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On the suitability of 1 sec geophone for ambient noise measurements in the 0.1-20 Hz frequency range: experimental outcomes

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Abstract

Following the ongoing debate about suitability of short-period sensor for seismic noise measurements at frequencies lower than 1 Hz, in this study we compare recordings from two different seismometers (Güralp CMG-3ESPC and Mark L4C-3D) installed side by side in the GeoForschungsZentrum laboratory. The comparison carried out in terms of Power Spectral Density and coherency analysis shows an excellent agreement between the short-period and the broad-band recordings in the frequency band 0.2-20 Hz. Therefore, this result highlights that with a calibrated short-period sensor one can obtain the same results that would be obtained by using a broad-band seismometer in the band of engineering interest.

In the last decade the number of studies dealing with the analysis of seismic noise has dramatically increased. This is mainly due to the fact that the Nakamura technique (Nakamura, 1989), that consists of estimating the fundamental resonance frequency of a site by the horizontal-to-vertical (H/V) spectral ratio of seismic noise, can be applied to measurements taken nearly everywhere (a condition very important for urban area microzonation) and for relatively short periods of time (from some minutes to about one hour). Unfortunately, with the increasing number of studies dealing with the application of this technique, there does not correspond an increasing number of studies focused on the capability of the used seismic instruments for properly

recording seismic noise over the whole frequency band of interest in engineering seismology. Attempts in this direction were done, for example, by Mucciarelli (1998), who came to the important conclusion that accelerometers should be avoided, and by Parolai *et al.* (2001) who compared the H/V spectral ratio results obtained by very popular 1 sec short-period seismometers with those derived by broad-band recordings. More recently, a systematic comparison of H/V results obtained combining several different sensors and acquisition systems was done by Guillier *et al.* (2007), while Strollo *et al.* (2008), using a theoretical approach, and Marzorati *et al.* (2006) who used empirical analysis, focused their attention on the influence of the short-period sensors spectral ratio results for frequencies lower than 1 Hz.

An interesting result obtained by the extensive study of Guillier *et al.* (2007) regards the performance of the short-period 1 sec Mark L4C-3D sensor. This seismometer is largely used when seismic surveys are carried out for microzonation projects or for estimating the fundamental resonance frequency of a site by noise measurements, because it is easy to install and relatively cheap with respect to broad-band sensors. The results of the instrumental test performed by Guillier *et al.* (2007) considering free field measurements led them to conclude that “*All tests including M1 (Mark 1s) sensor have demonstrated problems over the entire frequency range, either for spectral velocity curve or the H/V curve*” (Guillier *et al.* 2007, paragraph 5.4).

Although the authors stated that this problem might come from a malfunctioning of the instrument they had at hand “*It can however be a problem linked only to this particular seismometer used for the tests and no to any M1 seismometers*” (Guillier *et al.* 2007, paragraph 5.4), we were somewhat alarmed since most of our previous studies were carried out with this kind of geophone. Although we knew that we and other authors had already carefully checked the suitability of this sensor for noise measurements by means of comparisons with the short-period recordings from calibrated geophones with other instruments, such a statement was definitively worthy of attention.

The question was: Were all our previous results (like those of other several groups using this very popular geophone) affected by bias due to the choice of an inappropriate sensor?

In order to answer this question we decided to install in the subterranean laboratories of the GeoForschungsZentrum-Potsdam (GFZ) a broad-band seismometer (Güralp CMG-3ESP Compact, flat response from 60 to 0.02 seconds) and a calibrated 1 sec

short-period Mark L4C-3D sensor for recording seismic noise during one night. Both sensors were connected to an Earth Data Logger (EDL) acquisition system (24 Bit) that is routinely used by different groups at the GFZ.

Data were recorded with a sampling rate of 100 samples per sec and a gain of 10 was set for the channels occupied by the Mark sensors, since this value was shown to be optimal for increasing the signal-to-noise ratio in the frequency band lower than 1 Hz by Strollo *et al.* (2008). The acquisition design is shown in Figure 1.

