Attachment N.3H
Vibration Analysis of Category 1 Land Uses and Special Buildings

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Acronyms and Abbreviations

ACT	A Contemporary Theater
dBA	A-weighted decibels
FTA	Federal Transit Administration
Leq	equivalent sound level
L.S.T.M.	line source transfer mobility
M.R.I.	magnetic resonance imaging
N.M.R.	nuclear magnetic resonance
P.S.T.M.	point source transfer mobility
R.M.S.	root-mean square
SIFF	Seattle International Film Festival
V.C.	vibration criteria
VdB	vibration velocity decibels

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1 HARBOR ISLAND MACHINE WORKS

1.1 Description of Sensitive Spaces

Harbor Island Machine Works is a precision machine shop at 3431 11th Avenue Southwest on Harbor Island in the Duwamish Segment of the West Seattle Link Extension. The machine shop building is composed of an original structure with additions. Their equipment includes mills, lathes, computer numerical control tools, and other machining equipment. Some equipment relies on laser calibration systems, and it is important that high vibration levels not cause interference while machining parts. No photographs are allowed in the machine shop due to the potentially sensitive nature of parts being machined. Figure 1-1 shows a photograph of a mill provided by Harbor Island Machine Works.

The Federal Transit Administration (FTA) workshop criteria for vibration were applied to the Harbor Island Machine Works site. The workshop threshold of 90 vibration velocity decibels (VdB) are appropriate for areas where vibration can be distinctly felt but are not as sensitive to vibration as typical office spaces or institutional land uses. Even though the criteria for Harbor Island Machine Works are higher than Category 2 or 3 land uses, it is considered a Category 1 land use because vibration could interfere with operations. This distinction is particularly important when considering construction vibration limits. Construction vibration limits for Category 2 or 3 land uses is typically based on potential risk for damage, where construction vibration limits for Category 1 buildings is based on potential for interference.

Figure 1-1. Photograph from the Harbor Island Machine Works Machine Shop

Source: Harbor Island Machine Works 2021
(used with permission)

1.2 Existing Vibration Levels

Existing vibration levels were measured over three 15-minute periods at two locations at the Harbor Island Machine Shop. One sensor was in the more recent building addition, about 12 feet from the south wall of the building. The second sensor was about 68 feet from the south wall of the building in the original workshop. Normal business activity was on-going during the ambient vibration measurements.

The measured equivalent vibration levels (Leq) over the 45-minute duration of the measurement are shown in Table 1-1 for the two measurement positions. Figures 1-2 and 1-3 show the 1-second vibration levels over the measurement duration. Figure 1-4 shows the spectra of the vibration levels. At high frequencies, the existing vibration levels in the original workshop are higher than the vibration levels in the building addition. This may be due to the type of equipment that was operating nearby, or it may be due to differences in the building foundations. For both measurement positions, the existing vibration levels are relatively high at frequencies below 40 hertz.

Table 1-1. Background Noise and Vibration Levels at Harbor Island Machine Works

Monitoring Location	Vibration level (45 min Leq)
Building Addition	68 VdB
Original Workshop	68 VdB

Figure 1-2. Measured 1-second Noise Levels in the Harbor Island Machine Works Building Addition

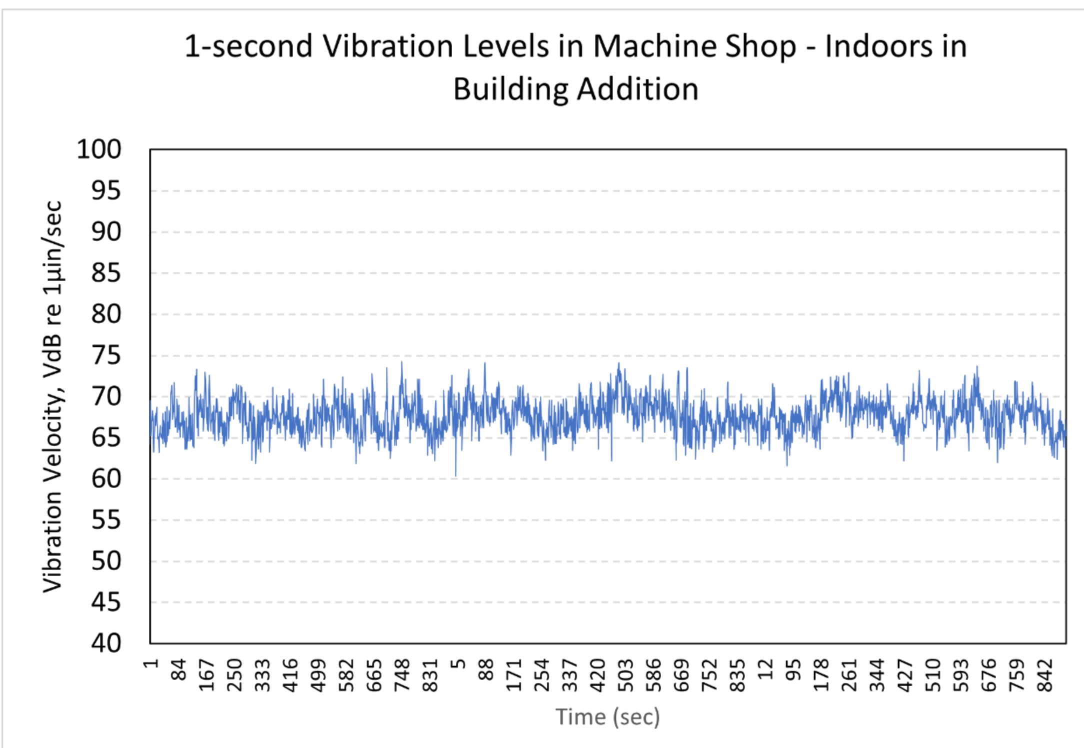


Figure 1-3. Measured 1-second Noise Levels in the Harbor Island Machine Works Original Workshop

