GROUND MOTION & COMPARISON of VARIOUS SITES

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Abstract

The study of ground motion and its impact on the International Linear Collider (ILC), where $e^+ e^-$ beams of the order of nanometers must collide with high luminosities, may not be negligible. All sources of vibration, including ground motion, can cause the beams to simply miss each other at the interaction region (IR).
In this paper, we describe a program of site characterization and comparison, via measurement of ground motion spectra, using inertial broadband seismometers. The emphasis is on using the same equipment and data analysis techniques as applied to all the sites studied. Our database of ground motion measurements for each site is available to the scientific community.

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1 Introduction

It is envisaged that ILC will collide nanometer-size e^+ e^- beams at a center-of-mass energy of 500 GeV, and possibly, up to 1 TeV, at a high luminosity (a few times 10^{34} cm^{-2} s^{-1}). Maintaining such beams in collision could be a major challenge and requires a detailed study of sources of degradation of machine parameters.

The influence of ground motion on the performance of the collider is not negligible. It can cause colliding beam offset in the IP region and beam emittance growth. It is imperative to understand the influence of ground motion, specific to each site, with respect to geological conditions and human activity, commonly known as 'cultural noise'.

A program of site characterization has been initiated in DESY where different sites have been studied using the same equipment and data analysis tools. Therefore, this database of accumulated measurements can be used for site comparison. The sites studied comprise high energy laboratories, synchrotron light sources and reference sites.

Reference sites chosen in this study are situated at geologically stable and remote locations. Reference sites facilitate a comparison base for 'noisier' sites with high cultural noise content. Moreover, each site is studied in different locations, such as, tunnel vs. surface, inside vs. outside a building etc. to get a better impression of the cultural noise situation. The measurement period is for 24 hours or in the majority of the cases, one week, so that variation with respect to day and night, weekday and weekend is apparent.

1.1 GROUND MOTION MEASUREMENTS

Güralp Broadband Digital Output Seismometers

Ground motion measurements are undertaken using state-of-the-art Güralp triaxial feedback seismic sensors [1]. There are three CMG-3TDs and two CMG-6TDs in our possession for this purpose. These seismometers can measure a frequency range of up to 80 Hz. They are hermetically sealed devices which produce a digitized voltage that is proportional to the velocity measured in each axis (east-west, north-south and vertical). They contain an inverted pendulum for the two horizontal axes, and a leaf-spring for the vertical axis. A feedback loop with a force transducer compensates the ground acceleration acting on a seismic mass. The feedback current is proportional to the ground acceleration, which is internally integrated, and therefore, is proportional to the ground velocity.

This voltage is then digitized with an internal 24 bit digitizer, without amplifier, with 200 Hz sampling rate, and is linked to a notebook/PC via serial data cables. The software used for data acquisition, is called 'SCREAM' from Güralp Systems Ltd by which, continuous velocity signal of all three components is digitized and stored in one minute files. The output voltage to ground velocity calibration is flat over the operating frequency range of the seismometers, and the resolution of the instrument is about 0.4 nm/s/bit, for all frequencies, which is sufficient to measure ground motion at quiet sites. The system is supplied with GPS antennas which can keep their internal clocks synchronized with satellite-based UTC time signals in order to provide a time reference signal with the data. It should be emphasized that seismometers measure absolute motion, since measurements are relative to an inertial frame. This is the preferred method over differential methods in which relative motions are measured.

1.2 ANALYSIS OF DATA

Power Spectral Density

The power spectral density (PSD) of a noise signal is defined as [2]:

$$S_x(f) = 2\lim_{T\to\infty}\frac{1}{T}\left[X(f)\right]^2 \qquad (1)$$

$X(f)$ is the Fourier transform of the noise signal defined as:

$$X(f) = \int_{-T/2}^{T/2} x(t)e^{-2\pi ift}\,dt \qquad (2)$$

The factor of 2 in (1) is because only positive values of frequency, f, have been used in the definition of the PSD.
Since, one cannot perform an infinite measurement in time, discrete Fourier transform is used where integrals are replaced by sums.
The sampling rate selected for a seismometer defines the upper frequency limit of the resultant data. In our case, 200 samples per second correspond to an upper frequency limit of 100 Hz (Nyquist criterion).
The dimension of the PSD is 'power' per unit frequency band, e.g., $(\mu m/s)^2/Hz$ for the PSD of velocity. Since displacement and velocity are related via $v = dx/dt$, their Fourier harmonics are related as follows:

