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A General Purpose Digital System for Field Vibration Testing

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Nomenclature

x, y, z	Measurement directions
x, y	Base displacement, coil displacement
H	Transfer function
ω, f	Frequency
e_{\max}	maximum coil excursion
\dot{U}_{noise}	Sensor noise floor
R	Signal-to-noise ratio
D	Dynamic range
G	Spectral density
S_{α}	Spectral density in α octave plot
σ_T	Time synchronization uncertainty
M	Number of independent data segments
N	Number of broadcasted messages
β	Noise floor reduction factor

Abstract

This paper describes the development and concept implementation of a highly sensitive digital recording system for seismic applications and vibration measurements on large Civil Engineering structures. The system is based on highly sensitive motion transducers that have been used by seismologists and geophysicists for decades. The conventional geophone's ratio of cost to performance, including noise, linearity and dynamic range is unmatched by advanced modern accelerometers. The unit comprises six independent sensor elements that can be used in two different configurations for noise reduction and extended dynamic range. The paper describes the basic principles in the system design and the resulting application properties.

1. Introduction

The instrument considered is the Pinocchio WL 380 which uses geophone sensors as the basic sensing elements. Six geophone sensor elements are used in a dual-coordinate configuration as shown in Figure 1. There are several reasons for using a dual sensor technology

- Improved security against loss of data
- Improved noise suppression
- Improved dynamic range

If one of the sensor elements or its corresponding input channel is damaged, the remaining corresponding sensor element can be used for recording. If two sensor elements are active in each direction, noise in the recorded data can be suppressed in the frequency domain by performing averaging between cross spectral densities of repeated measurements. This is elaborated in more detail in a section below on this issue. In case one sensor element is connected to an A/D converter with maximum sensitivity, this channel takes full advantage of the low noise floor of the sensor element, but such channel cannot at the same time accept high sensor outputs as this might cause clipping of the recorded time series. However, if the corresponding dual sensor is connected to an A/D converter with minimum sensitivity this channel can accept the high response signals. Thus if the signals of the two channels are combined, the user can take advantage of the expanded dynamic range and at the same time not have to worry about the right sensitivity setting – because the system is covering the full dynamic range of the data acquisition system.

The data acquisition system is based on a distributed design using 6 low noise 24 bit converters, each of which is mounted directly on each sensor in order to minimize noise introduced in the signal path between the sensor element and the A/D converter. The sensors are mounted in a closed metal block acting as electrical shielding and protecting the A/D electronics and the sensor elements from environmental influences such as moist, air pressure fluctuations etc, see Figure 1.

The instrument has a GPS unit for accurate time synchronization with other units. The instrument has a GSM line available for instrument control and data download. This GSM connection can also be used for time synchronization in case reliable satellite connection cannot be established by the GPS unit. The synchronization is essential for using the instrument in multi instrument configurations for modal analysis including mode shape estimation for large structures. The two synchronization techniques are explained further in the following paragraphs.

The noise floor of the sensor is shown in Figure 2 together with the well known New Low Noise Model (NLNM) from US Geological Survey, See Peterson [1]. As it appears, the instrument will ensure acceptable measurements using reasonable measurement times at any site in the frequency range 0.1 Hz to 10 Hz. For structural applications the vibrations are typically amplified 10-100 times, therefore the structural response curves due to microtremors alone will lie at a level that is at least 20 dB higher than the Low Noise Modal shown in Figure 2. It can be seen from this figure that for structural applications the instrument will be able to record the ambient response of any structure in the broad frequency band 0.01 Hz – 100 Hz.

The sensor elements are secured during transportation by heavily increasing the damping of the coil movement. The instrument box is water tight (IP 68, max 0.9 atm. pressure), which protects the electronic components from all kinds of weather conditions or harsh environmental situations. The instrument has a rechargeable battery that can operate the instrument during 24 hours of constant measurements or power the instrument for one month on a stand-by setting.

