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Ground Vibration Measurements at the Proposed ALBA Site in Barcelona

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Abstract

ALBA, a new generation synchrotron light source for Spain, is presently in the construction phase. The proposed site is located in Cerdanyola del Vallès, near Barcelona. Several ground vibration sources are in the surrounding area. Some planned experiments at the newest generation of synchrotron light facilities are sensitive to the source size and stability of the light beam. Therefore CELLS has asked DESY to measure the ground vibration at the proposed ALBA site. The data were taken over one night in August and during a longer period at the end of 2004. The results are presented in this paper. They can then be used to judge the suitability of the site.

1. Introduction

ALBA is the name of a new synchrotron light facility for Spain. It is constructed and will be operated by the Consortium CELLS Consorcio para la Construcción, Equipamiento y Explotación del Laboratorio de Luz Sincrotrón[2], or the Consortium for the Construction, Equipment and Exploitation of the Synchrotron Light Laboratory. It is cofinanced by the Spanish and the Catalan governments. The Alba site is located in Cerdanyola del Vallès, near Barcelona in the vicinity of the University UAB Universitat Autònoma de Barcelona. Figure 2 shows a topographic map with the location of the laboratory in the center (1). The university campus (3) is located in the north. The ALBA site is bounded by a local road (9) and a ceramic factory (11). A railway partially underground and a multi lane highway (4) are other possible sources of cultural noise.

Cultural noise from human activities like traffic and engineering works enhances the ground vibration spectra by several orders of magnitude at frequencies above about

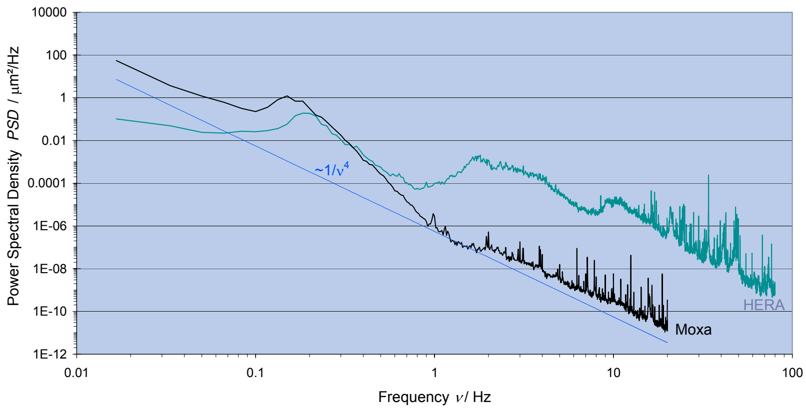

Figure 1: Power spectral density measured in HERA and at the quiet reference site Moxa together with a random walk noise trend.

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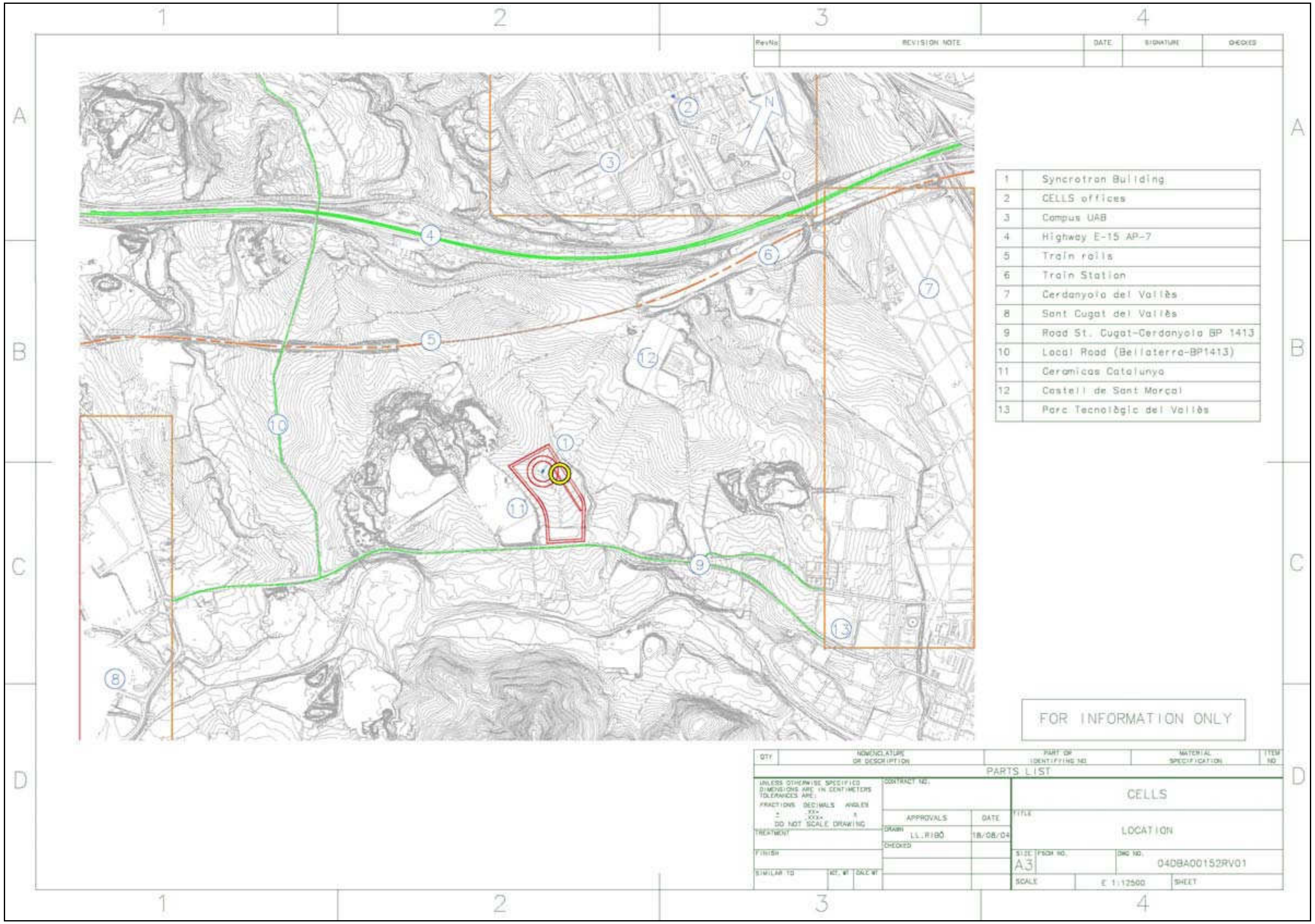

Figure 2: Proposed ALBA site in Cerdanyola close to UAB Universitat Autònoma de Barcelona. (The small circle in the center indicates the position of the seismic sensor during the one night measurement in August 2004.)

1 Hz and is mainly uncorrelated. Figure 1 shows the cultural (and the home made) noise measured in the HERA tunnel at DESY in Hamburg. The reference spectrum was taken at the relatively quiet German main seismic station Moxa. The signal at about 0.2 Hz is excited by ocean waves. The principle trend of the spectra proportional to $1/\nu^4$ corresponds to a random walk noise.