$$V(f) = -2\pi if\,X(f) \quad (3)$$

As the magnitude of the displacement experienced in a given frequency band is more informative, one can calculate displacement PSD defined as:

$$S_x(f) = \frac{S_v(f)}{4\pi^2 f^2} \qquad (4)$$

Equation (4) is used to extract displacement PSD from the measured velocity PSD with a unit of $(\mu m)^2/Hz$. It is customary to average a number of spectra in order to smooth out single event noise so that real features of the spectra are clearly visible. We have adopted the practice of taking average spectra every 15 minutes or longer depending on the analysis concerned. In most cases, no windowing is applied to the Fourier transform.
Average displacement PSDs of various sites are shown in Fig. 1.

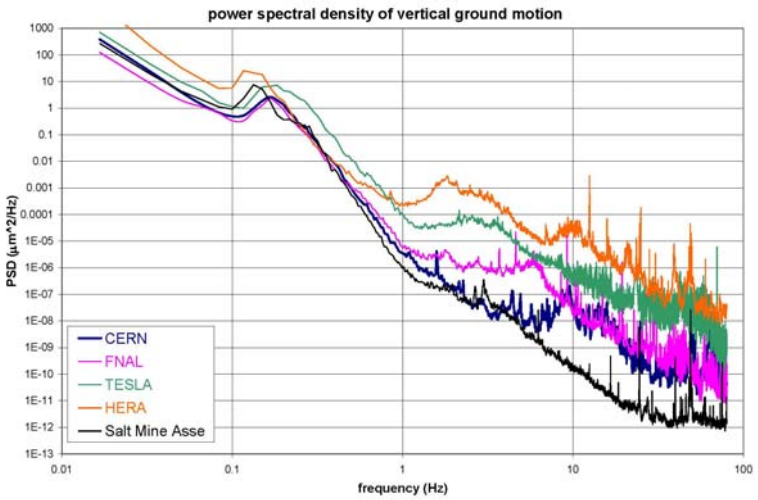

Figure 1: Average displacement PSDs for various sites, including a reference site (rock salt mine Asse in Germany)

Using displacement PSD, one can calculate total root mean square (rms) displacement over the whole frequency range (or in any frequency band desired, such as (f_1, f_2)). This is achieved by integrating the displacement PSD (e.g. in vertical direction, z) and taking the square root:

$$z_{rms}(f_1, f_2) = \sqrt{\int_{f_1}^{f_2} S_x(f)\,df} \qquad (5)$$

Integrated PSD spectra, calculated from the spectra in Fig. 1, are shown in Fig. 2. Our cut frequency value is usually at f > 1 Hz, as cultural noise is dominant at this frequency range and is uncorrelated. This region is therefore, of interest for ILC site comparison.

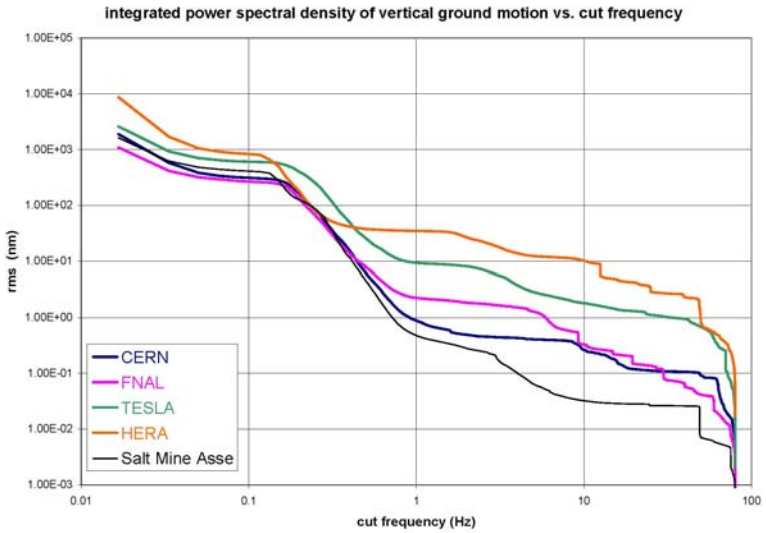

Figure 2: Integrated PSDs as obtained from Fig. 1

2 GROUND MOTION SPECTRA

Ground motion can be divided into two categories: slow motion, at f < 1 Hz, is referred to 'slow ground motion'. For example, microseismic peak at 1/7Hz (frequency range of 0.1 to

0.25 Hz), is caused by the coastal waves and can even be seen in the center of the continents. It is clearly visible in all the PSD spectra shown in Fig.1. The general shape of the PSDs follows $1/f^4$ behavior which is a random walk noise trend. This region of the seismic spectrum can also be affected by atmospheric changes.