2. Electro dynamic sensor technology

The design is based upon the classical geophone sensor element. In its simplest form, it is a coil suspended around a permanent magnet - just like a loud speaker coil/magnet system. When the coil moves relative to the magnet, a voltage is induced in the coil according to the Faraday law, Figure 3. The induced voltage is proportional to the relative speed, thus the geophone sensor element is measuring velocity. However, since the coil is suspended, the suspension systems acts as a second order high pass filter with the following transfer function, Brincker et al [2]

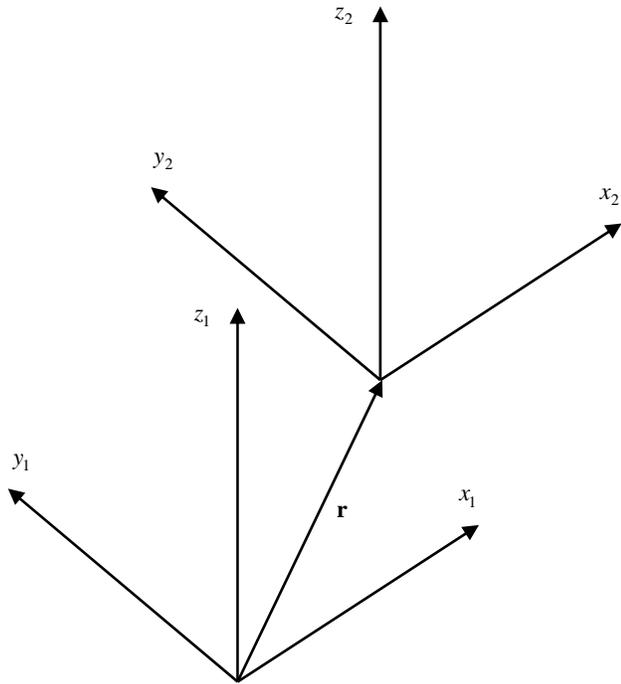


Figure 1. The WL 380 sensor block with 6 sensors in the dual coordinate system configuration. Left, schematic, right, photo of the sensor block, lower part of the sensor block correspond to x_1, y_1, z_1 , upper part to x_2, y_2, z_2 .

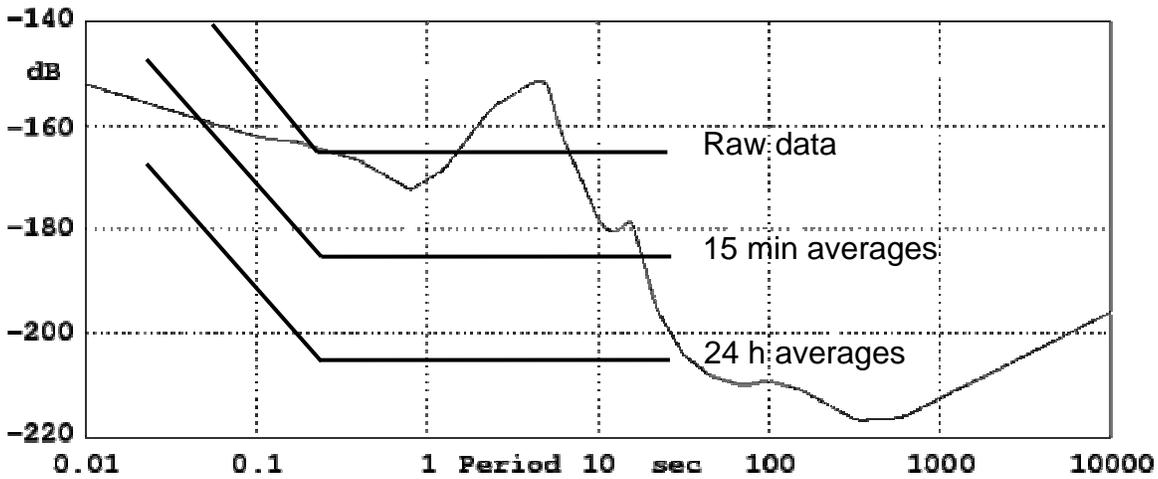


Figure 2. Comparison of the US Geological Survey New Low Noise Model (NLNM) of seismic noise amplitude expressed as RMS amplitude in dB relative to 1 m/s^2 in 1/6 decade with the noise floor of the instrument for different averaging times. The instrument noise floors assume a frequency resolution of 0.1 Hz.

$$(1) \quad H = \frac{Y - X}{X} = \frac{\omega^2}{\omega_0^2 + 2j\omega_0\omega\zeta - \omega^2}$$

