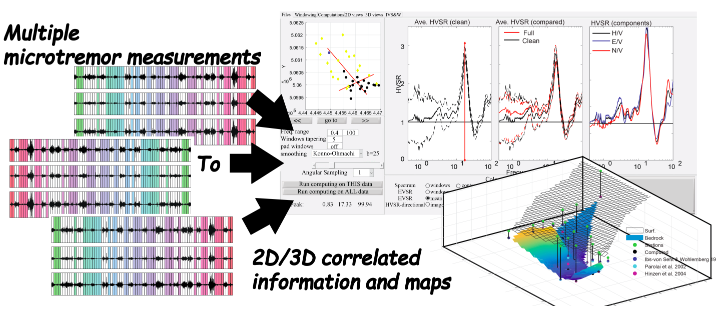
OpenHVSR -Processing Toolkit User Manual (Ver. 1.0)



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December 25, 2017

Last update: July 17, 2018.

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Chapter 1

About OpenHVSR-ProTO

1.1 Credits

"OpenHVSR - Processing Toolkit" is an algorithm developed in Matlab® (Release 2015b) by Ph.D. Samuel Bignardi. If you use this code for research purposes, please consider to cite:

- [ACCEPTED] Bignardi, S; Yezzi, A. J.; Fiussello, S.; Comelli, A.; (2018) OpenHVSR - Processing toolkit: Enhanced HVSR processing of distributed microtremor measurements and spatial variation of their informative content, Computers & Geosciences.
- Bignardi, S.; Mantovani, A.; Abu Zeid, N.; (2016). OpenHVSR: imaging the subsurface 2D/3D elastic properties through multiple HVSR modeling and inversion. Computers & Geosciences.
- Bignardi, S., 2017. The uncertainty of estimating the thickness of soft sediments with the HVSR method: A computational point of view on weak lateral variations. Journal of Applied Geophysics, 145C, 28-38, DOI 10.1016/j.jappgeo.2017.07.017
- Abu Zeid, N., Corradini, E., Bignardi, S., Nizzo, V., Santarato, G., 2017a, The passive seismic technique 'HVSR' as a reconnaissance tool for mapping paleo-soils: the case of the Pilastri archaeological site, northern Italy, Archaeological Prospection, DOI 10.1002/arp.1568.
- Abu Zeid, N., Corradini, E., Bignardi, S., Santarato, G., 2016, Unusual geophysical techniques in archaeology - HVSR and induced polarization, a case history, 22nd European Meeting of Environmental and Engineering Geophysics, NSAG-2016, DOI 10.3997/2214-4609.201602027.
- Bignardi, S., Abu Zeid, N., Corradini, E., Santarato, G., 2017, The HVSR technique from array data, speeding up mapping of paleo-surfaces and buried remains: The case of the Bronze-Age site of Pilastri (Italy), SEG

Technical Program Exp. Abstracts 2017, 5119-5124, DOI 10.1190/segam2017-17746745.1. Bignardi, S., 2017. The uncertainty of estimating the thickness of soft sediments with the HVSR method: A computational point of view on weak lateral variations. Journal of Applied Geophysics, 145C, 28-38, DOI 10.1016/j.jappgeo.2017.07.017

- Abu Zeid, N., Corradini, E., Bignardi, S., Nizzo, V., Santarato, G., 2017, The passive seismic technique 'HVSR' as a reconnaissance tool for mapping paleo-soils: the case of the Pilastri archaeological site, northern Italy, Archaeological Prospection, DOI 10.1002/arp.1568.
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- Bignardi, S., Abu Zeid, N., Corradini, E., Santarato, G., 2017, The HVSR technique from array data, speeding up mapping of paleo-surfaces and buried remains: The case of the Bronze-Age site of Pilastri (Italy), SEG Technical Program Exp. Abstracts 2017, 5119-5124, DOI 10.1190/segam2017-17746745.1.
- Bignardi, S. Fiussello, S., Yezzi, A., 2018, Free and improved computer codes for HVSR processing and inversions, 31st Symposium on the Application of Geophysics to Engineering and Environmental Problems, (SAGEEP 2018), Nashville Tennessee, USA March 25-29.
- Massolino, G., Abu Zeid, N., Bignardi, S., Gallipoli, M. R., Stabile, T. A., Rebez, A., Mucciarelli, M. 2018, Ambient Vibration Tests on a Building Before and After the 2012 Emilia (Italy) Earthquake, and After Seismic Retrofitting, 16th European Conference on Earthquake Engineering (16ECEE) June 2018, Thessaloniki, Grece.
- Obradovic, M., Abu Zeid, N., Bignardi, S., Bolognesi, M., Peresani, M., Russo, P., Santarato, G., 2015; High resolution geophysical and topographical surveys for the characterization of Fumane Cave Prehistoric Site, Italy, Near Surface Geoscience 2015, DOI, 10.3997/2214-4609.201413676.
- Herak, M, 2008. ModelHVSR—A Matlab tool to model horizontal-to-vertical spectral ratio of ambient noise. Computers & Geosciences vol. 34, pp 1514-1526.

1.2 License

1.3 Aknowledgements

OpenHVSR - Processing Toolkit (OpenHVSR-ProTo) is a signal processing toolkit. It includes some publicly available routines directly derived from the program "OpenHVSR" (Bignardi et al. 2016, [1]). The latter program is devoted to HVSR curve inversion and, despite the fact tat it is a completely independent program, together the two codes constitute a complete workflow for the HVSR method from the field data to the subsurface model.

Definitions

- Survey: the activity of acquiring data, at multiple geographical locations.
- Dataset: the entire collection of measurements acquired during a survey.
- Station: a specific location where data was collected.

1.4 What is OpenHVSR - Processing Toolkit

OpenHVSR- Processing Toolkit (OpenHVSR-ProTo) is a computer program developed in the Matlab environment (Release 2015b), specifically engineered to:

- Perform data processing of large ambient microtremor datasets (i.e. comprising multiple recordings, acquired at multiple locations over a geographical area), using the *Horizontal to Vertical Spectral Ratio* (HVSR) technique, as introduced by Nogoshi and Igarashi (1970, 1971) and largely disseminated by Nakamura [8, 9]). The typical workflow starts from the rough data to the computation of the corresponding spectral ratio curves. We aimed to include in one bundle all the most efficient processing tools, separately existing in other commercial and non-commercial software, and make it freely available to the scientific community. Whenever possible, such tools were improved and new functionalities introduced.
- Evaluation of directional effects in the acquired dataset, performed by computing a series of H/V computed from 0° to 180°, with different choices of angular discretization.

