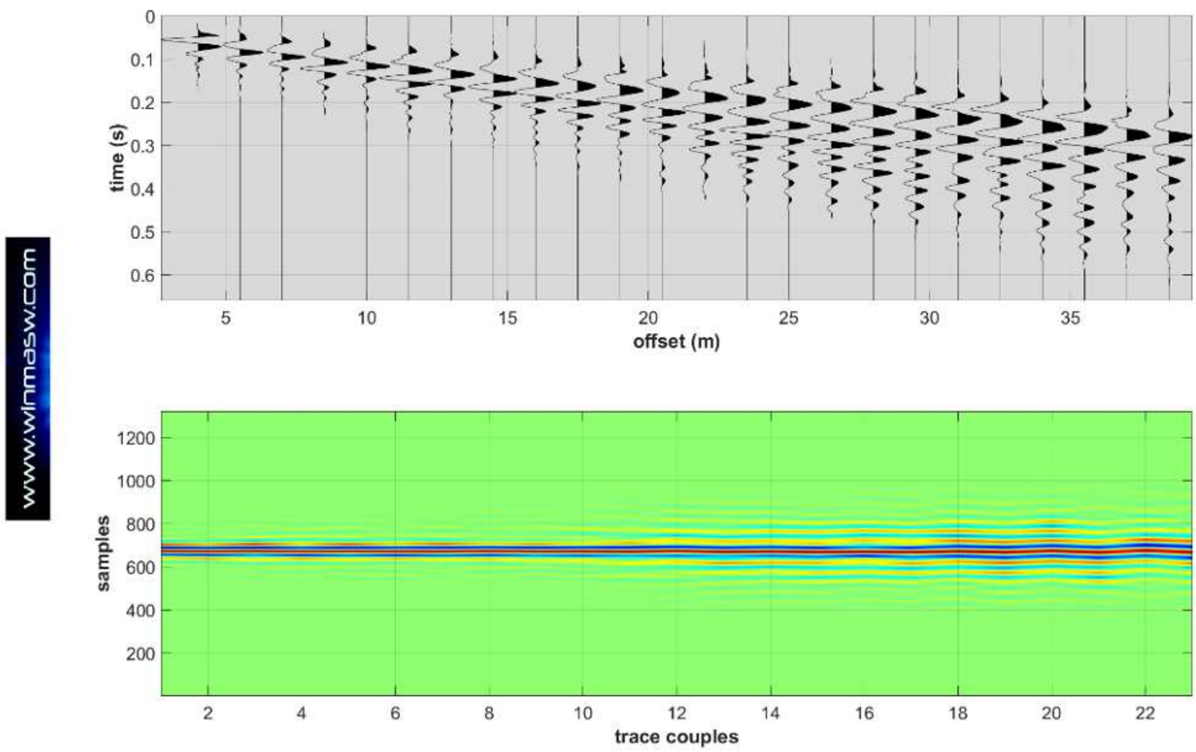
We can compare the frequency range obtained considering the P-wave refraction with the frequency content of Rayleigh waves (which, being slower, arrive later).

The following snapshot does that: the very different spectral content and the way amplitude decreases with the offsets are apparent (compare with the minor amplitude decrease that characterize the P-wave refracted waves – previous snapshot).



4.1.3 Trace polarity check (winMASW® Academy)

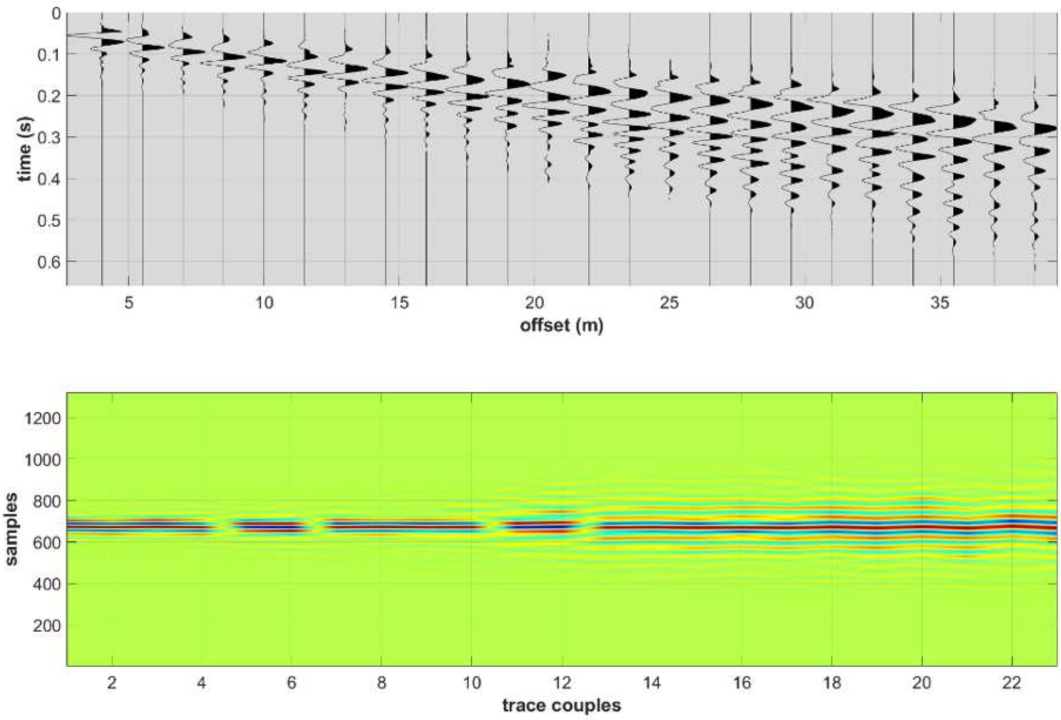
The quality of the phase velocity spectra computed from multi-offset data clearly depends on the quality and accuracy of the recorded seismic traces.
In some cases (poorly-designed *acquisition systems*), traces can have inverted polarities (this can occur because the geophones are not homogenous or because of problems in the cable/seismograph system – see the concept of "*acquisition system*" as described in the Springer 2020 book – "*Efficient Joint Analysis of Surface Waves and Introduction to Vibration Analysis: Beyond the Clichés*").
In that case the phase-velocity spectrum we obtain is clearly poorly/badly defined. The software winMASW® Academy allows you to quickly verify the polarity. After you upload your field data, you can clean a bit the data (as usual) and then compute the phase-velocity spectrum/a. When you click the "phase velocity" button (aimed at computed the phase-velocity spectra) a dialog box will ask you if you want also compute the correlations among adjacent traces (this is the way you can verify whether a polarity issue affects your dataset)
The image below is what you get in case you decide to compute such correlations (i.e. in case you positively answer to such a question).
In this case there is no polarity issue as demonstrated by **the continuity of the correlations** shown in the lower panel.



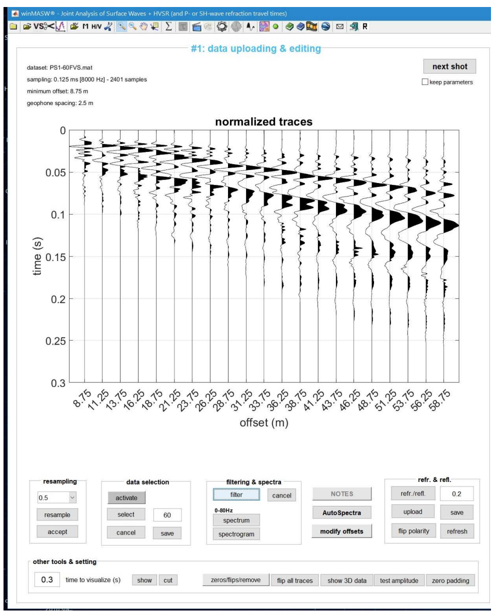
On the other side, due to some problem with the *acquisition system*, polarities can be erroneous. What do the correlations between adjacent traces look like in case the polarities of some traces are reversed?

Example of dataset where two traces (#6 and #12) have reversed polarity (carefully examine the image below).

This is actually the same dataset shown in the previous figure after we intentionally inverted the polarity of the trace #6 and #12. Once we compute the correlation (lower panel) we clearly realize the presence of a few "discontinuities" due to the erroneous polarities: we have four "holes", due to the four correlations 5-6, 6-7, 11-12 and 12-13.



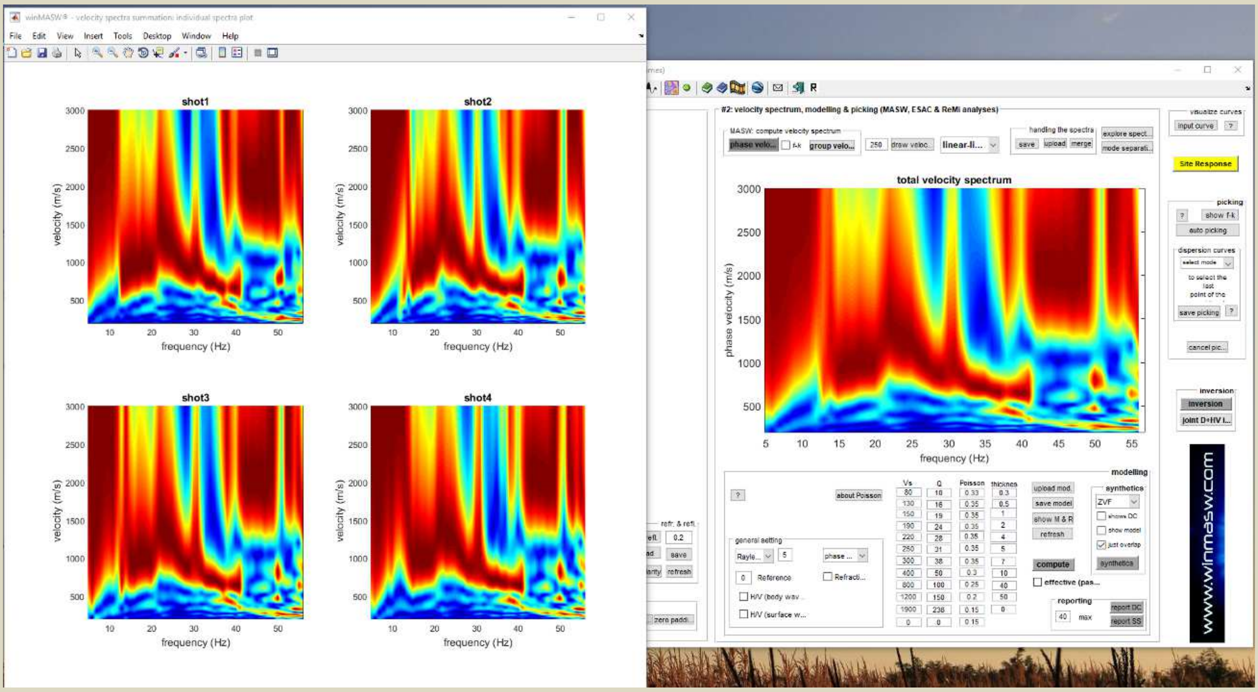
Remember that, in case you realize that your data suffer for this kind of issues, you can fix the problem with the **"zeros/flips/remove" tool** available among the several editing tools (see image below).



Average phase-velocity spectrum

Once you compute and save a series of velocity spectra (for instance from a series of reverse and direct shots) you can upload *all* the saved spectra with the "upload" button (in the "handling the spectra" group) and create the average velocity spectrum (you can select/upload multiple spectra by simply holding the "Ctrl" button and selecting all the spectra you want).

From a scientific point of view, the actual usefulness of this operation is quite questionable but since somebody thinks this can be "useful"...

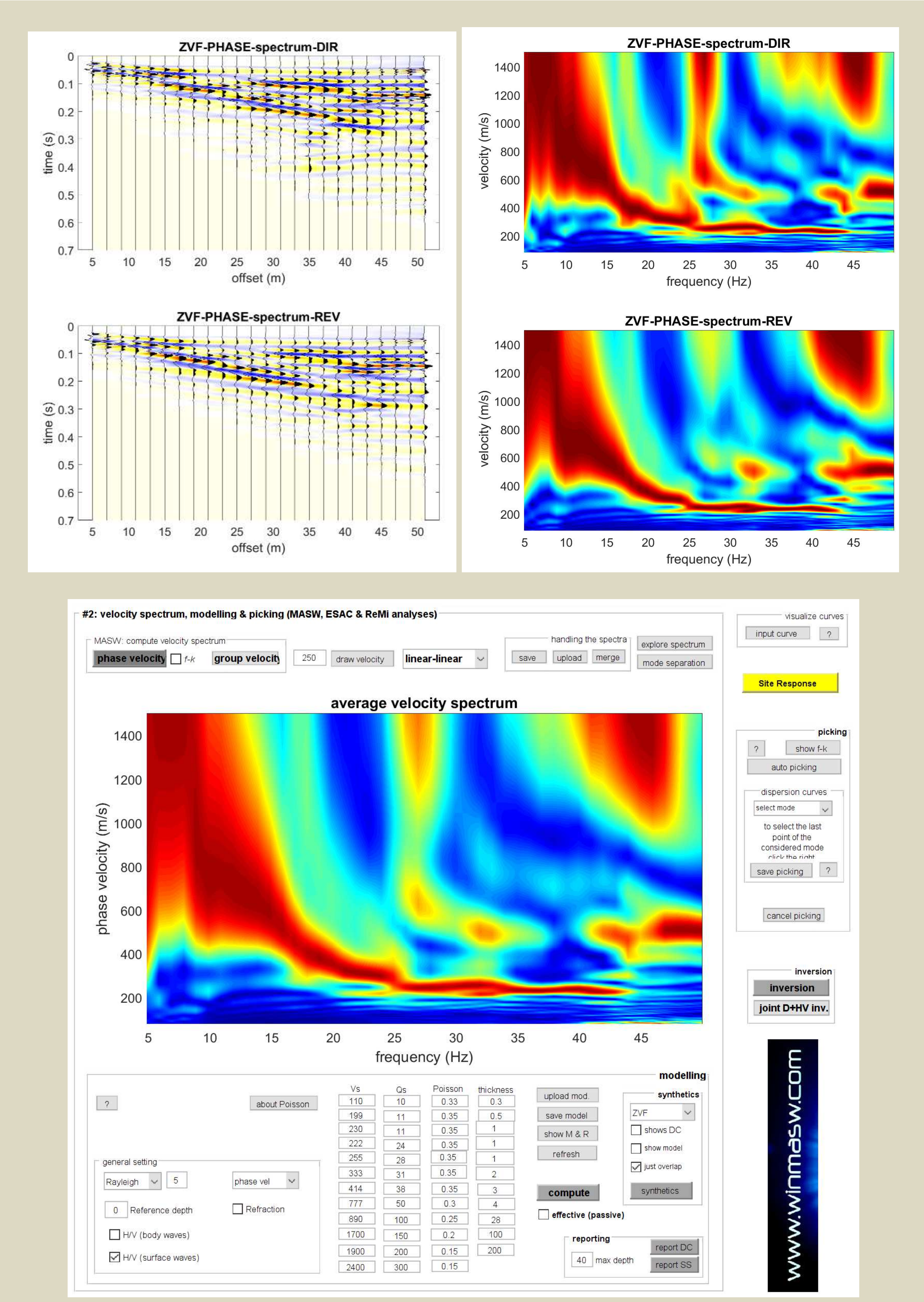


In the *Academy* version, while the software computes the average spectrum, a series of plots are automatically shown and saved (in the working folder)::

1) the traces of each individual dataset (IndividualTraces.png);

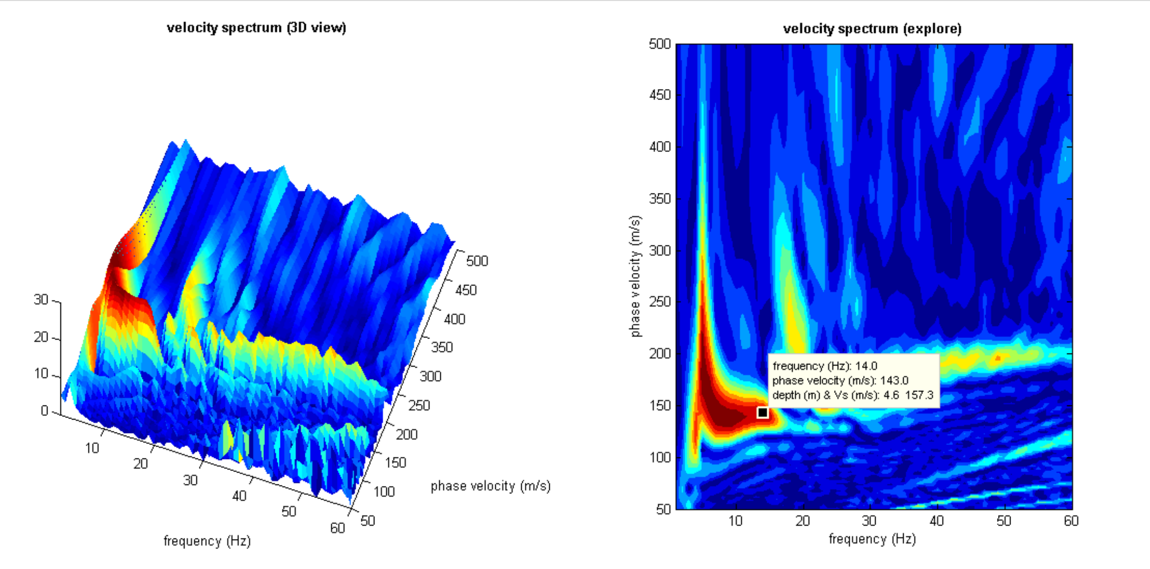
2) their velocity spectra (IndividualSpectra.png)

3) the *snapshot* of the average spectrum (AverageSpectrum.png) (see following images).


ZVF-PHASE-spectrum-DIR
time (s)
offset (m)
velocity (m/s)
frequency (Hz)
ZVF-PHASE-spectrum-REV
#2: velocity spectrum, modelling & picking (MASW, ESAC & ReMi analyses)
MASW: compute velocity spectrum
phase velocity
f-k
group velocity
250
draw velocity
linear-linear
handling the spectra
save
upload
merge
explore spectrum
mode separation
visualize curves
input curve
?
Site Response
average velocity spectrum
phase velocity (m/s)
picking
show f-k
auto picking
dispersion curves
select mode
to select the last point of the considered mode
save picking
cancel picking
inversion
joint D+HV inv.
modelling
about Poisson
Vs
Qs
Poisson
thickness
upload mod.
save model
show M & R
refresh
compute
synthetics
ZVF
shows DC
show model
just overlap
effective (passive)
general setting
Rayleigh
5
phase vel
0
Reference depth
Refraction
H/V (body waves)
H/V (surface waves)
reporting
40
max depth
report DC
report SS
www.winmasw.com

Exploring the phase-velocity spectrum

The button "*explore spectrum*" allows to visualize the velocity spectrum in 3D (on the left) also having (on the right) approximate V_S values based on the "*Steady State Approximation*". The goodness of such approximation is related to the specific site: in case you have strong V_S variations (especially if already for shallow depths) the values given by such approximation are not reliable. In other words the approximation is reliable only when the V_S gradient does not vary abruptly.

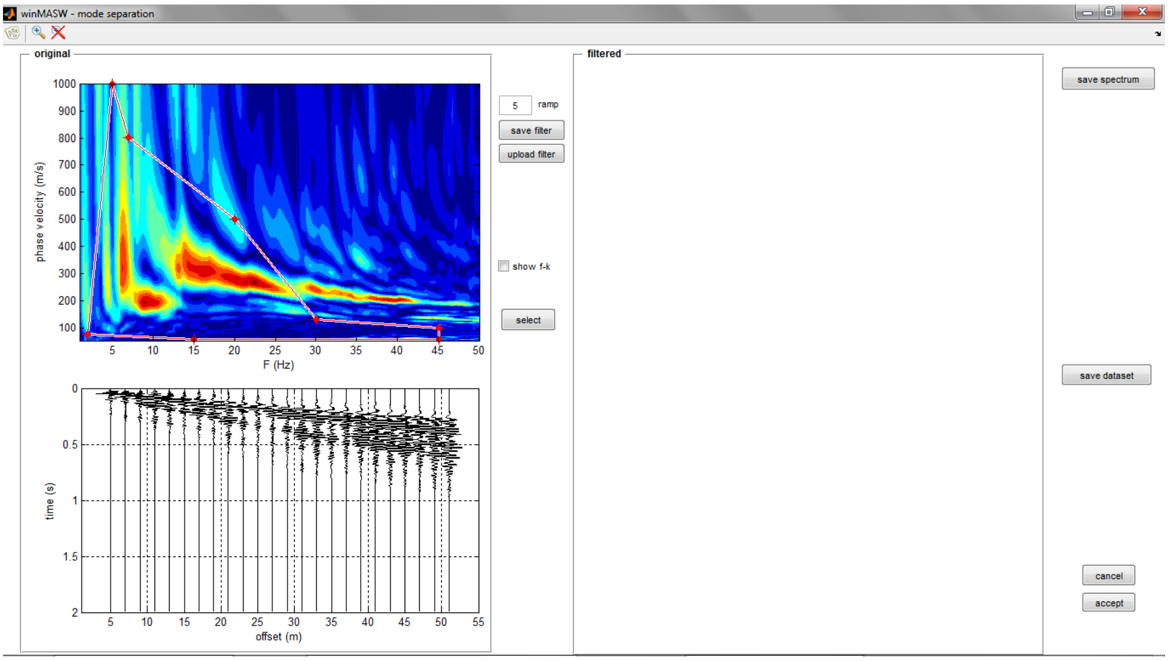


Mode identification and separation

Such a procedure can be applied to active data used to define the phase-velocity spectra.

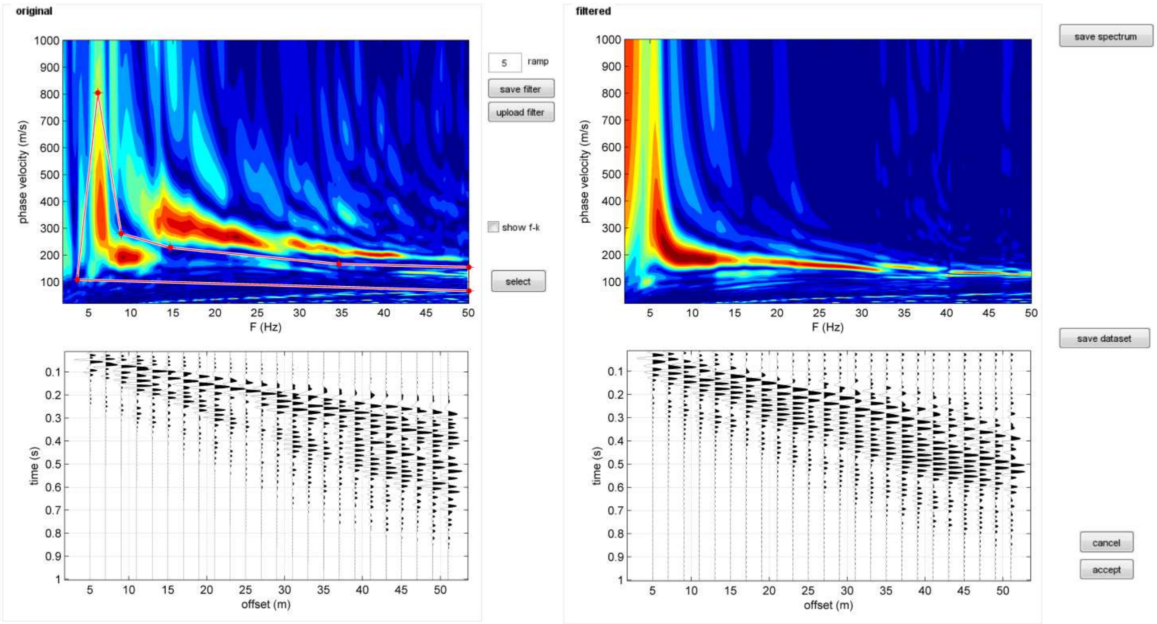
From the main panels ("*Velocity spectrum/a, modelling & picking*") the user can access to a tool useful for mode separation ("mode separation" button).

After having uploaded a dataset, by clicking the "mode separation" button, the following panel appears:

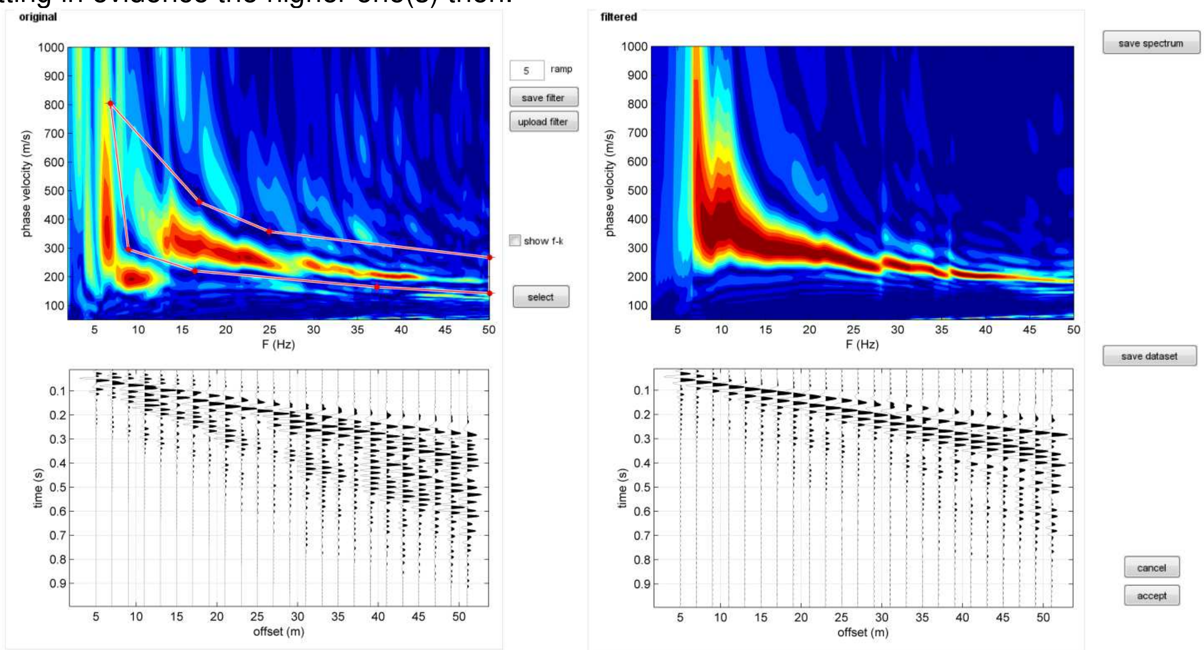


On the left side are reported the original data (in the f-v and x-t domains). By moving the points of the polygon evident in the velocity spectra (f-v domain) it is possible to draw a polygon that will be successively adopted as filter: **by clicking the "select" button only the data within the polygon will be kept, while data external to it will be removed (the filter actually works in the f-k domain).**

An example will clarify the point. In the following on the left side are reported the original data while on the right side the data after having removed the portion of data external to the chosen polygon (user moves the vertices of the polygon and then click the "select" button). We first decided to put in evidence the data in the "area" where fundamental mode was supposed to be (the very high amplitude of the higher mode(s) for frequencies higher than 13Hz prevents to see it).



If instead of putting in evidence the fundamental mode we decide to remove such a mode and putting in evidence the higher one(s) then:



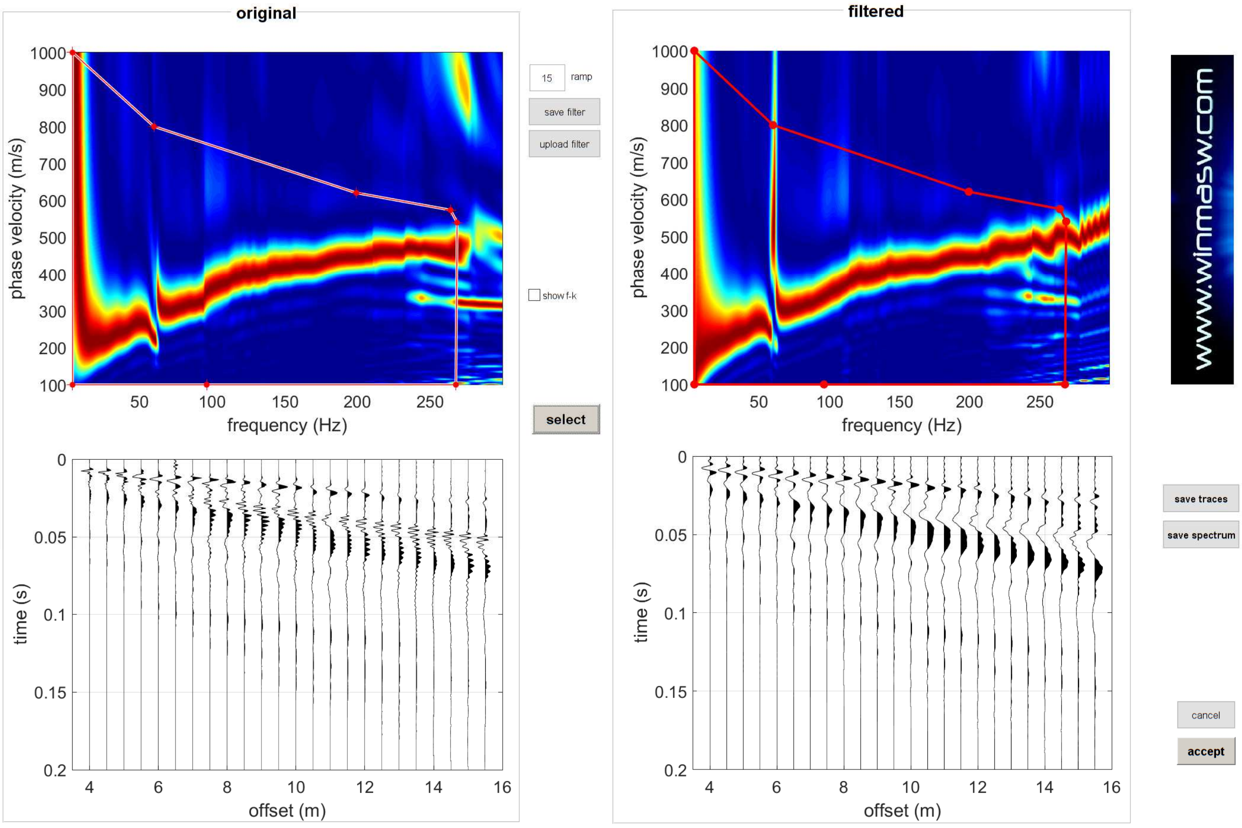
The "ramp" represents the value of the ramp of the filter (i.e. how quickly we pass from 0 to 1 in the mask/filter) too-low values might create oscillations in the filtered data (in the x-t domain), while too-high values risk not to remove data we actually want to remove. It is also possible (not necessary):

- To save (or upload) a filter ("save filter" & "upload filter" buttons)
- To save a filtered spectrum ("save spectrum" button)
- To save a filtered dataset ("save dataset" button) as segy file

If we like the action of the adopted filter and want to get back to the main panel considering the filtered dataset, it is sufficient to click the button "Accept". Otherwise, by clicking the "cancel" button we will close this panel and get back to the original (unfiltered) dataset.

Please, use this tool only if you perfectly know what you are doing. Artefacts due to improper use of it might "appear".

Please, note that this tool can be used for a myriad of applications even completely different from the "main" goal described above. Below, we can see an example of how the *fk* filtering can be applied even if you want to remove some undesired component from the field seismic traces. In this case we want to remove some very high frequency which (see seismic traces in the lower-left panel), afflicts the field data: note the difference between the field traces (bottom left) and filtered ones (bottom right).



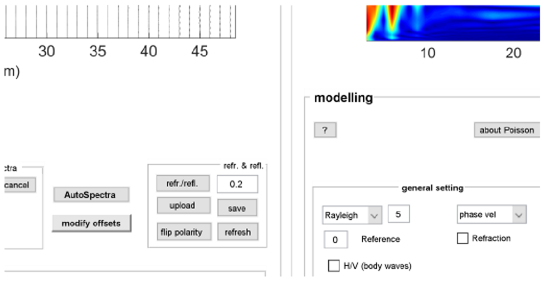
Non-equally spaced MASW data (*winMASW®* Academy)

winMASW® Academy can handle non-equally spaced MASW data. When you upload the field data, the software does not know the actual offsets and is therefore necessary to modify the *offsets* in agreement with the actual geometry (in this case, in fact, the *geophone spacing* – dx – is not constant).

Here the sequence of operations to accomplish:

1) Upload your data as usual. Provide the *mo* [*minimum offset*] and *dx* [*geophone spacing*] values (insert the *mo* value but don't worry about the *dx* value);

2) Click the "*modify offsets*" button and input the actual offset values;

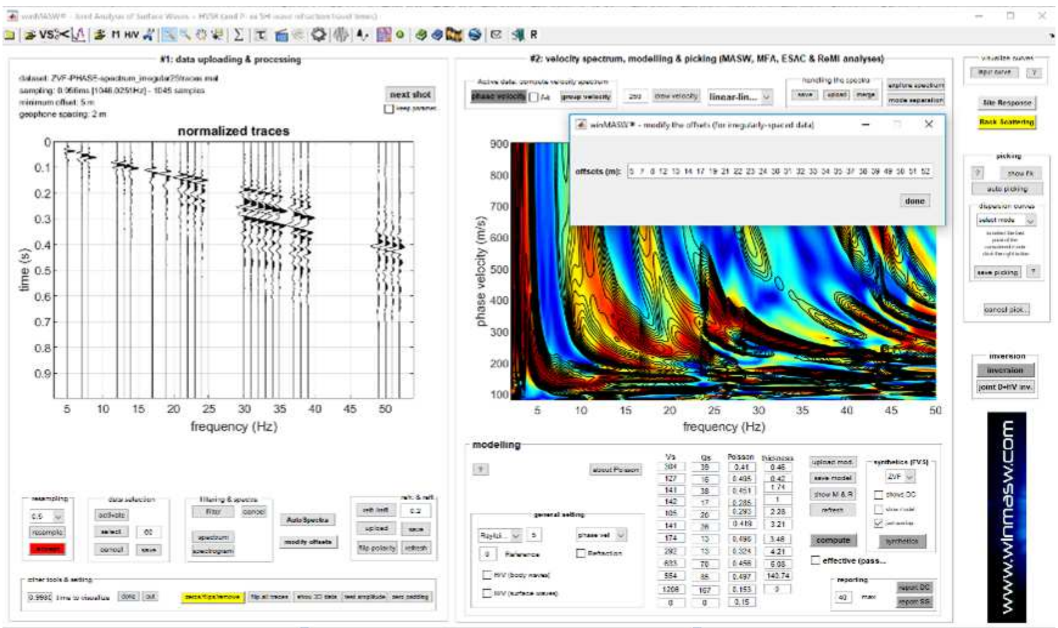


3) compute (as usual) the phase velocities ("*phase velocities*" button);

4) save the velocity spectrum ("*save*" button in the "*handling the spectra*" group).

The saved spectrum will contain not only the velocity spectrum but the seismic traces as well (with the correct *offset* values).

If, in the future, you wish to re-analyze the data, you will upload the saved spectrum (with the correct offset values) and it won't be necessary to modify again the *offsets*.



Please, notice that: for the analysis of non-equally spaced MASW data, it is recommended the FVS approach and not the one based on the modal dispersion curves [see example above reported].

4.2 Reconstruction of 2D V_S profiles through active data (*roll along*)

In *winMASW® Academy*, in order to simplify the procedures necessary to analyze several shots (e.g. for the reconstruction of 2D sections according to the *roll along* technique, in the single-component panel we added the **"next shot"** button.

Procedure to analyze several shots (recorded for instance according to a roll-along acquisition procedure):

1) <u>Preparing the folder and the data</u>. Save the data in a single folder, by adopting a clear nomenclature explicitly reporting the shot number as the very final information, separated from the previous letters by a "-" (minus) sign:

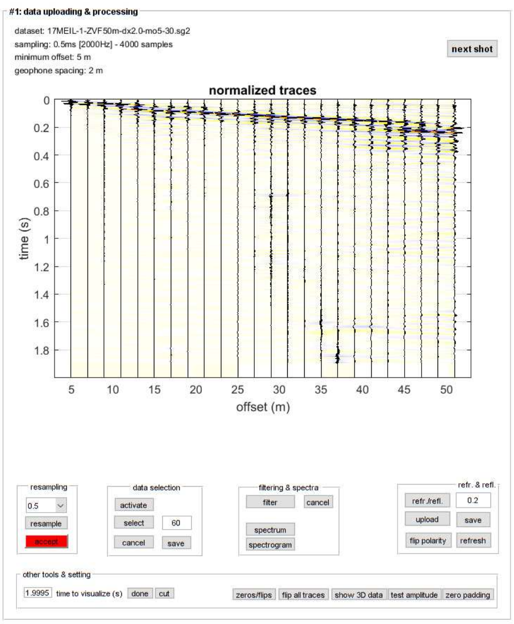
Examples of meaningful file names (see nomenclature in the *Elsevier* book, Paragraph 2.2):

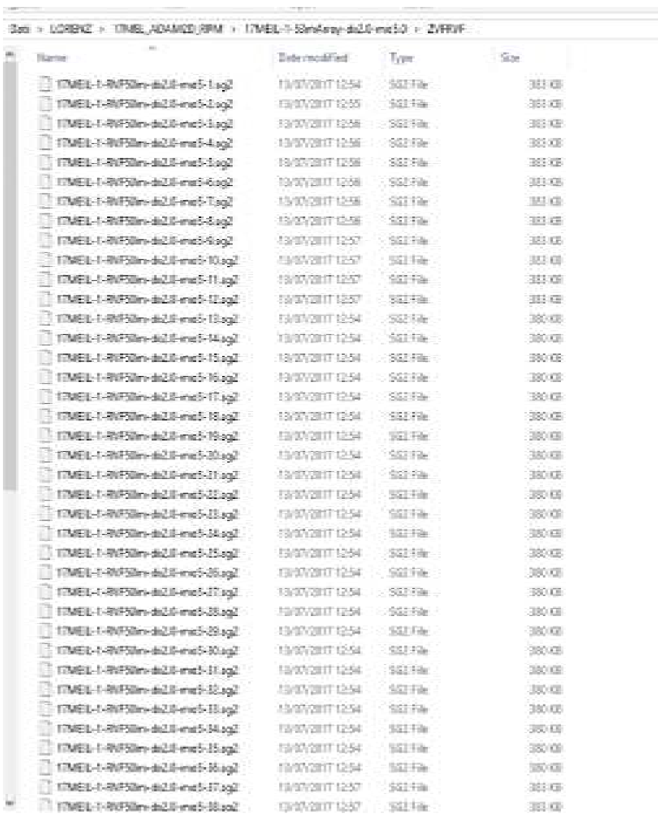
ZVF_dx2_mo5_dataset-1.sg2

THF_dx3_mo6-1.sg2

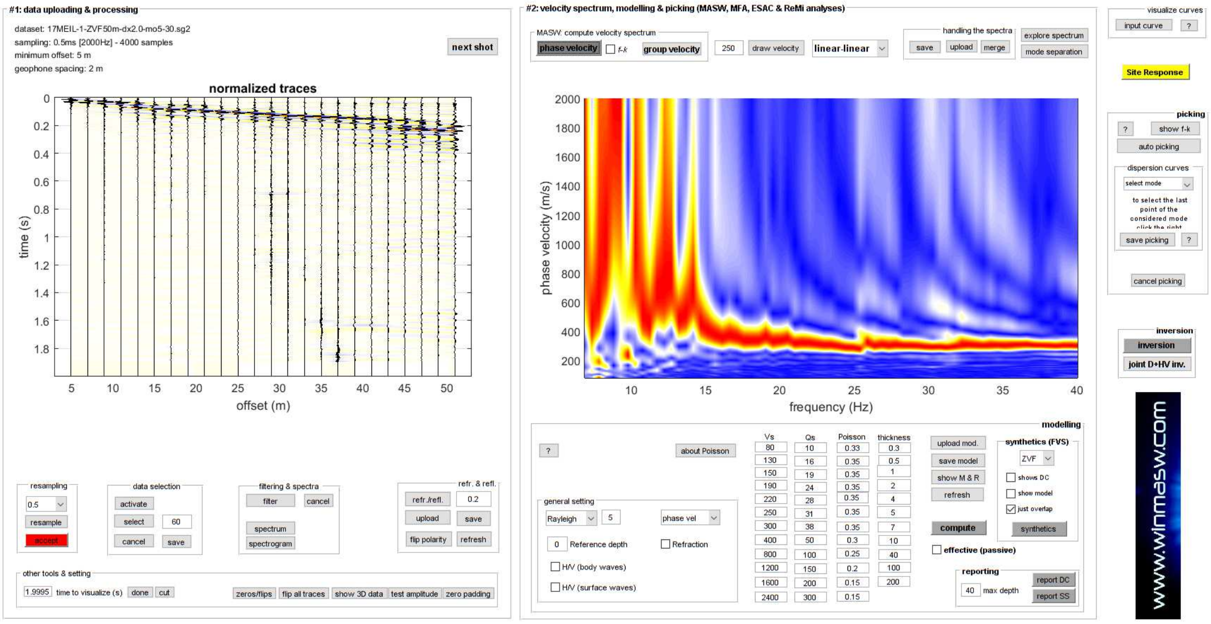
RVF_dx2_mo5_shot-1.sg2

See the example in the figure down here (on the right), where is shown the folder with the first 28 shots/datasets of the RVF component.





2) <u>Upload the first dataset, clean it and compute its phase-velocity spectrum</u>:

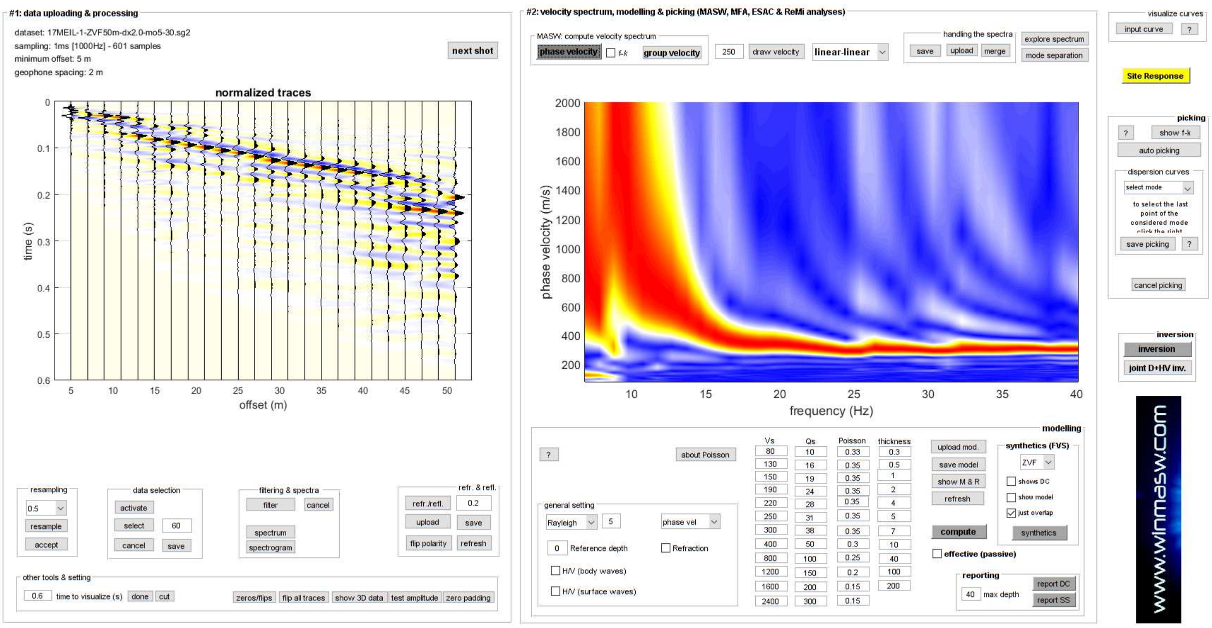


In this case we uploaded the file "17MEIL-1-ZVF50m-dx2.0-mo5-**30**.sg2" (so we started from the shot/dataset#30).

As it can be clearly seen in this snapshot, since the raw data are often noisy, the quality of the obtained phase-velocity spectrum can be quite poor.

As a consequence, it can be necessary to clean the seismic traces.

In the following snapshot you can see the cleaned dataset on the left (we resampled the dataset to 1 ms [raw data were sampled at 0.5 ms], reduced the time to 0.6 s and kept only the Rayleigh waves - "data selection" tools). The phase-velocity spectrum (on the right) is now clearly much clearer.



3) Model it and save the result (*report DC* or *report SS*) (to learn how to model the dispersion according to the modal dispersion curve or the FVS approach see the rest of this manual): your model will be saved in a subfolder named after the shot you are considering. If, for instance, you are analyzing the shot#30, your modelling will be saved in a subfolder named "**reportDC30**" in case you are considering the modal dispersion curves of "**reportSS30**" in case you are working according to the FVS approach.

Now we are ready to analyze the *next shot*.

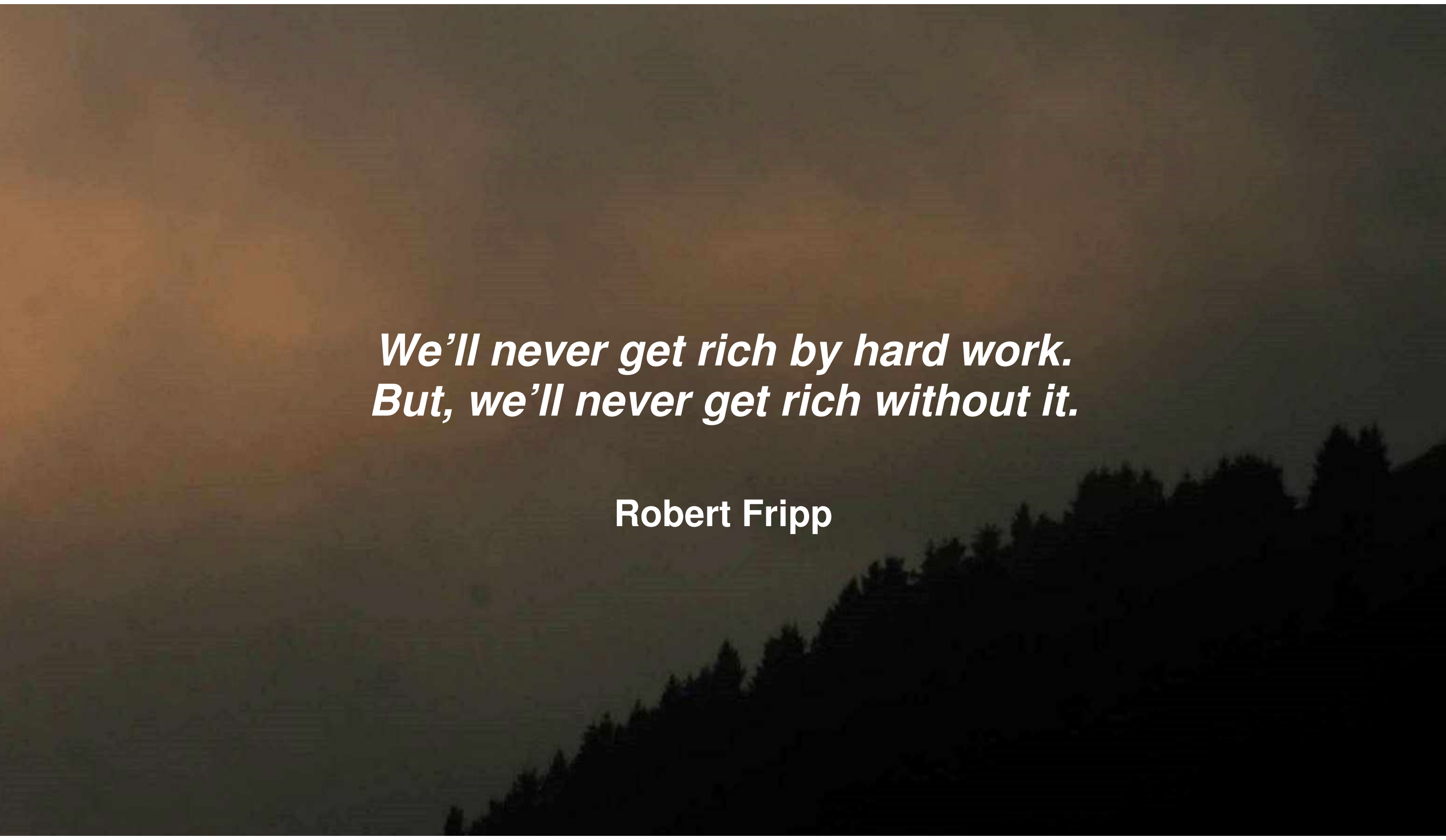
4) uploading the next shot

Once you click the **"next shot" button** (top-right corner of the seismic traces), you will automatically upload the next file/shot (in this example *17MEIL-1-ZVF50m-dx2.0-mo5-**31**.sg2*) and will be (also automatically) computed the phase-velocity spectrum.

You can now clean the dataset, model it and save it (as for the previous shot).

In the end you will end up with a series of subfolders were each model is saved as model30.mod (shot#30), model31.mod (shot#31) and so on.

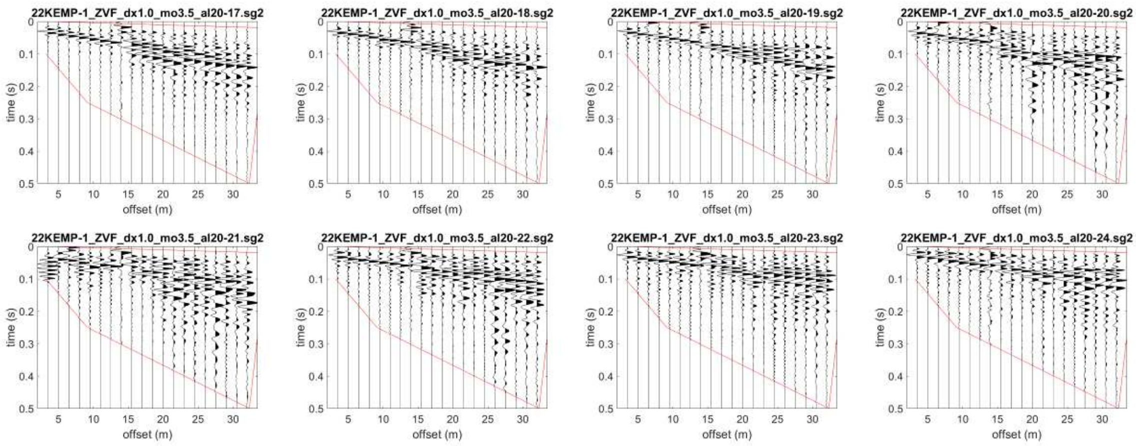
Now, in order to obtain a 2D section, it is necessary to create a small project file (**see** Appendix E: Creating 2D sections).



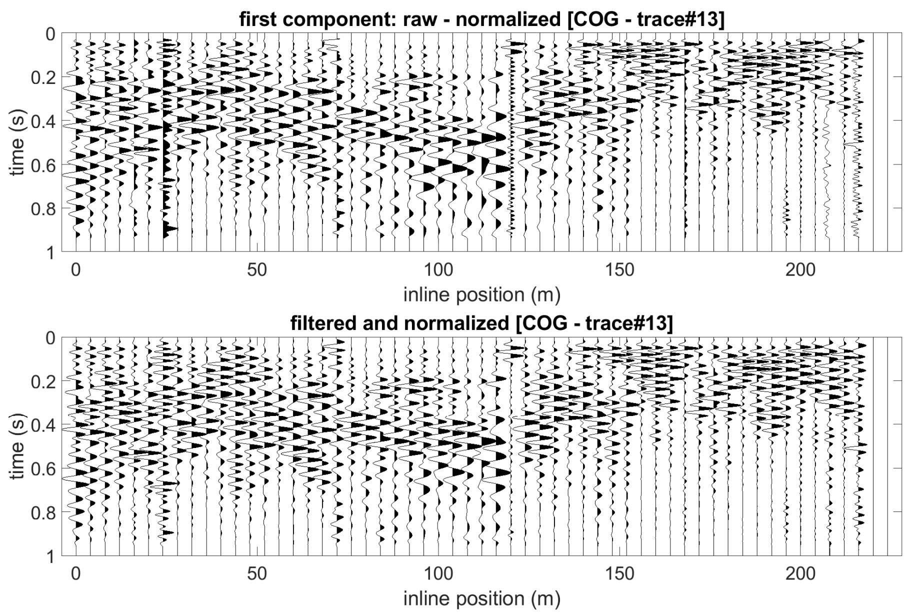
The ADAM-2D data processing service we offer

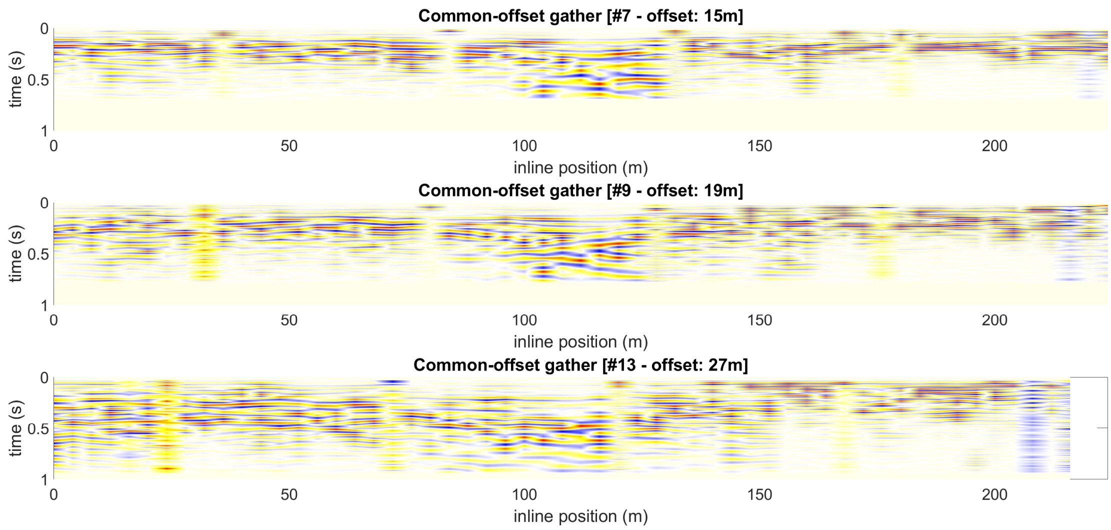
While for short 2D section you can surely use the tools that winMASW® Academy offers you, in case you need to explore larger areas (according to advanced data processing), ADAM-2D is a data-processing service we offer in order to analyse large amount of data and reconstruct the 2D V_S section thanks to the joint analysis of multi-component data (such approach is the only one that can provide reliable V_S values free from ambiguities and/or pitfalls that would inevitably affect any kind of analysis based on just one component- for details, please have a look to our *Elsevier* and *Springer* books).
Here few snaps of what we can do with your (possibly multi-component) data. In order to understand *what is what*, carefully read the title of each figure and the x and y-axis labels. In this case the goal was to verify the presence of a paleo-channel (entering the nearby lake) and which is now completely covered by recent alluvia deposits (flat topography).

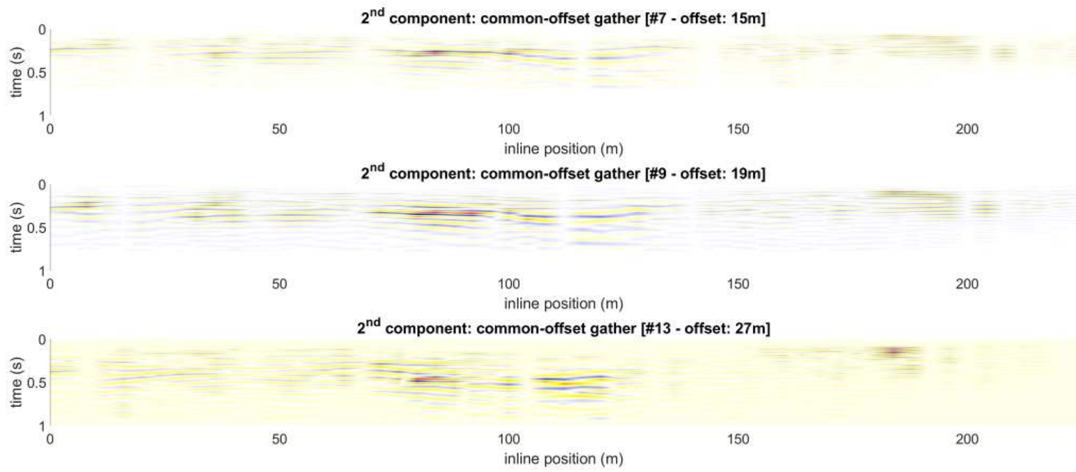
Example#1

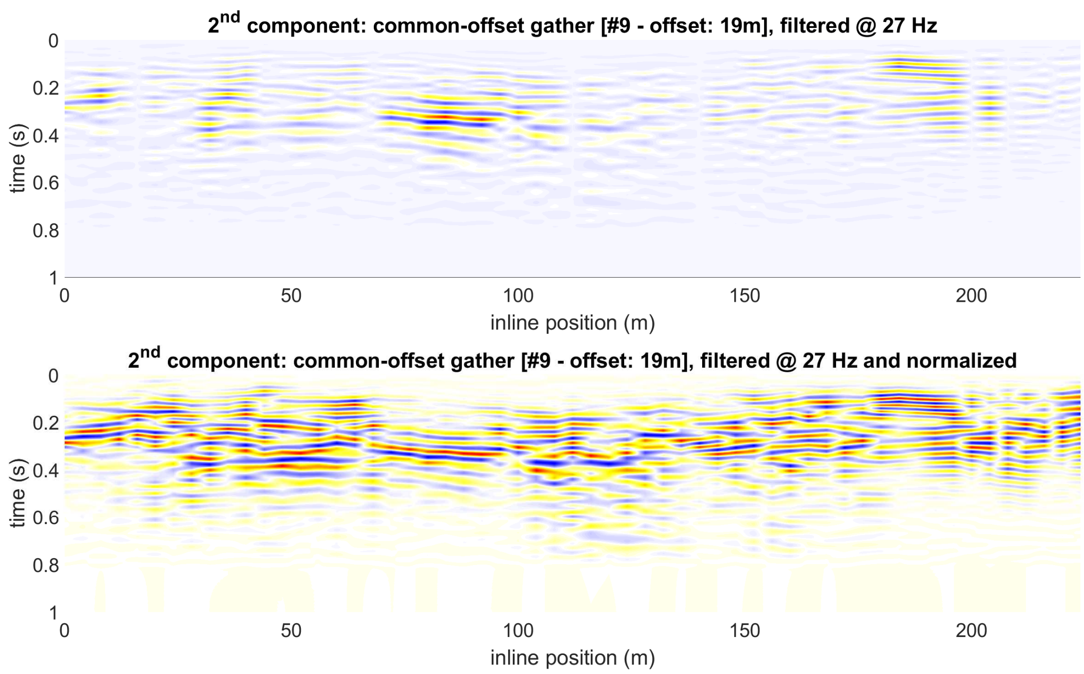


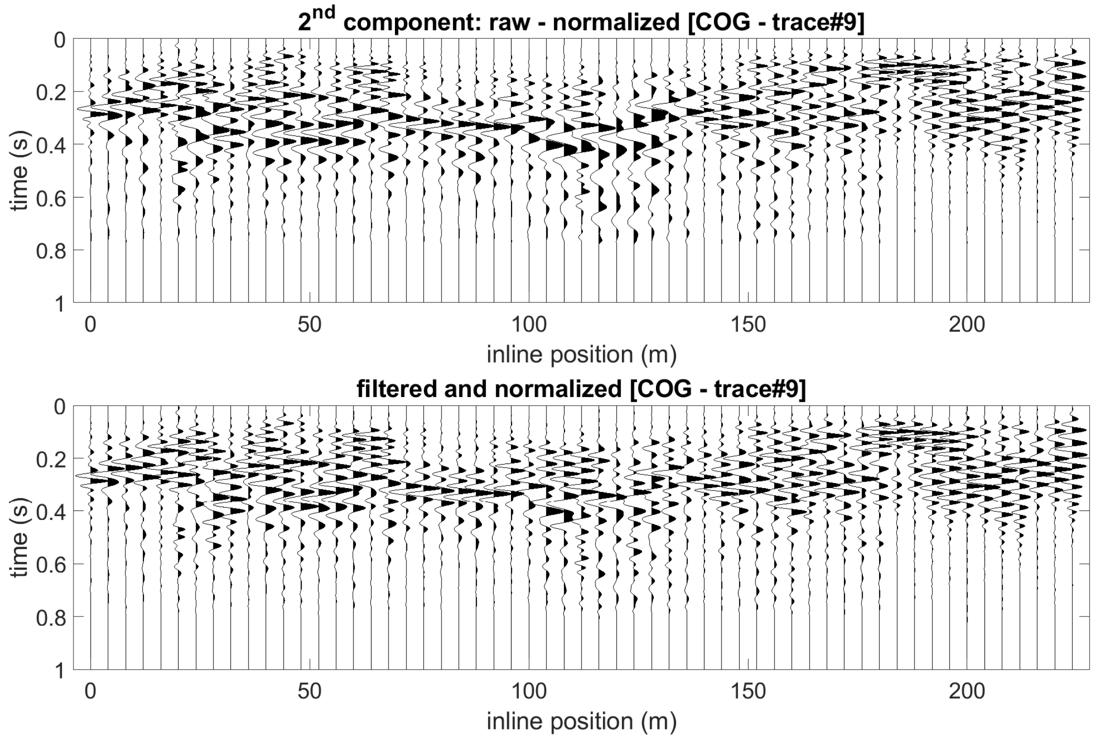
An example of 8 successive shots (Z component) [see the increasing suffix numbers] that can be jointly analysed together with the R (radial) or T (transversal – Love waves) components so to obtain a highly-constrained inversion process.

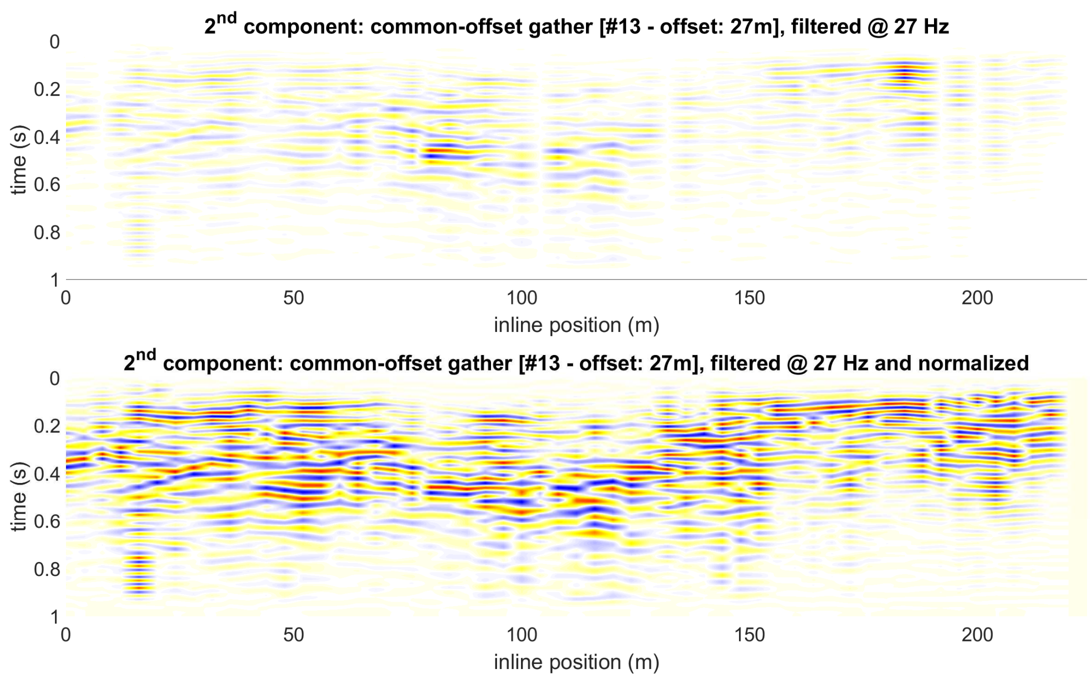


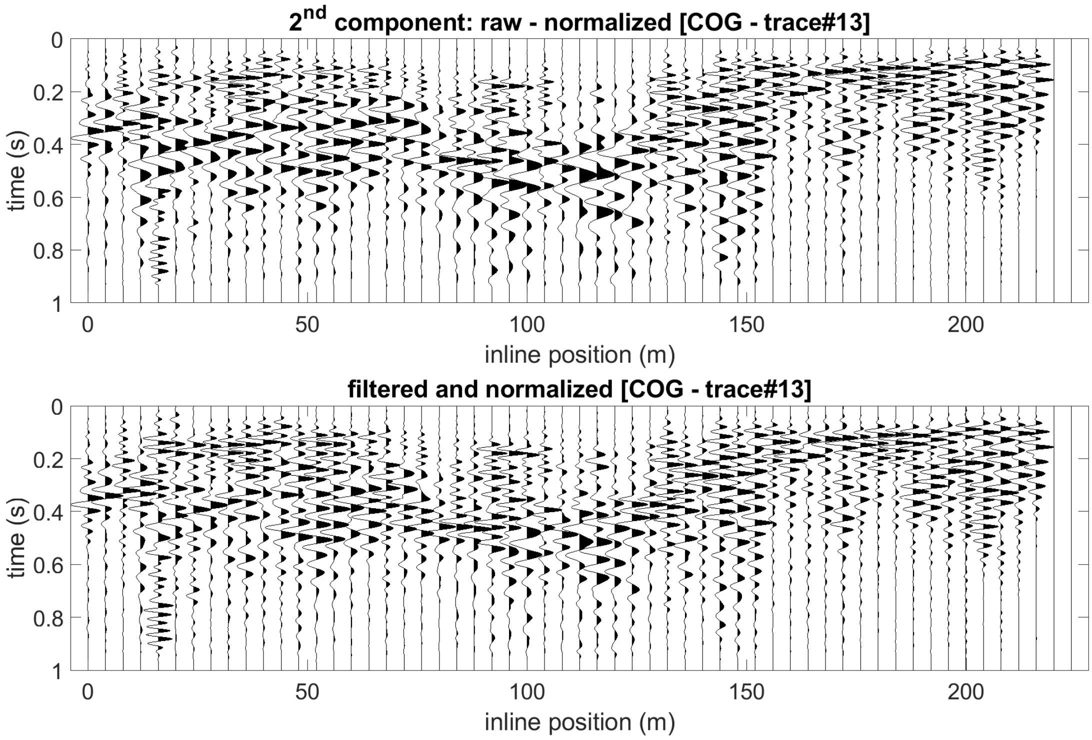

Common-offset gather [#7 - offset: 15m]
Common-offset gather [#9 - offset: 19m]
Common-offset gather [#13 - offset: 27m]
time (s)
inline position (m)
0
0.5
1
50
100
150
200

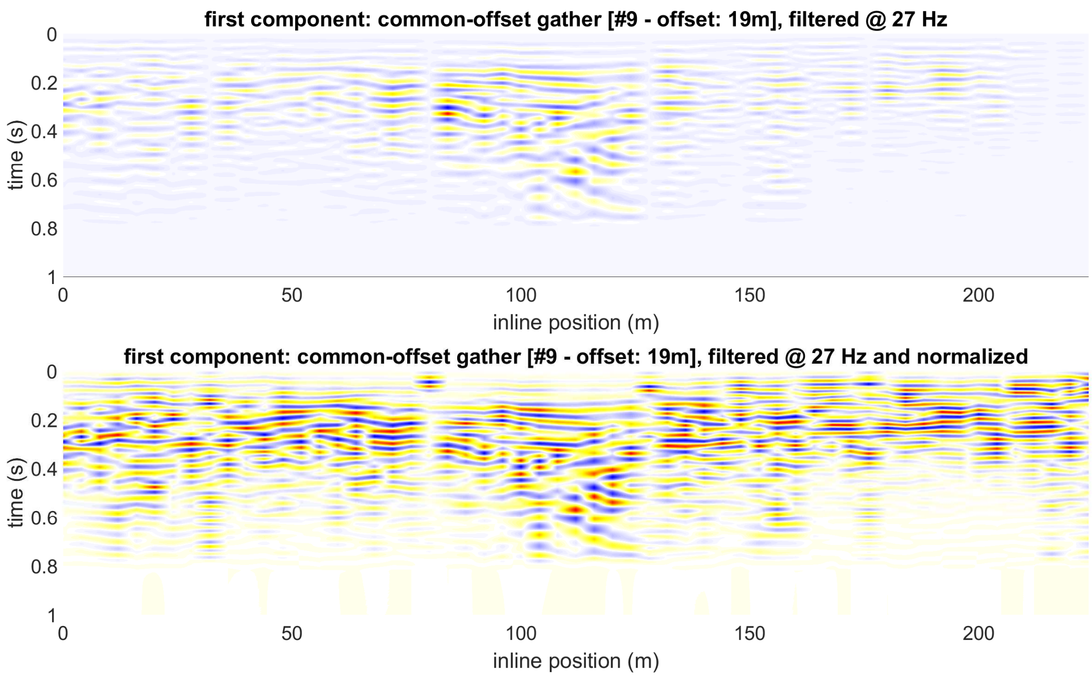

2nd component: common-offset gather [#7 - offset: 15m]
2nd component: common-offset gather [#9 - offset: 19m]
2nd component: common-offset gather [#13 - offset: 27m]
time (s)
inline position (m)
0
0.5
1
50
100
150
200

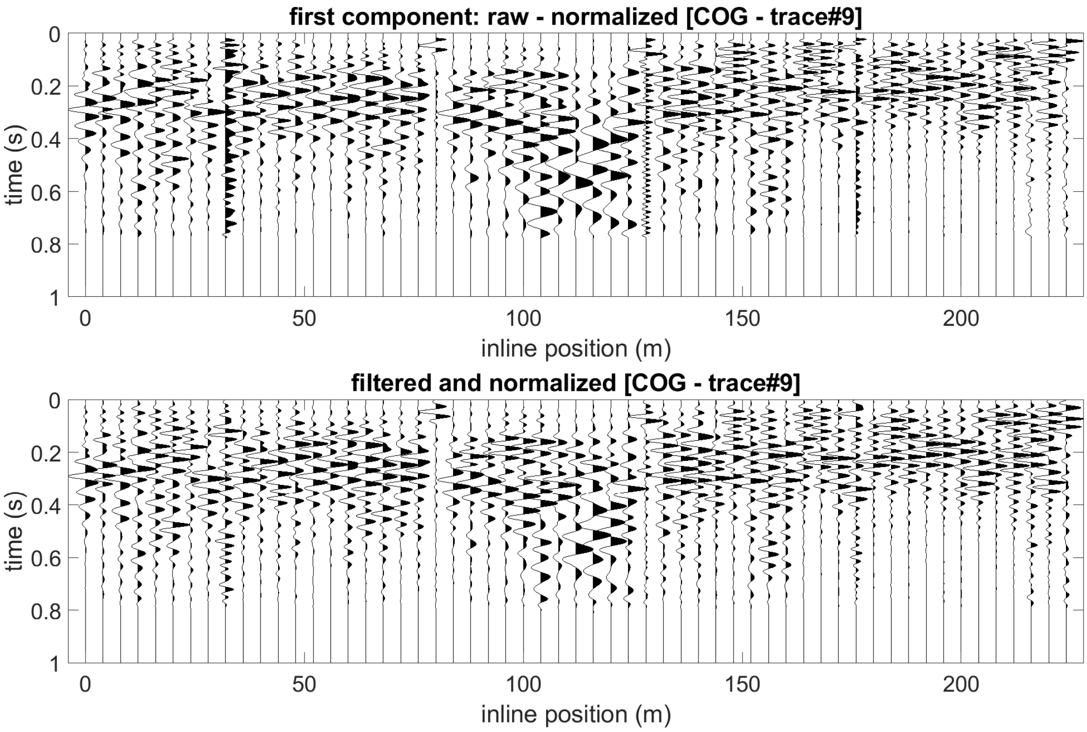

2nd component: common-offset gather [#9 - offset: 19m], filtered @ 27 Hz
2nd component: common-offset gather [#9 - offset: 19m], filtered @ 27 Hz and normalized
time (s)
inline position (m)
0
0.2
0.4
0.6
0.8
1
50
100
150
200

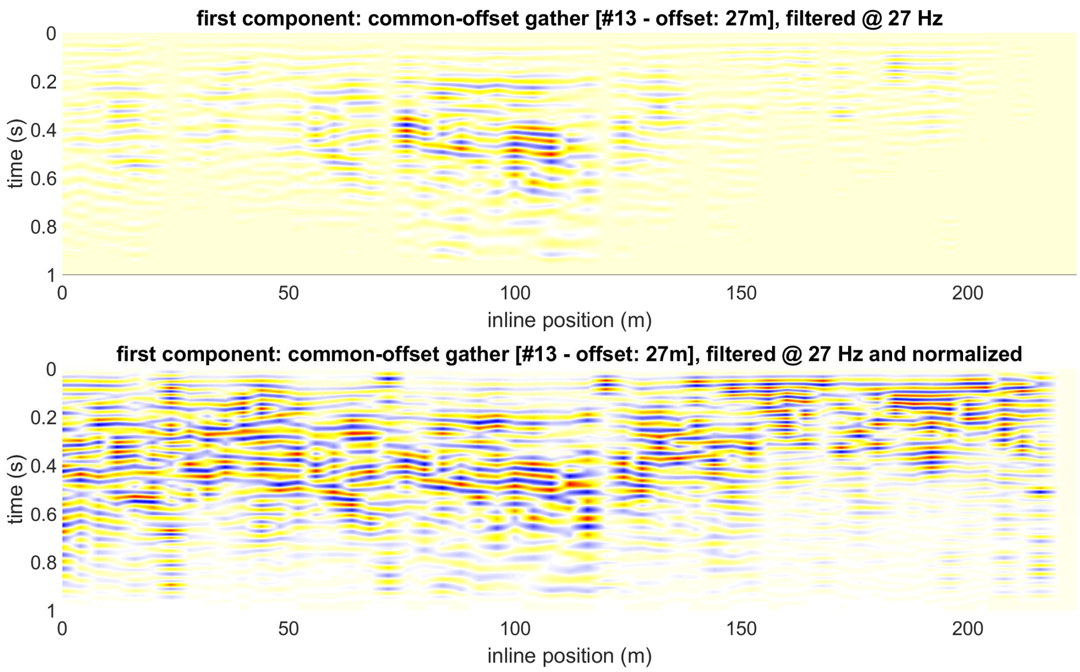

2nd component: raw - normalized [COG - trace#9]
time (s)
inline position (m)
filtered and normalized [COG - trace#9]
time (s)
inline position (m)

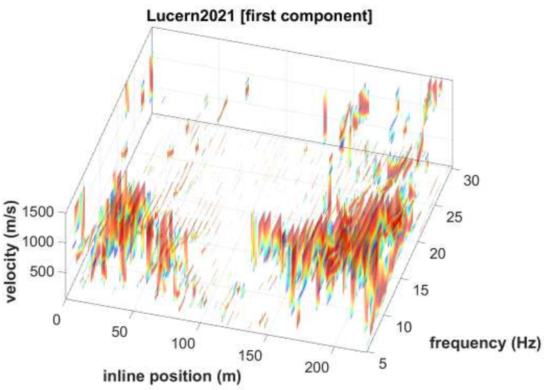

2nd component: common-offset gather [#13 - offset: 27m], filtered @ 27 Hz
time (s)
inline position (m)
2nd component: common-offset gather [#13 - offset: 27m], filtered @ 27 Hz and normalized
time (s)
inline position (m)

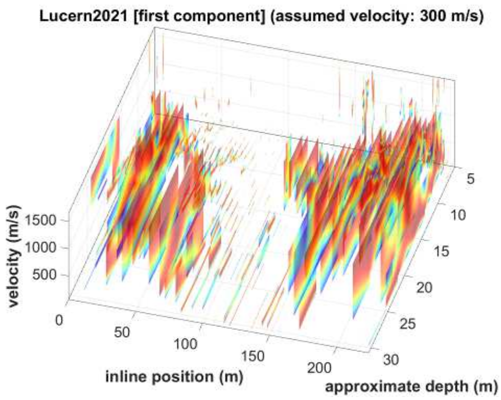

2nd component: raw - normalized [COG - trace#13]
time (s)
inline position (m)
filtered and normalized [COG - trace#13]
time (s)
inline position (m)

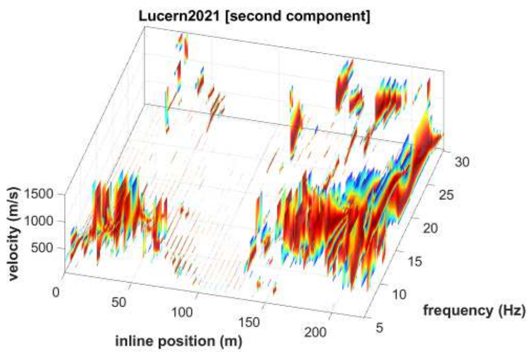

first component: common-offset gather [#9 - offset: 19m], filtered @ 27 Hz
time (s)
inline position (m)
first component: common-offset gather [#9 - offset: 19m], filtered @ 27 Hz and normalized
time (s)
inline position (m)

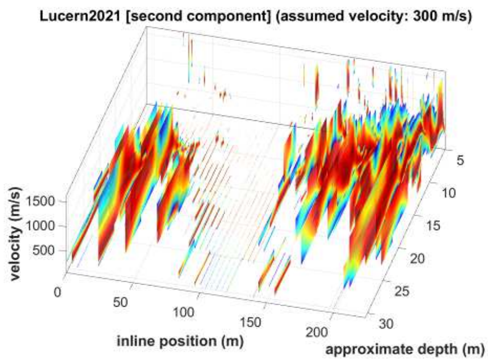

first component: raw - normalized [COG - trace#9]
time (s)
inline position (m)
filtered and normalized [COG - trace#9]
time (s)
inline position (m)

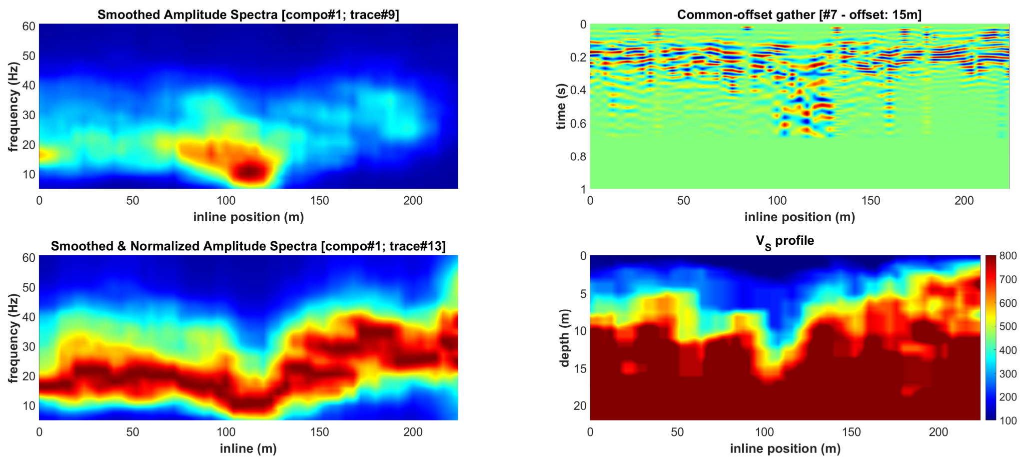

first component: common-offset gather [#13 - offset: 27m], filtered @ 27 Hz
time (s)
inline position (m)
first component: common-offset gather [#13 - offset: 27m], filtered @ 27 Hz and normalized
time (s)
inline position (m)

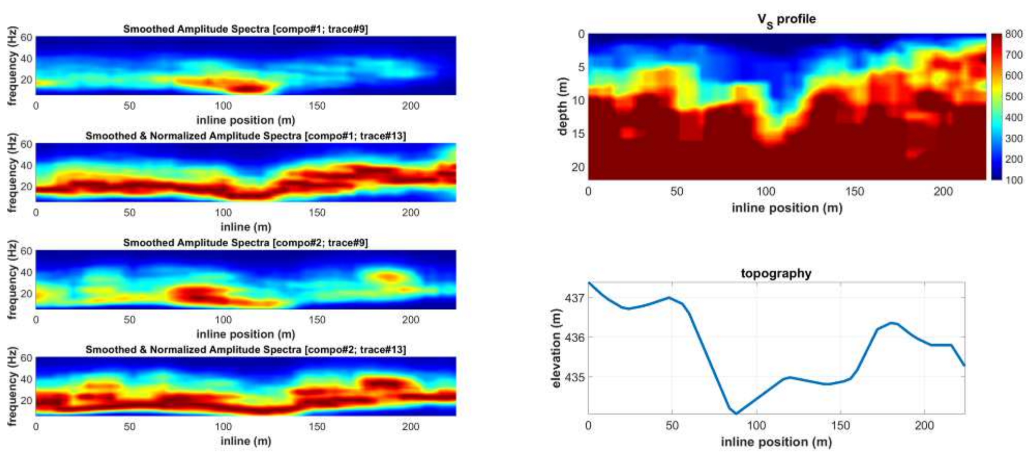

Lucern2021 [first component]
velocity (m/s)
inline position (m)
frequency (Hz)

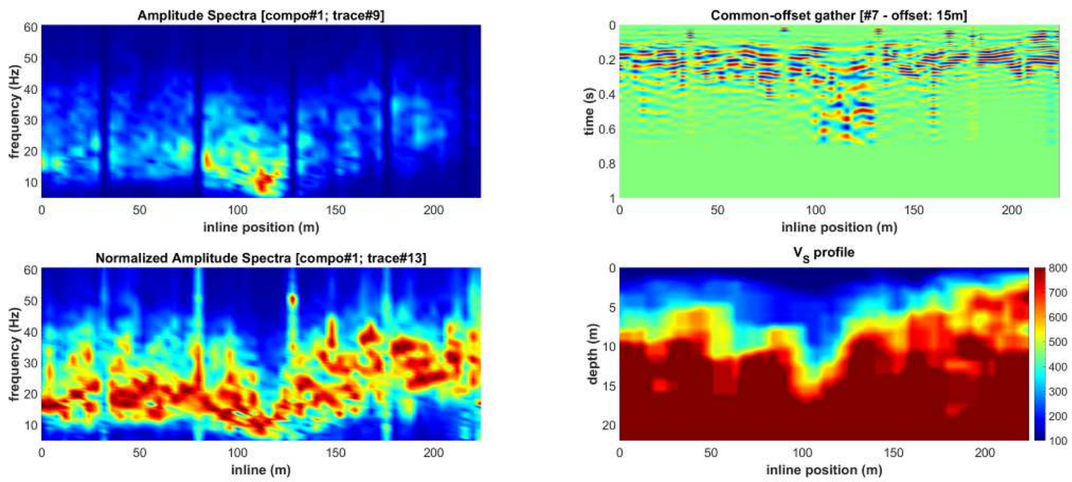

Lucern2021 [first component] (assumed velocity: 300 m/s)
velocity (m/s)
inline position (m)
approximate depth (m)

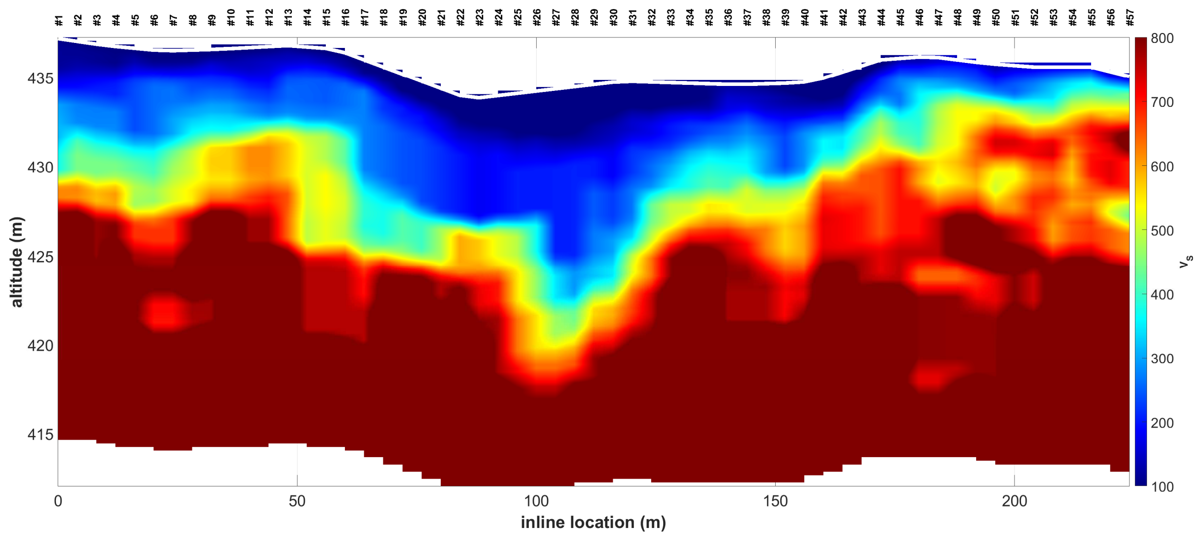

Lucern2021 [second component]
velocity (m/s)
inline position (m)
frequency (Hz)

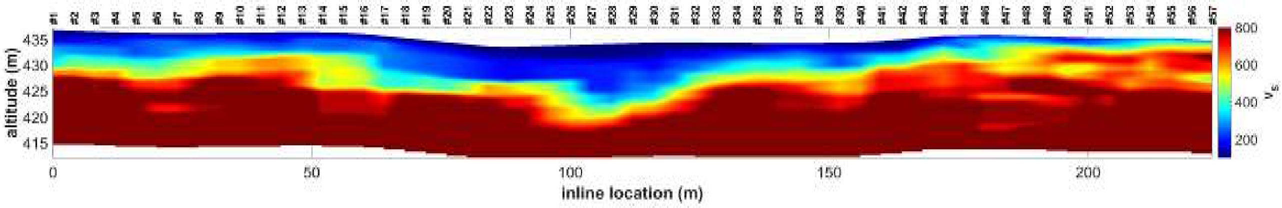

Lucern2021 [second component] (assumed velocity: 300 m/s)
velocity (m/s)
inline position (m)
approximate depth (m)


Smoothed Amplitude Spectra [compo#1; trace#9]
frequency (Hz)
inline position (m)
Common-offset gather [#7 - offset: 15m]
time (s)
inline position (m)
Smoothed & Normalized Amplitude Spectra [compo#1; trace#13]
frequency (Hz)
inline (m)
V$_S$ profile
depth (m)
inline position (m)


Smoothed Amplitude Spectra [compo#1; trace#9]
Smoothed & Normalized Amplitude Spectra [compo#1; trace#13]
Smoothed Amplitude Spectra [compo#2; trace#9]
Smoothed & Normalized Amplitude Spectra [compo#2; trace#13]
frequency (Hz)
inline position (m)
inline (m)
V$_S$ profile
depth (m)
inline position (m)
topography
elevation (m)
inline position (m)

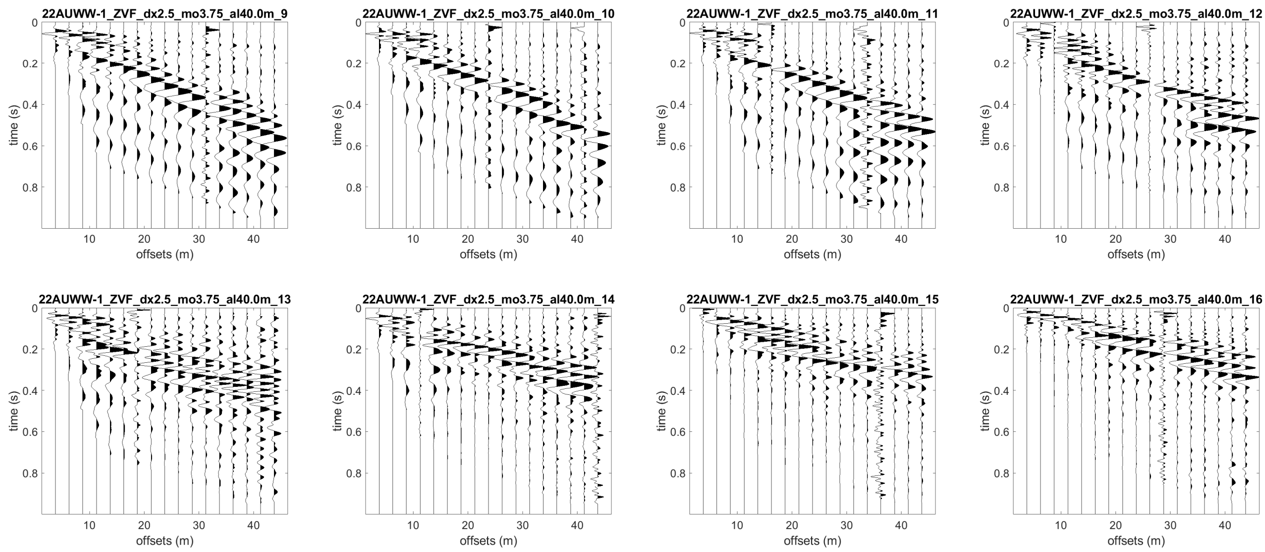

Amplitude Spectra [compo#1; trace#9]
frequency (Hz)
inline position (m)
Common-offset gather [#7 - offset: 15m]
time (s)
inline position (m)
Normalized Amplitude Spectra [compo#1; trace#13]
frequency (Hz)
inline (m)
V_S profile
depth (m)
inline position (m)


altitude (m)
inline location (m)
v_s

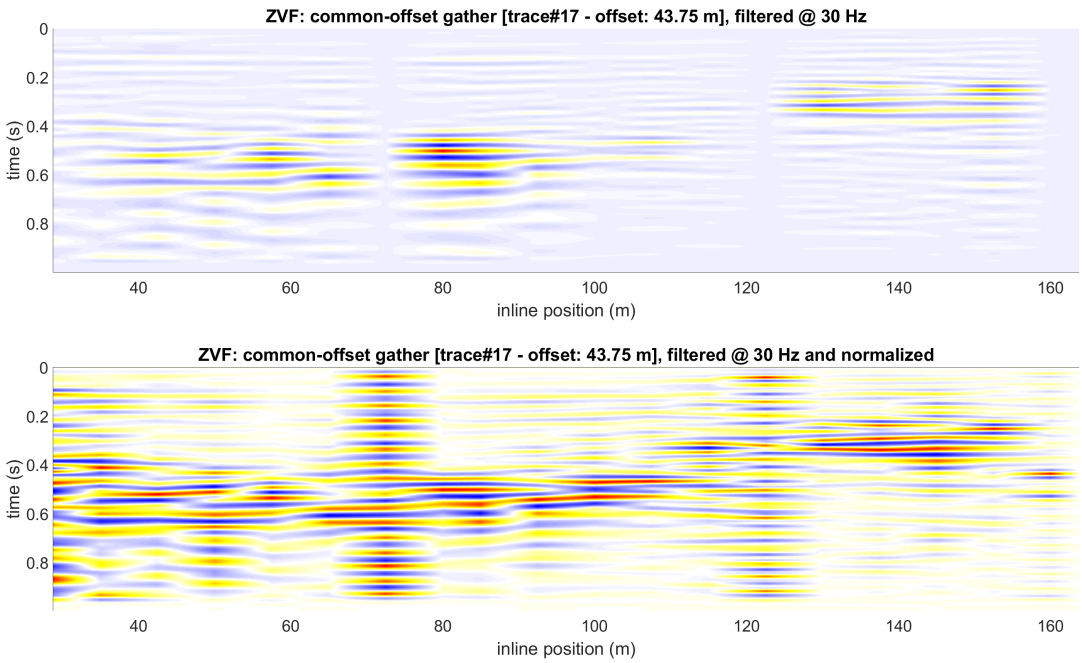

altitude (m)
inline location (m)
v_s

Example#2

Here a further example for the identification of the lateral variations of the *bedrock* along a 160 m line.



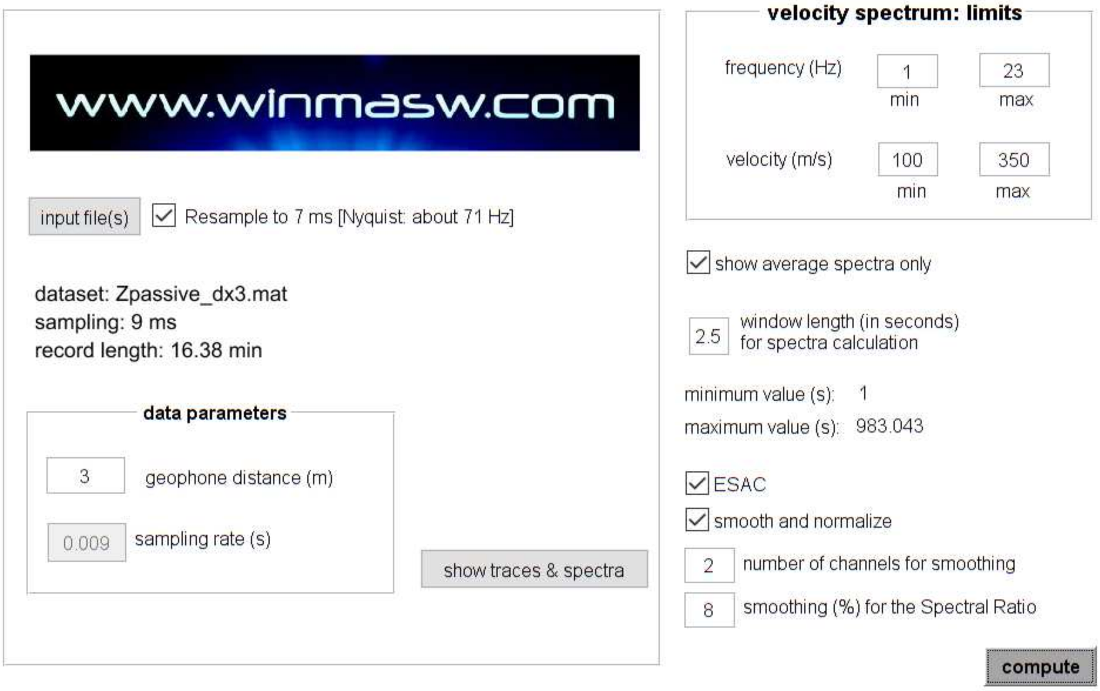
Some of the recorded shots (here the ZVF component)



COG section (offset 43.75 m)

4.3 *ReMi* panel [also for non-equally spaced data]

From the main panel, by clicking on the "ReMi spectra" button, you can access the section dedicated to the analysis of those spectra obtained by analysis of passive seismic data (*seg2* and *segy* formats, as well as the Matlab format used in *winMASW*®)



Clicking on "input file(s)" you select the seismic (passive) files. You can simultaneously upload several files (use the key CTRL button while selecting all the files you want to upload). **<u>All the files must have all same acquisition parameters (geophone distance, number of traces and sampling interval)</u>**.
In order not to overload the computer memory we suggest not to upload more than 5 dataset at once (for instance 65 seconds long each, such value depending anyway on the computer features, therefore even longer)

Once the geophone distance, as used in the acquisition phase, and the length of the window to consider are set (the same "sampling rate/interval" can be modified but the read and proposed value is likely to be correct every time and you can modify it only if the seismograph really has some problems or you are confident you're doing the right thing; consider also that the length can be changed as many times as you need to reach better spectra) you just need to click on "spectra calculation".
At the end of all operations a window like the one below will show.

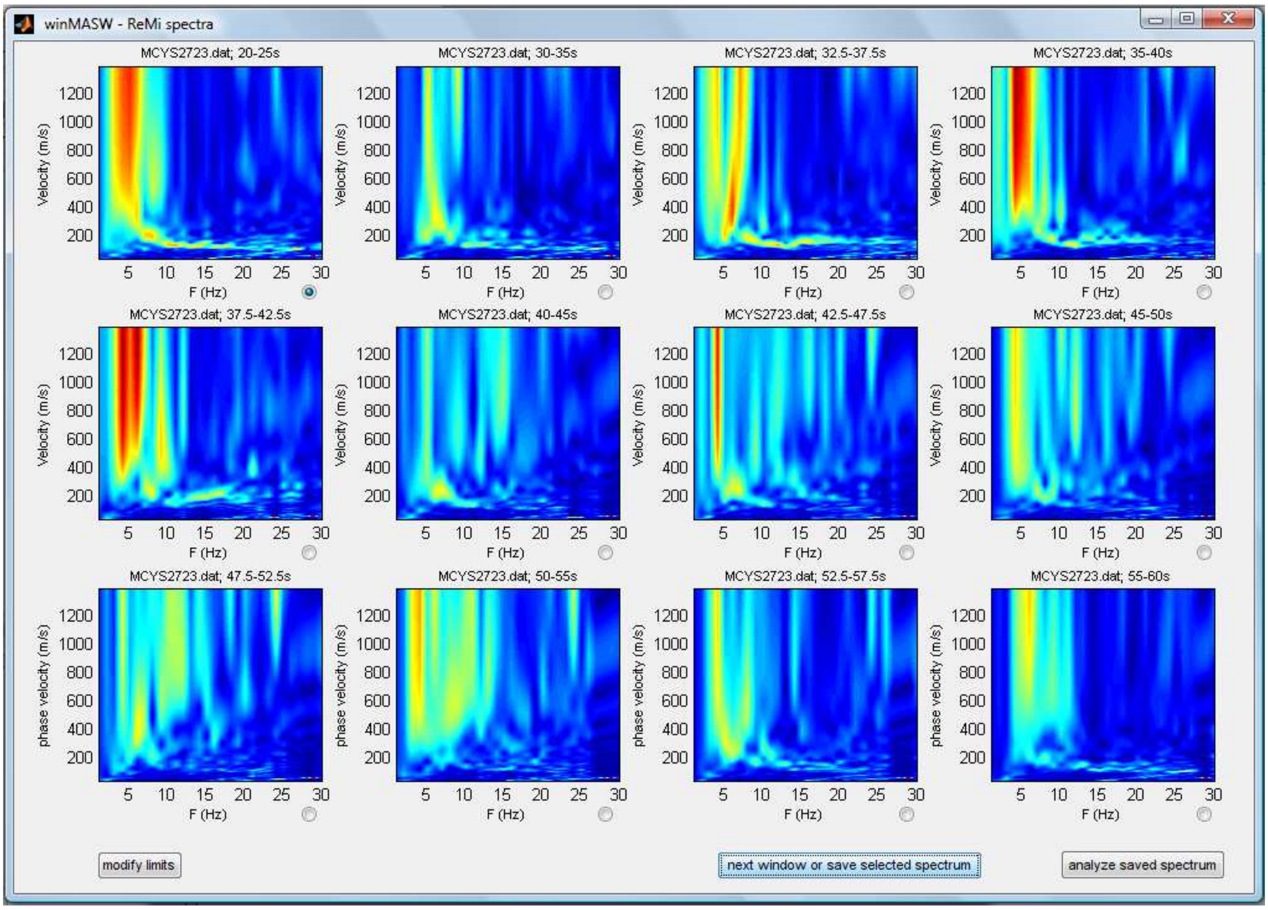
The software splits the dataset (or datasets) in many windows of equal length like the one indicated by the user (the value must rank between 2 seconds and the length of each single dataset)

According to the ratio between the dataset and the window dimension, different windows could show like the one displayed on top.

The user has to select the best defined spectrum by means of the little button on the right side below of each spectrum. The chosen spectrum in the screen will be displayed again on the top left side of following screen (achieved clicking on "next window" or "save selected spectrum").
When the last window finally is reached, you'll save the selected spectrum clicking on that same button.

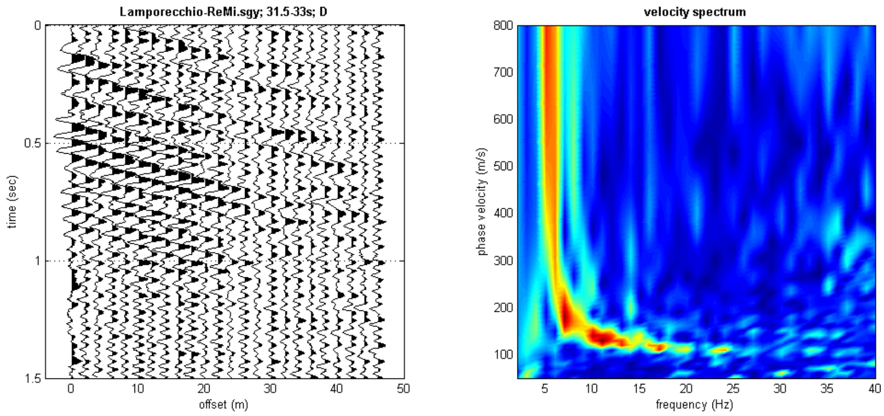
Once the clearer spectrum (therefore more useful to our analysis) is saved, we'll get access to the module "*Velocity spectra, Modelling, Picking*" clicking on "*Analyze saved spectrum*".

Here, in section "*#2: velocity spectrum, modelling & picking (MASW & ReMi analyses)*", we'll upload the just saved spectrum clicking on "*upload ReMi spectrum*".



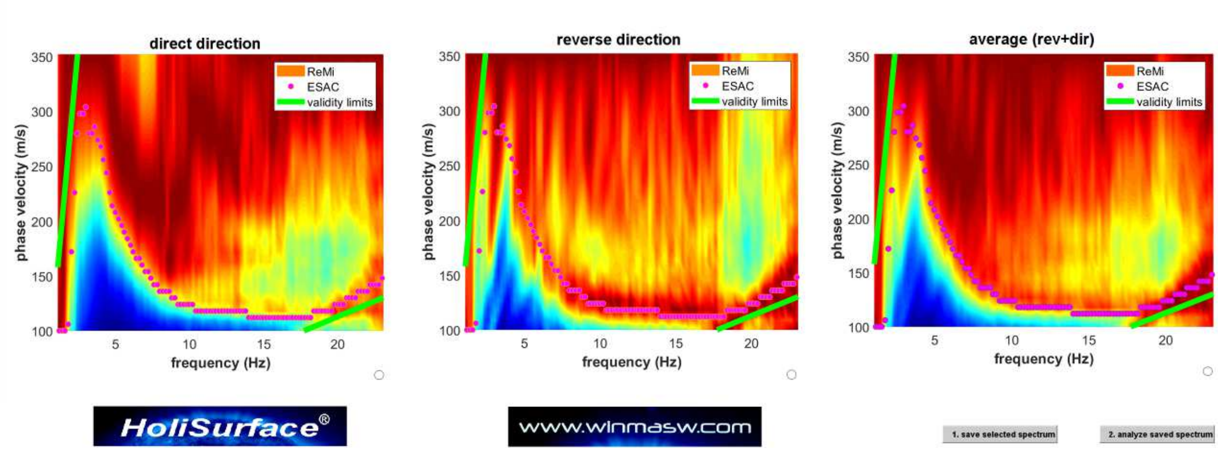
The last three plots refer to the average spectra: the first 2 related to the 2 possible direction (so to say: one from left, the other from right), the last one is the total mean spectrum.

If, instead of choosing an average spectrum, a single-event spectrum is preferred, when the user will eventually click on "*next window or save selected spectrum"* (to save the spectrum) the event (i.e. the time window of the seismic dataset) will also pop up:



On the left the selected event (please notice the passage of the surface waves) and, on the right, the selected spectrum.

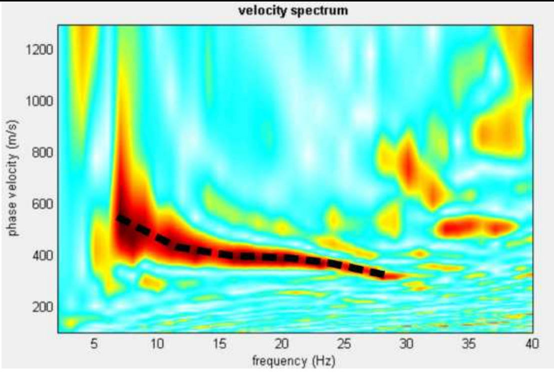
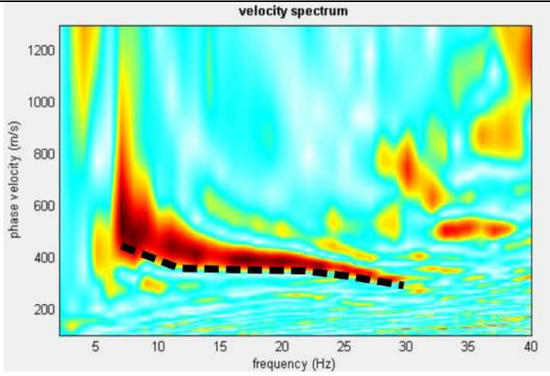
In case you choose to visualize the average spectra only (just select the "show average spectra only" check box) you will clearly obtain only the 3 average spectra:



Shown phase-velocity spectra (the user now have to choose the best one): shown also the validity limits (data are reliable only within the two green lines) and the dispersion curve obtained by means of the ESAC processing.

About the validity limits:
the lower one (highest reliable frequency) is due to the *spatial aliasing* and is related to the geophone spacing while the upper one (lowest reliable frequency) depends on the total length of the array but it is really site and data dependent (so it does not have to be taken exceedingly seriously).

Now, you can upload the chosen velocity spectrum in the "single-component panel" and model the dispersion carefully considering the specific modelling criterion for ReMi data: the dispersion curve has to stay in the lower part of the red signal:

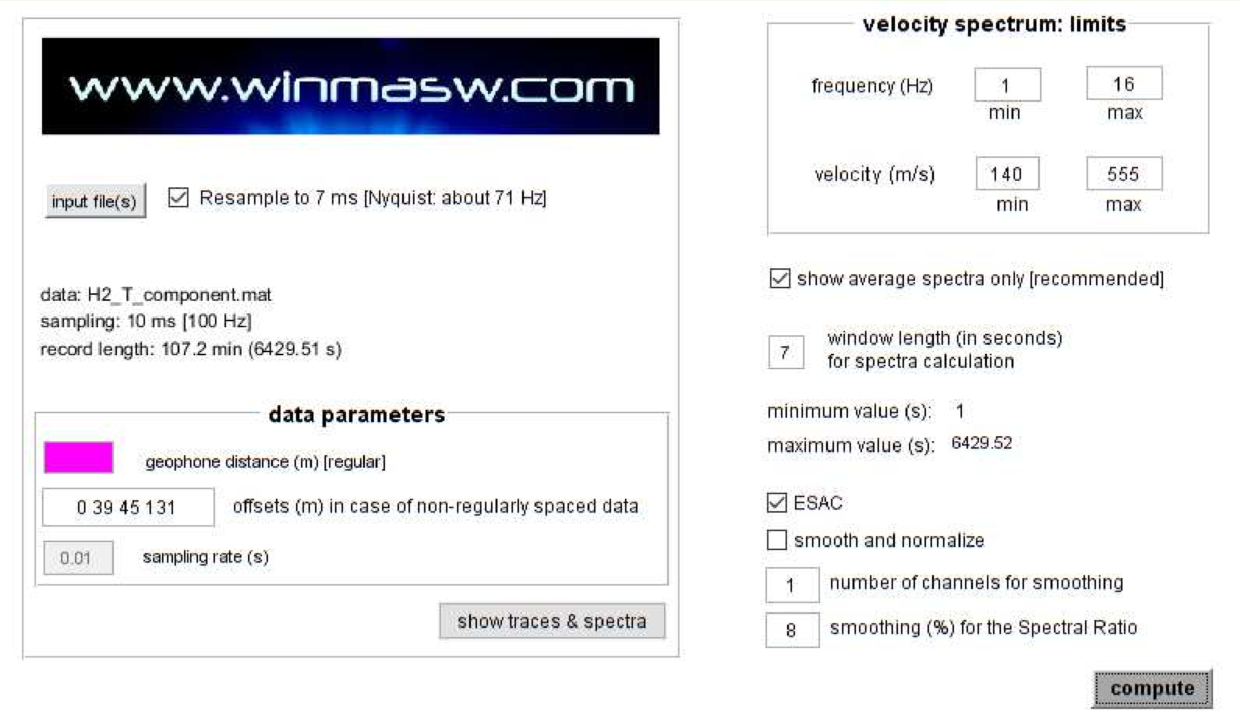
	
Dispersion in case of *MASW* (active) data	Dispersion in case of *ReMi* (passive) data

Modelling/picking criteria for both data types (active or passive seismics).

While considering passive data and ReMi processing, in most cases the actual dispersion lies in the "lower" boundary of the signal. But in case the main microtremor sources are in-line with the linear array different paradigms need to be used [see the paper "*Determination of the V_S profile in a "noisy" industrial site via active and passive data: the critical role of Love waves and the opportunities of multi-component group-velocity analysis*" by Dal Moro & Mazanec, 2024].

NEW in winMASW® Academy

ReMi analysis with non-equally spaced data



From the 2023-beta release, ReMi technique (i.e. phase shift performed on passive data) can be performed also considering non-equally spaced data. This can be useful in order to obtain good-quality phase-velocity spectra with a limited number of geophones/channels which, for ordinary arrays of few tens of meters, can be from 6 to 12.

In order to process non-equally spaced data you need to set to zero (0) the “geophone distance” and fix the proper offsets in the “offsets” box.

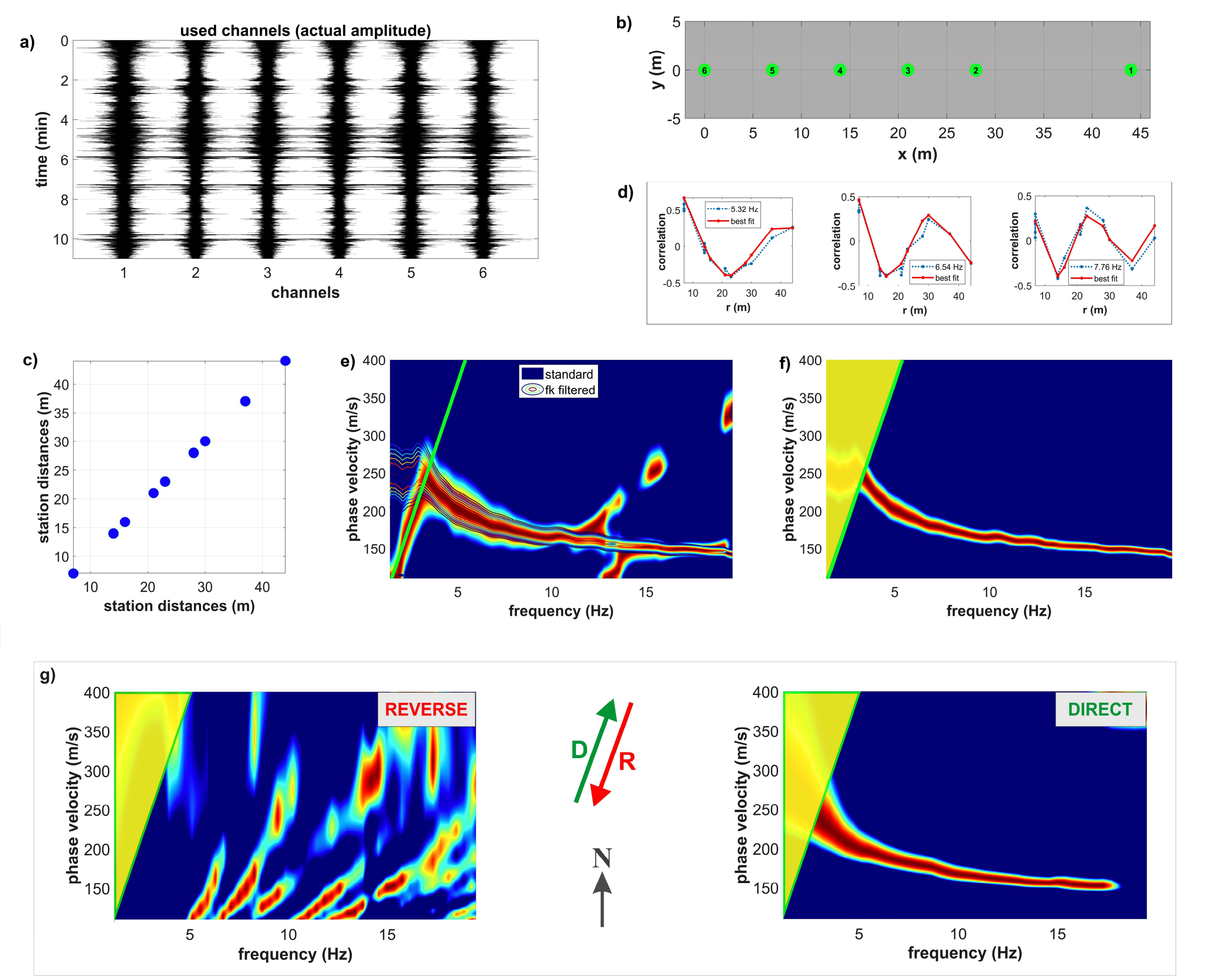
In case you decide to exploit this opportunity, you have to be careful about the correct channel sequence. In simple terms: you might for instance deploy your geophones with a certain distance sequence (e.g. 0, 3, 5, 8, 12, 16, 25, 35, 50 m) but, depending on the way your *acquisition system* considers the channel sequence, the correct sequence to set could be “0, 2, 5, 8, 12, 16, 25, 35, 50” or the opposite (“50, 35, 25, 16, 12, 8, 5, 2, 0”). So, to be very concrete, you always need to verify where is the first channels (in our example, at 0 or at 50 m?)

Always remember that you can analyze dispersion of any component (Z, T or R – this latter is often the trickiest one and, in general, **we recommend to consider the Z and R components**).

The following example is about the **T-component (Love wave) dispersion retrieved considering a non-equally spaced linear 6-channel array**.
We consider both the **results obtained via ESAC and ReMi** since the two techniques can provide interesting information.

As a matter of fact this is a special case since, in this case, the microtremor field is dominated by an nearby industrial facilities (factory) and the array is spread so to be "in line" with it [if you consider the following figure and the array shown in the figure **b)** you should imagine the source on the left side] (it is somehow like an "active source" acquisition where the source is a sort of "continuous microtremor source").

The following data/analyses are extracted from Dal Moro & Mazanec (2024).



T component (Love waves) passive data: a) field traces; b) channel location map; c) distances between pairs of channels; d) Bessel's functions (ESAC) for three sample frequencies (shown the experimental curves [blue dotted] together with the ones associated to the identified propagation velocity [red continuous]); e) obtained phase-velocity spectrum (background colors report standard ESAC while the overlying contour lines refer to the same frequency-velocity matrix after a *fk* filter is applied); f) *fk*-filtered phase-velocity spectrum obtained via ESAC (same shown in the previous graph as contour lines); g) phase-velocity spectra computed according to the phase shift technique considering the two possible propagation directions (direct and reverse). For all the velocity spectra we also show the lowest reliable frequencies according to Ohori et al. (2002).

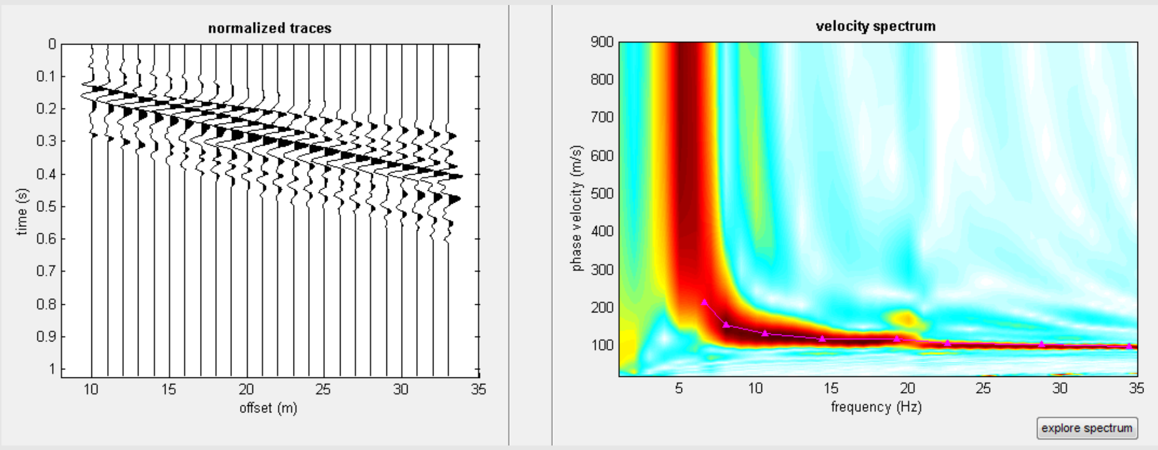
A possible [not recommended because unnecessary] procedure
[an approach from the early times of Rayleigh-wave analysis]

If you want to “compare” the dispersion curve picked from a vertical-component *MASW* velocity spectrum and the velocity spectrum obtained from a *ReMi* (vertical component) dataset, you can follow this procedure:

1. compute the velocity spectrum from a MASW dataset, pick the dispersion curve(s) according to your (subjective!) interpretation and save the picked curve (.cdp file)
2. Analyze *ReMi* data (in the end you need to save the best velocity spectrum as described in the previous pages - .mat file)
3. Now, in the “single-component analysis” panel, upload the saved ReMi spectrum (.mat file to upload clicking the “upload” button in the “handling the spectra” group) and the picked dispersion curve of the *MASW* data (button “input curve” top right in the section “visualize curves”)

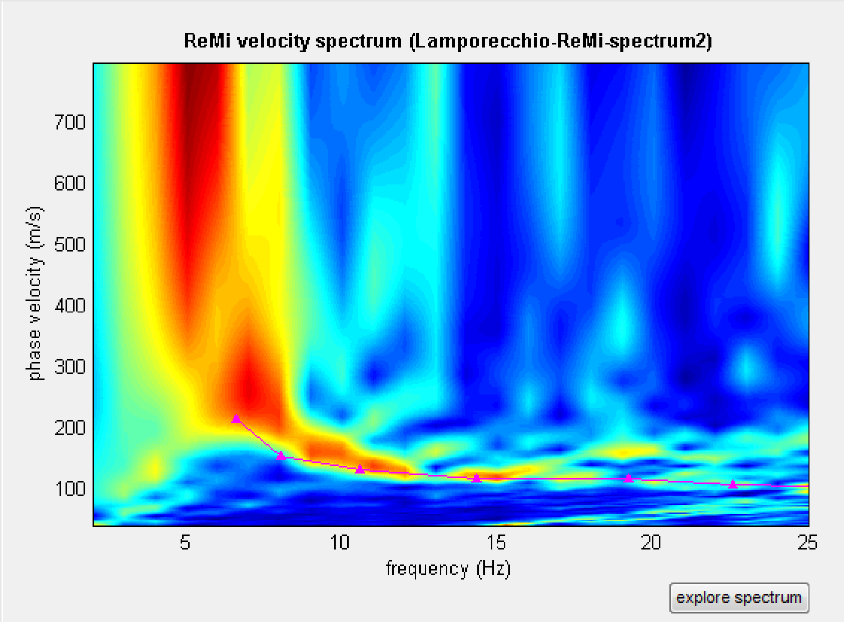
Among the data provided in the winMASW® USB/DVD for your own self-training, you can find the “Lamporecchio” dataset with active dataset for the ZVF and THF components and a passive dataset (linear array just for the Z component).

About the two following *figures*:
The first one is about active data (Z component) [fundamental-mode dispersion curve is picked down to about 6 Hz while at lower frequencies the spectrum is very likely about the first higher mode];
The second snapshot (below) is about standard ReMi (Z component) [the overlaying dispersion curve is the one picked from the MASW data]. You can see that the picking from the active data lies along the “lower limit” of the ReMi signal (and not on the peak as it happens with MASW data).



***MASW data*: traces, velocity spectrum and picked curve**

Consider that in case you want to obtain dispersion data from passive data, we recommend the <u>multi-component ESAC approach</u> [due to the different mathematics, performances are definitely better compared to ReMi]



Phase-velocity spectrum from *ReMi* analysis (background colors): note that dispersion curve picked from MASW data (Z component) lies along the *lower limit* of the velocity spectrum obtained via ReMi.

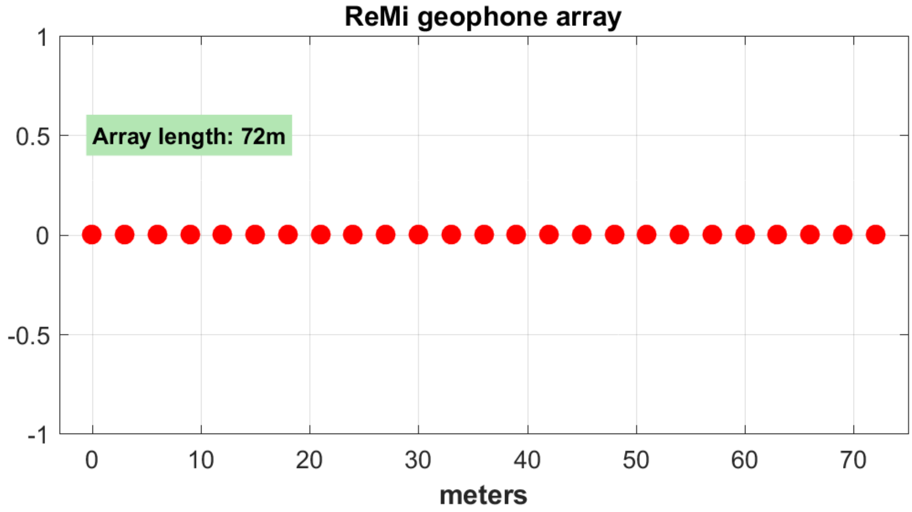
IMPORTANT NOTE

Remember that the best and simplest approach for obtaining a robust V_S profile is the joint analysis of Rayleigh and Love waves + HVSR. See recommendations and examples reported in the Appendices as well as in our *Springer* and *Elsevier* books.

Please, consider that because of a series of technical aspects (the main one is probably related to the directionality of the signal and all its consequent problems) **we highly recommend to use the ESAC technique and not the ReMi one.**

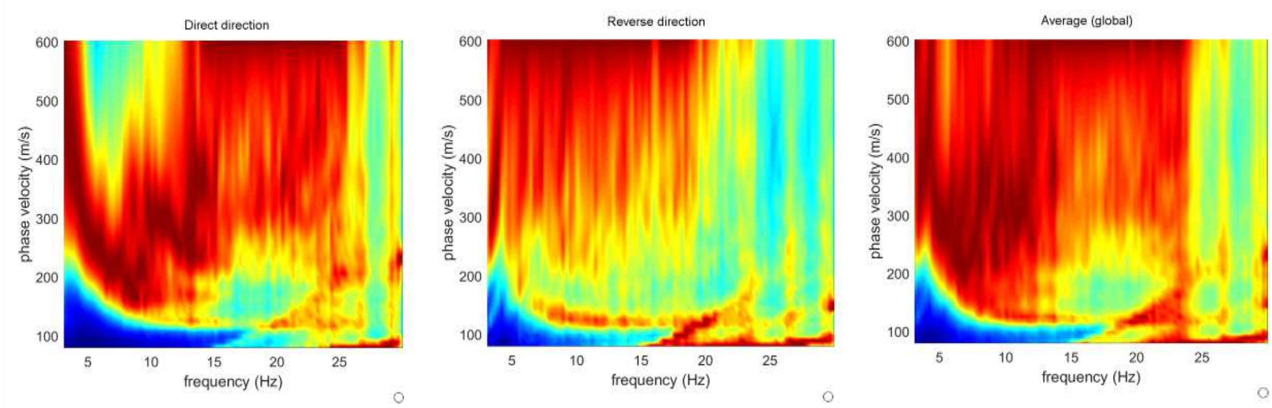
The ReMi panel (*winMASW® standard*, *Pro* & *Academy*)

In the recent *releases* performances have been generally improved.
You will obtain a scheme of your geophone array (number of channels and geophone spacing).



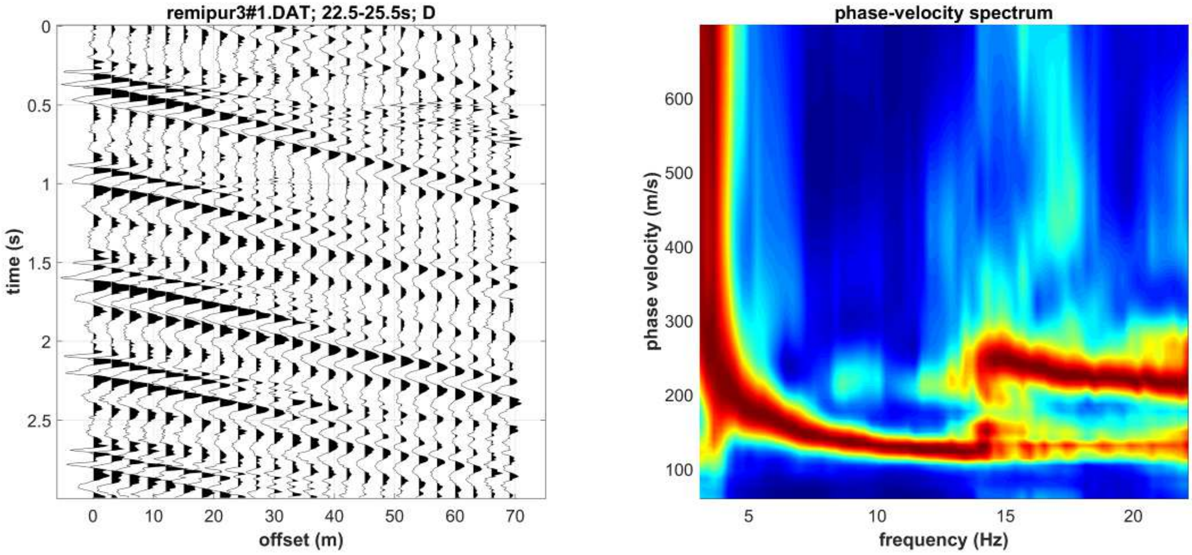
Now a normalization process (frequency by frequency) allows a better visualization of the dispersion also at the very high frequencies (where the microtremor energy is very limited).

In the following scheme the three average velocity spectra immediately obtained if you choose to compute only the average spectra). The Direct and Reverse spectra are computed while considering the signals coming "from left" or "from right". The third is the average:



The best spectrum depends on the site (i.e. on the characteristics of the microtremor field (in this case, for instance, the best spectrum is probably the first on the left).

The next figure reports the velocity spectrum (and the pertaining traces) in case you decide to select a single event/window (please be aware that this is not the ReMi method *sensu scricto*).



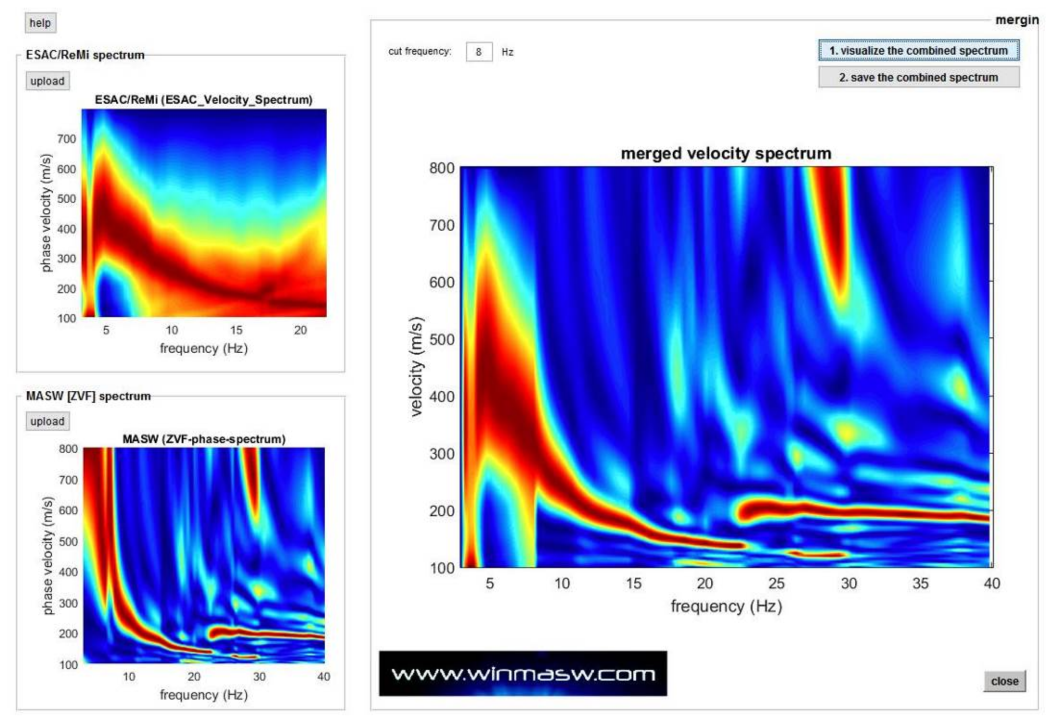
Because of the problems that a linear array necessarily creates while considering passive data (see also the box in the next page and the Elsevier book), we would strongly recommend you to use the ESAC approach rather than the ReMi technique.
The different mathematics ensures clearer results (especially at the very low frequencies) [see also next box].

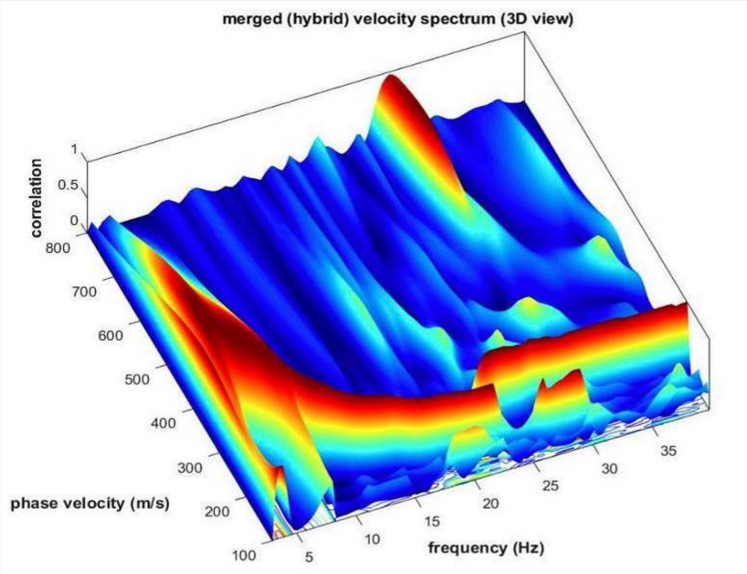
The "spectra merging" tool

By means of this tool it is possible to merge two velocity spectra obtained from MASW and ESAC/SPAC/ReMi.

Of course to obtain the ESAC velocity spectrum you need to have *winMASW Academy*, which has also a further importance advantage: you can deal with the *effective dispersion curve*, which is the curve that results from the combination of all the modes (*this means that you do not have to give any interpretation of the curve in terms of modal dispersion curves*).

Example#1 (ESAC + MASW):





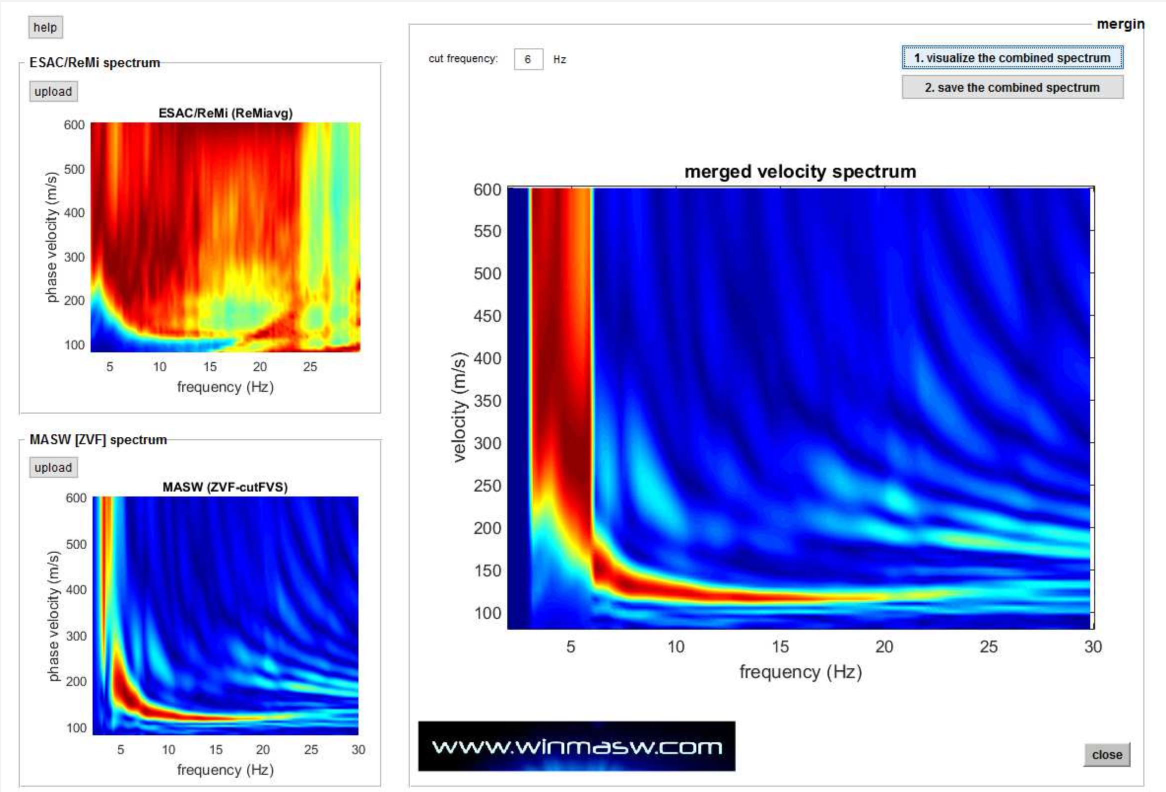
Do you see that by using the ESAC spectra you get continuous data?!

In this case data above 8 Hz belong to the MASW data while data below 8 Hz to the ESAC data).

In *winMASW® standard* it is possible to merge only ReMi (see next example) + MASW spectra.

Please, notice that the ESAC and MASW spectra are "continuous" (while if you are trying to handle the ReMi + MASW case not necessarily - see next example).

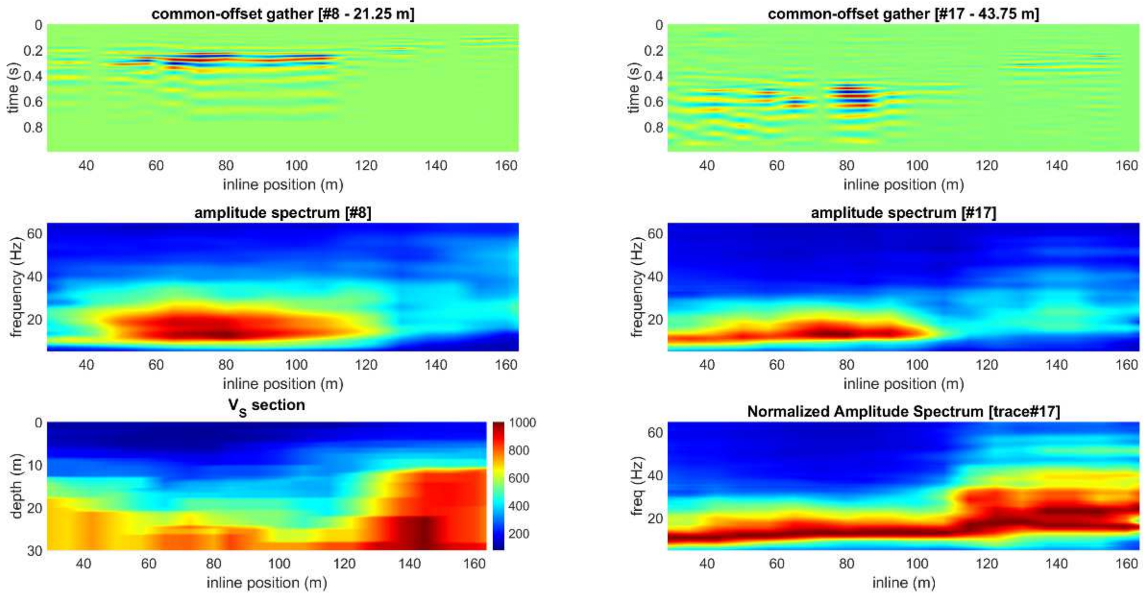
<u>Example#2 (ReMi + MASW)</u>:
Here below the *merging* of a standard MASW phase-velocity spectrum (ZVF component) [on the left] and the ReMi phase-velocity spectrum [up, on the left]:



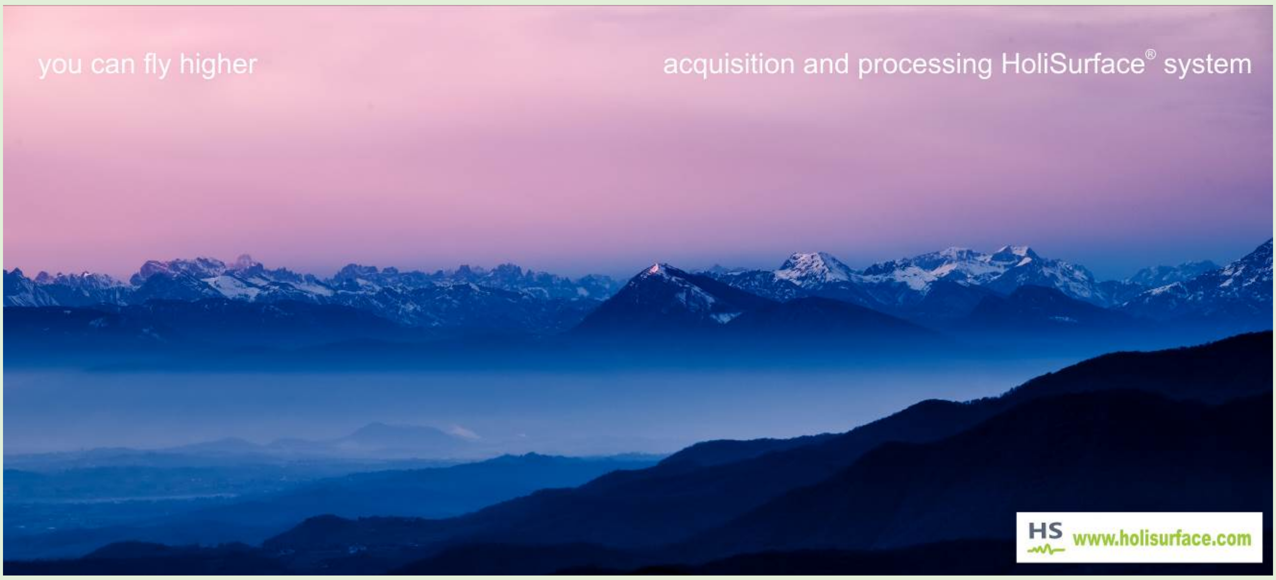
Below 6 Hz it is possible to see the "jump" due to the different way a linear array works in a passive (ReMi approach - you must follow the "ambiguous" area between signal and non-signal) or active (MASW approach) way.

By considering ESAC and MASW data this is not a problem (the two spectra are "continuous" - see previous example).

But the bottom line point is: does it make sense (for ordinary surveys) to perform such a complex procedure (acquisition and processing of both active and passive data) when the low frequencies (necessary to obtain information about the deepest layers) can be easily extracted and modeled while considering the HVSR?
Remember our key recommendation: for most of the ordinary surveys, the easiest way to obtain reliable V_S profiles is the joint analysis of RVF+THF+HVSR (see introductory section of this manual and guidelines in the Appendix).



Final figure summarizing the main outcomes: the consistency between the results of the dispersion analysis and the amplitude spectra of the raw data is apparent.



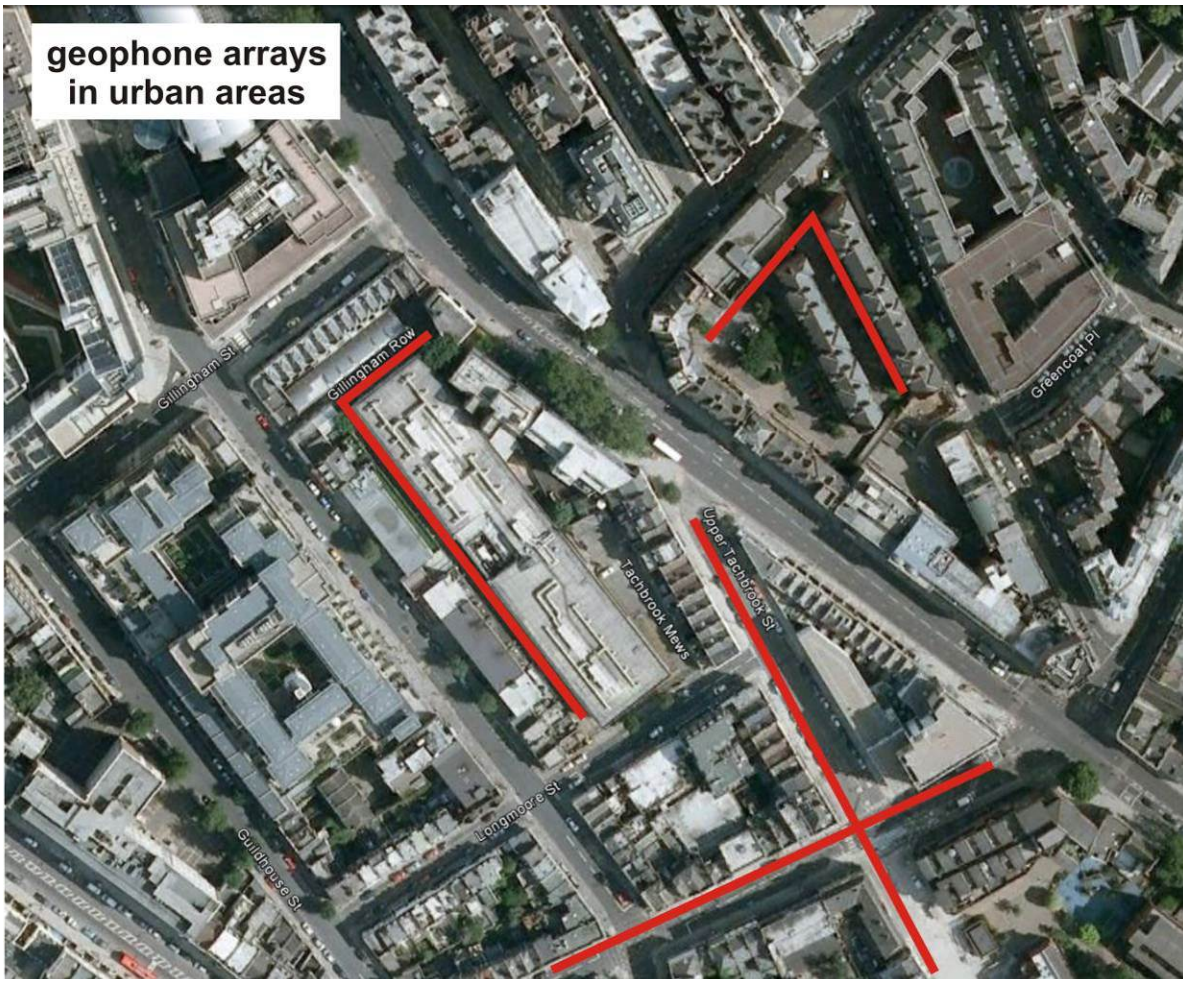
Do you want to do the same for one of your next surveys?

1. Record your (possibly multi-component) data and save them according to the nomenclature we recommend (e.g. ZVF_dx5_mo5.sg2 and RVF_dx5_mo5.sg2)
2. Take a few pictures of the area during your data acquisition
3. Give us the stratigraphic information you have about the site
4. Give us the location (and, in case, topography) of the central point of the array for each shot

winMASW@winMASW.com

4.4 ESAC [Extended Spatial AutoCorrelation] (Academy version)

ESAC is particularly suited for the analysis of passive datasets acquired while adopting bi-dimensional (2D) geometry. That means that geophones are planted not in a straight line but following 2D geometries (circles, L-shaped, crosses or "random" distributions).
It goes without saying that ESAC mathematics can also be applied to linear arrays and in several cases this is preferred (see for instance the **2D-SuPPSALA** procedure).



Some introductory notes

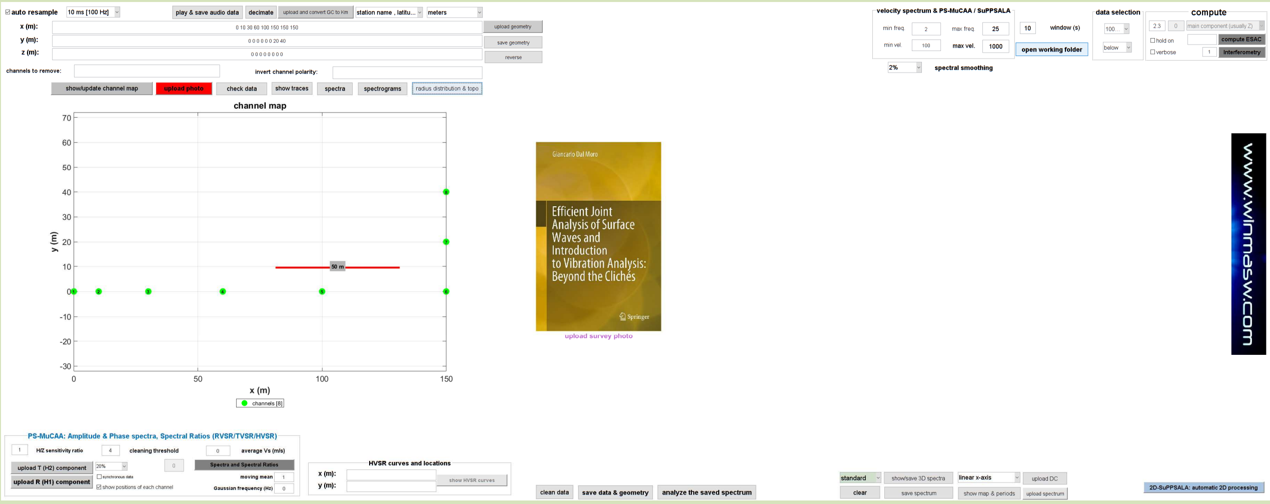
- the possibility of analyzing data acquired considering a 2D geometry allows to overcome the directionality issues which somehow influence the ReMi approach (but is a 2D array really necessary?)

- there is no "ideal" geometry. The way you are able to deploy your geophones depends on local conditions. The easiest geometries are clearly those that require the minimum effort (L-shaped or linear); often the circular one is the most difficult (please consider that the location/coordinates [*x, y*] of the geophones must be accurate). The origin of the Cartesian system to adopt is absolutely irrelevant, so your [0, 0] point can be anywhere.

- since these methodologies assume the *plane-wave condition*, it is important that the main "sources" are distant enough to meet such condition (consequently do not use these methods for analyzing datasets acquired while nearby microtremor sources are present)

ESAC main panel

In the upper-left area it is possible to insert the [*x, y, z*] coordinates (which can be actually written/saved in a simple ASCII file - see next pages for the format). In a further line ("channels to remove") it is possible to indicate traces that we want to exclude from the analysis (for instance because too noisy).



Positioning of the channels (pay attention)

Coordinates of the channels/geophones must be accurately fixed

Non-expert fellows (not fully familiar with their own acquisition system) might misconstrue the correct sequence of channels (i.e. they may think that the actual channel#1 is the channel#24 or *vice versa*).
A simple way to verify the actual channel sequence is to take a hammering at the beginning of the acquisition (this way it will be clear the actual channel sequence/position).

In the upper-right corner of the ESAC panel user can set the parameters to consider for the ESAC analysis.

By activating the option "*verbose*" you will obtain a series of "intermediate" outputs useful to check the data quality etc. (see next pages).

In the lower area of the ESAC panel there are numerous tools that we invite you to explore (always remember that by hovering the cursor over the button, a brief description of the type of operation performed by that tool appears).

In the 2023 release (of winMASW® Academy) you can also analyze **multi-component data** (see PS-MUCAA and 2D-SuPPSALA tools). For this reason, in the lower left corner of the ESAC panel there are two buttons aimed at uploading the horizontal components (R and/or T). For mere commercial reasons (several users still work with vertical geophones), the vertical one is considered the “main component” and data are uploaded from the toolbar at the top of the ESAC panel.

ESAC data acquisition

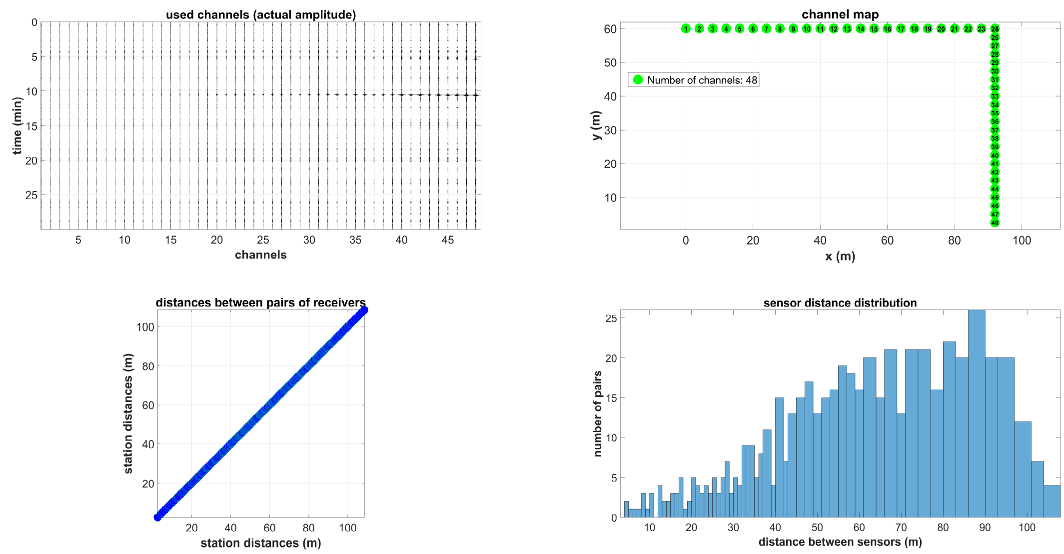
- **record length**: how long should be a dataset to safely perform this kind of analysis? There is no magic and universal number since it depends on the site (its stratigraphy and the characteristic of the background microtremor field) and on the goals (what's the lowest frequency we wish to accurately sample?). As a general rule 10 minutes can be sufficient but it is definitely better to acquire more

- **number of channels**: for standard 1D surveys a reasonable number is between 9 and 16 (for 2D analyses 24 is the minimum – see **SuPPSALA procedure**).

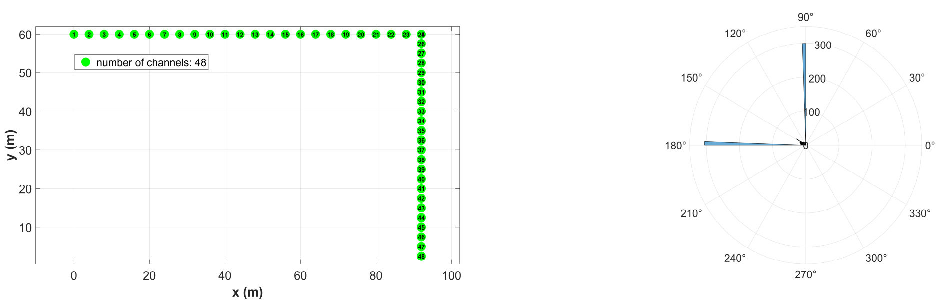
- sampling interval/rate: 5 ms (200 Hz) is ***much*** more than enough (always remember the **Nyquist-Shannon theorem**)

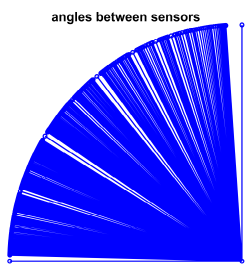
If you acquire with a higher sampling frequency, in order to avoid higher computational times it is recommended to ***re-sample*** the data (**"decimate" button**)

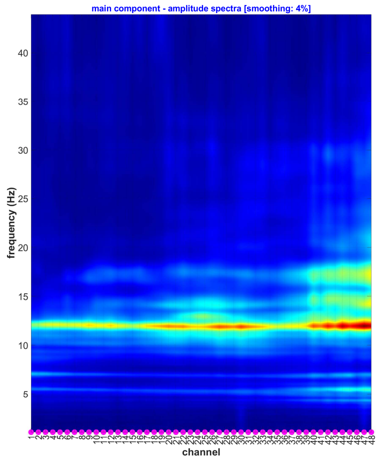
The following plots show an example of a possible (and easy to manage) geometry (L-shaped) [please consider that for ordinary 1D surveys, 48 channels are absolutely useless].

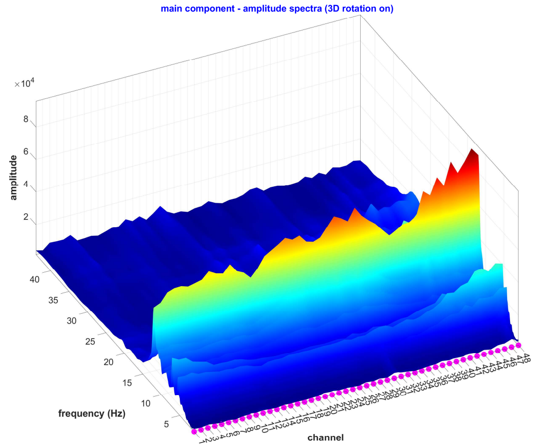


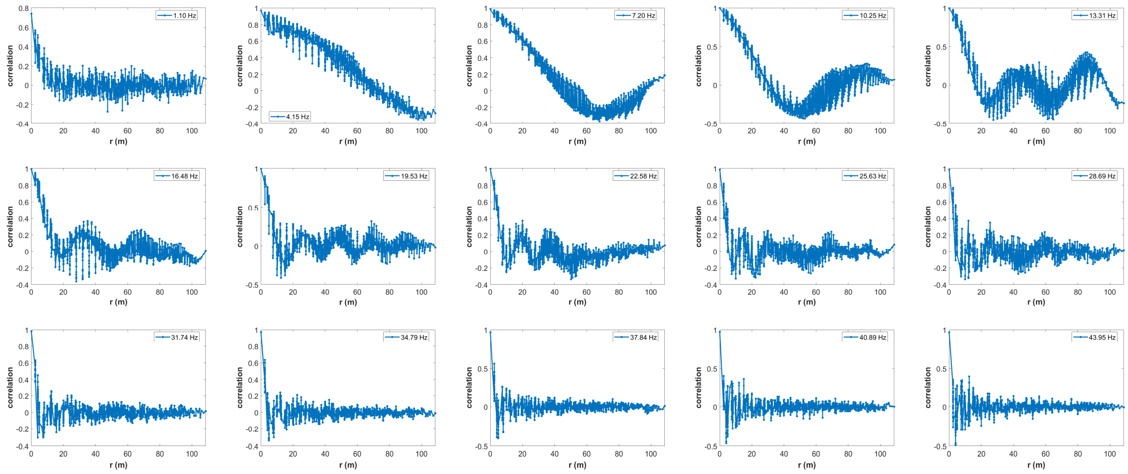
Since these techniques are particularly useful for retrieving the dispersive properties at the lowest frequencies, it is important to underline that the equipment should be properly set (good seismograph, low-frequency geophones and large arrays).



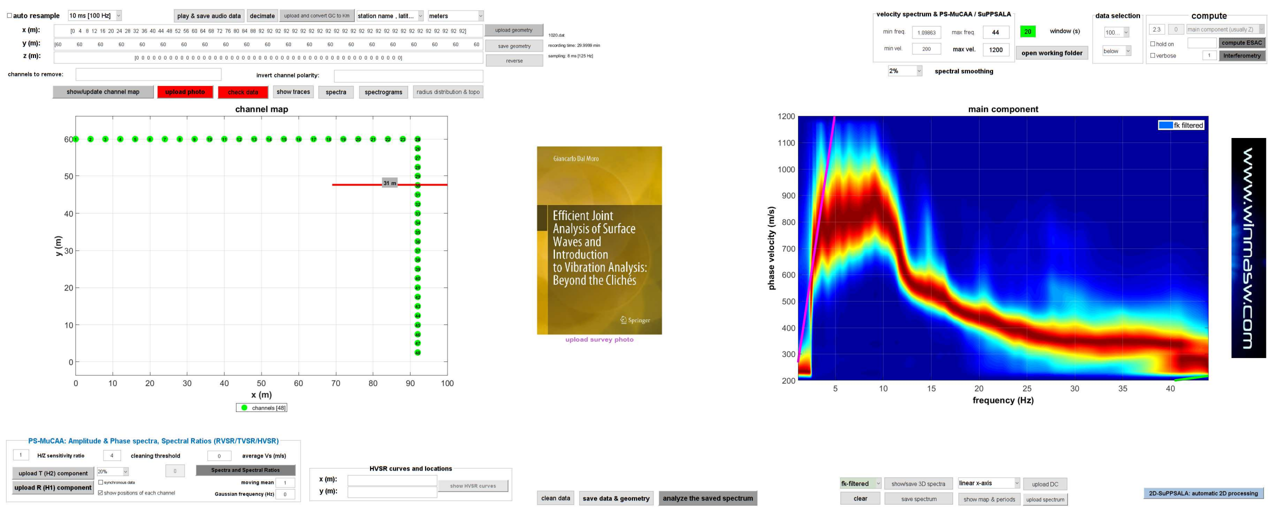




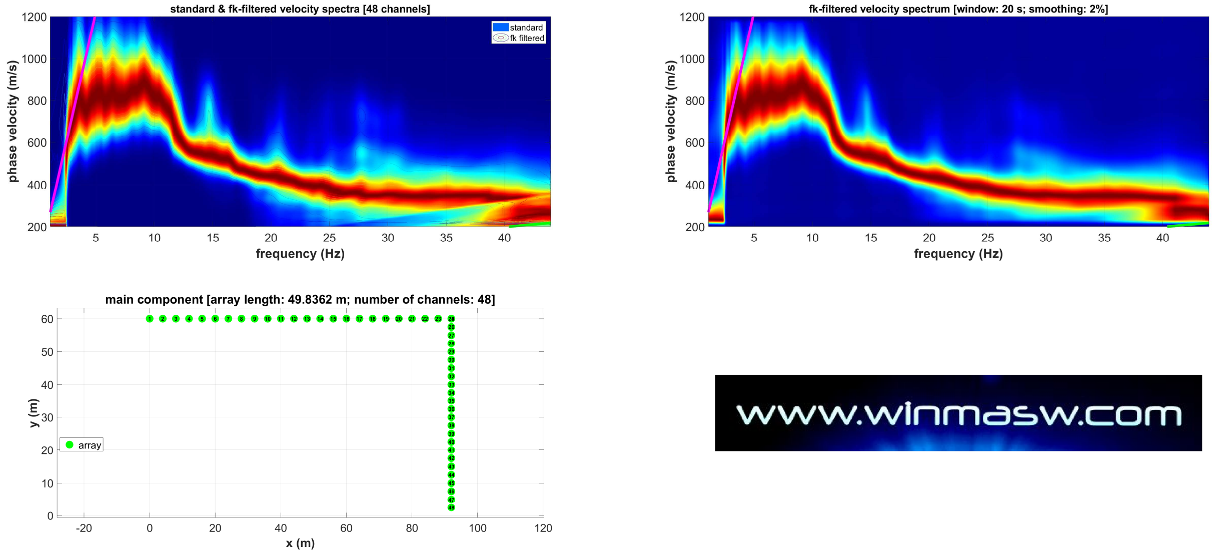




In the following snapshot, the obtained dispersion (main ESAC panel). The magenta line is about the **largest wavelength** which is possible to identify. This value is site/data depended and can be modify in the box within the "compute" group (upper right corner) [default value 2.3 – for details see Ohori et al. 2002).

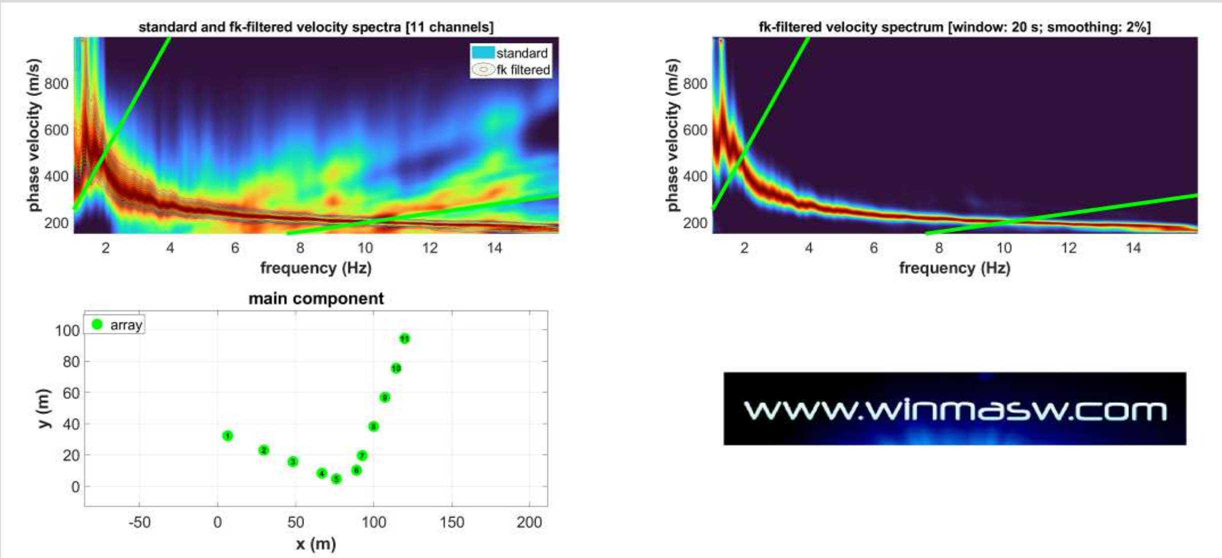


The following figure shows the phase velocity spectra obtained considering both the ordinary (**standard**) ESAC processing as well as after a mild f-k filtering (see our "***Efficient* joint analysis of surface waves and introduction to vibration analysis: beyond the clichés**" 2020 Springer book).



Minimum and maximum reliable frequencies in ESAC/SPAC analysis

While the *maximum* determinable frequency (high-frequency green line – see figure) is clearly/objectively determined by the *spatial aliasing*, the minimum reliable frequency is more difficult to fix. The low-frequency green line shown in the next figure is based on Ohori et al (2002) ("… twice the largest sensor spacing as the maximum wavelength.") but it must be pointed out that such a value is really site and data dependent. So, we cannot objectively determine the lowest reliable frequency and during the joint analysis of the dispersion and the HVSR [see for instance our case studies from our web site and our publications], in the very low-frequency range, we should therefore give a bit more credit to the HVSR match.



ESAC/SPAC analysis: only the curve within the two shown green lines is fully reliable, while at higher and lower frequencies we need to carefully and mindfully evaluate the data, case by case.

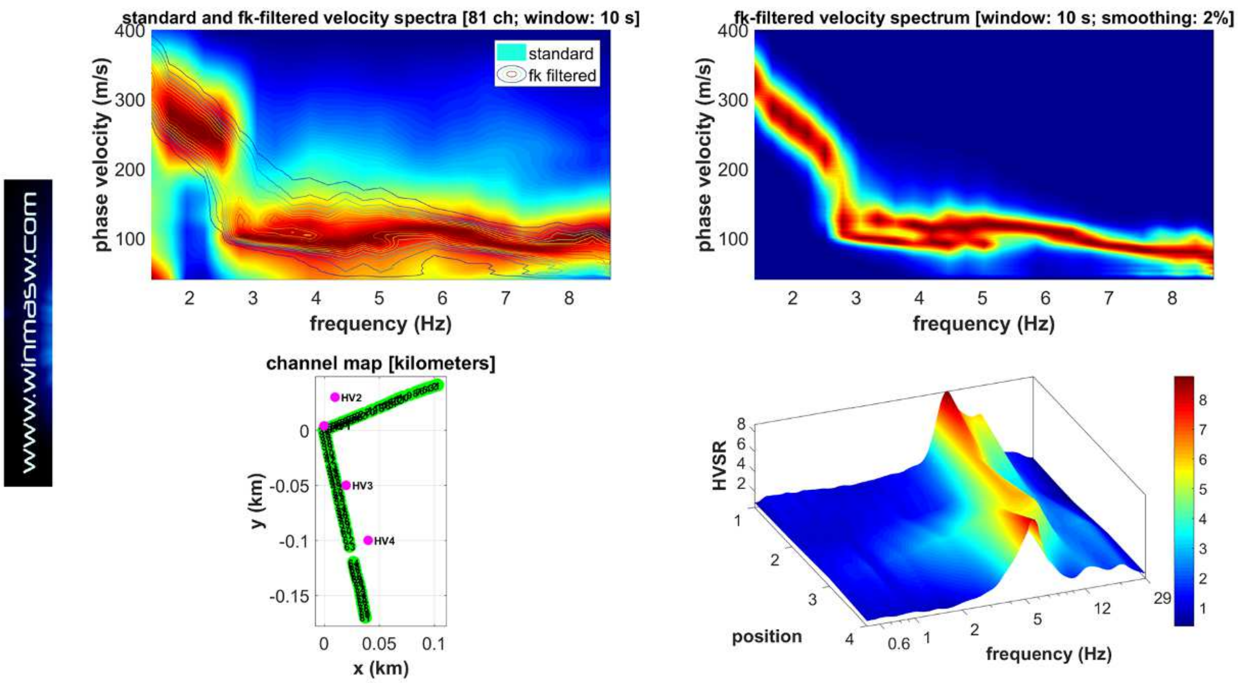
ESAC data: linear or bi-dimensional arrays?

