NSLS II Vibration and Acoustic Criteria

Vibration – Experiment Hall

The vibration limits of the experiment hall are those associated with the user-supplied research instruments, which are not well defined at this time. It may only be possible to represent the vibration requirements of this space using generic vibration criteria. The vibration needs of the vast majority of research equipment available today would be satisfied by a floor meeting vibration criterion VC-E or NIST-A.[1] At frequencies less than 20 Hz, the NIST-A criterion is more stringent than VC-E.

Vibration – Storage Ring

The vibration requirements for the storage ring have been provided in a much different manner. The RMS amplitude[2], *R*, is to be less than 20 to 30 nm, where *R* is defined as

$$R = \sqrt{\sum_{f=50}^{f=4} \Delta(f) \times \delta f}$$

where $\Delta(f)$ is the displacement power spectral density spectrum (in units such as m^2/Hz, where the frequency term in the denominator is the measurement bandwidth) and δf is the frequency resolution of the spectrum. The lower and upper bounds of the summation are 4 and 50 Hz, respectively. Frequency components outside this range may be neglected. The vibrations associated with fluid flow should meet the condition $R < 20$.

Acoustic Noise

The facility will have two primary groups of noise sources: (1) the facility's mechanical systems, such as air handlers, and (2) the user-provided research equipment. The noise control associated with the first group is within the purview of the NSLS II design team, but the ability to mitigate noise associated with the second group is somewhat limited. It can be anticipated via passive room noise control measures incorporated into the design, but it cannot be controlled via mechanical constraints such as airflow velocities, fan selection, or silencers, concepts typically employed for the first group.

Studies carried out during the design of the Advanced Photon Source determined that final operational room noise in the Experiment Hall would be a mix of sound from both groups of sources, and that NC-60 to NC-65 would be achievable from a combination of

---

[1] Vibration criteria VC-E and NIST-A are defined in **H. Amick**, M. Gendreau, T. Busch, and C. Gordon, "Evolving criteria for research facilities: vibration," *Proceedings of SPIE Conference 5933: Buildings for Nanoscale Research and Beyond*, San Diego, CA. Criterion VC-E has a one-third octave band rms velocity amplitude of 125 microinches/sec at frequencies between 1 and 100 Hz. Criterion NIST-A has a one-third octave band rms displacement amplitude of 1 microinch at frequencies between 1 and 20 Hz and a one-third octave band rms velocity amplitude of 125 microinches/sec at frequencies between 20 and 100 Hz.

[2] Simply stated, *R* is the area under the displacement PSD spectrum (m^2/Hz) between a lower and upper bound frequency.

mechanical system noise control measures on the proposed air handling system and room absorption made part of walls and ceiling.[3] This is the noise range found in many industrial cleanrooms. In the absence of absorptive material, the noise at APS was predicted to be on the order of NC-70. In order to achieve this, the recommended noise goal of the mechanical systems alone is NC-50 to NC-55.

[3] The results of the study were reported in "Acoustical Evaluation of Experiment Hall: Argonne National Laboratory", A. M. Yazdanniyaz & S. K. Bui, Acentech Report No. 56, January 1991. The noise from the experimental equipment was included in the model via sound power estimates based on measurements made at NSLS in 1989 by Acentech Incorporated as part of the APS design effort, reported in "Measurement of Noise and Vibration: National Synchrotron Light Source, Brookhaven National Laboratory", Hal Amick & Colin G. Gordon, Acentech Report No. 11, June 1989.

Site Vibration Study

Figure 1 shows an aerial photograph of the portion of the BNL complex containing the NSLS II site. Nearby are the site of the Center for Functional Nanomaterials (CFN), now under construction, and the existing NSLS. Vibrations were measured at all of these locations, as well as at Location 'A' and at a remote location to the north east of the indicated portion of the BNL campus.

Figure 2 shows a plan view of the proposed NSLS II, indicating Locations 1-6 at which ambient vibration measurements were made on the afternoon of 14 June 2006.[1] Vibrations were measured at each of these locations in each of three principal directions (vertical, north-south, and east-west). Each measurement lasted approximately two minutes, and produced an energy-averaged constant-bandwidth (FFT) rms velocity spectrum with 400 data points, 0-100 Hz frequency range, Hanning windowing, and 90% overlapping. The sensor, a seismic accelerometer, was supported on a 12" steel stake with a flat top, driven into the ground such that the flat top was flush with the ground.

The data were analyzed "live" and saved as spectra to the internal memory of the portable analyzer. The spectra were downloaded to a laptop computer and subsequently post-processed to obtain one-third octave band velocity spectra and 400-line displacement power spectral density (PSD) spectra. The PSD spectra, in turn, were processed to calculate RMS displacement amplitudes using numerical summing between a lower-frequency cutoff (CO) and 50 Hz. Nominally, the lower cutoff was 4 Hz for consistency with the particle ring criterion.

As noted previously, the nominal lower cutoff was 4 Hz for consistency with the particle ring criterion. However, in some cases the spectra below 6-7 Hz was contaminated by instrumentation noise floor. As a result, all of the RMS amplitudes are reported with low-frequency cutoff of 4, 6 and 8 Hz.

Figure 2(a) and (b) show a statistical representation of the vertical and horizontal vibrations, respectively, at the NSLS II site, in terms of one-third octave band rms velocity. These measurements were made during the mid-afternoon. Shown for reference are the VC-E and NIST-A criteria.

It should be noted in Figure 2 that the vibrations easily meet VC-E, but do not meet the NIST-A requirement. A similar observation was made at the time of the CFN vibration survey, and an additional study (using measurements at Location 'A') demonstrated that the low-frequency component which exceeds NIST-A disappears at night, and is thought to be due to traffic, probably on the Long Island Expressway.

The daytime and nighttime measurements at Location 'A' are represented in Figure 4 by open and closed triangles, respectively. At frequencies of 20 Hz and greater, the

---

[1] At the suggestion of BNL personnel, vibrations were not measured in the wooded areas, in order to avoid ticks.

difference is visible though not as significant as that observed at frequencies near 4 Hz. The log mean of the vertical vibrations at the NSLS II site, represented in Figure 4 using diamond symbols, lies between the two Location 'A' spectra at frequencies of 10 Hz and less.