The sensor element has a natural frequency at 4.5 Hz and an internal damping of 56 %. The sensor signals are corrected by inverse filtering as described in Brincker et al [2]. The noise floor of the sensor element in the frequency domain is $\dot{U}_{noise} = 0.1 \text{ nm/s}\sqrt{\text{Hz}}$ corresponding to an electrical signal of $V_{noise} = 3 \text{ nV} / \sqrt{\text{Hz}}$. If we assume a constant output noise floor, then the noise floor of the corrected signal becomes

$$(2) \quad \dot{X}_{noise} = \dot{U}_{noise} / H$$

The maximum sensor signal is determined by the maximum coil excursion e_{max}

$$(3) \quad X_{max} H_0 = e_{max}$$

The corresponding noise floors and maximum input floor for displacement and acceleration are found by division (integration) and multiplication (differentiation) by the frequency respectively. The results are shown in Figure 4. Even though the curves have a kink at the natural frequency of the sensor element, the dynamic range of the sensor element is free of such kink, see Figure 5.

The maximum sensor output and noise defines the signal-to-noise ratio R and the corresponding dynamic range D as

$$(4) \quad R = \frac{|X_{max}|}{|X_{noise}|} = \frac{\omega e_{max}}{\dot{U}_{noise}}$$

$$D = 20 \log(R)$$

The result is shown in Figure 5. The acceleration noise floor is symmetric around the natural frequency of the sensor element, each response leg showing a linear transfer function in a log-log plot. The left leg (below the natural frequency) is approximately proportional to f^{-1} , similarly the right leg is approximately proportional to f . The minimum noise occurs at the natural frequency and is equal to $a_{noise} = 3.2 \text{ nm}/(s^2 \sqrt{\text{Hz}})$. We can calculate the corresponding curve for 1/6 decade response by integrating the spectral density

$$(5) \quad S_{\alpha} = \int_{f_c/\alpha}^{f_c\alpha} G(f) df$$

where f_c is the centre frequency of the filter, and where for a 1/6 decade filter $\alpha = 10^{1/12} = 1.212$. Now assuming that the spectral density is approximately constant

$$(6) \quad S_{\alpha} \cong G(f_c) f_c (\alpha - 1/\alpha)$$

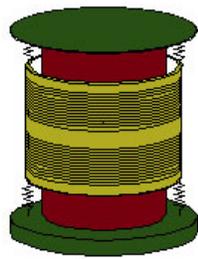
Thus in a 1/6 octave picture, the left leg becomes approximately horizontal, and the level is easily found at the natural frequency of the sensor element

$$(7) \quad a_{1/6} = 5.5 \text{ nm} / s^2$$

Corresponding to a constant level of -165 dB in a log-logl plot. This is the background for the "raw data" curve shown in Figure 2 showing the 1/6 decade plot as a function of the period $T = 1/f$.

3. A/D converter technology

The applied A/D converters are extremely low-noise, 24-bit analog-to-digital (A/D) converters. The converter is comprised of a 4th-order, delta-sigma modulator followed by a programmable digital filter. A flexible input includes circuitry to verify the integrity of the external sensor connected to the inputs. The input circuitry also allows for high input impedance and the low-noise programmable gain amplifier (PGA) provides gains from 1 to 64 in binary steps. Communication is handled over an SPI-compatible serial interface that can operate with a 2-wire



↑ $y(t)$, coil displacement
 ↑ $x(t)$, base displacement

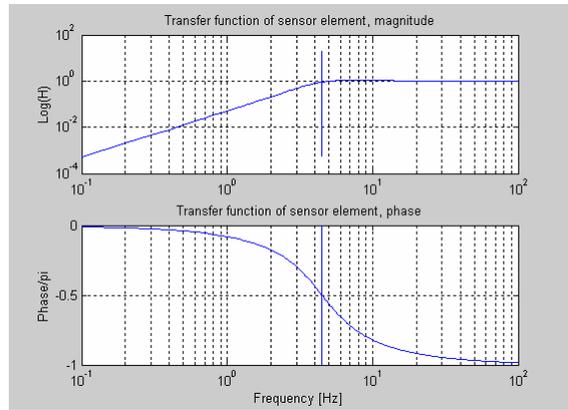


Figure 3. Left: WL 380 sensor element. Right: the sensor element transfer function as given by Eq. (1).