Let us see a couple of examples aimed at understanding whether 2D arrays are really necessary to perform reliable ESAC,

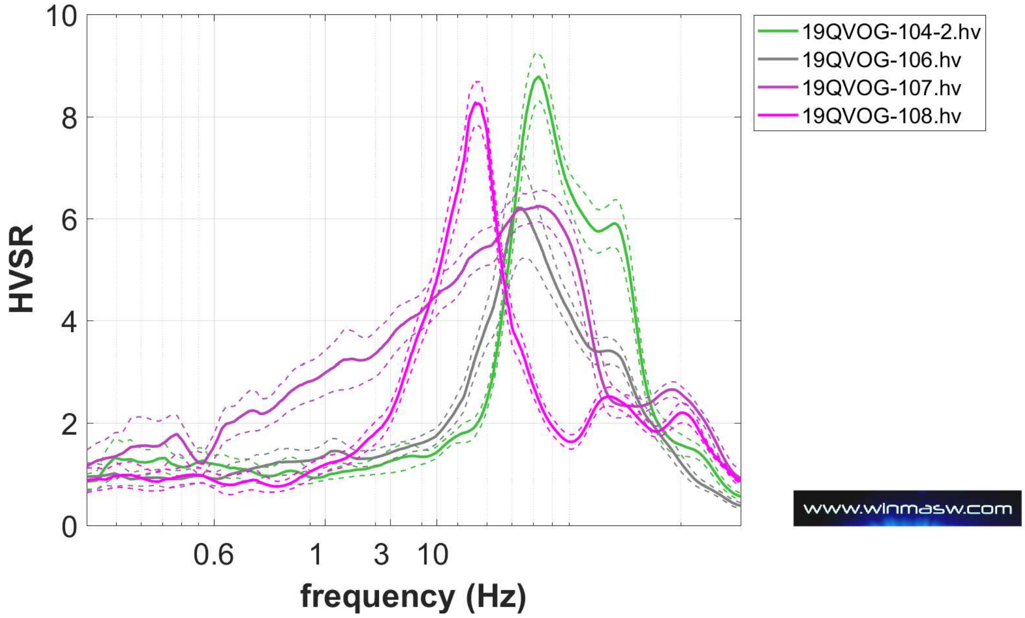
dataset#1

For this first example we consider a 2D *array* with just vertical (Z) geophones. Along the array we also have 4 HVSR curves.

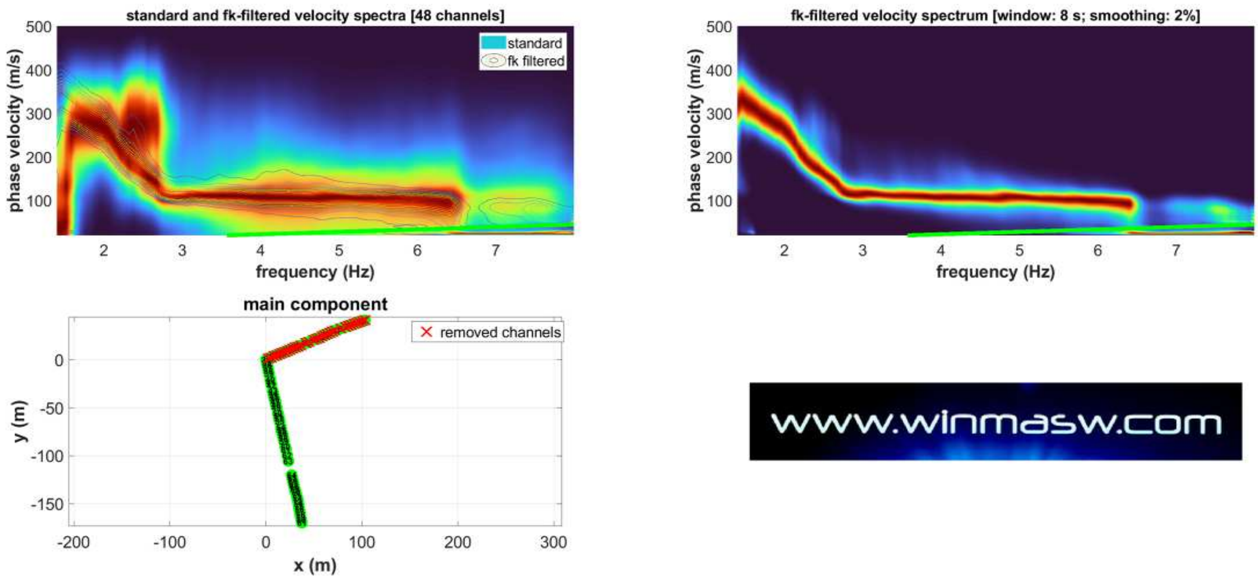
In the following figure are shown the channel map and the obtained phase-velocity spectra (original and fk-filtered) in case we keep all the 2D channels (about the fk filtering, please see the Springer 2020 book). In the lower right corner and in the successive figure are also shown the 4 available HVSRs (see map in the lower left corner).



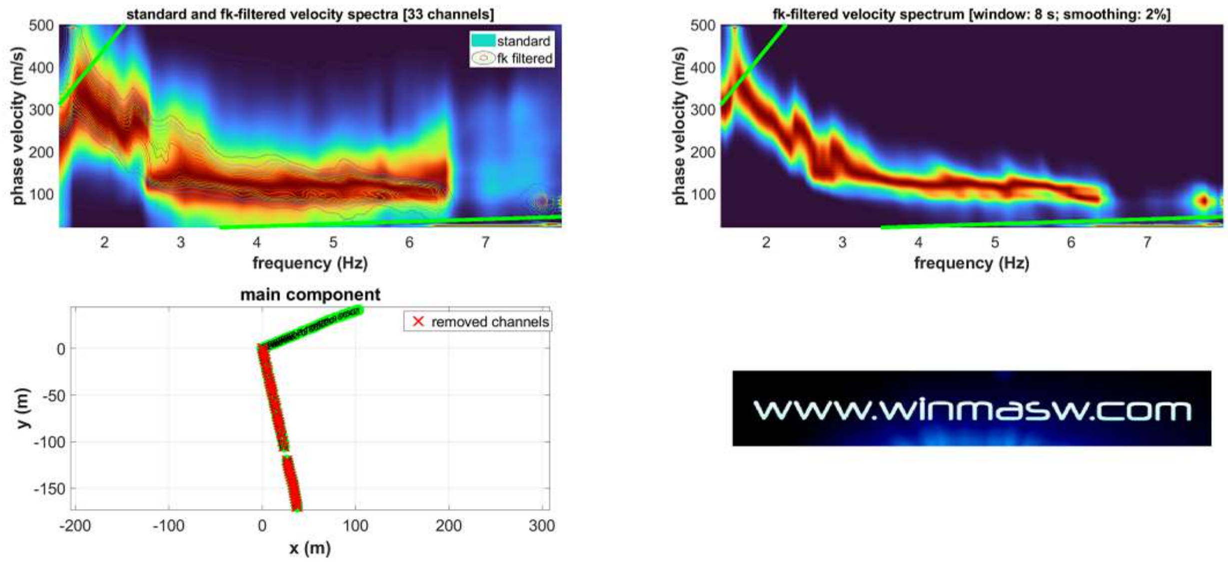
If we compare the 4 HVSR curves we clearly highlight the fact that the area is not homogenous (the 4 curves show some relevant difference) and some non-irrelevant lateral variation occur (please consider that the phase-velocity spectrum we obtain while considering all the channels is clearly just an average spectrum representing the whole area in general terms).



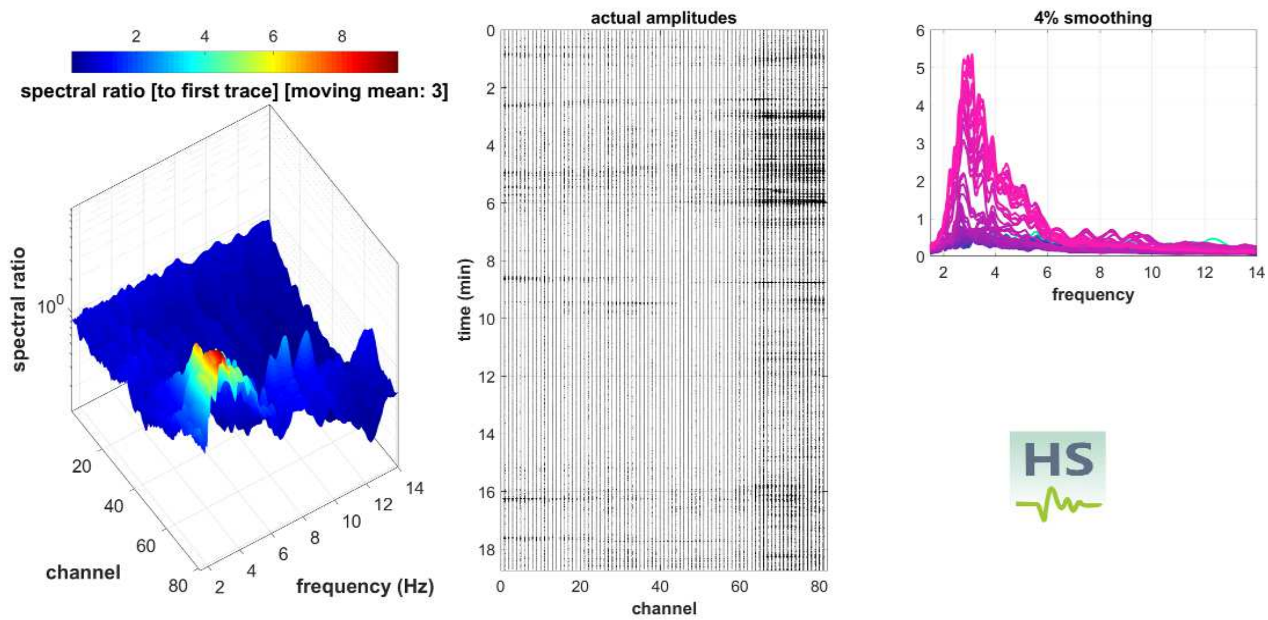
We now keep just the channels along the NS direction (i.e. we remove the channels marked with a red cross in the following snapshot) and compute the phase-velocity spectrum according to the ESAC processing.
Do you see any really significant difference compared to the velocity spectrum obtained while considering all the 2D channels (see previous figure)?
Clearly nothing really significant and the small differences are surely due to the lateral variations clearly demonstrated by the differences in the 4 HVSR curves.



We finally do the "opposite" (we keep the channels along the EW direction and remove the channels along the NS direction – see channel map in the following figure).
Again: do we see any significant difference in the phase-velocity spectrum?
Again nothing really significant and the small differences are surely due to the lateral variations clearly demonstrated by the differences in the 4 HVSR curves.



Thanks to the *spectral ratios* that you can compute from the ESAC panel, we can verify that the last channels show larger amplitude spectra because we are close to the main road which, as we have shown, does not create significant problems while considering linear geometry instead of a 2D array.



What does that mean? This demonstrates that the mathematics of the ESAC processing is such to allow also linear arrays and this opens up a series of interesting possible applications: the **PS-MuCAA** approach presented in the next pages. A few recommendations about the data acquisition in case of linear arrays are reported in the PS-MuCAA section of this manual.

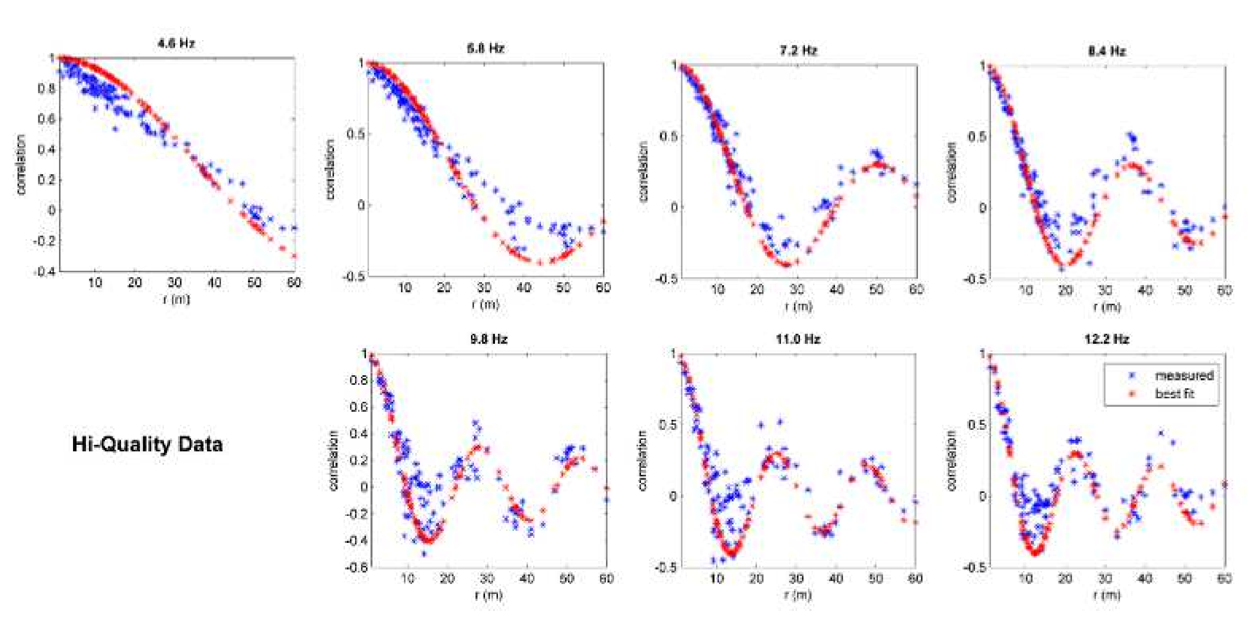
dataset#2

work-in-progress [stay tuned]

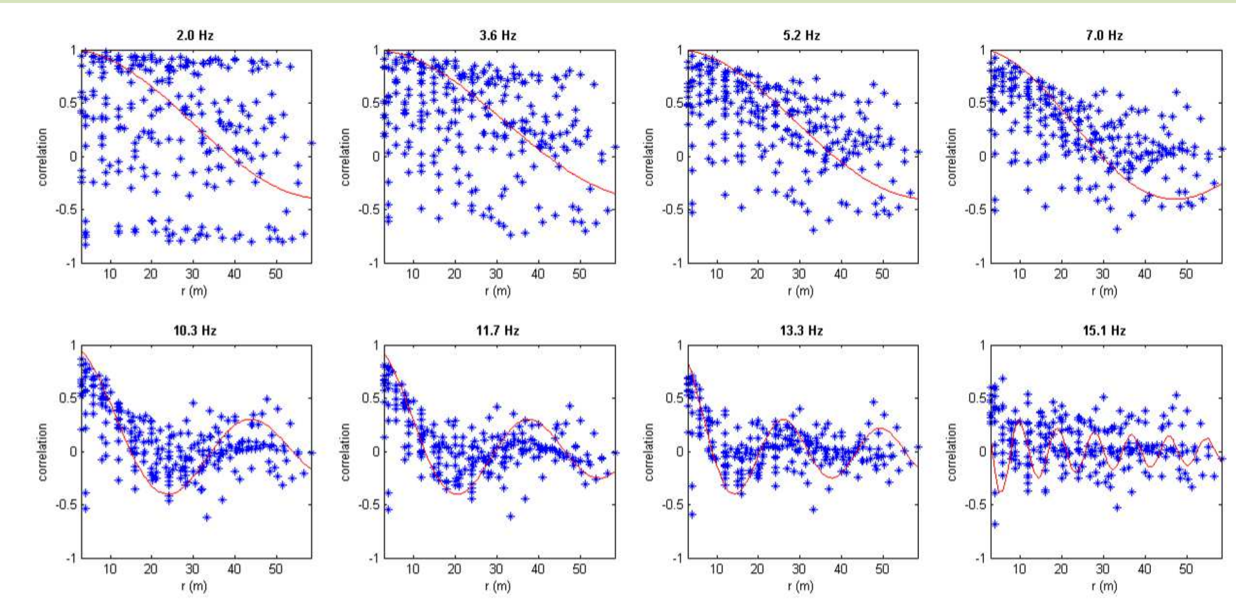
Understanding the data quality

Through the assessment of the spatial correlations (from ESAC) it is somehow possible to understand the overall data quality.

The following graph are associated to high-quality data (blue dots represent observed correlations, red data are the best-fit *Bessel* functions).



Next plots report the same quantities for a lower-quality dataset (same data presented in the previous box), which depends on several factors: site characteristics in terms of both lithology and environmental noise/signal, length of the array (and positions of the geophones, quality (and setting) of the hardware equipment (seismograph, geophones, cables etc.).



Data input and parameters

It is possible to upload several datasets together (as common in *Windows*, to do it is sufficient to use the *ctrl* button). In fact, some seismographs can record at the most 1 minute: by recording several datasets (each for instance 1-minute long) it is then possible to acquire a sufficient amount of data to perform all the analysis based on passive acquisitions (ReMi, ESAC, FK) (most of the times 15 minutes are enough).

Some points:

- The *"Resampling"* option: to reduce the computational times it is absolutely recommended (this option is active by *default* but can be de-activated).
- Computational load for the FK method are higher than for ESAC and strongly depend on the adopted parameters. We recommend to consider frequencies not higher than about 30-40 Hz. High frequencies are in fact better imaged via active data. The lowest useful frequency depends on the array length/dimensions, the characteristics of the site and on the *eigen frequency* of the used geophones.
- The positions of the channels/geophones can be reported manually in the pertinent windows or can be written in a simple ASCII file according to the syntax indicated in the following box (the file must have a header line and the *.pos* extension).

File ASCII (*.pos* extension)

```
Xcoordinates  Ycoordinates Z (topography)
-48    0    101
-44    0    101.2
-40    0    102
-36    0    102.1
-32    0    102
-28    0    103
-24    0     101
-20    0    102
-16    0    102
-12    0    103
-8     0    104
-4     0    104.4
0      3    105
0      6    105
0      9    105.5
0      12   106
0      15   106.6
0      18   107
0      21   107.3
0      24   108
0      27   108.4
0      30   109
0      33   109
```

- O*utputs*: by *default* it is computed (and saved) only the ESAC dispersion curves and its respective "pseudo velocity spectrum" (this is just the *misfit* between the observed correlations and the values obtained by the *Bessel* function computed for the different phase velocities).

Outputs

Log file, images and files automatically saved (in the "working folder")

When the analyses are accomplished, in the working folder you will find the following files (automatically saved):

logESACFK.txt (log file summarizing the performed operations)

ESACdc.cdp (dispersion curve saved as *effective* curve - Tokimatsu et al., 1992): since - compared to modal dispersion curves - the computation of the effective curve requires heavier computational load, its automatic inversion requires state-of-the-art PC (recommended an *esacore* CPU).

ESACpsvelspe.mat (pseudo velocity spectrum determined through the ESAC analyses)

snapESACFK.png (snapshot of the main panel with the resulting spectrum and the dispersion curves)

Moreover, if you activated the "verbose" option you will also get the following files:

CrSpVsFr.png (+ .fig): Cross-spectra versus frequency

ESACdata.png (+ .fig)

2Dpassivedata.png (+ .fig): data, channel positions, radii

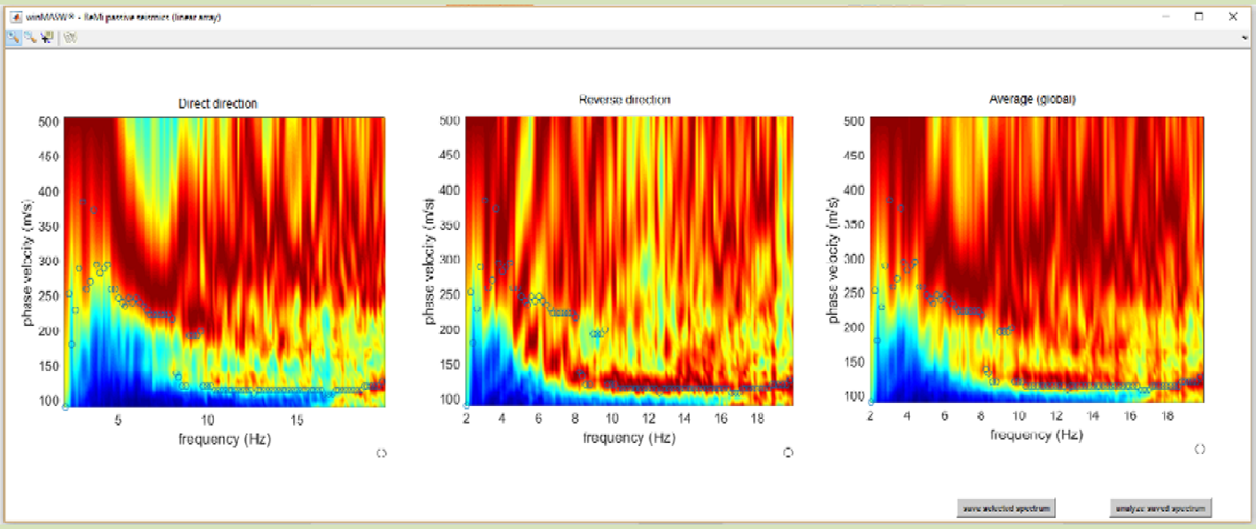
Remember that the.cdp files are simple ASCII files which can be uploaded in *winMASW* ("input curve" button - see next pages).

ReMi spectra and ESAC processing

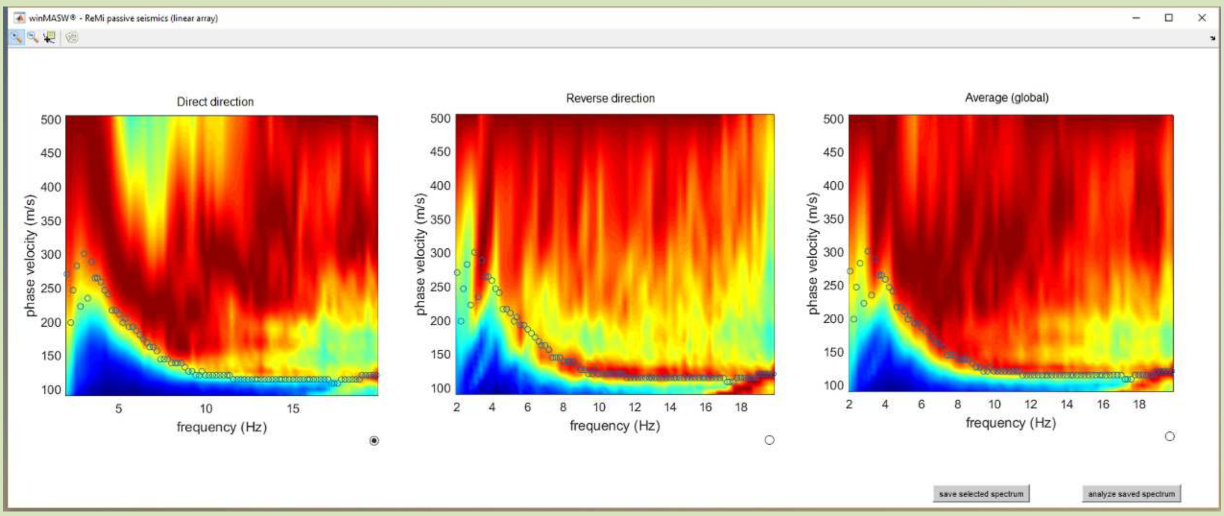
In the ReMi panel (<u>where purely-linear arrays can be analyzed</u>) it is possible to activate the ESAC option. By doing that we will obtain an overlap of the ReMi spectra and ESAC dispersion curve.

Dataset "Purgessimo" (provided as example dataset together with the software).

Analyzing just a couple of files (total length 2 minutes) we obtain a clear evidence of a mode jump around 9Hz (which is absolutely not so common while analyzing passive data, but which is absolutely useful for our analysis).



Analyzing the entire dataset (more than 16 minutes) we get the following data:



In both cases the lowest frequency which is actually possible to safely consider for the ESAC dispersion curve is about 3Hz (below this value the velocity decreases, losing its "meaning"). It is very likely that analyzing a non-linear (i.e. bi-dimensional) array with longer radii, such lowest frequency would decrease thus allowing the reconstruction of the V_S of deeper levels.

Pay attention: these evidences cannot be generalized. The aim of these notes is to help the users to get familiar with data, analyses and phenomena.

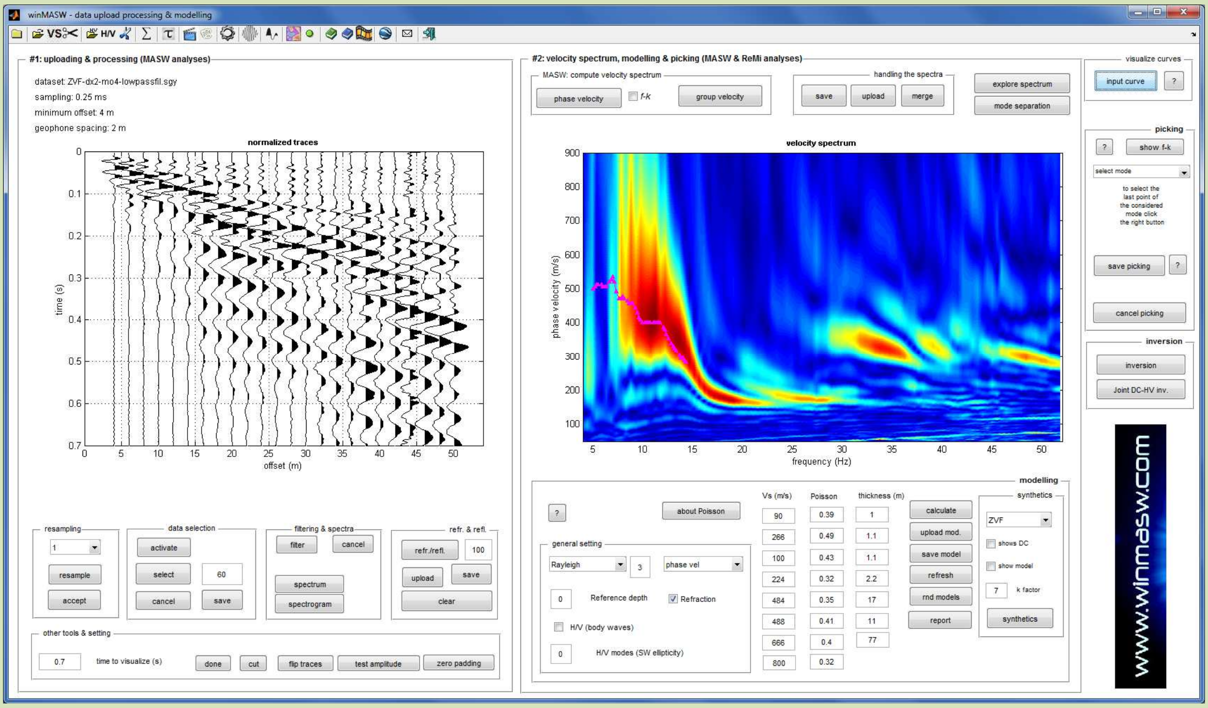
Rayleigh and/or Love?

These methodologies can be easily used for determining the dispersive properties of Rayleigh waves, by considering the vertical motion (which is not influenced by Love waves).
In order to analyze Love waves (in the horizontal plane), things become more complex (see e.g. Tokimatsu, 1995; Di Giulio et al., 2006; Kohler et al., 2007). We then suggest to all the beginners to deal with Rayleigh waves (vertical component).

On the other side, you can also consider the horizontal components and obtain many more information about the subsurface conditions (see the "**Multi-component analysis of passive data in the new ESAC panel: the PS-MuCAA methodology**" section of the manual).

Integrating MASW and ESAC dispersion curves and some recommendations

ESAC is useful especially in the low-frequency range (active methods such as MASW or MFA can instead better perform in the high-frequency range).
Anyway a crucial point to properly image the low-frequency dispersion curve is the total length of the array. ReMi and ESAC (or any other array-based passive method) cannot be properly used if you consider short arrays. As a consequence, if your array is less than about 70m (but possibly much longer) passive techniques are quite useless and it is better to go for a joint MASW+HVSR analysis.
<u>Please remember that ESAC/SPAC is much better than *ReMi* because - thanks to the bi-dimensional array – it better handles the signal directionality.</u>
The following snapshot shows the phase-velocity spectrum obtained via active data with, overlaying, the effective dispersion curve obtained via ESAC: it is quite clear that the ESAC allows to "see" frequencies lower than the ones possible while considering the MASW acquisitions. On the other side MASW data are much better at high frequencies.



Almost useless to remark that the results of your analysis depends first of all by your expertise/skill both from the theoretical and "practical" points of view.

4.4.1 Multi-component analysis of passive data: the PS-MuCAA tool [ESAC panel]

manual-in-progress

PS-MuCAA stands for **P**assive **S**eismics – **Mu**lti-**C**omponent **A**mplitude **A**nalysis and it is a way of considering multi-component passive data and retrieve information about the V_S distribution along the considered profile (also identifying possible lateral 2D variations).

In case you record and upload multi-component data, remember you need to use the same **unit of measurements** (e.g. mm/s, m/s, cm/s or counts) for all the components.

Data acquisition

Recording time: usually 10-20 minutes are enough, depending on the characteristics of the site and on the goals.

Data need to be recorded in a quite classical fashion: a linear array is spread and multi-component passive data are recorded.

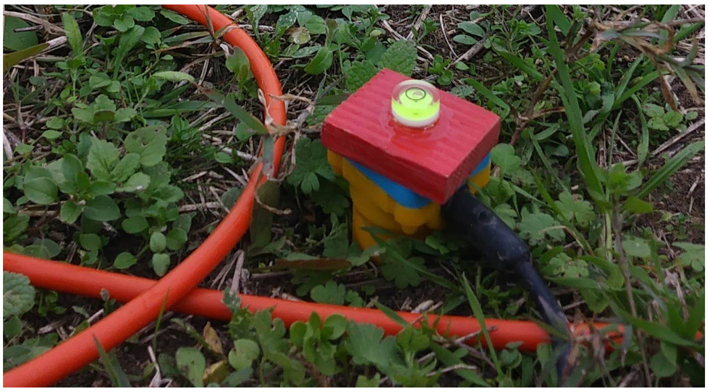
Let us consider a 21- or 24-channel array for the acquisition of passive data for all the three components or, if there is no time, only for the Z and T components.

How to record multi-component passive data?

Two common options are:

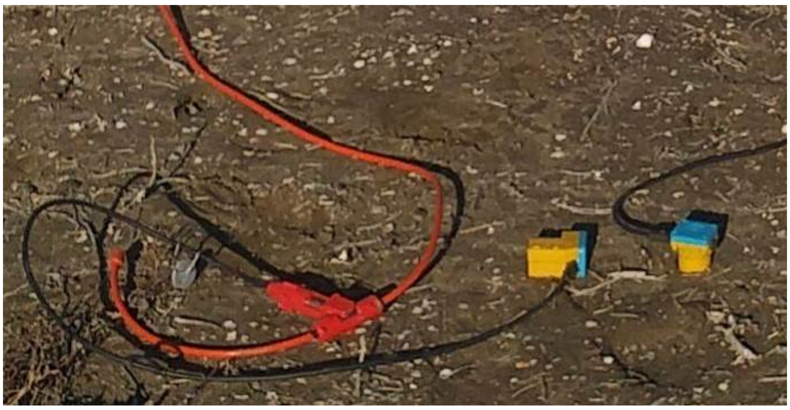
option#1

If you are using a "classical" acquisition system (seismograph and seismic cables), you can record the Z and T (and possibly R) components in successive acquisition (you first connect the vertical geophones and record n minutes of passive data, then connect the horizontal geophones to record the T component [finally you can rotate the geophones and record the R component])



Acquisition of the Z component considering a classical system (seismograph + seismic cables): when you plant your Z geophones, you should carefully verify that the geophone is really vertical (a simple and cheap bubble is enough).

Linear array for the dispersion and amplitude analysis to identify possible lateral variations (**PS-MuCAA tools**): we can see one seismic cable (classical acquisition system) and both horizontal and vertical geophones deployed so to collect multi-component data. You first connect the Z geophones (and record your passive data) and then the horizontal geophones (for the acquisition of the T component – you can then also record the R component by simply rotating the horizontal geophones by 180°).



option#2

If you are using a 3-component (e.g. wireless) system, you can record simultaneously all the three components necessary to perform our multi-component analysis for the analysis of both the dispersion and amplitude (PS-MuCAA).

Acquisition of 3-component data using a wireless system composed of several (in this case 12) 3-component geophones (each box is a 3-component geophone).
Close up of the previous photo: on the right, a vertical (Z) geophone and, on the left, a horizontal geophone rotated so to collect the T (transversal) component. By rotating the horizontal geophone by 90° we will then collect the radial (R) component.

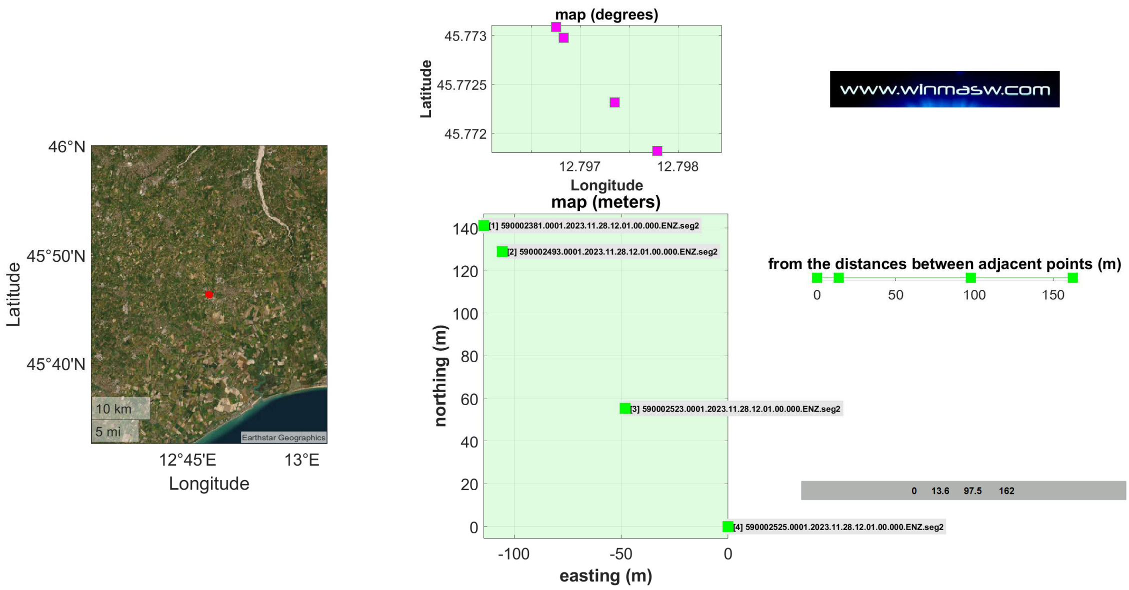
courtesy of ***roXplore.ch***

Easy management of SmartSolo data in the ESAC panel (winMASW® Academy)

Continuous (passive) data recorded with the **SmartSolo system** can be easily upload and processed in the ESAC panel. Please, remember that ELIOSOFT can provide you with both traditional acquisition systems (with cable) as well as with the SmartSolo cableless system (independent 3-component geophones synchronized via GPS).
The easiest acquisition procedure is according to a **linear array** and in the following "educational" example (aimed at showing you how simple is the procedure) we will use the data from just four **SmartSolo IGU-BD3C-5 units**.

Acquisition

Four (4) **SmartSolo IGU-BD3C-5 nodes** are deployed according to a linear array. The "North" of the nodes **is not oriented according to the geographical North** but according to the seismological components: the "North" is the direction of the array (in seismological terms this is called the **radial component**) and, necessarily, the EW direction is actually the transversal component (which is perpendicular to the radial component). Therefore, we do not speak about NS and EW but, in addition to the vertical one, we consider the **radial and the transversal components** which are the direction of the array and the axis perpendicular to it, respectively.
We highly recommend to deploy the nodes using a simple rule: the increasing Serial Number (i.e. at your first point you deploy the node with the smallest serial number and then deeply the other nodes using the nodes with an increasing Serial Number).



Here below, an example of array with just four (4) SmartSolo nodes (i.e. SmartSolo 3-component geophones). **In order to easily (straightforwardly) analyse the radial and transversal components, the geophones are deployed with the NS direction inline with the direction of the array. In other words, our "relative North" (which coincides with the direction of the array and represents the radial component) is pointing to (more or less) N35W.**

While dealing with a linear array (usually recommended), the North of the SmartSolo node does not have to point to the geographical North. It must coincide with the direction of the array.

Converting the SmartSolo data

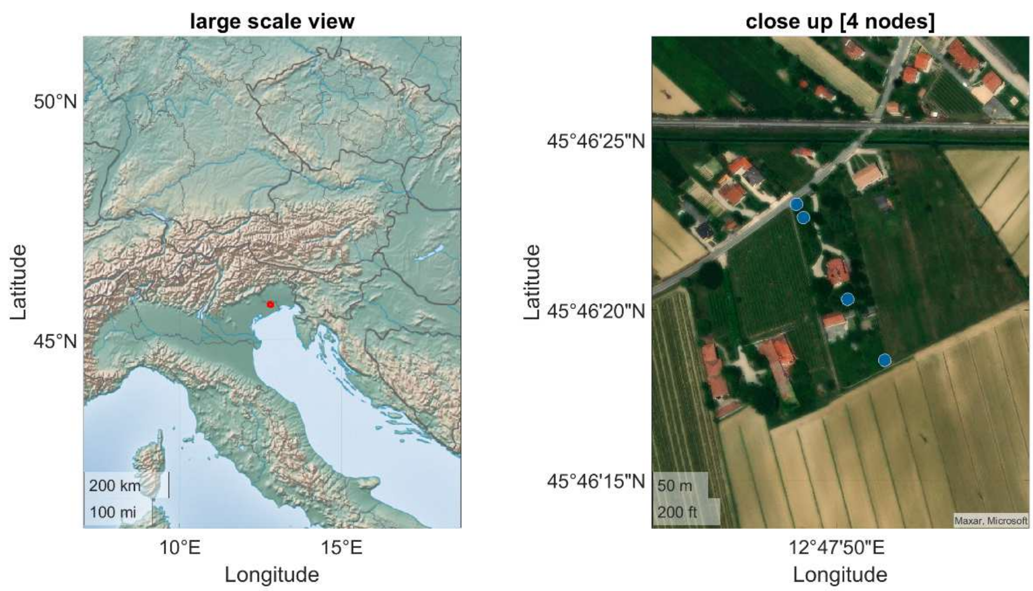
Once you are at home, with the software provided with the SmartSolo nodes, you will save/convert the data from your nodes in a series of files (one for each node) with the 3-component data. This means that, in our case, we obtain four files (one for each node) containing all the three components. By default, you will obtain four files with this kind of filenames:

590002381.0001.2023.11.28.12.01.00.000.ENZ.seg2
590002493.0001.2023.11.28.12.01.00.000.ENZ.seg2
590002523.0001.2023.11.28.12.01.00.000.ENZ.seg2
590002525.0001.2023.11.28.12.01.00.000.ENZ.seg2

The first series of digits are the **Serial Number of your nodes and the nodes need to be deployed following an increasing Serial Number – see map shown previously: we started from the upper left corner [1 -** 590002381**], then moved to the second point [2 -** 590002493**]**, the third [**3** - 590002523] and finally the forth one [**4** - 590002525]. The last three letters in the filename mean that the first trace is about the EW (transversal!) component, the second about the NS (radial) component and the last one about the vertical one.

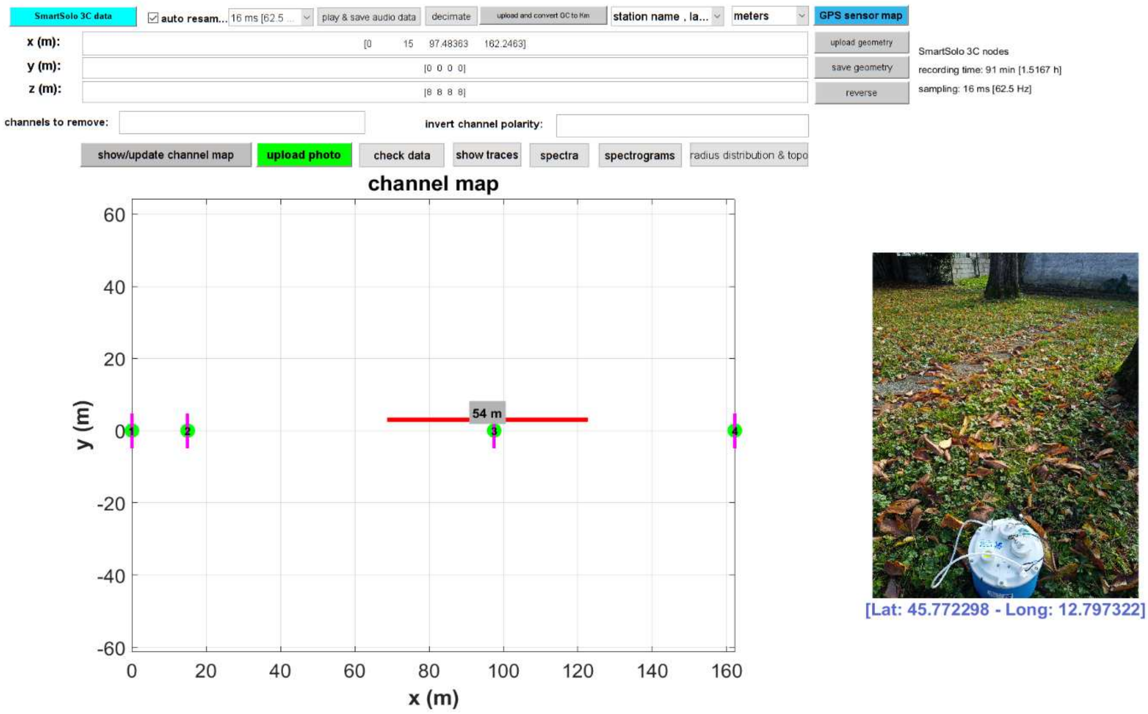
Uploading the data in the ESAC panel

In the upper left corner, a light-blue button (“upload SmartSolo 3C data”) allows you to upload all your four files at once. The winMASW® software will extract the GPS information from the seismic data and automatically create all the maps you can see in this section. Of course, this information is usually not extremely precise but you can easily (manually/personally) modify the distances (offsets). In very practical terms: inaccuracies should be personally adjusted/modified **when the sensors are relatively close to each other** but can be ignored for very distant nodes. In the present case we easily measured the distance between the sensor #1 [590002381] and #2 [590002493] and modified the value according to the actual measurement (15 meters instead of 13.6). **For very distant nodes** [in our case the nodes 590002523 and 590002525], in case it is not possible/easy to measure the actual distances we can work with the values automatically extracted from the GPS data since the error is usually small enough not to create serious problems (an error of 2 meters for two sensors 80 meters apart is small enough that it should not cause too much concern). Always consider that this kind of techniques are important especially for obtaining large-scale and deep (low frequencies) information.



Throughout the procedure, a few dialog boxes will help you in properly uploading the data and obtaining what you exactly want.

IMPORTANT NOTE: In fact, at the very end of the uploading procedure, the software will ask you if you want to work with an “**optimized” linear array** (i.e. if you want to ignore and remove the small deviations from a perfectly-straight line) and, in case you answer positively, from the dataset recorded according to the array shown above, you will obtain an array like the one shown below. This is useful in case you are dealing with analyses aimed at obtaining a standard 1D profile but is mandatory in case you are using several (minimum 20) nodes and wish to obtain a 2D V_S profile according to the **SuPPSALA** and **PS-MuCAA** procedures.



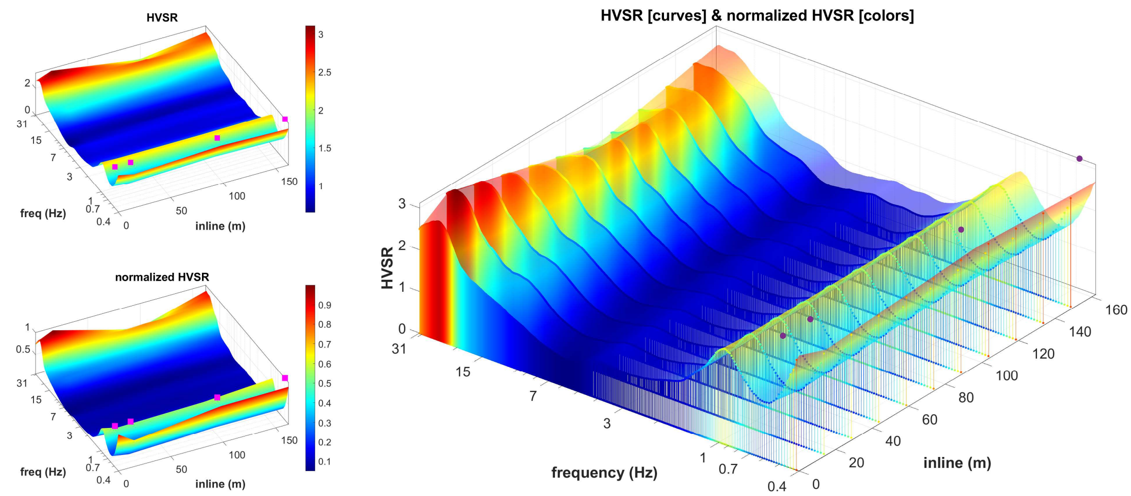
Once you have properly recorded and uploaded your data, you will be able to **work with all the three (seismological) components: vertical, radial and transversal**. The first two refer to Rayleigh waves while the third one to Love waves (reading the paper Dal Moro and Mazanec, 2024 is mandatory).

Data analysis

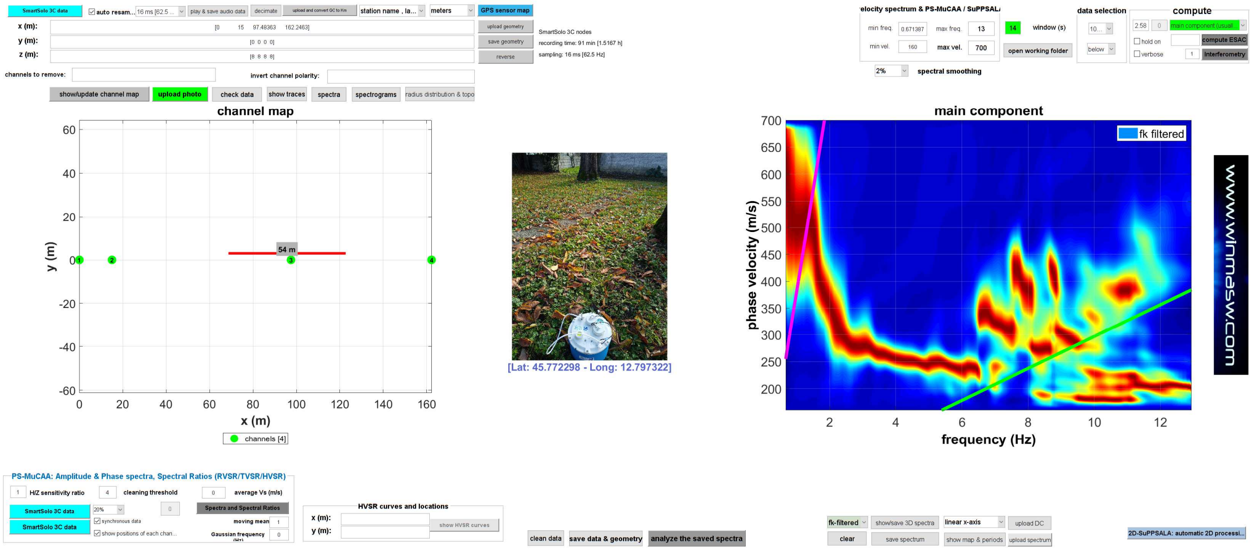
In this case (we just consider four SmartSolo nodes), we can easily obtain seven "objects" (to jointly analyse): **four HVSR curves and the dispersion data for the Z, R and T components**

The four HVSR curves obtained from the ESAC panel (PS-MuCAA tool)

The real four points are those marked with the magenta square while the rest are obtained by interpolating the values over the whole array.

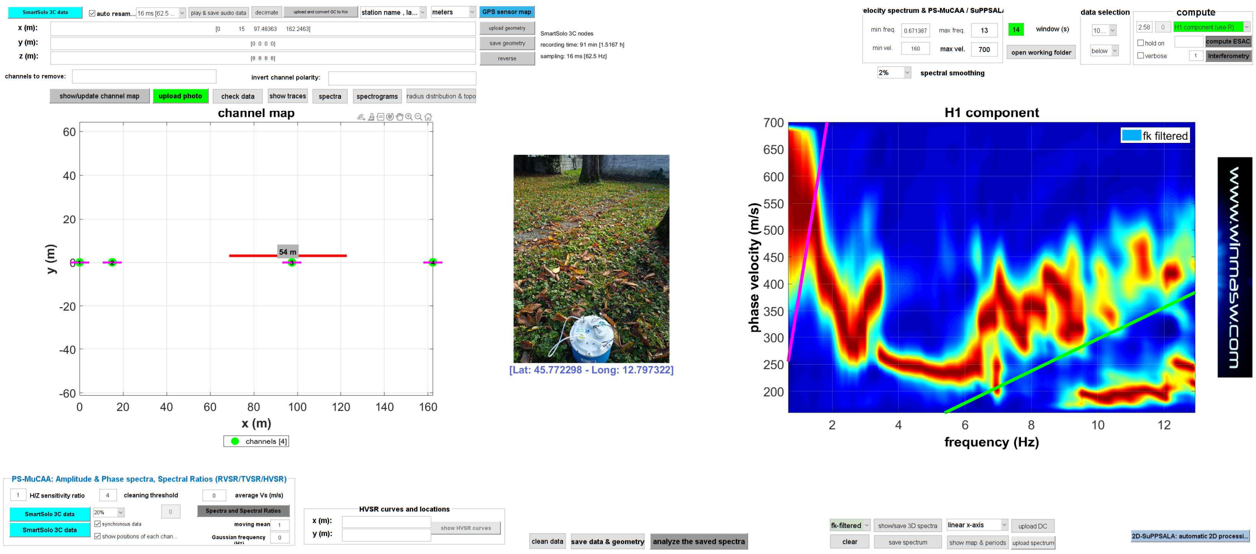


Dispersion for the vertical component of Rayleigh waves (main component)

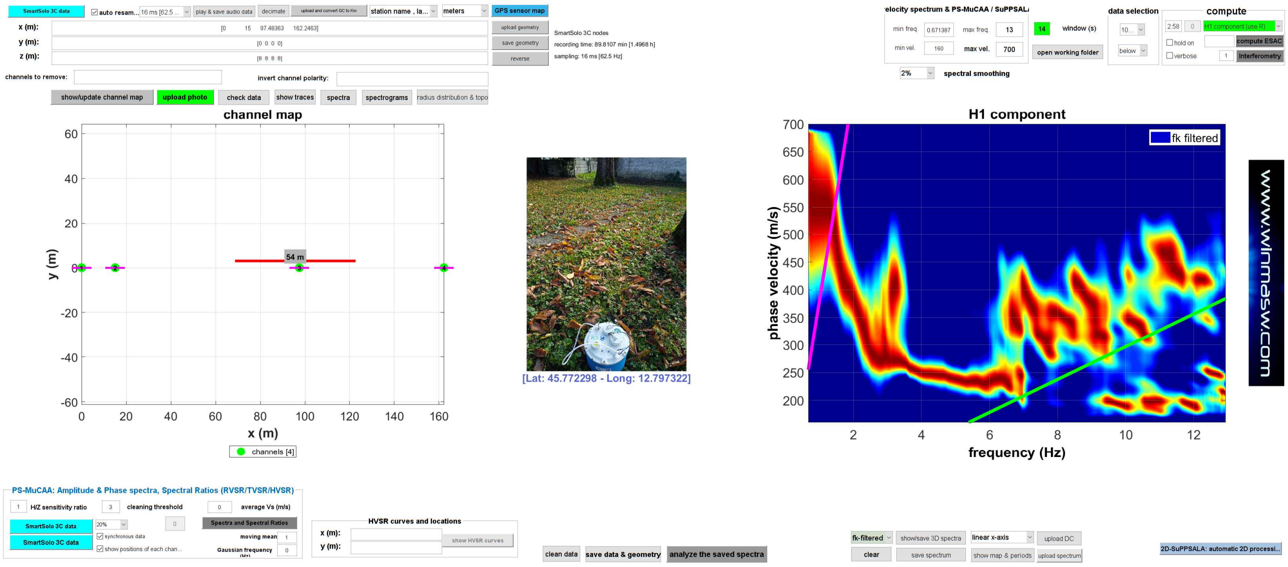


The dispersion for the radial component of Rayleigh waves (H1 component)

The trend around 3 Hz is due to the limited number of traces used (just four) [aliasing phenomena]. This can be attenuated/avoided using a larger number of nodes although in the next winMASW® release a new interesting tool will be added aimed at avoiding this kind of artefacts using a limited number of sensors.

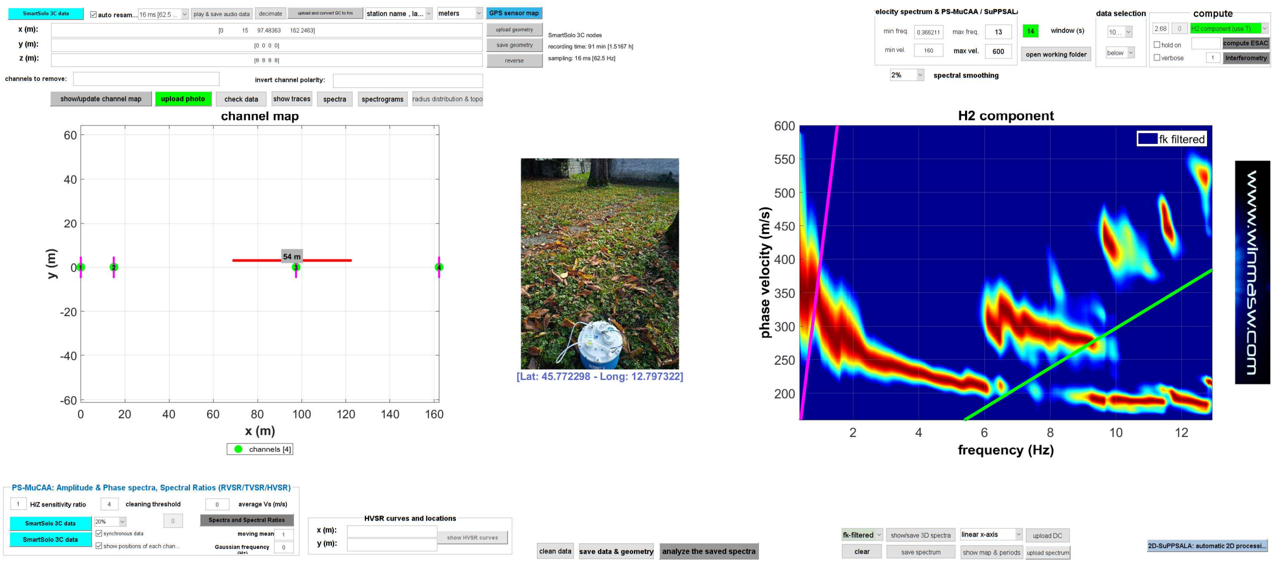


A brutal way to reduce this kind of phenomena is the application of a "severe" *fk* filter (using a small *fk* parameter) during the ESAC processing (a dialog box automatically appears) but this can be done only by expert users with excellent signal processing *know how*. The following snapshot shows what you can get through a heavy *fk* filtering (compare with the previous figure).



Dispersion for the transversal component (Love waves) (H2 component)

Also in this case *spatial aliasing* is responsible for the curve around 1.8 Hz (see comment about the radial component).



Not bad, if we consider that we recorded the data with just four sensor, isn't it?

NEW OPPORTUNITIES

ESAC: what can you do you with just a few 3-component sensors?

In the 2024 release, we will add a further **new tool aimed at properly assembling the passive data recorded with a limited number of 3C sensors** (now often called "nodes") [e.g. 4 nodes] and obtain the data useful to obtain a well-defined dispersion from **ESAC**. In simple terms: with, for instance, just four 3-component sensors/nodes, you can record a first (passive) dataset while the sensors are deployed pretty far apart while a second dataset can be recorded after having moved the sensors at four new/different positions (an example of the data processing necessary to handle and merge this sort of "mixed" data will be provided).
On the other side, in case you are interested in the **SPAC technique** (which requires just 4 sensors), you can work with the ***HoliSurface®*** software application (https://www.winmasw.com/_uk/prodotto.asp?IDp=1) which was designed in order to exploit the (active and passive) data from just a very few sensors.

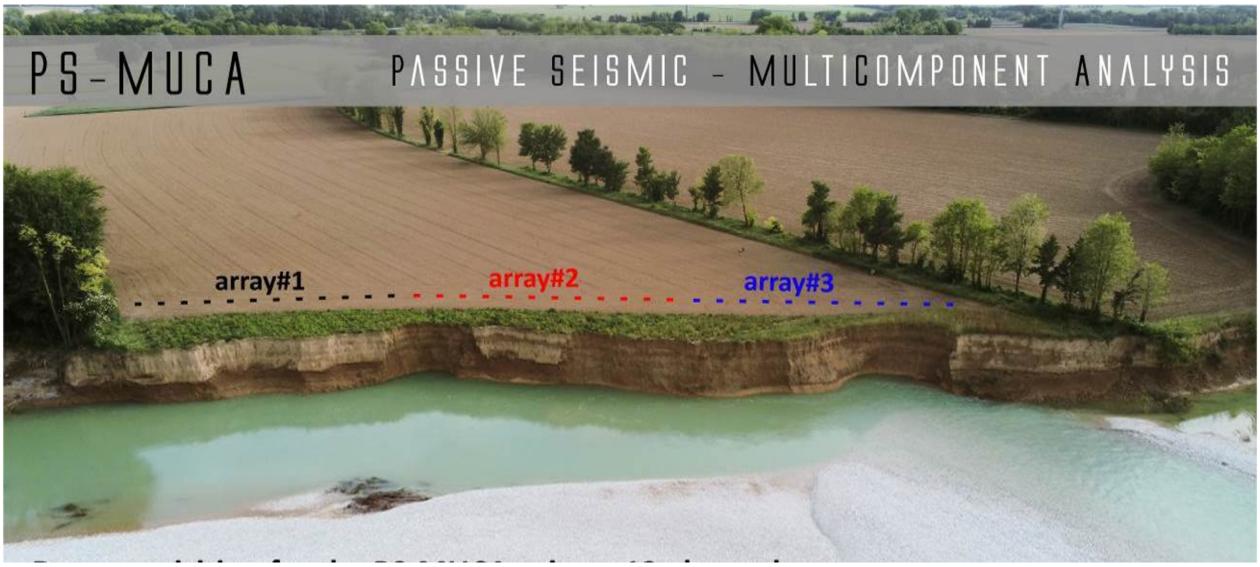
What's the *concrete* **difference between the SPAC and ESAC** in terms of performances? The answer could be extremely wide but the very first point to consider is that, compared to SPAC, the investigated frequency range is much larger for ESAC (this is inevitable cause, thanks to the much larger number of sensors, the wavelengths investigated via ESAC are many more).

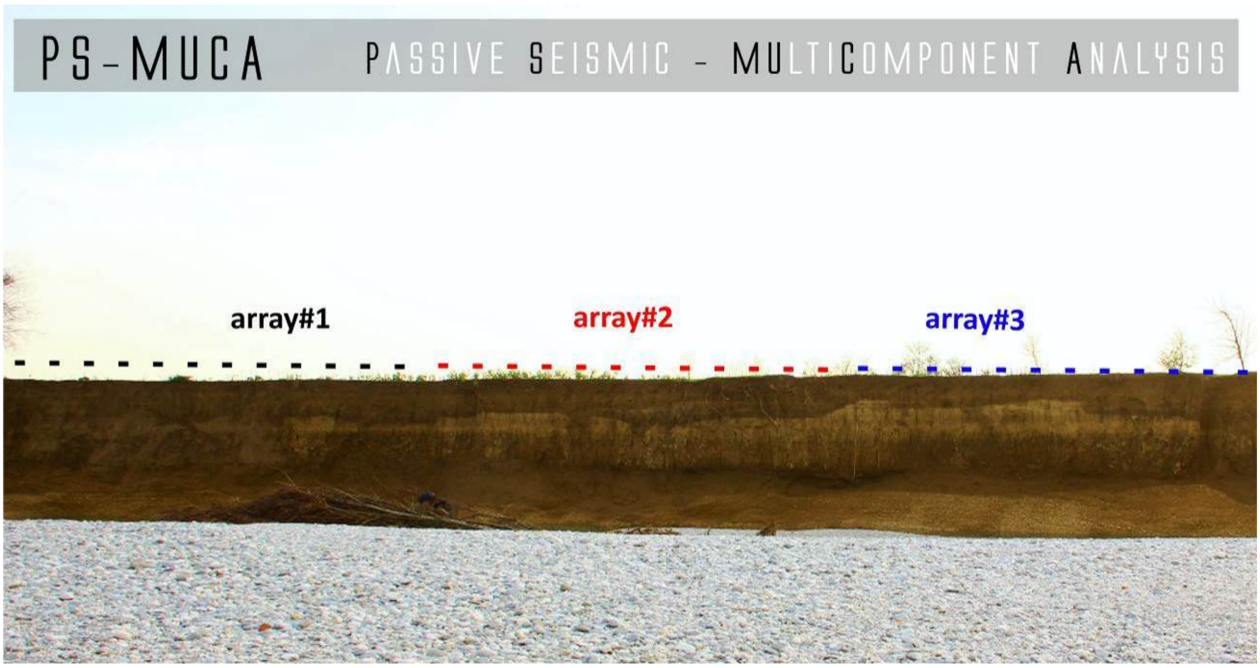
Long(er) profiles

<u>In case the profile to investigate is longer than our array</u>, once we have recorded the data considering the first array, we can move the whole array in a successive position (see arrays #1, #2 and #3 in the next two figures).

Example: we want to investigate a 248 m profile with a 21-channel acquisition system.

In this case we can consider three (3) successive arrays (21 channels each) with *dx* (geophone spacing) equal to 4 m (see the two following figures).





We will then end up with three sets of data to properly use for the analyses. It must be clearly understood that the <u>analysis of the dispersion</u> and the <u>analysis of the amplitudes</u> is totally different.

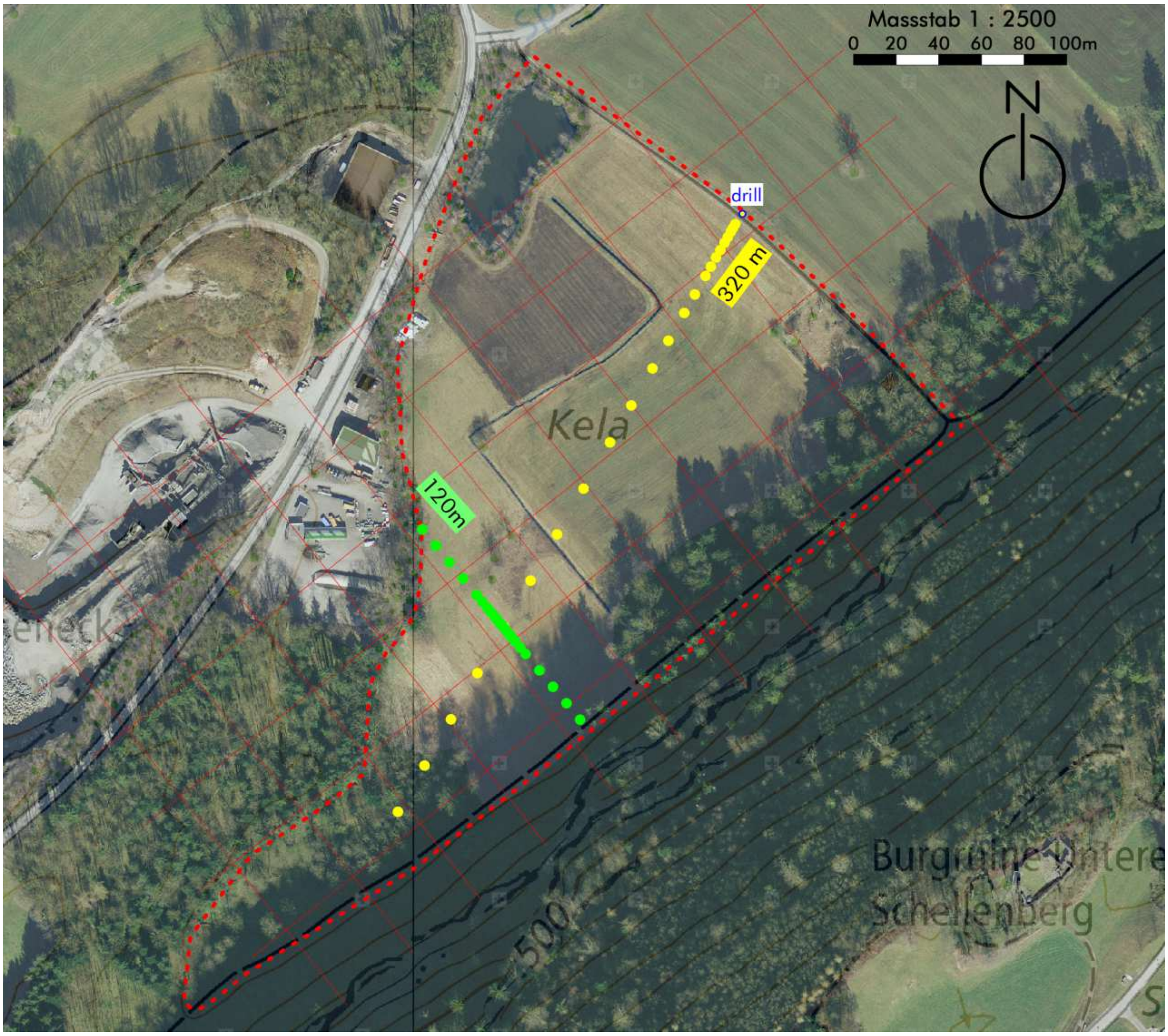
Data acquisition: few notes

Recording time
Follow the usual reasoning to apply for dispersion analysis from passive data (it depends on the goals and site characteristics). For common applications 20 minutes are fine.

Geometry (*dx* values)
In case you suspect (or know) that along the profile are present different terrains, *dx* can be variable. Because of the *spatial aliasing*, it needs to be relatively smaller over the softer sediments and relatively larger over the stiffer materials.

PS-MuCAA: example of variable-dx survey. In order to depict the 2D structure of this small valley two crossing lines [yellow and green] are designed so to properly manage the different terrains (the central part of the area is dominated by peats). Each point represent a 3-component sensor.

Courtesy of *roXplore.ch*



Data processing

step#1 - amplitude analysis
(mainly aimed at verifying possible lateral variations)

key fact in case we consider the data recorded by different arrays (see figures in the previous page): if we record the data during the same few hours (with no change in the weather conditions) and consider sufficiently-long time series and clean the data so to keep only the background microtremor field (removal of transient large-amplitude events), the amplitude of the different arrays we are considering can be compared. This means that all the possible spectral ratios are meaningful even when we consider the data collected along the array#1, #2 and #3.
Of course, in case we record the data of the array#1 in the early morning during a sunny day with no wind and the array#3 in the late afternoon when the sky is now cloudy and the wind is blowing, we risk not to be able to compare the amplitudes (and probably the spectral ratios) of the two arrays.

Gauss frequency/ies: Please, notice that you can input more than one value. If for instance you want to analyze the amplitudes at two different frequencies (e.g. 2 and 5.5), you can input both the values and the software will show you (and save) the amplitudes for both the frequencies.

Cleaning threshold: Value multiplied by the trace standard deviations so to fix the maximum amplitude allowed (larger-amplitude data are removed).

Moving mean: bla bla

H/Z sensitivity ratio: bla bla

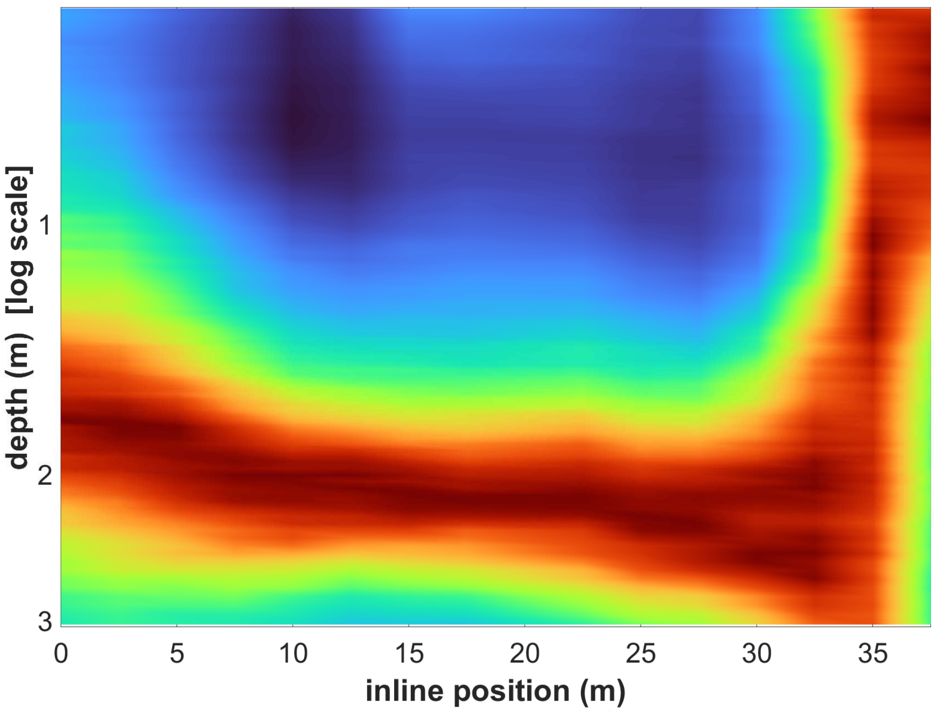
Average V_S: bla bla

Dispersion analysis for any component: bla bla

manual-in-progress

step#2 - dispersion analysis
(aimed at defining the V_S profiles where subsurface conditions are homogenous – see previous step)

key fact in case we consider the data recorded by different arrays (see figures in the previous pages): in order to analyse the surface-wave dispersion **<u>we need to deal with synchronous data</u>** so we cannot consider the data of the three arrays (see previous figures) altogether. We can analyse dispersion along the three arrays separately.



Example of pseudo 2D section obtained by using the described procedure: the blue area is about a peat channel (V_S of about 50 m/s) while on the right a paleo sandy dune (V_S of about 250 m/s) (see also the Appendix “batch processing of multiple HVSR data” – the second reported example).
More details and analyses about this case study in the paper *Tools for the efficient analysis of surface waves from active and passive seismic data: exploring a NE-Italy perilagoon area with significant lateral variations* (Dal Moro & Stemberk, 2022) - see *References*.

Outputs:

1) In case you uploaded just the Z (main) …

2) In case you uploaded the Z and H1 components you will obtain the H1VSR data in terms of images and H1VSR.hv curves (H1VSR1.hv, H1VSR2.hv, H1VSR2.hv etc.)

3) In case you uploaded all the three components (Z H1 and H2) you will obtain the H1VSR data in terms of images and H1VSR.hv curves (H1VSR1.hv, H1VSR2.hv, H1VSR2.hv etc.)

4.4.2 SuPPSALA: 2D V_S profiles from multi-offset passive data [ESAC panel]

There are at least three possible approaches for the 2D reconstruction of the subsurface properties:

1) body-wave (P and SH) seismic **tomography**

2) Surface wave analysis from passive data: **SuPPSALA** technique

3) HoliSurface or MASW (active) techniques according to a roll-along procedure [from the practical point of view, a series of standard 1D profiles are obtained from a series of successive shots recorded according to a roll-along procedures, i.e. you tow your geophone array along the section you intend to investigate; obtained V_S profiles are then arranged with the tool available in HS and *winMASW® Academy* so to obtain a 2D V_S section].

For the first two approaches, 12 channels are usually not sufficient since we need to work with 24 (or even more) channels.

With body-wave tomography one can work with both SH and P waves (but beware of the effect of saturation conditions on P waves and consider the fact that the investigated depth is limited), while with surface waves it is possible to define only V_S values (in case you also consider the HVSR, investigated depth is potentially much greater compare to body-wave tomography).

Clearly, since performances depends on site characteristics and specific goals, there is no “best method” in universal terms.

The acronym **2D-SuPPSALA** stands for **2D *Subsurface Profiling via Passive Surface wave data Analysis from Linear Array***. This means that the goal is to define a 2D V_S section from passive data collected along a linear array. This technique somehow replaces or integrates the SH-wave tomography refraction.

Data acquisition: some recommendations

1) Data quality is crucial: geophones must be accurately tested to make sure that response curves and polarity are the same

2) Geophones need to be deployed (“planted”) with great care: perfect coupling and perfectly vertical/horizontal

3) While recording the field data, we recommend using **HS-QC software** to verify data quality (see pertinent section of the winMASW®/HoliSurface® manual)

4) Use, in general, the same spacing between geophones (*dx*), but in case you suspect that an abrupt lateral variation occurs at a certain location, around such a point a smaller *dx* can be used

5) In general, it is recommended to consider the T component (i.e. Love waves). In case you want to take full advantage of the **PS-MuCAA procedure** (i.e., computation of various spectral ratios for each point of the array), you can also record the Z (vertical) component but in general it is strongly recommended to record (also) the T component

6) As for refraction tomography, for the reconstruction of the 2D V_S section, 12 channels are not adequate and we should work with 24 (or more) geophones/channels.

Processing

There are several possible approaches to obtain 2D V_S sections via SuPPSALA and we will show only a couple of possible approaches/examples. The SuPPSALA tool is actually pretty flexible and the procedure you can decide to follow depends on how strong is your theoretical background and should be tailored based on actual needs and site characteristics. Attending courses and workshops is clearly strongly recommended.

Few details about 2D-SuPPSALA and PS-MUCAA

In order to reconstruct the subsurface V_S model with a good (large) investigated depth, we need to deal with two "objects": **1) dispersion data**; **2) spectral ratios** (e.g. HVSR or, similarly, the simpler but fundamentally identical TVSR)

Dispersion data along the array are obtained through the **"2D-SuPPSALA" button** (lower right of the new ESAC panel): the array (as for refraction seismics, 24 channels is the minimum recommended) is then divided in a series of subsets of smaller arrays. In case *for instance* you choose to consider 6-channel subsets, you will obtain the dispersion for the following subsets: 1-2-3-4-5-6 then 2-3-4-5-6-7 then 3-4-5-6-7-8 and so on and on.

The computation of the **spectral ratios** are then computed for each point with the **PS-MuCAA routine** (lower left of the new ESAC panel).
In case you uploaded just the T component (as H2 data) and the Z component (as main component), you will obtain the TVSR curves while in case you also uploaded the R component (as H1), you will also obtain the HVSR (and the RVSR). Please note that TVSR RVSR and HVSR are typically almost identical (only possible industrial components are usually affected by significant directivities).

Of course, for the very initial and final points, where it is not possible to compute a dispersion curve, we take/extend the dispersion of the first (and last) useful subsets, which are anyway associated to the actual/real HVSRs.

We can eventually analyze what we need to get a 2D V_S model: just the dispersion (in this case the penetration depth will be limited by the lowest reliable frequency) **or the dispersion + HVSRs** (in this case the investigated depth will be significantly larger).

In case you want to analyze just the dispersion (for very shallow studies), in the "**single-observable inversion"** panel (from the main winMASW® panel) you will upload the dispersion file obtained via 2D-SuPPSALA and saved in the "array_dispersion_curves" output subfolder (file "2DSuPPSALA_dispersion_curves.mat" or similar file name).

On the other side, in case you want to jointly invert dispersion data (e.g. about the T component) and one spectral ratio (e.g. the TVSR), you will use the **"Joint Inversion of Rayleigh/Love + HV"** panel (from the main winMASW® panel). You will upload the dispersion data (same file as for the previous case) and the spectral ratios .hv files saved in the PS-MuCAA output folder (e.g. "PS_MuCAA_frequency2_22Hz_movingMEAN1"). In such a folder files are saved with the number of channels. For instance: H2VSR_channel_1.hv, H2VSR_channel_2.hv, H2VSR_channel_3.hv and so on).

PS-MuCAA [Passive Seismic - MUlti-Component Amplitude Analysis]: is about the computation of the spectral ratios that the considered data allows (in your case also the HVSR but it can be TVSR or RVSR, which are actually VERY often the same thing!]
SuPPSALA (SUbsurface Profiling via Passive Surface wave data Analysis from Linear Array): is it about the determination of the dispersion processing (point#1).

CASE STUDY#1: SINGLE-COMPONENT ANALYSIS (DISPERSION ANALYSIS ONLY)

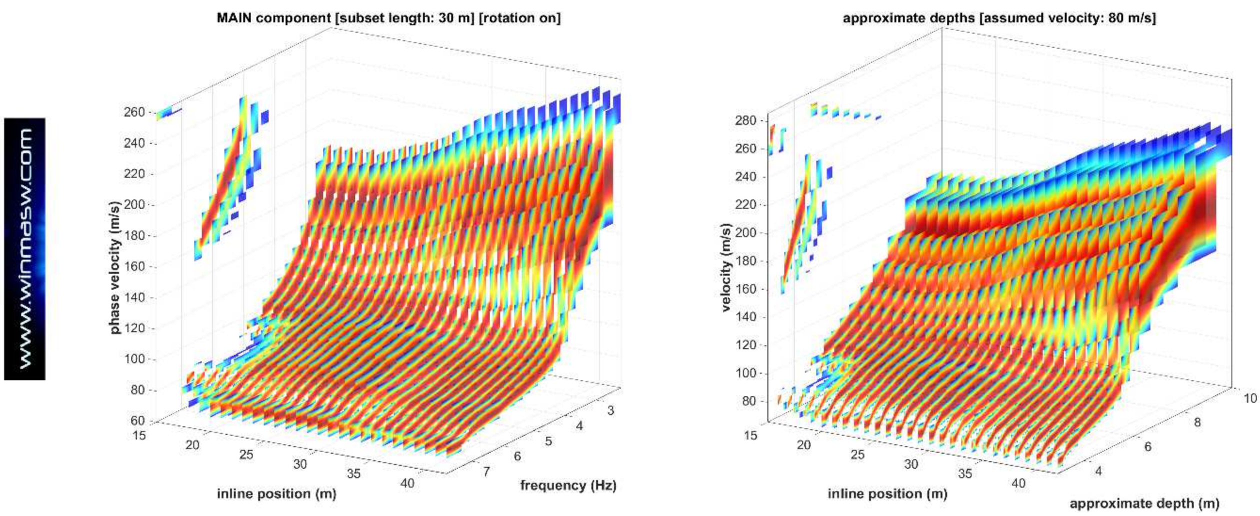
Please, remember that it is strongly recommended to use the T component (Love waves). By analyzing only the dispersion (of one component), the kind of results that can be obtained (2D V_S section) is in general comparable to what would be obtained via SH-wave refraction tomography.

For the example shown below (just for educational purposes) only 12 channels are used but for serious professional jobs it is recommended to work with 24 (or more) channels. The same applies to refraction tomography.

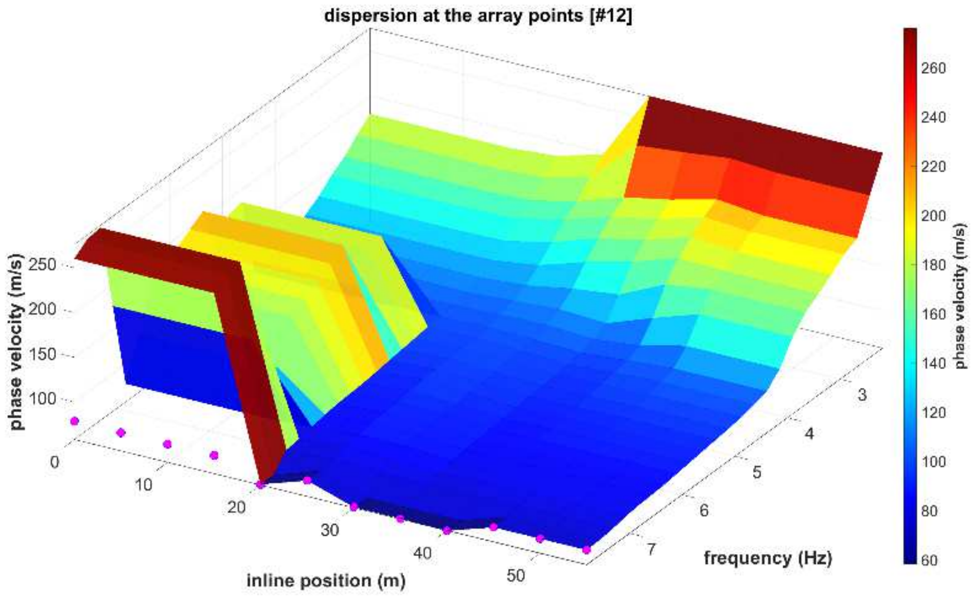
Step#1 - Determination of the dispersive properties

Once the single-component passive data have been uploaded (having in case removed all the traces that for whatever reason should not be considered [poor quality etc.]), one must identify the most appropriate processing parameters for the type of sites and data we have available. Since this is an operation that requires considering many aspects, it is not possible to summarize all the necessary reasoning.
Since, the **SuPPSALA** procedure is based on the analysis of subsets of data/channels (i.e. shorter arrays), it is clear that the minimum frequency cannot be the same used while considering the entire dataset for the standard 1D case (long array).
After launching the procedure (**2D-SuPPSALA button**), we are asked a few things (read carefully and make appropriate choices). The most important parameter to fix is certainly the ***number of channels*** to be used to define the subsets/arrays (for most of the applications the number is between 6 and 8).
Once we have provided all the required parameters, the procedure continues eventually providing a series of outputs/graphs such as the ones shown here below (read the graphs carefully). This step/procedure does not require any particular computational effort.

Clearly, the dispersion values at the edges cannot be determined and are therefore "copied" (extended) from the nearest curves (consider carefully the values of the in-line positions reported in the two figures below).



Step#1: obtained dispersion curves (the amount of curves is interpolated in order to make the overall trend more readable).

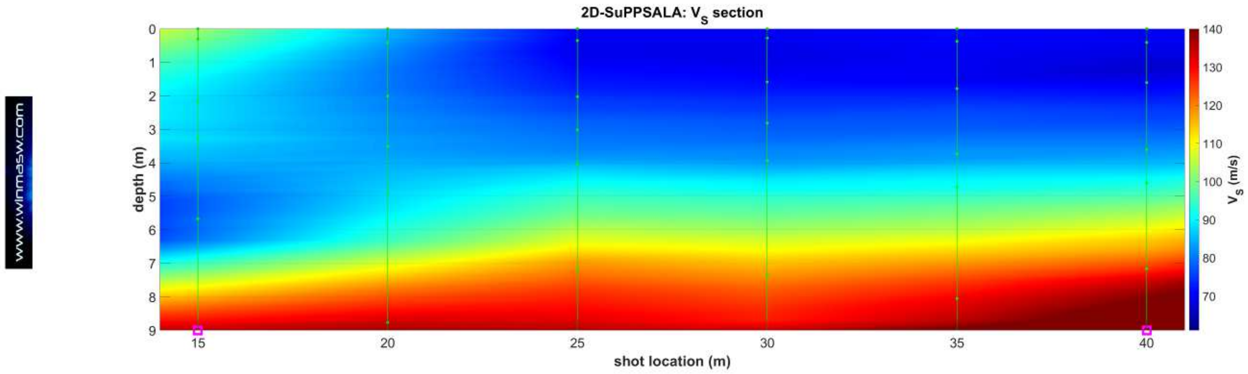


Step#1: extending the dispersion curves to the edges of the array in order to cover the entire array (compare the inline positions shown here with the one of the previous figure). These are the curves that are going to be inverted (step#2).

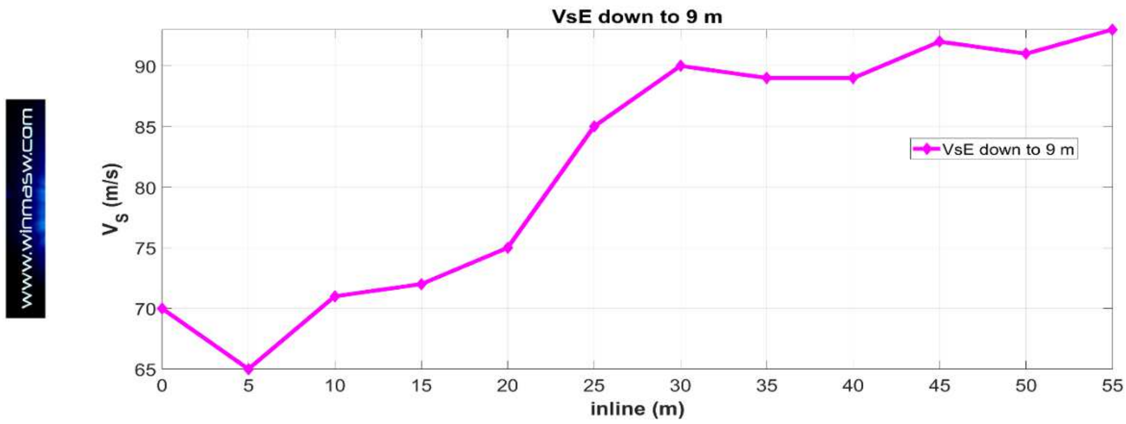
Step#2 - Inversion of previously-retrieved dispersion curves

During this second step the computational load is definitely heavier (see section about *System Requirements*) but the procedure extremely simple.

From the "single-observable inversion [dispersion data; also 2D-SuPPSALA]" panel, we now upload the **2DSuPPSALA_dispersion_curves.mat file saved in the "array_dispersion_curves" subfolder** during the step#1.
We then set the appropriate inversion parameters (it is necessary to start from a starting model previously identified through the forward modeling of one of the dispersion curves automatically saved during the previous step in the "**array_dispersion_curves**" folder) and launch the inversion. We eventually obtain a series of outcome including the following two:



The magenta squares along the x axis of the final 2D V_S section indicate the range within which the solution is "real" (outside these limits the solution is so-to-speak interpolated).



Values for the "equivalent Vs" computed up to the depth of 9 m: note the increase in mean Vs related to the shallower contact between the surface peat-like sediments (V_S < 80 m/s) and the deeper "normal" sediments (V_S > 130 m/s). Note the general consistency between previously shown (and inverted) phase velocity spectra and the final result shown here.

In addition to the several images produced at the end of the step#2 and automatically saved in the **SuPPSALA output folder**, an Excel file is also produced showing the matrix of vertically interpolated V_S values with a distance *dz* indicated by the value given in the file name itself: *smoothresampledVSsection_dz0.3m.xls* means 2D V_S section with vertically interpolated values every 0.3 m.

CASE STUDY#2: MULTI-COMPONENT DATA ANALYSIS

The new ESAC panel enables multi-component passive data analysis and this allows a large-number of possible acquisition-and-analysis strategies.
The simplest one for those who have a "classical" acquisition system with two 12-channel cables is to arrange the two cables parallel to each other and connect the Z geophones along one cable and the horizontal ones on the other (for the T component). This will provide the data for analyzing Rayleigh (Z component) and Love wave (T component) dispersion, as well as the HVSR curves at each point/channel. In this case the problem can be related to the limited number of considered points (just 12).
Another possible strategy is to deploy the two cables along a single linear array (12 + 12 = 24 channels/points) and "plant" both the vertical and horizontal geophones (see figure below). We then first connect the Z-component and record a passive dataset. Successively we connect the horizontal geophones and record the T component. Incidentally this is what can be done also in case you have a single cable.

In case we have a wireless system with 3C sensors, things are easier and we simply need to deploy the 3C nodes along a line. **Remember that we do not have to consider the NS and EW geographical directions but the <u>seismological components</u>**: the 3C geophones need to be rotated in order to have one H component parallel to the line (**radial component**) and the second H component perpendicular to it (**T componen**t).

For the example briefly present below, data were collected with a set of wireless 3C geophones along a linear array of more than 2 km.

Step#1 - Determination of the dispersive properties and HVSR

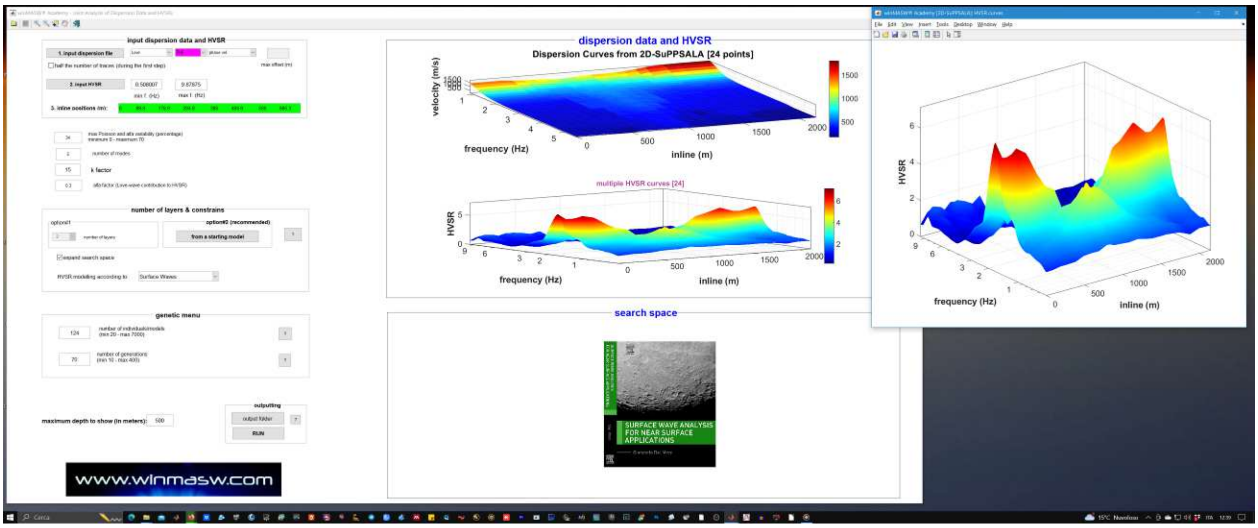
As shown also for the previous small case study, while 2D dispersive properties are defined by clicking the **2D-SuPPSALA button** (remember to carefully set the processing parameters), for defining the HVSR curves (for each point) we use the **PS-MuCAA procedure**.

We first need to upload at least 2 components: the vertical (Z) and the transversal (T) ones.

Since in this case we were working with a set of 3C geophones, we can actually work with all three components. The HVSR is computed considering all of them (but results are usually pretty much the same in case we consider just the Z and Tcomponents only), while for the dispersion we will work (as we often recommend) with the T component (Love waves) [the component to be considered is chosen from the pop-down window in the upper left corner, within the **compute** group].

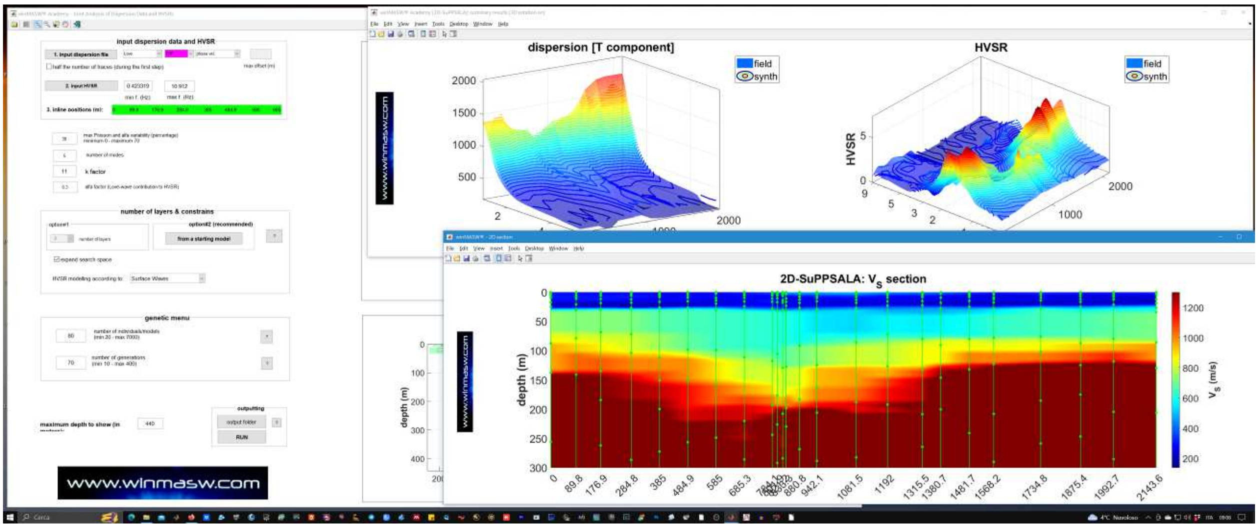
Step#2 - Joint inversion of the T-component dispersion (Love waves) + HVSRs

In the "Joint Inversion of Rayleigh/Love + HV [single or 2D-SuPPSALA]" panel, we now upload the 2DSuPPSALA_dispersion_curves.mat file automatically saved in the "array_dispersion_curves" sub-folder during the step#1 of the **SuPPSALA** procedure and the HVSR curves produced by means of the **PS-MuCAA tool** (these latter are ordinary .hv files). We then set the inversion parameters (to do this we clearly need a real in-depth understanding of what we are doing) and then launch the joint inversion (RUN button).



Step#2 (joint inversion): uploading the dispersion data and the HVSR curves.

What we obtain in the end is summarized in the following image: the field data, the synthetics of the identified vertical profiles and the 2D V_S section.



Very brief introduction to interferometry

work-in-progress next release()

Interferometry can be proficiently used only when we are dealing with large arrays that ensure clear a clear dispersion pattern.

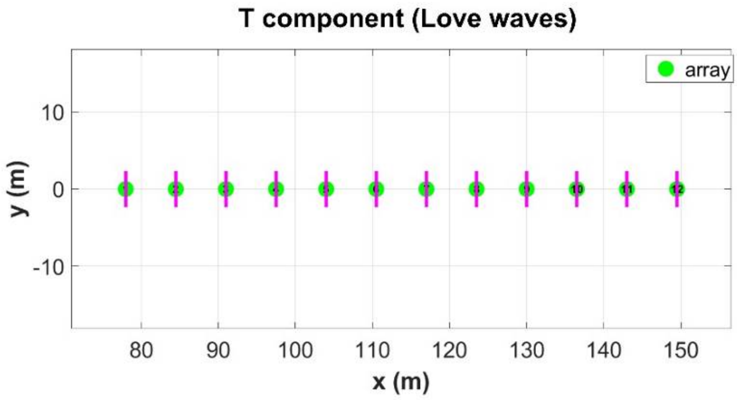
Main Pros:

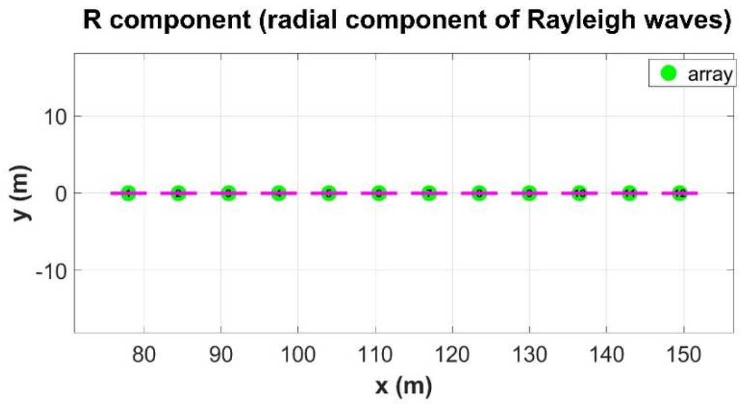
a) Working with simple linear arrays
b) Clear phase-velocity spectra with, in some cases, the possibility to separate different modes (if present)
c) Possibility to identify the position main microtremor source
d) For large datasets (several tens of channels and several tens of minutes of data) computational load can be lower when compared to ESAC processing

Recommended acquisition parameters

1) **Recording time**: 20-30 minutes. Actually very variable: it depends on the minimum frequency we intend to analyze (in case we intend to consider very low frequencies, longer acquisition length and very large arrays are necessary); **sampling frequency**: 250-500 Hz [2-4 ms]

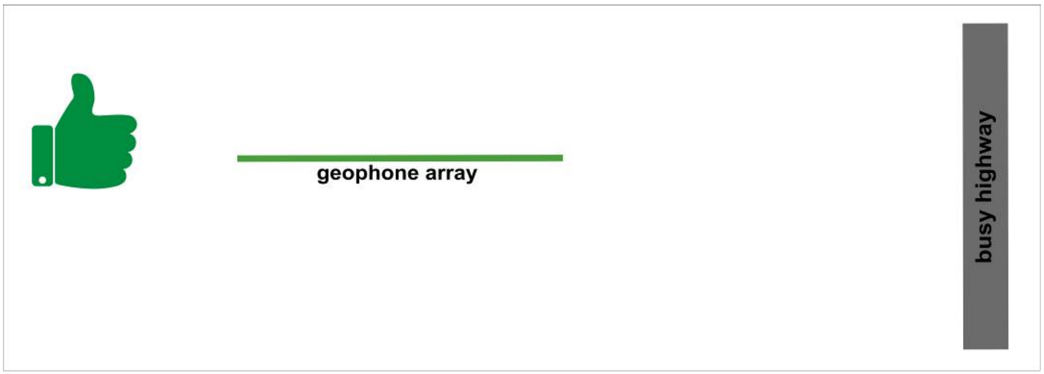
2) **Consider more than one (single) component** [vertical, radial, transversal – see figure here below]

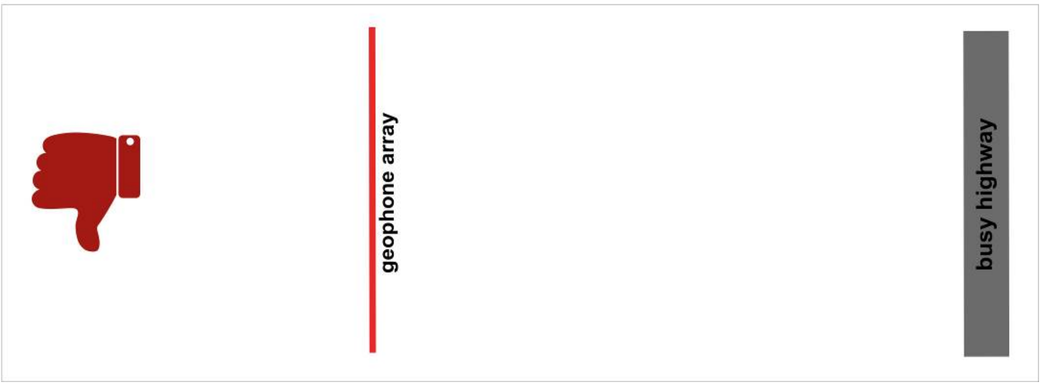




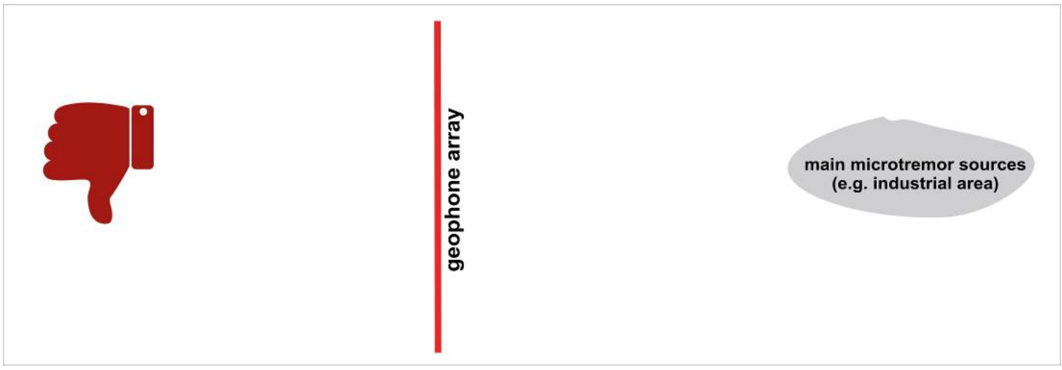
Orientation of the horizontal geophones for the acquisition of the radial (R) and transversal (T – Love wave) components

3) **Linear arrays** in line with the main microtremor source(s) [see figures here below]





Recommended array deployment/orientation in case of busy highways/streets



Recommended array deployment/orientation in case of localized microtremor area

Validity limits: the lowest reliable frequency can be defined in a similar way as for the ESAC technique, through the green lines shown in the obtained velocity spectra.

Comparing ESAC and interferometry:
example#1 [Z component, vertical component of Rayleigh waves]

Phase-velocity spectrum from ESAC analysis

Phase-velocity spectrum from interferometry

work-in-progress

Comparing ESAC and interferometry:
example#2 [T component, Love waves]

Phase-velocity spectrum from ESAC analysis

Phase-velocity spectrum from interferometry

4.5 Group velocities: MFA (*Multiple Filter Analysis*) (Academy version)

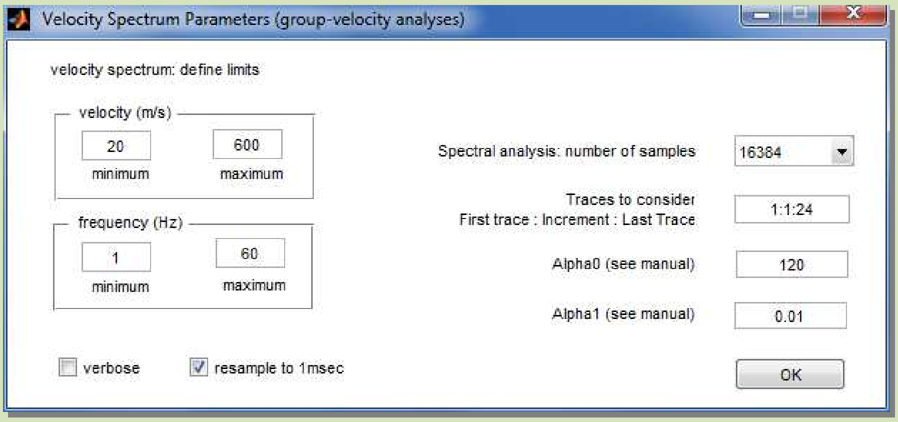
This method allows to define dispersion curves for group velocities (not for phase velocities), anyway the procedures are in general absolutely similar to the ones adopted for phase-velocity analyses (*MASW* or *ReMi*).
First (as usual) upload the *common-shot gather* (icon top left). Theoretically to perform *MFA* analyses one trace could be sufficient, nevertheless the resulting spectrum will surely result more robust when obtained as the average of several traces (we may suggest 3-6 traces at least).
It is not possible to summarize in a manual all the characteristics and the *pros & cons* of a methodology, and we will limit the presentation to 2 points only:

1. the link between V_{SupPH} (phase velocity of the surface wave) and V_{SupGR} (group velocity of the surface wave) and V_S (shear-wave velocities in depth) is different (in other words the relationship frequency – V_S and frequency-V_{SupPH} is different from the one between frequency – V_S and V_{SupGR}).
2. with respect to V_{SupPH}, V_{SupGR} seem (sometimes) more sensitive to V_S variation in depth (see e.g. Luo et al. 2010).

For these reasons we suggest the joint analysis MASW + MFA (+ possibly HVSR) (button "*Joint Analysis of Phase & Group Velocities*").

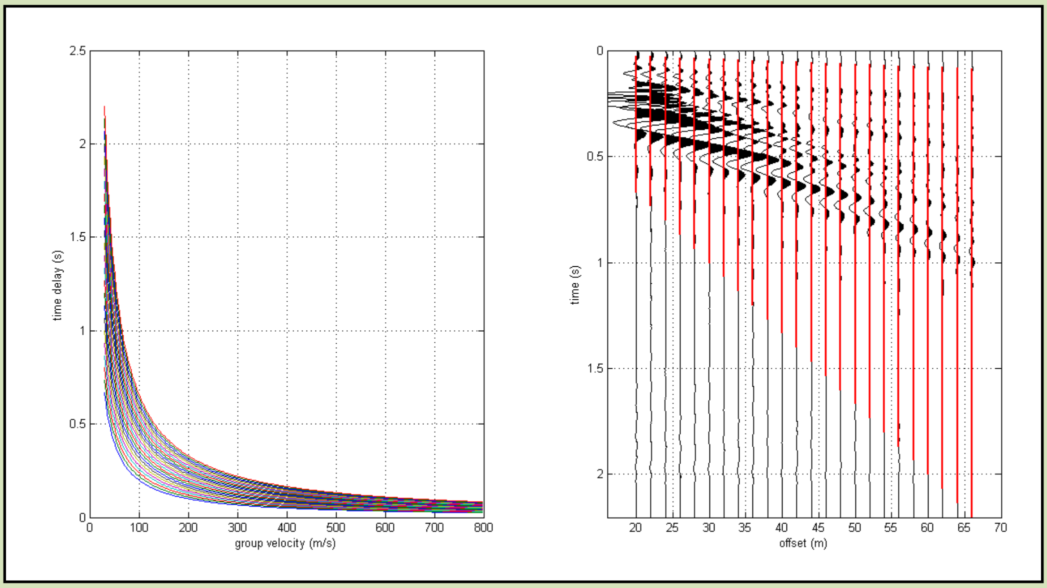
Parameters Alpha0 & Alpha1

The Gaussian filter used during *MFA* depends on 2 parameters: Alpha0 and Alpha1. There are no universal values suitable for any dataset as these values depend on the specific dispersive properties of the considered dataset. Anyway, thanks to some improvements present in the 4.7 version we would suggest 2 fix values: 120 and 0.01, respectively. It is also recommended a re-sampling to 1msec (see panel down here).

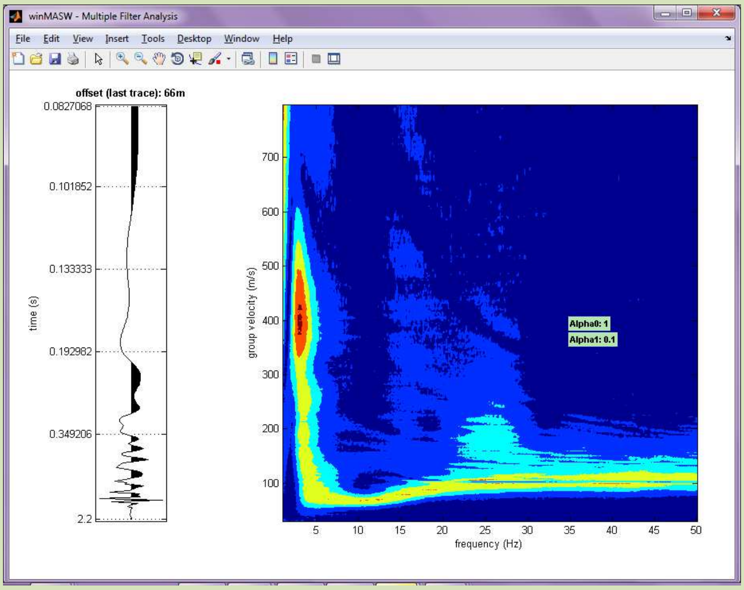


By activating the *verbose* option you will also obtain the 2 following windows.

The first one reports the delays as a function of the offset



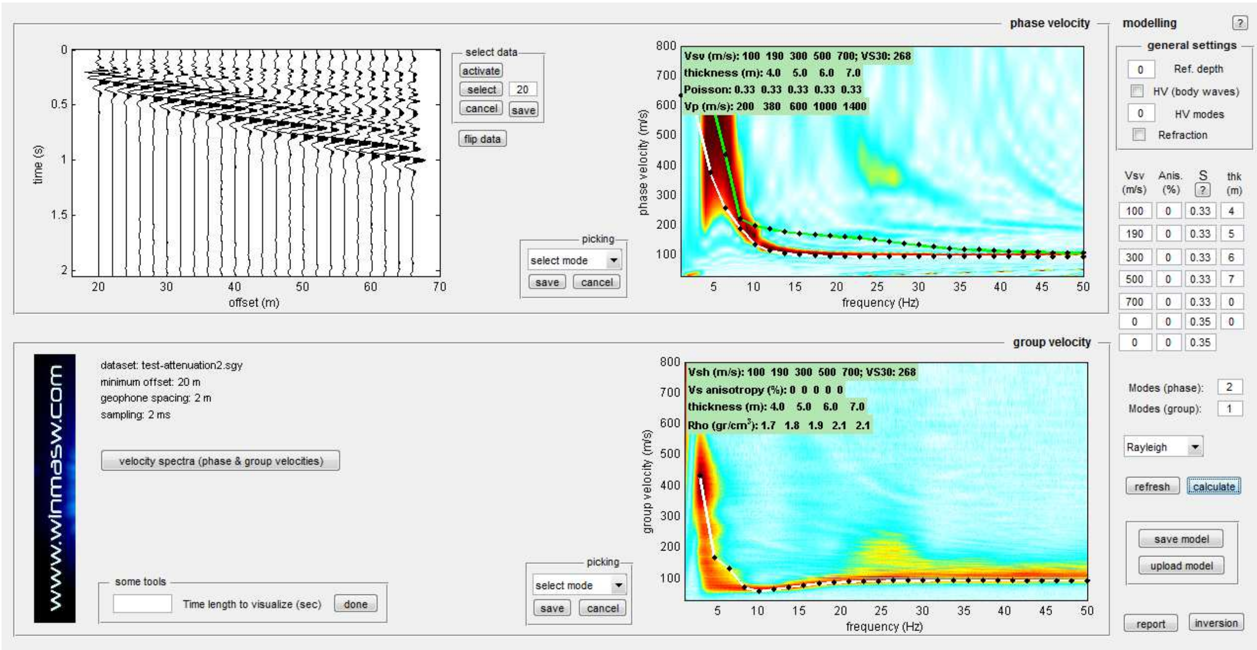
while the second one presents the last considered trace (on the left) and the obtained velocity spectrum (on the right).



Please notice that MFA analyses cannot be applied to ReMi-like acquisitions because in that case time and position (thus distance) of the source(s) is not known.
In seismology it is possible to apply MFA technique only once the epicenter is defined, thus its time and position is determined with respect to the receiver.

The joint modelling is then performed in the usual way (see example down here): from the uploaded dataset it is computed the velocity spectrum representing the phase velocity (MASW technique) and the group velocities (MFA technique).

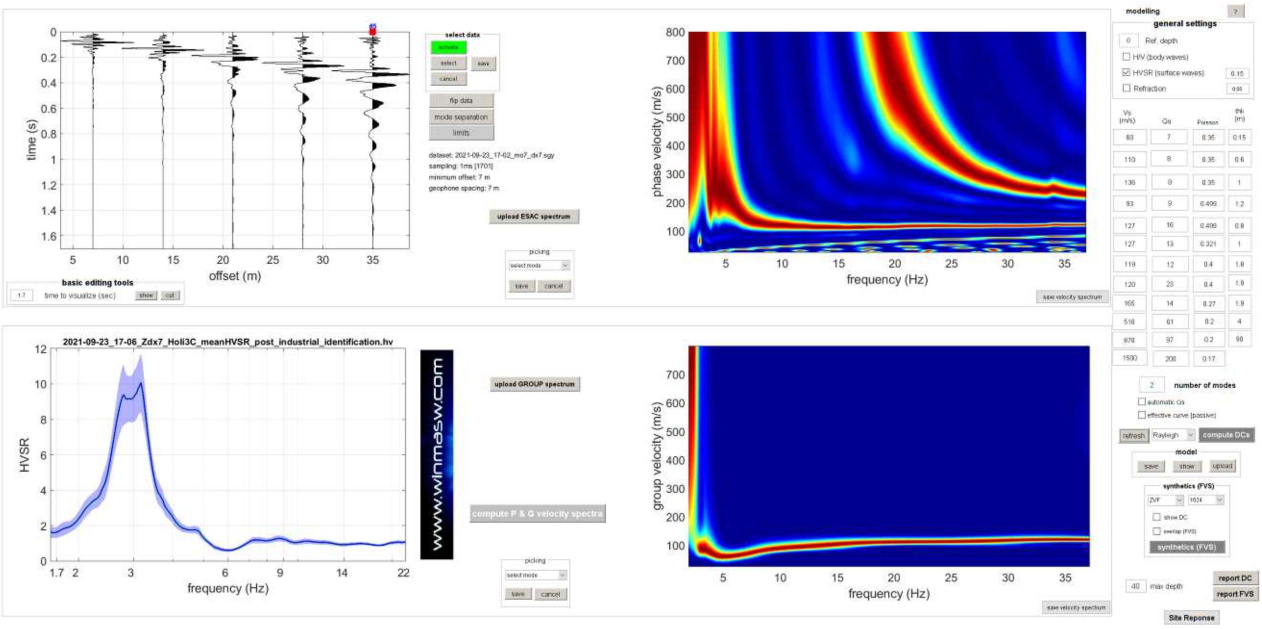
Of course it is also possible to upload an H/V curve and perform a 4-observable analysis: phase velocities + group velocities + HVSR + refraction travel times.
In case you upload a Z or R active dataset, dispersion and refraction is about Rayleigh and P-wave, respectively. On the other side, if you upload a T-component dataset, dispersion and refraction are about Love and SH-wave respectively.



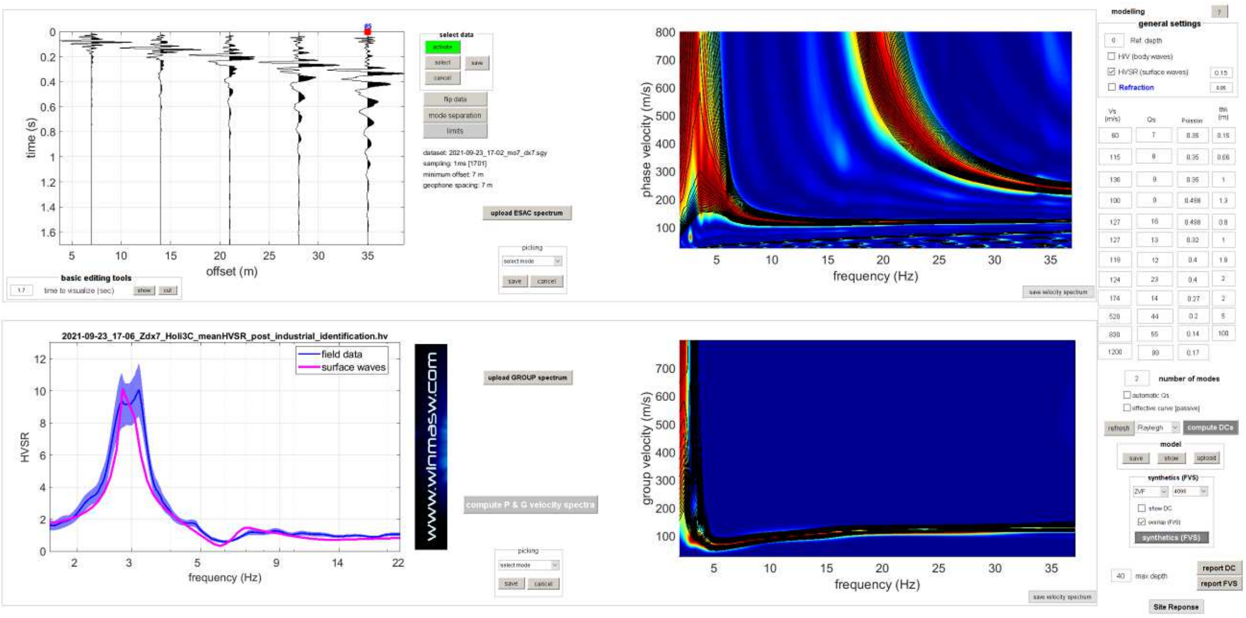
4.5.1 Panel for the joint analysis of group and phase velocities together with the HVSR and refraction travel times

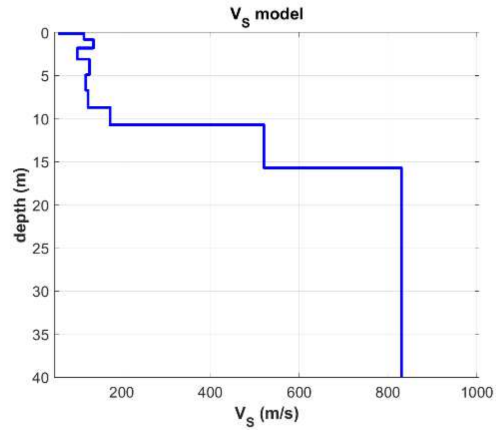
From the main panel of winMASW® [Academy] we can access the **Joint Analysis of Phase & Group velocities [+HV & refraction]** panel. Here we can upload an active dataset and the HVSR curve (which should always be the average of two HVSR curves taken at two different points of the array).
By clicking the **compute P & G velocity spectra button**, we compute the phase (considering all traces) and group (considering just one of the traces!) velocity spectra of the uploaded active dataset.

Here is an example of a screenshot where four "objects" (observables) are shown (from the upper left corner clockwise): active seismic traces obtained considering 5 geophones [ZVF component], phase velocities (the high frequency and high velocity signal is due to *spatial aliasing* but, since this is extremely clear and cannot misinterpreted as higher mode (or whatever), it does not create any problem/concern), group velocity (referring to the farthest trace - see red square on the last seismic trace), uploaded HVSR curve.

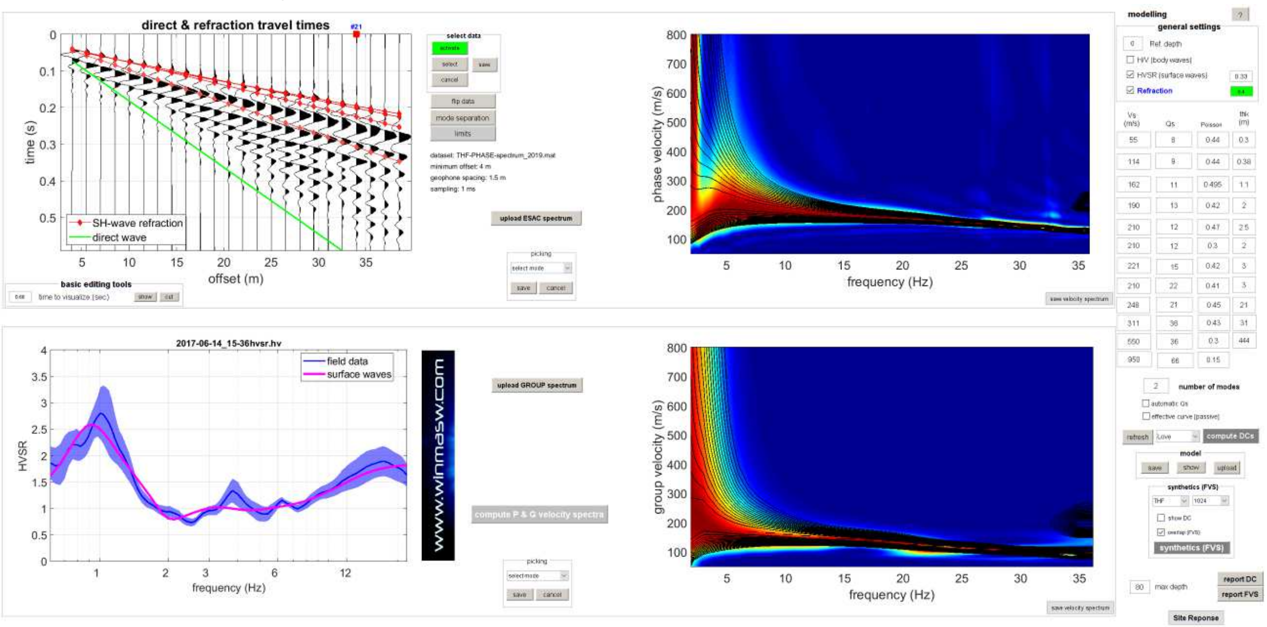


With some forward modelling (using both modal curves and FVS) we can eventually converge to the model shown below (the congruity between campaign data and model is obvious).
As always, we can decide whether to get the final report by referring to the modal curves [DC report button in the bottom right corner] or the FVS solution [by far more robust] [FVS report button at the bottom right corner].





Regarding the **refraction modelling** (it is activated with the option in the upper right corner of the panel), if we are analyzing the Z or R components, the modeling will (clearly and necessarily) refer to P waves, while if we are analyzing the T component, the refraction will refer to S waves. Here below an example of the same joint modeling considering THF data (i.e. Love-wave phase and group velocities + SH-wave refraction travel times + HVSR).



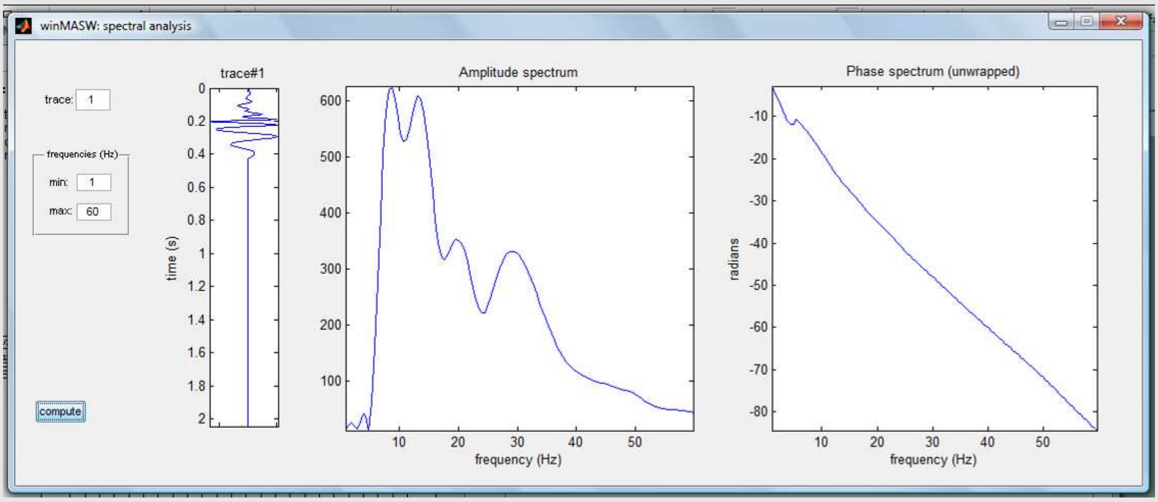
Spectral analysis (in particular for active data)

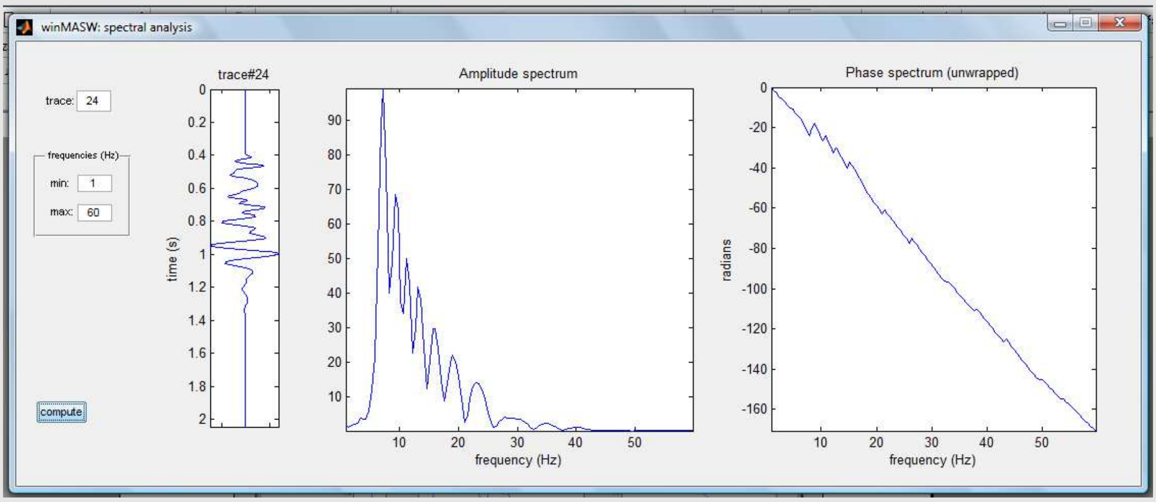
A tool for traditional spectral analyses is also available (calculation of an amplitude and phase spectra): button “Spectrum” in the group “filtering & spectra”

Considerations must be done according to the selected component (surface waves only, refracted waves, air waves, etc.),
For instance, while analyzing surface waves only, you’ll notice the “erosion” of the high frequencies (i.e. the disappearing/attenuation of high frequencies at large offsets), due to geometrical spreading and viscosity (attenuation).
The soil (especially if made of unconsolidated materials) acts in fact as a filter, thus attenuating especially the high frequencies (see the chapter dedicated to the attenuation of the Rayleigh waves).

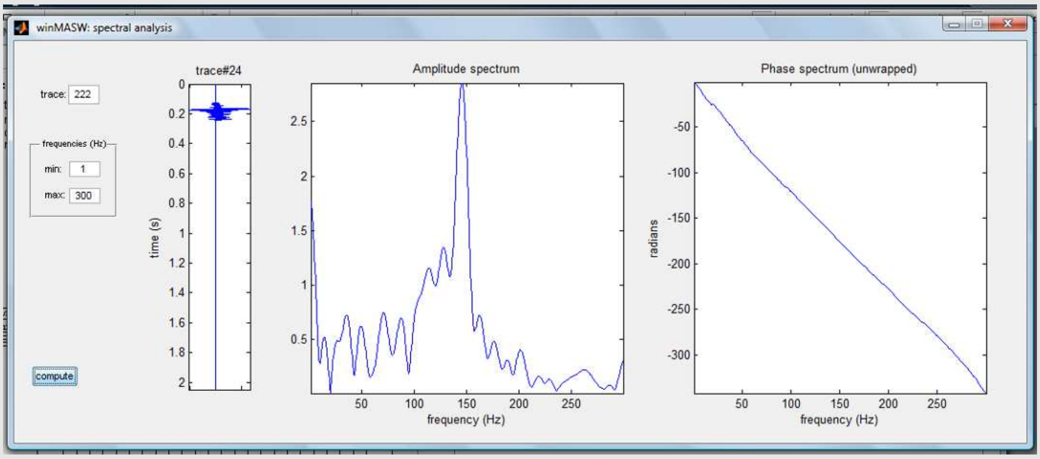
Here following the figures relevant to the spectra of the first and last traces of the dataset *test-attenuation2.sgy*:

1. due to attenuation phenomena the amplitude of both traces is quite different (the peak related to the first trace is over 600, while it decreases to about 100 for the last trace)
2. compared to low frequencies, the highest result more attenuated





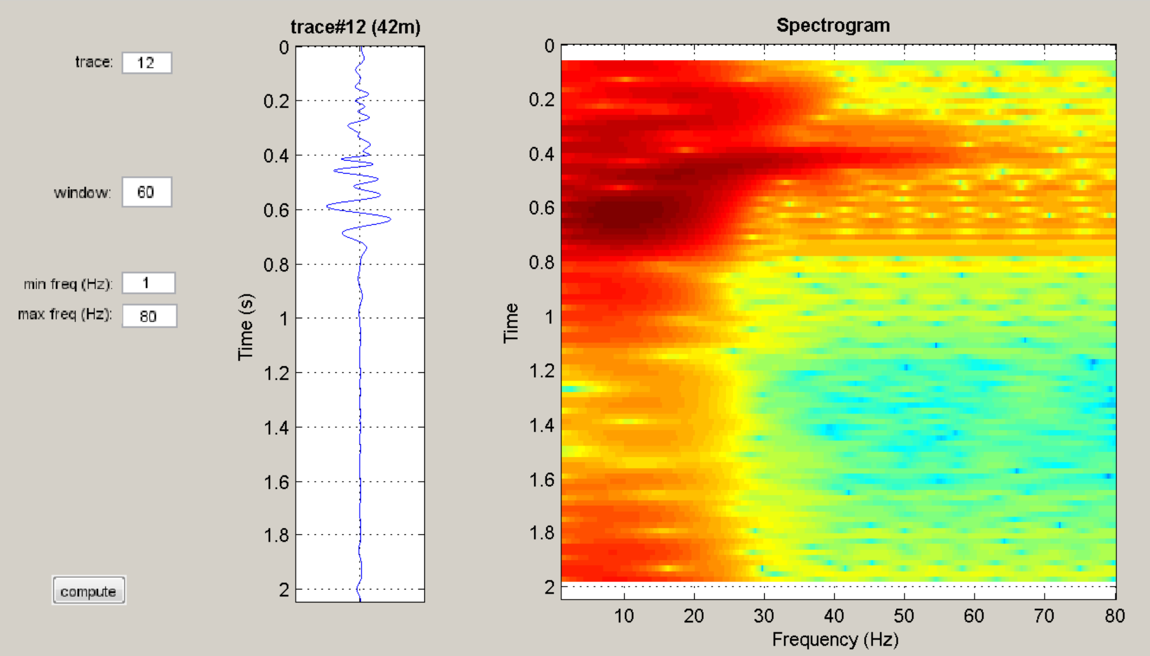
Here below the amplitude and phase spectra of the air wave: note the high frequency characterizing the signal (peak around 145 Hz).



Consider the potentiality of this tool when selecting a data portion: if in that portion there are frequencies incompatible with the component you aim to isolate/investigate, that can be useful to redefine the selection polygon.

Spectrograms

In the "utilities" section the button "spectrogram" will give the possibility of computing the spectrograms of the uploaded dataset (trace by trace). This will allow the user to evaluate the spatial and temporal change in the frequency content due to seismic wave propagation and attenuation.



Picking of the dispersion curve

To pick the dispersion curve (i.e. to select those points that, according to the user, belong to a particular propagation mode of the surface wave) it is necessary to:

1. choose the mode from the scroll menu
2. click (left mouse button) the points along a certain coherence that the user identifies and understands as a particular "mode" (see example in figure 2)
3. save the *picking*

If there are more datasets in our "mode", just pass to the other one scrolling down the menu (once you've done and saved the picking of a mode). Different modes will be marked in different colors.
The new data, relevant to the second mode, will be saved in the formerly indicated file. The final inversion will finally consider the whole of data.

The picking file is a three columns ASCII file (.cdp-curve of dispersion in Italian): the first shows the frequencies, the second the velocities and the third the mode (as chosen by the user scrolling down the menu). We suggest to save the dispersion curve in the default directory "dispersion curves".

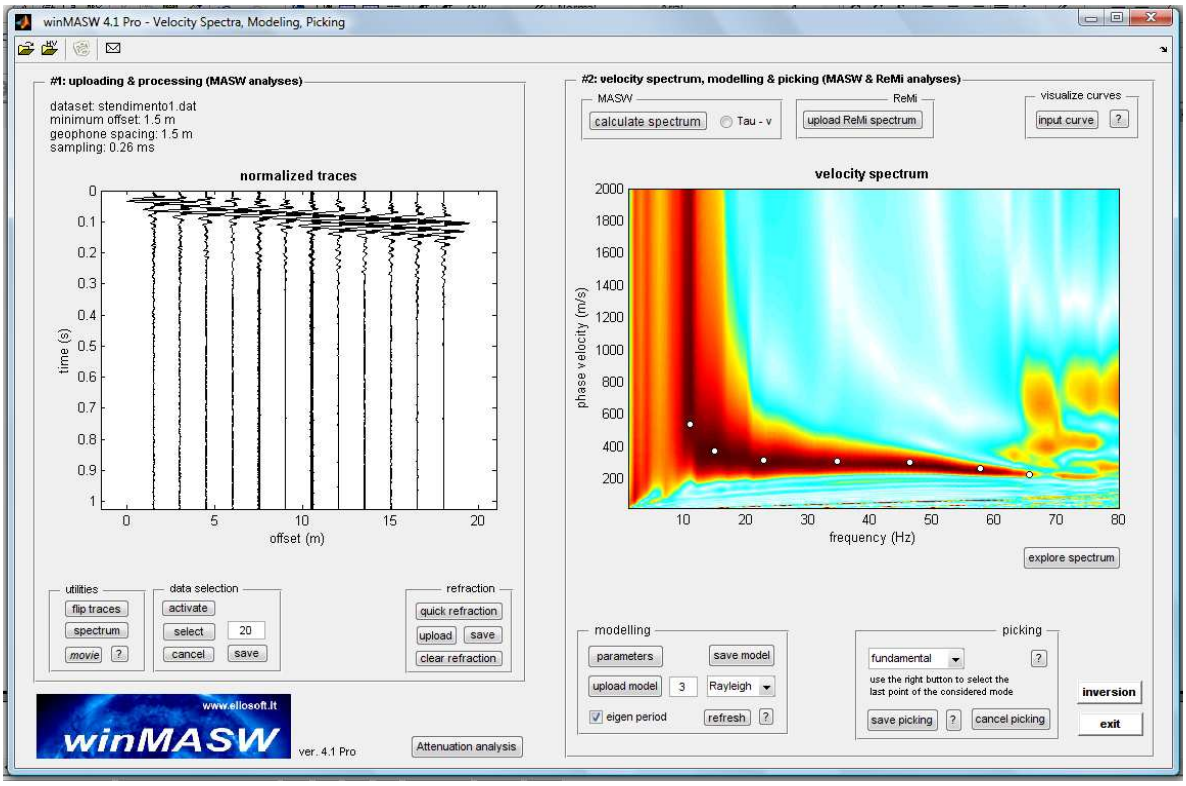


Figure2. *Picking* of the dispersion curve

Identifying and picking the dispersion curve is of course an operation of crucial relevance for the final result.
The user should have the necessary confidence to do that operation.
A misunderstanding (curve profile or assigning the mode) could lead to inconsistent results.
In order to have a clearer view on the dangers following article is suggested:
Velocity Spectra and Seismic Signal Identification for Surface Wave Analysis (Dal Moro et al., 2006) and *Possible Effects of Misidentified Mode Number on Rayleigh Wave Inversion* (Zhang & Chan, 2003).

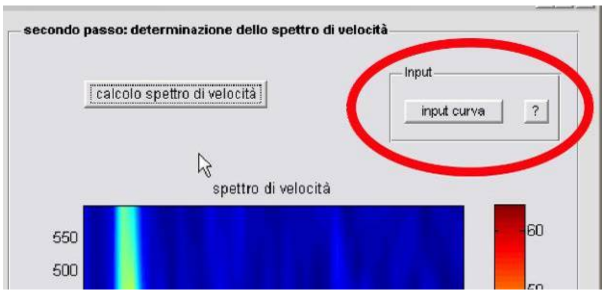
"Picking" a too dense dispersion curve won't give better results but a longer computational time.
We generally suggest to concentrate on not more than 15 couples of points (couple frequency-velocity).

Structure of a *picking* file (.cdp)

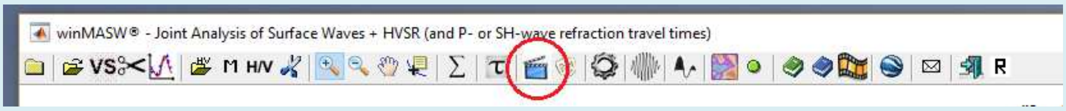
FREQUENCY (Hz)	VELOCITY (m/sec)	MODE
15.9956	1135.77	0
19.1886	815.43	0
17.9342	929.45	0
20.557	761.134	0
22.0395	733.986	0
25.1184	685.12	0
26.4868	668.832	0
28.3114	641.684	0
31.8465	592.818	0

Visualizing different curves (*picking* or output curves)

Clicking on the button top right of the screen you will visualize and compare different formerly picked dispersion curves (.cdp) and/or dispersion output curves (.cdo). They will show over the velocity spectrum in use.



The "movie" button **(in *winMASW® Academy* its full implementation)**



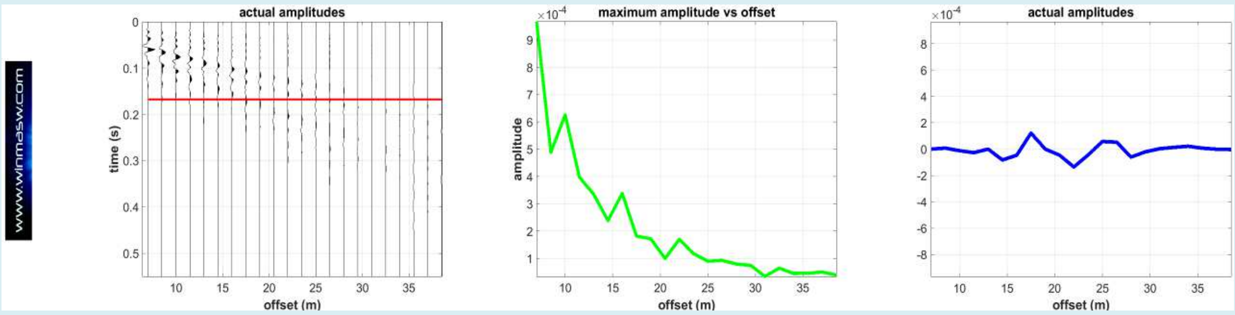
You data in motion (some fun, but also for educational purposes).

Among the several facilities for the visualization of your data this single-component movie (automatically saved in the working folder).

Two videos are shown and automatically saved in the working folder:

1) the animation of the normalized data (saved as "winMASW_Seismic_Movie_normalized amplitudes.mp4")

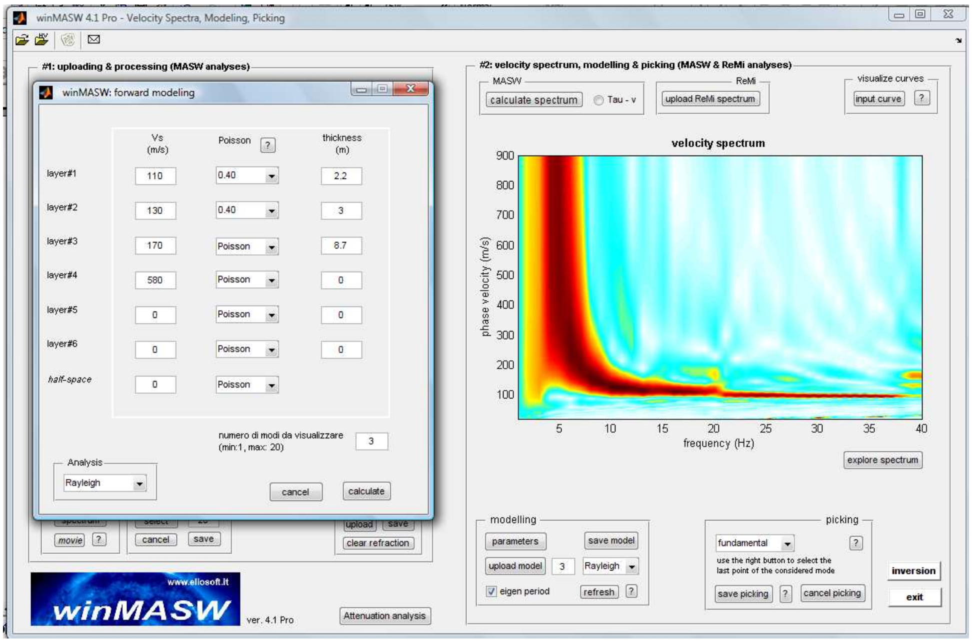
2) the animation of the actual-amplitude data (saved as "winMASW_Seismic_Movie_actual amplitudes.mp4").



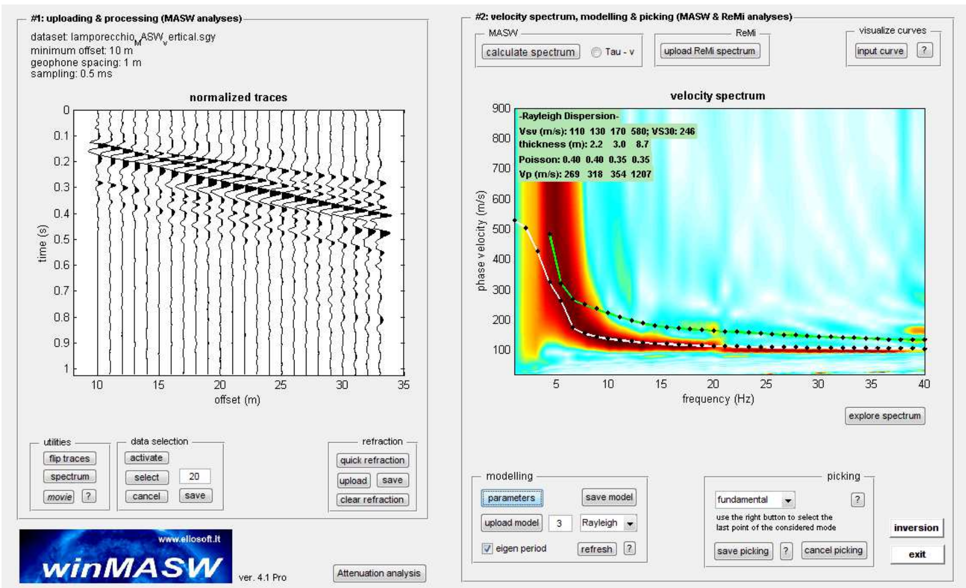
Do you see what attenuation does?!

Dispersion modelling: the modal dispersion curves

Beneath the velocity spectrum there is the section “direct modelling”, that allows the user to calculate the dispersion curves of a model up to seven layers whose parameters can be fixed by the same user clicking on the displaying menu on “parameters”
The calculated curves are screen shown and saved on an ASCII file (Frequency- V_R) in the file *.modelladiretta.txt* in the file *winMASW/output*.
The aim is to get the evaluation of a possible mode in respect of an observed spectrum.
In the case of geological complex situations (i.e. seismic data of hard interpretation) this is a very useful method and generally the interpretation is enough (as an inversion is no longer necessary).
It is clearly possible to fix different values of the Poisson ratio (in order to modify the V_P/V_S ratio): you’ll notice that the V_P values (once the value of the V_S has been fixed, as modifying the Poisson ratio means modifying the V_P) are not that relevant if compared to the role of the thickness and shear-wave velocities (V_S).



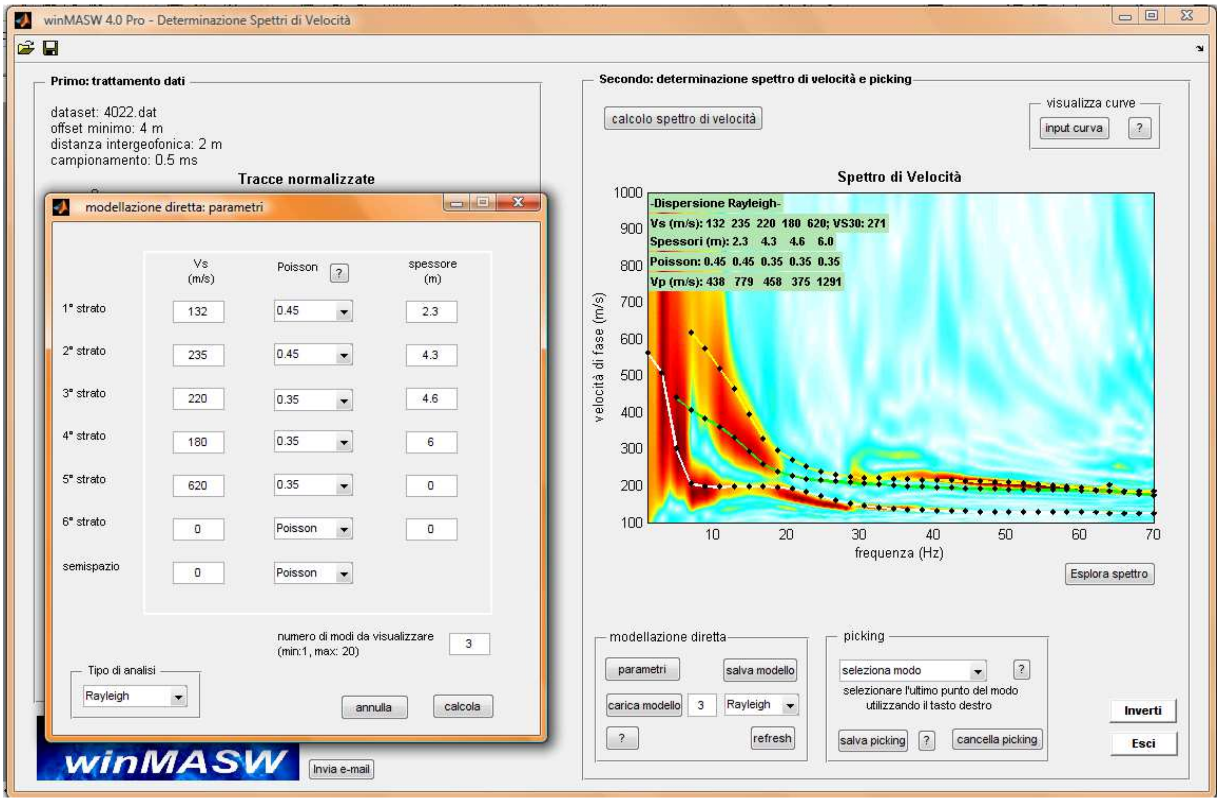
a)



b)

Figure 3. Direct modelling: calculation of the dispersion curve (laid on the observed velocity spectrum) of a supplied model by the user.

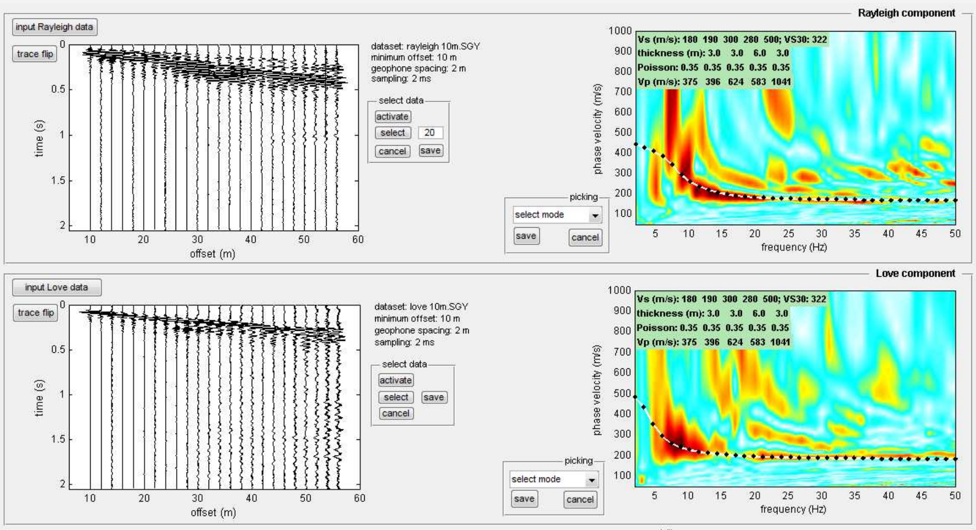
About the final (deepest) layer: in the figure example below only 5 layers have been input (the last one being a semi-infinite layer and therefore without any thickness value - leave the value equal to zero).



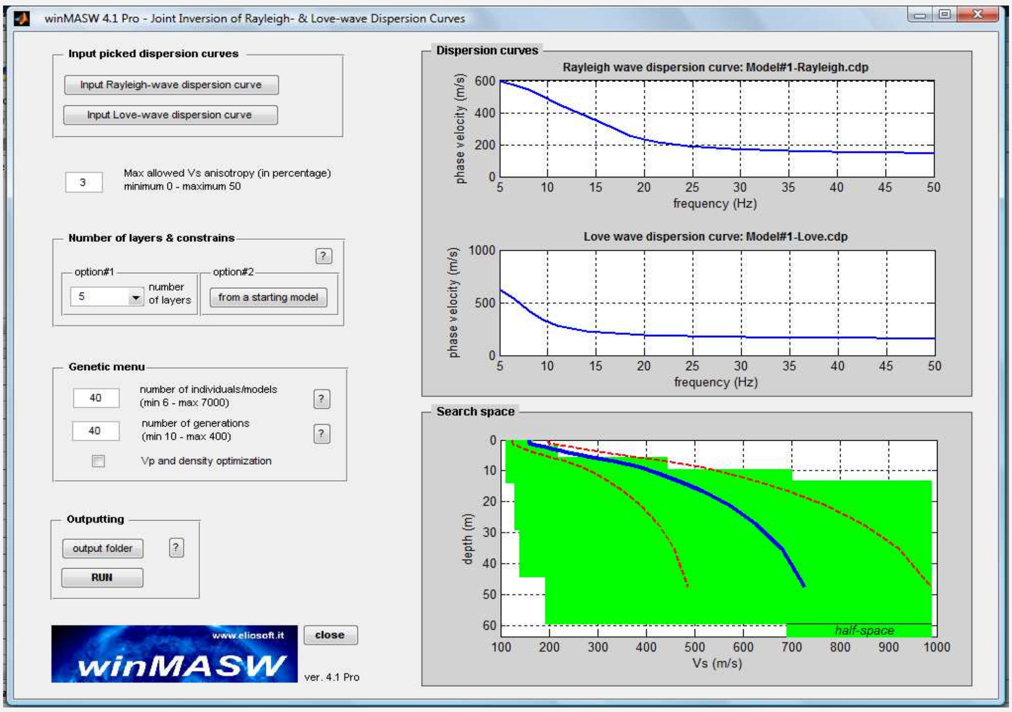
3C, Professional and Academy Versions

Joint analysis of Rayleigh and Love waves

Since the 4.1 version both dataset relevant to Rayleigh and Love analyses can be jointly analyzed. For this reason the main *winMASW®* screenshot displays a "group" dedicated to a joint analysis of Rayleigh and Love ("Joint Analysis of Rayleigh & Love").
Clicking on "Velocity Spectra, Modelling & Picking" the window containing uploading, picking and modelling of both datasets (one relevant to Rayleigh and the other relevant to Love) displays.



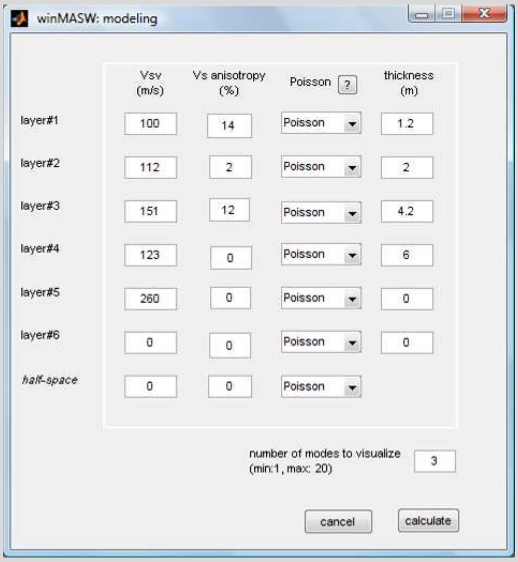
Clicking instead on "Rayleigh & Love joint inversion" you'll get access to the section aimed to the joint inversion of Rayleigh and Love dispersion curves



Since the close analogy between the two of them, this chapter is going to show the only procedures involved in the standard analysis of one component, focusing on some features only

3C, Professional & Academy Versions

Joint modelling Rayleigh & Love: anisotropy V_{SH}-V_{SV}



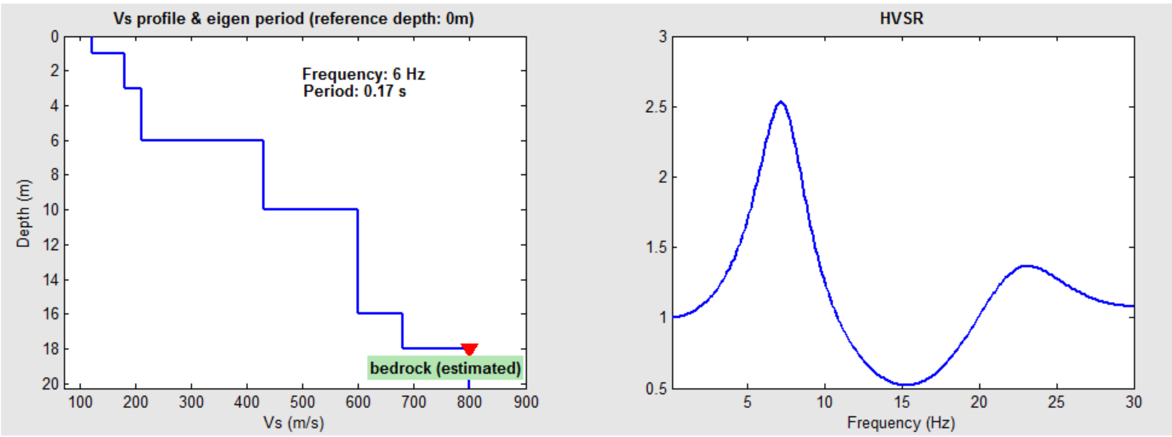
The window where model parameters can be input also displays a column for anisotropy V_S.
This parameter determines (supplied in percentage values) how bigger is the V_{SH} (that rules the dispersion of the Love waves) than the V_{SV} (that determines the dispersion of the Rayleigh waves)

H/V Spectral Ratio from body waves

In the *3C*, *Professional* and *Academy* versions it is possible to compute the H/V spectral ratio and model it both according to body waves (Herak, 2008) and Surface Waves (Lunedei & Albarello, 2009).
Click on the third little icon from left on the tool bar to upload the dataset relevant to that observed ratio H/V (the traditional yellow folder named HV)
The software reads ASCII files and assumes that the first column reports the frequency and the second the spectral ratio H/V (possible “header” lines to be ignored and can’t affect the reading/analysis)

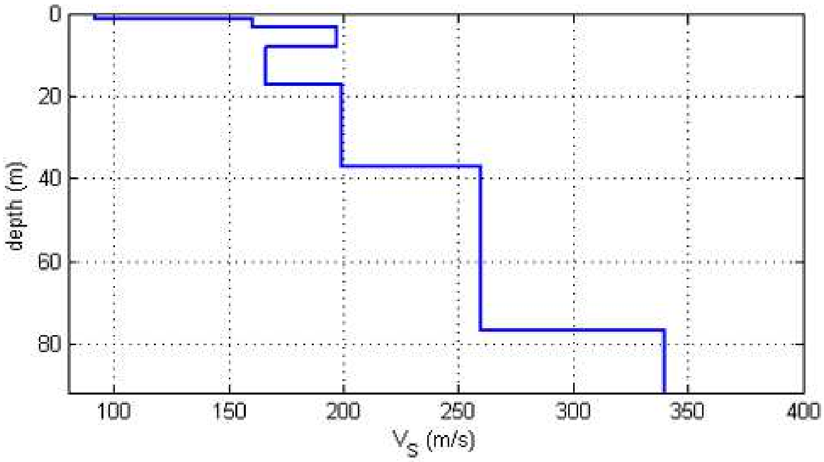
In other words the file format is:

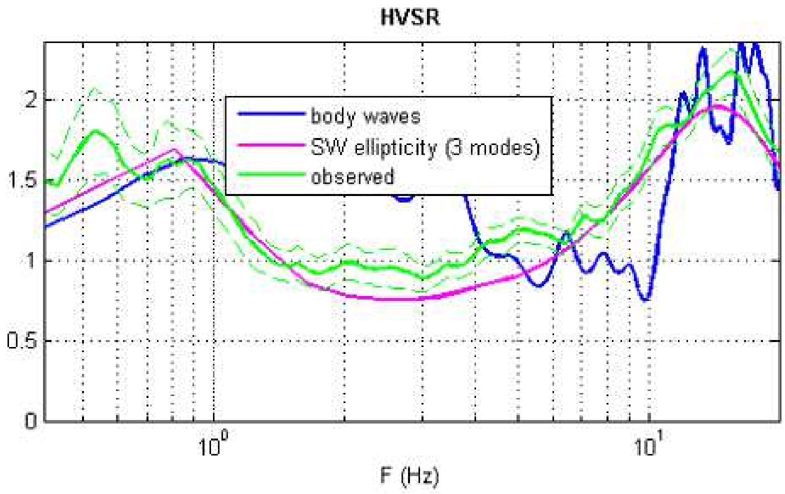
```
line#1 (example of site name)
line#2 (example of frequency sampling)
…
line#n

F(Hz)    H/V
0.1      1.00
0.15     1.05
0.20     1.11
0.25     1.09
…
30       1.05
```



On the left the Vs profile of the considered model with site eigen period as from the resonance equation; on the right the H/V ratio according to Herak (2008): if no relevant velocity inversion happens, the value determined by the equation and the one determined by the spectral ratio H/V are typically very close.

If a formerly observed HV is uploaded, and a model for forward modelling is introduced and its dispersion curves are calculated (having selected the option “eigen period”) both the theoretical HVSR curve (in blue according to body waves and in magenta according to Surface Waves) and the observed curve (in green) are displayed.





Example of observed and modelled (according to body and surface waves) HVSR.

Some notes on the H/V spectral ratio

Regarding the nature of the ratio H/V (i.e. those events determining the value as observed in nature) the academic debate is quite lively (not only because of technical-scientific matters but also because of party interests)

Following some of the most agreed upon general concepts:

- The value of the H/V ratio as observed depends on a complex relationship between surface waves (both Rayleigh and Love) and partly on body waves. The relative importance of the different components depending on the site characteristic (see for instance Bonnefoy-Claudet et al., 2008).
- Despite any chosen modelling, don't ignore the role of quality factors Q (in our case we assume Q_S value to be the same as V_S divided per 10, and $Q_P=2Q_S$)
- When adopting different modelling types (i.e. based on only Rayleigh waves, or on Rayleigh and Love, or body waves or all of them together summed up) the spectral ratio changes but the main peak (determining the eigen period) appears at the same frequency, generally speaking.
- From the only H/V value it is impossible to get any information on the V_S (that's why in this case you need to consider the MASW/ReMi values and compare)
- It isn't possible as well to directly compare the value of the H/V peak and the value of the lithologic *amplification factor*: to get this last we suggest to refer to the specific relevant regional rules or guidelines.

To recap, if in possession of an experimental H/V value and needing to find a model considering both the dispersion of the surface waves and the H/V observed curve, we suggest to focus on chasing the right peak frequency without trying to find the perfect balance with the amplitude (the H/V value)

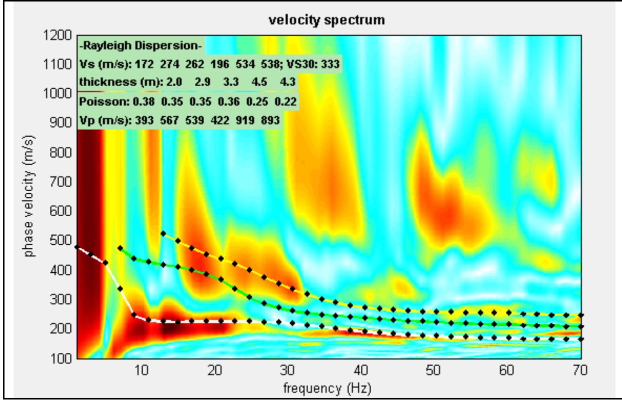
Note as well (figure on top) that the H/V values allow to identify possible strong contrasts of V_S deep underground (remember though that to constrain the V_S you need MASW/ReMi values that can give clear details about the V_S) and that it is most important to reproduce the correct frequencies when the peak shows. In the case on top for instance a strong discontinuity at about 60 cm depth is clear (it represents an alpine valley covered in a large quantity of fluvio-glacial sediments)

Modelling refraction (Pro & Academy) & reflection (Academy)

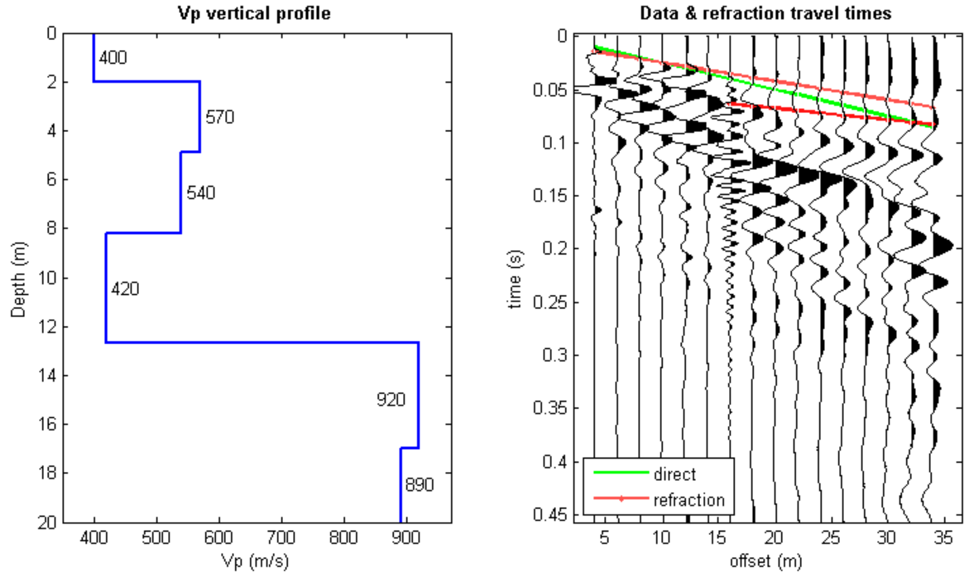
This section allows the user to model the arrival times of refraction events by means of very similar procedures to those used in the" modelling of dispersion curves" section.
Before starting consider that:

- The adopted calculation tool allows the insertion of channels with inversion of velocity, a thing that the traditional refraction method (utilized as only method) can't evaluate (this refers to the known problem of low velocity channel). In our case, making the most of all information from the dispersion curves and refraction we can evaluate inversions of velocity even according to V_P (remember you can't get solid information about it from the dispersion of surface waves).
- Consider that in order to get a refraction effect of noteworthy amplitude the acoustic impedance jump (i.e. the result of V_P multiplied for the density) must be significant
- a V_P decrease according to depth doesn't result in a refraction event
- the file of the saved or uploaded model has the same format of the one used to model the dispersion curves.
- If a modelling of the dispersion has preliminarily been executed (and therefore some V_S can be predicted) V_S as well as V_{SV} and V_{SH} will be considered as same when writing the refraction model (button "save"). In the opposite case in the .mod file, V_S values according to an assumed Poisson value around 0.35 will be reported.

As an example look below at a "joint modelling". The same model is considered from a dispersion curves and first arrivals times point of view.



Dispersion of the first three modes of the Rayleigh waves for the model top left



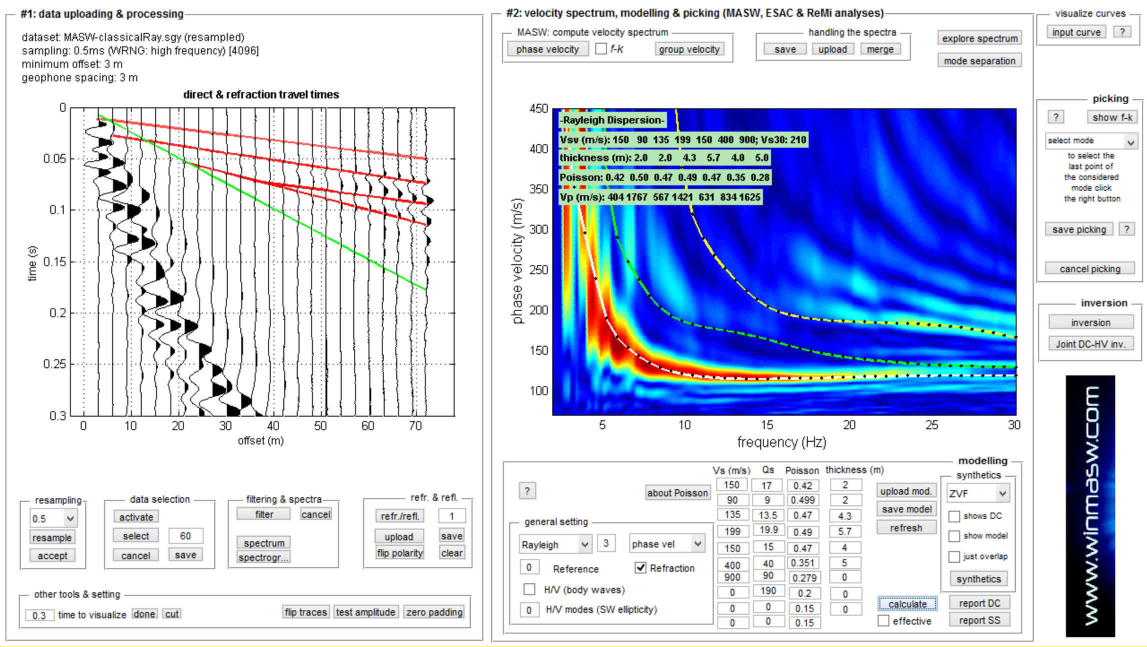
In red the arrival times of two refraction events relevant to the 2 only interfaces having a positive impedance jump; in green the arrival times of a direct wave.
In the *Academy* version also reflection travel times are shown.