The data from the NSLS II measurement locations, as well as from Location 'A', were taken with the sensor supported on a steel stake. It is known that a "free-field" measurement made in this manner produces a spectrum with a higher amplitude at most frequencies than one made on a slab of significant size or inside a building.[2] Discussions of this effect in the context of the NSLS II measurements suggested the desirability of carrying out vibrations inside a building with a similar thick slab, at night when the vibrations were at their least. The vertical spectrum obtained in this manner in the partially-completed microscopy suite in CFN is shown with circle symbols, and is thought to be representative of the performance of the eventual nighttime performance of the Experiment Hall slab in NSLS II.

The constant-bandwidth FFT velocity spectra saved to the portable analyzer and downloaded to a spreadsheet on a laptop were transformed to rms displacement spectra by dividing each point in a spectrum by 2π times the frequency of that point. The rms displacement spectra were then transformed to displacement PSD spectra by squaring the amplitude and dividing each squared amplitude by the measurement bandwidth (0.375 Hz). The statistical displacement PSD spectra are shown in Figure 5(a) and (b), for vertical and horizontal vibration, respectively. The log mean (the heavier red line) will be used for comparative purposes in a discussion that will follow.

As noted previously, the vibration criterion for the ring is defined in terms of R, the area beneath the PSD spectrum $\Delta(f)$ between cutoff frequencies f_1 and f_2, defined as 4 and 50 Hz, respectively. For the discrete spectra being used in this study, this may be defined as

$$R = \sqrt{\sum_{f_2=50}^{f_1=4} \Delta(f) \times \delta f}$$

where δf is the frequency resolution of 0.25 Hz. However, it was observed during post-processing that some of the spectra were contaminated by system noise at low frequencies (found after the fact to be due to connection noise in a cable), so values of R were calculated using additional f_1 frequencies of 6 and 8 Hz. The R values are summarized for the NSLS II site in Table 1. When the lower cutoff frequency f_1 is set to 4 Hz, the RMS quantities do not meet the criterion of 30 nm specified by BNL, but when f_1 is increased to 6 Hz, the quantity is within the prescribed limits. As noted previously, the PSD content at frequencies below 6 or 7 Hz is thought to be due to system noise, not actual vibration.

---

[2] H. Amick, T. Xu, and M. Gendreau, "The Role of Buildings and Slabs-on-Grade in the Suppression of Low-Amplitude Ambient Ground Vibrations," *Proc. 11th Intl. Conf. on Soil Dyn. & Earthquake Engng. (11th ICSDEE) & the 3rd Intl. Conf. on Earthquake Geotech. Engng. (3rd ICEGE)*, 7-9 January, 2004, Berkeley, CA.

Supplemental measurements were carried out on 31 Aug 2006 and 1 Sept 2006. The results of those measurements, along with some taken at Location 'A' for the CFN site study, are summarized in Table 2. The most important data are likely those taken in the microscopy lab at CFN, where the RMS amplitudes at both measurement times are 20 nm or less, in any direction. (The amplitudes calculated using 6 Hz and 8 Hz cutoff frequencies are shown for interest, but the CFN space meets the most stringent interpretation of the NSLS II criterion. This demonstrates that the building effect impacts the RMS amplitude, as well as the one-third octave band spectrum (shown in Figure 4).

Vibrations were measured on the floor at Beam Line X1 in NSLS, around midnight, to provide a comparison with the vibrations measured in CFN. These results are also shown in Table 2, as Location 9. The difference between the two is quite dramatic, 71 nm for NSLS compared to 20 nm in CFN. (The same low-noise setup was used in both cases.)

BNL provided collected PSD spectra measured at several other light source facilities. The log mean PSD for the NSLS II site are shown superimposed on these data in Figure 6. The arrow indicates the NSLS II spectrum. It should be noted that the data from other facilities represent several different quantities of data points (the present data containing 200 points between 0 and 50 Hz) and quantity of averages. Either a smaller number of data points or a greater number of averages (or both) will produce a smoother spectrum. (For example, the vertical PSD spectrum from ESRF (shown in red) contains a very large number of data points, but most likely resulted from less than five spectra being averaged.) However, it is the fundamental nature of PSD spectra that spectral amplitude of stationary random vibration is roughly independent of bandwidth.

The data in Figure 6 initially suggest a rather unfavorable comparison between the NSLS II site and the other light sources. This was one of the reasons that nighttime data were subsequently measured in NSLS and CFN, such that the presence of a building could be taken into consideration, and at a remote location on the BNL property, so that proximity to the campus energy sources could be removed from consideration.

Data measured at the following locations were used for comparison:

- Microscopy suite of CFN, under construction
- Foundation of a light standard near CFN, prior to installation of the pole; this may be considered a "free-field" location, unstiffened by the presence of the building
- The floor of NSLS, directly beneath Beam Line X1 in the Experiment Hall
- A remote location near the northeast corner of BNL campus, on a hard surface at the center of a fire access road

Figure 7 shows the vertical Log Mean of site vibrations at NSLS II site (red curve marked by red arrow), expressed as PSD, compared with similar data from ALS, ESRF and SPRING-8 (using data provided by BNL). Shown also are PSD spectra measured at NSLS Beam Line X1 just after midnight, the "free-field" location near CFN, and the microscopy suite at CFN (identified by the black arrow). The vertical red dashed line indicates 4 Hz. The legend indicates the RMS amplitude using summation between 4 and 50 Hz, except for the NSLS II log mean, which is summed with a 6 Hz lower cutoff.

The vibrations near Beam Line X1 lie well above all the others, particularly at frequencies associated with rotating mechanical equipment, such as 18 Hz and 30 Hz. The data from the CFN microscopy suite lies below all the other BNL locations and ties with ALS for the -lowest RMS amplitude, at 20 nm.

Figure 8 compares the "best" BNL location—the CFN microscopy suite—with Location 'A' measured night using a stake and with the remote location simply measured on a road surface at noon. In this comparison, the remote location lies somewhat higher than the CFN spectrum at frequencies less than 8 Hz, but lies well below it at frequencies between 10 and 25 Hz. Recall from Figure 4 that there was a reduction factor of 3 to 5 times (in terms of amplitude) at frequencies below 8 Hz. In terms of power (i.e., PSD) this reduction factor becomes 9 to 25 times, which would suggest that the *surface* nighttime vibration at the remote location is less than that inside CFN, and would be lower yet inside a building at that location. Even though vibrations were not measured at night at the remote location, it is suggested that there is a cultural effect in the diurnal vibrations on the BNL campus, and that a remote site farther from the utility plant and the expressway might be worthy of consideration as design progresses.