On the other hand, f > 1 Hz, where 'cultural noise' prevails, is referred to 'fast ground motion' [3]. In this region, the shape of the PSDs can change drastically from site to site, as seen from Figs 1 and 2. One can clearly see the deviation from $1/f^4$ behavior of HERA spectrum compared with rock salt mine Asse in Germany. On the other hand, the spectrum measured at CERN has much smaller amplitude at f > 1 Hz. Fermi laboratory and the proposed TESLA IR, measured in Ellerhoop, 17 km northwest of Hamburg, Germany, fall between the HERA and CERN maxima and minima respectively. Cultural noise stems mainly from human activities in the vicinity or at a site. Comparison of measured ground motion spectra at several sites, including DESY, with a simple ground mechanical model confirms an earlier, independent conclusion, based on the extensive measurements, that traffic (both road and railway) might be the main source of cultural noise [4].

3 CHARACTERIZATION OF SITES

All sites have been measured with the same equipment and data analysis techniques. This facilitates comparison between sites. In many cases, simultaneous measurements with more than one seismometer, placed at a distance from each other, provides better information on the sources of ground vibration as this method of measurement, provides correlation information of the seismic signals [5, 6].
In most cases, data is taken for a long period, one week or longer which includes weekends. An example of rms spectrum of vertical displacement (in nm) versus time, in calendar days, at a cut frequency of f > 1 Hz, is shown in Fig. 3 for the HERA tunnel. The two peaks at lower amplitude (right most corner of the figure) highlight reduction of cultural noise during weekends compared with weekdays. In addition, day and night variations are also clear.

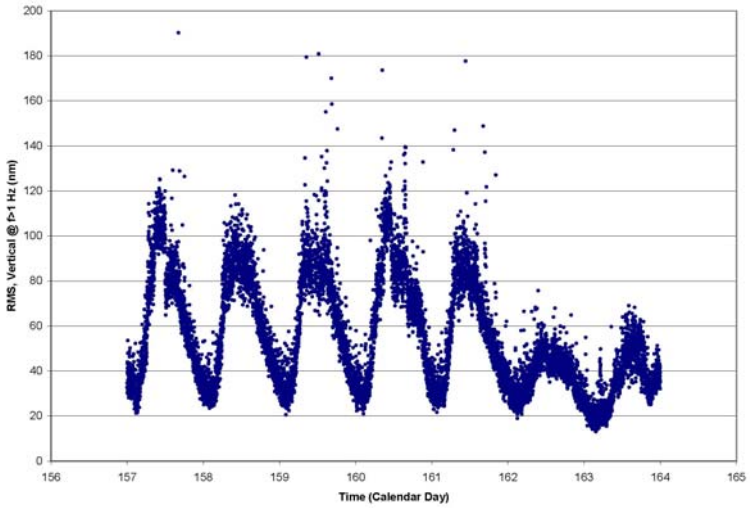

Figure 3: Weekday and weekend variation of ground vibrations (vertical direction) as experienced in the HERA tunnel. Weekend peaks with reduced amplitude are seen on the right.

Histograms of rms values, for a complete measurement period, (for vertical motion, in most cases) are one way to characterize a site as ‘quiet’ or ‘noisy’ as shown in Figs. 4 and 5.