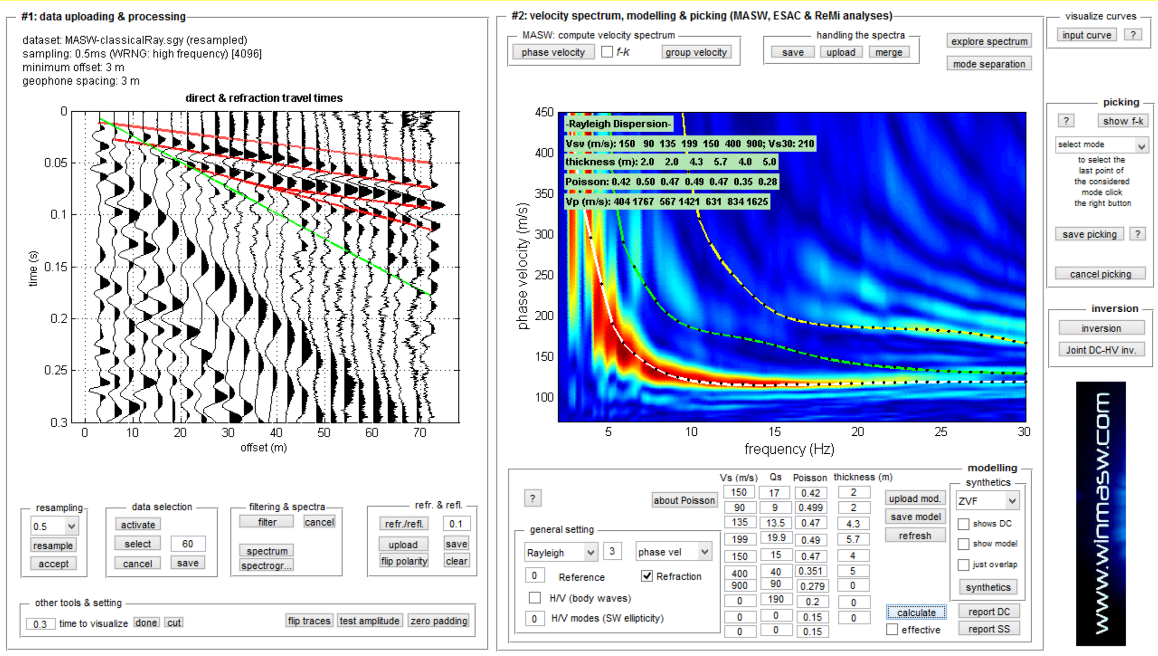
The AGC value

When the "Refraction" option is active, an AGC (*Automatic Gain Control*) is applied to the traces (its value - see value in the box just by the "refl./refl." button - can be clearly modified).

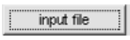
The value represents the window (in seconds) within which the energy is kept "constant" by modified the amplitude of the trace (in order to put in evidence low-amplitude signals usually associated with refraction event).

Here two snapshots obtained using two different values (it is apparent that the second case allows a clearer identification of the refraction events):





5. Inversion of picked (i.e. interpreted) dispersion curves

Once you have interpreted the velocity spectrum and picked your dispersion curves, the next step to obtain the V_S vertical profile is the inversion of the picked curve(s).
Please remember and consider that we **suggest to proceed with the forward modelling procedure** by personally modifying the V_S and thickness values of the model (see the modelling section in the "**Velocity spectrum/a, Modelling & Picking**" panels).
If you decide to follow the picking + automatic inversion procedure, we give you here few hints.
Figure 4 shows the main window of single-component inversion panel.
First of all you need to select the picked dispersion curve you intend to invert (button ).
Once curve(s) is/are uploaded, they will show up in the upper part of the panel.

We now need to define the *search space*. **There are two options**:

1) its automatic definition (click on the **number of layers** you wish to consider). In this case, it is obvious that, based on the site geological characteristics, user can/should modify the default values.

2) you can start from a model you were previously modelling during the data processing (see data modelling procedures) [such a model will be optimized based on your picked curves].

Once the limits of the *search space* are fixed, you need to fix/modify the parameters of the genetic inversion to perform (see **Table 1**).

Now it is time to launch the inversion (click the "run" button).

Two fundamental points to keep in mind. This *standard approach* to surface wave analysis has *two major problems*:

1) You are not inverting the ***data*** but your ***personal data interpretation*** (which can be wrong or meaningless);
2) Even in case your interpretation is correct the solution of the analysis of one single observable (component) is inevitable non-unique [see introductory section of this manual and recommended procedures based on the joint analysis of Rayleigh + Love waves + HVSR].

Note on the Poisson's ratio

Surface-wave dispersion depends mainly on the V_S and thickness of layers. Since density and V_P play a **very minor role** (try to play with different values of Poisson's ratios in the *direct modelling* section), you cannot obtain them from surface-wave analysis.
We need to remember that hard rocks have usually Poisson's ratios between 0.15 and 0.30, while soft/loose materials (sands, silt and clays) value between 0.35 and 0.4999 (depending on the saturation conditions).
Generally speaking, if no detailed information are at hand, it is recommended to choose a value of 0.2 for rocks and of 0.35 for loose sediments (0.45 in case of loose saturated sediments).

A note: when dealing with the energy distribution among different modes Poisson values (i.e. V_P) play major role! (see the FVS approach to surface-wave analysis)

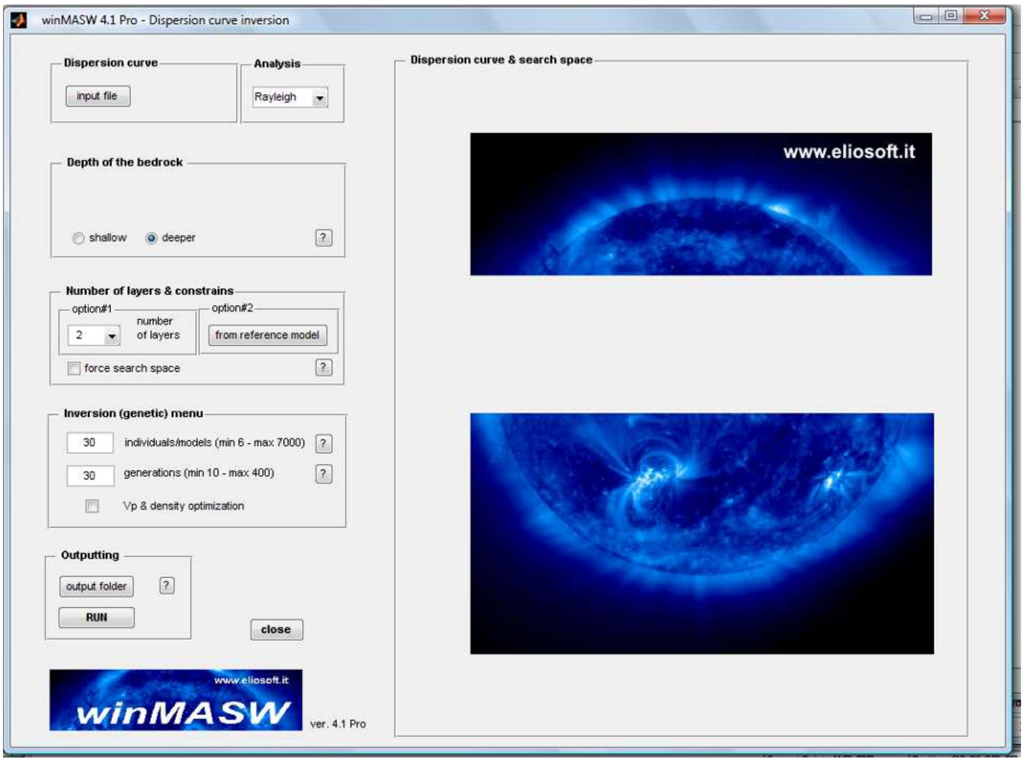


Figure 4. Starting window of the single-component inversion panel.

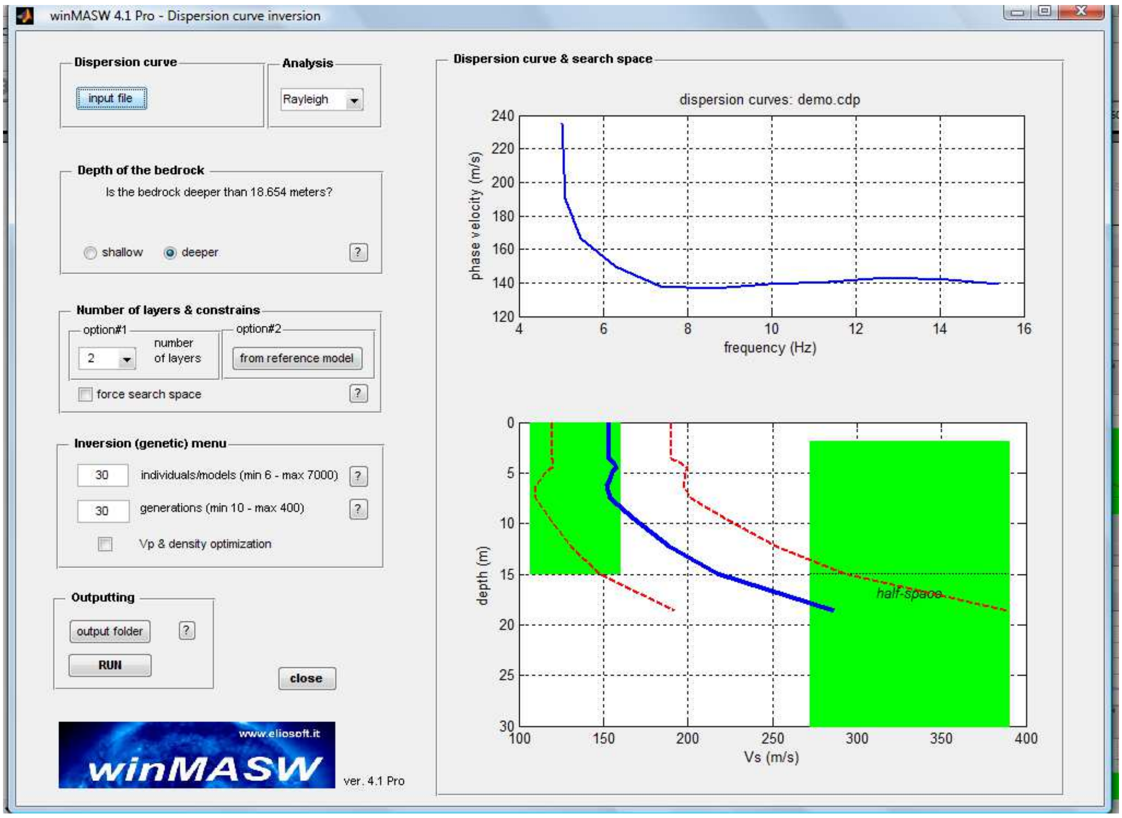


Figure 5. Definition of the *search space*. The user can modify it according to the geological characteristics of the site.

Inversion parameters

Parameter	Meaning	Recommended value
Number of layers	Number of layers used to rebuild the vertical profile	4-6 Normally 4-5 layers , but 5-6 if a layer with inversion of velocity is suspected
Search space	Limits for the thickness and V_S of each layer.	We would highly recommend to fix the search space starting from a starting model previously evaluated and saved during a forward modelling session (see also our *video tutorials*).
Number of individuals/models	Number of models constituting the number of people evolving to better solutions. The higher the number of layers, the more numerous the model to be considered.	80
Number of generations	Number of generations through which new models are explored, that get better and better with time	80

Table 1. Inversion parameters.

Max allowed V_S anisotropy (in case of joint Rayleigh + Love inversion)

In case of joint inversion Rayleigh + Love you can let the algorithm free considering
V_{SH} (from Love) different from V_{SV} (from Rayleigh) (the number we herewith consider is the possible percentage difference between these 2 parameters).
This may allow to mark some anisotropies up (see for instance Safani et al., 2005) or, easier, (for less expert users) to consider a sort of tolerance in the optimization/inversion process.
Possible anisotropies only have a value according to the user's experience. Therefore consider them in this view.

Expand the search space

By activating this option, the software is allowed to search for solutions (models) outside the *search space* (min and max values for V_S and thickness) originally defined/set by the user.

V_P and density optimization

If you activate such an option the software will also consider the optimization of the Poisson's ratios so to better match the experimental data.

Bi-objective space (in case of joint inversion procedures)

If this option is active, a “full complete” joint inversion is processed.
This means that during the optimization process each model misfit is calculated (both for Rayleigh and Love). In the opposite case optimizations come separately.
This option slows calculation times a bit, but allows the expert user to check the distribution of models in the so called bi-objective space (refer to relevant literature on how to proceed) (Dal Moro & Pipan, 2007, Dal Moro, 2008; Dal Moro, 2009).

Once launched the inversion, a state bar will show both the elapsed and the remaining time:

Warning

Remember that if you choose to follow the *picking-inversion* approach, the results will depend NOT on the data but on <u>YOUR PERSONAL INTERPRETAION</u> of the data.

The software inverts YOUR picking (i.e. your personal *interpretation* of the data) and NOT the *data*.

If you pick an erroneous/inaccurate/meaningless dispersion curve, you will necessarily obtain a meaningless V_S profile.

This is why we recommend to jointly model three observables:

Rayleigh and Love waves (possibly according to the FVS approach) + HVSR curve (see our video tutorials).

It is extremely important to attend one of our workshops (and you can organize one in your area) and/or studying our papers and books.

Results are supplied both graphically and as text files (.txt and .html format, see table 2) and are automatically saved in the folder "output" (or any other file as chosen by the user).
Every time the user launches the inversion process all the files in the output folder are deleted. Therefore, if you keep your results in the folder "output", save the inversion files in another one (named as wished).
You'll notice two models: the "best" model (in terms of lower misfit, i.e the discrepancy between the observed and the calculated curve) and a medium model calculated by means of MPPD (*Marginal Posterior Probability Density*, see ref. "Rayleigh Wave Dispersion Curve Inversion via Genetic Algorithms and Posterior Probability Density Evaluation" – Dal Moro et al., 2006).
Consider this as your final result (however the two models don't differ significantly). The final screenshot (figure 7) displays different information. Top left the observed data, the curve of the best model and the medium one-often the two curves are one over the other therefore not clear. Below you can see the graphic "misfit-generation" that provides the evidence of the improvement of the model according to advancing generations. On the right, the V_S profile according to velocity.

Quality of the inversion process

Two main facts determine the quality of the inversion process:

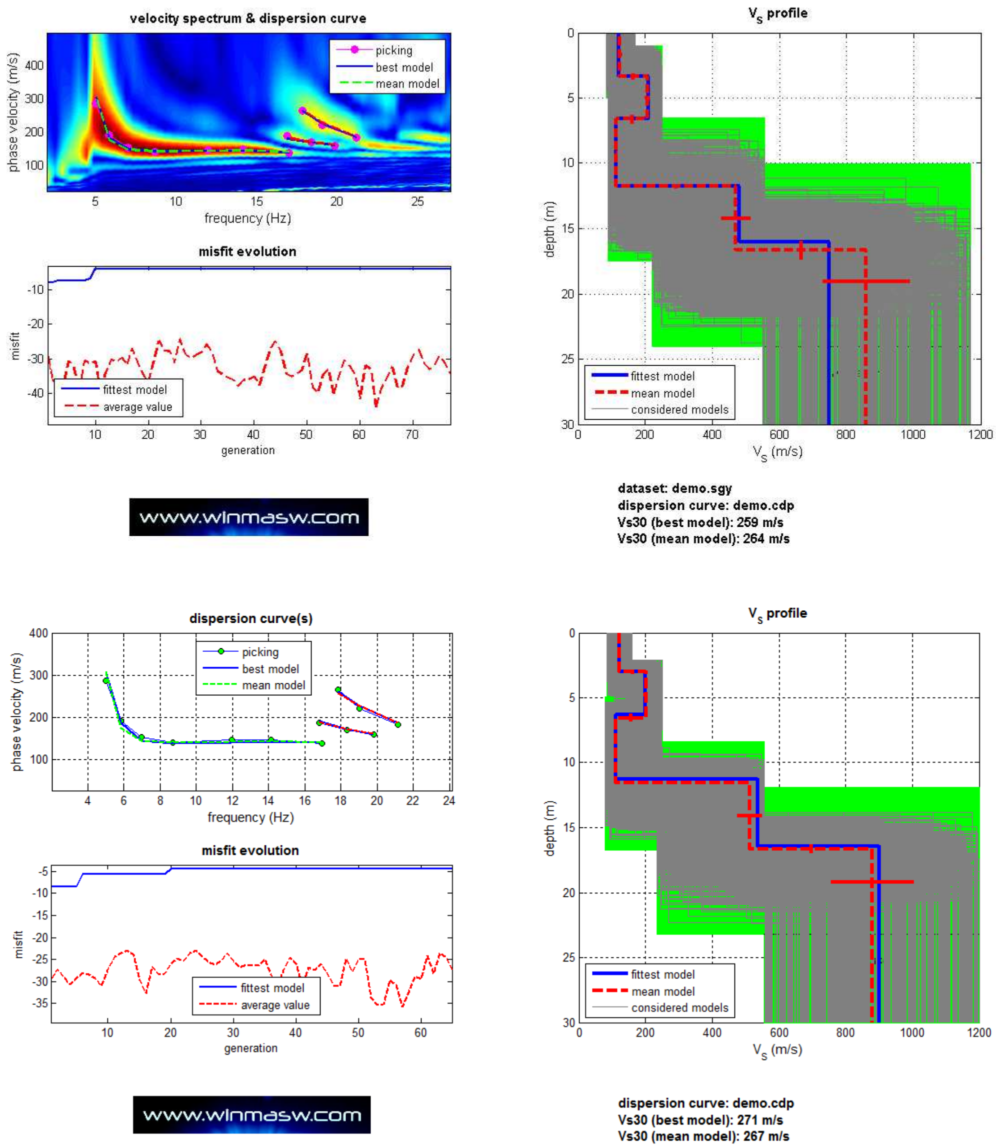
1. picking a meaningful dispersion curve (if your picking is wrong, the inversion will also be necessarily meaningless!);

2. properly setting up the inversion (numbers of layers, V_S variability range and thicknesses, number of models and generations).

Maximum penetration depth

This value is the outcome of the relationship between velocity and the frequencies represented in the dispersion curve. Always deeper layers influence as a matter of fact always lower frequencies (wider wave lengths) so that the lowest frequency will determine the higher depth of penetration. This value is determined by the approximation $\lambda/2.5$ (or $\lambda/2$), therefore it only is indicative.

Example:
If for your dispersion curve the value of the phase velocity (V_R) corresponding to the lower frequency is 500m/s and the frequency is 6Hz, the max wave length will be 83 mt and, consequently, the max depth of penetration will be between 35and40 mt.



a)

b)

Figure 7. Final screenshot (automatically saved in the “output” folder). If you get in the section “inversion of the dispersion curves” after the analysis of the dataset in the section “determination of the velocity spectrum” you’ll get a plot similar to the one on top (case a), In this case you can associate a curve to the relevant spectrum. If you instead get in the section “Inversion of the dispersion curves” directly from the main winMASW screenshot, uploading a formerly picked curve, that won’t be possible, and you’ll get a plot like the one below (case b) (there is no velocity spectrum on the background of the dispersion curve).
The representation reported on top is definitely to prefer.

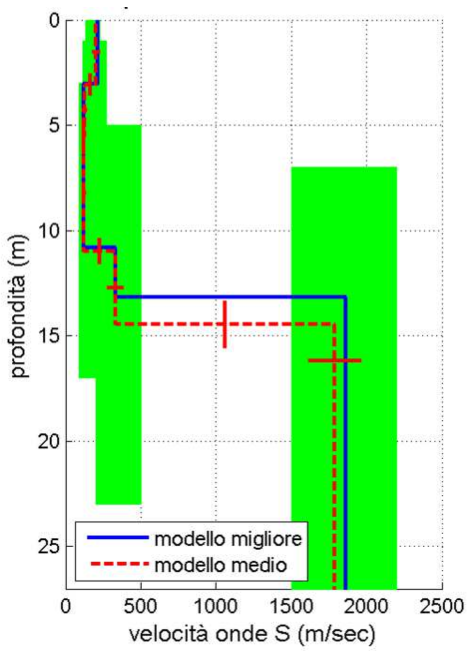


Figure 8. Example of final result: mean and best models (in green the adopted *search space*).

In Figure 9 you can see two examples of inversion obtained on a synthetic 6 layers model. Left, the result of the inversion when using 6 layers, right the result when using 10.

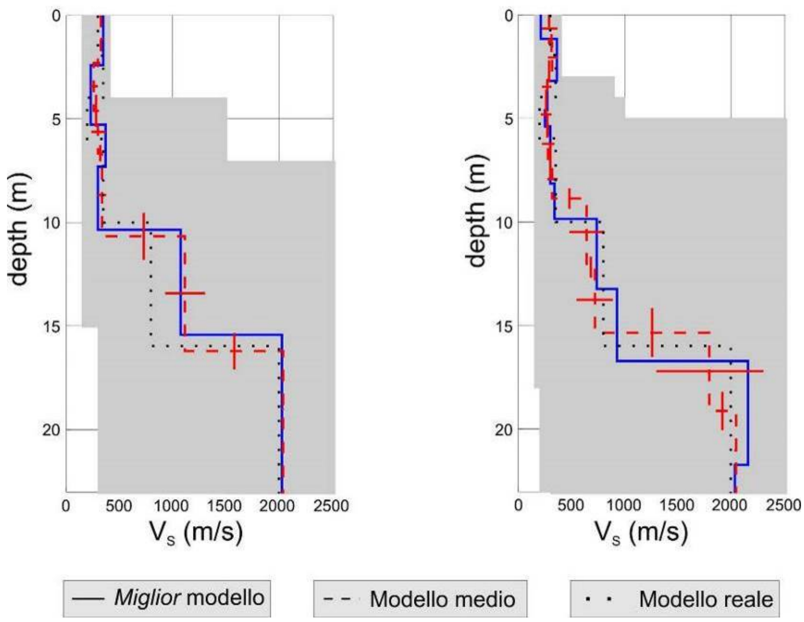


Figure 9. Example of results for a synthetic model. For the inversion on the left 6 layers were used, for the one on the right 10 (in pale grey the search space)

6. About Love waves

Love waves are generated by a shear-wave source (a standard sledgehammer over a wooden beam or similar solutions).

Unlike Rayleigh waves, Love waves only respond to V_S, thickness and density of the strata (and, of course, to the quality factors Q_S): V_P values do not appear in the constitute equations.

It is clear that the joint acquisition and processing of both Rayleigh and Love waves is of paramount value since it significantly help in understanding the velocity spectra and in better containing the inversion process, thus leading to a more robust V_S profile (Dal Moro and Ferigo, 2011; Dal Moro et al., 2015; Dal Moro, 2019; 2020; 2023).

Why analyzing Love waves: reason#1

There are two reasons why you should include Love waves in your analyses. As already pointed out in Safani et al. (2005), messy higher modes often are less prominent and velocity spectra are usually far better defined compared to the ones obtained for Rayleigh waves.

Note that Love-wave dispersion depends on the horizontal component of the shear-wave velocities (V_{SH}) while Rayleigh waves on its vertical component (V_{SV}).

Therefore, if you can accomplish a good joint analysis of both, you'll be able to obtain some information about the seismic anisotropy related to the stratifications and/or joints and fractures (see again Safani et al., 2005 and Gaherty, 2004).

Please, carefully read at least Dal Moro and Ferigo (2011), Dal Moro et al. (2015), Dal Moro (2019; 2020; 2023) and the *Elsevier* and *Springer* books.

Why analyzing Love waves: reason#2

Love waves are extremely useful also in case a stiff shallow layer is present since, in that case, the shear-wave velocities of the deeper layers are immediately evident already at the very high frequencies and the peculiar mode excitation immediately reveals the presence of such a shallow inversion.

Please carefully read the following (open access) paper:

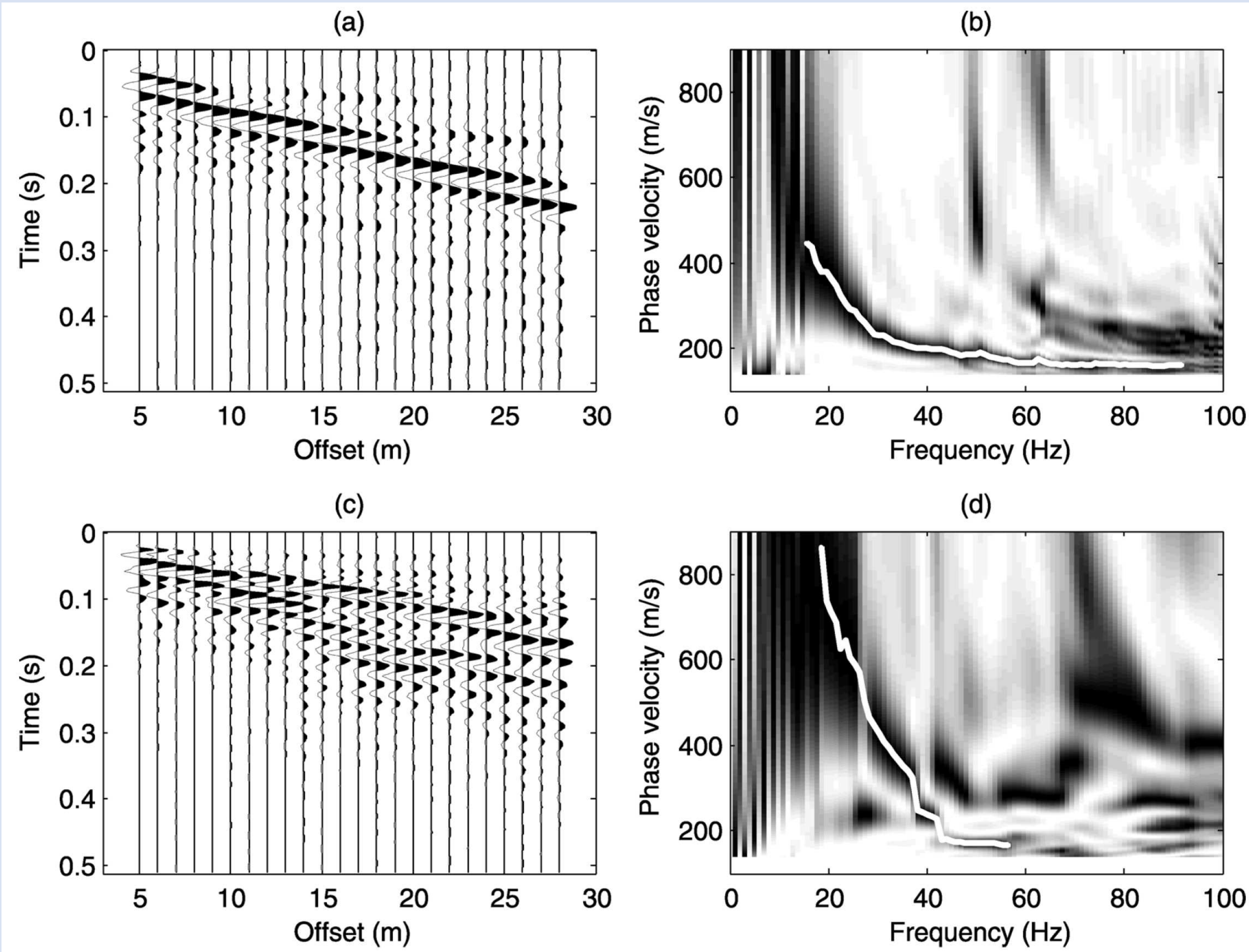
Dal Moro, G., 2020. ***The magnifying effect of a thin shallow stiff layer on Love waves as revealed by multi-component analysis of surface waves***.

Scientific Reports **10,** 9071, https://www.nature.com/articles/s41598-020-66070-1
(also available the presented dataset)

Love (upper panel) and Rayleigh-wave (lower) phase velocity spectra for a test site. Which one is more "understandable"? How can you be sure that your understanding/picking is correct when the velocity spectra of the Rayleigh waves are so often very messy? Go for Love waves!

For many more examples see our *Elsevier* and *Springer* books and our papers

www.winMASW.com



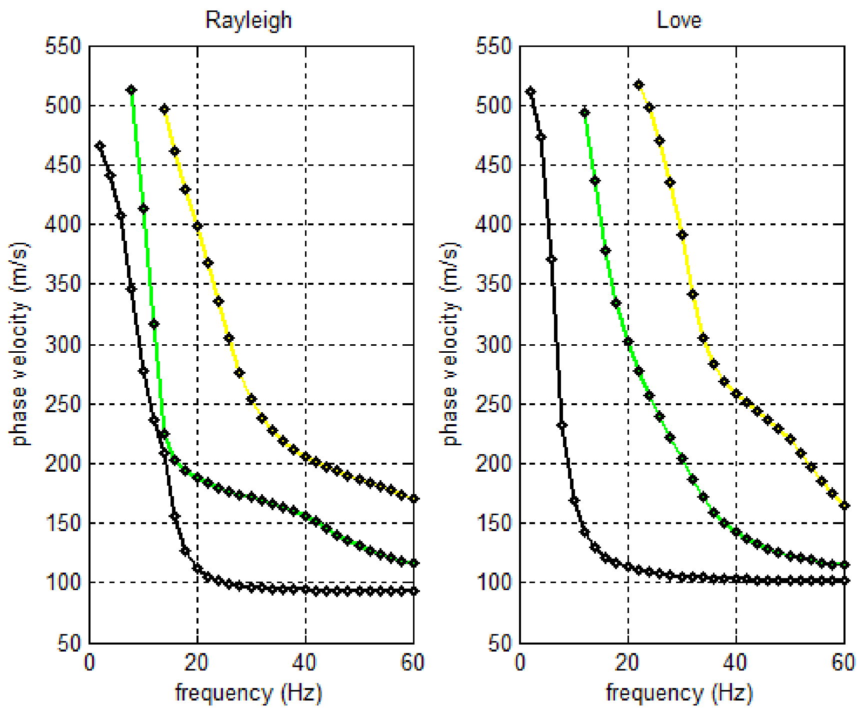
From Safani et al. 2005: "**Applications of Love Wave Dispersion for Improved Shear-wave Velocity Imaging**" - **https://doi.org/10.2113/JEEG10.2.135**

Producing Love waves in a classical way. It is sometimes useful to tilt a bit the trigger geophone in order to better "feel" the shot. In the photo below an alternative way to obtain the same thing: the plate is simply put in a small (shallow) hole.

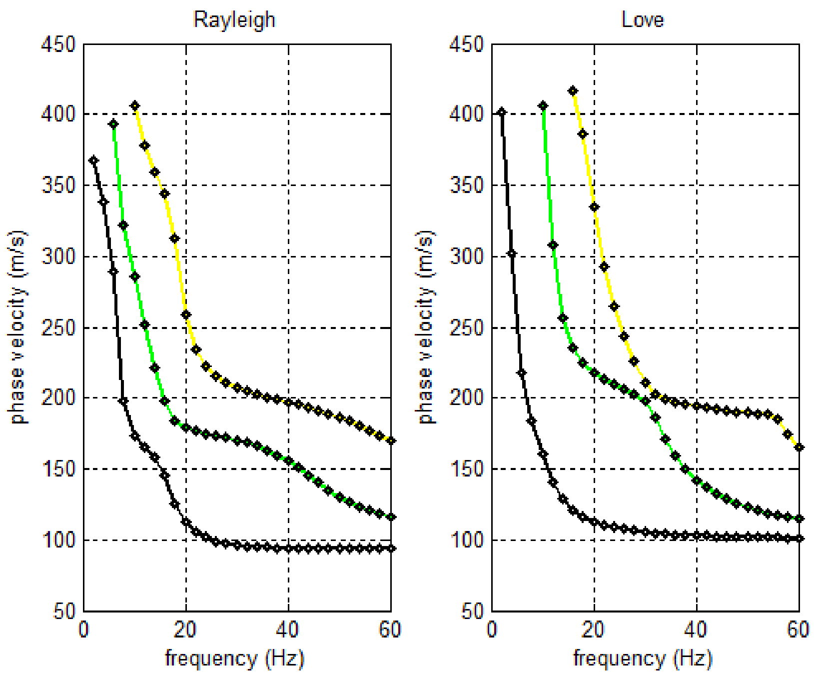
The model (*file* model.mod) in case of Love-wave analysis

In the case you analyze the dispersion of Love waves no information about compression waves (V_P) can be obtained (their dispersion depends just on V_S, thickness and density).

Model
thickness (m): 2.5, 3.5, 5
V_S (m/s): 100, 230, 380, 520
V_P (m/s): $2V_S$



Model
thickness (m): 2.5, 3.5, 5
V_S (m/s): 100, 230, 180, 420 (notice the V_S dispersion deep)
V_P (m/s): $2V_S$



7. Synthetics and FVS (Full Velocity Spectrum) analysis

In the *Academy* version, *winMASW®* also generates synthetic seismograms computed via *modal summation*.

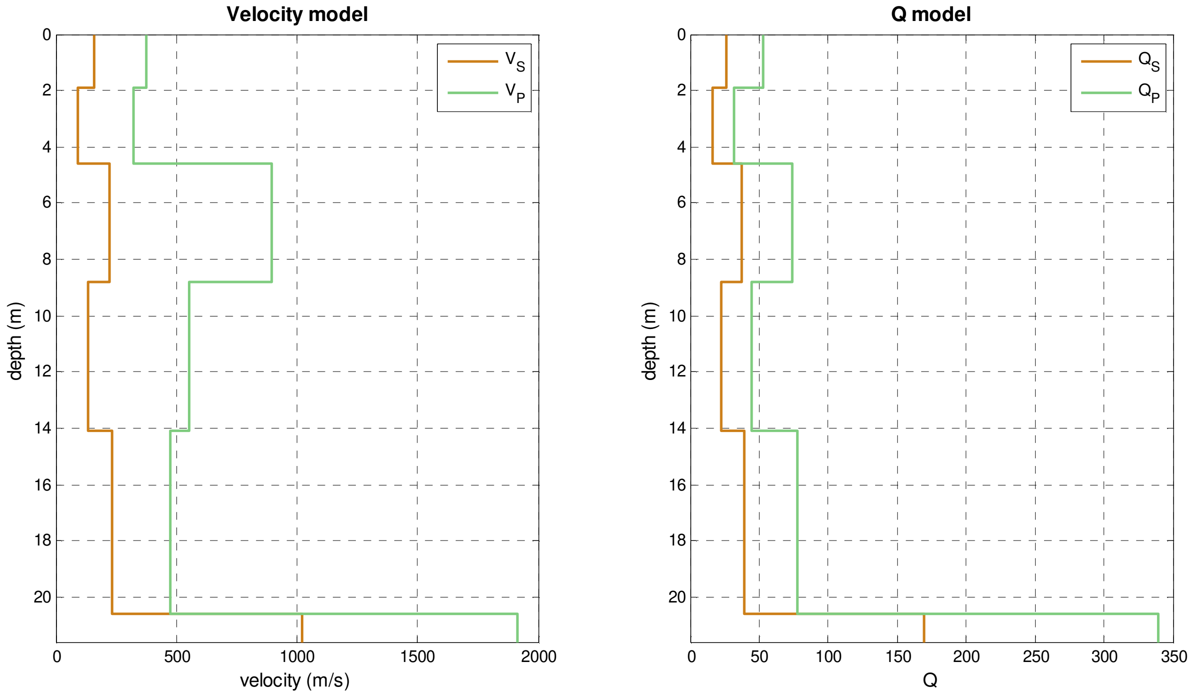
Quite clearly to properly use these tools it is necessary to be familiar with several aspects related to seismics (also including signal processing) (this is why the tools are available only for the *Academy* version).

Modelling: main points

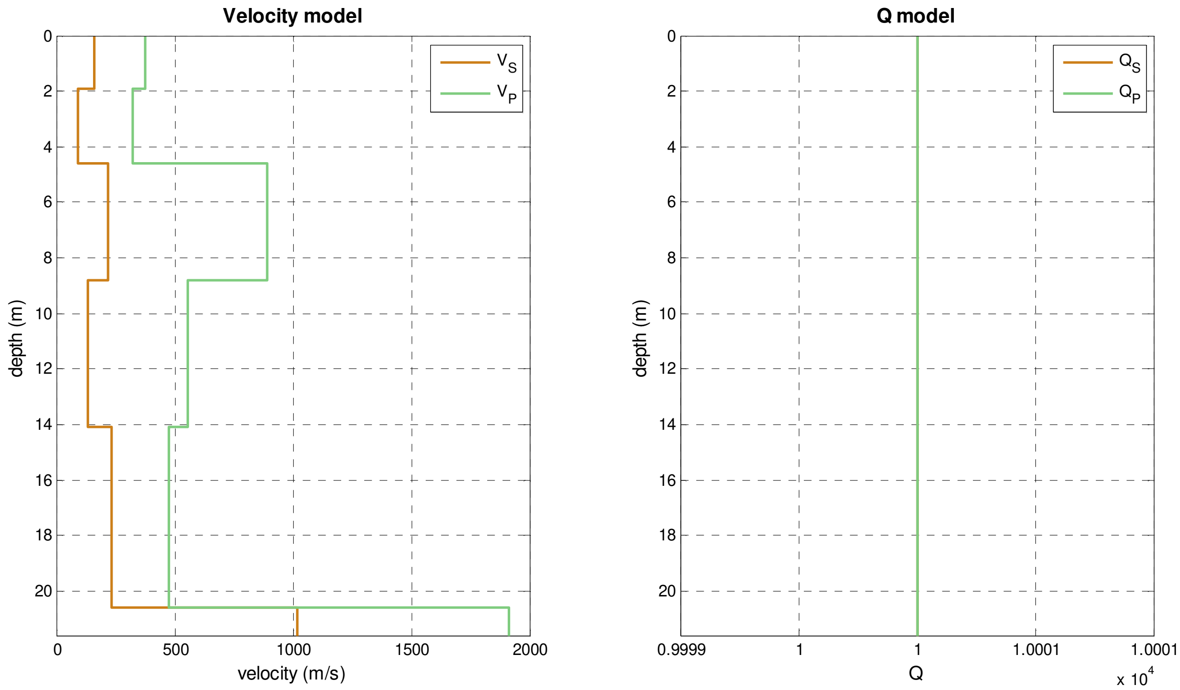
- Minimum and maximum frequencies considered while generating synthetics are the same of the currently-considered velocity spectrum ("*phase velocity*" button in the "*MASW: compute velocity spectrum*" group)
- The adopted number of modes is the same as the number indicated in the "*general setting*" sub-group (see "*modelling*" group –by default 3 modes are considered).
- Source: while analyzing Rayleigh Waves we consider a *Vertical Force* (VF) (user can choose whether to consider the vertical component ZVF or the radial one, RVF – see Herrmann's terminology). While analyzing Love wave we are dealing with a shear source (perpendicular to the array –THF, *Transversal Horizontal Force*).

The computed synthetic dataset is automatically saved ion the working folder as SEGY file (the name also reports the fact whether the file refers to Rayleigh or Love waves - *synthRayleigh.sgy* and/or *synthLove.sgy*).

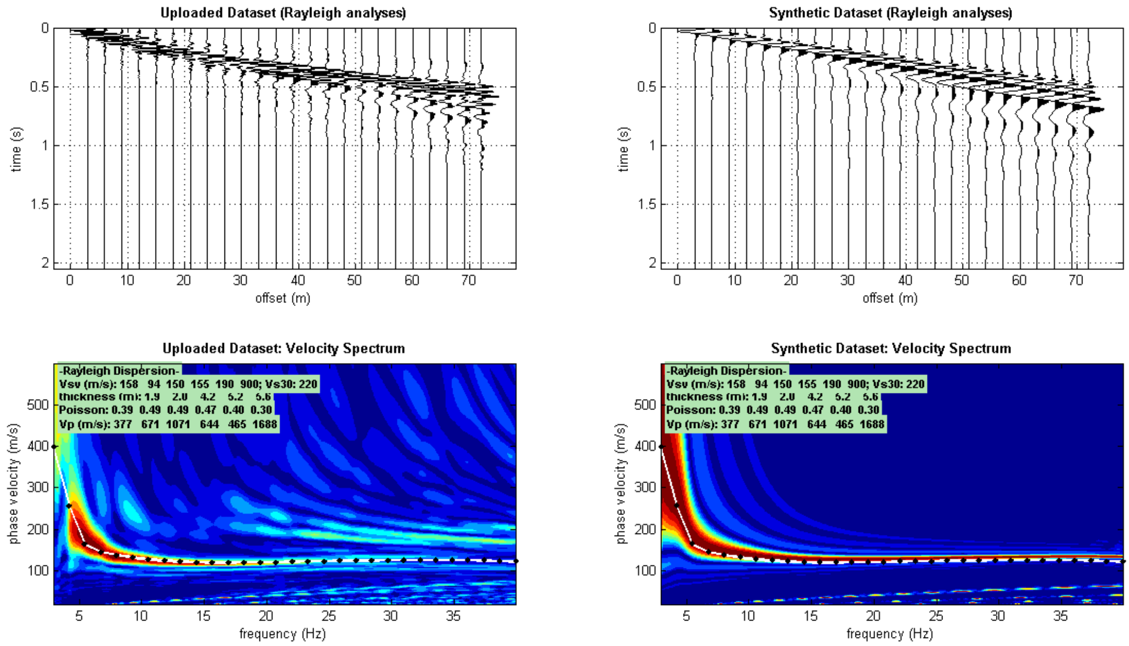
While considering the visco-elastic case (thus the "elastic" *check box* is inactive) for the modelling we will assume $Q_S=V_S/5$ (and $Q_P=2Q_S$) as simple *rule of thumb*. For further information see also next chapter on velocity spectra inversion.



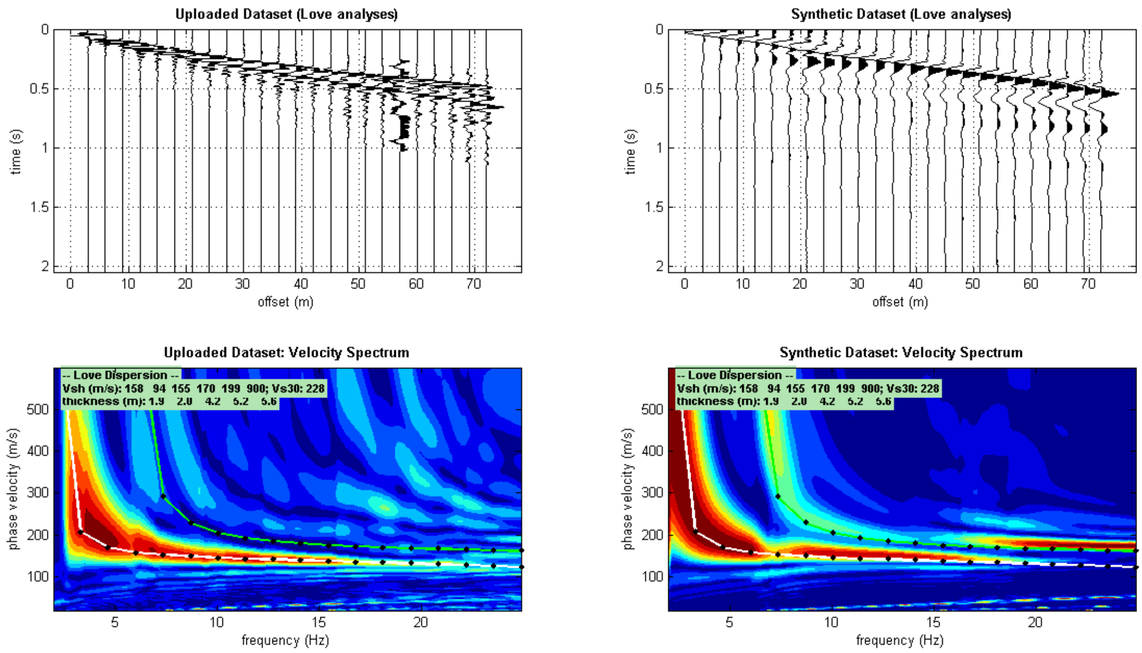
Otherwise it is assumed that $Q_S=Q_P=10000$ (see following plots):



Example: Rayleigh + Love



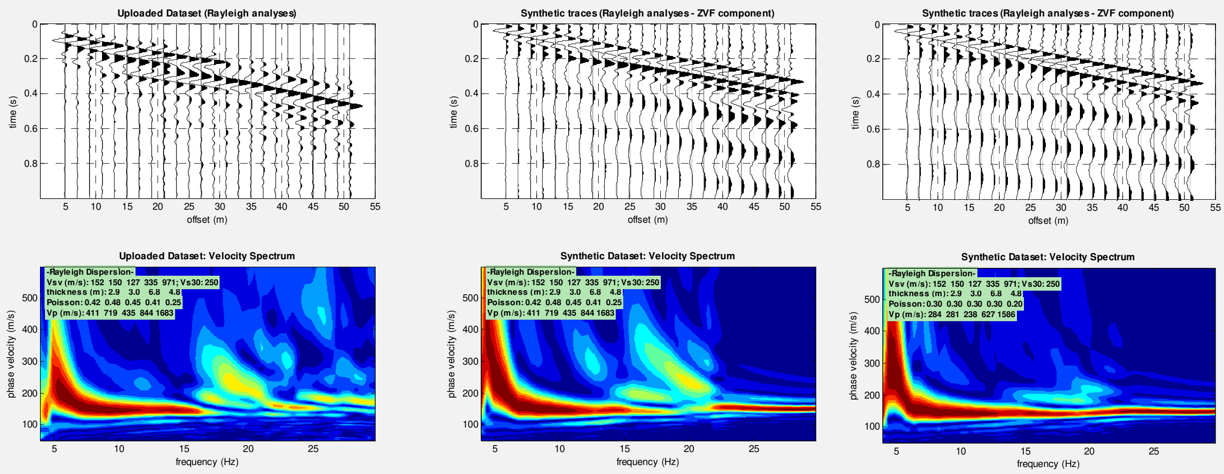
***Rayleigh*: on the left the field data, on the right the synthetics.**



***Love*: on the left the field data, on the right the synthetics.**

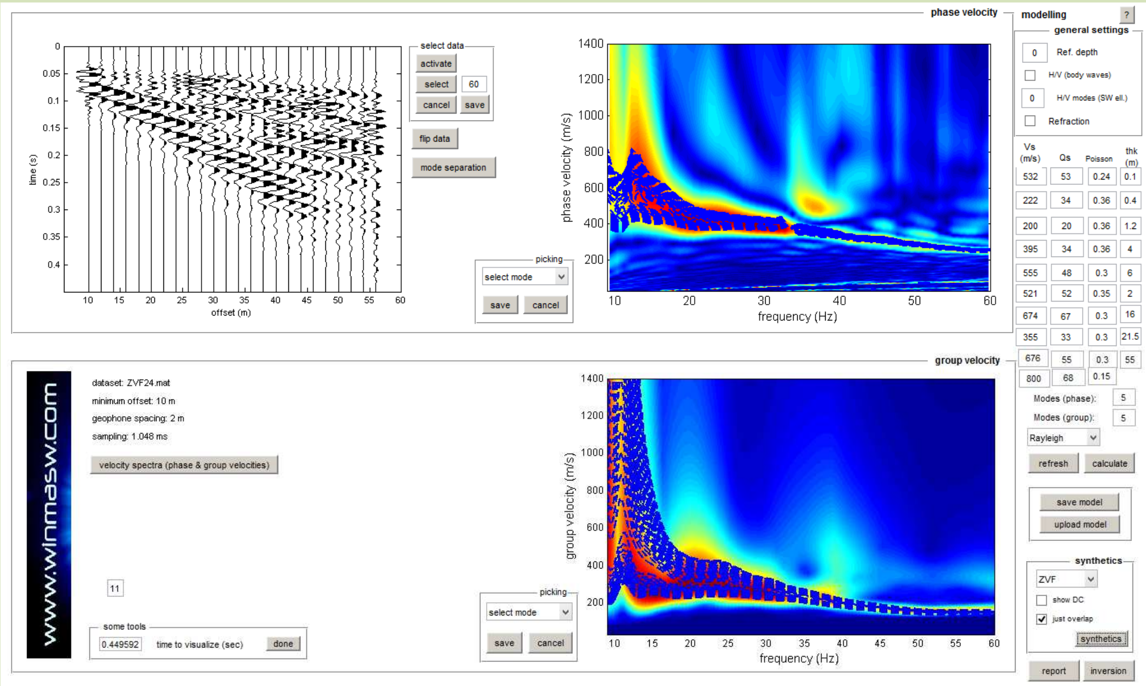
Poisson and energy distribution

V_P are surely not very important in determining the dispersion curves but have a profound effect on the energy distribution among different modes. That means that modifying the Poisson values (i.e. V_P) you will modify the energy distribution among different modes. Down here an example: on the left a real dataset; on the left and in the central panels two synthetic models with the same V_S–thicknesses but different V_P values. Notice the different energy distribution (quite often higher Poisson values determine more energetic higher modes).



If while computing synthetic seismograms the "*just overlap*" option is selected, what you get is a plot where the *contour lines* of velocity spectrum of the synthetic seismograms is overlapped with the velocity spectrum of the field dataset (background colors).

Down here an example from the "joint phase and group velocity analysis" panel: please notice how the blue contour lines of the synthetic model reproduce quite well the actual field data (colored velocity spectra in the background - this clearly means that our tentative model is good).



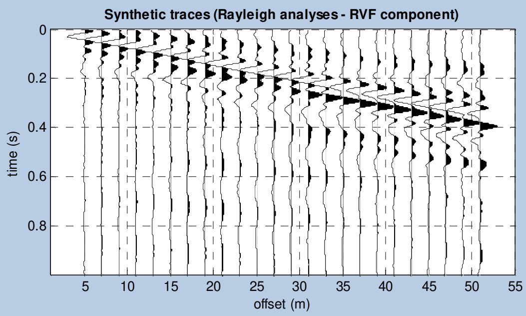
As a matter of facts, this approach is similar (and for some reasons even better) than the "effective dispersion curve" approach (e.g. Tokimatsu et al., 1992).

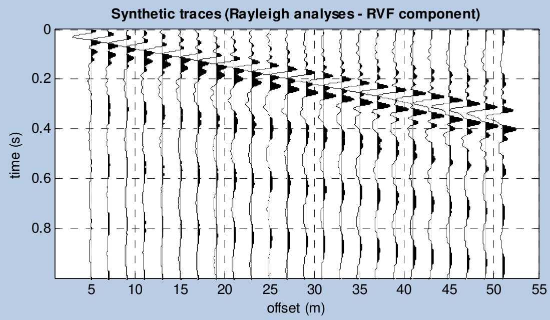
ZVF, RVF, ZEX, REX or THF?

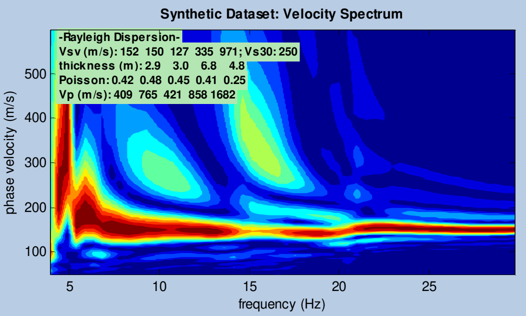
In the terminology adopted by Prof. Herrmann, VF stands for "*Vertical Force*", HF for "Horizontal Force", while EX for "Explosive". These letters clearly refer to the kind of source. About the receivers, these can be vertical ("Z") horizontal radial ("R") or horizontal transversal ("T"). As a consequence synthetic seismograms can relate to different acquisitions:

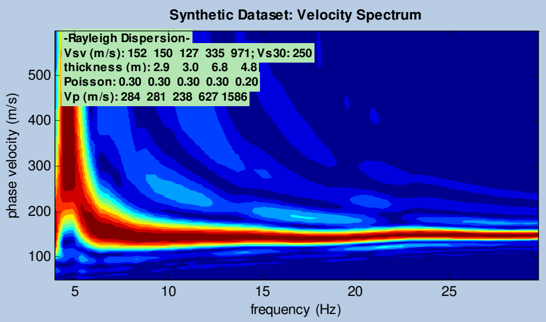
ZVF: Vertical Force (e.g. vertical sledgehammer) and vertical geophones (for Rayleigh waves)
RVF: Vertical Force (e.g. vertical sledgehammer) and radial geophones (for Rayleigh waves)
ZEX: Explosive source and vertical geophones (for Rayleigh waves)
REX: Explosive source and horizontal (radial) geophones (for Rayleigh waves)
THF: Horizontal Force (shear-wave source) and horizontal (transverse) geophones (for Love waves)

See also our "guidelines" for a good data acquisition in the "Documents" folder (within the *winMASW* installation folder).
Down here the same models reported in the "Poisson and the Energy Distribution" box (different Poisson values) but, in this case, for the radial component. Please notice the different energy content for the different modes. As this dataset was acquired using vertical geophones the correct comparison must be done with the synthetics datasets reported in the previous box related to the ZVF component – see the very good agreement between the field dataset (on the left on the "Poisson and Energy distribution" box) and the central model characterized by high Poisson values).







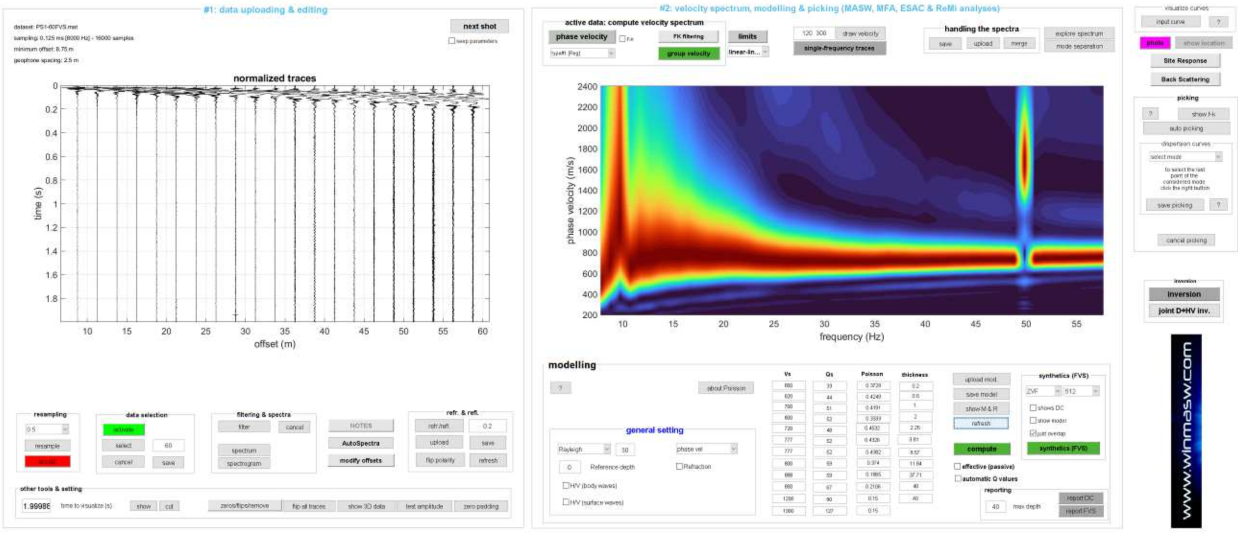


FVS analyses: record length and number of samples of the synthetic seismographs

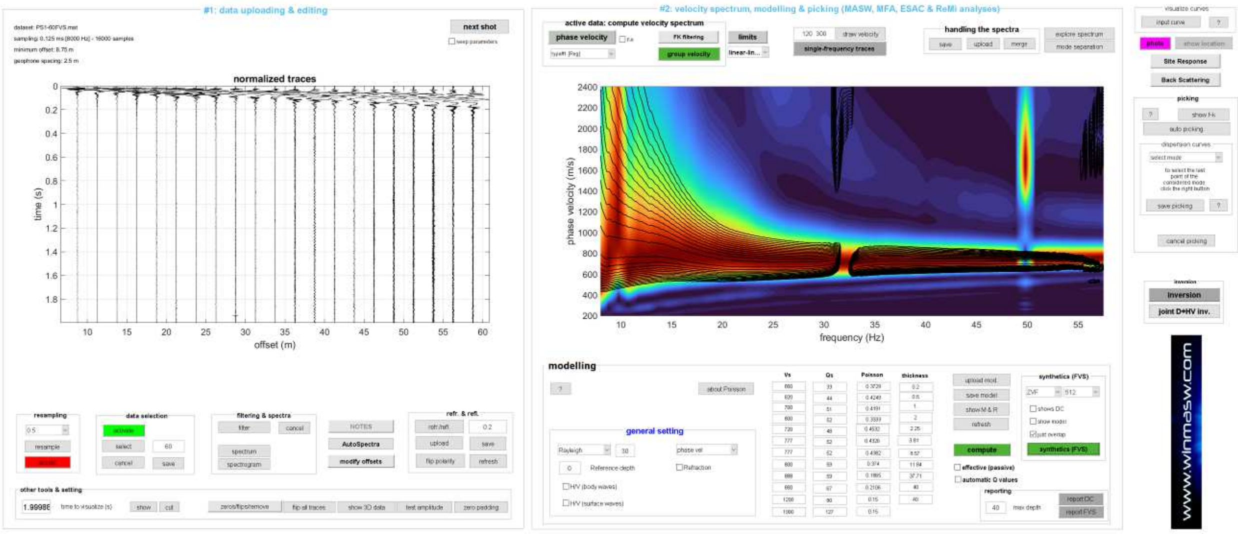
When carrying out FVS analyses (both as forward modelling as well as in the automatic inversion), it is important to minimize the length of the recording and clean the data with the *data selection and cutting* tools. Considering just the portion of the data in which there is the signal we are interested in allows for improved quality of the created synthetic seismograms (and thus the velocity spectra computed from them for the FVS analysis). The "cut" button is used to reduce the recording time (which, during acquisition, may have been set too long).

Let us see an illustrative example

Here below a dataset recorded with an obviously-unnecessarily large record time (2 s) and sampling rate (0.125 ms) (note how the software warns you about the unnecessarily high sampling both with an audio message and with the red color of the button to use in order to halve the sampling – lower left "accept" button).

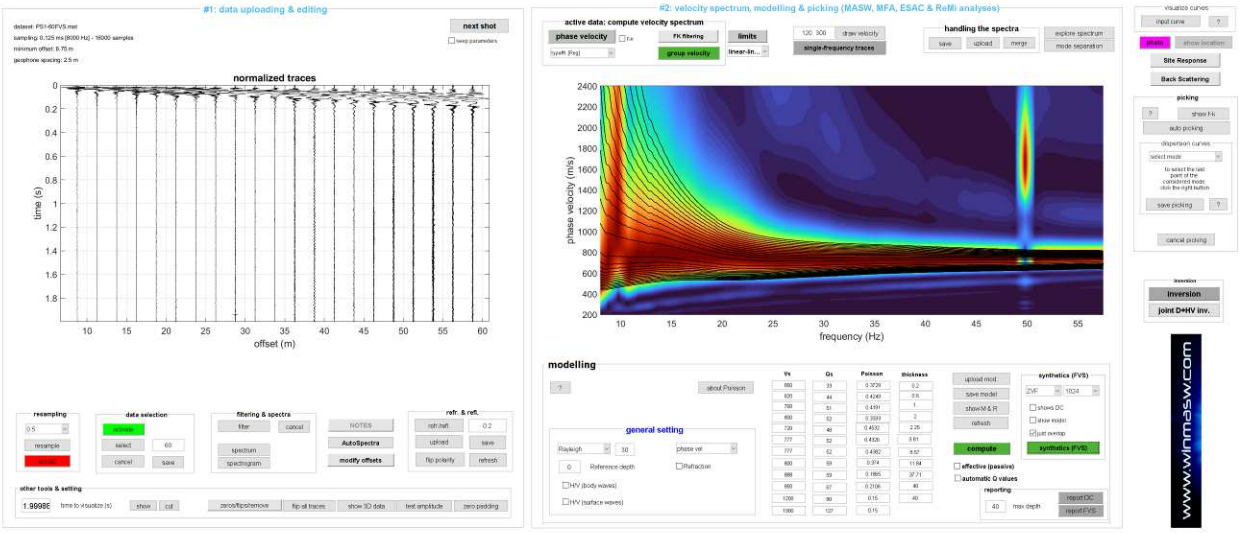


Below the FVS forward modelling considering 512 samples (default value of the popup window in the "FVS group" at the bottom right). You can see a small "problem" around 32 Hz.



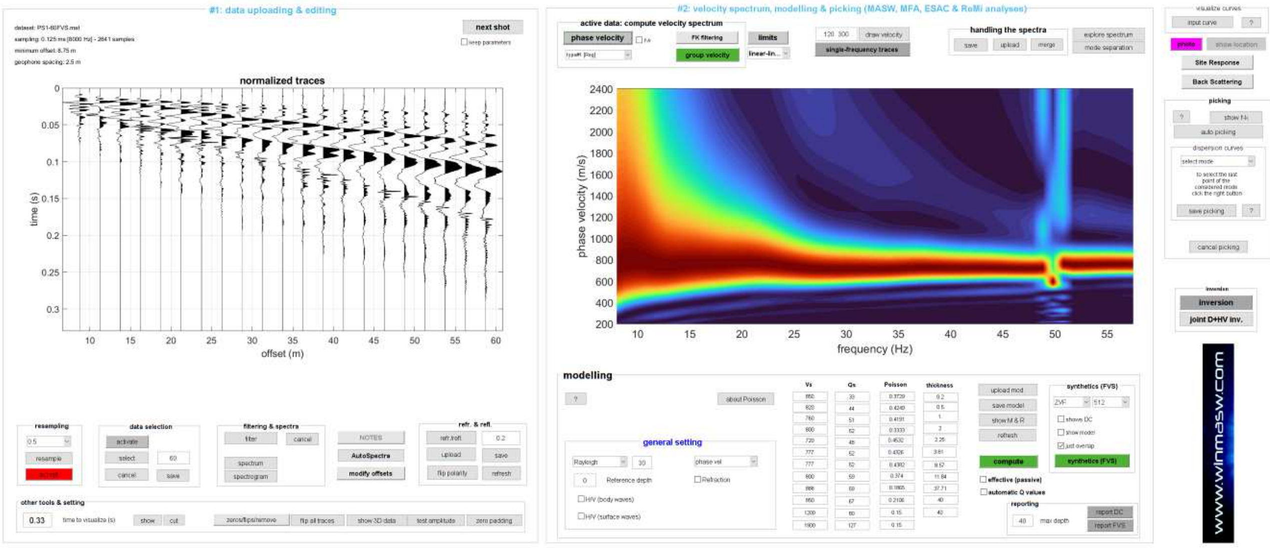
There are now two possibilities (one 'illogical', the other sensible).

The first (illogical): we increase the number of samples of the synthetic seismograms to 1024. In this case we obtain (with an increased computational load) the following modelling:

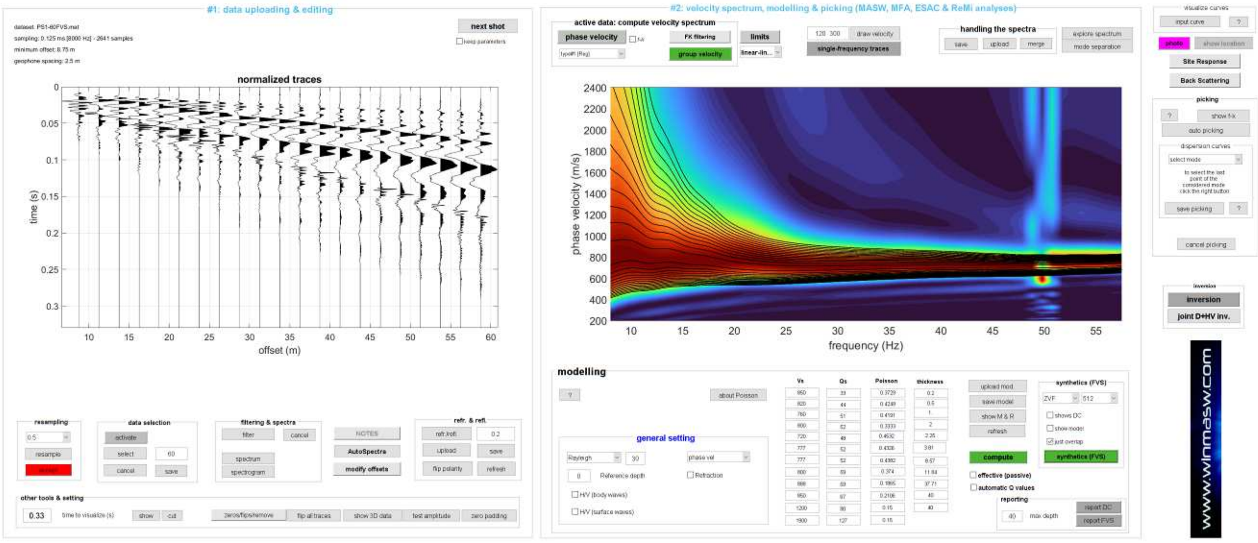


Now the small problem previously highlighted has disappeared (but at the cost of an increased computational load).

Second option (the sensible one): we reduce the time of the data to 0.33 seconds [*cut* button] and take the opportunity to clean up the data with the “data selection” tools. We obtain the following.



We now re-fix to 512 the number of samples used for the computation of the synthetic traces and re-compute the phase velocity spectrum of the model (FVS button in the bottom right). We obtain the following:



It is clear that the correct (*logical*) way of doing things is the latter.

These same considerations also apply in the case of **automatic FVS inversion** (i.e. in case you want to upload a saved velocity spectrum in the “single-observable inversion” panel and go for an automatic inversion): the data must be previously reduced to the minimum necessary length (in this case about 0.33 s) and after such a elementary operation you can then compute the velocity spectrum/a to be saved and (automatically) inverted.

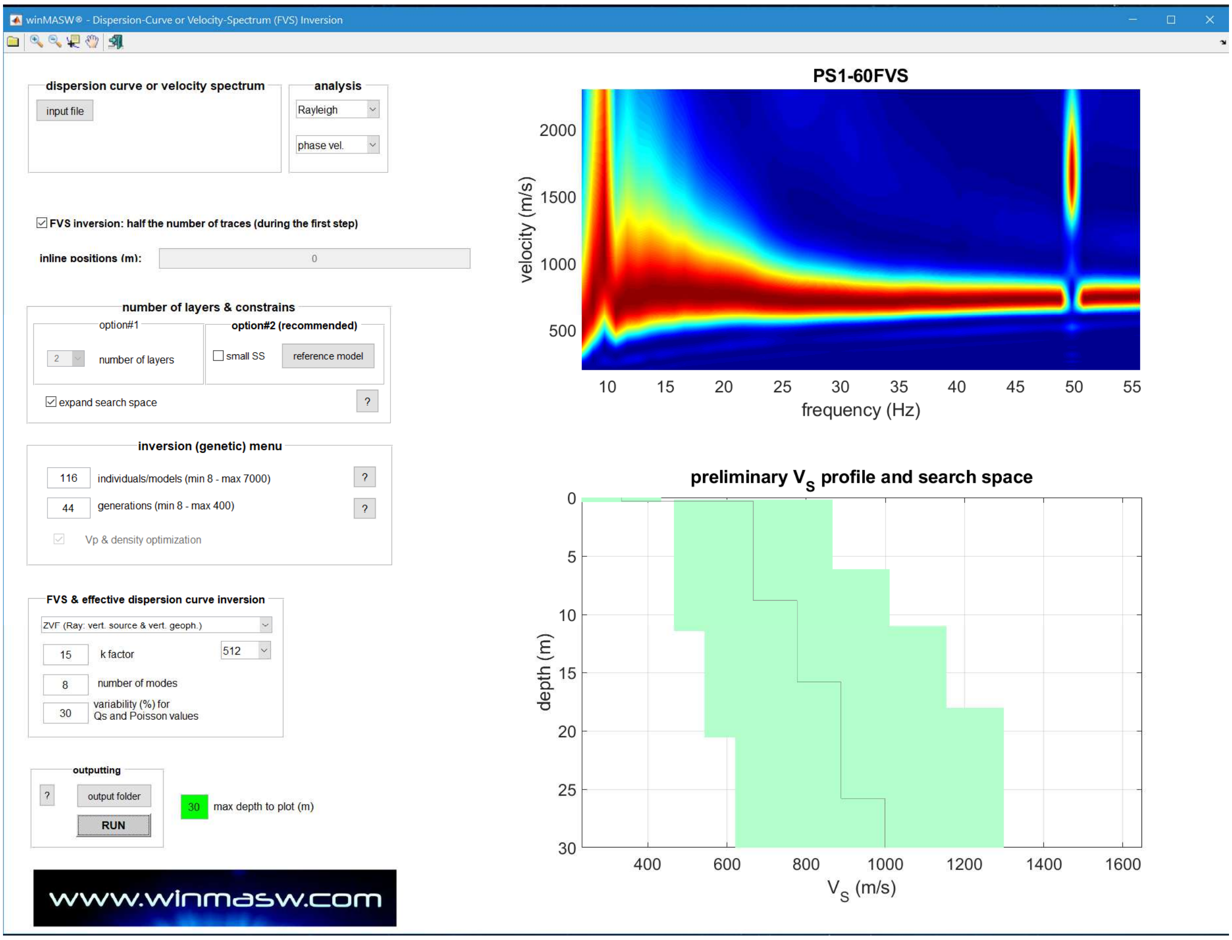
When does it make sense to increase (during the forward modelling or the automatic inversion) the number of samples? When we are dealing with very large offsets and/or very low velocities and/or very high frequencies (remember that for common geological applications frequencies above about 50 Hz rarely make sense). In those cases, the recording time may be very high and the number of samples required higher than the default 512 value.

These considerations apply both in the case of **phase and group velocities**.

Therefore, in the case we need to deal with very long time series and/or extremely high frequencies (i.e. sampling) motivated by *real* needs (we recommend to carefully consider the meaning and practical consequences of the *Shannon-Nyquist theorem*), it is advisable to increase the number of points/samples used to compute the synthetic seismograms (possible values are 512, 1024, 2048 and 4096). Clearly, the greater the number of samples used, the heavier the computational time (which is why it is good to understand what is really needed).

8. *Full Velocity Spectra* (FVS) automatic inversion

This method is meant to invert velocity spectra and not (as in the standard approach) the (picked) dispersion curves (see e.g. O'Neill et al., 2003; Dal Moro et al., 2015).
That means that no picking must be performer by the user. To invert a velocity spectrum it is necessary to input ("input file" button) a previously saved velocity spectrum.



After that, similarly to the standard approach (the inversion of picked dispersion curves) user must set a geologically meaningful search space.

<u>Some relevant points (see also the "synthetic seismograms" Chapter):</u>

1. The method is based on the generation of synthetic seismograms via *Modal Summation* (see "Synthetic seismograms" Chapter).

2. Computational times are necessarily quite heavy. It is then suggested a high-performance PC (e.g. a 8-core (or more) workstation). It is also <u>highly recommended</u> to start (*option#2*) from a model previously-identified (and saved) via forward modelling
   Reduce "*individuals/models*" and "*generations*" ("number of layers & constrains" group) to 40 and 40, respectively.

3. It is essentials to consider (i.e. save and upload) a velocity spectrum which contains only information/signals related to surface waves. As a consequence:
   - before computing (and saving) the velocity spectrum, clean carefully your data (e.g. by removing refraction events) and, by removing useless data and re-sampling the traces, try to obtain a dataset with 512 samples
   - fix velocity and frequency limits within which signals are related to surface waves (thus avoid too high – or too low - frequencies and velocities).

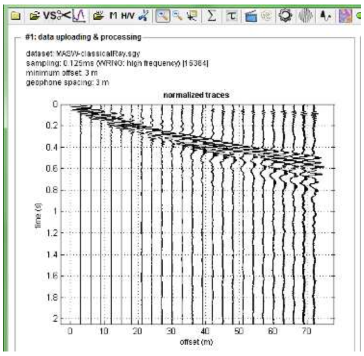
   <u>A correct determination of the velocity spectrum is clearly vital for a meaningful inversion.</u>

An example

Raw data

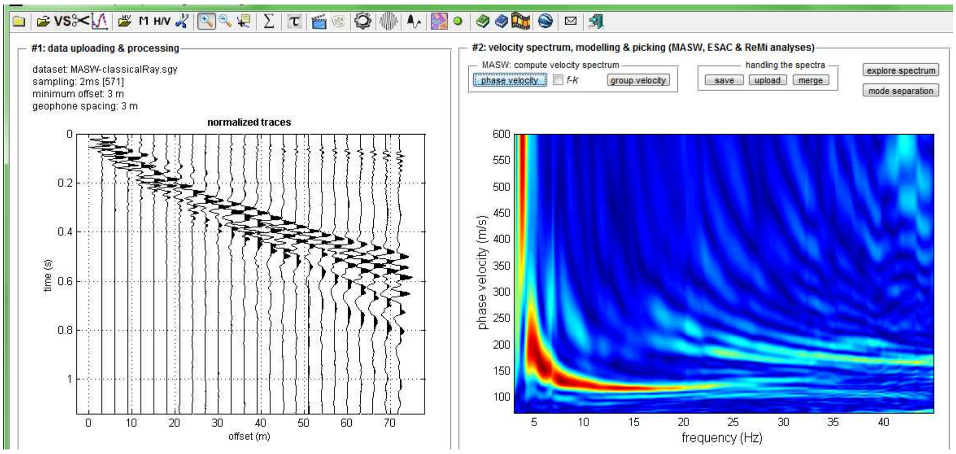
24 traces; *dt*=0.125ms (incidentally too much - 1 msec is absolutely sufficient);
acquisition length: 2.024 seconds;
number of samples 16384

reduce *dt* to 1 ms and keep the data only down to about 1.2 s

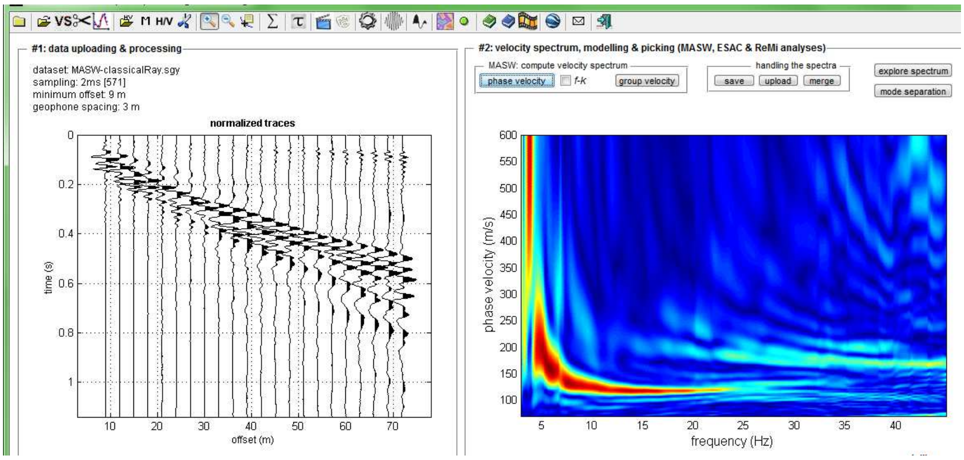


Data optimized for the FVS inversion:

cut the data ("DONE" and "CUT" buttons) and re-sample ("RE-SAMPLE" button)
[dt=2ms, acquisition time kept: 1.14 seconds; number of samples 571]



Furthermore, let's remove the first 2 traces (scissor button in the toolbar). This way we avoid "near-source effects" also reducing the computational load:



4. Even if it is not necessary to pick any dispersion curves, it is anyway necessary to perfectly understand the procedures and all the relevant points (e.g. be careful when higher modes are heavily dominating the dataset).

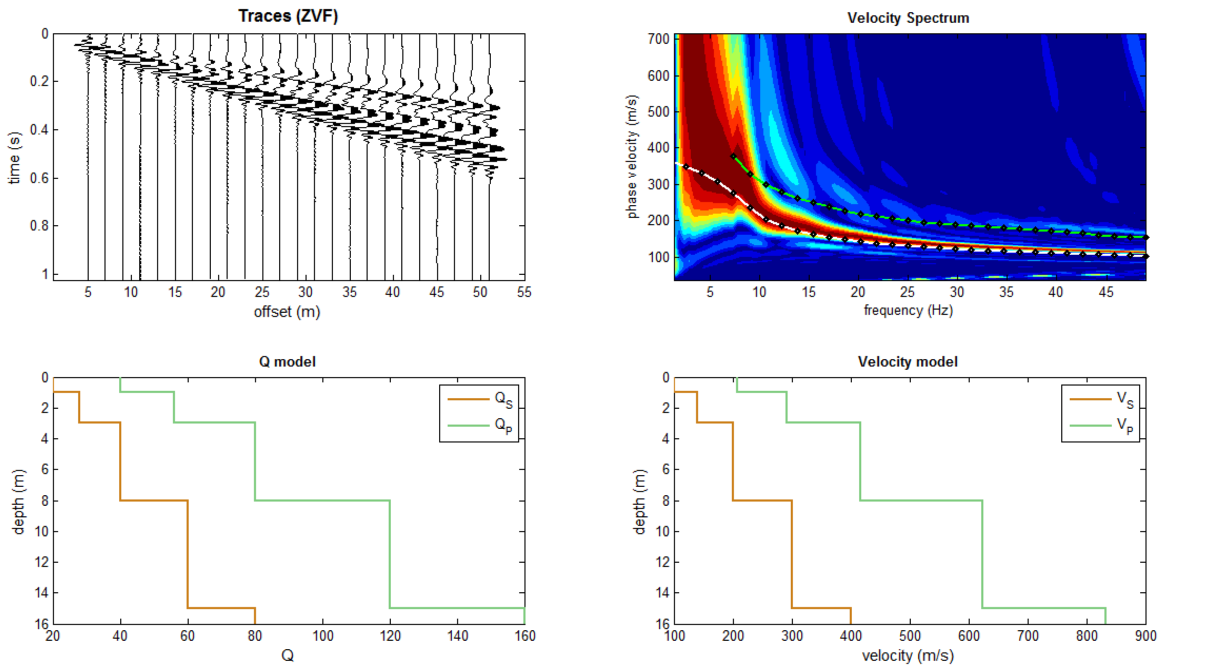
5.

6. Poisson moduli are essential in determining the energy distribution among different modes (see the box "*Poisson and the Energy Distribution*"). We therefore recommend to fix their values (while setting the *search space*) according to realistic consideration (consider the presence of water etc.).

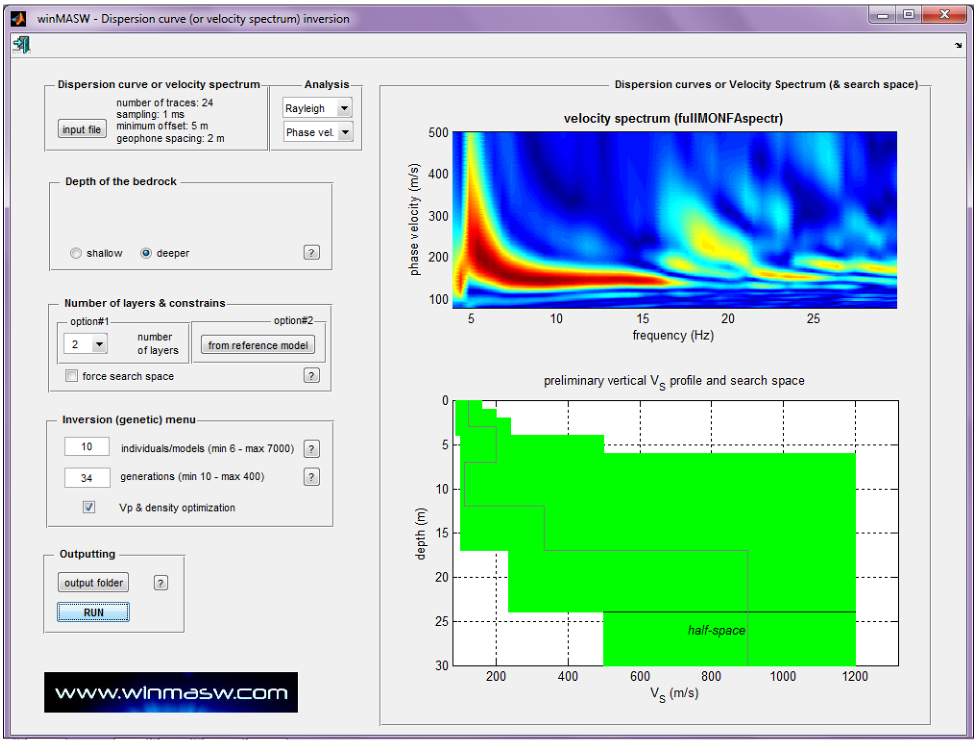
7.

8. As we are dealing with attenuation as well, it must fixed a K factor ($Q_S=V_S/k$) (see also next box). If you are not an expert please avoid this approach (or ask for our help).

Example of (small!) "disagreement" between the velocity spectrum got from a synthetic dataset computed considered also the attenuation and the modal dispersion curves computed to the simple elastic case.



Please notice how – especially in the 12-22 Hz frequency range – the dispersion curve computed considered the elastic case is slightly "slower" than the spectrum computed considering synthetic seismic traces calculated considering attenuation as well.
Also notice that the signal between 8 and 10Hz is related to the first higher mode.

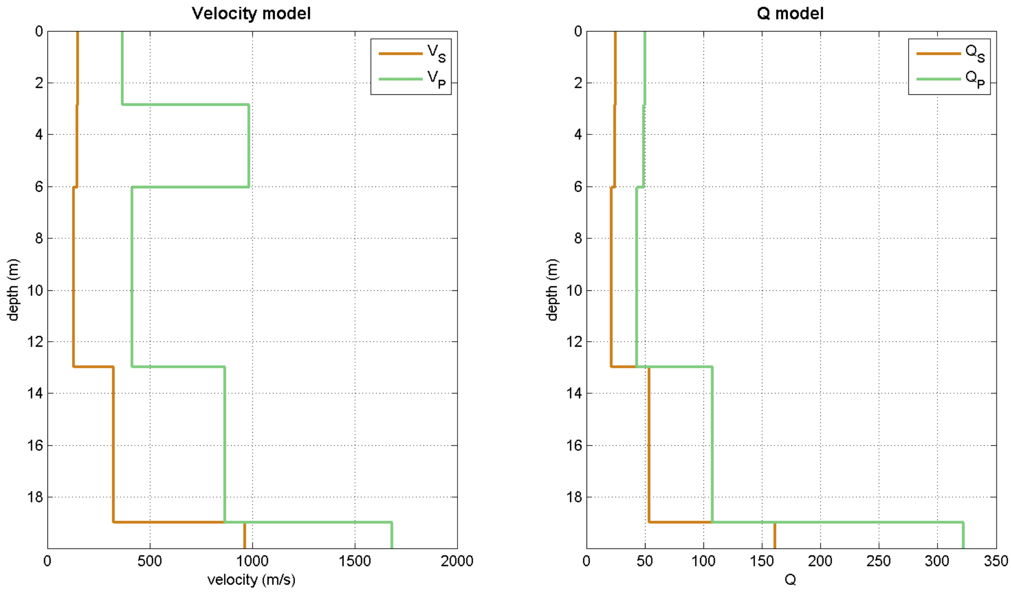


Inversion is finally launch by clicking the "RUN" button (as usual user can set the output folder).

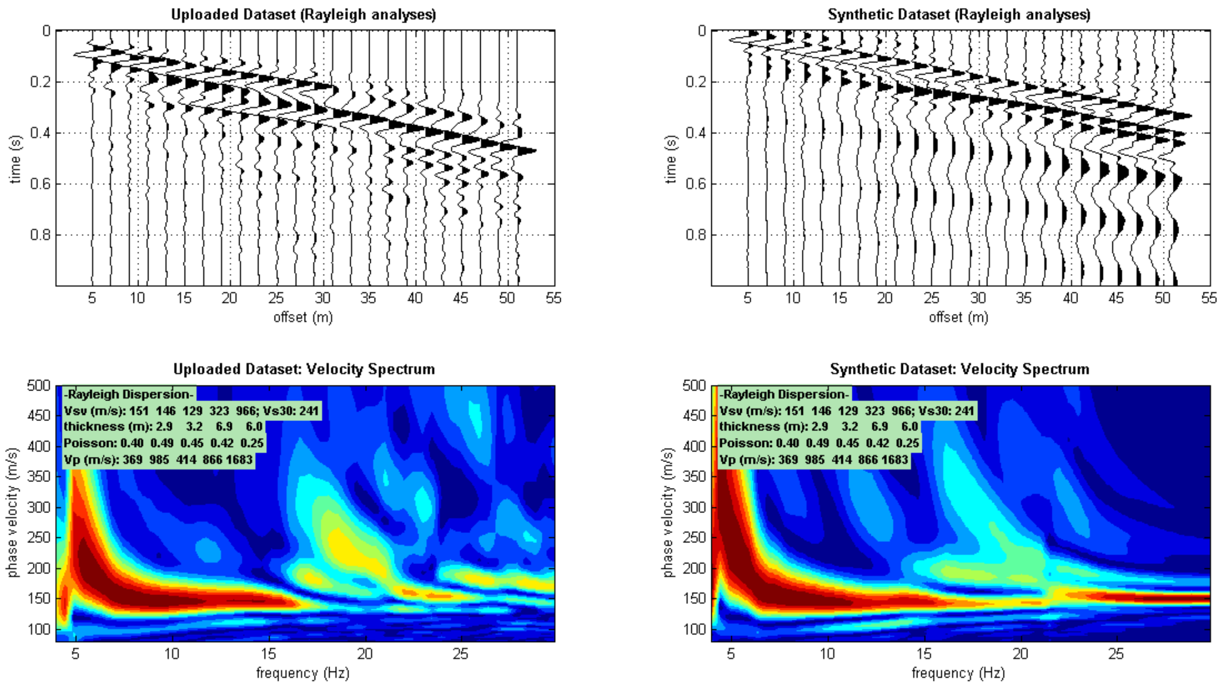
Results

At the end of the inversion procedure the following plots will be shown:

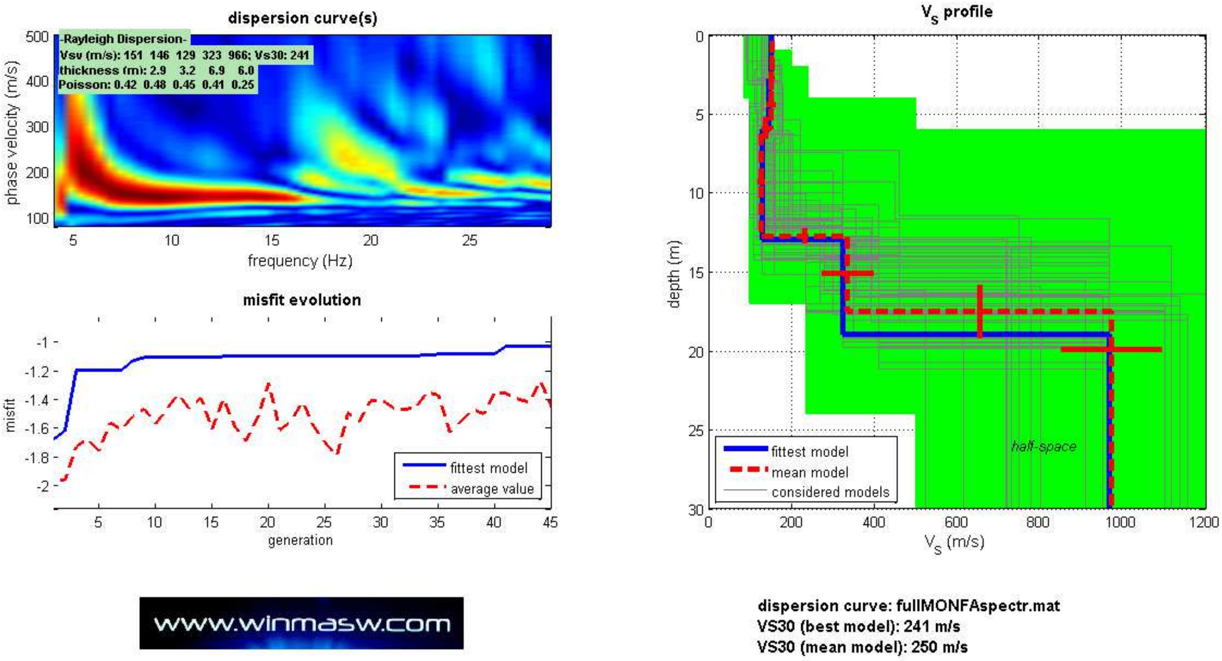
Best (identified) model (*velocities and quality factors Q*)



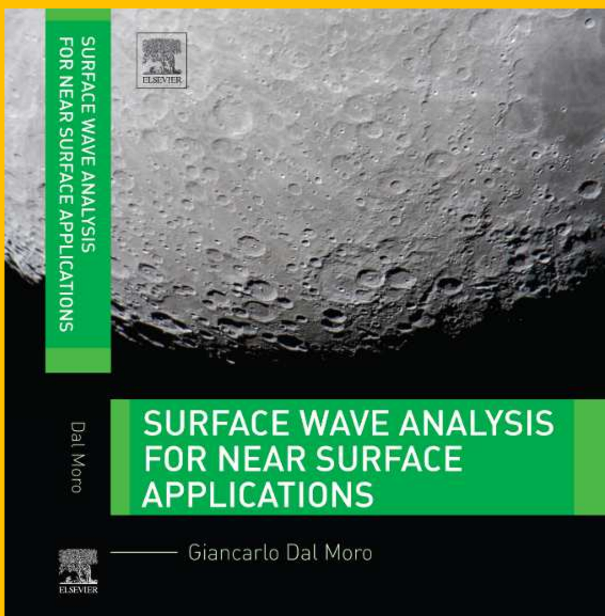
<u>Seismic traces and velocity spectrum:</u>
<u>observed data (on the left), best identified model (on the right)</u>



Summary plots:
upper left panel the observed velocity spectrum
lower left panel the misfit evolution
on the right the final retrieved models over the *search space*



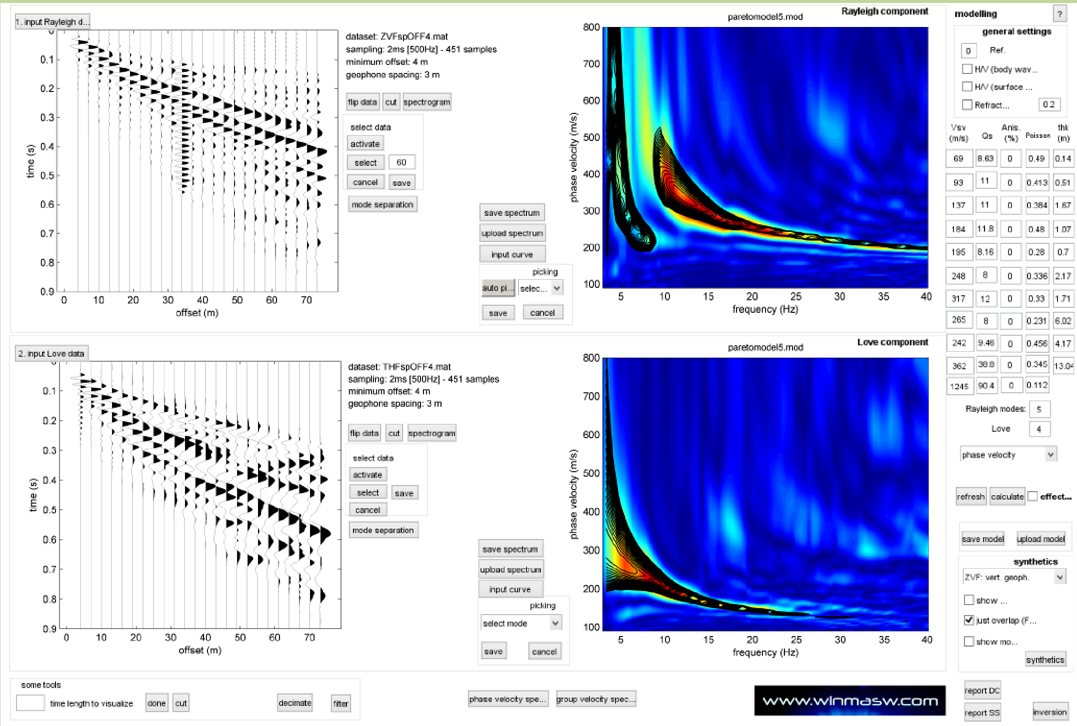
A number of case studies solved via FVS are available from our web site as well as in several papers and in the "Surface Wave Analysis for Near Surface Applications" book (Elsevier)

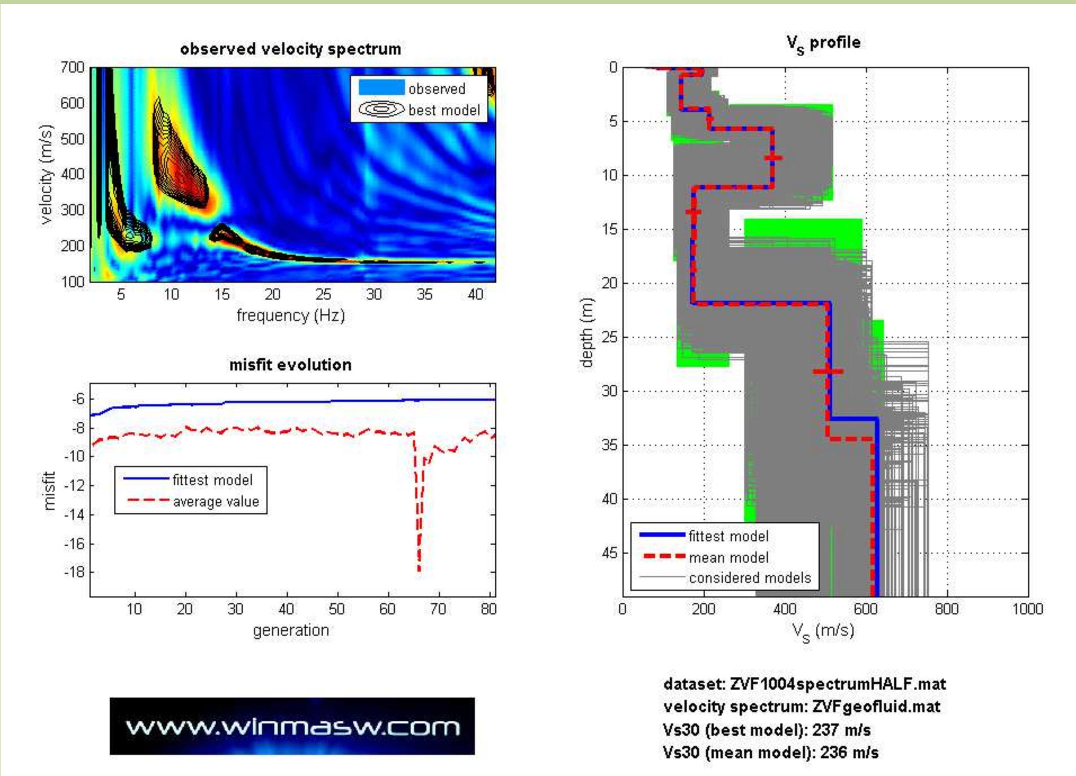


Full Velocity Spectrum (FVS) analysis: two examples

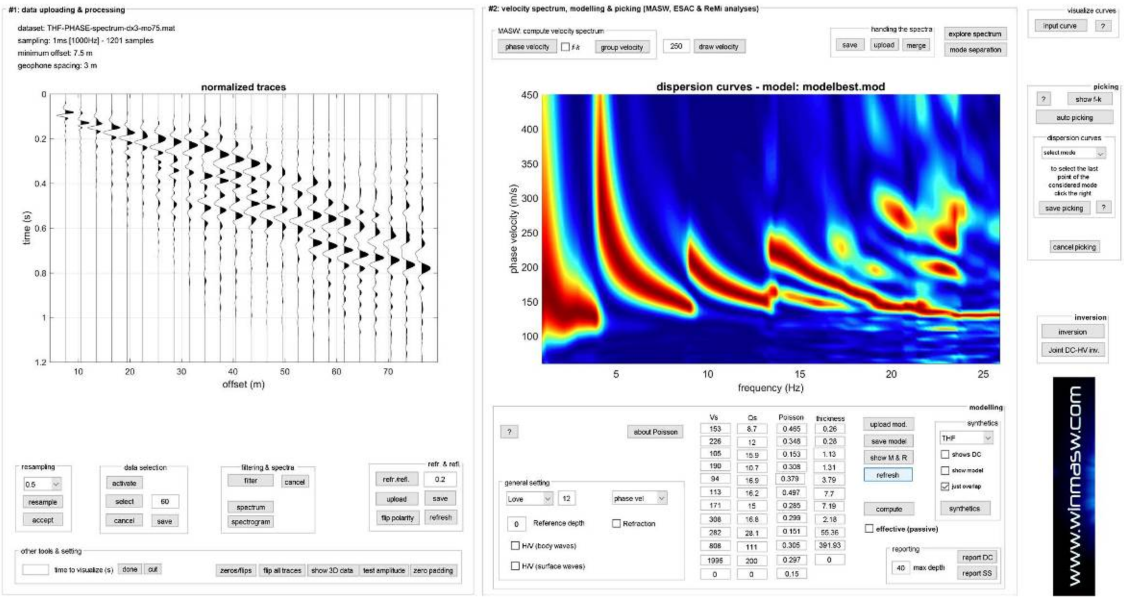
Background colors report the velocity spectra of the field data while black contour lines (overlaying over them) are the velocity spectra of the synthetic data (the identified model).

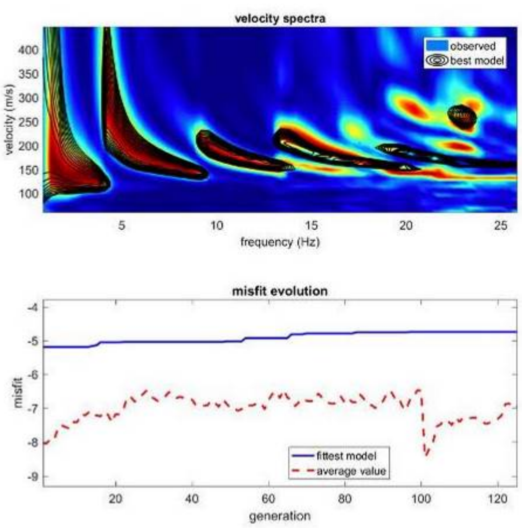
Please notice the very good match between experimental and synthetic data.

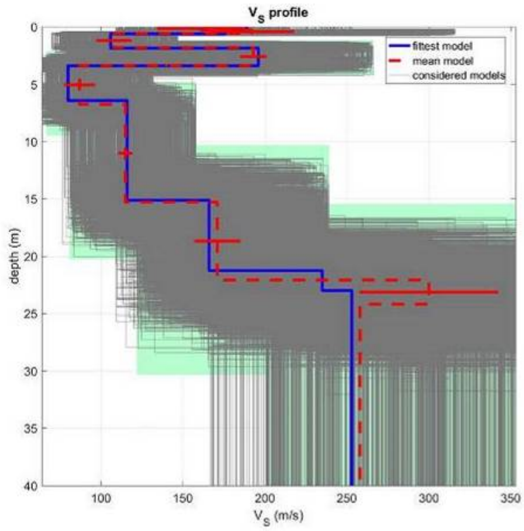




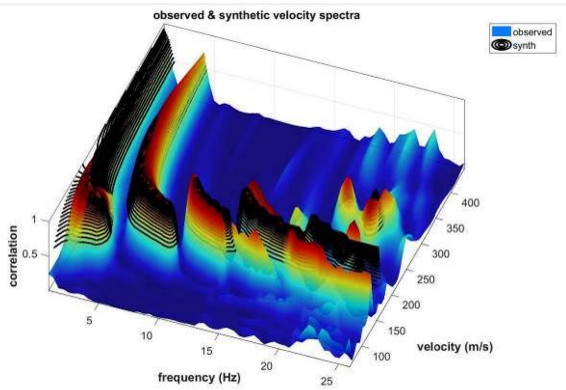
Further example of FVS analysis (in this case the THF component - Love waves)







velocity spectrum: THF-PHASE-spectrum-dx3-mo75.mat
Vs30 (best model): 144 m/s
Vs30 (mean model): 146 m/s



layer	Vs (m/s)	thickness (m)
1	189	0.2985
2	176	0.3117
3	106	1.2496
4	196	1.5365
5	80	3.0414
6	116	8.6914
7	166	6.1315
8	235	1.7395
9	253	39.5429
10	908	433.6953
11	1591	0

As also theory indicates, here an example where a shallow "*stiff layer*" (in other words a deeper low V_S layer) "excites" Love-wave higher modes.

In general terms: if Love waves show a great evidence of higher modes, it means that there should be a significant low V_S layer (Rayleigh waves are by far more complex and you can have dominant higher modes even if no decrease in V_S is actually present - see papers in the Reference list).

9. Few basic recommendations about automatic inversion

Before trying to give your interpretation of the velocity spectra, you should get familiar with the general concepts regarding seismic data acquisition and analysis. Carefully check your seismic data and remember the well-known GIGO acronym: **Garbage In, Garbage Out**. If your theoretical background is not sufficient, your data and analyses risk to be meaningless.

The inversion procedures implemented in *winMASW®* are based on a series of optimized genetic algorithms. This kind of approach allows to obtain better results compared to the traditional inversion approach based on the *Jacobian Matrix*.

While inverting your data (or data interpretations) you can start from a saved model (.mod) you have identified while trying to model the data.

If you use this approach (**option#2** in the inversion panel), such a model is the starting point for the optimization procedure aimed at finding the model that better fit the picked curve(s).

Recommendation#1: *number of models* and *number of generations*

In general, these 2 parameters should be proportional to the number of considered layers and the amplitude of the *search space*.

In a common case of single-component inversion using 7-8 layers, 80 & 80 can be reasonable values

Recommendation#2: *search space*

The *search space* has to be fixed on the basis of known geological information. If little or no information are available, a wider search space is needed, together with a high number of models/individuals and generations.
If you activate the option "**expand search space**", the software will seek for solution also outside the search space fixed by the user.

Recommendation#3: get acquaintance with the methods and their limits

Upload a dataset and calculate its velocity spectrum. Try to reproduce the observed data introducing models in the section direct modelling. Modify a parameter at once and note how curves change.
What happens if you increase the depth of a fast layer? What happens when inserting a velocity inversion in depth? What is the ratio between the V_S layer, its depth and phase velocity of the wave observed on surface?
These kind of trials and exercises (see the direct modelling) are very helpful to get confident with the methods.

Recommendation#4: number of layers to use

We suggest to use at least 7-8 layers. It is not recommended to use less than 5, even when you suppose that we are dealing with a simple stratigraphy.

10. Joint inversions: just few tips

If at site both dataset have been registered (using therefore the vertical geophones with the shared vertical source to obtain data re the Rayleigh waves and the horizontal geophones with shear wave source to obtain data re the Love waves), it is now possible to jointly invert them (at the same time) in order to have a more solid model and to highlight possible wrong interpretations through the evaluation of the relationship between both components misfits.

Upload the dispersion curves (both Rayleigh and Love) already picked in it, as previously done with the single dispersion curves and proceed as usual.

Together with the output we already are confident with, among the most relevant we'll also get (if activating the option "*bi-objective space*") a relevant graph to the values of the 2 considered misfit (both Rayleigh and Love).

If the picking was done correctly like the inversion, the result in the figure should be quite linear converging to the point [0, 0].

If instead one of the curves (or both) was misinterpreted (picked) or if the number of layers and the search space is not adequate, the result will be quite irregular (the more irregular the more mistakes you made).

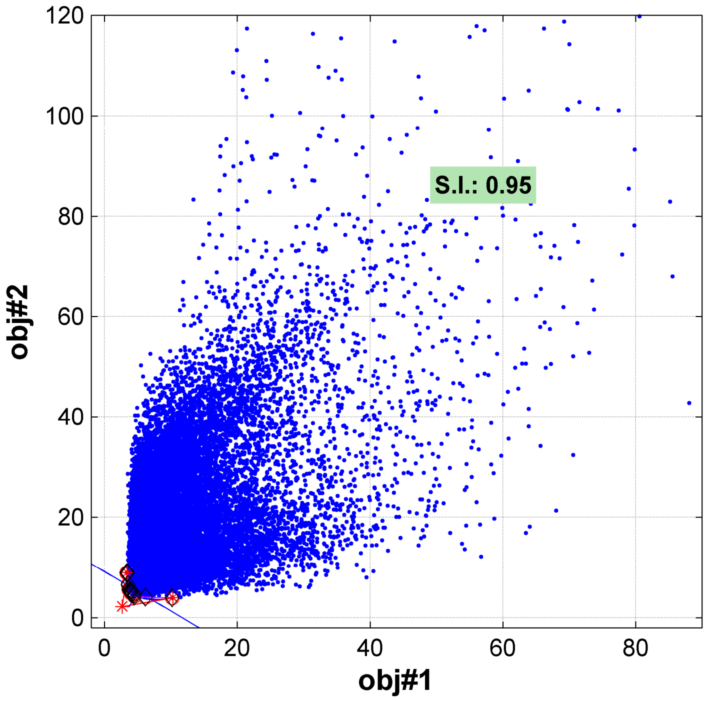
The V_S anisotropy is computed as it follows (percentage values):

$$\eta = \frac{(V_{SH} - V_{SV})}{V_{SH}} \cdot 100$$

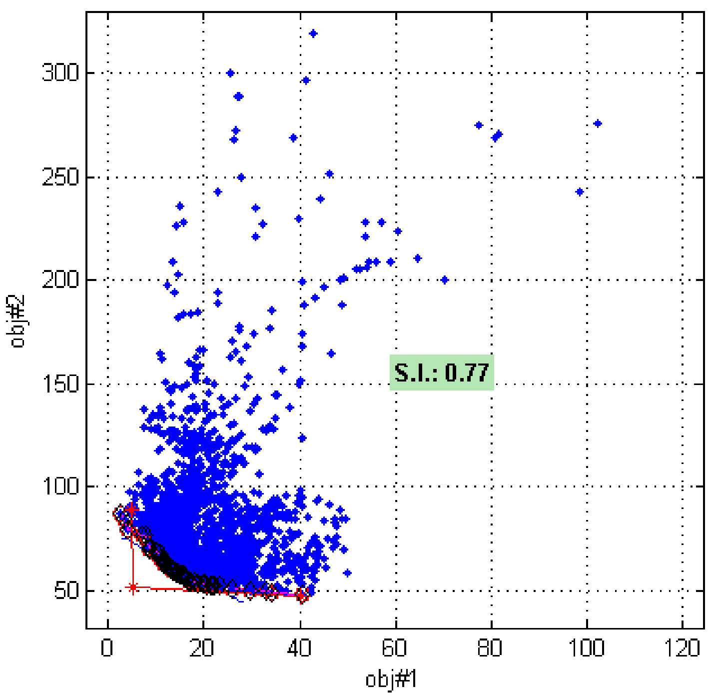
Notice that the percentage of anisotropy can also be considered as a tolerance as to wrong values in dispersion curves picking. This means that imprecise picking values can be kept under control by means of introducing a difference between the V_{SV} (relevant to the dispersion of the Rayleigh waves) and the V_{SH} (relevant to the dispersion of the Rayleigh waves).

Needless to say that the correct assessment of the anisotropy requires specific expertise.

Distribution of models in the bi-objective space and Pareto front symmetry

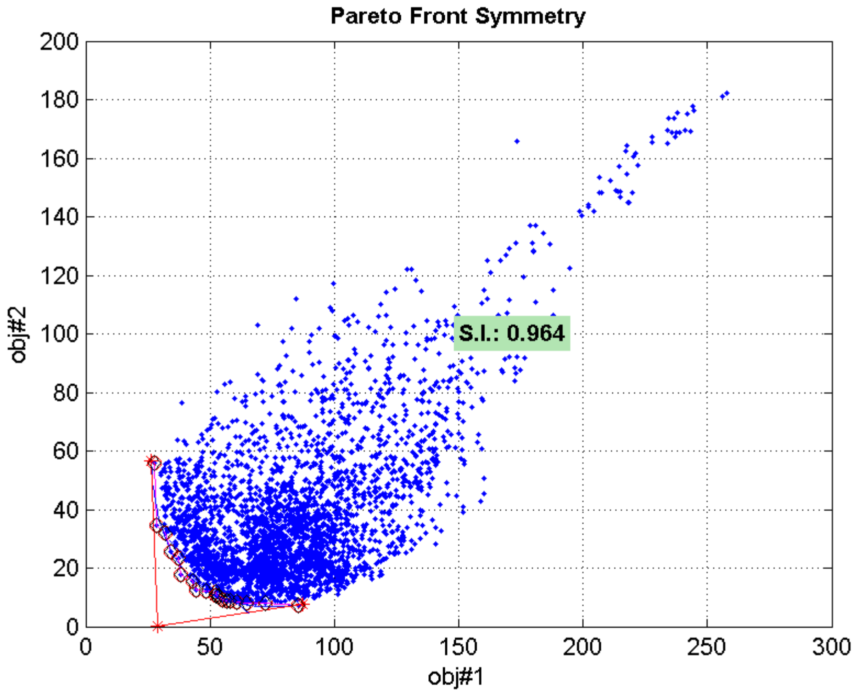


Model distribution in case of consistency between the two objectives: the front if pointy and the symmetry of the Pareto front models with respect to the rest of the models is quite high.



Model distribution in case of some inconsistency between the two objectives: the front if quite large and the symmetry relatively modest.

Symmetry Index (SI)



While performing a joint inversion (e.g. Rayleigh + Love or Surface Waves + HVSR), one of the final plots reports the evacuate models in the bi-objective space also indicating a quantitative value (SI) ex pressing the symmetry of the Pareto front models with respect to the universe of the models (1 means perfect symmetry, 0 completely asymmetric).
Quite clearly a simple visual evaluation is more than sufficient and user should not stick to much to SI. Incidentally the symmetry is not the unique parameter to consider to evaluate the overall congruency of the performer inversion process.

For more information about Pareto symmetry:

Dal Moro G. and Ferigo F., 2011, *Joint Inversion of Rayleigh and Love Wave Dispersion Curves for Near-Surface Studies: Criteria and Improvements*, *J. Appl. Geophysics, 75, 573-589*

Dal Moro G., 2011. *Some Aspect about Surface Wave and HVSR Analyses: a Short Overview and a Case Study*, BGTA (Bollettino di Geofisica Teorica e Applicata), *invited paper*, 52, 241-259

Dal Moro G., 2010. *Insights on Surface Wave Dispersion and HVSR: Joint Analysis via Pareto Optimality*, *J. Appl. Geophysics*, 72, 29-140

Dal Moro G., 2008, V_S and V_P Vertical Profiling via Joint Inversion of Rayleigh Waves and Refraction Travel Times by means of Bi-Objective Evolutionary Algorithm, *J. Appl. Geophysics*, 66, 15-24

Dal Moro G. and Pipan M., 2007, *Joint Inversion of Surface Wave Dispersion Curves and Reflection Travel Times via Multi-Objective Evolutionary Algorithms*, *J. Appl. Geophysics*, 61, 56-81

11. Attenuation analysis

Leaving theoretical details and underlying that the best way to improve your knowledge is attending to one of our *workshops*, it is anyway useful to remember that seismic waves decrease in amplitude while propagating, for two reasons:

1. because energy distributes on an always wider area (this reduces energy, therefore amplitude)
2. because of complex energy absorption/conversion, depending on the soil they're passing through

The first aspect is called "geometric component", while with the second we refer to the Q quality factors describing the viscose quality of a mean (high Q values represent a good elastic mean that doesn't absorb seismic energy that much).

The traditional method to analyze seismic attenuation develops in 3 phases:

a. determination of the soil elastic method (V_S, V_P, density and thickness)

b. determination of the attenuation curve (attenuation coefficient depending on the frequency)

c. inversion or modelling of the attenuation curve or modelling of the observed attenuation curve, once fixed (see point a) the elastic part (i.e. the soil model V_S, V_P, density and thickness).

From a practical point of view first proceed with the analysis of the dispersion curve of the Rayleigh waves (that is the procedure used to determine the vertical model V_S to estimate the Vs30).
The result will be the model (file.mod) from where you can start to model/invert the attenuation curve.

Remember the analysis of the Rayleigh waves gives a good esteem of the V_S, thickness and density but the V_P value can be estimated only in an approximate way (on the basis of the Poisson's value chosen by the user and modified by optimization algorithm).
In the case detailed information about V_P values are available (for example from refraction studies or borehole data), it is possible to modify the values in the file .mod (that is a common file ASCII).

You can access the section about the analysis of the attenuation both from the main panel of *winMASW* and from the section "determining the Spectrum".
Here, after uploading the dataset you need to analyze (and in case displaying the velocity spectrum to have a view on the present mode) you'll analyze (button "calculate curve") the attenuation curve in the proper frequency interval.
Then upload the previously determined soil model that represents the elastic part (files .mod). Now we could model or invert the observed attenuation curve (expression of the viscose part).
Since even in the case of attenuation same considerations are valid like those for the dispersion curves we always suggest to joint model (Rayleigh+Love+HVSR) instead of inverting a picked curve.

Once you identify a model whose attenuation curve is close enough to the observed one the analysis ends and can give the model of quality factors Q (see further how and where to save the result).

Some general notes

- during the modelling or inversion procedures the only variables are the Q values, not the layers thickness. These last are in fact fixed by the model .mod we uploaded (after we determined it through the analysis of the dispersion curves). This makes the modelling of the dispersion curve easier than the analysis of the inversion curves (for which we had to play both with the V_S and the thicknesses)
- it is very important to highlight that the attenuation curves, in order to be sufficiently detailed, should refer to the fundamental mode of the Rayleigh waves
- if your dataset shows different modes (at same frequencies) you should avoid the analysis of the attenuation (see box dedicated to the section "verbose")
- how to read the attenuation curves: the rule is traditionally the same valid for the dispersion curves: high frequencies refer to the near surface part, while the low ones refer to the deepest part.

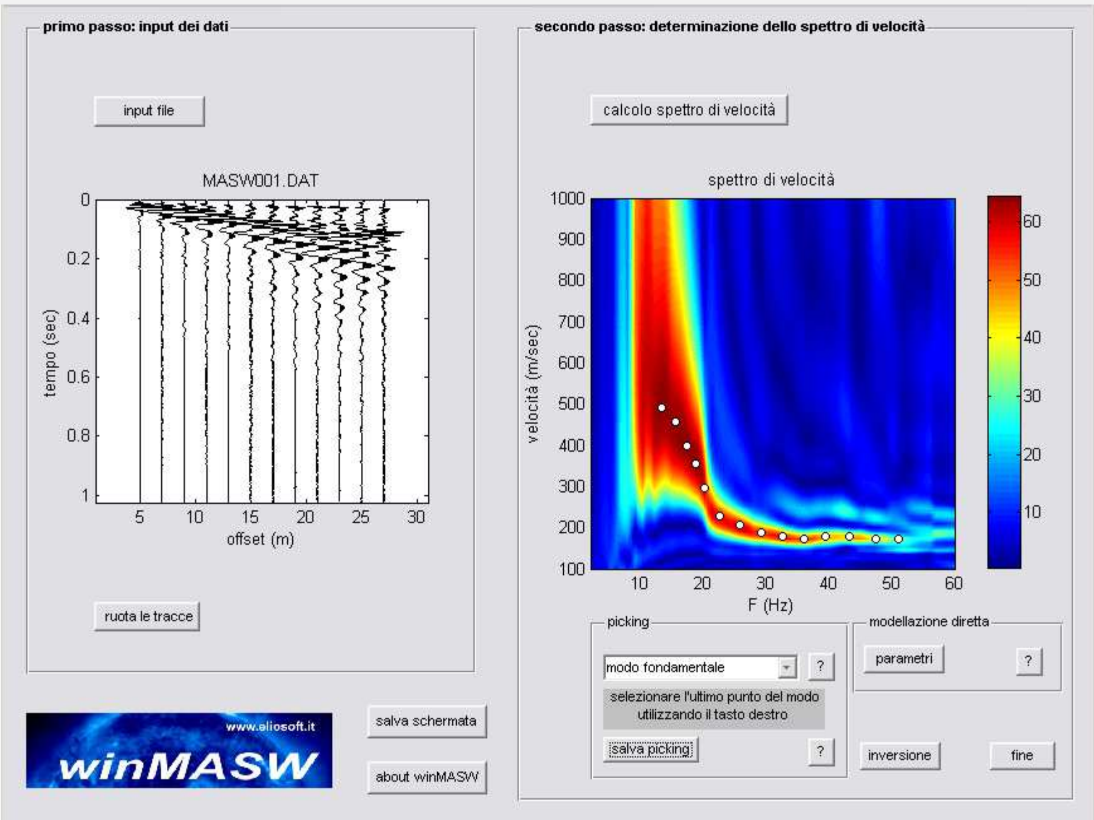
GEOMETRIC CORRECTIONS

When this option is selected, some geometric correction takes place before the analysis of the attenuation.
For those analyzing data got at site this selection has to stay selected (this can be avoided only in case of the elaboration of specific datasets already resulting from detailed academic studies)

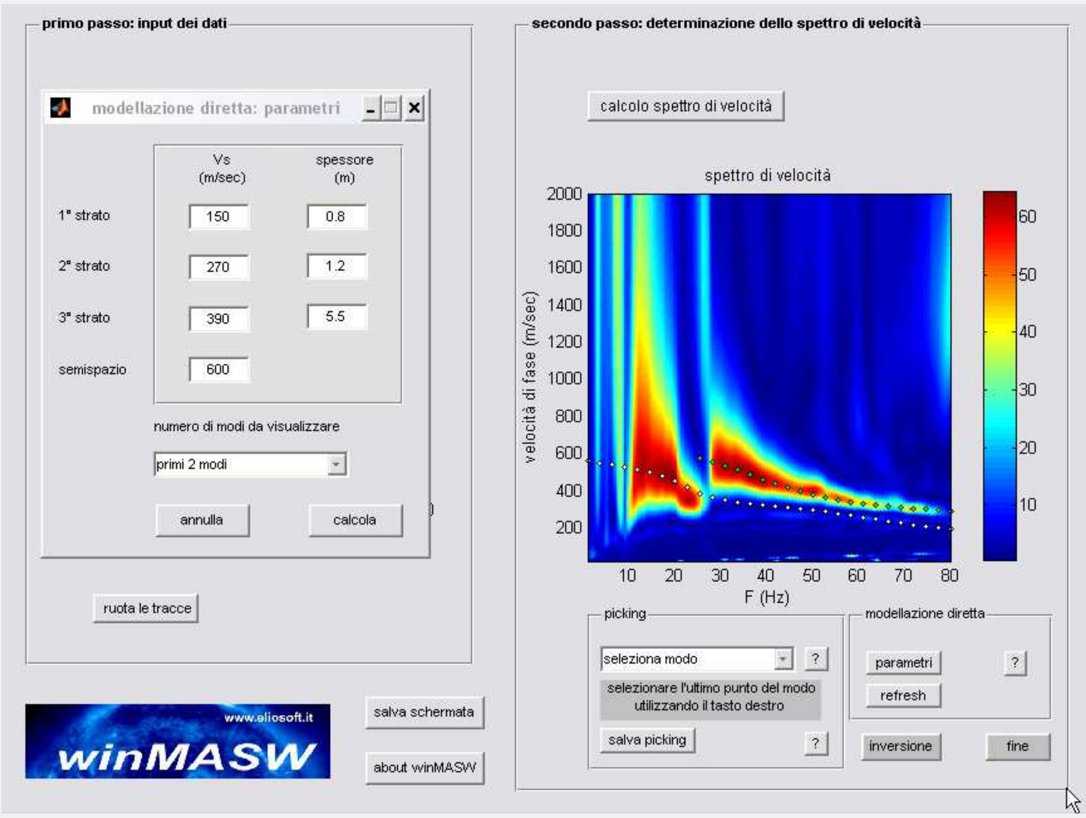
SPECTRAL RATIO (SR) AND MATCHING

The software proposes two attenuation curves: one is achieved through the "Spectral Ratio" (SR) method (the average value is shown considering different couples of traces), the other through the "Matching" method (amplitude versus offset-see window with 6 plots generated by the option "verbose"-see Tonn, 1991) (the obtained values are by the way similar).
In the case you go on with the inversion of the attenuation curve, take as reference the resulting curve from the Matching method.

Suitable Dataset to attenuation analysis



One only mode is visible (and very clear), the fundamental mode



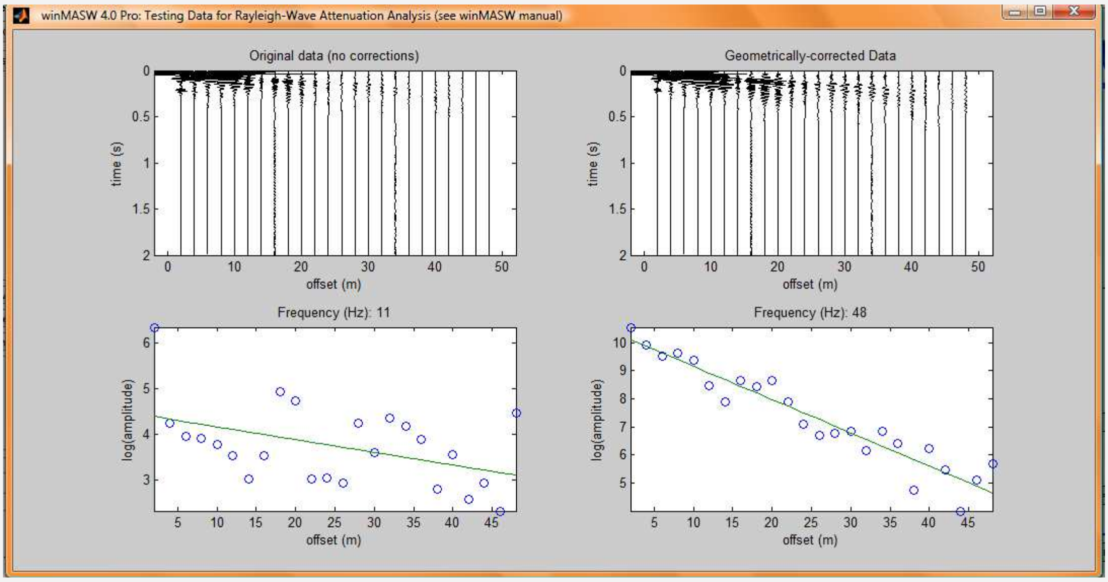
To be considered only up to 28 Hz (after that value the first superior mode shows).

“Test amplitude” button

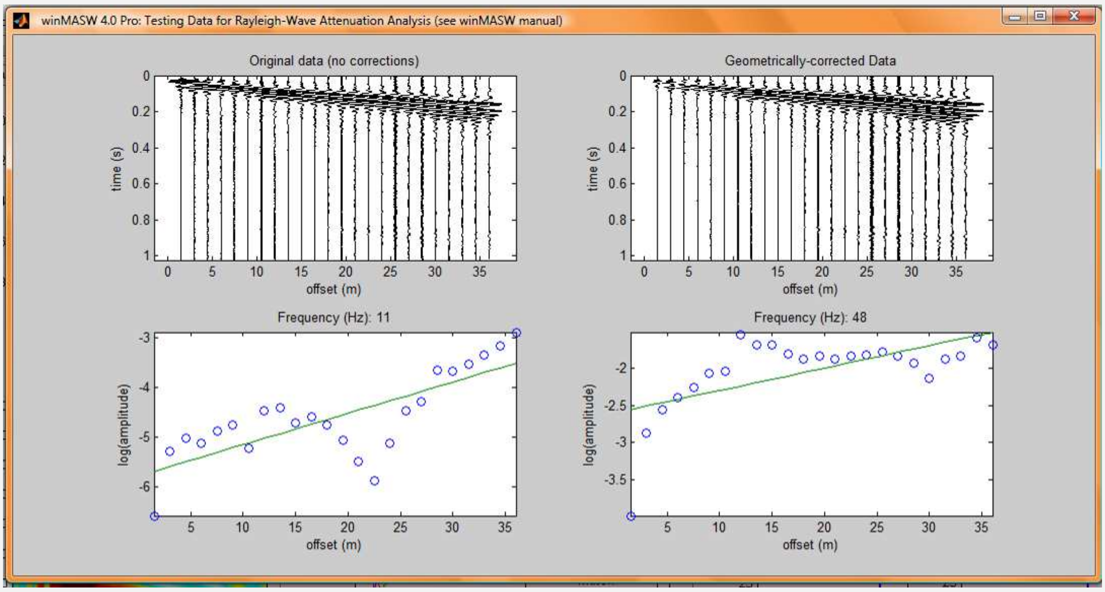
The button “test amplitude” opens a window with reported seismic data and the graphic of the amplitude logarithm compared to the offset for both the two indicated frequencies in fields “Min & max frequencies” on panel “Step#2: calculate attenuation curve”.
Depending on the “geometric correction” being active (on) or inactive (off), two different windows will display.

Geometric corrections on

Starting from the corner top left and following clockwise you can read: seismic traces in their original recording amplitude, corrected seismic traces, thanks to the geometric correction (therefore on the basis of offsets given when uploading the data), chart of the amplitude logarithm compared to the offset (in this case the graphics refer to corrected data in its geometric component).



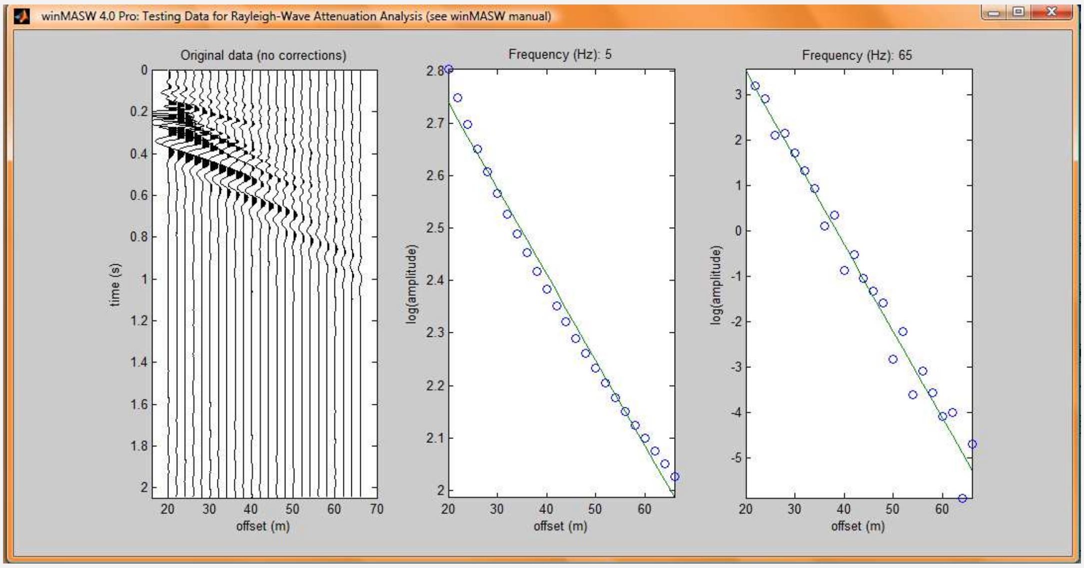
Example of dataset acquired keeping the same gain for all the channels (amplitude falls according with the offset), therefore theoretically suitable to analyze the attenuation. Notice however some amplitude “changes”(jumps) (compare for instance amplitude of the traces at offset 26 and 30) that can be due to various problems (i.e. to a bad coupling geophone-soil, or the use of different quality geophones

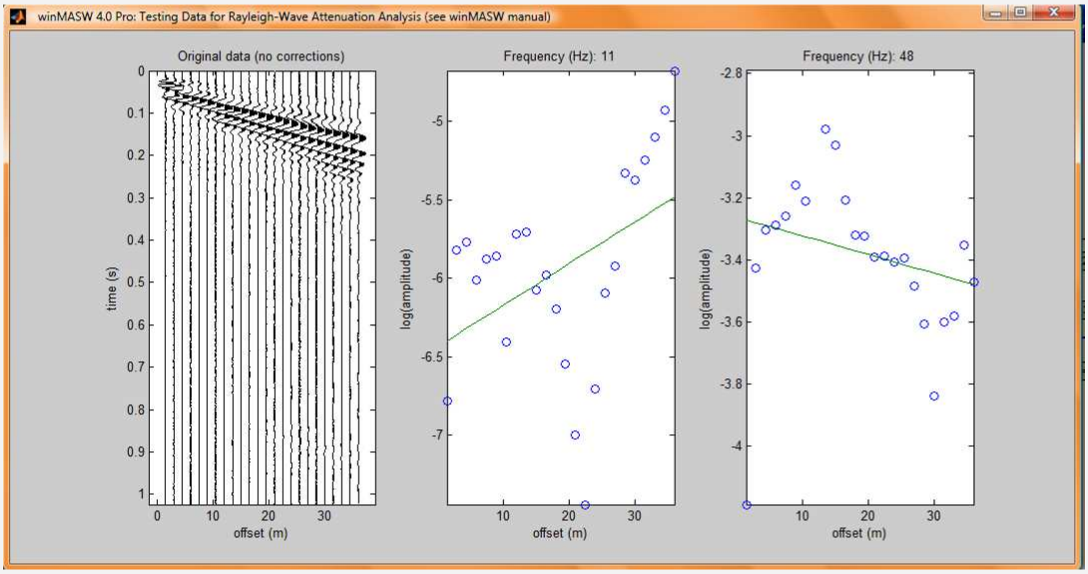


Example of dataset acquired using different gains for each channel (trace), therefore unsuitable to analyze the attenuation of the seismic data (notice how the amplitude doesn’t fall according with the offset, because the distant channels have higher gain than the near ones).

Geometric corrections off

In the case the geometric correction is off (“no geometric corrections”) a window with three graphics will show: the amplitude –offset one refers to the data not corrected by geometric component.





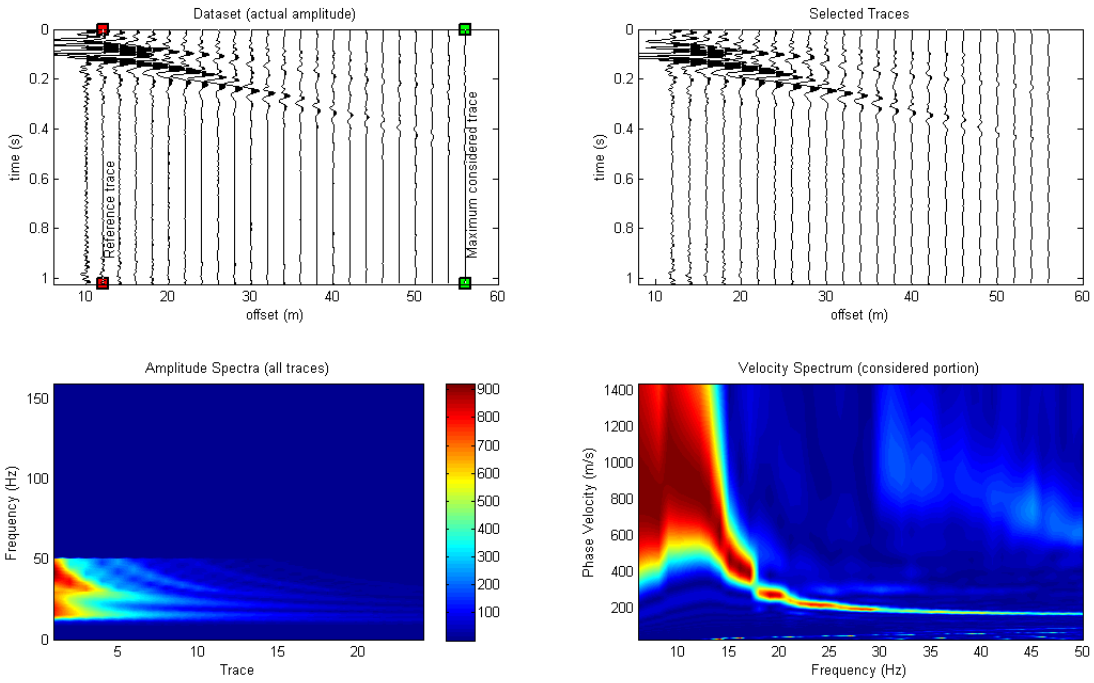
Example of dataset obtained with different gains for each channel (trace) and therefore not suitable to analyze the attenuation of the seismic data (notice how amplitude does not fall with the offset).

To clarify the meaning of these graphics refer to the box about the acquisition of data for the analysis of the attenuation In Appendix A.

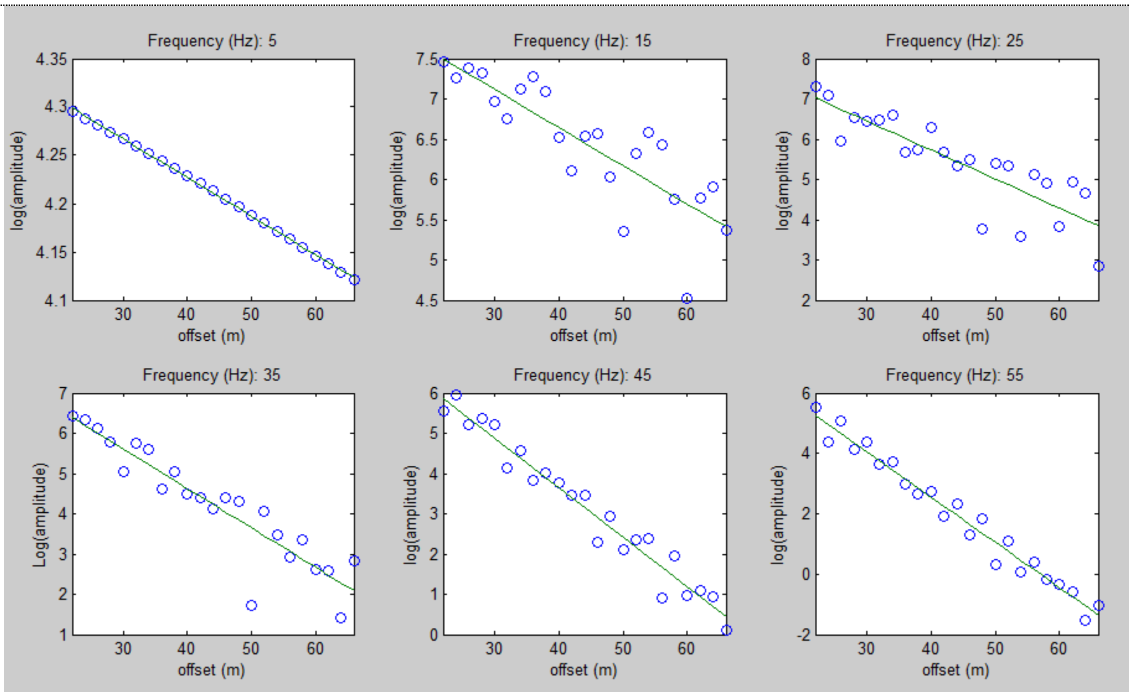
The "verbose" button

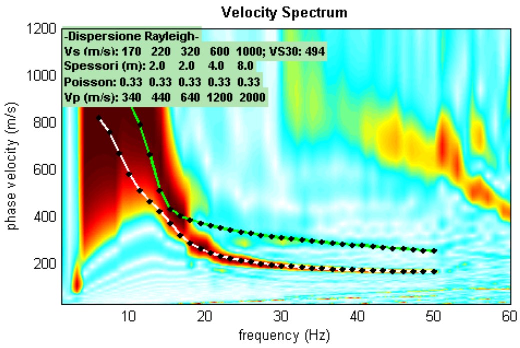
When calculating the attenuation curves (button "calculate curve") if you click on "verbose" you'll get three windows:

The first window shows the dataset with highlighted the first and the last considered traces for the analysis of the attenuation.
The reason for this option is (such traces need to be defined in the main window of both "Reference trace" and "Maximum considered trace" fields) that for some acquisitions the effects due to proximity of the source (presence of direct waves) can be verified, that not needed to be put in relation with the propagation of the surface waves would lead to a worse quality of the analysis.
This can happen if the distance between the first geophone and the source is too small and a series of *near field* effects occur. We'd suggest not to use offsets lower than 5-10 m.
Therefore, when the amplitude of the first traces is much higher than the general trend, do not consider those traces during the attenuation analysis.
Therefore the following will show: total dataset, selected dataset, amplitude spectrum of the traces and velocity spectrum in the frequency wished range.

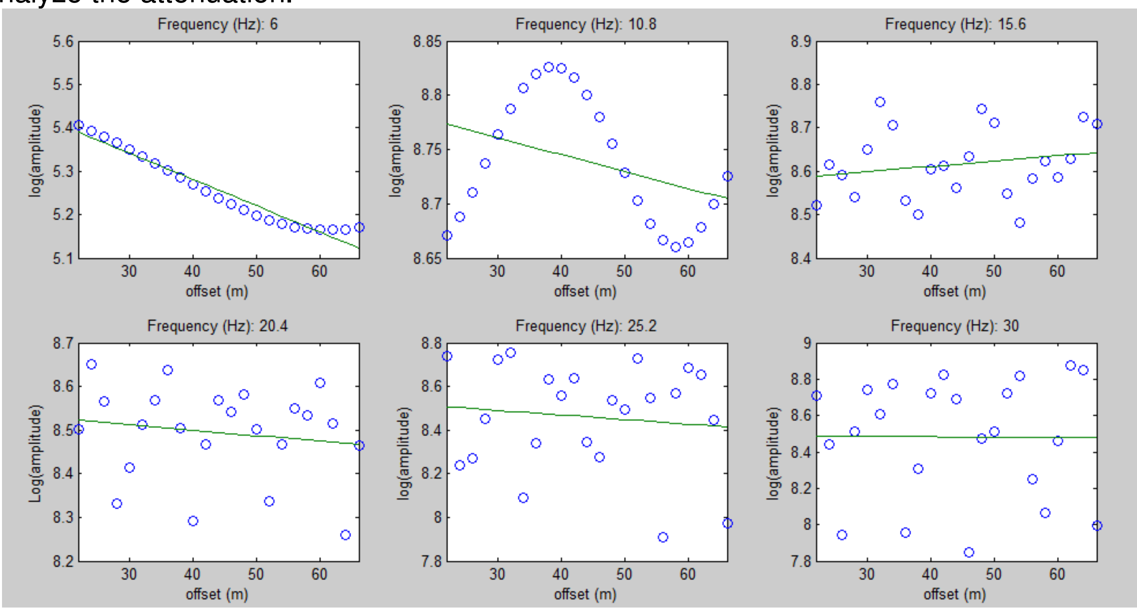


Following figure reports 6 plots for 6 different frequencies (from the min to the max). These graphics show how the amplitude logarithm changes according to the offset for a given frequency value.
These trends help understand in which range we can have good quality data and what frequencies are instead to avoid (because, for instance, at those frequencies the result is more modes or different modes or no signal even).
Obviously, what we aim to demonstrate is the fall of the amplitude according to the offset.
A different trend means that the data are not suitable for attenuation analyses.
The following plots refer to the *test-attenuation-50Hz.sgy* dataset and show coherent trends but the user should consider that for frequencies lower than about 18Hz the dominant mode is the first higher one (not the fundamental one). That means that the frequency range to consider for good attenuation analysis is only 18-50Hz (there is no signal for frequencies higher than 50 Hz).





Quite clearly in case of datasets like the one reported down here it is not possible to analyze the attenuation.

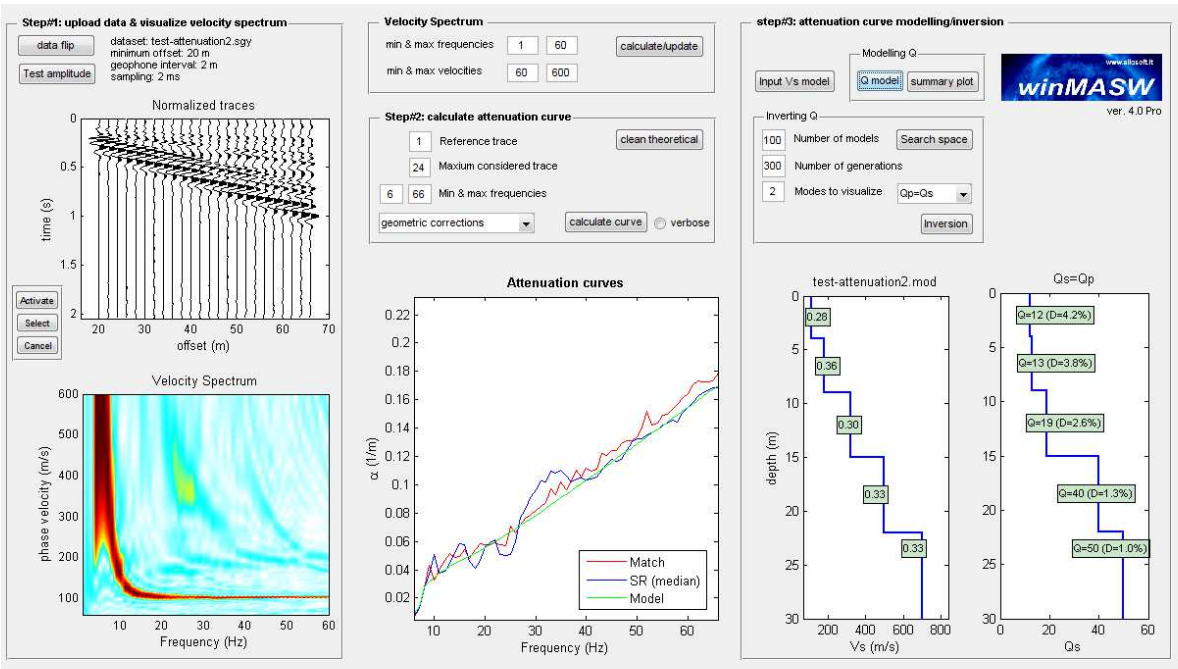


To recap:

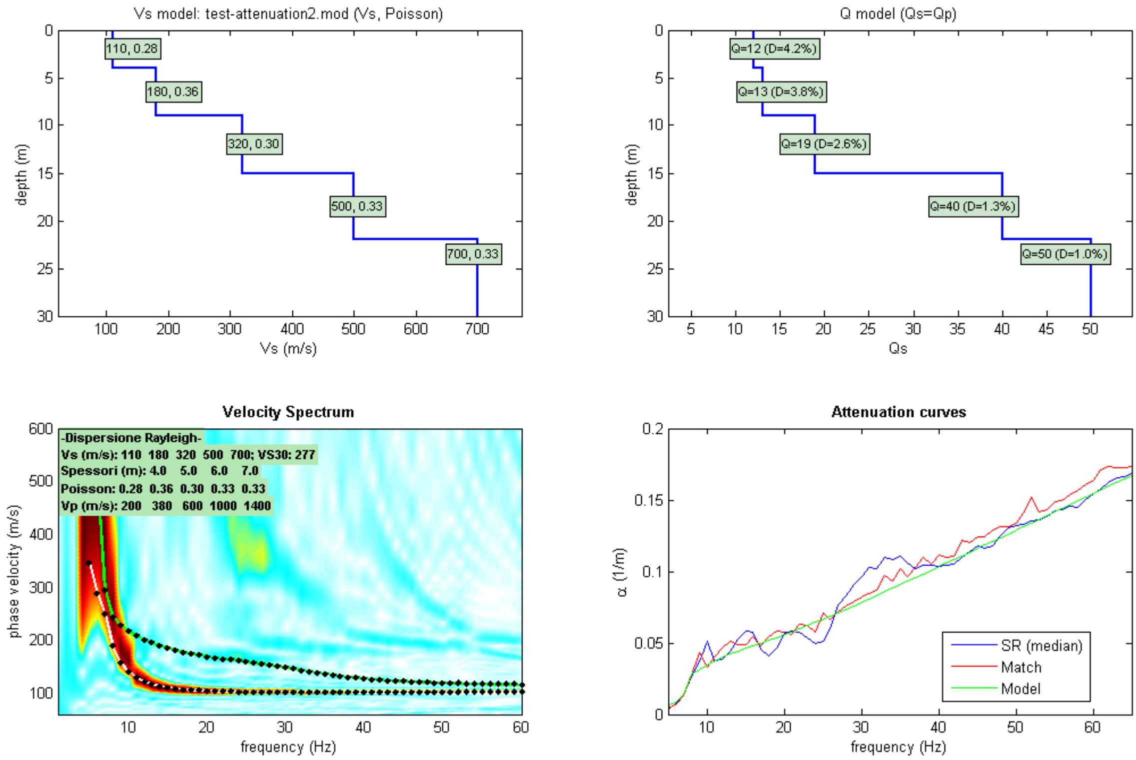
Once uploaded the dataset (top right), visualized the velocity spectrum (bottom left) and calculated the dispersion curves (box in the middle) upload the model of the soil that was previously calculated through the analysis of the dispersion curves (the obtained .mod file). To do that, click on "Input V_S model" and search for the proper .mod file in the output folder of the analysis of dispersion curves.
At this stage the V_S profile will display in the dedicated window.

a) Modelling

If we choose the direct modelling (always suggested!) just click on "Q model".
As soon as we identify the wished model (because in accordance with the observed curved) click on "summary plot" to visualize a summary screenshot of the model (see further box). That screenshot is automatically saved in .png format in the folder "…\winMASW\outputattn\" but can be saved wherever and in another format as usual (File → Save As…).



SUMMARY PLOT



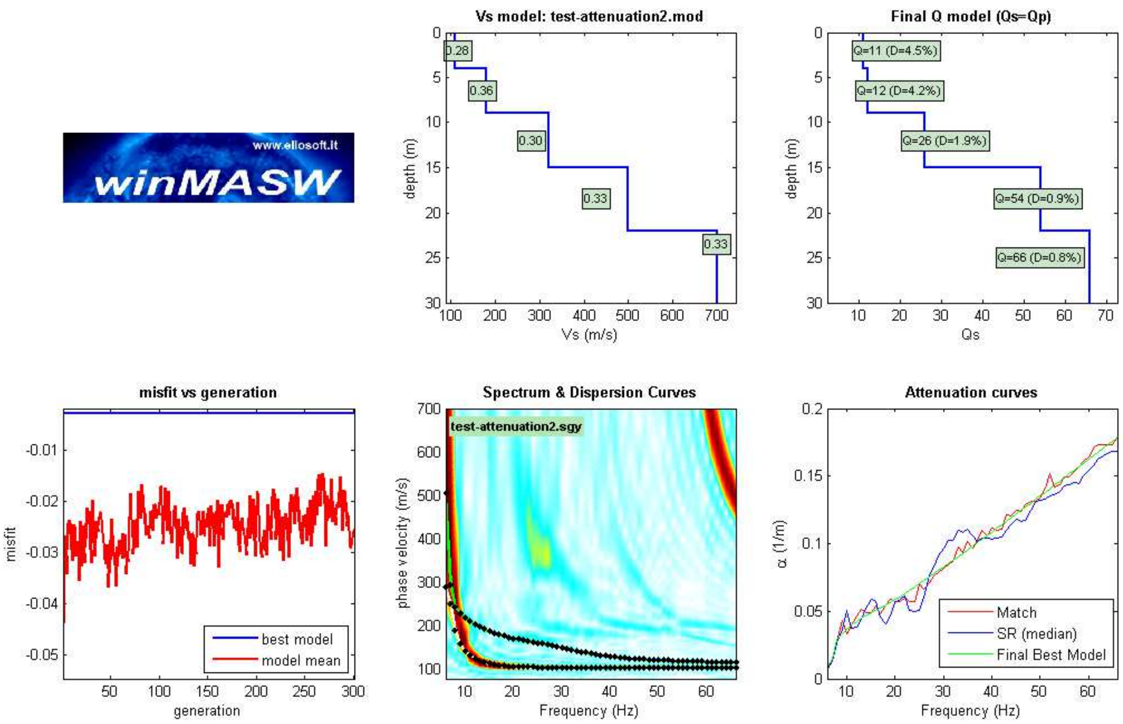
Example of figure resulting when clicking on "*summary plot*" after the identification (modelling) of the Q model that best approximate our attenuation curves.
The number of dispersion curves (modes) to visualize over the velocity spectrum (bottom left) is fixed by the parameter "Modes to visualize" in the panel "Inverting Q"

b) Inversion

Both parameters "Number of models" and "Number of generations" have the same meaning of those met in the inversion of dispersion curves, so there's no need to recap.
Since modelling modalities, the suggested numbers are respectively 100 and 300 ("in seconds" calculation times)
Before launching the inversion, you need to choose a search space (fix it after some direct modelling and bearing in mind the traditional values of Q for different materials-from a min of 3 for highly dissipative soils to over 100 for healthy rocks)
In order to be sure an inversion gives satisfactory results you can compare the final misfit value with the attenuation curve medium one: a value about 10% is typical of a good result.
Example: if the final misfit value is 0.004 while the medium value of the attenuation curve is around 0.006, then the final misfit is about the 7% of the medium value, that meaning the model is acceptable.

FINAL SNAPSHOT OF THE ATTENUATION CURVE INVERSION

(automatically saved as .png file in the subfolder ../winMASW/outputattn/ , but can be saved wherever and in other graphic format)



The number of dispersion curves (modes) to visualize over the velocity spectrum (bottom right) is fixed by the parameter "Modes to visualize" in the panel "Inverting Q"

Q_S=Q_P or Q_P=2Q_S?

During the modelling or inversion procedure you're invited to choose whether to adopt a model for which is valid either **$Q_S=Q_P$** or **$Q_P=2Q_S$.**

Q_S is the quality factor of the transverse waves (S), Q_P is that of the compressional waves (P).

Several authors disagree with the relationship between Q_S e Q_P.

The matter seems purely academic and an only irrevocable answer is impossible.

Just consider that (apart very rare cases) in the attenuation of Rayleigh waves the dominant factor is Q_S (while Q_P has a minor role): you'll understand if you play a bit with the direct modelling proving both options alternatively.

This also means that what really can be supplied in detail from the analysis of surface waves is Q_S whereas Q_P only can be estimated (in general, the value ranges between Q_S and $2Q_S$).

Typical values for the quality factors Q

In low quality soils Q_S values range between 3 and 20; unconsolidated soils with higher cohesion can reach up to 40-60.
Massive rock materials can reach values of about 100-200 (Granite, Peridotite etc) but sedimentary rocks can have a Q_S value equal to just 10-50.
In general the error in the Q value obtained from data analysis is proportional to the Q value: high Q values are therefore less accuracy compared to lower values (see e.g. White, 1992).

Incidentally, the relationship between the ***damping factor D*** the **quality factor Q** is described by the following equation:

$$D = \frac{1}{2Q}$$

12. Computing, assessing and modelling the HVSR

Analysis: HVSR computation

The few parameters to be set are clearly readable (see also SESAME, 2005): if you are not sure of the value and weight of the parameters involved, it is worth attending a few workshops; of course, this tip applies to any method you decide to use.

The basic format used is the official SESAME project format (SAF = *SESAME* ASCII data format) but you can also upload seg2 data/files..

SAF data format

The SAF format (*SESAME* ASCII data format) is an ordinary ASCII file that can be opened with any word editor.

The *winMASW®* and *HoliSurface®* software assume that the 3 columns represent respectively:

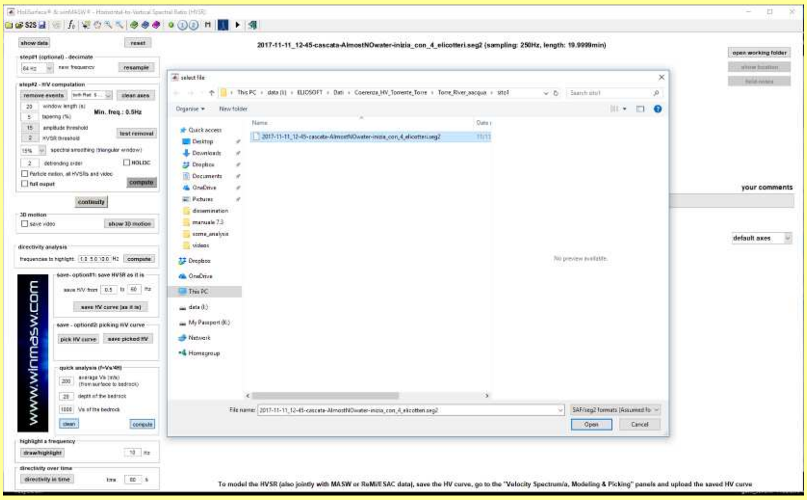
first column: vertical component
second column: NS component
third column: EW component

by the way, while uploading the data you can specify any other possible format/sequence.

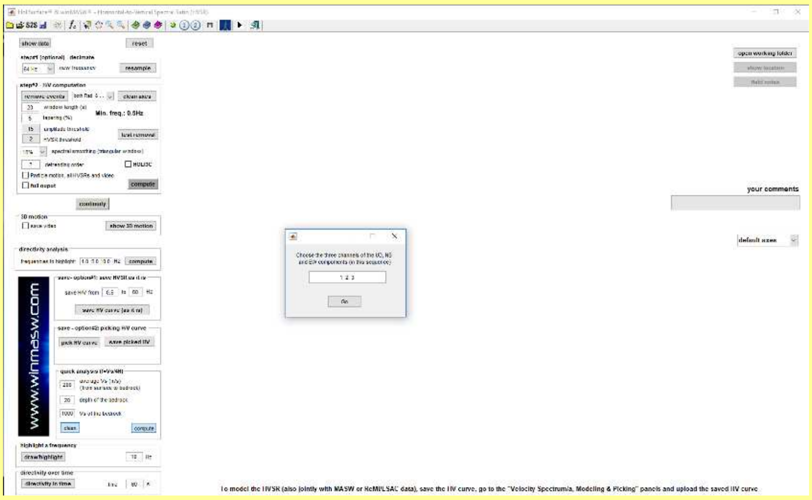
Moreover:
Two parameters are by the *header*:
the sampling frequency (“SAMP_FREQ =”)
the date (“START_TIME = ”)

As you can guess, it is absolutely necessary to have the sampling frequency ("SAMP_FREQ =").
On the other hand, the date ("START_TIME = ") is not a necessary parameter and in case of its absence a simple "warning" will be displayed that lets you proceed with the analysis anyway.

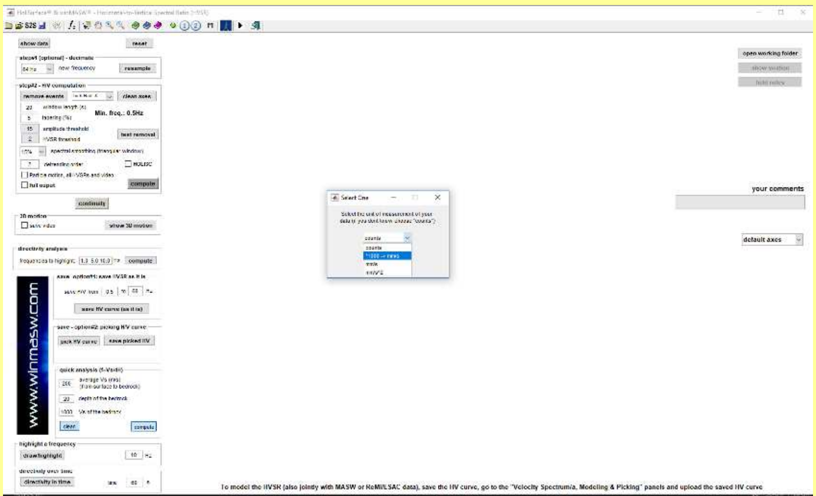
Reading files in SEG2 format



Open/select the file (seg2 format)



Define the sequence of channels containing, in order, the UD, NS and EW components



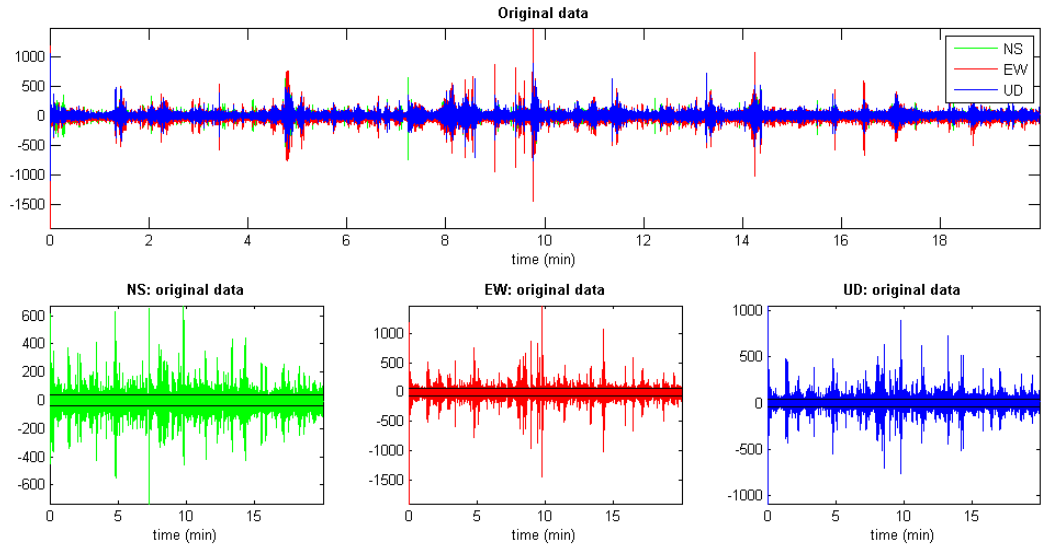
Define the unit of measurement of the data (if you are using our *HoliSurface*® acquisition system following the correct acquisition procedures, select the option highlighted in the snapshot above and you will get the data in mm/s).

Protecting the 3C geophone against the wind

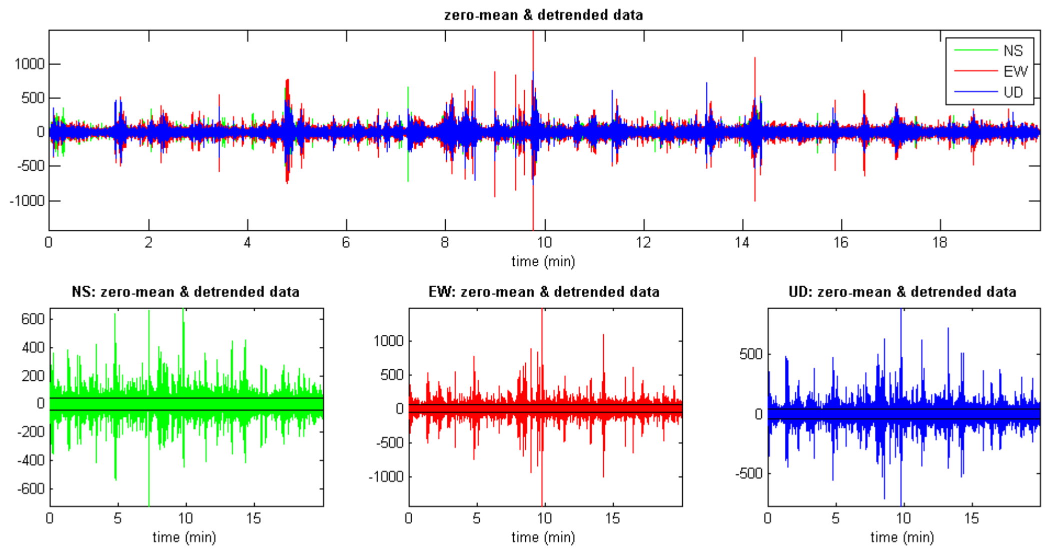
Data display

If the option "*show data*" is activated, the following 2 windows will be shown

Original data



Data after basic processing (zero mean and detrending)



"Show location" button

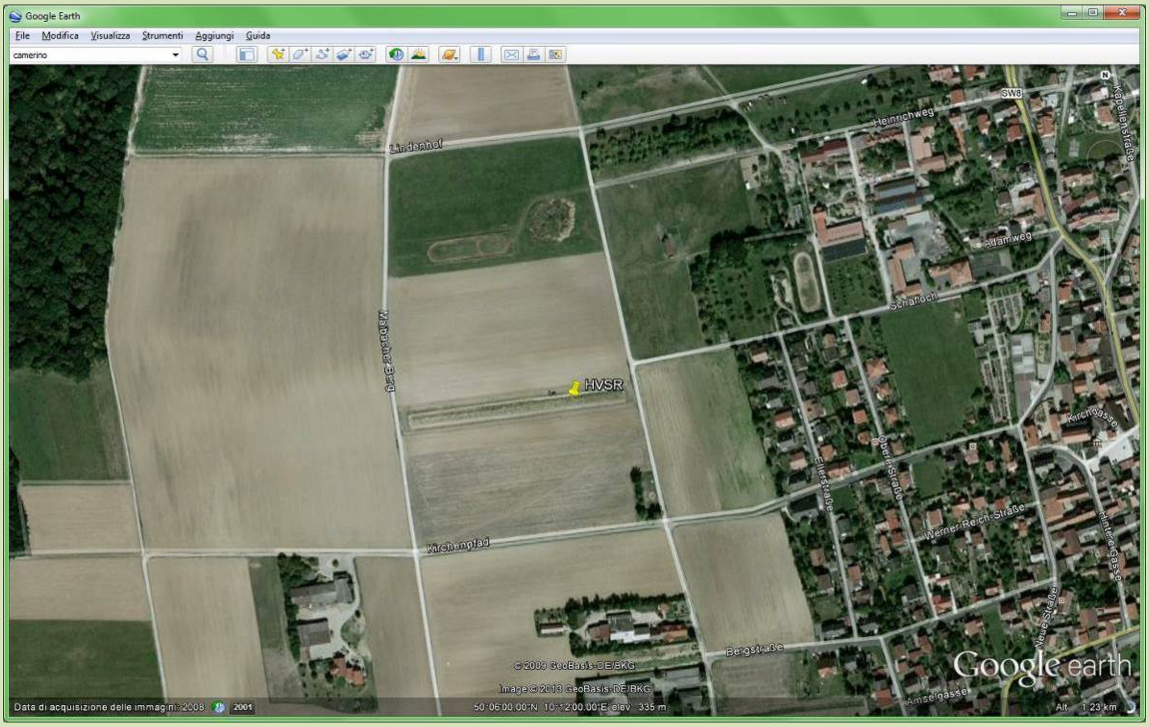
If you have a GPS-equipped 3-channel geophone, you can now view the location of the measurement on *Google Earth* (which clearly must have been installed beforehand) with a simple click.

Geographical data are those indicated in the SAF file (according to the SAF format) in the fields EVT_X (longitude), EVT_Y (latitude) and EVT_Z (altitude)

Example of geographical data in the SAF file:

EVT_X = 10.2
EVT_Y = 50.1
EVT_Z = 0

If these data are present, the "show location" button is activated and it is therefore possible to quickly and automatically obtain a screen like the one shown below



To find out if your 3-channel geophone (and the related acquisition software) are equipped with this option, consult the manufacturer of the 3-channel geophone.

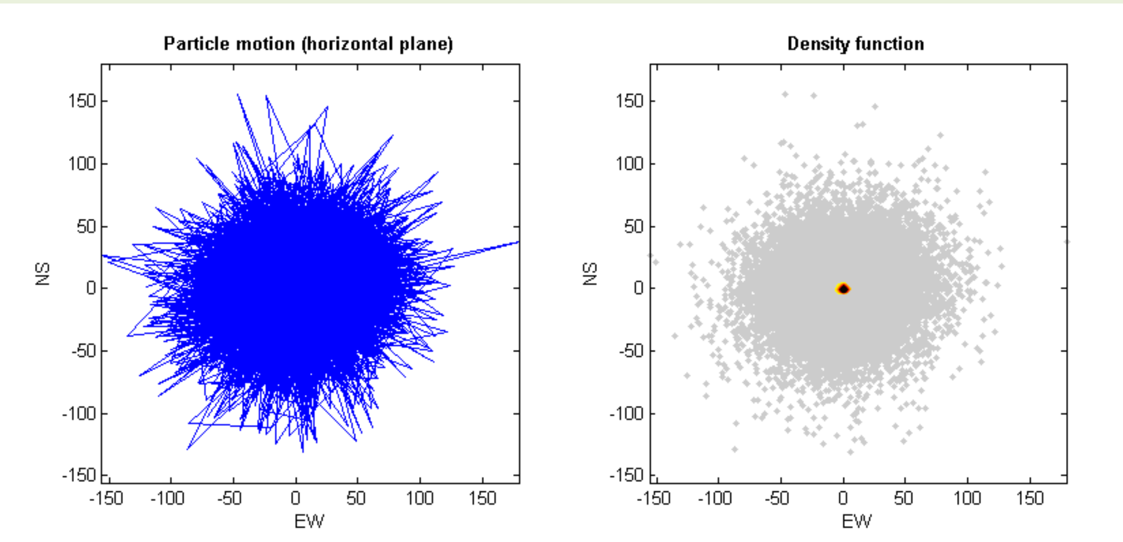
Sampling and re-sampling

What are the most interesting frequencies from a geological and engineering point of view? Generally speaking, from 0.5 to 20 Hz.
Since it is necessary to sample at least twice that frequency in order to identify a certain frequency, it goes without saying that by sampling a signal of at least 40Hz we should be able to bring home sufficiently detailed data for the main geological purposes.
A series of other considerations that cannot be made here in full suggest acquiring at least 128 Hz.
According to some, it is even advisable to acquire data at even higher frequencies (256 or 512 Hz) and then resample them (decimate them) at a lower frequency.
In order to avoid increasing the calculation time unnecessarily, it is important to analyse data at a frequency not exceeding 128 Hz.