- Spatial correlation of different forms of informative content from the data, (e.g. main resonant frequency, main peak amplitude, the signal's preferential arrival direction), and visualization of the results in 2D and 3D. All data are loaded in the same environment and a choice of processing parameters can be immediately applied to all the data, so minimizing the computational times.

- The interface is designed to be user friendly while tightly binding processing and visualization, so that the effect of different processing parameters choices can be immediately evaluated.

- Bedrock mapping capability, as introduced by Ibs-von Seht and Wohlenberg [6]. This function support computation of bedrock depth both by using a set of published regressions, or alternatively, when bedrock depth is known at a sufficient number of locations, by computing a regression customized for the site at hand.

- Linear profiles can be investigated using the HVSR-profiling approach as introduced by Herak [5, 4]. This feature was improved allowing multiple profile creation and allowing the user to selectively include or exclude stations to any profile.

We expect this program to be of great use to the researchers and we hope it will constitute the basis for further collaborative developments oriented at exploring the full potential of the HVSR technique.

1.4.1 Known issues

The program is continuously improved and, despite I strive to carefully test every new feature, some minor error may occur. Known issues are typically related to the interface and does not impact the computational routines, which are carefully tested.

Some issues that the user may experience:

- Due to changes between different Matlab versions, issues may arise when the program is used on Matlab versions other than 2015b. Typically connected with the Matlab functions “uitab”, “griddata”, and “boundary”.

- From time to time, Matworks declares some of their functions as “deprecated”. If this occurs, the command window will display some warnings to inform the user than the related functions will be removed in future Matlab releases. The user should not be concerned with these warnings.

- I implementd right-click context menus on all the images on the program interface. To take advantage of Matlab's graphical tools, I retained the Matlab graphical toolbar on the top part of the program interface. This toolbar contains functions such as: “Zoom In”, “Zoom out”, and others (Figure [fig:Matlab-toolbar]). User must be advised that, if any of these

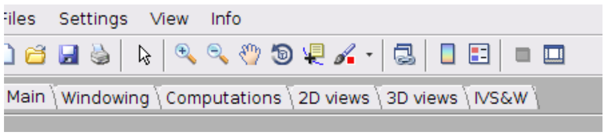

Figure 1.1: Matlab's graphical toolbar

tools is selected, right-clicking on the figure will open the tool's context menu rather than the desired figure's menu.

If any problem occurs, please do not hesitate to contact me at the following email: sedysen@gmail.com .

1.4.2 Compatibility Notes:

The program was developed with MAtlab R2015b and it should run on any operative system for which a matlab implementation exist. So far it was successfully tested on releases: R2015b, R2017a, R2017b. The following operative systems were used as well: Windows 10 Desktop, Windows 10 Home, Linux Ubuntu 16.04, Centos 6.9.

Back-compatibility: In general, to the best of my knowledge, the program is fully compatibile at least down to R2014b. In more detail:

- **GUI creation and use:** R2010b and higher
- **Internal computational routines:** Any Matlab Release.
- **2D/3D plots:** R2014b and higher.

  In 2D/3D plots the Matlab's function "*boundary.m*" (introduced in R2014b) is used.
  In earlier Matlab releases most part of the program (Tabs 1, 2 and 3) and in particular all computational routines and result export functions should behave normally. Visualization on Tabs 4, 5 and 6, described in sections 3.5, 3.6 and 3.7 respectively, were implemented to avoid errors in the program behavior but visualization of 2D masks will be of low quality, while 3D surfaces plot is not available.

Chapter 2

Getting started

Place the program at any location in your computer, say for example in /my/folder/OpenHVSR-ProTO/, then

1. Start Matlab
2. Navigate to the /my/folder/OpenHVSR/ folder
3. open the file "src/START_OpenHVSR_ProTO.m" and make it run

2.1 Load one of the examples provided

We provide five examples which can be found in the "OpenHVSR_ProTO/EXAMPLES" folder. All examples contain the same field measurements but illustrate different functionalities.

- Examples 1: Project containing *.saf files
- Examples 2: Project containing *.saf files (edited in expert mode)
- Examples 3: Project containing non-saf ascii files. Files have a header/-data structure.
- Examples 4: Project containing data-only ascii files (without header).
- Examples 5: A minimal example elaboration ready to be resumed.

Examples 1-4 are loaded by going in the menu "files" and selecting "*Load Project*". Example 5 is loaded by selecting "*Resume elaboration*".

2.2 Create your own project

As brief overview, input to the program is performed creating a "*Project*" which comprise

- *project-file:* (section 2.2.2), which describes what is being input to the program: locations of the measurements, how data-files will be read, and if optional information (if present).
- *data-files:* (section 2.2.1) a set of files containing the microtremor recorded on the field. One file for each geographical location.
- Optional: *well-files*: describing drilled wells (One file per well).
- Optional: *extra topographical points*: A file containing a list of topographical locations, not associated with any measurement, which sole purpose is to refine the geometry.

2.2.1 The data files

Various format of data files can be used as input. I strived to introduce maximum flexibility on this aspect. In general, the field data files are expected to possess a data section organized in colums. At least three columns must exist, and, regardless of the order, they are expected to contain at least three columns containing the components of motion. A project usually includes multiple data files. Length of the recorded signal does not need to be the same across different data files, neither does the sampling frequency. A mix of data formats can cohexist in the same project even if is not recomended. The internal convention regarding the reference system adopted in this program is: X=East, Y=North, Z=Vertical. The user may specify a rotation angle when thd data were collected with a different orientation. The latter capability is location-specific so that a mix of data acquired with different orientations of the sensor is acceptable.

