Statistics on the Performance of Instrument Types and Significance of HVSR for Shallow V_S Joint HVSR/DC Inversions

A Result from the Large-N Maupasacq Experiment (Southern France)

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Outline

Introduction and Motivation

Introduction

- Horizontal-to-vertical spectral ratio (HVSR) widely used to constrain shallow structures
- Predominantly a tool for soft sediment thickness estimations and seismic hazard analysis
- Practical and cost efficient

Motivation

- Maupasacq experiment attempts to shed light on the crustal structure of the Mauléon Basin
- Large-N array designed to infer about performance of passive seismic methods like local earthquake tomography (LET), ambient noise tomography (ANT) and, intrinsically, HVSR
- HVSR can supply constrains on the near surface model parameters that allow to distinguish otherwise equally valid models and therefore, complementing LET and ANT.

Methodology and Objective

- Semi-automatic inversion of HVSR jointly with dispersion curve data for a large-N arrays
- Comparison of our models to results from 3D local earthquake tomography
- Statistical analysis of data misfit and model variability
- Estimation of benefit of including HVSR to 1D inversions of Rayleigh wave velocity dispersion for shallow V_S structure

Maupasacq Experiment

Survey Area and Geology

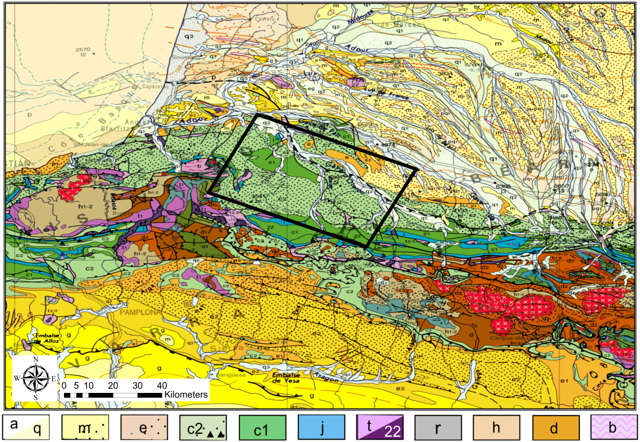

Figure: Regional geology depicting the predominantly cretaceous formations in the main area of the Maupasacq experiment. a: Quaternary alluvial deposits; q: Plio-Quaternary colluvium; m: Miocene; e: Eocene; c2: Upper Cretaceous; c1: Early Cretaceous; j: Jurassic; t: Triassic, 22: Ophites; r: Permian; h: Carboniferous; d: Devonian; b: Cambro-Ordovician.

The Mauléon-Arzacq rift system is situated in the French Basque country in the Western Pyrenees. The roughly EW-oriented system consists of four main domains. In this study we focus on the Mauléon Basin bounded by the North Pyrenean Frontal Thrust (NPFT) to the north and the Igountze-Mendibelza Thrust (IMT) to the south. The Mauléon Basin is characterised by thick (up to several kilometres) Cretaceous sedimentary successions over hyper-extended crust.

Maupasacq Experiment

Survey Layout and Acquisition Details

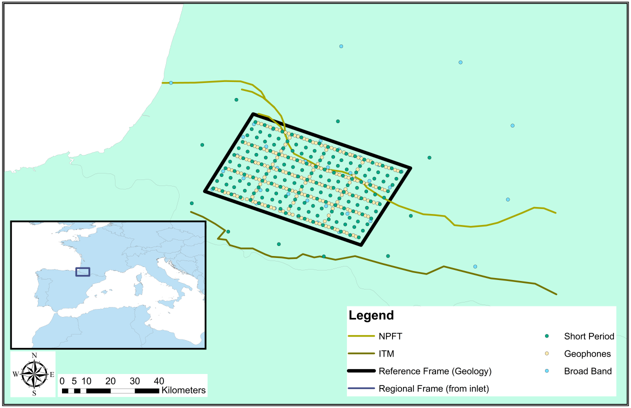

Figure: Placement and site layout of the Maupasacq experiment. Highlighted are site locations for the three employed sensor types, and two regional fault systems, the North Pyrenean Frontal Thrust (NPFT) and the Igountze-Mendibelza Thrust (IMT).

