Bull Earthquake Eng
DOI 10.1007/s10518-007-9039-0

ORIGINAL RESEARCH PAPER

Influence of instruments on the H/V spectral ratios of ambient vibrations

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Received: 22 May 2006 / Accepted: 17 May 2007

Abstract For an optimal analysis of the H/V curve, it appears necessary to check the instrument signal to noise ratio in the studied frequency band, to ensure that the signal from the ground noise is well above the internal noise. We assess the reliability and accuracy of various digitizers, sensors and/or digitizer-sensor couples. Although this study is of general interest for any kind of seismological study, we emphasize the influence of equipment on H/V analysis results. To display the impact of the instrumental part on the H/V behavior, some series of tests have been carried out following a step-by-step procedure: first, the digitizers have been tested in the lab (sensitivity, internal noise...), then the three components sensors, still in the lab, and finally the usual user digitizers-sensors couple in lab and outdoors. In general, the digitizer characteristics, verified during this test, correspond well to the

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manufacturer specifications, however, depending on the digitizer, the quality of the digitized waveform can be very good to very poor, with variation from a channel to another channel (gain, time difference etc.). It appears very clearly that digitizers need a warming up time before the recording to avoid problems in the low-frequency range. Regarding the sensors, we recommend strongly to avoid the use of "classical" accelerometers (i.e., usual force balance technology). The majority of tested seismometers (broadband and short period, even 4.5 Hz) can be used without problems from 0.4 to 25 Hz. In all cases, the instrumentation should be checked first to verify that it works well for the defined study aim, but also to define its limit of use (frequency, sensitivity…).

Keywords H/V technique · Instrumentation · Microtremors · Site effects

1 Introduction

Ambient vibration recordings for site effect estimation have grown in interest in recent years. The H/V method (Nakamura 1989) is considered by many authors as giving a good estimation of the fundamental frequency resonance, even if the corresponding amplification is not constrained (Lachet and Bard 1995; Goula et al. 1997; Mucciarelli 1998; Lebrun et al. 2001). So this technique is commonly used in microzonation projects (e.g., Monge et al. 1999; Guéguen et al. 2000; Régnier et al. 2000) in order to identify possible site effects. Considering that such field works are inexpensive and do not require heavy seismic sources nor drilling, the passive recording of ambient vibrations may provide a low-cost mapping tool of site features, even in urban areas, where geotechnical information is usually difficult to obtain. One of the aims of the European Site Effects Assessment Using Ambient Excitations (SESAME project) (Bard 2002; Bard and the SESAME team 2003, 2004) is to investigate the influence of the instrumentation on the H/V ratio (Guillier et al. 2002a, b).

The purpose of this paper is to report the results of basic tests regarding the seismological equipment, documenting the influence of different combinations of commonly used digitizers and sensors on the final results of H/V spectral ratios. This is based largely on the results of a workshop held in Bergen, Norway at the Department of Earth Science, University of Bergen on October 2001, within the framework of the SESAME project. A total of 12 digitizers and 18 sensors were tested and compared. Only few investigations are available on this topic, the main one by Mucciarelli (1998), concluding with the suggestion to avoid the use of accelerometers because of their low sensibility to ambient noise.

As the tested instruments are seismological equipment, the results of these studies are of interest not only to H/V technique users, but also to any person working with such equipment.

2 Experimental setup

During the Bergen workshop, a series of tests were conducted in order to compare the behavior of different currently used equipments. For the sake of homogeneity, data collected for these tests were converted into a common format and identically processed with the same software. The first set of tests was devoted to analyze the physical properties of the digitizers and the minimum noise value they were able to record for different gains and with different sensors. The second set of tests was dedicated to the sensor analysis, where we checked the response of each sensor connected to the same digitizer. The last set of tests regards the overall performance of the digitizer/sensor couples. In order to evaluate the digitizer-sensor

Table 1 List of the digitizers tested during the Bergen Workshop

CODE	Digitizers/recorders	Constructor	Owner
HA	Hathor-3	Leas	CETE, France
TI	Titan 3	Agecodagis	LGIT, France
RE	Reftek 72A07	Reftek	INGV, Italy
MA	Mars88	Lennartz	INGV, Italy
IN	INGV self-made	INGV Italy	INGV, Italy
ET	Altus-Etna int. Digitis.	Kinemetrics	ITSAK, Greece
GB	GBV 316	GEOSIG Switzerland	UiB, Norway
NH/NL	Nanometrics CH1–3	Nanometrics	UiB, Norway
LE	CityShark	Leas	LGIT-IRD, France
ML	MarsLite	Lennartz	U. Potsdam, Germany
SS	Kinem. SSR	Kinemetrics	ICTE, Portugal
E3/E6	Earth Data 3CH	Earth Data	UiB, Norway

In the text and on the figures, we used the code name. Note that two stations (NH/NL and E3/E6) appear twice because they have two different gains

behaviors, simultaneous ambient vibration measurements have been conducted at two locations, a concrete pier installation (coupled directly to the bedrock in the laboratory), as well as an outside free-field site.

While these tests have been carried out in order to check the impact of the instrumental part of the data on H/V curves, they present a flat trend, except for the test done on grass. This flat trend is useful to check the impact of various parameters (sensor, digitizer, couple digitizer-sensor) on the H/V curve (creation of false peaks), but is less useful to check the impact of these parameters on H/V peaks. Moreover, as shown later on, on all sites, the natural background noise energy is concentrated below 1 Hz, so the impact of the parameters below 1 Hz is the easiest to measure using the absolute spectra, while a lack of energy abnormally highlights the impact of the instruments in the higher frequencies.

2.1 Digitizers

During the experiment, 12 digitizers have been used (Table 1), including a digitizer with an automatic variable gain (NH-NL) and a seismic station recording synchronously two sets of three channels, three at low gain and three at high gain (E3–E6). The others stations have a dynamic range from 16 to 24 bit. Performances have been analyzed through four different parameters: internal noise, stability over time, sensitivity of the digitizer and channel consistency.

2.2 Sensors

Eighteen sensors have been tested (Table 2), divided in three categories: accelerometers (three sensors), broadband seismometers with a low frequency cut-off between 30 and 100 s (three sensors, but only two different) and short period seismometers from 0.2 to 4.5 Hz (12 sensors of nine different types).

Table 2 List of the sensors tested during the Bergen Workshop in the SESAME marks.

CODE	Type	Constructor	Characteristics
L1	LE-3Dlite 1 Hz	Lennartz	1 Hz seismometer
L2–L5	LE-3D 5 s	Lennartz	5 s seismometer
L6	LE 3D Classic	Lennartz	1 Hz seismometer
M1	Mark L4-C	Mark Product	1 Hz seismometer
M2	Mark L-22	Mark Product	2 Hz seismometer
M4	Mark L-28B	Mark Product	4.5 Hz seismometer
CH	CD-S2A	Chinese Republic	2 Hz seismometer
R1	Kinem. Ranger SS1	Kinemetrics	1 Hz seismometer
SN	Sensor GBV	Sensor Netherland	4.5 Hz seismometer
GI and GS	Guralp CMG-40T	Guralp	Broadband, 30 s
KS	Geotech KS 2000		Broadband, 100 s
KE	Episensor	Kinemetrics	Accelerometer
GA	Guralp CMG-5T	Guralp	Accelerometer
KG	Altus-Etna Internal Episensor	Kinemetrics	Accelerometer

The code name is used in the text and the figures. Note that L2 to L5 correspond to the same type sensor. In the R1 case, three 1-C seismometers were used

2.3 Data processing

Data have been processed using the SEISAN software developed at the University of Bergen (Havskov and Ottemöller 2000). SEISAN has been chosen (1) in order to provide a uniform processing platform for the entire data set, and (2) because of the existing facilities within SEISAN to convert data from different formats. Finally, for H/V calculations, a specific software code developed at the University Joseph Fourier, Grenoble (Guillier et al. 2001) has been used. For the entire experiment, the same computational H/V parameters were used for automatically selecting the time-intervals (windows) along the recorded traces (Chatelain et al. 2005):

- Window length variable from 25 to 32 s;
- STA: 1 s;
- LTA: 30 s;
- Anti-trigger threshold: between 0.3 and 2.0;
- Konno and Ohmachi (1998) smoothing, defined with a constant of 40.

3 Tests on Digitizers

In order to evaluate the possible influence of the digitizers on H/V results, several tests have been performed to check sensitivity and polarity, internal noise and stability, and finally channel consistency.

Table 3 Summary of the digitizer sensitivity tests

Code	LE	TI	ET	ML	RE	MA	IN	HA	SS	GB
Sampling rate	100 Hz	125 Hz	100 Hz	125 Hz	125 Hz	125 Hz	50 Hz	50 Hz	200 Hz	100 Hz
Dynamic (bit)	24–6 (mask)	131.1 dB 21.5 bits	108 dB 18 bits	120 dB 20 bits	140 dB 24 bits	120 dB 20 bits	140 dB 24 bits	24–5 (mask)	16	16
GAIN	1	256	1	32	1	1	1	1	1	1,000
Manufacturer = theoretical value of one count (μV/counts)	19.073	0.58	0.30	32.00	1.91	1.00	0.85	9.539	76.29	0.0763
Battery voltage (avg absolute)	1.547 V	1.546 V	–	0.439 V	1.579 V	0.840 V	1.547 V	1.548 V	1.48 V–1.5 V	4.67 mV
Battery voltage (avg.: max-min)	3.094	3.092	–	0.878	3.158	1.68	3.094	3.096	2.98	9.33 mV
Z MEASUREMENT (avg. max-min)	161,599	5,149,256	–	27,818	1,656,376	1,679,748	3,642,154	323,200	38,826	121,960
N-S MEASUREMENT (avg max-min)	161,589	5,143,398	–	27,821	1,656,665	1,679,104	3,640,689	323,264	38,984	121,326
E-W MEASUREMENT (avg. max –min)	161,601	5,141,723	–	27,819	1,656,458	1,681,592	3,641,245	323,136	36,263	121,484
Z channel (μV/counts)	19.146	0.600	0.298	31.562	1.907	1.000	0.849	9.579	76.753	0.0765
Z deviation from theoritical value:	0.38%	−3.53%	0.67%	1.37%	0.02%	−0.02%	0.06%	−0.42%	−0.60%	0.26%
N-S channel (μV/counts)	19.147	0.600	0.298	31.559	1.906	1.001	0.850	9.577	76.442	0.0769
NS deviation from theoritical value:	0.39%	−3.45%	0.67%	1.38%	0.04%	−0.05%	0.02%	−0.40%	−0.19%	0.78%
E-W channel (μV/counts)	19.146	0.600	0.298	31.561	1.906	0.999	0.850	9.581	82.177	0.0768
EW deviation from theoritical value	0.38%	−3.45%	0.67%	1.37%	0.03%	0.09%	0.03%	−0.44%	−7.71%	0.65%
mean deviation from theoritical valus (in %)	0.38	3.48	0.67	1.37	0.03	0.05	0.04	0.42	2.83	0.56
Polarity	normal	normal	normal	normal	normal	normal	normal	normal	normal (pb on EW neg)	normal