The vibration study indicates that following the installation of the ring structure and experiment hall, which will significantly stiffen the site, the vibration environment will be comparable to that of other light source facilities. Additional modeling studies are recommended as the design progresses to examine the building and slab effect in greater detail, as much of the published experience deals with rectangular buildings, rather than toroidal. The dynamics are likely to differ to some extent.

Greater insight would be gained from carrying out a continuous vibration survey of 24 hours or more, in order to better document the diurnal variation of vibration at the site. This could be done at the ring site, using simultaneous multiple recording locations distributed around the ring. With data taken simultaneously, it may be possible to glean additional insight into the mechanism(s) and source(s) involved in the vibrations between 1 and 10 Hz.

The researchers may also benefit from a statistical representation of the temporal variation of vibration.[3]

---

[3] This is discussed at length in H. Amick, M. Gendreau, & N. Wongprasert, "Centile spectra, measurement times, and statistics of ground vibration," *Proceedings of the Second International Symposium on Environmental Vibrations: Prediction, Monitoring, Mitigation and Evaluation (ISEV2005)*, Okayama University, Okayama, Japan (20 to 22 September 2005)

Table 1. Summary of RMS amplitudes at NSLS II site, mid-afternoon

Location	Position		Vertical			North-South			East-West		
		f_1:	4 Hz	6 Hz	8 Hz	4 Hz	6 Hz	8 Hz	4 Hz	6 Hz	8 Hz
1	8 o'clock		69	29	23	45	23	19	35	24	21
2	10 o'clock		52	29	24	37	25	22	42	28	25
3	11 o'clock		43	26	20	30	20	17	29	19	16
4	1 o'clock		44	30	26	34	25	21	33	25	21
5	2 o'clock		36	26	22	30	23	21	46	36	33
6	7 o'clock		30	21	18	26	16	12	26	13	10

Table 2. Summary of RMS amplitudes at supplemental locations, various times

Location	Description	Time		Vertical			North-South			East-West		
			f_1:	4 Hz	6 Hz	8 Hz	4 Hz	6 Hz	8 Hz	4 Hz	6 Hz	8 Hz
7	Microscopy Lab in CFN	730pm		20	15	14	12	8	7	19	9	7
		1120pm		20	14	13	11	6	5	13	7	6
8	Free-Field, Foundation of Light Standard at CFN	1140pm		24	19	17	41	37	35	38	35	34
9	Beam Line X1 at NSLS	Midnight		71	48	42	12	9	8	13	9	7
10	Remote Site, on Wellhead	Noon		24	12	8	27	16	15	33	15	10
11	Remote Site, on Road	Noon		21	9	6	25	14	12	26	12	9
12	Location "A"	315pm		80	53	46						
		1030pm		35	29	27						

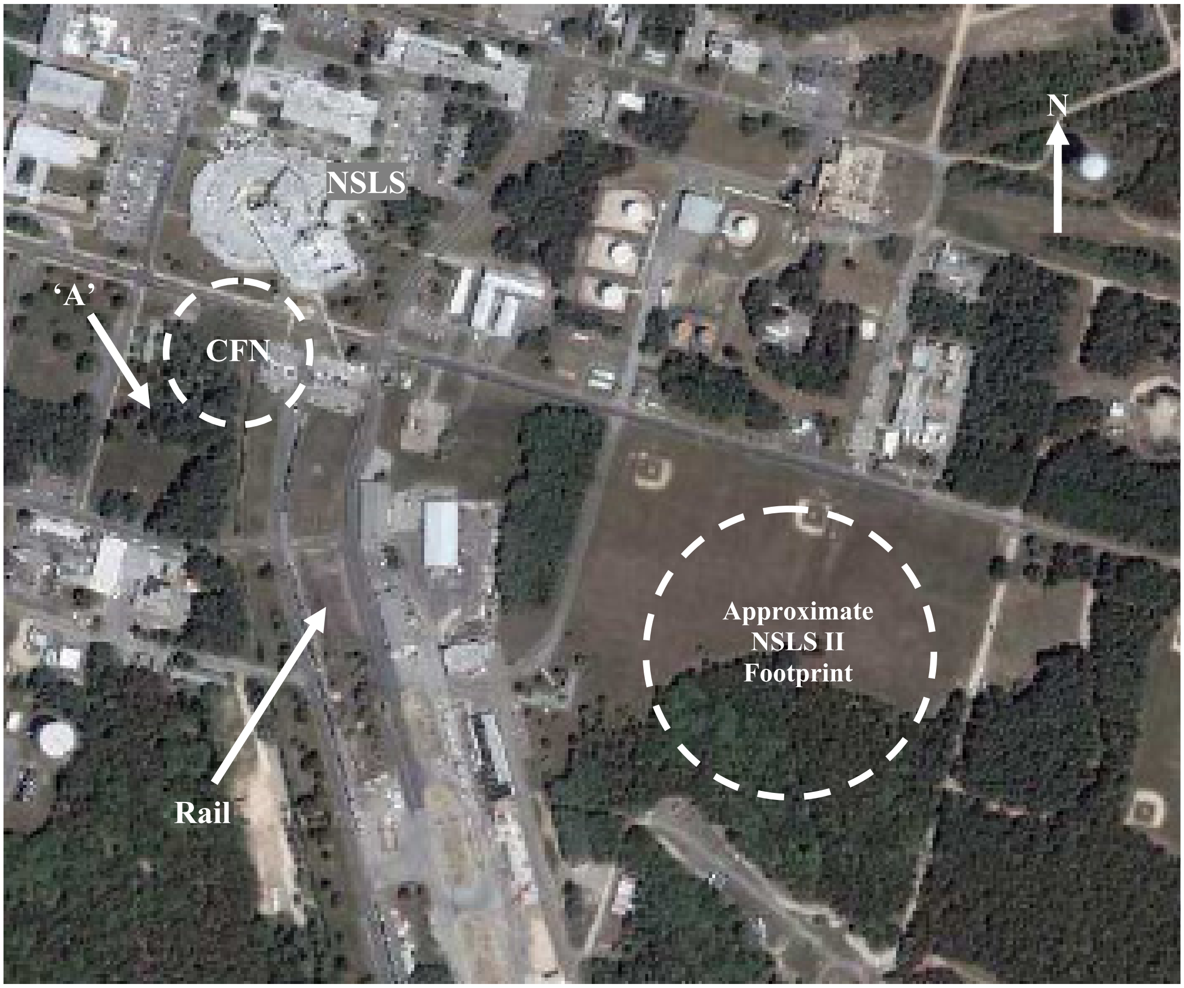

Figure 1. Aerial photograph of a portion of BNL showing approximate location for NSLS II and other relevant locations