For geological/engineering purposes, it is completely useless to analyse data at a sampling rate higher than 128 Hz. Actually we recommend re-sampling at 64 Hz - which still allows you to see up to 32 Hz (which is by far much more than what we need).

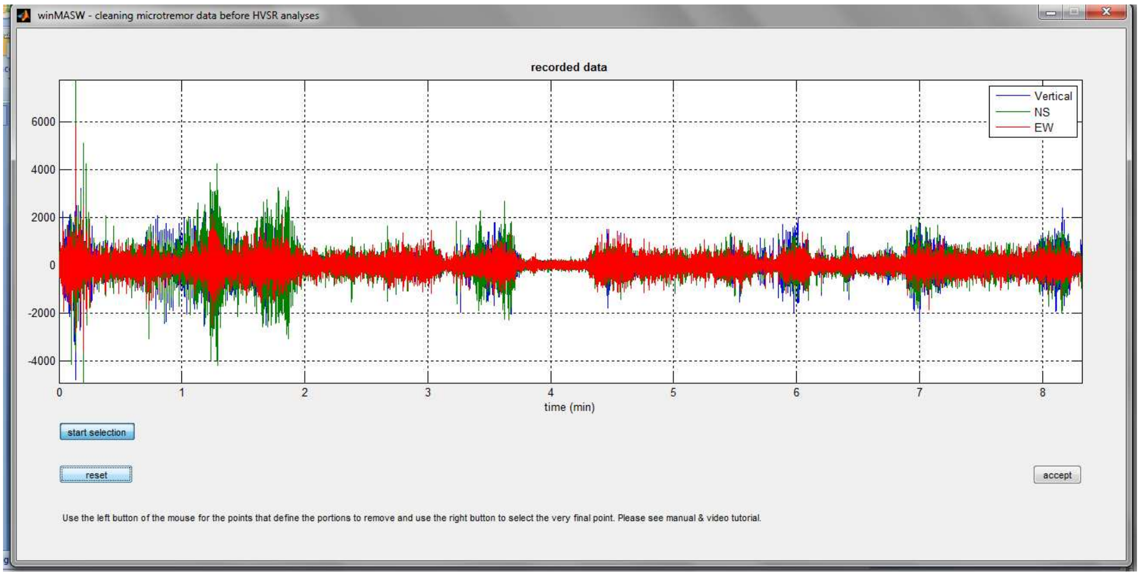
Particle motion

If the option "*show particle motion (of the original data)*" is selected, the plot of the soil motion will be obtained along the three sections *vertical-NS*, vertical-EW and *horizontal* (NS-EW) (clearly of the original data).

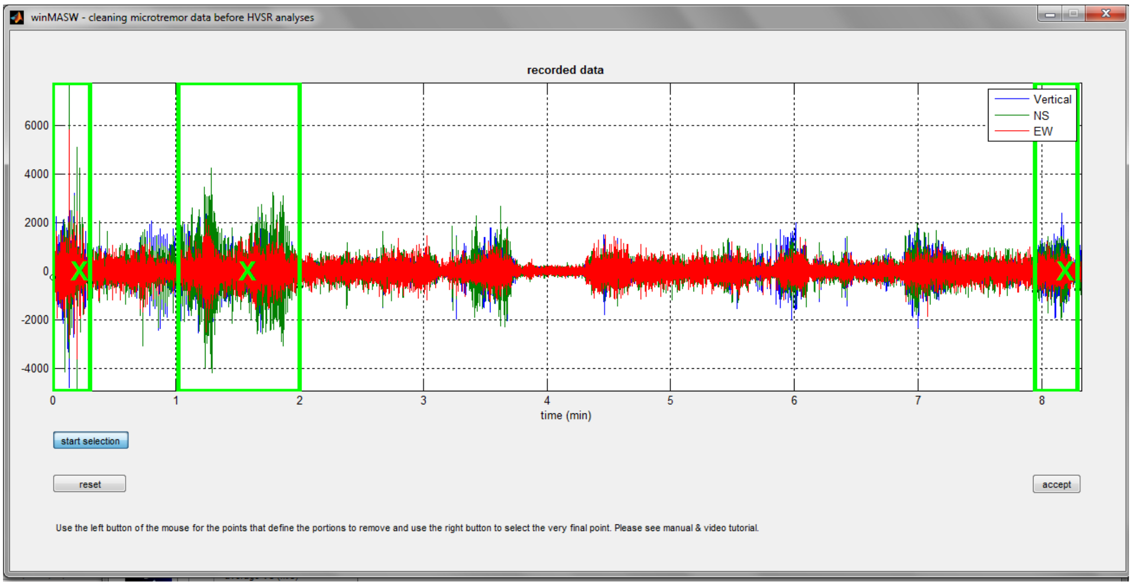


Removing events (transients) before calculating the H/V spectral ratio

By clicking the "remove events" button, the following screen will appear:

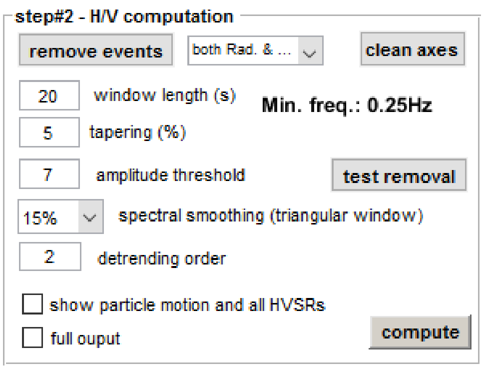


The user can now select specific events (signals) to be removed. To do so, click on the "start selection" button and use the left mouse button to define each point (note that each event is defined by a start point and an end point). To select the last point, use the right button. In the example below there are 3 selected events (to be removed). These events are clearly defined by 6 points. The first 5 must be identified using the left button and the last (in this case almost at the end of the dataset) with the right button.
If the selection works, we will click at this point the "accept" button to return to the main screen; otherwise we can make a new selection resetting the previous one ("reset" button).

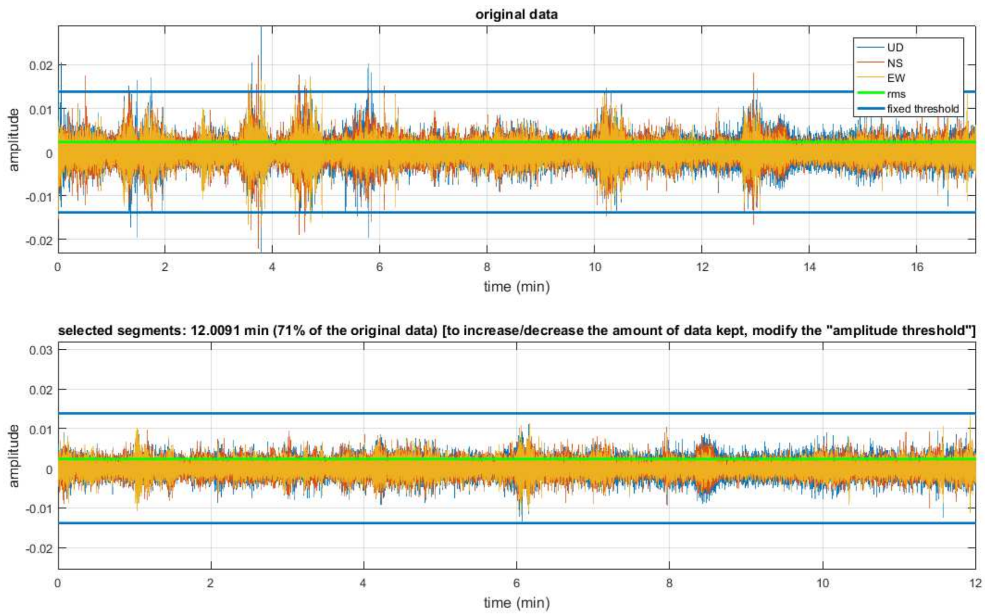


<u>Automatic</u> removal of events with amplitude above an amplitude threshold set by the user

Among the parameters to be set for HVSR processing, there is also the amplitude threshold used to automatically remove all those windows within which there are events with amplitude.
In summary, the root mean square amplitude of the traces is calculated and then multiplied by the amplitude threshold set by the user.
If a window contains an event with a larger amplitude, this window is deleted from the analyses.
Clearly, the lower that value, the more data/windows will be removed.



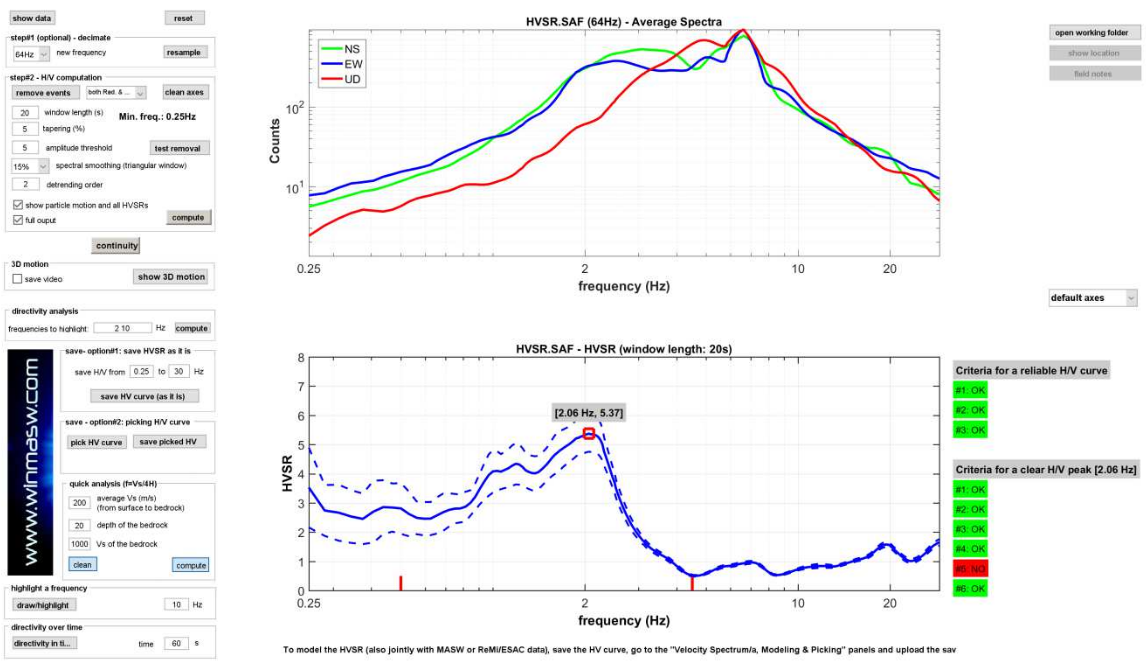
With the "test removal" button, you can check how this automatic cleaning of the data works and we can increase or decrease the automatic cleaning of the traces before proceeding with the final calculation (done by ticking the option "*full output*").
Below is an example of data before and after removing windows in which the amplitude exceeds the set threshold (see blue line).



Main screen

The screen is easy to read. As a first step, load the dataset you want to analyse (classic icon at the top left end of the toolbar).

Then set the various parameters as needed and launch the analysis with the "compute" button. Once the analysis is complete, the screen shows the spectra of the three components and the H/V ratio:

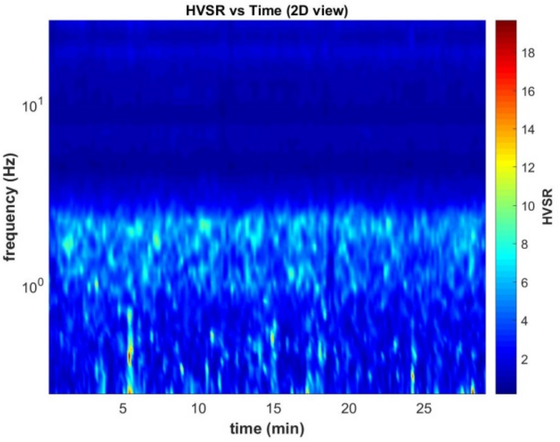


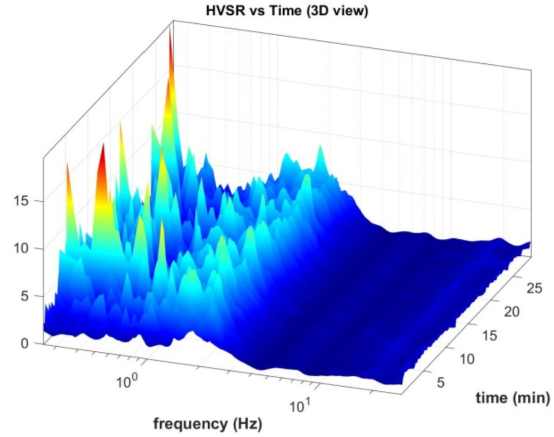
If the 3-channel geophone used also included a GPS and the SAF file obtained contains the geographical indications of the site (fields "EVT_X", "EVT_Y" and "EVT_Z"), it is possible ("show location" button) to get the automatic display of the site on Google Earth (which must clearly have been previously installed).

Once a good HVSR curve has been obtained by changing the processing parameters, at that point it is possible to carry out the "complete" calculation of everything that can be calculated. To do so, simply activate the "full output" option. As a result, a series of outputs (images and text) will be saved in the working folder. The main one is an HTML file (an ordinary file in web format manageable with any browser): clicking on it opens the analysis report.

The red dots (see screenshot above) indicate HVSR values below the unit (*possible* velocity inversion index).

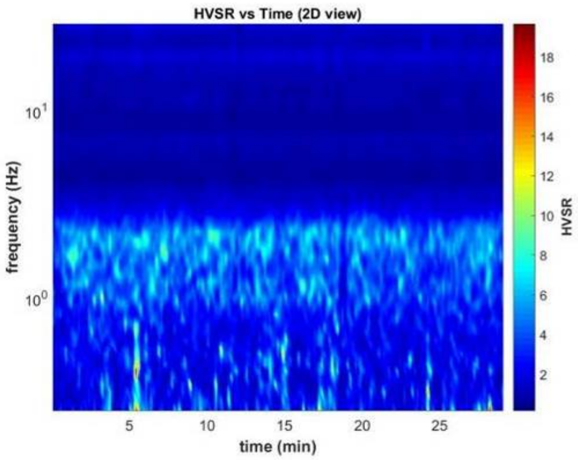
The various outputs also include the "continuity" of the HVSR during acquisition (in this case a little less than 18 min), i.e., the value of the HVSR on each window considered:

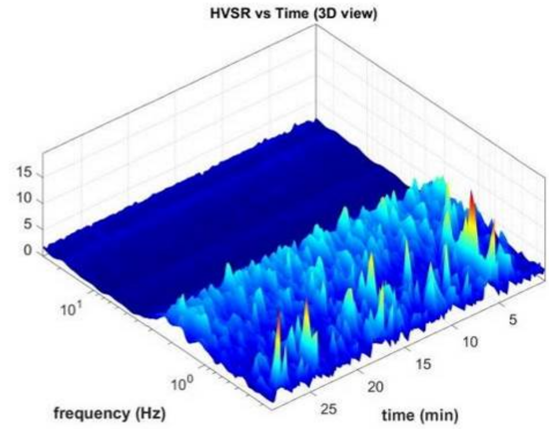




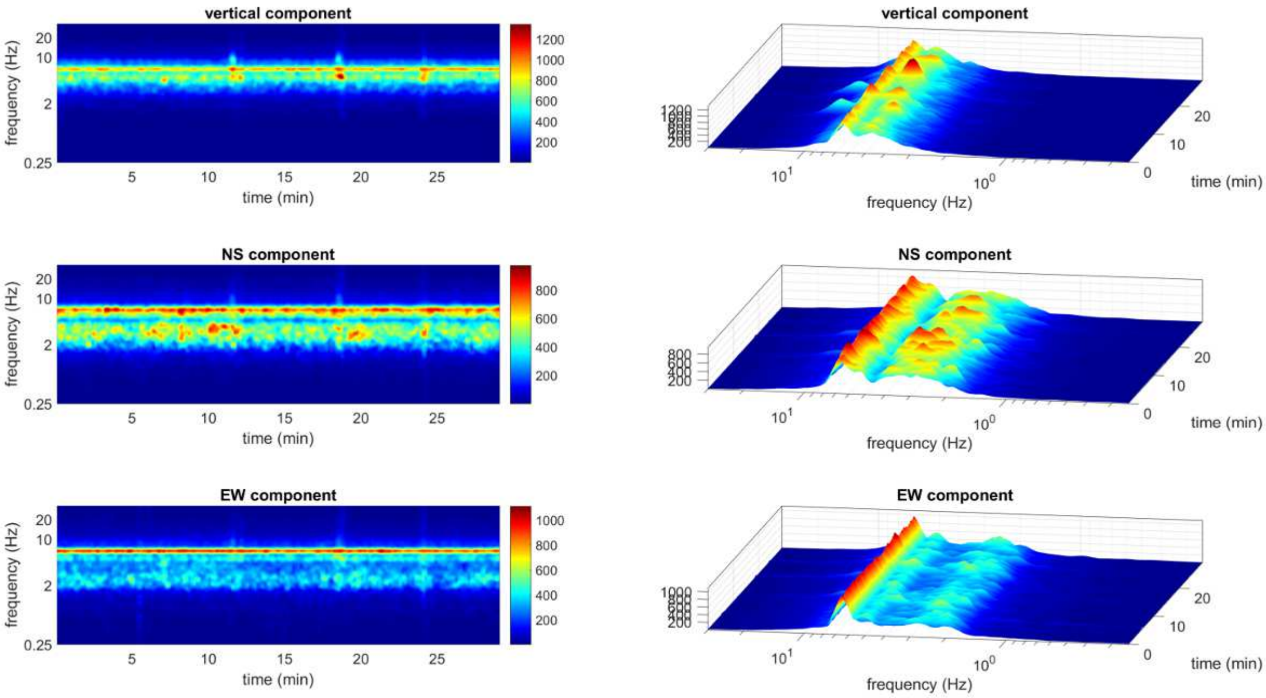
Continuity is presented both in the classic two-dimensional (on the left) and three-dimensional (on the right) visualization.

A series of tools is as always present in the bar. For example, it is possible to display the color scale (which in this case represents the values of the H/V spectral ratio - see image below).





Amplitude spectra of the individual components as a function of time.



Minimum frequency of the HVSR curve

In accordance with SESAME guidelines, the minimum frequency that can be displayed depends on the value of the analysis window. Since at least 10 cycles are required, the minimum frequency that can be determined in a robust way is therefore equal to f=10 / l_w (10 divided by the length of the window in seconds).

If you want to go down to 0.1 Hz, for example, you need to set the analysis window to 100 seconds and write 0.1 in the field relating to the minimum frequency in the group "**save - option#1: save HVSR as it is**"

HVSR Report and SESAME criteria

At the end of the calculation of the HVSR curve a report (.html file) summarizing all the parameters used and the results of the analysis is provided (the file is automatically saved in the working folder).
SESAME criteria regarding the reliability of the H/V curve and its peak are also evaluated. Analyses using SESAME criteria are carried out considering the data in the 0.5-15 Hz range (engineering) but this range can be modified using the f_c button in the toolbar at the top. The complexity of this kind of evaluation is such that it is necessary to have a "critical" look by the user who must be well aware of the subject. It is therefore necessary that the user has well assimilated the SESAME guidelines (considered as a minimum prerequisite) and all subsequent literature.

Among other things, the output provides the following outcomes:

```
=============================================================
In the following the results considering the data in the 0.5-15Hz frequency range
Peak frequency (Hz): 3.2 (±0.3)
Peak HVSR value: 5.5 (±0.5)

= Criteria for a reliable H/V curve ===================================
#1. [f0 > 10/Lw]: 3.2 > 0.25 (OK)
#2. [nc > 200]: 6314 > 200 (OK)
#3. [f0>0.5Hz; sigmaA(f) < 2 for 0.5f0 < f < 2f0] (OK)

= Criteria for a clear H/V peak (at least 5 should be fulfilled) ===============
#1. [exists f- in the range [f0/4, f0] | AH/V(f-) < A0/2]: yes, at frequency 2.0Hz
(OK)
#2. [exists f+ in the range [f0, 4f0] | AH/V(f+) < A0/2]: yes, at frequency 4.2Hz
(OK)
#3. [A0 > 2]: 5.4 > 2 (OK)
#4. [fpeak[Ah/v(f) ± sigmaA(f)] = f0 ± 5%]: (OK)
#5. [sigmaf < epsilon(f0)]: 0.313 > 0.157 (NO)
#6. [sigmaA(f0) < theta(f0)]: 0.642 < 1.581 (OK)

Please, be aware of possible industrial/man-induced peaks or spurious peaks
due to meaningless numerical instabilities.
```

Few tips in this regard:

- do not consider the SESAME criteria as, so-to-speak, the Bible
- changing the processing parameters (analysis window length, transient removal, etc.) necessarily leads to changes that can also be reflected in the

SESAME criteria.
- criterion#5 (among the "*Criteria for a clear H/V peak*") is often among the most restrictive. Beyond its rigorous formulation, the data should be evaluated using common sense (always necessary for any method).
- by default the criteria are calculated in the 0.5-15 Hz range (usually the one of greatest engineering interest), but this range can be changed with the *fc* button in the toolbar.
- pay attention to possible industrial signals/components (see e.g. Dal Moro, 2012; 2014; 2020).

Saving the H/V curve

At the end of the analysis you can save an H/V curve (here too in the standard format of the SESAME project). There are 2 possible options:

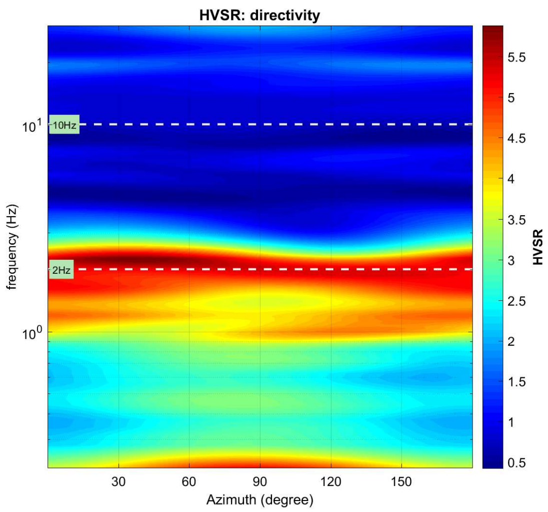
“option#1 - save HVSR as it is”
“option#2 – picking H/V curve”

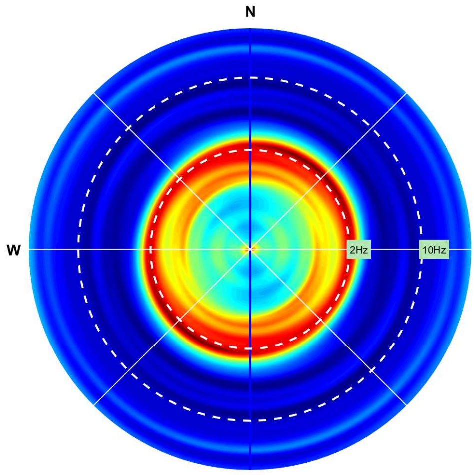
In the former case you save the calculated H/V curve (visible at the bottom of the screen) in the frequency range indicated.

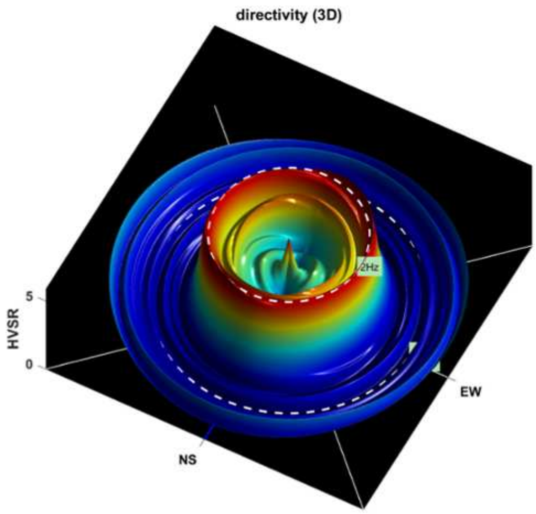
In the second case, it is possible to pick the H/V curve, thus making it possible to eliminate possible peaks due to anthropic "artifacts" not linked to lithological amplification signals.
winMASW® and *HoliSurface®* users who are subscribers of our mailing list will receive further information.

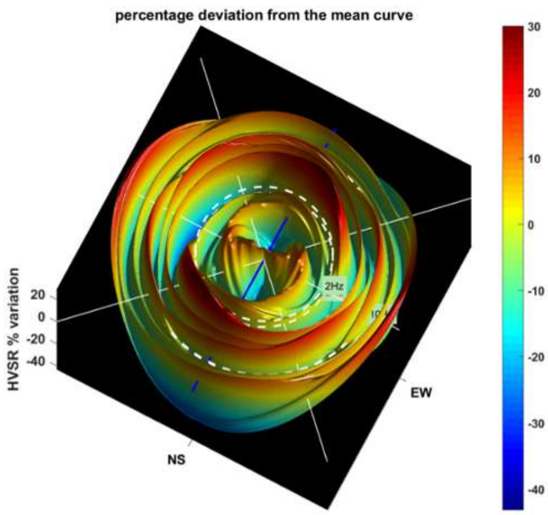
Directivity

Once the mean H/V curve has been calculated, it is also possible to calculate the directivity of the signal up to a specified frequency (see above for the relevant frequencies).







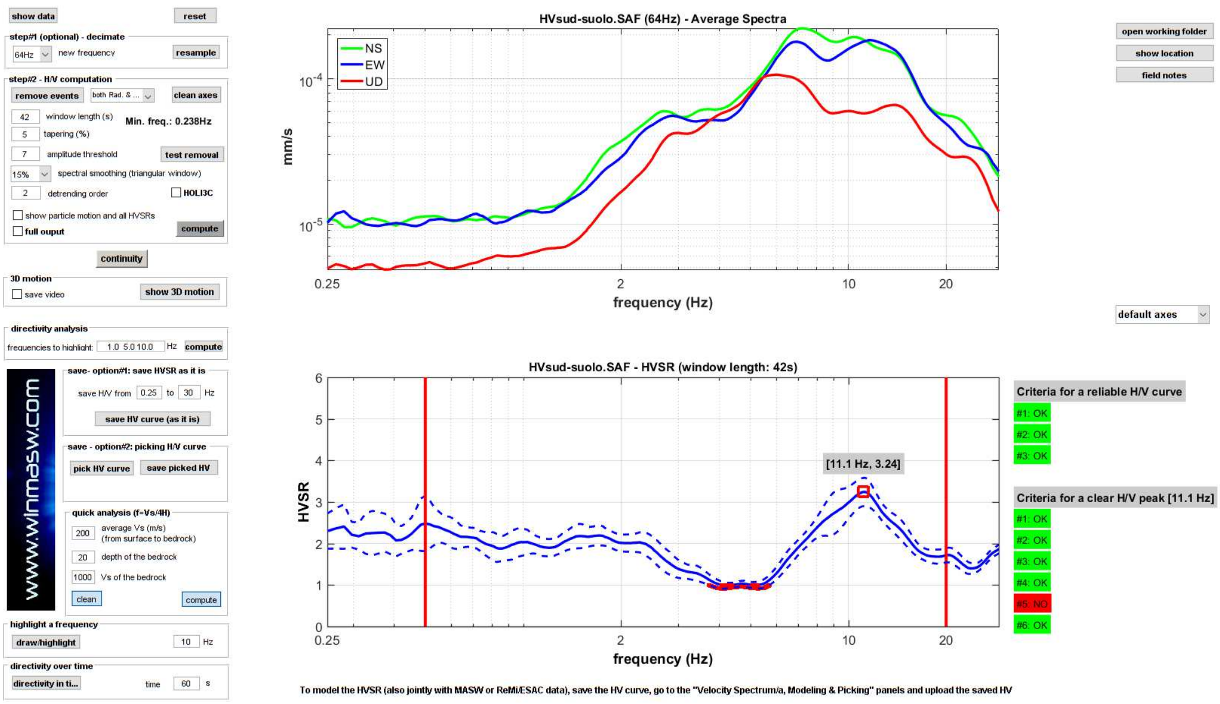


Consider that while in one case (left) the frequency scale is logarithmic, in the other case (right) it is linear. The figure is automatically saved in the previously indicated working/output folder ("working folder") but can also be saved manually by the user in any of the many possible formats.

The HVSR analyses in <u>two steps</u>

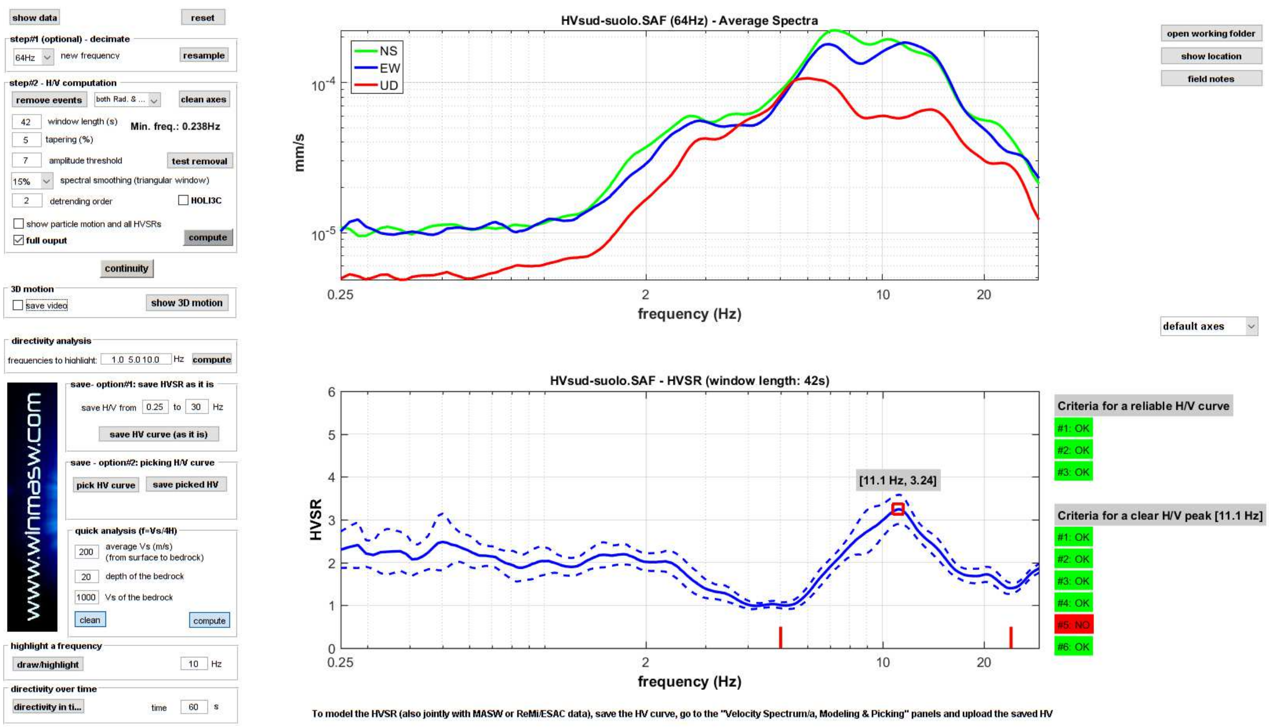
In a **<u>first step</u>** (clicking on "compute" without having activated any particular option) we calculate only the HVSR curve to understand which parameters (*smoothing*, window length, etc.) are most suitable for the dataset considered.

In this phase, two vertical red bars are also highlighted, indicating the minimum and maximum frequency within which the SESAME criteria are calculated:



It is the user's responsibility to modify these limits ("*fc*" button on the toolbar) to include the peak to be evaluated based on the SESAME criteria.

In the **second step**, once the limits have been modified and the "full output" option has been activated (to carry out all the possible directivity, continuity analyses, etc.), we obtain a graph like the one below (in which the limits are now indicated in a more "discreet" way and the values below the unit are not highlighted):

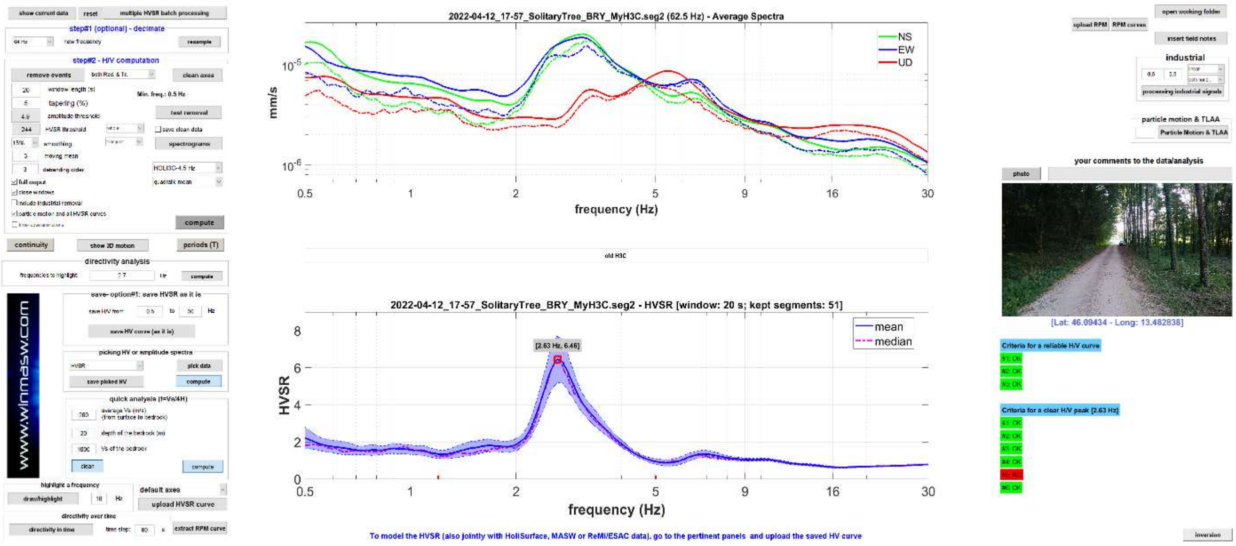


In fact, if there is more than one peak in a curve, they will have to be evaluated (based on the SESAME criteria) individually/separately (see the *winMASW-HVSR-SESAME.rar* "package" in the "Documents" folder in the *winMASW®* and *HoliSurface®* installation folder and refer to our workshops and the book that should be published by Springer in February 2020).

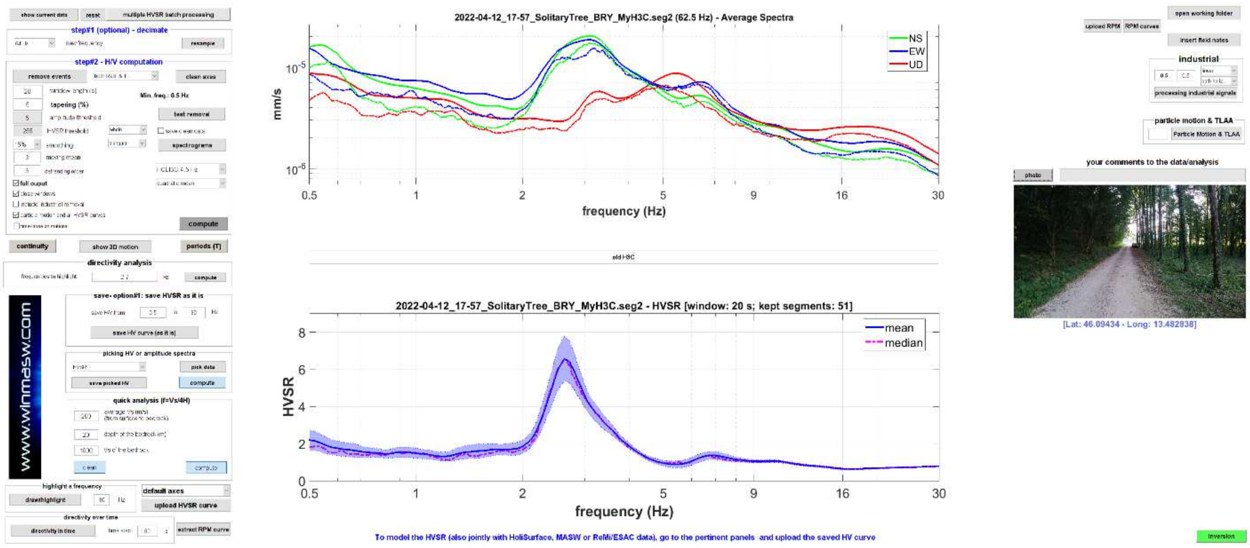
So (in case of multiple peaks) the SESAME criteria should be considered for each peak (having to launch the calculation for each individual peak - after having clearly modified the *fc* limits to include the peak you want to consider from time to time).

SESAME or not SESAME?

By default, the software computes the SESAME criteria in the frequency range specified by the user - see previous pages and the article Dal Moro & Panza (2022). A plot similar to the following is obtained:



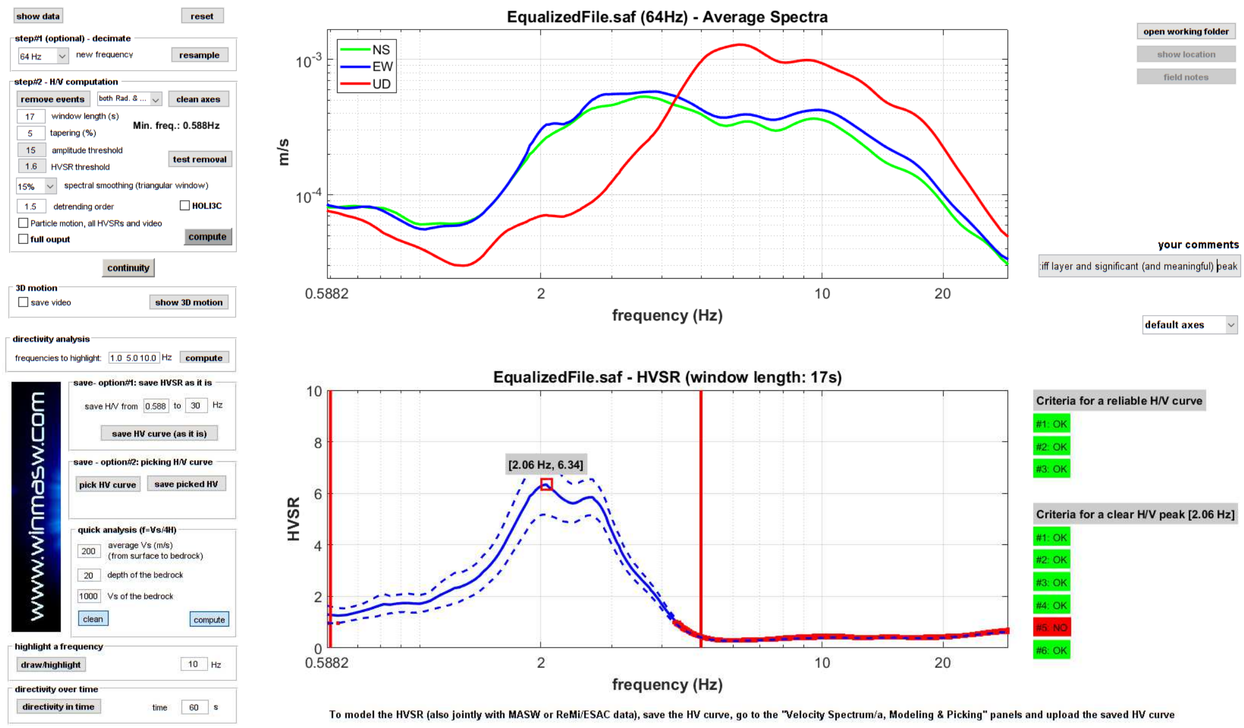
In case you do not want to compute and show the SESAME criteria (and the indication of the "peak" – see red square in the upper plot), you can disable the SESAME criteria calculation by simply "cancelling" (inserting null values) the two f_c values. This way you will then get a plot like the one shown below.



YOUR COMMENTS

It is also possible to add comments to the data and analysis (see the grey box "your comments" to the right of the amplitude spectra graph).

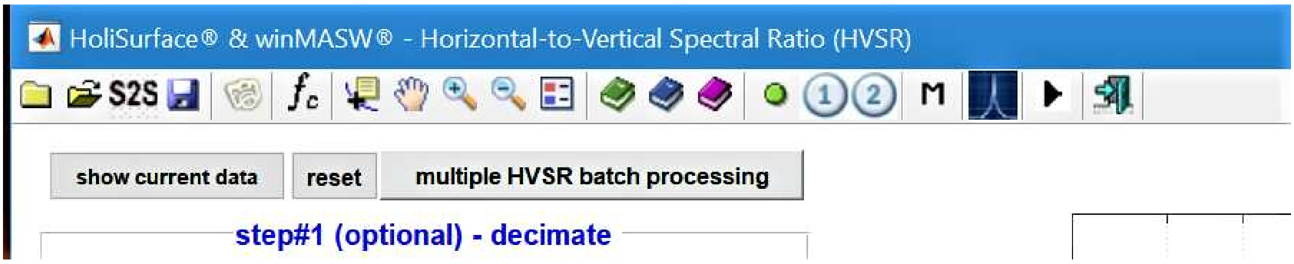
The comments will be automatically reported at the bottom of the final report obtained by computing the HVSR having activated the "**full output**" option.



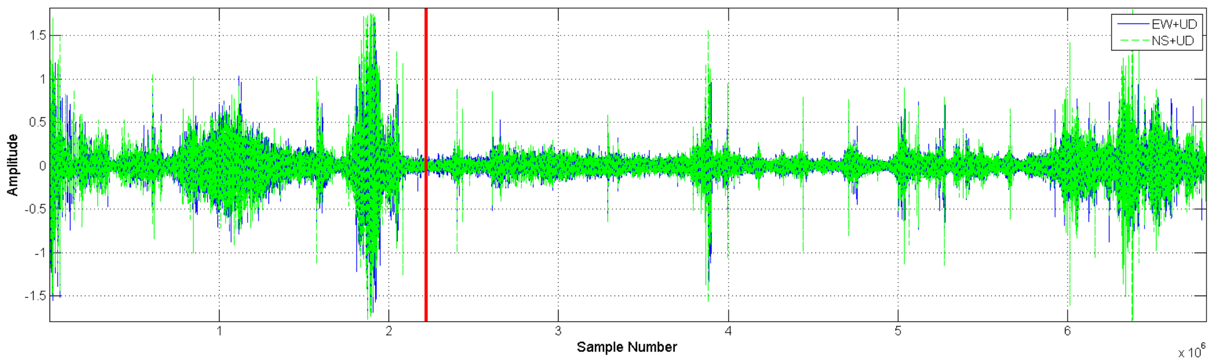
Listen to your microtremors

From the HVSR panel (► button along the toolbar) it is possible to listen to your microtremor. Click that button and choose one of the two possible options: 1) just listen to the audio version of your microtremors [“**simple**” **option**] or 2) show the time lapse spectrogram animation [**visualization [longer]**” **option**].

Data are reproduced with a velocity about 10 times faster that the actual data (a 10-minute dataset will be then played in just 1 minute).



Just a funny curiosity? Not necessarily. Attend one of our workshops and discover that our ears can help us also in the assessment of the microtremor data.

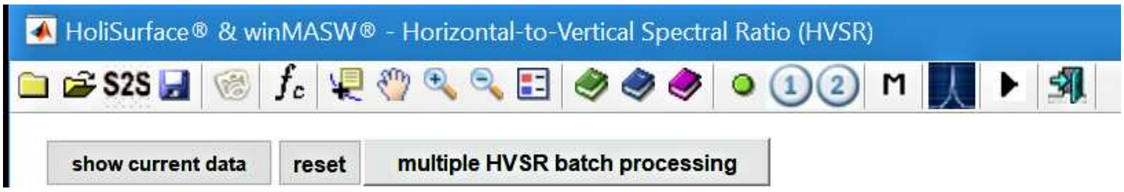


The audio is also automatically saved as *flac* file in the working folder and can therefore be played on any device.
IN order to appreciate the sound of our *Mother Earth*, we would like to recommend you to use a good sound system or your headphones.
Consider that in order to preserve the high frequencies, you should perform this operation before resampling the data.

The same tool is also available in the ESAC panel ("**play & save audio data**" button).

Time Lapse of your microtremor data in the frequency domain

From the HVSR panel (► button along the toolbar) it is also possible to visualize a time lapse animation of the spectr4igrams of the three components and of the HVSR itself..

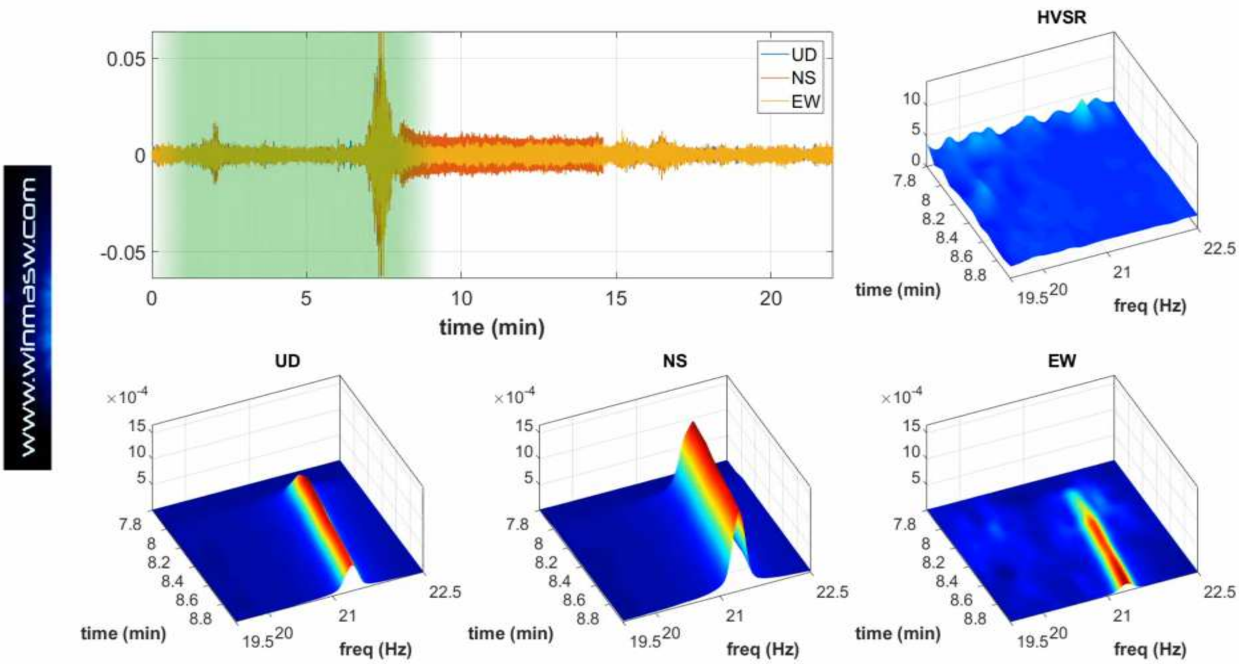


Click the same button and, instead of choosing the "simple" option (see previous section), choose the "**visualization [longer]" option.**
This can be useful in case you want to monitor/visualize the persistence of a specific industrial component.
The minimum and maximum frequency (i.e. the frequency range shown) are the same specified for the minimum and maximum values for the HVSR (see the two values to specify in the "**save – option#1**" group).

In case you also select the "time-lapse animation" option (in the "step#2" group), the shown video will be saved in the working folder as **mp4 file**.

An example of data characterized by a clear industrial component (that also changes its frequency) is shown here: https://www.youtube.com/watch?v=NW1e_q09g-c

Such example is analysed in detail in the paper "*On the identification of industrial components in the Horizontal-to-Vertical Spectral Ratio (HVSR) from microtremors*" (Dal Moro, 2020).



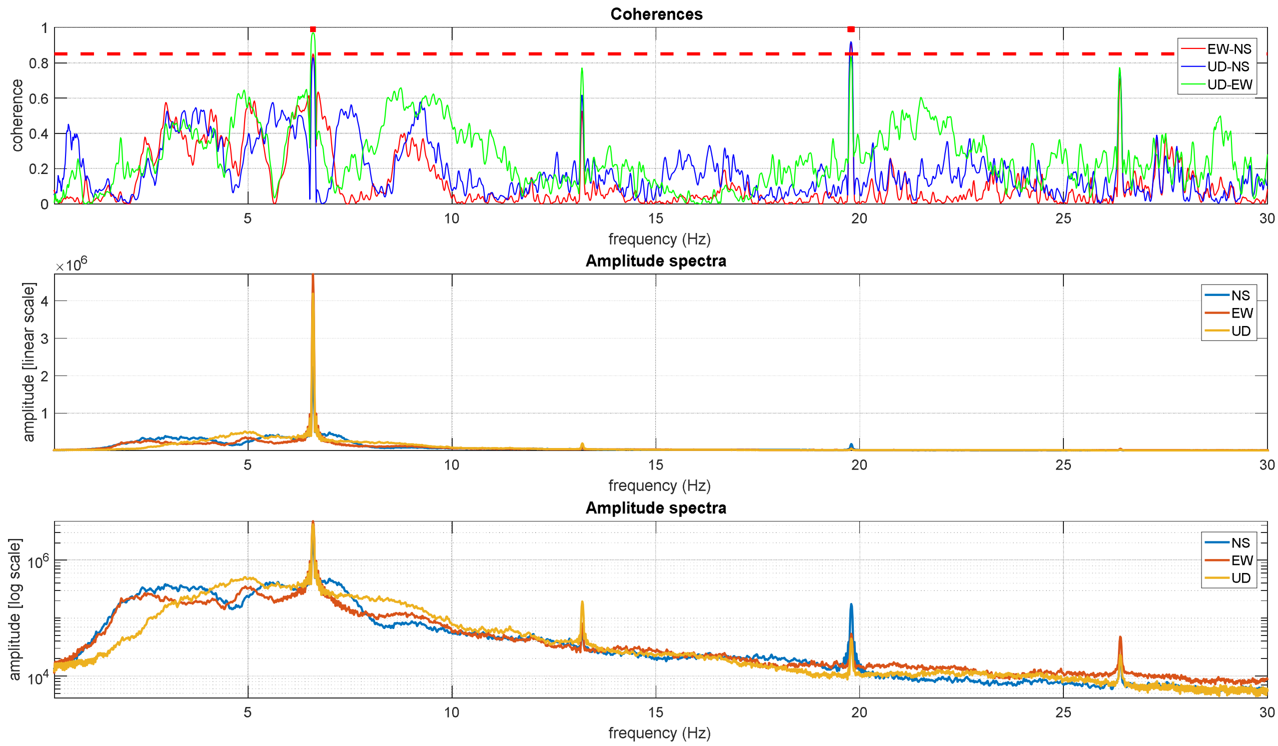
Industrial components

The amplitude spectra of the three components with linear frequency scales (both log and linear amplitude scale) and the coherences between the various pairs of sensors (EW versus NS, EW versus UD and NS versus UD) are also shown.

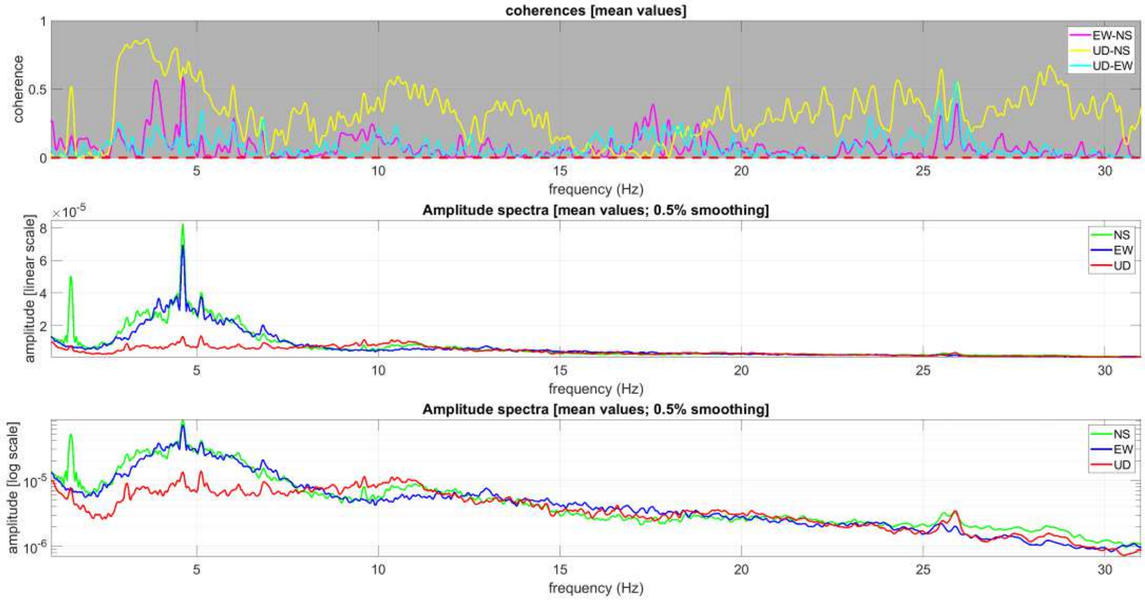
This way it is possible to better highlight possible industrial components

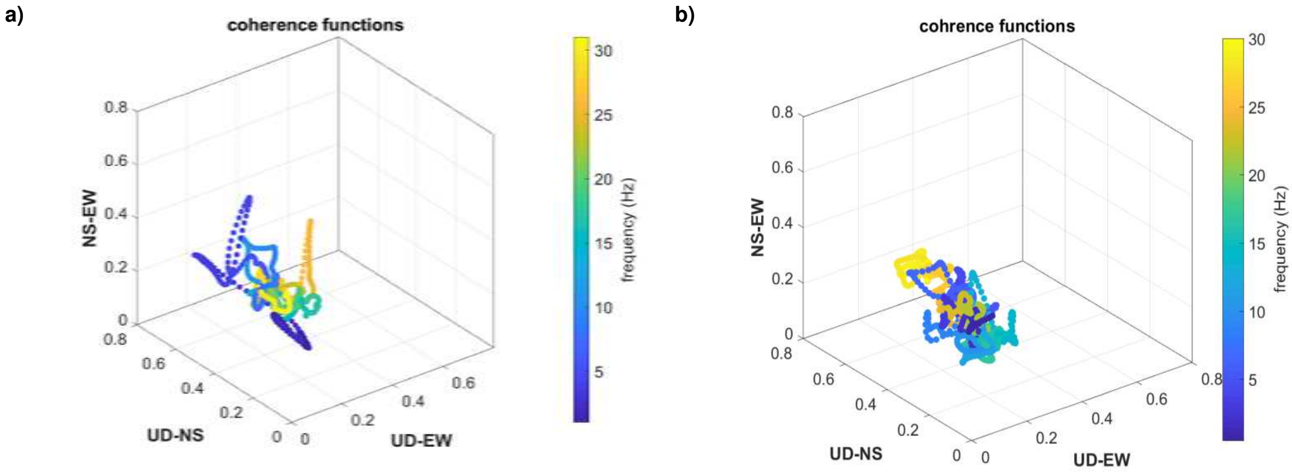
We would strongly recommend to study the paper *On the identification of industrial components in the Horizontal-to-Vertical Spectral Ratio (HVSR) from microtremors* (Dal Moro, 2020 – Pure and Applied Geophysics – **https://doi.org/10.1007/s00024-020-02424-0**

In the example below the presence of a series of "artificial" (industrial) peaks at 6.6, 13.2, 19.8 and 26.4 Hz is evident (note that - in this very peculiar case - you can see the fundamental frequency of an industrial component [at 6.6 Hz] with a series of higher harmonics).



In the next example you can note the presence of a couple of industrial signals at about 1.56 and 4.63 Hz.





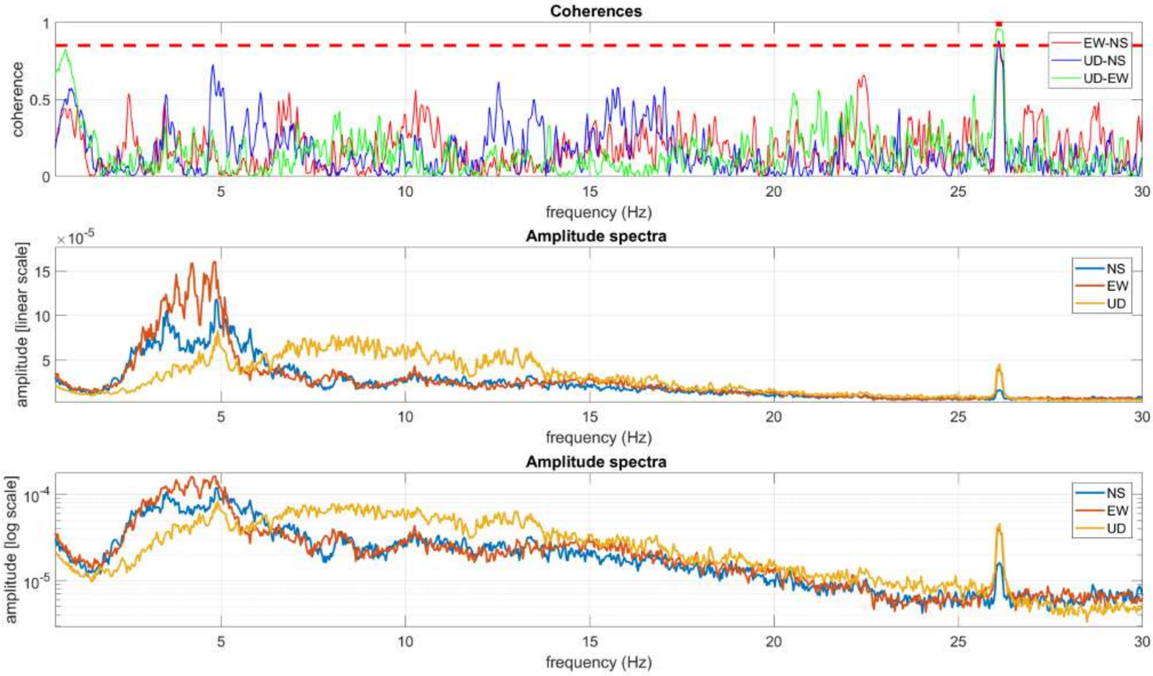
Two examples of coherence functions displayed in 3D mode with the color scale representing their frequency: on the right a case where no significant industrial components are evident, on the left a complex dataset with a couple industrial components.

With regard to the data in the left plot see also the two images below related to:

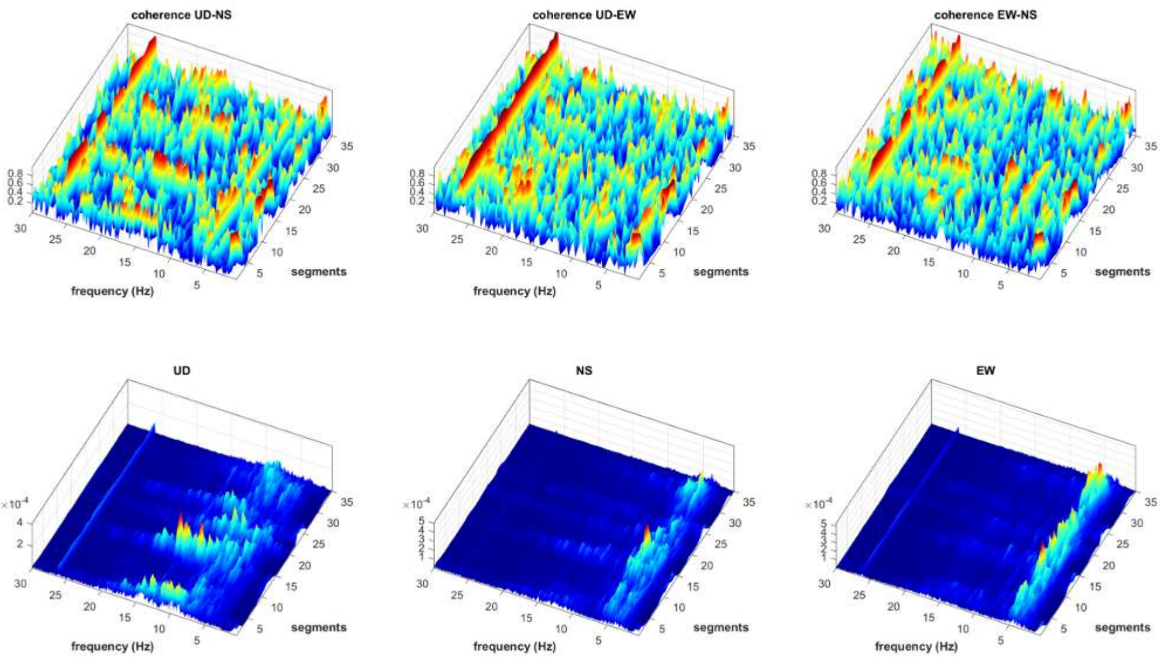
1) frequency coherence functions (for all three combinations NS-EW, EW-UD, and NS-UD) and linear and logarithmic amplitude spectra (smoothed by only 3%);

2) coherence functions and spectrograms (time-dependent).

1)


Coherences
coherence
EW-NS
UD-NS
UD-EW
frequency (Hz)
Amplitude spectra
amplitude [linear scale]
NS
EW
UD
frequency (Hz)
Amplitude spectra
amplitude [log scale]
NS
EW
UD
frequency (Hz)

2)


coherence UD-NS
coherence UD-EW
coherence EW-NS
UD
NS
EW
frequency (Hz)
segments

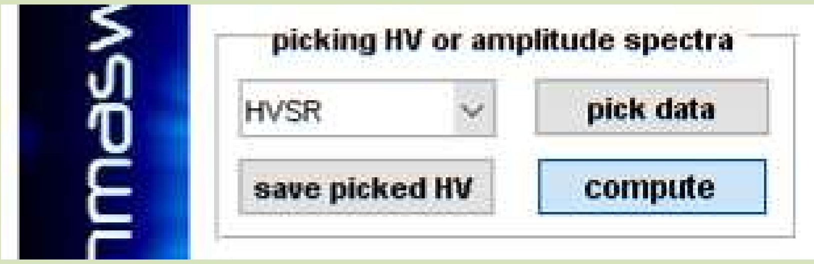
Managing (manually) the industrial components

There are two ways to attenuate/reduce/delete industrial signals:
1) massively smooth the spectra (50% and more [see parameter *spectral smoothing*]);
2) manually picking the HVSR curve or, if the situation is complex, the amplitude spectra of the UD, NS and EW components.

The first approach does not require much clarification and is therefore not discussed here.
Let us see some details on the other two approaches, it being understood that in order to implement them seriously it is necessary to attend our training courses.
It should be emphasized that the quality of this type of operation depends entirely on the level of theoretical knowledge of those who carry them out.

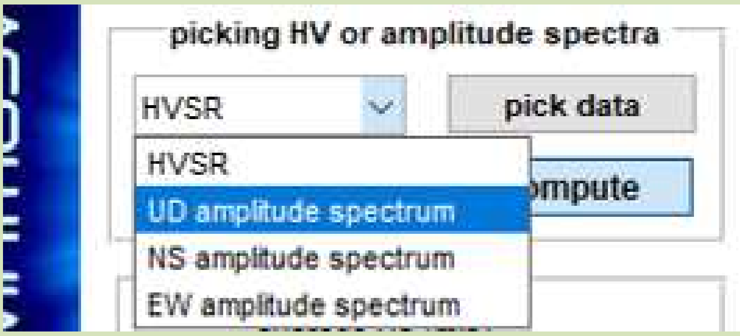
a) picking of the HVSR curve

In this case, the HVSR curve potentially "contaminated" by industrial signals is picked directly.



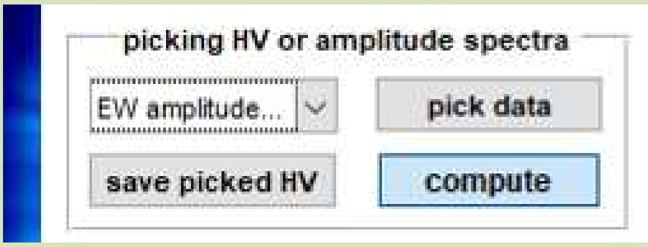
1) In the drop-down menu, select the "HVSR" option;
2) Click the "pick data" button;
3) Start picking the desired curve (to close picking, use the right mouse button);
4) Save the picked curve by clicking on the "save picked HV" button.

b) picking of the amplitude spectra of the three components and related recalculation of the HVSR curve:



1) HVSR calculation with limited smoothing (approximately 2-3%)
2) In the drop-down menu, select the component to be picked (all three components must be picked in sequence);
3) Once the component has been selected, click on the "pick data" button;
4) Start picking the selected amplitude spectrum (we recommend that you always follow the same order): UD, NS and EW; to close picking, use the right mouse button);

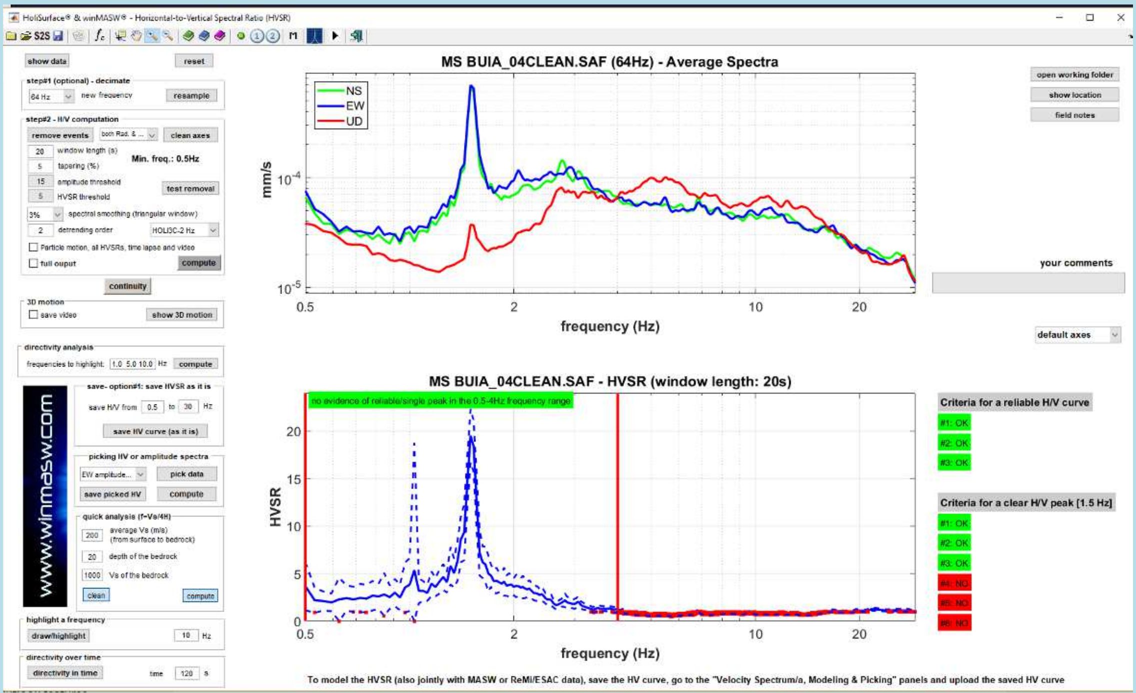
Points 2, 3 and 4 are repeated so to pick the amplitude spectra for all the three components (UD, NS and EW).



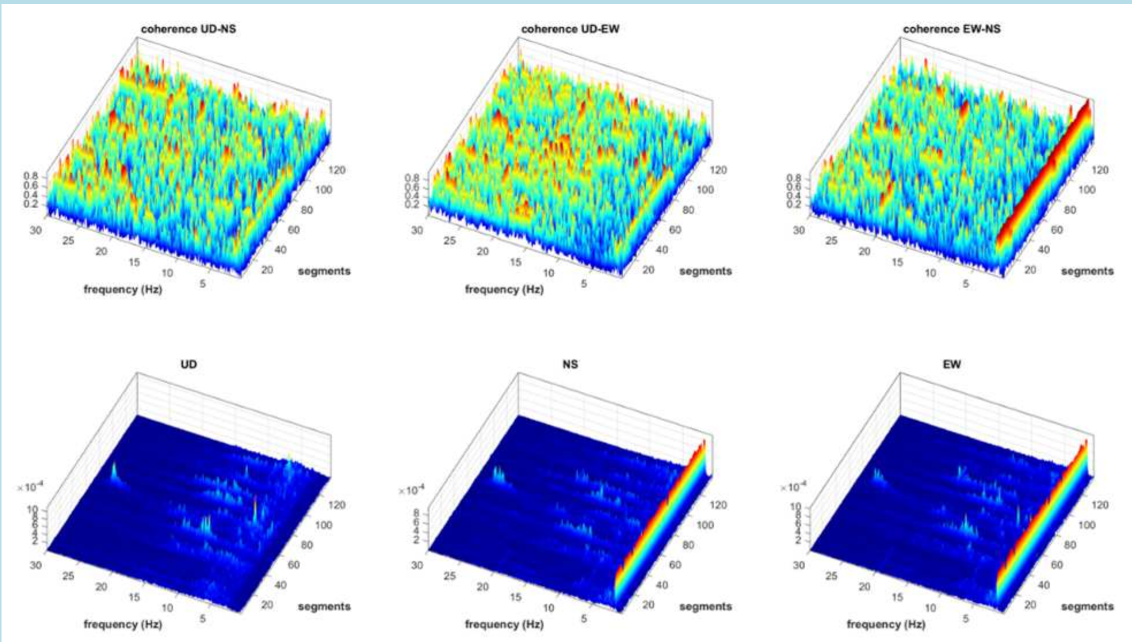
5) Once the last component has been picked, the use must (re)compute the H/V ratio based on the amplitude spectra of the picked three components. To do so, press the "compute" button. At this point, a summary screen will be displayed and the re-computed HV curve will be automatically saved in the working folder as a file with the same name as the field datafile with the additional suffix "_reconstructed.hv".

A quick example

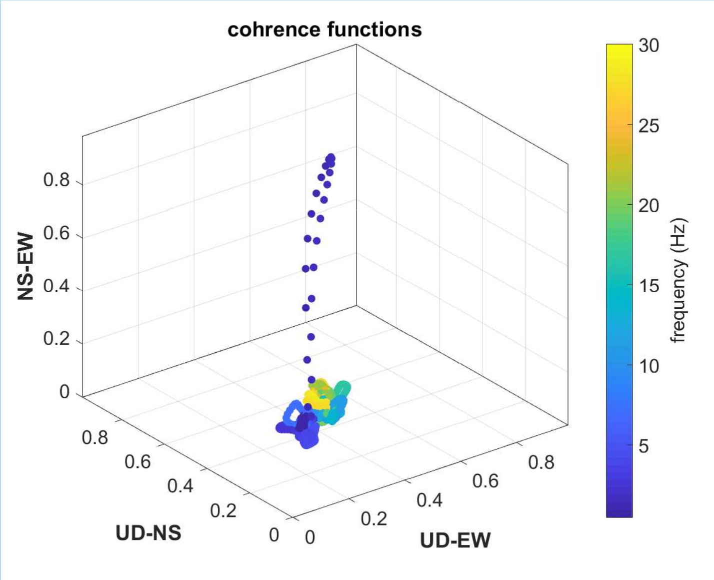
1) computation with 3% smoothing (incidentally, in this way the SESAME criteria are completely out of sync). The well-known 1.5 Hz industrial component is evident (common throughout Friuli and beyond).



During this first phase you will get, among other things, also the following two graphs:

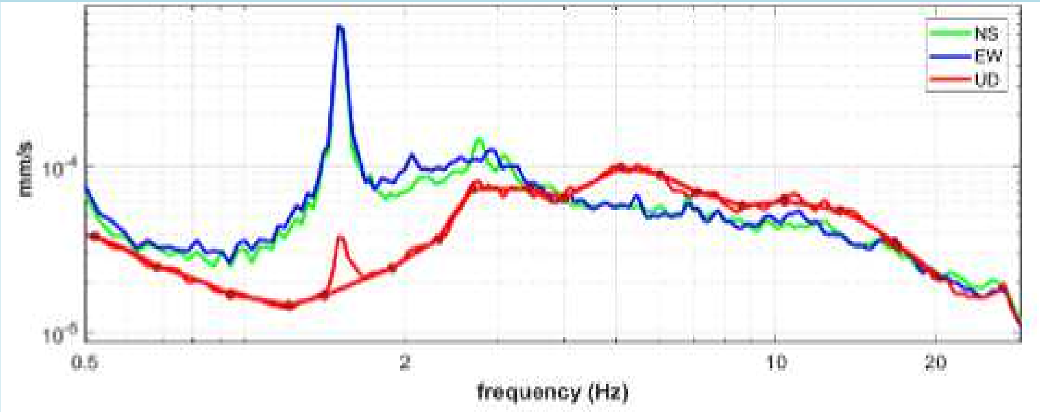


Top: graph of the coherence functions of the three possible combinations as a function of time; **bottom**: amplitude spectra as a function of time (spectrograms). The industrial signal at 1.5 Hz is clear.

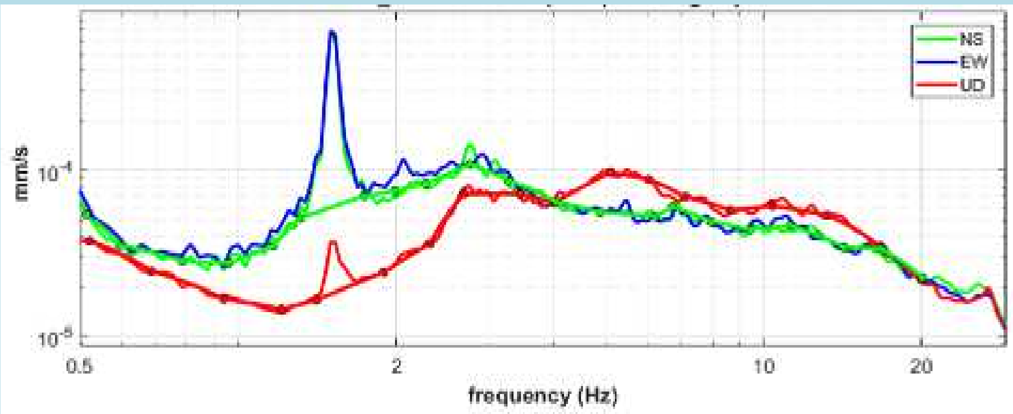


Coherence functions (3D view): colours relate to the frequency of each point. The industrial signal at 1.5 Hz is apparent.

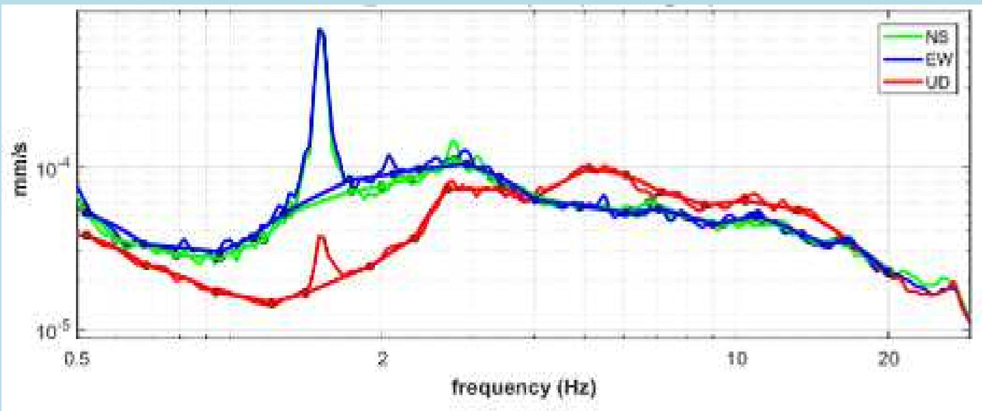
2) picking of UD component



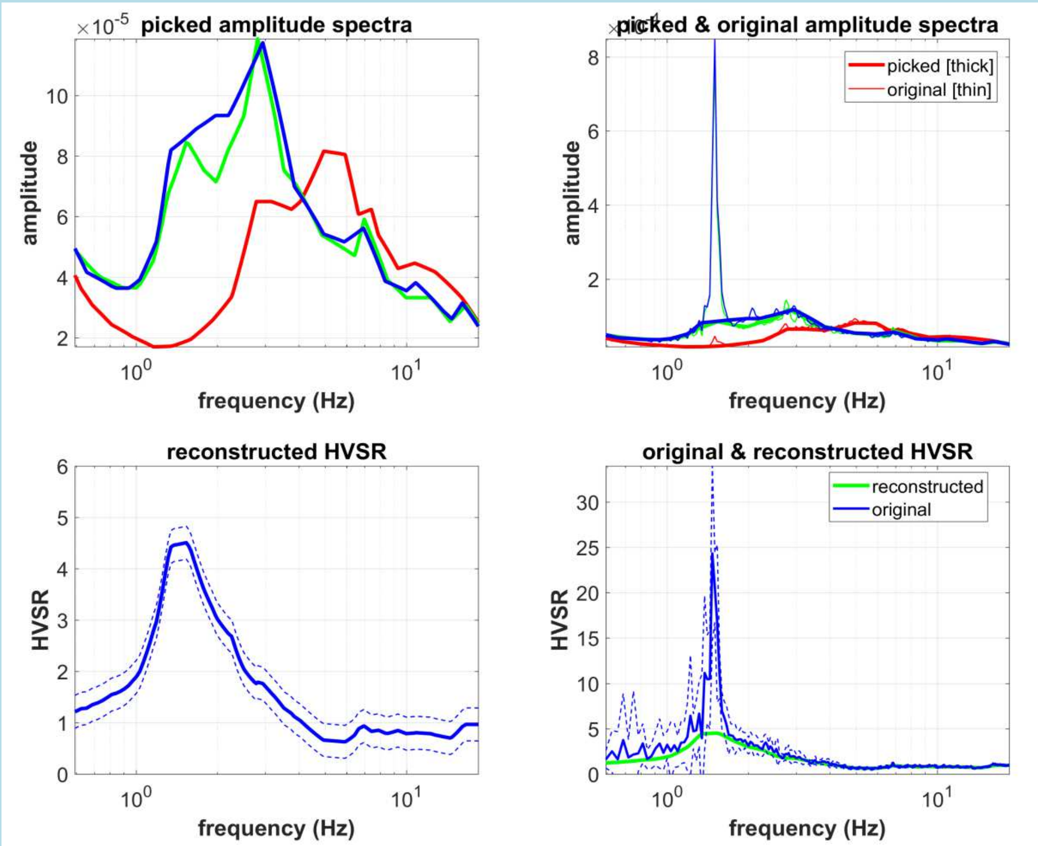
3) picking of NS component



4) picking of EW component



5) calculation of HVSR from the peak amplitude spectra to obtain the following graph and its .hv file



Please note and bear in mind that, for statistical reasons, the average of the HVSR curves is not identical to the HVSR calculated from the average of the amplitude spectra. This means that at low frequencies (more "unstable") the two curves may differ slightly. If all the operations involved in the analyses have been carried out correctly, the two curves fall within the margins of uncertainty (see curves relating to standard deviations). You should also bear in mind that for these picking operations we are working and need to work with very little smoothed data (about 2-3%) and therefore with non-ideal curves.

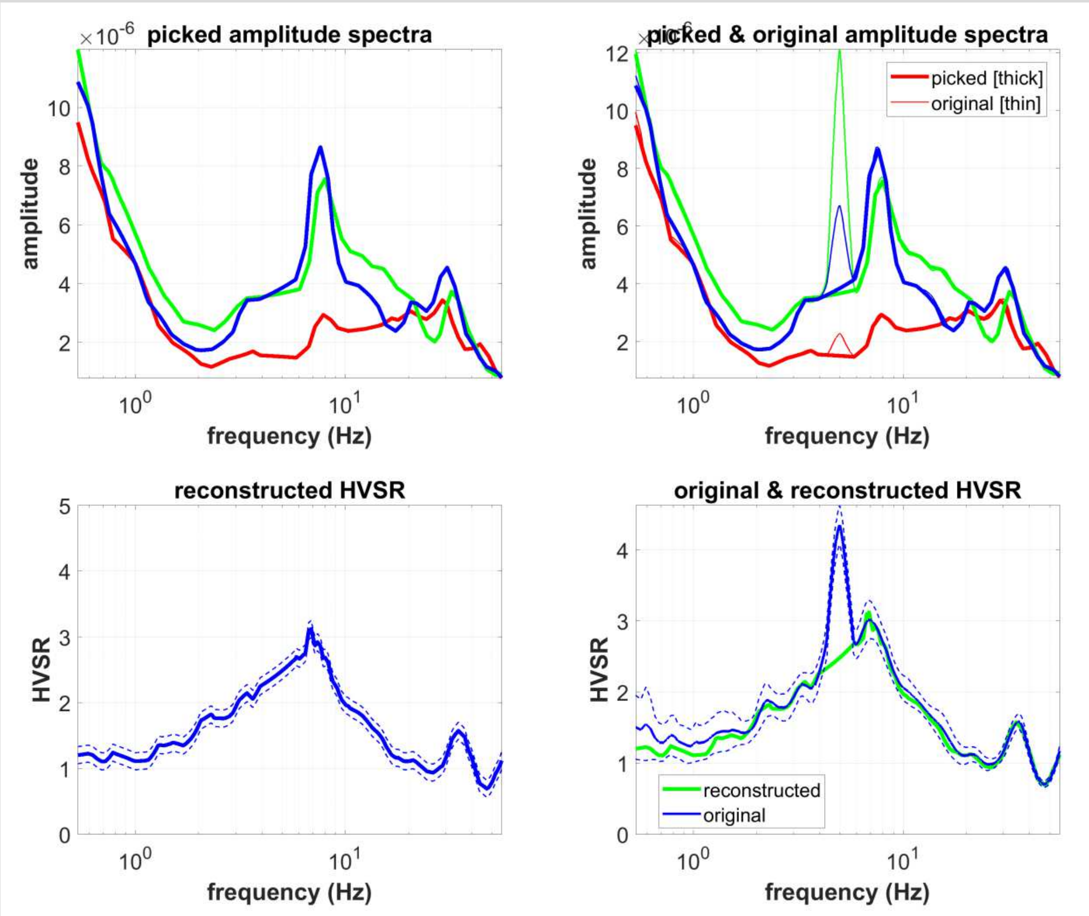
SESAME criteria of the reconstructed HVSR curve

Clearly, with this type of processing/reconstruction, we work with the final mean curves (of the amplitude spectra and of the HV).
Since the first 3 SESAME criteria (for the whole curve) and the criteria 4, 5 and 6 for the evaluation of a "peak" work instead (according to "statistical" criteria) considering **all** the HVSR curves of each window, it is not possible to calculate all the SESAME criteria of the reconstructed curve (since we only have the final mean curves available here).

Only the first 3 criteria for a reliable peak can be "calculated" (at sight).

The first two require that the value of the curve drops to at least half of the value of the peak in the $f_0/4 - 4*f_0$ frequency range (f_0 being the frequency of the peak considered).
The third is even more trivial (the value of the peak must exceed the value of 2).

If we consider the following example (the 5 Hz signal is clearly of an industrial nature), we can see that (also considering the standard deviations) all the first three criteria for a "reliable peak" and relating to the reconstructed curve (green curve in the lower right box) are certainly met [f0 equal to about 7 Hz and frequency range to be considered equal to 1.75-28 Hz].



Automatic removal of industrial signals

In the upper right corner of the HVSR panel there is the "**INDUSTRIAL**" group. By setting the appropriate parameters you can use the "**process industrial signals**" button to automatically remove (or attenuate) possible industrial components that alter the HVSR curve. Always remember that the "right" parameters are data dependent and it is impossible to define universal values.

The procedure basically consists of three steps: a) identification of the industrial signals; b) removal from the data; c) interpolation from the surrounding data.

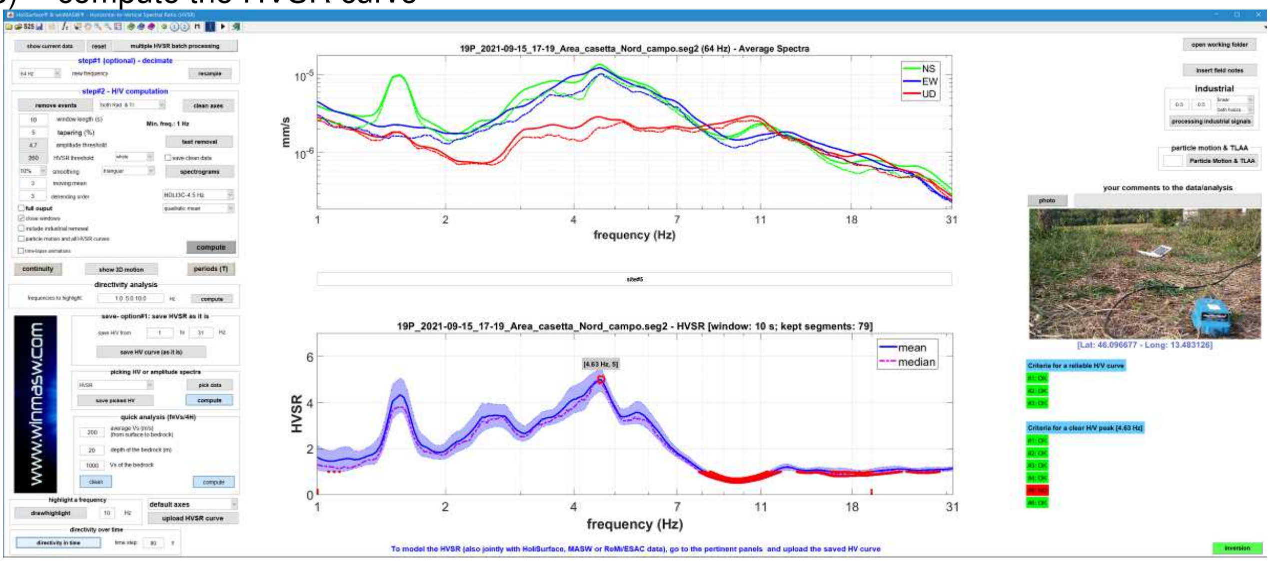
There are four "parameters" to set up:

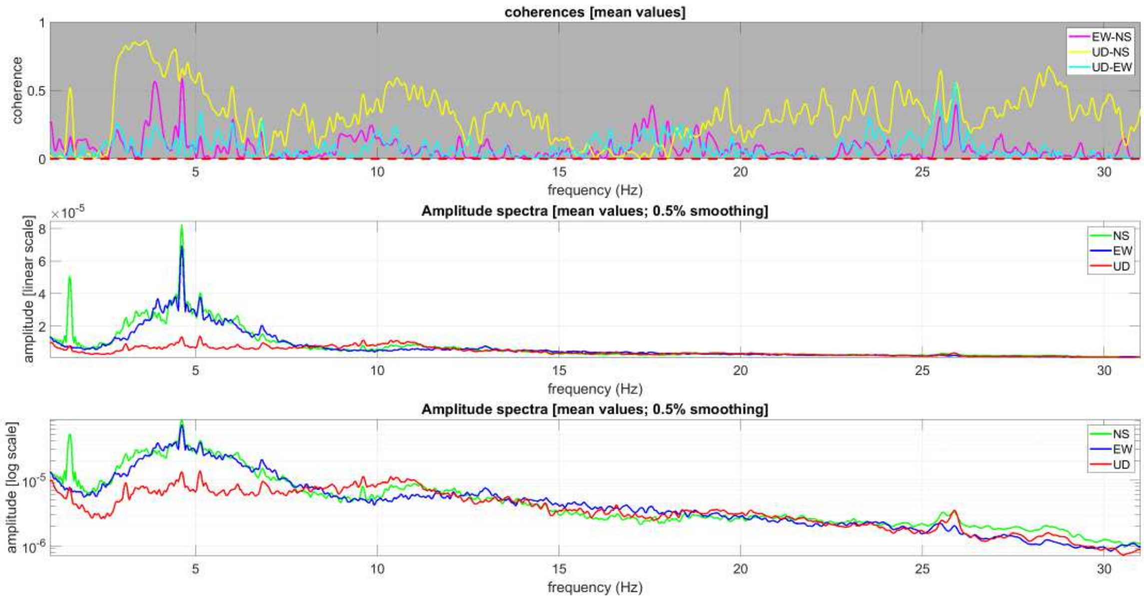
1) the threshold value for the coherence function (values higher than the specified value are considered expression of an artificial/industrial signal);
2) the threshold value for the derivative of the amplitude spectra (values higher than the specified value are considered expression of an artificial/industrial signal);
3) the components (Z, NS and/or EW) to use for the computation of the (average) amplitude-spectra derivatives;
4) the type of interpolation to use to interpolate between the points removed cause attributed to an industrial component.

Here an example that should clarify how it works:

a) upload the microtremor data and the georeferenced photo

b) compute the HVSR curve

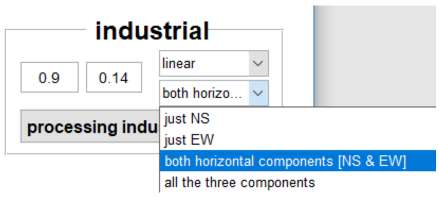




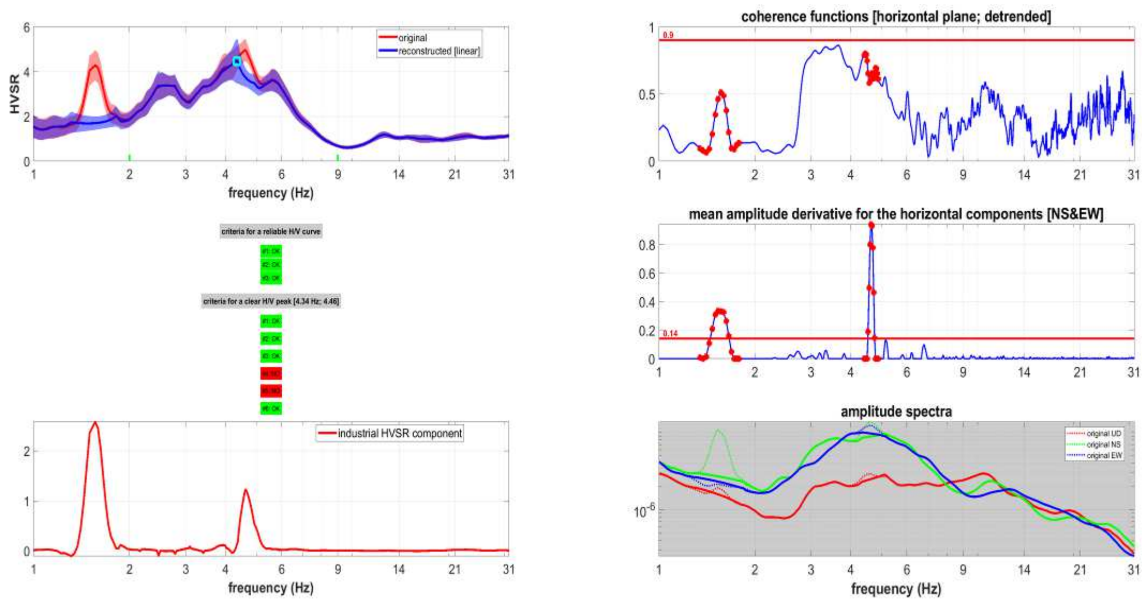
In this case the presence of **two industrial components at about 1.5 and 4.6 Hz** in pretty clear especially in the almost-unsmoothed (5%) amplitude spectra while the coherence functions are, in this case, pretty complex and can just confirm the 1.5 Hz signal (while are otherwise extremely complex – this is actually a pretty unusual dataset).

In order to try to remove the influence of these signals on the HVSR, we:

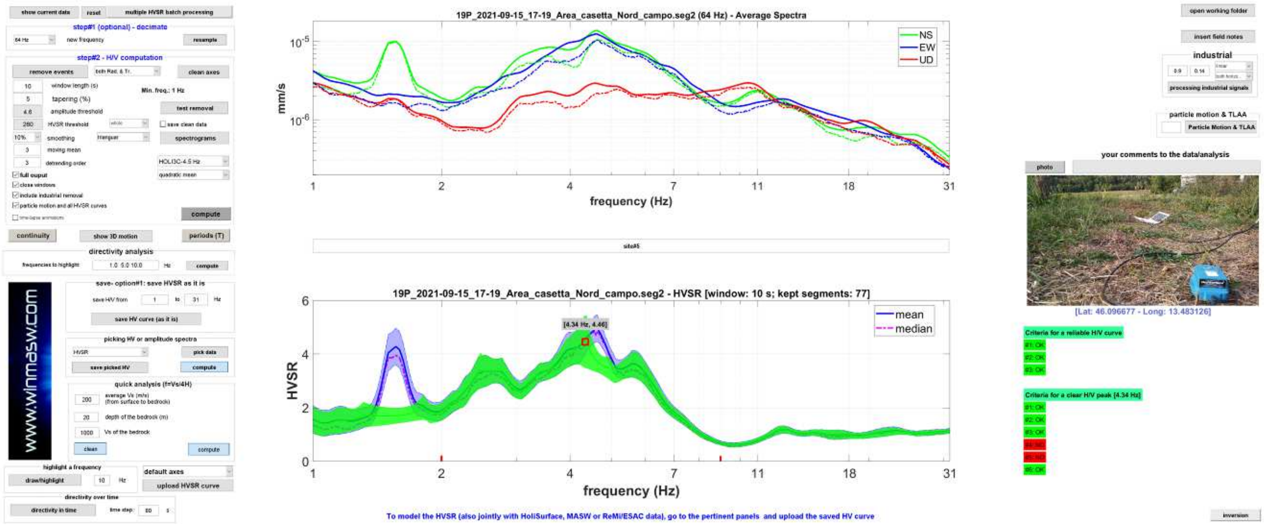
1) set a very high value for the **coherence functions threshold** (since, in this case, we do not want to use the coherence function to identify the industrial components) and a low value for the derivative; since the 4.6 Hz industrial component is clear especially along the NS and EW components – see amplitude spectra reported in the previous figure) we choose to consider the average derivative from **both the horizontal components**



We can now click the "**processing industrial signals**" button and obtain this result:

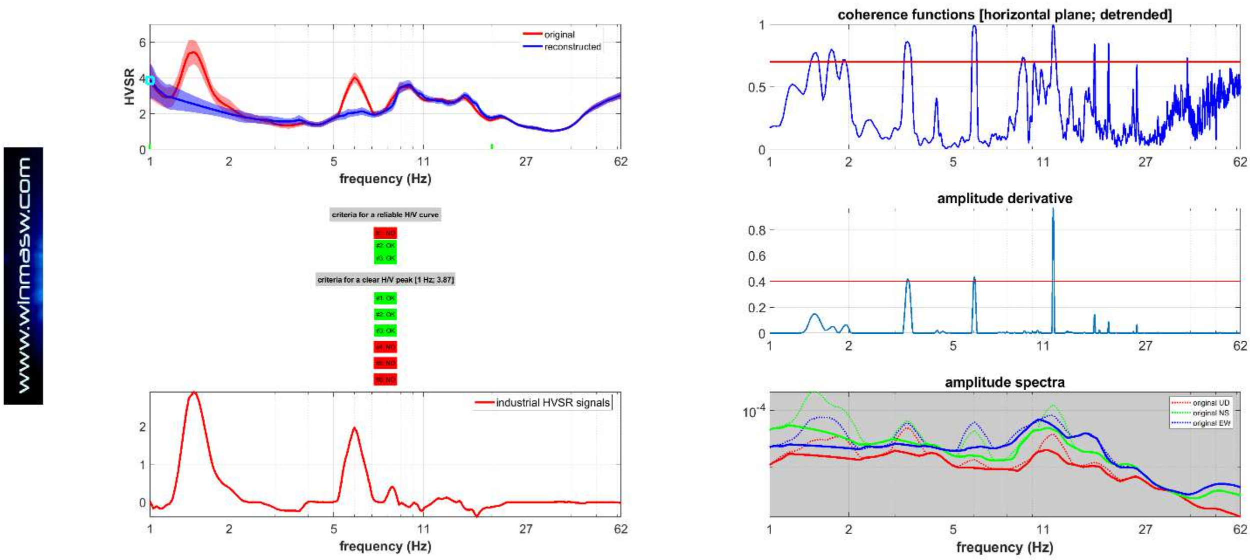


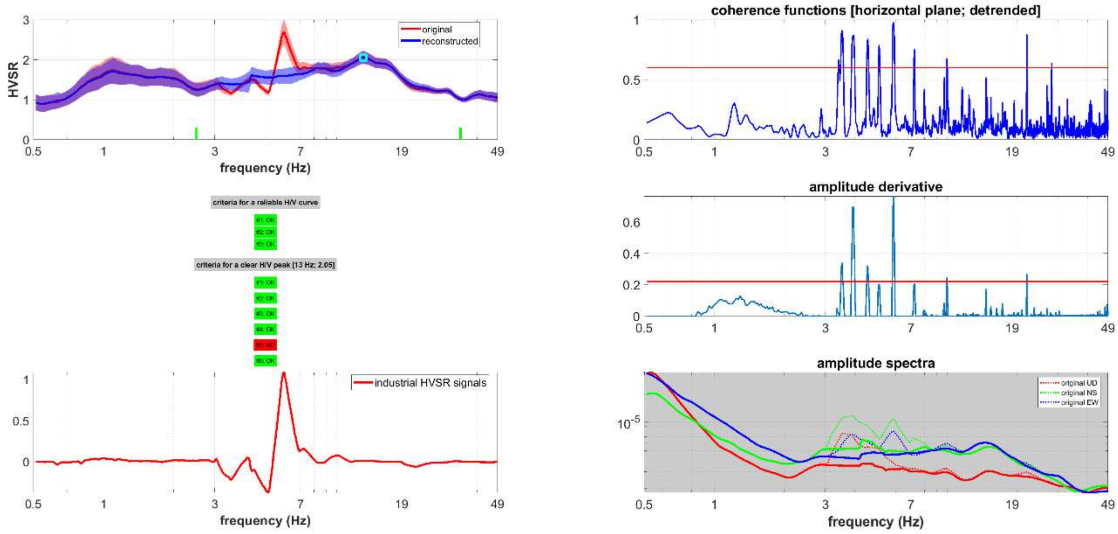
Two quick notes: a) since we decided to fix a very large (0.9) threshold for the coherence functions, the selection of the industrial signals is not based on the coherence functions; b) since we fixed a very small threshold value for the amplitude derivative, the two industrial signals were properly identified by means of them (the amplitude-spectra derivatives – see the "mean amplitude derivative for the horizontal components [NS&EW]" plot).

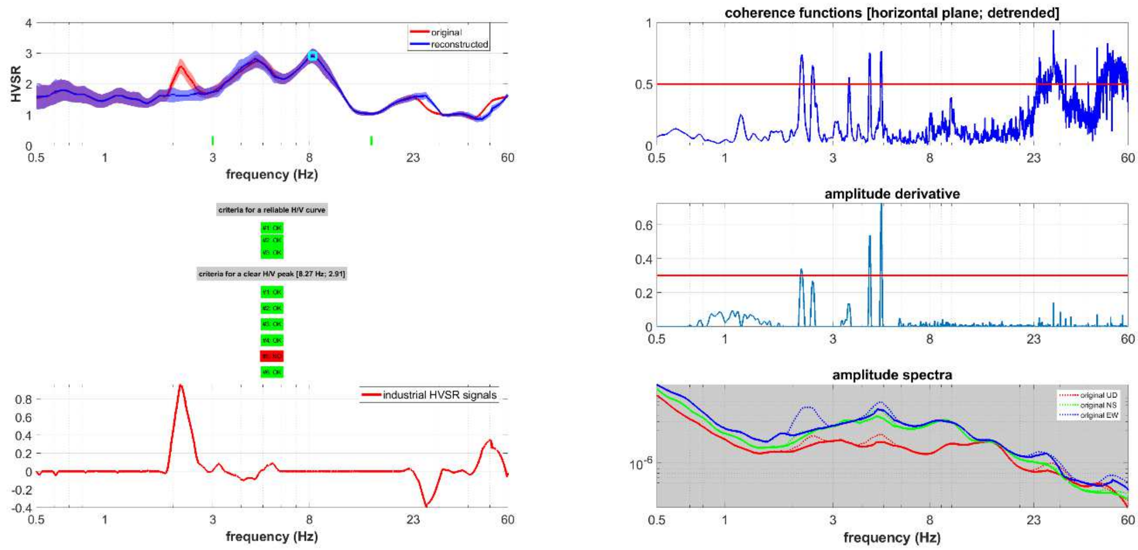


In the HVSR mean maple the green curve represents the "cleaned" HVSR curve free from the industrial components identified through the correct parameters above described. Once again we need to underline that the correct parameters are data dependent and need to be properly set by the user (who need to understand how the procedure works).

In the following, few more examples of the performance of the tool for the automatic removal/attenuation of the industrial signals (in the upper left corner are reported the original HVSR curve [in red] and the "cleaned" one [in blue]). As you can see, the parameters used to remove the industrial signals are different for each dataset.

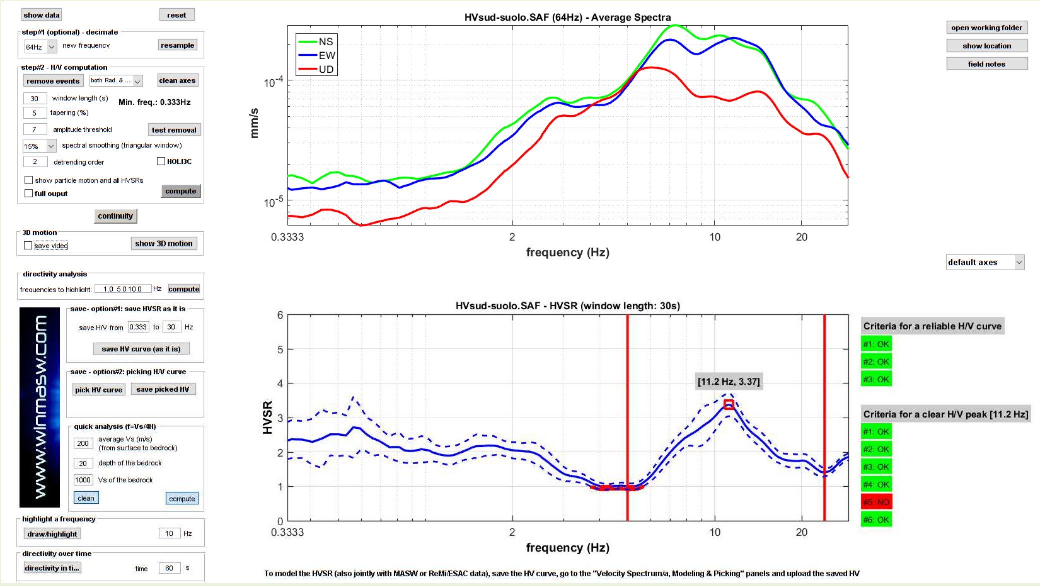



HVSR
original
reconstructed
frequency (Hz)
criteria for a reliable H/V curve
criteria for a clear H/V peak [13 Hz; 2.05]
industrial HVSR signals
frequency (Hz)
coherence functions [horizontal plane; detrended]
amplitude derivative
amplitude spectra
original UD
original NS
original EW
frequency (Hz)

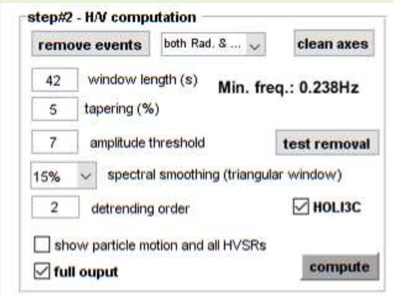

HVSR
original
reconstructed
frequency (Hz)
criteria for a reliable H/V curve
criteria for a clear H/V peak [8.27 Hz; 2.91]
industrial HVSR signals
frequency (Hz)
coherence functions [horizontal plane; detrended]
amplitude derivative
amplitude spectra
original UD
original NS
original EW
frequency (Hz)

"HOLI3C" option (equalization of our 2 and 4.5 Hz geophones)

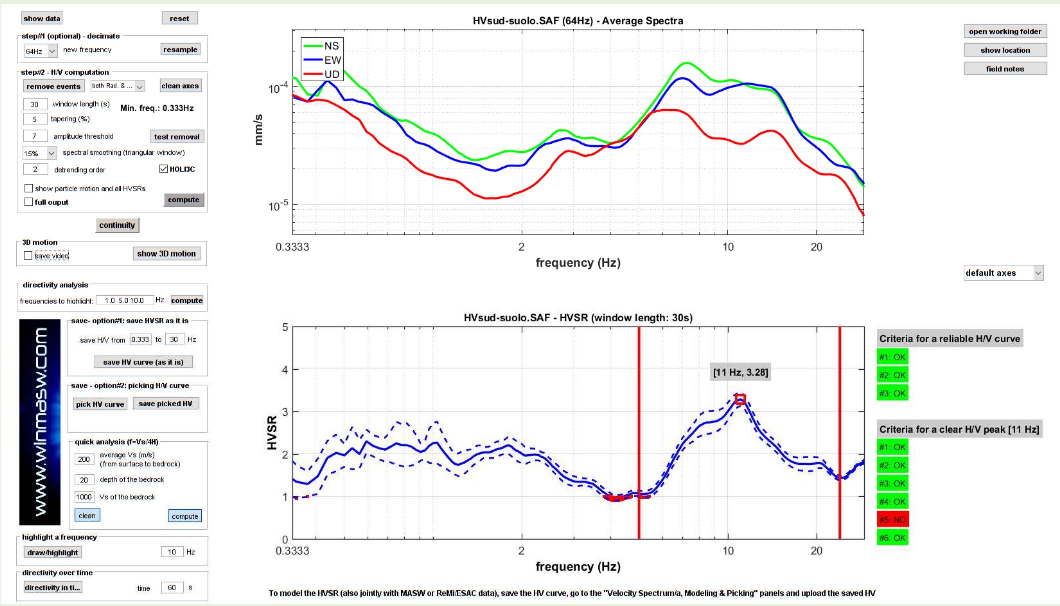
If you have acquired the data using one of our three-component geophones [HOLI3C geophone], activating the HOLI3C option, you obtain the equalization of the traces with recovery (at their real amplitude) of the very low frequencies.



HVSR analysis without trace equalization (HOLI3C option not activated)



Activating the HOLI3C option (from release 2018 you can choose between 2 options depending on the purchased HOLI 3C geophone).

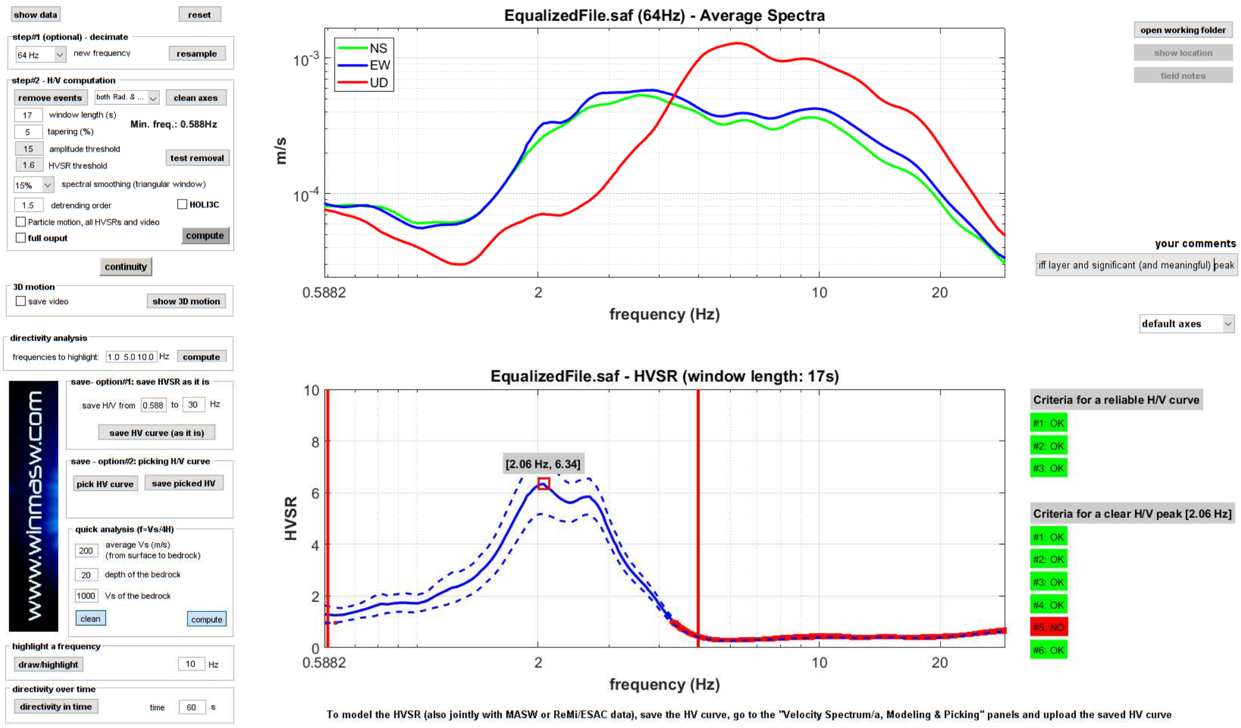


HVSR analysis with trace equalization (equalization option activated): note the recovery of real amplitudes (amplitude spectra)

Enter your comments

It is now also possible to enter comments on the data and analysis (see the grey box "your comments" to the right of the amplitude spectra).

The comments will be automatically reported at the bottom of the final report obtained by calculating the HVSR having activating the "full output" option.

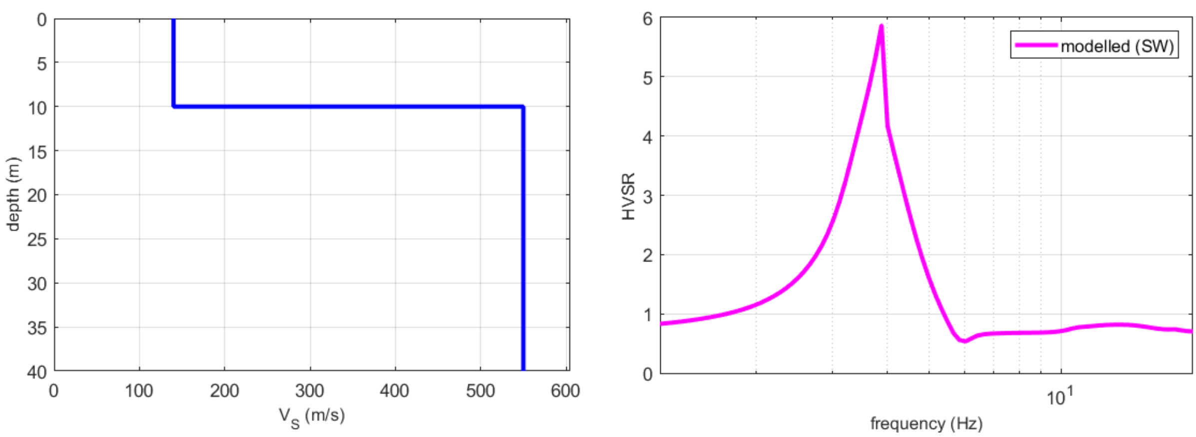


A further note

Both during direct modelling and automatic inversion it is good practice (we would say absolutely recommended) to always insert a very deep and very fast layer that serves to stabilize the mathematics behind the HVSR calculation.
In practice, this means that the actual situation must be reproduced in the most correct way.
If in your area there are, for example, (let's simplify things) 10 meters of clay and then several meters of gravel, to correctly simulate the peak related to this contact it is also necessary to introduce a deep contact between the gravel and what there must be below it even if this deep contact is of no interest to you and is not actually "visible/identifiable" with your data.

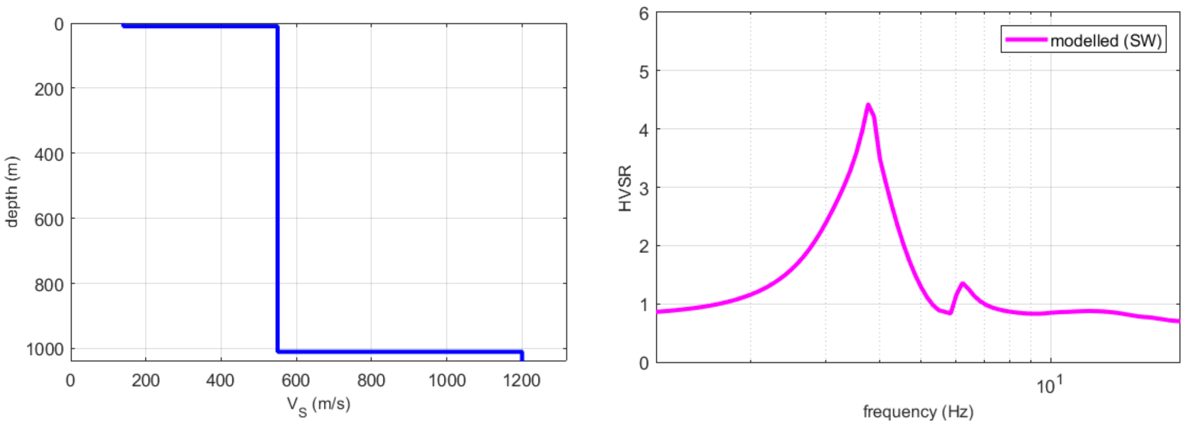
Therefore, a model that for you is:
10 m of silt (V_S: 140 m/s)
gravel half-space (V_S: 550 m/s - for several dozens or hundreds of metres)

should be considered/modelled as:
10 m of silt (V_S: 140 m/s)
1000 m of gravel (V_S: 550 m/s)
rocky half-space (V_S: 1200 m/s)



Adding a fast deep layer (actually "invisible") will produce the following result:

layer	Vs (m/s)	thickness (m)	depth (m)
1	140	10	10
2	550	1000	1010
3	1200	0	0

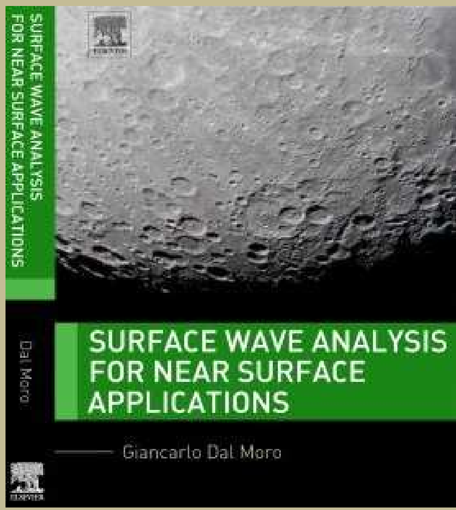


As you can see, now the peak relating to the silt-gravel contact is smaller (it was about 6 and now is about 4.4) and the shape of the HVSR curve is slightly different.

It should be stressed that this is related to the mathematics of the HVSR (in the final report you do not have to include this deep level if there is no evidence of it in the data - evidence should be at very low frequencies).

Also bear in mind the role of the alpha (α) factor (gradually lower values make the HVSR curve lower).

The H/V spectral ratio and the Love waves: the α factor

Extracted from 

The experimental HVSR is basically the result of the joint action of the Rayleigh and Love waves according to the following equation:

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

being H_R and V_R the contribution of Rayleigh waves (in terms of power spectra - see Arai and Tokimatsu, 2004) on the horizontal (H) and vertical (V) component, and H_L the contribution related to Love waves (the parameter α can therefore be considered as the contribution of Love waves to the experimental HVSR).

For a complete modelling of the observed HVSR, the value of the parameter α must be considered appropriately, i.e., the relative quantity of Love waves which, incidentally, is probably a function of the specific weather/seasonal conditions

The modelling presented in Figure A shows the effect of Love waves: the same V_S profile is used to compute the HVSR considering two different (extreme, α = 0.2 and α = 0.9) values of the parameter α.

Two consequences are straightforward:

1. The relative amount of Love waves (expressed by the α – *alpha* - factor) should be considered as one of the variables in the inversion/modelling of the HVSR curve (experience teaches that this value usually takes a value between 0.3 and 0.5).

2. The HVSR curve alone is absolutely insufficient to limit the definition of a V_S profile even when stratigraphic/geological information is available and the only solution is provided by joint analysis with other geophysical data (such as surface wave dispersion).

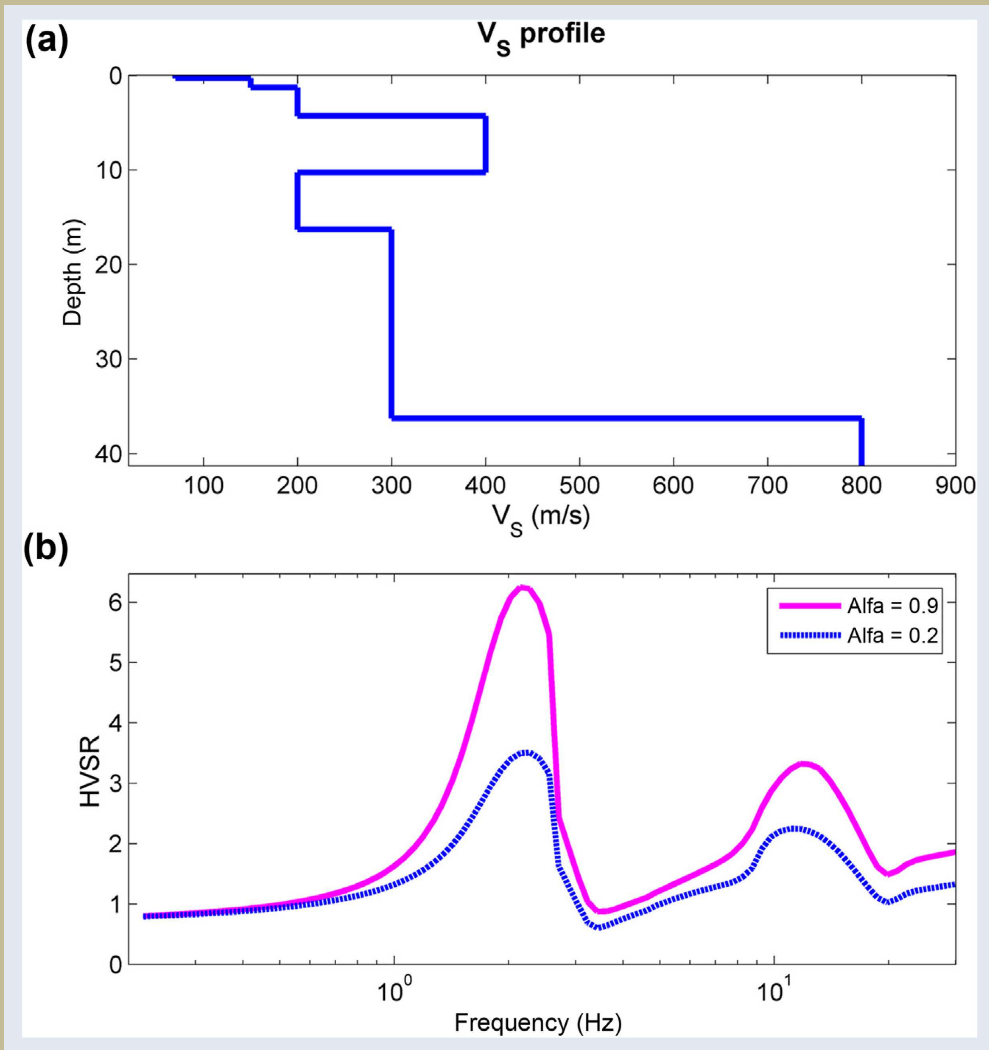


Figure A Effect of Love waves on the HVSR curve: (a) V_S profile considered; (b) HVSR curves obtained considering a different "quantity" of Love waves (α factor).

More details in ***Surface Wave Analysis for Near Surface Applications*** (Dal Moro G., 2014 - Elsevier, 252pp).

The *winMASW®* software allows modelling the HVSR both according to body (e.g. Herak, 2008) and surface waves.

About this last possibility**, *winMASW®* 3C, *winMASW®* Pro** and ***winHVSR*** works as a graphical interface for the executable by Albarello & Lunedei (2009).

If you are working with *winMASW® Academy* or *HoliSurface®*, you do not need such a .exe file since the HVSR modelling is performed thanks to a very complete tool also capable of handling a user-specified amount of Love waves (see α factor box).

If you activate the HVSR modelling and set a number of modes higher than zero you will get the modelled HVSR both according to body waves and surface waves (in case the number of modes is set to zero you will get HVSR only according to body waves).
.

In order to approach this method please read (at least) the following papers:

Dal Moro G., 2011. *Some Aspect about Surface Wave and HVSR Analyses: a Short Overview and a Case Study*, BGTA, 52, 241-259 (visit www.winmasw.com for a draft of it)

Albarello D. and Lunedei E., 2010. *Alternative interpretations of horizontal to vertical spectral ratios of ambient vibrations: new insights from theoretical modelling*. Bulletin of Earthquake Engineering 8, 519–534.

Dal Moro G., 2010. *Insights on Surface Wave Dispersion and HVSR: Joint Analysis via Pareto Optimality*, *J. Appl. Geophysics*, 72, 29-140

Lunedei E. and Albarello D., 2009, On the seismic noise wavefield in a weakly dissipative layered Earth, *Geophys. J. Int.*, 177, 1001-1014

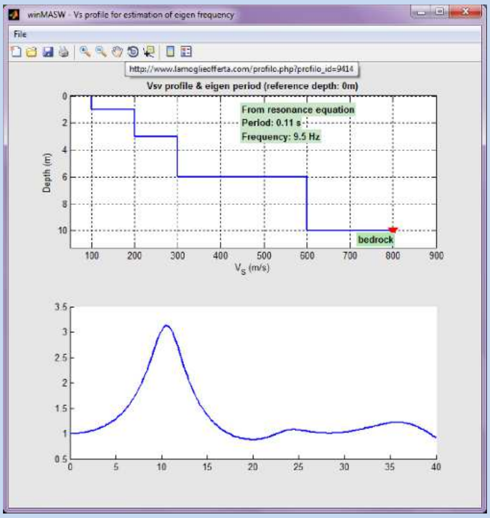
By studying the mentioned papers it will be possible to understand under which conditions the different approaches must be considered valid. In a nutshell: usually body waves properly explain HVSR only for the fundamental frequency while higher frequencies are better explained in terms of SW ellipticity (the problem is sometimes to understand the appropriate number of modes to adopt – also always considering the attenuation).

About the *winHVSR*, *winMASW® 3C* and *Professional* versions

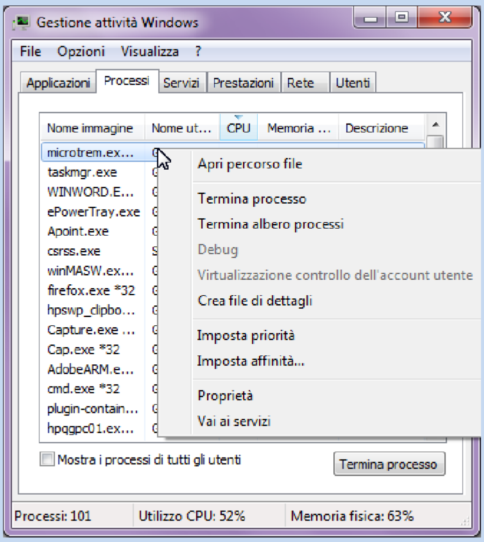
In case you decide to use the Lunedei & Albarello (2009) code (*microtremor.exe*) it is necessary to quote the Authors (you would otherwise break the related copyright law): Albarello D. & Lunedei E. (Lunedei E., Albarello D., 2009, On the seismic noise wavefield in a weakly dissipative layered Earth, *Geophys. J. Int.*, 177, 1001-1014).

Problems in HVSR computation using *Surface Wave ellipticity* (*microtremor.exe*) [only for the 3C and Pro versions - in the *Academy* version and in *HoliSurface®* the HVSR computation is independent and more detailed (see the *α factor* box in the next pages)]

Under some circumstances it is possible that *microtremor.exe* so-to-say "stalls".
If, after few seconds the HVSR window does not react (see image down here)



It is then necessary to interrupt the process "mictrotremor.exe" in the Activity Manager of the *windows* operating system (*Ctrl+Alt+Canc* buttons)

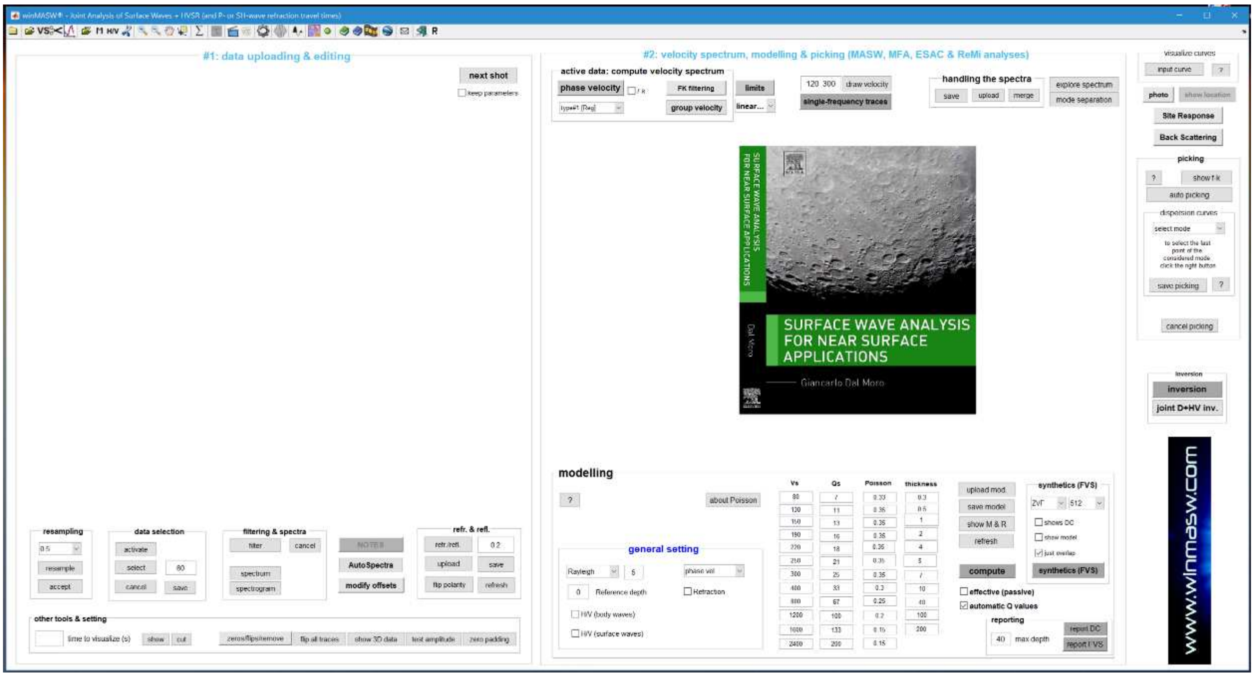


Select the microtremor.exe button and terminate the process.

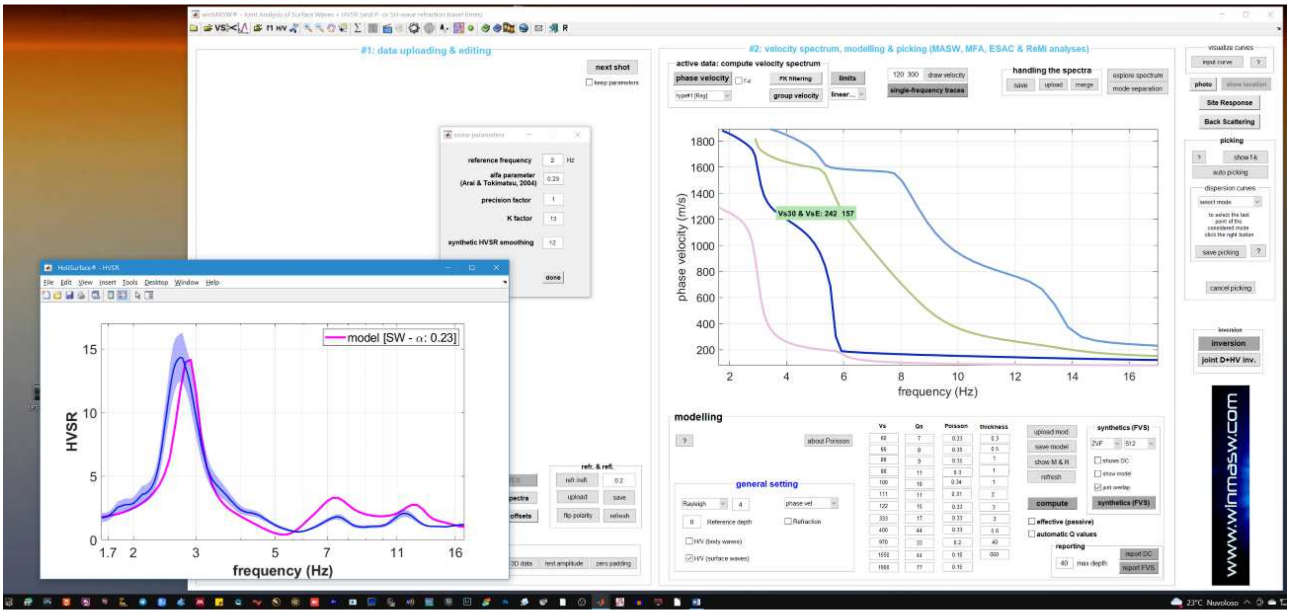
To go head it is now necessary to modify the model (as the previous one was responsible for some problematic event in the HVSR computation).

Modelling the HVSR (alone) in *winMASW®*

If you wish to model (i.e. invert) just the HVSR curve, you can do it from the single-component analysis panel ("Velocity Spectrum, Modelling & Picking"). You simply need to upload the HVSR curve with the button on the toolbar (HV icon with the yellow folder in the background) and proceed with modelling (change V_S and layer thicknesses).



Beware that the HVSR significantly suffers from the non-uniqueness of the solution (different models have the same HVSR curve), which is why it is always preferable to model it jointly with dispersion data.
The screenshot below shows a modelling in progress. Consider and remember that, from the window that shows up once you click the "R" button in the toolbar, it is possible to change certain parameters related to HVSR modelling and in particular the α factor (amount of Love waves in the modelled microtremor field) and the smoothing (expressed as a percentage) of the synthetic HVSR curve.



HVSR and site resonance frequency: almost an hoax

The topic is actually extremely complex and this manual is not meant to be a text book.

Here we just recall the fundamental equation regarding the HVSR peak (that surely cannot be used in a simplistic way):

$$T_o = \frac{4H}{V_S}$$

where:
V_S = mean V_S down to the horizon responsible for a HVSR peak
H = thickness of the sediments over the considered horizon/contact

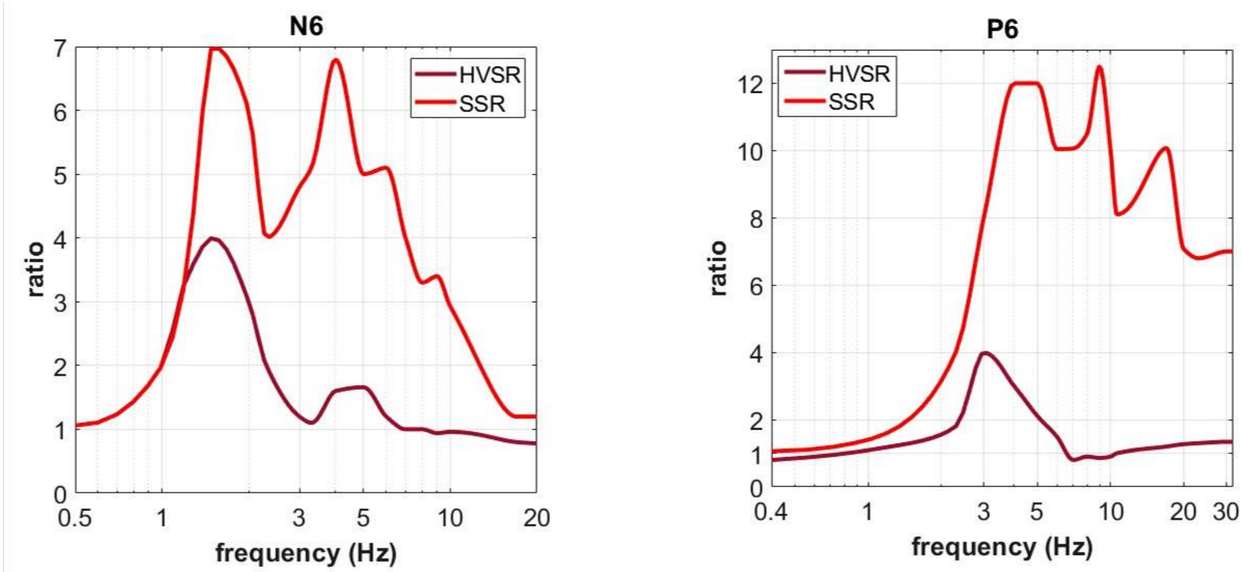
For instance, in case there is a strong V_S increment at a depth of 37 m (e.g. 37 meters of unconsolidated sandy materials [average V_S value equal to 250 m/s] over a thick gravel layer), we should obtain a HVSR peak at about 1.7 Hz.

Remember that an HVSR peak does not necessarily means *bedrock* (see e.g. Dal Moro 2018 - ***Effective Active and Passive Seismics for the Characterization of Urban and Remote Areas: Four Channels for Seven Objective Functions***).

But, does the peak in the HVSR represents the resonance frequency?

No. See for instance Perron et al (2018) and the few evidences summarized also in our 2020 Springer book mentioned throughout this manual.

The HVSR has been in use in seismology since about the late 1960^s (e.g. Mark and Sutton, 1975). In the 1980^s, in Japan, some studies were carried out in order to evaluate its possible use in the seismic-hazard assessment (see Nakamura's papers in the References). As a matte of fact, the relationship between the amplification during a quake and the HVSR curve has never been clearly demonstrated and theoretical considerations and experimental data do not support this idea which is unfortunately very popular.
Several studies (e.g. Perron et al., 2018 and references therein) have shown that the amplification actually recorded during an earthquake significantly deviates from the HVSR curve; see for instance the data in the following Figure.

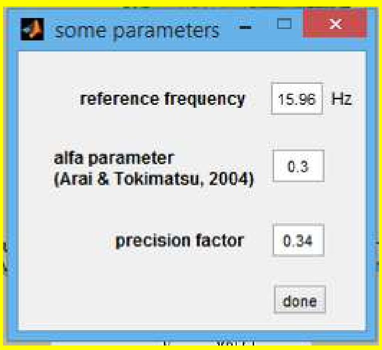


Comparison between the HVSR curve and the actual amplification curve obtained from SSR (Standard Spectral Ratio) analysis from a series of accrual earthquakes (after Perron et al., 2018). Note the significant difference between the HVSR curve and actual measured amplification.

Therefore, the HVSR represents a valid observable to estimate the V_S of the deeper layers (e.g. Arai & Tokimastu, 2005; Dal Moro, 2015; 2020), but it should not be considered as an estimate of site amplification.

The α factor in *winMASW® Academy* and *HoliSurface®*

In *winMASW Academy* (in the single and double-component "**Velocity Spectrum, Modeling & Picking**" panels), the α factor (i.e. the amount of Love waves to be used in the HVSR modeling) can be modified by clicking the "R" button in the upper right area of the *toolbar:*



Here it is also possible to set the reference frequency and the precision of the mathematical solution sought for computing the dispersion curves as well as the synthetics and the HVSR (details are provided during our technical workshops).

Automatic inversion of the HVSR curve alone

*Available in **HoliSurface®** – a software application designed in order to exploit all the active and passive data recorded by a couple of 3-component geophone (etc.).*

In winMASW® Academy you can anyway model it. Just upload a HVSR curve in the single-component panel and modify the subsurface model (*forward modelling*) so to obtain a good match between the observed curve and the one of your model.

13. Joint inversion of dispersion data and HVSR

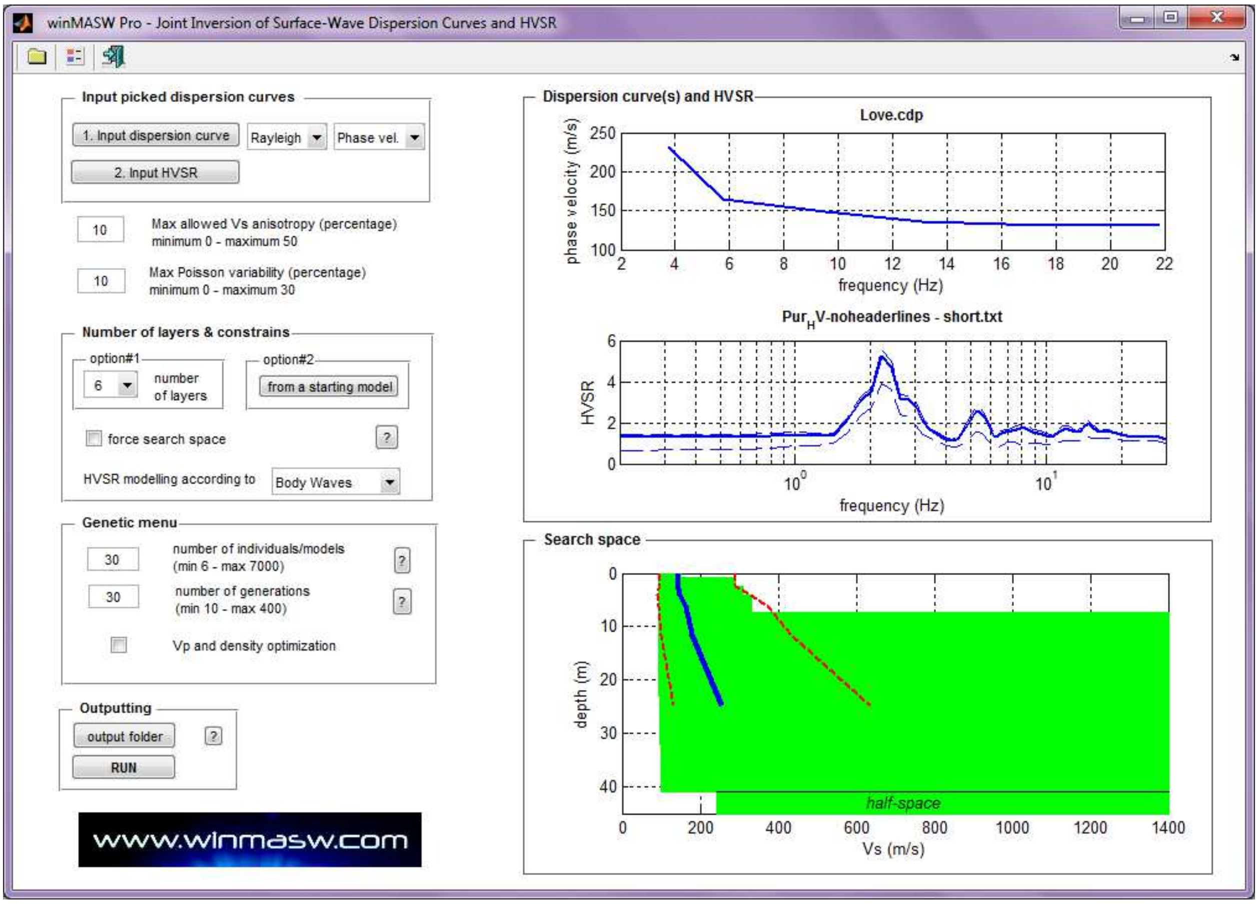
For details about the HVSR, please read the chapter about the HVSR modelling ("*Modelling HVSR*"). Due to several possible issues, in order to properly perform the automatic joint inversion it is highly recommended to read (and fully understand) the following papers:

Dal Moro G., 2011. *Some Aspect about Surface Wave and HVSR Analyses: a Short Overview and a Case Study*, BGTA, 52, 241-259 (visit **www.winMASW.com** for a draft of it)

Albarello D. and Lunedei E., 2010. *Alternative interpretations of horizontal to vertical spectral ratios of ambient vibrations: new insights from theoretical modelling*. Bulletin of Earthquake Engineering 8, 519–534.

Dal Moro G., 2010. *Insights on Surface Wave Dispersion and HVSR: Joint Analysis via Pareto Optimality*, *J. Appl. Geophysics*, 72, 29-140

The panel (see figure down here) is completely similar to that related to the joint analysis of Rayleigh and Love dispersion, thus it does not need any special description.



Some points must be kept in mind very carefully (especially about HVSR):

1. If you are using body waves you should consider fundamental period (resonance) only (thus remove from the HVSR curve all the data referred to higher frequencies – in the above-reported example we should remove the frequencies higher than about 4 Hz
2. If you are using surface waves (ellipticity) you must considering 2 main points:
a. large computational times
b. possible computational problems which can stop the inversion procedure (see box "Problems in HVSR computation using Surface Wave ellipticity (*microtremor.exe*)")

To get deeper into the topic you can read the two following paper:

*Alternative interpretations of horizontal to vertical spectral ratios of ambient vibrations: new insights from theoretical modelling (*Albarello D. and Lunedei E., 2010*)*. Bulletin of Earthquake Engineering 8, 519–534.

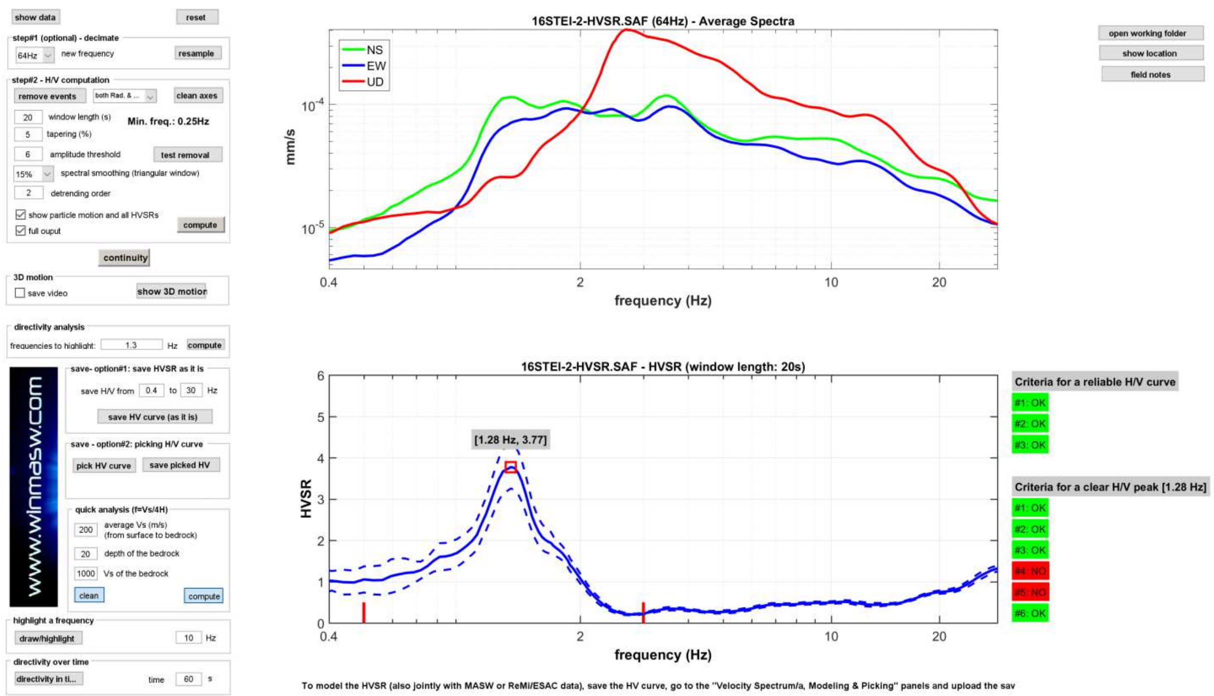
*Insights on Surface Wave Dispersion and HVSR: Joint Analysis via Pareto Optimality (*Dal Moro G., 2010*)*, *J. Appl. Geophysics*, 72, 29-140

For these and other reasons that we recall during our workshops, it is always preferable to adopt the *forward modelling* approach from the "Velocity Spectrum, Modelling & Picking" panel rather than the automatic inversion.

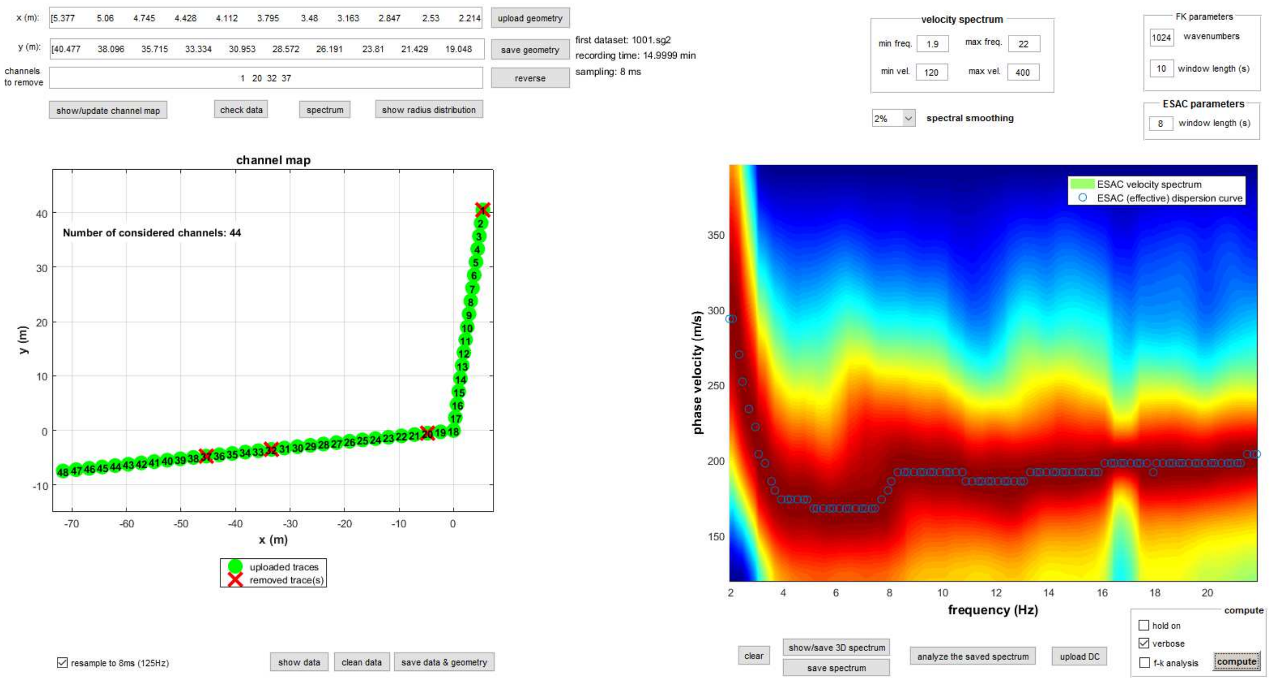
In the following figures an example of joint analysis of the HVSR curve together with the effective dispersion curve obtained from ESAC analysis

See also:
http://www.winmasw.com/download/prodotti/Report-ESAC-HVSR-winMASW.pdf

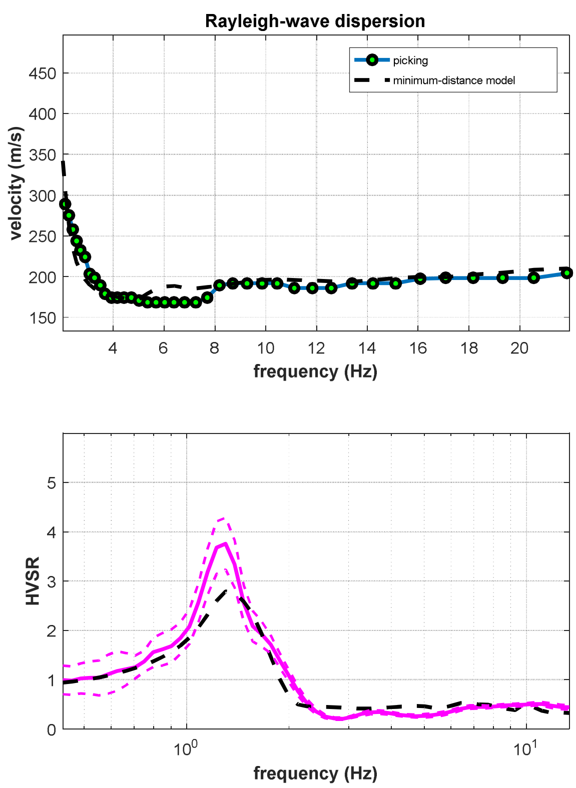
HVSR data

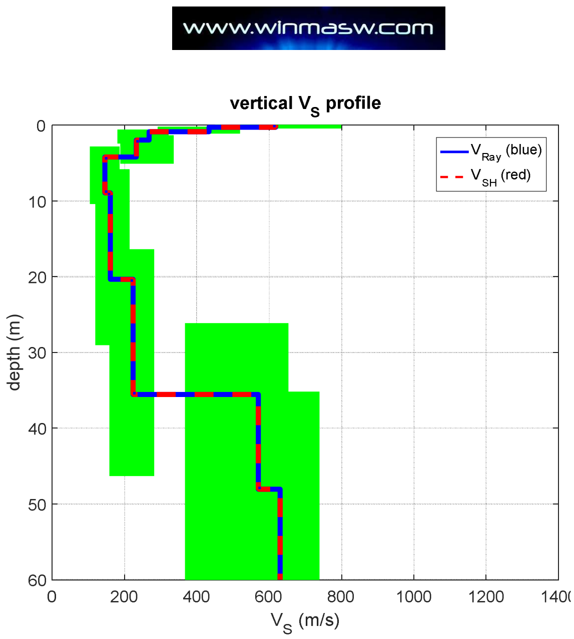


ESAC data



Joint inversion ESAC+HVSR





Rayleigh wave dispersion file: ESACdcORIGINAL.cdp
H/V curve: 16STEI-2-HVSR.hv
Vs30 (minimum-distance model): 183 m/s
Vs30 (mean model): 185 m/s

14. RPM analysis (jointly with dispersion data)

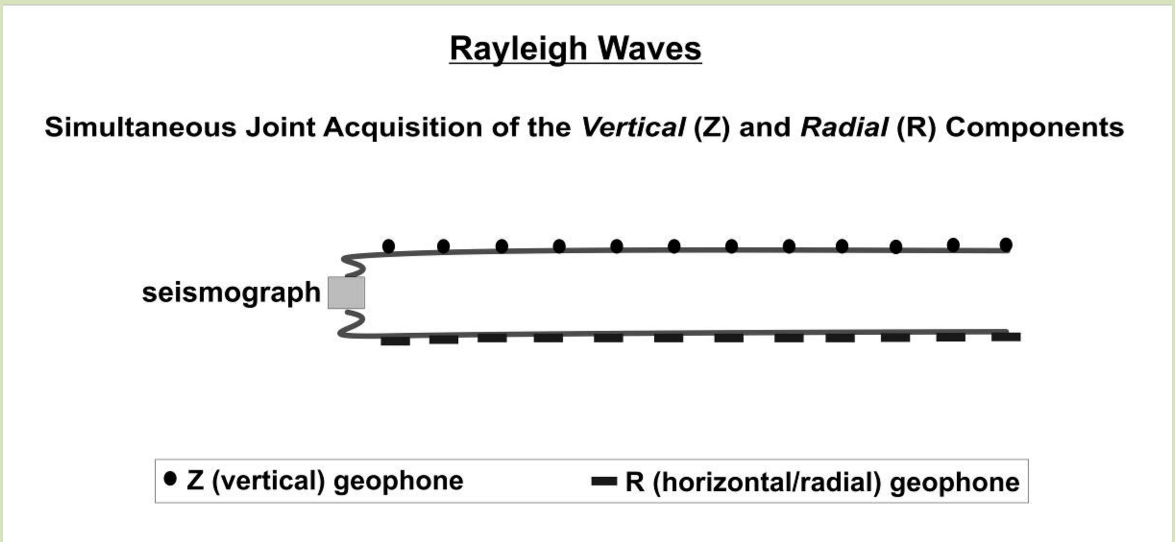
RPM analysis

The RPM (*Rayleigh-wave Particle Motion*) frequency curves were introduced in the "*Analysis of Rayleigh-Wave Particle Motion from Active Seismics*" paper (BSSA, Dal Moro et al., 2017).
The *RPM frequency-offset surface* is the so-to-speak extension of the RPM frequency curve in case we are dealing with multi-offset data.
The *RPM frequency-offset surface* is a further "object" that can be analyzed in order to infer further information about the subsurface conditions and the seismic hazard (see also the role of strong motion rotations in the response of structures near earthquake faults - Trifunac 2009, *Soil Dynam. Earthquake Eng.*, 29 382-393).

In the "joint analysis of Surface Waves" panel, you must upload the datasets of the Z (vertical) and R (radial) components of Rayleigh waves (so the ZVF+RVF or ZEX+REX files).

Data acquisition for the analysis of the RPM (frequency-offset) surface

The RPM analysis necessarily requires the acquisition of both the vertical and radial components of Rayleigh waves.
This can be accomplished by adopting an acquisition setting like the one shown the figure (two seismic cables: one with *n* vertical geophones and a second cable with n horizontal geophones, set radially with respect to the source).

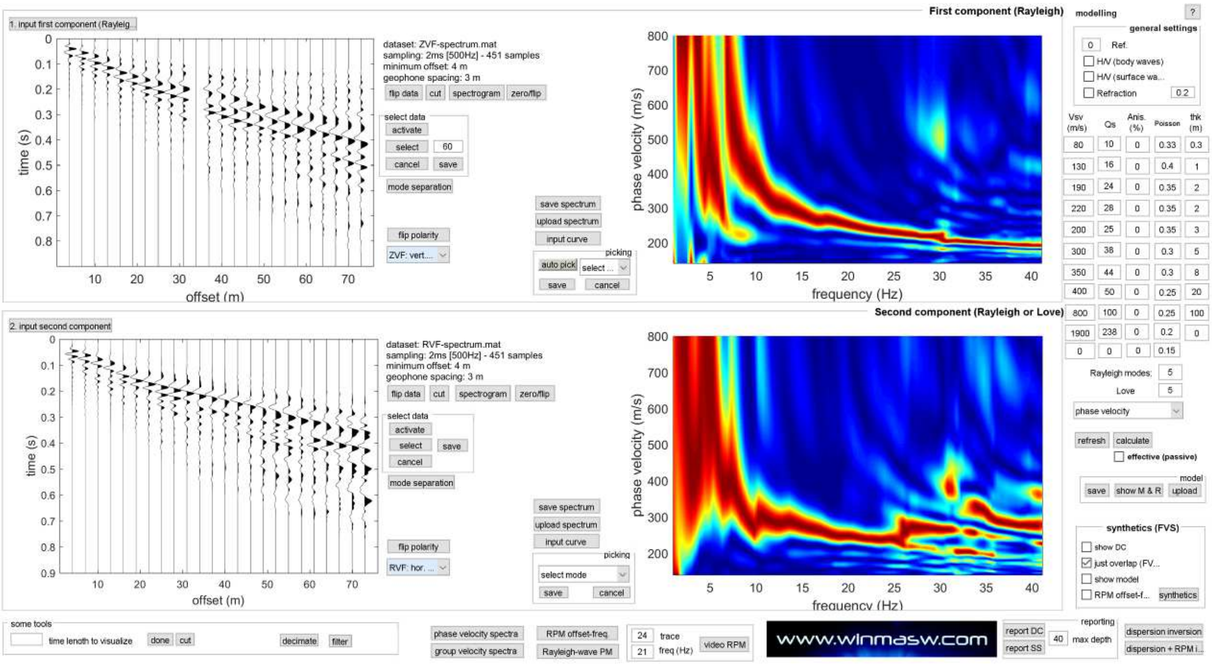


This way you will simultaneously acquire both the components.
But you can also decide to acquire the data in two steps (this is for instance necessary in case you have only 12 channels): first you use the vertical geophones and acquire the Z component, and then you change the geophones and acquire the radial (R) component. In other words the acquisition of the two components does not have to be simultaneous.

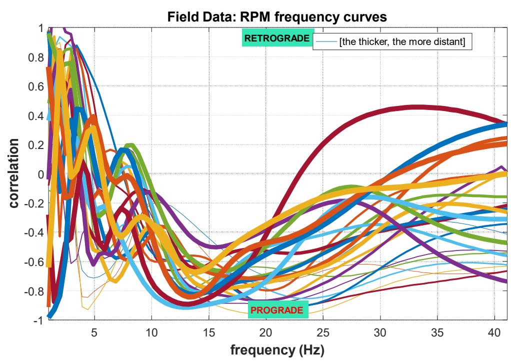
Once you have uploaded and possibly cleaned a bit the data, with the "*RPM offset-freq*" button you will compute the *RPM frequency-offset surface* of the uploaded data.

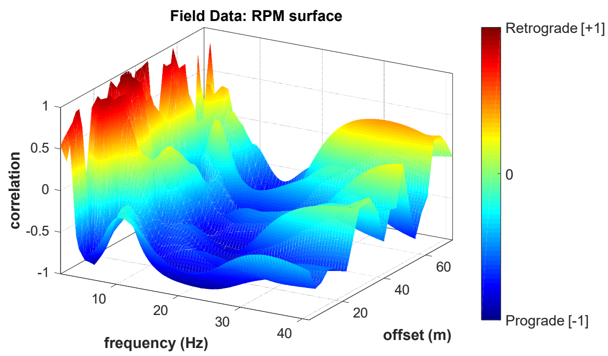
Please notice that the novelty of this technique(s) definitely requires some training (that we provide during our workshops).

Here an example [the *dataset* is clearly about the Z (vertical) and R (radial) components]:



We here must assume that the polarity of your data is the correct one (see the "*Polarity of the geophones*" box later on).
By clicking the "RPM offset-freq" button (in the lower/central part of the panel), you will obtain the RPM frequency curves for each offset and the *RPM offset-freq surface*:

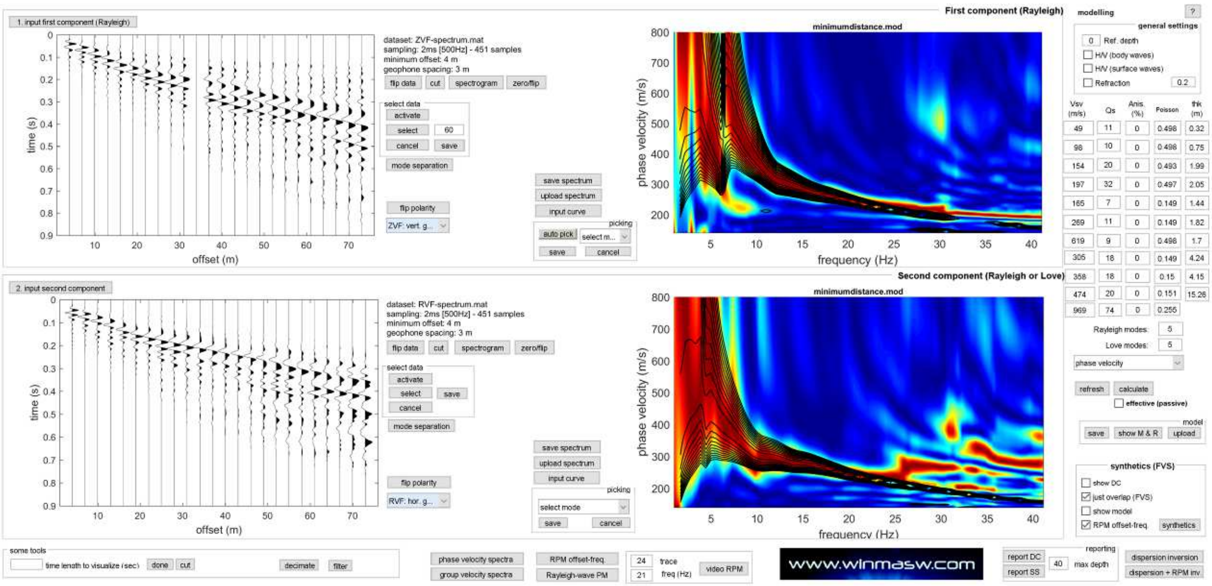


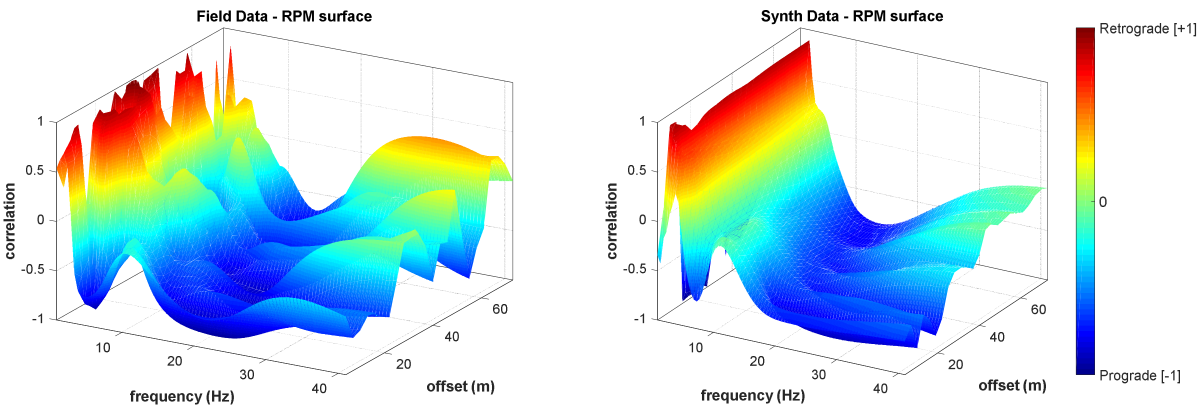


Such a "surface" can be analyzed together with dispersion data of the two (Z and R) considered components.

In the "forward modelling" approach (i.e. by manually modifying the model parameters (in the right part of the panel), you can compute the synthetic spectra of the Z and R components and, having computed the RPM surface of the field data (such a operation

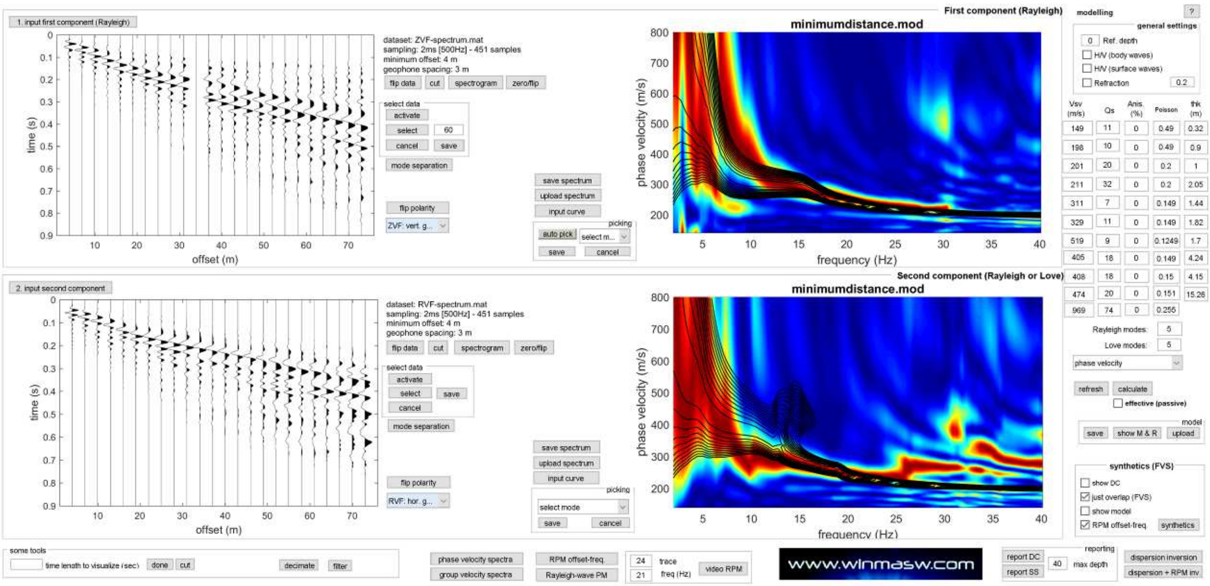
will automatically activate the "RPM" option in the "synthetics (FVS)" group [lower/right part of the panel]), the synthetic RPM as well.
This way you can "visually" verify the overall consistency of your tentative model.
If you find a model which is "good but not great", you can save it ("save model") and use it as starting model to optimize in the "*Joint inversion of Rayleigh waves (disp + RPM)*" panel (see next paragraph).
After playing a bit with the model, if you end up with an overall consistency such as the one shown in the next two figure, it means that your model is good enough (i.e., your model generate synthetic data which are very close to the observed one).