3.1 Sensitivity and polarity

The aim of this test was to check the sensitivity of the digitizers given by the manufacturers against sensitivity measured in the laboratory. The test has been performed for ten out of the 12 digitizers (Table 3). In order to evaluate the sensitivity and verify the polarity, a DC voltage was sent synchronously to the three channels of each of the digitizers with a normal and an inverse polarity. To verify the DC voltage sent, we used an 8-bit resolution tester, which is definitely lower than the resolution of all the tested digitizers (Table 3). First, the offset was removed by subtracting the positive and negative levels, and then experimental sensitivity was computed by dividing the measured DC voltage by the average digital counts measured on the recordings. From these results (Table 3) we conclude that:

- polarity is almost always correct. However we strongly recommend to check polarity to avoid error in the wiring;
- differences between theoretical values and calculated values are generally low: 7 digitizers show a sensitivity close to the one given by the manufacturer with an error smaller than 1%;
- the 3 different channels of a given digitizer have generally very similar sensitivity (except for SS station), indicating that the gain is similar for the three channels.

3.2 Internal noise-stability

Internal noise of ten digitizers was measured by short-circuiting the sensor outputs. 10-min duration signals, both at cold and warm start, were studied. In a first step, these data (cold and warm records) allowed the study of the standard deviation of the internal noise and the measurement of typical baseline offsets for the individual digitizers (Table 4, Fig. 1).

3.2.1 Cold start recording

For most digitizers, the standard deviation of the internal noise is less than 20 digital counts. We consider this value as relatively low compared to the signal level recorded for ambient vibrations. The "cold start" data of the ten tested digitizers demonstrate that offsets are highly variable. The majority of data loggers show additionally spurious jumps in the offset levels, some of the recorders exhibit drifting, and others contain even long period oscillations in the records.

3.2.2 Warm start recording

After a 1-h warming up, internal high frequency noise is similar to the data coming from the cold start recording, indicating that the warm up of the digitizer is not mandatory to reduce internal high frequency noise. However, after warm up, the digitizers do not anymore show jump, drift and long period fluctuation (except for TI station), while the offset has partially decreased but is still present.

In order to evaluate the digitizers potential with different sensors, the noise power spectral densities were calculated for each digitizer assuming the parameters of three possible sensors: the least sensitive (4.5 Hz seismometer), the most usual (1 Hz seismometer) and the usual sensor used by each group during their own experiments. We call this "virtual sensors" since no sensors were connected. In this way the power spectral density plots will show the lowest possible noise level in the whole frequency band of interest that can be resolved at any site

Table 4 Summary of the absolute values of the internal noise for "cold start" (first record after the digitizer has been unpowered during at least 12 h) and "warm start" (recording after the digitizer has been powered for at least 1 h)

	Gain	Z (DC)	NS (DC)	EW (DC)	Drift (DC/600s)	Offset (DC)	comments
	COLD START						
HA	16	6	6	6	0	160	
TI	–	–	–	–	–	–	
RE	32	9	9	9	30	230	
MA	32	6000	6000	6000	0	12,500	
IN	10	8	8	8	100	100	
ET	10	40	40	35	0	70	
GB	–	3	3	3	25	280	
LE	512	13	31	15	0	84	
ML	8	6	6	6	0	7	
SS	1,000	9	8	28	10	28	
	WARM START						
HA	16	6	6	6	0	157	No observable drift, very low bit noise, equally distributed
TI	256	9	8	9	8	20	
RE	32	8	8	8	0	80	Warm records taken after 20 hours! Very strong drift on long time. Very long period instabilities
MA	32	6,000	6,000	6,000	0	13,500	
IN	6	6	6	6	0	5	Warm records taken after 20 hours! Strongest drift of all digitizers. Very long period instabilities
ET	10	50	50	50	0	40	

Table 4 continued

	Gain	Z (DC)	NS (DC)	EW (DC)	Drift (DC/600s)	Offset (DC)	comments
GB	–	2	2	2	0	273	Drift within first 10 minutes, offset, after warm-up +/− 1 bit noise max
LE	512	11	12	11	0	5	
ML	8	5	5	5	0	7	First block scrambled
SS	1,000	20	7	12	0	23	

Z, NS, and EW are the internal noise standard deviation in digital count (*DC*) for the vertical, north–south and east–west components respectively. The offsets and drift, during the 10 min record, are given in digital counts (for the worst channel)

assuming the given virtual sensor. Since these spectra also are compared to the Peterson's curves (Peterson 1993), they also give a good absolute reference to the resolving potential.

Then, the initial records coming from "cold and warm recordings" are convolved with the response of the three virtual sensors in order to test the sensitivity of various possible combinations (see example in Fig. 1). For each recording, three different gains were applied (i.e., the low, the high and the usual gain). Then, the results were compared with Peterson's curves (Peterson 1993).

3.3 Channel consistency

Channel consistency concerned the verification of both synchronism and gain of the digitalization of the three channels. Possible differences between channels can be related to time (digitization of the channels at significantly different times) and amplitude (corresponding to a gain difference). The possible effects of such differences, on the H/V ratio, were first investigated for simple signals (triangular waveform), evaluating the influence electronic noise, synchronization between channels and difference of gain between channels. Sending the same waveform to the three components of a digitizer, the H/V ratio should be equal to 1 in the whole frequency range.

3.3.1 Modeling a simplified waveform

From this modeling (SESAME team, 2002), the main impacts of the channel consistency on the H/V ratio are related to:

(a) the level of electronic noise compared to the level of the recorded waveform. This factor affects only the higher frequencies (>20 Hz), generating instabilities proportionally to the ratio [amplitude of electronic noise/ amplitude of recorded data] (Guillier et al. 2002a, b);
(b) the gain difference between channels. Depending on the value of the gain difference, the H/V ratio is simply translated upward if the gain error corresponds to an amplification of the digitized values, and downward in case of a reduction (SESAME team 2002);

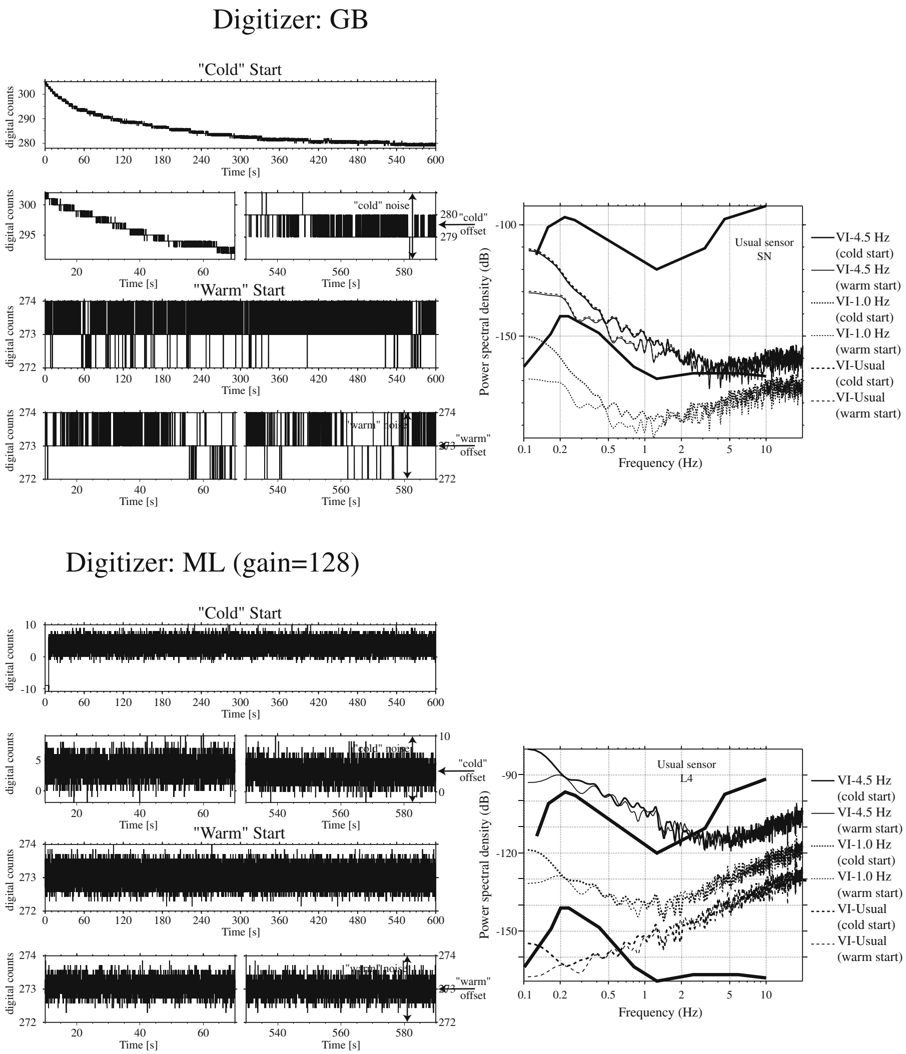


Fig. 1 Digitizer internal noise tests with two virtual sensors (4.5 and 1 Hz) and the usual sensor for the digitizer. These tests have been performed for cold and warm start records. For the power spectra graphs, the two heaviest lines are the high-noise and low-noise models from Peterson (1993). The upper part of the figure presents the results for the GB-digitizer connected to its usual SN sensor, when the lower part corresponds to the ML-digitizer connected to the L4 sensor

(c) the lack of synchronization between channels. The lowest detectable time shift (measured in samples) for a digitizer is its number of samples per second divided by the maximum amplitude (which depends on the gain and the noise measurement level; Guillier et al. 2002a, b). This factor mainly influences the H/V ratio (up to 80%) in the upper frequency range;

