Site Effects Assessment Using Ambient Excitations

SESAME

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University of Bergen, Norway

WP02

Controlled Instrumental Specifications

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Summary

In the following we report the preliminary results from a workshop arranged at the Institute of Solid Earth Physics, University of Bergen, in the period 22-26 October 2001 in Bergen, Norway. The workshop was arranged under the framework of the **SESAME Project** (Site Effects Assessment Using Ambient Excitations, EC-RGD, Project No. EVG1-CT-2000-00026 SESAME), Task A (H/V technique), Work Package 02 (WP02 – Experimental conditions).

Chapter 1: Introduction

The aim of the workshop was to investigate the influence of different instruments (that are currently in use in the participating institutions) in estimating the local site response using H/V technique on microtremor data. In total eight groups were involved and a large number of instruments were tested. There were 4 major tasks performed during the workshop, which consisted of testing the digitizers (Task 1), sensors (Task 2), simultaneous recordings both outside in the free-field (Task 3) and at the lab (Task 4) for comparisons. In addition, an initial test data (Task 0), were also collected to provide individual noise data sets for each system. All measurements in the laboratory were performed on two concrete piers coupled directly to the bedrock. Free-field measurements were done at a location where the ground coupling was on either a grass-cover or on concrete. The underlying units consist of a thin layer of soft sediments over the Palaeozoic bedrock. Figure 1-1 shows the different locations used in the measurements.

Chapter 2: The experiment

2.1. Instruments used

The list of instruments that are used is shown in the following table.

Table 1. List of digitizers used

CODE	Digitisers/recorders	Constructor	Owner
HA	Hathor-3	Leas	CETE France
TI	Titan 3	Agecodagis	UFJF Grenoble 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	Nanometrics CH1-3	Nanometrics	UiB Norway
NL	Nanometrics CH4-6	Nanometrics	UiB Norway
LE	CityShark	Leas	IRD Paris
ML	MarsLite	Lennartz	U. Potsdam Germany
SS	Kinem. SSR	Kinemetrics	ICTE-UL Portugal
E3	Earth Data 3CH	Earth Data	UiB Norway
E6	Earth Data 6CH	Earth Data	UiB Norway

Table 2-1. List of the seismometers used

CODE	Type	Constructor	Owner
L1	LE-3Dlite 1Hz	Lennartz	Lennartz Germany
L6	LE 3D Classic	Lennartz	ICTE-UL Portugal
L5	LE-3D/5s	Lennartz	CETE France
M2	Mark L-22	Mark Product	UFJF Grenoble France
M4	Mark L-28B	Mark Product	UFJF Grenoble France
CH	CD-S2A	Chinese Republic	UFJF Grenoble France
M1	Mark L4-C	Mark Product	INGV Italy
R1	Kinem. Ranger	Kinemetrics	UiB Norway
SN	Sensor GBV	Sensor Netherland	UiB Norway
L2	LE-3D/5s	Lennartz	INGV Italy
L3	LE-3D/5s	Lennartz	INGV Italy
GS	Guralp CMG-40T	Guralp	UiB Norway
L4	LE-3D/5s	Lennartz	Univ. Potsdam Germany

Table 2-2. List of the broadband sensors used

CODE	Type	Constructor	Owner
GI (INGV)	Guralp CMG-40T	Guralp	INGV Italy
KS	Geotech KS-2000	Geotech	Univ. Potsdam Germany
GS	Guralp CMG-40T	Guralp	UiB Norway

Table 2-3. List of the accelerometers used

CODE	Type	Constructor	Owner
KE	Episensor	Kinemetrics	IFJF UiB, Norway
GA	Guralp CMG-5T	Guralp	LGIT Grenoble France
KG	Altus-Etna int. Episen.	Kinemetrics	ITSAK, Greece