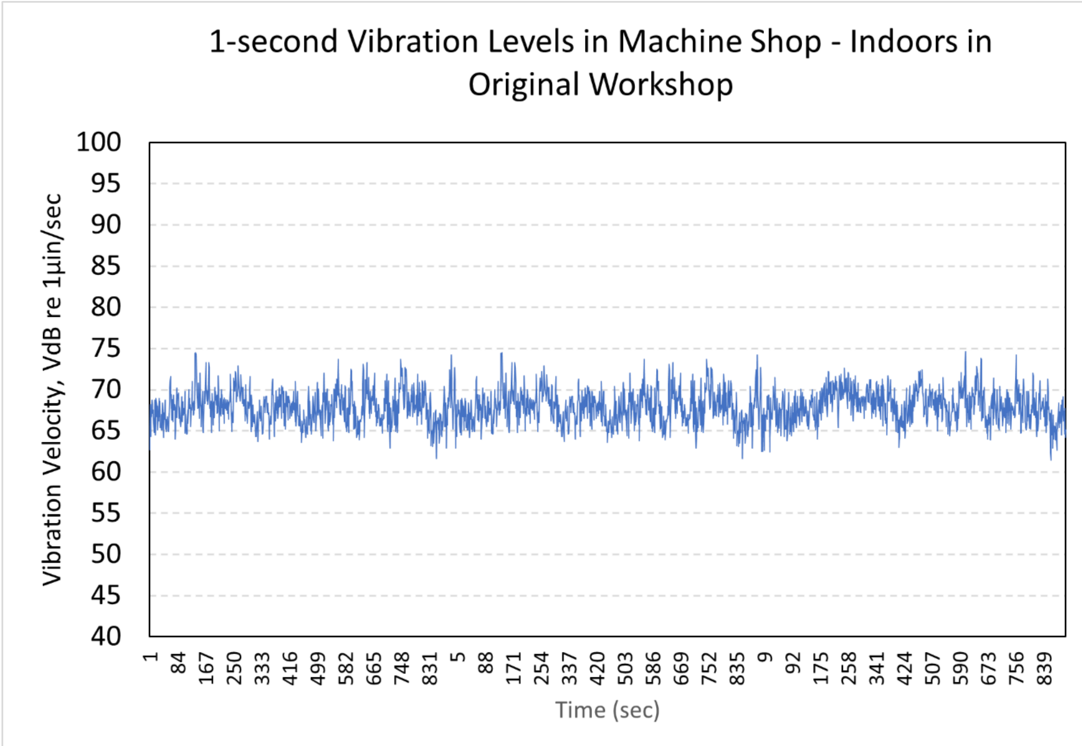
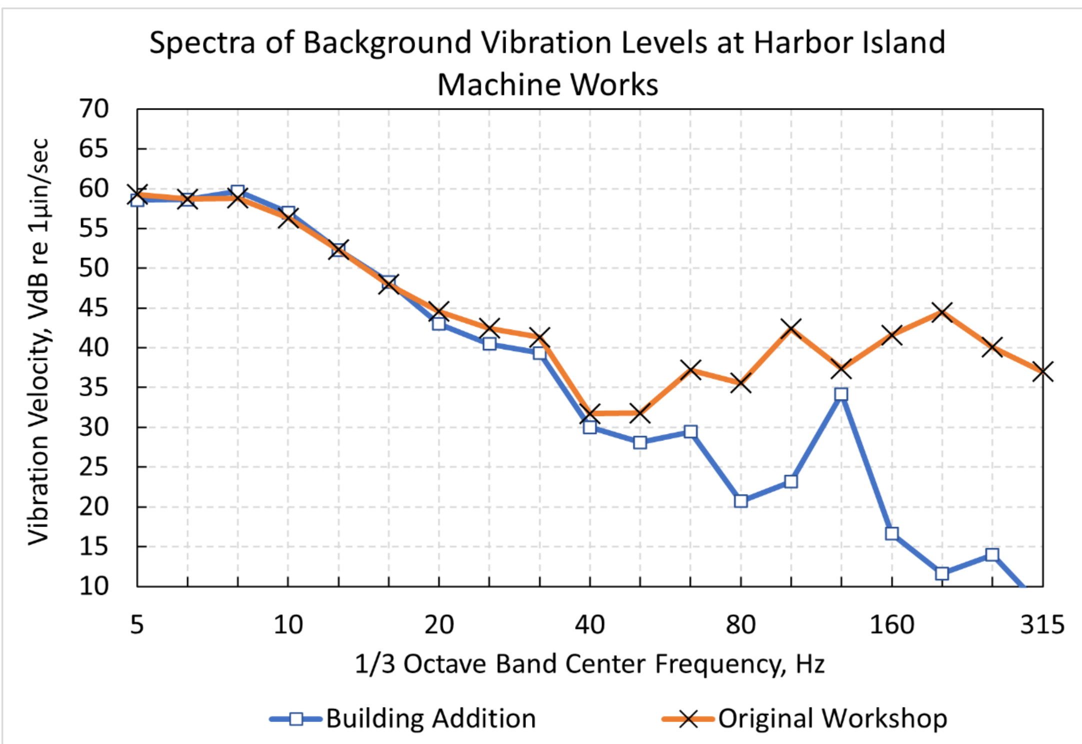