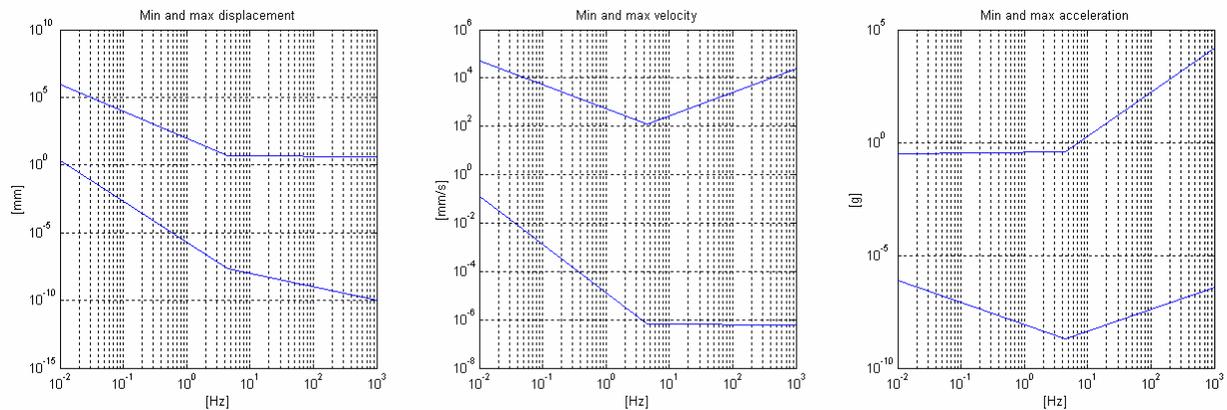


Figure 4. Noise floor and maximum input in terms of displacement, velocity and acceleration.

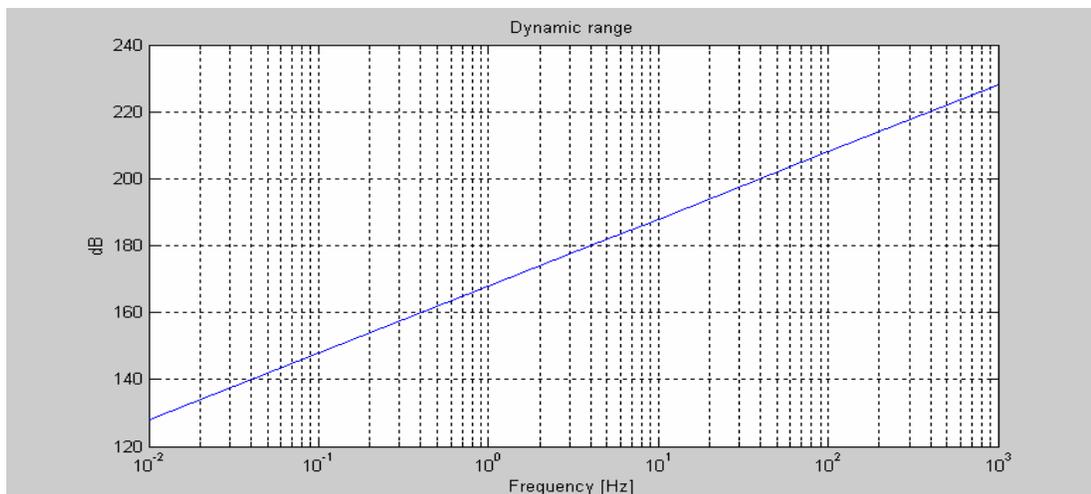


Figure 5. Dynamic range of the WL 380 sensor element.