SAF format: Microtremor data files in "*.saf" format (SEASAME ASCII data Format, Version 1.0 [3, 2]) are automatically recognized. Minor variations to the standard *.saf format, such as those produced using MAE (http://www.mae-srl.it/), Tromino (http://www.tromino.it) and Pasi (http://www.pasisrl.it) instruments are automatically managed as well. For the saf format, sampling frequency and signal components are automatically recognized and managed without intervention by the user.

General ascii format, containing a header/data structure: All data formats comprising a header+data structure (may have any file extension except ".saf"), can be load with minimum intervention, provided they are in ASCII encoding system (i.e. text files). It is sufficient to insert a simple line of text between header and data sections. The project-file (described in the following section) must be edit accordingly.

Numerical-only ascii formats: Any file containing a table of numerical values (may have any file extension except ".saf") can be load, provided is simple text (ASCII). The project-file (described in the following section) must be edit accordingly.

2.2.2 The project-file

Input to OpenHVSR - ProTO is provided trough a "project-file", which actually is a regular text file (ASCII) but it is used as Matlab script, and therefore it must have the ".m" file extension. The user can create a project-file by simply editing one of those provided as example, or alternatively, by using the program's dedicated graphic tool (see sect. 3.1.1). To understand and edit the project-file requires a basic understanding of the Matlab language, hencefor I will provide few necessary notions. As a first notion, it useful to recall that in Matlab any character on a line, following a "%" is considered a comment. Any project file provided as example is commented.

The most general project-file specifies:

1. location of measurements,
2. data filenames (and paths)
3. (only when not *.saf) sampling frequency of data
4. (only when not *.saf) descriptive information about how to read the data files

All the examples in the "OpenHVSR_ProTO/EXAMPLES/" folder contain project-files with increasing levels of complexity. Comments were added so to make them self explanatory. However, minimal project-file structures are reported in tables 2.1 and 2.2.

The primary element that must always be present in the project file is the cell variable "SURVEY". This variable use the "cell" feature of Matlab which creates a container that has the same structure of a matrix, but it can contain different of items, for example:

```
SURVEYS{3,2}
```

is the element of the SURVEYS cell at line 3 and column 2.

Each row of the "SURVEYS" variable contains a description of one measurement. Columns have the following meaning:

- Column 1 contains the coordinates (x,y,z) of a measurement location (organized as a 1x3 vector and enclosed in squared brackets)
- Column 2 contains the path to the corresponding data file.
- Column 3 specifies the sampling frequency

- Column 4 defines a rotation for horizontal components. Positive value (in degrees) corresponds to a conter-clockwise rotation.

For example

```
SURVEYS{1,1}=[0,0,0];%Location [x,y,z] or
                              %[East,North,Elevation]

SURVEYS{1,2}='DATA/data_1.saf';%microtremor data.

SURVEYS{1,3}=200;%sampling frequency (Hz)

SURVEYS{1,4}=37;%conter-clockwise
                       %rotation (degrees)
```

means that the microtremor contained in file "DATA/data_1.txt", was recorded at the location (0,0,0) using a sampling frequency of 200 Hz. Horizontal components will be rotated of 37 degrees after loading.

When data are in "*.saf" format:

When data is in "saf" format, columns 1 and 2 of variable SURVEYS completely specify the input, while all other formats require the input to be modified accordingly.

Table 2.1 shows a minimal project-file which describes a survey where three microtremor recordings (*data_1.saf, data_2.saf, data_3*.saf), acquired at three different locations, and located in the "DATA" folder.

```
% USING THE ".saf" FORMAT: (this line is a comment)

SURVEYS{1,1}=[0,0,0];%Location [x,y,z] or
                              %[East,North,Elevation]

SURVEYS{1,2}='DATA/data_1.saf';%microtremor.


SURVEYS{2,1}=[100 0 5];
SURVEYS{2,2}='DATA/data_2.saf';


SURVEYS{3,1}=[200 0 5];
SURVEYS{3,2}='DATA/data_3.saf';
```

Table 2.1: Example of a minimal input project-file for ".saf" data

When files possess the header/data structure

When data files contain a first part of text describing the file content (header), followed by a data section, it is said to possess a header+data structure. To load this kind of files, user must manually specify the sampling frequency as follows (see line 5 in the table)

```
3  SURVEYS{1,1}=[0,0,0];%Location [x,y,z] or
4                                %[East,North,Elevation]
5
6  SURVEYS{1,2}='DATA/data_1.txt';% microtremor data
7  %(any extension accepted provided the file is ASCII)
8
9  SURVEYS{1,3}=250;% sampling frequence (Hz).
```

Two more variables must be defined:

- datafile_columns
- datafile_separator

The datafile_separator variable can be any string. In order to tell the program where data begins the user must insert this string in every (non-saf) datafile, right between the header and the data section. Be advised that if the *datafile_separator* specified in the project-file and the string inserted in a data-files are not perfectly identical the file will not load. In this context, misplaced spaces or tab characters will lead to "invisible" errors capable of preventing the data from load for no apparent reason.

The *datafile_columns* variable specifies the column ID's where the program is expected to find the [Vertical, East, North] components of motion. In table 2.2, for example, the program will look for the string "*data_begins_here*" in order to find where the data-section of the file begins. It will read the data section as a matrix and it will interpret column 2, 3 and 6 as the Vertical, East and North components respectively.

```
 1  % Data Section:
 2  SURVEYS{1,1} = [   0 0 0];          % Location [x,y,z].
 3  SURVEYS{1,2} = 'DATA/data_1.txt'; % microtremor file
 4  SURVEYS{1,3} = '200';
% sampling frequency
 5
 6  SURVEYS{2,1} = [100 0 5];
 7  SURVEYS{2,2} = 'DATA/data_2.txt';
 8  SURVEYS{2,3} = '200';
 9
10  SURVEYS{3,1} = [200 0 5];
11  SURVEYS{3,2} = 'DATA/data_3.txt';
12  SURVEYS{1,3} = '200';
14  % optional section
15   datafile_columns   = [2 3 6];
16   datafile_separator = 'data_begins_here';
```