Figure 1-4. Spectra of Existing Vibration Levels at Harbor Island Machine Works



1.3 Vibration Propagation Measurement Description

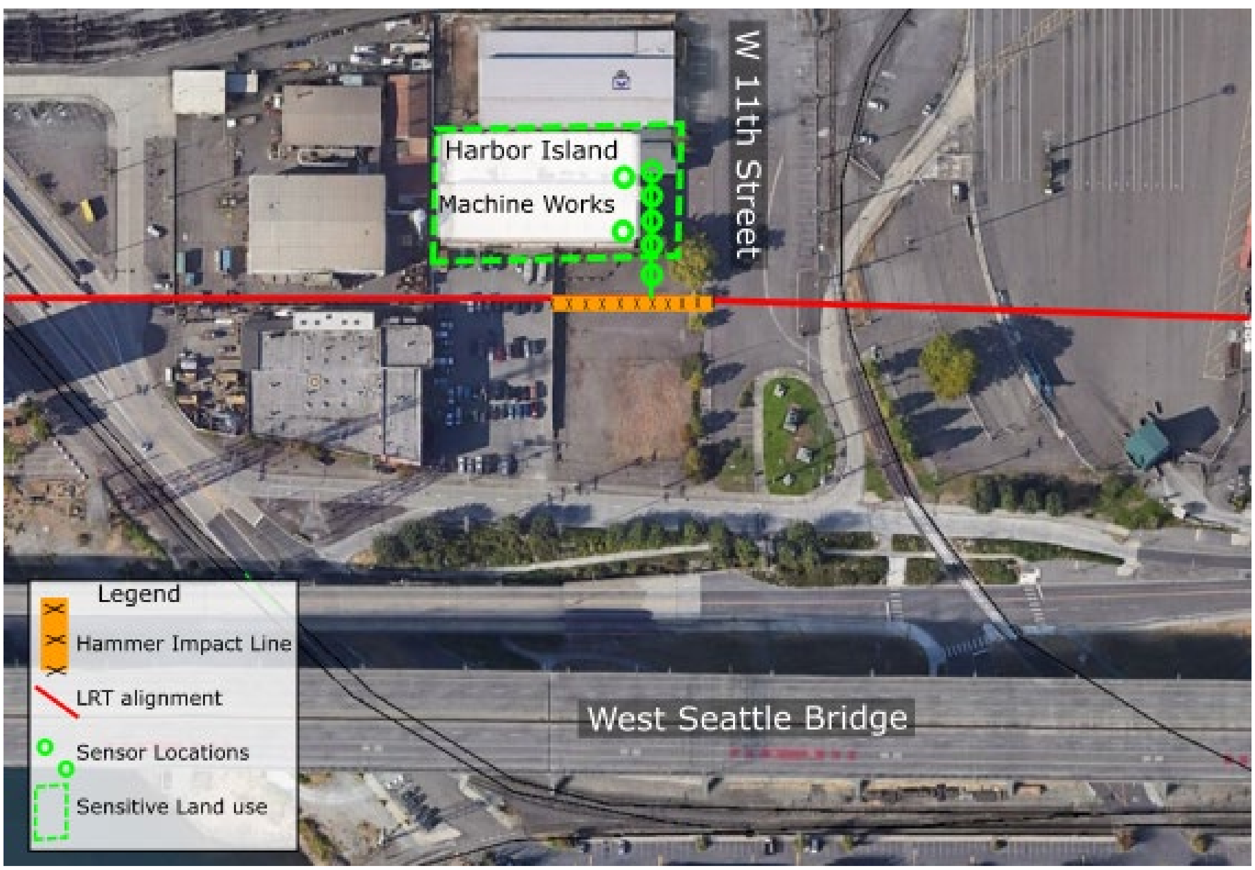
In the vibration propagation measurement, an impact hammer was used near the proposed location of the light rail trackway to impart a force into the ground. The vibration response was measured at representative locations. At Harbor Island Machine Works, the impact hammer was positioned in the parking area 48 feet from the south façade of the building. The hammer was operated at 11 positions spaced 15 feet apart to simulate the length of a train.

The vibration levels were measured at five outdoor positions and two indoor positions. The outdoor measurement locations are used to quantify how vibration levels decrease with distance from the impact force. The outdoor vibration measurements are also used as a reference to examine how levels change as the vibration travels from the soil into the building structure.

The two indoor measurement locations are the same locations where existing vibration levels were measured: (1) in the building addition, about 12 feet from the south building façade and (2) in the original workshop, about 68 feet from the south building façade.

Figure 1-5, which is an aerial photograph of the measurement location, shows the hammer impact line in the parking area and the approximate locations of the accelerometers extending north from the impact line. The proposed light rail alignment would be parallel to the West Seattle Bridge, about 85 feet from the Harbor Island Machine works façade.

Figure 1-5. Aerial Photograph of Harbor Island Machine Works Measurement Site



1.4 Vibration Propagation Measurement Results and Predicted Levels

The result of the vibration propagation test is the line source transfer mobility (L.S.T.M.), which is a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the L.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The L.S.T.M. and coherence results for the indoor measurement positions near the impact line and the closest outdoor measurement positions are shown in Figures 1-6 and 1-7. The outdoor measurement positions are labeled with their distance from the hammer impact line in the figures. Observations from the L.S.T.M. and coherence results are as follows:

- The L.S.T.M. from the outdoor and indoor measurement positions have relatively high levels at low frequencies. The low coherence at low frequencies and the high existing vibration levels at low frequencies indicate the high L.S.T.M. values are likely an overestimate due to poor signal-to-noise ratio between the input force and the measurement vibration response.

- The outdoor measurement position at 60 feet has a peak in the L.S.T.M. at 50 hertz. There is also a peak in the coherence at this frequency, which indicates there is efficient propagation at 50 hertz to this sensor position. The outdoor measurement position at 116 feet does not show a similar peak at 50 hertz. It is not clear if the peak at 50 hertz is unique to the sensor position, or if there is similarly efficient propagation at 50 hertz and 60 feet throughout the property.

- The L.S.T.M. in the original workshop trends up at higher frequencies, but there is low coherence at these frequencies. These results at high frequencies are likely an overestimate due to poor signal-to-noise ratio.