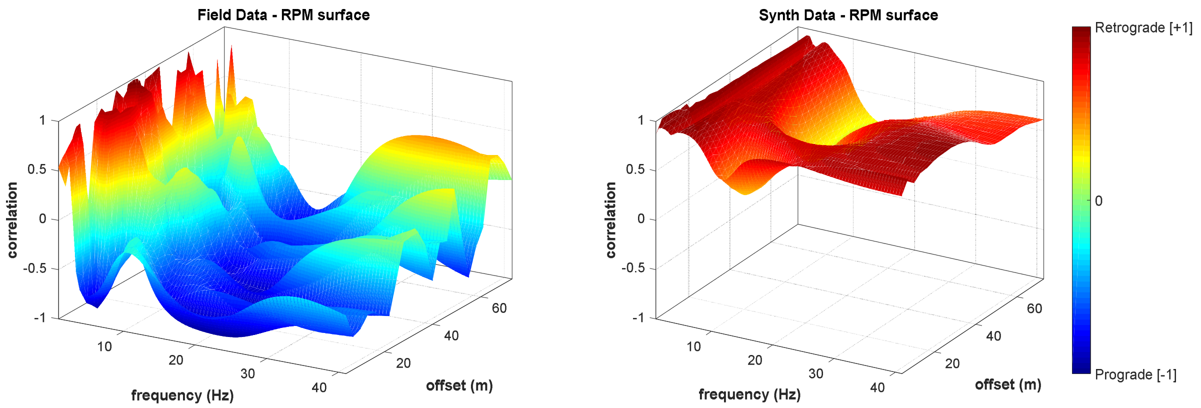




In fact, you can clearly see the overall congruency of the field and synthetic data (incidentally, in this case, you can clearly see that, for frequencies higher than about 5Hz, this site determines a strongly prograde motion of the Rayleigh waves).

On the other side, it is equally clear that the bad consistency obtained in the following case (see next two figures) is the evidence that the subsurface model is not the "right" one (the difference between the field and synthetic data is definitely too large).





Important: the polarity of the geophones

In order to properly process the data (thus get the right RPM surface) it is clearly crucial to know the polarity of your vertical and horizontal geophones and properly orientate the horizontal ones (about the polarity we fundamentally adopted the same convention used by Prof. Herrmann).

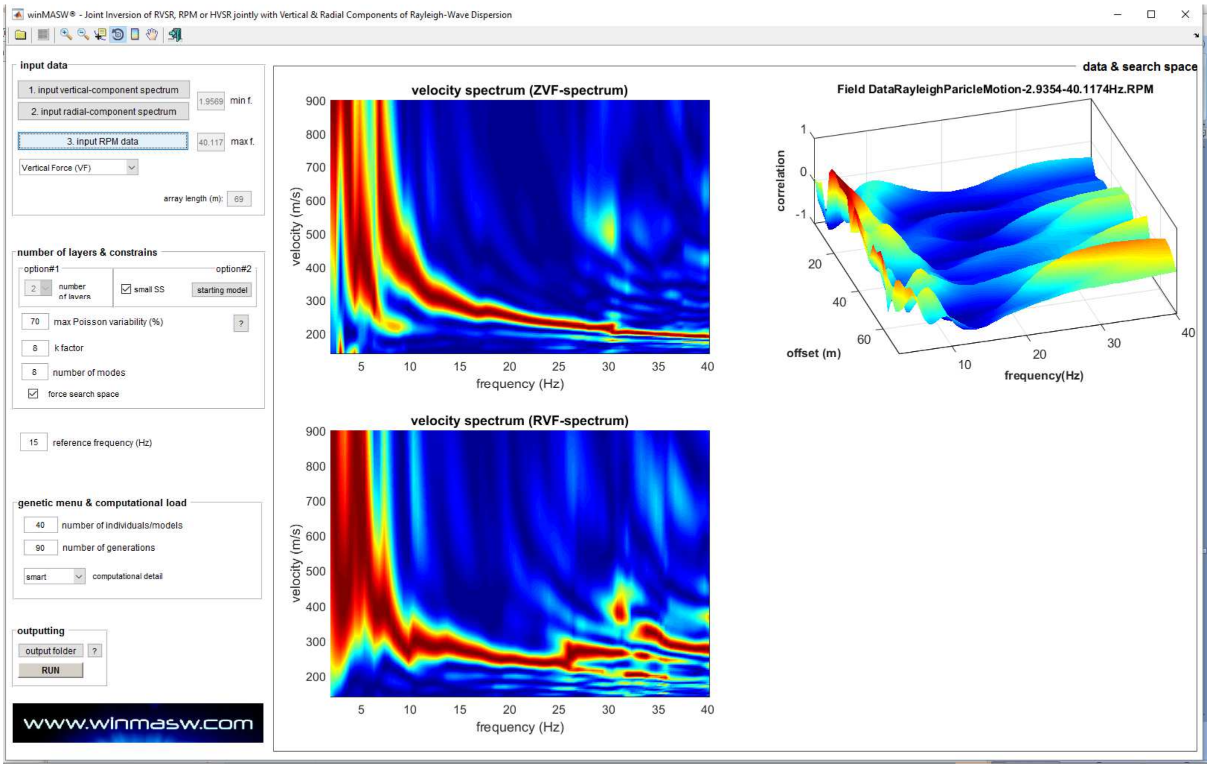
It is in fact clear that if you rotate your horizontal geophones by 180°, you will end up with a different (reversed) RPM surface (so, in order to get the *right* data, you must know the theory behind and the characteristics of your equipment).
Please notice that we can provide tested geophones (together with our *Holi* acquisition system [see our web site - **www.holisurface.com**]).

Joint ("automatic") inversion: ZVF+RVF (FVS approach) + RPM surface

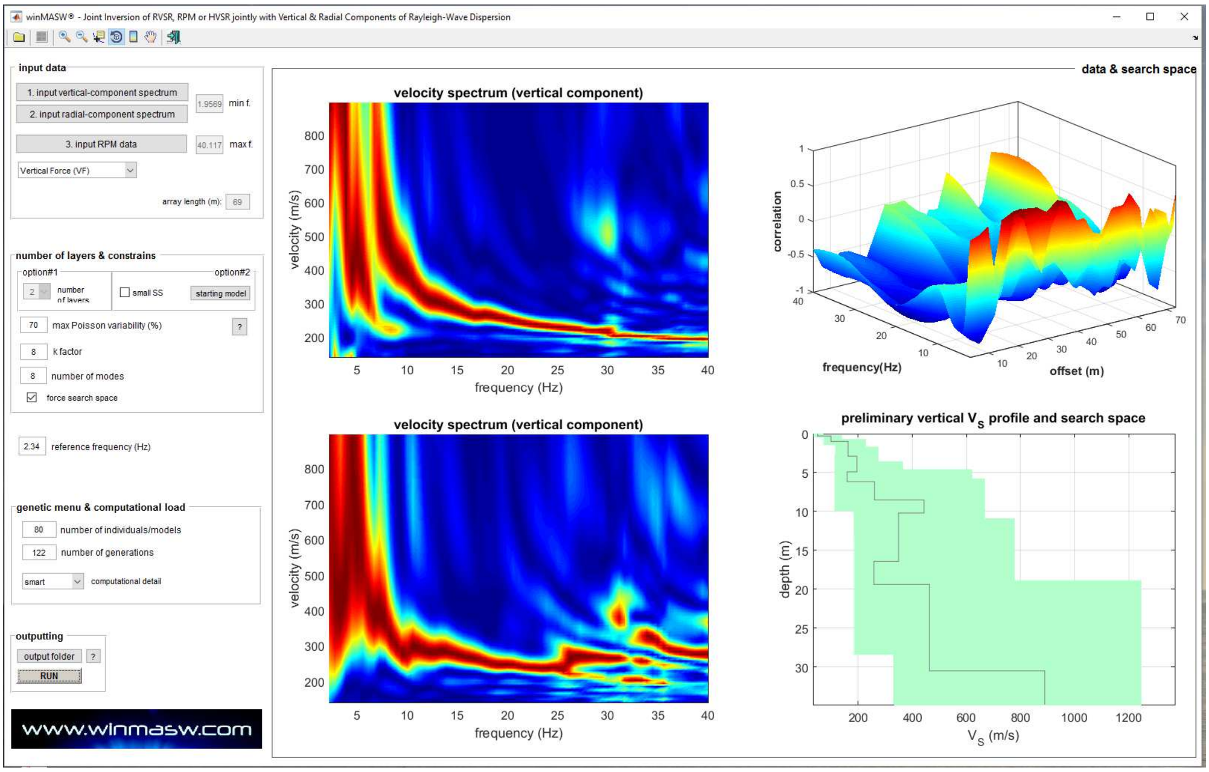
The "*Joint inversion of Rayleigh waves (disp + RPM)*" panel allows the uploading of the two (Z and R) velocity spectra (we do not deal with dispersion curves!) and the RPM surface for the automatic inversion.

Please, notice that this sort of inversion (involving the FVS approach, i.e. the creation of synthetic traces/data) it is necessary a very good CPU (the software relies on the parallel computing).
For details see the “**System requirement**s” section of this manual.

We then upload the three "object" that we want to (automatically) invert:

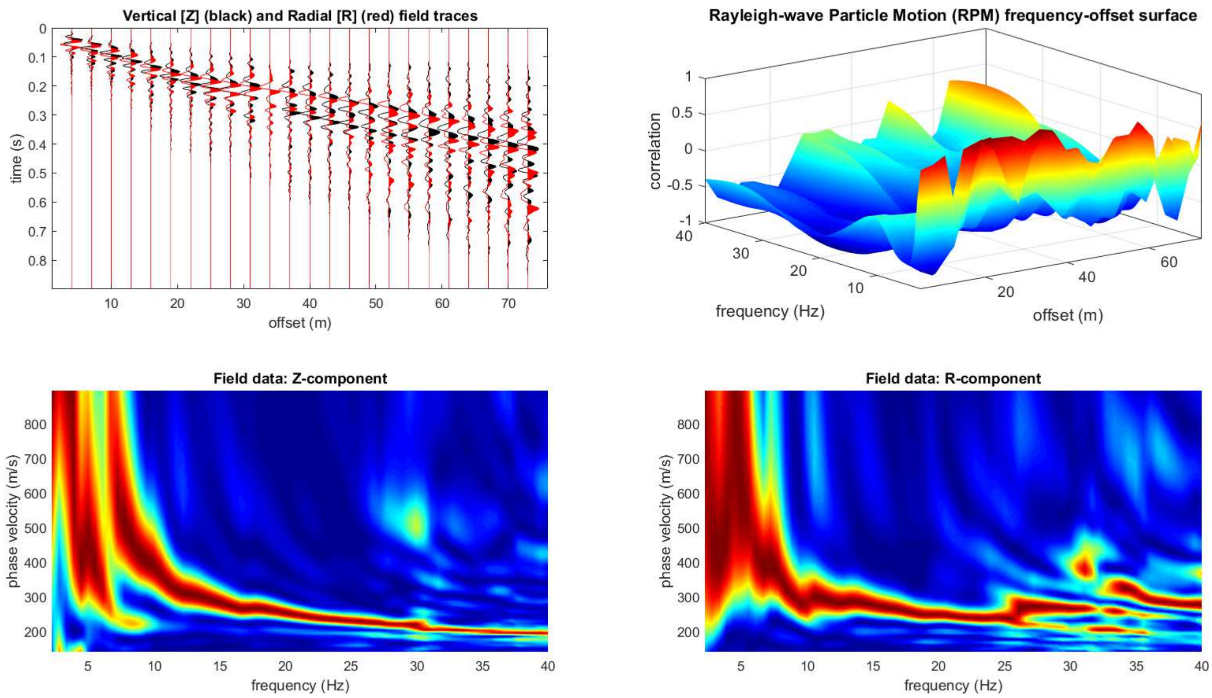


We must then fix the "search space" starting from a model that you were previously working with in the "forward modelling" section (see previous paragraph) and, once you fix the inversion parameters /(basically the number of individuals/models and the number of generations) and the depth down to which you want to plot the final models (by default such a value is fixed to 2/3 - two thirds - of the array length), you can eventually launch the inversion process (RUN button).

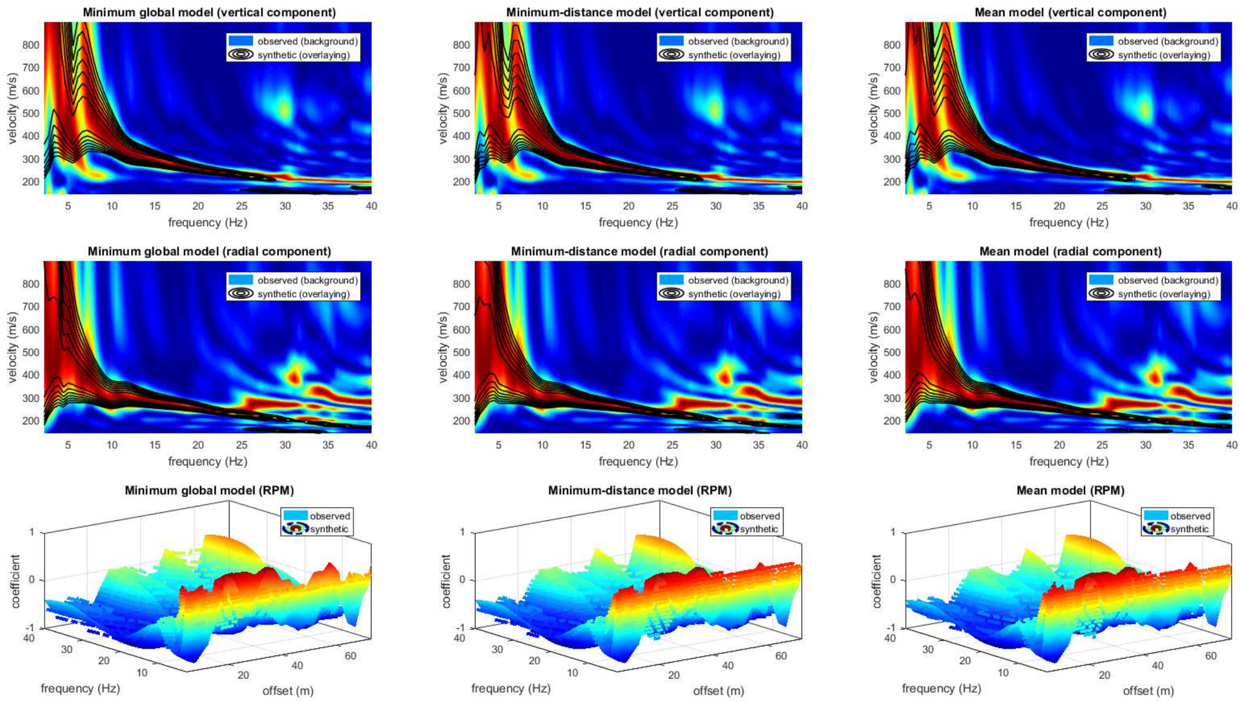


The final outcome can be summarized in the following *snapshots* (and the related html report file).

Plot reporting the input data:

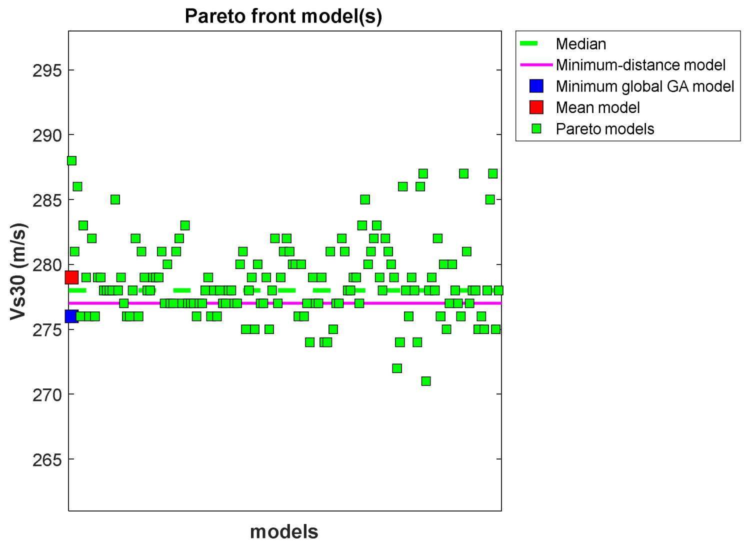


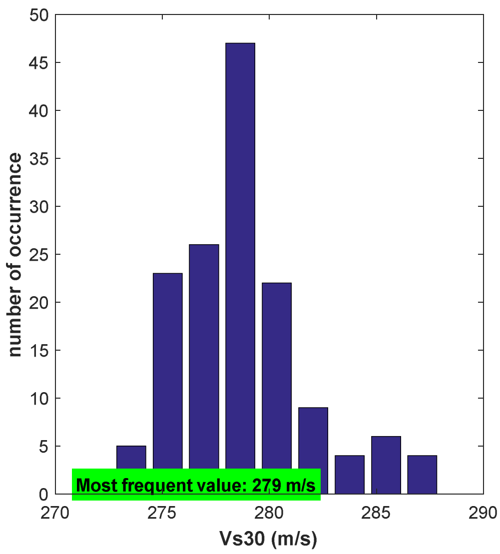
The 3 "most important" final models (minimum global, minimum distance, mean model):



(actually the most important ones are the minimum-distance model and the ,mean one (obtained as mean/average model of all the Pareto-front models)

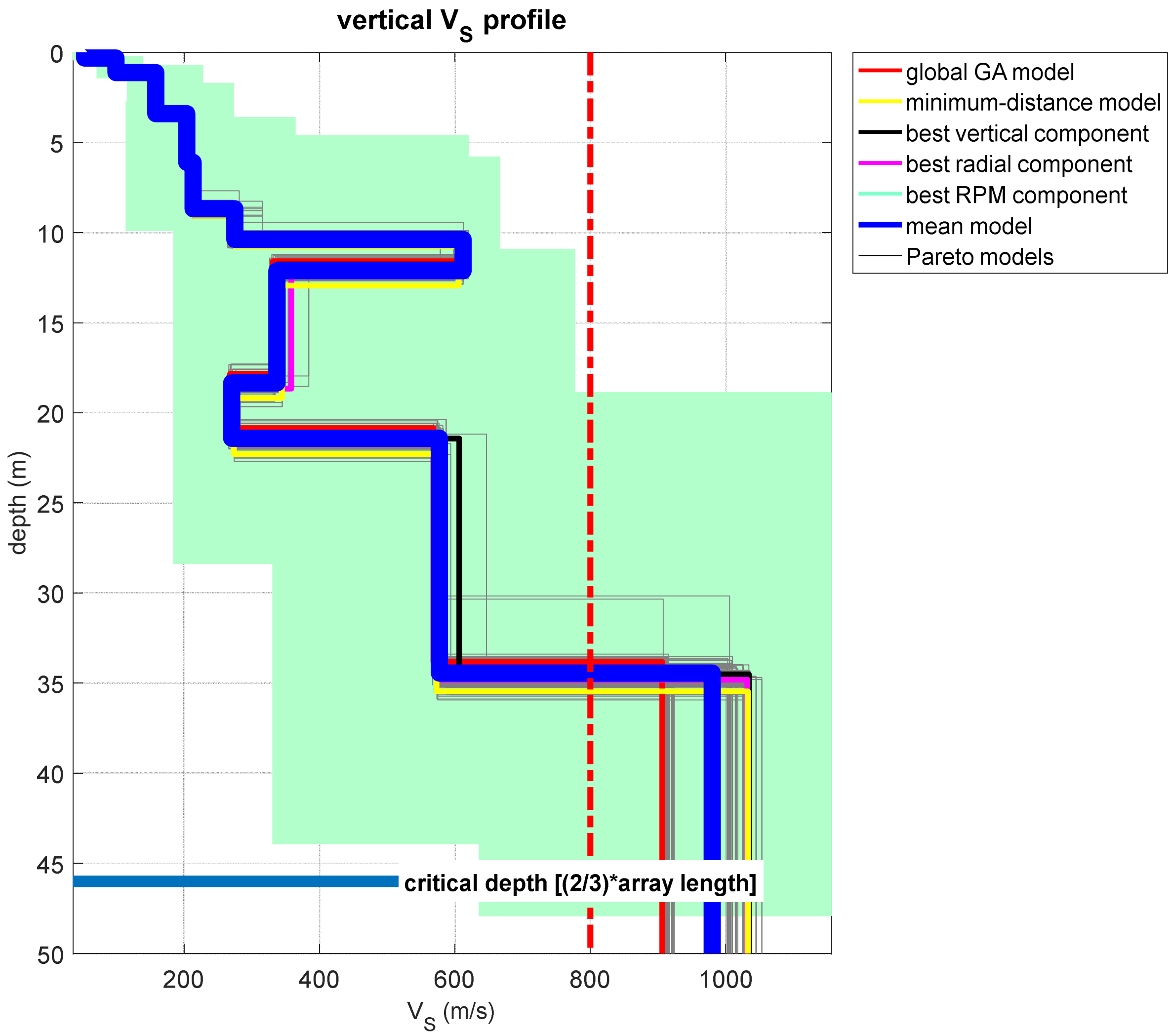
Brief statistical analysis (focused n the Vs30 parameter) of the Pareto-front models:





Useless to underline that this sort of analyses can be proficiently performed only after a sufficiently-serious *training* on both some theoretical and practical aspects.

Vs vertical profiles of the final "best models": if the Vs profiles are sufficiently similar, it means that the data were good and the inversion procedures was properly set up.



Please visit regularly our **web site** and social media (**facebook** and **youtube**) to keep up to date with our case studies, video tutorials etc.

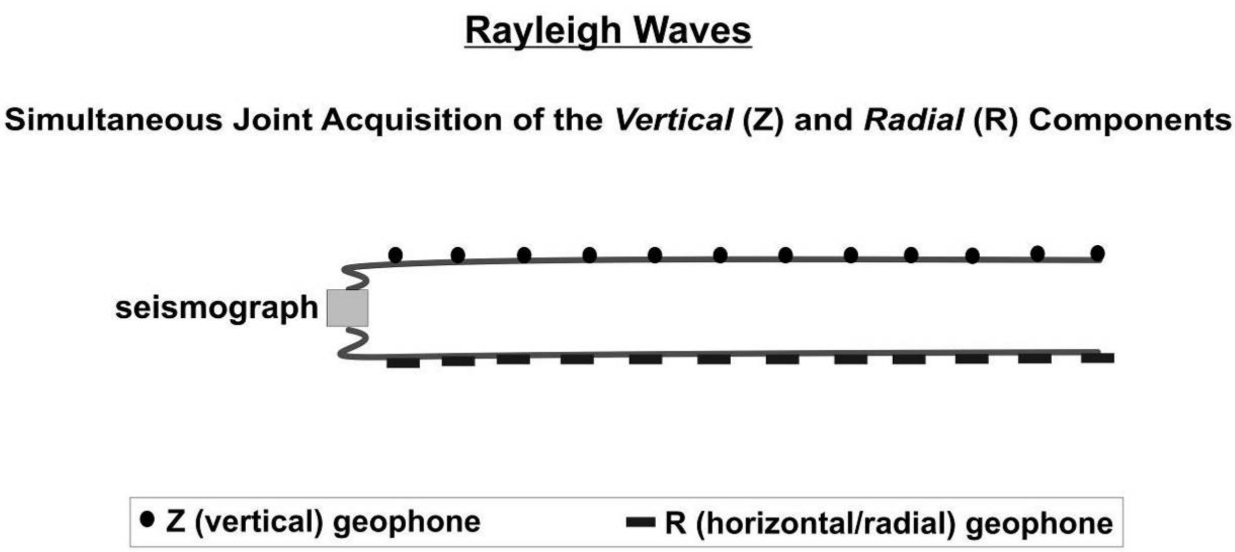
RVSR analysis

In winMASW® Academy, together with the RPM curves, you also obtain the RVSR (*Radial-to-Vertical Spectral Ratio*) curves for all the offsets (see for instance the "*Shear-wave velocity profiling according to three alternative approaches: a comparative case study*" paper).

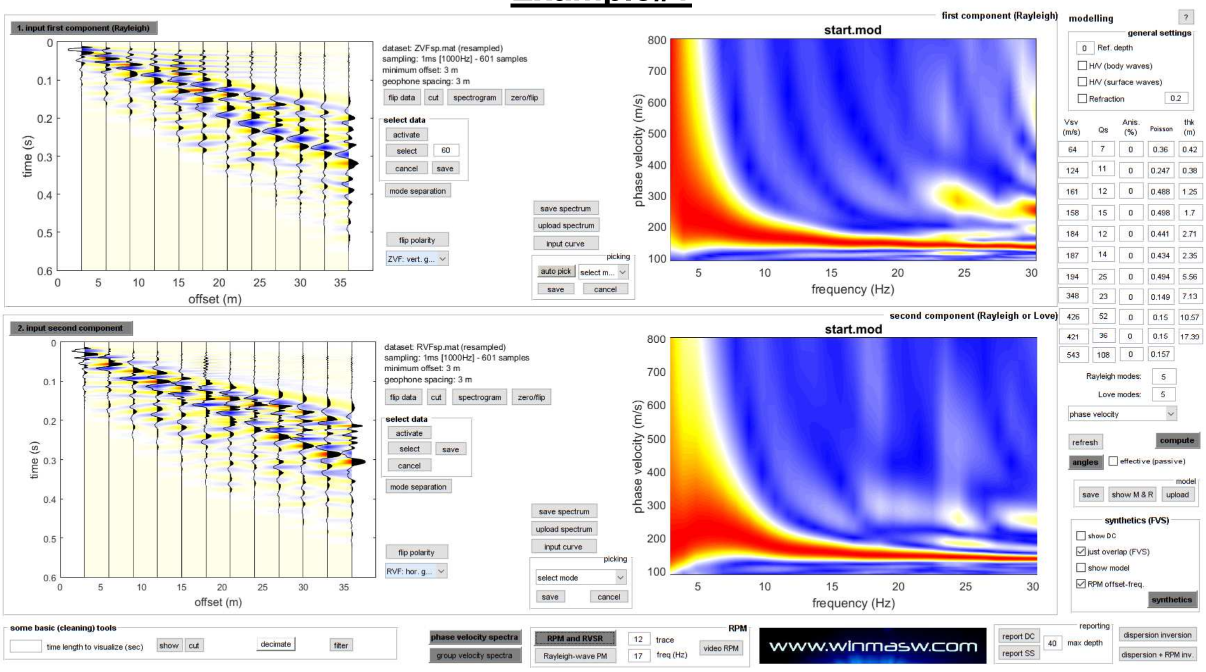
Recommendations:

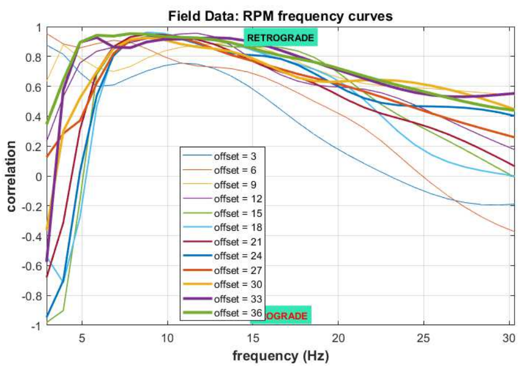
1) to analyze the RVSR you need to use vertical and horizontal geophones with the same response curve;

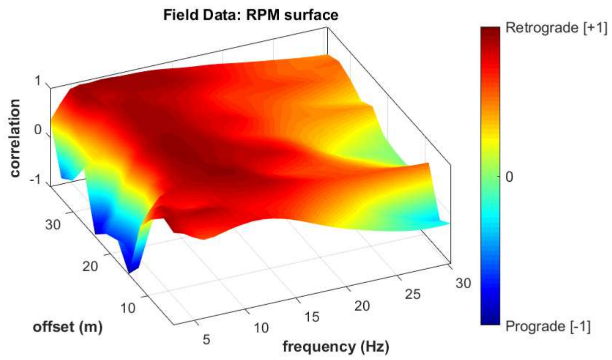
2) ideally, the acquisition of the Z (vertical) and R (radial) components is accomplished simultaneously (see scheme reported below); in case you want to acquire the two components separately (e.g. first the Z and then the R component), please use a large value for the stack (not less than 8) and try to use the same force for all the shots.

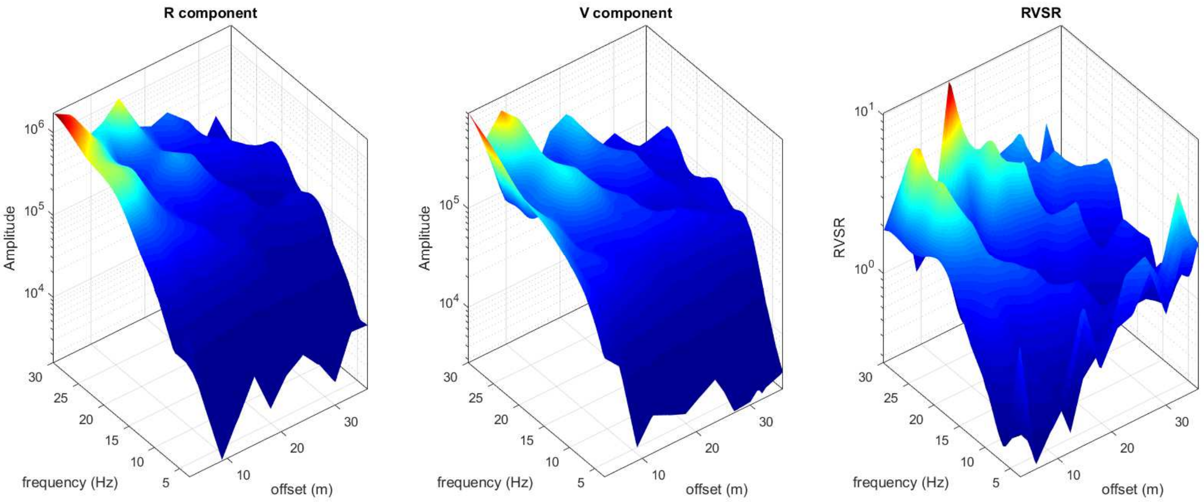


Example#1

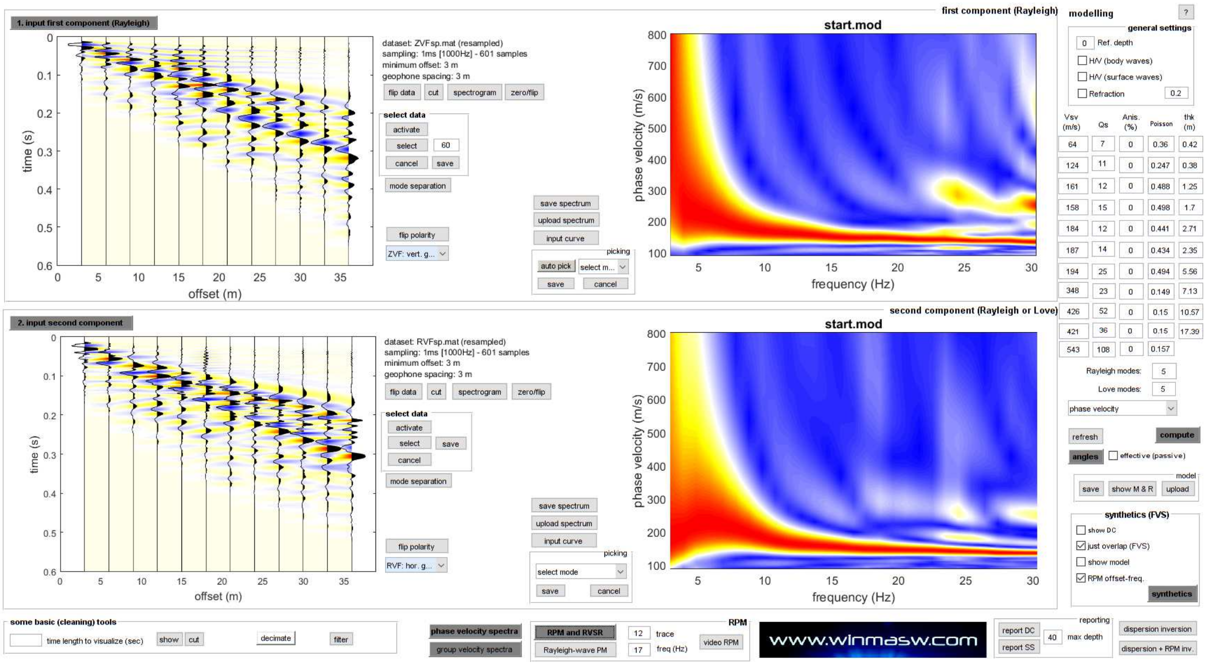

1. input first component (Rayleigh)
time (s)
offset (m)
dataset: ZVFsp.mat (resampled)
sampling: 1ms [1000Hz] - 601 samples
minimum offset: 3 m
geophone spacing: 3 m
start.mod
first component (Rayleigh)
phase velocity (m/s)
frequency (Hz)
2. input second component
dataset: RVFsp.mat (resampled)
sampling: 1ms [1000Hz] - 601 samples
minimum offset: 3 m
geophone spacing: 3 m
second component (Rayleigh or Love)
modelling
general settings
Rayleigh modes:
Love modes:
synthetics (FVS)
some basic (cleaning) tools
phase velocity spectra
group velocity spectra
RPM and RVSR
Rayleigh-wave PM
www.winmasw.com
reporting
dispersion inversion
dispersion + RPM inv.

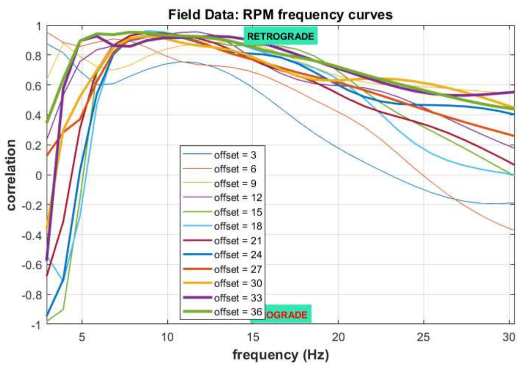

Field Data: RPM frequency curves
RETROGRADE
PROGRADE
correlation
frequency (Hz)
offset = 3
offset = 6
offset = 9
offset = 12
offset = 15
offset = 18
offset = 21
offset = 24
offset = 27
offset = 30
offset = 33
offset = 36

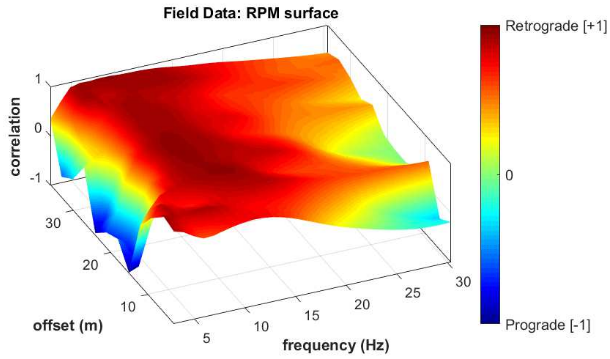

Field Data: RPM surface
correlation
offset (m)
frequency (Hz)
Retrograde [+1]
0
Prograde [-1]

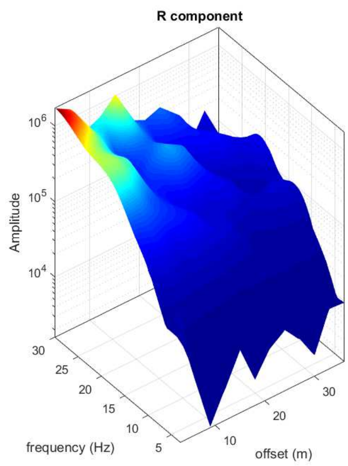

R component
V component
RVSR
Amplitude
RVSR
frequency (Hz)
offset (m)

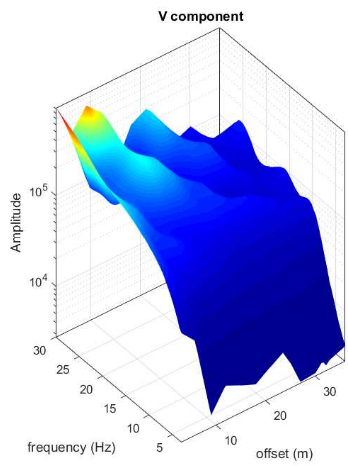
Example#2

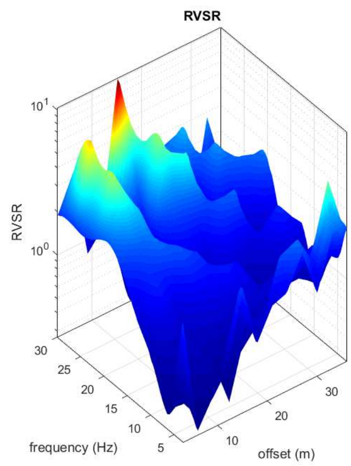

1. input first component (Rayleigh)
dataset: ZVFsp.mat (resampled)
sampling: 1ms [1000Hz] - 601 samples
minimum offset: 3 m
geophone spacing: 3 m
time (s)
offset (m)
start.mod
first component (Rayleigh)
phase velocity (m/s)
frequency (Hz)
2. input second component
dataset: RVFsp.mat (resampled)
second component (Rayleigh or Love)
modelling
general settings
some basic (cleaning) tools
phase velocity spectra
group velocity spectra
RPM and RVSR
Rayleigh-wave PM
www.winmasw.com


Field Data: RPM frequency curves
RETROGRADE
correlation
offset = 3
offset = 6
offset = 9
offset = 12
offset = 15
offset = 18
offset = 21
offset = 24
offset = 27
offset = 30
offset = 33
offset = 36
OGRADE
frequency (Hz)


Field Data: RPM surface
correlation
offset (m)
frequency (Hz)
Retrograde [+1]
0
Prograde [-1]


R component
Amplitude
frequency (Hz)
offset (m)


V component
Amplitude
frequency (Hz)
offset (m)


RVSR
RVSR
frequency (Hz)
offset (m)

15. Site Response and Response Spectra

Brief introduction

The actual and main problems of the estimation of the site effects are:

1. Many of the V_S profiles used are significantly incorrect (because are based on interpreted single-component data);

2. The probabilistic approach (PSHA) used to select the input earthquakes is strongly criticized by a large part of the scientific community.

Given these bottom-line problems, it is completely useless to try to be exceedingly "sophisticate" about secondary aspects such as, for instance, the G/Go curves and so on. Always consider the warning by Matthew (the *Gospel* according to Matthew, 23-24): "*You blind guides! You strain out a gnat but swallow a camel.* "

So, please, consider that the first two problems to face and properly solve are:

1. define an accurate subsurface model from the **joint analysis** of Rayleigh + Love + HVSR (see our recommended procedures)
2. define the input quakes in a professional way (see e.g. Fasan et al., 2016).

Here few further reasons why not to waste too much energy on insignificant aspects:

1. *response spectra* are defined for a SDOF (Single Degree Of Freedom) model, which is a first approximation valid only for buildings with a very simple behavior;

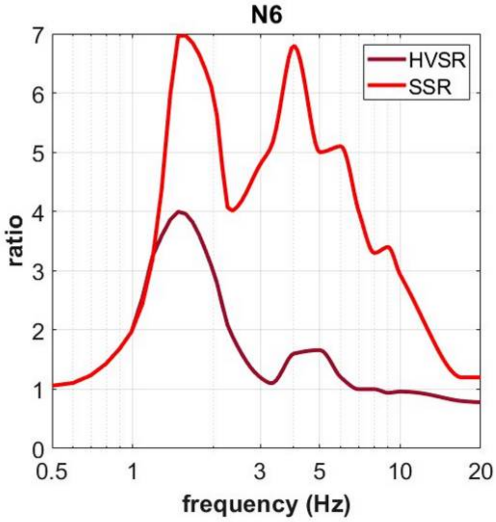
2. the damping factor of the structure (usually monolithically fixed at 5%) is a further question mark (i.e., a variable). Trying to vary the damping of the structure from, for example, 3 to 7% you can see how it also has a weight in determining the final response spectra. To realize how much the damping of a structure can vary in relation to the amplitude of the input, see for example Naito & Ishibashi (1996).

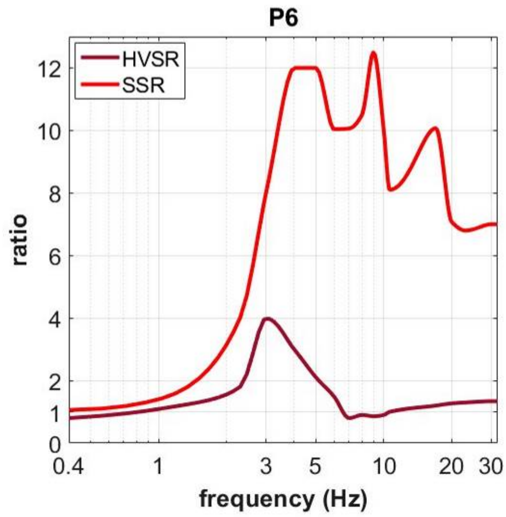
3. the Q factors (damping) of the subsurface model are difficult to estimate (and lab tests often provide values that cannot be easily attributed to large-scale structures).

It is therefore recommended to do everything that can and should be done in order to get the real point, without wasting time in negligible secondary aspects.

Among the several misconceptions often adopted while assessing the so-called site effects, we can recall that the idea that the HVSR curve represents the so-called *site amplification* is erroneous. This is known both from theoretical considerations as well as from experimental data. You should give a look, for instance, to the article by Perron et al. (2018) where the actual amplification obtained from the SSR is compared with the HVSR (see figure here below).

As you can see, the difference is huge.





Two types of quakes (and spectral shapes)

Depending on the characteristics of the earthquakes characterizing the local seismotectonic regime, the EC8 considers two types of sources:

•**Type 1**-High and moderate seismicity regions (*M*s > 5.5)
•**Type 2**-Low seismicity regions (*M*s ≤ 5.5) [near field earthquakes]

Depending on the chosen regime, the spectral shapes change (please, refer to your local national regulations).

Quality factors and *damping*

Always remember to properly set the quality factors (Q) of your model. A simple rule of thumb is that, roughly speaking, the Qs factors are approximately equal to the Vs values divided by a factor that can vary from about 10 to 15 (in the software this factor is called *K factor*). Also remember that:

$$D = 1 / 2Q$$

The *damping* value (D) is usually expressed as a percentage; therefore such a value is multiplied by 100.

How the site effect panel works (in brief)

The determination of the local site effects (and computation of the response spectra) requires the following three steps to be accomplished very carefully:

1) accurate (non-ambiguous) determination of the V_S profile down to the *bedrock*

2) determination of a series of "reference quakes" at the local *bedrock*

3) simulation of the shaking effect and computation of the Response Spectra

Errors in the V_S profile and/or in the chosen reference inevitably lead to the definition of inaccurate or erroneous response spectra.

With respect to **point #2**, we recommend you to attend our workshops and/or read the specialized literature. The issues related to quake generation/selection is rather complex - see the debate on the correctness of the probabilistic approach (PSHA - *Probabilistic Seismic Hazard Assessment*) compared with the *physical approach* (NDSHA - *NeoDeterministic Seismic Hazard Assessment*). The fundamental difference is that the reference quakes are chosen according to a “probabilistic scheme” in the first case while modelled according to the regional seismotectonic regime in the second case.
The quakes that you will decide to upload for the computation of the final Response Spectra are your responsibility (winMASW® / HoliSurface® does not generate them) and should be chosen according to scientific considerations and/or your national regulation.

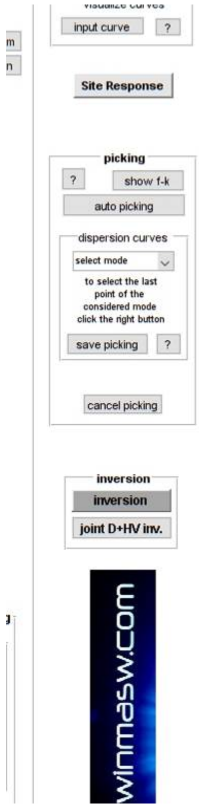
In short terms:

1) determine an accurate V_S (and Q_S) profile through the joint analysis of seismic data possible with winMASW® / HoliSurface®
2) In the *Site Response* panel, upload the obtained subsurface model together with the HVSR curve
3) Upload the “reference quakes” (i.e. the acceleration at the local bedrock) following the “line” that your national regulation suggests [be aware of the differences between the PSHA and the NDSHA approaches]
4) Compute the site response (“Compute site response” button in the lower right corner)

In the following are described the parameters to set up.

Setting the parameters

Once defined the right Vs profile (which must be consistent with all the available data) you can access to the panel by clicking the **Site Response** button:



The following panel will show up:

By default the model uploaded is the one active in the moment you click the "Site Response" button, but it can be modified by uploading a different (previously-saved) model by clicking the "**input subsurface model**" button.

Parameters to set up:

reference depth (m)

Depth of the foundation of the building (output results are computed while considering such a depth as the free surface).

"input quake(s)"

Specify the unit of measurements (m/s^2 or cm/s^2).
Fix the number of ***header lines*** in the data (accelerograms) you are going to upload.
You can upload **two kinds of time series**:

1) with **two columns** the first one represents the time (in seconds), the second one the accelerations)
2) with just **one column** (just the accelerations)

In case you have only the acceleration column (this is the case of the format used by REXEL LITE), you must specify the sampling interval (in seconds). You can find the sampling interval in the header lines (for instance "SAMPLING_INTERVAL_S: 0.005000" means that the sampling intervals is 5 ms, i.e. 0.005 s).

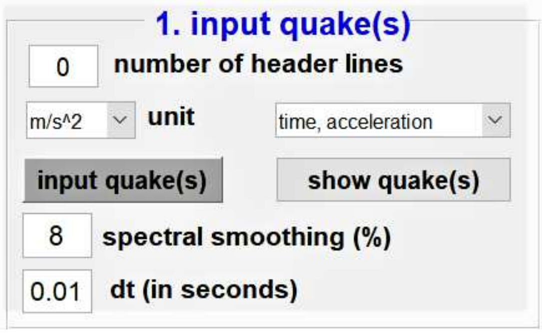
Also fix the *smoothing* to apply while processing the spectra.

In the following are reported some examples of possible file formats. Fixing the correct parameters is clearly crucial.

Example#1

Example of acceleration history/file with no *header line* (header value: 0) and acceleration expressed in m/s^2:

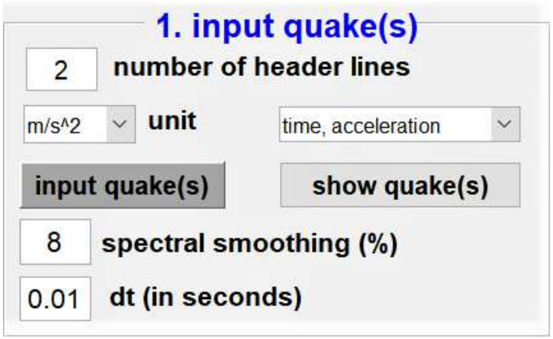
0.0000000e+000 0.0000000e+000
5.0000000e-003 -3.2748000e-004
1.0000000e-002 -6.6074000e-004
1.5000000e-002 -6.6930000e-004
2.0000000e-002 -6.7780000e-004
2.5000000e-002 -6.8632000e-004
3.0000000e-002 -6.9493000e-004
3.5000000e-002 -7.0372000e-004
4.0000000e-002 -7.1276000e-004
4.5000000e-002 -7.2215000e-004
5.0000000e-002 -7.3195000e-004
...



Example#2

In case, for instance, the first line would report the site name and the second its coordinates (or any other information), we should indicate "2" *header lines*.

Berlin
52°31′00″N 13°23′20″E
0.0000000e+000 0.0000000e+000
5.0000000e-003 -3.2748000e-004
1.0000000e-002 -6.6074000e-004
1.5000000e-002 -6.6930000e-004
2.0000000e-002 -6.7780000e-004
2.5000000e-002 -6.8632000e-004
3.0000000e-002 -6.9493000e-004
3.5000000e-002 -7.0372000e-004
4.0000000e-002 -7.1276000e-004
4.5000000e-002 -7.2215000e-004
...



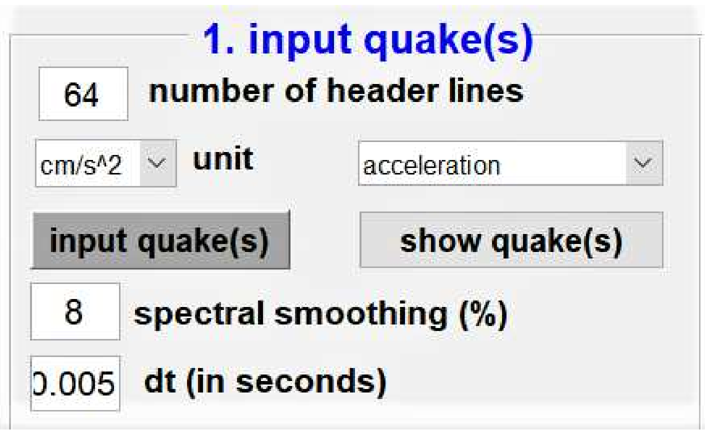
Example#3 [REXEL lite]

In this case we have 64 header lines, just one column with the accelerations, the accelerations expressed in cm/s^2 and the sampling interval equal to 5 ms

EVENT_NAME: CENTRAL_ITALY
EVENT_ID: EMSC-20161030_0000029
EVENT_DATE_YYYYMMDD: 20161030
EVENT_TIME_HHMMSS: 064018
EVENT_LATITUDE_DEGREE: 42.8322
EVENT_LONGITUDE_DEGREE: 13.1107
EVENT_DEPTH_KM: 9.2
HYPOCENTER_REFERENCE: INGV-CNT_Seismic_Bulletin
MAGNITUDE_W: 6.5
MAGNITUDE_W_REFERENCE: INGV-webservice
MAGNITUDE_L: 6.1
MAGNITUDE_L_REFERENCE: INGV-CNT_Seismic_Bulletin
FOCAL_MECHANISM: NF
NETWORK: IT
STATION_CODE: MMO
STATION_NAME: Montemonaco
STATION_LATITUDE_DEGREE: 42.899300
STATION_LONGITUDE_DEGREE: 13.326800
STATION_ELEVATION_M: 1030
LOCATION:
SENSOR_DEPTH_M: 0.0
VS30_M/S:
SITE_CLASSIFICATION_EC8: A*
MORPHOLOGIC_CLASSIFICATION:
EPICENTRAL_DISTANCE_KM: 19.2
EARTHQUAKE_BACKAZIMUTH_DEGREE: 247.2
DATE_TIME_FIRST_SAMPLE_YYYYMMDD_HHMMSS: 20161030_064005.480
DATE_TIME_FIRST_SAMPLE_PRECISION: milliseconds
SAMPLING_INTERVAL_S: 0.005000
NDATA: 12000
DURATION_S: 60.000
STREAM: HGN
UNITS: cm/s^2
INSTRUMENT: sensor = Unknown [Unknown] | digitizer = Unknown [Unknown]
INSTRUMENT_ANALOG/DIGITAL: D
INSTRUMENTAL_FREQUENCY_HZ:
INSTRUMENTAL_DAMPING:
FULL_SCALE_G:
N_BIT_DIGITAL_CONVERTER:
PGA_CM/S^2: -185.085632
TIME_PGA_S: 22.245000
BASELINE_CORRECTION: BASELINE REMOVED
FILTER_TYPE: BUTTERWORTH
FILTER_ORDER: 2
LOW_CUT_FREQUENCY_HZ: 0.050
HIGH_CUT_FREQUENCY_HZ: 30.000
LATE/NORMAL_TRIGGERED: NT
DATABASE_VERSION: DYNA 1.0
HEADER_FORMAT: DYNA 1.2
DATA_TYPE: ACCELERATION
PROCESSING: manual (Paolucci et al., 2011)
DATA_TIMESTAMP_YYYYMMDD_HHMMSS: 20170711_162914.567
DATA_LICENSE: CC-BY3_0-IT (http://creativecommons.org/licenses/by/3.0/deed.en)
DATA_CITATION: Luzi L, Puglia R, Russo E & ORFEUS WG5 (2016). Engineering Strong Motion Database. Istituto Nazionale di Geofisica e Vulcanologia, Observatories & Research Facilities for European Seismology. doi: 10.13127/ESM

DATA_CREATOR: ESM working group
ORIGINAL_DATA_MEDIATOR_CITATION: Ufficio Rischio Sismico e Vulcanico del Dipartimento della Protezione Civile (http://www.protezionecivile.gov.it/)
ORIGINAL_DATA_MEDIATOR: Rete Accelerometrica Nazionale - RAN Download (http://www.mot1.it/randownload/)
ORIGINAL_DATA_CREATOR_CITATION: Italian Strong Motion Network, Italian Civil Protection Department http://www.protezionecivile.gov.it
ORIGINAL_DATA_CREATOR: network: IT (Italian Strong Motion Network); owner: Dipartimento Della Protezione Civile
USER1: /home/dyna/processing-itaca/processing.py /var/www/processing//tmp/Lucia//IT.MMO..HGE.D.20161030.064018.X.ACC.ASC /var/www/processing//tmp/Lucia//IT.MMO..HGN.D.20161030.064018.X.ACC.ASC /var/www/processing//tmp/Lucia//IT.MMO..HGZ.D.20161030.064018.X.ACC.ASC --tmp /var/www/processing//tmp/Lucia/ --le 0.050 --he 30.000 --ln 0.050 --hn 30.000 --lz 0.050 --hz 30.000 --fo 2 --ca -10 --cz 130 --ta 5 --tz 5 --mf 1 --rf 0.005 --tr NT
USER2:
USER3:
USER4:
USER5:
0.000000
0.033719
0.067431
0.067420
0.067407
0.067392
0.067376
0.067357
0.067337
0.067316
0.067292
…

Therefore you will you have to fix the following parameters:
Number of header lines: 64
Unit: cm/s^2 (see header lines)
Data format: just acceleration (one column)
dt (sampling interval in seconds): 0.005 (see header lines)



ag (g) [peak acceleration in Earth gravity unit]

In the PSHA approach, the quakes are normalized/scaled to the peak acceleration value defined by your national regulations. Such a peak value depends on the kind of building you are considering and on the chosen return period.
If you specify an **ag** value higher than zero, the input acceleration (which must be in m/s^2 or cm/s^2) are scaled so that the maximum acceleration of each quake is equal to the specified ag value (which is in g - earth gravity - unit).
In case you do not want to scale (i.e. modify the amplitudes) your quakes (as for instance in the NDSHA approach), just let zero (0) the **ag** value.

building damping (%)

Response Spectra are computed while considering such a damping value.
Usually the value is fixed to 5% but the structural engineer might ask for a different value which better expresses the characteristics of the building under study (see e.g. Naito and Ishibashi, 1996).

reference depth (m)

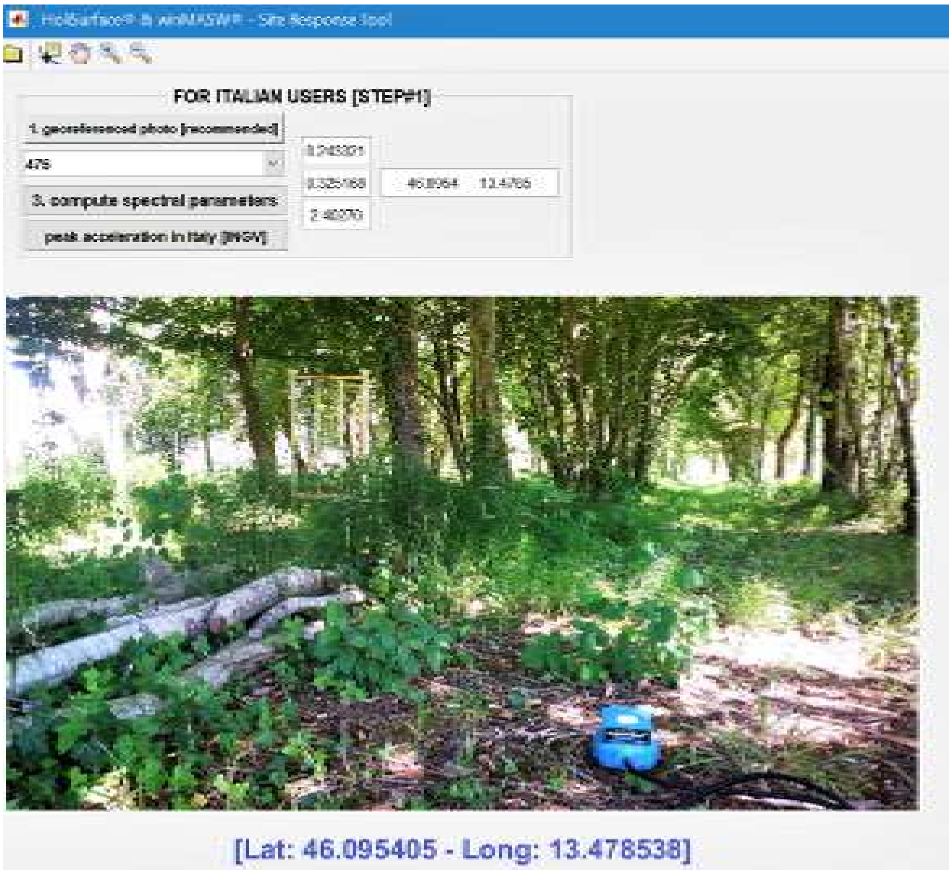
It is the depth where you want to compute the site effects. In simple terms: in case the foundation level of the building is for instance at 1 m from the surface, you should put 1.

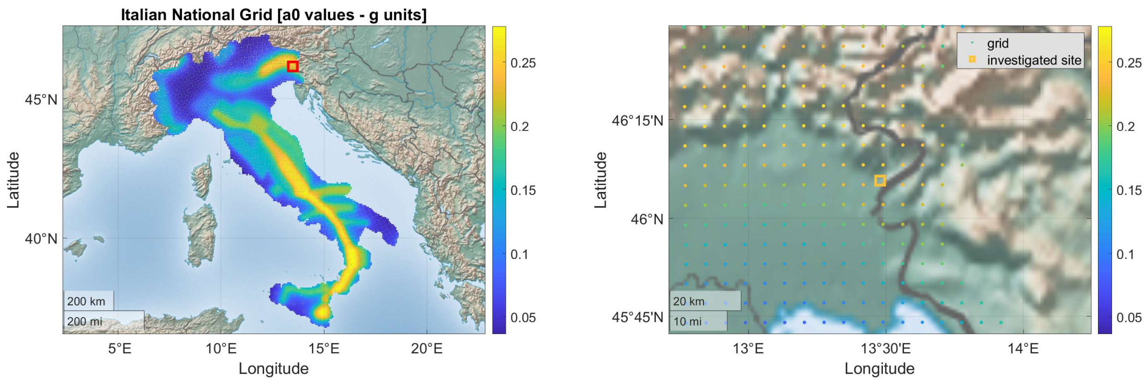
For Italian users following the PSHA: defining the ag Tc & F0 parameters

1) upload a georeferenced photo [see button in the upper left corner of the panel]

2) fix the return time [*tempo di ritorno*], which depends on the structure you are going to assess and the local regulations

3) *click* the "compute spectral parameters" button so to obtain the **ag Tc** and **F0** values necessary for the computation of the final response spectra (based on the PSHA approach).

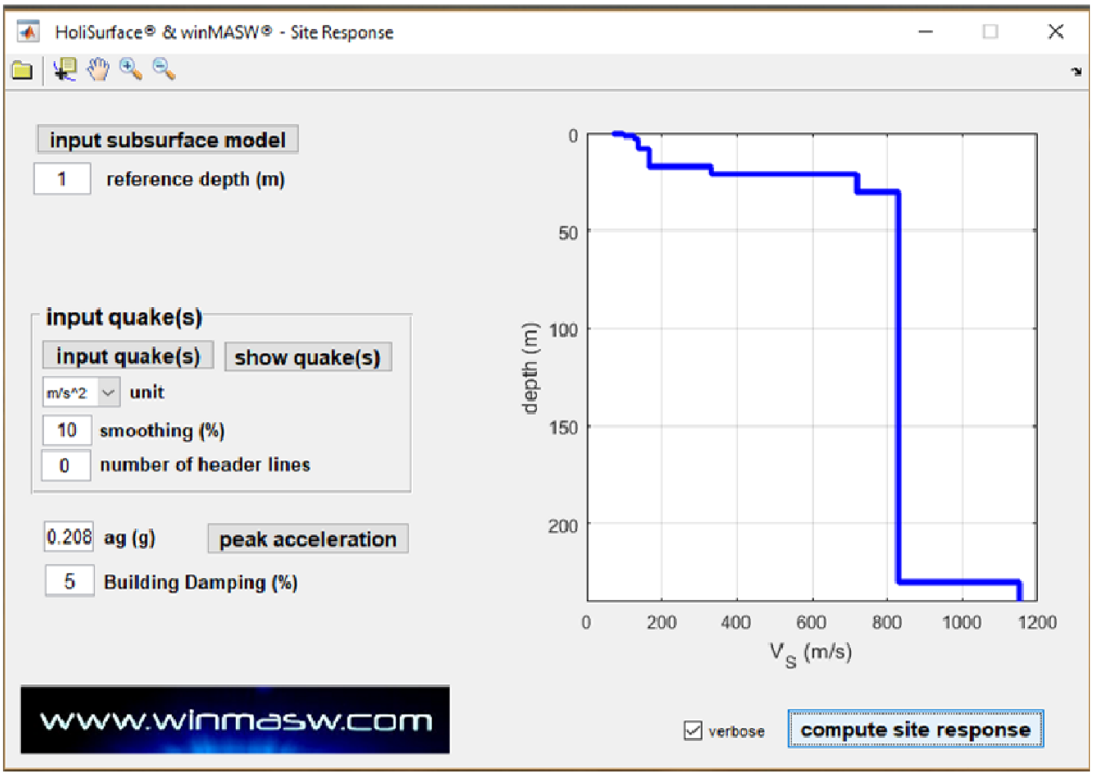



Italian National Grid [a0 values - g units]
Latitude
45°N
40°N
5°E
10°E
15°E
20°E
Longitude
200 km
200 mi
0.25
0.2
0.15
0.1
0.05
grid
investigated site
46°15'N
46°N
45°45'N
13°E
13°30'E
14°E
20 km
10 mi

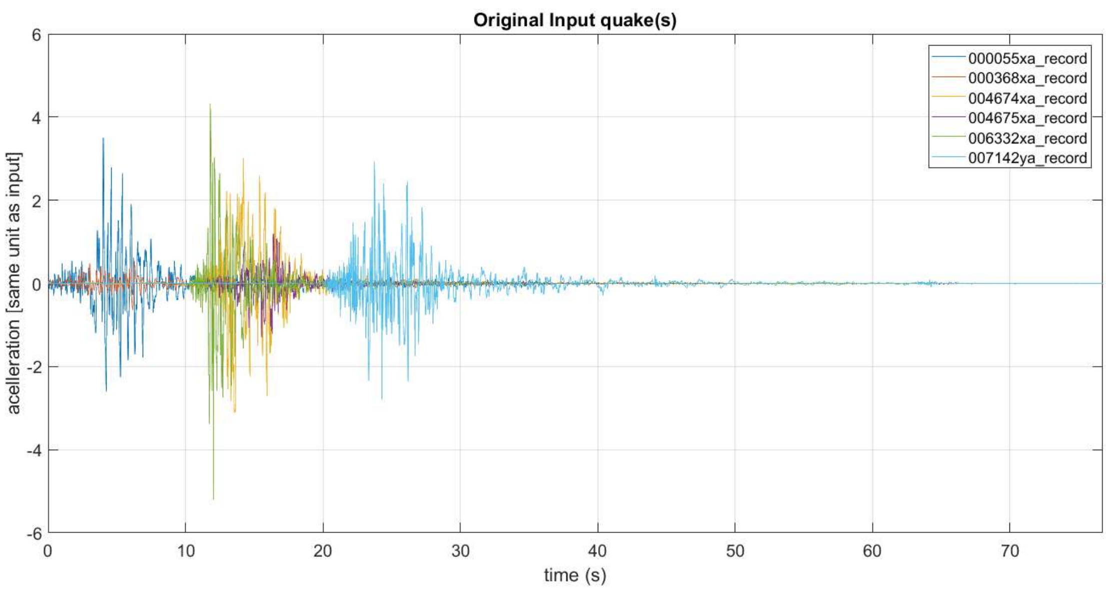

www.winmasw.com
Tr: 475 years
Long, Lat: 13.4785 46.0954
Tc: 0.32517
F0: 2.4028
a0: 0.24332

An old example

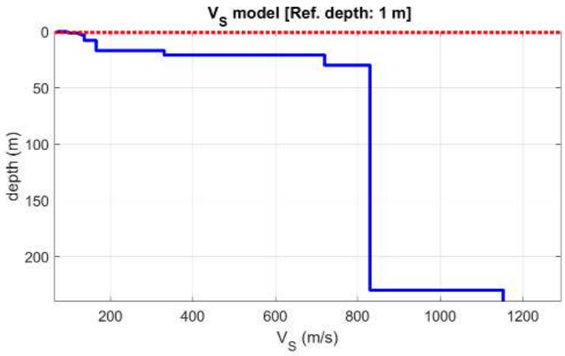
Please, notice that several data/spectra are reported both as a function of frequency and period. As usual, all the figures are automatically saved in the *working folder*.

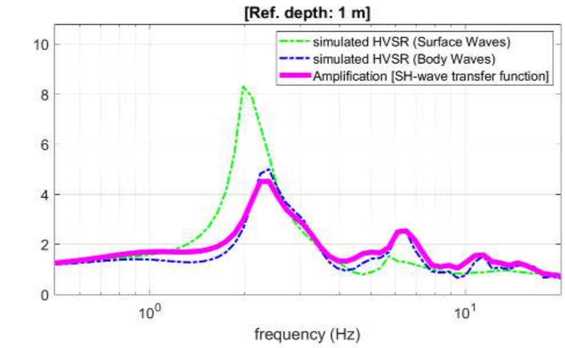


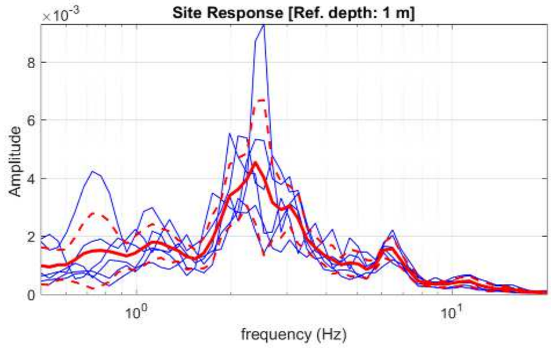
Uploaded quakes (with their original amplitudes):



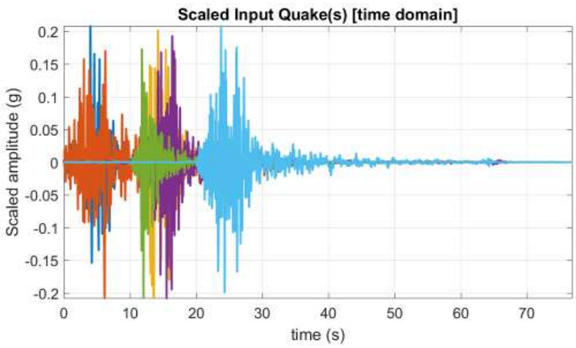
Uploaded V_S model, modelled HVSR (from surface and body waves) together with the SH-wave transfer function [often improperly considered the "amplification curve"] and, in the lower right corner, the amplitude spectra at the chosen reference depth (see "reference depth (m):" in the main panel):

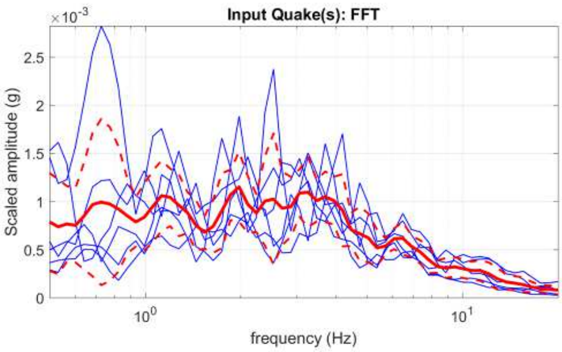


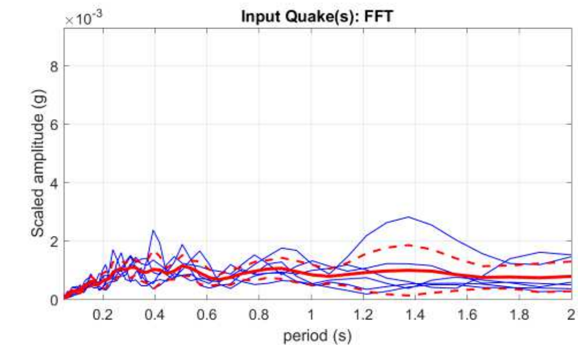


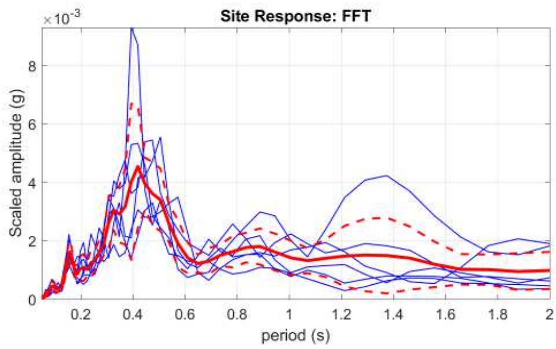


Normalized quakes (time series are multiplied so that the maximum value is set equal to the specified **ag** value – standard PSHA approach), FFT of the input quakes (normalized) as a function of both frequency and period, amplitude spectra at the reference depth:

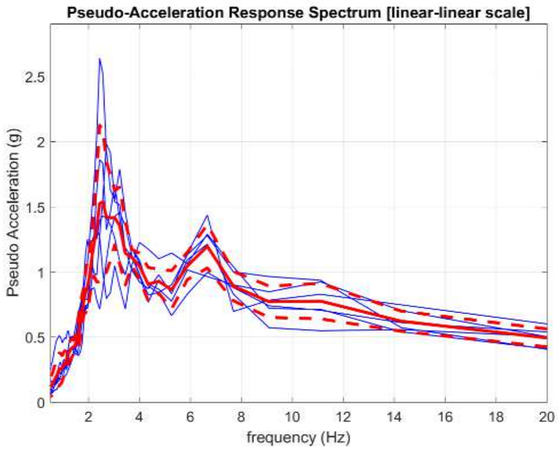


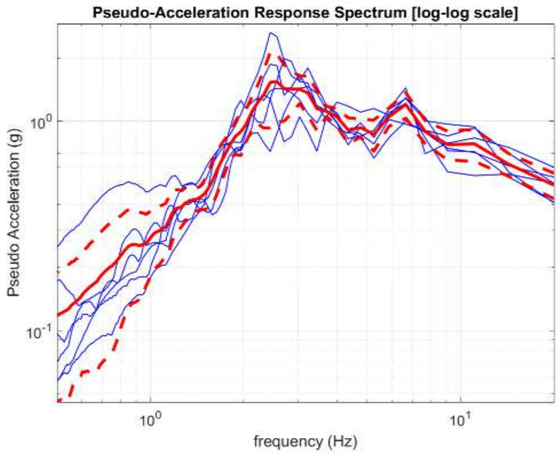




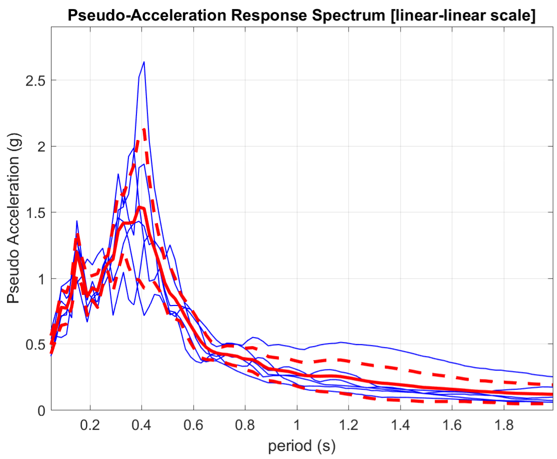


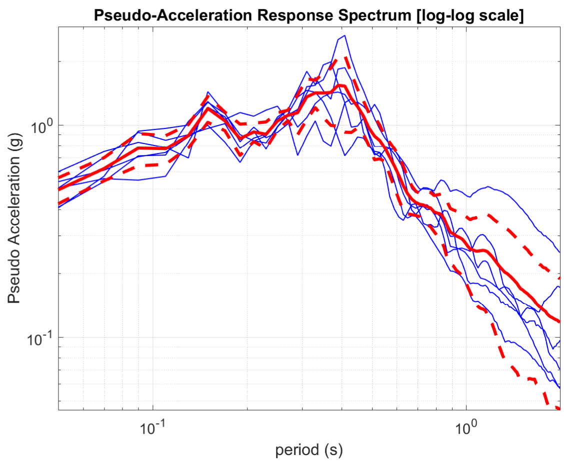
Response spectra at the reference depth (in this case 1 m from the surface) as a function of the frequency (linear and logarithmic scales).





Response spectra at the reference depth (in this case 1 m from the surface) as a function of the period (linear and logarithmic scales).

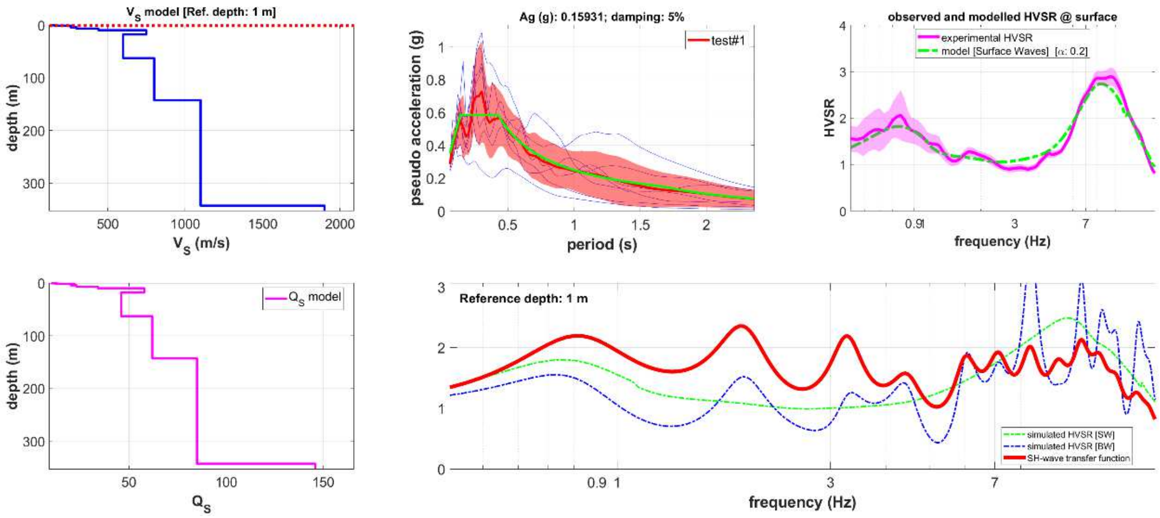




The response spectra are automatically saved as ASCII files in the *working folder* with file names that clearly indicate the content:

All_Response_Spectra_Frequency.txt
All_Response_Spectra_Period.txt
Mean_Response_Spectrum_Frequency.txt
Mean_Response_Spectrum_Period.txt

The following snapshot reports an example of the verey final figure summarizing the main facts (from another site/silutation). Each plot clearly reports the meaning/labels of the shown curves/functions.



Shown:

1) the V_S and Q_S values of the upload model;
2) the uploaded and modelled HVSR curves [upper right graph];
3) the SH-wave transfer function [red line] together with the uploaded and modelled [according to both surface and SH waves] HVSR curves;
4) the response spectra for all the uploded input quakes together with the mean curve and the regularized one (see “spectra regularization” box in the next pages) [central upper plot].

Site Response in the recent *releases* of winMASW® Academy & HoliSurface®

Once the correct V_S profile has been obtained (a model can be considered correct only if it is in agreement with multi-component data – see all the examples shown in this manual), click the "Site Response" button and access the **Site Response tool**.

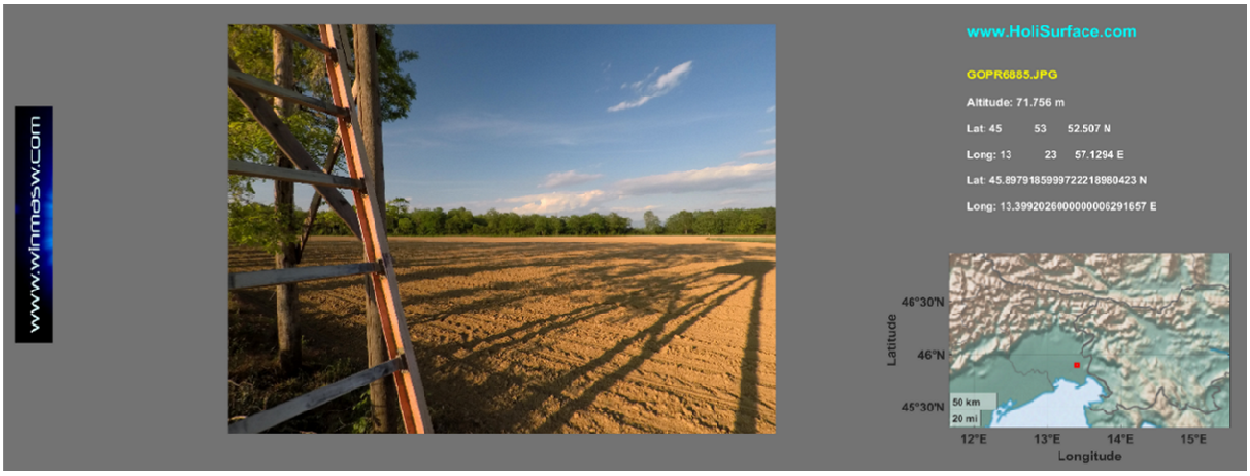
In case you click the “Site Response” button from the analysis panels, the subsurface model and the HVSR curve are automatically uploaded but it is possible to (re)upload both ("upload subsurface model" and "upload HVSR curve" buttons in the Site Response panel).

Remember that by simply hovering the mouse over a button, a brief description/help shows up.

Sequence to follow:

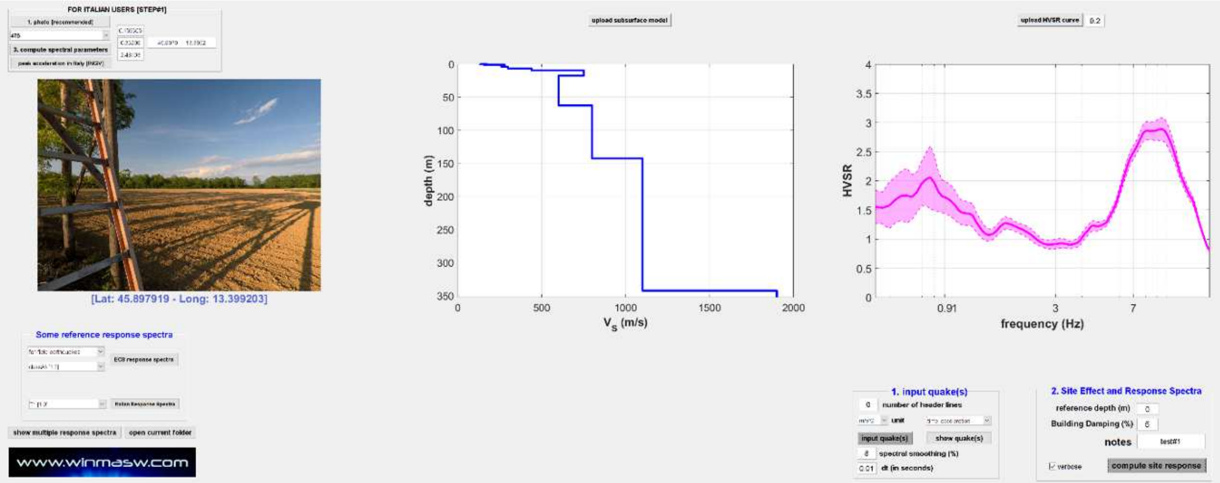
The first three operations can be performed only by Italian users (since, so far, the table data are available only for Italy). In case you are working in a different country, you must set the **ag**, **Tc** and **F0** value by yourself (following your national building codes).

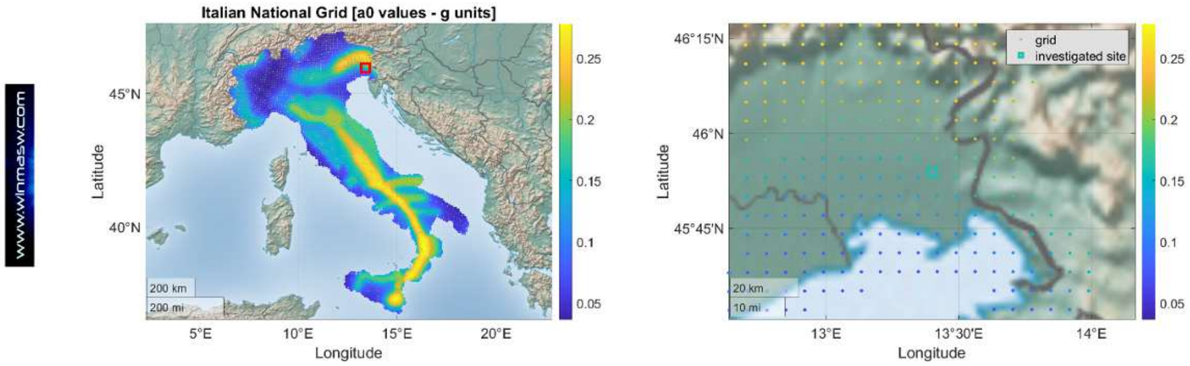
1) Optional but recommended: upload the georeferenced photo [button "photo [recommended]" top left] so that the software can automatically obtain the latitude and longitude [alternatively, if you do not have a georeferenced photo, enter these values manually];



2) set the value of the ***return time*** (which depends on the type of work under study);

3) Click the "**compute spectral parameters**" button (top left), thanks to which we will obtain the parameters (**ag, Tc and F0**) used for the following operations;



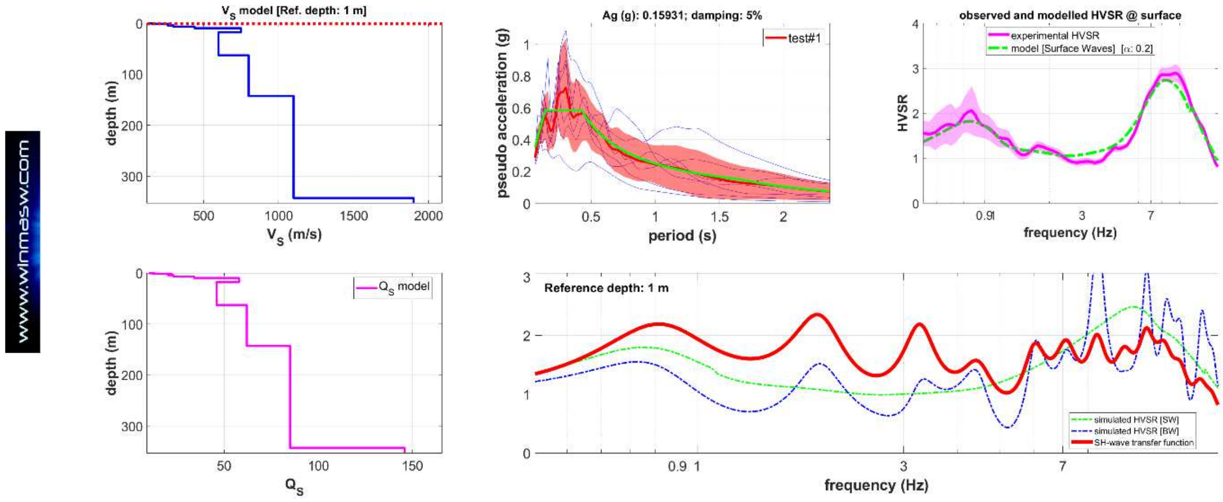


Spectral parameters determined on the basis of the site (latitude and longitude) and return time. So far this operation can be done automatically only for Italian users. For studies outside the Italian territory, the ag, Tc and F0 parameters need to be fixed manual (based on the values tabled the local national building codes).

4) Now, after checking the correctness **ag, Tc and F0** parameters, you can upload the reference earthquakes (referred to the local *bedrock*) [use the "input quakes" button in the "1. Input quake(s)" group box];

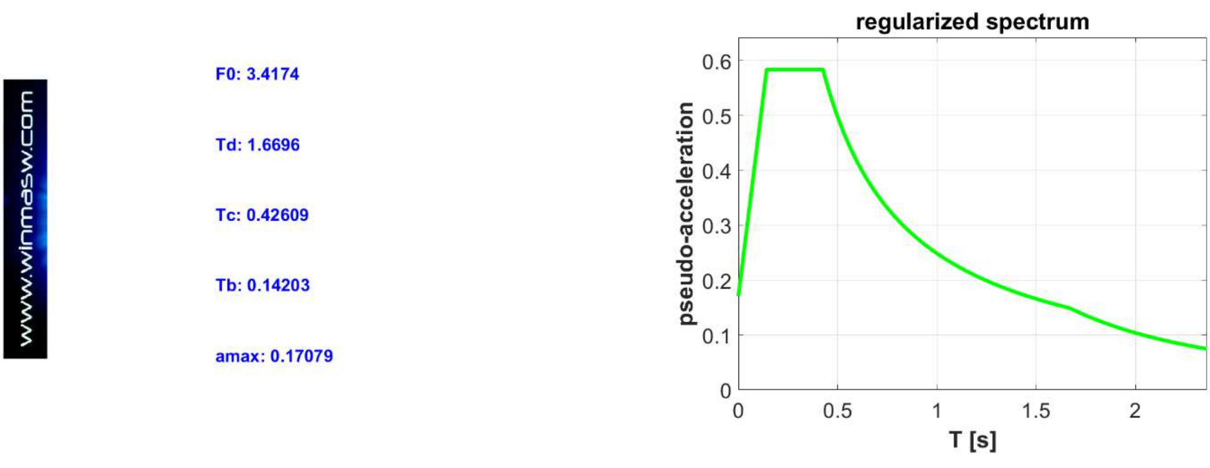
We are now ready for the final computation: click the **"compute site response" button** in the "2. Site effect and Response Spectra" group of the panel.

An example of what you get in the end:



Seismic Response Spectra and computation of the SH wave transfer function (red curve in the bottom right plot - this curve is usually improperly considered as the *amplification curve*). In this case the foundation (reference) depth was 1 m.

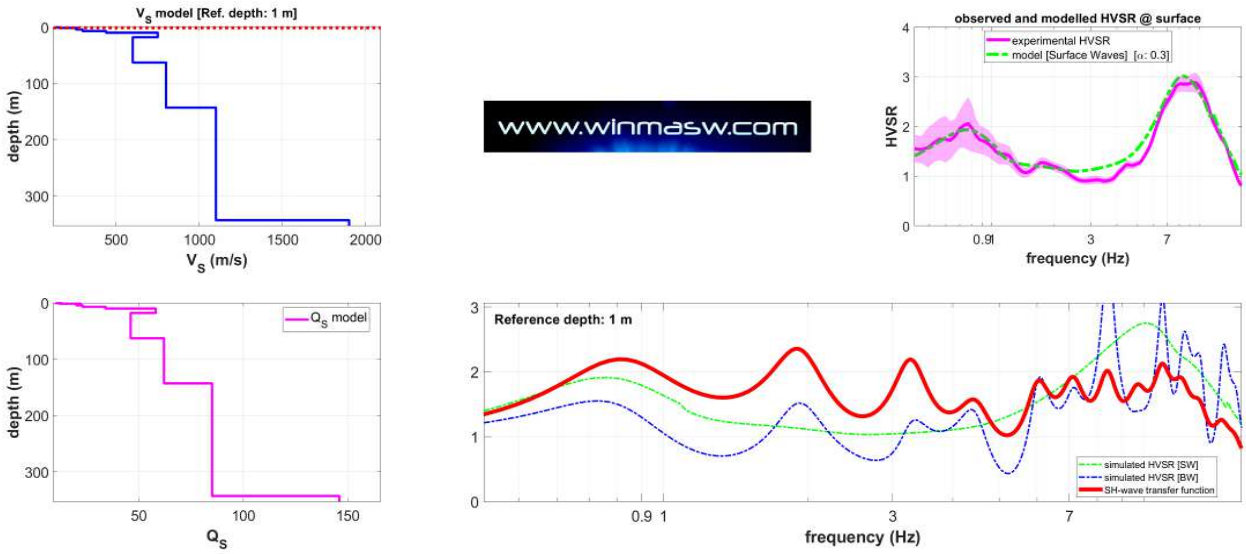
Note how the response spectrum/a is/are also provided after regularisation (see box in the following pages).



Some 'guidelines' require that such simulations are carried out for a number of so-called *limit states* which depend on the structure we are considering. The specific *limit state* can be reported in the 'notes' field so that it appears in the legend of the obtained plots. For details refer to your national building codes.

Some relevant notes

In case you do not upload any quake, the tool will provide you just the outcomes shown in the following snapshot, i.e. the uploaded and modelled HVSR curves and the *SH-wave transfer function*. Compare the following snapshot with the one shown in the previous page (obtained while having uploaded a series of quakes).



As a matter of fact, the *SH-wave transfer function* does not represent what happens during a real earthquake since the actual wave phenomena are much more complex and depends on the kinds of quakes, the azimuth with respect to the source and much more. The wave distortion due to the local site effects are different for the body and surface waves (and, clearly, the *SH-wave transfer function* cannot consider the surface waves - see Bowden and Tsai, 2017);

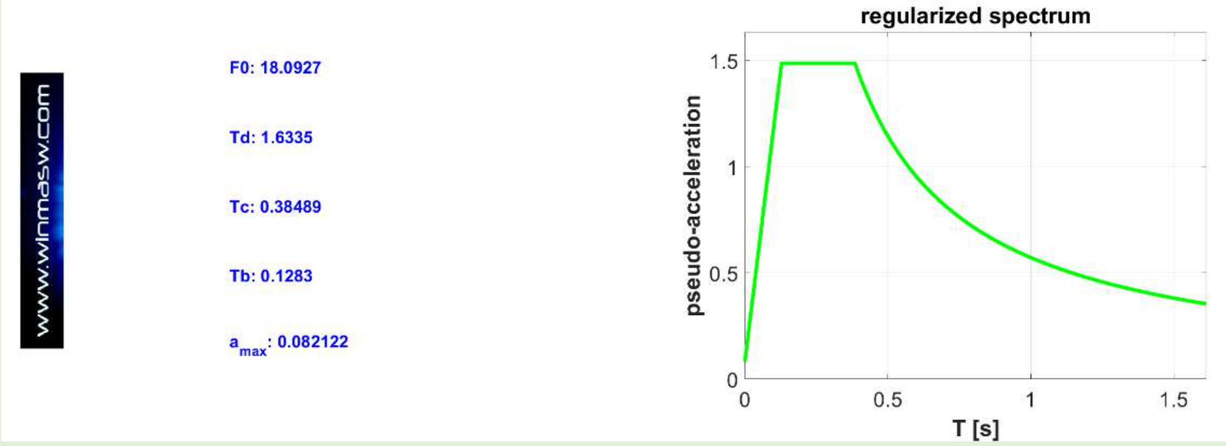
Remember that the final **accuracy of the obtained response spectra** depends on the accuracy of two key parameters:

- ➔ the subsurface model (Vs and Qs values – these latter determine the attenuation)
- ➔ the accuracy of the input (reference) quakes [i.e. the quakes at the local *bedrock*]

You should also always consider that the “unknown variables” are innumerable and it is therefore pretty naïve to put too much emphasis on singular/specific aspects. So just be sure that your V_S (and Q_S) model is well constrained and invest some of your time in studying all the problems and ambiguities of the PSHA approach (i.e. on the way you choose the reference quakes).

If you attend a course/lecture/workshop about the computation of the local site effect (and the response spectra) be careful and try to understand whether it is a serious course about *the physics* of the considered wave phenomena or if it is a meeting about the *national regulations* about it. This is a crucial point: do they want to teach you how seismic waves propagates (and modify their amplitudes) or do they want to tell you the “legal” aspects and the “practical steps” to perform in order to obtain some curve to sell to your final client without let you understand *what* and *why* from a scientific point of view?

SPECTRA REGULARIZATION



The final mean response spectrum is also "regularized" so to obtain the standard F0, Td, Tc, Tb and a_{max} values. This is done according to the schemes presented in:

Newmark N.M. and Hall W.J., 1982. Earthquake spectra and design. EERI Research Report, 82- 71183, 103 pp.

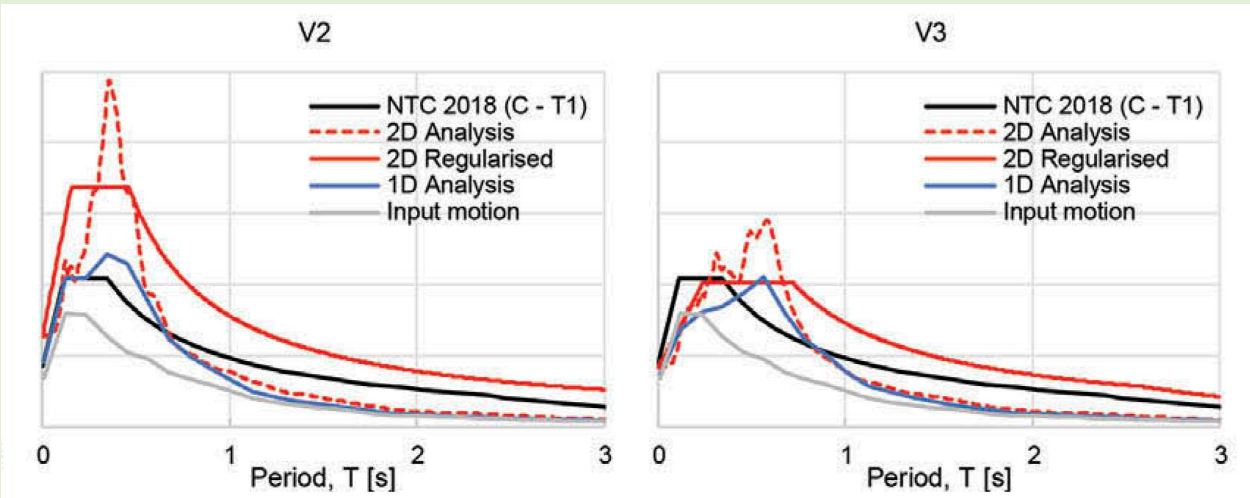
Italian users can also refer to:

Liberatore D. and Pagliaroli A., 2014. Verifica della sicurezza sismica dei Musei Statali. Applicazione O.P.C.M. 3274/2003 s.m.i. e della Direttiva P.C.M. 12.10.2007. Convenzione Arcus – DG PaBAAC Rep n. 113/2011 del 30/09/2011

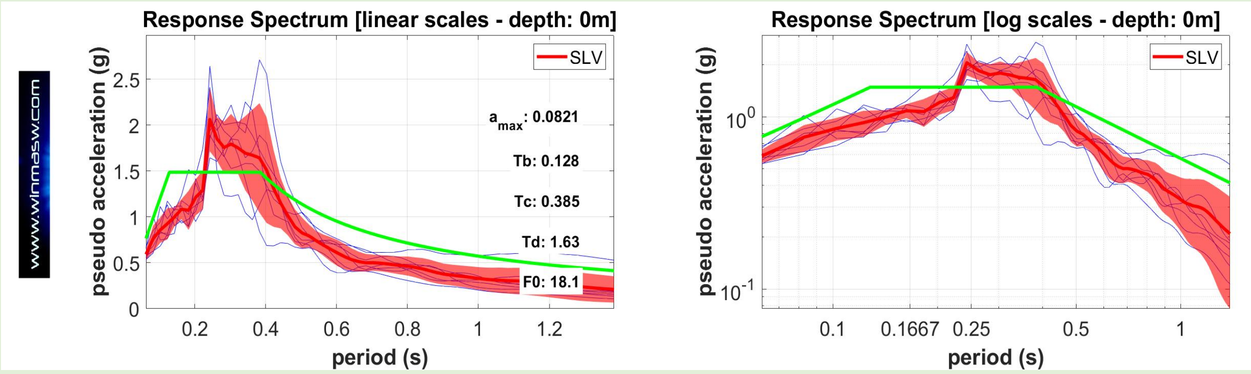
Decreto n. 55 (April 24 2018) and NTC 2018 (Italian seismic regulations)

Chapter 2.5.4.3.1 of the "Indirizzi e criteri per la Microzonazione Sismica" volume of the *Dipartimento di Protezione Sismica* (*Editors* Bramerini, Di Pasquale, Naso, Severino).

Please, note that *regularization* is questionable because it alters the response spectra that you computed while considering the actual V_S profile and the input reference quakes. It is done to facilitate the work of the engineers that are not able to consider the actual shape of the computed response spectrum but its cogency is questionable.
Note that when the actual shape of the mean response spectrum is particularly complex irregular and sharp, the regularized spectrum can significantly differ from the original computed spectrum.

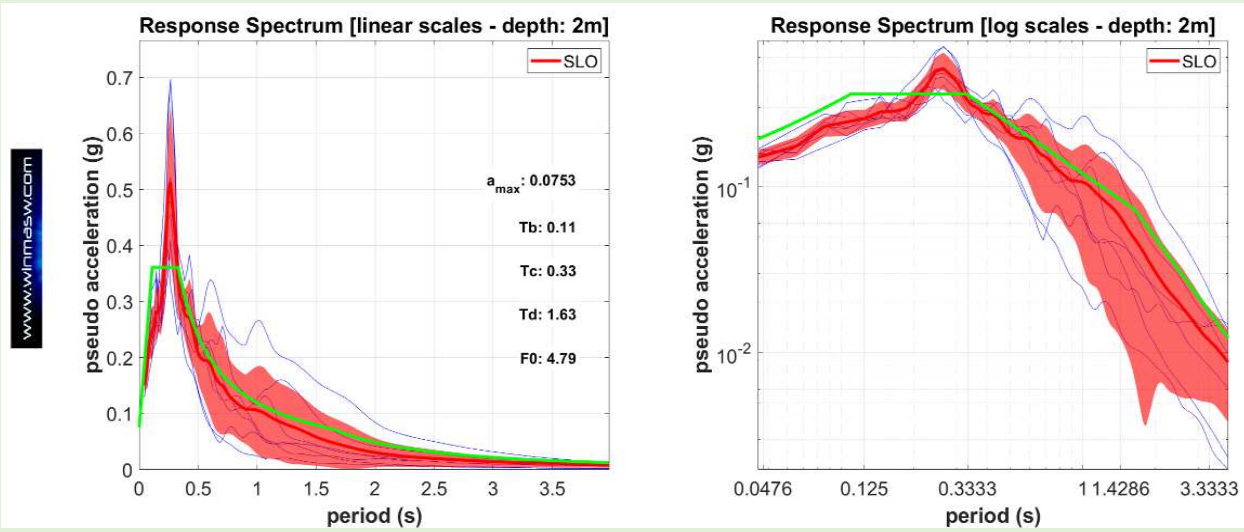


Example of regularised response spectrum [continuous red line] (see the significant difference with the Analysis [dashed red line]). From Pagliaroli et al. (2019).



A further example of regularised response spectrum [green line] (see the significant difference with the mean response spectrum obtained through the analysis [red thick line]).

Below, a final example where the regularized spectrum is not too far from the computed one [red thick line]: this happens cause the computed spectrum has a pretty “simple” shape not far from the one expected on the basis of the regulation assumptions.



16. Back-scattering analysis

Tool available in the *Academy* version

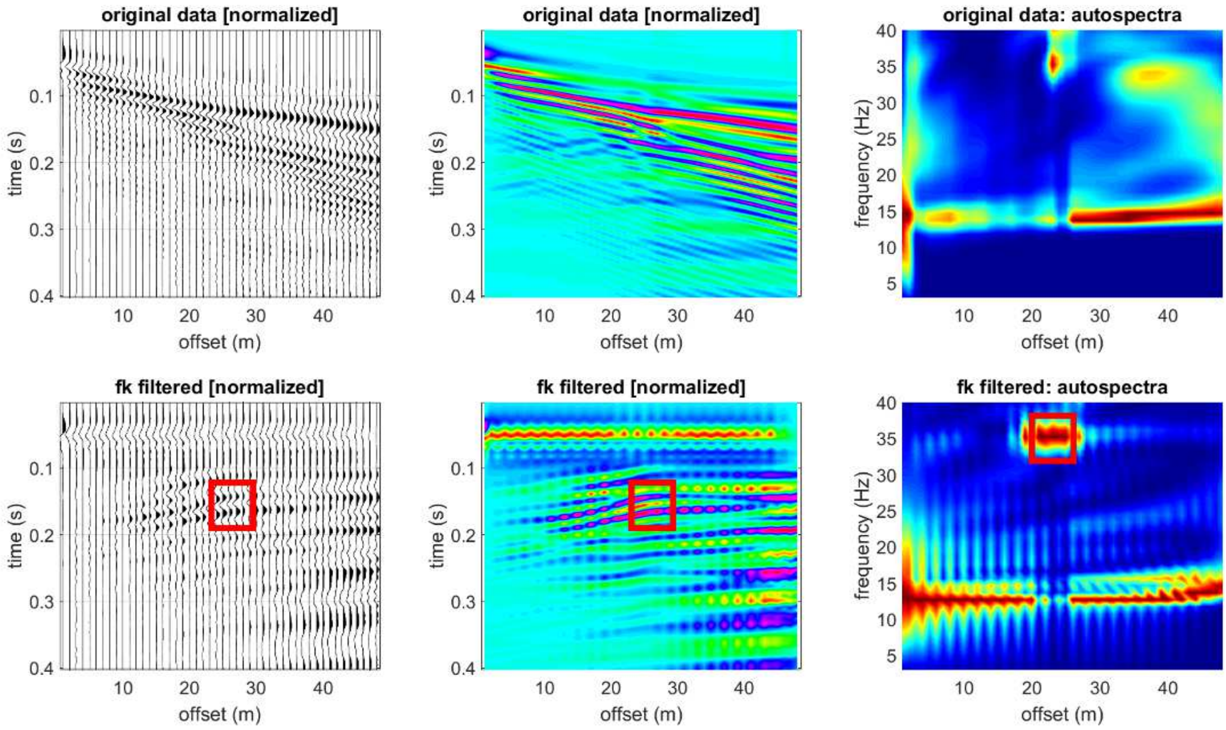
In both the single- and double-component analysis panels, a tool for the *back-scattering analysis* is available (*Back-scattering* button). Such an operation is performed via *fk* filtering and spectral analysis (details are illustrated during our workshops).
Through the back-scattering processing, it is possible to analyze the seismic signal in order to identify/highlight possible *backscattered* energy possibly related to the presence of inhomogeneities in the subsurface (e.g. cavities or intrusions).
In case such inhomogeneities are large enough (and not too deep) it is possible that some Energy is "reflected" (*back scattered*). The analysis here described is aimed at verify if any backscattered energy is actually present.

How deep and large must be a cavity/intrusion to be identified by the back-scattered energy?
As a matter of fact, it is pretty impossible to provide a precise and universal answer. Roughly speaking, we might think that we have the chance to see the back-.scattered energy only for cavities at a maximum depth of about 3-4 m and with dimensions non smaller than a couple of meters.
This is one of those situations where it is impossible to provide general answers and simplifications are, as usual, pretty dangerous.

It is important to underline that, unlike the analysis of the dispersion for the determination of the V_S profile, for this kind of analyses it is important to deal with datasets with a large number of traces (and with a small geophone spacing): 24 is the very minimum value but 48 is surely better – please, remember that in order to have a 48-trace dataset you can use a 24-channel acquisition system and follow the procedures useful to double the number of traces [see the "*combine 2 datasets*" appendix].

Once you upload your data and perform some basic and general data cleaning, through the ***Back Scattering*** button it is possible to perform the analysis aimed at highlighting possible backscattered energy.

In the following an example (from a synthetic dataset where a cavity is present depth of 2 m) while considering the ZVF component (if you have multi-component data the backscattering analysis can be performed on both the components in the "*Joint Analysis of Surface Waves – Velocity Spectra, modelling etc.*" panel).



The upper plots refer to the original uploaded data. From left to right:
a) uploaded seismic traces (classical *wiggle* visualization);
b) uploaded seismic traces visualized according to a color scale;
c) spectral analysis *trace by trace*.

The lower plots refer to the same data but after the *fk* filtering that tends to highlight possible *back-scattered* energy (with a slope opposite to the "regular one").
You can see (red square) the position of the inhomogeneity (in this case a cavity) that produces a "reflection" (to be more precise a *back-scattering* phenomenon).

In case of multi-component analyses, the same plots are reported for both the components.

See also, for instance, the following paper:

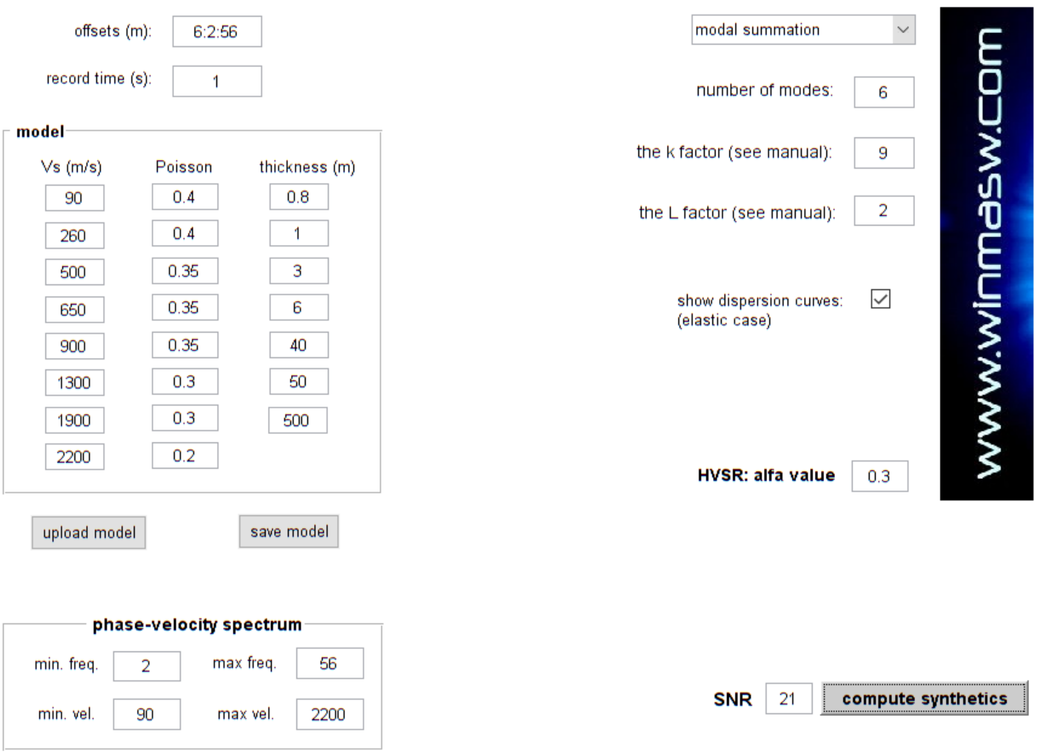
Rahnema, H., Mirassi, S. & Dal Moro, G., 2021. **Cavity effect on Rayleigh wave dispersion and P-wave refraction.** *Earthq. Eng. Eng. Vib.* **20,** 79–88. https://doi.org/10.1007/s11803-021-2006-y

17. Multi-component active and passive synthetics: an educational & planning tool

The button "**SYNTHETICS**" (in the main panel) gives access to the panel to use to generate purely synthetic datasets (via *modal summation*).

Such a thing can be useful for at least two reasons:
1) educational goals: let you students or colleagues to play with different models and realize how the way modes can excite (depending on the model parameters) and for the different possible components (vertical, radial and transversal);
2) simulate specific and peculiar conditions so to **define the best acquisition parameters for a future survey according to different scenarios**.

Together with the phase velocity spectra of the synthetic active data, this tool also computes the RPM and RVSR curves/surfaces. Furthermore, are also shown the ***effective dispersion curves*** in case of passive seismics and the related validity limits (for the considered array).



In the following the list of parameters you need to define:

geometry: in the "offset" box you simply need to fix the values of the array you want to simulate. **Please note that traces do not have to be equally-spaced (see the second example shown in the following pages).**

record time: length of the synthetic data you want to compute (in seconds).

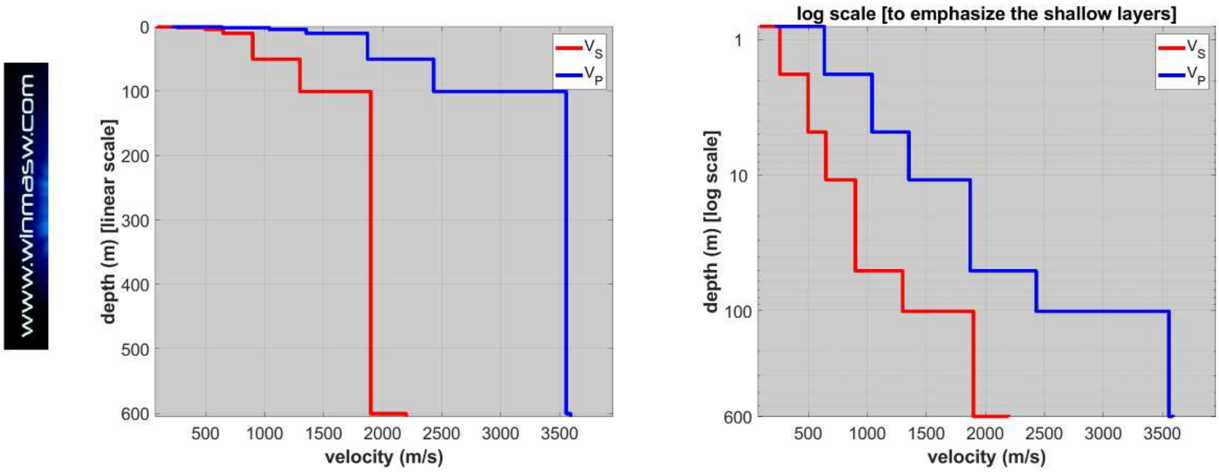
Number of modes: number of modes to use for the generation of the synthetic traces (generated via *modal summation*).

k factor: parameter used to fix the Qs from the Vs values: Qs=Vs/k [Qp values are fixed proportionally to the Vp values]

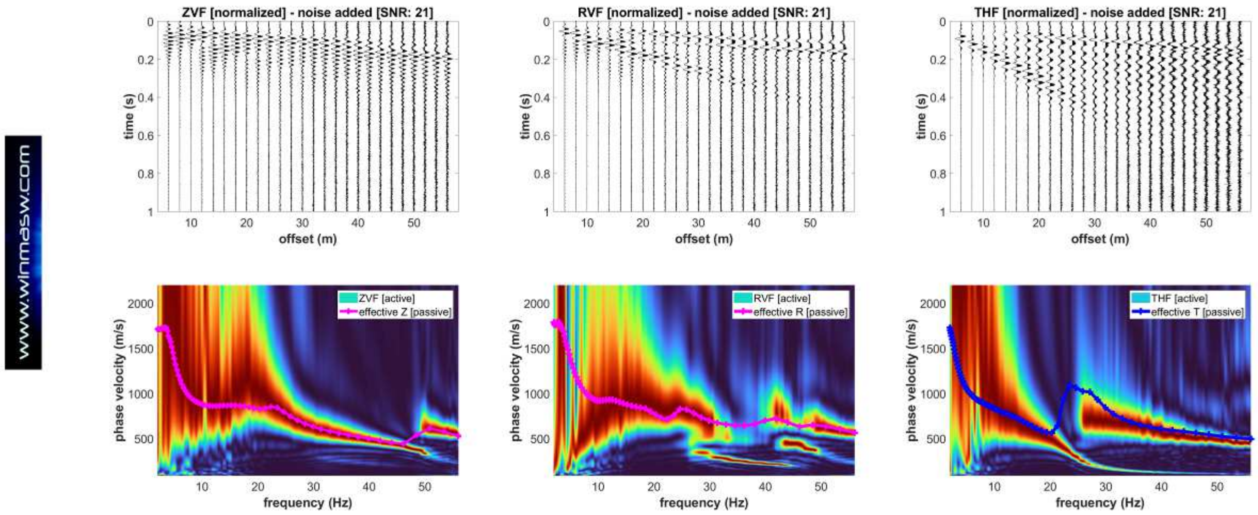
SNR: Signal-to-Noise Ratio: if larger than 0, a certain amount of noise is added to the data (a value around 20-22 can create data a bit more "realistic")

α factor: amount of Love waves in the microtremor background field (0-1) [see the section about the HVSR and the Springer 2020 book]

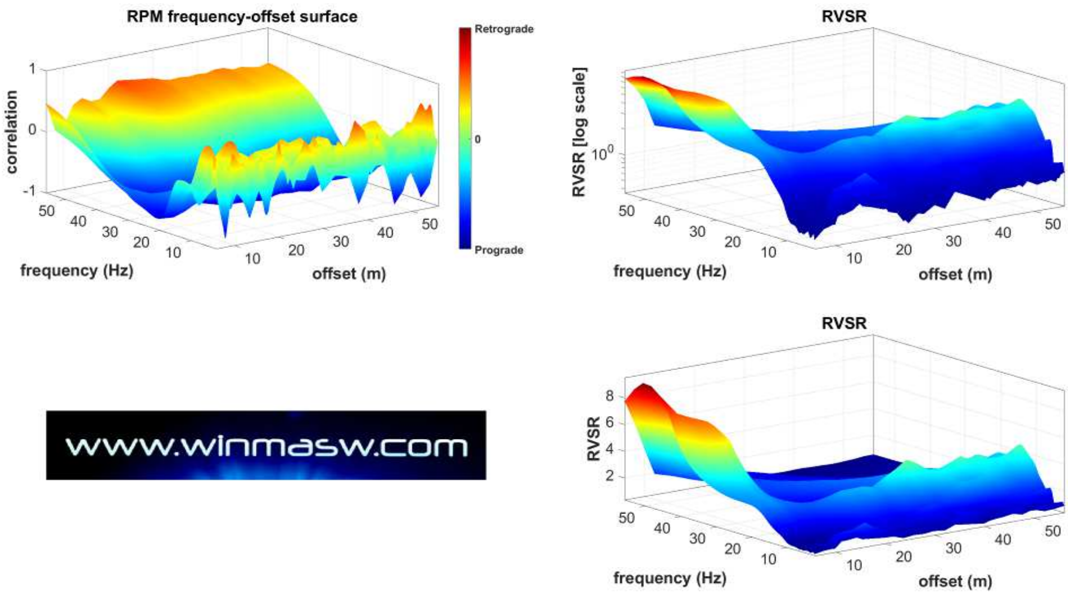
Example#1



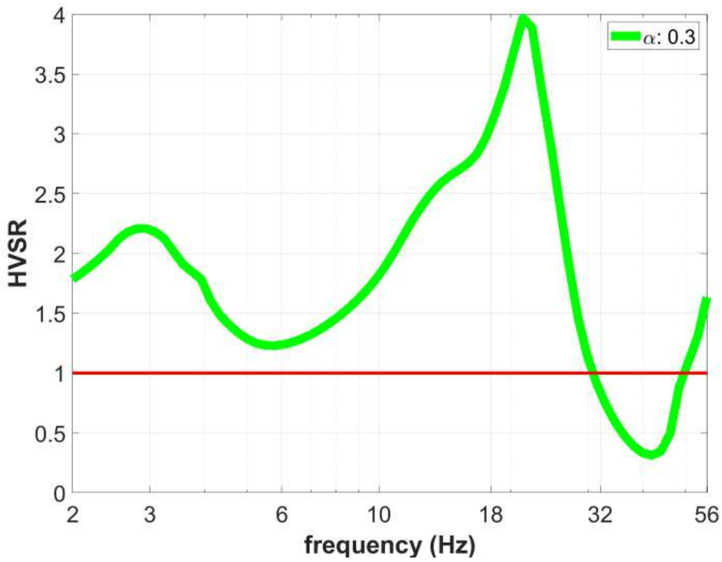
V_S and V_P model with the depth in both linear and logarithmic scale (this second option is useful to better highlight shallow details).

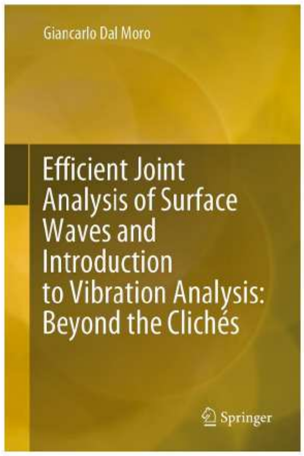


Synthetic traces and phase-velocity spectra for the three considered components: ZVF and RVF (Rayleigh waves) and THF (Love waves).
Also shown the ***effective* dispersion curves** and the validity limits in case of passive-data acquisitions. While the ***effective* dispersion curves** depend on the model, the validity limits depends on the length of the array (try to modify the values so to understand how it works). While analyzing passive data you can rely just on the data between the two green lines (validity limits).



RPM frequency-offset surface and RVSR surface (for all the offset)



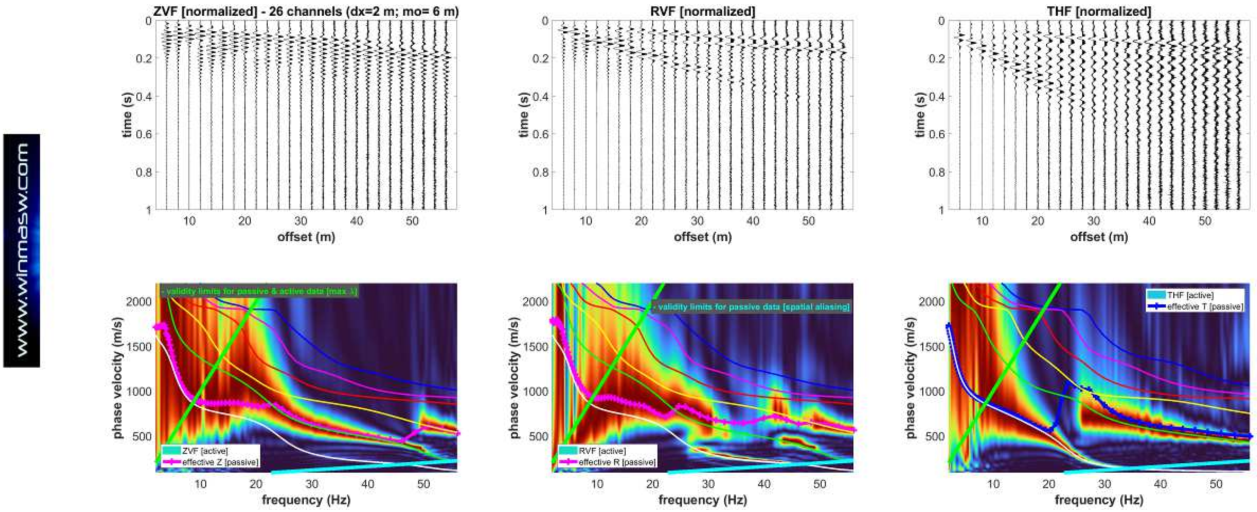


HVSR computed for the considered velocity model

All the figures are (as always) automatically saved in the *working directory* together with the model ("current_model.mod" file).

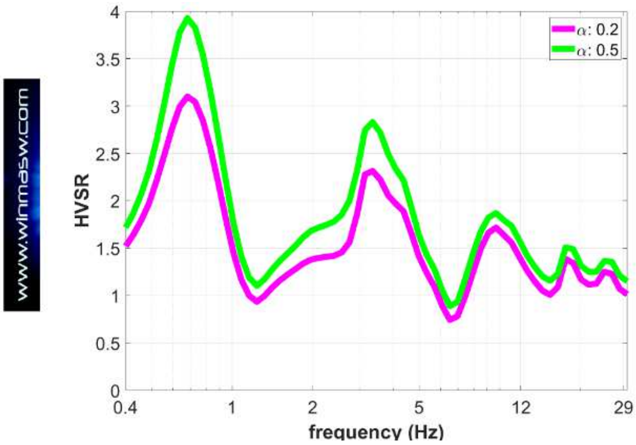
If the **"show dispersion curves"** option is activated, in the next figure (where the meaning of each curve is explained) are also shown the ***modal*** dispersion curves (for the elastic case).

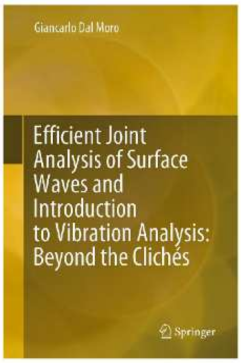
Please, note that (in agreement with the theory) the "difference" between the signals on the velocity spectra and the elastic dispersion curves increases proportionally to the increase of the attenuation (i.e. decreasing the quality factors): the lower the Q values, the larger the "deviation" from the elastic case.



In any case, the most important thing that this example allows us to understand is that in some cases the fundamental mode can be almost completely absent in the Rayleigh-wave data (especially along the Z component - note that along the R component the fundamental mode appears between about 25 and 42 Hz). Therefore multi-component analysis (possibly according to the FVS approach) is the only way to avoid pitfalls/misinterpretations that inevitably lead to erroneous (overestimated) V_S profiles. Love waves (THF component) is (almost always) very clear and simple to understand and prevent us from erroneous understanding of the (more complex) Rayleigh waves.

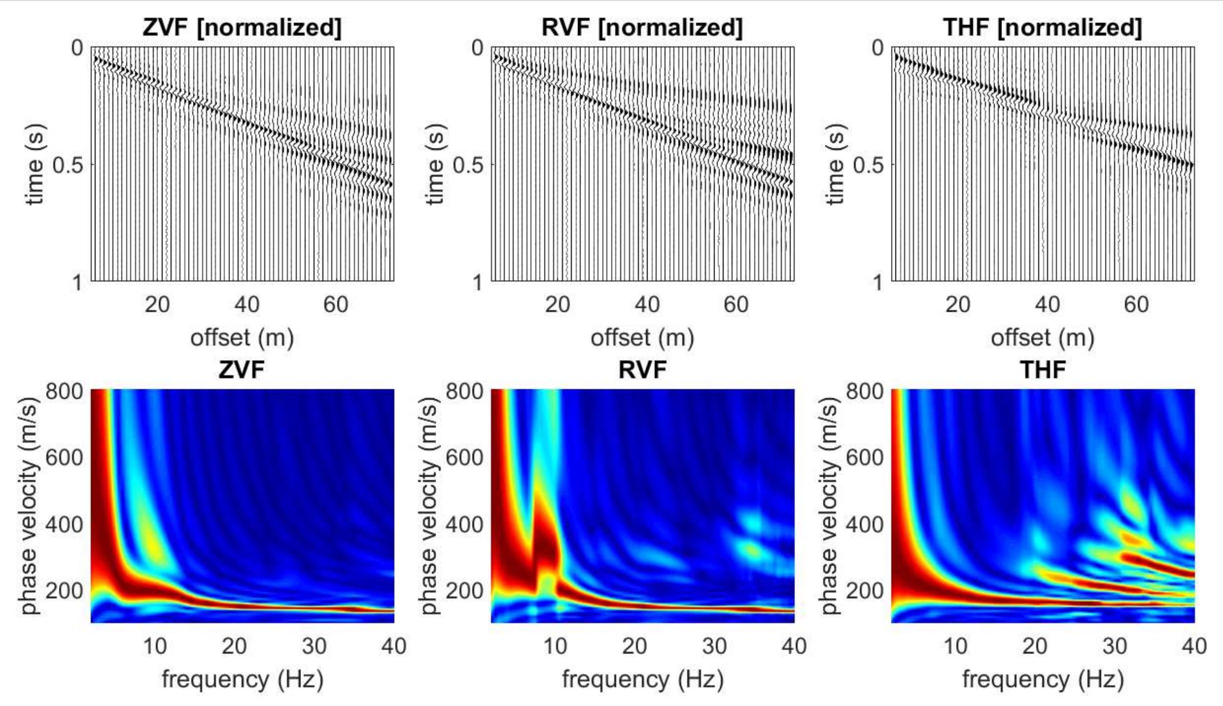
Below the HVSR curves computed for another velocity model while considering two different amount of Love waves in the microtremor background field (α = 0.2 and 0.5).

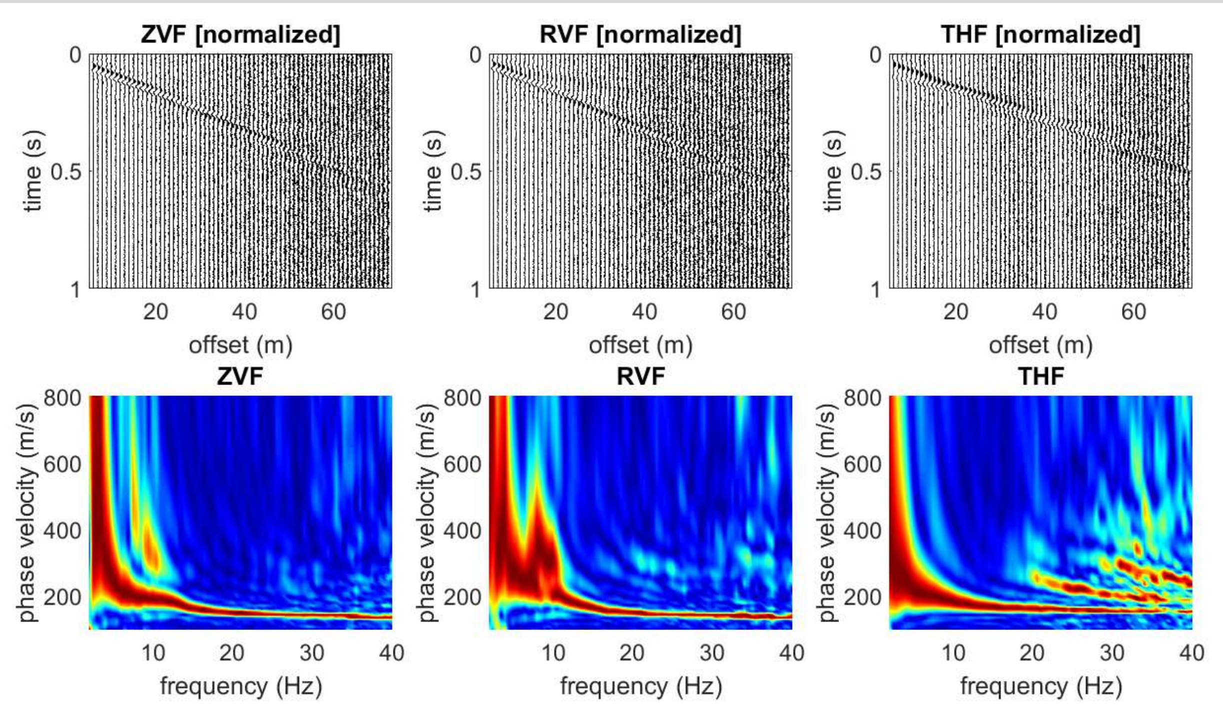




Adding noise to synthetic traces

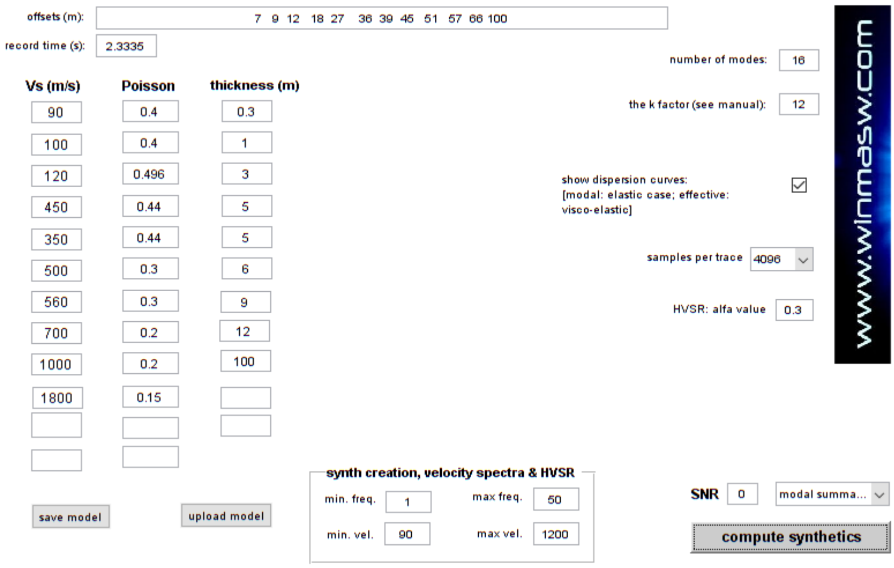
Through the SNR (*Signal-to-Noise Ratio*) value, it is also possible to add some white Gaussian noise to the synthetic data (so to make them more realistic). In the following snapshots you can see the difference between an “ideal” case (no noise) and the case where some noise (SNR equal to 0.6) is added.
The SNR value represent the Signal-to-Noise ratio per sample in dB.



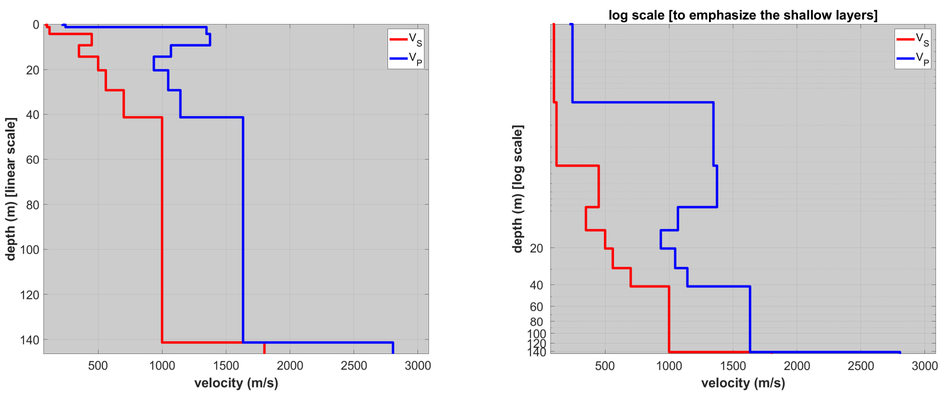


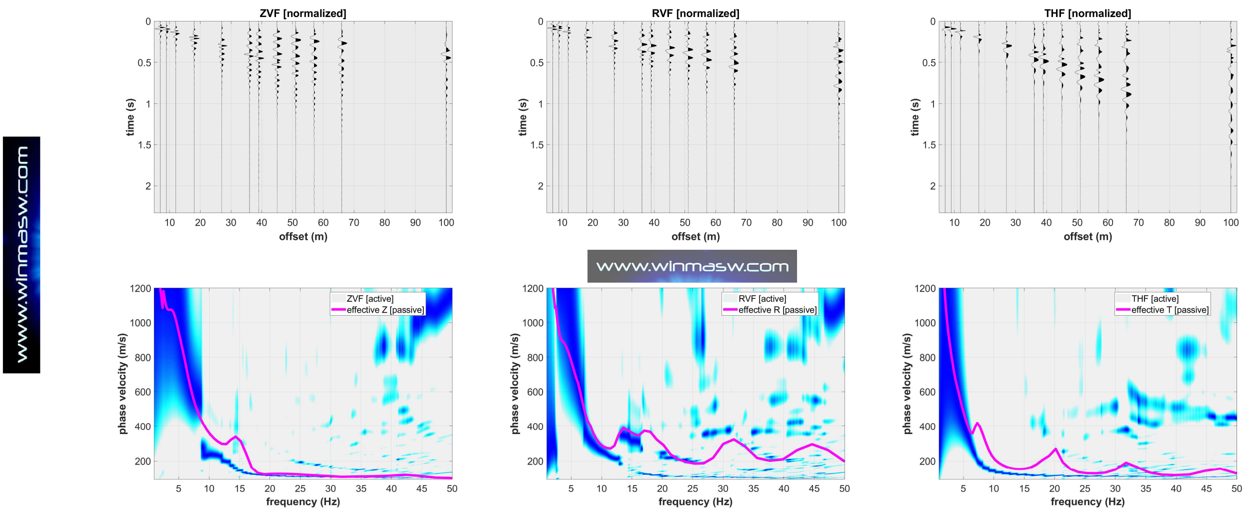
Example#2

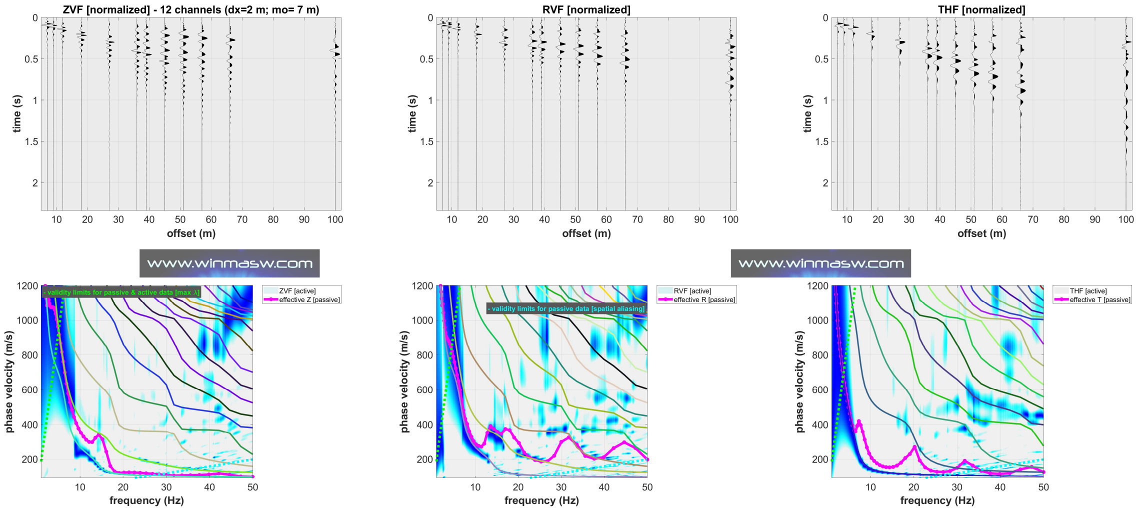
For this second example, we create a **non-equally spaced dataset**. Obtained data allow to understand several important facts related to the actual propagation of surface waves (we leave the study and comprehension of these data as an exercise).



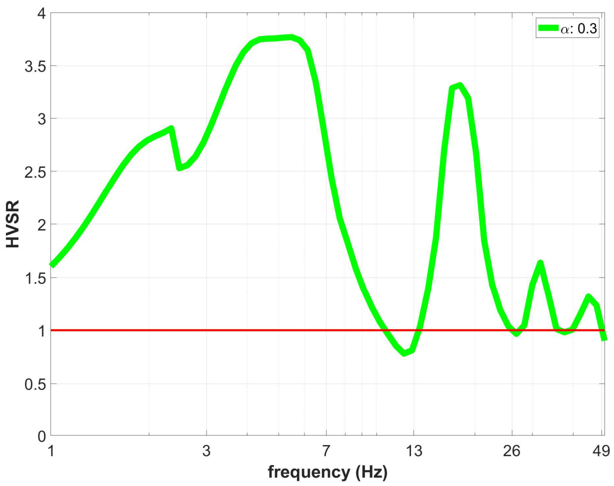
A snapshot of the main panel is automatically saved so to keep track of the adopted parameters.



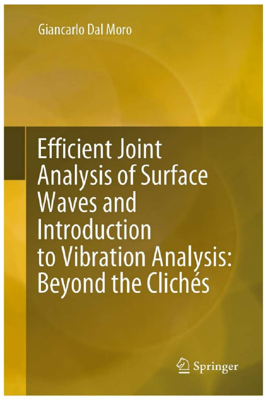




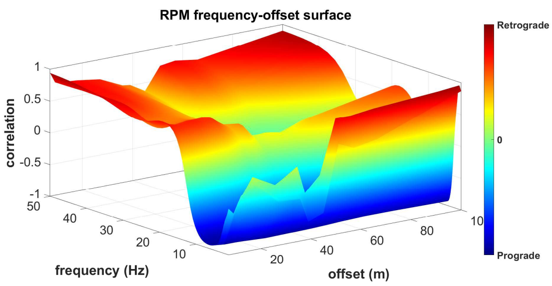
ZVF [normalized] - 12 channels (dx=2 m; mo= 7 m)
RVF [normalized]
THF [normalized]
time (s)
offset (m)
www.winmasw.com
phase velocity (m/s)
frequency (Hz)
ZVF [active]
effective Z [passive]
RVF [active]
effective R [passive]
THF [active]
effective T [passive]
validity limits for passive data (spatial aliasing)



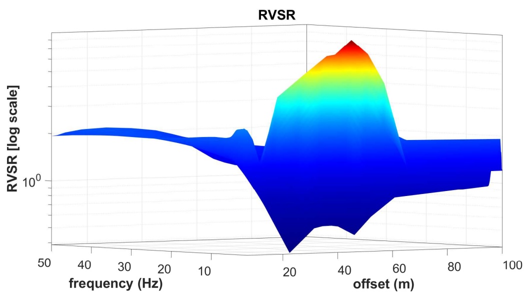
HVSR
frequency (Hz)
α: 0.3



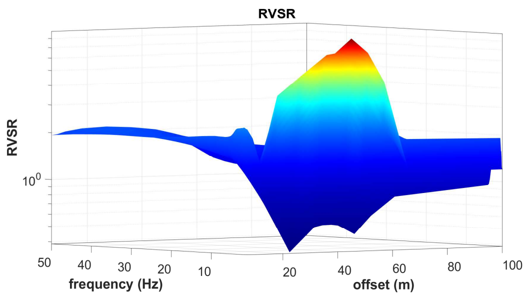
Giancarlo Dal Moro
Efficient Joint Analysis of Surface Waves and Introduction to Vibration Analysis: Beyond the Clichés
Springer



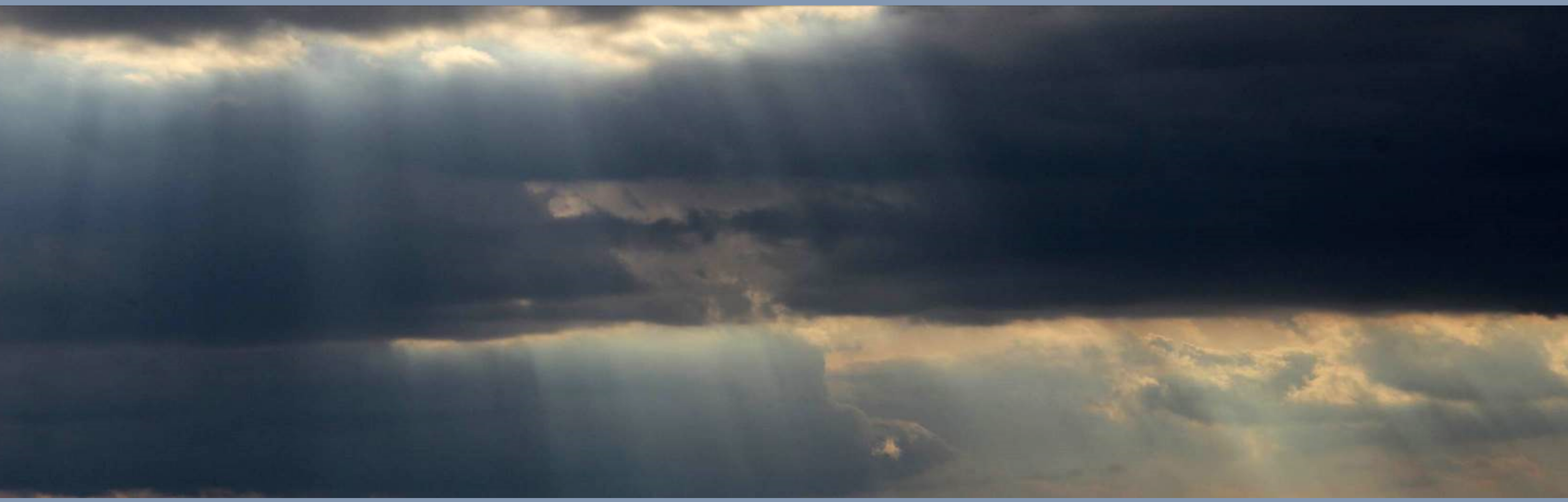
RPM frequency-offset surface
correlation
frequency (Hz)
offset (m)
Retrograde
Prograde



RVSR
RVSR [log scale]
frequency (Hz)
offset (m)



RVSR
RVSR
frequency (Hz)
offset (m)



18. *Demo* and training data

Demo version?

The *winMASW®* application (in particular the *Academy* version) is a highly-sophisticated tool that, in order to be fully and properly used, requires some training that we are glad to provide to all our clients.
If you try to use *winMASW®* while keeping in mind simplistic and erroneous assumptions (for instance about the way modes appear and disappear in a velocity spectrum - unfortunately real-world data can be extremely counterintuitive), you risk not to catch the real point(s) that *winMASW®* (with all its tools) attempts to address through the joint analysis of several "objects".
A series of video tutorials, papers and case studies are available from our web site but the best way to learn to efficiently and jointly acquire and analyze surface waves is visiting us.
For all these reasons, no *Demo* version is currently provided: if you are not already fully aware of the minimum approach we are suggesting (joint analysis of the RVF+THF+HVSR), the *learning curve* might require a certain effort that most of the people do not apply while playing with a *demo* version.

In fact, a *demo* software is something people quickly download just to have the chance to *randomly* click a series of buttons without taking the trouble to study the theory necessary to understand what we are actually doing.

You can evaluate your background by yourself answering the following questions:
1) why multi-component analysis is the only way to obtain reliable V_S profiles?
2) why using vertical geophones (alone) I cannot get the correct V_S profile?
3) do I fully understand the meaning of the RPM, FVS, ZVF, THF, RVF, RVSR, SPAC and ESAC acronyms?
4) do I know that the HVSR has little to do with the actual site effects?
5) do I know the difference between the *modal* curves and the *effective* one?
6) do I know the difference between *group* and *phase* velocities?
7) when it’s particular important the FVS analysis?
8) why P-wave refraction is pointless in case of saturated sediments?

Explanations are illustrated in detail in the books published for Elsevier (2014) and Springer (2020), as well as in several papers (see our web site).

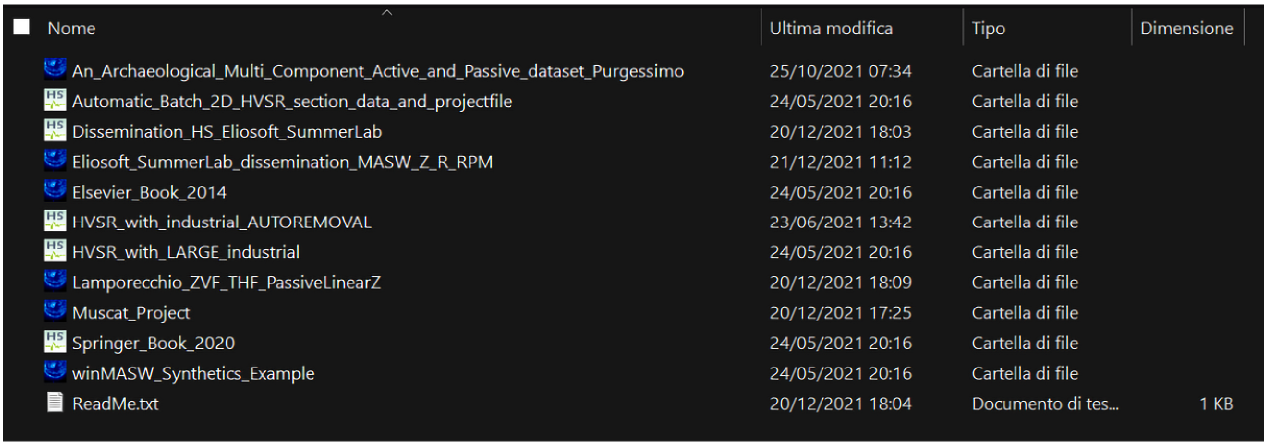
In some cases we are willing to analyze for you one of your datasets (please, ***strictly*** follow the recommendations provided in our guidelines and the nomenclature illustrated in the Elsevier book - paragraph 2.2).

"Quality is never an accident; it is always the result of intelligent effort.”

John Ruskin

Supplied training data

A series of datasets are supplied in the **“Self_Training_Data_Dissemination” folder** if the winMASW®/HoliSurface® USB stick.
Most of such data are analyzed and widely discussed in the **two books** we recommend to carefully study (Elsevier 2014 and Springer 2020).



Nome	Ultima modifica	Tipo	Dimensione
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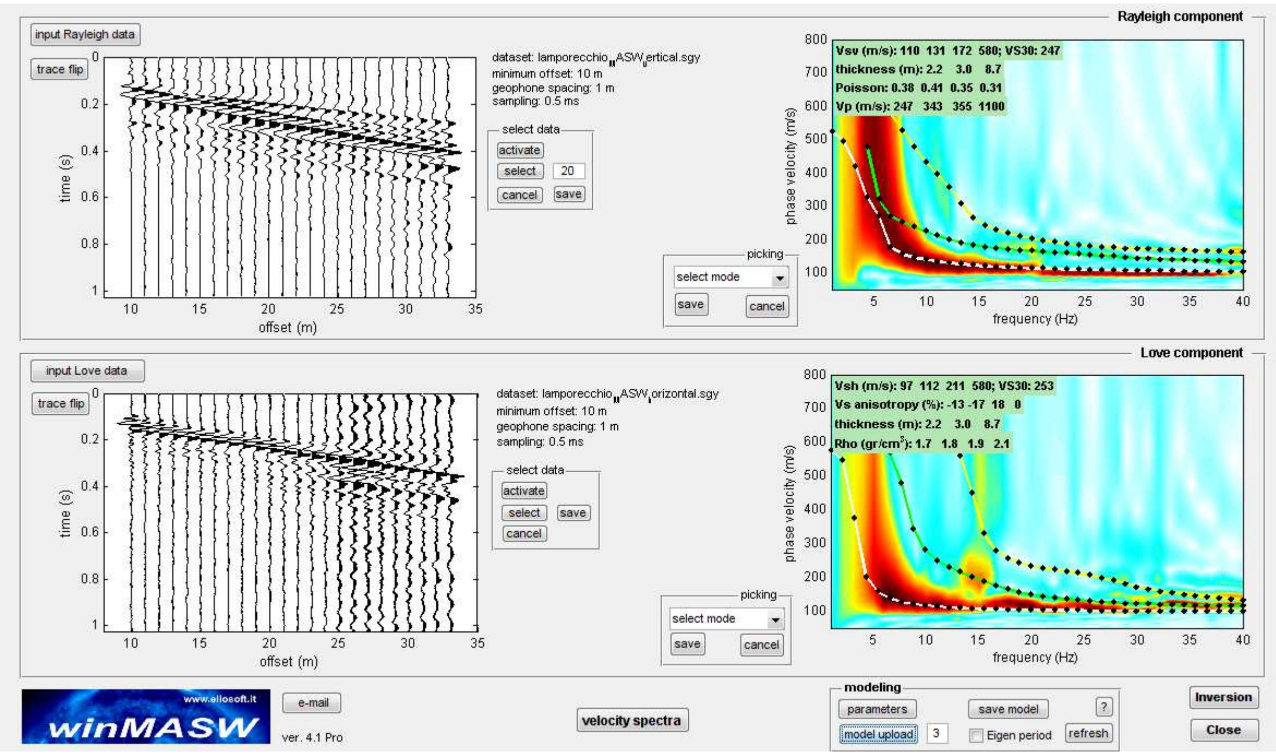
Automatic_Batch_2D_HVSR_section_data_and_projectfile	24/05/2021 20:16	Cartella di file	
Dissemination_HS_Eliosoft_SummerLab	20/12/2021 18:03	Cartella di file	
Eliosoft_SummerLab_dissemination_MASW_Z_R_RPM	21/12/2021 11:12	Cartella di file	
Elsevier_Book_2014	24/05/2021 20:16	Cartella di file	
HVSR_with_industrial_AUTOREMOVAL	23/06/2021 13:42	Cartella di file	
HVSR_with_LARGE_industrial	24/05/2021 20:16	Cartella di file	
Lamporecchio_ZVF_THF_PassiveLinearZ	20/12/2021 18:09	Cartella di file	
Muscat_Project	20/12/2021 17:25	Cartella di file	
Springer_Book_2020	24/05/2021 20:16	Cartella di file	
winMASW_Synthetics_Example	24/05/2021 20:16	Cartella di file	
ReadMe.txt	20/12/2021 18:04	Documento di tes...	1 KB

The data folder in the “**Self_Training_Data_Dissemination**” folder: try to reproduce the analyses and results presented.

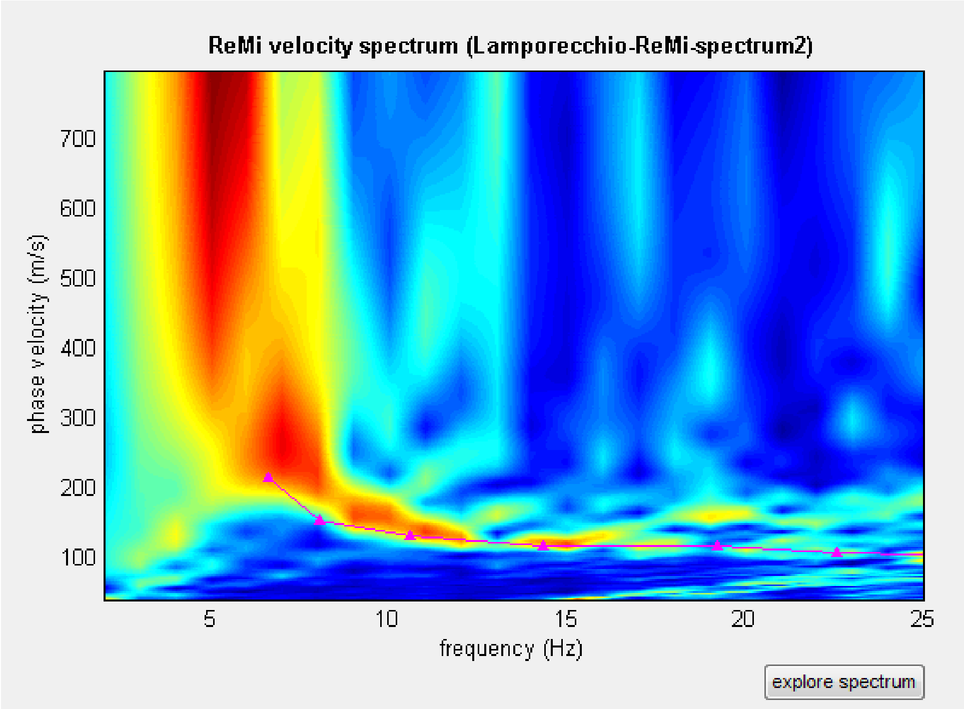
An old dataset for *ReMi* and joint analysis of Rayleigh and Love waves from active data

Among the datasets provided in the winMASW® USB/DVD, there is a very old dataset recorded during a workshop in Tuscany (IT) [Lamporecchio folder].
The user can play with the data so to get familiar with the joint analysis of Rayleigh and Love data, considering that the solution is not far from the following:

thickness (m)	V_{SV} (m/s)	V_{SH} (m/s)	V_P (m/s)
2.2	110	100	247
3.0	130	112	343
8.7	170	210	355
-	580	580	1100



If you compare the dispersion for the Z component from the active and passive data, you'll see that, according to the theory, the curve from active data lies along the lower limit of the velocity spectrum obtained from ReMi.



Please, consider that because of a series of technical aspects (the main one is probably related to the directionality of the signal and all its consequent problems) <u>we highly recommend to use the **(multi-component) ESAC technique** and not the ReMi one</u>.

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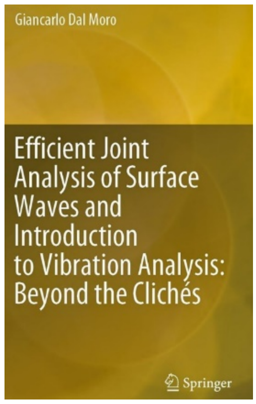

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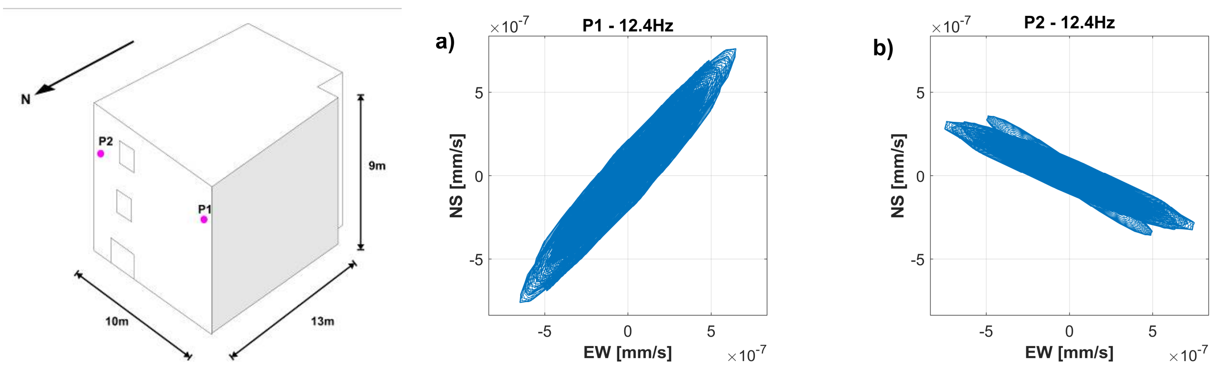

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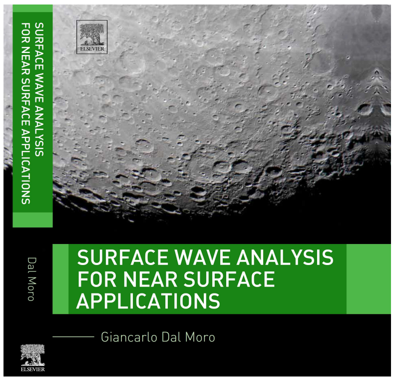

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APPENDICES

Appendix A: Surface-wave data acquisition

Please, see also *Guidelines for MASW, ReMi, ESAC and HVSR acquisitions.pdf* enclosed in the *winMASW* installation folder (subfolder "documents")

The acquisition of data aimed to MASW analyses is not that different from similar acquisition aimed to refraction studies.
You just need to array geophones (standard vertical component geophones if we need to analyze Rayleigh waves or traditional horizontal component geophones if we need to analyze Love waves) lined up with the source (see Figure A1) using a source with vertical hammer impact to generate Rayleigh waves or a "transversal" one for the Love ones.

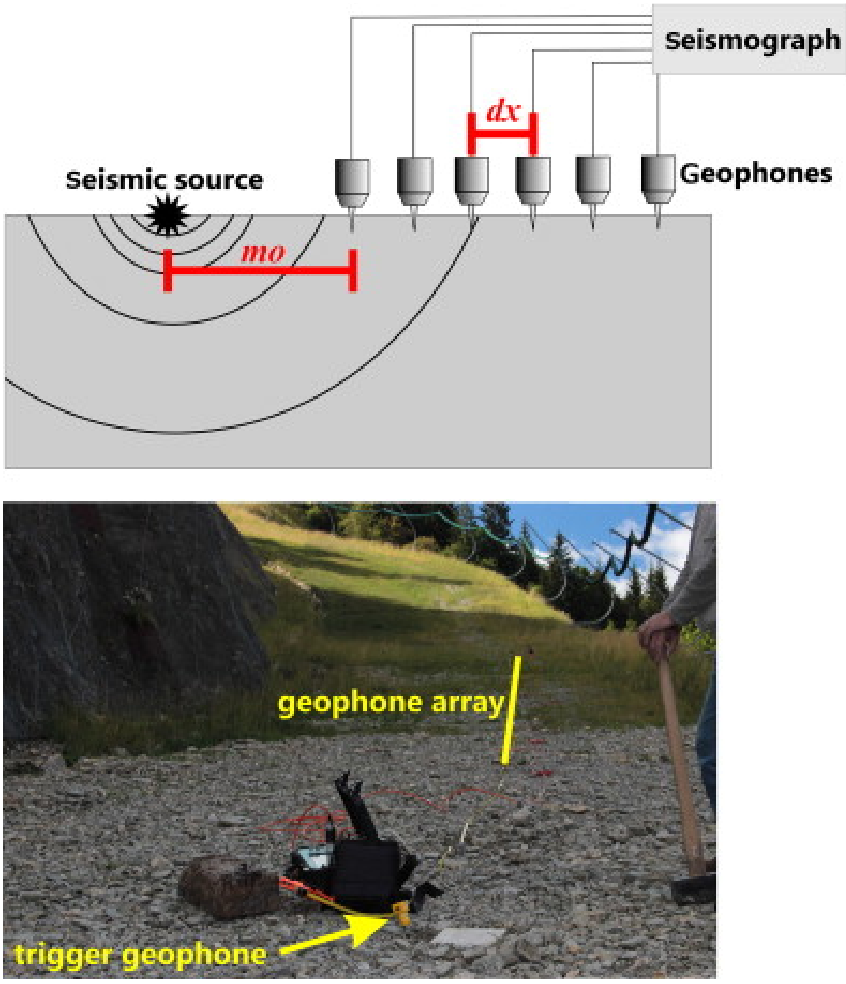


Figure A1. Seismic array. In case you use a vertical impact source (the traditional hammer blow) and vertical component geophones, you'll acquire data useful only for the vertical component of Rayleigh waves. Using horizontal-component geophones you can record both Love and Rayleigh waves (see the Elsevier book or our *Guidelines* in the *documents* folder).

Remember that horizontal geophones can be used to record both Love waves and Rayleigh waves (radial component), thus optimizing the acquisition procedures (see Figure A2, the Elsevier book and all our articles and case studies available on our web site).

Please, use them instead of using the vertical geophones (which can record only the vertical component of Rayleigh waves - often very problematic in terms of complexity of the velocity spectrum to interpret).

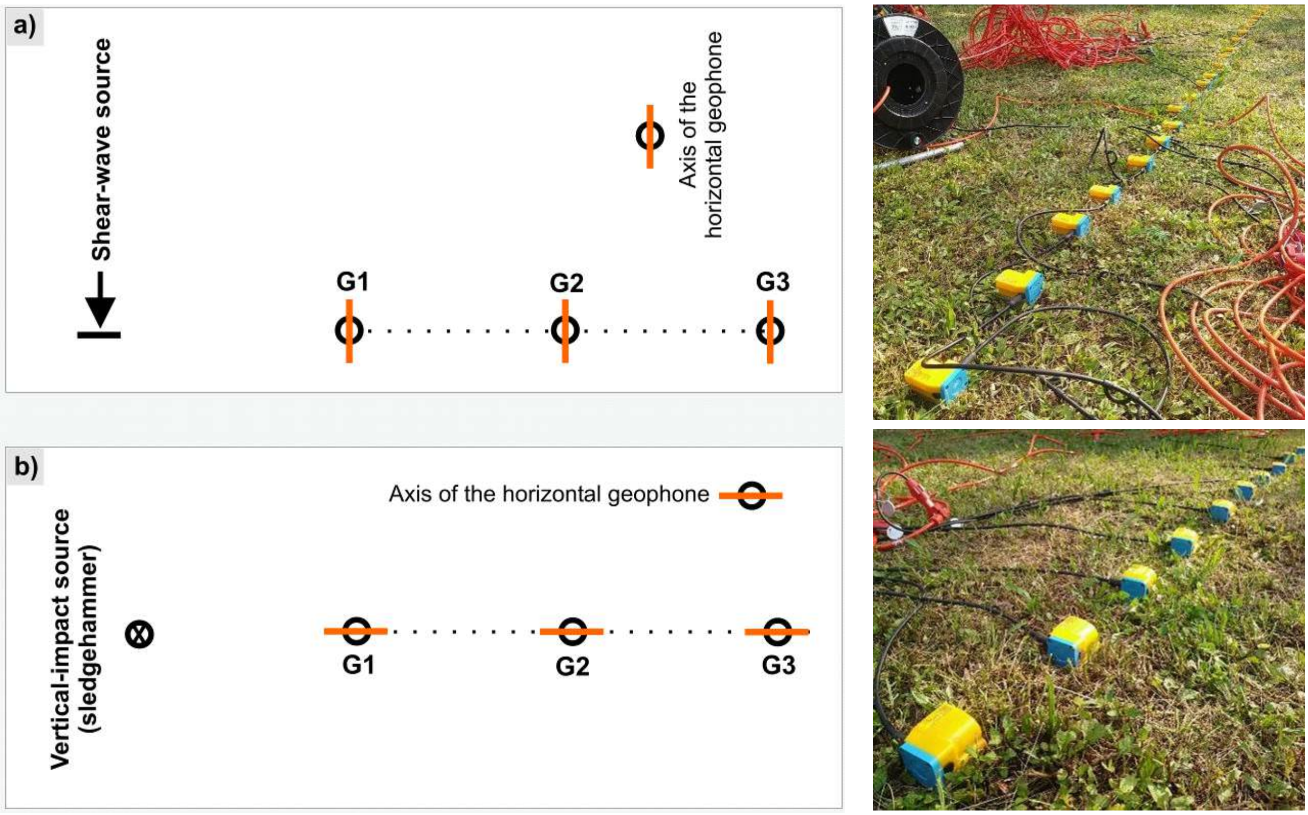


Figure A2. Data acquisition using only horizontal geophones: a) geophone array for SH-wave refraction and Love waves; **b)** geophone array for Rayleigh waves (radial component). Of course, Rayleigh waves can be detected using also vertical geophones but in case you are using horizontal geophones, you can record both Rayleigh (their radial component) and Love waves and, therefore, you can jointly analyze them and obtain a much more reliable V_S profile.

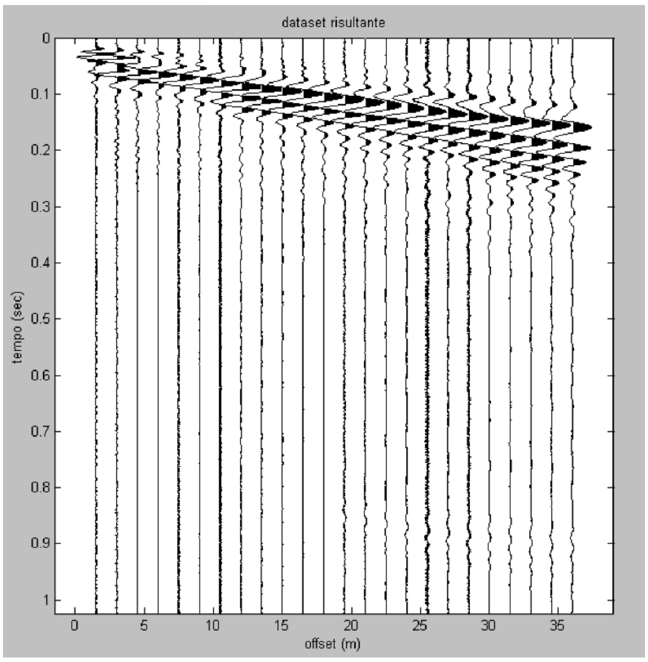


Figure A3. Example of *Common shot gather*: The widening of the initial signal, due to the dispersion of the surface waves is clear. During the acquisition, it is important to make sure that the surface waves trend is not cut by a reduced acquisition time. In the shown case an acquisition time lower than about 0.40 seconds would have caused the loss of the useful signal.

In the case as reported in **Figure A3** an acquisition time of half second could have been enough. By the way, problems coming from the cut of the data (see box "effect of data cut off") should be avoided, avoiding as well to get more than useful data.
In the actual case (as in most, as a matter of fact) 1 second is more than enough: excessively increasing the registration time would give an increase of the relevance of the data without a relevant enhancement of the dataset quality.

Material	V_S (m/s)
Incompetent soils and peat	60 – 180
Competent soils	180 – 350
Very competent soils and gravels	350-600
Weathered rock	600-1000
Solid rock	> 1000

Table A1. Typical V_S values for different common materials.

For recording multi-offset data useful to define the phase velocities, just keep in mind few simple and general things:

1) the **longer the array**, the better are defined the low frequencies (so use all the available space)
2) the **geophone spacing** is not important (carefully study our *Elsevier* and *Springer* books)
3) the ***minimum offset*** (i.e. the distance between the source and the first geophone) should be as large as possible
4) data **stack** is crucial to obtain high-quality data
5) record multi-component data

For instance, if you are working on a big field with plenty of space and have a 12-channel seismic cable with channel spacing of 8 meters, we should spread your seismic cable so to record two seismic datasets (for the R and T components) so to obtain the two following datasets (please, see the "2.2 ACTIVE METHODOLOGIES" section of the Elsevier book, where we explain in detail how to work on the field and how to properly name the files):

RVF_mo8_dx8.seg2

THF_mo8_dx8.seg2

[mo = minimum offset; dx = geophone spacing]

Passive seismic acquisition (*ESAC/SPAC* and *ReMi*)

In a ReMi acquisition our interest is registering the dispersion of surface waves generated by microtremors. Regarding these low frequencies (that characterize the microtremor data) some points should be highlighted:
In order to register with enough quality the signal coherence at low frequencies, two aspects should be considered:

1. we need long arrays (but it actually depends on the specific purpose of the survey)
2. we need to work with good-quality 4.5 Hz (or less) geophones

A last consideration on the dataset length useful to the ReMi analysis.
Aim of the ReMi analysis is the registration of events which we don't know the place of origin and the moment when they are likely to happen. Therefore we switch on the seismograph and, through the 24 geophones, we register what happens in the hope a useful signal reaches us.
This means that the registrations need to be long. Many seismographs are limited though. We consequently advise to make different one by one registrations (in order not to weigh too much on the software as well) in order to get at least 5 minutes registrations (the length of each dataset not being less than 30 seconds)
If for instance our seismograph allows to take a data for a minute, we'll make 5 acquisitions of 1 minute each. Thanks to winMASW we then will be able to upload and analyze all data and choose the most defined velocity spectrum.