Table 2.2: Example of a minimal input project-file

When data is a text-only

When data is provided with a (ASCII) file containing only columns of numbers and no header, the same strategy of table 2.2 is used, with the line 16 modified as *datafile_separator = 'none'*;

```
12
14  % optional section
15   datafile_columns   = [2 3 6];
16   datafile_separator = 'none';
```

Expert's mode projects

For the experienced Matlab user, the project-file can be made very flexible in deciding which data must enter the processing. This is achieved by using the optional variable "*idx*", see:
EXAMPLES/Example2_saf_files_expert_mode/OpenHVSR_ProTO_project.m

This enables to discard any measurement by just commenting the corresponding line. For example, a project can list the whole survey, the user may want to process only a subset. Is the case of the data at line 4, which is present in the project file, but because it is commented (using %) it will be skipped by the program when loading the project.

```
1 % ADVANCED MODE (this line is a comment)
2 id=0;
3 id=id+1; SURVEYS{id,1}=[0 0 0]; SURVEYS{id,2}='DATA/data_1.saf';
4 % id=id+1; SURVEYS{id,1}=[100 0 5]; SURVEYS{id,2}='DATA/data_2.saf';
5 id=id+1; SURVEYS{id,1}=[200 0 5]; SURVEYS{id,2}='DATA/data_3.saf';
```

Table 2.3: Example of a minimal input project-filefor ".saf" data

Retrieving the correct portion of the data

While data in ".saf" format are automatically recognized and managed, other file formats need minimum editing.

Almost any data file structure is loadable provided it is an ASCII file. Files containing a header can be loaded with minimum effort by placing any string between the header and the data section of the file, for example in the following data-file

```
# device:          MAE VIBRALOG
# samples:           900001
# channels:          3
# sampling freq. (Hz):    250
# units:           mV
# amplifications (dB): 36      36      36
# components: Vert      E–O     N–S
data_begins_here
 −0.0620   0.0486          0.0050
 −0.0274  −0.0736  −0.0470
 −0.0107  −0.0403  −0.0273
```

the string "data_begins_here" was chosen and inserted as separator. The user must tell OpenHVSR-ProTo that the data-files include a header by inserting the line "*datafile_separator = 'data_begins_here'*" in the project-file (e.g. tables 2.1 and 2.2).

By default OpenHVSR-ProTo assumes that the Vertical, East, and North component of motion occupy the columns 1, 2 and 3 respectively, however, the user can customize the column order by modifying the "datafile_columns" variable as explained in above.

Rotating Horizontal components

When the horizontal components of a data file were acquired with an orientation of the sensor different from the internal convention of the program such components may be rotated. To define a rotation of axes the user must specify an angle value in degrees in the forth column of the SURVEYS variable (see table 2.4 as an example). A positive angular value α means a counter-clockwise rotation as described in figure 3.2.

```
% Data Section:
SURVEYS{1,1}=[0 0 0];% Location [x,y,z].

SURVEYS{1,2}='DATA/data_1.txt';% microtremor file

SURVEYS{1,3}='200';% sampling frequency

SURVEYS{1,4}='37';% rotation in degrees

% positive angle = counter-clockwise rotation

...
```

Table 2.4: Rotation of horizontal components

Chapter 3

Interface description

The algorithm is composed of several routines integrated into a main graphical user interface (GUI), which is organized in tabs.

3.1 Overview

3.1.1 Scrool-down menus

The GUI contains four scroll-down menus:

- Files
- Settings
- Views
- Info

Files Most of the input/output functionalities are managed in this menu.

- "***Create/Edit project***" opens a graphical interface to create a prioject-file. The reccomended project-file creation is by editing one of those provided as example. The functionality of this menu was added in order to facilitate users unfamiliar with Matlab.
- "***load project***" loads an existing project-file
- "***Save Elaboration***" saves the program status "as is" so to continue in a later time. When an elaboration is saved a set of files ".mat" stored on the disk. The set comprise a file for each measuring locations and a file (ending as "*_MAIN.mat*").
- "***Resume Elaboration***" resume an elaboration. When resuming an elaboration the file ending as "*_MAIN.mat*" must be selected.

- "***Save HVSR curves (txt)***" output hvsr curves in text fotmat (extension .hv).
- "***Save Full Output set (txt)***" obtain a full output of the computed quantities in text format. Output files are corredated of a header describing their content.
- "***Export as OpenHVSR project***" create a OpenHVSR project-file (Bignardi et al., 2016) ready for inversion.

Settings:

- "***Enable log***" enables program log can be activated."

Views: This menu contains many visualization preferences and its structure shold be self-explaining. Some of the available choice are tab specific.

Info: Credits

3.1.2 General features

3.1.2.1 Mouse-over tips

Hovering with the mouse over the GUI controls, such as buttons, textboxes etc. will trigger popup tips which are intended to guide the user and complement the information on this manual.

3.1.2.2 Figures

Each figure on the interface possess a context-menu which is activated **by right-clicking on its axes**. Some options are present for all figures:

- set the axis limits
- export the figure in an external window, where it can be edited using Matlab's graphic tools.

WARNING: the image context menu will be available only when none of the Matab's editing tools (in the top toolbar) is selected.

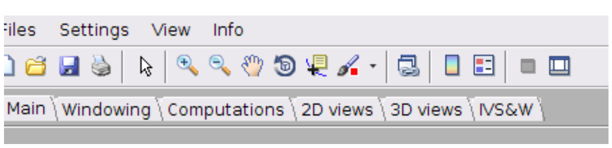

Figure 3.1: Matlab graphical toolbar

3.1.2.3 Customizable features and default parameters

User may customize some aspects of the program and the default parameters by editing the files:

- DEFAULT_VALUES.m
- USER_PREFERENCES.m

3.2 Data processing workflow

The interface comprise six tabs:

1. Main
2. Windowing
3. Computations
4. 2D views
5. 3D views
6. IVS&W

Tabs 1-3 are devoted to signal processing and decision making. Tabs 4 and 5 are devoted to visualization, while Tab 6 is devoted to bedrock mapping [6].

3.2.1 obtain spectral ratio curves

The logical workflow to perform the H/V spectral ratio analisys consists of:

1. Load a project or resume an elaboration (using: *menu->Files*)
2. Tab-1: Inspect the general view of the survey.
3. Tab-2:
   ▹ Set the desired parameters related to data windowing. If desired, parameters can be chosen different from one measurement to another.