Moreover, if there is no digitization difference, the channel-to-channel differences (NS-EW, NS-Z, and EW-Z) should be zero. From the modeling of the triangle waveforms recorded

Table 5 Summary of results for the triangular waveform used for the channel consistency test

Station name	Maximum channel amplitude	Maximum difference between channel	Percentage of error	Wave-form shape cases	Time shift	Digita-lization problem
ET	3,458,162	434	0.01255	1	NO	NO
LE	82,583	21	0.02543	1	NO	NO
IN	2,211,167	1018	0.04604	3	YES	NO
RE	515,836	247	0.04788	1	NO	NO
HA	190,176	128	0.06731	1	NO	NO
ML	1,048,575	746	0.07114	1	NO	NO
NL	30,736	3,456	11.24414	1	NO	NO
NH	137,792	1,088	0.78959	1	NO	NO
TI	1,523,470	2,308	0.15150	1	NO	NO
MA	503,936	1,088	0.21590	1	NO	NO
GB	10,201	40	0.39212	3	YES	NO
E3	27,238	271	0.99493	1	NO	NO
E6	290,246	3,414	1.17624	1	NO	NO
SS	43,987	10,945	24.88235	4-a	NO ?	YES

Waveform shape cases are defined in the text. Time shift: existence of a notable difference in time during the digitization of the three channels. Digitization problem: the digitized waveform is notably different from the original waveform

synchronously on three channels, we can observe the following possible differences waveform shape cases:

(1) the waveform of the difference is similar to the digitized one. It witnesses a difference in gain between channels;
(2) the waveform of the difference shows a square shape. This is witnessing a constant delay in the digitization between channels. As the waveform is oversampled, a sample on a channel is digitized at T0 (sample S[T0]), when in some cases the digitization of the same sample on the next channel occurs at $T0+\Delta t$ (sample $S[T0+\Delta t]$), where Δt is less than the sampling rate but proportional to the oversampling rate. In this case, even if the waveform is the same on both channels, depending on the amplitude of the digitized waveform, the sampled values at T0 and $T0+\Delta t$ can be different. In the simplistic case of a triangle waveform, the difference of amplitude is the same if the digitization is done with a homogeneous difference of Δt, except that the difference (channel1-channel2) is negative if the waveform is increasing and positive if the waveform is decreasing;
(3) the waveform of the difference shows a combination of the two previous ones. This reflects a mix of gain and time differences;
(4) finally, any other kind of waveform indicates (a) a misfit between the real waveform and the digitized one, in case of a high difference amplitude, or (b) a perfect digitization without gain nor time difference in case of very low difference amplitude, i.e., of the same order of magnitude as the electronic noise.

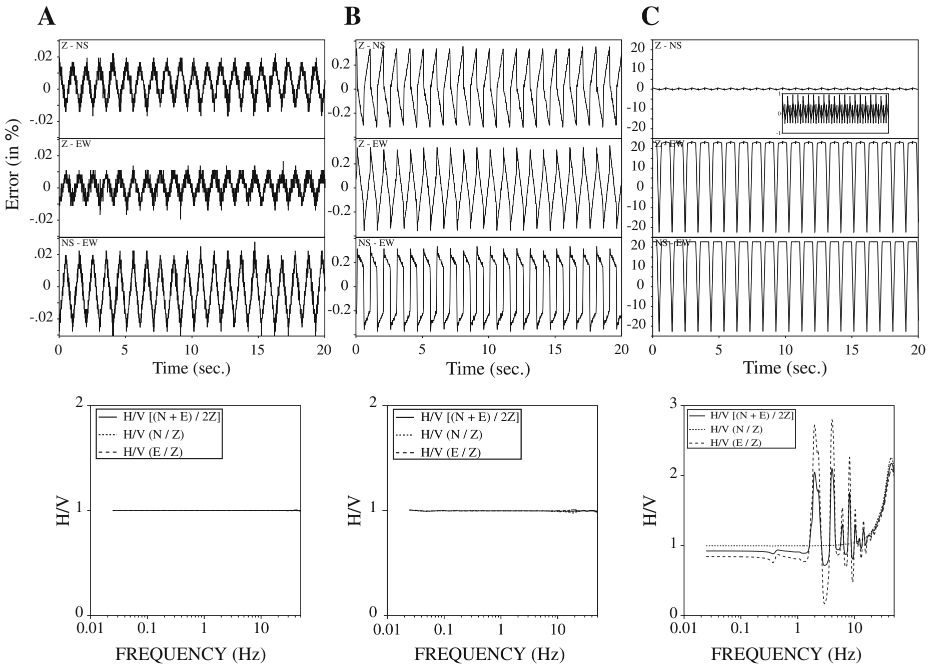


Fig. 2 Channel consistency tests. The same 1 Hz triangle waveform was recorded simultaneously on the three channels of each recorder. **(A)** LE recorder; channel to channel differences and H/V ratio showing the error due to a gain difference between channels. **(B)** GB recorder; channel to channel differences and H/V ratio showing the error due to a difference in time digitization between channels, probably coupled to a gain difference. **(C)** SS recorder; channel to channel differences and H/V ratio showing the misfit between the received waveform and the digitized one

3.3.2 Experimental tests on a simplified waveform

To generate data usable for the four types of differences, a 1 Hz triangle waveform was sent synchronously to the three channels of each digitizer. All the channel-to-channel differences (NS-EW, NS-Z, and EW-Z) have been calculated after offset removal. From the 14 tested recorders (Table 5), 11 show a pure gain difference between channels (example shown on Fig. 2A) with errors varying from 0.01% to more than 11%, two show a time shift (Fig. 2B) and one exhibits a significant problem during the digitization (Fig. 2C). The impact of gain difference between channels on the H/V ratio is most often very low (Fig. 2A), although in a case a strong difference generates a non-negligible effect on the H/V ratio (Fig. 2B). Finally, the strongest impact on the H/V ratio is observed with the station SS (Fig. 2C; Table 5).

Another way to study the time shift is to order the differences between channels, analyzing the difference between channels through the distribution of residuals. If there is no time shift, the distribution of the difference between 2 channels, digitizing the same waveform, should be Dirac-like at zero if there is no electronic noise, while if there is electronic noise the distribution of the classes should be close to a Gaussian curve centered on 0. This Gaussian curve is due to the difference of electronic noise between channels (Fig. 3A) and could reach the sum of the maximum of each channel electronic noise. The results for the two stations showing a time shift (Fig. 3B, 3C) demonstrate that the digitization has been done with an easily detected time shift:

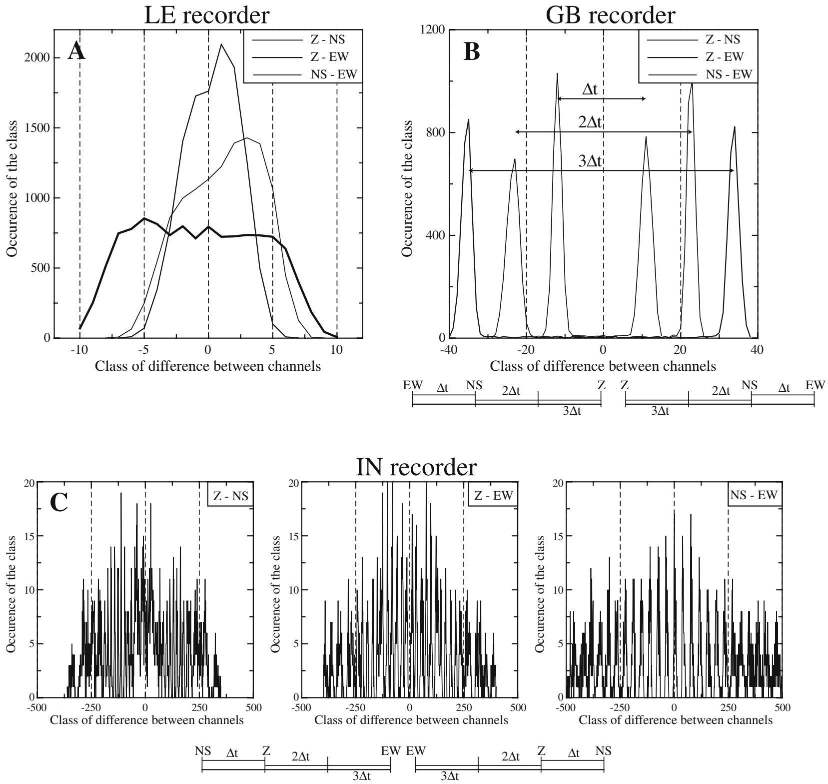
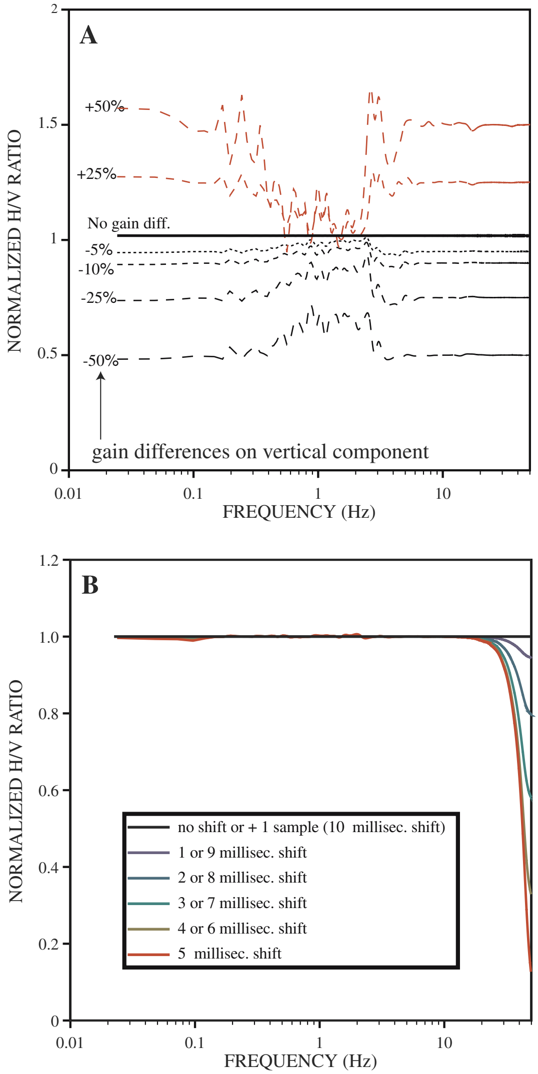