Ground vibration excites vibration of the quadrupoles in the storage ring of a synchrotron light facility which can be increased or damped by the resonance behavior of the supports. If the motion of the lenses is uncorrelated then the emittance of the stored beam will be increased, especially in the new generation low emittance machines. Additionally the stability of the photon beam is decreased due to the tilt jitter of the source point. For a synchrotron light source a typical specification can be given that the electron beam motion must not exceed 10 % of the beam size in the transverse planes [1]. Therefore ground vibration measurements were done at the proposed ALBA site to evaluate the influence of cultural noise sources. A stored beam in a synchrotron light source is flat and therefore much more sensitive to the vertical displacement of the quadrupoles than to the horizontal. Thus mainly vertical ground vibration measurements are presented in this paper.

2. Description of the Ground Vibration Measurement Method

The ground vibration measurements at the proposed ALBA site were made using Güralp tri-axial feedback seismic sensors CMG-3T [2]. These seismometers measure the ground acceleration $\ddot{x}$ which is integrated internally. Figure 3 shows the principle layout of one axis of a velocity broadband seismometer. The position of the seismic mass M, mounted as an inverse pendulum, is measured capacitively. A feedback loop with a force transducer compensates the ground acceleration acting on the seismic mass. The resonance frequency of the mass spring system can be significantly reduced by proper choice of the parameters of the feedback loop. The feedback current is proportional to the ground acceleration. The voltage across the capacitor C is a time integral of the current, and thus proportional to the ground velocity. This voltage serves as the output signal. The seismometer constant C_s is the output voltage U_i per ground velocity $\dot{x}_i$:

$$C_s = \frac{U_i}{\dot{x}_i} \propto \frac{M}{C}.$$

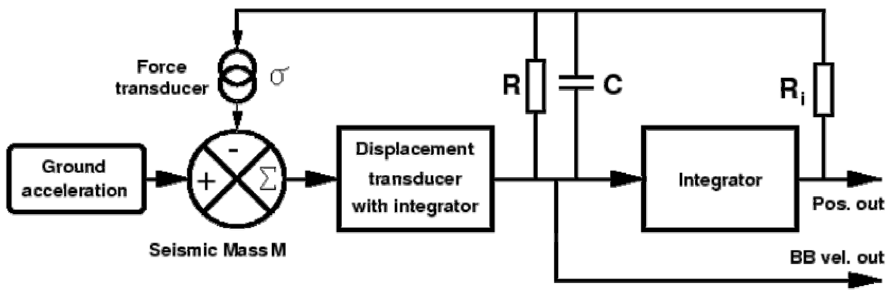

Figure 3: One channel of a velocity broadband seismometer feedback circuit [3].

The CMG-3T seismic sensors are hermetically sealed three-axis devices with an internal 24 bit digitizer (1.3 µV/bit) without amplifier, N/T = 200 Hz sampling rate and a seismometer constant of C_S = 3 kV/m/s. The resolution of the instruments is about 0.4 nm/s/bit or 0.07 nm/bit @ 1 Hz, which is sufficient to resolve the power spectra even at quiet sites. The frequency bandwidth is between 360 s for the instrument S1 and S2, respectively 120 s for the instrument S3 and 80 Hz. The CMG-3T uses a quiet stable

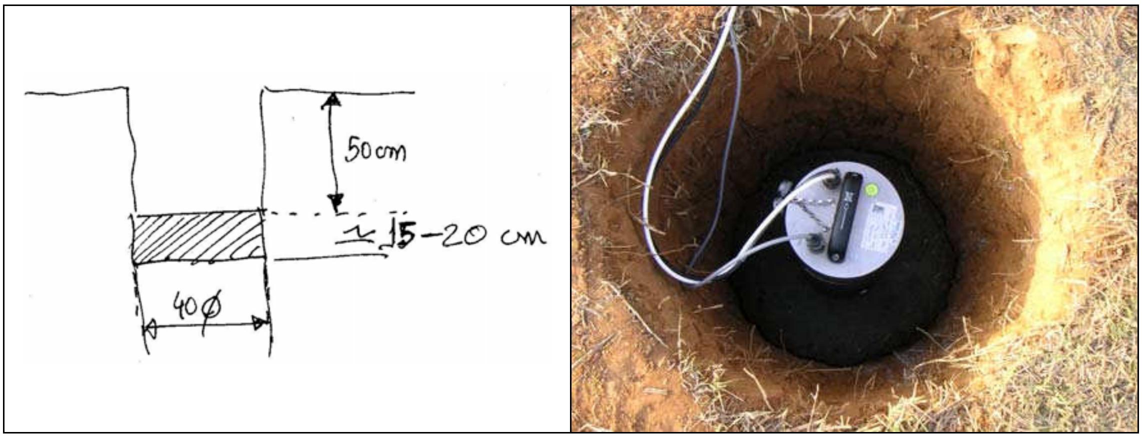

Figure 4: Dimensions of and seismic sensor CMG-3T from Güralp inside a pit at the ALBA site.

internal clock as a time base. An additional GPS time-code antenna can keep the internal clock synchronized with satellite-based UTC time signals.

The ground at the proposed ALBA site consists mainly of red clay. The dry ground is nearly like concrete. During the first over night measurement the instrument was placed directly on the ground. For the second period approximately 50 cm deep pits were prepared for temperature stabilization and to shield the seismometers against excitation from the wind. The pits were covered during measurement. The sensors were placed on a 20 cm concrete base to provide a stable surface for the instruments.

3. Analysis of the Measurements

The seismic sensors are linked to a Personal Computer via serial data cables. Every minute the data of all three components are stored in data files (measurement time $T = 1$ min). Table 1 shows part of a sample file.

n	dz/dt/ bit	dx/dt/ bit	dy/dt/ bit	t/s	dz/dt/ µm/s	dx/dt/ µm/s	dy/dt/ µm/s
0	60657	227	-106670	0,000	26,3	0,1	-46,2
1	57205	4972	-109060	0,005	24,8	2,2	-47,2
2	53883	8932	-104130	0,010	23,3	3,9	-45,1
3	52707	4106	-100260	0,015	22,8	1,8	-43,4
4	54822	-1508	-104880	0,020	23,7	-0,7	-45,4
5	57825	2102	-103750	0,025	25,0	0,9	-44,9
6	56535	6549	-103980	0,030	24,5	2,8	-45,0
7	58002	1950	-105870	0,035	25,1	0,8	-45,8
...	...	...	...	...	...	...	...
11992	44262	-44067	-131690	59,960	19,2	-19,1	-57,0
11993	51037	-43240	-127190	59,965	22,1	-18,7	-55,1
11994	55558	-38336	-119250	59,970	24,1	-16,6	-51,6
11995	60070	-41598	-128950	59,975	26,0	-18,0	-55,8
11996	69172	-46590	-134400	59,980	29,9	-20,2	-58,2
11997	81540	-44333	-134010	59,985	35,3	-19,2	-58,0
11998	89275	-38007	-131150	59,990	38,7	-16,5	-56,8
11999	84321	-38240	-125280	59,995	36,5	-16,6	-54,2

Table 1: Part of a data file with ground velocity data and calculated values (grey background).