   Note: *If necessary, to facilitate the automatic window selection through the STA/LTA ratio, data can be filtered. When a filter is defined and successfully applied the user can select wich version (original or filtered) of the data is displayed (figure 3.3c). The selection is performed using the control at the bottom of panel (b)*

   ▹ Press the "*Window this data*" or the "*Window ALL data*" button.
   ▹ Select/Deselect unwanted data windows (by right-clicking on the figure axis).

4. Tab-3:
   ▷ Set the desired parameters for HVSR curve computation. If desired, parameters can be chosen different from one measurement to another.
   ▷ If a directional analisys of the data is desired, set an angular discretization.
   ▷ Press the "*Run computing on THIS data*" or the "*Run computing on ALL data*" button.
   ▷ Perform a data cleaning by discarding "bad" windows. This can be performed almost in every wiew mode (3.4c) by right-clicking the figure's axis.

5. Result can be inspected in tabs 4 and 5.

3.2.2 perform an angular analisys

Follow section 3.2.1 and set the "*angular sampling*" value other than "off".

On the angular analisys

The horizontal components of motion, E and N, originally oriented according to the axis of our reference system (X,Y), are projected onto a rotated system of axes (X',Y'). The horizontal component along the X' direction is then used to compute the directional spectral ratio H_α/V, whereα is the angle between the X and X' axes (see the reference system in figure 3.2). Spectral ratio curves for angles between 0 and 180 degrees are computed to investigate whether data contain directionally-dependent (i.e. non-isotropic) components. Directional spectral ratios are tiled to form the columns of a matrix $\boldsymbol{R}$ so that different rows (i) and columns (j) correspond to different values of frequency (f_i) and angular direction (α_j) respectively. The matrix $\boldsymbol{R}$ as described in the following, is displayed on the interface and labelled "*HVSR-Directional*". Users familiar with Geopsy will recognize the general idea behind the HVSR-rotate tool.

We further developed the concept of directional analysis by introducing the "*preferential signal arrival vector*". For each row m (i.e. each frequency) of matrix $\boldsymbol{R}$, the maximum amplitude in the row A^m_{max}, the corresponding direction α^{max}_n(let's say occurring at column index n), and the average amplitude along the row A^m_{mean}, are extracted. Ideally, if no directional effect is present it is expected that $\|A^m_{max} - A^m_{mean}\| \approx 0$. Therefore, for each row i of matrix $\boldsymbol{R}$ we build a vector having direction defined by the angle α^{max}_n and modulus $\|A^m_{max} - A^m_{mean}\|$. Finally, each station of the survey will be associated with a directional analysis matrix (shown on tab 3.4) and frequency-dependent preferential direction of signal arrival (shown on tans 3.5 and 3.6) . The latter feature is shown in the subsequent Tabs.

3.2.3 setup and display linear profiles

After a project is loaded, linear profiles can be defined at any time. There is no limit to the number of profiles. However, each profile must comprise at least two stations and it is necessary to complete the data processing (section 3.2.1) before visualization.

1. Tab-1: Right-click on one of the main survey map axis to access the image's context menu and select "Define 2D profile" .
   ▷ Click on the profile's desired starting point.
   ▷ Click a second time to select the desired end point. A black line will appear on the map and a pop-up window will show up.
   ▷ In the pop-up window write the ID of one of the stations. This station, and all those at shorter distance will be included into the profile. For example if the desired station is shown on the main map as "R13" its ID will be "13"
   ▷ The profile is now created and shown on the survey map with a red line.

2. In "Profiles" section of Tab-1:
   ▷ Buttons "<<" and ">>" in the "Profiles" section on the left panels (c) can be used to swich between the general view and the profile inspection mode. When inspecting a profile, stations included and not included are shown in green and black respectively. The same buttons perform navigation across different profiles.
   ▷ Buttons "add" and "remove" are used to individually add or remove stations from the profile

3. Profile visualization: Tab-4
   ▷ Use the buttons "-", "+" or "go to" to select a profile to be viewed.
   ▷ Use the buttons "HVSR", "E/V" and "N/V" to visualize the corresponding spectral ratio profiles

3.3 Tabs description

3.3.1 Tab 1. Main parameter settings and 2D profile creation

Tab 1, "Main" (fig. 3.2) is dedicated to the general view of the survey. The top-right panel a) shows an aerial view of the survey including: measurement points "stations" (black dots), optional topographic points (yellow diamonds) and existing (i.e. specified by the user) wells (blue squares). The location corresponding to the data undergoing processing is highlighted by a red circle. User-defined profiles of interest, which will be used in subsequent tabs to display HVSR-profiling images, are shown with red lines.

The left panel b) hosts the controls to navigate through different locations, wells, and profiles (when defined by the user). In particular buttons "<<" and ">>" in the "Profiles" section will cause the image of panel (a) to change to "Profiles inspection mode" where the stations included or excluded in the viewed linear profile are highlighted in green and black respectively. User may selectively add or remove stations from the profile by operating the buttons "add" and "remove."

The panel displays the basic information regarding the measurement currently considered for processing, such as sampling frequency and data length, while processing parameters are summarized in the bottom section (c).

In section (c) the status of each station can be set as

- *Unlocked*: Station can be individually processed. It is included in all batch elaboration processes. It is included in the construction of every image, map, and data volume rappresentation.
- *Locked*: All processing performed and results for the Station cannot be changed by further processing operations (i.e. user wants to keep it unchanged). It is included in the construction of every image, map, and data volume rappresentation.
- *Excluded*: Station is excluded from processing and results.

The filename associated with the highlighted station is shown both on top of panel (b) and on panel (d).

For clarity sake, we superimposed to the image the reference system which is used troghout the program.