A data set consisting of more than 10 hours of continuous recording was analysed following the procedure of McNamara and Buland (2004) using signal windows of 10 minutes length. The Power Spectral Densities (PSDs) against time shown in Figure 2 (top) for the vertical component (similar results have also been obtained for the horizontal components) highlight the great consistency of the results obtained using the broad-band and the short-period seismometer for frequencies higher than 0.2 Hz. The excellent agreement of the PSDs is well depicted in Figure 2 (bottom) where each single ten-minute window spectral density is shown. Note that above 0.2 Hz even the details of the spectra are nearly identical. Below 0.2 Hz instrumental noise dominates the recordings obtained with the short-period sensor. Only when stronger microseismic-activity related signals are recorded, it is possible to obtain reliable results at lower frequencies from the short-period seismometers (Marzorati *et al.*, 2006; Strollo *et al.*, 2008). No spurious spectral peaks (that also cannot be seen in the broad-band recordings) are observed on the short period recording spectra.

Following McNamara and Buland (2004), the Probability Density Function (PDF) of the PSD distribution was computed. Figure 3 shows that between 0.2 and 20 Hz even the 5th percentile of the distributions are nearly identical and that below 0.12 Hz the 5th percentile relevant to the short-period recordings follows the same trend of the self noise of the Mark-EDL combination derived by coherency analysis (Holcomb, 1989). Finally, we calculated the coherency $C(f)$, over the 0.1-20 Hz frequency range, between the noise time series simultaneously recorded by the short-period and broad-band seismometers. $C(f)$ was estimated as the cross power spectral density normalized to the power spectral density of the two time series filtered between 0.06 and 40 Hz using a six-order a-causal Butterworth filter.

The results in Figure 4 show that between 1 and 10 Hz the coherency is practically 1. The PDF of the coherency distribution (Figure 4 bottom), computed considering bin 0.01 coherency unit wide, shows that between 0.2 and 1 Hz and between 10 and 20

Hz more than 95% of the analysed windows show coherency larger than 0.99. Values larger than 0.8 are obtained for frequencies down to nearly 0.15 Hz.

The agreement between the spectra computed for the Guralp and Mark sensors produces consistent Nakamura ratios. Figure 5 shows the amplitude of the spectral ratio between the north-south and the vertical components for both sensors: a near-perfect match is achieved for frequencies higher than 0.2 Hz. The issues that arise when applying the Nakamura technique using instruments with a limited exploitable frequency range has been discussed by Strollo *et al.* (2008), and the reader is referred to that work for additional details.

These results clearly show that with a calibrated short-period sensor one can obtain the same results that would be obtained by using a broad-band seismometer, at least in the frequency range 0.2-20 Hz (of engineering interest).

Accordingly, in agreement with Guiller *et al.* (2007), we suggest that before being used, the correct functioning of the equipment is checked and a calibration is necessary when passive electromagnetic sensors are used.

Hoping to have clarified an important open issue and to have, if necessary, reassured many researchers who have used 1sec short-period sensors for seismic noise analysis, we can confirm that these sensors are a good choice (in the sense of a good compromise between ease of installation, portability, cost, and quality of the results) for seismic noise measurements over the ~0.2-20 Hz frequency band.

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Identifying the name of the instrument's manufacturers is not meant to be an endorsement of their products. K. Fleming kindly improved our English. Comments from an anonymous reviewer and the guest editor P.-Y. Bard are also acknowledged.

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Figure 1. Seismometers tested in the GeoForschungsZentrum Potsdam lab.

Figure 2. Top: PDS against time of the Guralp CMG-3ESPC. (left) and of the Mark L4C-3D (right). Color scale is in decibels with respect to velocity $(\text{m/s})^2/\text{Hz}$. Bottom: PDS for every 10-minute seismic noise window recorded by the Guralp (left) and by the Mark corrected for instrumental response (right).

Figure 3. 5th percentile of the PDF calculated from the recordings of the Güralp CMG-3ESPC (black line) and of the Mark L4C-3D (red line) corrected for instrumental response. Self noise of the Mark-EDL combination (blue line) was derived by coherency measurements (Holcomb, 1989). Dashed lines are the New Low Noise Model (dark grey line) and New High Noise Model (grey line) of Peterson (1993).

Figure 4. Top: Coherency computed between Güralp CMG-3ESPC and Mark L4C-3D signals against time. Middle: Coherency curve for each of the analysed 10-minute seismic noise window. Bottom: PDF of the coherency distribution plotted in the middle panel.

Figure 5. Mean $\pm$ one standard deviation of the north-south to vertical spectral ratio for the Guralp CMG-3ESPC (white line and dark grey area) and the Mark L4C-3D (black line and light grey area) sensors.