- dense network
- 441 3-C instruments
- 190 geophone nodes (SG-10 3C SERCEL)
- 197 short period instruments (3C Seismotech)
- 54 broadband stations (Guralp CMG40, Trillium Compact and Trillium 120)
- 6 months recording (April-October 2017)
- total area of 1500 km^2
- roughly a regular 3 km grid for short periods
- $6-7\,\mathrm{km}$ grid for broad bands
- 5 inline and 3 cross line configurations with 1 km site spacing for nodes
- generally good data quality observed

Analysis Results

First Look at HVSR Peak Frequency: Inversion Required

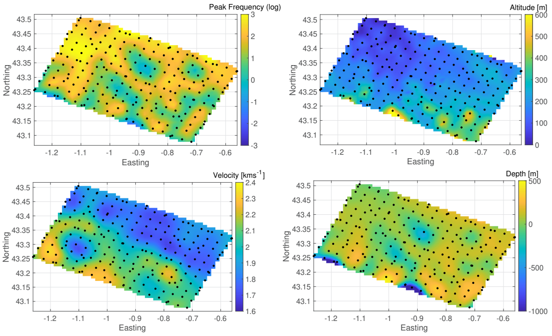

Figure: From left to right, then up to down: Maps of smoothed peak frequency, altitudes, V_S proxy and associated depth.

- peak frequency map of such a large area is difficult to work with, issues may be:
  - more than one interface may cause peak
  - inhomogeneous topography
  - varying dominant V_S
- we use V_S from Rayleigh wave group velocity DC data as proxy
- associated depth $d_p = \text{altitude} - \frac{V_S}{4f_p}$ yields a first approximation of the local near surface structure
- interpretation of peak frequencies and/or associated depth is daunting in this scenario and does not provide much insight; therefore, we must perform a data inversion

Joint HVSR/DC Inversion - Strategy

top depth	layer thicknesses			top depth
initial	step 1	step 2	steps 3-5	final
0	1	1	1	0
1	8	3	1	1
			2	2
		5	2	4
			3	6
9	20	7	3	9
			4	12
		13	6	16
			7	22
29	58	22	10	29
			12	39
		36	16	51
			20	67
87	157	59	26	87
			33	113
		98	43	146
			55	189
244	428	162	71	244
			91	315
		266	116	406
			150	522
672	1163	439	192	672
			247	864
		724	317	1111
			407	1428
1835	3165	1194	523	1835
			671	2358
		1971	863	3029
			1108	3892
5000	∞	∞	∞	5000

Table: 1D Model layer thicknesses and top depths in meters. The thick black line indicates the lowest depth that is considered for the 3D model.

Inversion Strategy

- joint inversion of HVSR and DC
- mean and covariance for χ^2 misfit calculation
- five distinct steps with an increasing number of layers with fixed thickness and increasing parameter freedom
- only layers above 1 $\mathrm{km\,b.s.l.}$ are interpreted
- inversion strategy is repeated 20 times with random starting models
- all models are saved and results in $100'000$ to $200'000$ models at each site
- χ^2 misfit is assumed to represent the negative log-likelihood of the evaluated 1D models
- sites with lowest $\chi^2 > 14$ are discarded
- models' mean and standard deviations are computed with weights according to the models' estimated probability

Joint HVSR/DC Inversion - Parameters

step	# layers	V_P	V_S	density	step
1	9	0.4 to 7 $\mathrm{km/s^{-1}}$ (free)	0.2 to 4 $\mathrm{km/s^{-1}}$ (increasing)	2 $\mathrm{t/m^{-3}}$ (constant)	1
2	16				2
3	30				3
4	30		0.2 to 4 $\mathrm{km/s^{-1}}$ (free)		4
5	30			1 to 3 $\mathrm{t/m^{-3}}$ (free)	5

Table: 1D inversion strategy and model parameter bounds.

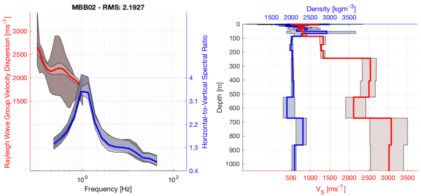

Figure: Examples of HV and DC data (left) with modelled responses are displayed next to their respective 1D data inversion results (right). Light shades represent the confidence in inversion results (model and data), while dark shades correspond to confidence in measured data. Solid lines represent the weighted mean of the inversion results and modelled responses.