Fig. 3 Channel consistency tests. The graphs show the difference between channels by class value, in count. In case of no time shift, the difference between two channels, digitizing the same waveform, must be as close as possible to a Gaussian curve centered on 0, highlighting the distribution of electronic noise and the gain difference between channels. **(A)** LE recorder, without clear and/or detectable time shift. **(B)** GB recorder, with a clear time shift. **(C)** IN recorder, with no real clear time shift, this case is more difficult to interpret

(a) for the GB recorder (Fig. 3B), the graph clearly shows that the three channel differences do not have a Gaussian shape; each difference shows two peaks, with peak to peak differences of X, 2X and 3X. If we assume that this difference is a time shift, the digitization difference between NS and EW channels is Δt, 2Δt between NS and Z, and finally 3Δt between Z and EW. So, the order of digitization is either EW-NS-Z or Z-NS-EW. In both cases, the digitizer is “doing something else” between the NS and Z digitization. A possibility is that the A-D card has four channels and does not use the channel between channels NS and Z;

(b) for the IN recorder (Fig. 3C), the graph is more complex. All the signal differences are of the same order of magnitude. However, for the Z-NS difference, there are 36 peaks in an interval of 500, defining an inter-peak of 14; for the Z-EW difference, there are 19 peaks in an interval of 500, so an inter-peak of 28, and finally for the NS-EW difference, there are 13 peaks in an interval of 500, so an inter-peak of 42. If we assume that the inter-peak represents a time shift, the inter-peak of 14 can be assimilated to Δt, the inter-peak of 28 to 2Δt and the inter-peak of 42 to 3Δt. The same analysis as for the GB recorder, gives an order of digitization of NS-Z-EW or EW-Z-NS, with a forth channel digitizing between the EW and Z channels.

Fig. 4 Channel consistency tests on natural data (LE-L2 couple, digitization at 100 Hz). These graphs show the impact of a gain difference between channels and the time shift on the H/V ratio. **(A)** Gain difference impact on H/V ratio with various changes of gain. **(B)** Time shift impact on H/V ratio. For the frequencies higher than 20 Hz, the impact increases when the shift increases toward 0.5 sample and then decreases to come back to the original H/V ratio that is reached when the time shift is close to 1 sample (10 milliseconds)



3.3.3 Tests on natural waveforms

After outlining the principal differences, impacting on H/V ratio, we consider natural record 15 min long (considered as the reference) that we modified by:

(a) arbitrary gain changes on channel;
(b) a time difference, corresponding to an interpolation of the preexistent waveform. This time lag can be done on any channel.

We take the computed H/V ratio of the original waveform as the H/V reference, and for each modified waveform, we compute the H/V spectral ratio and compare it to the reference.

Influence of gain (Fig. 4A): The impact of gain variation between channels on the H/V ratio is visible if the difference of gain reaches at least 15%. In the case of gain reduction, the impact on the H/V ratio is visible from the lowest reduction tested (0.1%). The impact of gain variation on the H/V ratio is not the same over the whole frequency range. From 0.01 to 0.15 Hz as well as above 5 Hz, the impact corresponds to a simple translation. The problem is raised by the non-systematic error observed between 0.15 and 5 Hz, by a variable impact all along the frequency range.

So, the gain difference between channels changes the H/V ratio. In medium-low frequencies range, the shift is not predictable, whereas in high and very low frequency ranges, changes on H/V are proportional to the difference in gain. Finally, the influence the gain difference depend on the amplitude of the recorded waveform: if the record has a small amplitude, the influence of the gain difference is low, whereas a high amplitude digitization increases the influence of the gain difference.

Influence of time-shift (Fig. 4B): The impact of the time difference on H/V ratio is increasing when this difference increases (maximum of 80% reached at 0.5 sample) and decreases gradually when the difference returns progressively to 1 sample.

Depending on the difference in time, the time shift modify the H/V ratios mainly at the higher frequencies over 15 Hz. So, the affected frequency range decreases when the time difference is increasing. In the lower frequencies (<0.1 Hz), the time shift does not modify significantly the H/V ratios (difference less than 1%).

3.4 Conclusion on digitizer tests

In general, the tests demonstrate that the sensitivities of the tested digitizers are close to the manufacturer's specifications, with a correct polarity. For all digitizers, the internal high frequency noise does not depend on how long the digitizer has been warmed up, even though the warm up allows to reduce the offset value. During the first minutes of warm up, digitizers can present some jumps, drift and long period oscillation, but the effect have such a long period that is does not notably influence the H/V curves in the usual frequency range of 0.1–25 Hz. However, to avoid any problem, it is strongly recommended not to use data during the first 10 min after the digitizers have been switched on. Finally, tests on channel consistency show that the H/V ratio is sensitive first to a possible difference in time of digitalization at different channels, especially over 10 Hz, and second to a difference of gain between channels, which is unpredictable in the 0.2–5 Hz frequency range, this might be due to the widening. Among the tested digitizers, only one digitizer presented major problem, related to digitalization, strong enough to modify notably the H/V ratio.

4 Test on sensors

The question addressed here is whether the type of sensor has any influence on H/V results. In that aim, we have recorded 2 min of ambient seismic noise, connecting two different sensors (reference and tested sensor) to the same NL-NH digitizer (low and high gain). Sensors have been set up next to each other on a concrete pier, which is coupled directly to the bedrock, inside the Bergen University laboratory. Finally, signals have been corrected for instrument response. We always use the same reference sensor: the GS sensor (Table 2). Eighteen sensors have been tested: 3 accelerometers, 3 broadband and 12 short period seismometers ($\geq$ 0.2 Hz, see Table 2). The sensors responses were systematically checked to make sure that the instrument corrections were done correctly (as well as polarity).

Table 6 Summary of the tests on the sensor impact on H/V ratio

	Time domain analysis			Spectral domain analysis			H/V results	
	Signal Form	Signal Amp.	Polarity	Spectra			NS/Z	Acceptable for H/V
				Z	NS	EW		
L1	Very good (>1 Hz)	+100% (< 0.2 Hz)	OK	OK (>0.3 Hz)	OK (>0.2 Hz)	OK (>0.1 Hz)	Similar	Yes
L2	Very good (>0.1 Hz)	±15%	OK	OK	OK	OK (>0.3 Hz)	Similar (>0.1 Hz)	Yes
L3	Very good (>0.1 Hz)	±15%	OK	OK	OK	OK (>0.3 Hz)	Similar (>0.1 Hz)	Yes
L4	Very good (>0.1 Hz)	±5%	OK	OK	OK	OK (>0.2 Hz)	Similar (>0.1 Hz)	Yes
L5	Very good (>0.1 Hz)	Good	OK	OK	OK	OK	Similar	Yes
L6	Very good (>0.3 Hz)	±10%	Reversed	OK (>0.2 Hz)	OK (> 0.2 Hz)	OK (>0.2 Hz)	Similar	Yes
M1	Very good (>0.1 Hz)	±20%	OK	OK (>0.2 Hz)	OK (>0.2 Hz)	OK (>0.2 Hz)	Similar	Yes
M2	Very good (>0.3 Hz)	±5%	OK	OK (> 0.2 Hz)	OK (>0.2 Hz)	OK (>0.4 Hz)	Similar	Yes
M4	Good (>0.4–0.5 Hz)	±15%	Reversed	OK (>0.4 Hz)	OK (> 0.4 Hz)	OK (>0.4 Hz)	Similar (>0.4 Hz), pb at 3 Hz	Yes (>0.3 Hz)

Table 6 continued

	Time domain analysis			Spectral domain analysis			H/V results	
	Signal Form	Signal Amp.	Polarity	Spectra Z	Spectra NS	Spectra EW	NS/Z	Acceptable for H/V
CH	Good (>0.3 Hz)	±15%	Reversed	OK (>0.2 Hz)	OK (>0.2 Hz)	OK (>0.2 Hz)	Similar (>0.2 Hz)	Yes
R1	Very good (>0.3 Hz)	±10	Reversed	OK	OK	OK	Similar	Yes
SN	Not so good (>0.4 Hz)	+30%	1 channel reversed	OK (>0.3 Hz)	OK (>0.5 Hz)	OK (>2 Hz)	Similar, some diff.	Yes (>0.3 Hz)
GI	Very good	±25%	OK	OK	OK	O K	Similar	Yes
KS	–	–	OK	OK	OK (>0.2 Hz)	OK	–	Yes
KE	Not so good (>5 Hz)	±100%	OK	OK (>0.5 Hz)	OK (>0.4 Hz)	OK (>4 Hz)	Not similar	No
GA	Not so good (>5 Hz)	+15 to 100%	OK	OK (>8 Hz)	OK (>8 Hz)	OK (>8 Hz)	Not similar	No
KG	Not possible	????	????	OK (>0.5 Hz)	OK (>0.3 Hz)	OK (>3 Hz)	Not similar	No

The results from each tested sensors are compared to the GS results. In the R1 case, three 1-C seismometers were used