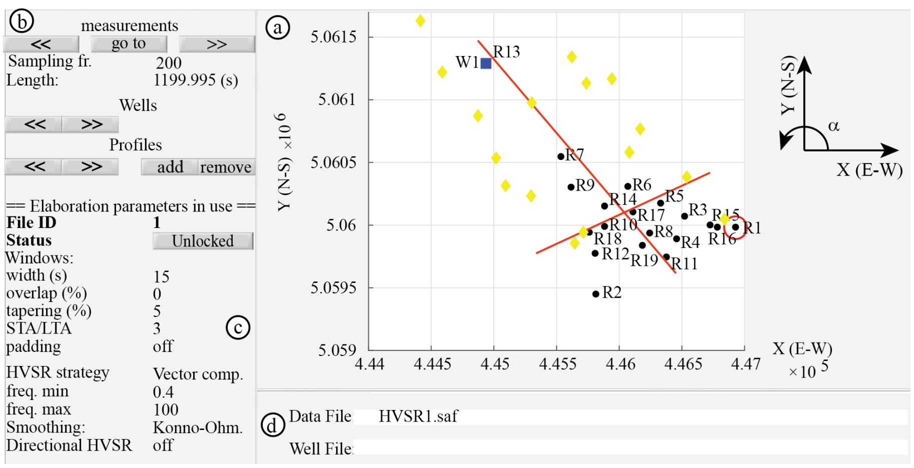

Figure 3.2: View of tab 1: The main view

3.3.2 Tab 2. Windowing

Tab 2, "Windowing" (fig. 3.3), is devoted to the data windowing and splitting. The aerial view of Tab 1 (Fig. 3.2) and the file name of the data under investigation are replicated in the top-left of the tab (panel a), while the left-bottom panel b) contains the subset of processing parameters specific to the windowing operation:

- *Windows width (s)*: length of individual time-windows (in seconds), used to split the recorded data.

- Windows overlap (%): percentage of window length which will overlap with the next window.

- *Filter*: This line of commands enables data filtering. Bandpass, lowpass and highpass filters are implemented. Cutoff frequencies are set by editing the two text fields. The the magnitude response of the digital filter can be inspected by pressing the "*FR*" button.

- *Filtered data*: decide how to use the filter.
  ▷ "*use only for STA/LTA automatic window selection*" : Use the filtered data only to automatically discard windows (through STA/LTA ratio algorithm). Computations are performed on original data.
  ▷ "*use filtered data for all computations*": Use the filtered data to discard windows and in all subsequent computationscomputation.

- *STA window (s)*: length of Short Term Average time-window used to compute the STA/LTA ratio.

- *LTA window (s)*: length of Long Term Average time-window used to compute the STA/LTA ratio.

- *STA/LTA*: ratio, here computed as the L1 norm. Data time-windows exceeding this value are considered as containing transient signals and automatically discarded [11].

- *Data to show*: this control is enable when a digital filter is successfully defined and applied. It controls which data, either the original or filtered are shown on panel (c).

Selection of windows (to either be enabled or discarded) can be performed by right-clicking on the figure's axes of panel (c). Right-click to access the context-menu, either select "Delete windows" or "Resume windows", go with the mouse near the windows of interest, press the mouse button and drag the pointer to create a squared box. Windows included in the box will be affected by the command. Visualization preferences are accessed through the same menu. Figures on this tab are automatically updated. Further ways for data window selection are available on Tab 3, as detailed in the following.

Note: When any windowing parameter is modified the user MUST run the windowing operation again in order for the change to take effect.

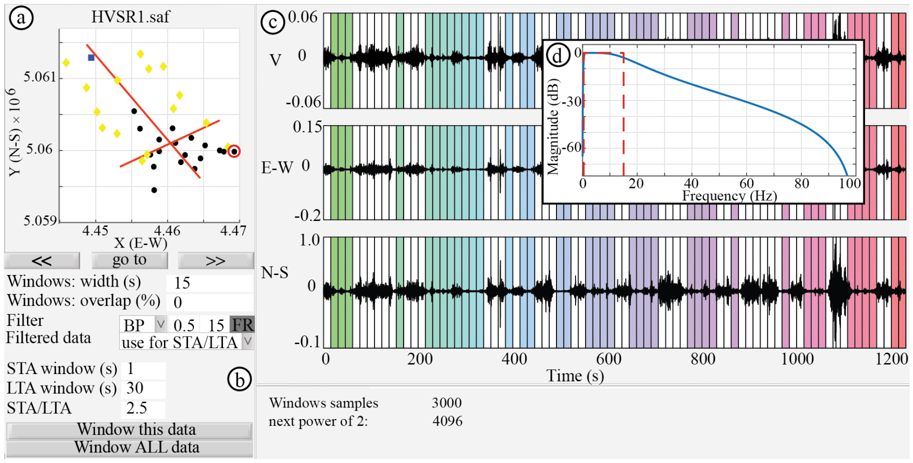

Figure 3.3: View of tab 2: Windowing.

3.3.3 Tab 3. Computations

Tab 3, (Fig. 3.4), "Computations" possesses the same layout of Tab 2, with the survey map, filename and navigation controls replicated on the top-left panel (a). Controls for selecting the data processing parameters lie within the bottom left panel (b) and include:

- *HVSR:* select how the horizontal components are combined during computation of the spectral ratio curve $HVSR = H/V$. Options available:

$$\begin{aligned} \mathit{Average\ Squared}: \quad H &= \sqrt{\frac{E^2+N^2}{2}} \\ \mathit{Simple\ Average}: \quad H &= (E+N)/2 \\ \mathit{Total\ Energy}: \quad H &= \sqrt{E^2+N^2} \end{aligned}$$

- *Freq. range*: the frequency range of interest.

- *Windows tapering*: Data windows are tapered at both ends using a cosine function. This value, expressed as percentage, describe the portion of data samples to be tapered at each end of the windows .

- *pad windows*: When a custom value is set each data time-window is lengthened to the requested number of samples. The value specified by the user is always substituted te the next power of 2. The custom value is automatically check not to be smaller than the original data window length.

- *smoothing*: Describe the smoothing strategy to be aplied to the HVSR curve. Options available are Konno-Ohmachi [7] and moving average. The amount of smoothing is controlled by the corresponding slider.