The mean value $\langle \dot{u}_n \rangle$, the root mean square $\sqrt{\langle \dot{u}_n^2 \rangle}$ and the root mean square in reference to the mean value $\sqrt{\left\langle \left(\dot{u}_n - \langle \dot{u}_n \rangle \right)^2 \right\rangle}$ are calculated directly from the raw data:

$$\langle \dot{u}_n \rangle = \frac{1}{N} \sum_{n=0}^{N-1} \dot{u}_n \ ,$$

$$\sqrt{\langle \dot{u}_n^2 \rangle} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} \dot{u}_n^2} \text{ , and}$$

$$\sqrt{\left\langle \left(\dot{u}_n - \langle \dot{u}_n \rangle\right)^2 \right\rangle} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} \left(\dot{u}_n - \langle \dot{u}_n \rangle\right)^2} \text{ ,}$$

where $\dot{u}_n$ is one of the three ground velocity components. The mean value has no meaning for the ground motion due to the lower limit of the sensor bandwidth. More information about the ground vibration can be obtained in the frequency domain. Thus the data are Fourier transformed either online or offline. For N discrete values measured in the time T the power spectral density (PSD) S_k of the motion is defined as:

$$S_k = T \frac{\tilde{\dot{u}}_k \tilde{\dot{u}}_k^*}{(2\pi k / T)^2} \text{ ,}$$

where $k = \nu T$, an integer between 0 und $N/2$, is the normalized frequency and $\tilde{\dot{u}}_k$ the Fourier transform of the velocity. The formula takes into account that the Fourier transform of the motion and velocity are related by:

$$\tilde{u}_k = -i \frac{\tilde{\dot{u}}_k}{2\pi k / T} \text{ .}$$

For n numbers $\dot{u}_n$ the discreet Fourier transformation is defined in general by

$$\tilde{\dot{u}}_k = \frac{1}{N}\sum_{n=0}^{N-1} \dot{u}_n e^{-ik\frac{2\pi}{N}n} \quad \text{and}$$

the reverse transformation is given by

$$\dot{u}_n = \sum_{k=0}^{N-1} \tilde{\dot{u}}_k e^{ik\frac{2\pi}{N}n} \text{ .}$$

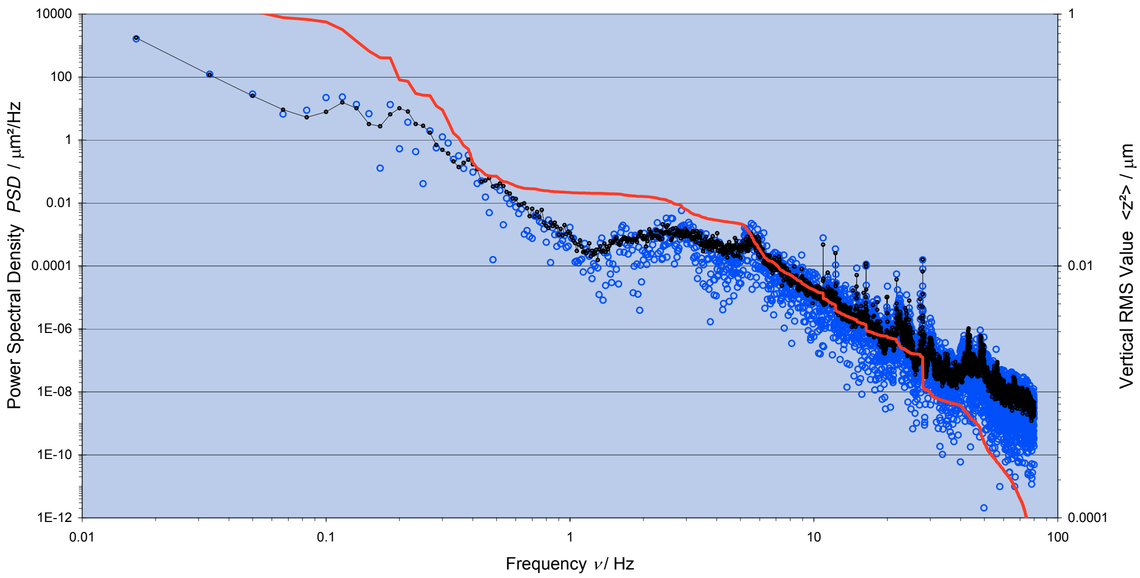

Figure 5: Vertical power spectral density (open points) and root mean square value (thick line) calculated from a one minute date file taken at 12:00 h on December 9, 2004. The thin line with the filled points is the average over 15 minutes of the PSD.

The RMS displacements $\sqrt{\left\langle u^2 \right\rangle_k}$ above the frequency k/T can be easily calculated from the power spectral density:

$$\sqrt{\left\langle u^2 \right\rangle_k} = \sqrt{\frac{1}{2T}\sum_k^{N/2} S_k} \ .$$

Figure 5 shows an example of a vertical power spectral density and RMS displacement measured at the proposed ALBA site. The values are calculated from a one minute data file. For better resolution of details the spectra can be averaged over 15 minutes or even longer periods. The average over 15 minute is additionally shown in the example (thin line with filled points). Now two micro-seismic peaks from sea waves at 0.11 and 0.22 Hz are resolved beside other sharp peaks above 10 Hz.

The normalized spectrum of correlation or cross-correlation spectrum K_k of two synchronous signals u_n and z_n is defined as [4]:

$$K_k = \frac{\tilde{u}_k \tilde{z}_k^*}{\left|\tilde{u}_k\right|\left|\tilde{z}_k\right|} \ .$$

K_k is a complex number. The real part of the correlation is the cosine of the spectral phase difference. The mean value over different measurements of this real part is defined as the coherence C_k:

$$C_k = \left\langle \Re\left(\frac{\tilde{u}_k \tilde{z}_k^*}{\left|\tilde{u}_k\right|\left|\tilde{z}_k\right|}\right)\right\rangle = \left\langle \frac{\Re\tilde{u}_k \Re\tilde{z}_k + \Im\tilde{u}_k \Im\tilde{z}_k}{\left|\tilde{u}_k\right|\left|\tilde{z}_k\right|}\right\rangle .$$

An example of the coherence measured at the ALBA site is shown in Figure 6. The correlation value is roughly one up to 2 Hz and drops for higher frequencies. The dots are the values from one Fourier transform and the black line is an average over 15 minutes.

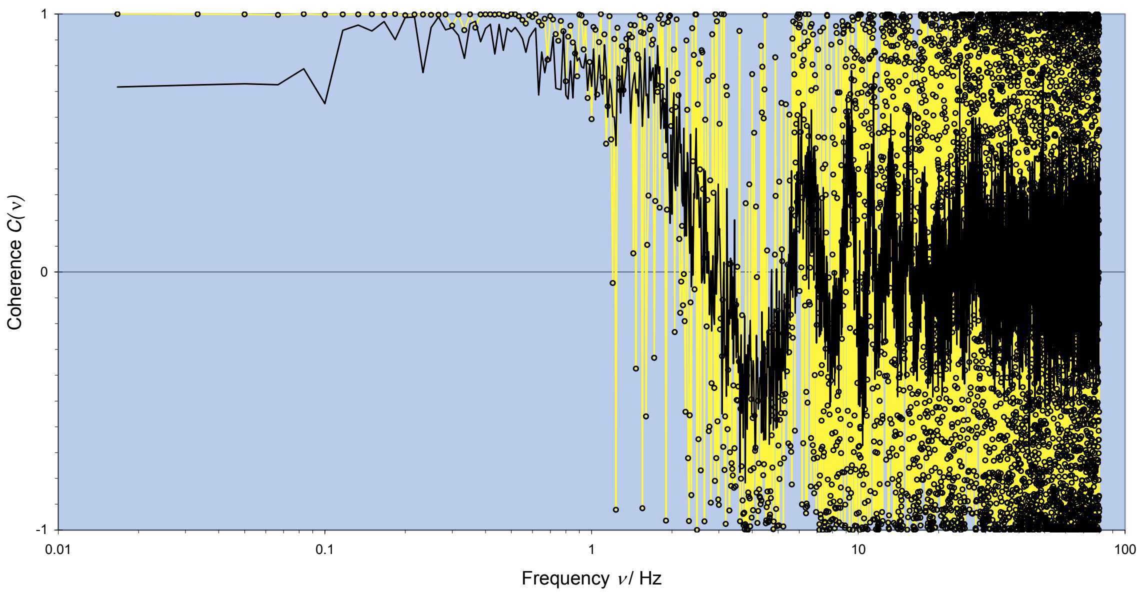

Figure 6: Example for a cross-correlation spectrum (bright line with open points) and coherence spectrum (black line) measured at ALBA.