Table 3-1. Technical parameters of the used seismometers

CODE	Type	T0 s	Damping	GE V/(m/s)	filter	
L1	LE-3Dlite 1Hz	1	0,707	400	HP 1-pole	0,335Hz
L5	LE-3D/5s	5	0,707	400	HP 1-pole	0,07Hz
L6	LE-3D Classic	1	0,707	400	HP 1-pole	0,335Hz
M2	Mark L-22	0,5	0,46 (Re=open)	139		
M4	Mark L-28B	0,22	0,727 (Re=39k)	97,4		
CH	"chinese" 2Hz	0,5	0,70 (Re=39k)	38		
M1	Mark L4-C	1	0,7	175		
R1	Kinem. Ranger	1	0,7	145		
SN	Sensor GBV	0,22	0,7	27,6		
L2	LE-3D/5s	5	0,707	400	HP 1-pole	0,07Hz
L3	LE-3D/5s	5	0,707	400	HP 1-pole	0,07Hz
L4	LE-3D/5s	5	0,707	400	HP 1-pole	0,07Hz

Table 3-2. Technical parameters of the used broadband sensors

CODE	Type	T0 s	Damping	GE V/(m/s)	filter	
GI (INGV)	Guralp CMG-40T	30	0,71	800		
GS	Guralp CMG-40T	30	0.71	800		
KS	Geotech KS-2000	100	0.707	2000		

Table 3-3. Technical parameters of the tested accelerometers

CODE	Type	Constructor	Owner	Sensitivity V/g
KE	Episensor	Kinemetrics	UFJF Grenoble France	80V/g
GA	Guralp CMG-5T	Guralp	LGIT Grenoble France	10
KG	Altus-Etna int. Episen.	Kinemetrics	Greece	1,25

Table 4. List of tested digitizers

CODE	Digitisers/recorders	Condition	Sensitivity counts/V	Constructor	Owner
HA	Hathor-3	Gain=128	6,711E+06	Leas	CETE France
TI	Titan 3	Gain=1, 4, 256	1,670E+06	Agecodagis	UFJF Grenoble France
RE	Reftek 72A07		5,250E+05	Reftek	INGV Italy
MA	Mars88		1,000E+06	Lennartz	INGV Italy
IN	INGV self-made		1,165E+06	INGV Italy	INGV Italy
ET	Altus-Etna int. Digitis.		5,240E+04	Kinemetrics	ITSAK Greece
GB	GBV 316		1,310E+07	GEOSIG Switzerland	UiB Norway
NH	Nanometrics CH1-3		7,350E+06	Nanometrics	UiB Norway
NL	Nanometrics CH4-6		1,310E+06	Nanometrics	UiB Norway
LE	CityShark	Gain=512	2,684E+07	Leas	IRD Paris
ML	MarsLite		0,800E+06	Lennartz	U. Potsdam Germany
SS	Kinem. SSR	Gain=1	13107	Kinemetrics	ITSAK Greece
E3	Earth Data 3CH	Gain=1	1,00E+06	Earth Data	UiB Norway
E6	Earth Data 6CH	Gain=1	1,00E+06	Earth Data	UiB Norway

2.2. Data Processing

All processing was done using the SEISAN (Havskov and Ottemöller, 2000) software developed at the University of Bergen. The complete software can be downloaded from the following address: www.ifjf.uib.no/Seismologi/software/software.html

The choice of SEISAN was made in order to provide a uniform processing platform for the entire data set. In all spectral processing the frequency window used is between 0.1 – 20 Hz. Different recorders have different waveform formats. These are all converted to the SEISAN waveform format. The format conversion programs are explained in the SEISAN manual. The detailed procedures followed for the conversion of the formats are given in Appendix 1.

Chapter 3: Influence of the digitizers

In order to investigate the possible influence of the digitizers, we have performed the several tests to quantify the experimental sensitivity, internal noise, stability and channel consistency.