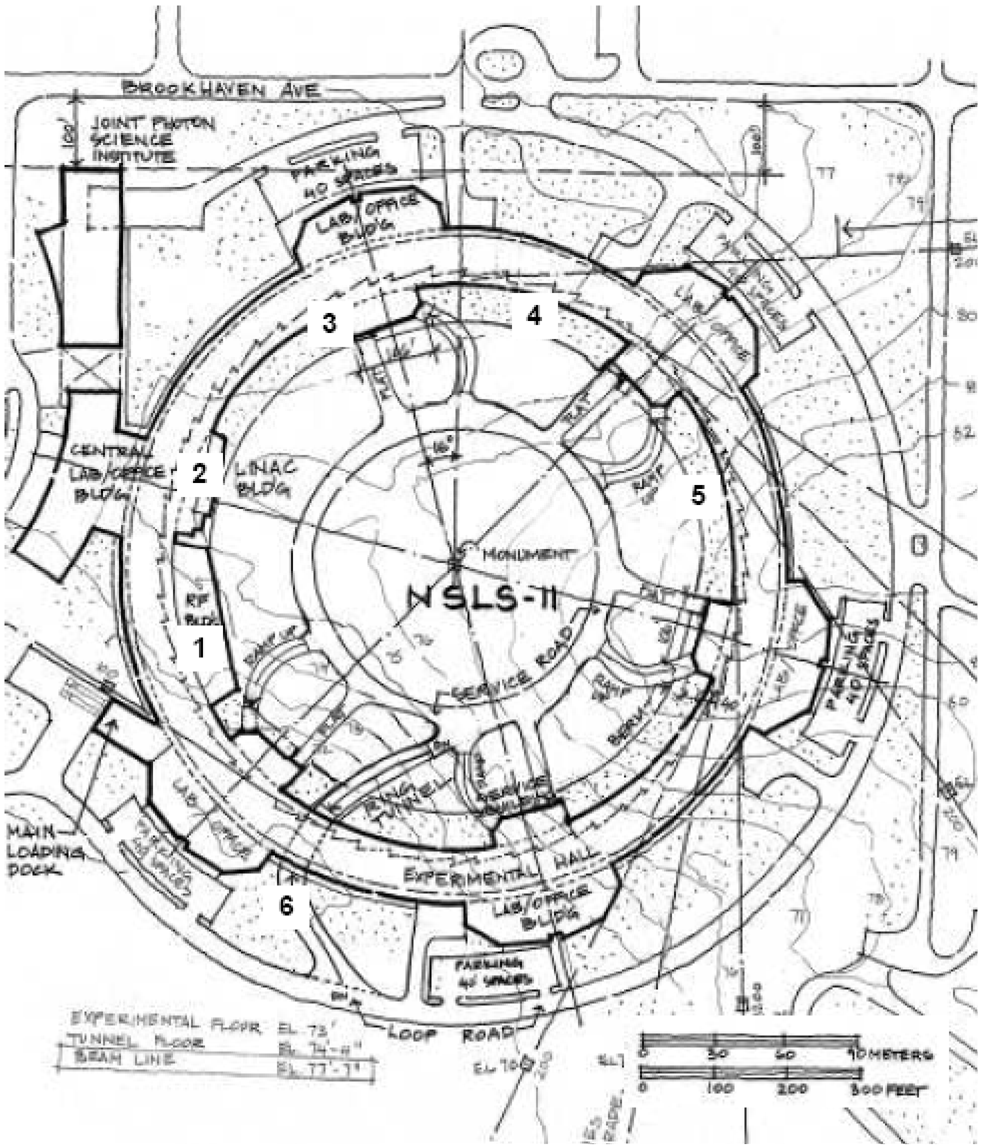

Figure 2. Site plan showing approximate location of NSLS II and the measurement locations used in this study