Figure 1-6. L.S.T.M. and Coherence in Harbor Island Machine Works Building Addition Workshop

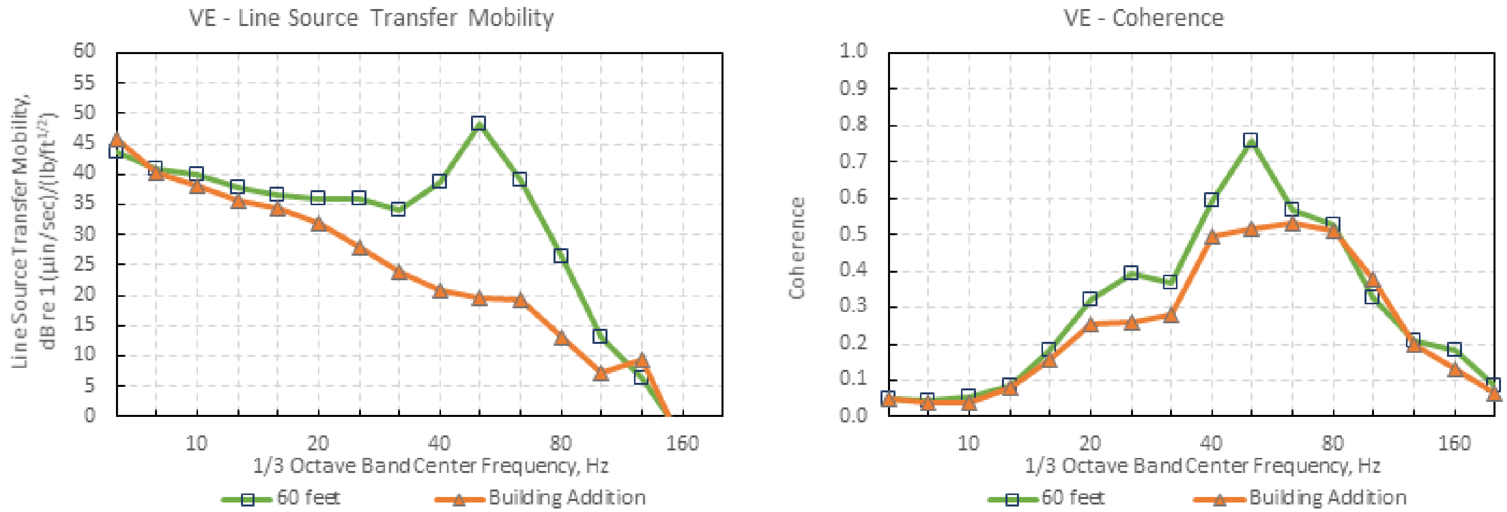
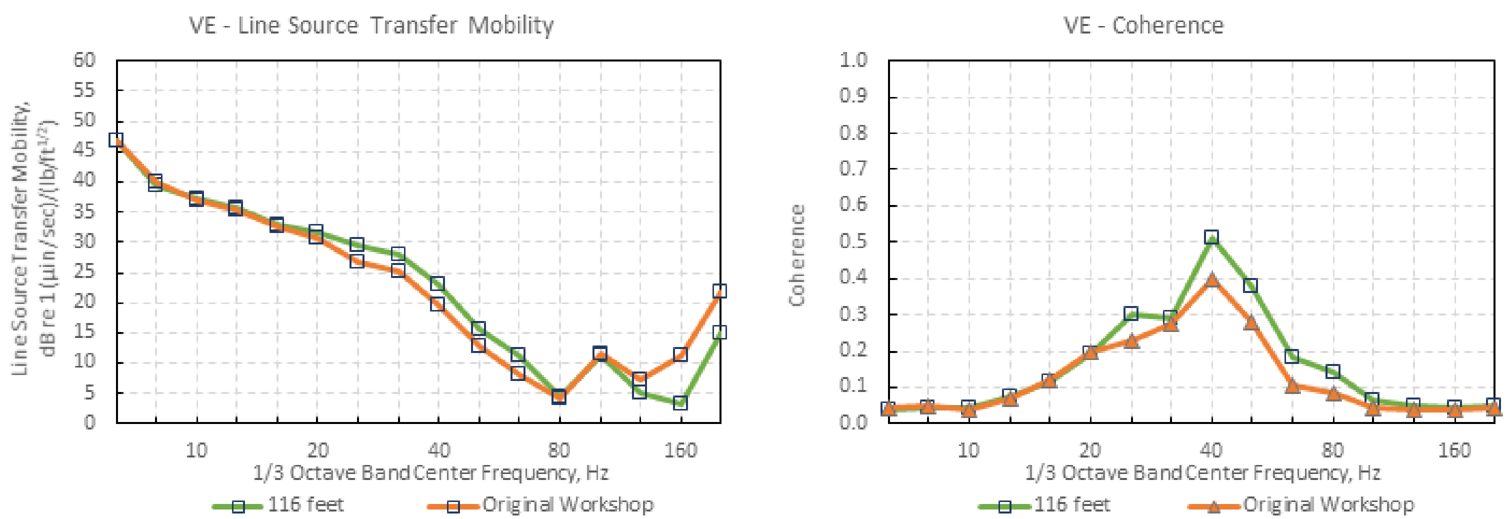
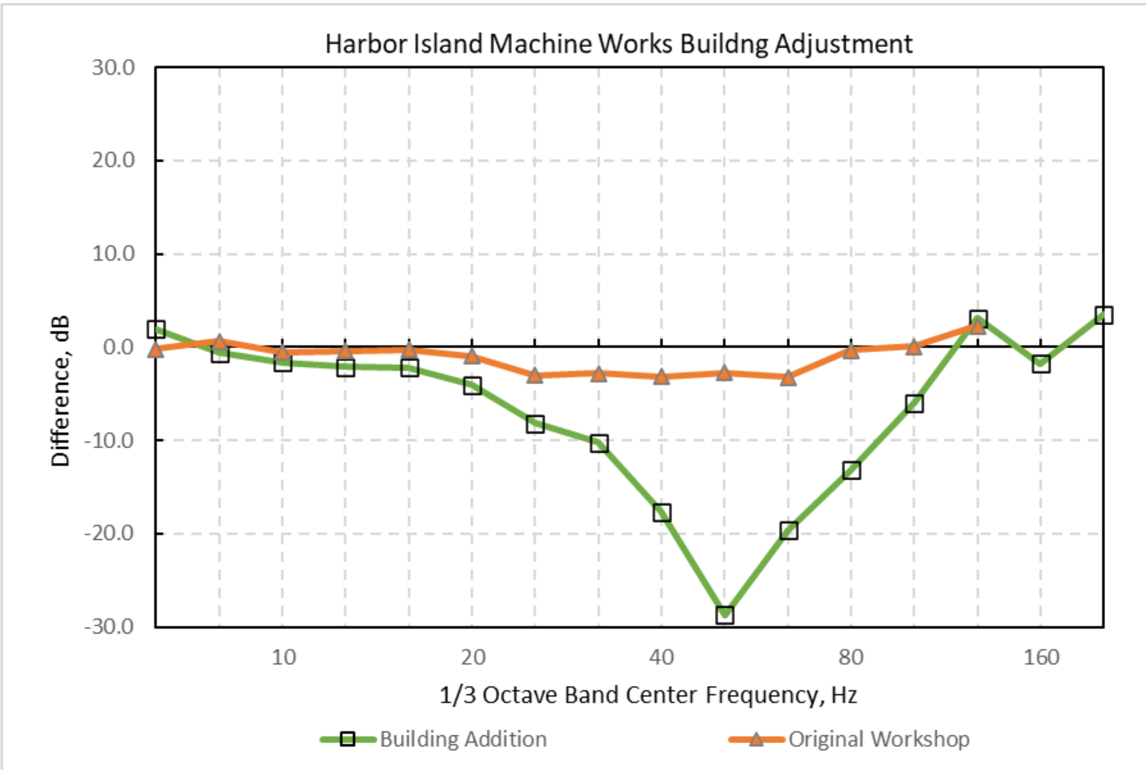