3.1. Experimental sensitivity as compared to the manufacturer specifications

The aim of this test was to compare the sensitivity of the 10 digitizers that were used in the workshop between the manufacturer's specifications and those that are experimentally measured in the laboratory. In order to measure the sensitivity and verify the polarity, a DC voltage was sent contemporarily to the three channels of each of the digitizer at normal and inverse polarity. The experimental sensitivity was computed by dividing the DC voltage measured through a multimeter (normally around 1.5 V) to the average digital counts as measured on the recordings. The offset was removed by subtracting the positive and negative levels. The following table summarizes the results.

Table 5. Technical specifications of the Instruments used	CITY SHARK	TITAN	Kinemetrics Etna	Mars-Lite	Reftek 72A07	Mars 88 type	INGV Self-Made	Hathor 3	Hathor 3	Hathor 3	Kinemetrics SSR	GEOSIG
	LGIT, France	LGIT, France	ITSAK, Greece	IGUP, Germany	INGV, Italy	INGV, Italy	INGV, Italy	CETE, France	CETE, France	CETE, France	ICTE-UL, Portugal	UiB, Norway
	LE	TI	ET	ML	RE	MA	IN	HA	HA	HA	SS	GB
Sampling rate	100 Hz	125 Hz	100 Hz	125 Hz	125 Hz	125 Hz	50 Hz	50 Hz	100 Hz	250 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)	24 - 6 (mask)	24 - 9 (mask)	16	16
GAIN	1	256	1	32	1	1	1	1	1	1	1	1000
Manufacturer = theoritical value of one count (µV/counts)	19,07	0,58	0,30	32,00	1,91	1,00	0,85	9,54	19,07	152,59	76,29	0,0763
Z channel	18,751	0,600	0,298	31,562	1,907	1,000	0,849	9,579	19,146	153,275	76,753	0,0765
Z deviation from theoritical value:	1,69 %	-3,53 %	0,67 %	1,37 %	0,02 %	-0,02 %	0,06 %	-0,42 %	-0,38 %	-0,45 %	-0,60 %	0,26 %
N-S channel	18,751	0,600	0,298	31,559	1,906	1,001	0,850	9,577	19,143	153,207	76,442	0,0769
NS deviation from theoritical value:	1,69 %	-3,45 %	0,67 %	1,38 %	0,04 %	-0,05 %	0,02 %	-0,40 %	-0,37 %	-0,41 %	-0,19 %	0,78 %
E-W channel	18,750	0,600	0,298	31,561	1,906	0,999	0,850	9,581	19,146	153,275	82,177	0,0768
EW deviation from theoritical value	1,69 %	-3,45 %	0,67 %	1,37 %	0,03 %	0,09 %	0,03 %	-0,44 %	-0,38 %	-0,45 %	-7,71 %	0,65 %
polarity	Normal	normal	normal	normal	normal	normal	normal	normal	normal	normal	normal (pb on EW neg)	normal
Battery voltage (variation)	1,515 V	1,546 V	_	0,439 V	1,579 V	0,840 V	1,547 V	1,548 V	1,547 V	1,548 V	1,48 V to 1,5 V	4,67mV
mean total variation in volt	3,03	3,092	_	0,878	3,158	1,68	3,094	3,096	3,094	3,096	2,98	9,33mV
Z MEASUREMENT total variation	161599	5149256	_	27818	1656376	1679748	3642154	323200	161600	20199	38826	121960
N-S MEASUREMENT total variation	161589	5143398	_	27821	1656665	1679104	3640689	323264	161628	20208	38984	121326
E-W MEASUREMENT total variation	161601	5141723	_	27819	1656458	1681592	3641245	323136	161600	20199	36263	121484

3.2. Internal noise

The internal noise of the digitizers was measured experimentally by short-circuiting the digitizer inputs. The recorded signal of 10-minute duration (one with cold and one with warm start) was then convolved with the response of several virtual sensors in order to test the sensitivity at worst possible combinations (i.e. with the least sensitive sensors). In addition, the sensor, which is usually used by each digitizer, was also included. The three virtual sensor responses used were: (i) VI: 4.5 Hz velocity sensor, (ii) 1H: 1Hz velocity sensor and (iii) the usual sensor used by each group during the other experiments. For each recording three different gains were applied (i.e. the low, the high and the usual gain). The results were compared with the Peterson's curves (Peterson, 1993). Sampling rate used was minimum 100. Some example results are shown in Figures 3-2-1 and 3-2-2. The remaining test results are given separately in the Appendix 2.