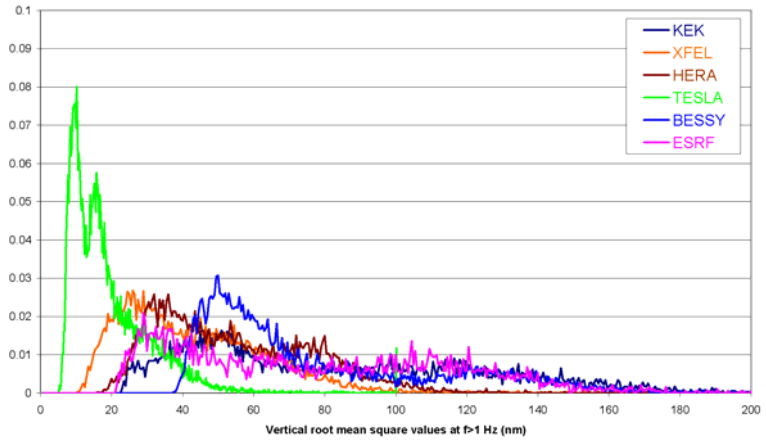

Figure 4: Vertical rms distributions of ‘noisy’ sites as defined in the text

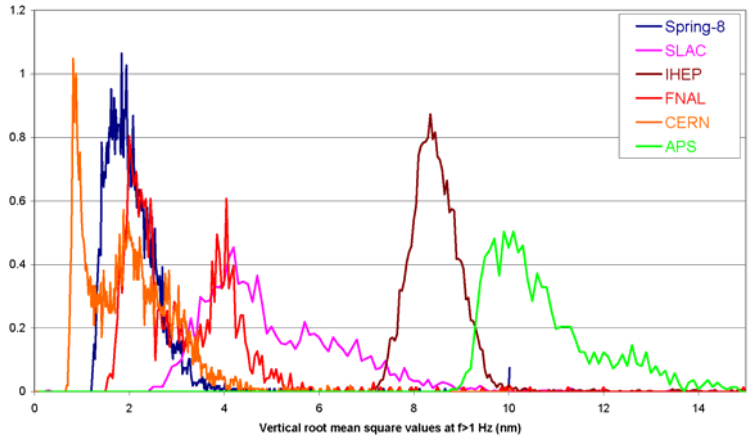

Figure 5: Vertical rms distributions of ‘quiet’ sites

The shape of the distributions differs from site to site, as many spectra have two maxima, signifying day and night variations of cultural noise. In these figures, rms distributions with vertical motion of less than 15 nm are classified as ‘quiet’, and the rest as ‘noisy’.

Another method which does not rely on Fourier transform is the numerical calculation of displacement maxima and minima, after seismometer calibration values have been applied, for the one minute raw data files. In this method, numerically integrated ground velocities (within 1 s time window) are binned into peak-to-peak histograms, as shown in Figs 6 and 7.

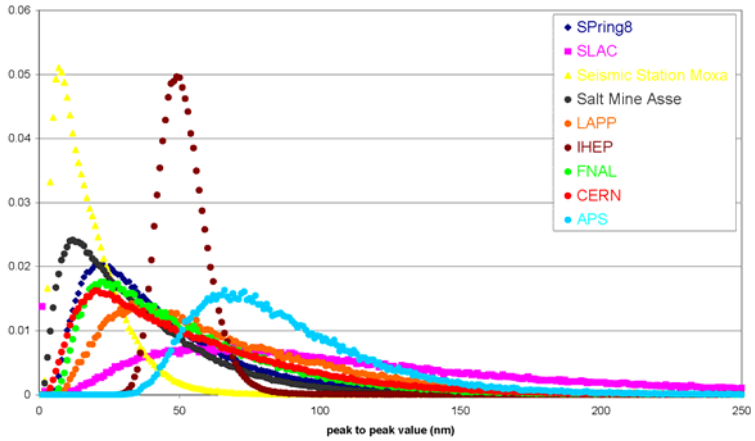

Figure 6: Normalized displacement peak-to-peak histograms of vertical motion for 'quiet' sites

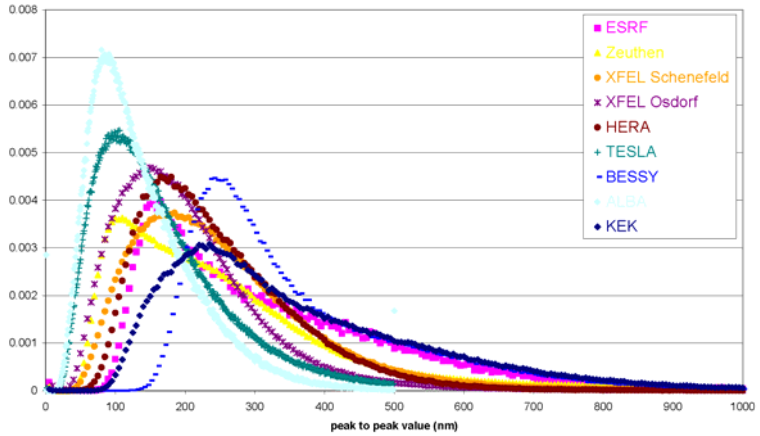

Figure 7: Normalized displacement peak-to-peak histograms of vertical motion for 'noisy'sites