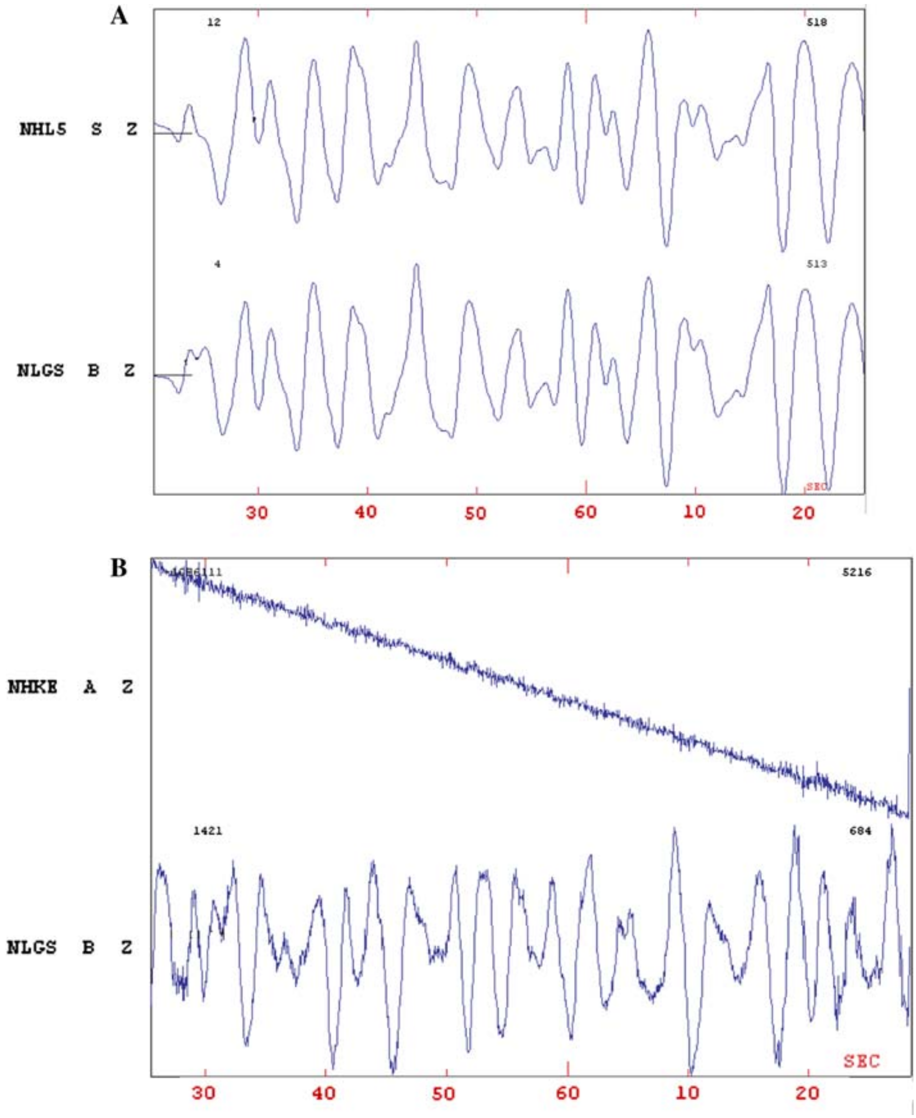


Fig. 5 Comparisons of channels, to the reference sensor (GS), completed for a short period seismometer **(A)** and an accelerometer **(B)**. The numbers above the traces to the right are the maximum amplitudes (in nm) and the numbers on the left the offset (in nm). **a** very good similarity in displacement field for the 0.1–1 Hz frequency band between the Z-channel L5 seismometer (upper waveform) and the same channel of the reference broadband seismometer GS (lower waveform). **(B)** original signals for the vertical components of the KE accelerometer (upper waveform) and the reference broadband seismometer GS (lower waveform). The figure shows the original signals. Note the DC drift of the KE sensor

Comparisons are related to time domain signals (form, amplitude, polarity), spectral amplitude (Vertical, North–South and East–West), and H/V ratio. All sensors, showing a H/V difference of <2 with the reference over the whole H/V curve, are assumed to be acceptable for the H/V technique. Results are summarized in Table 6.

4.1 Comparison in time domain

Each pair (reference and tested sensor) was compared using instrumental correction in order to check similarity. The signals were plotted together in different frequency bands and visually compared. For each sensor, a qualitative evaluation is given in the "time domain analysis" part of Table 6. For seismometers (Fig 5A), the results are that the signal shapes and the signal amplitudes are pretty consistant with the reference one, for frequencies above the natural frequency of the tested seismometer. Below the natural frequency, results remain quite acceptable. However, several sensors had a polarity problem. Accelerometer waveforms (Fig 5B) are very different from the reference waveforms (especially below 5 Hz), with errors in amplitude reaching ±100% and randomly varying with the frequency. In some cases, this is due to low accelerometer sensitivity.

4.2 Comparison in frequency domain

We compared the results of the tested sensors in the frequency domain, using spectral amplitude ratio of the reference sensor to the tested sensor. For seismometers, results are rather good (see "spectral domain analysis" part of Table 6). The agreement between reference and tested seismometers reaches frequencies lower than the natural frequency of the tested seismometer. L1 to L6 show good to very good results, especially L2 to L5 seismometers are the best performing in terms of frequency range and sensitivity, and seem to be the overall best sensors if a response down to 0.1 Hz or less is required. M1 to M4 seismometers give variable results, the poorest one being the 4.5 Hz, which nevertheless gives good results down to 0.4 Hz. The accelerometers were in general very poor, and in some cases not sensitive enough, especially in the lower frequencies. The KE accelerometer was unstable and therefore very poor at low frequencies.

4.3 Results on H/V

We compared the H/V ratios from the tested seismometers and the reference sensor, with synchronous windowing (see the "H/V results" part of Table 6). The results are very good for seismometers, demonstrating a consistence of the tested seismometers down to frequencies much lower than their natural frequencies. In particular, the H/V ratio from the seismometer with the highest natural frequency (M4, 4.5 Hz) is very similar to the GS H/V ratio down to 0.4 Hz and only slightly different down to 0.1 Hz. On the contrary, the accelerometers are not similar at all to the GS results. Additionally, the following remarks can be made:

- the H/V ratio of the site is rather flat (pier coupled to the bedrock), and therefore may not be the best condition to perform the test;
- the recording length (2 min) is certainly too short to resolve frequencies below 1 Hz, where the lowest record time must be 10 min (Koller et al. 2004).

4.4 Conclusion on sensor tests

The main results of this test are (1) that the seismometers are generally good, even at frequencies lower than their natural frequencies, and (2) that the classical force balanced accelerometers have to be discarded for H/V noise studies. Another conclusion is that a 4.5 Hz sensor can be used down to 0.4 Hz, depending on the noise level at the site and on the electronic noise level of the digitizer. A lack of energy in the lower frequencies or a lack of sensitivity can generate a false peak or suppress a real one. As Bergen is a coastal site, the energy content in the microseism band allowed us to evaluate the data with high confidence even for this frequency band. It is therefore very important to first check the specific site noise level by calculating a noise spectrum and compare it to the instrument theoretical noise spectrum.

5 Test on digitizer-sensor combinations

In order to evaluate the digitizer-sensor combination and its impact on the H/V curve, four tests have been performed. The first test was to record as many digitizer-sensor combination waveforms as possible to compare the resulting H/V curves. The second test has been done to check a limited set of six digitizer-sensors pairs by simultaneous recordings. Both of these tests have been conducted in the laboratory on a concrete pier directly coupled to the bedrock (flat H/V ratio). The two last tests have been performed outside, on grass and on a concrete slab, respectively.

5.1 Tests digitizer-sensors combinations

In total, 24 digitizer-sensor combinations have been tested: 19 with seismometers and 5 with accelerometers (Fig. 6A; 6 with digitizer LE, 6 with digitizer TI, 5 with digitizer HA, 2 with digitizer ML and 1 with each of the RE, MA, IN, GB, ET digitizers). For the seismometers, results are homogeneous in term of H/V results, except for five combinations:

(a) the two combinations using the M1 seismometer (HA-M1 and MA-M1), exhibit a very clear peak close to 20 Hz on H/V curves, while this peak is not present on the other curves. Taking into account that the HA digitizer does not show this peak when combined with other sensors, it seems that the tested M1 sensor has serious problem over 15 Hz;
(b) the LE-M4 combination presents a strong increase in the lower frequencies (<0.2 Hz), but, unfortunately, it is the unique combination integrating the M4 sensor. It is understandable to have some problems in the low frequency range, as the natural frequency of the M4 seismometer is 4.5 Hz. Moreover, this result confirms previous sensor test, limiting the use of this sensor to frequencies above 0.4 Hz;
(c) the ML-KS combination, the only one integrating the KS broadband sensor, presents a very large and strong peak centered on 0.7–0.8 Hz. The ML-digitizer cannot be blamed because it works well when used with other sensors. The problem is probably coming from the necessary time stabilization of the KS-broadband seismometer.
(d) finally, the couple GB-SN shows a H/V curve with a more or less flat trend, but to the contrary of other curves, with a very oscillatory shape. There is probably a problem with this couple, but as neither the digitizer nor the sensor have been tested in another configuration, it is impossible to define what goes wrong.

The results for the five accelerometer-station couples are very heterogeneous (Fig. 6B). Two of them are way out of the reference behavior (TI-GA and the 5 V/g TI-KE), and can be discarded without question. While the 80 V/g TI-KE curve is close to the reference curve, beside a peak around 0.2 Hz it is almost a straight line. The amazing difference observed between the two TI-KE couples, cannot be charged to a station problem, as this kind of difference is not encountered when coupling different seismometers with this station. Therefore the TI-KE presents an erratic behavior that makes it delicate to use for ambient noise recording. The ET-KG behaves the same way as the 80 V/g TI-KE, i.e. a small peak below about 0.2 Hz, followed by a straight line. This straight line is most certainly due to the weakness of the

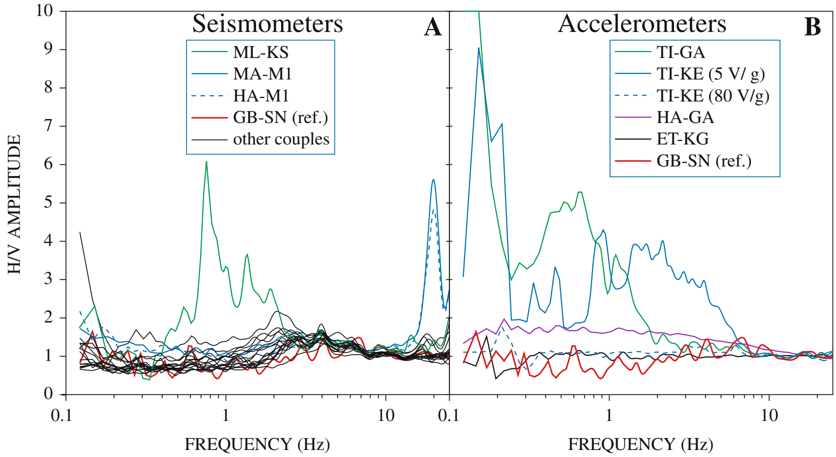


Fig. 6 Test on digitizer-sensor combinations. Records have been performed on a concrete pier coupled to bedrock. **(A)** H/V curves of the 19 couples using seismometers. **(B)** H/V curves of the five couples using accelerometers

signal recorded by these two couples, and raises an issue as the smooth bump observed with the seismometers between 2 and 7 Hz (Fig. 6A) does not show up, and as smooth bumps on H/V curves have been shown to be significant when recorded over a broad area (Guillier et al. 2005).