- *Angular sampling*: select the angular sampling in which the interval $[0, 180]$ degrees is discretized during the directional analisys. As this feature is moderately time cunsuming, this option is turned off by default.[1]

As in the previous tab, the parameters can be used both for processing the displayed data or the entire dataset. Panel (c), on the top-right, is used to display various visualizations, selected in the bottom-right panel (d). Figures on this tab are automatically updated after computation or when the data to be visualized is changed. The user may force update of figures by pressing the "update" button.

Available visualizations are:

1. Tiled view of all windows' spectra. Vertical, East, and North components are shown within the left, central and right axes respectively. Horizontal and vertical ranges may be customized to zoom in and better investigate the details of the image. To our knowledge, this mode is not present in other software packages and enables window selection based on spectral investigation of any motion component.

2. Tiled view of the HVSR for all windows. It implements a display strategy similar to the Grilla program. The window selection strategy was enhanced by allowing the user to investigate the N/V and E/V spectral ratios along with the classic HVSR. The prior visualization modes and zooming features are also available.

3. Mean HVSR (mode a), "mean" option: The final average curve and 95% confidence intervals (Picozzi 2005, [10]), are displayed within the left axes. Mean curves and confidence intervals before and after data-cleaning are shown in the center to allow the user to investigate both the impact of different parameter choices and the effectiveness of the data cleaning operation. The HVSR curve, labeled H/V, and the mean curves for the ratios E/V, and N/V are compared on the right. In this viwew the user may right-click on the left image axes to open the figure's context menu and select "Use Manual Peak" option to perform a custom selection of the fundamental mode peak. After selecting the option user is required to press the mouse button at one point of the figure, drag the pointer so causing a rectangle to be visualized and release. The point of maximum amplitude of the HVSR curve enclosed in the rectangle will be the new peak. Selection can be undone by selecting "*Use Auto Peak*" of the context menu.

4. Mean HVSR (mode b), "H-V" option: The same left and right figures described at the previous point are shown. With this option, however, the

[1] Reader must be advised that directional analisys, especially if performed with fine angular discretization, will require a considrable amount of RAM. Consequently, saving the result of processing on file will require an equal amount of disk space.

central figure shows a comparison of the smoothed East, North and Vertical spectra so to allow the user to investigate if the peaks can confidently recognize to have lithological origin.

5. Mean HVSR (mode c), "all" option: Shows the spectral ratio of all windows associated to the investigated station. HVSR is displayed (as in Geopsy) within the left axes, while plots for the E/V and N/V ratios are added within the central and right axes respectively. This mode accommodates window selection through user highlighting of anomalous curve segments within any of the three images.

6. Directional HVSR (mode a): A contour plot of the directional analysis matrix $\boldsymbol{R}$ is displayed. On the left the image is not normalized, while frequency-wise and angle-wise normalized images, are displayed in the central and right axes respectively. The average HVSR curve and the line corresponding to unit amplitude of the spectral ratio are superimposed for legibility sake.

7. Directional HVSR (mode b): A contour plot of the directional analysis matrix $\boldsymbol{R}$ is displayed within the left axes, while the central axes contain the HVSR curves computed at each angle step as frequency-amplitude graphs. (the axes on the right are not used in this case).

Views 1 and 2 accommodate windows selection (to either be enabled or discarded) by right-clicking on the figure's axes of panel (c). Right-click on one figure axis to access the context-menu, either select "Delete windows" or "Resume windows", go with the mouse on the image, press the mouse button and drag the pointer to create a squared box. Windows included in the box will be affected by the command.
View 5 accommodates windows selection through direct selection of anomalous curves. Right-click on one figure axis to access the context-menu, either select "Delete curves" or "Resume curves", go with the mouse on the image, press the mouse button and drag the pointer to create a squared box. Curves which partially fall into the box will be affected by the command.

Note: When any processing parameter is modified the user MUST run the computation again in order for the change to take effects. The computation must be performed again when a windowing parameter on Tab-2 (figure 3.3) is changed. The "Update" button on this tab only forces update of display without triggering any computation.

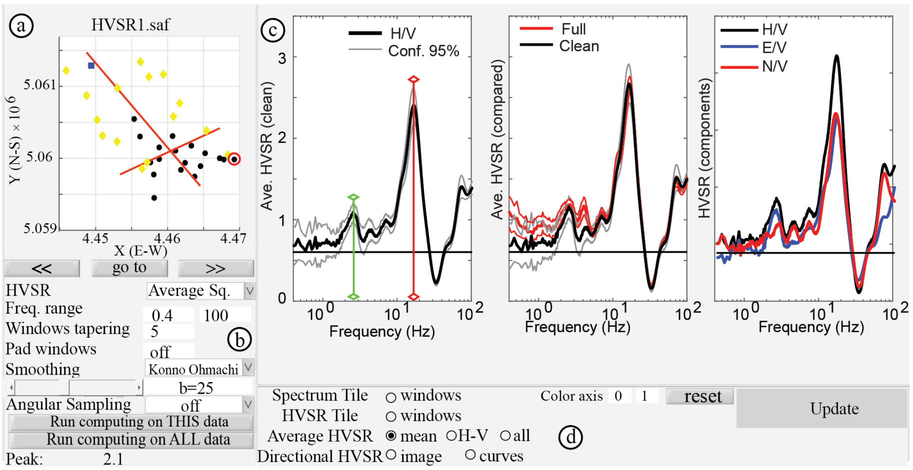

Figure 3.4: Tab 3: Processing, data-cleaning, manual picking and result inspection

3.3.4 Tab 4. 2D Views

Tab 4 (Fig. 3.5), "2D Views", is dedicated to aerial map visualizations. Filled and unfilled colored contour plots of the investigated area are shown on panel (b) to image the spatial distribution of (see controls on panel (a)):

1. main resonant frequency values
2. amplitude at main resonant peak
3. preferential direction of incoming waves (i.e. directional HVSR)
4. navigable frequency dependent amplitude pattern

The tab is used to display interpolated linear profiles as well. The controls for the latter are placed in the "Profiles" sction (c). Figures on this tab are only partially automatically updated. The user must use the "update" button after a different visualization mode is changed. Visualization of 2D maps is available only if three or more station are present and properly processed.