4. Results of Ground Vibration Measurements at ALBA

4.1 Results from the First Short Measurement Period

The ground vibration was measured first with one single instrument from August 26 to 27, 2004 for about 17 hours. Figure 1 shows a map with the proposed ALBA campus (1). A broadband Güralp feedback seismic sensor CMG-3T (S3) with a bandwidth between 120 s and 80 Hz was used for the measurements. The small circle in the center of Figure 1 indicates the position of the instrument which was placed directly on the dry and relative hard red clay ground without any additional thermal insulation. A car battery powered the computer for the data acquisition and an additional small battery pack the seismic sensor.

Figure 7 shows the root mean square (RMS) over one minute of the vertical displacement above 1 Hz (up to 80 Hz) versus the time of day. The effect of the noise produced by human activities can be clearly seen. On average during the night it is quieter (5 nm) than during the day (40 nm). Probably the main noise sources are the highway

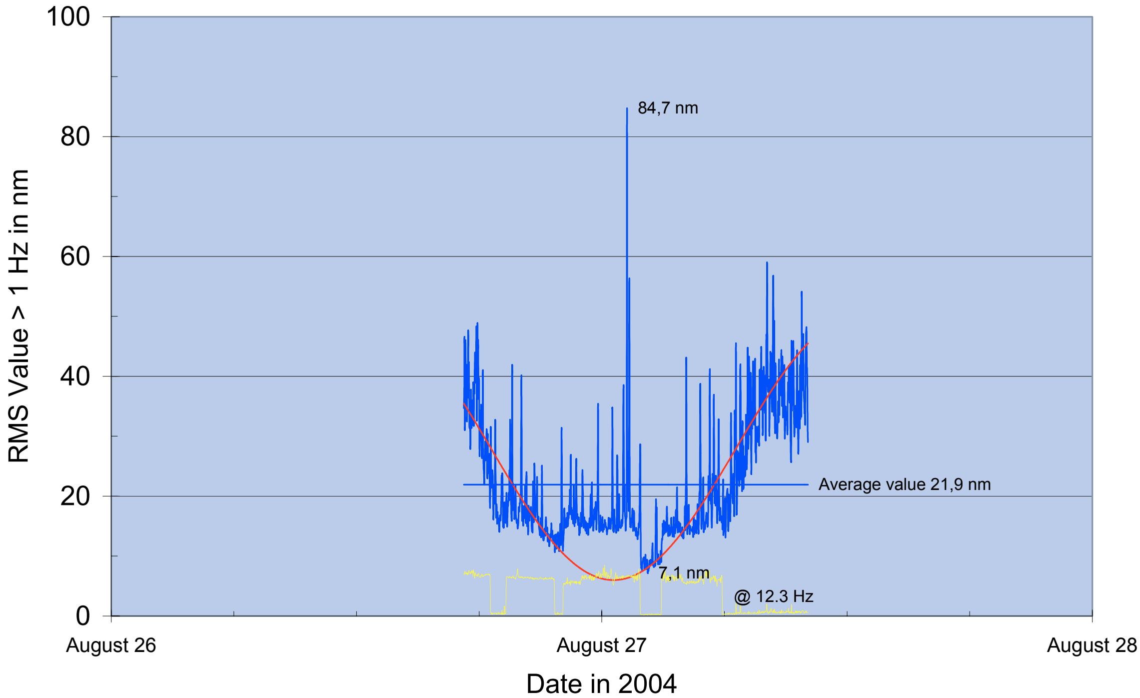

Figure 7: Root mean square of the vertical displacement above 1 Hz versus the day time measured at the proposed ALBA site in Barcelona. Additionally the values at around 12.3 Hz are shown, which are probably excited by AC-motors.

(see Figure 2 (4)) and the railway (5) north-west of ALBA, the local roads (9 and 10) in the west and south and mainly the ceramic factory (11) at the western boarder of the proposed site. The huge spike (84 nm) is perhaps induced by a freight train in the night and the smaller spikes by passenger trains (about eight per hour in the evening and in the morning). In the north-north-west is an end station (6) of a local train connection to downtown Barcelona. The constant vibration comes likely from rotating machines and the activity in the factory. Probably the machines were switched off two times over night.

Figure 8 shows the power spectral density of the vertical displacement. The stored beam in a synchrotron light source is flat and therefore much more sensitive to the vertical displacement of the quadrupoles than to the horizontal. The spectrum (line with

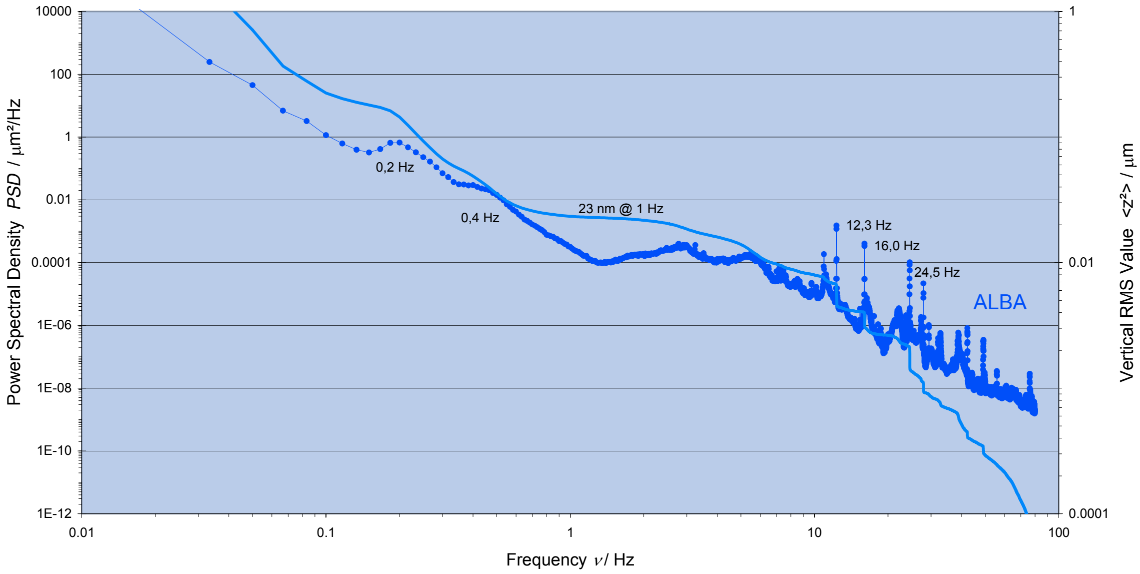

Figure 8: Power spectral density (line with points) and root mean square (line) of the vertical displacement versus the frequency.