3.3. Stability

This test was performed to investigate the stability of the digitizer after a cold start. H/V ratios were computed on two windows of 1-minute duration at the beginning and at the end of each of the cold and warm 10-minute data. For the MarsLite, the first two seconds of data should not be used. The GB is exceptionally good. Most of the digitizers show ca. 10 minutes of drift time before stabilization. We observed during the first 10-minutes, such as jumps in the level, drift and long period ringing. However, the variation in counts is less than 20 counts for most cases. It is concluded that after 10-minutes of stabilization H/V ratios will not be affected by these disturbances. Special care must be taken in to account for the lower frequencies in connection with the low-sensitivity sensors.

Data preparation
In the last (follow-up) instrument workshop, which was held in Potsdam 7./8.01.2002, every group (partner) has been asked to prepare 6 SEISAN waveform files for his/her digitizer with short circuited channel input.
The requirement was to record for three different gain settings of the digitizer one 10 min sample "cold start" and one 10 min sample "warm start" record. "Cold start" was defined as at minimum 12 h without power for the digitizer, whereas the "warm start" record should be taken after minimum 1 hour of power (or previous recording). The data was acquired to both addresses the question of stability of the electronic noise of the digitizer as well as to determine the level of the internal noise for the instrument.

Until 19.04.2002, data has been available from 6 Digitizers (downloadable from anonymous ftp-server at UiB ftp://ftp.ifjf.uib.no/pub/sesame/COLD-WARM/):

From INGV:
- Reftek 72A07 – RE
- Lennartz Mars88 – MA
- INGV-digitzer (self-development) – IN

From UiB:
- GBV - GB

From CETE:
- LEAS Hathor-3 - HA

From IGUP:

Lennartz Marslite – ML

Data processing

For each digitizer, a plot has been made to show the raw time series (vertical component, “cold start” and “warm start” records for each gain. Additionally the spectral ratio for both horizontal components relative to the vertical are evaluated in three different time windows of one minute – “cold1”: beginning of cold record (10-70s from start of record), “warm1” end of cold record (530-590s from start of record), “warm2” end of warm record (after 1 hour –> 530-590s after start of warm record).

The time histories and spectral ratios for the short-circuited records are shown in Appendix 2. The following table summarizes the mean and standard deviations calculated for the recorded time windows and give some summary comments for peculiarities of single digitizers.

Table 6. Summary of the digitizer stability tests.

DIG f_{dig} [Hz]	GAIN SENSITIVITY	Cold all [digital counts]	Cold 1 [digital counts]	Warm 1 [digital counts]	Warm all [digital counts]	Remarks
ML/125	2 uV/C 5e+5 C/V	-44±64	-41.6±2.1	-37.0±2.1	-27.7±2.3	First block scrambled, no observable drift
ML/125	8 uV/C 1.25e+5 C/V	-8±10	-8.1±1.6	-6.9±1.7	-5.8±1.7	First block scrambled, no observable drift
ML/125	32 uV/C 31250 C/V	1.5±3.5	1.5±1.5	1.5±1.5	1.2±1.5	First block scrambled, no observable drift
ML/125	128 uV/C 7812.5 C/V	3.6±2.0	3.8±1.5	3.5±1.5	2.4±1.5	First block scrambled, no observable drift
MA/250	2 uV/C 5e+5 C/V	-17.0±2.6	-16.3±2.5	-18.1±2.5	Data file corrupted	
MA/250	32 uV/C 31250 C/V	-25.6±1.6	-25.5±1.6	-25.8±1.7	27.5±1.6	
MA/250	128 uV/C 7812.5 C/V	-26.0±1.6	-26.1±1.6	-26.0±1.6	-27.2±1.6	
GB/100	0,076 1.311e+7 C/V	284.8±5.6	295.9±2.6	279.5±0.5	273.1±0.4	Drift within first 10 minutes – offset – After warmup +- 1Bit noise max
RE/125	2 525000 C/V	-84.5±16.8	-115.2±3.6	-70.2±2.1	77.0±1.9	Warm records taken after 20 hours! Strongest drift of all digitizers - Long period instabilities
RE/125	32 (~ 30.1 dB) 16406,25 C/V	-227.1±9.8	-236.2±2.7	-218.4±2.5	-78.9±2.6	Warm records taken after 20 hours! Long period instabilities
IN/50	1	296.3±14.5	270.8±2.7	313.0±1.6	-1.5±1.6	Warm records taken after 20 hours! Long period instabilities
IN/50	10	75.2±25.0	33.8±3.0	104.8±2.3	2.9±2.6	Warm records taken after 20 hours! Long period instabilities
HA/100	1 52429 C/V	-148.9±1.0	-148.3±0.9	-149.4±0.9	-150.9±0.9	No observable drift, very low bit noise, equally distributed
HA/100	16 838875 C/V	-157.4±0.9	-157.8±0.9	-157.3±0.9	-160.4±0.9	No observable drift, very low bit noise,