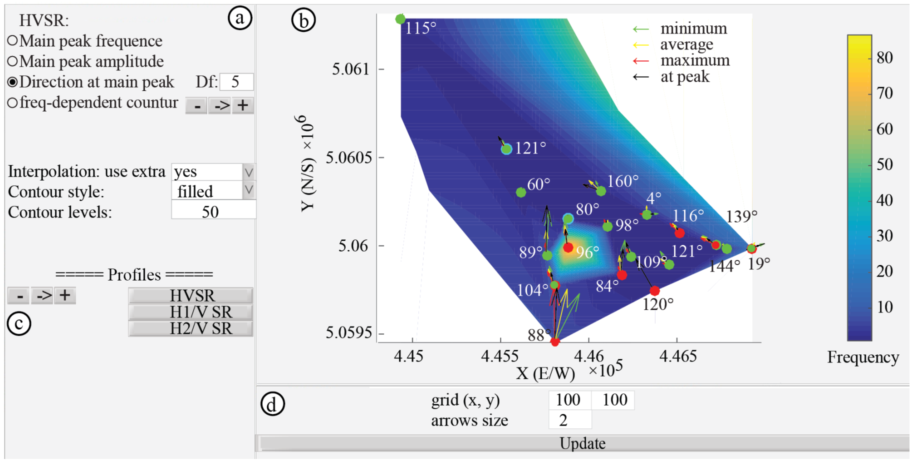

Figure 3.5: View of tab 4. 2-D visualizations

3.3.5 Tab 5. 3D Views

Tab 5 (Fig. 3.6), “3D Views”, is devoted to displaying processing results in three dimensions, in order to visually facilitate their interpretation. Options available include:

1. plot of the main resonant frequency as function of spatial coordinate X (E/W) and Y (N/S), to gain insight into the bedrock morphology across the area.

2. plot of the main resonant frequency as function of space coordinates X and Y, with preferential signal’s arrival direction attached to the data points, to discern whether or not a connection between bedrock geometry and directional contributions exists.

3. frequency dependent directionality of the signal (one curve at a time).

Figures on this tab are only partially automatically updated. The user must use the “update” button after a different visualization mode is changed. Visualization of 3D surfaces is available only if three or more station are present and properly processed.

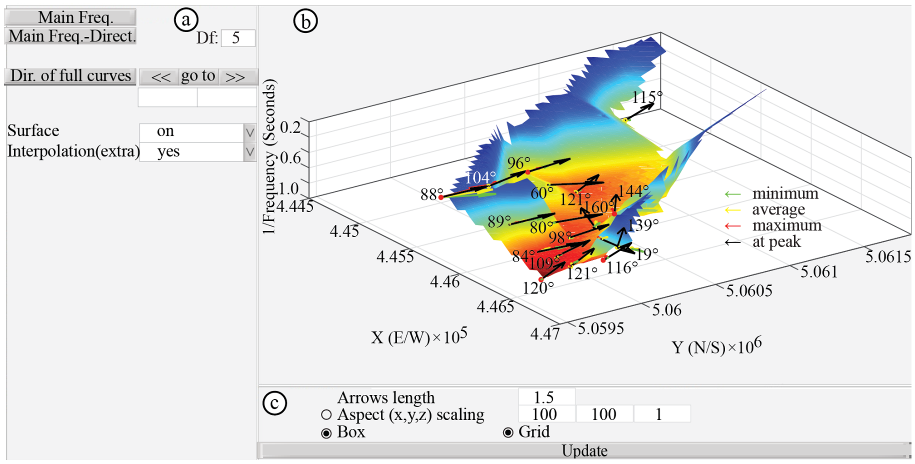

Figure 3.6: View of Tab 5. 3-D visualizations

3.3.6 Tab 6. IVS&W

Tab 6 (Fig. 3.7) "IS&W", is named from an acronym that refers to the bedrock mapping method introduced by Ibs-von Seht & Wohlemberg [6]. Regression laws available in the literature and usable to compute the bedrock depth are shown in figure (c). Bedrock depth estimates obtained using the regressions of figure (c) are shown using a set of color coded points placed beneath the points representing the measuring stations in (d). The topographic surface of the terrain is produced using the coordinates of stations and, if available, futher topographical locations defined by the user. A surface representing the estimated bedrock can be shown (for one regression at a time) to build a comprehensive view of the sedimentary system. Further, if either a sufficient set of well files were included in the project, or alternatively, if the user manually specifies the bedrock depth at a sufficient number of locations (by editing the "*Bedrock depth*" text field), a custom regression is computed and shown in plot (c). In this case, the corresponding bedrock depth estimates and reconstructed geometry can be shown as well.

Figures on this tab are automatically updated. The user may press the "update" button for a forced refresh. Visualization of image in paanel (d) is available only if frequency-depth pairs are known at least for three stations.

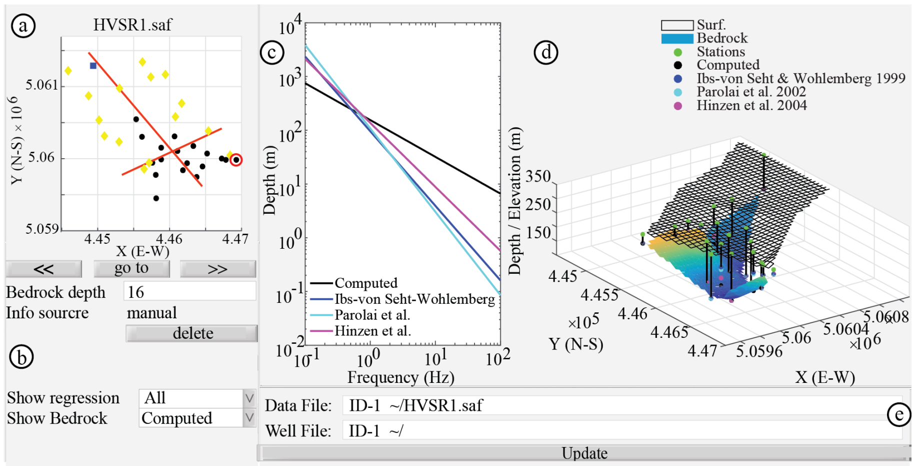

Figure 3.7: View of Tab 5. Tools for the Ibs-von Seht & Wohlemberg method

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