Therefore, as Mucciarelli (1998), we conclude that present-day accelerometers should definitively be avoided for ambient noise H/V studies, either because they amplify the real H/V behavior when they record a strong enough signal or because they erase the curve details when recording a weak signal.

5.2 Simultaneous in-lab measurements

The goal of this test is to compare the commonly used recording instruments. It is the best-controlled test since it was performed in the laboratory. All instruments were placed on a concrete pier and simultaneous recordings were performed with all instruments. We can therefore assume that the input signal was nearly identical for all instruments, particularly at frequencies below 1 Hz, where most instruments deviate. The instrument corrected spectra velocity amplitude were calculated as well as the H/V ratios using uncorrected signals. The first step consisted in comparing the waveforms over the whole frequency band, the second step was a comparison of the spectral amplitudes for each couple of instruments and the third step allows to check the homogeneity of the H/V curves coming from all couples, using the same time window.

The original traces look alike only when sensors are similar (Fig. 7A, data have been converted to displacement). Some traces, such as trace 3, have inverted polarity. After correction for instrumental response in the frequency band 1–20 Hz (Fig. 7B), waveforms appear very similar and the maximum displacement amplitude is nearly identical. This is quite good, considering that only manufacturers information have been used for the instrument response. The deviating sensors are the accelerometers, which obviously cannot resolve the noise and consequently electronic noise produces large artificial amplitude. The three last channels are from a different time window and present different waveforms, however, they show very

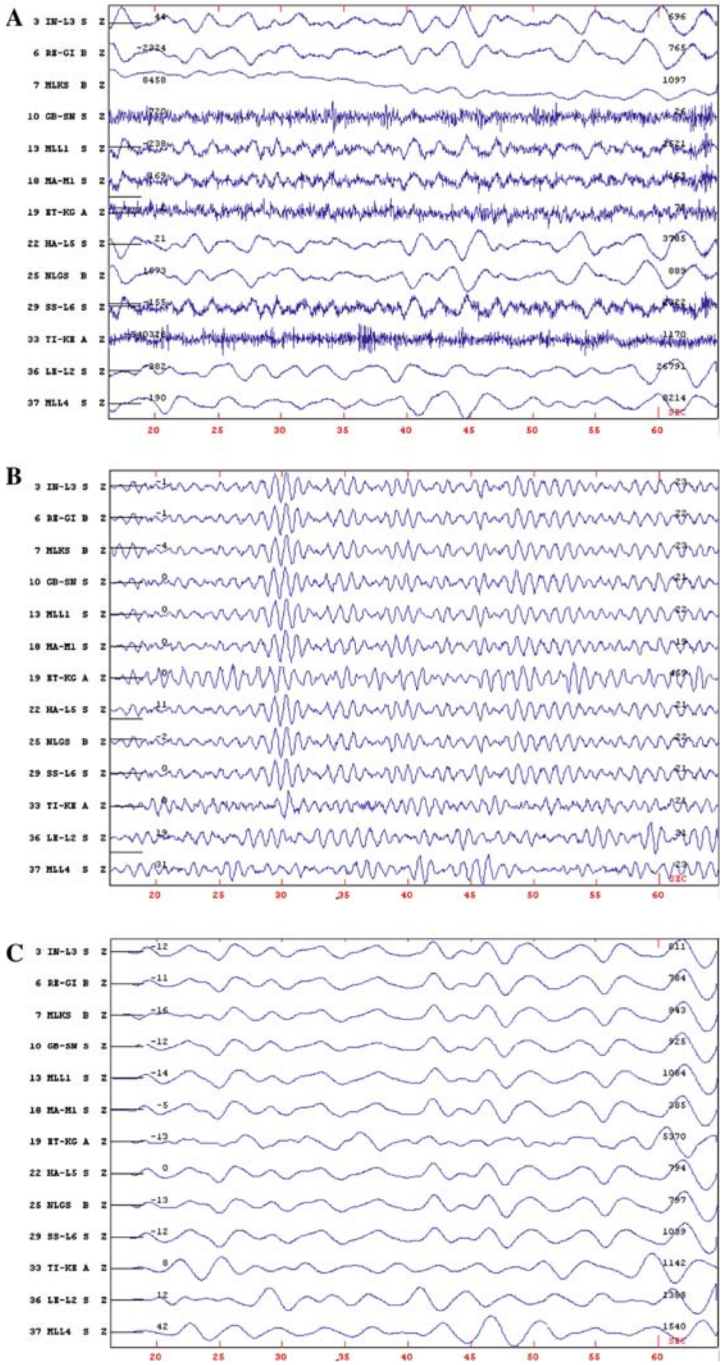


Fig. 7 Small window of the common traces for the Z-channel for tested user couples. The traces have been corrected for the instrumental response, all data have been converted to displacement. The three last channels of the graphs are from another time window. The numbers above the traces to the right are the maximum amplitudes (in nm) and the numbers to the left the offset (in nm). **(A)** displacement in the whole frequency band. **(B)** displacement in the 1–20 Hz frequency band. **(C)** displacement in the 0.2–1.0 Hz frequency band

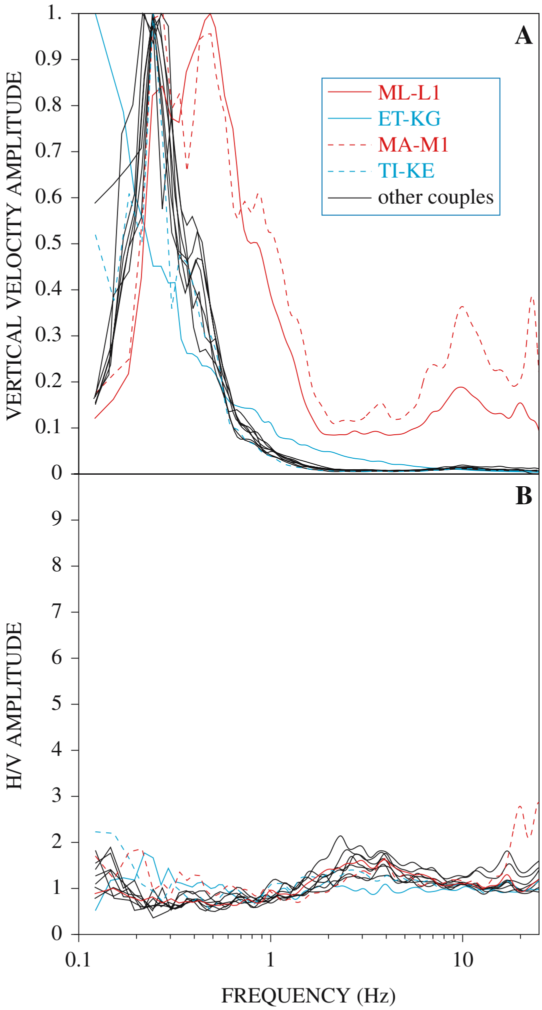


Fig. 8 Test of simultaneous in-lab recordings, for 11 digitizer-sensor couples routinely used by the participants. The computation of the curves is the same for all the data with, whenever possible, the same windowing. Line encoding shown in 8A applies also to 8B, for A and B blue curves represent accelerometers. **(A)** Normalized vertical spectral velocity amplitude curves for the 11 couples. **(B)** H/V curves for the same couples

similar absolute amplitudes, indicating that (1) the natural background noise is stable over time, and (2) the calibrations are good. From these traces, we can conclude that all the seismometers perform equally well, this is also to be expected since most seismometers have a flat response above 1 Hz, it demonstrates however that the 4.5 Hz sensor (trace 10) performs equally well.

Figure 7C shows displacements in the 0.2–1 Hz range. This limit has been fixed since the sensor tests described above showed that 0.2–0.3 Hz was a critical limit for several sensors. Down to 0.2 Hz waveforms look similar, but the absolute amplitudes start to deviate for some sensors, particularly for the L1 (1 Hz) and SN (4.5 Hz) sensors. If the lower frequency range is extended to 0.1 Hz, still more deviation is seen, especially for the L1 (1 Hz) and SN (4.5 Hz) sensors. It is most likely caused by sensor and/or digitizer noise when the sensor output is small compared to the digitizer sensitivity. Incorrect calibration information however could also be a problem, although it is less likely.

Figure 8A shows the spectral velocity amplitudes for the vertical component. If we consider the whole data set, a “normal curve” should show a strong peak at 0.2–0.3 Hz with a constant decrease of the amplitude when the frequency increases. From this “normal curve”, one couple slightly differs (ET-KG) and two others strongly differ (MA-M1 and ML-L1):

- results from the ET-KG couple (accelerometer) show a singular curve strictly decreasing on the whole frequency band, without peak at 0.2–0.3 Hz. Moreover, this couple has a higher amplitude than the normal curve in the 0.7–7.0 Hz frequency range;
- curve from the MA-M1couple shows three other peaks than the “normal” spectral velocity amplitude curve, with an amplitude systematically higher than the “normal” one over 0.4 Hz. One peak is below 1 Hz, one close to 10 Hz and the third one over 20 Hz. These results confirm (1) that the tested M1 seismometer has a problem in the higher frequencies (10–20 Hz), and (2) that it presents a problem in the lower frequencies (1 Hz);
- the curve from the couple ML-L1 is very close to the MA-M1 curve, but with a lower amplitude. As the MA-M1 curve, it shows three more peaks than the “normal” spectral velocity amplitude curve, with an amplitude systematically higher than the “normal” curve over 0.4 Hz, with the same three peaks as the MA-M1 curve. This curve, associated to the MA-M1 curve, highlights that the 1-Hz tested seismometers are experiencing some problems, even though they are of different types : M1 and L1, which have some problems are, respectively, real 1- and 4.5-Hz electronically driven to 1 Hz sensors, while L6, a real 1-Hz sensor which does not show any problem, and R1, a combination of 3 1-C real 1-Hz sensors, do not present any problem.