						equally distributed
HA/100	128 6711000 C/V	-210.8±2.8	-212.0±2.1	-214.4±1.2	-216.7±1.7	Jumps up/down of few counts within “cold” record, long period ringing

In general we have found that all digitizers need some warm up time to show a stable base line. We have observed both amplitude jumps and drifts in the baseline within the first minutes of registration for several instruments, however the absolute value in counts for those undesirable instabilities is quite low. All digitizers show a better stability in the recordings after some minutes of warming up. As a rule of thumb we would give 10 min for most instruments to assure that the baseline is more or less stable. We have not considered the observed offsets here, as they should always be removed in any processing of real data and especially for the task of computing H/V ratios. None of the instruments showed such a strong offset that influenced severely the symmetry of the input voltage range (which would lead to a reduced dynamic range for the digitizer). Some examples for the performed tests are shown in figures 3-3-1 to 3-3-6.

Summarizing the observations of the stability test and taking into account the spectral ratios (see figures in the Appendix for each digitizer) we find in general no severe restriction for the use of the evaluated digitizers for the application of H/V measurements. We have selected four criteria in order to determine some relative ranking of the digitizers for this test.

- “Readiness”: How fast the digitizer internal noise is stabilized?
- “Standard deviation”: Deviation from mean taken over record
- “Long period stability”: Amplitude of long period instabilities
- “Offset”: Absolute offset values

Table 7. The ranking of the tested digitizers (from 1 to 7, where 1 is best).

Digitizer	Readiness	standard dev.	Long period stab.	Offset	Total
ML (all gains)	2	3	3	1	**3**
MA (all gains)	2	3	3		**3**
IN (all gains)	5	3	5	3	**5**
RE (all gains)	6	3	5	3	**5**
GB (gain 1)	3	1	1	3	**2**
HA (gains 1,16)	1	1	1	2	**1**
HA (gain 128)	6	3	7	3	**7**

3.4. Channel consistency (syncronization)

This test has been done to verify the consistency (in time and amplitude) between channels for the different digitizers present in the Bergen Workshop, so to check the stability of the digitizer for each channel relative to the other channels. To do this test, we connected the three channels of each digitizer to a waveform generator, each digitizer receiving synchronously a 1 Hz triangle wave. Here, we defined the main parameters influencing the H/V ratio using models, real data coming from the Bergen workshop and the alteration of real noise by these parameters to evaluate the impact on real H/V ratio.