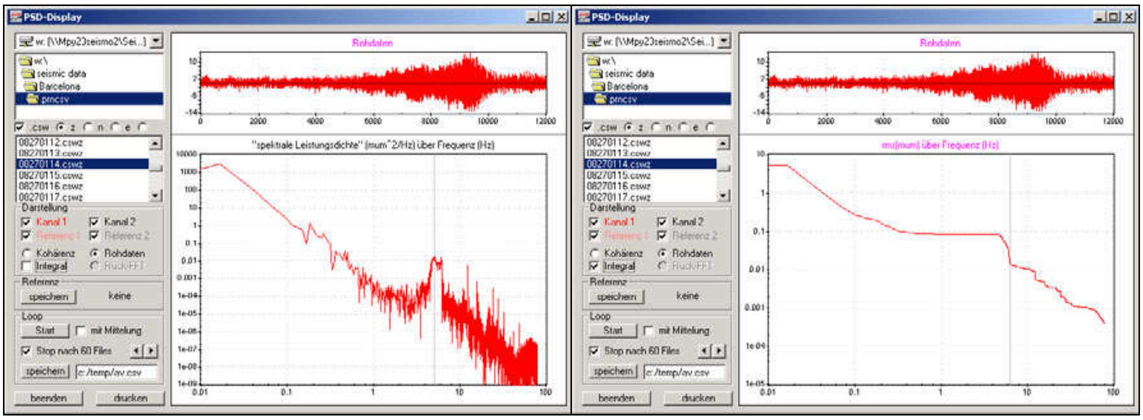

Figure 9: Power spectral density (left) and RMS values (right) of the vertical displacement versus the frequency taken at 1:14 h on August 27, 2004. The upper curve in each window is the vertical raw signal of the seismic sensor.

points) and the RMS values (line) are averaged over the whole period of 17 hours. The broad lines at 0.2 and 0.4 Hz are from ocean waves. The most dominant sharp lines at 12.3 Hz, 16 Hz and 24.5 Hz are typical for rotating machines driven by 50 Hz asynchronous motors. The RMS value for only the 12.3 Hz lines was calculated additionally. The result is shown in Figure 7 which confirms the suspicion that the activity in the ceramic factory influences the ground vibration on the site.

Figure 9 shows the power spectral density (left) and RMS values (right) of the vertical displacement versus the frequency taken at 1:14 h; probably a freight train was passing by at that time. The small windows in the top show the raw data (vertical velocities) from the sensor. The main peak of the spectrum is at 5 to 6 Hz which is typical for trains.

4.2. Results from the Second Long Measurement Period

In a second period the ground vibration was measured at the proposed ALBA site from December 3 to 13, 2004 with two seismic sensors (S1 and S3). Through this the measurements from August 2004 should be complementary. In particular the vibration sources should be better located by using more than one instrument. Figure 10 shows

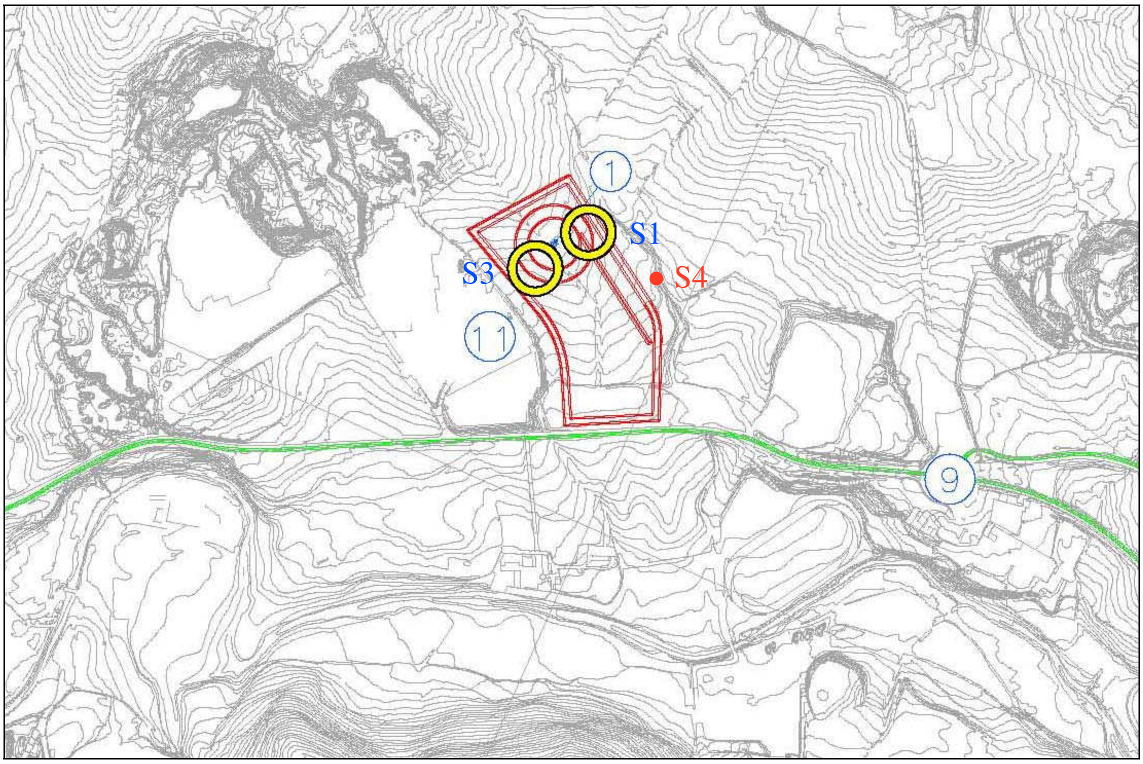

Figure 10: Position of the two seismic sensors S1 and S3 during the long-term measurements at the proposed ALBA site in December 2004.

the position of the sensors during the measurement period. They were placed on the circumference of the planned ALBA storage ring roughly orthogonal to the fence of the ceramic factory (11). The diameter *d* of the machine is about 84 m. Both seismometers were placed pits as shown in Figure 4 and two GPS antennas kept the internal clocks synchronized. The sensors and the computer were powered by the mains of the ceramic factory via long cables. The measurement started on a Friday. Monday to Wednesday of the following week were season holidays in Spain. The measurement was finished on Monday a week later. The on-time of the main machines in the ceramic factory each shift was recorded.

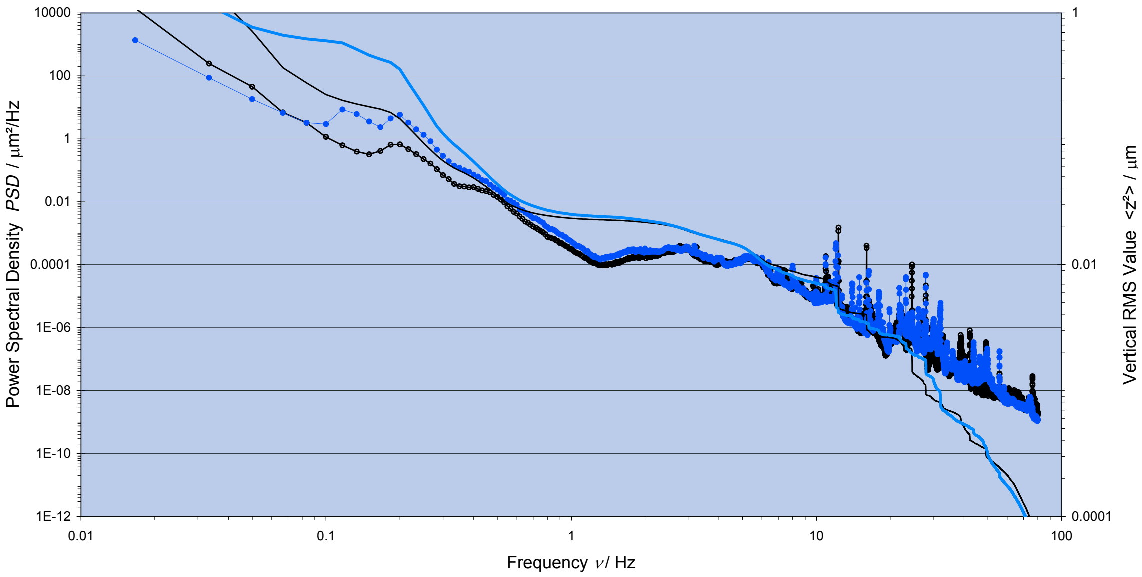

Figure 11: Comparison of the power spectral density (lines with points) and RMS values (lines), averaged over 17 hours, taken in August and in December.