Figure 1-7. L.S.T.M. and Coherence in Harbor Island Machine Works Original Building Workshop



The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances is the difference between the outdoor L.S.T.M. at an equivalent setback distance and the indoor L.S.T.M. The building adjustment for the workshops at Harbor Island Machine Works is shown in Figure 1-8. No building adjustment is applied for the original workshop at 160- and 200-hertz 1/3-octave bands because the L.S.T.M. and coherence data indicate there is a poor relationship between the force and the measured vibration response. Figure 1-8 shows significant vibration reduction from the building addition, between 30 hertz and 100 hertz. The data may be overstating the building loss due to unusually efficient vibration propagation to the outdoor sensor position. The data for the original workshop shows building loss between 0 decibel and 5 decibels across the mid-frequencies, which is typical for slab-on-grade buildings.

Figure 1-8. Measured Building Adjustment at Harbor Island Machine Works



The predicted levels using the L.S.T.M. coefficients for site V-E (Harbor Island Machine Works) and the building adjustment in Figure 1-8 are presented in Table 1-2 for the Duwamish Segment Alternative DUW-2. The other Duwamish Segment alternatives would be south of the West Seattle Bridge and more than 500 feet from the Harbor Island Machine Works building. The levels are predicted for the building addition, the original workshop, and without any building adjustment. There is no safety factor added to the predicted levels because the predictions use site-specific L.S.T.M. levels and there is a 3-decibel safety factor built-in to the force density level.

The spectra of the predicted vibration levels are plotted in Figure 1-9. The 1/3-octave bands with the highest predicted vibration levels are 10 hertz and 12 hertz, where there was relatively high L.S.T.M. and force density levels, but low coherence. Where there are relatively high L.S.T.M. levels with low coherence, the vibration predictions are likely to be an overprediction due to high background levels.

The predicted vibration levels from train operations would not exceed the FTA criteria, so no mitigation measures are proposed. However, pile-driving during construction could exceed the FTA criteria. Vibration from construction is addressed in Section 6.4 of the Noise and Vibration Technical Report.

Table 1-2. Predicted Vibration Levels at Harbor Island Machine Works with North Crossing Alternative (DUW-2), Duwamish Segment

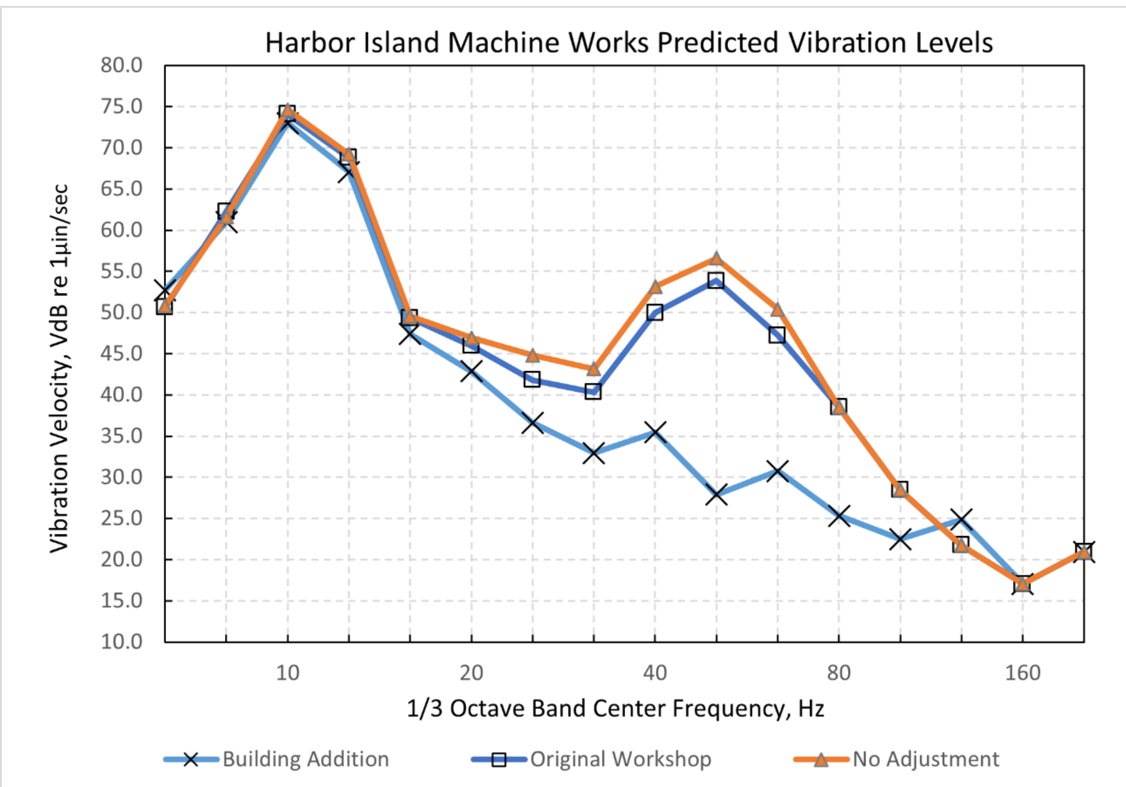
Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Amount Exceeds, (decibels) [c]
Building Addition	85	55	73	90	Does not exceed
Original Workshop	85	55	74	90	Does not exceed
No Building Adjustment	85	55	75	90	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (A-weighted decibels [dBA]) exceeds the applicable criteria.