MODELS – We made models to check the influence of various parameters (electronic noise, no synchronism between channels, difference on gain between channels, etc.). Sending the same waveform on the three components, the H/V ratio must be equal to one on the whole frequency range. The main impacts on the H/V ratio come from:

- The level of electronic noise compared to the level of recorded waveform. This factor affects only the upper frequencies, generating instabilities proportionally to the ratio electronic noise/recorded data.
- The lack of synchronization between channels. The lowest detectable shift for a digitizer is it frequency sampling rate divided by the maximum amplitude (depends on the gain etc.). This factor influences mainly the H/V ratio in the upper frequency range.
- The gain difference between channels. Depending on the value of gain difference, the H/V ratio is simply translated upward if the gain error corresponds to an amplification in the digitized values, and downward in case of reduction.

TESTED DIGITIZERS – From the 13 tested digitizers, only two show a visible shift in time. For the gain, all the digitizers have a difference, from 0.013% (Kinemetrics-Etna) to close to 25% (Kinemetrics-SSR; for this digitizer the error comes from a gain error). Following, we present a table with the maximum error for the gain difference between channel for each digitizer. Additionally, the time problem detected were indicated (if the time problem is not detected, the digitizer may contain errors in time synchronization of the channels, but with the current data set it would not be possible to locate this problem) (see figure 3-4-1). See also Appendix for other tests.

Table 8. Ranking of the digitizers after the channel consistency test.

STATION NAME	MAXIMUM CHANNEL AMPLITUDE	MAXIMUM DIFFERENCE BETWEEN CHANNEL	MAXIMUMPE RCENTAGE OF ERROR	RANKING	TIME PROBLEM
Kinemetrics-Etna	3458162	434	0.012550019	1	NO
CityShark	82583	21	0.025428962	2	NO
INGV-Self Made	2211167	1018	0.046039037	3	YES
Refteck 72A07	515836	247	0.047883436	4	NO
Hathor 3	190176	128	0.067306074	5	NO
Mars Lite	1048575	746	0.071144172	6	NO
TITAN	1523470	2308	0.151496255	7	NO
Mars 88	504896	1088	0.215489923	8	NO
GeoSIG GBV 316	10201	40	0.39211842	9	YES
Earth3C	27238	271	0.994933549	10	NO
Earth Data	290246	3414	1.1762436	11	NO
Nanometrics	30736	3456	11.24414368	12	NO
Kinemetrics-SSR	43987	10945	24.8823516	13	NO

APPLICATION TO NATURAL DATA – In this section, we evaluate the effect of gain and time shift on the H/V spectral ratio of a previously recorded ambient noise data (see figure 3-4-2).

Gain influence

In case of amplification on one or two channels, the impact on the H/V ratio is visible if the amplification reaches at least 15%. In case of reduction on one or two channels, 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 on all the frequency range. From 0.01 to 0.15 Hz, the impact corresponds to a simple translation, like over 4 Hz. The problem is the non-systematic error between 0.15 and 4Hz, by variable impacts along the frequency range.

The gain difference between channels changes directly the H/V ratio, proportionally to the gain, especially in the lower and upper frequencies. Moreover, the gain difference is a function of the amplitude of the recorded waveform. If the record is done with small amplitude, the influence of the gain difference is low, when a digitalization with high amplitude increases the influence of the gain difference.

Shift in time influence

If a channel is digitized at T0 and another channel at T0+Δt, the difference [first channel minus second channel] must be negative if the digitized waveform is increasing and negative if the digitized waveform is decreasing, so there is an opposition of phase. In case of time shift, a difference [ch1 minus ch2] in opposition of phase with initial data would say that the channel ch2 has been digitized later than the channel ch1. If the difference [ch1 minus ch2] is in phase with initial data, it would say that the channel ch1 has been digitized later than the channel ch2.

However, the shift in time could be invisible. The visibility of the shift in time depends on one hand of the sampling rate of the digitizer and on the other hand of the maximum amplitude of the record. If a station has a digitizer working at Sdigi Hz with recorded amplitude of AmpMax, the ratio Sdigi/AmpMax defines the lowest shift in time (in sample) allowing the visibility of the shift.