First the power spectral density and the RMS value above 1 Hz measured at about the same position in August and in December were compared. The average PSD measured from December 9, 17:30 h to December 10, 9:30 h was compared with the spectrum from August. Figure 11 shows the result. The spectra are almost identical except the relatively weak high frequency spikes measured in December. A first conclusion is that the seasonal influences are probably small.

The variation of the ground vibration over short distances can not be ignored. Figure 12 shows the comparison of the power spectral density and RMS values, averaged over 17 hours, taken in December at the two positions. At both positions the spectrum increases similarly above 1 Hz. This could be explained as the influence of the long-distance cultural noise. Also the sea wave peaks at 0.1 and 0.2 Hz are identical. The very low frequency difference is an error from the non periodic time windows. This error could be decreased by a longer measurement time *T* and or the use of special filters. This is not necessary for cultural noise measurements. Remarkable is the difference at the two positions above 5 Hz. The RMS values above this frequency differ by about a factor two. This is a clear influence of the factory activities which will be investigated in more detail.

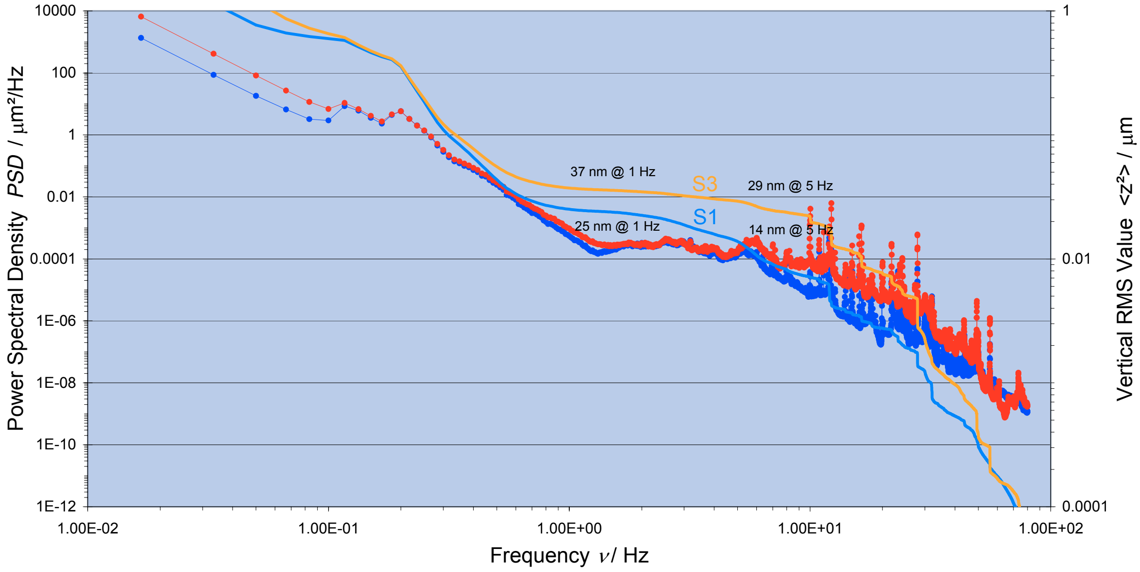

Figure 12: Comparison of the power spectral density and RMS values, averaged over 17 hours, taken in December at the two positions.

Figure 13 shows the root mean square of the vertical displacement above 1 Hz versus the time of day measured at both positions (see Figure 10). The sensor S3 is closer to the factory and the ground vibration is mainly higher. The daily and weekly variation is clearly detectable. Over night it is quieter than during the day. The signals are higher on working days (December 3, 9, 10 and 13) compared to the weekend and the holidays. Perhaps typical for the Mediterranean area is the dip in the ground vibration during lunch time seen on each working day.