Figure 1-9. Predicted Vibration Levels at Harbor Island Machine Works



2 5TH AVENUE THEATRE AND ACT THEATER

2.1 Description of Sensitive Spaces

The 5th Avenue Theater is located on 5th Avenue between University and Union streets in Downtown Seattle in the Downtown Segment of the Ballard Link Extension. It is in the historic Skinner Building, which is listed on the National Register of Historic Places. This theater is currently operated as a venue for nationally touring Broadway and original shows by the non-profit 5th Avenue Theater Association. The building is owned by the University of Washington. The FTA criteria for theaters is applied to the performance and seating area of the building.

A Contemporary Theater (ACT) Theater is Downtown Seattle at 700 Union Street in the historic Eagles Auditorium. There are two mainstage theater spaces—one below-grade (Gregory A. Falls Theater) and one above ground (Allen Theater). ACT Theater is a regional, non-profit theater organization. The FTA criteria for theaters is applied to both mainstage theater spaces.

2.2 Predicted Vibration Levels

The vibration prediction model quantifies how efficiently vibration propagates through the soil and into a building using vibration propagation tests. Site-specific vibration propagation measurements were planned for the 5th Avenue Theater; however, the property owner has indefinitely postponed right-of-entry to the project team to complete the measurements due to the COVID-19 pandemic. No site-specific vibration propagation data were collected at the ACT Theater because it is at least 300 feet from either Downtown Segment alternative. In place of using site-specific vibration propagation data, the average of the Downtown Segment measurement sites was applied in the prediction model. Those are the same data applied for the residential and institutional land uses in the Downtown Segment and are discussed in Section 5.3.2 of the Noise and Vibration Technical Report.

At most highly vibration-sensitive (Category 1) land uses, vibration propagation measurements inside a building are used to develop a “building adjustment” based on the building coupling loss and any floor resonances, which are then applied to the prediction model. Because no site-specific data are available, the building adjustment for the 5th Avenue Theater and ACT Theater is assumed to be 0 decibels. Many of the large buildings along the light rail alignments showed greater vibration attenuation than -5 decibel, so the building adjustment of 0 decibels is likely a conservative estimate.

Because site-specific vibration propagation and building adjustment data could not be measured at the two theaters, a safety factor of +2 decibels is included in the prediction model. There is also a 3-decibel safety factor incorporated into the force density level used in the prediction model.

The predicted vibration levels for Preferred Alternative DT-1 are presented in Table 2-1, and the predicted levels for Alternative DT-2 are presented in Table 2-2. The results show there is no predicted impact for either alternative. For Preferred Alternative DT-1, the alignment runs almost directly under the 5th Avenue Theater at a depth of about 150 feet. With the relatively deep alignment in this area, then predicted vibration levels would be well below the impact threshold. No vibration mitigation measures are proposed.

Table 2-1. Predicted Vibration and Groundborne Noise Levels at 5th Avenue Theater and ACT Theater with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
5th Avenue Theater	153	55	50	72	20	35	Does not exceed
ACT Theater	679	55	31	72	<0	35	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 2-2. Predicted Vibration and Groundborne Noise Levels at 5th Avenue Theater and ACT Theater with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
5th Avenue Theater	225	55	43	72	10	35	Does not exceed
ACT Theater	371	55	37	72	<0	35	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

3 UW MEDICINE SOUTH LAKE UNION CAMPUS

3.1 Description of Sensitive Space

The UW Medicine South Lake Union campus, which is in the Downtown Segment of the Ballard Link Extension, has six buildings (A, B, C, D, E, and F) at 850 Republican Street and 750 Republican Street, four of which contain research facilities. The campus is bounded by Mercer and Republican streets to the north and south and by 9th Avenue and Dexter Avenue to the east and west, respectively. Building C is used for administrative purposes, and Building F is a medical outpatient clinic. Neither Building C nor Building F have research space.

Table 3-1 lists the vibration-sensitive research equipment by building within the UW Medicine South Lake Union campus based on information gathered during a site visit in August 2019. The two magnetic resonance imaging (M.R.I.) units, the most sensitive pieces of equipment, are mounted on vibration isolation springs. The remainder of the equipment does not have vibration isolation.

Table 3-1 presents the vibration limit applied to each of the sensitive pieces of equipment. The vibration limits are based on the FTA *Transit Noise and Vibration Impact Assessment Manual*, which uses the industry-standard vibration criteria (V.C.) curves, and on the National Institutes of Health *Design Requirements Manual* Table 5.2.2 (2019). The V.C. curves are defined in Section 3.2.1 of the Noise and Vibration Technical Report. The National Institutes of Health manual recommends a limit of 48 VdB for mass spectrometers.