Deviations at low frequencies do not affect H/V curves if the deviation is related to instrumental parameter and similar on all components, while if caused by electronic noise, the ground motion information is lost or distorted and cannot be extracted. Also, as developed above (sensor tests), it is expected that all seismometers should give acceptable performance down to 0.2 Hz. This is confirmed by the H/V curves (Fig. 8B), where the results are stable and homogeneous. As shown above, there is a problem for the MA-M1 couple that gave a peak close to 20 Hz, not appearing on other sensor-digitizer couples.

It could be argued that the problem comes from the reference sensor-recorder, for which only manufacturers data have been used for instrument correction. However, since several sensor-recorders have noise spectra nearly identical to the reference sensor-recorder, we assume that the reference is reliable.

5.3 Free-field measurements

Two series of recordings were performed: one on grass, and the second on a concrete slab. All data have been processed with the same program using the same processing parameters (LTA/STA, smoothing,...). Evaluations of results are based on the spectral velocity amplitude curves, as well as on H/V curves.

5.3.1 Test on grass

For this test, six couples have been checked. Two spectral velocity amplitude curves (Fig. 9A) are very different from the four others:

- the GB-SN curve highlights a problem over the whole frequency band, especially in the 2–10 Hz frequency range;
- the MA-M1 curve shows a very strong peak at 14–16 Hz, raising a new problem for the M1 seismometer, in the higher frequencies. Moreover, in the lower frequencies (less than

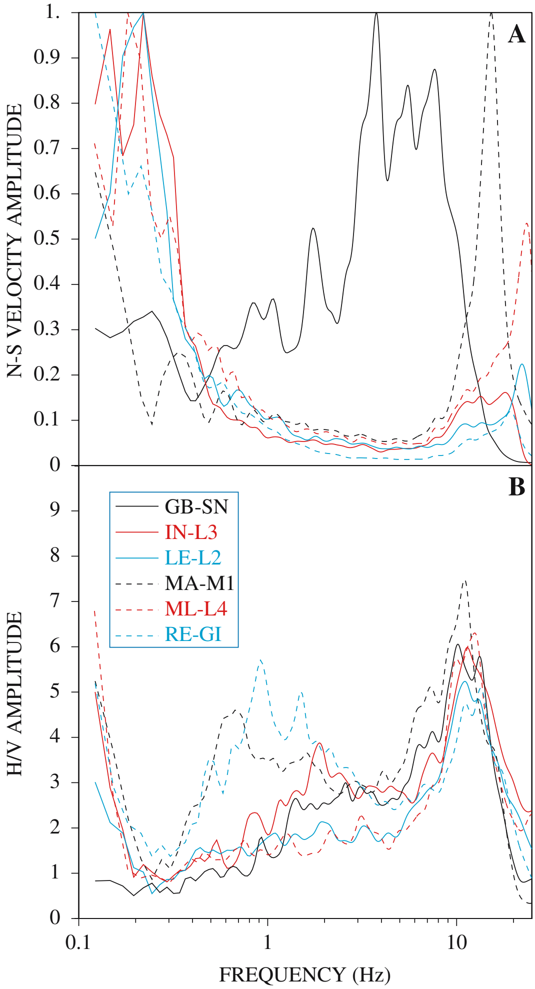


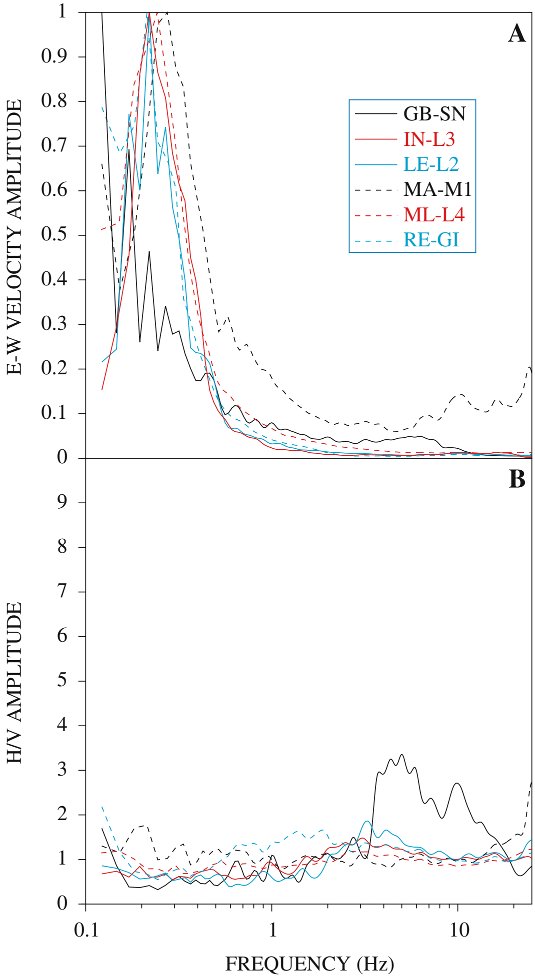
Fig. 9 Results for records performed outdoor on grass. Tested user digitizer-sensor couples show a clear peak close to 12–13 Hz with a relatively good homogeneity in amplitude. Line encoding shown in 9B applies also to 9A. **(A)** Normalized North–South spectral velocity amplitude curves for the six users-couples. Couples GB-SN and MA-M1 present clear problems in the energy release definition along the frequency spectrum. **(B)** H/V curves for the same couples. Two couples show a large peak below 1.0 Hz (RE-GI and MA-M1) and two other couples present a noticeable bump between 2 and 5 Hz (IN-L3 and GB-SN). It is interesting to notice that, even when the velocity spectrum amplitude is corrupted, the H/V curve is not much affected

1 Hz), the M1 sensor shows oscillation instabilities, confirming the problem found in the previous in-lab measurements.

All 6 H/V curves show a clear peak close to 12–13 Hz, corresponding to the soil fundamental frequency, with a relatively good homogeneity in amplitude (Fig. 9B), while results vary dramatically in the lower frequencies:

- the RE-GI couple presents a large peak close to 0.9–1.0 Hz, which appears only on this curve. It is probable that the problem comes from a lack of stabilization of the sensor after moving it from the lab onto the free-field (cold start for this broadband seismometer);
- the MA-M1couple presents a large peak close to 0.6–0.7 Hz, which appears only on the results from this couple. As this couple has previously presented problems in the high frequencies, these results are raising a new problem in the lower frequencies, may be related to the natural frequency of the seismometer (1 Hz). As this couple shows a very strong velocity amplitude peak at 14–16 Hz, while it does not present any H/V peak at this

Fig. 10 Results for records performed outdoor on a concrete slab. Tested user digitizer-sensor couples show a more or less flat trend with a relatively good homogeneity in amplitude. Line encoding shown in 10B applies also to 10A. **(A)** Normalized East-West spectral velocity amplitude curves for the six couples. Couples GB-SN and MA-M1 present clear problem in the energy release definition along the frequency spectrum **(B)** H/V curves for the same couples. Only the GB-SN couple curve shows a strong difference with others curves, with the presence of a bump between 3 and 20 Hz



frequencies, we can deduce however that the response of each of the three components is the same in the 14–16 Hz frequency range;

- H/V results from the IN-L3 and GB-SN couples show higher amplitudes in the 1–6 Hz frequency range. As the IN-L3 couple did not present any problem in the in-lab tests, this observation in the lower frequency range is hard to explain. This observation for the GB-SN couple can be explained by its weird velocity amplitude curve inside this frequency range.

It is worth to notice the fact that even when a velocity spectral amplitude curve of a couple is strongly different from the others, its H/V curve looks quite similar to the others close to the H/V peak, even though problems can appear in the lower frequencies, away from the fundamental frequency of the soil.

5.3.2 Test on concrete slab

The second test consisted in simultaneous recordings performed in the free-field on a concrete slab. As in the grass case, six couples were checked. All velocity amplitude curves show a strong peak at 0.2–0.3 Hz (Fig. 10A). Differences appear on the results of only two couples:

- the GB-SN couple shows a very unstable energy spectrum below 1 Hz, instead of a single peak;
- the MA-M1 couple has a higher amplitude, above the 0.2–0.3 Hz peak, with some small "peaks" close to 20 Hz, again confirming the problem of the M1 sensor in the higher frequencies.

All H/V curves are very similar (Fig. 10B), i.e., a flat curve, very close to the curves from the lab tests. However, the GB-SN couple shows a very marked deviation from the others curves, displaying a broad bump above 3 Hz. Moreover, test on concrete slab that confirms the M1 problem observed in the medium-high frequency range from the others tests.

5.4 Conclusion on digitizer-sensor tests

All tests including the M1 sensor have demonstrated problems over the entire frequency range, either for the spectral velocity curve or the H/V curve. Problems from the digitizers can be discarded, as when used with other sensors the problem disappears. It can however be a problem linked only to this particular seismometer used for the tests and no to any M1 seismometers. The problem observed for the GB-SN couple might be due to a very low signal/electronic noise ratio.

Variations in instrumentation can easily produce a variation in H/V curves, but do not change noticeably the frequency value of the peaks (e.g., the test on grass).

It is anyway strongly recommended, whatever the shape of the H/V curve, to undertake a very careful calibration of the instruments before use.

6 Discussion

Before drawing general conclusions from these tests, one should keep in mind that:

- the tested sensors and digitizers were taken as they were. Most of the tested equipment was single piece, it is therefore impossible to discard the possibility that encountered problems are only due to the particular tested unit and may not reflect a trend of all this type of equipment;
- on the site where this experiment took place, most of the noise energy is concentrated below 1 Hz. This can raise the following problems: (i) - all sensors will detect energy in the frequencies below 1 Hz, even if their natural frequencies are higher, (ii) - the lack of energy over 1 Hz can lead to an enhancement of small deviations in the higher frequencies. Moreover, there is more signal from the city above 1 Hz compared to a site in the countryside, so the instrument has to be at least sensitive enough to work on this test site;
- except for the grass test, the sites where recordings took place have flat H/V curves, thus allowing to check carefully the impact of the equipment on, for example, the creation of artificial peaks, but discarding the possibility to verify the impact on true H/V peaks;
- the recorded duration was not adequate to check the behavior of the H/V curves in the lower frequencies (Koller at al. 2004).

Most characteristics of the tested digitizers correspond well to the specifications (sensitivity, polarity...) given by the manufacturers. However, from one digitizer to another, the quality of the time series ranges from very good to very poor, with variations from a channel to another. Digitizers can influence the results by (1) a difference in gain between channels, (2) a difference in time-digitization between channels, and (3) their internal electronic noise level.