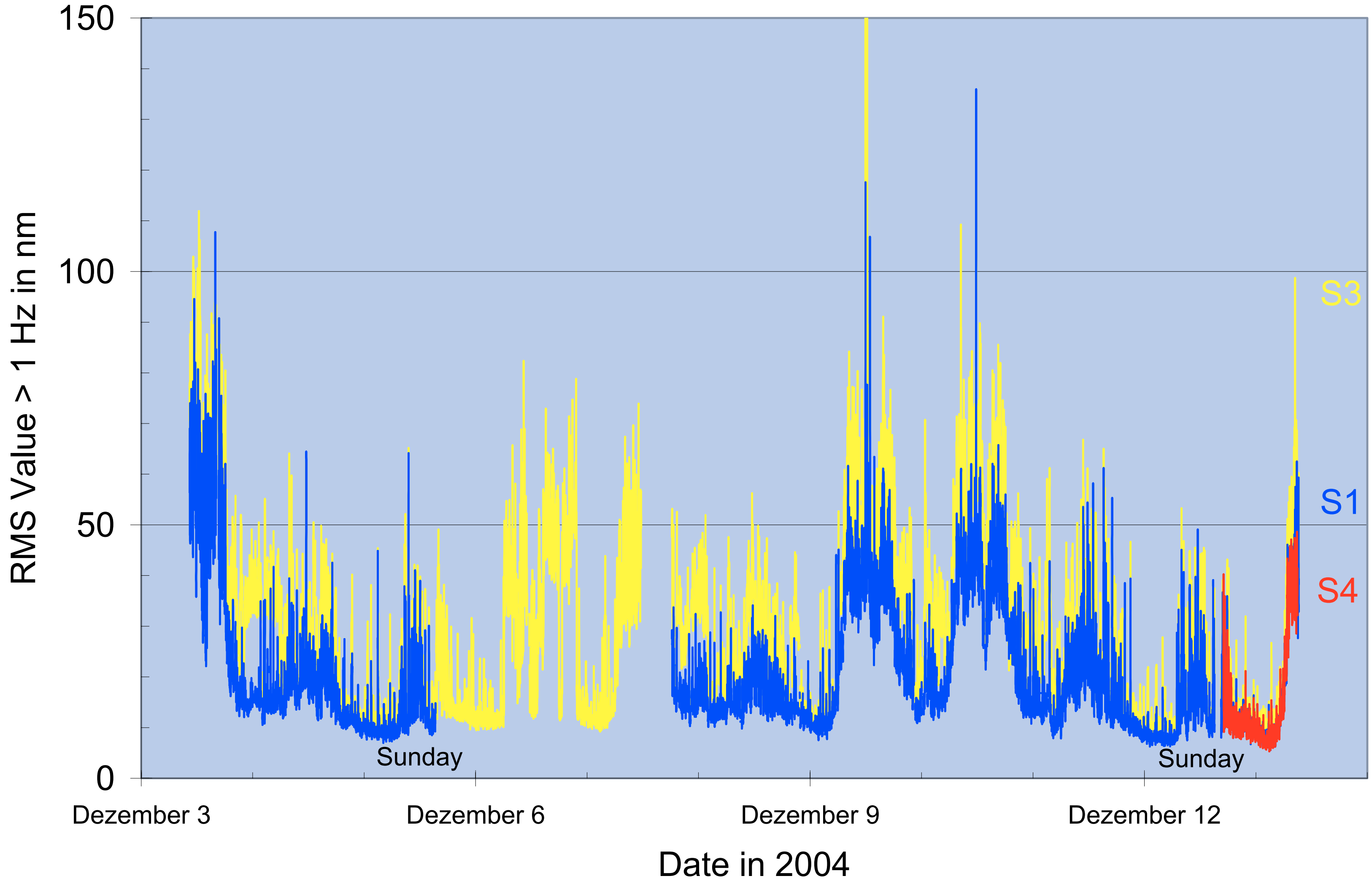

Figure 13: Root mean square of the vertical displacement above 1 Hz versus the day time measured at two places on the proposed ALBA site.

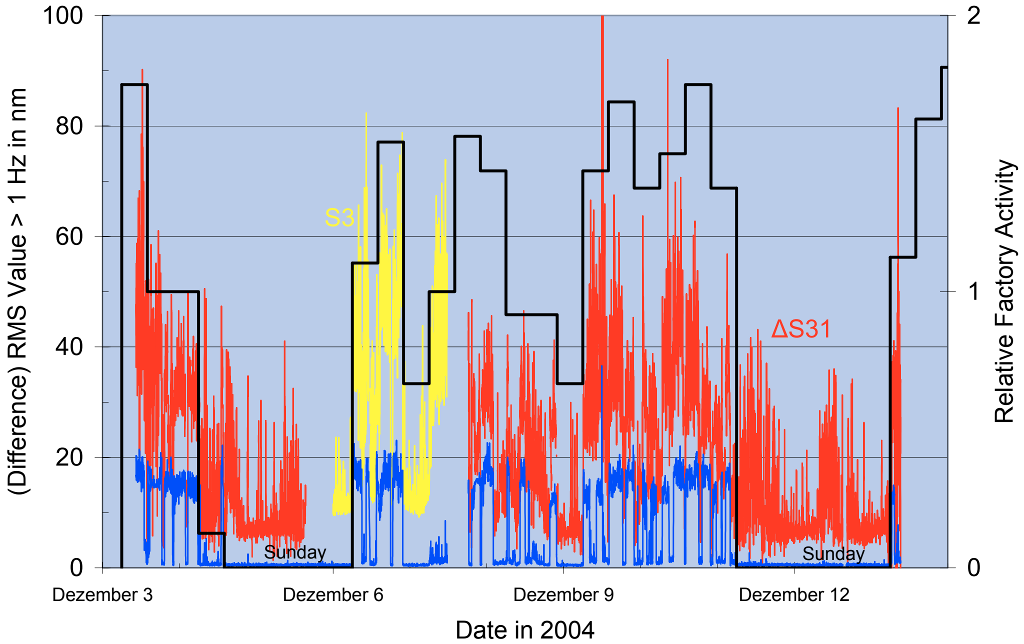

Figure 14: Quadratic difference of the RMS value $\Delta S31 = \sqrt{\langle z_3^2 \rangle_{1\,\mathrm{Hz}} - \langle z_1^2 \rangle_{1\,\mathrm{Hz}}}$ measured at both position and the relative factory activity (thick line) versus the time of day. Additionally the values at around 12.3 Hz of the sensor S3 are shown.

Figure 14 shows the quadratic difference of the RMS value above 1 Hz measured at both positions together with the relative factory activity and the RMS at 12.3 Hz measured with the seismic sensor S3. The activity of the ceramic factory was roughly recorded during the measurement period. The on-time of the grinders, the molding machines and the kilns (oven for firing ceramics) each shift was written in a journal. The kilns were on continuously. The sum of the relative on-time each shift of the other two sources is shown in Figure 14. The ground vibration is well correlated with the factory activity. Especially the RMS value at 12.3 Hz fits perfectly with the activity of the grinder. The grinder seems to rotate with 738 and the molding machine with 960 revolutions per minute.

At the end of the measurement period an additional seismic sensor CMG-6T from Güralp (S4) was used to get more information about the machinery noise. The bandwidth of this instrument type is from 60 s to 80 Hz and the seismometer constant $C_S = 1$ kV/m/s. The sensor was placed at a greater distance from the factory directly on the ground. The position is marked in Figure 10. The RMS value is shown in Figure 13 together with the results from the other two instruments. The values at the positions of S1 and S4 are nearly identical. From this follows that at these positions the distance to the factory is great enough to suppress sufficiently the machinery noise. If it is not possible to move the storage ring to this distance from the factory then a more efficient vibration insulation of the main machines would improve the stability of the synchrotron light facility.

The root mean square values were investigated for different lower cut-off frequencies (1, 5. 10, 15, 20 and 40 Hz) to get further information about the noise sources and their significance. The result is shown in Figure 15 where the results from sensor S1 are shifted by 50 nm for a better separation. The clearly detectable machinery noise is in the high frequency range and the cultural noise at lower frequencies.

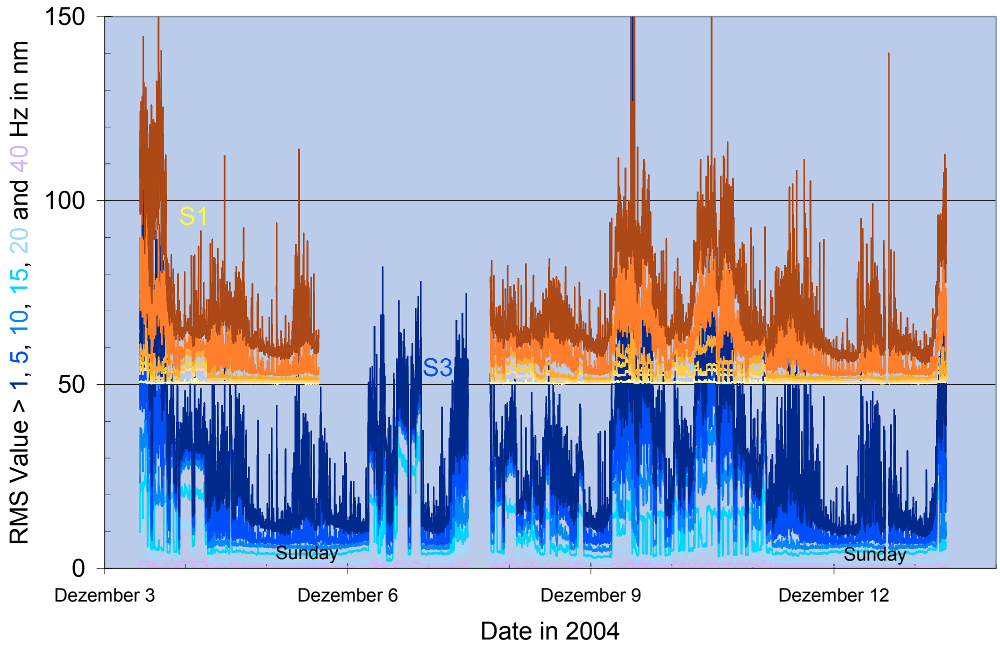

Figure 15: Root mean square of the vertical displacement for different lower cut-off frequencies measured at two places on the proposed ALBA site. The results from sensor S1 are shifted by 50 nm for a better separation.