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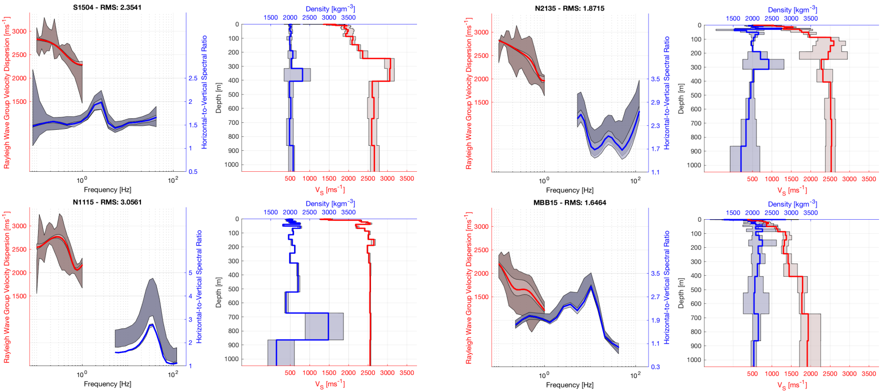
Joint HVSR/DC Inversion - Results and Data Fit



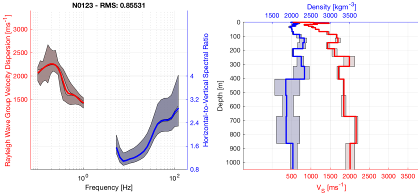


Figure: Examples of HV and DC data (left) with modelled responses are displayed next to their respective 1D data inversion results (right). Light shades represent the confidence in inversion results (model and data), while dark shades correspond to confidence in measured data. Solid lines represent the weighted mean of the inversion results and modelled responses.

Inversion Results

Improvements Compared to Pure DC Inversion

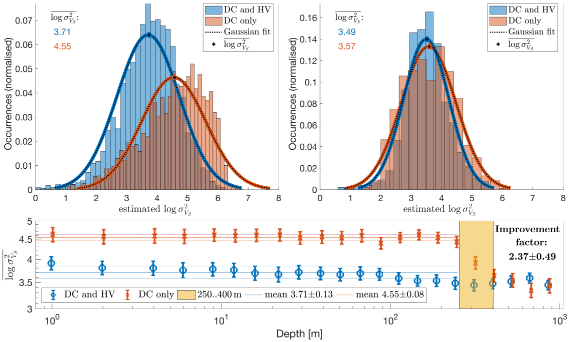


Figure: Final V_S models' variances are compared for DC inversions and joint inversions of DC and HVSR. (upper panels) Depicted are distributions of variance estimates from short period data inversions for two distinct layer depth ranges; (left) layers from 0 to 300 m depth, (right) layers from 300 to 1000 m depth, and (lower) the mean variance with 95 % confidence for each layer.

Question

Which specific improvements can we expect from joint HVSR/DC inversion?

Method

- Data misfit not suitable to answer this question, joint inversion must compromise and usually result in worse data fits for all data
- Compare final model confidences, which reflect how well a model can be ascertained with a given strategy

Answer

- 0 to 300 m: joint inversion improves V_S variances by a factor of 2 to 3
- $>$ 300 m: V_S variance estimates are equal between both strategies
- Important to note: for optimal joint inversion, data types' depth sensitivities must overlap sufficiently
- In practice, HVSR data may be used to substitute very short period DC data that may be more difficult to obtain

Performance of Different Instrument Types

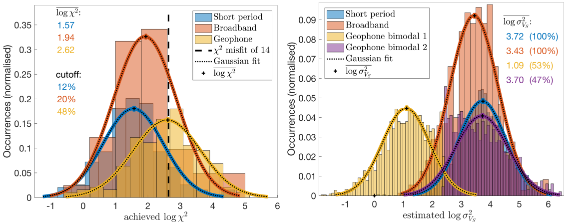
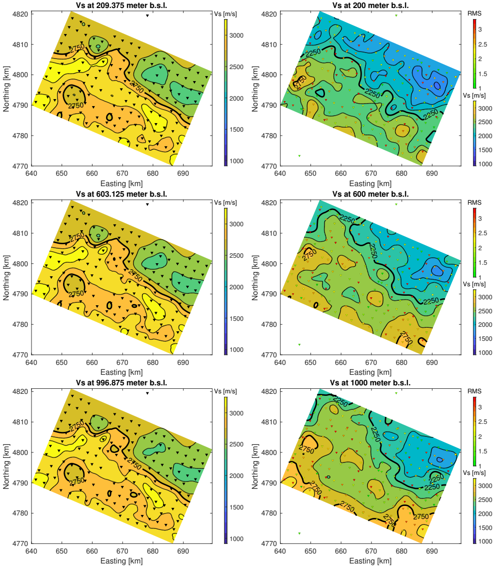


Figure: Final HVSR and DC joint inversion model statistics are compared for different instrument types. (left) Short periods provide most consistent HVSR converging to lowest χ^2 misfit, Broadbands are close second but half of the Geophone data inversions did not reach an adequate misfit for a reliable interpretation. (right) Short periods and Broadbands provide comparable confidence and Geophone inversion's confidence estimates yield a bi-modal distribution.