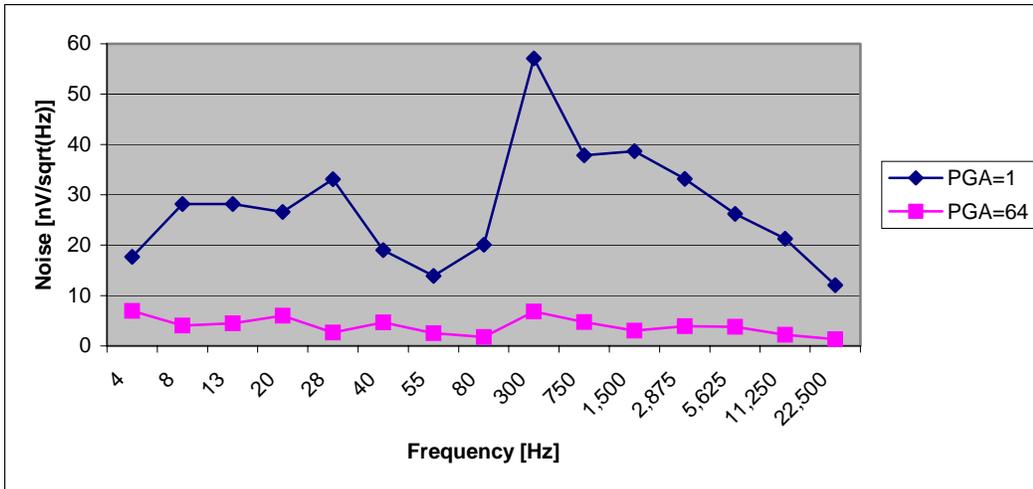


Figure 6. Input noise floor of the A/D converter with the programmable gain amplifier (PGA) set to unity amplification and 64 times amplification.

connection. Onboard calibration supports both self and system correction of offset and gain errors for all the PGA settings.

The input noise floor of the A/D with maximum and minimum sensitivity is shown in Figure 6. The average value over the entire frequency range of the input noise floor of the A/D on maximum sensitivity was found to $3.9 \text{ nV} / \sqrt{\text{Hz}}$. Thus, the applied A/D converter in its most sensitive mode matches the low noise floor of the sensor element. The average noise floor of the A/D converter using no amplification (PGA=1) in the frequency region of interest DC-100 Hz is found to $23.3 \text{ nV} / \sqrt{\text{Hz}}$. Thus since the maximum input is $\pm 5 \text{ V}$, the dynamic range of the A/D converter is

$$(8) \quad D_{AD} = 20 \log(5 / (23.3 \times 10^{-9})) = 166 \text{ dB}$$

corresponding to a bit equivalent of approx 27.7 bits. Using the RMS noise for a given frequency span gives more conservative values of for instance 23.4 effective bits for a sampling rate of 100 Hz and 24.8 effective bits for a sampling rate of 10 Hz.

4. Time synchronization

Normally the time synchronization will be performed using the internal GPS module of the instrument. However, this requires that at least 4 satellites are detected by the GPS unit. If this is the case, then the real time clock in the GPS unit is automatically calibrated and synchronized with the universal time down to a micro-seconds level of accuracy. In order to take advantage of this high accuracy, and to simplify the communication between the measurement loop software and the GPS unit, the measurement process is triggered by a hardware interrupt from the real time clock in the GPS unit. The achieved accuracy of the so defined time synchronization is better than 50 μs .

If a connection to the satellites cannot be established, time synchronization is performed using a GSM line. The algorithm that is used via the GSM is a general purpose time synchronization algorithm that can be used in all systems with random delays of messages. The present algorithm is protected by a pending patent.

The algorithm is not based on the idea of securing a common clock definition for all sensors, but on the idea of letting the individual clock uncertainty exist during a measurement session and then later identify and correct for the clock errors. The clock errors are identified by broadcasting messages to all sensors; the messages are then received by the sensors and send back to the host attached to the data stream. The position of the returned messages in the data series from the sensors identifies the time each sensor has received the messages, and

using a simple linear regression algorithm allows for the identification of the time when the sampling process was started. Using simple regression theory the resulting uncertainty can be estimated to

$$(9) \quad \sigma_T = \frac{2\sigma_x}{\sqrt{N}}$$

where σ_x is the inherent time uncertainty in the system, and N is the number of broadcasted messages. Thus by broadcasting a large number of messages, the time uncertainty can be significantly reduced. As an example, if the inherent uncertainty is 50 ms, then by broadcasting 100,000 messages (for instance by sending 100 messages per second during a 15 min measurement session), the time uncertainty is reduced to approximately 300 μ s.

If we accept a phase uncertainty of 5 degrees, then a time uncertainty of 50 μ s corresponds to 275 Hz bandwidth and a time uncertainty of 300 μ s corresponds to 45 Hz bandwidth. A bandwidth of a few hundred Hz is ideal for all seismic and structural engineering applications; however a reduced bandwidth of about 45 Hz is an acceptable frequency band for most seismic and structural applications.