Geophone spacing (m)	Array must be as large/long as possible **ReMi**: use the same geophone spacing **ESAC/Ps-MUCAA**: geophone spacing can vary
Type of geophones	vertical geophones in case you want to analyze the vertical component of Rayleigh waves and horizontal geophones in case you want to analyze the radial and/or transversal components (see what is actually possible with the PS-MuCAA and SuPPSALA tools) Eigen period: 4.5 Hz (or less)
Record length/time	For ordinary applications 15-20 minutes For very large arrays 1 h
Number of channels /traces geophones	For most of the common applications (arrays up to about 80 m), 16 channels are usually sufficient but everything depends on the specific goals
***dt* (sampling interval)**	0.004 s (4 ms, 4 milliseconds) and up to 8 ms
Recommendations	No AGC (*Automatic Gain Control*) No filter

Table A2. Summary data regarding the suggested parameters for passive seismic acquisitions (ReMi or ESAC)

Note to *ReMi* acquisitions

The reason why ReMi measures are sometime requested instead of (or together with) the MASW ones is that they can catch lower frequencies making the users' investigations deeper.
This is not wrong. But some problems inside the same analysis of the surface waves dispersion make this a bit unrealistic (practically speaking).
To cut it short, we remind you that to have good results at low frequencies you should need quite long arrays and very sensitive (low frequency) geophones.
About passive (array) measurements **we highly recommend ESAC** (being based on bi-dimensional acquisition geometry the directivity problem is solved and the overall robustness of the mathematics behind is such to provide much better results).

If you are not completely sure about the best type of equipment to buy for analyzing surface waves (type and number of geophones and type of 3-component geophone for HVSR measurements), please email us and we will give you our recommendations.

Some recommendations about the data acquisitions for the analysis of the attenuation (active MASW data)

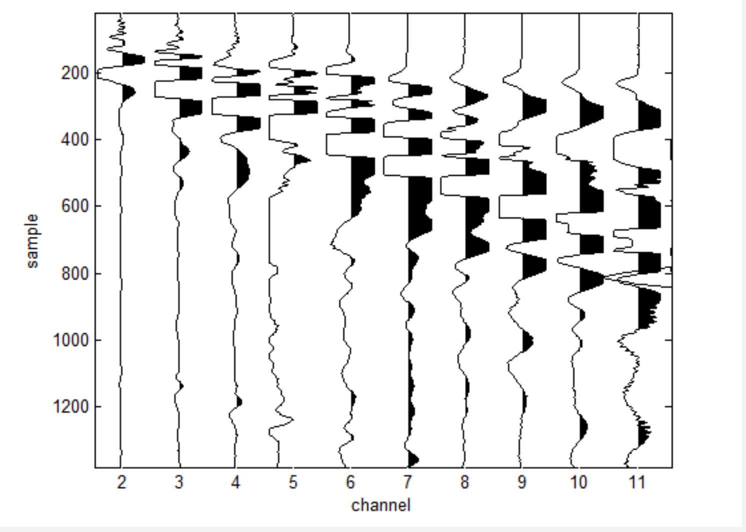
If you wish to analyze the attenuation of the seismic signal (in order to estimate the Q_S quality factors) data acquisition should be *perfect*.

The introduction of filters, gains, etc., alters the actual natural conditions and should be therefore applied only if we perfectly and actually master the whole thing.

For analyzing the data attenuation there are few crucial points to consider during the data acquisition:

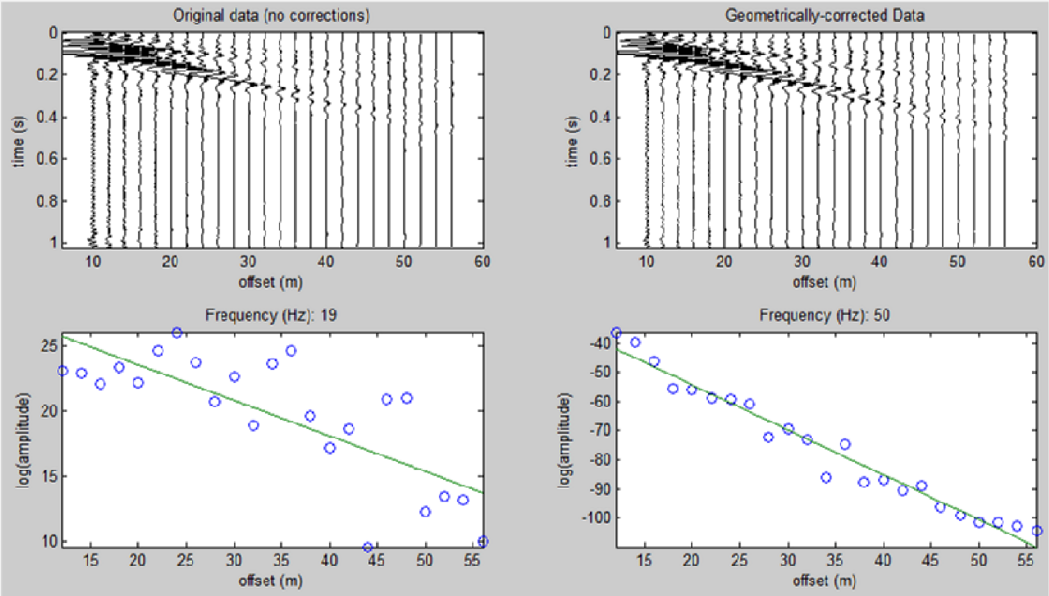
1. **the gain value has to be the same for all channels**
2. **no signal saturation**
3. **make sure you have a good geophone-soil coupling**

The reason for that prudence (to be followed in whatever acquisition) lays on the fact that the analysis of the seismic attenuation are aimed to quantify the decrease of the seismic signal amplitude according to distance (and to the different frequencies making the signal)
It should be clear that alterations can damage the analysis of signal attenuation.
Since attenuation varies according to frequency (as for dispersion, lower frequencies are sensitive to deeper soils features) any filtering is not allowed (unless you are aware of the consequences during the analysis)
Finally, since bad coupled geophones lead to a worse data quality in the altered amplitudes, make sure the geophones are permanently coupled to the soil.
What is the signal "saturation"? Following figure clarifies the problem. As you can see some portions of the traces result cut off because the signal has gone over the registration instrument dynamic range, as an excessive gain was defined during acquisition.



Such problem has to be avoided all times you deal with analysis in the area of frequencies (both for the analysis of the dispersion curves and the attenuation)
It is obvious as well that the gain value mustn't be excessive (to avoid saturation) and of the same value for all traces (if we need to evaluate the amplitude decrease with the offset).

In *winMASW®* you can verify the real traces amplitude clicking on "test amplitude" in the section dedicated to attenuation.
Once uploaded the dataset you wish to analyse, click on "test amplitude": the following reported window opens showing the original data and the corrected one by means of the geometric correction.



As you can see, the geometric correction slightly increases amplitudes.
In fact following analysis aims to measure the value of the amplitude decrease linked to the only viscose component and not to the geometric factor linked to the distribution of energy over an always wider front. Such component is called "geometric".
In the bottom of this window you can see the amplitude decrease for both limit frequencies as specified on the main window ("Min & Max frequencies" fields).
In the reality, what is plotted according to the offset is the amplitude logarithm. This way, the link between amplitude and offset (in itself exponential) becomes linear.
The larger data scattering, as observed, for low frequencies can be due to different reasons: problems related to *near field* effects (bigger for lower frequencies) or to components linked to body waves, data noise, appearing of different modules of the surface wave, etc

File naming: a key point

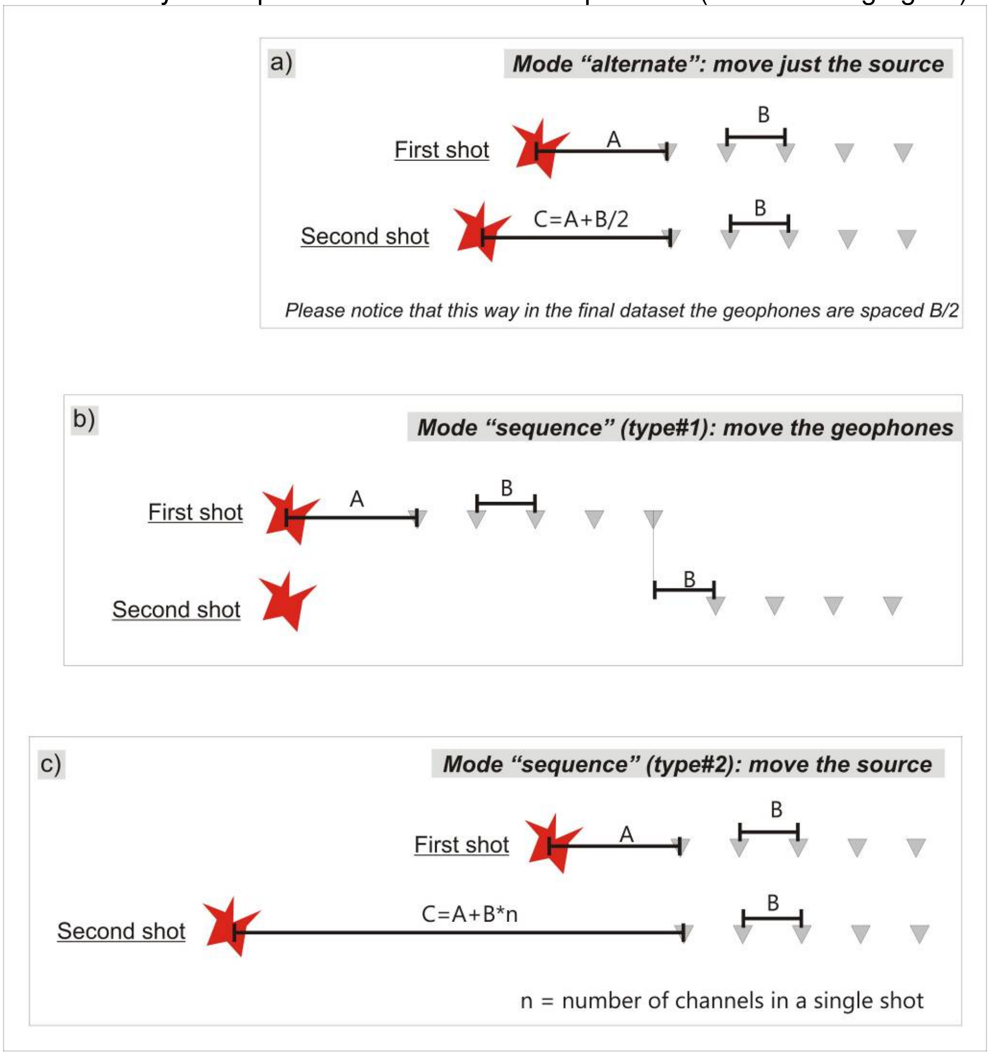
We highly recommend to follow the recommendations explained in the *Elsevier* and *Springer* books so to provide all the details of the geometry and components already in the file names. For instances:

ZVF_dx4_mo6.sg2
RVF_dx5_mo8.sg2
THF_dx5_mo8.sg2
HVSR_central_position.sg2
HVSR_near_source.saf

Appendix B: combine 2 active datasets

This utility allows you to combine two datasets acquired separately with two different but **consistent geometries**. The traditional case is that of two dataset each made of 12 channels (many users don't dispose of 24 channels seismographs). The aim is to obtain an only 24 channels dataset able to generate more detailed velocity spectra.
To do that, make sure you executed both acquisitions correctly.

There are at least 3 way to acquire data useful for this operation (see following figure).



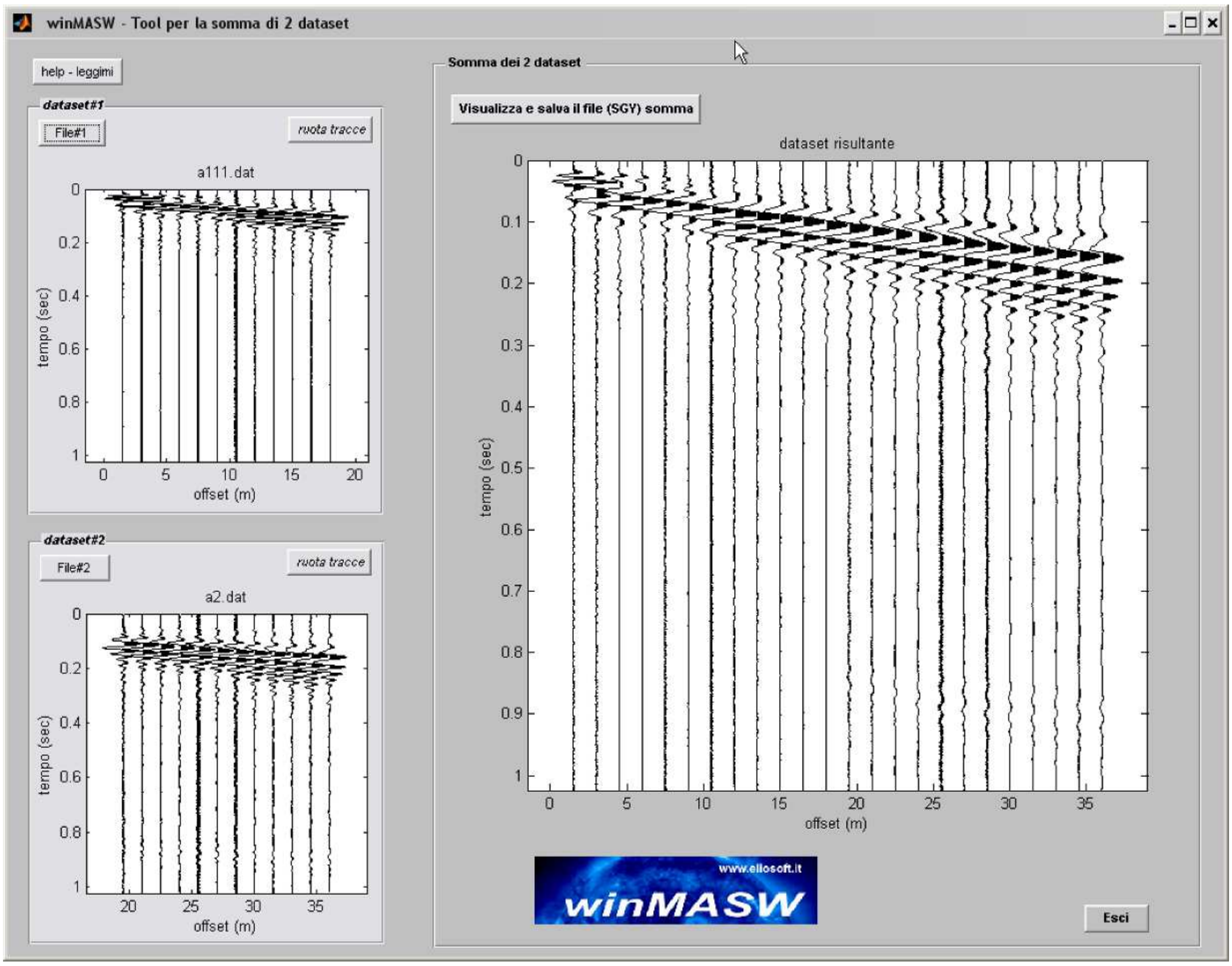
The fastest one is surely the first one (a). With *winMASW®* you can deal with all of these 3 cases. In the following an example of acquisition performed while considering the third type (mode "sequence" (type#2).

Remember: what is actually important is *not* the number of channels (typically 12 are absolutely sufficient - see e.g. Dal Moro et al., 2003) but the total length of the array (see the Elsevier book - paragraph 2.2.1).

Two datasets have been acquired according to following features:

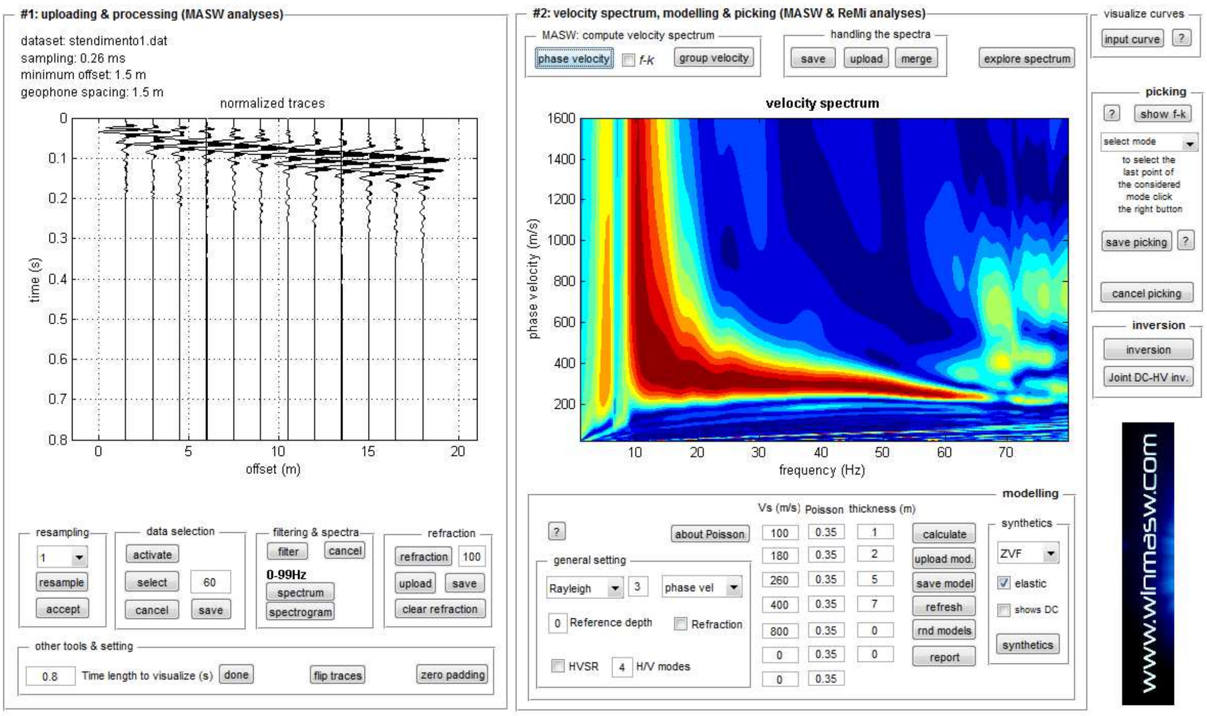
dataset#1: distance between geophones 1.5m, min offset: 1.5m
dataset#2: distance between geophones 1.5m, min offset: 19.5m

It's obvious the distance between geophones has to be the same and the min offset of the second dataset has to be equal to the last offset of dataset#1 plus a value equal to the inter-geophone distance

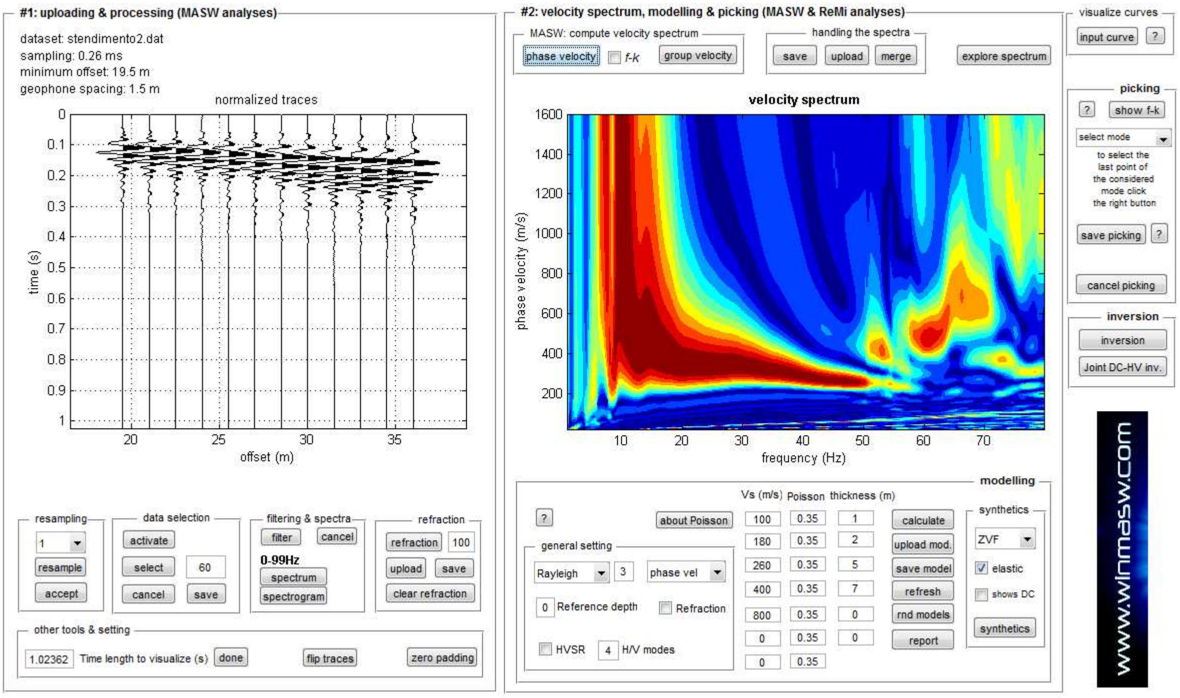


To point out the importance of the use of 24 channels datasets we've reported windows relevant to velocity spectra obtained when considering the spectra as separated and, finally, windows referring to the final total 24 channels dataset outcome of the 2 initial 12-traces-each datasets.

Obtained Velocity spectrum considering the only dataset#1 (near offset)

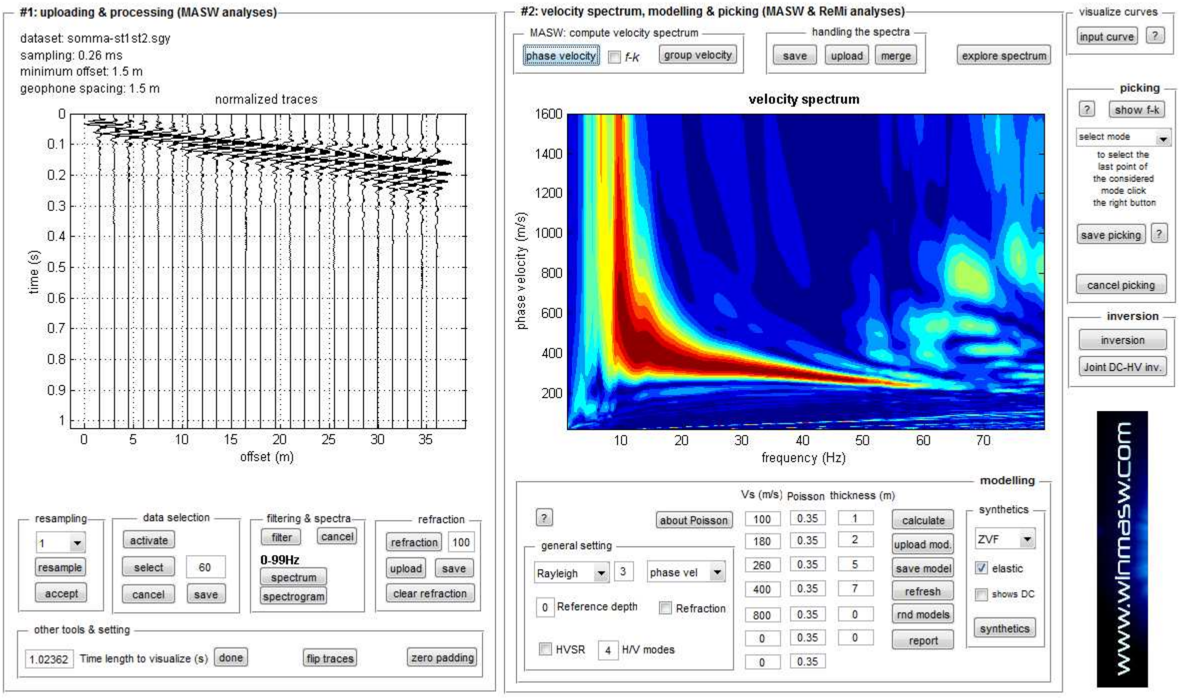


Obtained Velocity spectrum considering the only dataset#2 (far offsets)



With distanced offsets low frequencies are evident but the most proper velocity value to be picked results quite unclear (since the scarce number of traces) and depending on the user's choices; what velocity has to be picked at 10 Hz?

Obtained velocity spectrum considering the whole dataset (i.e. the combination of two single/separate datasets)



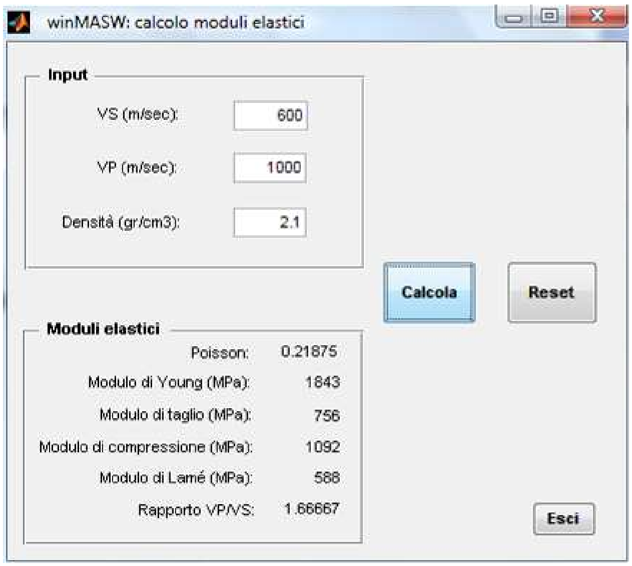
In this case the velocity spectrum is better defined (compare the amplitude of the red coherence bar with the former ones). For relative amplitude reasons low frequencies don't have the same strength of high ones, but we are now allowed to better identify the velocity relevant to 10 Hz (approximately 600m/s)

Combining two SAC datasets

SAC *datasets* are made of 1 trace only (such a format is usually adopted in passive seismology). It is possible to combine two (or more) SAC datasets (using the *sequence mode*) and eventually obtain a datasets useful for MASW and MFA analyses.

Appendix C: Computation of the elastic moduli

From the main panel, a *utility* to calculate a series of elastic modules (from the values of V_S, V_P and density).
Velocities have to be expressed in m/s, and density in gr/cm^3 while the calculated moduli (Young modulus, shear modulus, compression modulus and Lamé λ modulus) have to be expressed in MPa (Mega Pascal) (Poisson modulus and ratio V_P/V_S are dimensionless)
Remember the estimated V_P from MASW analysis mustn't be considered (and largely depends on the Poisson value you set up before launching the inversion).
The only modulus we can consider as a good estimation of the real value is the shear modulus, (that doesn't depend on the V_P).
This utility is very useful because considering the obtained V_S by MASW analysis and the obtained V_P by refraction studies we can get an approximate estimation of the moduli.



Formulas to express the moduli according to V_S, V_P and density:

Poisson modulus (dimensionless)	$(V_P^2 - 2V_S^2)/[2(V_P^2 - V_S^2)]$
Young modulus (in Pa)	$\rho V_S^2 (4 - 3k^2)/(1 - k^2)$
Shear modulus (in Pa)	ρV_S^2
Lamé λ modulus (in Pa)	$\rho V_S^2 (k^2 - 2)$
Compression modulus (in Pa)	$\rho V_S^2 (k^2 - 4/3)$

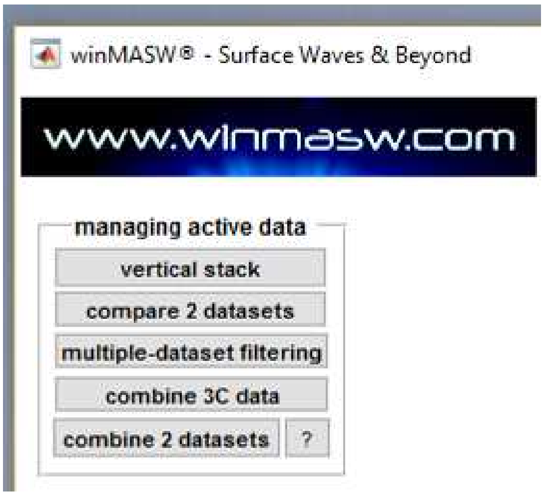
where:

$k = V_P/V_S$ (dimensionless)
ρ = density (kg/m^3)
V_S and V_P = velocity of shear and compressional waves in m/s

Of course, to change the Pascal value in Megapascal value just divide the value per 10^6 (Mega = 1 million)

Appendix D: Tool for the comparison of 2 active datasets

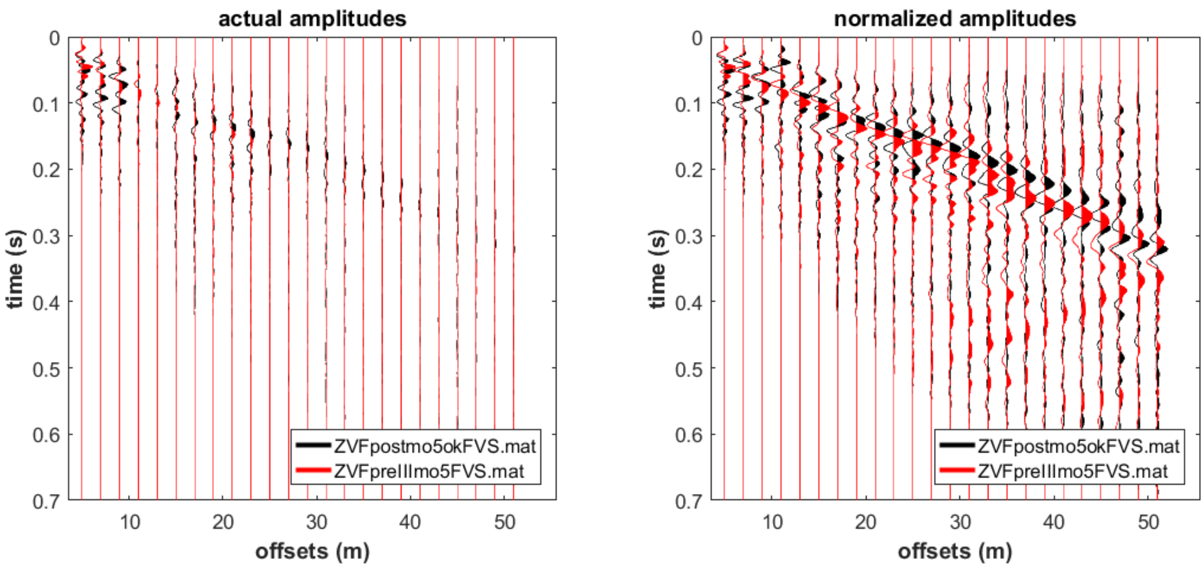
In the utility panel, there's the sub-.section "*managing active data*". One of its tools is "*compare 2 datasets*":



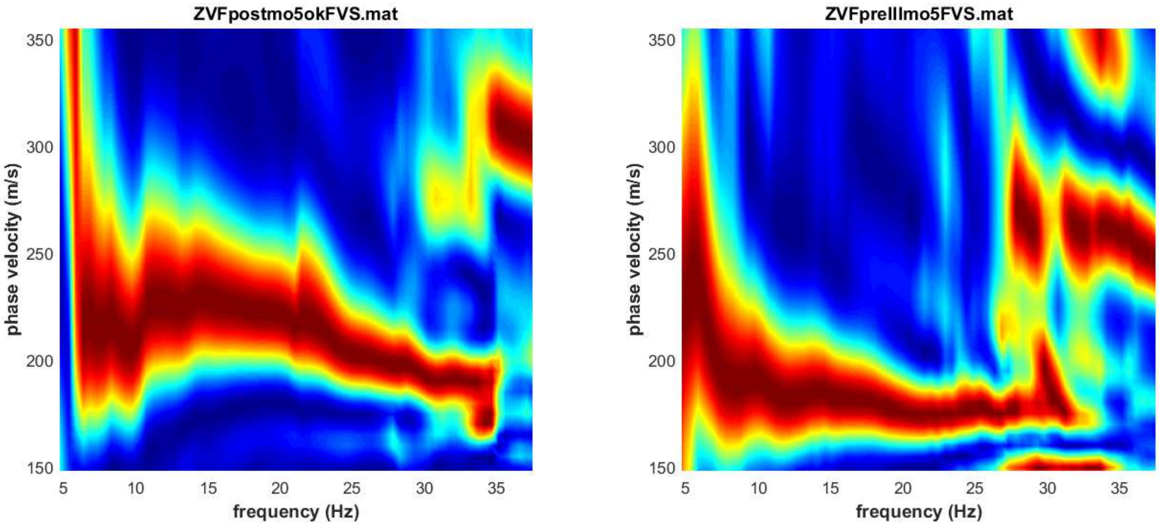
by clicking on it, you can upload 2 datasets (active seismics) recorded while considering the same acquisition parameters (sampling frequency, record time e array geometry).

These 2 datasets can be two different shots of the same acquisition, or the direct and reverse acquisition of the same array (gathered while moving the source at the opposite side of the array), or can be 2 datasets acquired on the same spot in two different days (for instance before and after a soil compaction process) etc.

What you will get is something like this (two kinds of outputs):



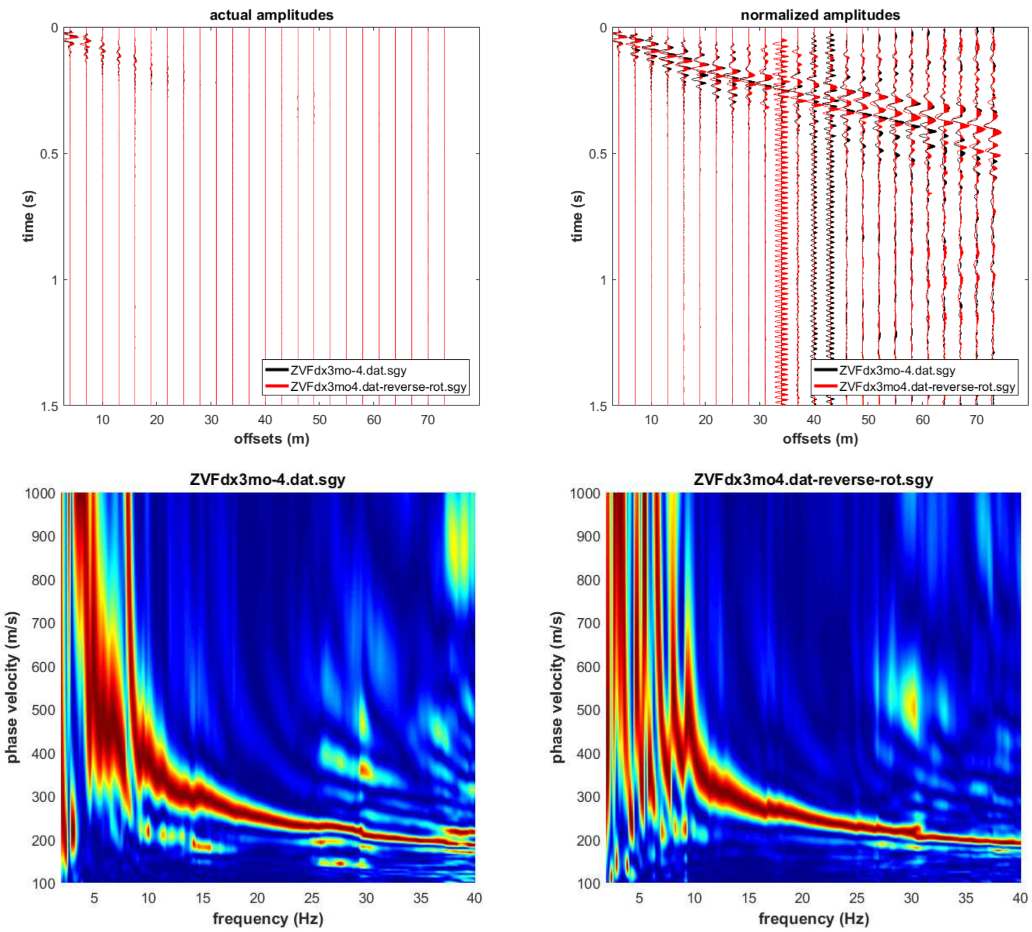
comparison of the acquired seismic traces (on the left the actual amplitudes, on the right the normalized amplitudes - trace by trace).



Phase-velocity spectra of the 2 datasets (indicated at the top of the plots)

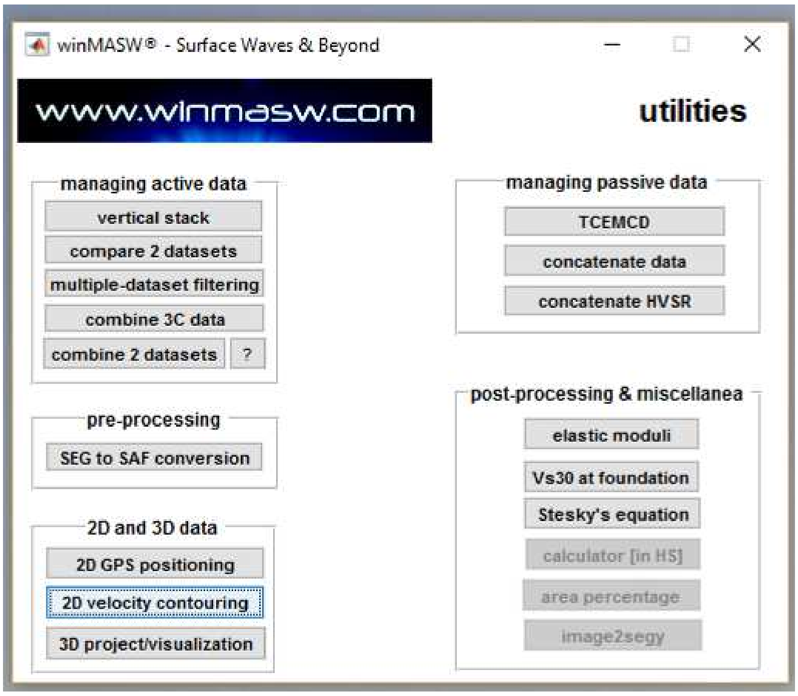
In this case the two datasets were acquired on the same spot, before (pre) and after (post) a soil compaction process (see ***Assessing ground compaction via time lapse surface-wave analysis*** - Dal Moro et al., 2016).

A further example: in this case the 2 datasets come from a direct and reverse acquisition (the source is moved on the two sides of the array) and in this case they are practically absolutely identical.



Appendix E: Creating 2D sections

In the *Academy* version (and in *HoliSurface®*), among the several utilities there's a tool ("*2D velocity contouring*") that can help you in creating 2D sections by considering a certain amount of V_S vertical profiles.



Everything is managed by means of a simple project file to save as simple ASCII (.txt) file.

Here a project file example (that you can also download from our internet site)

```
Swiss - profile#1
2
404.8000  404.2000  404.4000  405.2000  405.4000  405.8000  405.9000  406.3000
406.7000  407.2000  406.9000  407.6000  409.2000 409.7000  410.4000  411.5000
412.4000  414.5000  417.7000  424.1000
0 50 93 145 194 242 293 348 397 445 492 538 597 647 693 740 785 821 888 933
model1.mod
model2.mod
model3.mod
model4.mod
model5.mod
model6.mod
model7.mod
model8.mod
model9.mod
model10.mod
model11.mod
model12.mod
model13.mod
model14.mod
model15rep.mod
model16.mod
model17.mod
model18.mod
model19.mod
model20.mod
```

- ✓ On the **first line** you must write the name of the project;
- ✓ The **second line** is currently not considered but do not remove the line (just keep it like this);
- ✓ On the **third line** are reported the values of the topography for each considered point [in case you do not have these values, please just write a zero (0)];
- ✓ On the **forth line** is reported the position of each considered point for which you have a vertical V_S profile (i.e. model - see later on)

After that, you must report the file names of all the .mod files (one for each point).

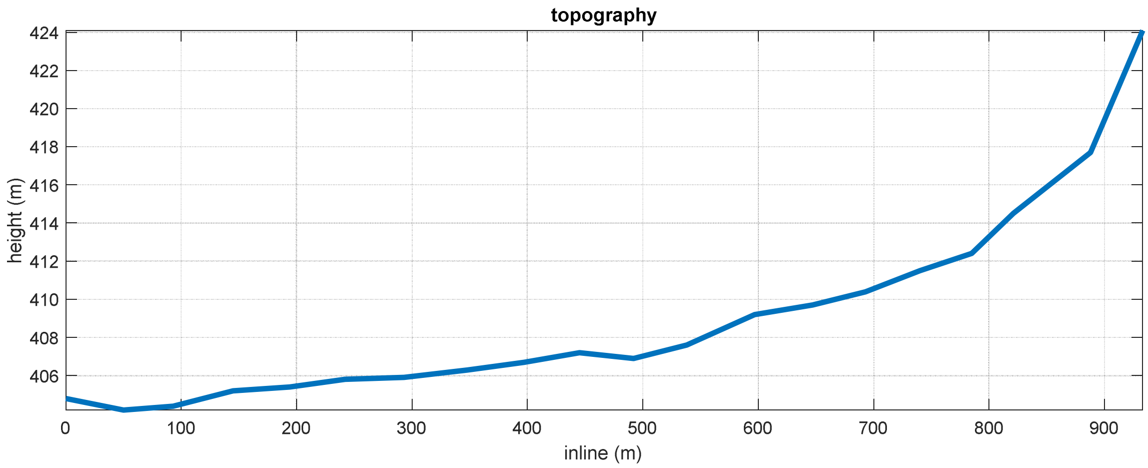
Be careful: all the models (.mod files) must have the same number of layers.

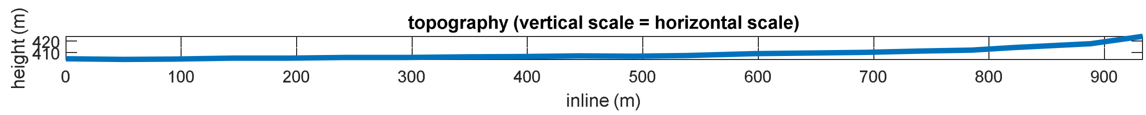
In our example (see above) we are dealing with a 2D section built by considering 20 points (i.e. 20 V_S vertical profiles represented by the 20 -mod files): the first point (model1.mod) refers to the point 0 (see the first value on the fourth line), the second point refers to the inline point 50 and so forth).

All the .mod files (reporting the V_S profiles for each single point) must be in the same folder as the project file.

The project used here as example (the figures here reported refer to it) can be downloaded from the following link: **http://download.winmasw.com/data/2Dsection.rar**

To play with it, download it, unzip it and upload the *NAGRA16_2Dprofile.txt* project file.

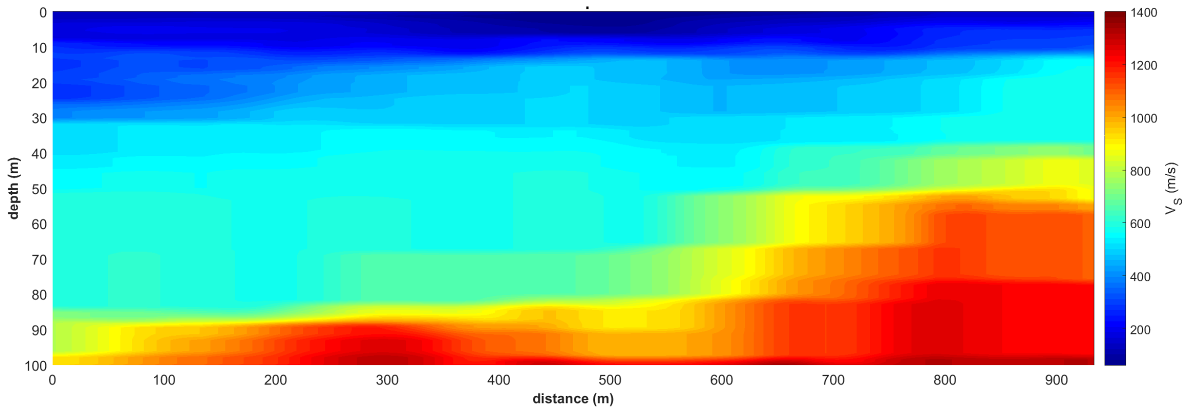




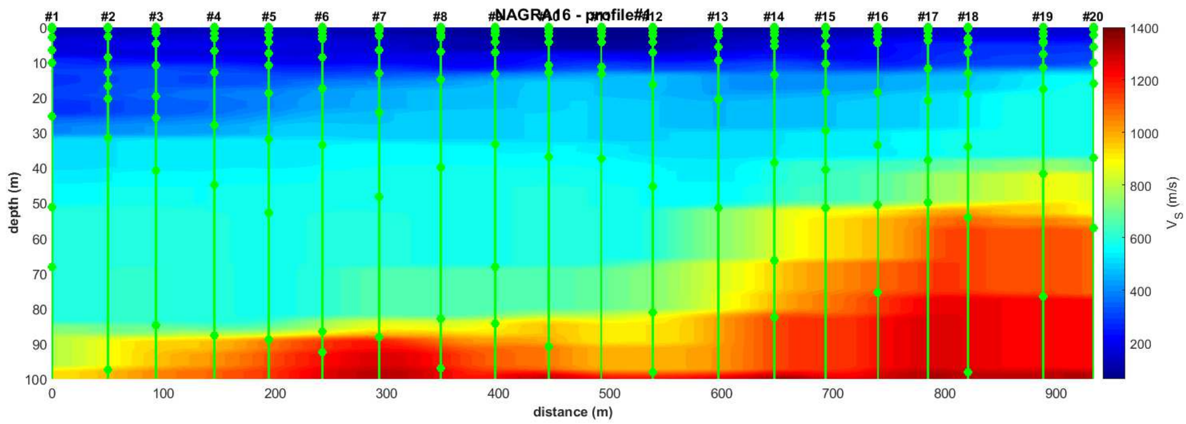
Once you upload your project, in the “depth” box is shown the depth of the deepest point of your .mod models.
The use must now define the maximum depth to adopt to visualize the 2D section/data (this is never the depth of the deepest point) and the maximum velocity of the colour scale.
A percentage of lateral smoothing can/must also be defined/modified.

Please try to modify these parameters (while using our data/example) so to get familiar with them (the best parameters to use clearly depend on the site, characteristics of the data and your actual goals (you might be interested in highlighting some features rather then others.

You can also choose whether highlight or not the points of your profile (just activate/deactivate the “*show profiles*” checkbox (see images here below).



2D section [the “*show profiles*” checkbox is not active]



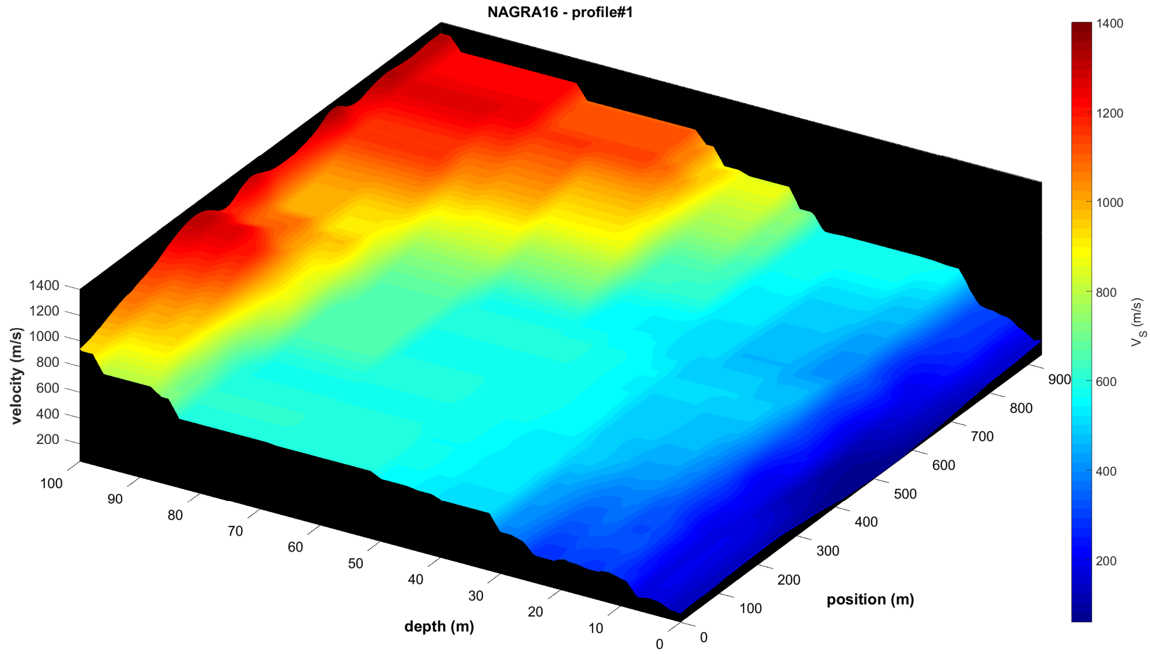
section [the “*show profiles*” checkbox is now active]

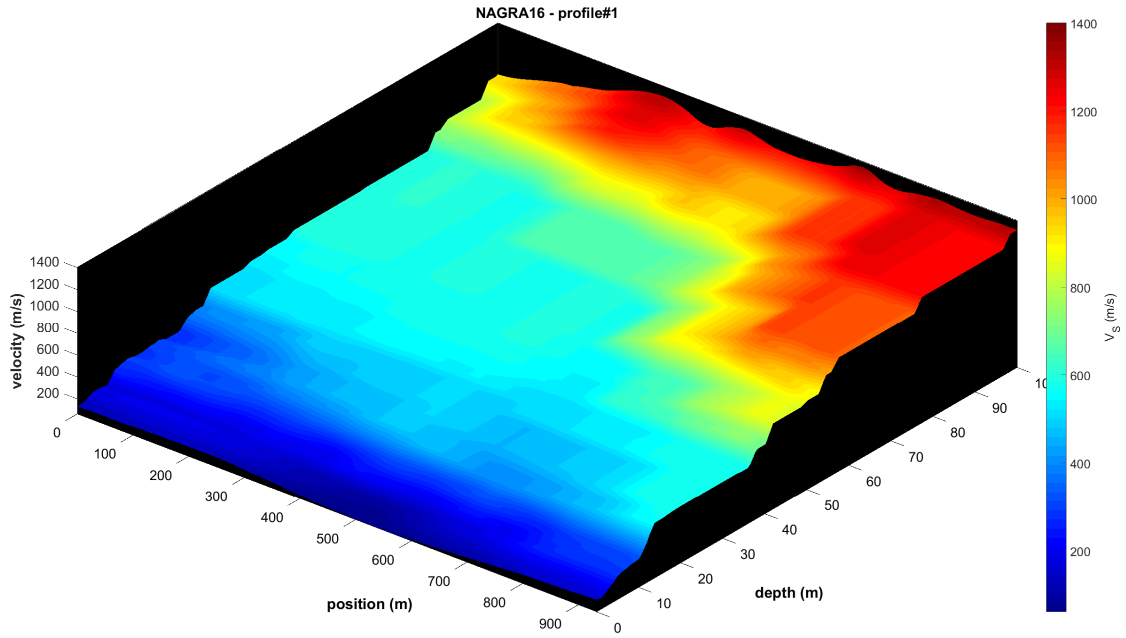
Output Excel file

In the working folder is also saved an Excel (xls) file with the obtained V_S matrix.

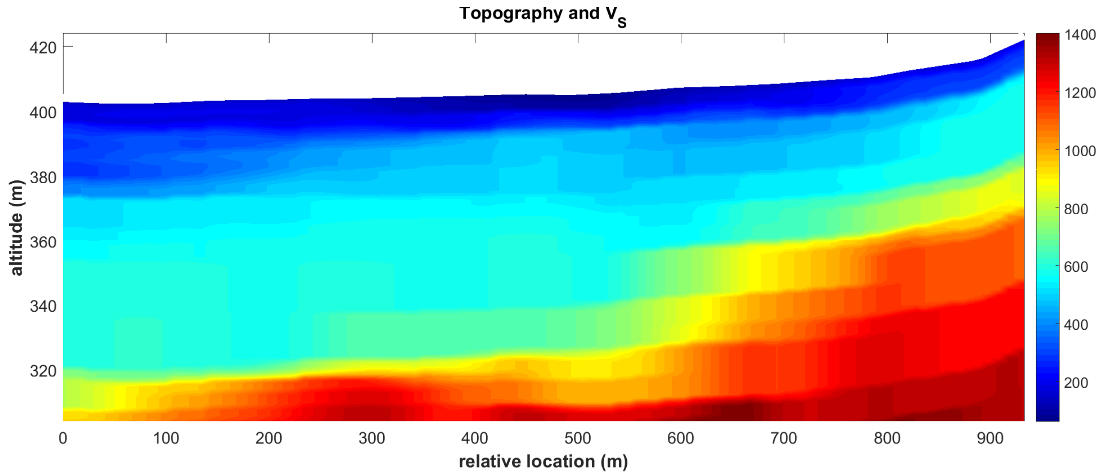
The file name (e.g. VsMATRIX_dx9m_dz0.6m.xls) reports the delta x (dx - along the inline direction) and delta z (along the vertical axis) of the reconstructed matrix. In the example file, the points are separated by 0.6 meters vertically and by 9 meters horizontally (inline direction).

See also: *Working for the reconstruction of 2D sections*

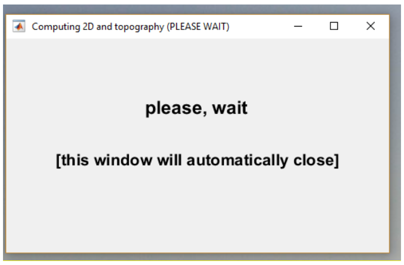




If you activate the "*show also topography*" option and in your project file is topography is (properly) reported (see third line of the file project), you will obtain this sort of image:

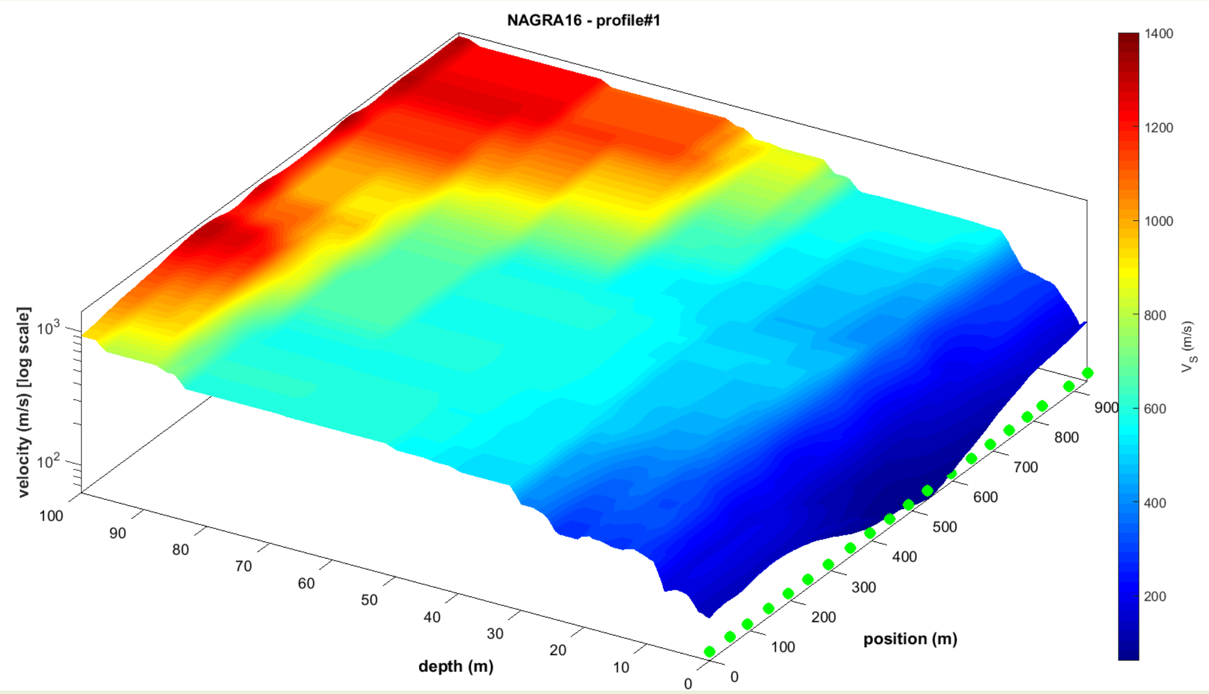


During the processing a window will show up (please wait until the work is done and the window automatically closes):



All the figures are automatically saved in the working folder, but you can save them elsewhere (and with whatever file name) by using the usual icons in the toolbar ("File -> Save as").

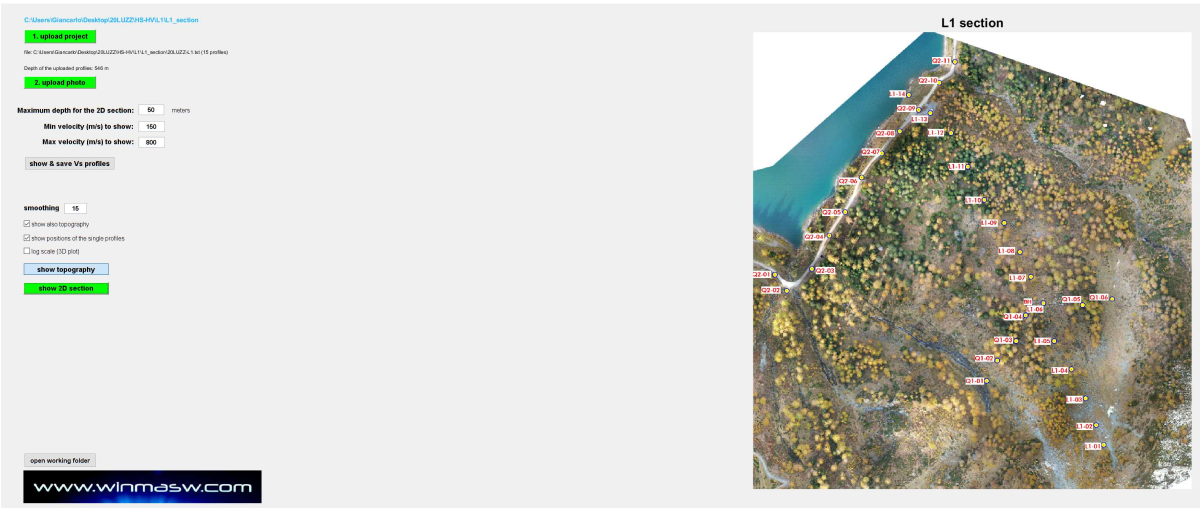
By activating the "log scale (3D plot)" option, the velocities are plotted according to a **logarithmic scale**, which can be useful to better highlight some kind of lateral variations.
In the example down here, the logarithmic scale allows to put in evidence the peat area (very low velocities) in the middle of the 2D section.
The green circles refer to the points of our data (the "*show profiles*" checkbox is on).

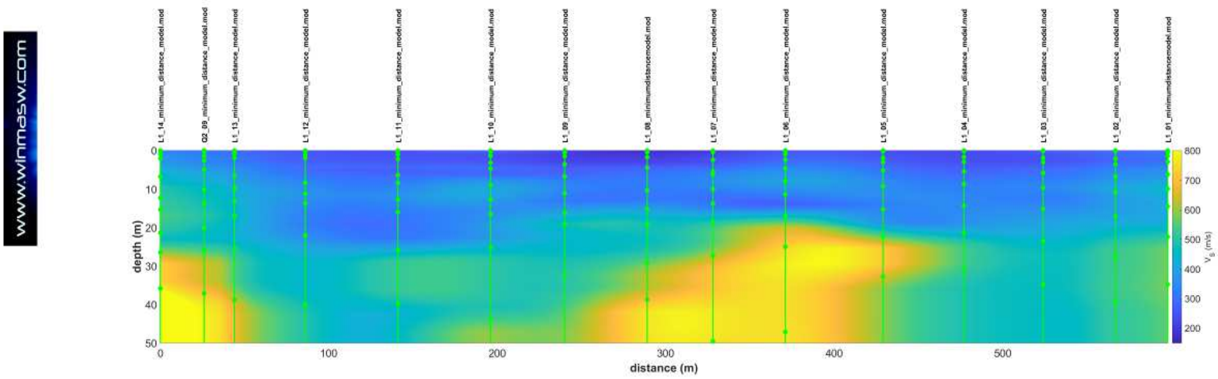


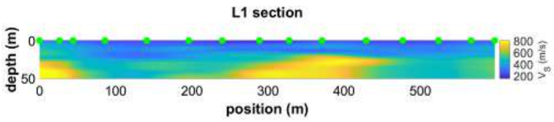
An example of 2D data [*winMASW®* Academy and *HoliSurface®* 2021]

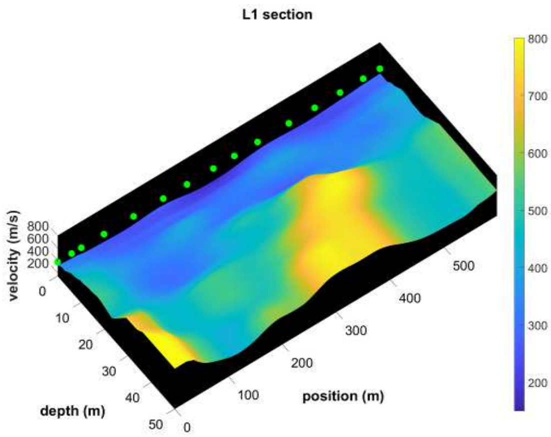
The project file (a simple txt file)

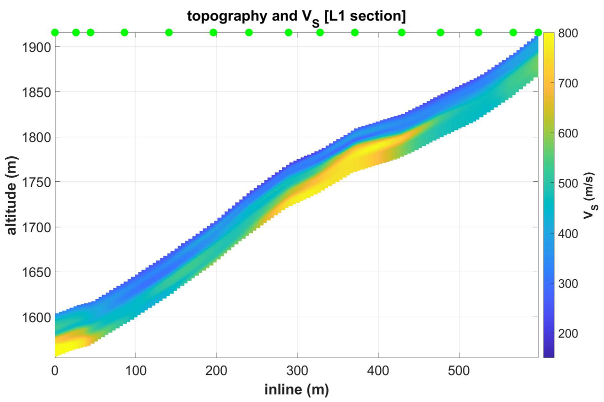
```
L1 section
2
1604 1613 1617 1640 1672 1707 1740 1771 1787 1810 1826 1848 1868 1894 1916
0 26 44 86 141 196 240 289 328 371 429 477 524 567 598
L1_14_minimum_distance_model.mod
Q2_09_minimum_distance_model.mod
L1_13_minimum_distance_model.mod
L1_12_minimum_distance_model.mod
L1_11_minimum_distance_model.mod
L1_10_minimum_distance_model.mod
L1_09_minimum_distance_model.mod
L1_08_minimumdistancemodel.mod
L1_07_minimum_distance_model.mod
L1_06_minimum_distance_model.mod
L1_05_minimum_distance_model.mod
L1_04_minimum_distance_model.mod
L1_03_minimum_distance_model.mod
L1_02_minimum_distance_model.mod
L1_01_minimumdistancemodel.mod
```

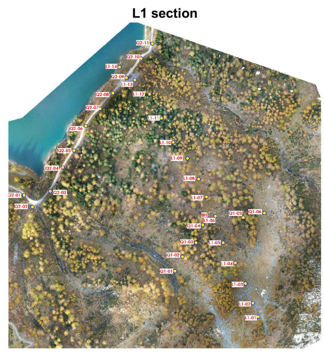


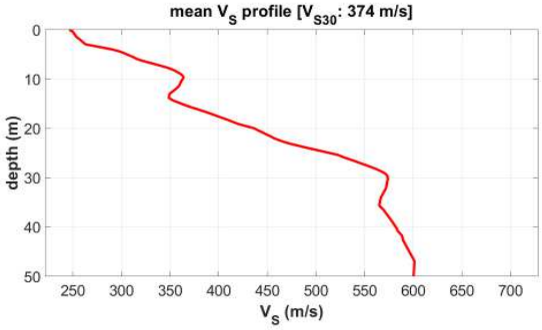


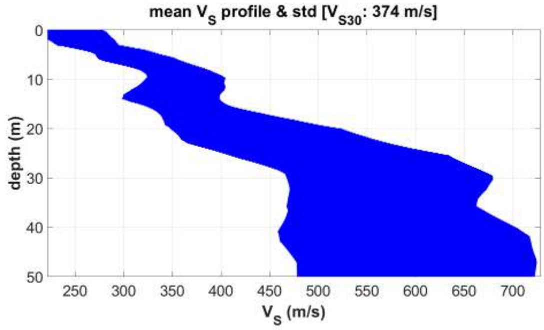

L1 section
depth (m)
0
50
0
100
200
300
400
500
position (m)
800
600
400
200
V_S (m/s)

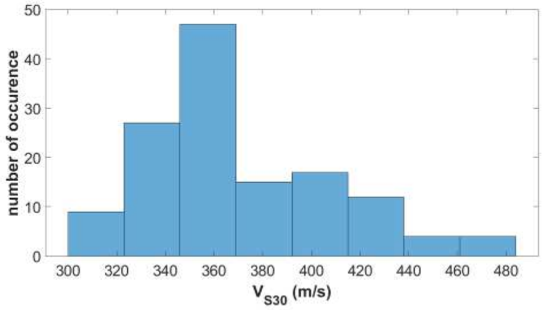

L1 section
velocity (m/s)
800
600
400
200
0
10
20
30
40
50
depth (m)
0
100
200
300
400
500
position (m)
800
700
600
500
400
300
200
V_S (m/s)


topography and V_S [L1 section]
altitude (m)
1900
1850
1800
1750
1700
1650
1600
0
100
200
300
400
500
inline (m)
800
700
600
500
400
300
200
V_S (m/s)


L1 section


mean V_S profile [V_S30: 374 m/s]
depth (m)
V_S (m/s)


mean V_S profile & std [V_S30: 374 m/s]
depth (m)
V_S (m/s)


number of occurence
V_S30 (m/s)

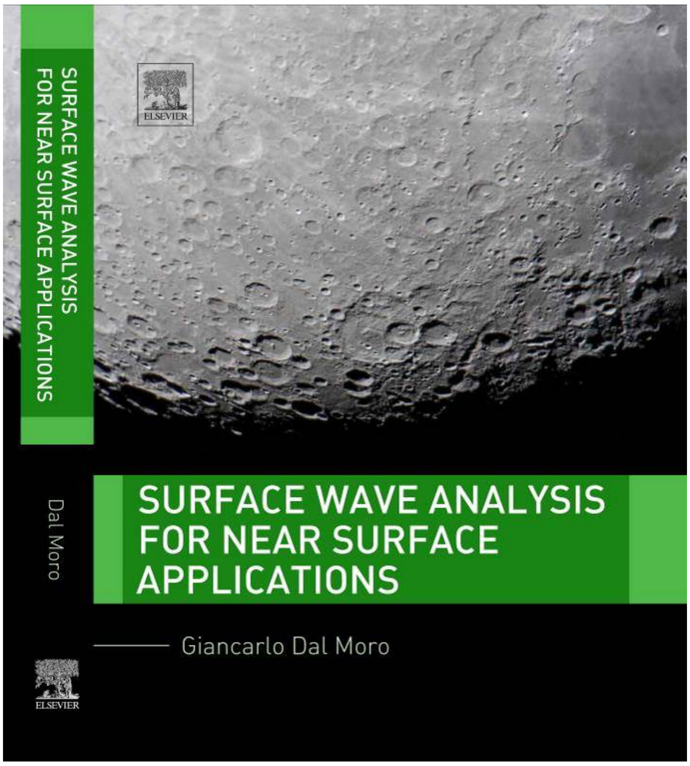

www.winmasw.com
www.HoliSurface.com
Altitude: 1623.509 m
Lat: 46 33 45.85 N
Long: 8 58 42.5 E
Lat: 46.562736111111142122354 N
Long: 8.9784722222222285381577 E
Latitude
Longitude
47°30'N
47°N
46°30'N
46°N
8°E
9°E
10°E
11°E

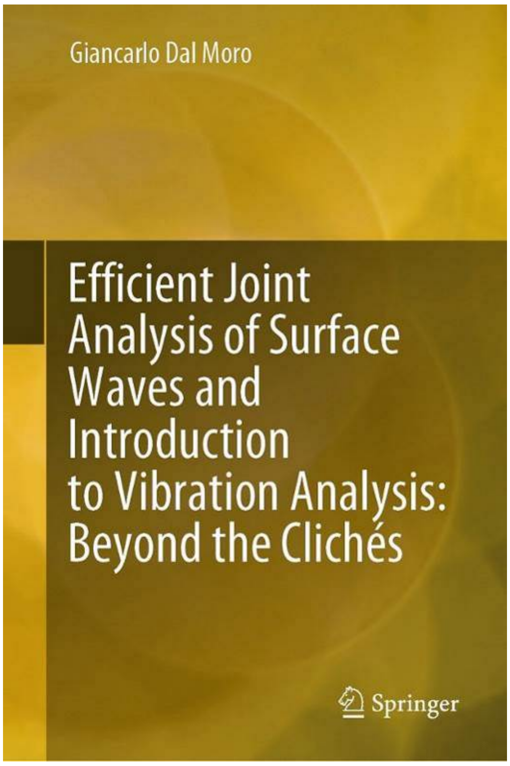
Appendix F: Few examples (case studies) of what you can do with *winMASW®*

Several papers, case studies and datasets (for your own training) are included in the winMASW® USB dongle together with the software but you can also our web site (**www.winMASW.com**).

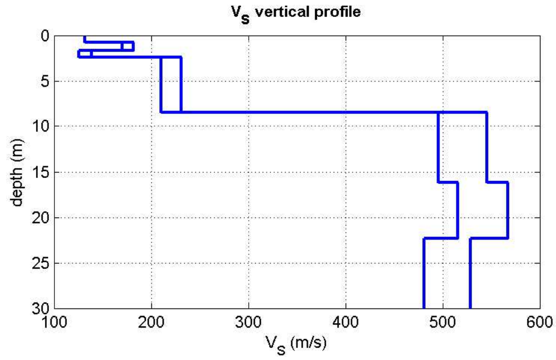
More case studies are sent to our users though our *newsletter*.

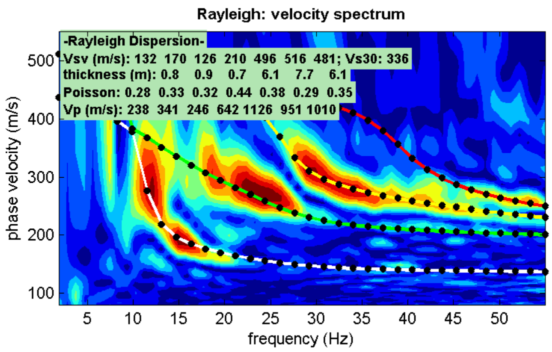
You can read the *Elsevier* & *Springer* books and study all the reported examples. Some of them are available in the *HoliSurface* / *winMASW* USB dongle provided with the software: you can use them for your self-training and compare the results with the analyses commented in the books

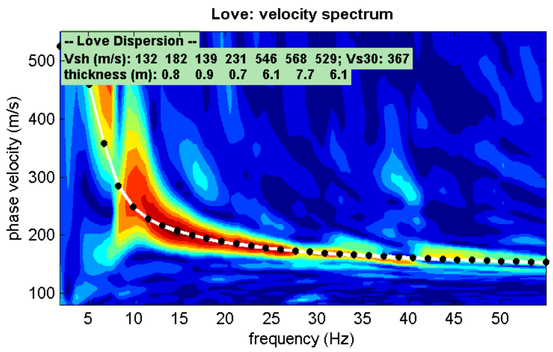




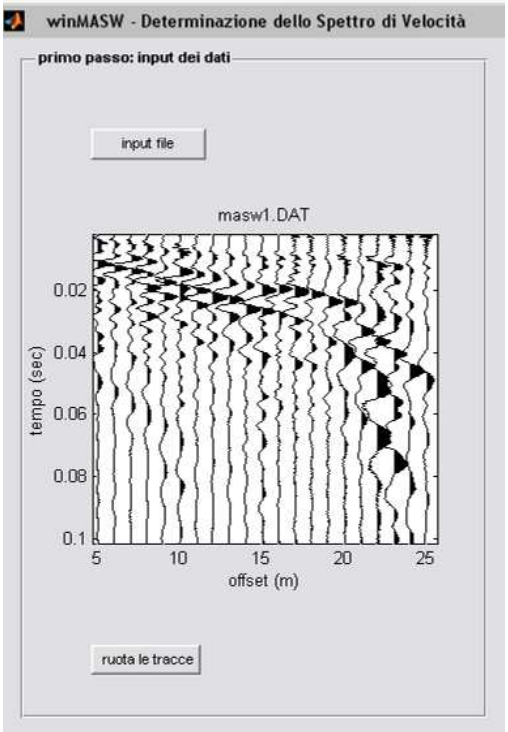
F1. Joint analysis panel: joint analysis (forward modelling) of Rayleigh & Love waves using the ordinary modal dispersion curves [old-fashioned approach]





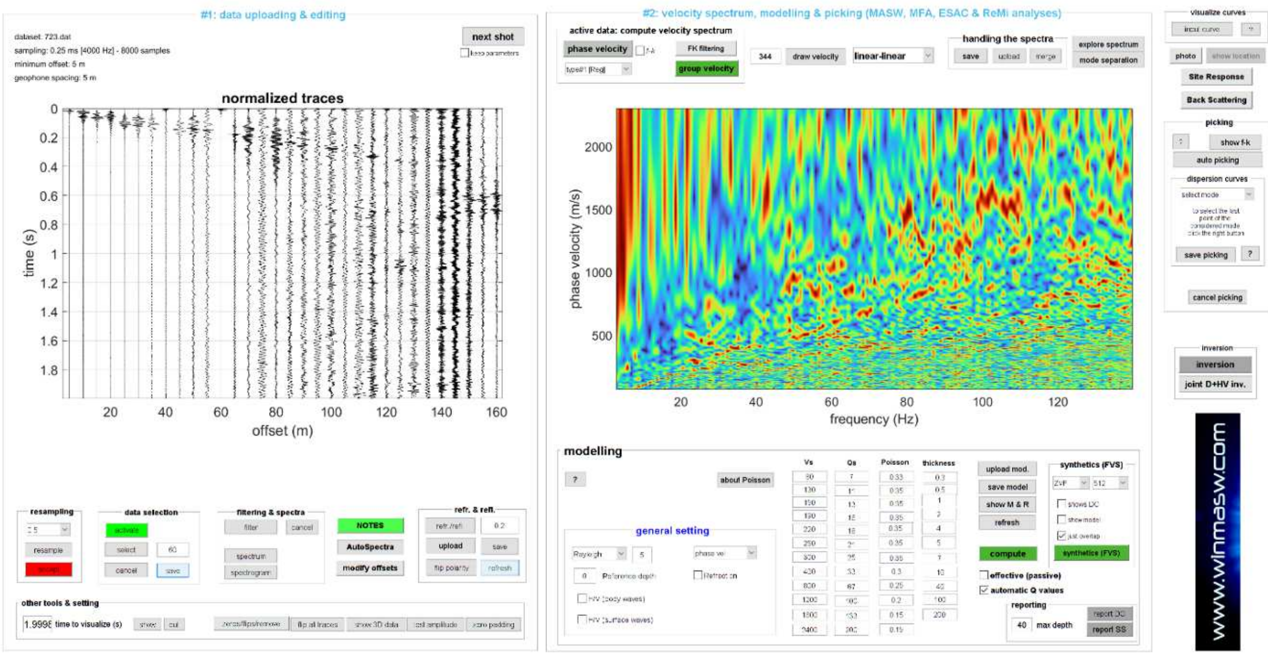


F2. Few examples of useless/problematic *datasets*



Note the sudden change of the trace characteristics from the offset 20 m on. Apparently: before that point the subsoil is stiffer (velocities higher) while after a sudden change of the subsurface properties occur (softer sediments with much lower V_R).

The following snapshot reports a totally-useless dataset (the vague signal you see on the field traces is about the *air wave* – you can easily verify that by using the **"draw velocity" button** with the pertinent velocity): it is not the amount of money you spent for your seismograph that ensures the quality of your work but the number of hours you spent (invested) studying the theory of seismic-wave generation and propagation that eventually leads you to accurate data acquisition and analysis.

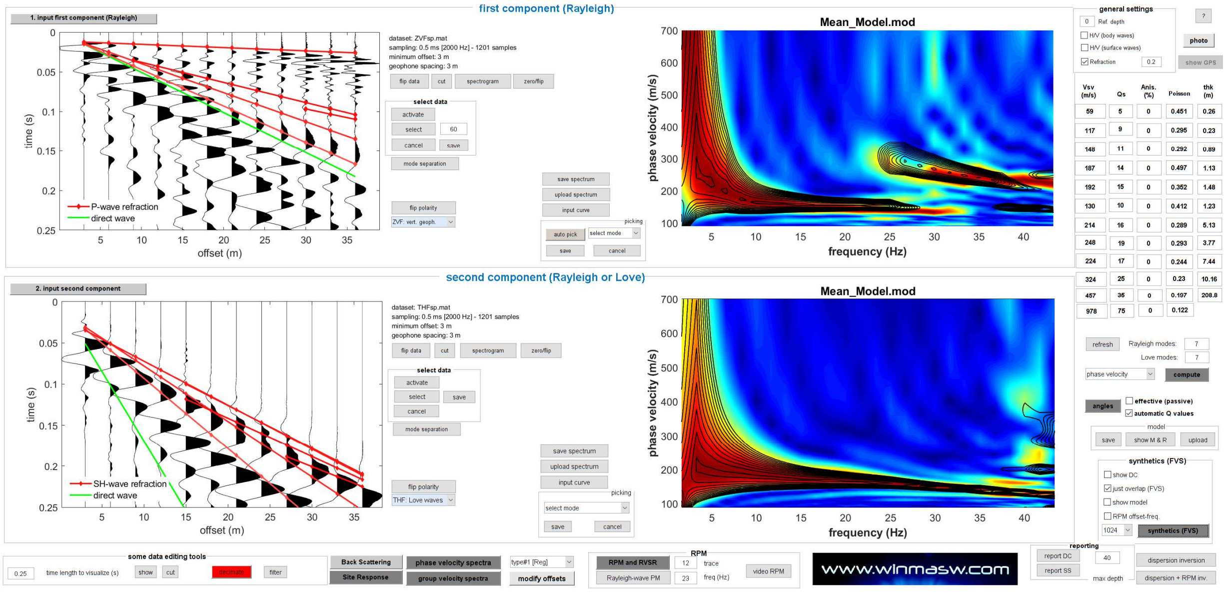


TWO NOTES

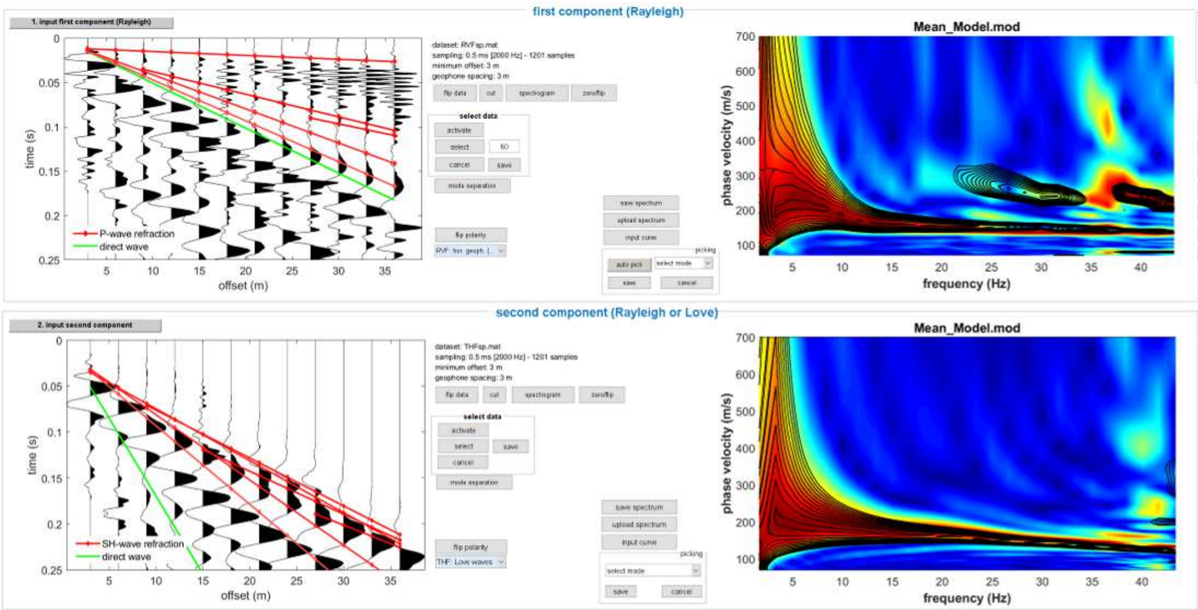
1) data acquisition is not a mere "mechanical operation": it requires excellent knowledge of *what* we are doing and *why*: the type of data and their quality will affect the analyses and therefore the final outcome;

2) the good quality of a (single) *dataset* does not mean that we can obtain the correct V_S profile out of it: only the joint analysis of different *observables* allows that (see section "*Introduction: the winMASW® holistic perspective*").

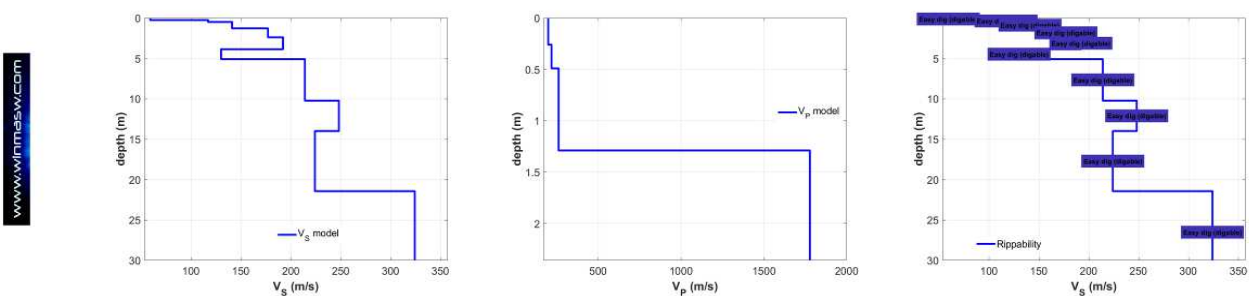
F3. Joint analysis panel: joint modelling of Rayleigh- & Love-wave dispersion (FVS approach) and P- and SH-wave first arrivals (refraction)



Joint modelling for the Z and T components: upper panel Rayleigh dispersion (on the right) and P-wave refraction travel times [in this case due to the shallow water table – see model below]; lower panel: Love-wave dispersion and SH-wave refraction arrivals.

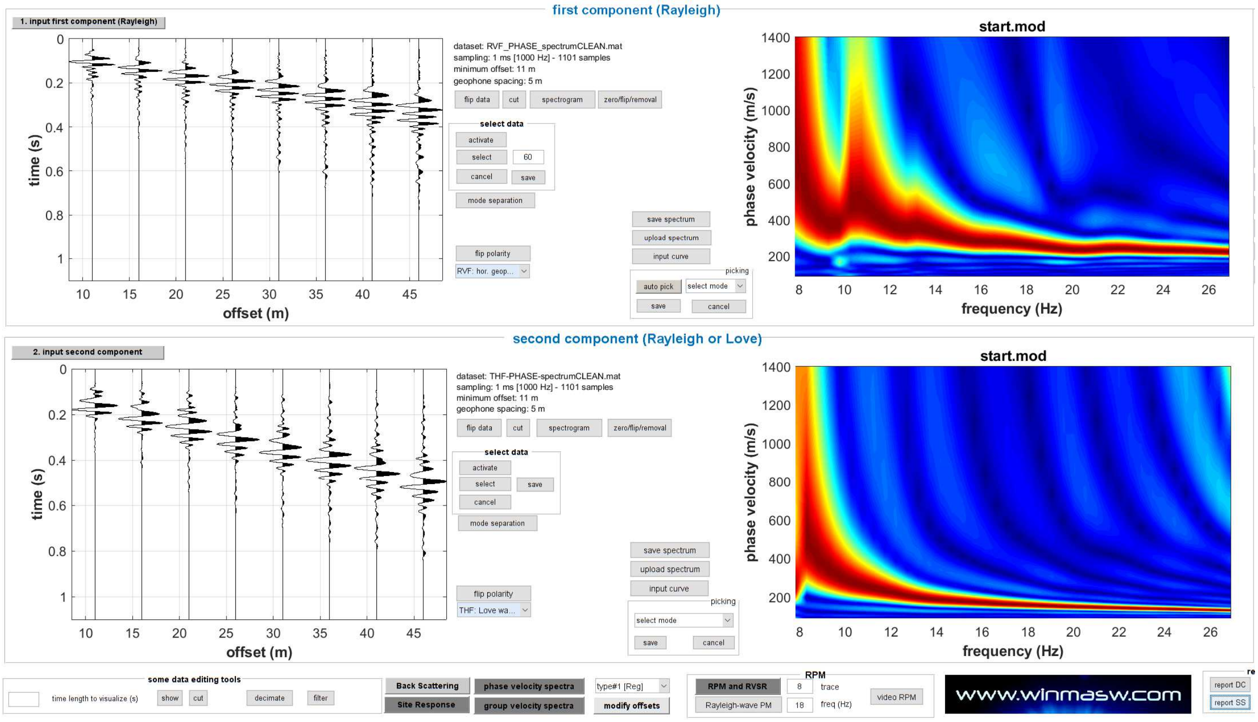


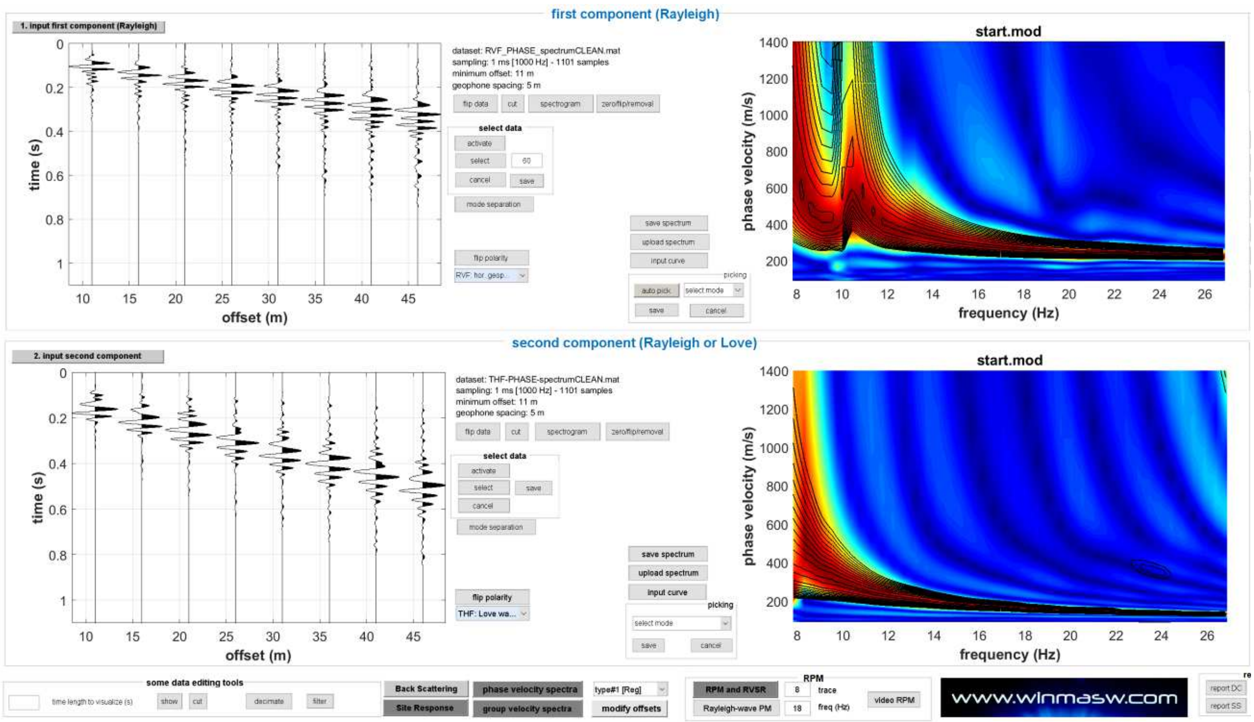
Same as for the previous figure but for the R and T components: as you can see, P-wave refraction is clearly visible also along the R (radial) component. This means that by simply using a set of horizontal geophones you can quickly do four things: analysis of the Rayleigh and Love-wave dispersion and of the P- and SH-wave refraction.



F4. Joint analysis panel: joint FVS analysis of Rayleigh- & Love-wave dispersion: do you see why Love waves are so important?!

Joint modelling for the R (radial component of Rayleigh waves) and T (Love waves) components: upper panel Rayleigh dispersion (on the right); lower panel: Love-wave dispersion.





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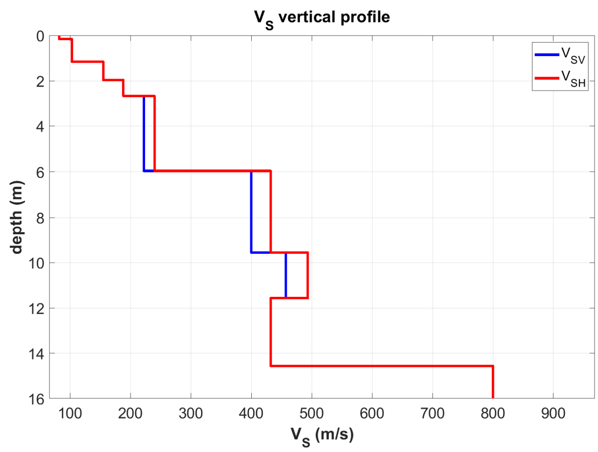


Comment: the signal that dominates the Rayleigh waves (R component) at frequencies higher than 10 Hz is due to the first higher mode while for lower frequencies is about the fundamental mode. Love waves are 99% of the times dominated by the fundamental mode.

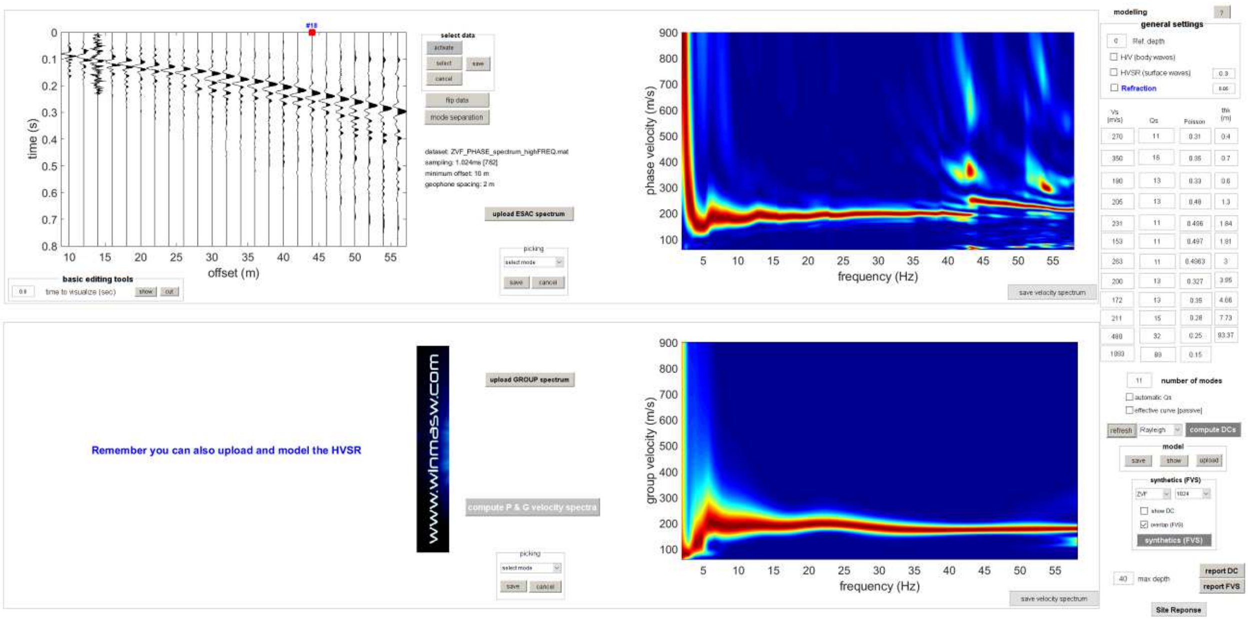
In order to obtain a good match it was necessary to introduce some anisotropy for some layers (see shown V_{SH} and V_{SV} model).

Important note: higher modes are not a problem in case you properly analyze them. On the opposite: they bring important information especially about deeper layers (because their velocity is higher). The problem is when you misunderstood them since this inevitably leads to overestimate the V_S values. The only way to properly understand the velocity spectra is to analyze two or more components (in this case we analyzed the R and T components recorded by just using a set of 4.5 Hz horizontal geophones).

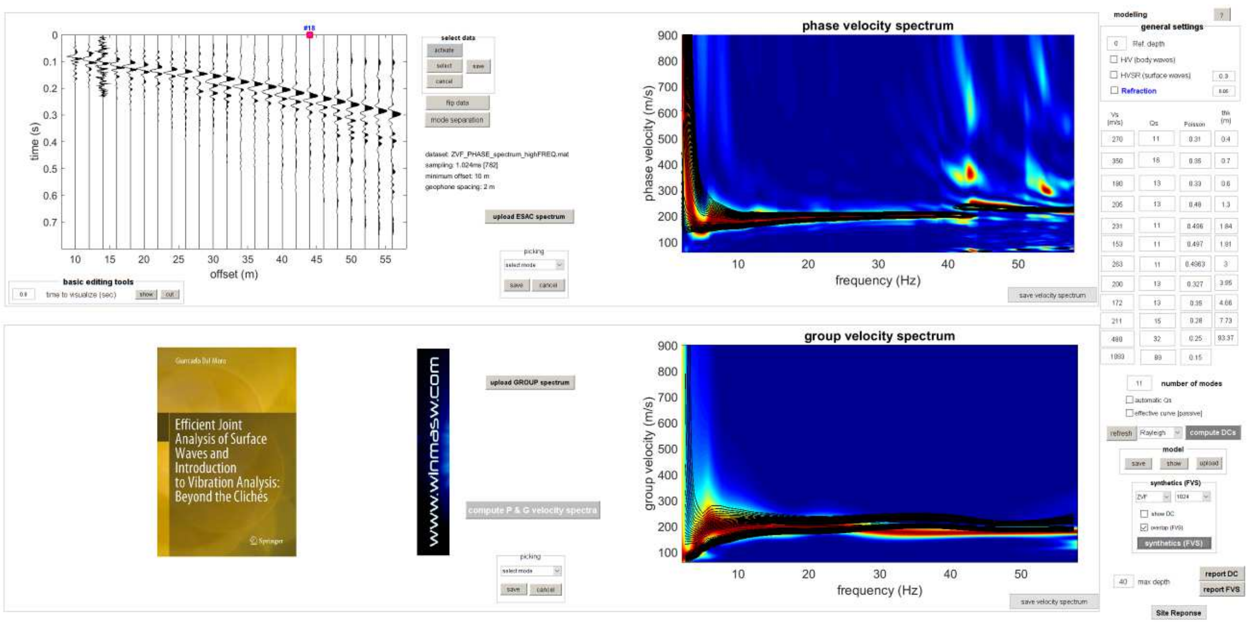
Can Love waves have large-amplitude higher modes? Of course. See the "***The magnifying effect of a thin shallow stiff layer on Love waves as revealed by multi-component analysis of surface waves***" paper (Dal Moro, 2020).

F5. From the panel "joint analysis of phase and group velocities" (just one component): joint modelling of the phase- and group-velocity spectra (FVS approach) – HVSR not available

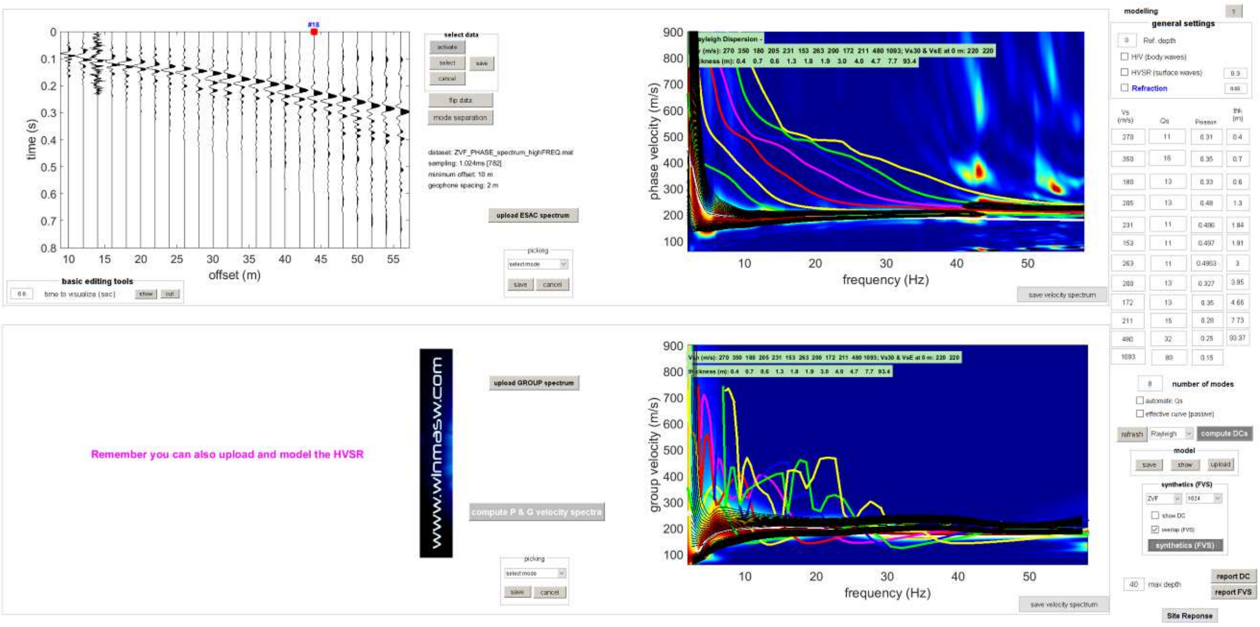
First of all, we must emphasize that if we wish to obtain the correct Vs profile, it is recommended to work with multi-component data (e.g. joint analysis of the R and T components together with the HVSR (computed as the average of the HVSRs acquired at two or more points along the array, so to verify possible lateral variations).,



Available data (ZVF component): phase velocity computed considering all the traces and group velocity computed considering only trace#18 [see red square]



Joint FVS analysis (phase and group velocities of the ZVF component)



FVS representation (see previous figure) with also the modal dispersion curves of the first 8 modes (for demonstration purposes)

The data and the quick accomplished modelling of the phase and group velocities via FVS shows that:

1) as a matter of fact, a single geophone is sufficient to analyze the dispersion since group velocity analysis (in this case accomplished considering trace#18) is so-to-speak equivalent to the analysis of the phase velocities. This means that a single geophone is sufficient to analyze the dispersion and obtain information about the subsurface V_S profile;

2) the critical point is to record and analyze **multi-component data** and that is why we always recommend the use of a set of horizontal geophones that allow to record the R and T components (see our HoliSurface® software application which is largely based on the group-velocity analysis of the data collected by a single 3C geophone used also for the HVSR etc.) [and here unfortunately we only had the Z component];

3) often it is not possible to work with the "concept" (and practice) of **modal curves**: here we work with the FVS analysis which shows that everything above 12 Hz is a complex coalescence of higher modes that cannot be separated (it is not possible to separate single modes);

4) the jump at about 42 Hz for the phase-velocity velocity spectrum is between the third and eighth mode: mode jumps do not follow any simple rule or ordered sequence (see extensive literature available on the topic);

5) there is a minor change in the Rayleigh-wave slope (the second half of the traces are apparently slightly slower), which suggests some (minor) lateral variations: winMASW® ACD allows you to split this [active] dataset into two sub-datasets (see the “zeros/flips/remove” tool in the *single-component analysis* panel) and analyze them separately;

6) the presence of a relatively-stiffer superficial layer can create a very interesting and useful phenomenon of Love-wave higher mode excitation – carefully read the following paper: *The magnifying effect of a thin shallow stiff layer on Love waves as revealed by*

multi-component analysis of surface waves - Dal Moro G., Nature - Scientific Reports 10, 9071 (2020). https://doi.org/10.1038/s41598-020-66070-1

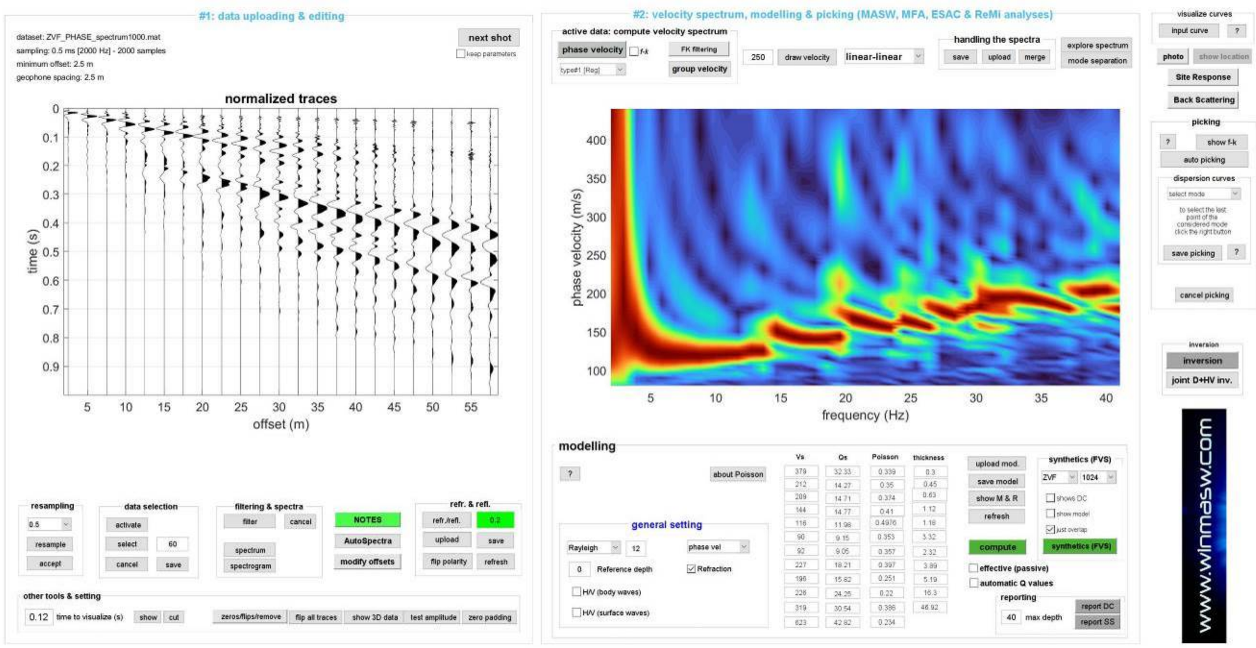
7) the **phase+group velocities panel** also allows the (joint) modelling of the refraction [P or SH] travel times (remember that refraction is useful only for the very shallow layer since has al limited penetration depth) and HVSR [not available for this site] (see further case study presented later on where such options are used).

Two important points:

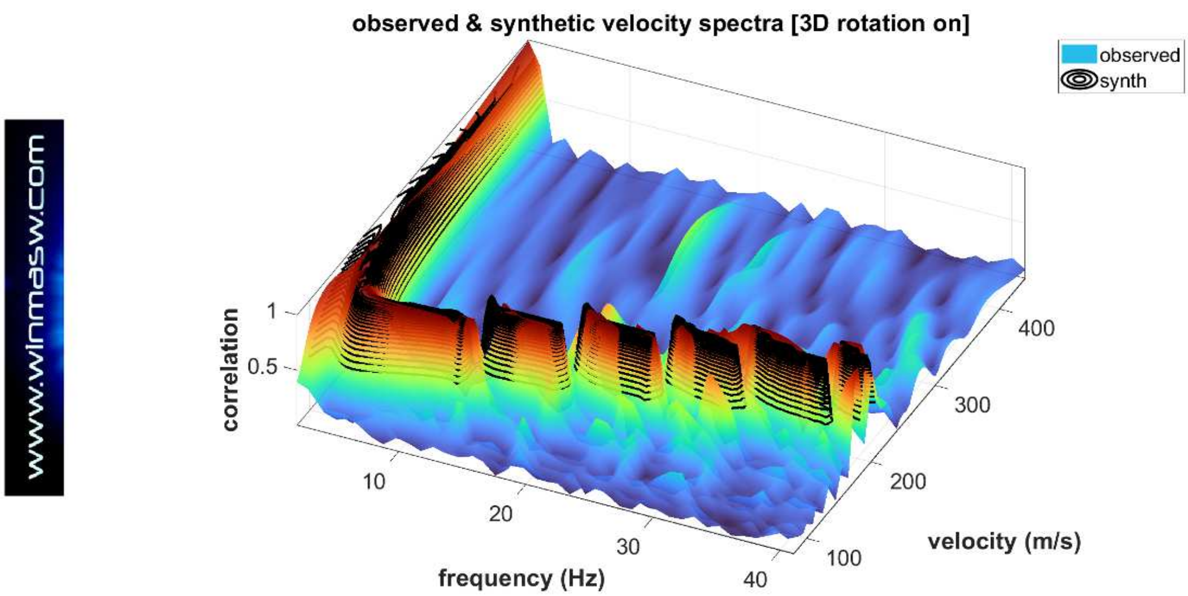
1) For complex data, if we wish to obtain correct Vs profiles we cannot rely on the analysis of a single component: for ordinary surveys, the “best” and easiest solution is the joint acquisition and of the R + T components jointly with the HVSR;
2) the **phase+group panel (+HVSR and refraction)** is a panel that has mainly an educational purpose: to show that working with phase or group velocities is completely equivalent and this leads naturally to working with the ***HoliSurface®*** method [HS] which rely on the **(active) data recorded by a single 3C geophone (i.e. multi-component data)**: https://www.winmasw.com/ it/prodotto.asp?IDp=1

F6. Single-component panel: joint analysis (modelling) pf the vertical component of Rayleigh waves (ZVF) and P-wave refraction travel times

Am ordinary (not recommended) dataset obtained with a set of 24 vertical geophones (the last one turned out not to work and the dataset was therefore reduced to the first 23 channels using the "zeros/flips/remove" button).
The phase velocity spectrum highlights a clear *mode splitting* phenomenon [see the "*Surface Wave Analysis for Near Surface Applications*" Elsevier book].



With some forward modelling and, if necessary, an automatic FVS inversion, we obtain a subsurface model whose phase velocity spectrum overlaps pretty well with the observed (field) one [see the two figures shown in the following].



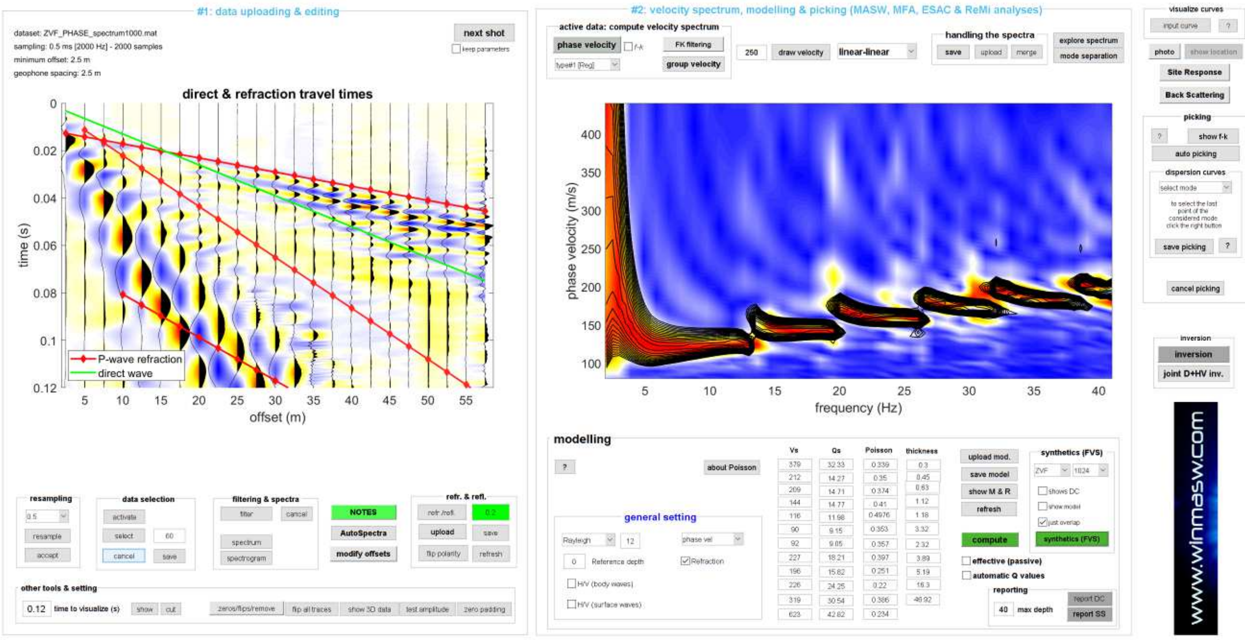
Now we can consider the model identified through the dispersion analysis (which depends primarily on V_S and thicknesses) and easily (manually/personally) optimize the V_P values using the Poisson's ratio values [forward modelling panel below the velocity spectrum].

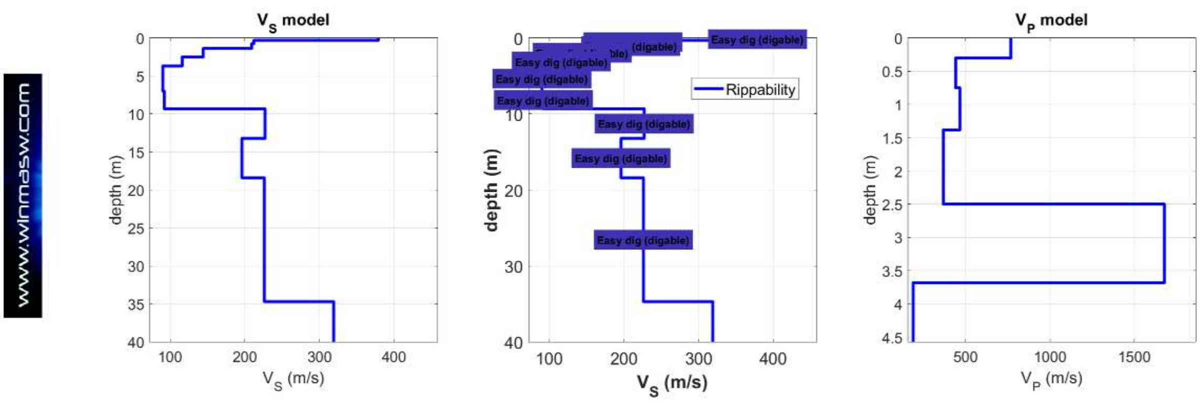
In order to better highlight the first arrivals of the refracted wave (having used vertical geophones we are dealing with the P waves), we can reduce the shown time [field "time to visualize" in the “other tools & setting” group under seismic traces] (in this case we set the value to 0.12 s).

We can now appreciate the good congruence of both dispersion and first arrivals of the P-wave refraction (image here below).

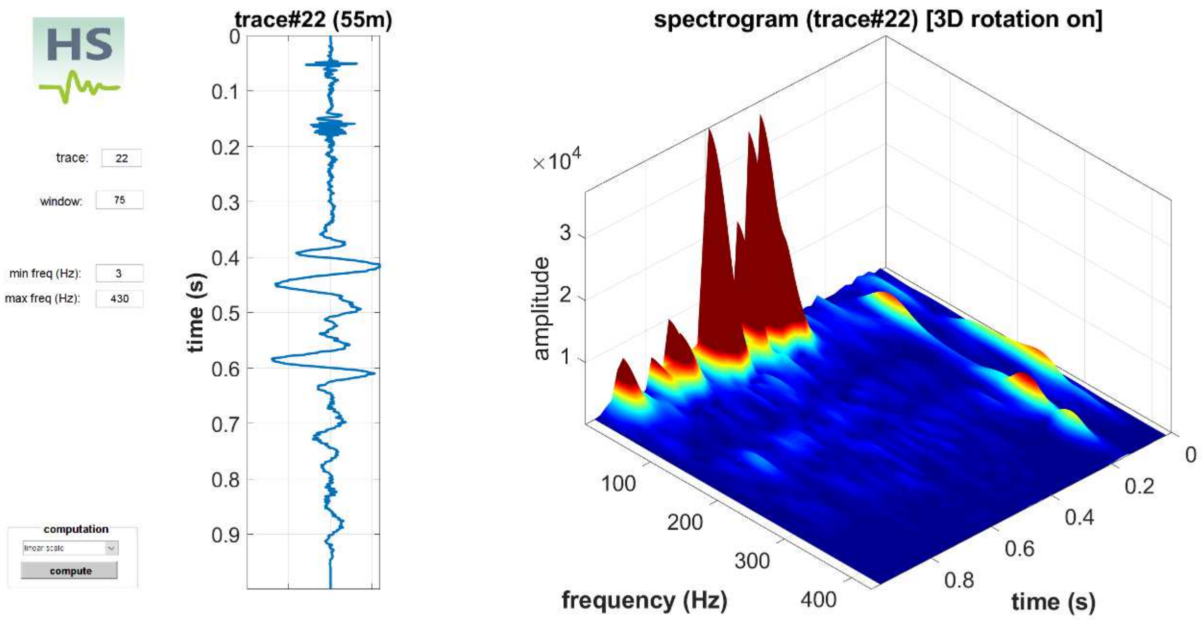
With respect to this latter *observable* (P-wave refraction) the problem is always the same (see our Elsevier and Springer books): P wave “see” the superficial refraction (clearly due to the water table at a depth of about 2.5 m) but cannot see anything below it. The V_P profile is therefore valid/significant only down to about 3 m but below such a depth we cannot say/see anything! On the other hand, dispersion allows us to get significantly deeper since shear waves - and therefore surface waves - are not significantly affected by the saturation conditions.

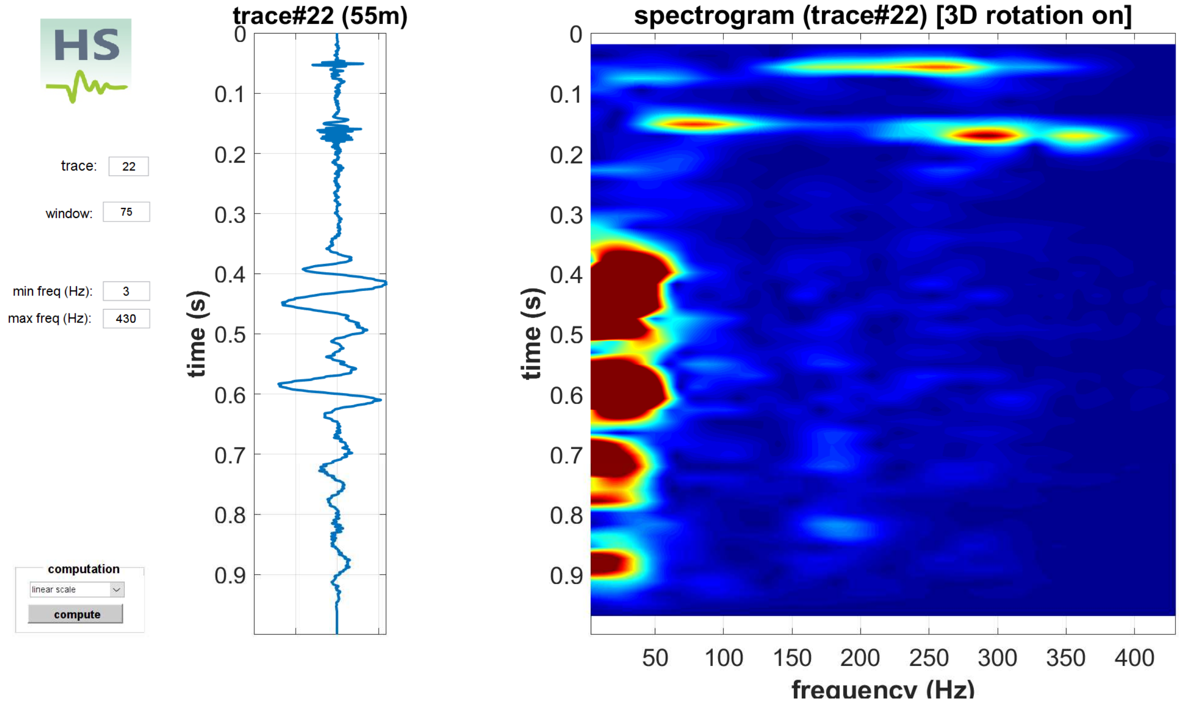
We could add many more facts and comments but the interested reader can refer to the two above-mentioned textbooks (from Elsevier and Springer).





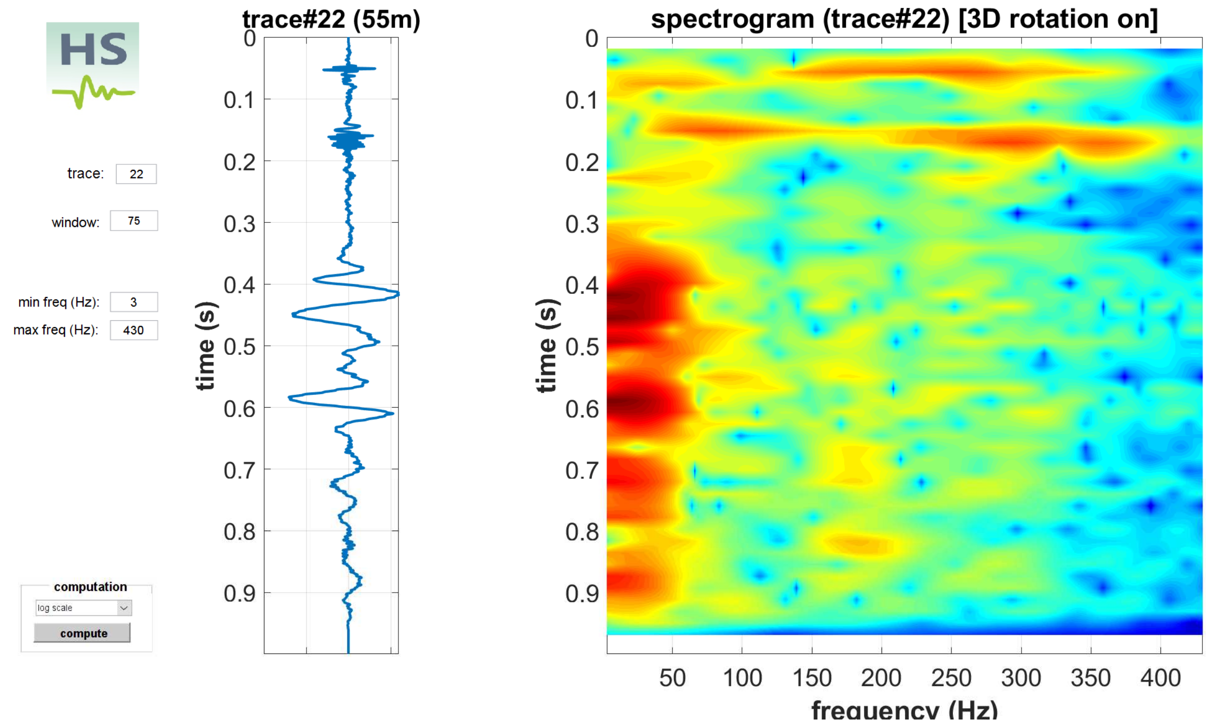
In the two figures below (in a 3D and 2D perspective), the spectrogram of the trace#22 is shown using a linear scale for the amplitude. You can clearly identify the arrivals of the surface waves [in this case the vertical component of Rayleigh waves] (slow and characterized by low frequencies) and two much faster events (with a higher-frequency content).
The first of these events is certainly connected to the P-wave refraction [see the figure with all the seismic traces reported on the previous page with overlaying the arrival times of the P-wave refractions of the model] the perfect continuity of the signal can be clearly seen.
To understand whether the second arrival is real or generated by some local accident, the continuity along all the traces should be assessed (not shown here for the sake of brevity).





The figure below refers to the same trace but is obtained using a logarithmic scale for the amplitudes, which in some cases is useful to better highlight low-amplitude components.

The scale is chosen via the small pop-up window above the 'compute' button.



F7. Single-component panel [using purely-passive data]: joint analysis of the phase velocities from ReMi (using the *effective* dispersion curve) and the HVSR

manual-in-progress

F8. Comparing the Z-component dispersion from ESAC [in *winMASW® Academy*] and MAAM [in *HoliSurface®*]

In both cases we are dealing with passive data. The mathematics of these two methods is radically different and is reflected in a number of characterizing points:

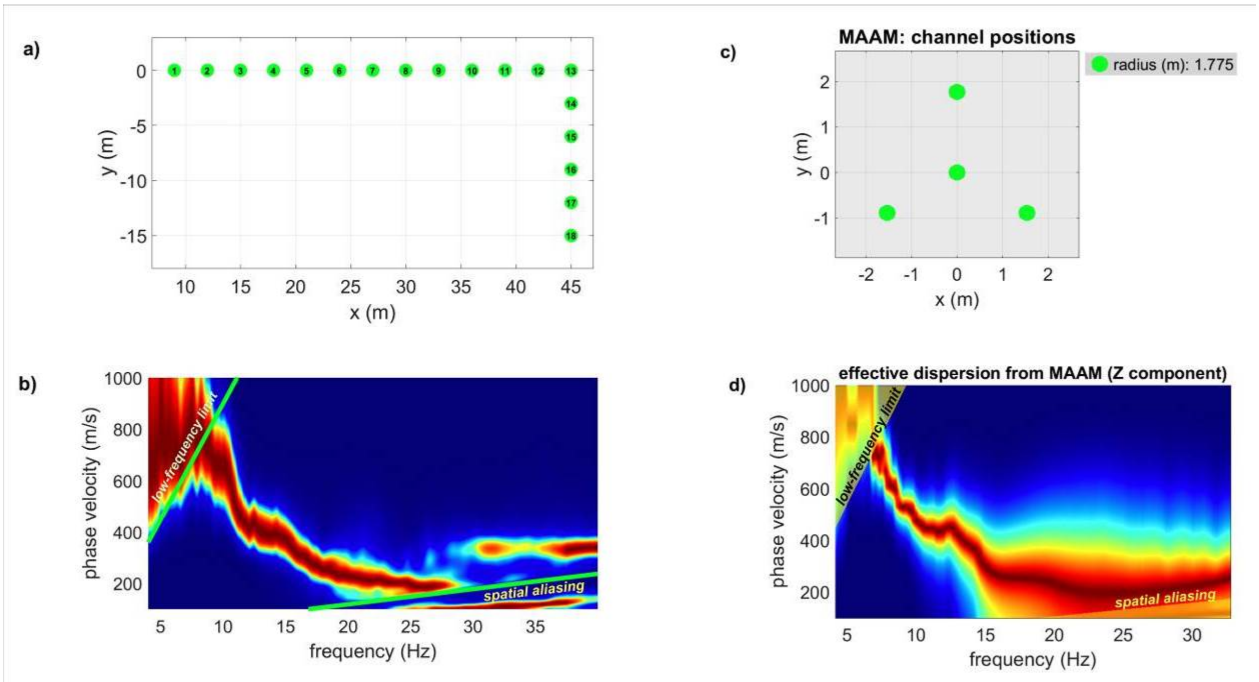
1) ESAC imposes very large arrays (in synthetic terms we can say that "it works with the wavelengths") and a significant number of channels; possible "imperfections" in some of the traces does not significantly affect the result [i.e. a few "noisy" traces do not represent a serious problem];

2) MAAM [implemented in the ***HoliSurface®*** software - HS] requires circular arrays with a limited number of channels (triangle or pentagon with a central geophone) and an extremely-small radius compared to ESAC (just a couple of meters compared to several tens of meters for ESAC). The quality of the **<u>data must be perfect</u>** (see *HoliSurface®* manual and pertinent literature).

The image below reports a comparison between the phase velocity spectra (Z component) obtained from ESAC and the MAAM for a test site. It can be seen that the velocities are fundamentally identical (the validity limits depend on the geometry of the respective arrays and are indicated).

It should be fully understood that (in both cases) we obtain the *effective* dispersion curve (<u>not</u> the fundamental mode). Furthermore, since the areas involved are very different, one should not overlook the fact that while ESAC identifies an average dispersion over a large area (several tens of metres), the MAAM dispersion refers to a very local portion/area (the radius is only a few metres).

The ESAC method is also applicable to the R and T components (see **PS-MuCAA and SuPPSALA techniques in winMASW® Academy**) while so far, the MAAM method can be used just to analyse the Z component of the Rayleigh waves.

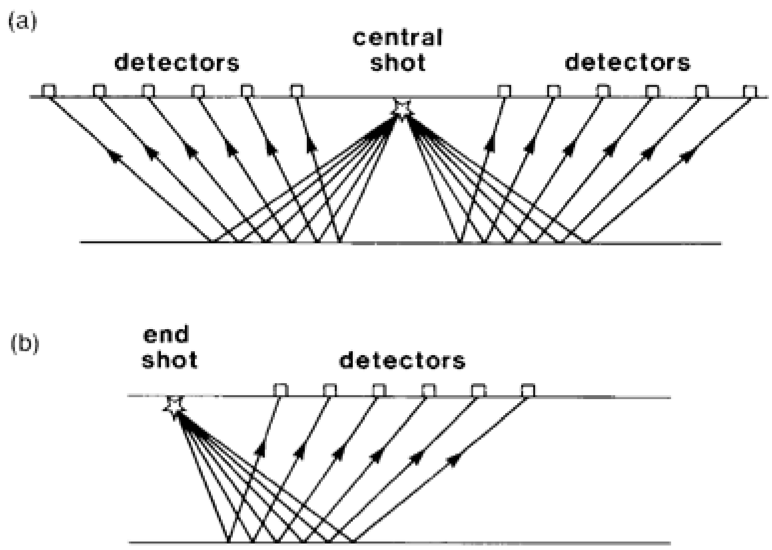


Example of a triangular array for MAAM acquisition: three geophones at the vertices of the triangle and a central one (very high-quality geophones are mandatory). Next to the central geophone you can see the 3C geophone (HOLI3C) used to determine the HVSR (which is then jointly analysed with the dispersion obtained from MAAM). All the geophones are connected to the same seismograph, thus obtaining a dataset with 7 traces efficiently managed by the HoliSurface® software.

In ***HoliSurface®***, together with the MAAM analysis, it is also possible to perform the SPAC analysis. Since SPAC follows the same logic/mathematics as ESAC, compared to MAAM it has an extremely limited frequency validity range and, therefore, can be used to verify/compare the phase velocities obtained through the MAAM only at the highest frequencies [see the pertinent section of the *HoliSurface®* manual].

F9. Utilities: comparison of active data. Comparison of the data from a central shot.

manual-in-progress

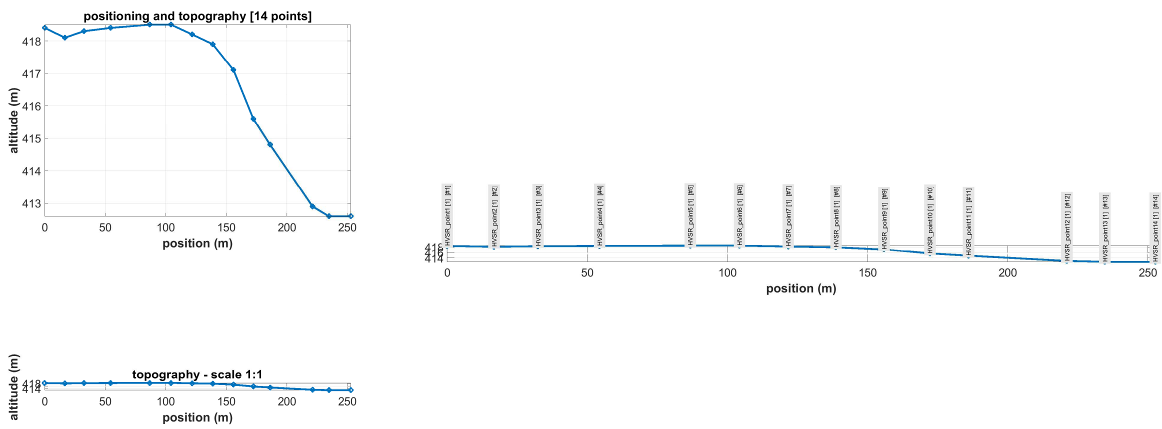


F10. Batch processing of several HVSR files (and fixing problems)

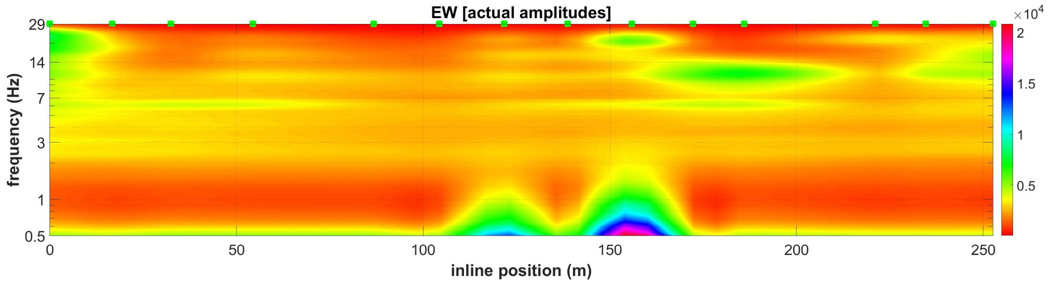
In case we have several HVSR files (SAF or seg2 format), we can process all of them according to a batch procedure (for details see the pertinent section in the manual).
Here is an example of a project file (a simple ASCII file) for a case where we have 14 points along a line.
As we will see, at two points data are problematic and it is shown how we can solve such problem using the features of this tool.

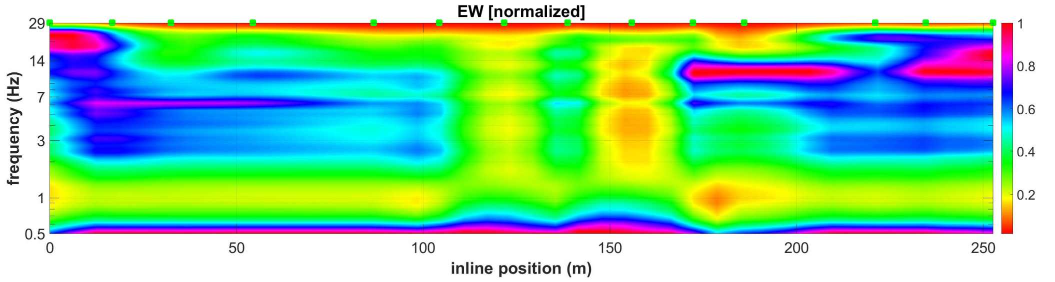
```
    www.winMASW.com
# HVSR batch processing #
0
0
0      16.71077      32.40386      54.37693      86.72191      104.2671      121.6846      138.7052      155.8513
172.2376      186.0155      221.1027      234.6533      252.6087
418.4        418.1        418.3        418.4        418.5        418.5        418.2        417.9        417.1        415.6
414.8        412.9        412.6        412.6
HVSR_point1.SAF 1 1 2 3 HVSR_point1.jpg
HVSR_point2.SAF 1 1 2 3 HVSR_point2.jpg
HVSR_point3.SAF 1 1 2 3 HVSR_point3.jpg
HVSR_point4.SAF 1 1 2 3 HVSR_point4.jpg
HVSR_point5.SAF 1 1 2 3 HVSR_point5.jpg
HVSR_point6.SAF 1 1 2 3 HVSR_point6.jpg
HVSR_point7.SAF 1 1 2 3 HVSR_point7.jpg
HVSR_point8.SAF 1 1 2 3 HVSR_point8.jpg
HVSR_point9.SAF 1 1 2 3 HVSR_point9.jpg
HVSR_point10.SAF 1 1 2 3 HVSR_point10.jpg
HVSR_point11.SAF 1 1 2 3 HVSR_point11.jpg
HVSR_point12.SAF 1 1 2 3 HVSR_point12.jpg
HVSR_point13.SAF 1 1 2 3 HVSR_point13.jpg
HVSR_point14.SAF 1 1 2 3 HVSR_point14.jpg
```

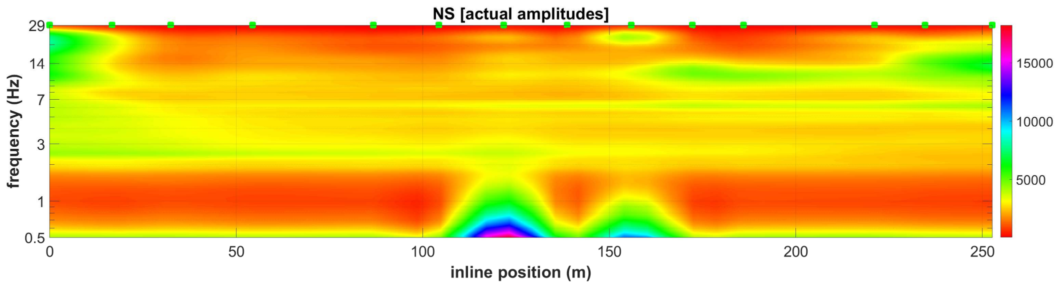
By uploading this project file from the HVSR panel ("**multiple HVSR batch processing**" button), we obtain the HVSRs for each point and a series of additional graphs that define, in a sense, a sort of 2D section of the microtremors (both the amplitude spectra of the individual components as well as the HVSR).

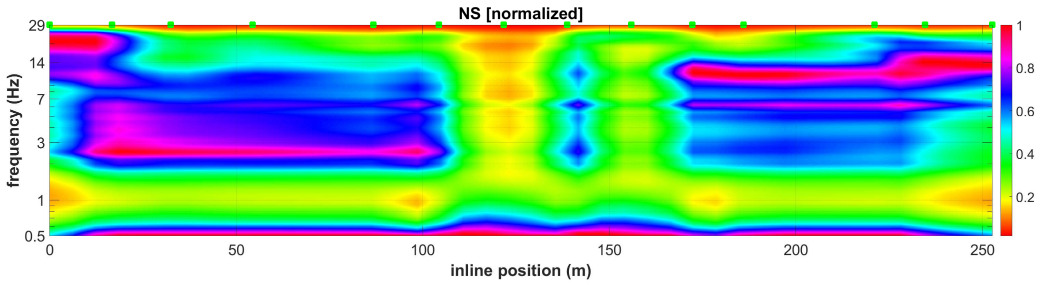


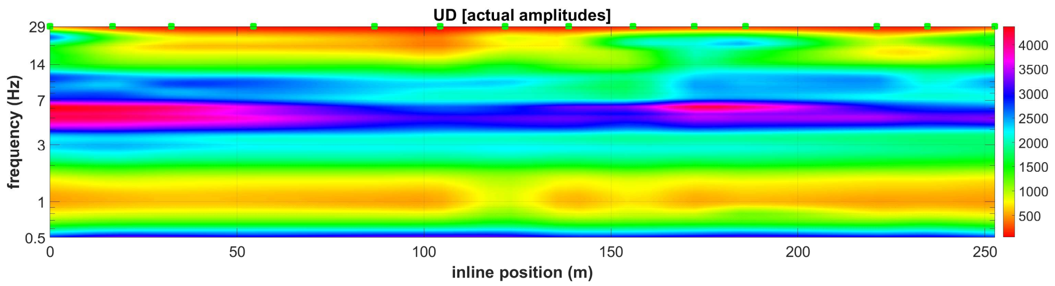
At the end of the processing you will also obtain the amplitude spectra for all the three components (EW, NS and Z), both with the actual/real amplitude as well as normalized.

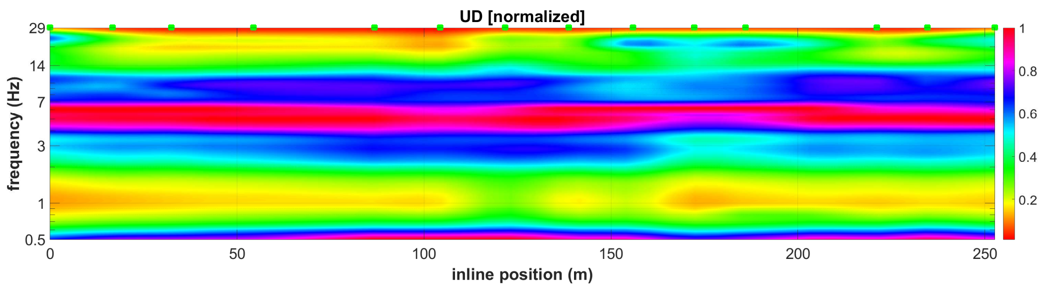




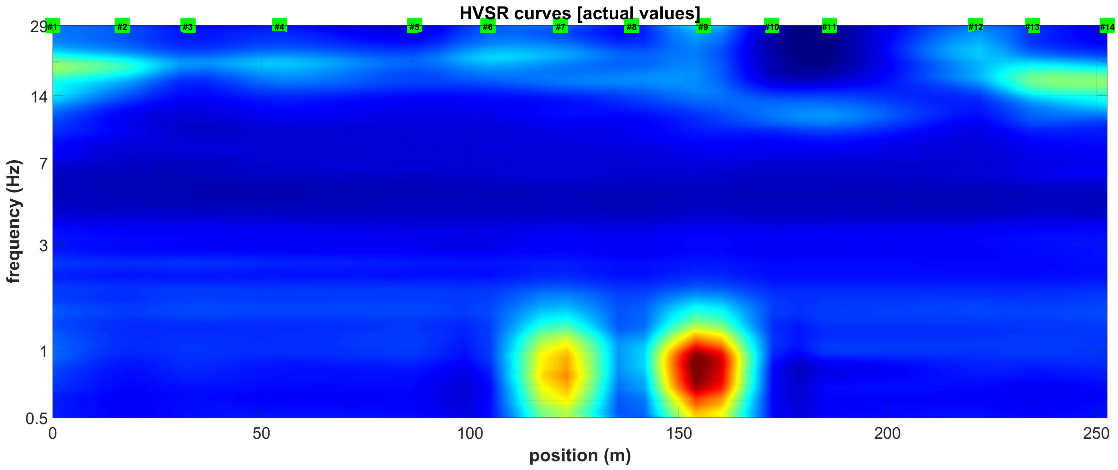


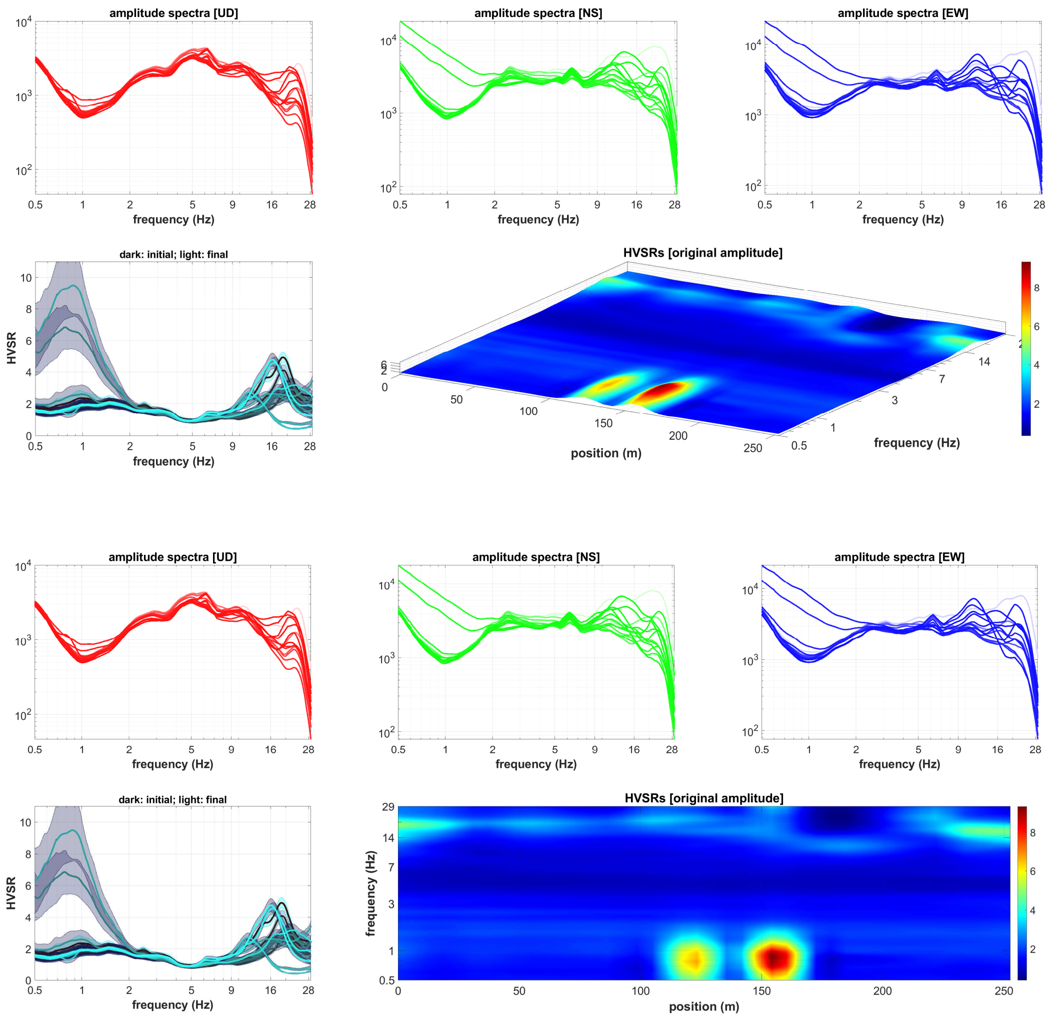






In the image below the HVSR “section” (actual curves). We can clearly see two points (#7 and #9) where, at low frequencies, the HVSR is completely inconsistent and such a problem (at those 2 points) was apparent also in amplitude spectra shown in the previous page.





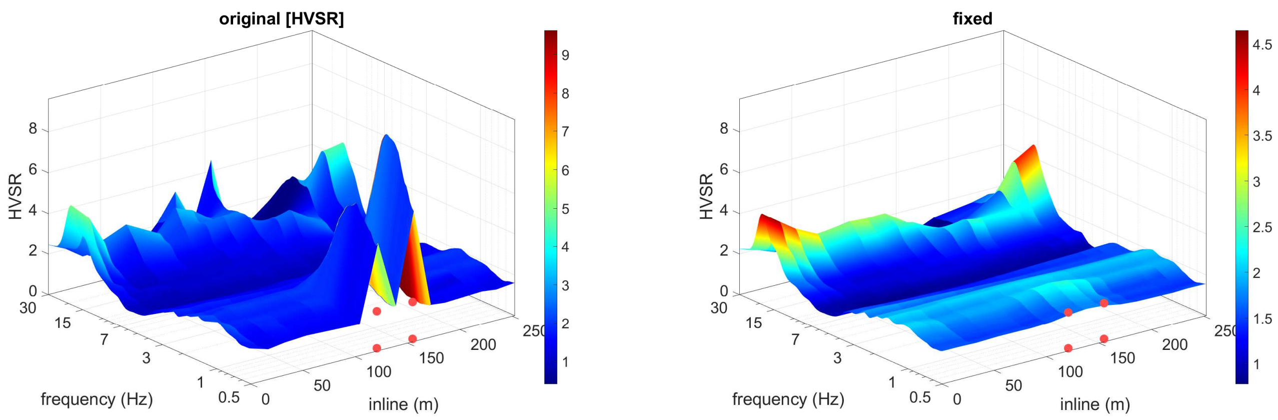
Amplitude spectra and HVSR
(actual amplitudes according to different perspectives)

It should be quite clear that the HVSRs at point#7 and #9 cannot be considered as reliable (they are completely meaningless). Fortunately, at the end of the routine, the software offers the chance to fix this kind of problems.

In fact, by showing the obtained HV curves, the software asks if there are any points to "fix".

In this case we can tell the software to fix (remove and interpolate the wrong/inconsistent HVSRs) for the points #7 and #9.

Here is what you get: on the left are the original HVSRs and on the right those obtained by removing and interpolating the point#7 and #9.



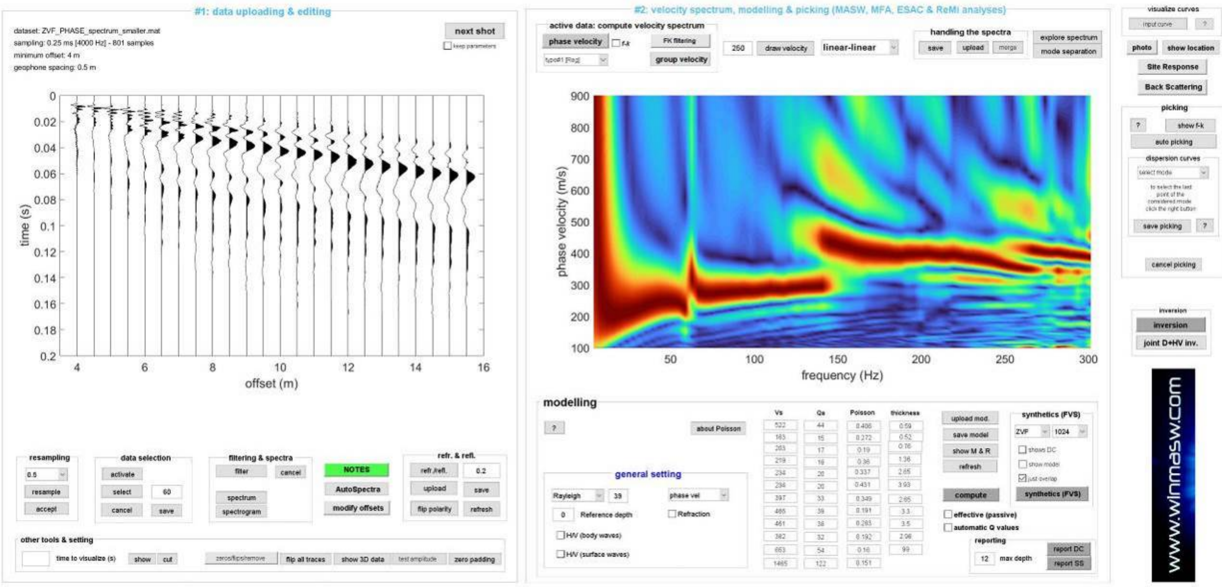
F11. ESAC panel: example of data processing for crustal studies [low-frequency seismological data]

manual-in-progress

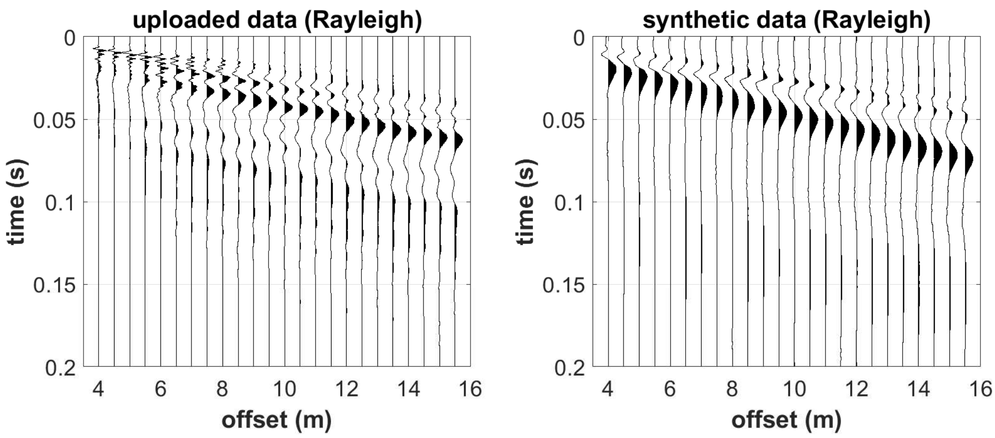
F12. Single-component panel: FVS analysis of the ZVF component only for a shallow (geotechnical) application [high frequencies]

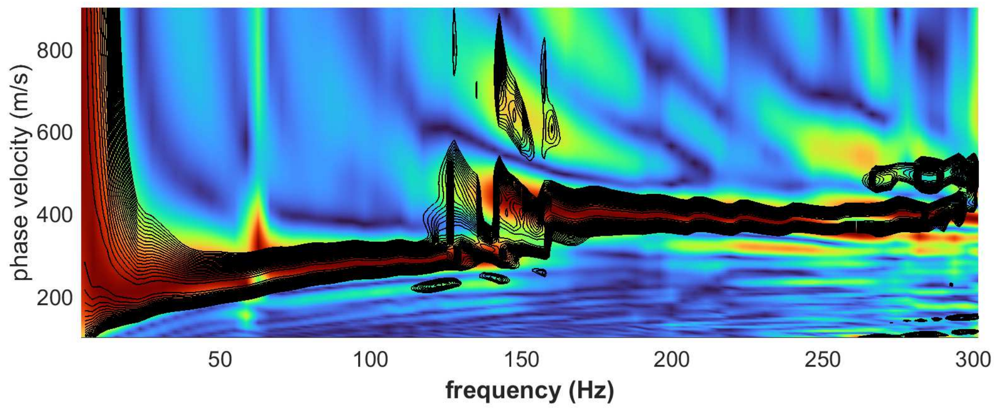
ZVF component, *mo* (minimum offset): 4 m, *dx* (geophone distance): 0.5 m

For this survey, only the ZVF component was used (vertical geophones). Data and analysis are reported and briefly commented in the following figures.
The small artefact around 60 Hz is the result of the 60 Hz Notch filter forgotten "on" during the data acquisition (no serious harm to the data).



Field traces and phase-velocity spectra (please, notice the frequency range)

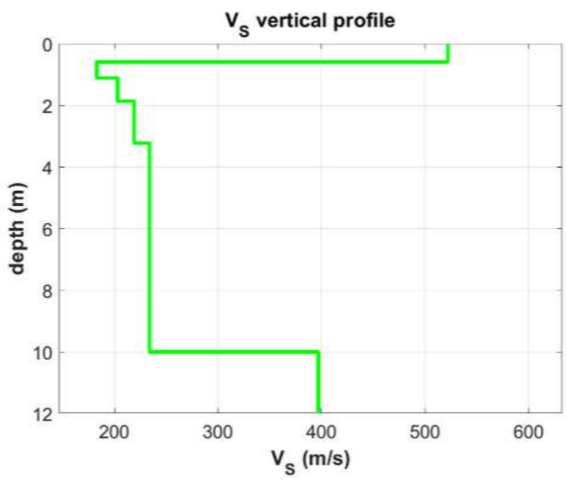




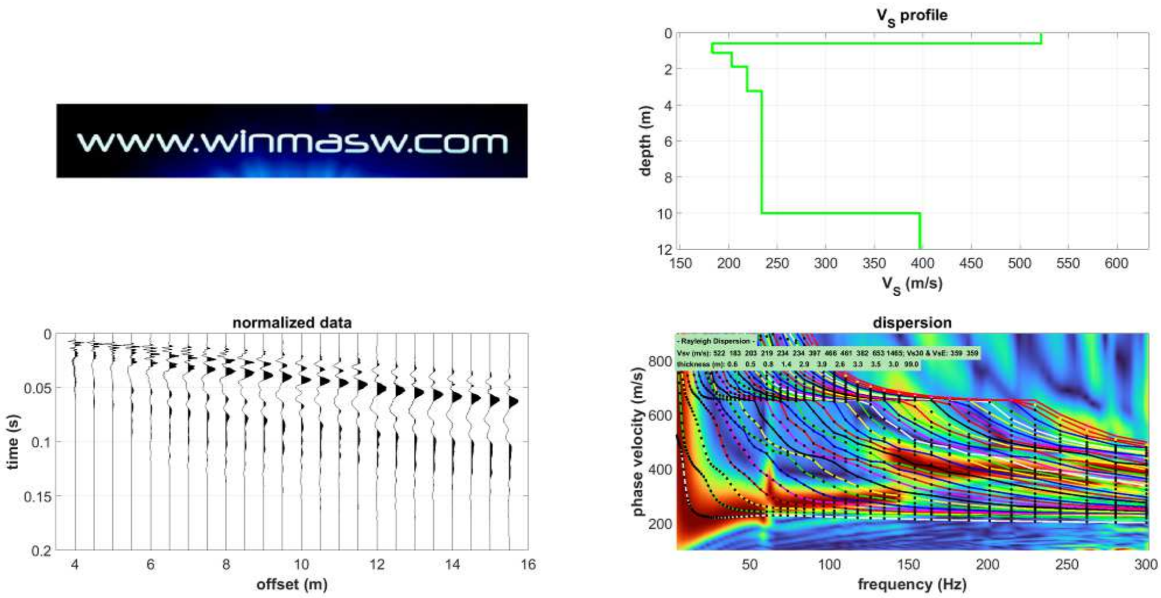
Result of the FVS [Full Velocity Spectrum] analysis:
do you see how the model is in good agreement with the field data?

The black contour lines (from the model) almost perfectly match the field velocities.

www.winmasw.com



Now we can try to plot the modal dispersion curves:

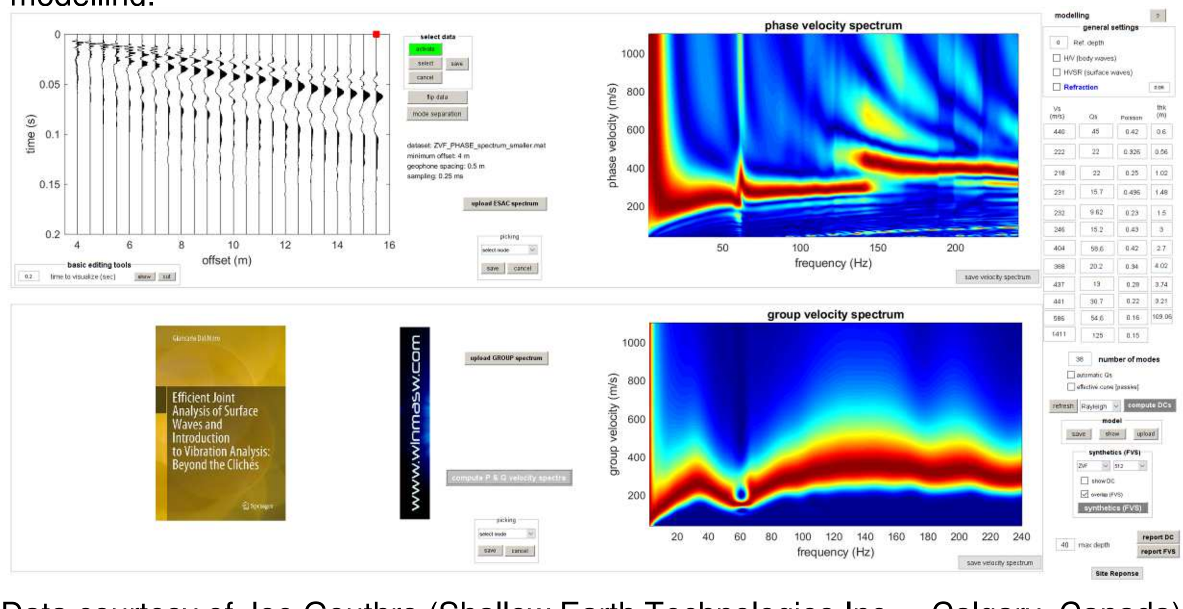


As you can clearly see, the signal is not about simple and "singular" modes. For instance, the signal between 1 and 150 Hz is about the fundamental mode (remember that the small "bump" at 60 Hz is due to the Notch filter used during the acquisition). The message (see our books and papers about it): **a continuous signal (in the phase velocity spectrum) is not necessarily due/attributed to a single mode since modes can merge and create a "misleading continuity".**

This is why we strongly recommend the joint analysis of multi-component data.

Suggested reading [see the "Documents" folder in the winMASW® installation directory]:
Surface wave analysis: improving the accuracy of the shear-wave velocity profile through the efficient joint acquisition and Full Velocity Spectrum (FVS) analysis of Rayleigh and Love waves, **Dal Moro G., 2019, Exploration Geophysics**

Suggested exercise (to try to verify if the solution found while considering the ***phase*** velocities is also in agreement with the ***group*** velocities): go to the "**Joint Analysis of Phase & Group Velocities**" panel, compute the two velocity spectra and go ahead with the modelling.

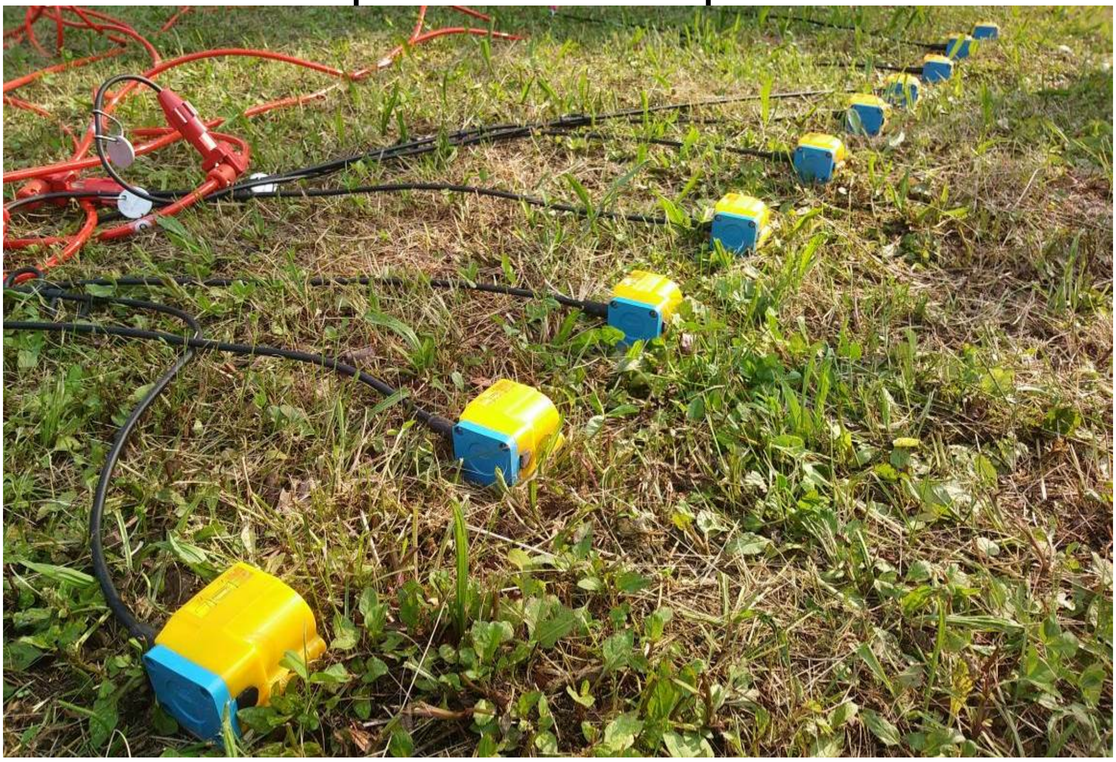


Data courtesy of Joe Gouthro (Shallow Earth Technologies Inc. – Calgary, Canada)

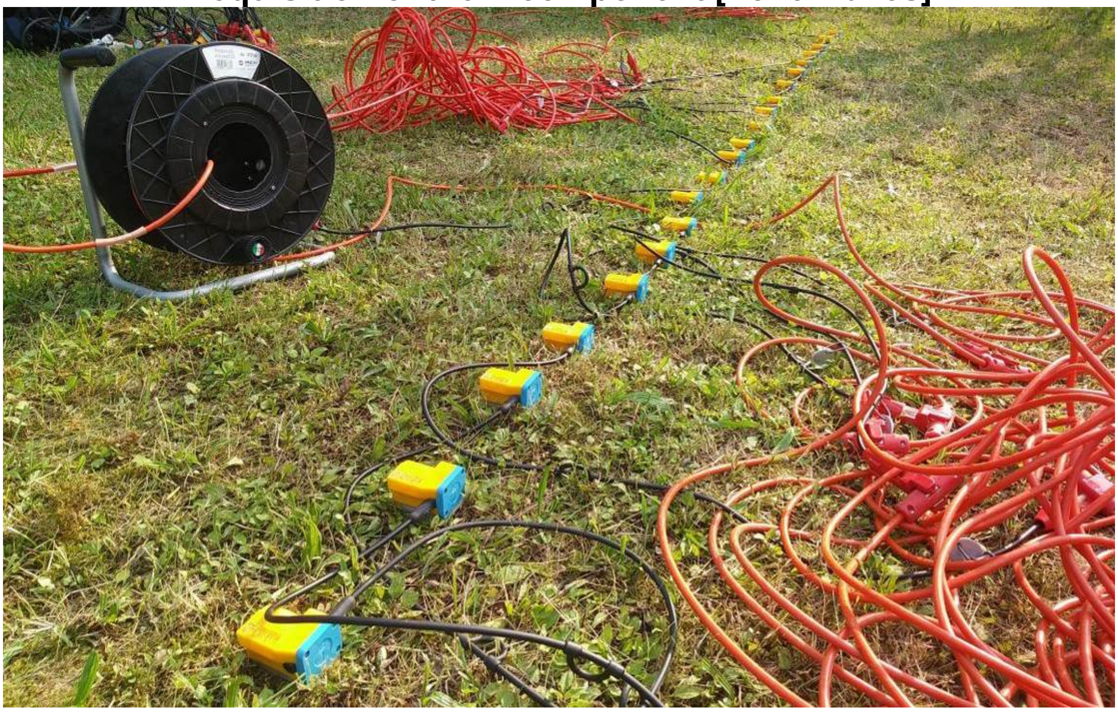
F13. Joint analysis panel: joint analysis of the two components of Rayleigh waves for very shallow studies [high frequencies]

In the next two pictures are shown the horizontal geophones used to record the R (radial) and T (transversal) components [acquisition of the Z component not shown for obvious reasons]. 21 channels were used with a geophone spacing of just 20 cm.

Acquisition of the R component



Acquisition of the T component [Love waves]

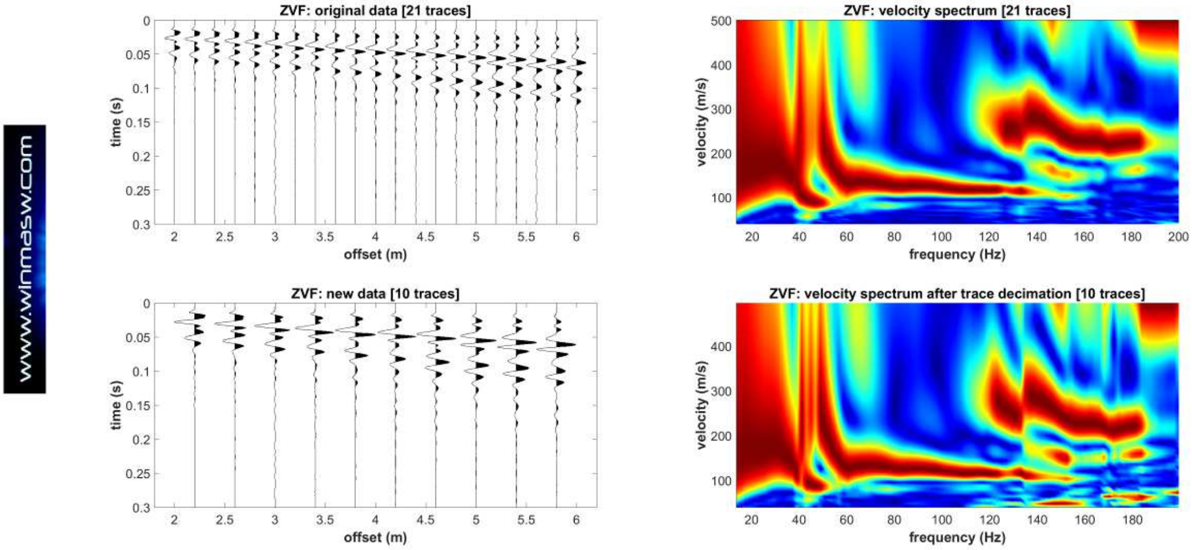


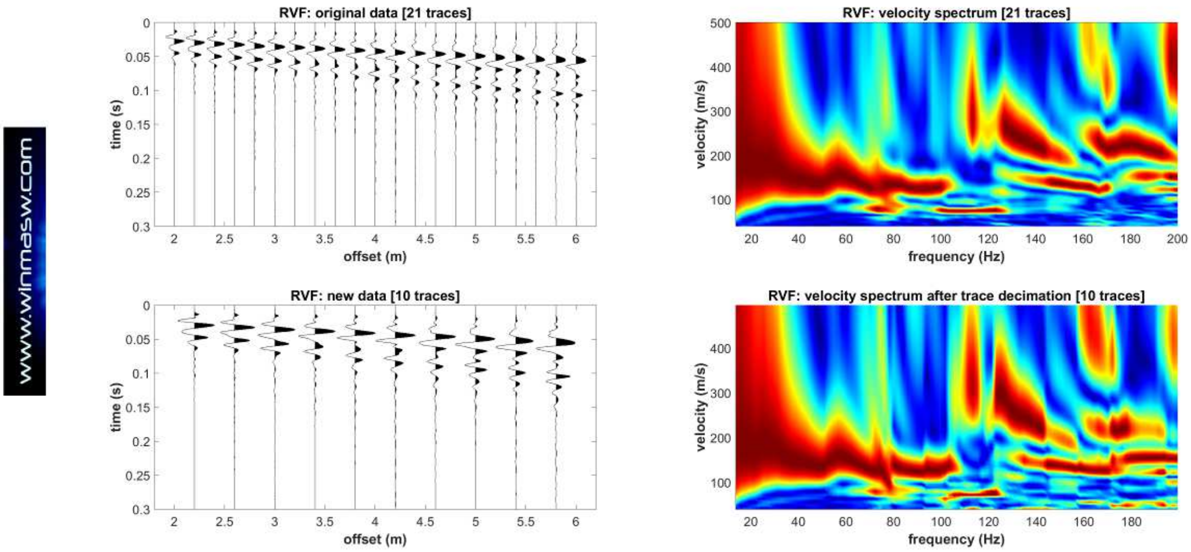
First "issue": are 21 channels (or more) necessary? The answer is widely explained and commented in our *Elsevier* and *Springer* books and is summarized in the next two figures that make clear that using 21 or 10 channels does not significantly alter the phase-velocity spectra.