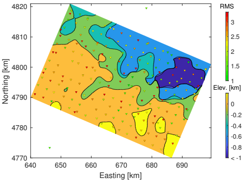
- Short periods and broad bands result in similar data misfits, model convergence and model variances
- Geophones exhibit poor convergence to an inferior data misfit with bi-modal model log-variances
- Geophones' performance caused by limited HVSR bandwidth due to relatively high cut-off frequency
- Joint inversion requires data to overlap with depth sensitivity, or convergence problems and overfitting may occur
- Examples of overfitted data and overconfident inversion results with poor data fit: N0123 and N1115 (slide 9), respectively
- N0123: modelled responses perfectly match observed data but inversion confidence is not reflected in observations
  - While possible that the found model is indeed correct, it is more likely that some of the found features, like the low velocity zones, are not required for a fit within data confidence and should be regarded as overfitting artefacts.
- N1115: inversion results suggest high model confidence even though data misfit is rather poor for HVSR data
  - Convergence of inversion failed consistently and only one data set (here DC) could be fitted well (incompatible data)
- Overfitting/-confidence dominant for geophones: Likely due to limited HVSR/DC bandwidth and ensuing sensitivity gap
- While technically not possible to obtain longer periods of HVSR data from geophones, it may be possible to mitigate these problems by employing DC data of shorter periods, which were not available for this study but generally can be obtained

3D Model and Comparison to Local Earthquake Tomography



Left Figure:
V_S results illustrated for (left panels) LE tomography and (right panels) Joint inversion of HVSR and DC data

Right Figure:
Depth of $V_S = 2kms^{-1}$ from 3D model.



3D Model of HVSR/DC Joint Inversion

- smoothed and interpolated 1D models
- north is lower in V_S than south
- regional anomalies align to some extent with features found in the geologic map
- southern border of northern basin shows sharp change in V_S (cp. Figure above) and may indicate the presence of a fault (presumingly the NPFT)

Comparison with LET

- independent V_S model of local earthquake tomography agrees qualitatively
- note, LET may overestimate V_S values at the nearer surface, i.e. above 1 km, which can be observed by indiscernible changes in V_S

Conclusions

- Studied utility and performance of HVSR in a large-N deployment with various instrument types
- For Joint inversion of HVSR and DC it is most important that both data types overlap depth sensitivity, which will depend on the instrument inherent cut-off frequency for HVSR data and the availability of shortest periods for DC data
- For the presented case (Maupasacq) broadband and short period instruments performed better than geophone nodes due to a gap in sensitivity (too short period HVSR due to cut-off, or too long period DC data)
- Data overfitting and estimated model parameter overconfidence are symptoms for sensitivity gaps between data types
- HVSR data (in a joint inversion) can be used to substitute short period DC data in order to obtain shallower models and avoid to obtain short period DCs which may be harder to obtain than HVSR
- Including HVSR to DC inversions can achieve confidence improvements of 2 to 3 times for the shallow layers that are, otherwise, not covered by the DC data
- HVSR/DC joint inversion may be useful to generate initial models for 3D tomographic inversions

References

J. Canérot.
The pull apart-type Tardets-Mauléon Basin, a key to understand the formation of the Pyrenees.
Bulletin de la Societe Geologique de France, 188(6), 2017; ISSN 17775817.

A. García-Jerez, J. Piña-Flores, F. J. Sánchez-Sesma, F. Luzón, and M. Perton.
A computer code for forward calculation and inversion of the H/V spectral ratio under the diffuse field assumption.
Computers and Geosciences, 97:67–78, 2016; ISSN 00983004.

E. Masini, G. Manatschal, J. Tugend, G. Mohn, and J. M. Flament.
The tectono-sedimentary evolution of a hyper-extended rift basin: The example of the Arzacq-Mauléon rift system (Western Pyrenees, SW France).
International Journal of Earth Sciences, 103(6):1569–1596, 2014; ISSN 14373262.

K. Polychronopoulou, A. Lois, N. Martakis, S. Chevrot, M. Sylvander, J. Diaz, and A. Villaseñor.
Broadband, short-period or geophone nodes? Quality assessment of Passive Seismic signals acquired during the Maupasacq experiment.
First Break, 36(April):71–76, 2018; ISSN 0263-5046.