6. Noise reduction by dual sensor technology

Normally when we calculate a spectral density we would use the well known Welch's averaged periodogram method. For instance calculating the power spectral density for the x-direction

$$(10) \quad \hat{G}_{XX}(f) = \frac{1}{M} \sum_{s=1}^M X_s(f) \bar{X}_s(f)$$

where $X_s(f)$ is the Fourier transformed of the data segment no s in the time series, the total length of the time series is $T_{tot} = MT$, where T is the length of one data segment. Let us assume that noise is present in the measured signal, then because it is the same noise that is present in both of the factors in Eq. (10), the noise will not average out, but will define a minimum noise floor that is equal to the spectral density of the noise source itself. If however we measure two independent signals x_1, x_2 representing the same physical signal, then we can estimate the auto spectral density function as a cross spectral density between the two signals

$$(11) \quad \hat{G}_{XX}(f) = \frac{1}{M} \sum_{s=1}^M X_{1s}(f) \bar{X}_{2s}(f)$$

In this case – in principle – the uncorrelated noise sources will average out. Thus inherent sensor element noise as well as A/D converter noise will average out and disappear. However, since for such estimate we will take the absolute value (to get rid of the unwanted phase on a auto spectral density function), and since there is a variance on the estimate due to limited amount of information, we will still observe a noise floor in the spectral density estimate. The observed noise floor is of the order of the standard deviation on the spectral estimate. The relative standard deviation on the spectral estimate can be taken from Bendat and Piersol [3]

$$(12) \quad \varepsilon_r = \frac{1}{\sqrt{B_e T_{tot}}}$$

Where B_e is the effective bandwidth of the filter considered. Now for an FFT taking the effective bandwidth equal to the width of one spectral line, thus $B_e = 1/T$ gives us the noise floor reduction factor

$$(13) \quad \beta = \frac{1}{\sqrt{M}}$$

Thus we have a reduction of the observed noise floor by a factor of 10 each time we extend the amount of data by a factor of 100, i.e. of 10 dB per decade of data we acquire. Going back to Figure 2, if we assume a data segment

length of 10 s corresponding to a frequency resolution of 0.1 Hz, then 15 minutes sampling will give about 100 averages, and thus lower the noise floor with approximately 20 dB. Similarly, 24 h sampling will give about 10,000 averages, and therefore lower the noise floor approximately 40 dB.

7. Extended dynamic range by dual sensor technology

Using the highest possible amplification, the noise floor is $3.9 \text{ nV} / \sqrt{\text{Hz}}$ as shown in Figure 6. Using the other sensor A/D with minimum amplification the maximum input is $\pm 5 \text{ V}$. This gives the system a total dynamic range of

$$(14) \quad D_{tot} = 20 \log(5 / (3.9 \times 10^{-9})) = 182 \text{ dB}$$

corresponding to a bit equivalent of approx 30 bits. As an example, let us say that x_1 is running at max sensitivity and x_2 is running at low sensitivity (maximum input). Then let us assume that during a certain time span $[t_1, t_2]$ the signal x_1 is clipping, i.e. the A/D converter is saturated. The signal is then restored by

$$(15) \quad x = w_1 x_1 + w_2 x_2$$

where w_1 is a window that is zero in the time span $[t_1, t_2]$ and has a smooth transition to unity, similarly w_2 is unity in the time span $[t_1, t_2]$ and has a smooth transition to zero such that for any time $w_1 + w_2 = 1$. Thus the clipping errors are removed by using the signal from the other sensor. The only price one has to pay is a local increase of the noise floor in the time span $[t_1, t_2]$ due to the lower sensitivity of that channel, and introduction of phase and amplitude errors due to differences between the two sensors. However, since the sensor signals are inversely filtered, and thus the main part of the sensor difference is removed before the windowing is performed, the introduced errors are minimal.

Conclusions

The new instrument described in this paper incorporates a rugged design that can be used in-the-field during all kinds of weather conditions. The instrument is based on a geophone sensor element, a sensor element that has proved its value and reliability for decades. A weak aspect of the geophone sensor element – the bad signal response below the natural frequency of the sensor element – is effectively removed by inverse filtering. A dual sensor technology is used to achieve noise suppression and extended dynamic range. The instrument can record ambient responses of soil sites and structures even at the most silent places on earth. The noise floor of the instrument at long measurements is lower than -200 dB (ref. m/s^2) in 1/6 decades and the dynamic range of the instrument is better than 180 dB.

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