Table 3-1. List of Vibration-Sensitive Equipment at UW Medicine South Lake Union Campus

Location	Vibration-Sensitive Equipment	Description	Vibration Limit
Building A (South)	Mass spectrometers	No isolation, less sensitive than mass spectrometers with N.M.R. in Building D.	48 VdB/V.C.-D
Building B (North)	14 Tesla M.R.I.	Mounted on pneumatic isolators, most sensitive equipment on campus, criteria supplied by manufacturer	48 VdB/V.C.-D below 20 hertz, 54 VdB/V.C.-C above 20 hertz, 48 VdB/V.C.-D 10-20 hertz, V.C.-E 48 hertz, below 10 hertz
Building C	none	Administrative office only	Not applicable
Building D (Brotman)	3 Tesla M.R.I.	Mounted on an isolated floor on basement level, criteria provided by manufacturer	48 VdB/V.C.-D
Building D (Brotman)	Mass spectrometers (two with N.M.R.)	Located on slab-on-grade floor on basement level, researchers noted occasional vibration interference when working with **N.M.R.** units.	42 VdB/V.C.-E below 10 hertz, 48 VdB/V.C.-D above 10 hertz
Building D (Brotman)	Basement	Research Area	66 VdB/V.C.-A
Building E	Basement	Research Area	66 VdB/V.C.-A
Building F	Outpatient medical clinic	No research spaces	72 VdB

Two of the UW Medicine mass spectrometers in Building D also have nuclear magnetic resonance (N.M.R.) units, which are particularly susceptible to vibration. The National Institutes of Health manual does not have recommended limits for M.R.I. or N.M.R. units, but only notes that they should be constructed on slab-on-grade. Criteria from the manufacturers for the two M.R.I. units were made available to determine appropriate limits. Criteria for the N.M.R. units on the mass spectrometers should be based on existing vibration levels, which were not available at the time of this assessment. Based on other similar equipment, a limit of 42 VdB is adopted for frequencies below 10 hertz, and a limit of 48 VdB is adopted for 10 hertz and above. The limit of 42 VdB (V.C.-E) may be lower than existing vibration levels in Building D.

Equipment-specific criteria were provided for the 3T M.R.I. and the 14T M.R.I. units. Figure 3-1 shows the criteria for 14T Bruker M.R.I. units along with the V.C. curves also provided for reference. The M.R.I. model at the UW Medicine South Lake Union campus is the Bruker Nano-C. The criteria in Figure 3-1 account for the pneumatic isolators on which the equipment is mounted. The criteria are frequency dependent. At frequencies 5 hertz and below, the criteria are equivalent to V.C.-E. However, this assessment does not consider frequencies 5 hertz and below because train vibration is typically below the levels of existing vibration in this very low frequency range. At frequencies 20 hertz and above, the criteria are equivalent to V.C.-C. Between 5 hertz and 20 hertz, the criteria are the linear interpolation between V.C.-E and V.C.-C.

Figure 3-2 shows the criteria for the 3T Phillips M.R.I. unit provided by the manufacturer in the top plot and the criteria adopted for the analysis in the bottom plot. The criteria provided by the manufacturer do not account for the air spring mounts. The 3T M.R.I. is mounted on Maxon Industries air springs MAS-12000 that have an approximate resonant frequency of 1.4 hertz. The criteria are presented in terms of peak-to-peak acceleration, but this vibration analysis considers root-mean square (R.M.S.) velocity. Integrating the criteria shown in the top plot of Figure 3-2 to convert from acceleration to velocity and using a crest-factor of 4 to convert from peak-to-peak to R.M.S., the criteria range from roughly 45 VdB at 5 hertz to a minimum of 31 VdB at 12 hertz, and increases up to 57 VdB at 50 hertz. However, Sound Transit expects the air springs to reduce vibration at frequencies above 1.4 hertz, thereby effectively allowing for higher vibration levels. Sound Transit has adopted criteria of 48 VdB (V.C.-D) for all frequencies, assuming that the air springs provide at least 17 VdB of attenuation at 12 hertz. The criteria converted to vibration decibels is shown in the bottom plot of Figure 3-2.

Measurements of existing vibration levels on the UW Medicine South Lake Union campus should be conducted to confirm the criteria for both the 14T M.R.I. and the 3T M.R.I., as well as the mass spectrometers with N.M.R.

Figure 3-1. Vibration Criteria for Bruker 14T M.R.I.