The 12.3 Hz signal was used to estimate the phase velocity of the Raleigh (surface) waves. This analysis indicates that the velocity is about 70 m/s (at 12 Hz). Table 2 shows the soil parameters measured at HERA in Hamburg and the calculated shear wave velocity. The Raleigh wave velocity is slightly smaller ($c_R / c_S \cong 90\,\%$ [5]). The measured value fits better to marl than to clay.

	Shear modulus G/MN/m^2	Density ρ/10^{3}kg/m^3	Shear wave velocity $c_s=(G/\rho)^{0.5}$/m/s
Sand	10 ÷ 30	1.9	73 ÷ 126
Glacial loam	4 ÷ 8	2.1	44 ÷ 62
Glacial marl	11 ÷ 35	2.2	71 ÷ 126
Tertiary clay	4 ÷ 7	2.1	44 ÷ 58

Table 2: Parameters of soil at HERA [6].

Sand was created by the moving ice cover of the glacial period. It consists mainly of silicates with a grain size smaller than 2 mm. Sand is a water conductor. Clay was created from the sediments of tertiary oceans. It consists of minerals with a grain size smaller than 2 µm. Clay is a water non-conductor but it can store water. Then it can swell up.

4.3. Comparison with Other Sites

Figure 16 shows the spectra measured at the proposed ALBA site and at different synchrotron light sources and reference sites [7]. These spectra were all taken at midnight on different days spread over some years. This figure is something like a ranking of the ground vibration conditions at the different sites. The lower spectra correspond to the better sites and the upper to the worse. In this sense ALBA lies between the APS and ESRF. But there the spectra were taken during full operation of the facilities. At ALBA home made noise will increase the vibration. The solid black curves are the RMS values of the three sites.

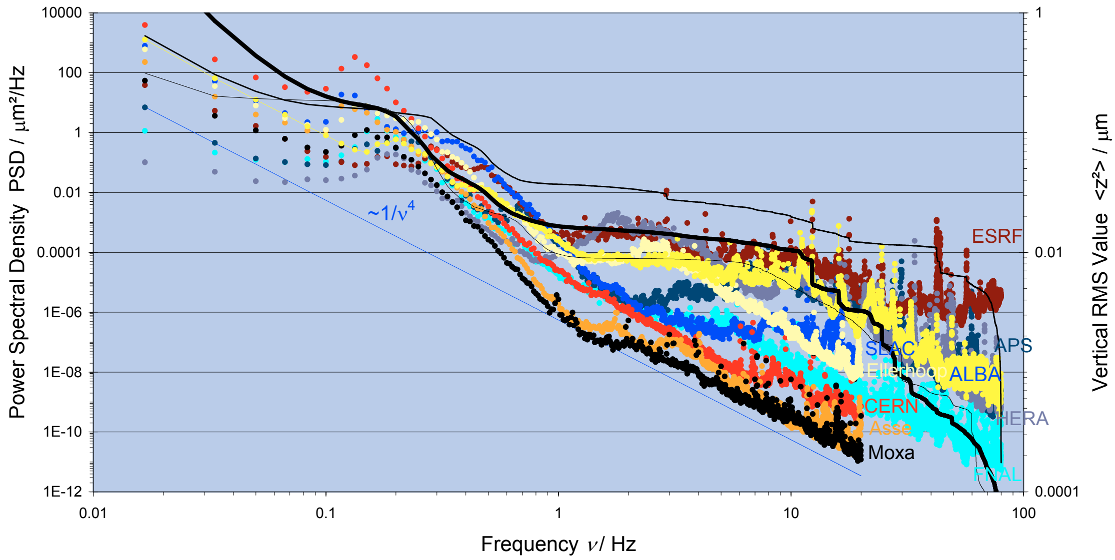

Figure 16: Power spectral density (points) and RMS values (lines) of the vertical displacement versus the frequency measured at synchrotron light sources and reference sites together with a random walk noise trend.

The peak-to-peak values at ALBA and different synchrotron light sources were also investigated. The ground velocities measured from a seismic sensor were numerically integrated over 1 second. Figure 17 shows the relative number of vertical displacement peak-to-peak values at ALBA, APS and ESRF. The integral over all values is set to 100 %. The distribution of the values indicates the number and strength or distances of the noise sources. At ALBA the seismic sensors were placed in a distance of 80 m and the instrument S3 was closer to the ceramic factory. The peak-to-peak values of this seismometer are clearly shifted to higher values.

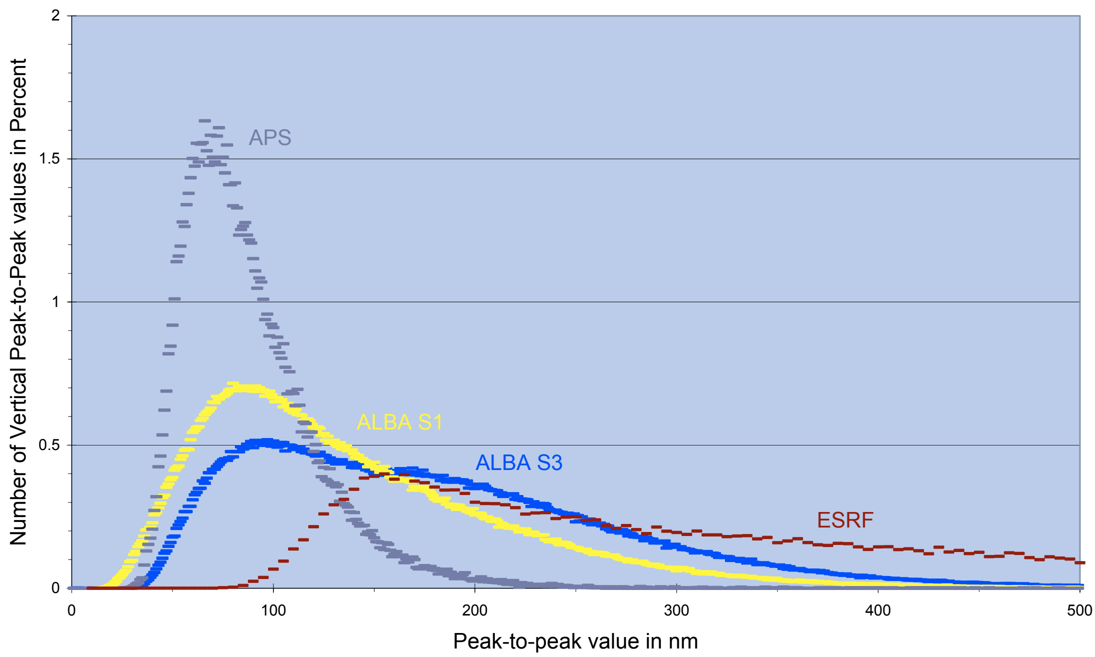

Figure 17: Relative number of vertical displacement peak-to-peak values at ALBA and two synchrotron light sources.

5. Summary

With respect to ground vibrations, the proposed ALBA site in Cerdanyola near Barcelona is not one of the best places for a dedicated synchrotron light source but in comparison with the ESRF site sufficient for the proposed purpose especially by scaling the circumference of the machines. Movement of the facility away from a factory by about 80 m and vibration insulation of the main sources would improve the situation significant.

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