The main problem comes from the necessary warming up of some digitizers, because their cold starts produce variable offsets, jumps, drifts and long period oscillations, even if they have too long period to notably influence the H/V ratio in the 0.1–25 Hz frequency range. The simplest way to escape this stability problem is to warm up the digitizer before any recording. Time of warming up depends on the digitizer and must be defined for each station, but a 10 min warming up is enough in most cases. Moreover, out of the 12 tested digitizers, only one exhibits problems after warming up which however do not influence the H/V curves. Of course, we cannot state if these conclusions can be extrapolated over time (aging of the digitizer) and if the temperature, humidity and others parameters of this order can have any influence.

We can distinguish between three categories of sensors: (1) accelerometers, (2) broadband seismometers (below 0.2 Hz), and (3) short period seismometer (less or equal to 5 s).

The use of accelerometers, at least those using the force balanced technology, is not recommended, as they are generally too unstable and not sensitive enough at low frequencies. For all of them, a warming up time is necessary. Therefore, as also proposed by Mucciarelli (1998), we conclude that accelerometers should be avoided.

Generally, seismometers are sensitive enough to record ambient noise, even at low frequencies, to be discriminating on H/V curves. The problem is at low frequencies (below 1 Hz), if the natural frequency of the seismometer is much higher than the H/V peak. In this case, the signal/internal noise ratio has to be significantly high, so it is mandatory to check the energy level all along the frequency band. For all sensors, if they are powered, warming up is mandatory before start of recording.

Broadband sensors are generally powered and therefore need a warming up before their use. They are sensitive enough in the 0.1–25 Hz range but, because of a long stabilization time, they are not easy to use in the field. Moreover, they are sensitive to temperature and pressure variation, so perhaps they are difficult to use outdoor.

Short period seismometers are generally found to be good to very good, especially the 5-s seismometers, even at frequencies below their natural frequencies. For example, the 4.5-Hz is usable down to 0.4 Hz, if the energy level below 4.5 Hz is high enough, as it is the case in our study, and if the digitizers and/or amplifiers have sufficient resolution. Surprisingly, 1-Hz seismometers performed only marginally better than the 4.5 Hz sensors.

Moreover, deviations at low frequencies do not affect H/V curves if and only if:

- these deviations are instrumental parameter dependant;
- these deviations are the same on all three components;
- the signal/noise ratio is strong enough to allow extraction of ambient vibration signal from the electronic noise.

7 Conclusions

Before using any digitizer or sensor, it is recommended to test them indoor in order to check their performances (sensitivity, polarity...), individually as well as associated, because even though the sensitivity and noise response of the sensors are reasonably good, the overall instrumental effect on the H/V ratios cannot be neglected.

Digitizers are generally very accurate (with, however, two exceptions), whereas the sensor influence is more complex and can generate some troubles. Depending on the sensitivity of the sensor and its natural frequency, it is necessary to check that the natural background noise level, at the site and in the whole frequency band, is high enough to allow recording the background noise signal at a level above the internal equipment noise, before any interpretation of the H/V curve. The use of accelerometers should definitively be avoided, because of instabilities, low sensitivity (especially at low frequencies) and consequent warming up time. If broadband seismometers are sensitive and stable enough, their use appears as difficult (warming up, stabilization. . .) in the field, whereas they can be good laboratory references. Short period seismometers, down to 5-s sensors, are the more efficient sensors for H/V studies. Even 4.5-Hz sensors could be used down to 0.4 Hz, if the energy released down to this frequency is reasonably high.

Digitizers, sensors or their combinations can influence the digital reconstruction of ambient vibration noise and consequently they can affect the H/V curves, but simple tests, as those presented in this paper, can be easily conducted to determine the level of this impact.

While digitizer performances are consistant with that given by the manufacturers, the sensors responses show more variations, probably related to their aging, and also to external factors such as temperature, pressure etc.

It would be of public interest to conduct periodical systematic studies on the at–the-moment available seismological equipments, as it is done, for example, for gravimetrical (e.g. Vitushkin et al. 2002) or magnetic equipment (e.g., IAGA workshop 2004).

Acknowledgements We would like to thank M. Mucciarelli for constructive criticisms. This work has been conducted within the framework of the SESAME Project (Site Effects Assessment Using Ambient Excitations) supported by the European Commission (EVG1-CT-2000-00026). We also thank the University of Bergen (UiB, Norway) for organizing the workshop. This work would not have been possible without the dedication of the researchers from public institutions of various countries, save public research.

References

Bard P-Y (2002) Extracting information from ambient seismic noise: The SESAME project (Site EffectS assessment using AMbient Excitations). European Project No. EVG1-CT-2000–00026 SESAME, 2002, http://sesame-fp5.obs.ujf-grenoble.fr Review meeting, Brussels, Belgium

Bard P-Y, the SESAME participants (2003) The EU SESAME project: presentation, latest results and perspectives. Workshop on Effects of Surface Geology on Seismic Motion, IUGG/IASPEI 2003, July 11 2003, Sapporo, Japan

Bard P-Y, SESAME participants (2004) The SESAME project: an overview and main results. Proceedings of the 13th World Conference in Earthquake Engineering, Vancouver, August 2004, Paper no 2207

Chatelain J-L, Guillier B, Duval A-M, Atakan K, Bard P-Y, the WP02 SESAME team (2005) Evaluation of the influence of experimental conditions on H/V results from ambient noise recordings, this volume

Goula X, Susagna T, Figueras S, Farres P, Cid X, Alfaro A, Barchiesi A (1997) Analysis of Site Effect in the City of Barcelona (Spain), XIX General Assembly of the IASPEI, Thessaloniki, Abstract Book, p 324

Guéguen Ph, Chatelain J-L, Guillier B, Yepes H (2000) An indication of the topmost layer response in Quito (Ecuador) using noise H/V spectral ratio. Soil Dyn Earth Eng 19:127–133

Guillier B, Chatelain J-L, Bard P-Y (2001) Bibliothèque de programme pour le calcul et la représentation graphique de H/V. Documentation interne, LGIT, Grenoble, France

Guillier B, Atakan K, Duval A-M, Ohrnberger M, Azzara R, Cara F, Havskov J, Alguacil G, Teves-Costa P, Theodulidis N, the SESAME Project WP02-Team (2002a) Influence of instrumentation on H/V spectra of ambient noise. EGS, 22–26 April 2002, Nice, France

Guillier B, Atakan K, Duval A-M, Ohrnberger M, Azzara R, Cara F, Havskov J, Alguacil G, Teves-Costa P, Theodulidis N, the SESAME Project WP02-Team (2002b) Influence of instrumentation on H/V spectra of ambient noise. European Seismological Commission, September 2002, Genova, Italy

Guillier B, Chatelain J-L, Hellel M, Machane D, Mezouer N, Ben Salem R, Oubaiche EH (2005) Smooth bumps in H/V curves over a broad area from single-station ambient noise recordings are meaningful and reveal the importance of Q in array processing: The Boumerdes (Algeria) case. Geophys Res Lett, 32:(24)L24306, doi: 10.1029/2005GL023726

Havskov J, Ottemöller L (2000) SEISAN The earthquake analysis software for Windows, Solaris and Linux (Ver. 7.1). Institute of Solid Earth Physics, University of Bergen, Norway 228

IAGA workshop on Geomagnetic Observatory Instruments (XIth), Data Acquisition and Processing, November 9–17 2004, Kakioka Magnetic Observatory, Japan, 2004. http://www.kakioka2004ws.org/

Koller MG, Chatelain J-L, Guillier B, Duval AM, Atakan K, Lacave C, Bard P-Y, the SESAME participants (2004) Practical user guideline and software for the implementation of the H/V ratio technique on ambient vibrations: measuring conditions, processing method and results interpretation. 13th World Conference on Earthquake Engineering Vancouver, BC, Canada August 1–6, 2004 Paper No. 3132

Konno K, Ohmachi T (1998) Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. Bull Seismological Soc Am 88(1): 228–241

Lachet C, Bard P-Y (1995) Theoretical investigation on the Nakamura's technique. Proceeding 3rd International Conference On Recent Advances in Geot. Earthq. Eng. & Soil Dyn., April 2–7, II, St Louis, MI, Paper no 10.06

Lebrun B, Hatzfeld D, Bard P-Y (2001) A site effect study in urban area: experimental results in Grenoble (France). Pure Appl Geophys 158:2543–2557

Monge O, Chassagneux D, Martin C, Sedan O, Vermeersch F (1999) Evaluation de l'aléa sismique local: partie 1, microzonages de Fort-de-France et Pointe-à-Pitre. Génie parasismique et réponse dynamique des ouvrages, proc. 5ème Coll. Nat. AFPS, Cachan, vol. 1, p. 407–414, 19–21 octobre 1999

Mucciarelli M (1998) Reliability and applicability of Nakamura's technique using microtremors: an experimental approach. J Earthq Eng 2(4):625–638

Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Q Rep Railway Tech Res Inst 30(1):25–30

Peterson (1993) USGS Open-File Report. Albuquerque, New Mexico, USA

Régnier M, Moris S, Shapira A, Malitzky A, Shorten G (2000) Microzonation of the expected seismic site effects across Port Vila, Vanuatu. J Earthq Eng 4(2):215–231

SESAME team (2002) WP02, Controlled instrumental specifications, university of Bergen. European Commission — Research General Directorate Project No. EVG1-CT-2000–00026 SESAME, report D01.02, 250 p., 80 figures.

Vitushkin L, Becker M, Jiang Z, Francis O, Van Dam TM, Faller J, Chartier J-M, Amalvict M, Bonvalot S, Debeglia N, Desogus S, Diament M, Dupont F, Falk R, Gabalda G, Gagnon CGL, Gattacceca T, Germak A, Hinderer J, Jamet O, Jeffries G, Käker R, Kopaev A, Liard J, Lindau A, Longuevergne L, Luck B, Maderal EN, Mäkinen J, Meurers B, Mizushima S, Mrlina J, Newell D, Origlia C, Pujol ER, Reinhold A, Richard Ph, Robinson IA, Ruess D, Thies S, Van Camp M, Van Ruymbeke M, de Villalta Compagni MF, Williams S (2002) Results of the sixth international comparison of absolute gravimeters, ICAG-2001. Metrologia 39:407–424