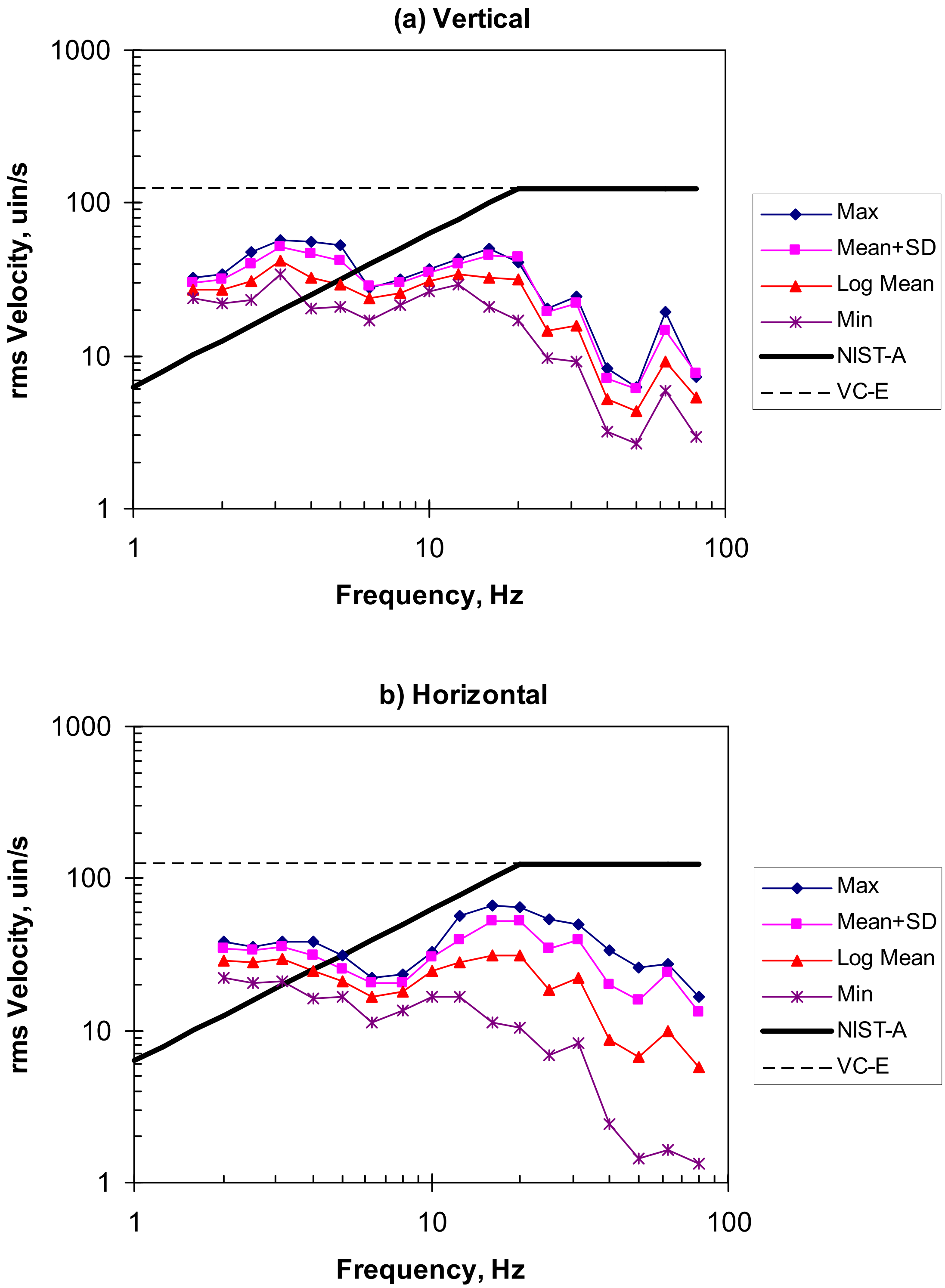

Figure 3. Statistical representation of daytime ambient site vibrations at Locations 1-6, NSLS II site

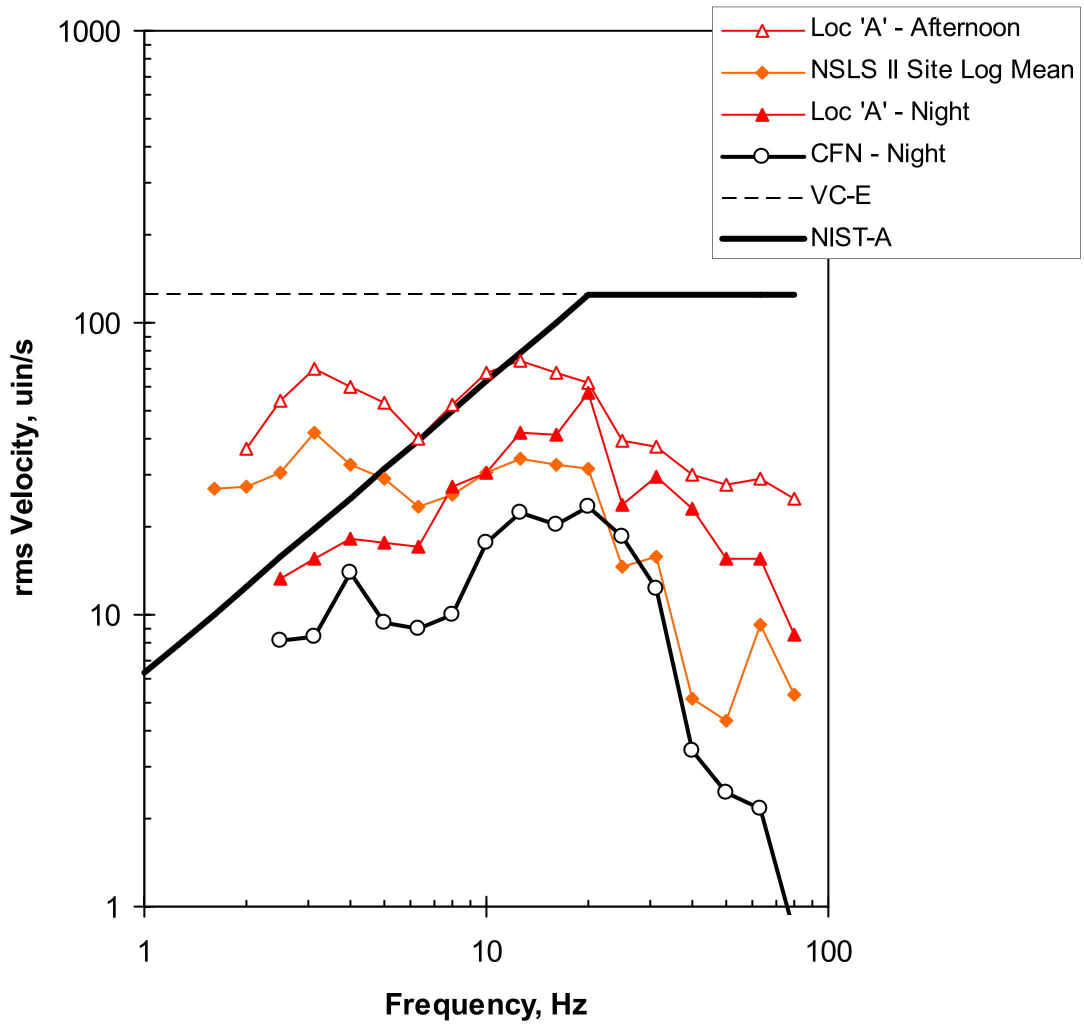

Figure 4. Comparison of one-third octave band vibrations at the NSLS II site, Location 'A', and at night in the CFN microscopy suite.