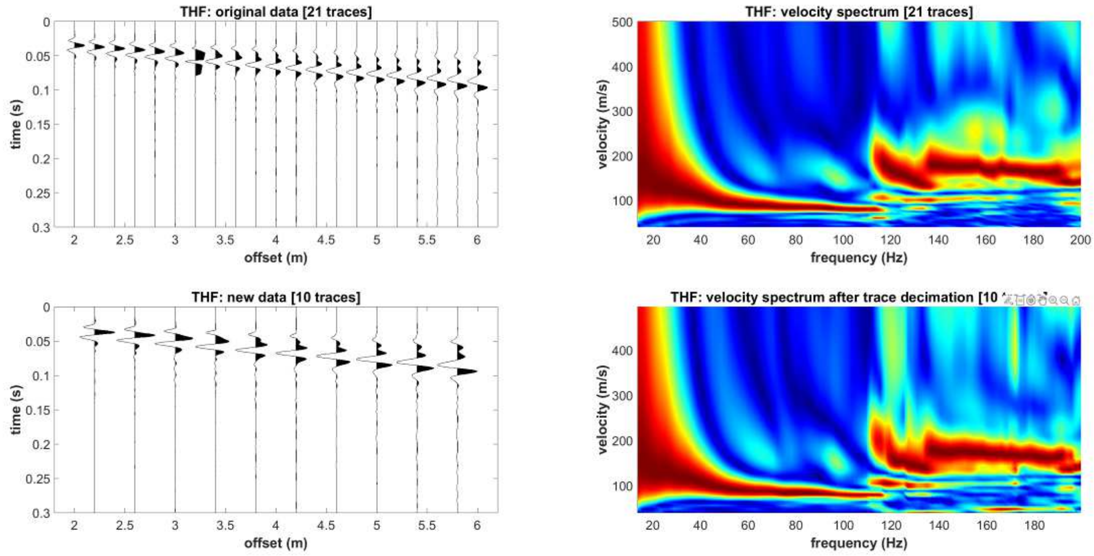
On the other side it must be **strongly underlined that** dealing with two (or more) components is a key point if we want to overcome the ambiguities necessarily present while analyzing surface data [see "**1.3 Non-uniqueness of the Solution: Problems and Solutions**" section of the Springer book].

If your purpose is to obtain the right (unambiguous) V_S profile, working with just one component is, quite simply, wrong/inadequate (in general terms).

Trace decimation for the Z, R and T components

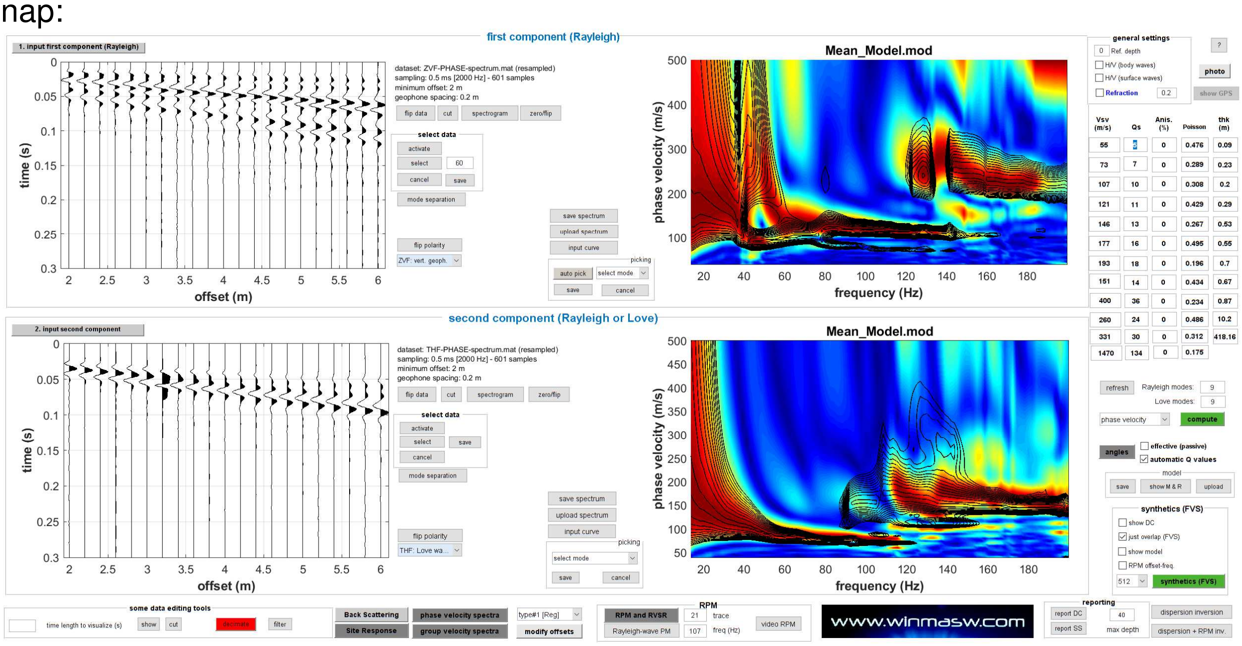




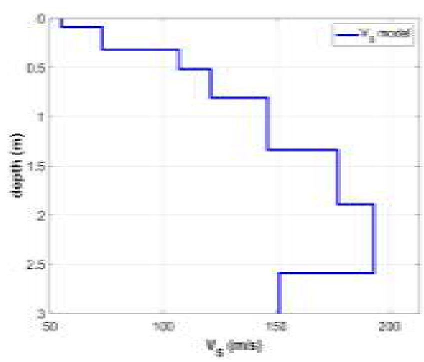


Some FVS modelling/inversion: Z+T [with no anisotropy]

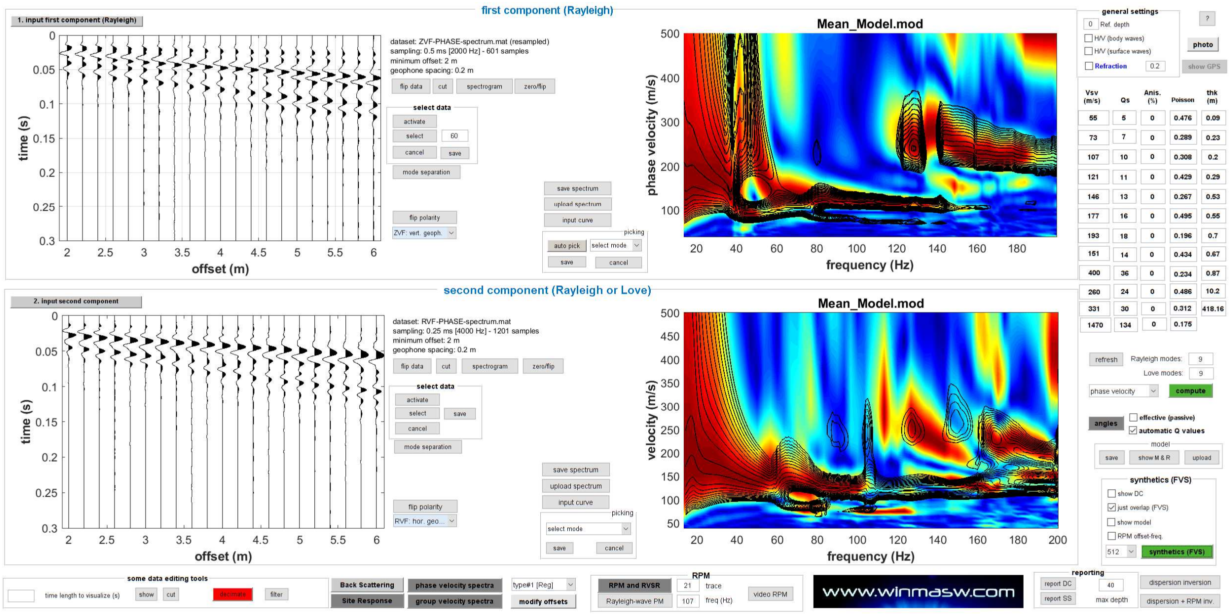
We selected the Z and T components (i.e. vertical component of Rayleigh waves and Love waves) and performed a joint FVS inversion with the results shown in the following snap:



Since the length of the array is just 4 m, we can consider the model sufficiently reliable only down to about 2-3 m:



The obtained model was then used also to check the consistency of the R component. Here the overall good agreement:



Few comments

Remember that surface waves can be used for several applications (not only for the notorious Vs30 parameter). Consider that:

1) only *joint inversion* can save us from all the possible ambiguities that can otherwise mislead our analyses (in case we deal with just one component/observable);

2) modal dispersion curves are often not adequate to properly “understand” complex datasets and the FVS approach is a powerful tool to learn to master.

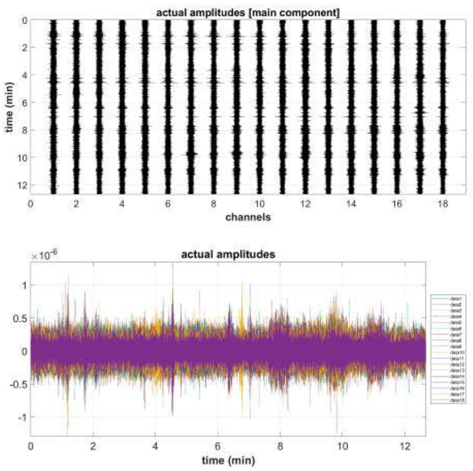
F14. ESAC panel – PS-MuCAA section: example of multi-component passive data for the verification of lateral continuity

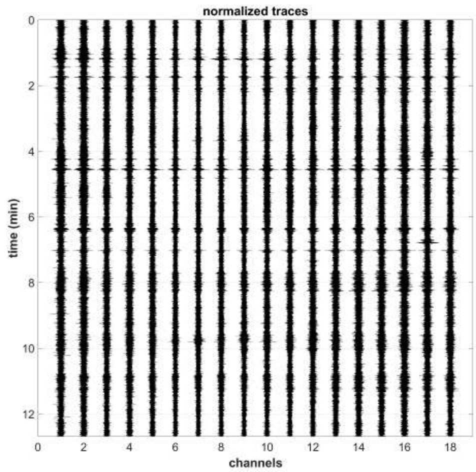
manual in progress

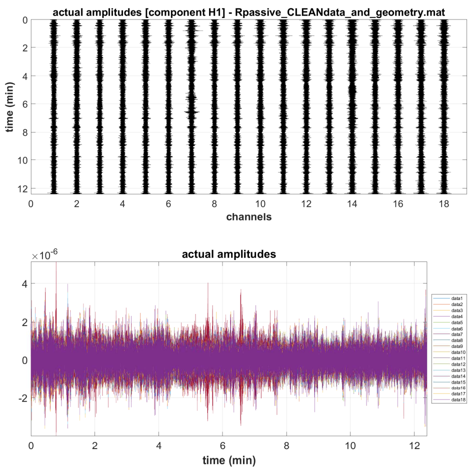
For the following example we recorded the 3 components (Z, R and T) using 18 channels. The three components were recorded not at the same time but in succession (first the Z, then the R and finally the T).

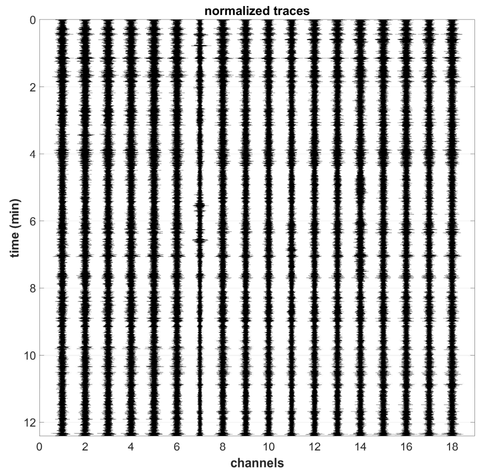
Acquisition of the R component: the axis of the horizontal geophone is parallel to the array

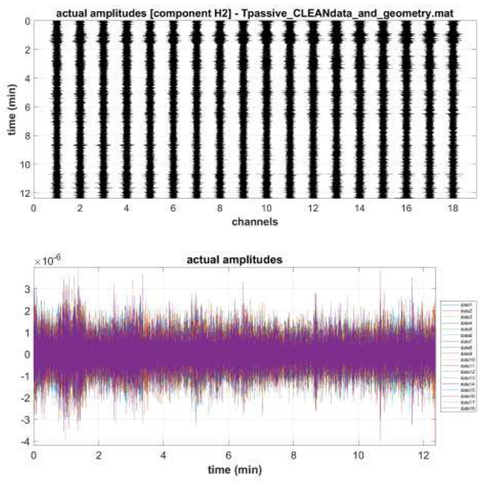
The data

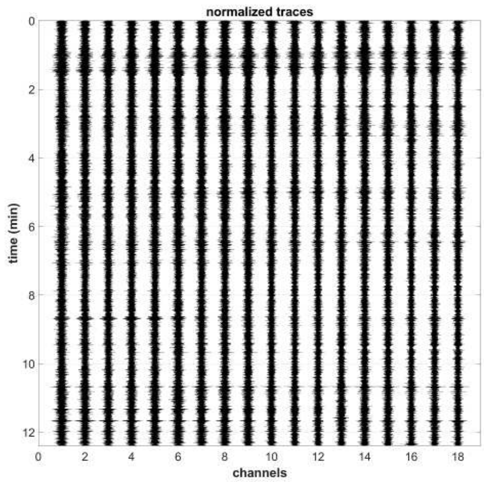












Comment:

F15. Joint inversion of the effective dispersion curves from of the R and T components from passive data

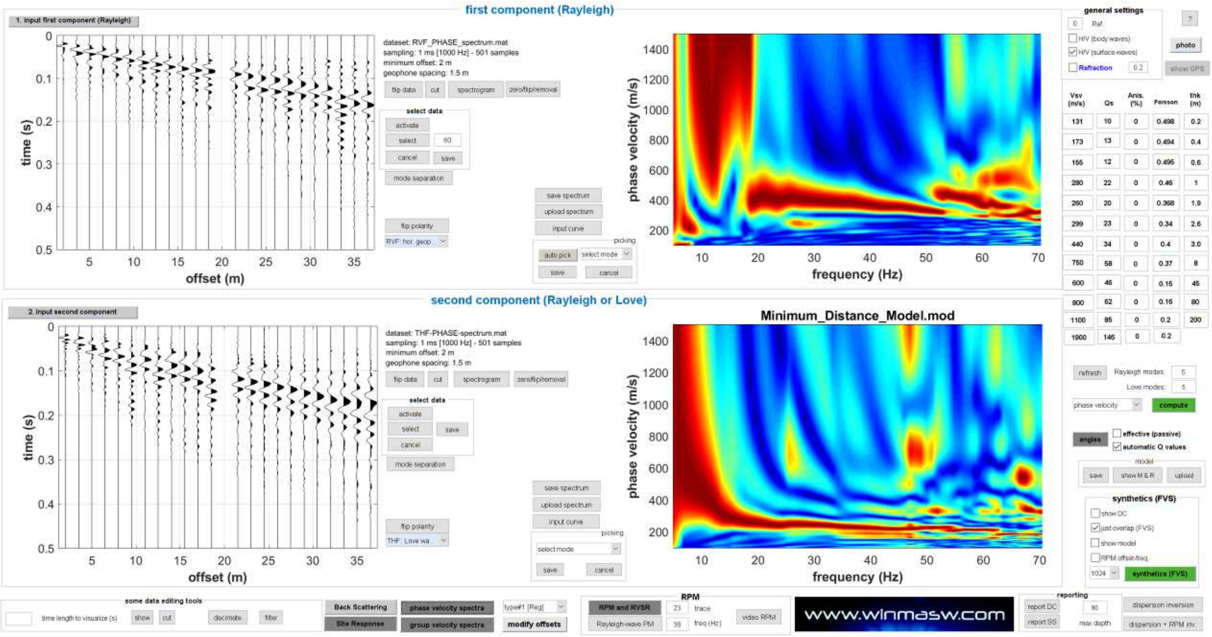
manual-in-progress

For the following example we recorded the 3 components (Z, R and T) using 18 channels. The three components were recorded not at the same time but in succession (first the Z, then the R and finally the T).

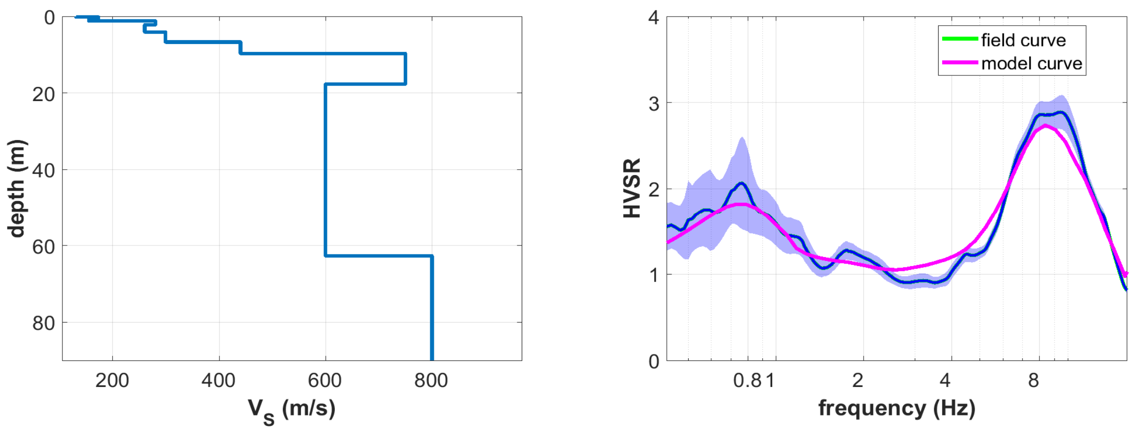
Acquisition of the R component

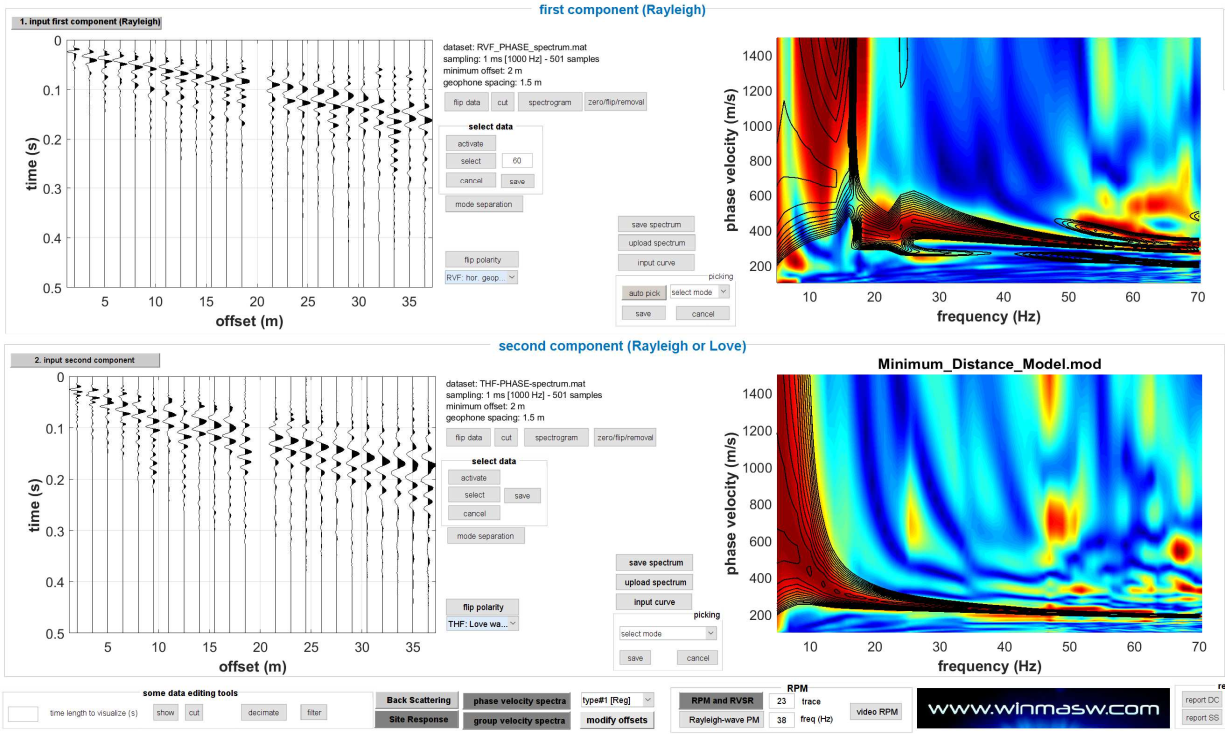
F16. A further example of joint (FVS) analysis of the R and T components jointly with the HVSR

This is the approach that we consider as "classic" (cause it is easily implemented) and that we strongly recommend for ordinary professional jobs: use just we a set of 4.5 Hz horizontal geophones (12 are actually more than sufficient for typical arrays up to 100 meters of so): we can record the radial component of Rayleigh waves and the Love waves (see guidelines about data acquisition).
In this case the traces of the 13th channel (offset 20 m) were removed due to the poor quality (remember that *winMASW®* can easily manage non-equally spaced data).

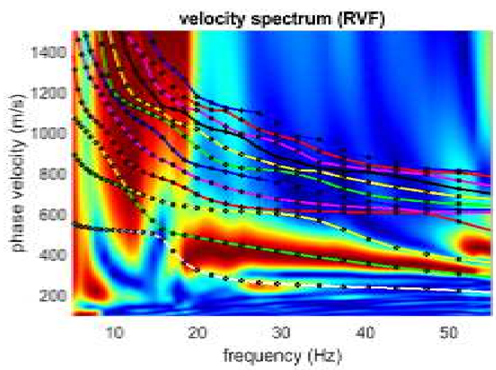


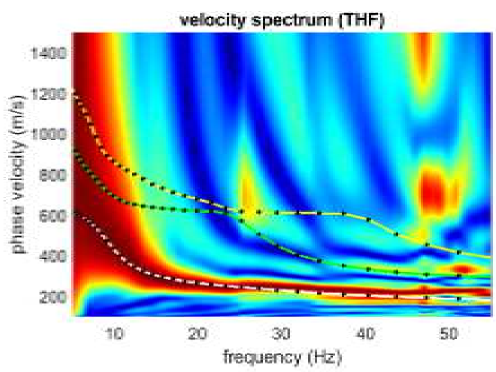
A trained eye can immediately realize that Rayleigh waves (upper part of the panel) are dominated by higher mode(s): the phase velocities are in fact **much** higher than the velocities of Love waves (lower panel).
Using just Rayleigh waves can be dangerous because the velocity spectrum can be misinterpreted: higher mode(s) can be considered as the fundamental mode thus leading to significantly over-estimate the final V_S profile (this is unfortunately a very common mistake when the "standard" MASW approach is applied).
After some forward modelling (also jointly with the HVSR curve), we can obtain a pretty good agreement between our mode and the field data (dispersion is processed according to the FVS approach):





In case we want to see how modal dispersion curves behave, we can have a look at the following figure. *Comme d'habitude*, Love waves are dominate [easily interpretable][by teh fundamental mode while Rayleigh waves are definitely much more complex and the fundamental mode is practically completely missing.

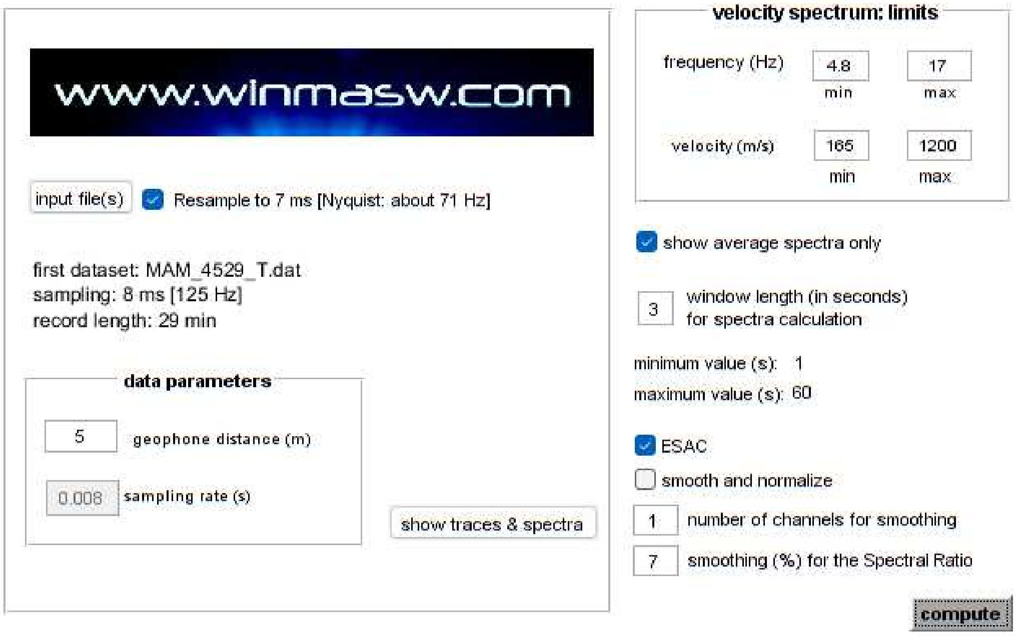




Please, remember that, when properly identified and modelled, higher modes are something extremely useful to constrain the subsurface model. The problem is that, in case you analyse just one component, modes can be *misinterpreted* thus leading to erroneous subsurface models. **Please, carefully consider the synthesis in the "Introduction: the *winMASW®* holistic perspective" section of this manual.**

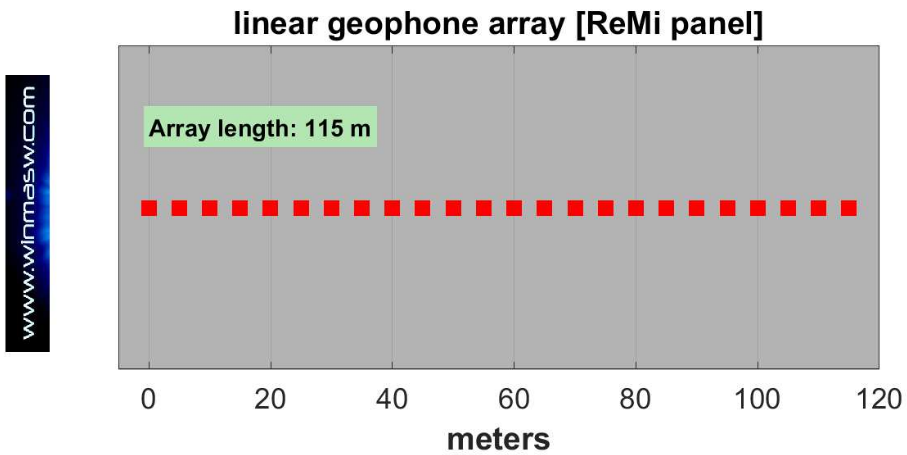
F17. Analysis of the T-component passive data (Love waves) obtained with a linear and equally-spaced array

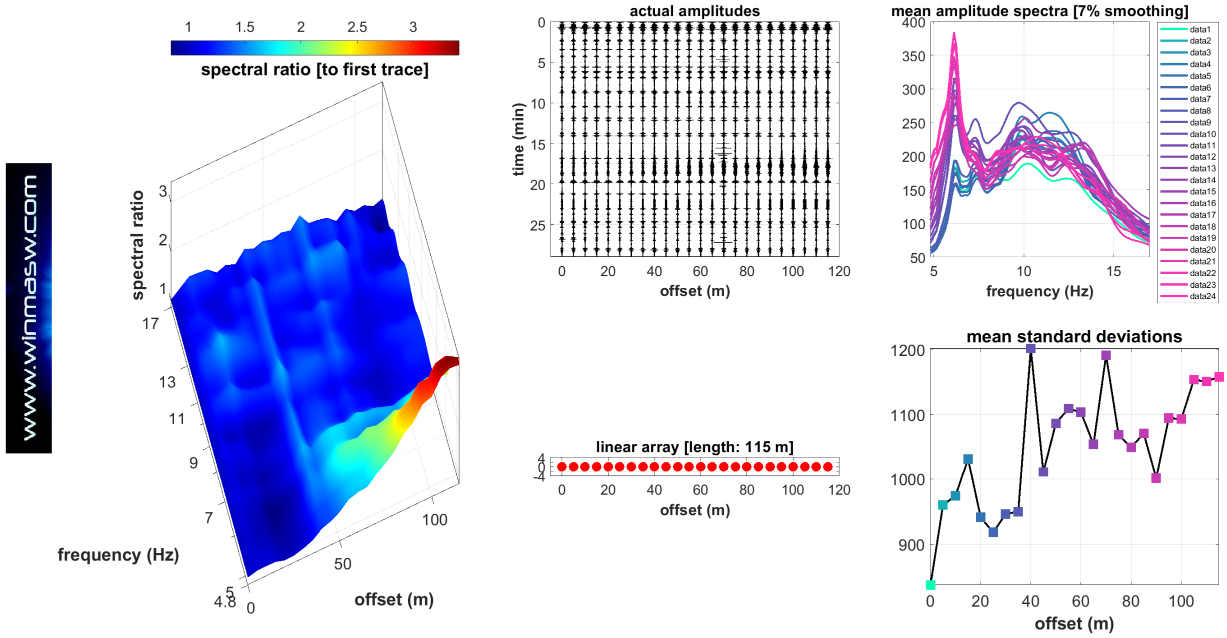
In the snapshot below, it is shown the **ReMi panel** (accessible from the main winMASW® panel). Here you can upload your data (equally or non-equally spaced) and, once all the relevant parameters properly set (correct geophone distance [in this case 5 meters], frequency and velocity limits, window length etc.), we can run the codes (in this case we ask the software to show only the **average phase-velocity spectra**).
In this case, we also activate the ESAC option so to compare the result obtained from the "ReMi approach" (i.e. the phase shift technique applied to passive data) and the one from the *Extended Spatial AutoCorrelation*.



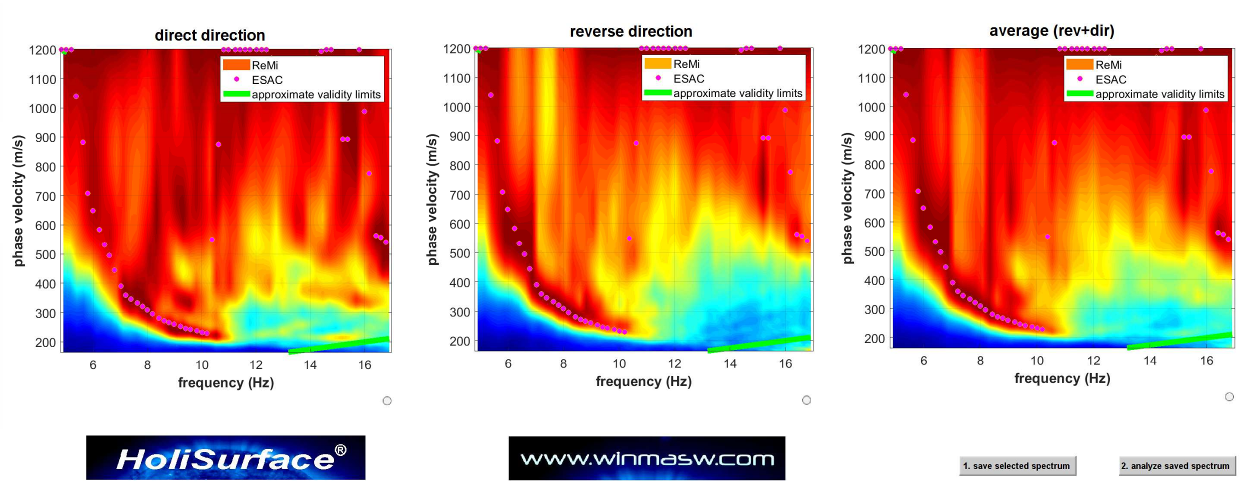
Once we click the "compute" button, we immediately obtain two figures:
1) the first with the array
2) a second one with the amplitude spectra of each channel and the spectral ratios with respect to the first channel (in order to understand what kind of information you can obtain from these graphs, please see Dal Moro & Stemberk, 2022).

Needless to say that, as for any (passive and active) seismic acquisition, acquisitions must be accomplished using homogeneous geophones (with the same identical sensitivity curve) and the same gain value (if any).



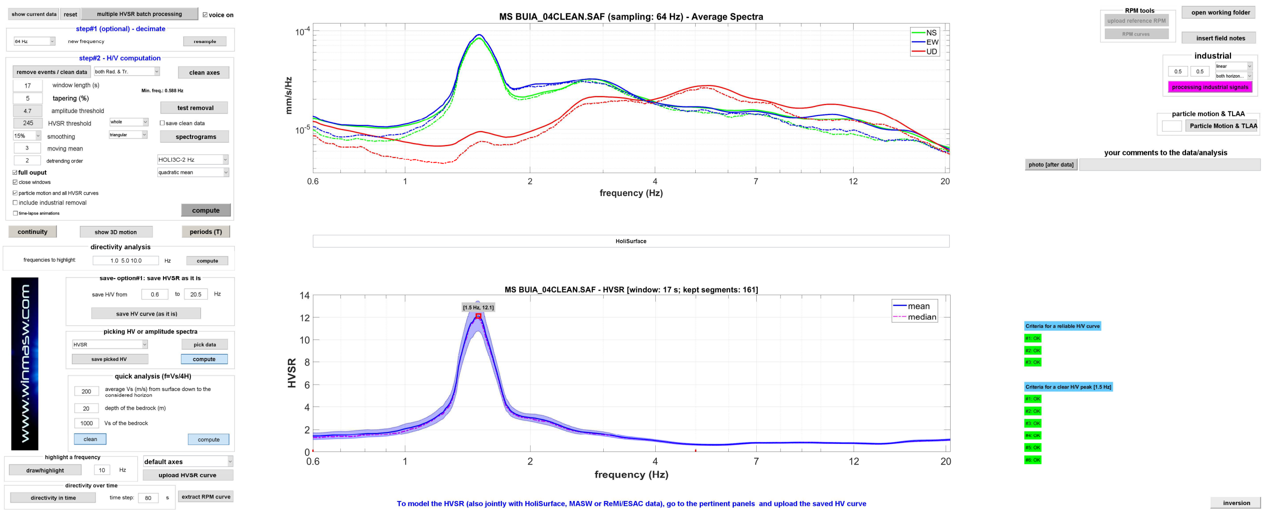


After a few seconds, you obtain the final figure with three phase velocity spectra: the one obtained considering the direction from the first to the last trace, the one considering the opposite propagation velocity and the mean one (obtained simply averaging the first two velocity spectra). Since in this case we also activated the **ESAC option**, overlapped with the three velocity spectra is also shown (dots) the dispersion obtained via ESAC.
A few comments about the obtained results can be briefly outlined. If we compare the velocity spectra from ReMi (i.e. phase shift) and the dispersion obtained from ESAC, we can point out a sort of "special feature" since they coincide (the maximum of the velocity spectra and the dispersion curve from ESAC have the same velocity). This is clearly *not* in agreement with the general paradigm often outlined while considering the "ReMi approach", where the dispersion is said to be represented by the "lower limit" of the obtained velocity spectrum (see pertinent literature). In this case, the correct/real velocity (identified through the ESAC) corresponds to the *maximum cohrence* of the velocity spectrum obtained from ReMi and not with the *lower limit*. The reason is quite simple: the microtremor field is not homogenously (azimuthally) distributed but there are dominating sources in line with the array (in this case the array was in fact perpendicular to two busy streets running one North of it and one South – one was closer than the other and this is shown by the amplitude spectra obtained at the very beginning of the computation).

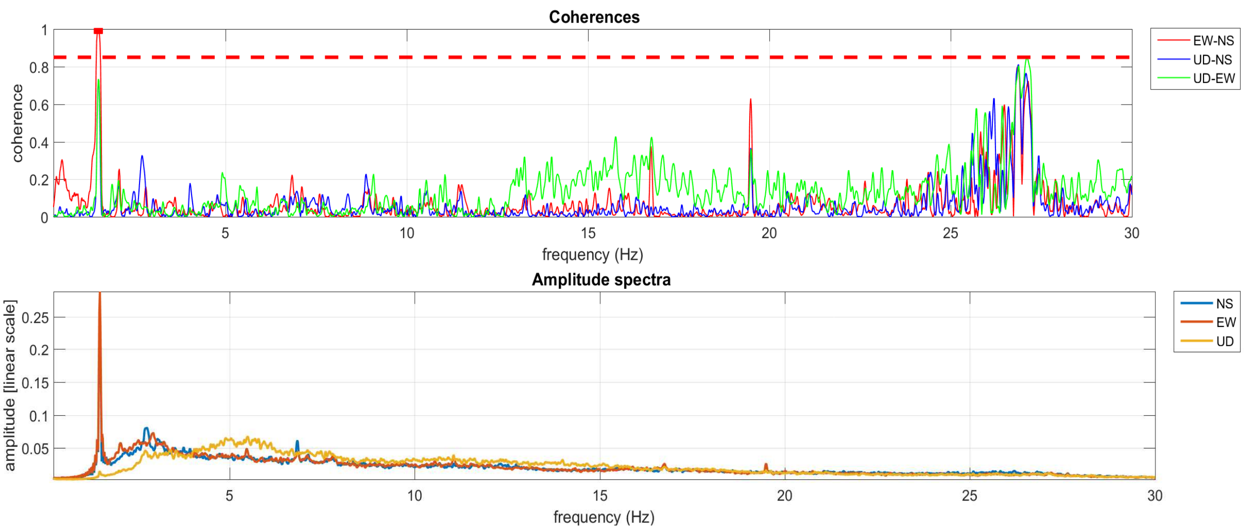


F18. Automatic removal of industrial components from the HVSR

In this example we show the removal of an important industrial component at a frequency where a real HVSR peak is also present.
First of all we compute the H/V spectral ratio in the usual way (see following snapshot).

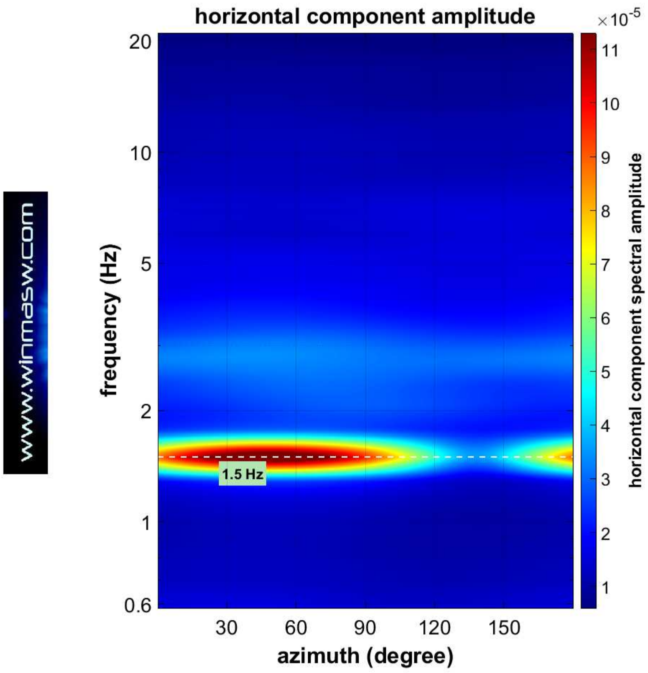


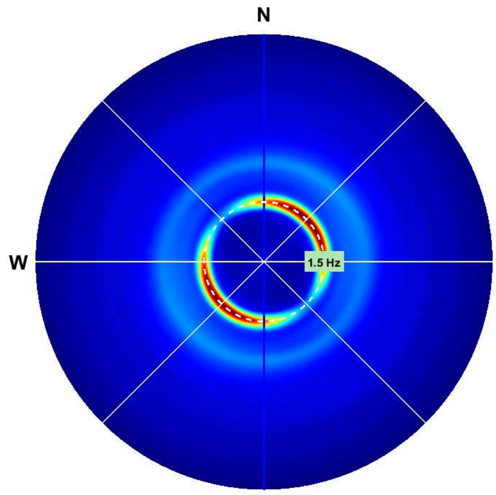
Together with the ordinary graphs, are also shown the coherence functions and the quasi-unsmoothed amplitude spectra (for details see the **"Computing, assessing and modelling the HVSR" section** of this manual).



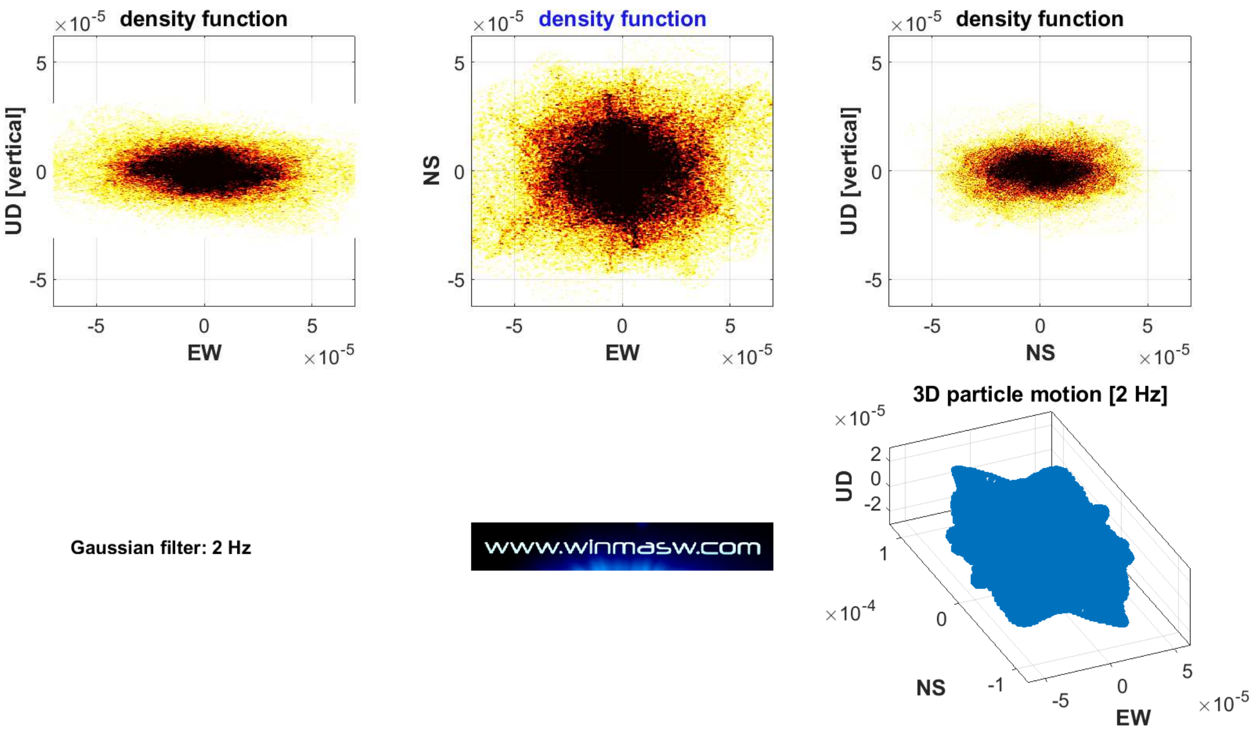
The presence of an industrial component at about 1.5 Hz is apparent but let's try to further characterize what happens at 1.5 Hz carefully assessing the following further graphs.

We can further verify the presence of industrial components through more in-depth analyses. In the following figure, it is shown the directivity of the horizontal component (i.e. the amplitude spectra on the horizontal plane as a function of the azimuth): at 1.5 Hz the amplitude is apparently very directive (it strongly varies with the azimuth).

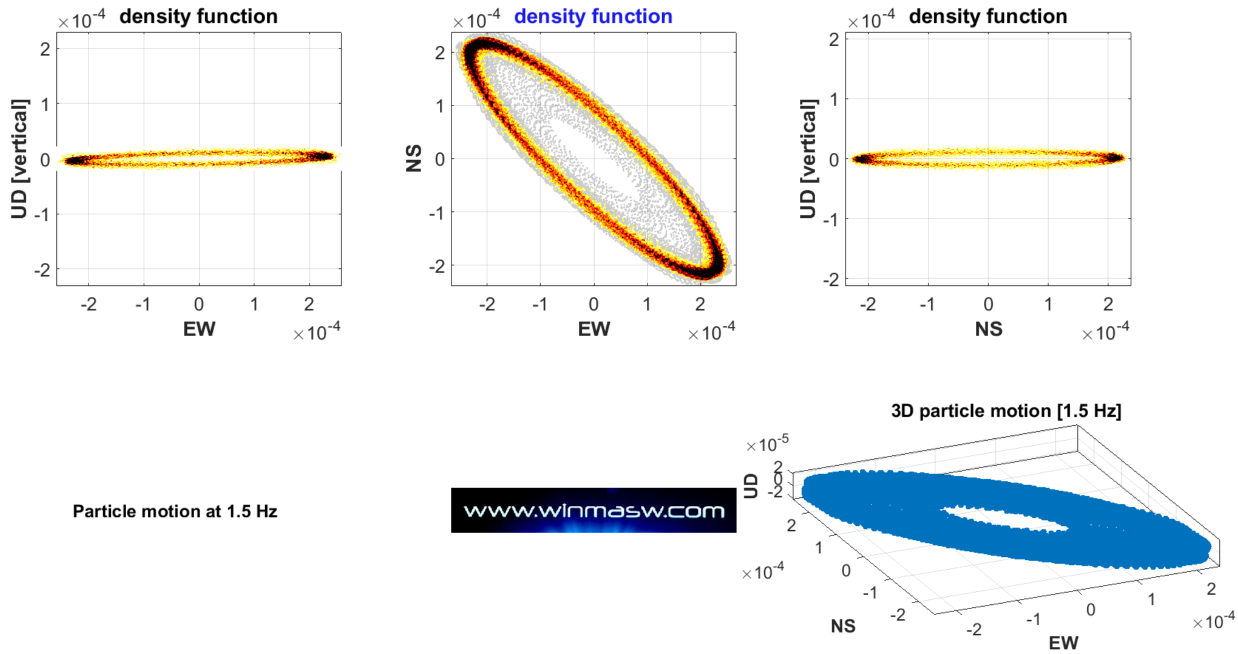




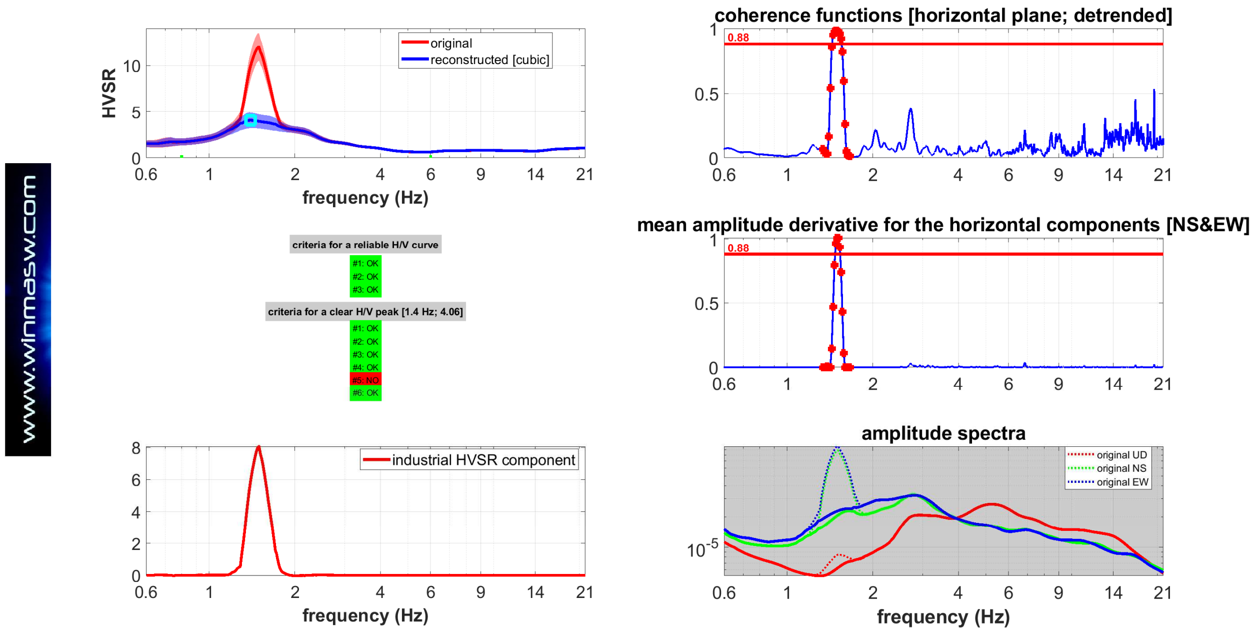
In case we compute the **particle motion along the three planes** considering the **raw data or a frequency where no industrial components are present**, we obtain a so-to-speak chaotic series of graphs without any specific trend (snapshot down below). Reminder: we obtain this kind of graphs with the "**Particle Motion & TLLA" button**: by leaving the field to the right of the button blank we will be dealing with the raw data, whereas if we wish to consider a specific frequency we just need to enter it in that box (left of the button). In the following snapshot we consider the 2 Hz frequency, where no industrial signal is present (this is why we obtain a chaotic particle motion).



On the other hand, in case we ask the software to show the particle motion at 1.5 Hz (by entering 1.5 in the box to the left of the “**Particle Motion & TLLA” button**), we obtain the following graphs, which clearly show the unnatural (i.e. artificial cause extremely regular and therefore not associate to the uncorrelated microtremor field associated to natural microtremor sources).



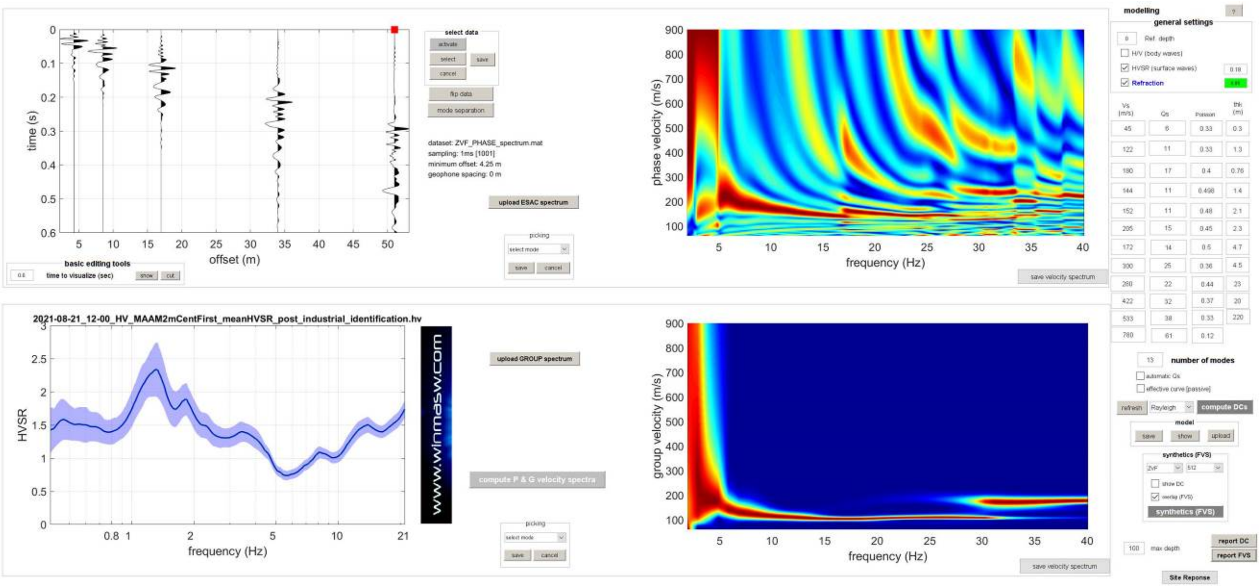
All these evidences clearly show the industrial origin of the 1.5 Hz component that we now wish to remove from the HVSR. We can easily doing it using the **“processing industrial signals” button** after having properly set the two simple related parameters in the two small boxes at the left of the button.



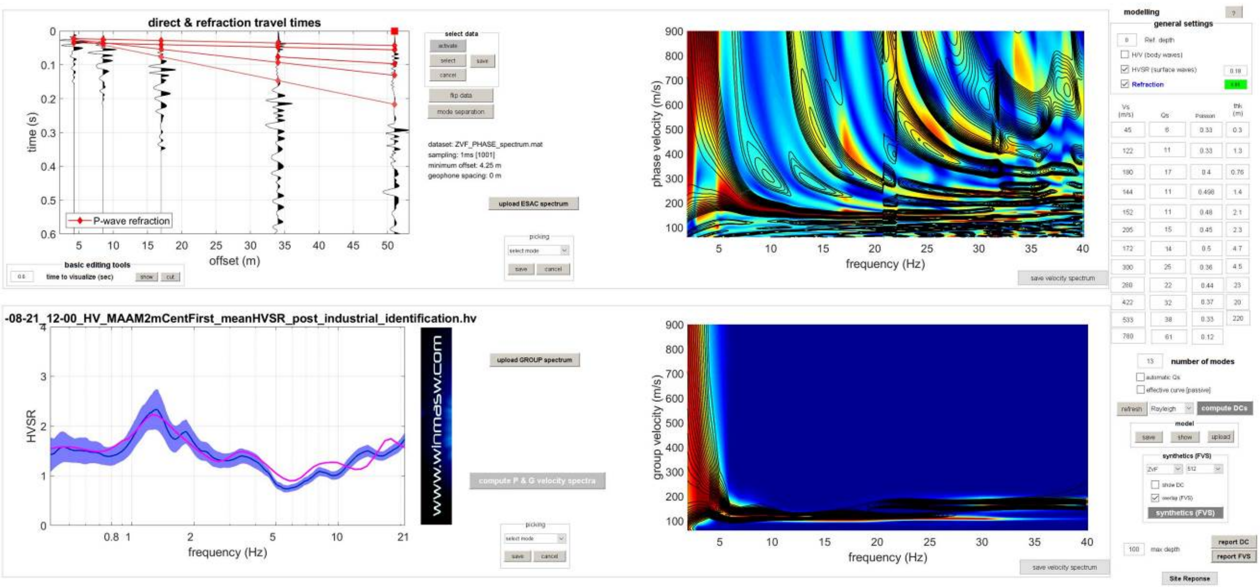
In the upper left corner the original HVSR [red curve] together with the processed one (free from the identified industrial component) [blue curve]. As usual, all the figures and related files are automatically saved in the working folder.

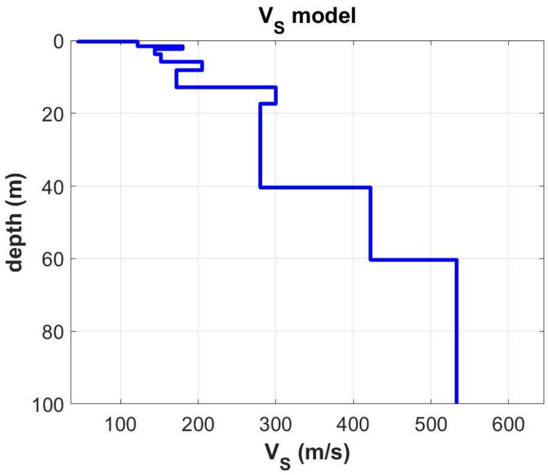
F19. From the panel "joint analysis of phase and group velocities" (just one component): joint modelling of the phase- and group-velocity spectra (FVS approach) together with the HVSR and refraction travel times

Here a non-equally spaced active ZVF dataset with just 5 traces that allows us to depict both the **phase and group velocities** (these latter defined considering just the last trace – see red square), **refraction travel times and the HVSR** curve from a passive acquisition. Since we are considering a very limited number of traces (length of the array 52 m), the phase-velocity spectrum shows also the effect of the *spatial aliasing*. This is not a real problem because the actual dispersion is perfectly clear (in the 5-17 Hz frequency range dispersion shows phase velocities of about 160-280 m/s). Of course, if we increase the number of traces the *spatial aliasing* disappears (see our Elsevier book).



The following snapshot reports the **joint modelling of four (4) observables**: the Rayleigh-wave group and phase velocities (via FVS), the HVSR and the P-wave refraction travel times (of course we can consider just the first arrivals). Needless to say that in case we analyse the THF component we consider Love waves and SH-wave refraction travel times.




VS model
0
20
40
60
80
100
depth (m)
100
200
300
400
500
600
VS (m/s)

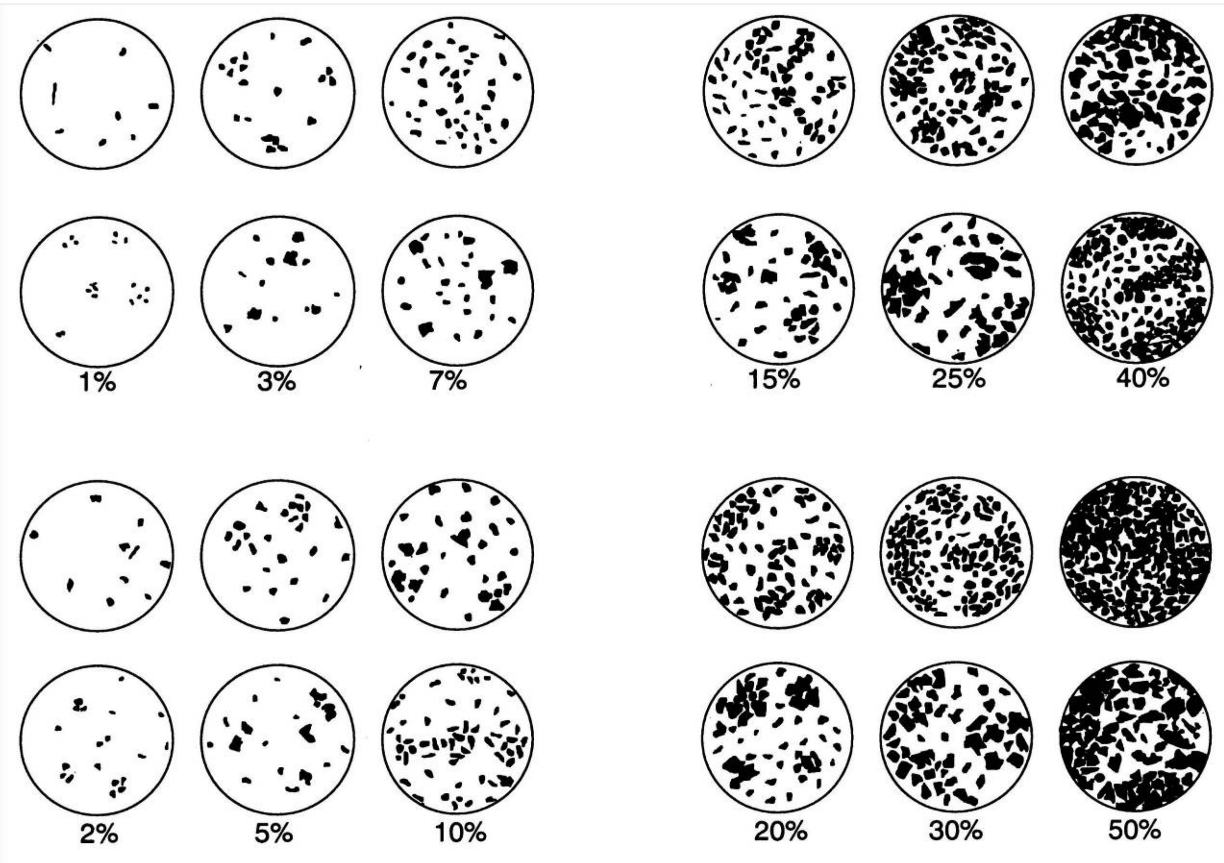
Appendix G: The Stesky's equation

Very often mixed materials such as the gravels can have very different V_S values (approximately ranging from 300 to 500 m/s), depending on the relative amount of cobbles and fine matrix (usually made of sand or clay - see Figure 1.16 of the "Surface Wave Analysis for Near Surface Applications" Elsevier book) .

In this respect it can be interesting to report the equation describing the resulting effective velocity when two different materials are mixed up (Stesky, 1978):

$$\frac{1}{V_m} = \emptyset \frac{1}{V_A} + (1 - \emptyset) \frac{1}{V_B}$$

where V_m is the velocity of the mixed media, V_A and V_B the velocities of the A and B materials, $\emptyset$ the volume fraction of the material A in the mixed media.



Appendix H: seg to SAF conversion

This tool can is used to convert seg2 data/files (with **three** traces) as SAF file. Please, notice that in order to compute the HVSR (or perform HoliSurface analyses) such operation is not necessary since in the HVSR and HS panels you can upload both SAF and seg2 files.

Now you can define:

1) unit of measurement: in case the data you get from your equipment have a physical meaning, you can define it here (velocity or acceleration). In case you don't know it, just let "counts";

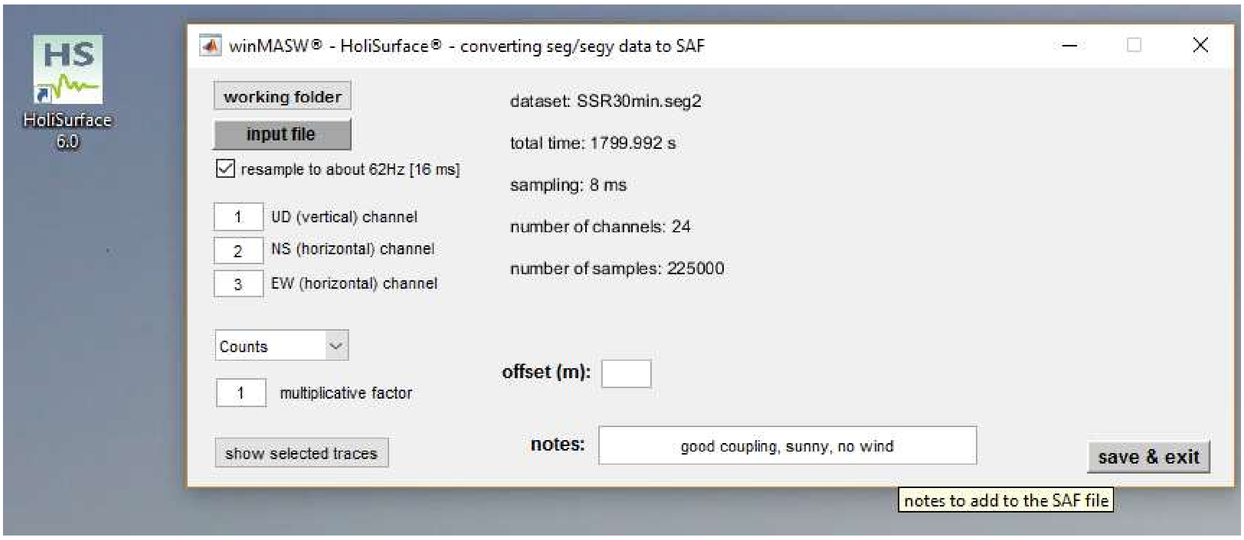
2) the *offset* (this is relevant for *HoliSurface®* data - active data acquired while considering a single 3-component geophone);

3) notes about the data/acquisition. This is extremely useful for instance in case you are converting a dataset for HVSR analysis since you can indicate ancillary information such as the coupling and weather conditions and any other fact that can be important to consider while you process this sort of data.
When you upload the obtained SAF file in *winMASW®* or *HoliSurface®* (for instance in the HVSR module), these notes will be automatically shown.

In any case remember that in our HVSR panel, you can upload directly the seg2 files you obtain from your seismograph.

No need to convert the data!

In the seg2SAF panel, it is also possible to define a multiplicative factor (see snapshot below). The data will be then multiplied by that factor and saved in the SAF file.



Appendix I: basic procedures in brief

Here following you'll find the sequence of the procedures to follow re the different available types of analysis. Refer to each relevant section to deepen needed details.

Independently on the kind of analysis you intend to perform, the very first action to do is the setting of the "*working folder*" from the main *winMASW®* panel (button "working folder"). This is a folder (previously created by the user) where all the field datasets were stored/copied and where the outputs of the performed analyses will be saved.

Single-component MASW analysis (Rayleigh or Love waves)

1. from the main panel open the panel about "*Velocity spectrum, Modelling & Picking*"
2. upload the field data (button along the toolbar)
3. compute the phase (or group) velocity spectrum with the "*calculate spectrum*" or "phase velocities" (depending on the version/release you have) (remember to *properly* choose the frequency and velocity limits, which depends on the data and site characteristics).

Now there are 2 possibilities:

a) do the forward modelling of the retrieved dispersion
b) execute the picking of the dispersion curve (that is our interpretation always), save the curve and proceed with the inversion section

We strongly recommend the first approach (*forward modelling*) since it allows a full control over the whole process: the user can understand the data on the basis of his stratigraphic knowledge.

In order to follow this mode, click on "*parameters*" in the section "*modelling*" and insert the relevant data to thickness and layers V_S .
The aim is to obtain dispersion curves that can perfectly lay over (coherently) the distribution of energy shown by the calculated velocity spectrum.

If you wish to make this process automatic (automatic inversion of some dispersion curve), you need to pick the dispersion curve(s) and then go to the inversion panel.
Here you need to choose the numbers of layers to use for the inversion or, in the case a starting model was previously obtained and saved during the forward modelling, you can upload it [**option#2**, *reference (i.e. starting) model*]. This later is the option we strongly recommend: first some forward modelling and eventually (if really necessary) the automatic inversion (i.e. optimization of the model).
Once fixed all the parameters involved in the automatic inversion (see specific sections in the manual) launch (button "RUN") the process.

Due to the problems related to data ambiguities (**see introductory section of this manual and related specialized literature**), if you only rely on the automatic inversion of one single component you always necessarily risk to obtain a solution which is mathematically correct/good but geologically meaningless.

ReMi analysis (in winMASW® Academy also for multi-component data)

1. from main window open the section "*ReMi spectra*"
2. once uploaded the data file (at least 1 minute long) and fixed the few parameters calculate the velocity spectrum launching the procedure with a click on "spectra calculation" (try different lengths of the analysis window, from a min of 4 seconds to the whole length of the dataset)
3. save the best defined spectrum (highlight it through the little button)
4. enter the section "*Velocity spectrum, Modelling & Picking*" clicking on "analyze saved spectrum"
4. in this section just upload the just saved spectrum clicking on "*upload ReMi spectrum*"

The rest of the operation (direct modelling and/or inversion) is absolutely similar to what before reported re the MASW analyses.
Remember that the interpretation/picking modalities for a ReMi dataset is different from that of a MASW velocity spectrum.

Few basic recommendations (in order to obtain reliable V_S profiles)

1. always work with **multi-component data**
2. have a look at our **video tutorials**
3. read our **books and papers** (and try to reproduce the same kind of analyses)
4. self-learning: work with the data provided with the winMASW® software and get familiar with *all* the ***several*** possible procedures

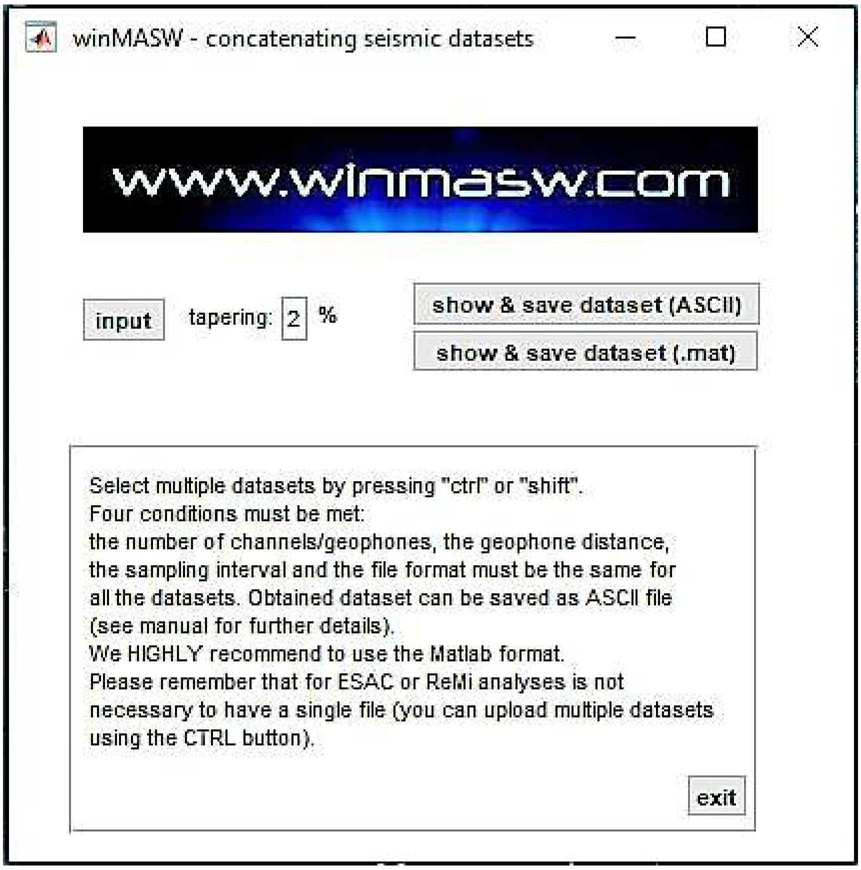
Appendix L: multi-channel data concatenation

Among the utilities, it is also present the "concatenate data" tool. Through it, you can concatenate two or more datasets. For instance, if you have 10 passive datasets each with 60 seconds, you can concatenate (unite) them so to obtain a single dataset (10-minute long).

Example:
Let us try to concatenate two *datasets* (*stendimento1.dat* and *stendimento2.dat*).

step #1:

Upload the *datasets* (use the "SHIFT" or "CTRL" buttons, so to select multiple files)



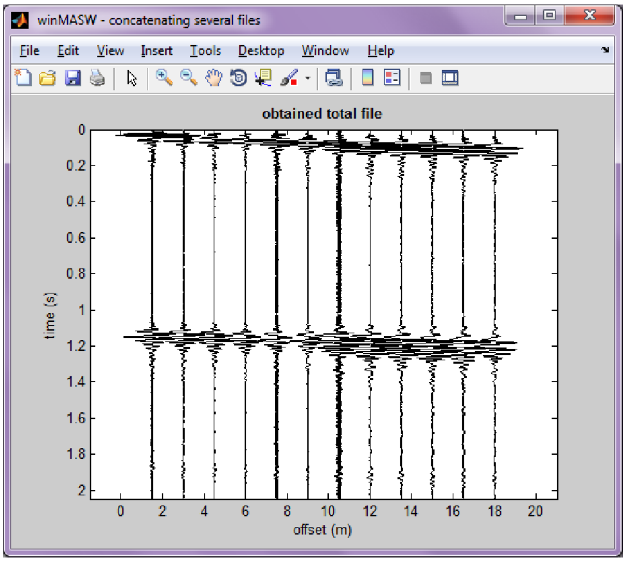
step #2:

Fix the *tapering* value (by *default* equal to 2%)

step #3:

click the "save obtained dataset" button choosing the format you need:
ASCII format (on the first line will be reported the sampling rate dt (in seconds) and the geometry information);
Matlab/winMASW (.mat) format

At the end of the operation the following window (reporting the concatenated dataset) till appear:



Of course, two conditions must be met:

1. the sampling rate (*dt*) must be the same (for all the datasets)
2. geometry and number of traces must be the same (for all the datasets)

IMPORTANT

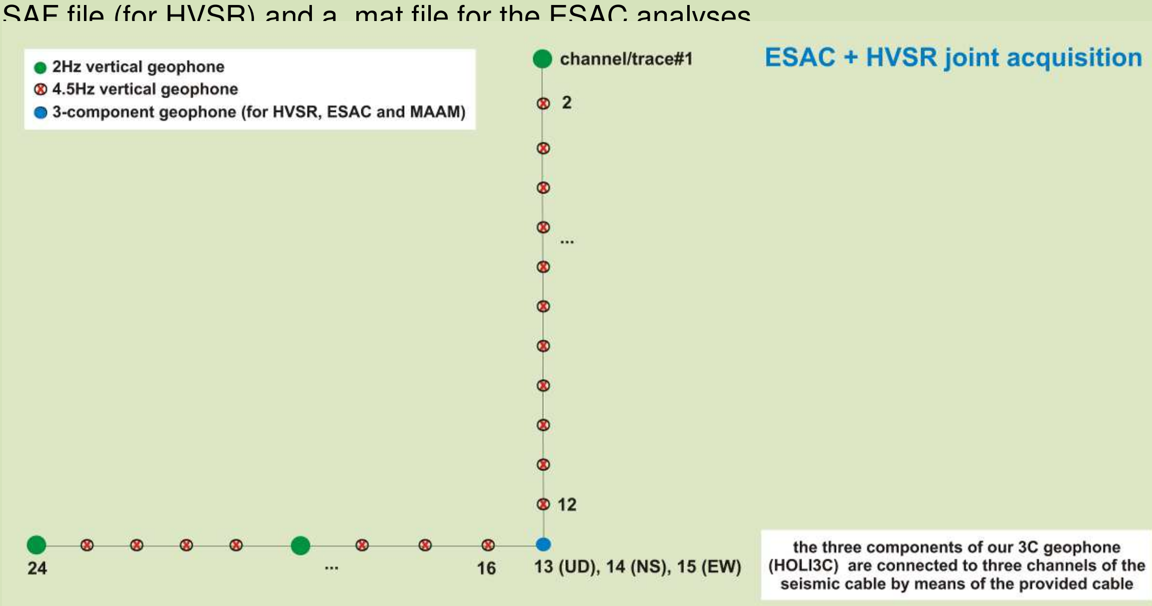
As a matter of fact, this operation is not strictly necessary to handle the data in *winMASW®*. In both the ReMi and ESAC panels is in fact possible to upload *n* files simply by selecting all the files as "multiple selection", i.e. by holding the CTRL or SHIFT button (as routinely done in all the *window* applications).

Appendix M: tool TCEMCD

Using our *HOLI3C* geophone and *winMASW Academy* (tool TCEMCD) you can efficiently acquire your passive data to process for ESAC and HVSR analyses (recommended *sampling rate*: 6 msec, 167 Hz).

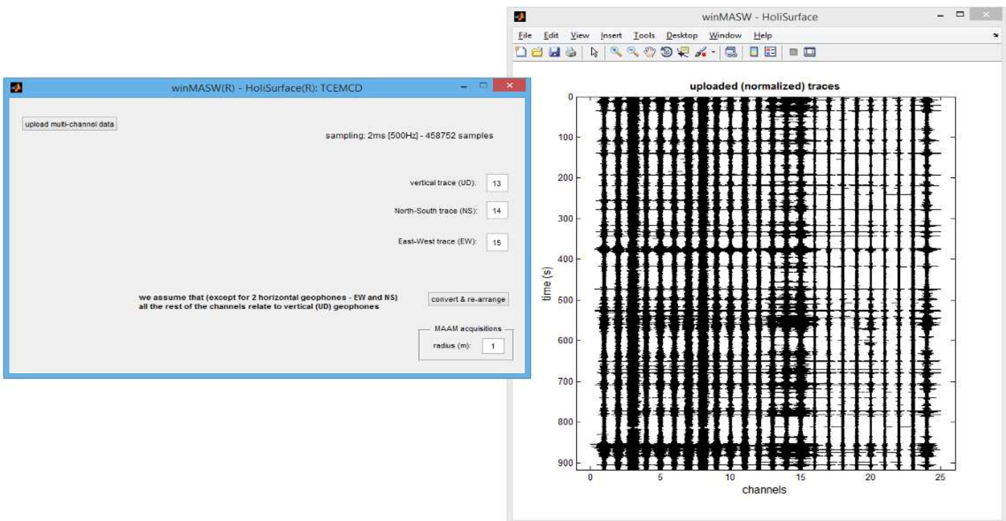
In the following figure is reported a typical acquisition setting: 21 vertical-component geophones and our **HOLI3C 3-component (2Hz) geophone** are (simultaneously) connected to a common 24-channel seismic cable.

Using the **TCEMCD** tool (in the *Academy* version) you can then extract the data for the ESAC and HVSR analyses (for their joint analysis/inversion): you will obtain a standard SAF file (for HVSR) and a .mat file for the ESAC analyses.

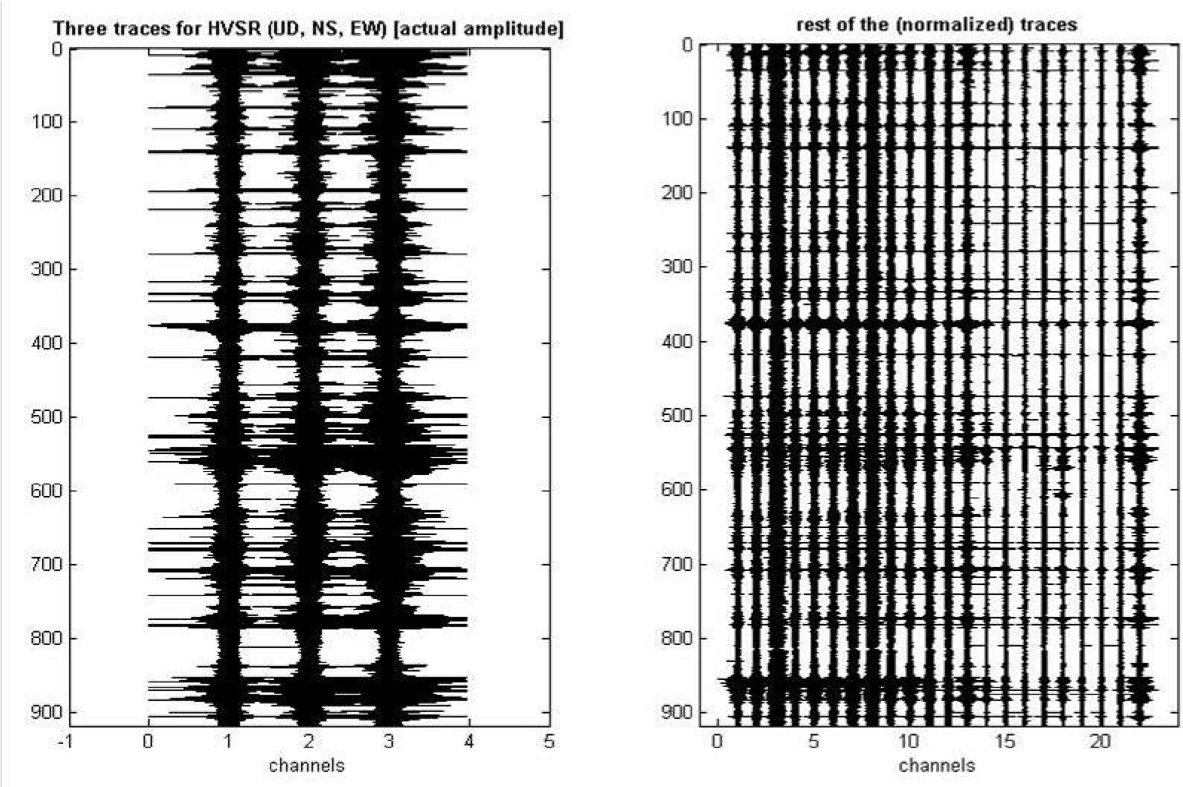


This way the vertical geophone of our **HOLI3C** is exploited also for the ESAC analyses.

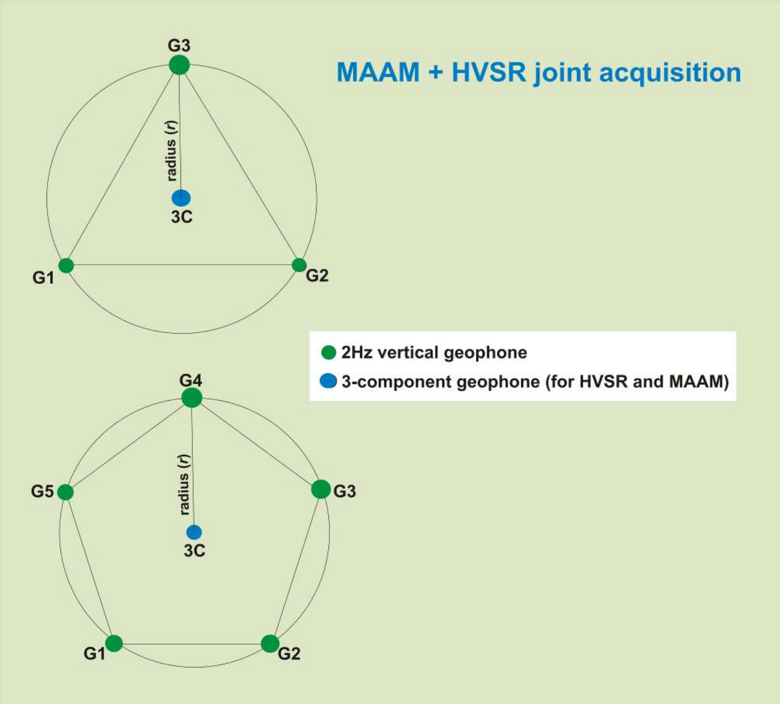
In the following snapshot are shown 960 seconds (about 15 minutes) of data. In this case the channels 13, 14 and 15 refer to the data collected using our HOLI3C geophone: channel#13 refers to the vertical geophone, channel#14 refers to the NS geophone and channel#15 refers to the EW geophone. By clicking "convert & re-arrange" you will obtain 2 separate files: the SAF file for HVSR analyses and a .mat file to upload in the ESAC panel.



Obtained data/files: on the left the data of the SAF file (for the HVSR analysis); on the right the 22 traces related to the vertical-component geophones to use for the ESAC analysis.



TCEMCD and *HoliSurface*®



The same tool (**TCEMCD**) is also present in our software *HoliSurface*® and can be used for the joint acquisition and analysis of data according to MAAM (*Miniature Array Analysis of Microtremors*) + HVSR (*Horizontal-to-Vertical Spectral Ratio*).

Appendix N: tool "combine 3C data"

This tool is basically a facility for the MOSR "method" described in Ryden et al. (2003).

Very briefly: some active 3-component geophones available on the market are designed to acquire active data at different offsets.
Typically you have your first acquisition at the most distance offset (e.g. 60 m from the source), then you get closer and closer to the source (so you record your next active data at 55, 50, 45, 40, 35 (and so on) meters from the source).
In the end you can gather all these data/files in a single multi-offset dataset and "simulate" a MASW acquisition.

How it works

The simplest way to understand how it works is to try by yourself using a small example (a test dataset provided with the winMASW DVD - see the folder "Demo_Datasets_dissemination/ProgettoMuscat")

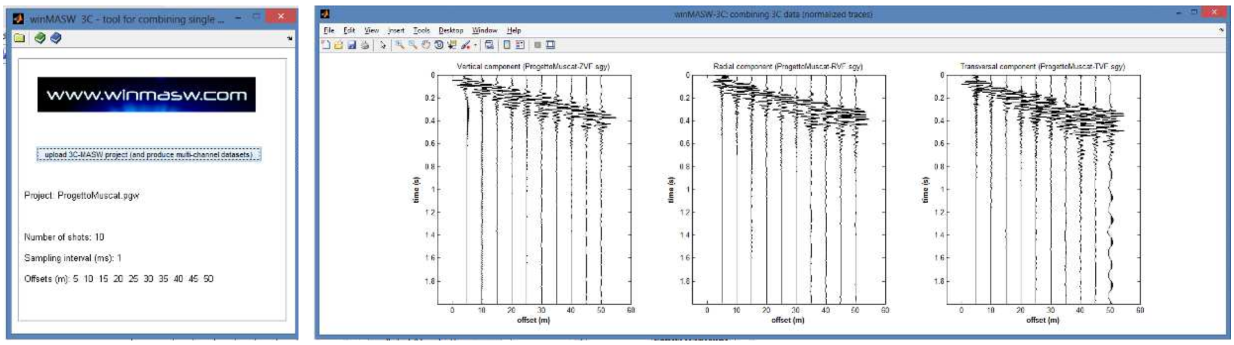
ProgettoMuscat.pgw

You can open such a project file with any text editor (e.g. notepad) and you'll see the following structure/information (the meaning is pretty clear):

It is a simple ASCII file with the .pgw extension

```
Project: Torviscosa
source: VF
sampling rate (s): 0.001
offsets: 72, 66, 60, 54, 48, 42, 36, 30, 24, 18, 12, 6
Torviscosa_HF#1.SAF
Torviscosa_HF#2.SAF
Torviscosa_HF#3.SAF
Torviscosa_HF#4.SAF
Torviscosa_HF#5.SAF
Torviscosa_HF#6.SAF
Torviscosa_HF#7.SAF
Torviscosa_HF#8.SAF
Torviscosa_HF#9.SAF
Torviscosa_HF#10.SAF
Torviscosa_HF#11.SAF
Torviscosa_HF#12.SAF
```

Once you upload the *ProgettoMuscat.pgw* project, the following panels will show up:



At the same time in the working folder six files will be automatically created: three *segy-* and three *Matlab* (*mat*)-format multi-offset files.

More precisely, if the source is a Vertical Force (VF), you'll obtain three datasets (in the double *segy* and *mat* formats):

RVF (radial component of Rayleigh waves)
ZVF (vertical component of Rayleigh waves)
TVF (the transversal component, which, in case you adopted an HF source, actually means the THF component, i.e. the Love waves)

Appendix O: data in mm/s with our HoliSurface® equipment

First of all, it is necessary to understand when it is or is not necessary that the acquired data are in physical units (mm/s is the best solution), always reiterating that acquiring all the data always and in any case in mm/s is a good habit.

HVSR: not necessary (but always useful)

Data for dispersion analysis (MASW, ESAC, ReMi, MFA/FTAN, HS, MAAM): not necessary

Vibration analysis on buildings: extremely useful (highly recommended)

Vibration analysis at construction site (UNI/DIN): absolutely necessary

We need to follow the right procedures in two moments:

1) during data acquisition

2) when uploading the data in the software application (HS or winMASW)

We will see below how to correctly carry out the operations both during acquisition and while loading the data.

1. Acquisition

See documentation provided with your *acquisition system*. Here the information about the geophones we provide.

The sensitivity of the **3C geophones** we supply is:

- 2-Hz 3C geophone (the red one with metal case): **2 V/cm/s**

- *Geospace-Eliosoft* 3C geophone (blue): **0.89 V/cm/s [equalized down to about 0.2 Hz via software]**

Single-component geophones (see label on their cable):

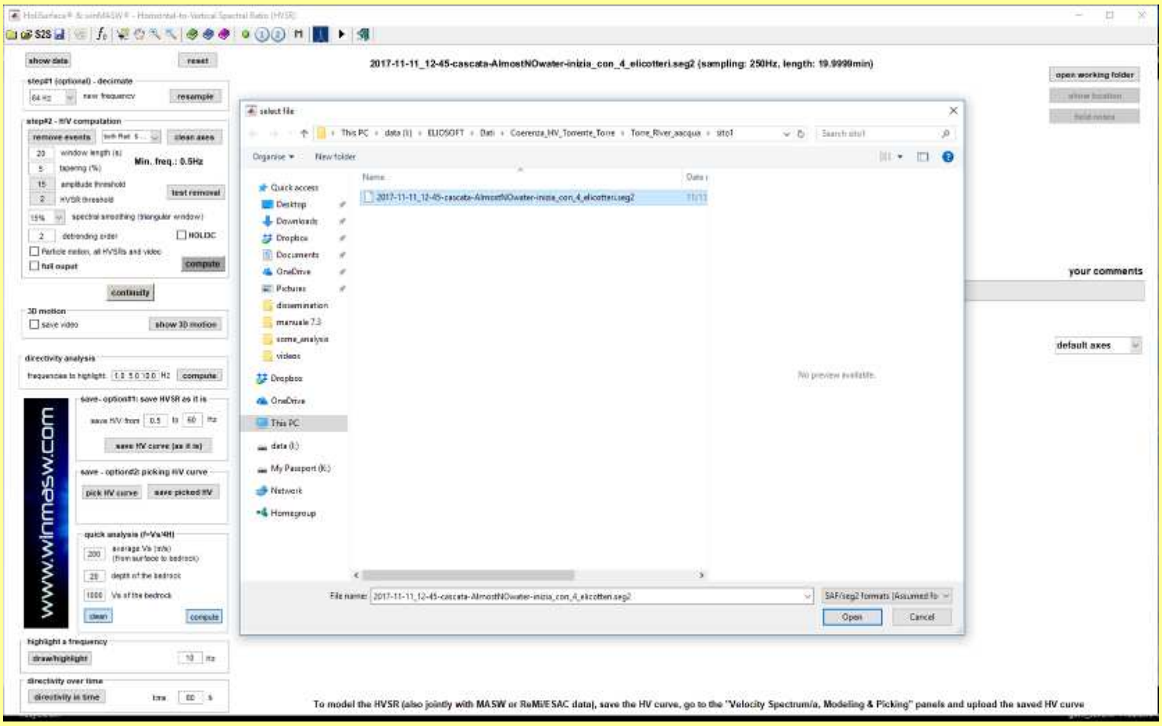
- model C1: **0.82 V/cm/s**
- model C: **0.92 V/cm/s**
- model B1: **0.29 V/cm/s**
- *Geospace-Eliosoft* model (blue) [recommended for MAAM, very useful also for ESAC]: **0.89 V/cm/s**

- model HL-3: **0.6 V/cm/s**

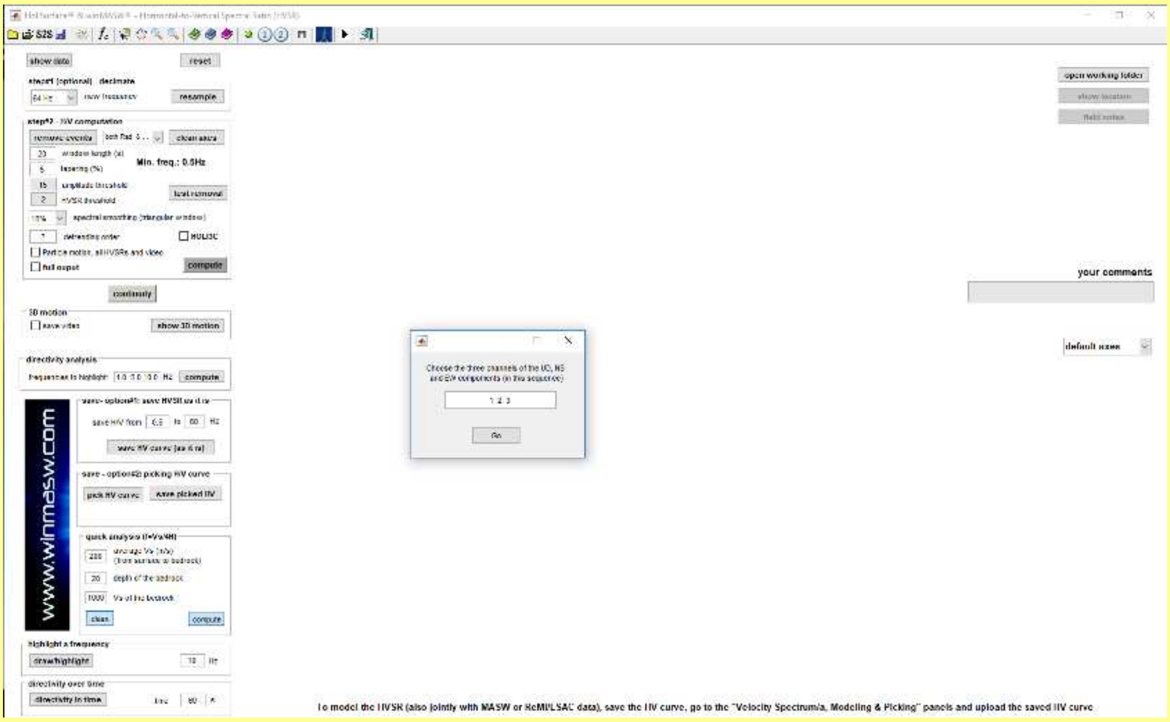
2. Data uploading for HVSR analysis

If you have recorded the data according to the instructions above, a dialogue box will ask you for the unit of measurement of the data when loading the seg2 file.

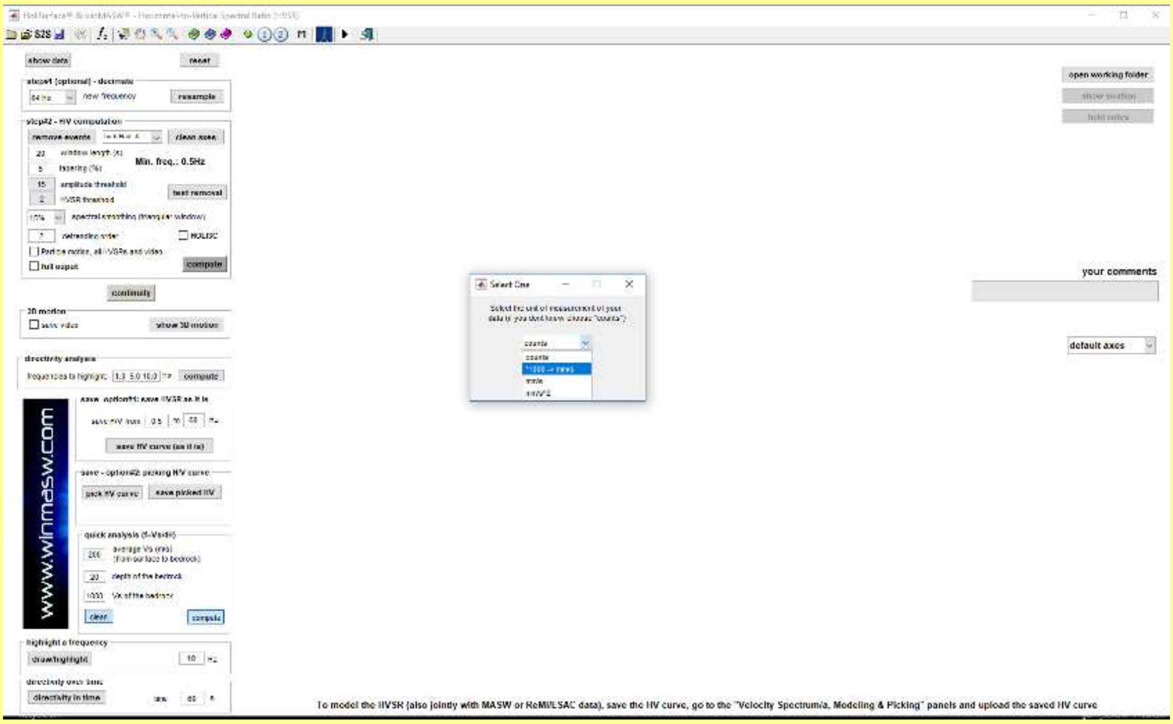
uploading files in SEG2 format



Open/select the file (seg2 format)



Define the sequence of channels containing, in order, the UD (vertical), NS (or radial) and EW (or transverse) component



Define the unit of measurement of the input data.

In case you are using our acquisition system and correctly following the acquisition procedures (see previous section), select the option highlighted in the snapshot above and you will get the data in mm/s.

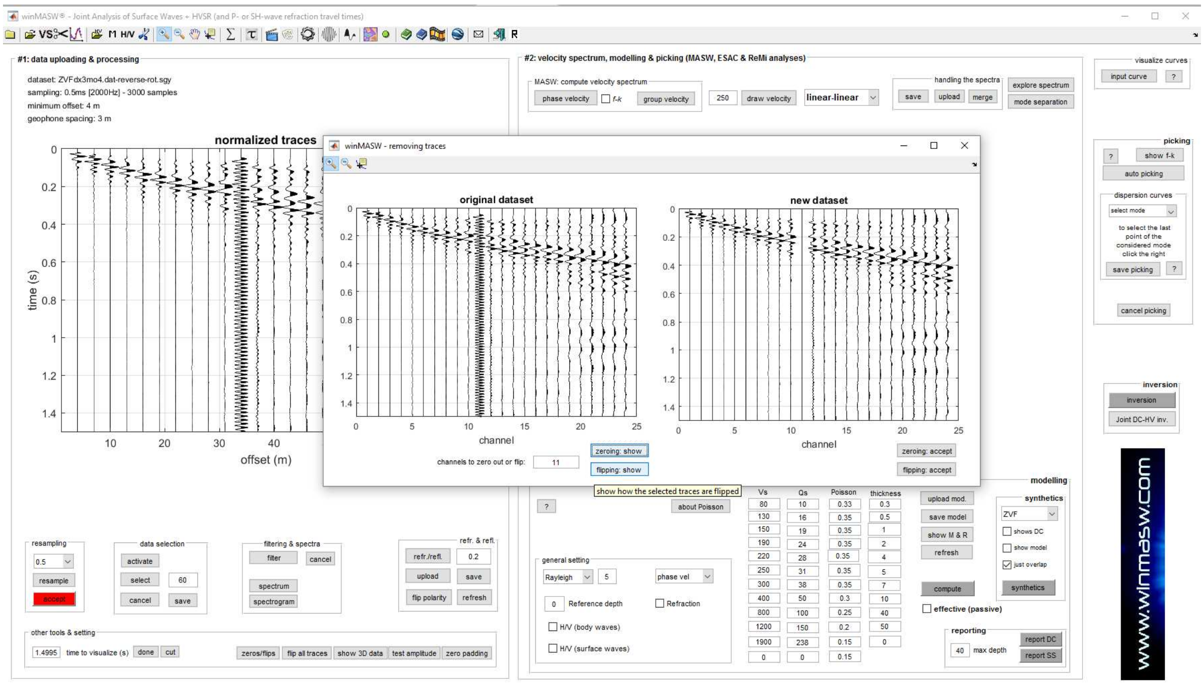
With this option, data are multiplied by 1000 so to obtain values in mm/s.

Appendix P: data editing - zeroing, flipping & removing traces

With this tool ("zeros/flips") it's possible to zero out or flip the polarity of single traces.

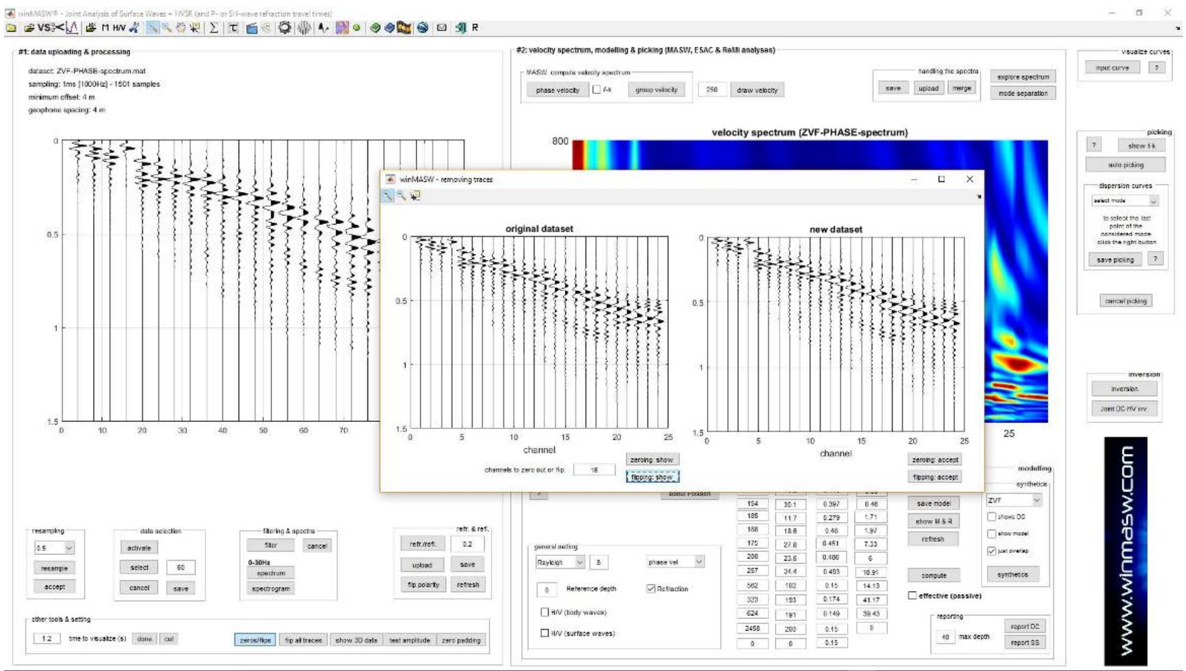
zeroing single traces

In the following *snapshot* you can see that the channel/geophone#11 is not working and we decide to zero the whole trace out as in the figure.



You can also notice the red colour of the "resampling" section: if the *dataset* was sampled at a frequency higher than 1 ms (which is completely useless- just consider the Nyquist- Shannon theorem), the software warns you about that and recommends you to resample the dataset [click on "accept" and you will obtain a re-sampled *dataset* (by *default* the resampling rate is 0.5, so in case your original dataset was sampled at 0.5 ms, you will obtain a new dataset @ 1 ms).

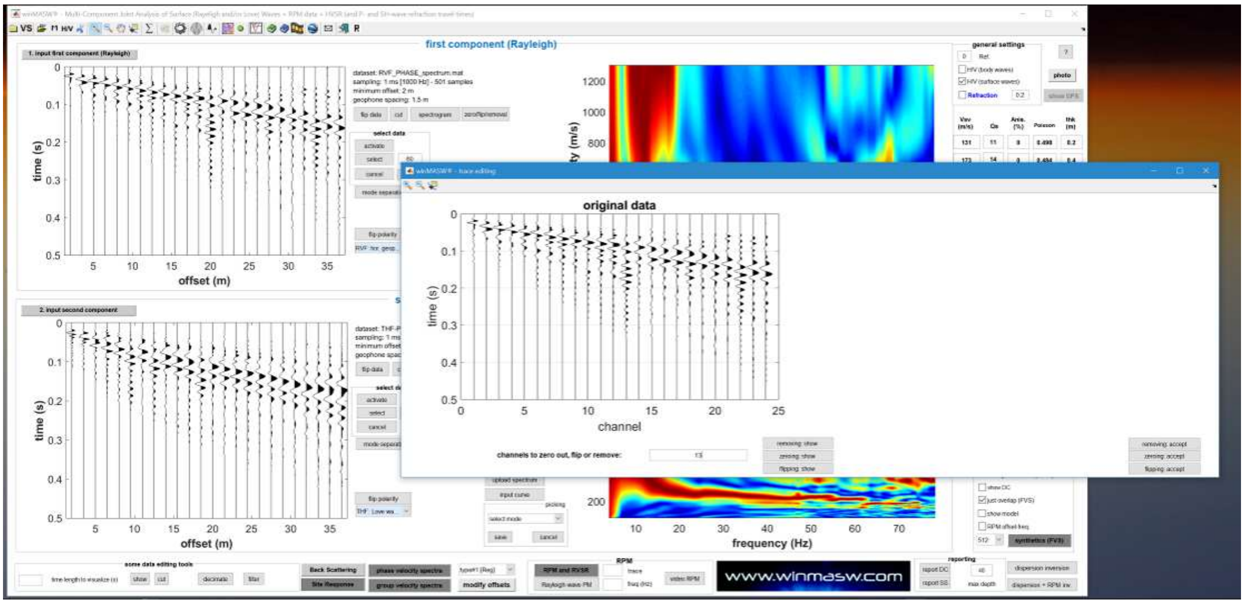
Flipping (flipping the polarity of single traces)



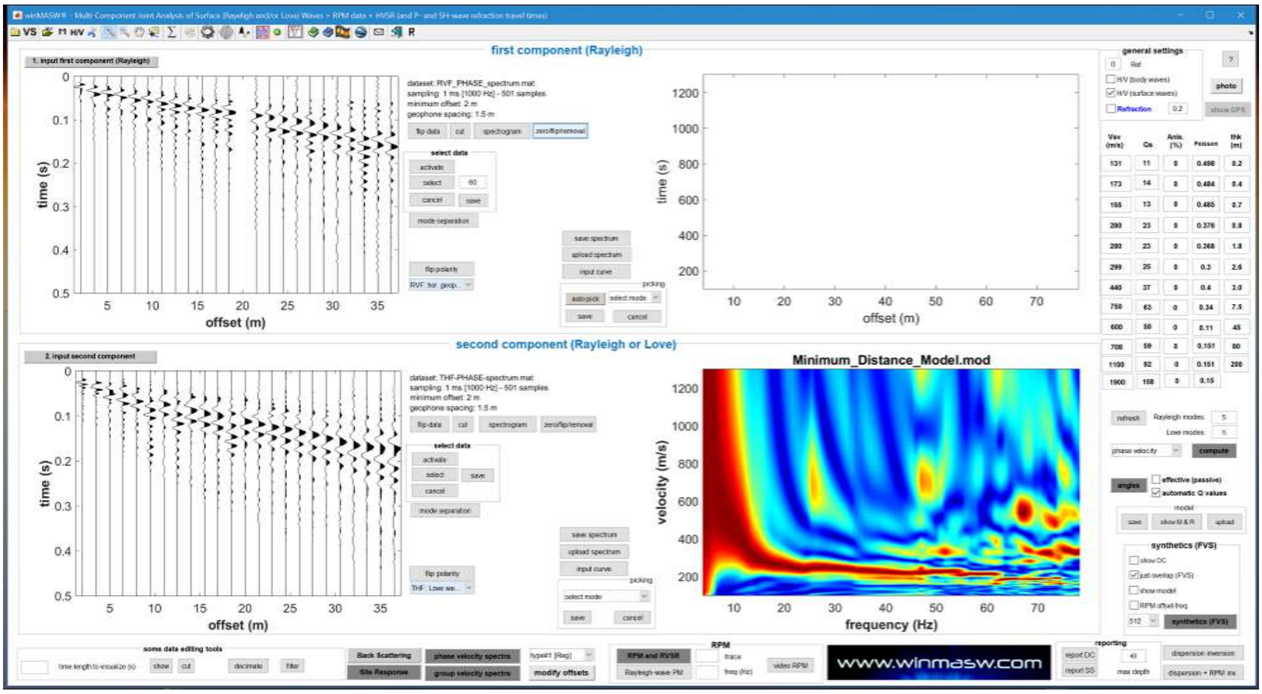
Do you see trace#16 (in the original dataset)? It is quite clear that that geophone/channel has a reversed polarity compare to the rest of the traces. On the right, the corrected *dataset* (trace#16 is flipped). You could also zero out trace#4 (geophone out of order).

***Removal* of single traces**

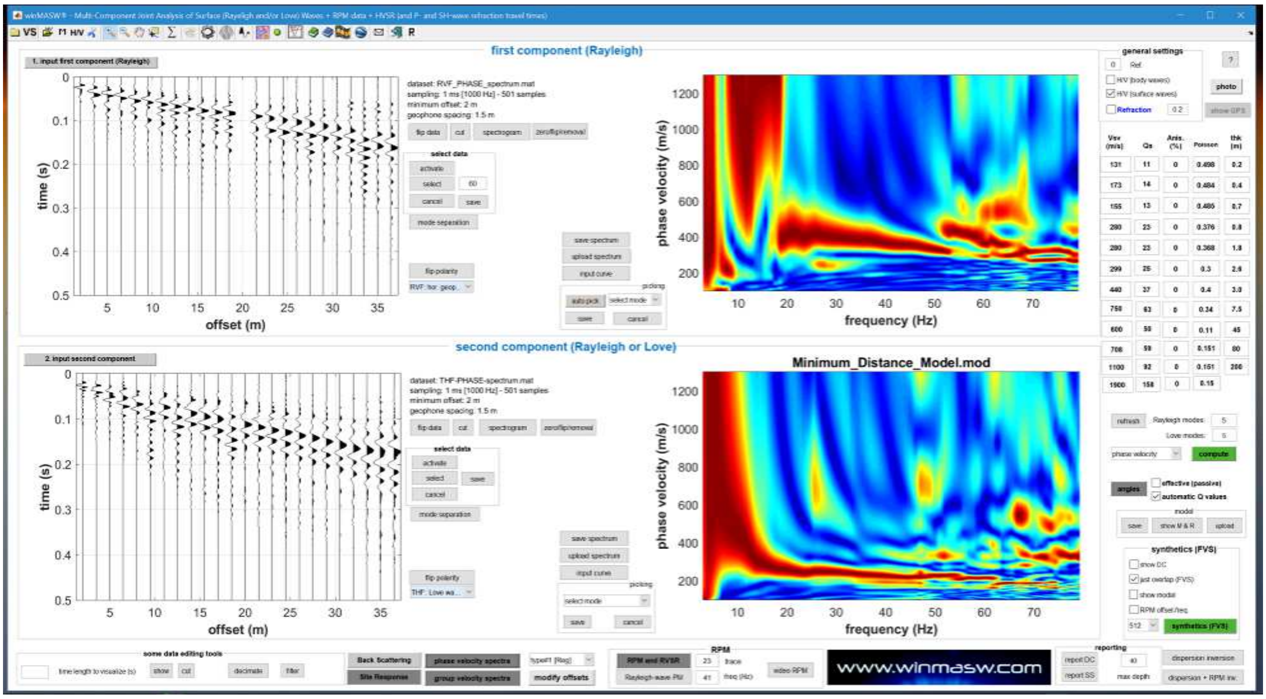
Let us see an example of this operation in the **joint panel**. In this case it is a dataset that we might consider the standard one for **multi-component and multi-offset (phase velocities) analyses**. Data were recorded using **just a set of 4.5 Hz horizontal geophones so to obtain the radial component of Rayleigh waves (RVF) and Love waves (THF)**.
If we have a look at the seismic traces, we can realize the relatively-low quality of the trace#13 for both the components.



We can therefore decide to remove such a trace (from one of for both the components). We click the "**removing: show**" in order to verify that is bad trace is actually the #13 and once we are sure about that we simply click the "**removing: accept**" button.
We are then back in the main panel and can note that that channel was actually removed (remember that ***winMASW® Academy* can easily handle non-equally spaced data).**



Now we can re-compute the phase-velocity spectra of the new (clean and non-equally spaced) data [the trace with an offset of 20 meters is now missing].

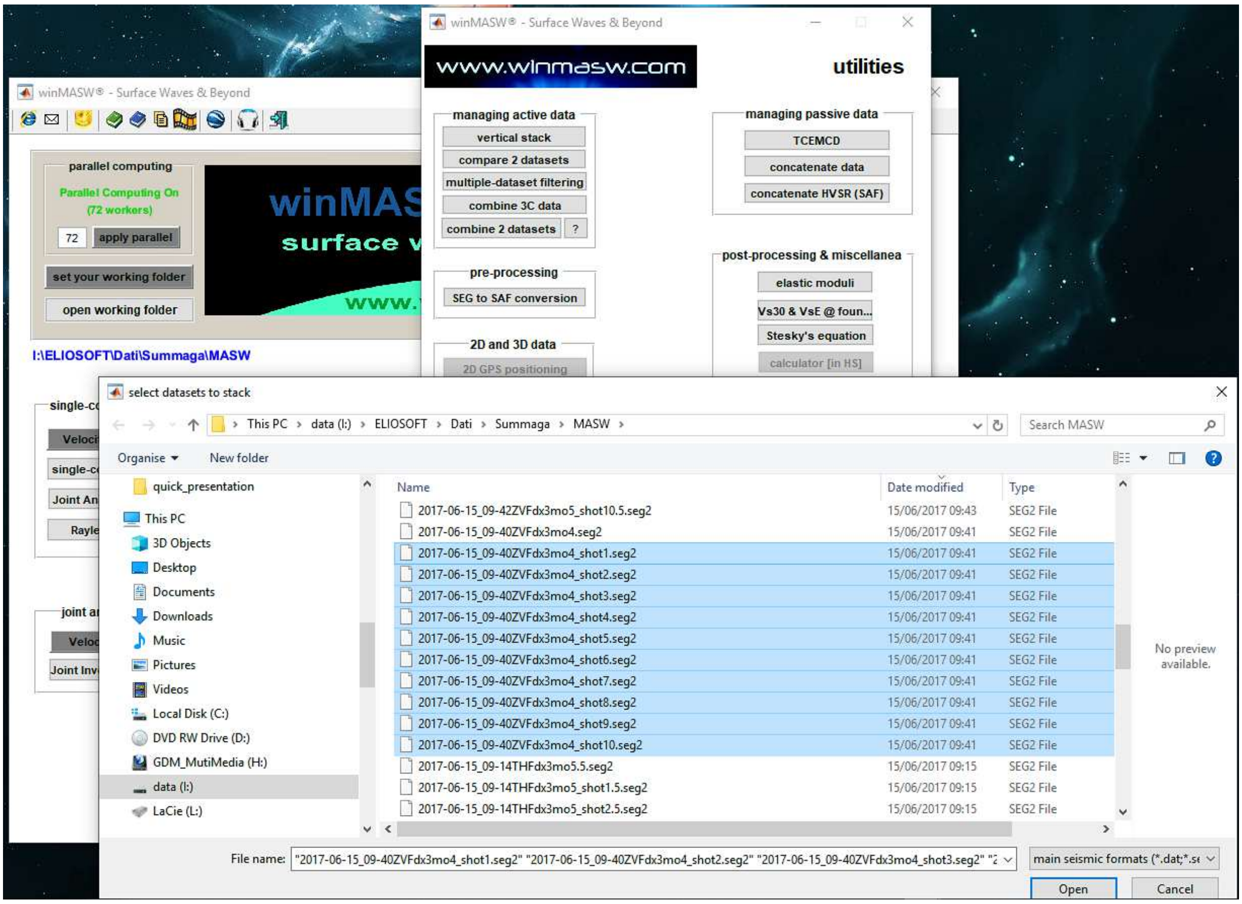


We can then decide to do the same thing for the second component (which in this case is the THF – i.e. Love waves).

Appendix Q: stack (Academy version)

This tool is available both among the "utilities" ("managing active data" group), both in the *toolbar* of the "**Velocity Spectrum/a, Modeling & Picking**" panels (**VS** button).

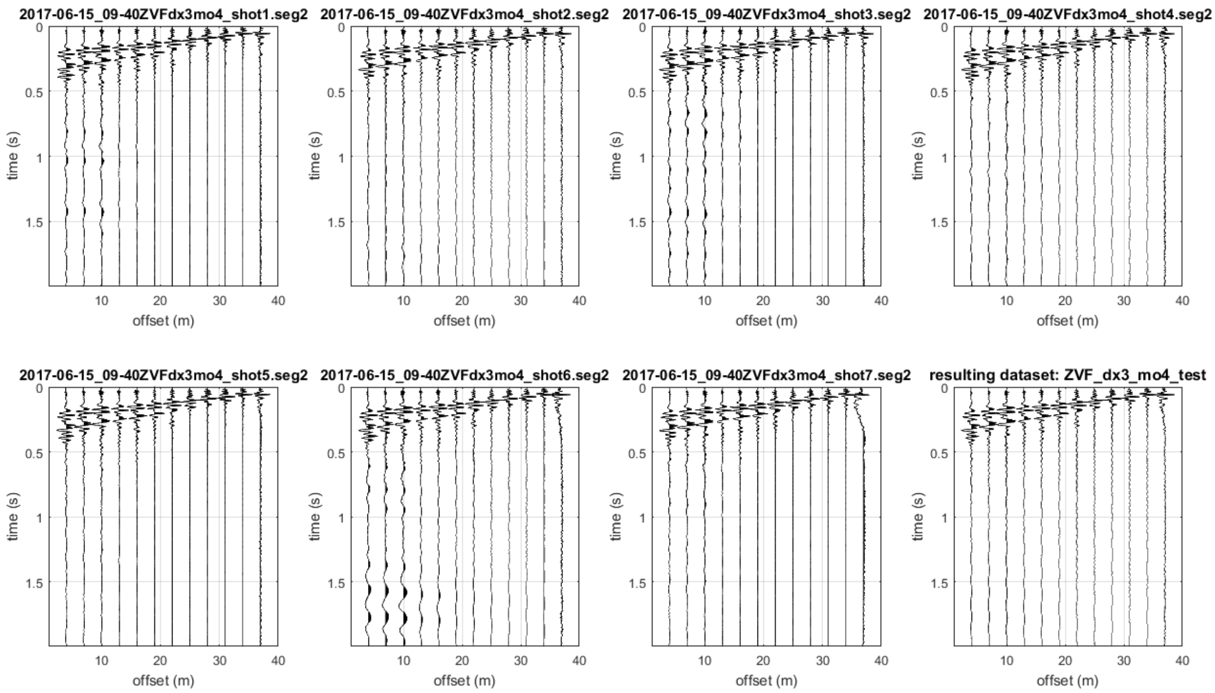
Once you click the "vertical stack" button, you'll be able to select all the files you want to stack (see snapshot here below).



Once you upload the data (also providing the geometry – i.e. the minimum offset and the geophone distance), you will then obtain the following figure (the very last plot reports the stacked data – as you can see the S/N ratio is now better).
The stacked data are saved (segy and *Matlab* format) in the working folder with the file name you will provide in the dialog window will appear.

In this example (see following picture), the (active) data were recorded with the channels "inverted".

When you upload them in *winMASW®*, you will be easily flipped them with the "flip traces/data" button.



***Vertical stack* of seven shots: the last one (on the right, lower panel) is the obtained seismic dataset.**

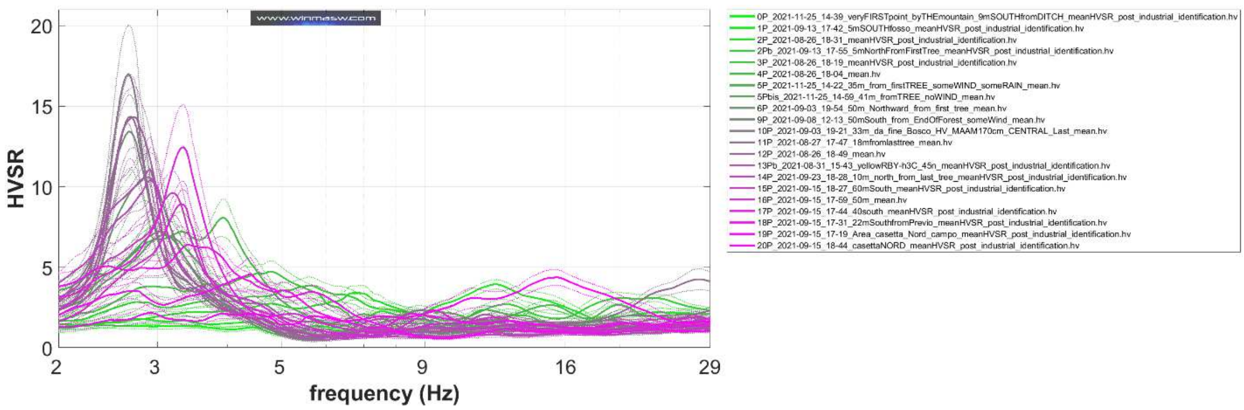
Do you know that we analyzed the surface waves recorded on the Moon during the Apollo missions (active and passive data)? Would you like to know what we found out? Have a look here:
https://www.sciencedirect.com/science/article/abs/pii/S0019103515001177

Appendix R: plotting multiple HVSR curves (2D HVSR sections)

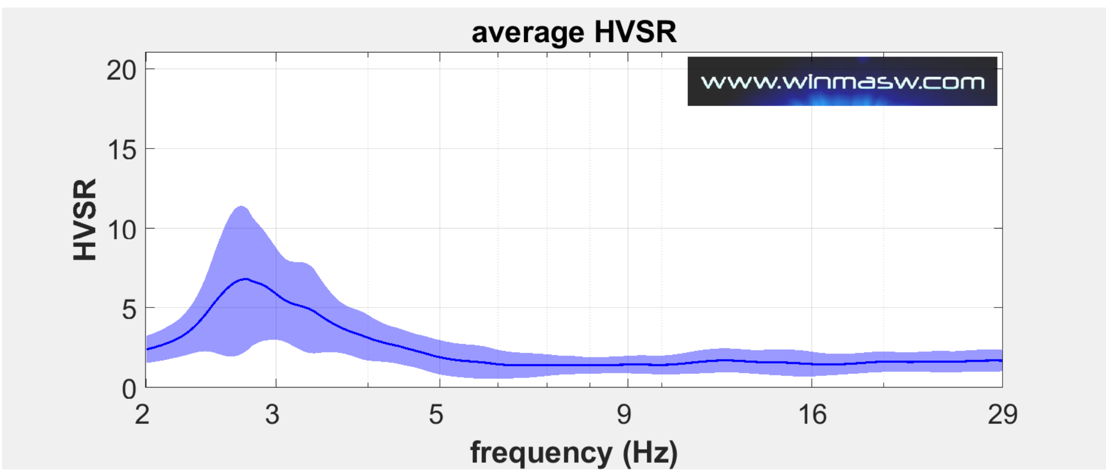
By clicking the "show multiple HVSRs" button <u>you can upload a series of HVSR curves (.hv format) previously saved in the same folder</u> and obtain the following plots (their use and meaning is clearly really wide and it depends on your "fantasy" and needs).
While uploading of the curves, it is possible (through two simple dialogue boxes) to fix the minimum and maximum frequency to plot and the specific positions of each HVSR curve (*inline positions*).

Two possible uses:
1) If we collected several HVSR at the same site, we can compare them using this tool;
2) In case we collected HVSR data at different points (e.g. across a valley), we can have an idea of the overall trend of the subsurface main features (e.g. the *bedrock*) and you obtain a sort of 2D HVSR section.

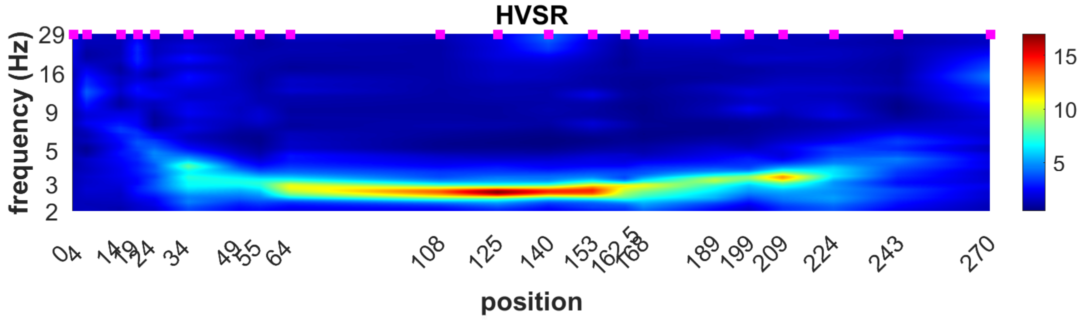
Visualizing all the uploaded HVSR curves:

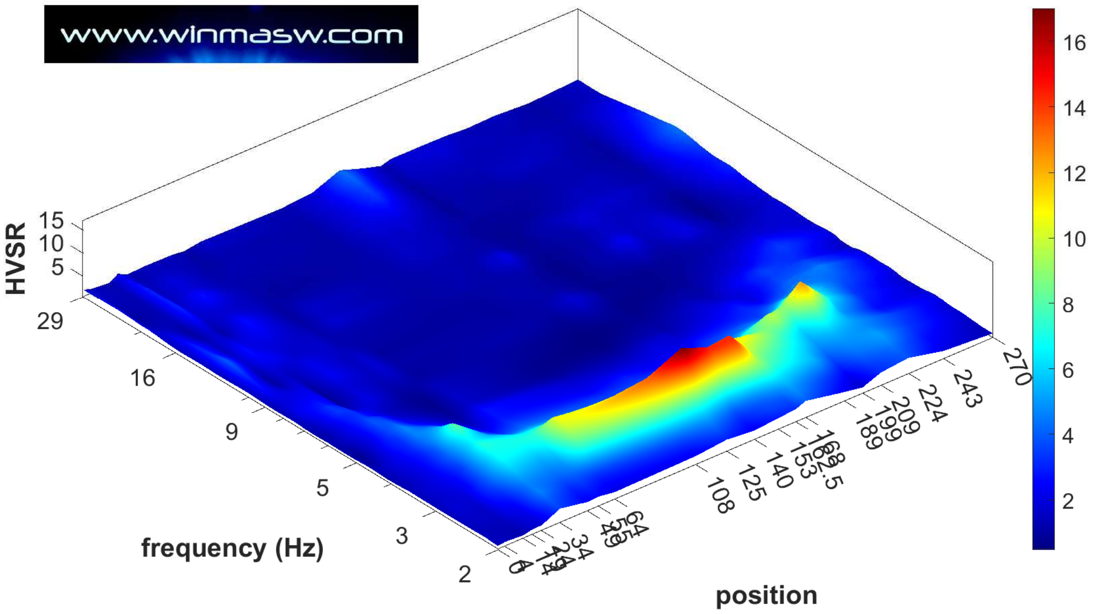


Average HVSR curve (shown and saved in the working folder)



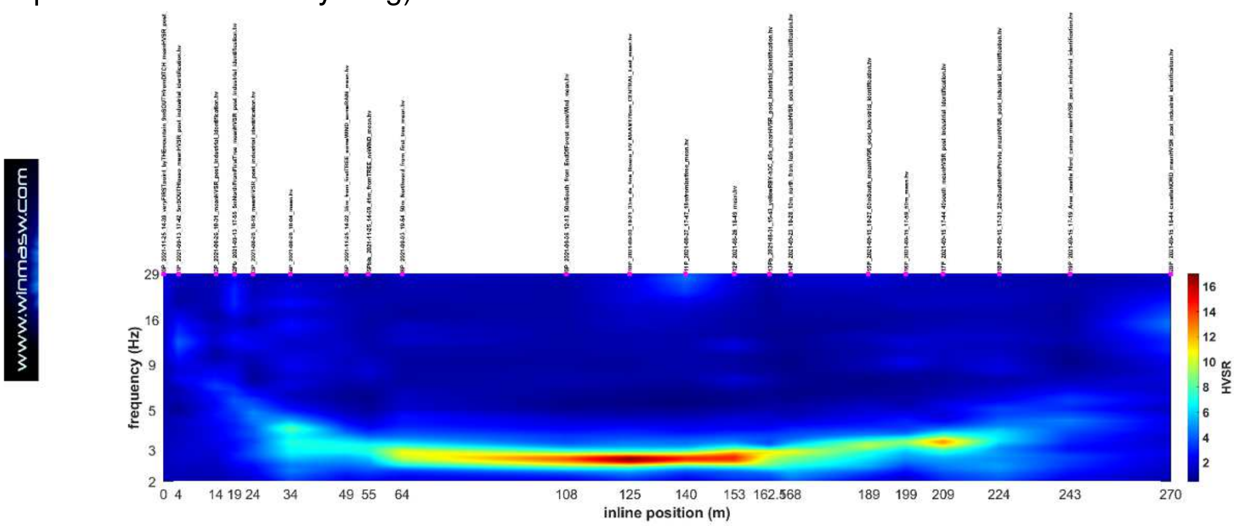
Plotting the original HV curves according to a 2/3D perspective





Small magenta squares report the position of the 21 curves considered for this example.

Summary image where are also reported the filenames of the uploaded curves (so to keep under control everything):



How to obtain the inline positions to use for your 2D HVSR section?

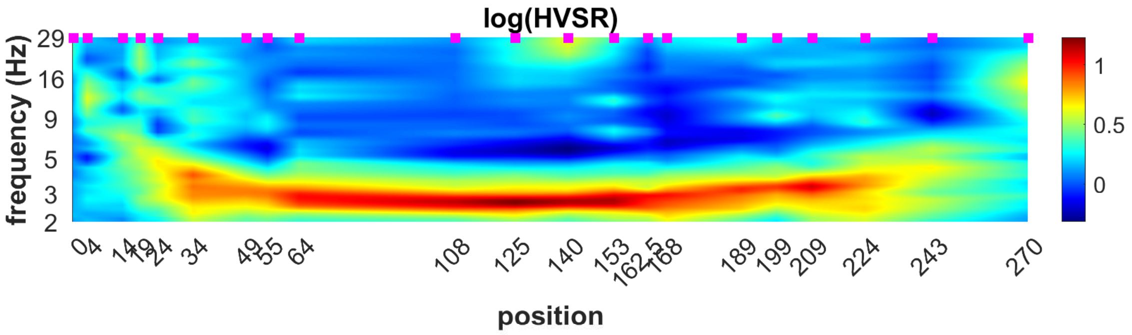
Three possible ways to do it (but you can maybe discover further ways to do it):

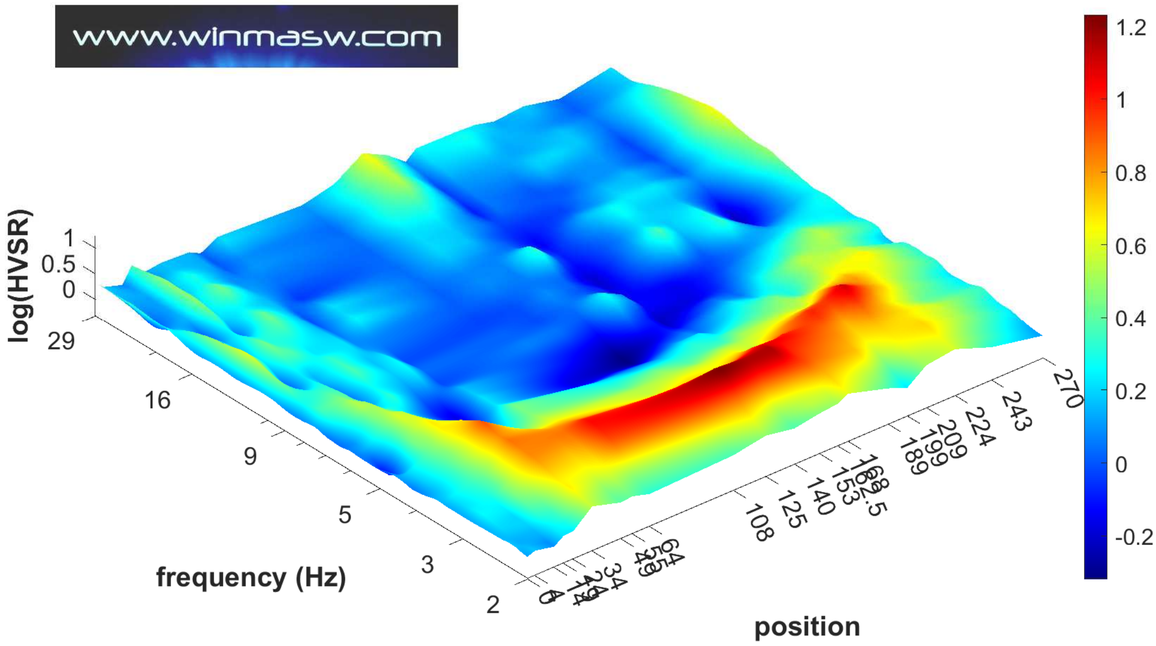
1) The most traditional way is the physical measurement on the field of the distances from the zero/reference point for instance with a ***measuring tape***;

2) **Using Google Earth** and its tool for measuring the distances from one point [of course you need to know the location of each single measuring point];

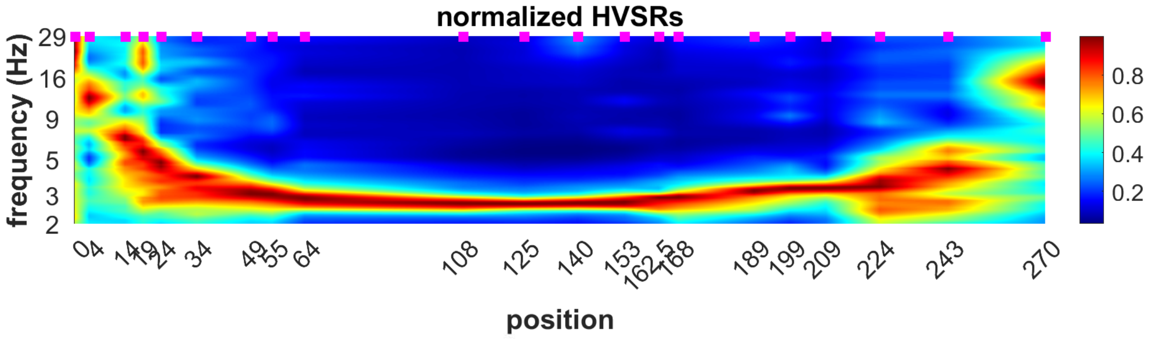
3) Using the **“multiple geo-referenced photo” tool** available in *HoliSurface®* and *winMASW® Academy* – see relevant Appendix). Of course the precision depends on the device/smartphone you used on the field (and on the satellite cover of the site). Usually this approach is fine in case you are exploring vast areas and there is no need for very-high accuracy.

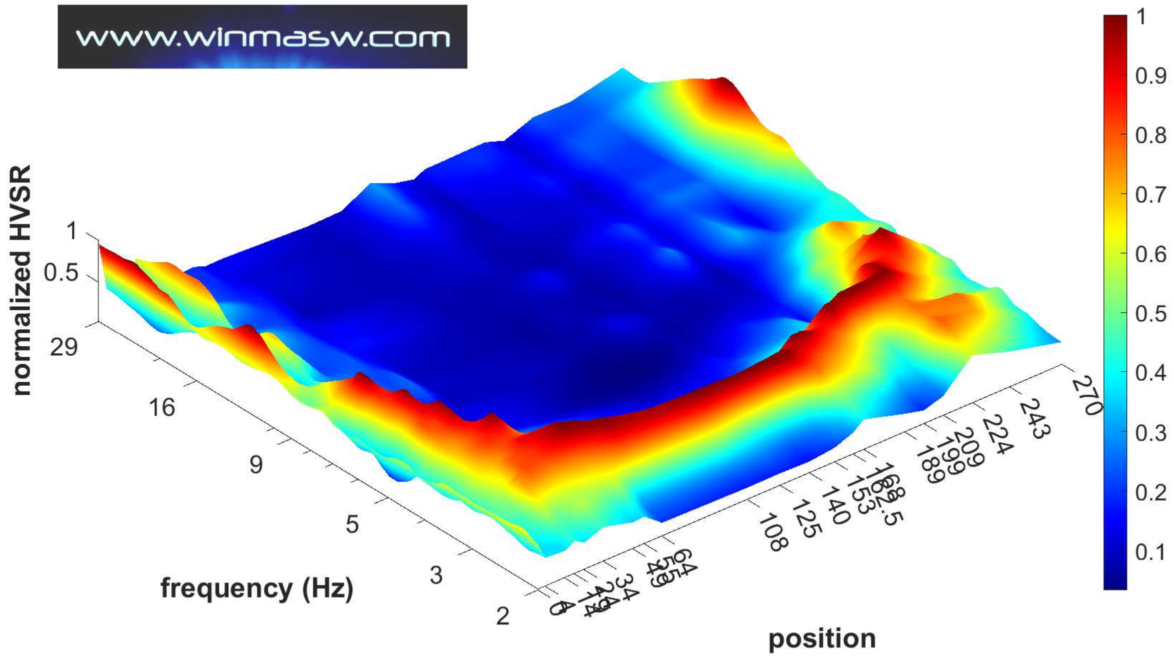
Plotting the logarithm of the HVSRs (so to better highlight the low amplitudes):





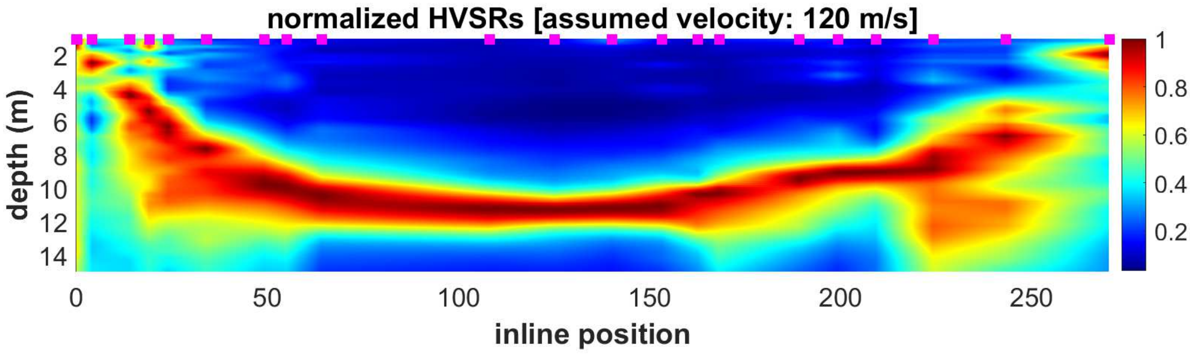
Plotting the normalized curves (to clearly follow the general trend):

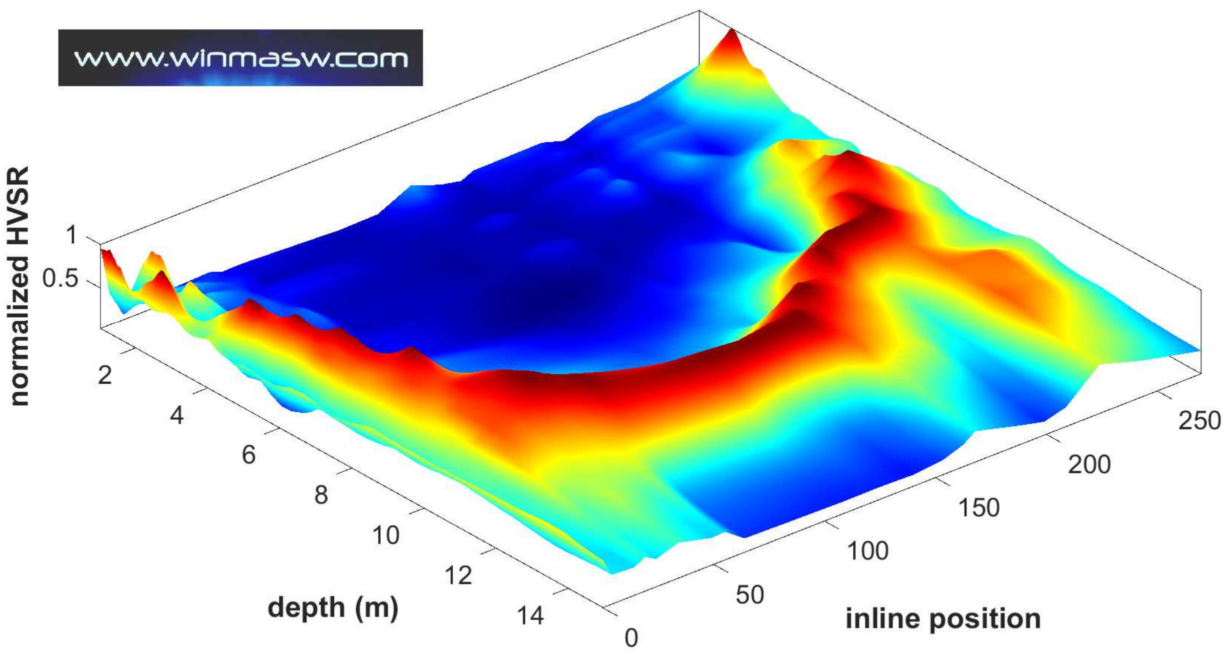




Frequency-depth conversion

In order to convert *frequencies* into *depths* (which is useful in the case the subsurface structure is particularly simple and we can believe that a certain "signal" [peak or not] is related to a specific stratigraphic horizon), a dialog box pops up at the end of the processing and the user needs to input the average velocity (V_S) down to the signal we want to focus on.
This can happen for example in case of a valley in which we have a roughly homogeneous coverage characterized by a certain V_S that depends on the nature of the sediments. Using the relation *f*=Vs/4H it is possible to obtain what is shown in the example shown below, where the *bedrock* is covered by a series of soft sediments with a mean V_S equal to 120 m/s.
The V_S value to input should clearly come from dispersion data (in this case from HoliSurface® analysis) and not from mere assumptions.





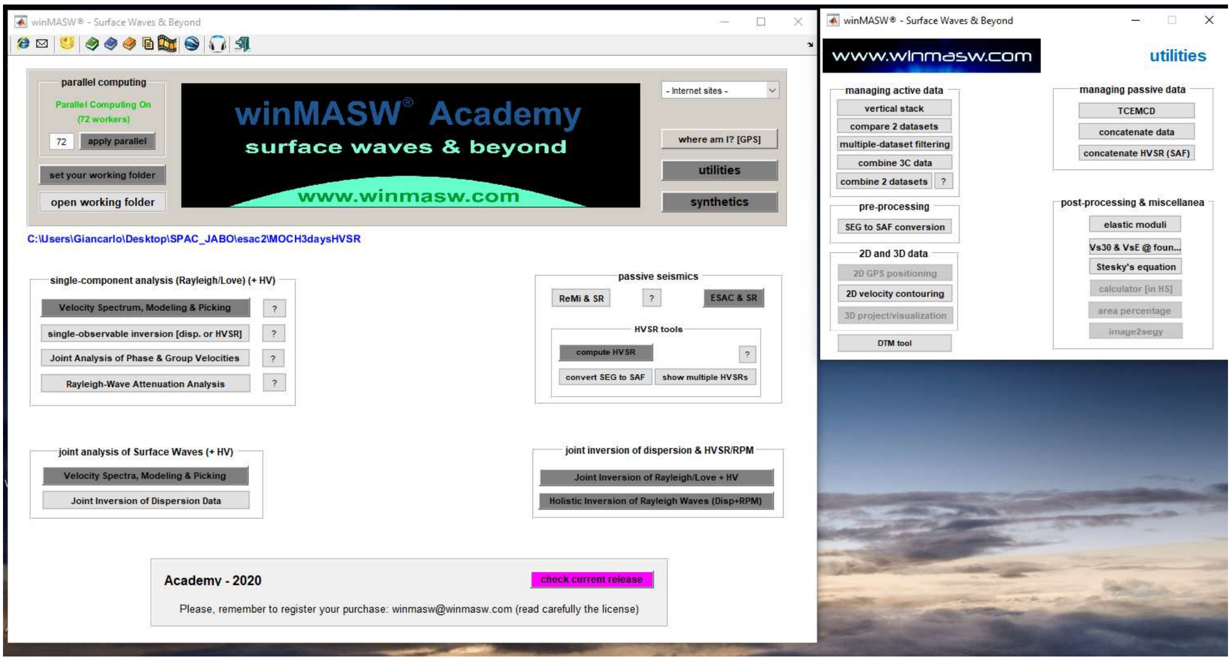
The image is saved in the working folder with a file name that also includes the input velocity used for the conversion. This is useful, for example, in case we have two or more peaks and, in order to obtain the trend of both the pertinent stratigraphic contacts, we perform two conversions (with two different velocities), the first with the mean V_S above the high-frequency peak and the second with the mean V_S above the low-frequency peak (in the working folder we will then obtain two files, related to two different velocities).

Appendix S: 3-component data concatenation (.SAF format)

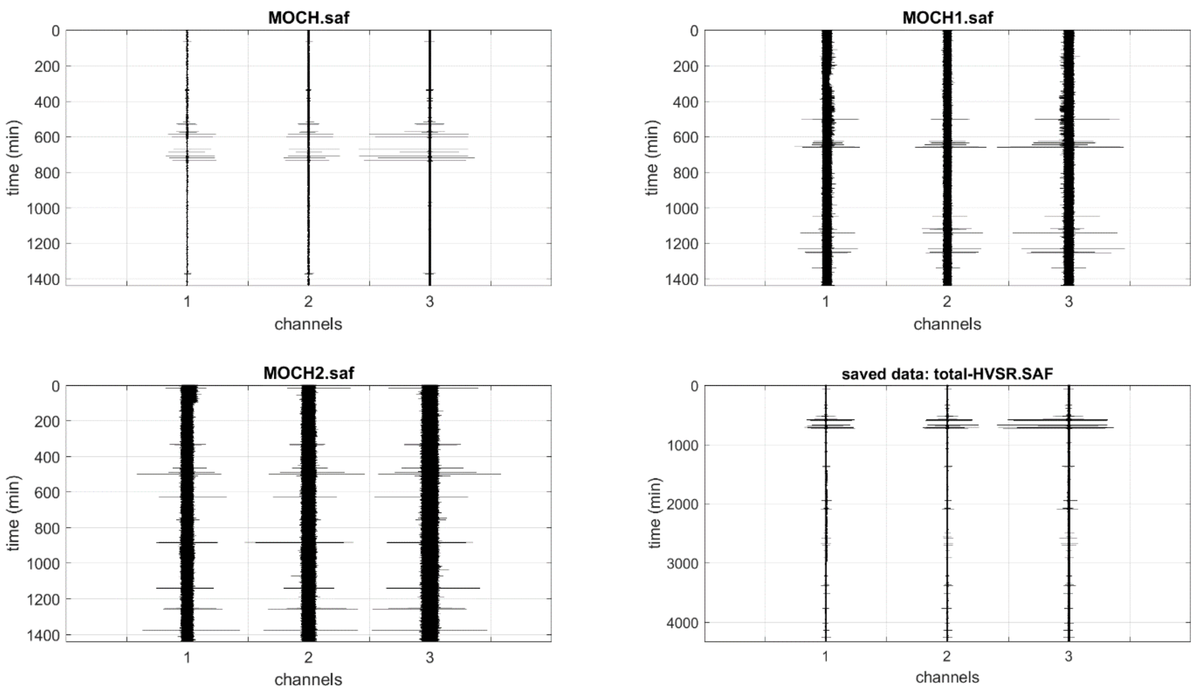
Among the *utilities* (in the "managing passive data" group), you can also find the "concatenate HVSR (SAF)" tool.

By clicking that button you will be able to upload a series of .SAF data (the standard format for microtremor data for the HVSR computation) and you will automatically obtain a (single) "total-HVSR.saf" file with all the uploaded data.

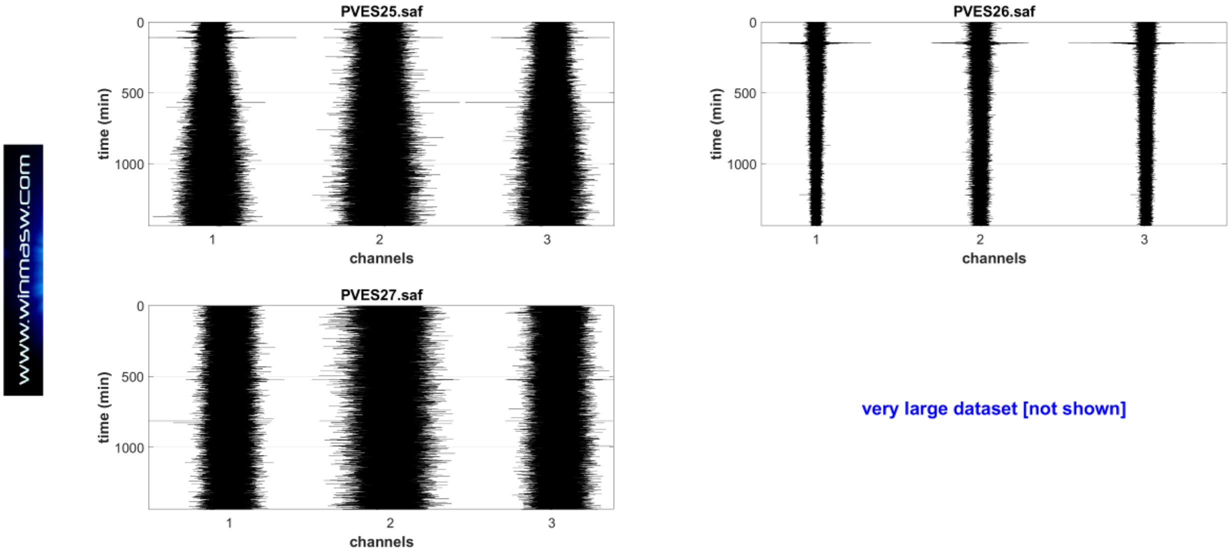
In the example here below, we uploaded three SAF files (each 24h long) so to obtain a single file with 3-day data.



Once the single SAF *files* are uploaded, you can specify the file name for the *total* dataset (again as a SAF file).



In case the *dataset* is exceedingly large (due to a high sampling frequency and/or because of a very long recording) the final (total) *dataset* is not shown (but it is clearly saved with the file name provided by the user):



Appendix T: managing multiple geo-referenced photos [exploration of wide sections]

This *tool* (among the utilities of winMASW® Academy and HoliSurface®) is meant to efficiently manage the exploration (especially via HVSR) of large areas/profiles, where the accuracy of the positioning is not an issue and a relatively-large error (usually 2-4 m) does not represents a real problem.

The point to address through a concrete example. Let us imagine we want to highlight possible lateral variations along a relatively-long profile via passive data (HVSR / ESAC or interferometry). Let's us now here consider the HVSR case.

step#1 (in the field)

At each measurement position of the 3C geophone take a picture with our ***smartphone***, action Camera or whatever - see the section "GPS data in our software applications (winMASW®, HoliSurface® & ELIOVSP®)".

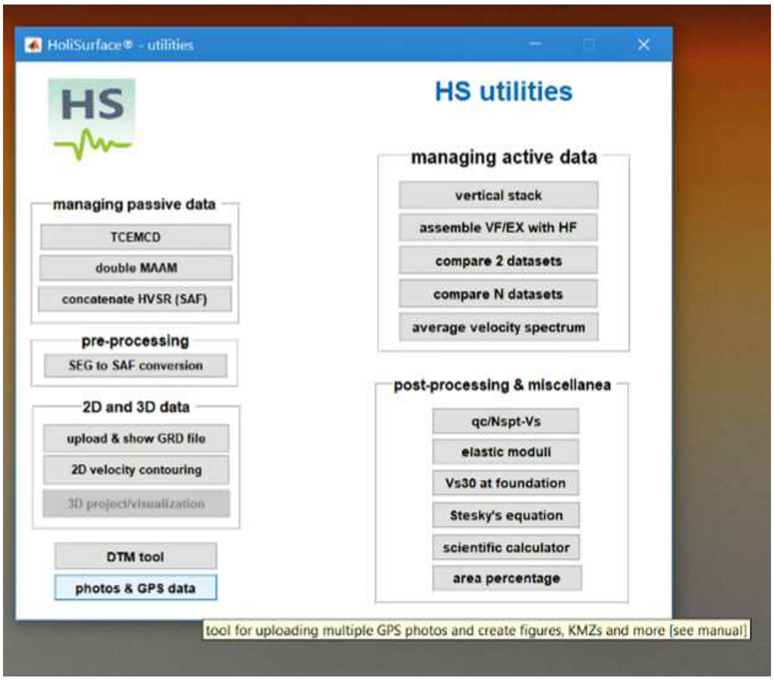
Let's imagine we want to consider 12 points/photos (in this case along a profile more or less 170m long).

step#2 (at home)

First we better **name (re-name) the photo files in a sequential way**. For instance: 1_site1.jpg; 2_site2.jpg; 3_site3.jpg; 4_site4.jpg etc.

step#3

Once we put all the photo files in the same folder (to set as working folder from the main panel of *winMASW®/HoliSurface®*, we can now click the **"photos & GPS data" button** (among the utilities) and upload the twelve (12) photos at once (multiple-file selection possible with the ***ctrl* button**).



As an alternative to uploading the 12 photos, it is also possible to create and upload a **"project file"** in the form of a trivial ASCII file (therefore with the.txt extension) in which the files of each photo are written (one per line).

Here is an **example of a project file** (example "project_file.txt") for uploading 4 photos:
2_20210826_181153_HDR.jpg
4_GPS_2021-09-08_12-07-36-968.jpg
9_2021-09-08_12-12-29-076.jpg
13_20210831_160123.jpg

What is the difference between uploading the *n* images and using a project file?
Only one (but from a practical point of view very important): if the files/images are uploaded directly, they must be re-named as indicated above (in case we want the correct sequence and therefore the correct lengths/distances).
If, on the other hand, we use a project file, it is not necessary to name the image files sequentially because the sequence will be the one indicated in the project file itself. In the latter case, the images may therefore have any name (e.g. sito1.jpg, 2ns_site.jpg, 2021-09-09.jpg etc.).

In any case you will automatically obtain the following figures/outcomes (automatically saved in the working folder):

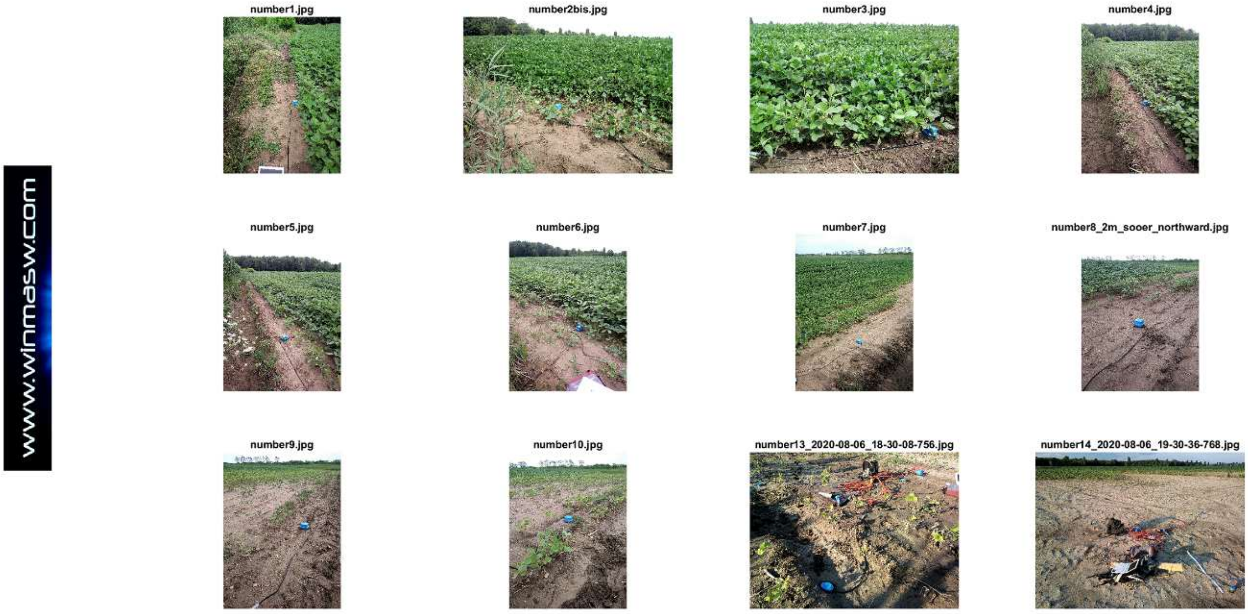


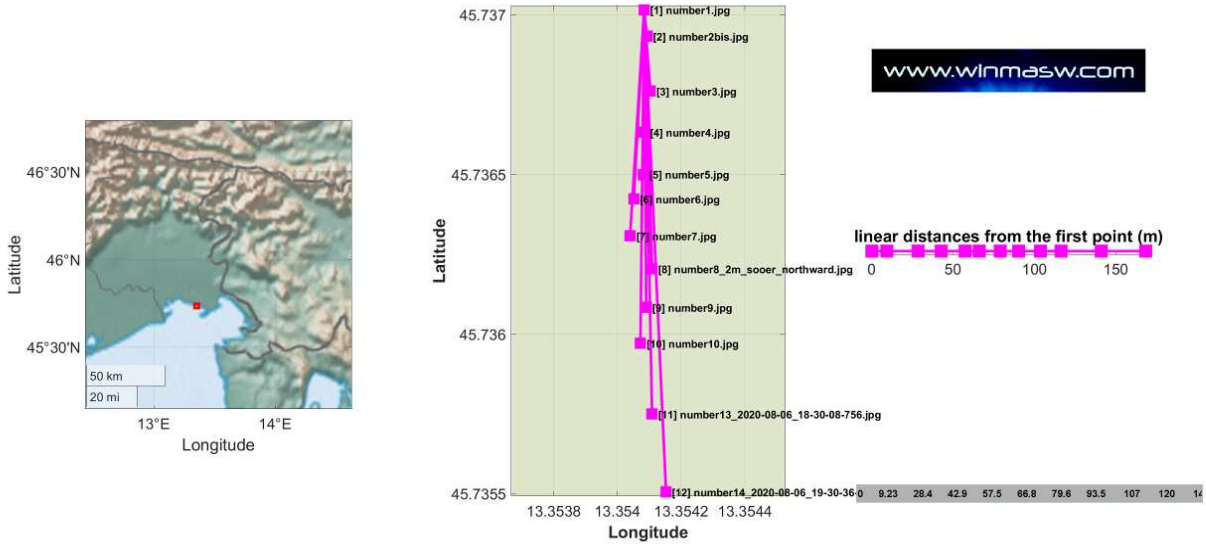
Figure with all the uploaded photos

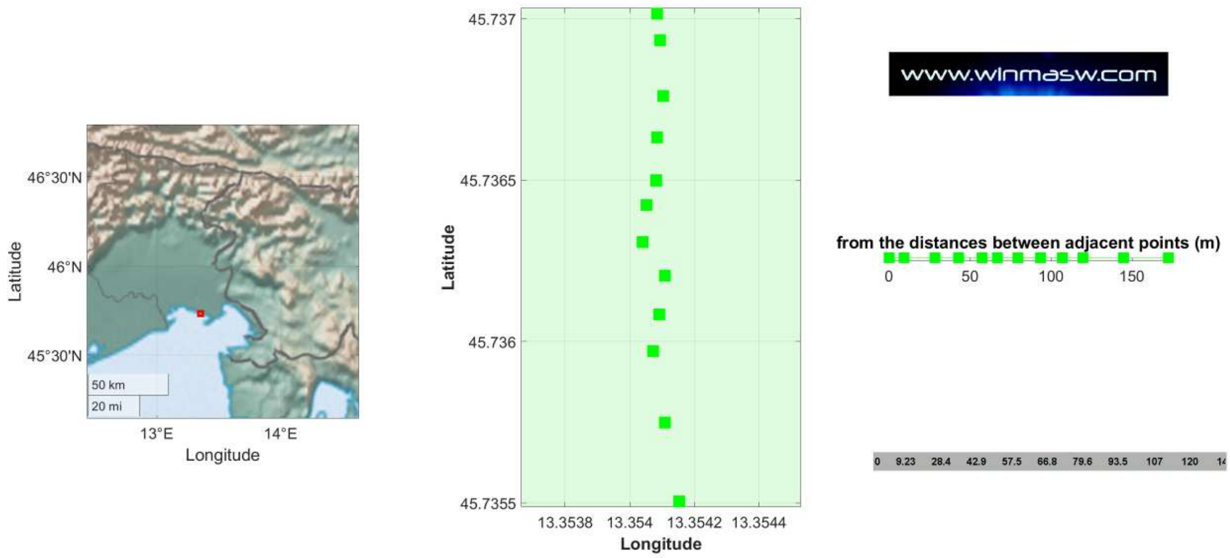
In the working folder, for each photo you will obtain a "**summary figure**" and a **kml file** with the same name as the uploaded photos (e.g. "SiteLocation_4_number4.kml") [of course they can be then easily uploaded/used in **Google Earth**].

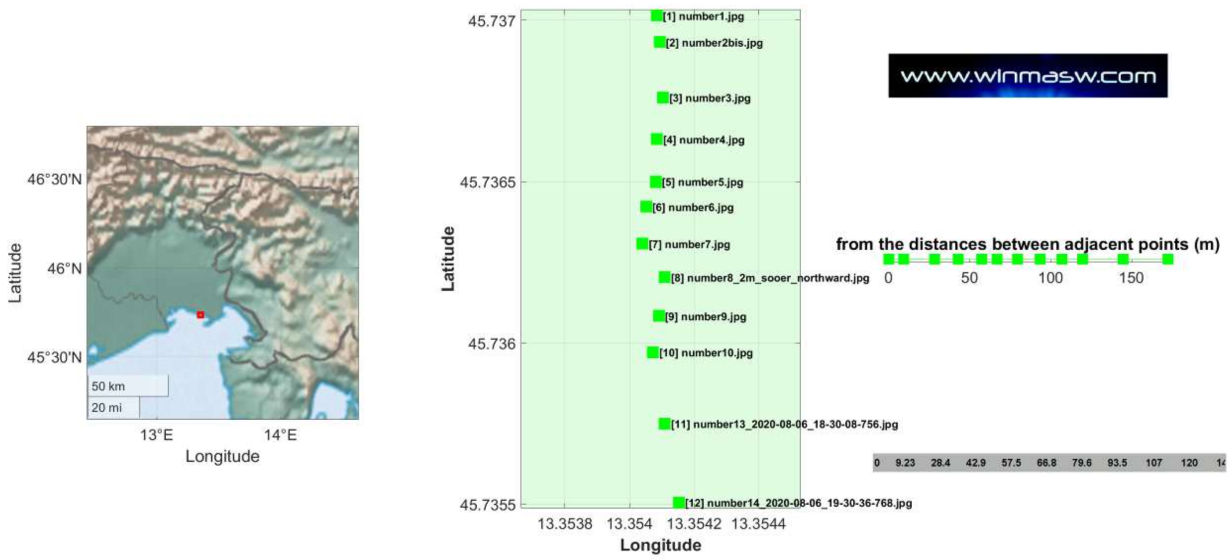
Three figures with the same meaning: the position of the twelve sites with three slightly-different ways to visualize such information (you can choose the one that better suits your needs and taste). **In the lower right corner are reported the (editable) linear distances from the first point. You can highlight the whole sequence and copy and paste the obtained values wherever you need to do it.**

For instance you can copy and paste such a sequence (i.e. the inline positions) in the *project file* that can be used to automatically batch processing all the HVSR data (see Appendix "batch processing of multiple HVSR data" – fifth line of the project file).

Needless to say that you can modify/correct large errors due to inaccuracy of the device you used to take the snapshots in the field.





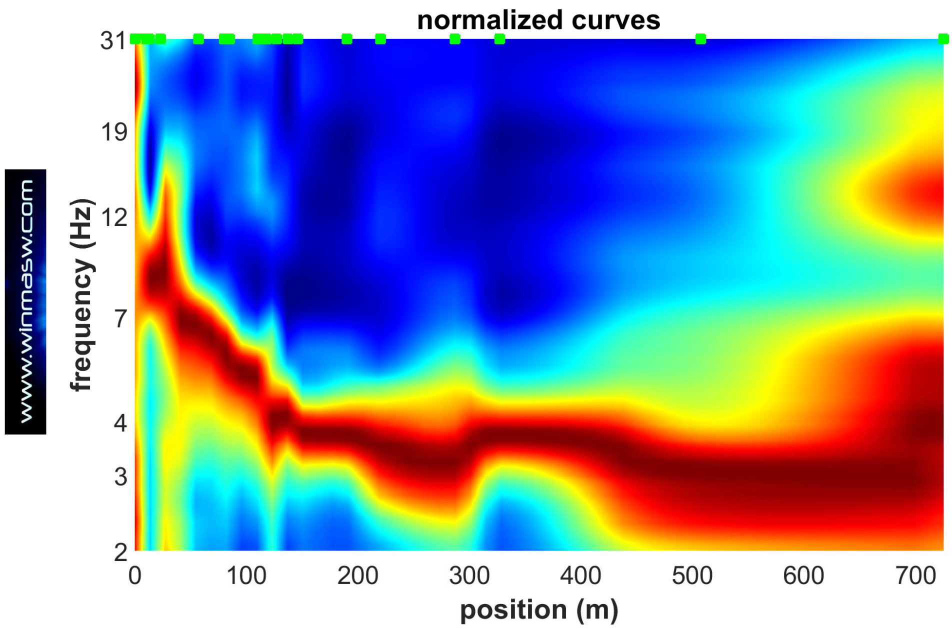


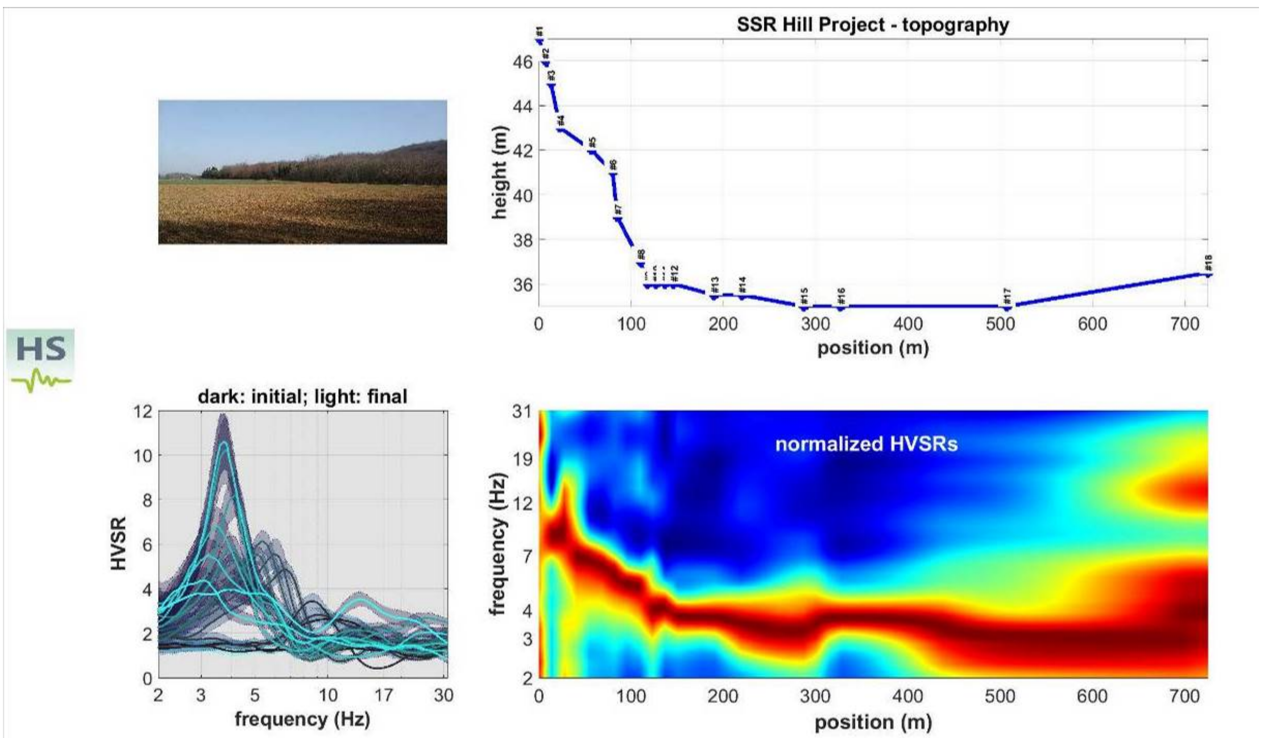
The following HVSR 2D section is just an example of a concrete application of the distances obtained considering the procedure described in the Appendix “**batch processing of multiple HVSR data**”.