Depending on the difference of time, the shift in time seems to modify the H/V ratios mainly on the higher frequencies. So, the affected frequency range decreases when the time difference is increasing. On the lower frequencies (< 0.1 Hz), the shift in time modifies the H/V ratios but less than in the higher frequencies.

Chapter 4: Influence of the sensors (one digitizer two sensors)

Influence of the sensors was tested by recording simultaneously two sensors (the reference sensor and the tested sensor) on the same Nanometrics digitizer. The reference sensor was a Guralp 40T broad-band. In total 17 sensors were tested. In general, signals look quite similar, as expected. However, the accelerometers were not sensitive enough for lower frequencies.

The Lennartz 5 sec sensors were the best performing in terms of the frequency range and sensitivity. Additionally following remarks can be made. The H/V ratio of the site was flat and therefore may not be the best condition to make the test. Stability is important for broad-band sensors and accelerometers. The length of the record used in the experiments for frequencies below 1 Hz is too short to resolve the details. In general 10 minutes of stabilization is required for all active sensors. Smoothing of the windows has an influence on different frequencies in the final records (due to the simple smoothing function used in the processing).

The response of the sensors, were checked systematically to make sure that the instrument corrections done were correctly. The only real wrong sensor response was CH, however several had wrong polarity. In general the signals look quite similar, as expected. In order to see the effect of differences in sensors for the H/V technique, spectral ratios were computed.

The accelerometers were in general very poor, and in some cases not sensitive enough. The episensor, which should have been very good, was unstable and therefore very poor at low frequencies. The Lennartz (LE-3D/5s) seemed the overall best sensor if response down to 0.1 Hz or below is required. It also seemed stable. The two Lennartz 1 Hz sensors tested gave variable results. In order to have common criteria for comparison, we have computed the difference between the H/V of the tested sensor and the H/V of the reference sensor. All sensors showing a difference in ratio of less than 2 are believed to be acceptable for the H/V technique. In the following table the results of the sensor tests are summarized.

Table 9. Criteria: (H/V of tested sensor) – (H/V of reference) < 2 = acceptable for H/V

Not acceptable for H/V	Acceptable for H/V only for frequency >0.3 Hz	Acceptable for H/V
GA : acc CMG5T Guralp KG:acc episensor Kinemetrics KE:acc episensor Kinemetrics	SN: vel sensor 4.5 Hz Sensor Netherland M4: vel sensor 4,5 Hz Mark product	M1: vel sensor L4C 1Hz Mark Product M2: vel sensor L22 2 Hz Mark Product L1 : vel sensor LE3D lite 1Hz Lennartz L6 : vel sensor LE3D classic 1Hz Lennartz L2, L3, L4, L5 : vel sensor LE3D 0.2Hz Lennartz KS : broad band sensor, KS2000; 0.01 Hz; Geotech CH: vel sensor, 2Hz, Chineese republic R1: vel sensor Ranger 1Hz; Kinemetrics GI: broad band sensor, CMG40T; 0.03 Hz; Guralp)

However, it should be noted that the H/V response was flat in the laboratory and this may not be the best condition to compare the influence of the instruments. In Appendix 4 all sensor comparisons are shown in detail. In addition, detailed comments are given for each individual sensor test.

Chapter 5: Comparison of the data recorded simultaneously (one digitizer-sensor against a reference system)

In order to compare the results from the different systems (combination of digitizer and sensors), we have performed simultaneous measurements in the laboratory and in the free-field (in two sites).

5.1. In the Laboratory

Simultaneous measurements were done on the concrete piers at the laboratory, which is coupled directly to the bedrock. Comparisons are made for each instrument with the reference system which consisted of the combination of a Nanometrics digitizer with the Guralp 40T broad-band sensor. The results are shown in superimposed spectral plots with each system together with the reference system. In addition H/V ratios were computed for each horizontal channel and plotted together with the H/V ratios of the reference system. A common time window of 1-minute duration is used for all recordings. The frequency range is 0.1 to 20 Hz.