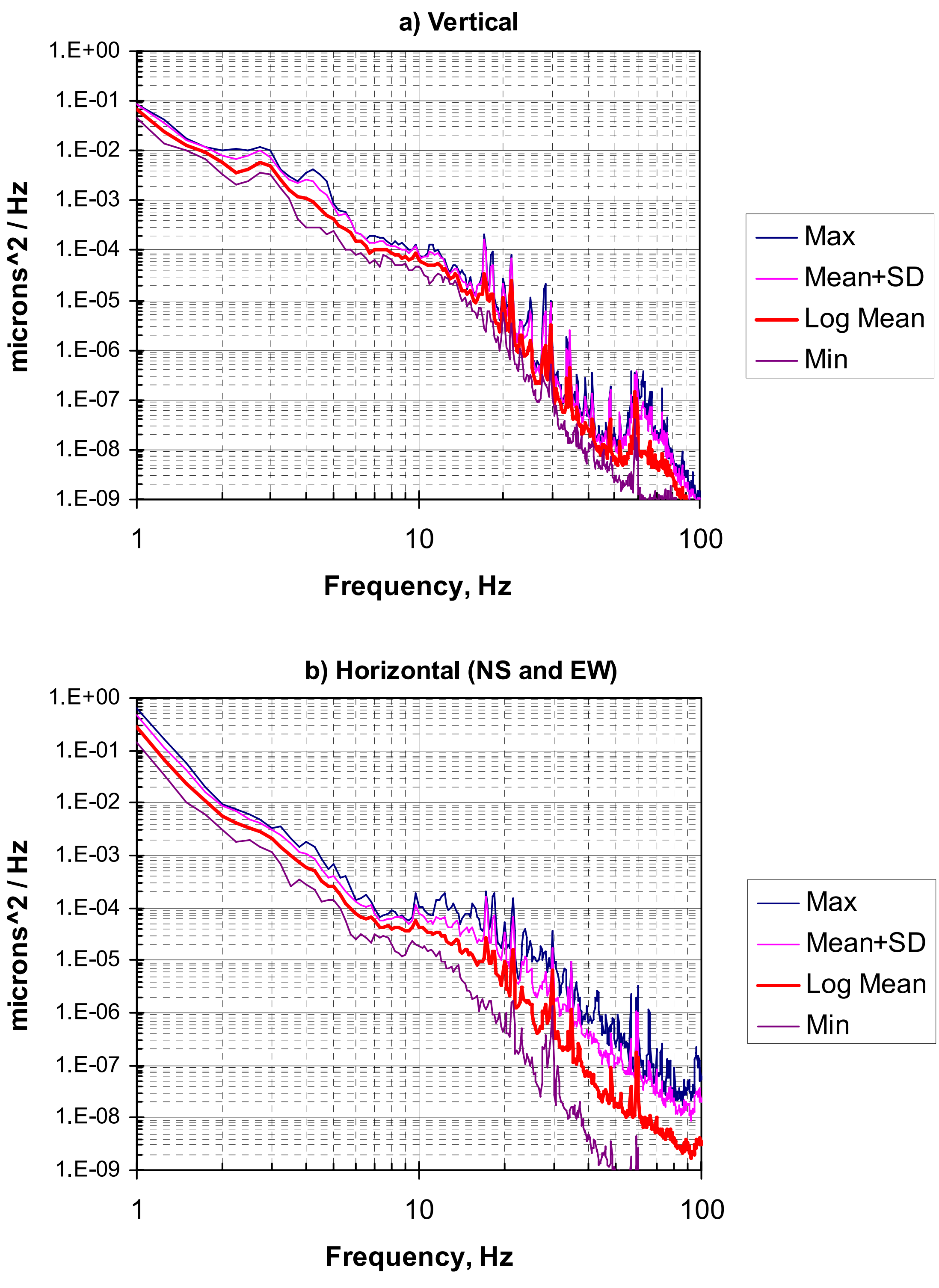

Figure 5. Statistical representation of daytime ambient site vibrations at Locations 1-6, NSLS II site, in terms of displacement power spectral density (PSD), 1-100 Hz