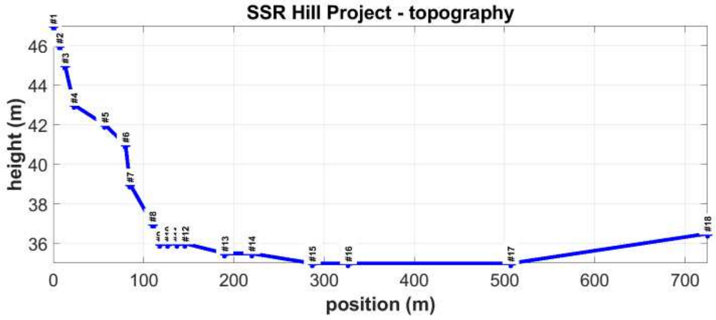
In simple terms: a series of HVSR data were collected along a profile. For each point a geo-referenced picture was taken.

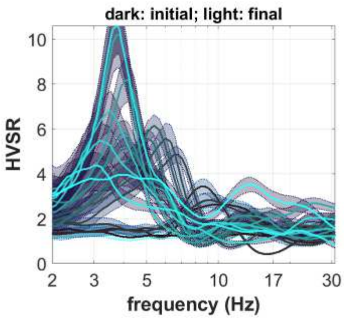
The photos were uploaded with the utility described in this Appendix and the point locations along the profile was therefore obtained (of course a simple straight profile is considered).

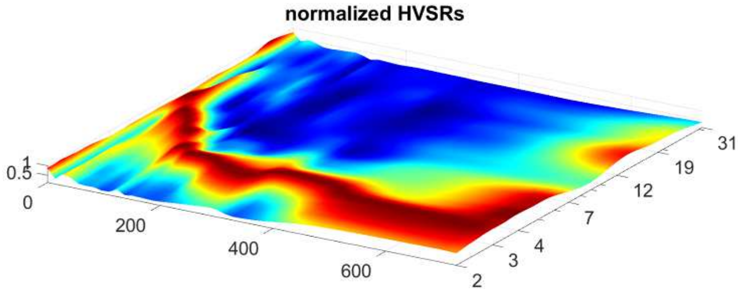
In this case the length of the profile is about 700 m and the considered number of points is 18 (with a better focus in the first 350 m [higher point density]).

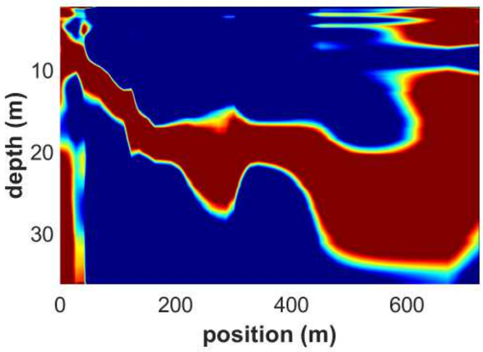


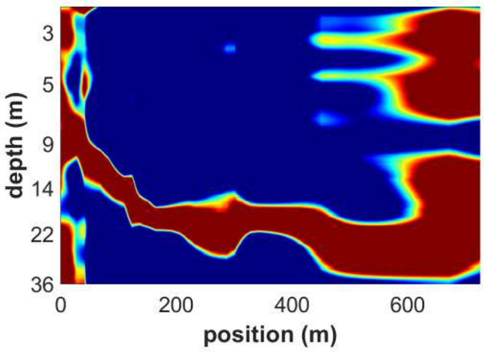








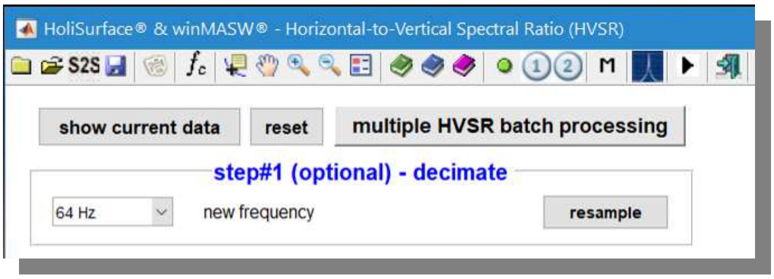




Please, see also the Appendix “**batch processing of multiple HVSR data**”.

Appendix U: batch processing of multiple HVSR data [also for 2D reconstructions]

Processing a large amount of HVSR data can be time consuming. In order to do it automatically (thus saving time and energy) you can use this tool (available in winMASW® Academy and HoliSurface®). A very simple ASCII project file need to be written and saved so to be uploaded using the **"multiple HVSR batch processing" button** in the HVSR panel.



All the files to be processed must be stored in the same folder where you also have your project file.

An example of data and project file is provided together with the winMASW/HoliSurface software in the "**Self_Training_Data_Dissemination**" folder (see subfolder "Automatic_2D_HVSR_section_data_and_projectfile").

The **project file** is a simple ASCII files with the following structure/content (try to open the "project_file_18points.txt"provided file):

```
The Hill Project
2D HVSR section#1
290 350
0
0  7  13  23  57  80  85  110  118  127  137  146  190  220  287  327  507  725
47  46  45  43  42  41  39  37  36  36  36  36  35.5  35.5  35.  35.  35  36.5
firstPOINT.SAF  1 1 2 3  photo_site1.jpg
secondPOINT.seg2 1 1 2 3  photo_site2.jpg
locationTHREE_doubleHOLI3C.seg2 1 1 2 3  photo_site3.jpg
locationTHREE_doubleHOLI3C.seg2 2 6 5 4  photo_site4.jpg
…
```

Meaning of each row

First line: project name
Second line: just a note for you
Third line: the average velocity (V_S) between the surface and the horizon/contact you want to follow (equivalent V_S). This can be for instance the contact between a shallow soft (e.g. silt) layer and a gravel layer (this kind of contacts can create very large HVSR

peaks) or the contact between a quaternary layer and the bedrock. Please, remember that an HVSR peak does not necessarily refer to the *bedrock*. If you insert two (or more) values, the conversion from frequency to depth will be accomplished for all the reported values.

Forth line: this is the "hibernate computer" flag. If "1" (one) at the of the batch processing the computer will automatically hibernate (this can be useful for instance in case you are batch processing a large amount of data and want to launch the procedure and forget about this); in case the value is "0" (zero), at the end of the procedure the computer will not hibernate.

Fifth line: the inline position of each point (in meters) [see also Appendix "*Managing multiple geo-referenced photos [exploration of large areas]*"]

Sixth line: the topography for each point (in meters). In case you are not interested in such a feature, just put one single zero (0) value.

Seventh (and successive) line(s). Along these lines must be provided four (4) information:

9) the filename of your microtremor data (considered both SAF and seg2 formats)
10) the number of the considered 3C geophone (a seg2 file can contain data about more than one 3C geophone! – see later on)
11) the sequence about the vertical, NS and EW traces for the considered geophone
12) the filename of a georeferenced jpg photo (see pertinent section of the manual). In case you do not have it, just write "photo1.jpg" [you *must* write something!]

About the "considered 3C geophone" number the point must be clear

With some acquisition system you can record several "HVSR" data at once, at multiple locations. For instance, with our *standard* system (and important news will be soon available), you can easily **connect two HOLI3C (3-component) geophones** and consequently record the data to obtain the HVSR curves at two different locations.

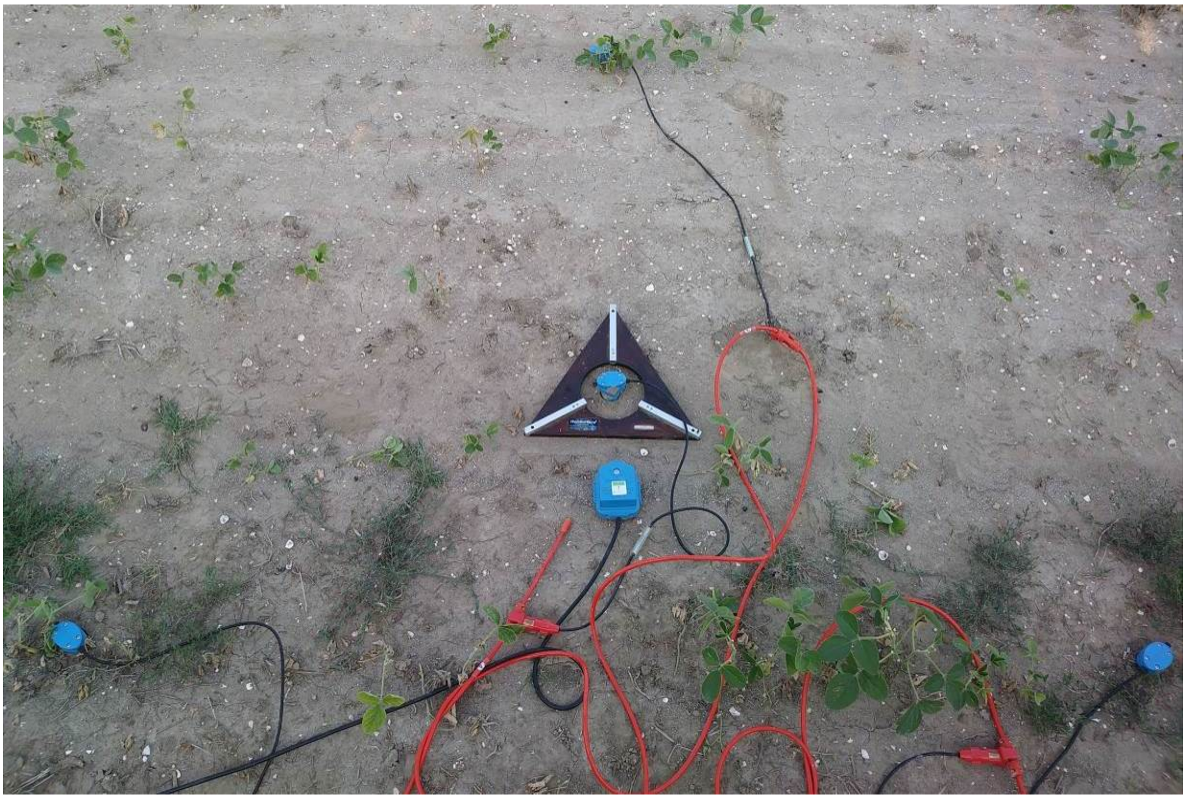
When you are using two (or more) geophones at once, your file will clearly contain more than just 3 traces. Let us here consider the simple case of 2 3-component geophones recording simultaneously the data. You will clearly have a final **dataset/file with 6 traces (3 about the first geophone/site and 3 about the second geophone/site)**.

In order to easily manage this sort of multiple-HVSR data in your project you can easily specify/define the meaning of your data file in the project file. If, for instance, the file is named "locationTHREE_doubleHOLI3C.seg2", you need to specify the meaning of the traces like this:

locationTHREE_doubleHOLI3C.seg2 **1** 1 2 3 photo_site1.jpg
locationTHREE_doubleHOLI3C.seg2 **2** 6 5 4 photo_site2.jpg

This way we tell the software that the first three traces [1 2 3] are about the first geophone (see the red number) while the traces 6 5 4 are about the second geophone (see the red number).
Of course, in case we are dealing with a single geophone we simply need to write something like "1 1 2 3" (in case the trace sequence is UD NS and EW) or "1 3 2 1" (in case the trace sequence is EW NS UD) [this depends on your *acquisition system*].

A further possible situation is when the HVSR must be computed while considering the data recorded considering a joint HVSR+MAAM set up (like in the following picture). For those who are not familiar with this technique, MAAM stands for *Miniature Array Analysis of Microtremors* (see our ***HoliSurface*** **software application** page and **this video**).



In this case our data file will have 7 traces: 3 about the 3-component geophone and 4 about the 4 vertical geophones used for the MAAM.
Also in this case we need to properly tell the software which ones are the UD NS and EW traces to use for the computation of the HVSR. If, for instance, the 3-component

geophone was connected to the first 3 channels of the seismograph the line will be something line:

2020-08-06_18-32_point13_HVSR_MAAM110.seg2 1 1 2 3 photo1.jpg

On the other side, if the 3-component geophone was connected to the last channels (so the first 4 channels were used for the 4 vertical geophones), the line could be for instance something like:

2020-08-06_18-32_point13_HVSR_MAAM110.seg2 1 7 6 5 photo1.jpg

In this case the system and the configuration is such that the 7th channel is about the UD (vertical) component, the sixth channel is connected to the NS component and the fifth channel to the EW component.

It is therefore of paramount importance that you know exactly how your *acquisition system* works (remember we provide all the necessary field equipment and software necessary for any kind of seismic application, please visit our **web site**).

Outputs:

At the end of the procedure you will obtain a series of folders where the full analysis of each dataset is stored. For instance, if the 17th file is named "8_2020-03-03_15-09HUNTERbis" the full analysis will be reported in a new **folder named** "HVSRoutput_17_8_2020-03-03_15-09HUNTERbis".

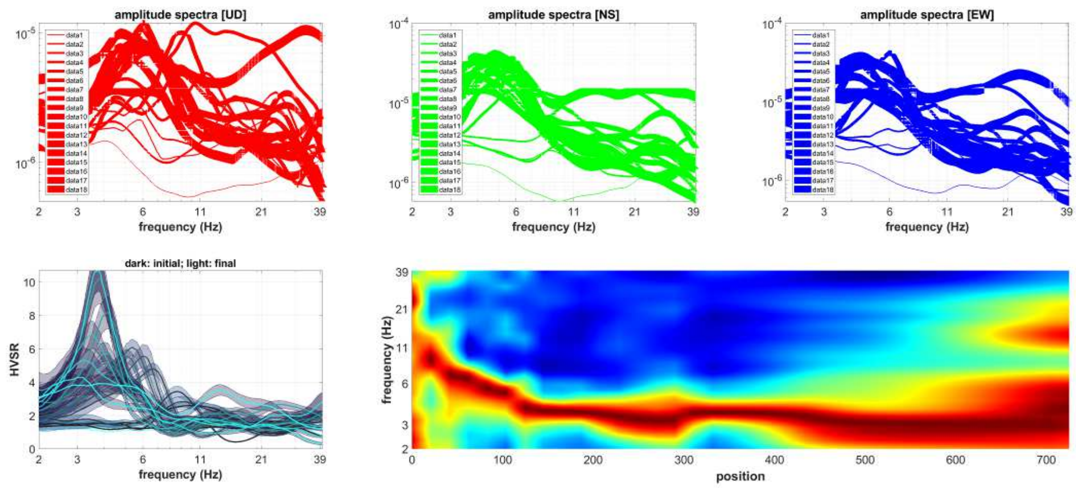
You will also obtain a series of figures with the reconstructed 2D data (see next pages).

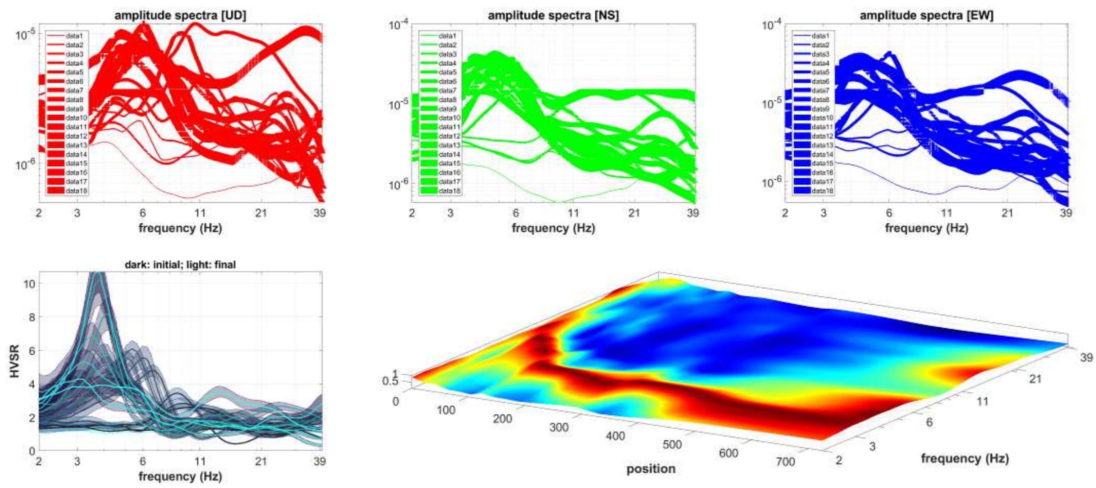
Recommended procedure (try to do it with the provided data):

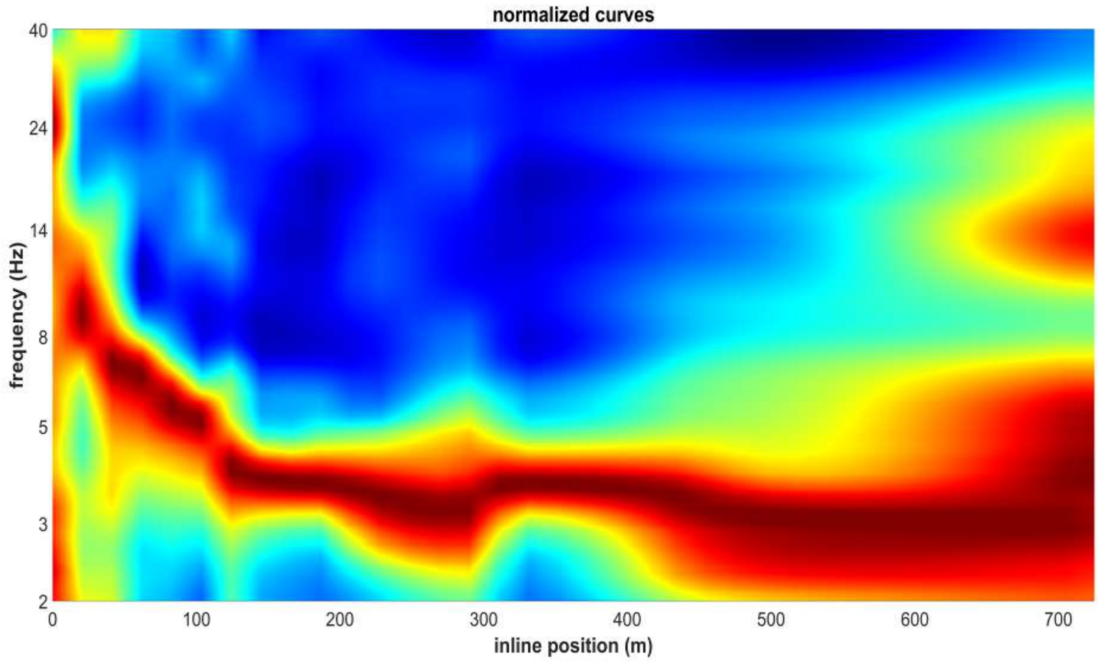
1) **set the working folder** (where all the data and project files are stored)
2) **upload a geo-referenced photo** of the area (this is optional but recommended)
3) **upload the first dataset** and do some processing aimed at defining the best parameters to use during the processing of all the data that will be batched processed
4) once the best processing parameters are chosen (length of the window, minimum and maximum frequency to consider, smoothing, equalization options etc.), activate the "full output" and the "close windows" options and upload the project file with the "**multiple HVSR batch processing**" button.

In the following pages, we report the outcomes you can obtain while adopting such a procedure (with the provided training data & project file).

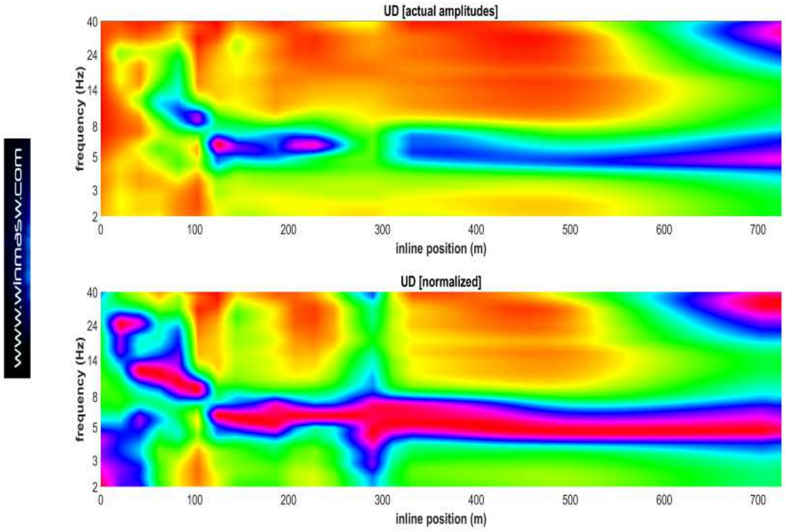
In the following figures are shown the amplitude-spectra curve and the normalized HVSRs (so to better emphasize the HVSR peaks and their continuity over the inline positions)

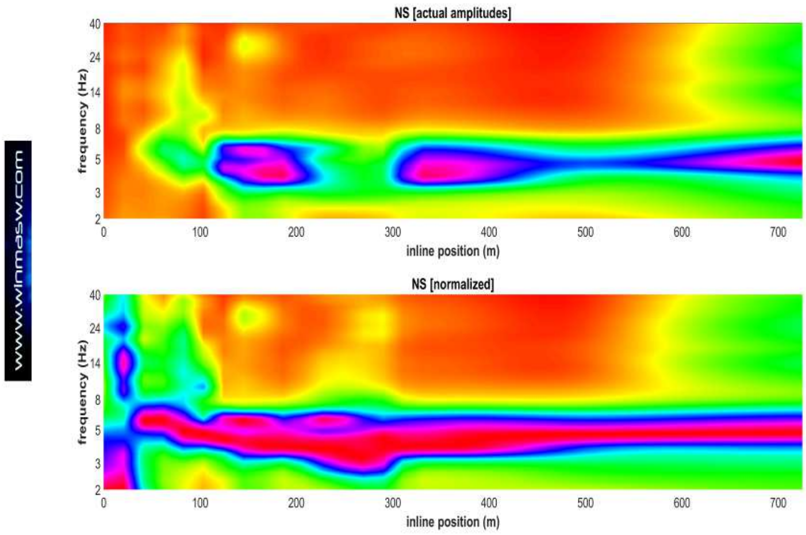


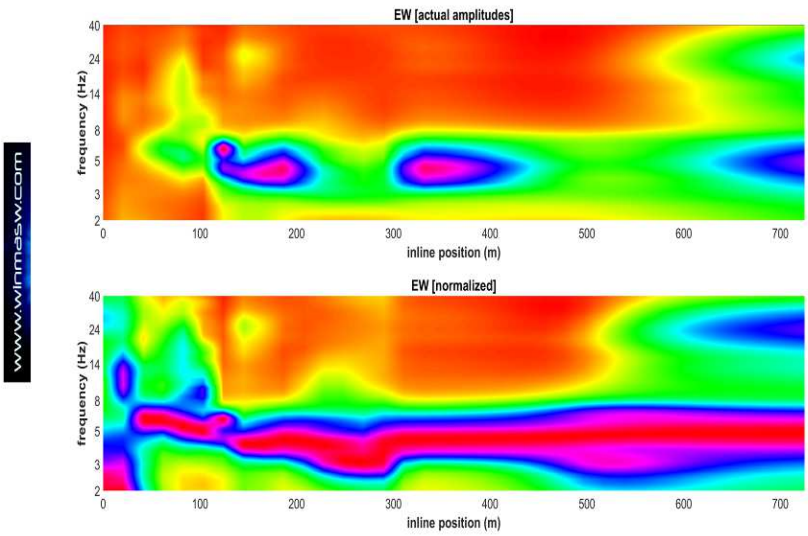



normalized curves
40
24
14
8
5
3
2
frequency (Hz)
0
100
200
300
400
500
600
700
inline position (m)

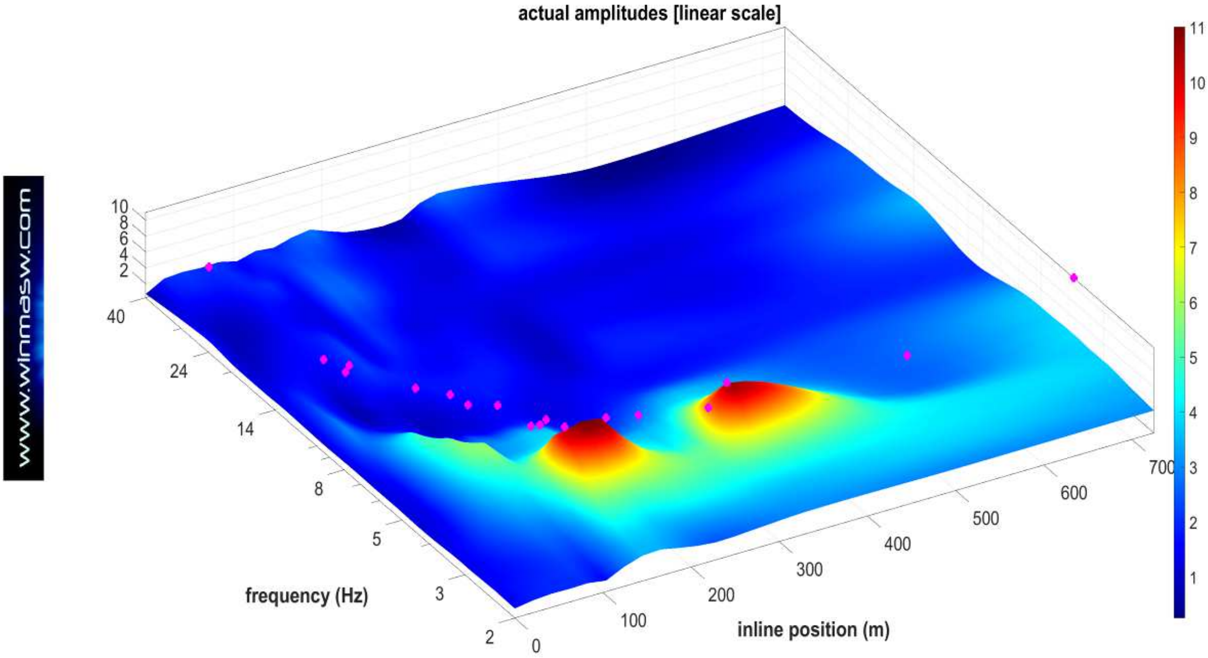
Amplitude spectra (actual and normalized amplitudes) for the three components [vertical, NS and EW].

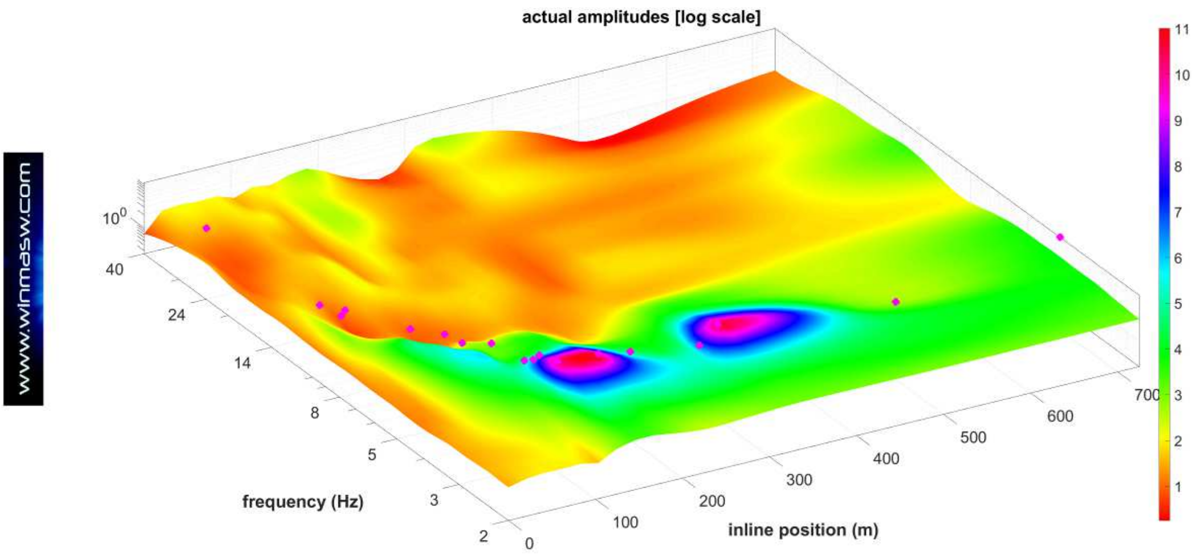




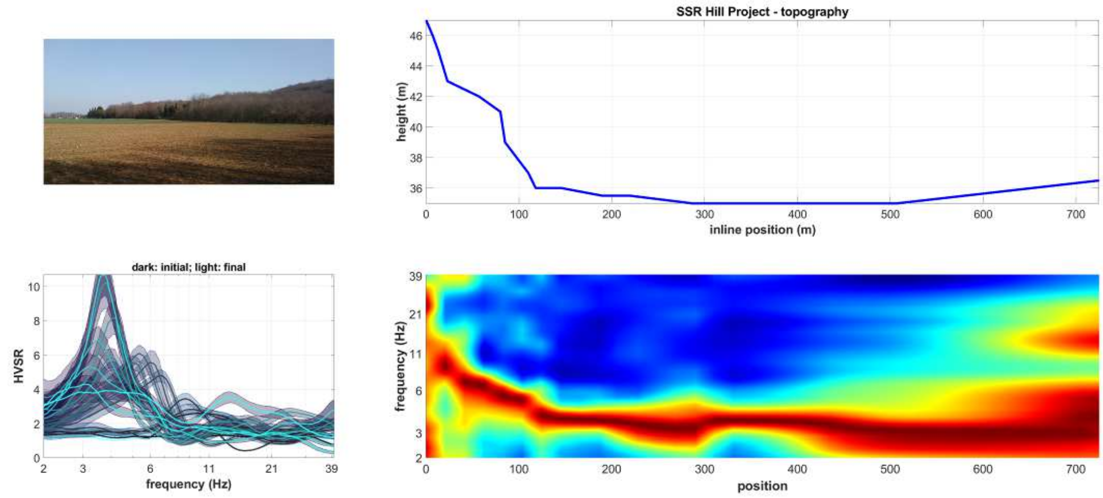


HVSRs (actual amplitudes) using two different color scales:



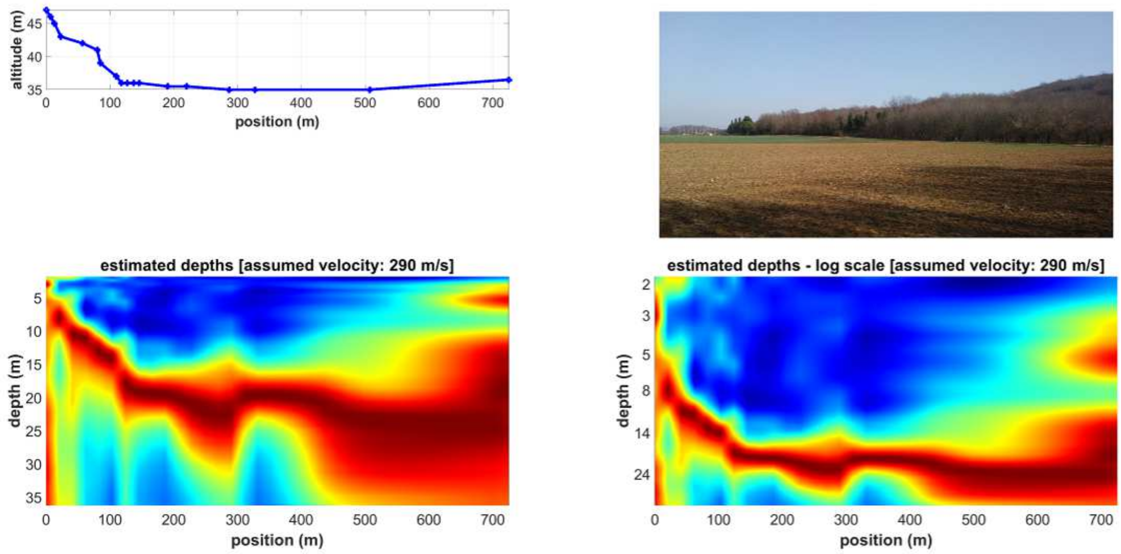


Further (final) figures



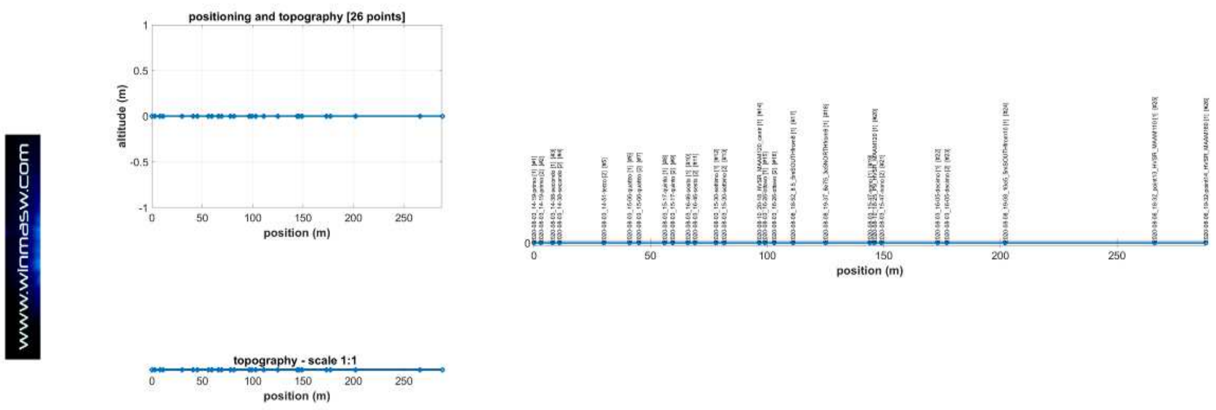
Depth conversion using the velocity reported in the third line of the project file (in this case 290 m/s).

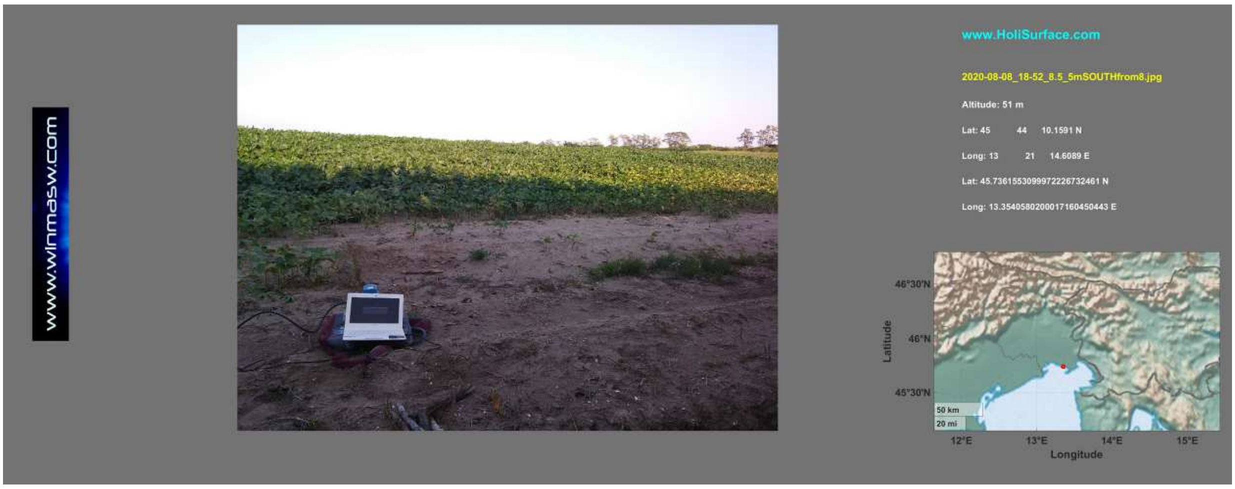
Topography, uploaded picture, depths (having used the average velocity provided in the project file) shown according to linear and log scales.

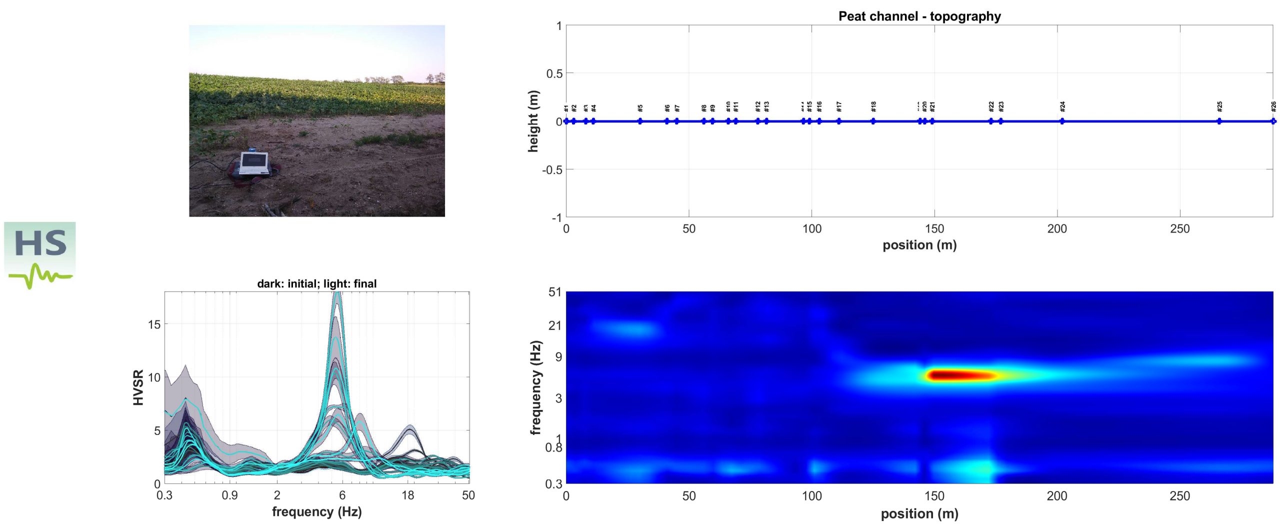


A second example

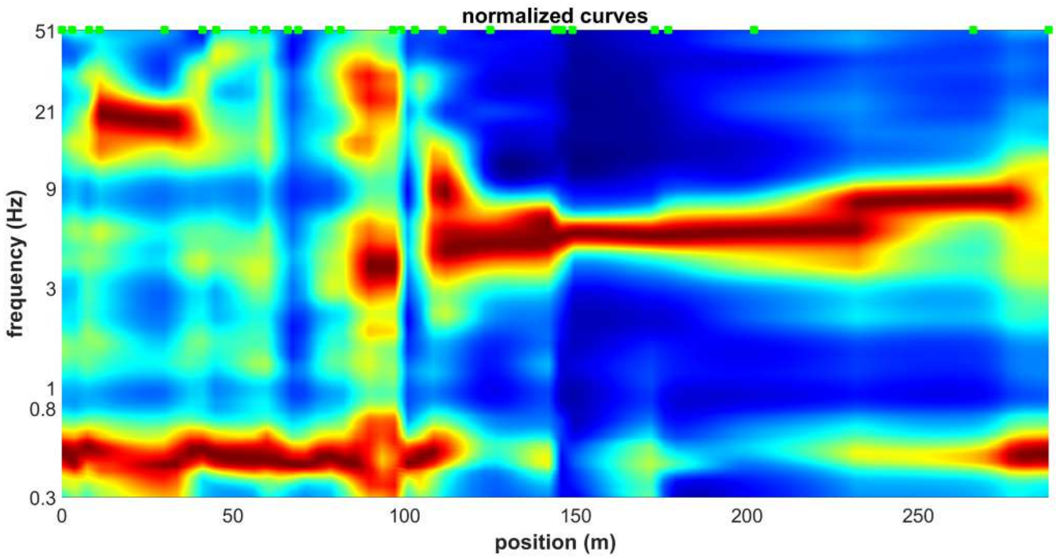
In the following figures, we can see the outcome in case no topography is considered.



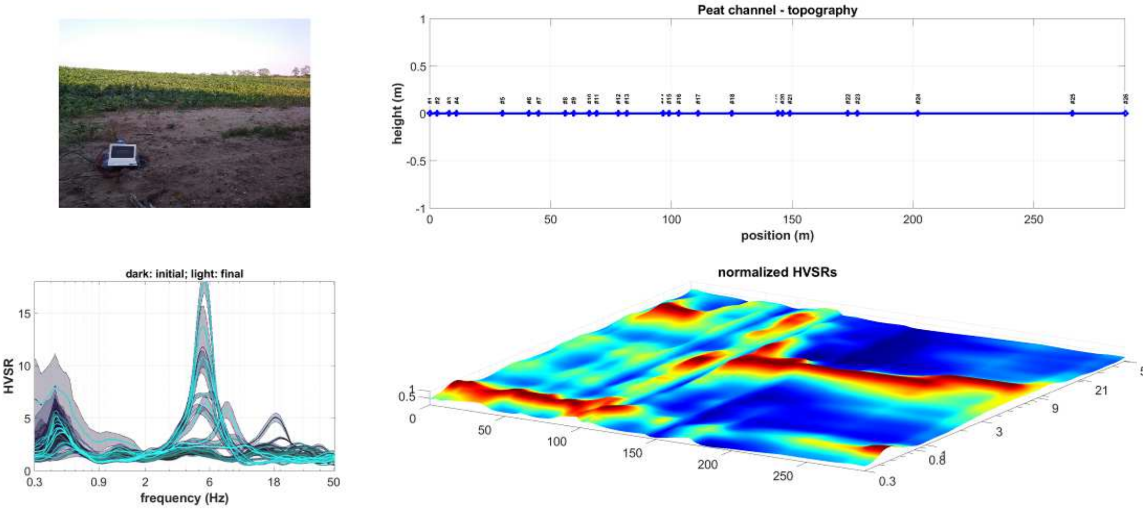




Actual amplitudes: the large peak at about 6 Hz is due to a shallow (local) peat channel while the peak at about 0.5 Hz is due to the deep bedrock



Normalized curves



Normalized curves (lower right corner)

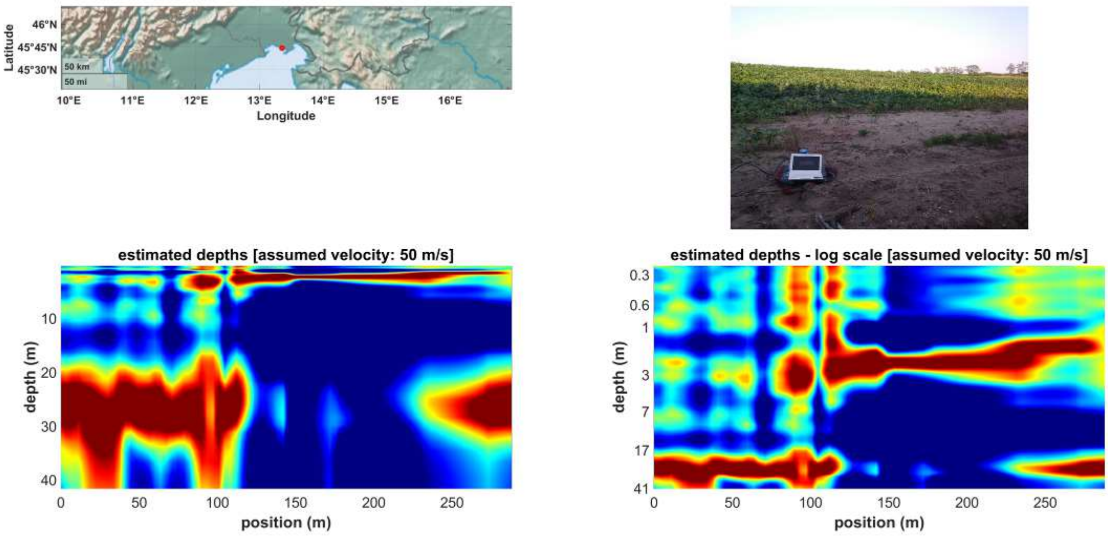
Depth conversion

The two figures shown here are obtained while considering two different mean V_S values (**third line in the project file**): 50 m/s and 380 m/s.

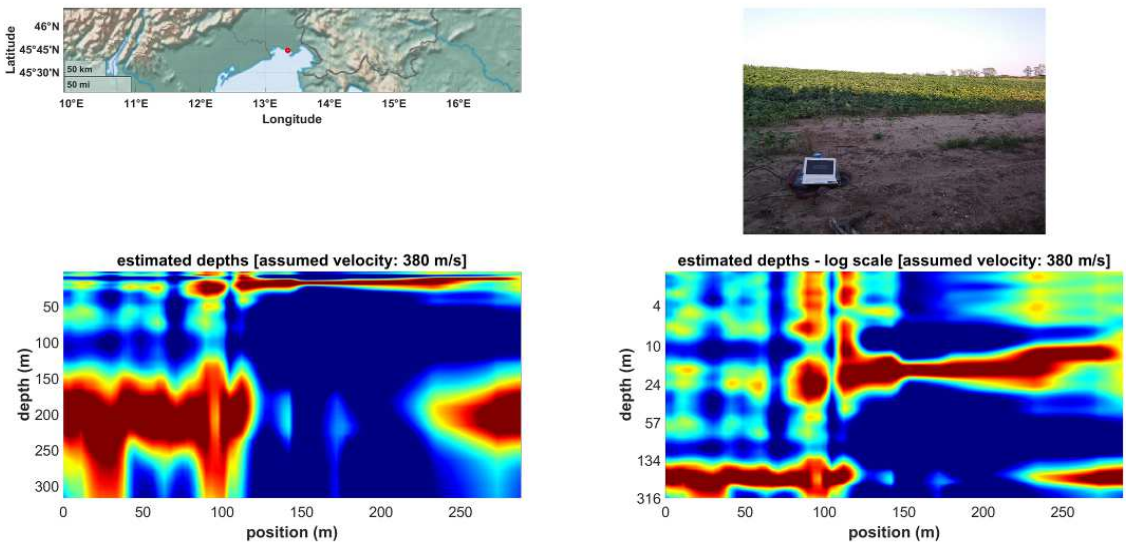
These two values were fixed considering the specific characteristics of the site. While the HVSR peak at about 0.5 Hz is about the deep bedrock, the large peak at 6 Hz is due to a peat channel. The local peats are characterized by a V_S value of about 50 m/s (such a value was obtained through the analysis of surface-wave dispersion – in this case via MAAM) while the average V_S value for the whole stratigraphic column down to the bedrock was estimated while considering ESAC data.

Using these two values (50 and 380 m/s) in the project file (third line) we can obtain the approximated depth of the peat channel (in this case about 3 m) and the depth of the *bedrock*.

www.winmasw.com



www.winmasw.com



Appendix V: HS-QC [Quality Check] software: your field assistant

Most of the acquisition software applications of the seismographs available on the market lack of tools for the assessment of the data quality. Once your (active or passive) data has been acquired it is in fact impossible to evaluate the actual quality in a clear and "quantitative" way.

For this reason, in order to not bring home poor-quality data, a **QC [Quality Check]** version of our software applications has been implemented.

From the 2021 *release*, *HoliSurface®* and *winMASW®* Academy users also receive a **USB dongle** for the **HS-QC software**, to use during your field acquisitions in order to verify the data quality.

The data quality can be evaluated **for both active (MASW and HS) and passive (HVSR, ESAC, ReMi, MAAM, vibrational) data**.

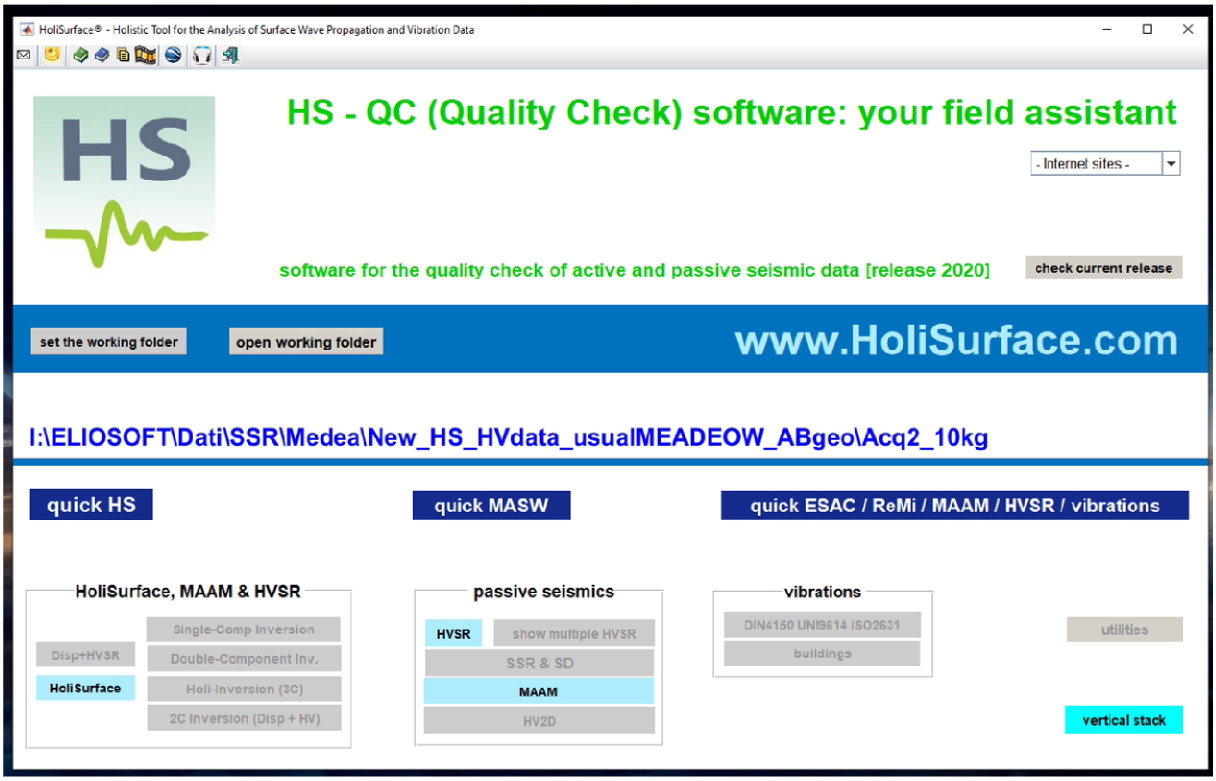
The software is clearly also available for those who do not own HS or winMASW ACD (at a small price).

There are two families of panels:

1) **quick analysis [dark blue buttons]**: they allow a very quick and immediate evaluation of the data;

2) **"full" analysis**: they allow you to upload the data and perform broader and more in-depth analyses (these are simplified versions of the analyses possible with HS).

A tool for the **stack** of your active data is also available (see bottom right button in the main panel here below).



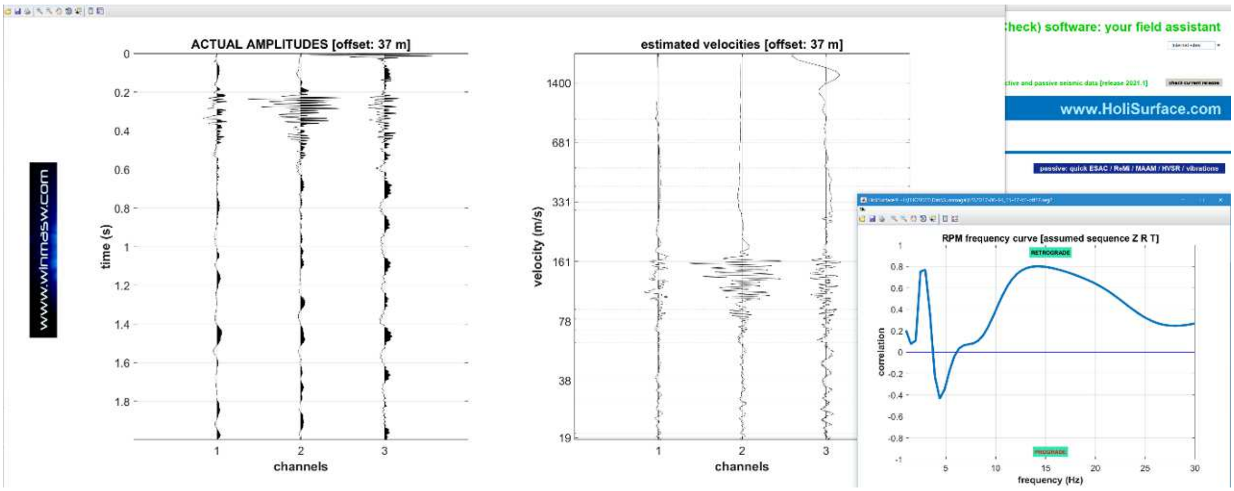
THE THREE QUICK BUTTONS

For the fastest quality check three **QUICK** button are avaialble from the main panel, depending on the type of data you are considering. After you click the pertinent button and upload the recorded dataset you automatically obtain one of the following outcome.

ACTIVE DATA

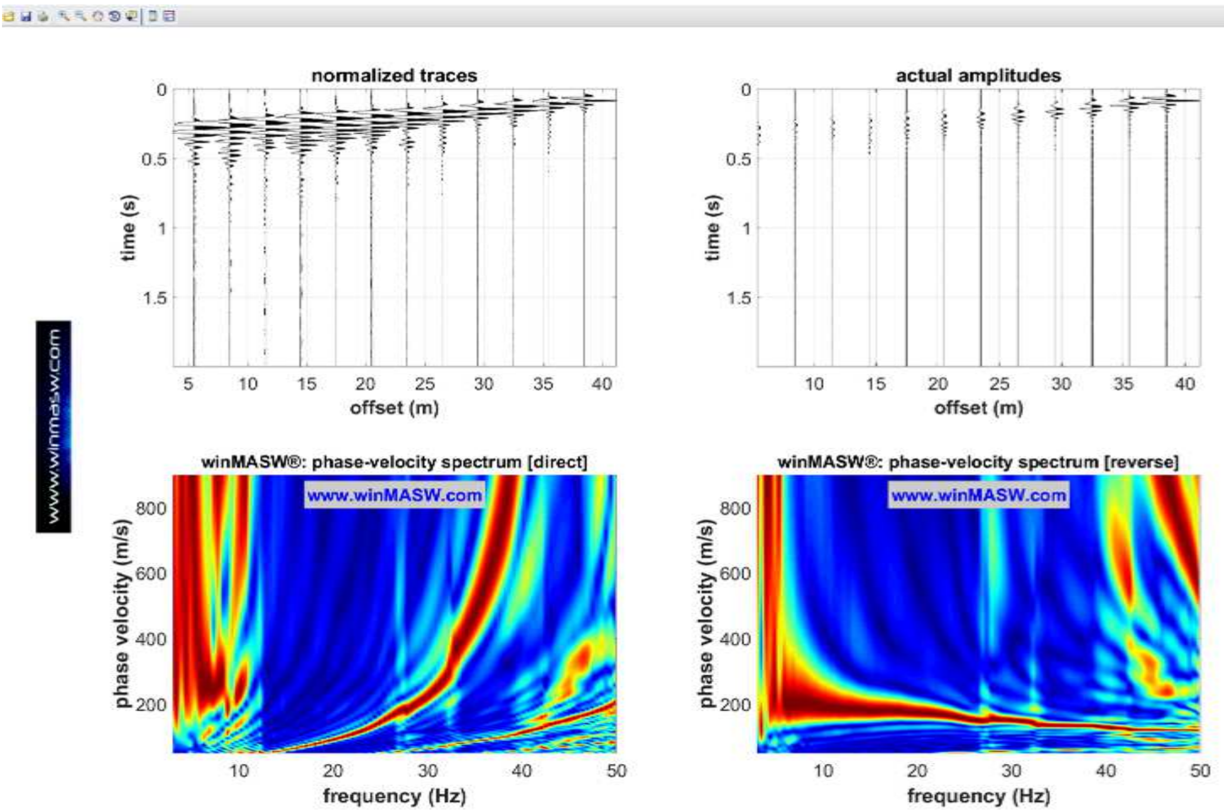
HS data [“quick HS” button]

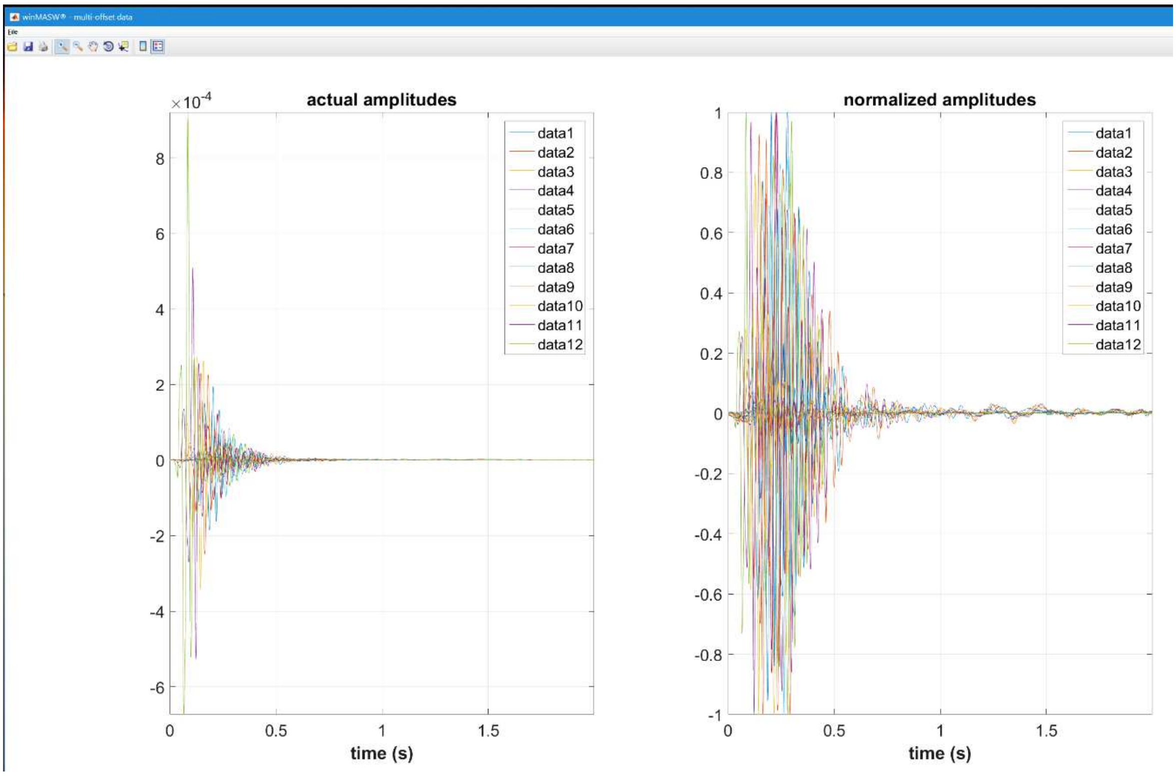
shown the traces, the RPM curve and the “velocity converted” traces



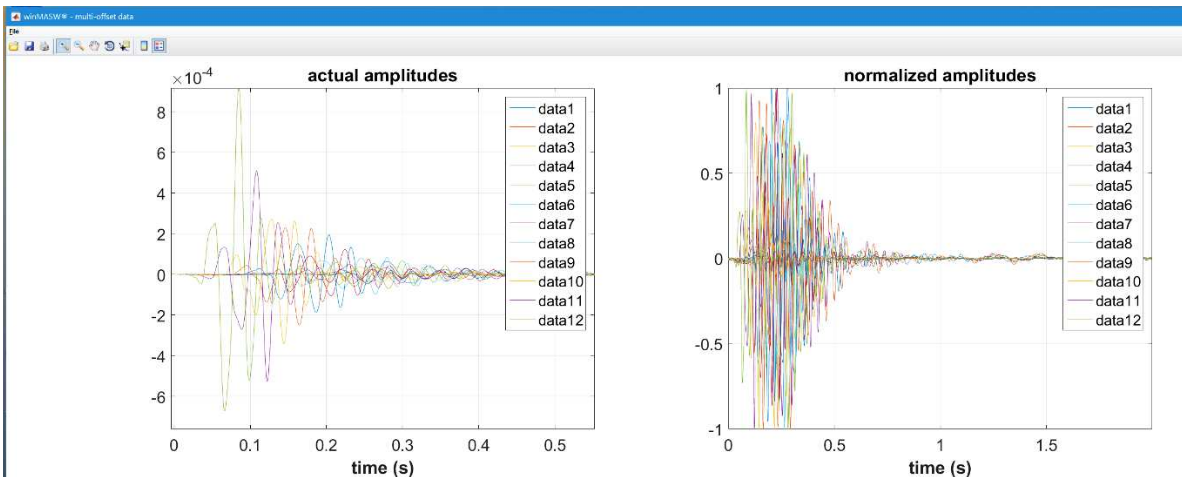
MASW data [“quick MASW” button]

shown the traces (actual and normalized amplitudes) and the phase-velocity spectra





A different way to show the traces

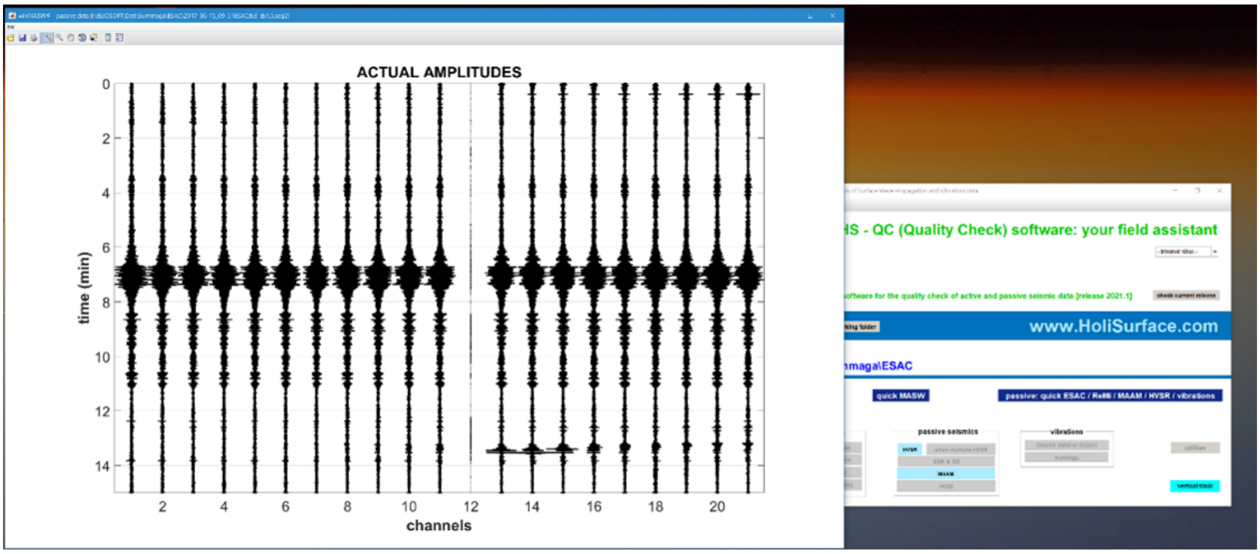


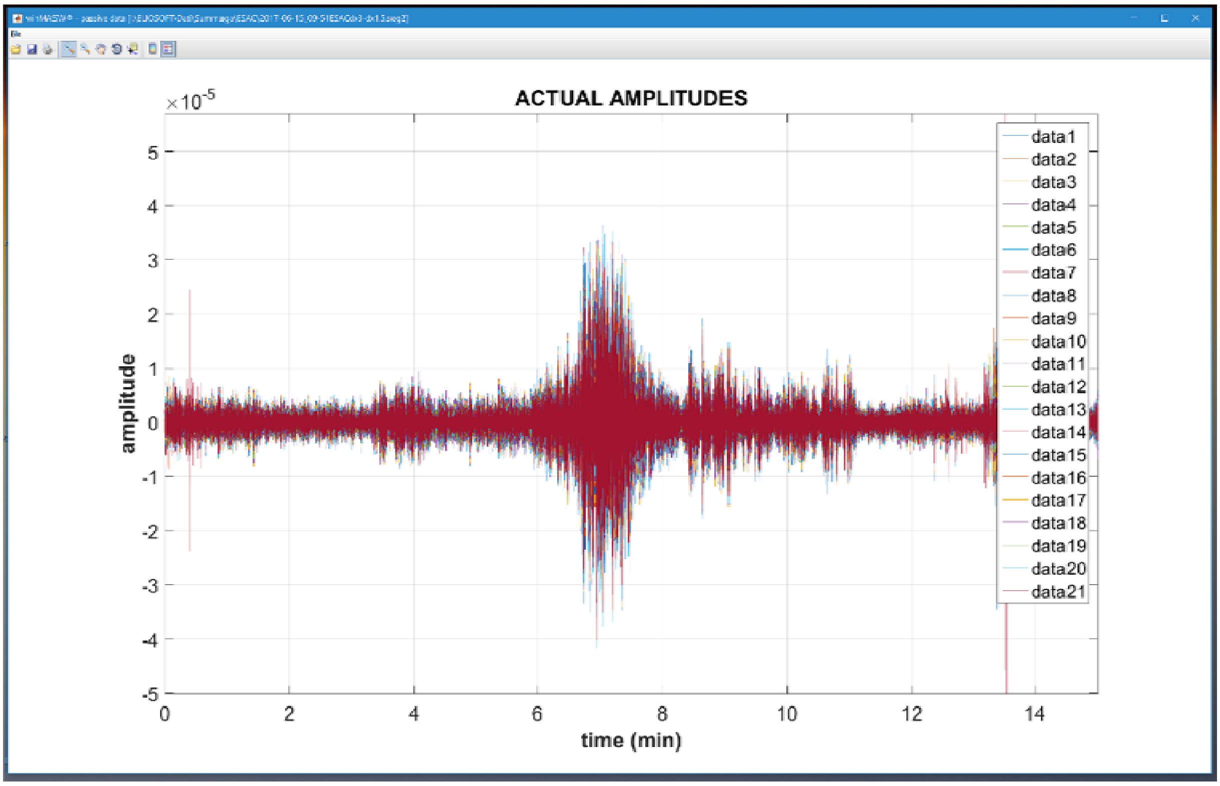
of course you can zoom in

PASSIVE DATA

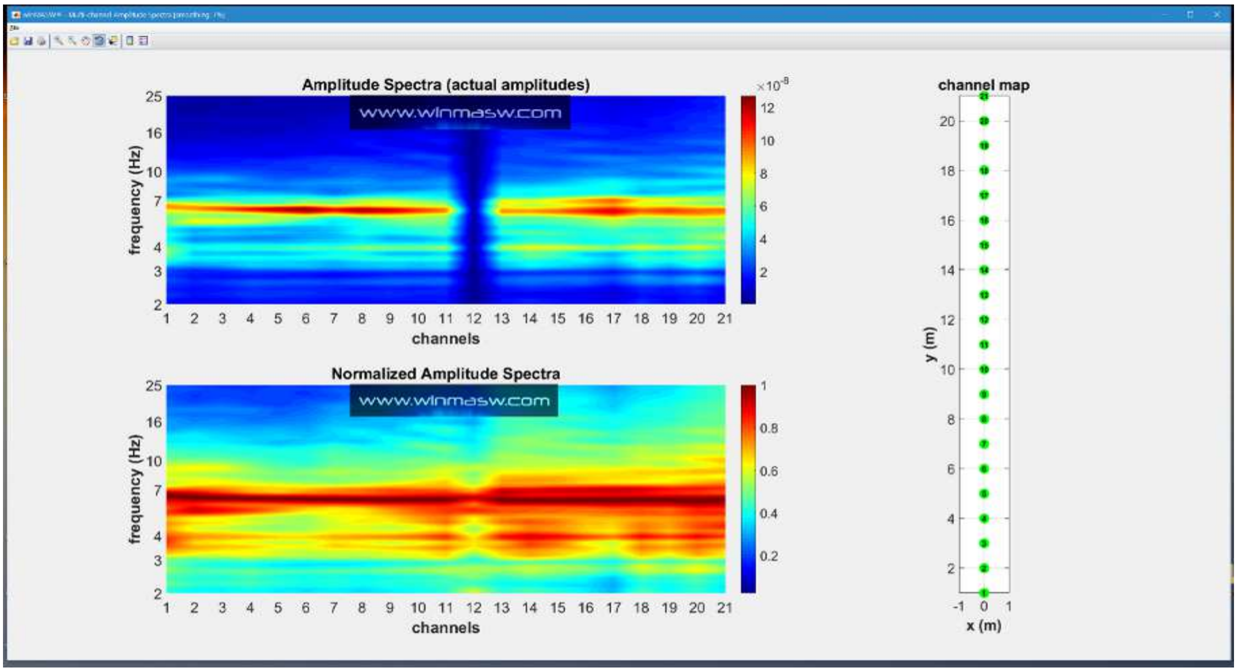
Button "passive: quick ESAC/ReMi/MAAM/HVSR/vibrations"

shown the traces with the actual amplitudes (in the example below there is clearly something wrong with the channel#12)

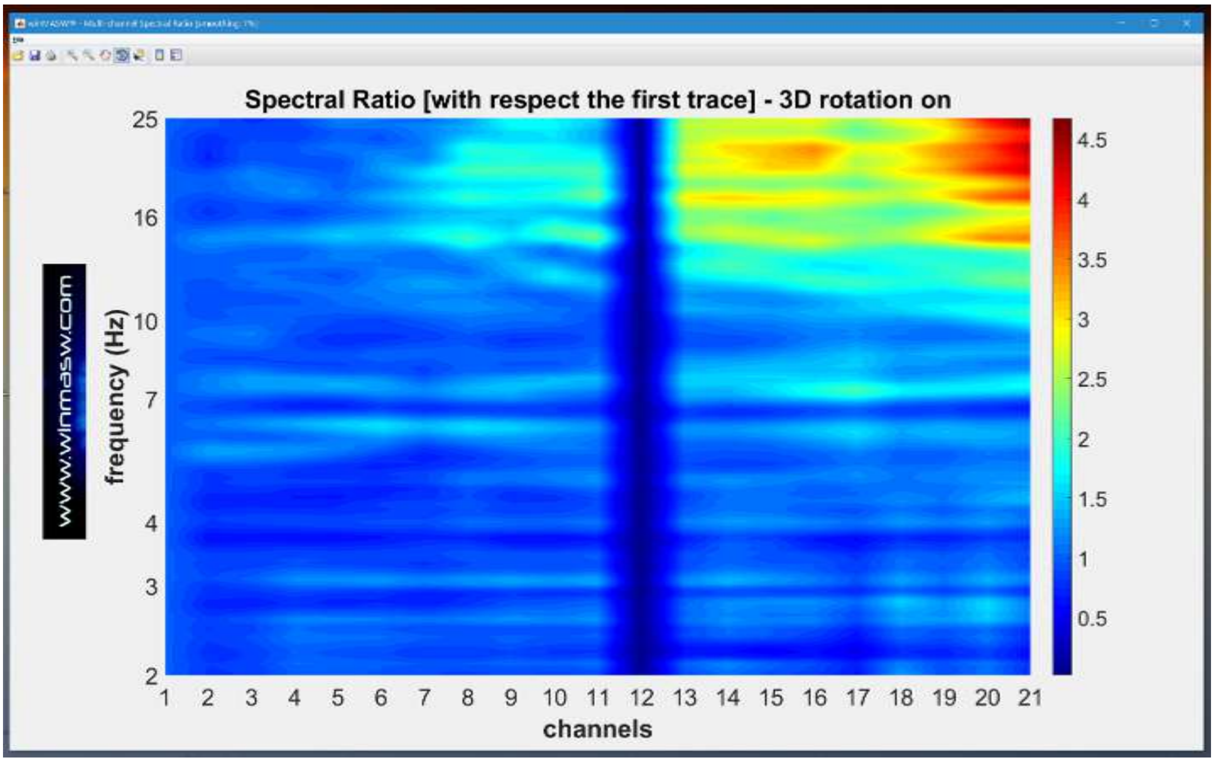




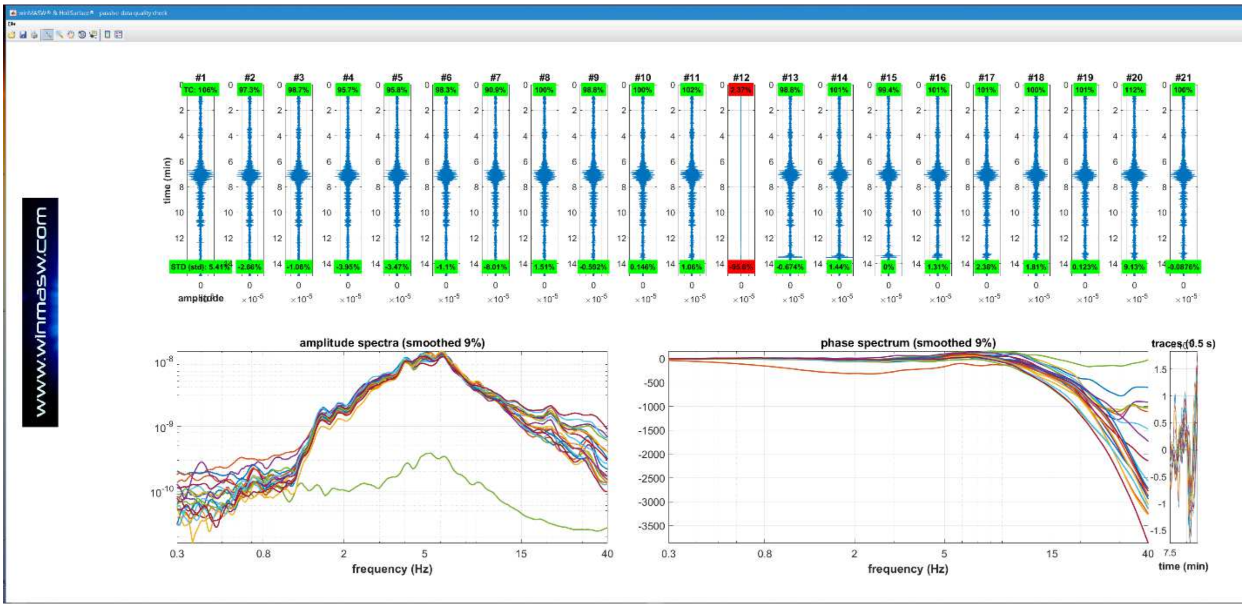
Also shown the amplitude spectra (actual and normalized values – again: the problem with the channel#12 is clear and you need verify the reason on the field: it can be a poorly connected geophone etc.)



A further output is the **Spectral Ratio of each trace with respect to the first trace**.

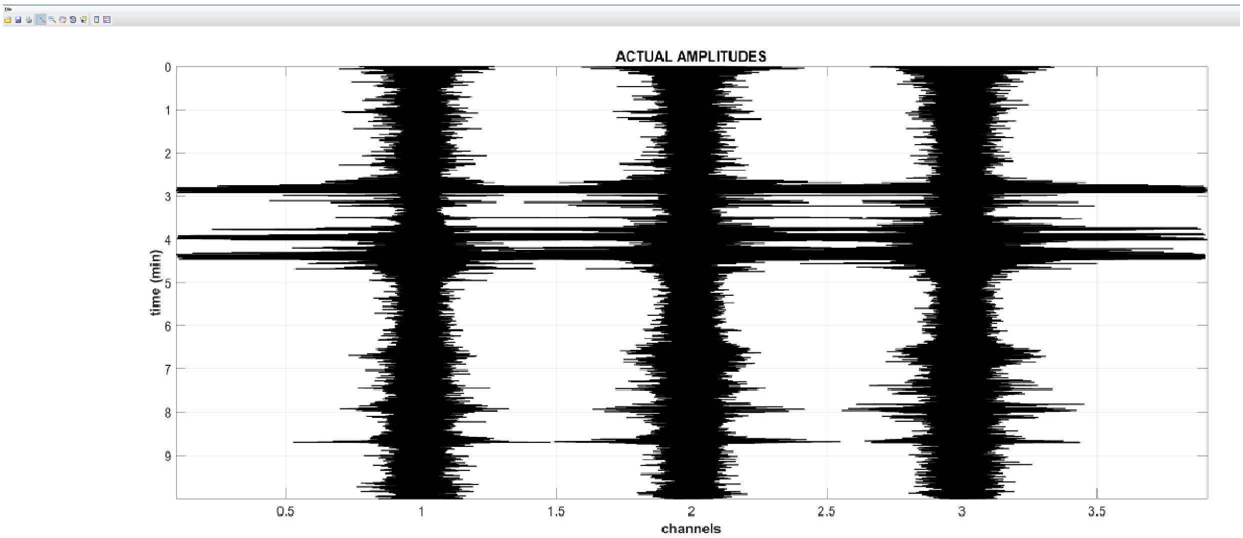


Traces, amplitude and phase spectra of the uploaded traces:
the presence of a bad trace is (again) apparent.

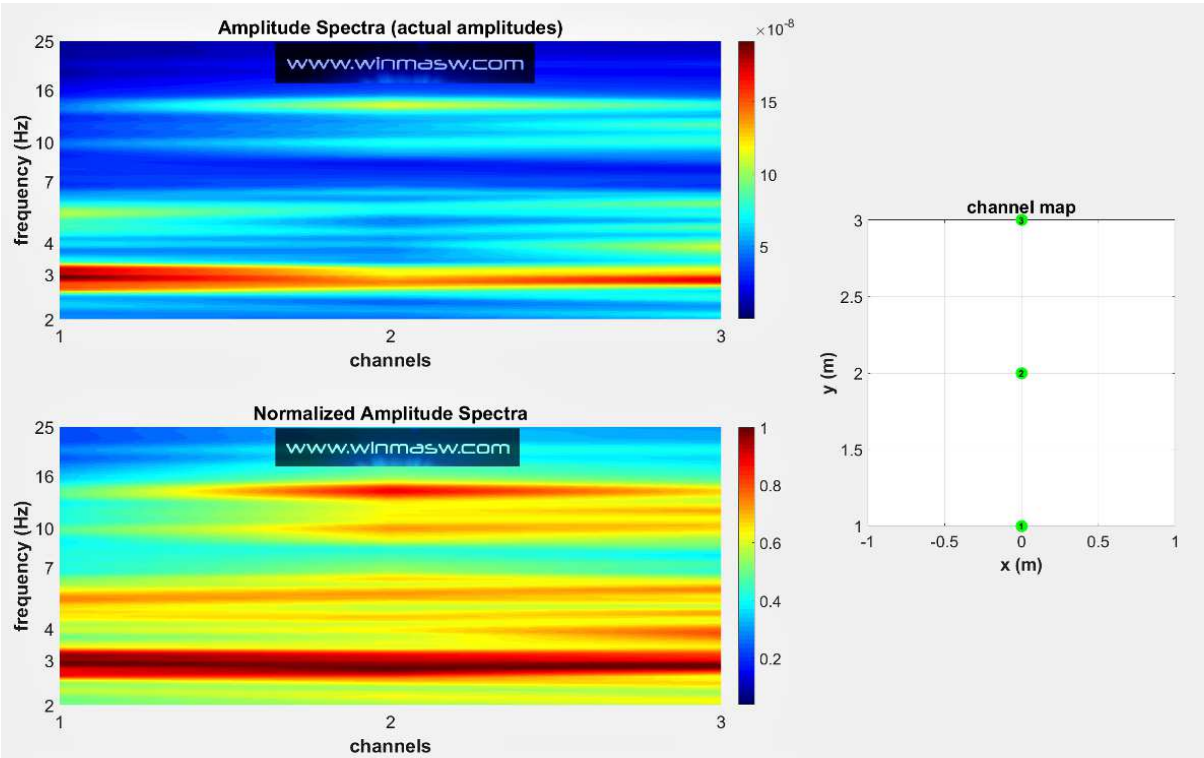


HVSR

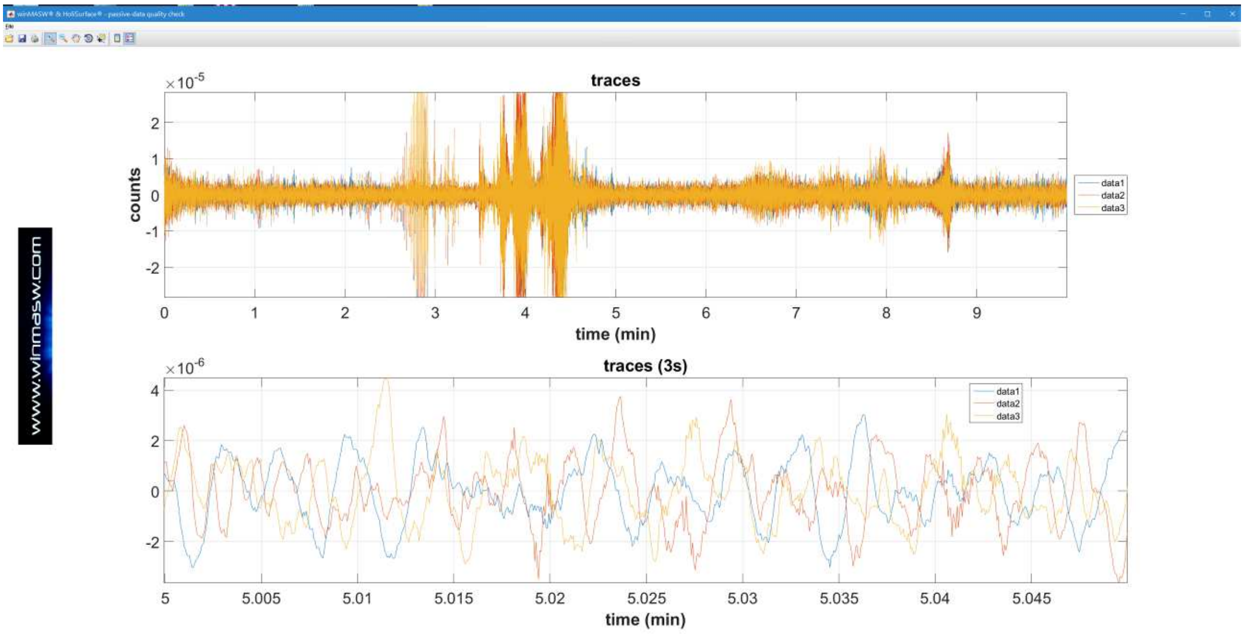
In case the uploaded dataset is composed of just three traces, the software considers the data as microtremor data for the computation of the HVSR and automatically computes and shows the following outputs



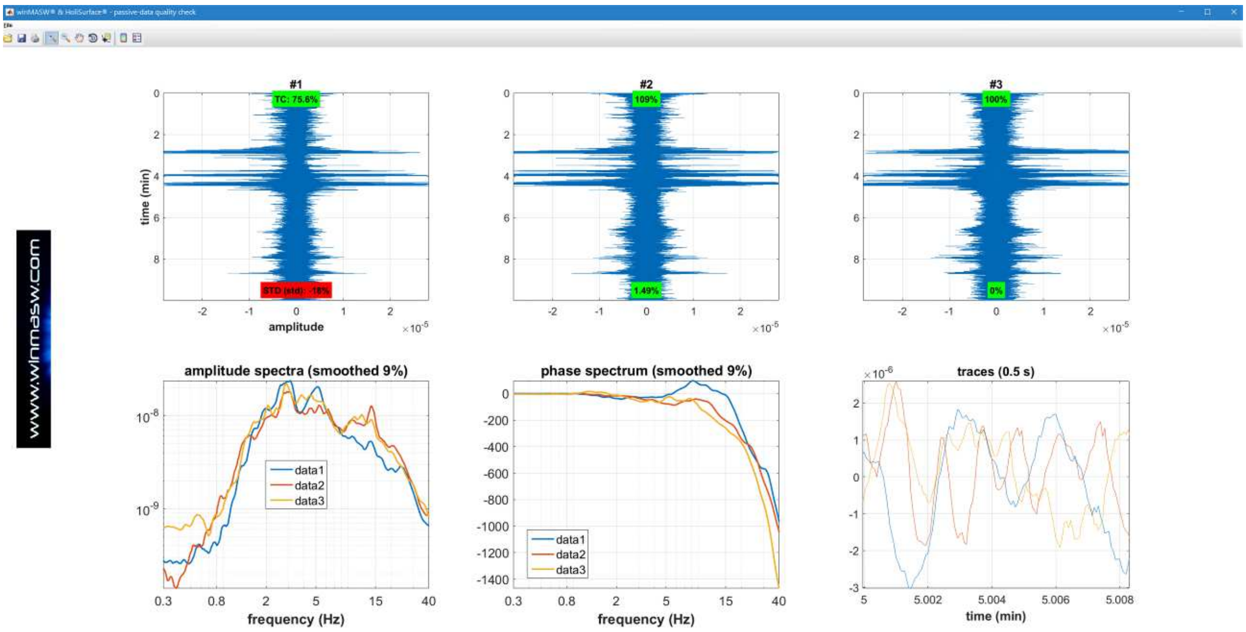
The three uploaded traces (actual amplitudes)



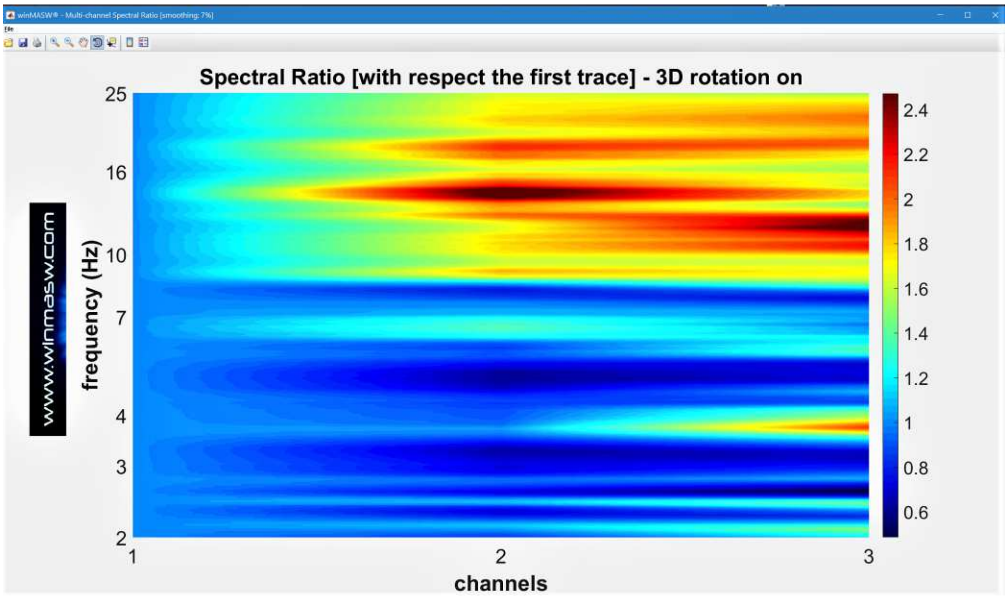
Amplitude spectra of the uploaded traces (actual and normalized amplitudes)



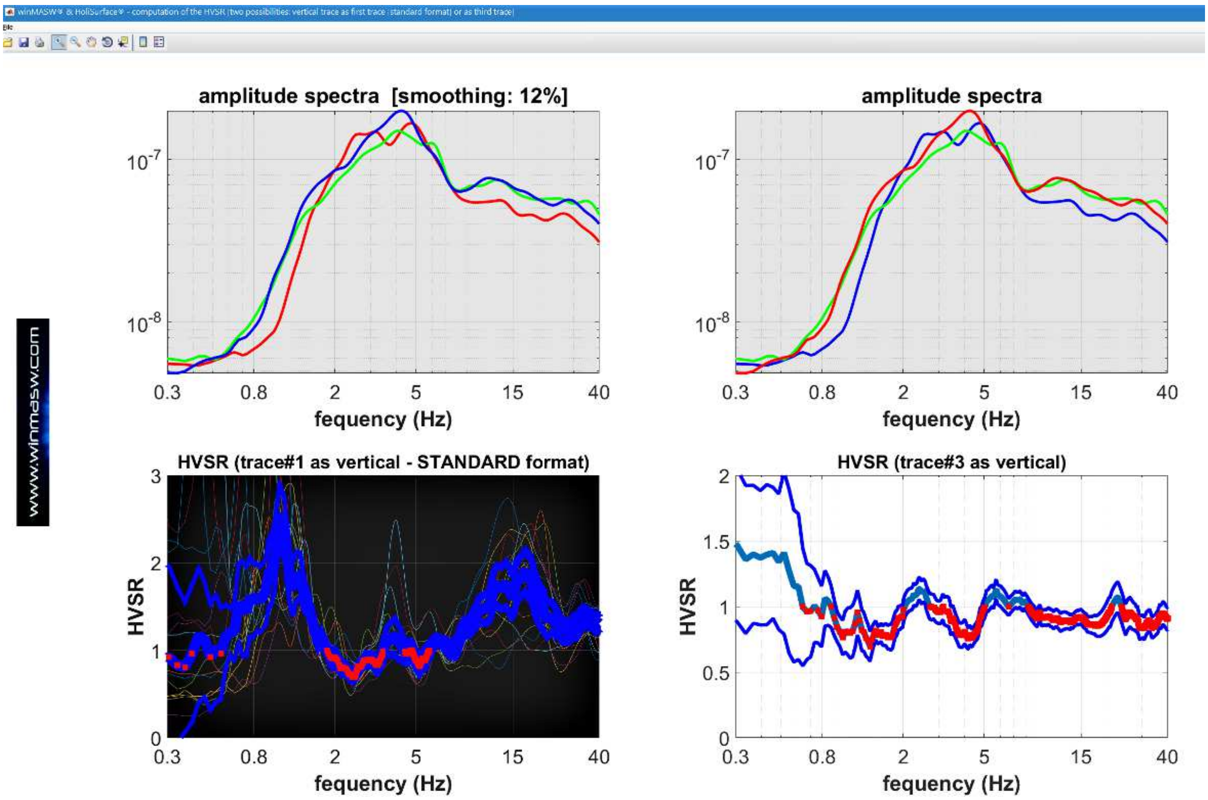
the uploaded traces (in the lower panel a detail/close up)



traces, amplitude and phase spectra of the three traces



Spectral Ratio of each trace with respect to the first trace



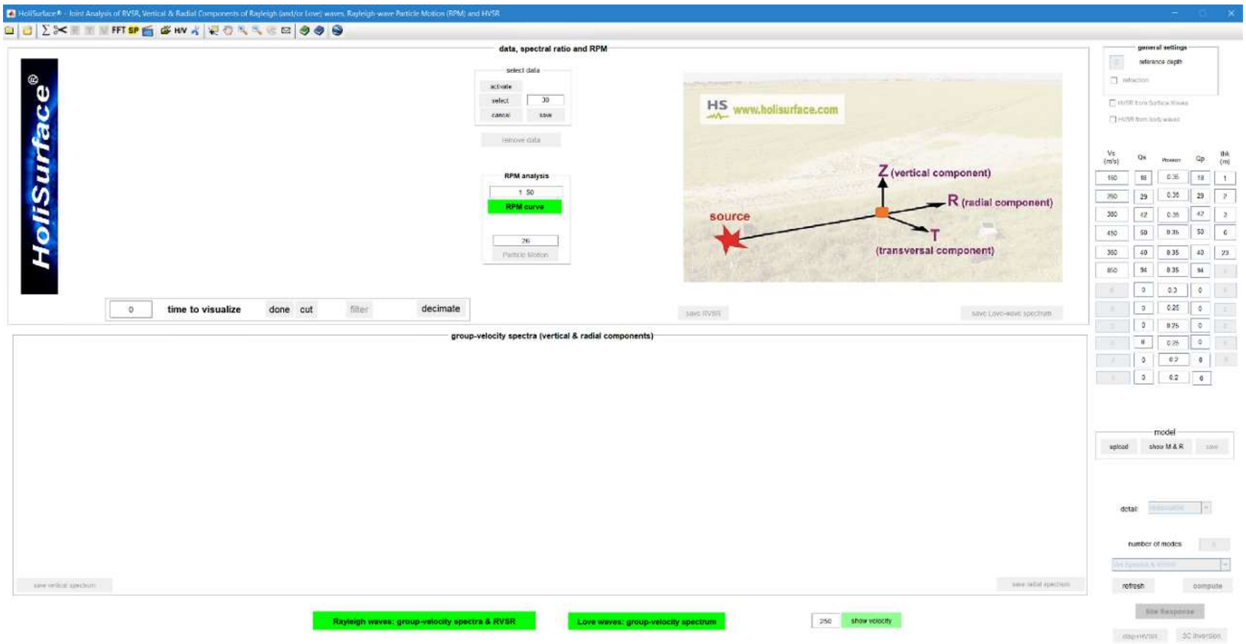
Smootghed (12%) amplitude spectra and HVSR computed considering two possible situations (which depend on the characteristics of your *acquisition system*):

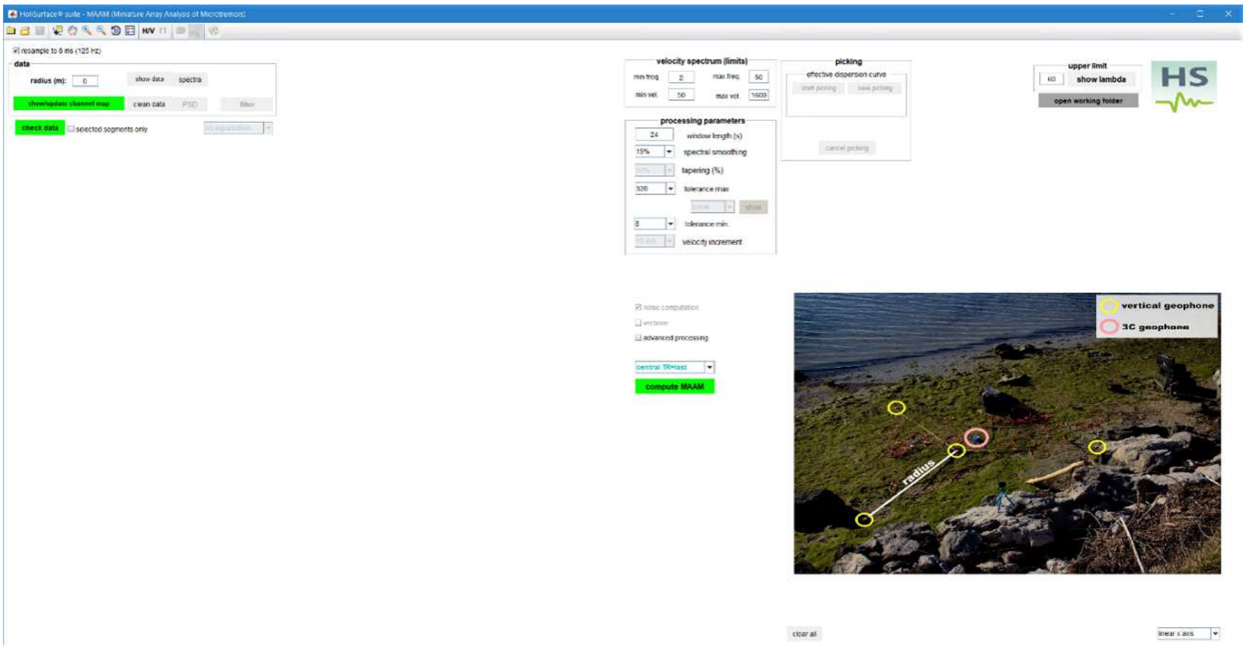
1) **on the left** the results in case the meaning of your traces is vertical, H1 and H2 (i.e. the vertical component is the first trace – standard format);

2) **on the right** the results in case the meaning of your traces is H1, H2 and vertical (i.e. the vertical component is the third trace).

THE "ORDINARY" (SIMPLIFIED) PANELS

In addition to the **QUICK** buttons/analyses, a simplified version of the ordinary panels are available, which allow some more detailed – but anyway simple – data analysis to perform already on the field during the data acquisition (in order to simply the field operations the active buttons are highlighted in **green**).





Appendix W: Setting up the HoliSurface® *acquisition system*

In order to record HS (HoliSurface®), HVSR or vibration data with a single 3-component geophone (HOLI3C):

1) Connect the (female) connector of the HoliSurface seismic cable to the (male) connector of the seismograph (channels 1-12)
2) Connect the HOLI3C geophone to the end of the HoliSurface seismic cable (female connector of the HOLI3C geophone to the male connector at the end of the HoliSurface seismic cable).

See also the following **video tutorial**: https://youtu.be/hqjJvAxL6xQ

Remember that, if you want to record the active data for the HoliSurface [HS] technique, the arrow of the HS sticker [on the HOLI3C geophone] must point the source.

3) Now, launch the acquisition software (that you previously installed) and fix the acquisition parameters suitable and necessary for the acquisition you are going to do (remember that, if you properly connected the HOLI3C geophone [for HS, HVSR or vibration data], you just need to activate the channels 1 2 and 3).

This way, the data file you will obtain will have just three traces: the first trace is the vertical component (Z), the second trace is the radial (R) component (or NS direction), then third trace is the transversal (T) component (or the EW direction).

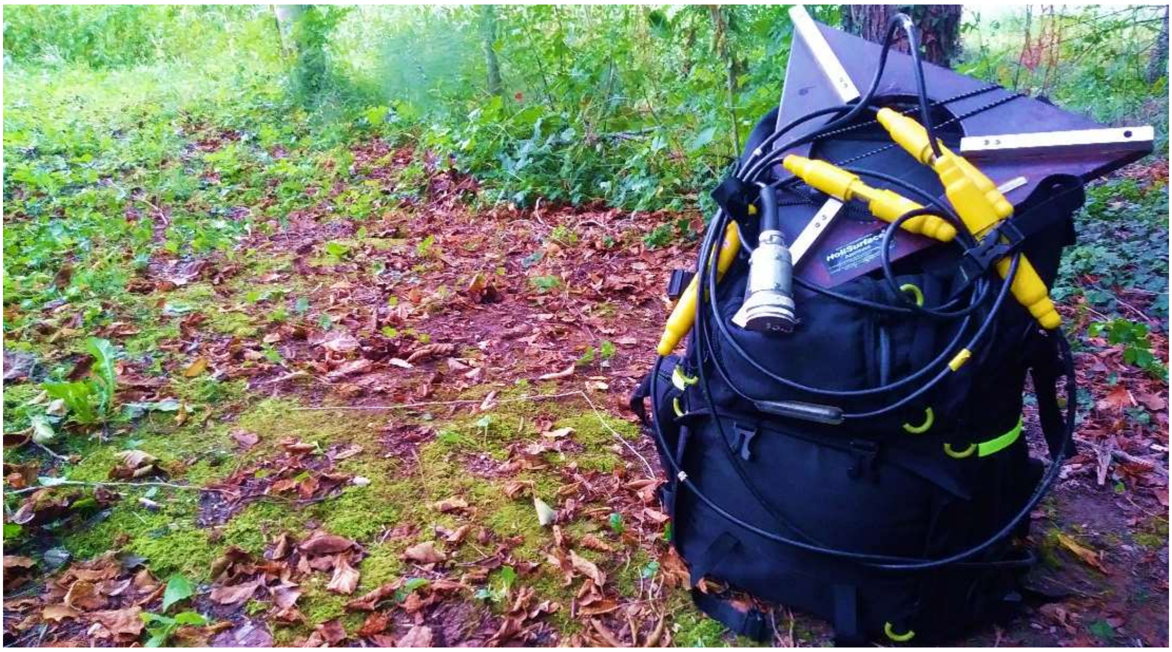
Two short notes

a. in case in just want to record some passive data (for instance to define the HVSR or to record vibration data for a structure/building – please see the "*Efficient Joint Analysis of Surface Waves and Introduction to Vibration Analysis: Beyond the Clichés*" book published for Springer), you can connect the HOLI3C geophone directly to the seismograph (without the HS seismic cable). If you connect it to the 1-12 connector, you need to activate the channels 1 2 and 3 (as we saw before while using the HS seismic cable). The meaning of the obtained traces will be the same: the first, second and third traces will be the Z, R (or NS) and T (or EW) components. On the other side, if you connect the HOLI3C geophone to the 13-24 connector, you need to activate the channels 22, 23 and 24, which (secularly/symmetrically) will be now the T R and Z components, respectively. In other terms, if you connect the HOLI3C geophone to the 13-24 connector, the three traces you will obtain will be: T (first trace), R (second trace) and Z (third/last trace).

b. As a matter of fact, in case we intend to perform an HS acquisition with a limited offset (say 2-4 m) it is possible to connect the HOLI3C geophone directly to the seismograph (without the HS seismic cable). This can be done in case we intend to investigate just the very shallow layers. Please, have a careful look at the following photo/example: the HOLI3C geophone (the blue small case on the left) is connected directly to the seismograph while the source is, together with the trigger geophone on the right (in this case the *offset* is 3.7 m and the joint analysis of the active data together with the HVSR allow to characterize the soil down to about 10-30 m).

How to easily obtain a multi-offset dataset (for *phase* velocity analysis - still often called "MASW)" with our *entry-level acquisition system* (4 single-component geophones + one 3C geophone)

The "basic" **HoliSurface® system** includes the HOLI3C 3-component geophone and 4 single-component geophones (the vertical ones are used for MAAM, but we can also work/provide with horizontal geophones, so to acquire the R and/or T components). Everything is easily packed in a backpack (see picture below).



We connect the HOLI3C geophone to the end of the HoliSurface® seismic cable (see, for example, the introductory video tutorial about the HS acquisition - **https://youtu.be/hqjJvAxL6xQ**) and the 4 single-component geophones (in this case the vertical ones) to 4 channels of the same seismic cable, as in the scheme shown below (for the adopted nomenclature, see our Springer and Elsevier books – ***dx*** is the geophone spacing and ***mo*** the minimum offset).
The HoliSurface® seismic cable is then connected to 1-12 block of the seismograph.

Note: if we are using a **9-channel *HoliSurface*® seismic case** and we connect the HOLI3C to its final connector, we can connect the single-component geophone to any/all of the 9 channels along the cable.
On the other hand, if we are using a **12-channel *HoliSurface*® cable** and have connect the HOLI3C geophone, the first three channels of the cable cannot be used since the signals from the 3C geophone travels along the first three channels (in this case channels/connectors 4 to 12 will be available, but not the first 3).

If we carry out only the first of the two acquisitions represented in the scheme below reported, we obtain a dataset with 7 traces [the 4 single-component geophones + the 3 traces of the HOLI3C geophone referring to the Z, R and T components].
If we then move the source away by a length equal to dx/2, we obtain a second dataset with similar characteristics but with different offsets/distances.
Let us imagine that we have 4 vertical geophones (the same ones used for the MAAM).

In the example shown below, the geophone distance (**dx**) and the minimum offset (**mo**) of the first datasets are both set equal to 7 m, while for the second acquisition the source is moved to 10.5 m from the first geophone (**mo** = 10.5 m). This value is simply the summation of the previous **mo** value (7 m) + half the geophone distance (7/2 = 3.5).

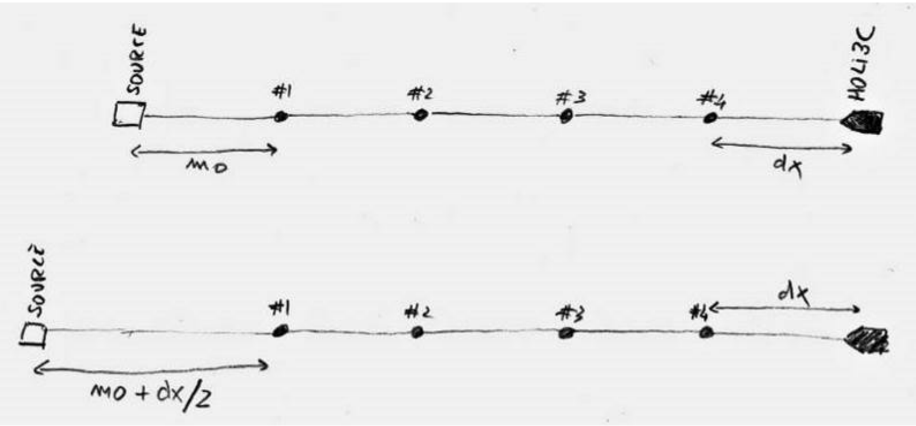
Removing the "wrong" traces

Now, in winMASW® Academy, from the *single-component analysis* panel, we upload the first dataset (where **mo** = 7 m). In order to obtain a homogeneous dataset (remember that now it also contains the R and T traces of the HOLI3C geophone), we have to remove the R and T traces of the 3-component geophone (HOLI3C). If we have recorded the data correctly, the second and third traces have to be removed. The first traces refers to the Z component of the HOLI3C 3-component geophone and must be kept (since along the cable we connected 4 vertical-component geophones). To remove these traces click the "**zeros/flips/remove**" button and follow the procedure aimed at removing the second and third trace.

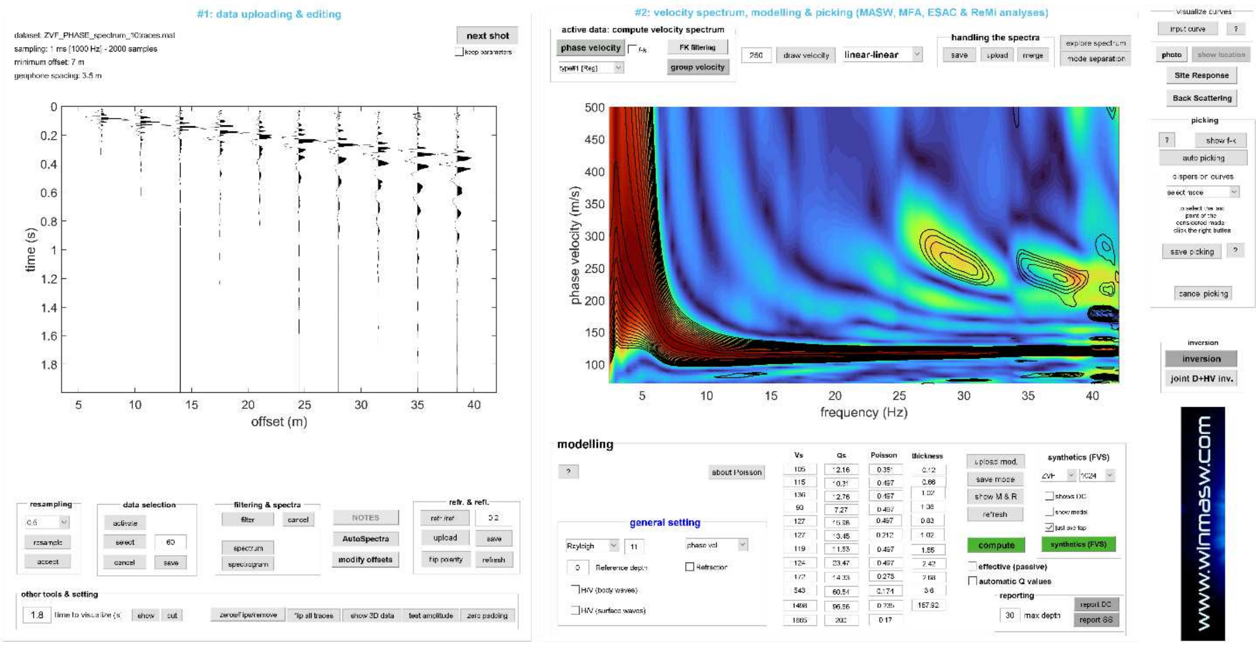
Modifying the offsets

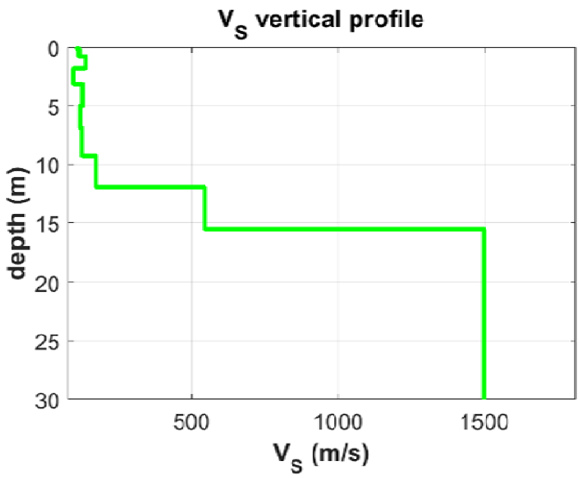
Having removed 2 traces, we must now modify the offsets by entering the correct values ("**modify offset**" button). Once we do it, we obtain a proper 5-trace dataset (referring to the same component) with the correct offsets.

If the array is not particularly long and we are not too interested in high frequencies, a 5-traces dataset may be sufficient (*spatial aliasing* is not a big issue - see e.g. Dal Moro et al., 2003) but if we want to double the number of traces (halving the geophone distance), we must also have recorded the second dataset (see image below) and perform the same operations described above for the first dataset.
At this point we have two 5-trace datasets (in this case all the trace refer to the Z component but we usually recommend to work with the T component, i.e. Love waves) that we can assemble together with the "**combine 2 datasets**" tool available among the winMASW® utilities.



In the following, an example of the 10-trace dataset obtained following this procedure (the dataset is analysed according to the FVS technique – see black contour lines that refer to the V_S model shown below and match very well the field phase-velocity spectrum [colours in background]).



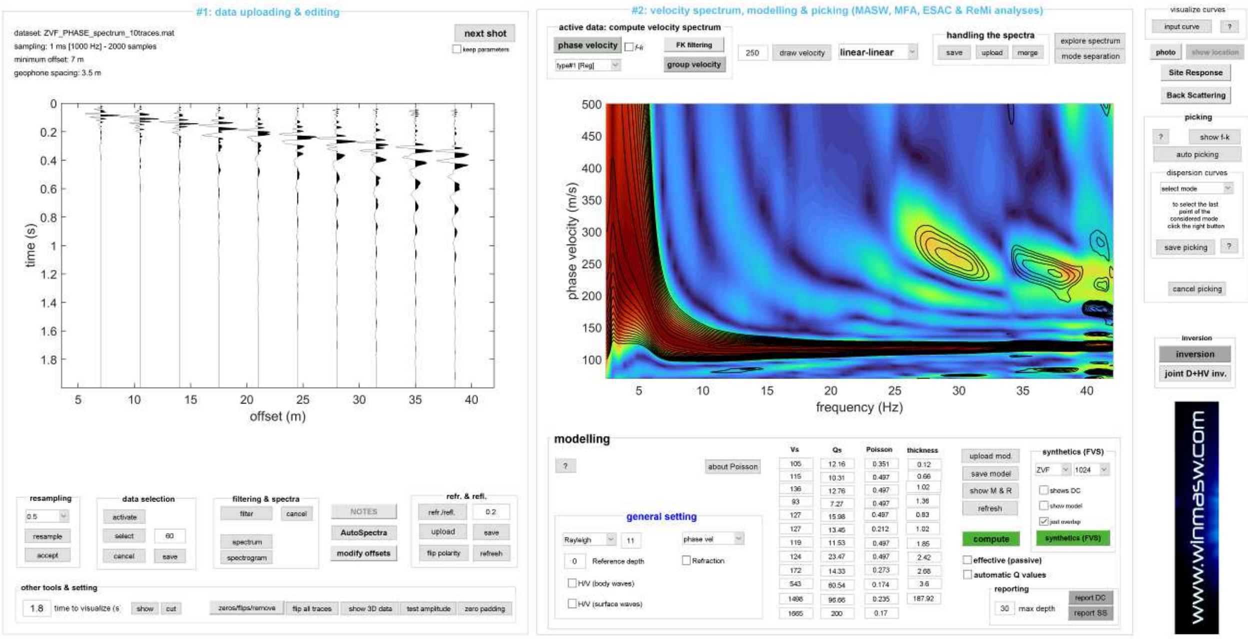


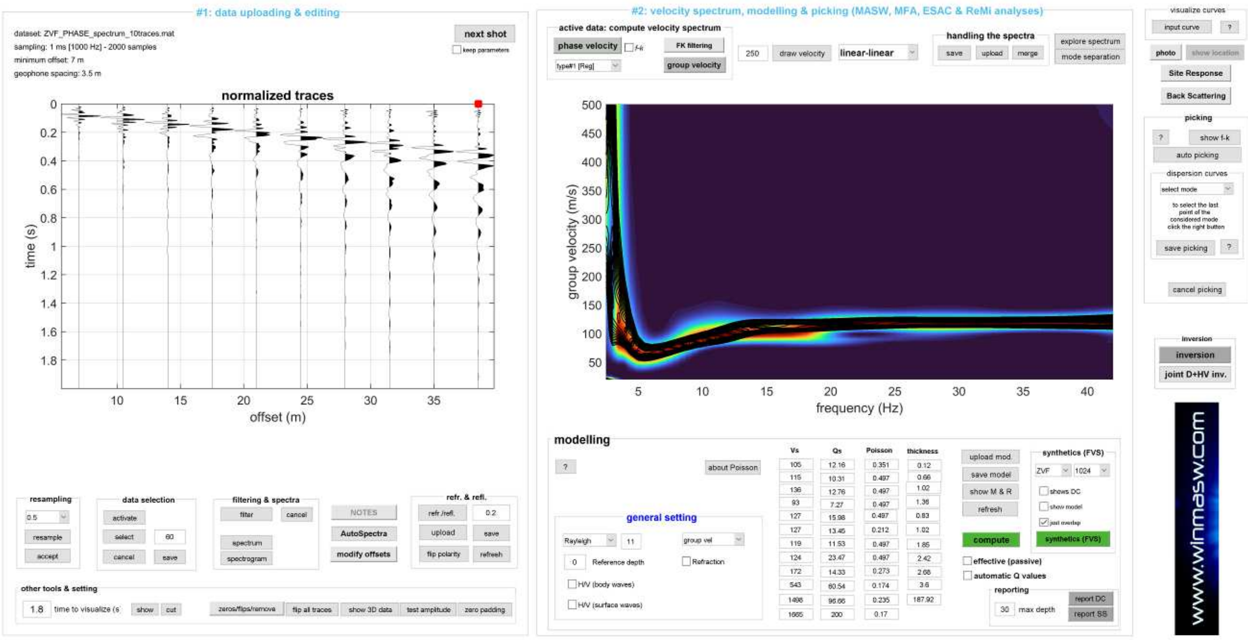
It is important to remember that for the **analysis of phase velocities ("MASW") it is often recommended to use horizontal geophones which allow working with Love waves (as well as the radial component of Rayleigh waves).**
The procedure is the same, with the only difference that if we were working with the T (transversal) component, the traces referred to the HOLI3C geophone to be eliminated would not be the second and third (as in the previous example) but the first and second (which, if the acquisition is performed according to the scheme we recommend, are the Z and R components respectively).

The bottom-line point

Of course, the question that should be answered is always the same: **why working with multi-offset data** (necessary for the determination of ***phase*** velocities) **when the same results can be obtained with the *group* velocities** (which can be computed using a single trace)**?**

Here is the **FVS analysis of the *phase* velocities** (**above**) computed considering all the available **10 traces** and the **FVS analysis of the group velocities** (**below**) computed considering **ONLY the last trace** (see red square at the last trace). The **subsurface model is the same.**



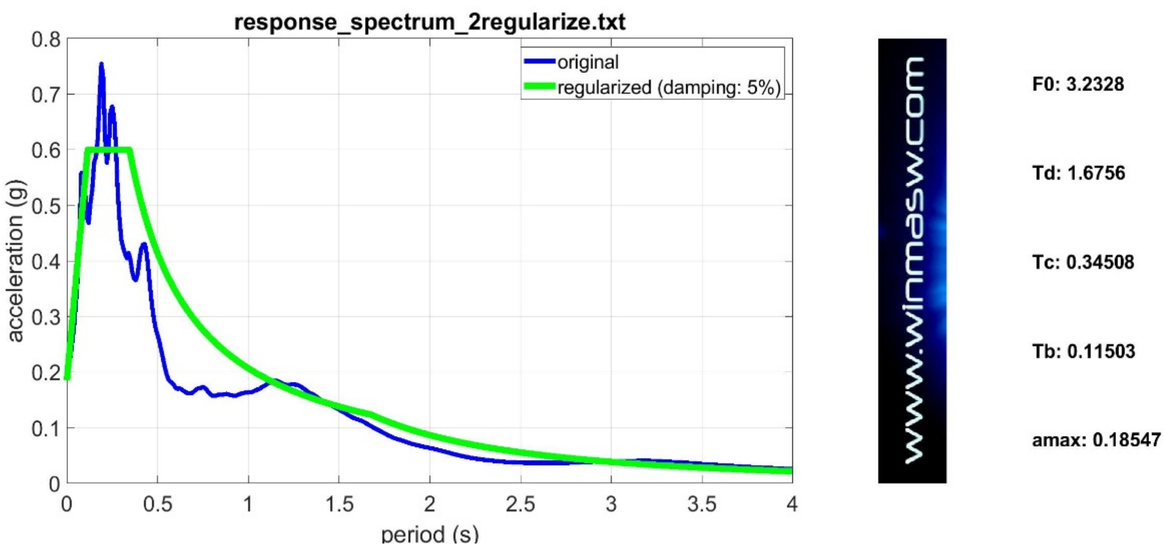


The answer to the bottom-line question cannot therefore be found by following logic and technical-scientific evidences, also considering that a professional/company is not paid to "perform a MASW" but to determine V_S values (following the most appropriate method according to the site and objectives – and there are really several possible methods [see the manual of the HoliSurface® software application]).

Appendix X: utility for the regularization of a response spectrum

The regularization of a response spectrum is a questionable operation since it modifies the result of a simulation aimed at representing the real conditions (represented by the actual V_S profile and the input quakes). Spectra regularization (carried out according to the procedures indicated in the *Seismic Site Response* section of this manual) can be applied to any response spectrum saved in a simple ASCII file like the one shown here:

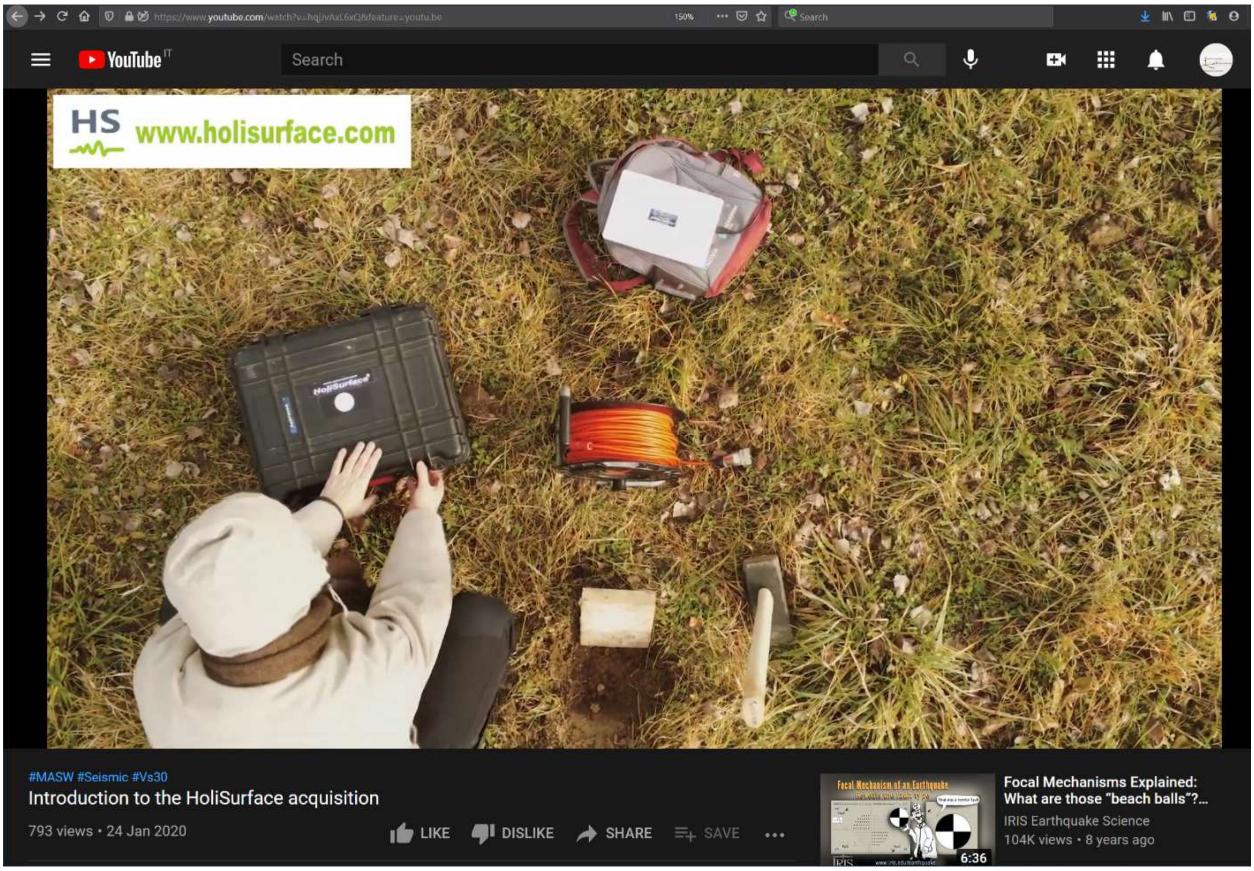
The first column reports the **period (T) in seconds** and the second column the **Accelerations (in units of g)**. When you upload this kind of file in the "**response spectrum regularization**" utility, the software will ask you how many *header lines* are present in your file (in this case there are two) and then what damping value (%) to use (it must be the same as the one used for the computation of the original response spectrum). As usual, the image and ASCII file you will obtain are automatically saved in the working folder (image and regularized curve in an ASCII file having the same format as the one above considered).



Appendix Z: the HoliSurface® technique in winMASW® Academy?

manual in progress

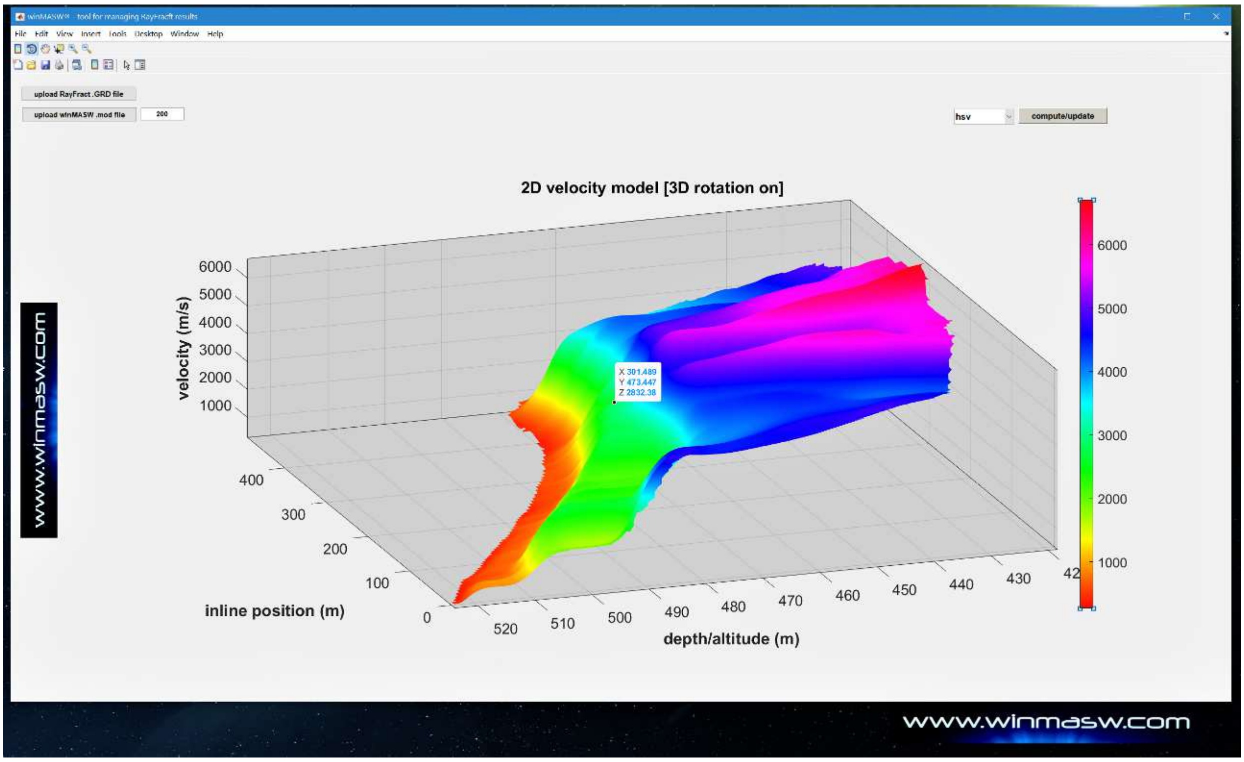
Remember that surface waves can be recorded and analyzed according to very simple procedures: **https://youtu.be/hqjJvAxL6xQ**

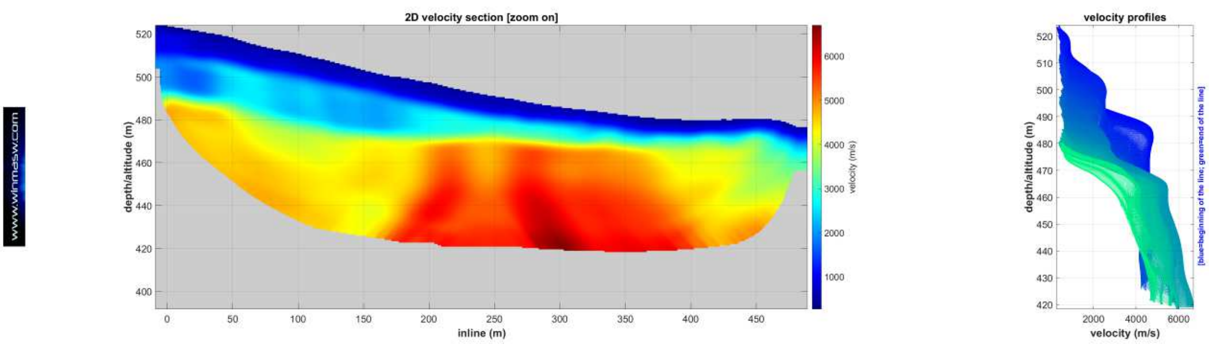


Appendix Zbis: managing files/results obtained via *RayFract*

Among the new *utilities* in *winMASW® Academy* you can also find the "**manage RayFract files"** tool. You can use it to upload and visualize the GRD files obtained with *RayFract* (a software for the refraction tomography that we distribute).

manual in progress
(here just few snapshots)





Troubleshooting and support

Any software can inevitably have some issues often due to the application of procedures different from those designed by the programmers.

Before contacting us, please carefully read this section of the manual

Please, report any other problems to winmasw@winmasw.com always indicating:

1) **the User ID (UID) and Serial Number (SN) of your USB dongle**
2) **your release (e.g., winMASW Academy 2021)**
3) **the operating system of your computer (e.g. Windows 10 – 64 bit)**

Both the error and the situation in which the error occurs **must** be **clearly** described:

4) **Always include the snapshot of the black (background) DOS window at the time of the error**

Some problems originate from the invasive influence of some **Antivirus software**

In those cases, before worrying try to disable your antivirus (or to add ELIOVSP to the software that the antivirus should trust and ignore).

Consider installing the AVG anti-virus (free and more discreet/reliable than many others).

Some important notes

1. Many problems are related to the operating system (remember that *winMASW®* and *HoliSurface®* and ELIOVSP only work on 64bit operating systems - we strongly recommend windows-10 and advise against windows-7 [which badly manages certain system privileges]).

2. Update often your operating system ("windows update")

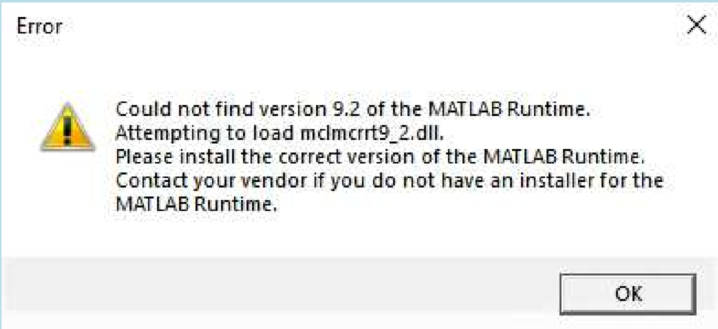
3. Some anti-virus software (currently with **AVAST, AVIRA, PANDA, Trend Micro Internet Security and Eset Nod32** - which we strongly advise against) may not be able to understand that the hardware protection system used for *winMASW®* and *HoliSurface®* is not a virus. The installer should be able to instruct the antivirus to ignore the contents of a certain installation folder. If you are not able to do so, we recommend a "smarter" anti-virus (e.g. AVG)

4. Pay attention to keep your PC in order with frequent cleaning and optimization operations possible with different software (for example Glary Utilities). A computer is a highly complex machine that must be taken care of (a *Desktop* with dozens of files and folders are usually the first evidence of dangerous deficiencies in this sense).

In the following few possible problems that can be easily solved by the user

First possible problem

If, when launching the software, you get an error window with a message similar to the one shown in the following window (the MATLAB Runtime version number changes over the years), the problem lies in the incorrect software installation; in particular, the Matlab libraries have not been (correctly) installed.
We recommend you to carefully read the "README.PDF" file available in the software DVD/USB and carefully follow the simple instructions (and check that the installation process is fully and properly carried out).



Error "**Undefined function or variable 'matlabrc'**"
(visible at program launch on the DOS window).

Solution:

1) activate (in your Operating System) the display of hidden folders and files (the procedure can be easily found on the internet);

2) manually delete the "temporary" folder of the *Matlab Runtime Compiler*.

Go to the folder *C:\Users [username]\AppData\Local\Temp[username]\mcrCache[version]* and erase it.

3) re-install the file *MCRinstaller.exe* in the "*prewinMASW*" folder of the *winMASW* installation CD (i.e., simply run the executable *MCRinstaller.exe*).

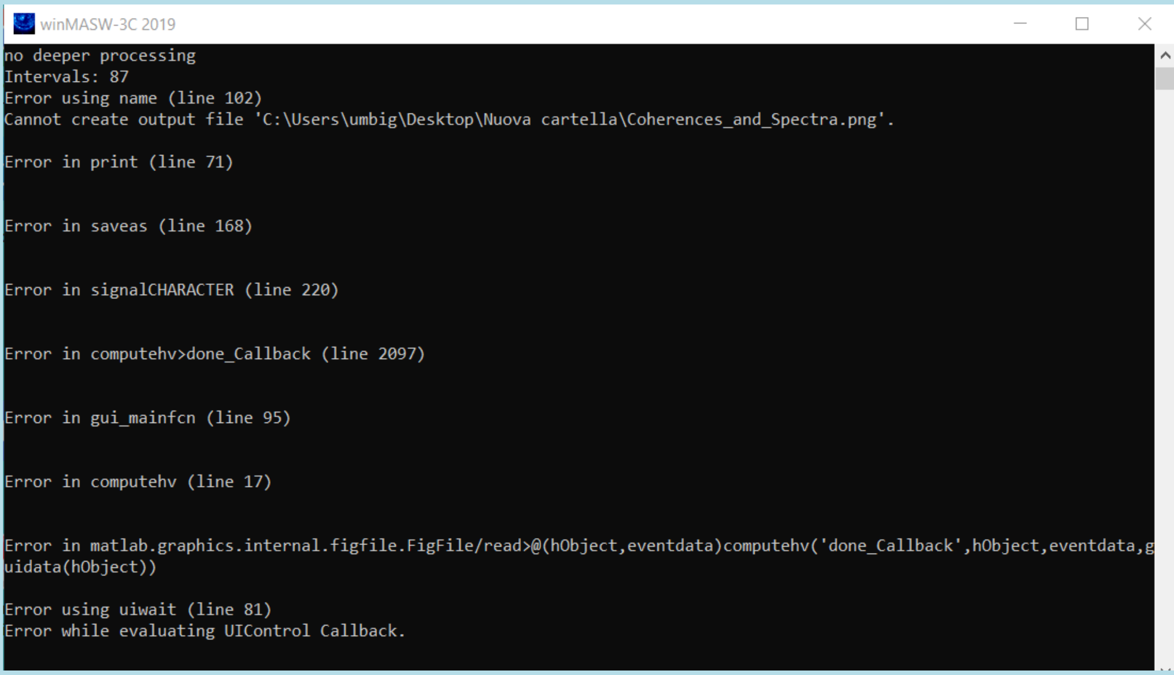
At this point everything should be fixed and you can try to run your *winMASW®*.

Error "**Starting parallel pool (parpool) using the 'local' profile** ... Error using parpool (line 103) **Not enough input arguments**.

or

Error "**Cannot create output file**" (or similar)

(visible at program launch on the DOS window).



Solution:

- *search* for the sub-folder "MathWorks" in the folder "users" (or "C:/users") and delete it. Attention, it is not a "C:/user/MathWorks" folder, it is a folder inside one of the "C:/user" folder, so search for "MathWorks".

- do the same for the *mcrCache* folder (always within the folder in C:/users). In some cases / systems, depending on your software release, the folder may also be called (for example) mcrCache9.2.
In some cases this folder is more easily identifiable with a search from C:/ (and not from the sub-folder C:/*users*). For example, you will find the folder "C:\Users\John\AppData\Local\Temp\John\mcrCache9.2", which must be deleted.
At this point everything should be fixed and you can try to launch ELIOVSP (*HoliSurface®* or *winMASW®*).

- if this does not work, re-install the *MCRinstaller.exe* file in the *"preELIOVSP"* folder on the *ELIOVSP* installation DVD (i.e., simply run the MCRinstaller.exe executable).

REMOTE SESSIONS

In case it is necessary a solution from ELIOSOFT, we can arrange a remote session via **AnyDesk**.

AnyDesk

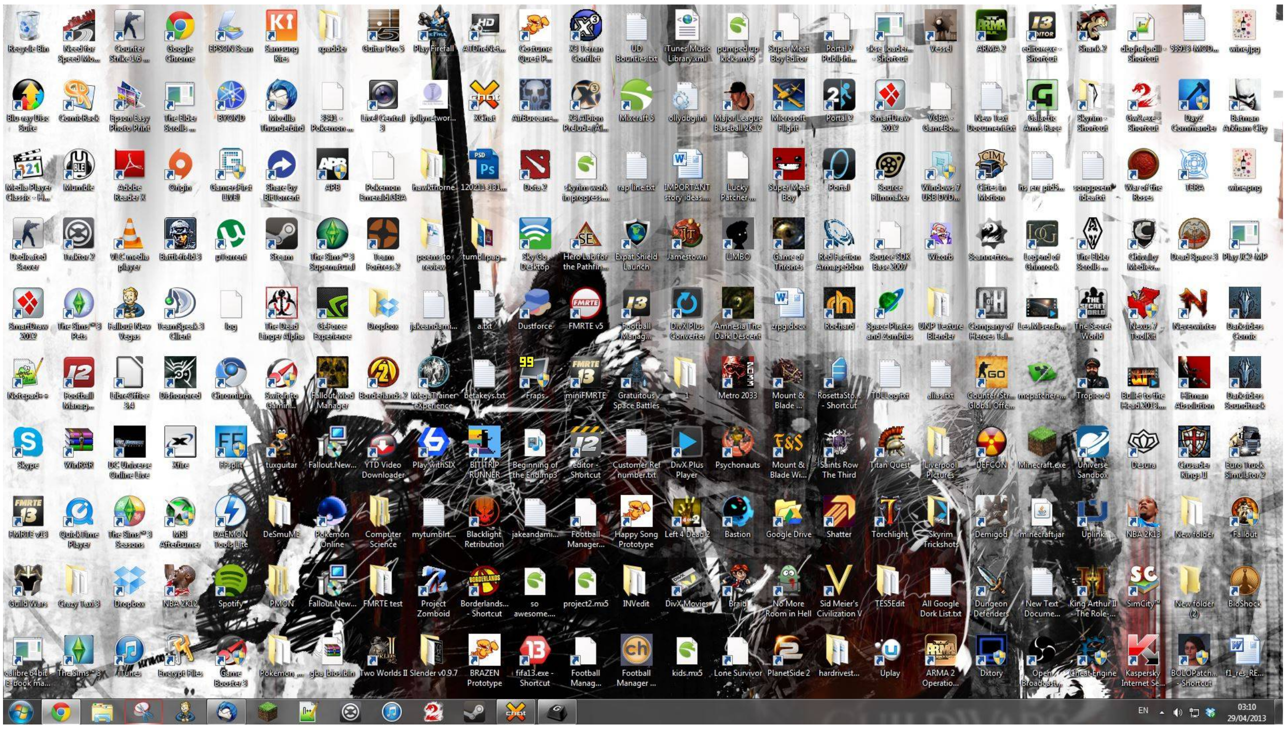
In that case:

1) download and install the **Anydesk** software (https://anydesk.com) and provide us with your ID (identification number of your PC)
2) send to winmasw@winmasw.com an appointment request for a remote session [it is important to be on time and carefully follow the provided instructions].

What is **AnyDesk**? You can have a look for instance here: https://www.youtube.com/watch?v=g3W1nBbtqEE

MESSY DESKTOPS → NO ASSISTANCE

In case your *Desktop* looks like the one in the following snapshot, we cannot provide any assistance. A computer is a sophisticated tool that requires care and awareness. We are all professionals and the hardware and software tools we use for our daily work need to be properly managed and maintained.



You record, we analyze: processing your data

Multi-component MASW (phase velocities) and MFA and *HoliSurface* (group velocities) [Rayleigh & Love], *ReMi, ESAC/SPAC, MAAM and HVSR* data

If you send us your data for **MASW/ReMi/ESAC/SPAC/MAAM/HoliSurface and HVSR analyses**, **please remember to provide us the necessary information about the data (geophone distance *dx*, minimum offset *mo*, etc).**

The best way to do that is to use the file naming described in the **Elsevier book** (see **paragraph 2.2**)

If you recorded your data for passive analyses (ESAC/SPAC/ReMi/HVSR/MAAM), please indicate the orientation of the array with respect to main noise sources such as streets, industrial facilities etc.

It is also necessary to provide us with some **information about the stratigraphy.**

Please, also provide us with a photo with the GPS coordinates of the site.
If you use your smartphone and the App ***MapCam*** or *GPS Map Camera*], the GPS information (Latitude, Longitude, Altitude) is automatically reported in the output report.

MapCam **GPS Map Camera** **Action cameras** **Drones**

Please, keep in mind that:

if you want to have a reliable V_S profile we strongly recommend you the acquisition and analysis of three *observables*:

Rayleigh waves + Love waves + HVSR

Therefore, we usually expect 4 seismic files (let's imagine *dx* is 4 m and *mo* is 8 m):

- RVF_dx4_mo8 (for the radial component of Rayleigh waves)
- THF_dx4_mo8 (for the transversal component,. i.e. Love waves)
- HVSR_central [3C passive data in the middle of the array]
- HVSR_EndArray [passive data in another point along the array, e.g. at the end of it]

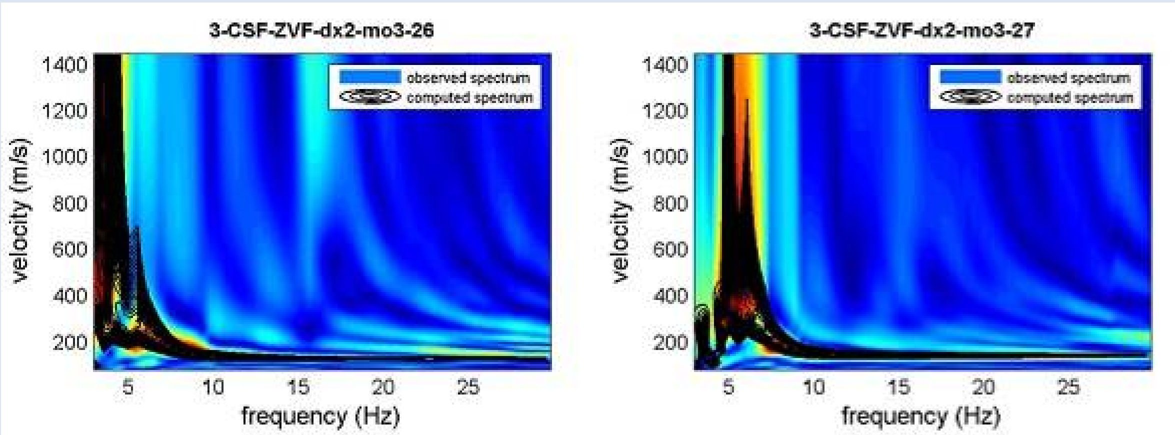
To keep it simple: it is often **impossible** to obtain the correct V_S profile through the analysis of the data recorded using (**just) vertical geophones** and the *interpretation* of the **modal dispersion curve(s)** (this is the standard approach that, unfortunately, some fellows still consider *the* MASW technique).

ADAM-2D

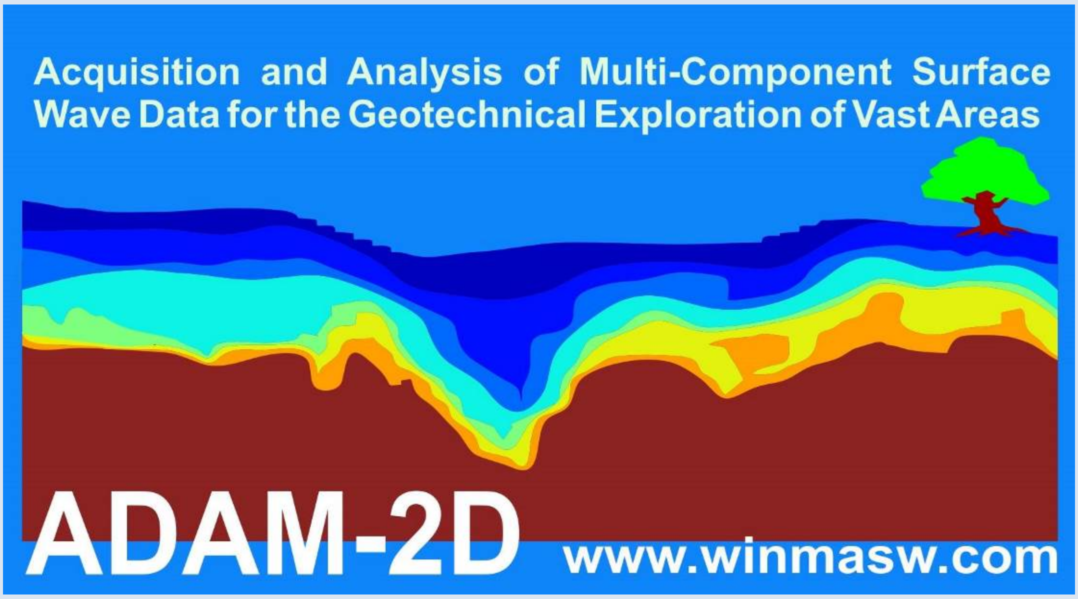
Apparent Dispersion Analysis of Multi-component Data - 2D

Acquisition and processing of multi-component data for the characterization of vast (2D) areas [see the "The ADAM-2D data processing service we offer" section of this manual]

Thanks to the opportunities which originated from the synergies with some European partner companies and our procedures based on multi-component FVS (*Full Velocity Spectrum* - Dal Moro et al., 2014) approach, we are now capable of acquiring and/or processing (multi-component) data aimed at characterizing large areas (2D and 3D) from the geotechnical point of view.



Observed and processed velocity spectra analyzed according to the procedure described for instance in Dal Moro et al, 2014 and Dal Moro et al., 2018).



Two versions of the 3-component geophone we provide: one with a Cannon (NK27) connector (on the left), the other with three connectors (on the right).

MASW and refraction/reflection geophones: commercial legends

Sometimes they propose you two sets of (vertical) geophones: the 4.5 Hz set for the so-called MASW and the 10 or 14 Hz for the refraction/reflection data.
Of course, if you know the fundamentals of seismics, you should understand by yourself that this is totally meaningless (so a huge waste of money) and that you actually just need the 4.5 Hz geophones.

Why?

For at least two very obvious reasons:

1. 4.5 Hz geophones "include everything" above a certain frequency (say above more or less 2 Hz - below that frequency the amplitude is normally too low). Low frequencies are necessary for analyzing the surface wave propagation (MASW/ReMi/ESAC/SPAC etc.)... but they say that for refraction studies you need to "focus" only on the high frequencies (say between 10 and 200 Hz - above that frequency the information is completely irrelevant for us).

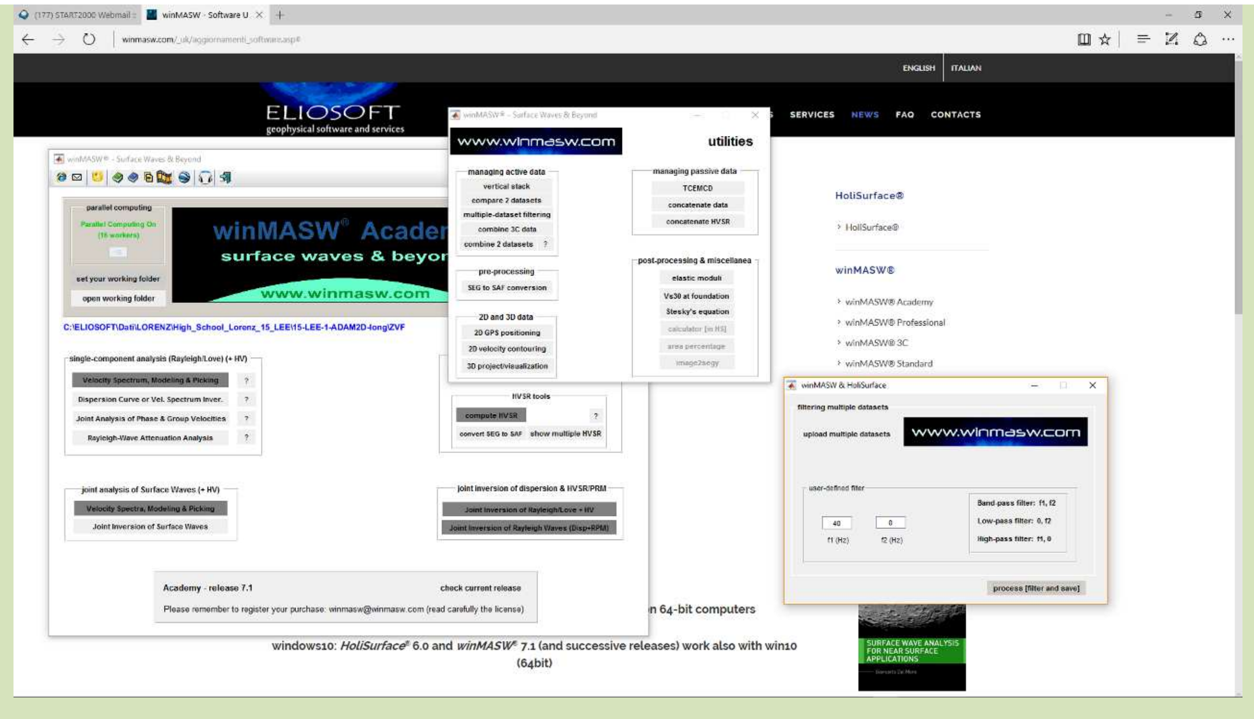
Well, if you acquire a dataset with your 4.5 Hz geophones, you can very easily remove the low frequencies with a simple high-pass filter. This way you can use the same data both for MASW (using the low frequencies) and, by removing the low frequencies with a simple click of the filter tool in *winMASW®*, for refraction/reflection studies.

2. But is it really necessary removing the low frequencies for analyzing the refracted events?!
Actually if you just focus on the very basic principles of refraction studies, you will easily understand that this is not even necessary.
Just consider the vertical component (so the Rayleigh waves and the P-wave refraction): Rayleigh waves are much slower than the refracted P waves (not by chance what you pick in a refraction study are the so called *first arrivals*). This means that Rayleigh waves arrive much later with respect to the first arrivals related to the P-wave refraction.
So, if you carefully analyze a dataset acquired using 4.5 Hz geophones you will see first the P-wave refraction and then (much later) the arrival of the Rayleigh waves. So there's no so-to-speak "interference" or problems in having (in the same dataset) both refractions and Rayleigh waves (things are actually different if you want to analyze the reflections, but in that case a simple high-pass filter will be enough).

So, save your money to buy a set of horizontal 4.5 Hz geophones for acquiring Love waves and the radial component of Rayleigh waves (and of course for SH-wave refraction/reflection studies)!

And always ask the polarity of the geophones (some techniques require to know it)!

winMASW® Academy has a tool for uploading and filter a series of datasets at once.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Rayleigh-Wave Attenuation Analysis
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Academy - release 7.1
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Low-pass filter: 0, f2
High-pass filter: f1, 0
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windows10: HoliSurface® 6.0 and winMASW® 7.1 (and successive releases) work also with win10 (64bit)
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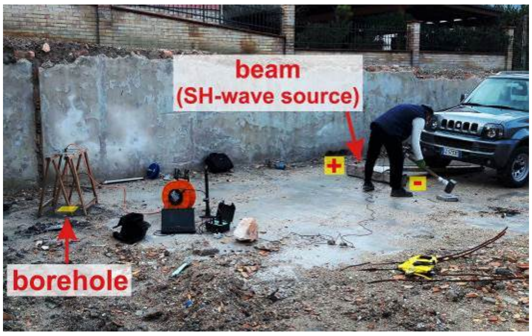
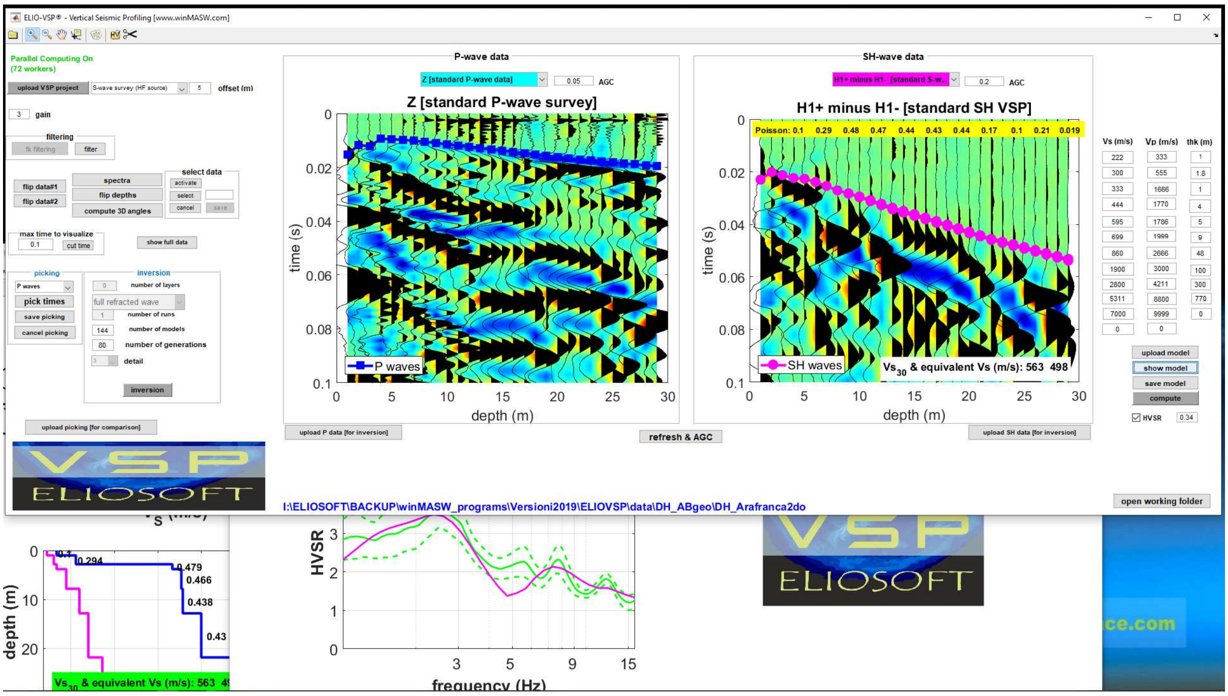
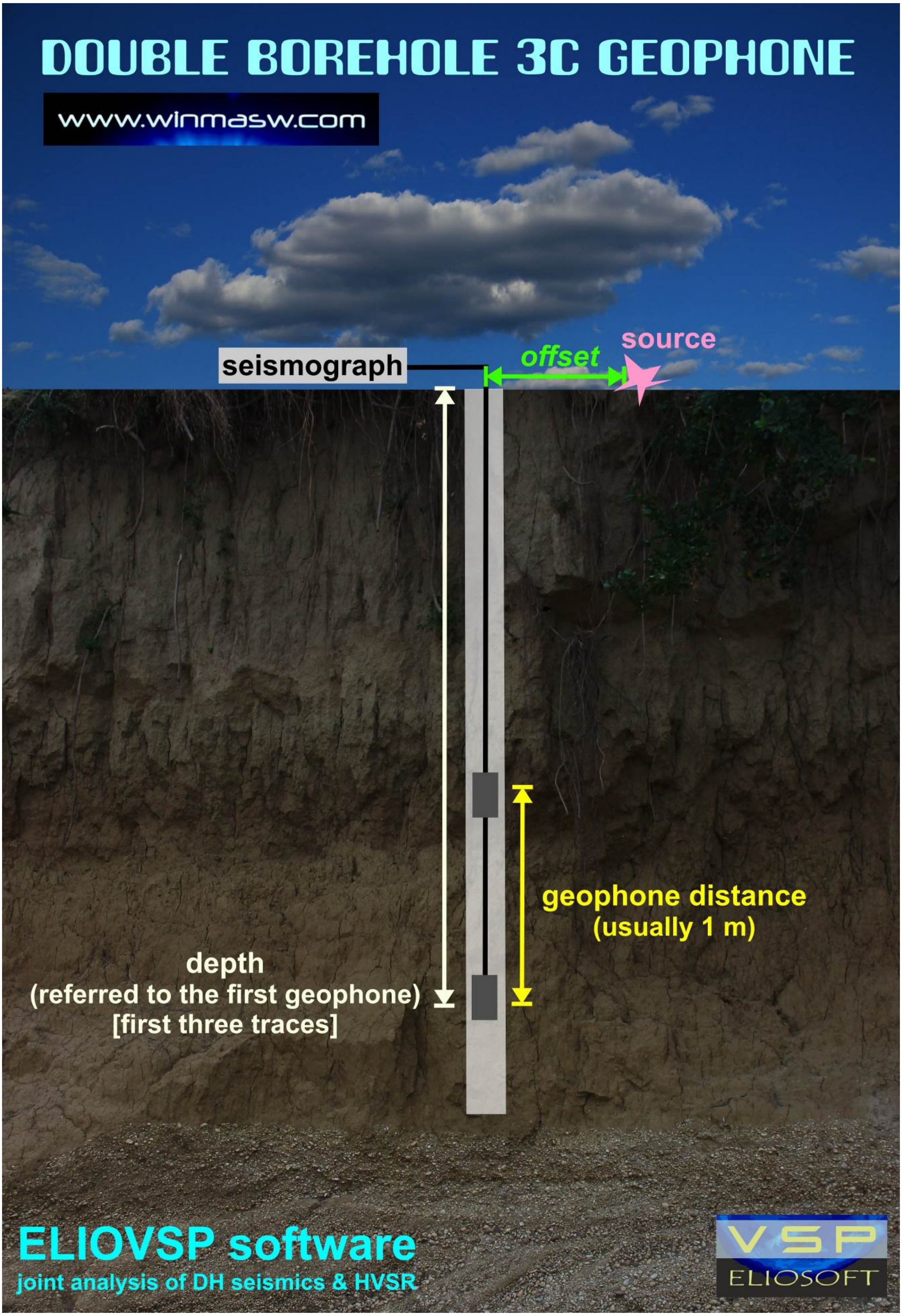




To get a copy of the ELIOVSP manual, send an email to winmasw@winmasw.com

You will discover a *new* (simple but comprehensive) way to handle *DH seismics*.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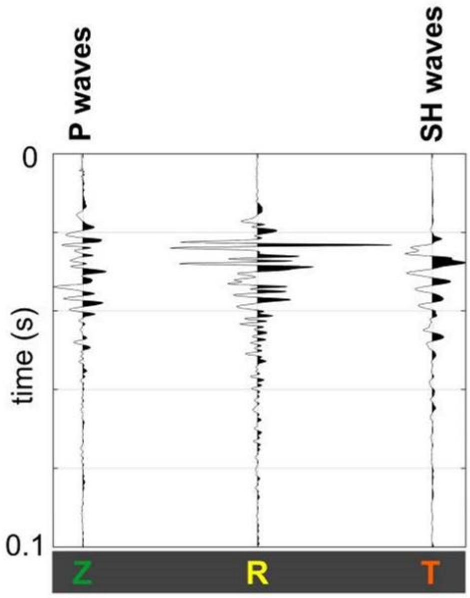
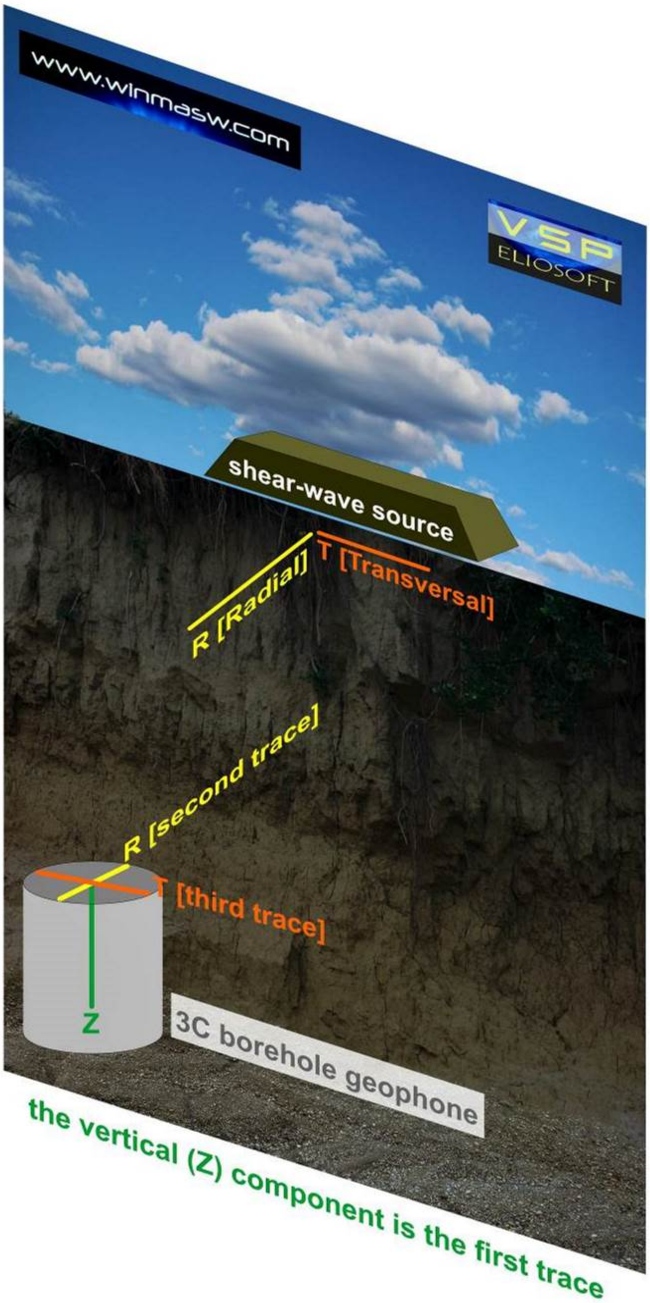

P waves
SH waves
0
time (s)
0.1
Z
R
T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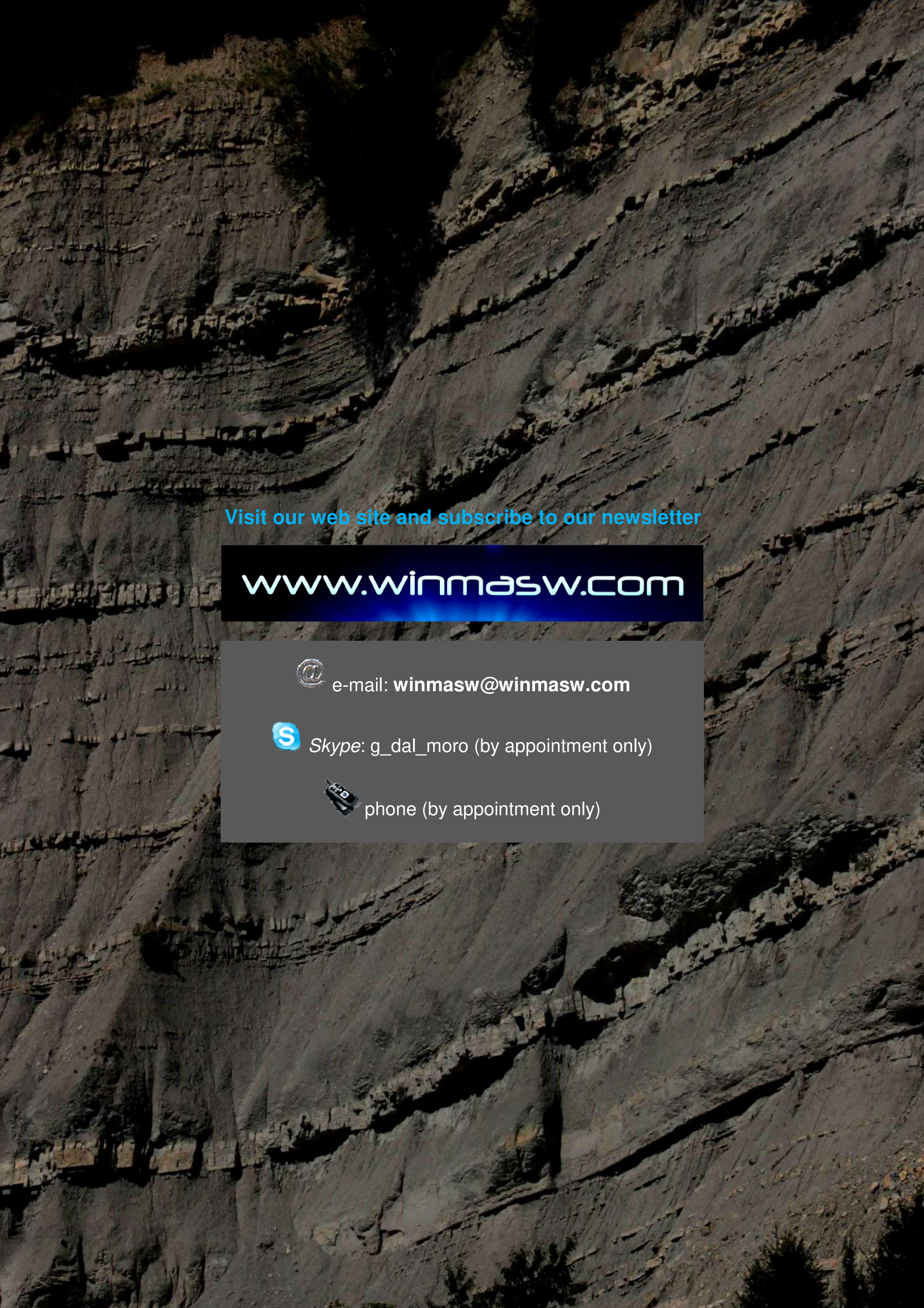

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