This method is an independent way to characterize a site. As it can be seen in the figures above, maxima, full width at half maxima (FWHM) and the shapes of the histograms differ from site to site. Peak-to-peak values are essentially the worst case scenario for ground vibrations for a specific site. Peak-to-peak calculation is sensitive to short bursts in the 1 minute raw data files, for example when a train passes nearby a site, a short time duration burst can be seen in the raw displacement/velocity data. Short duration 'events' as such, influence the peak-to-peak values. While on the contrary, rms calculation is not greatly influenced by these 'events'. However, short burst 'events' are ever present in each site with different magnitude and frequency, depending on each site studied, and may not be ignored in site comparison and characterization program.

Similar to the rms distributions shown above, the maximum value and the spread at FWHM indicate the number and strength of cultural noise sources [5, 6]. For example, the peak-to-peak distribution of IHEP (Beijing) is almost a Gaussian with a very small spread (please see Table 1), which indicates relative weakness of the sources of cultural noise and their variation, as seen in the peak-to-peak amplitude and FWHM respectively, compared with APS (Argonne), for instance.
In Table 1, we have summarized our compiled database of site measurements [7]:
Pk-Pk_{Max} (left most column), is the maximum peak-to-peak values (in nm), for vertical displacement, and their corresponding FWHM. The third and fourth columns from the left are

the average rms values for a complete measurement period, at f > 1 Hz frequency cut, and the corresponding standard deviation (SD) in nm. In this analysis, a cut of 5% to the highest rms values, in 1 minute data files, is applied.
The last two columns on the right are the average rms values, of vertical displacement at f > 1 Hz, for a snapshot period of one hour corresponding to quiet conditions, uaually around midnight, and noisy conditions, usually around midday.
These values are complementary to average rms values for the whole measurement period. For site comparison and characterization purposes, this database provides a reliable means of site evaluation to the scientific community [7].

Table 1: Site comparison

	Site Location	$Pk\text{-}Pk_{Max}$ (nm)	FWHM (nm)	RMS (nm)	SD (nm)	Quiest RMS	Noisy RMS
1	ALBA Cerdanyola	87	125	18.3	9.5	9.1	42.0
2	APS Argonne	68	56	10.5	1.0	9.8	11.0
3	BESSY Berlin	245	160	72.8	28.1	53.1	140.7
4	CERN Geneva	21	53	1.8	0.9	0.9	2.8
5	DESY TESLA	104	160	17.4	8.4	9.3	35.9
6	DESY HERA	170	200	51.8	18.9	34.8	77.0
7	DESY XFEL Schenefeld	180	245	38.7	16.6	35.1	70.0
8	DESY XFEL Osdorf	150	195	28.9	11.9	19.5	48.4
9	DESY Zeuthen	105	235	64.0	40.4	88.5	75.6
10	ESRF Grenoble	155	175	71.6	34.9	40.2	137.2
11	FNAL Batavia	23	49	2.9	0.9	2.2	4.0
12	IHEP Beijing	49	18	8.4	0.5	8.1	9.0
13	KEK Tsukuba	170	210	78.0	36.0	38.0	125.1
14	LAPP Annecy	35	59	3.3	1.6	1.9	7.0
15	Salt Mine Asse	12	35	0.5	0.1	0.5	0.7
16	Seismic Station Moxa	7	17	0.6	0.1	0.5	0.9
17	SLAC Menlo Park	60	105	4.8	1.2	4.1	7.4
18	Spring-8 Harima	22	40	2.0	0.4	1.8	2.5

SUMMARY

We have measured ground motion spectra, for various sites, some, which are potential sites for the ILC. In this project, we have used the same equipment and analysis techniques to facilitate site comparison. Our database is available to anyone interested in pursuing research on ground motion issues for accelerator stabilization. We are planning to continue to expand our database of sites and in particular, to study ILC potential sites in a greater depth via measurements of coherence between two signals and wave velocity measurements. We will use parameterization of the PSD spectra as yet another way to characterize a site.

Acknowledgement

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[6] W. Bialowons and H. Ehrlichmann, "Ground Vibration Measurements at the European XFEL Site in Hamburg", in preparation.
[7] DESY's recently upgraded homepage on ground vibrations: http://vibration.desy.de