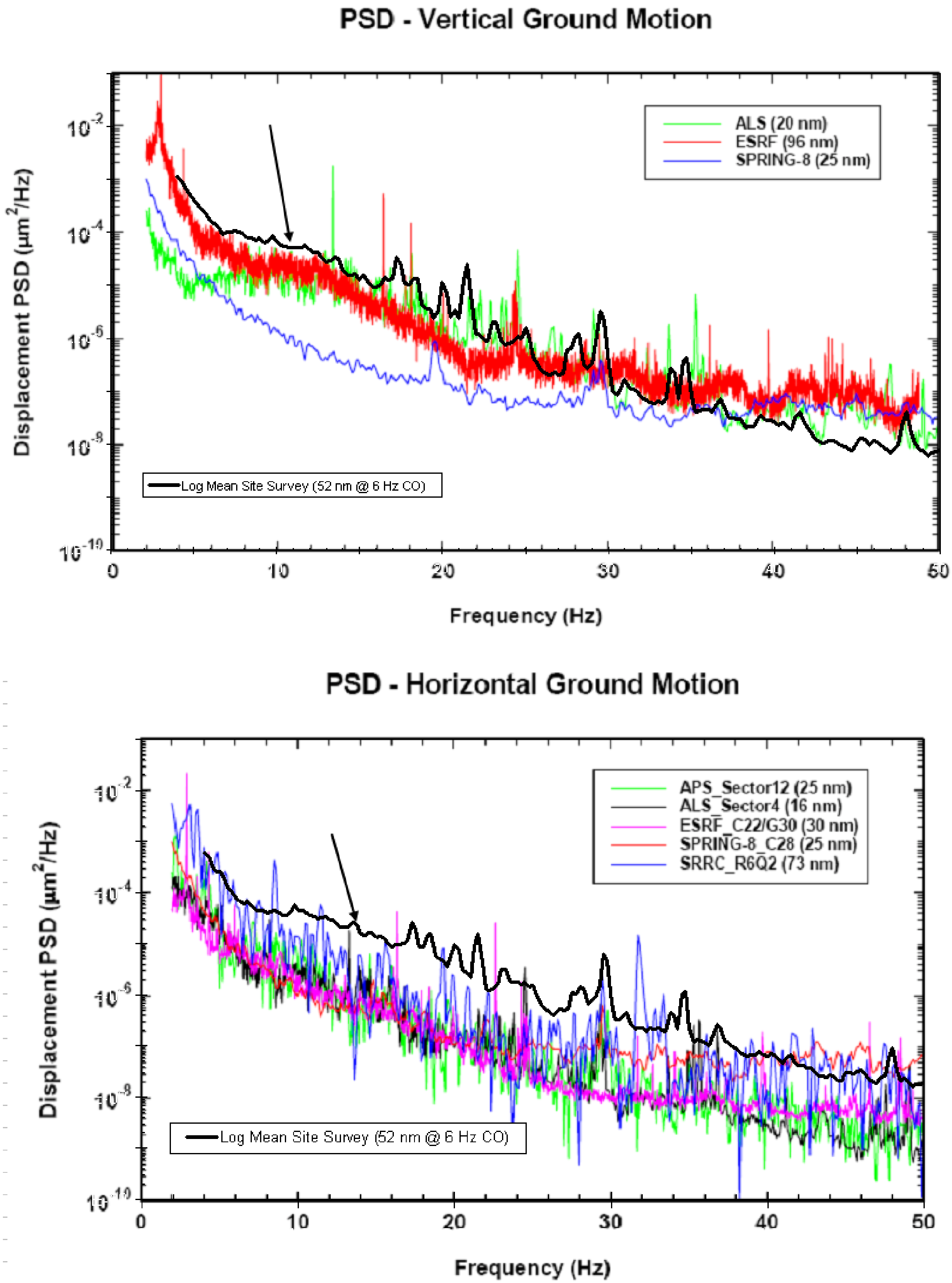

Figure 6. Log Mean of site vibrations at NSLS II site, expressed as PSD, compared with other sites (data for other sites provided by BNL)

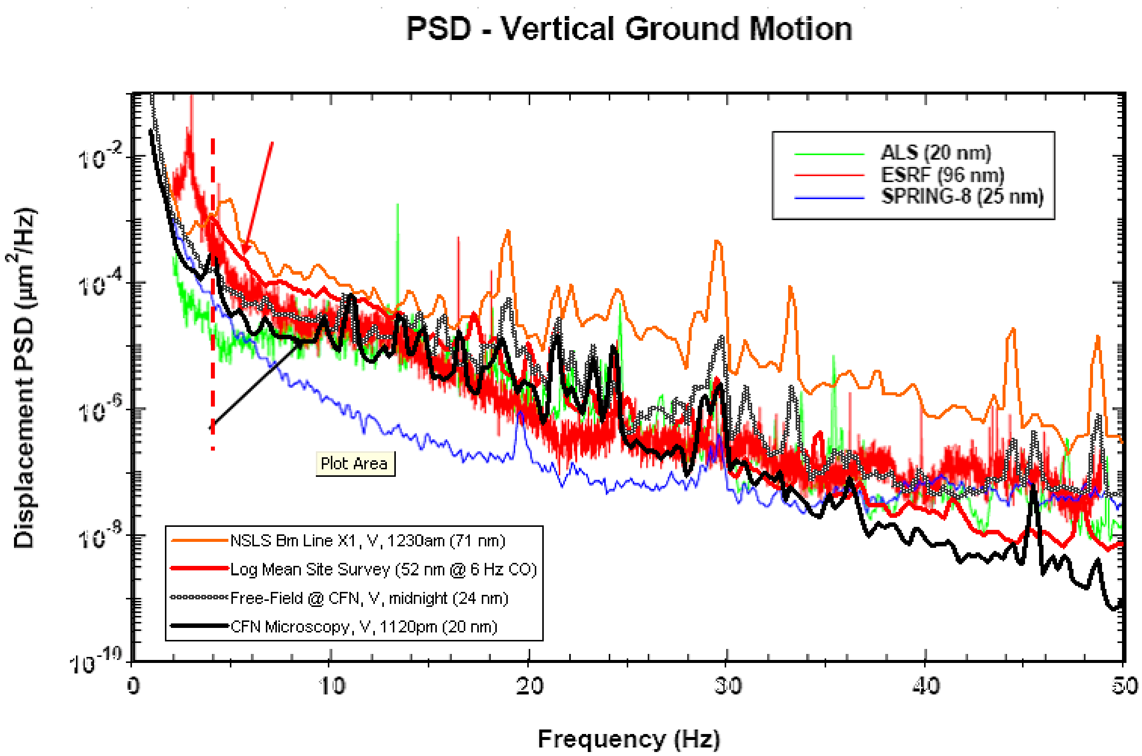

Figure 7. Log Mean of site vibrations at NSLS II site, expressed as PSD, compared with other sites (data for other sites provided by BNL) and with NSLS Beam Line X1, Free-Field at CFN, and the microscopy suite at CFN.