An identical time interval was collected for as many traces as possible by using the hammer pulses. Traces from 3 recorders were not recorded in the same time interval. These were included since the noise level should be very similar and therefore could be used for a general gain check of recorders. The recorders from a different time interval were:
TIKE, MLL4 and LE-L2.

The response files were checked and the following changes were made:

IN-L3: Polarity was reversed
MLL1: Changed ad gain from 80 000 to 800 000, and the high pass filter added
NLGS: Gain was lowered a factor of 2 as described under sensor tests.
GB-SN: Correct filters were put in

The original traces are seen in Figure 5-1-1. Only a small window is seen. The traces look different except when sensors are similar like trace 22 and 25. Some traces have inverted polarity like trace 3. However, all raw amplitudes are different due to different recorders and different sensitivity of sensors. When correcting for instrument response, the traces appear much more similar (see Figure 5-1-2).

In general signals on Figure 5-1-2 look similar and the maximum amplitude is nearly identical. This is quite good considering that only manufactures information have been used for the sensor and recorder specifications (the measured AD sensitivity was not used here). The deviating sensors are the accelerometers, which obviously cannot resolve the noise (as also shown above) and consequently, the pure electronic noise results in a large artificial amplitude. The last 3 channels, which are from a different time window, show different signals but the absolute amplitude is almost the same indicating that the natural background noise at the test site is quite stable over time and that calibration is OK. From this figure we can conclude that all seismographs performs equally well. This is also to be expected since most sensors have a flat velocity response above 1 Hz, however it shows that the 4.5 Hz sensor (trace 10) performs equally well.

Figure 5-1-3 and 5-1-4 show the displacement traces in the frequency bands 0.2 - 1.0 and 0.1 – 1.0 Hz respectively. These limits have been chosen since the sensor tests above showed that 0.2-0.3 Hz was a critical limit for several sensors. Down to 0.2 Hz, the signals look quite similar but the absolute amplitudes start to deviate for some sensors, particularly the Lennartz 1Hz. When extending the frequency band down to 0.1 Hz, still more deviation is seen, particularly for the Lennartz 1 Hz and the 4.5 Hz GBV. This is most likely caused by noise in sensor or noise in digitizer when sensor output is small compared to digitizer sensitivity. It can also be caused by incorrect calibration info, see also discussion in previous section. However, for systems with 1 Hz or 4.5 Hz sensors, it is clearly a bit problematic to get accurate ground displacement at 0.1 Hz considering that the output is very small and small errors in specification of damping and free period will affect response at low frequencies significantly. Similar comparisons were made with the other components and results were similar.

There does not seem to be any significant advantage of using the Lennarts 1 Hz versus using the 4.5 Hz directly, provided the digitizer has low enough noise. In the above tests, it actually seems that the GBV performs a bit better than the Lennartz 1 Hz sensor, probably due to the low noise digitizer in the GBV (see figure 5-1-5). One can consider the GBV as a digital 4.5 Hz sensor.

The deviations at low frequencies might not affect the spectral ratios if the deviation is instrumental parameter related and similar on all components (see ratio tests). However, if caused by electronic noise the ground motion information is lost or distorted and cannot be extracted. However, it is to be expected that all recorders tested here (except the accelerographs) should give acceptable performance down to 0.2 Hz. In Appendix 5 a complete set of figures for each system in comparison to the reference system are shown.

5.2. In the free-field

Measurements in the free-field were performed in two sites with different surficial cover at the same locality (see the pictures). **Site 1:** The surface cover in this site was grass. **Site 2:** The surface cover on this site was concrete. At both sites, the underlying soft sediments are the same. Three examples of the H/V ratios (only for the N-S components) are shown in the following figures. In figures 5-2-1 and 5-2-2 some examples of the H/V ratios are shown. Complete list of comparisons are included in Appendix 5.

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FIGURES

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Figure 1-1. The different site locations used for the measurements. Figures on the left (top, middle and bottom) are from the laboratory. Figures on the right are from the free-field measurements (top and middle right: Site 1; bottom right: Site 2).