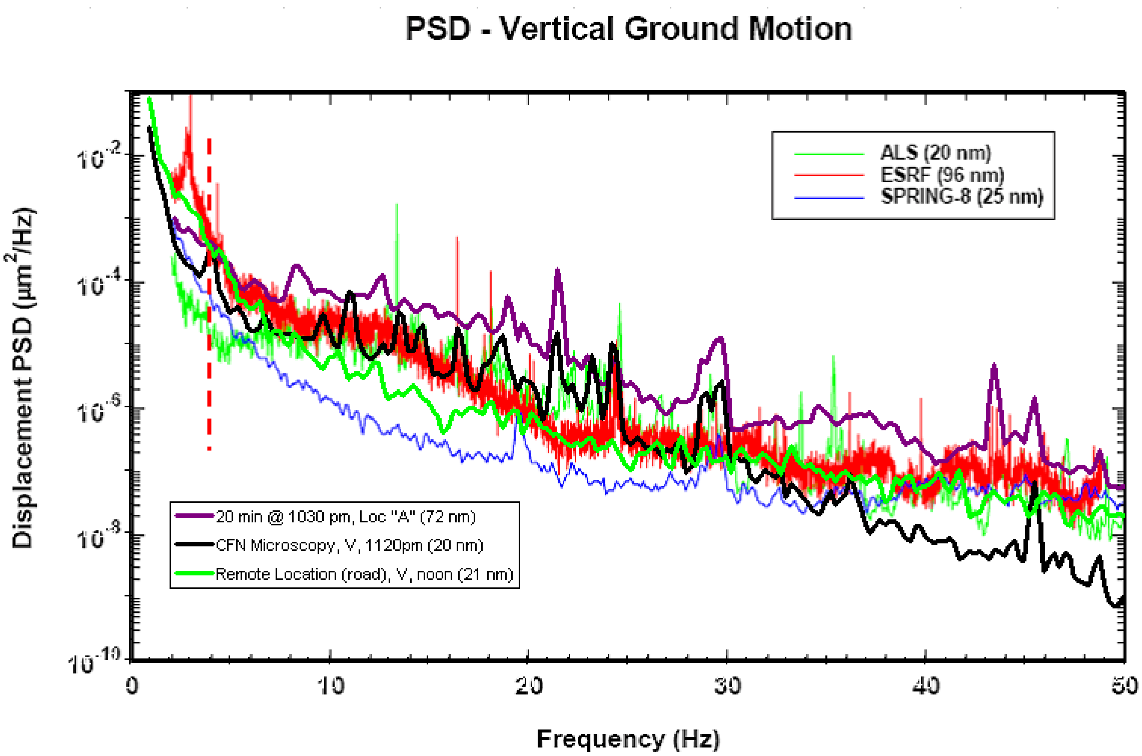

Figure 8. Comparison of PSD vibrations at three alternate reference locations, including Location ‘A’ and CFN Microscopy, both at night, and the remote location at noon.

Vibration and Acoustic Design Issues

Utility Distribution

Two utility concepts were examined during the course of this review. One was a distributed system along the lines of that used for APS, where the air handlers are placed at locations around the ring, perhaps along the outside of the experiment hall as at APS. The other concept was a centralized system, where the air handlers are placed at a central location and air distribution is via ducting. Each approach offers arguments pro and con, but examination of the issues specific to BNL philosophy and the proposed NSLS II layout led toward the centralized system.

From a vibration perspective, the difference between the two concepts lies in the amount of energy present in a concentrated area. (The distributed system works with a larger quantity of smaller air handlers, thus the maximum horsepower at any location near the ring is less, so there is a lower risk in placing the units closer to the ring.) However, a centralized system offers maintenance benefits, and the primary vibration control design issues become those of distance and conservative vibration isolation. It is important to maximize the distance between the air handlers themselves and the ring, though this will affect energy efficiency. A careful study of tradeoff between these two variables is recommended as design progresses.

A preference has been expressed to avoid vibration isolation on piping and ducting as much as possible. An important reason for this is that isolation works on the concept of exploiting a low resonance frequency of a sprung mass (the duct or pipe on a spring) and the random vibration energy in the duct or pipe is shifted to very low frequencies. Because the ring is sensitive to displacement, particularly at low frequencies, this is not a desirable feature. The alternatives for vibration control include low duct and pipe velocities (i.e., larger diameters) and long straight runs of mains. Both of these concepts can easily be incorporated as the design progresses.

Isolation of the Experiment Hall floor from the Ring tunnel floor

The outer corridor of the Experiment Hall will be separated from the floor slab of the Experiment Hall by means of a joint in the slab, following the APS model. This decouples the public corridor, which has pedestrian activities and deliveries, from the more vibration-sensitive Experiment Hall area.

Concerns have been expressed regarding the connectivity of the Tunnel and the floor of the Experiment Hall. This is not as simple a decision as that to decouple the outer corridor. The argument in favor of a joint is similar: it is desirable to mitigate “humming” and other vibration that might be generated by the equipment associated with the ring. The argument against a joint is that it introduces the risk of differential settlement between the Tunnel and Experiment Hall, which could cause a small, though quasi-static, beam misalignment.

The thick concrete slab of the Experiment Hall and Tunnel together will offer some improvement of the ground surface that might not be as dramatic if it is actually two ring slabs, one inside the other. This is an issue that can be addressed analytically as the design progresses.

An option worthy of consideration is the use of a damping admixture in the concrete beneath the ring. It would help to dissipate the high-frequency "humming" vibration. It could be placed as a topping on the concrete, as done in mechanical corridors at CFN. An unknown that would require evaluation is the severity of the radiation and how the polymer would respond to that radiation.

Acoustics of Experiment Hall

The Experiment Hall is a large open area which will have a vast quantity of user-supplied noise sources. A noise study was carried out in 1989 as part of the APS design effort, in part to develop a "typical" source sound power spectrum for design of the APS Experiment Hall.[1] At that time, the average noise level was found to be 69 dBA, though noise levels as high as 80 dBA were measured. It was assumed that the experiments themselves were not adversely affected (as noise protection could be built into the hutches), but the noise environment in the hall was a detriment to speech communication and contributed to researcher fatigue.

It might be worthwhile for BNL to consider imposing a limit on the allowable sound power associated with user-supplied equipment. However, the most proactive move is probably to use acoustically absorbent materials on walls and ceiling. The latter is relatively straightforward, by means of an acoustically absorbent roof deck. There are number of manufacturers of the product. Essentially it is a corrugated decking in which the grooves (as seen from above) are perforated and filled with acoustical material. The high spots are surfaces for supporting roofing or sheeting that supports concrete roof system. You can get very good performance from these systems. A facility with this kind of decking is the Experiment Hall at the Center for Advanced Microstructures and Devices (CAMD) at Louisiana State University. Some of the vendors of this product are Versa-Dek, United Steel Deck, and Vulcraft. A noise study should be carried out as the design progresses to the point that the mechanical system noise can be combined with the sound power for the research equipment.[2] That study can develop specific recommendations regarding the NRC of the decking and wall coverings and the optimal percentage of wall covering.

---

[1] Amick, H., and C. G. Gordon, "Measurement of Noise and Vibration, National Synchrotron Light Source, Brookhaven National Laboratory", Acentech Report 11 (June 1989).

[2] Sound power data for typical NSLS equipment were reported in "Acoustical Evaluation of Experiment Hall: Argonne National Laboratory", A. M. Yazdanniyaz & S. K. Bui, Acentech Report No. 56, January 1991. The noise from the experimental equipment was included in their noise model via sound power estimates based on measurements made at NSLS in 1989, see Acentech Report 11.