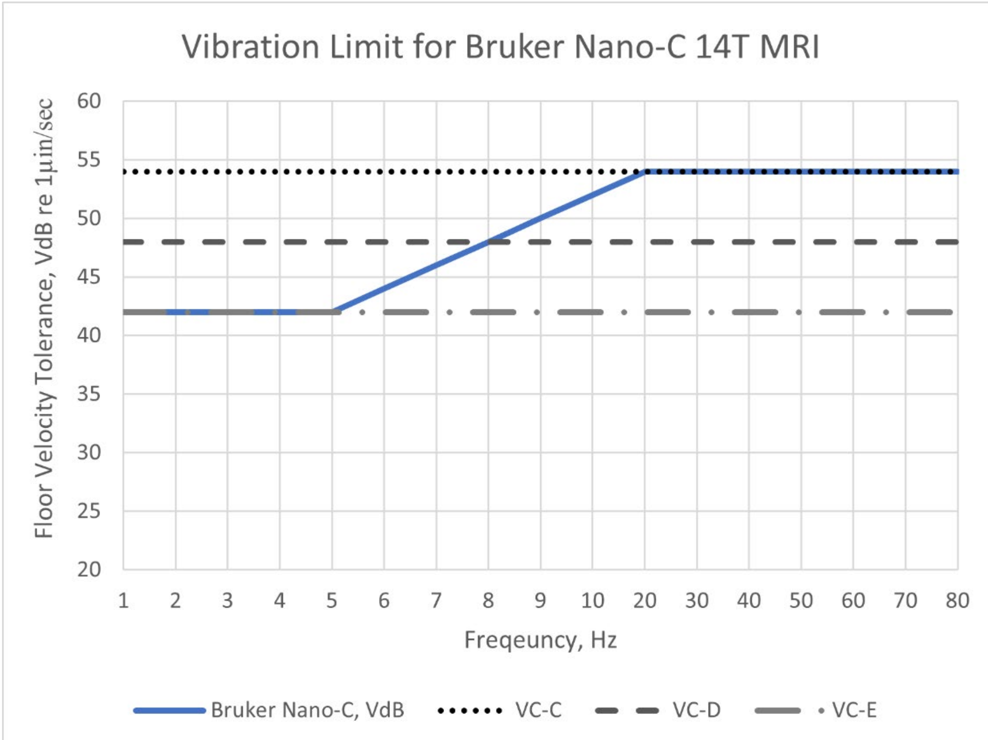
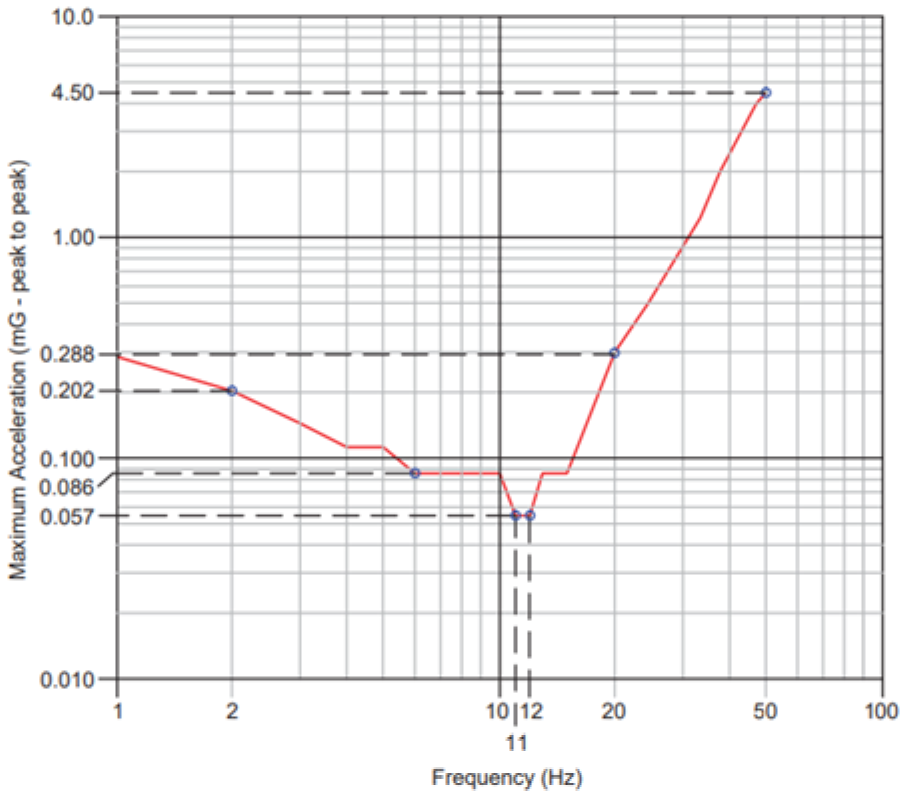
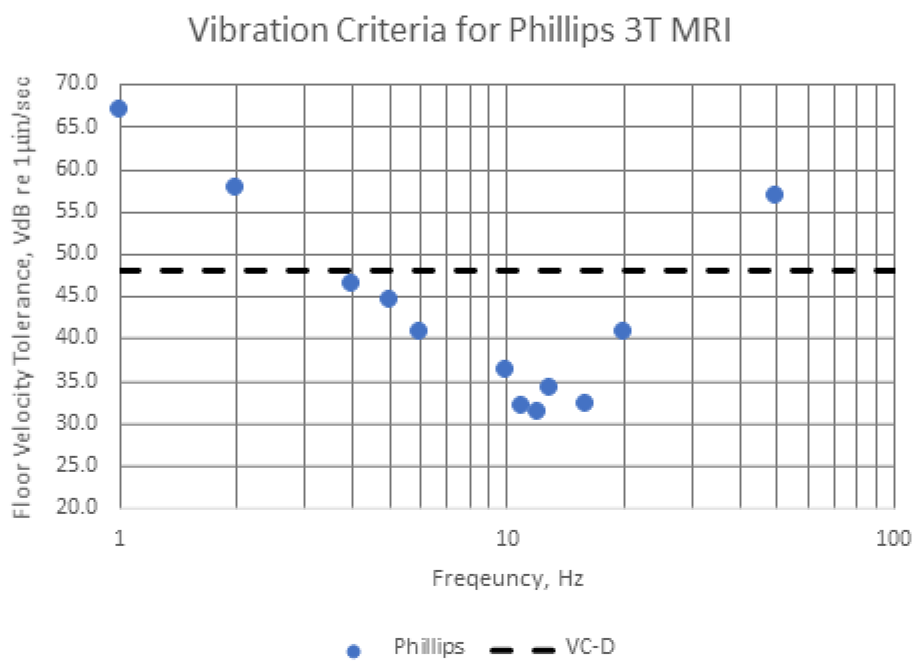


Figure 3-2. Vibration Criteria for Phillips 3T M.R.I.





3.2 Vibration Propagation Assumptions

Borehole vibration propagation tests are used to measure how efficiently vibration propagates through the soil and into buildings. Borehole vibration propagation tests were planned for several locations at the UW Medicine South Lake Union campus; however, the UW has indefinitely postponed right-of-entry to the project team due to the COVID-19 pandemic. Instead of using site-specific vibration propagation data, data from the following four closest measurement sites in the South Lake Union area were applied:

- V8 – 7th Avenue North and Westlake Avenue North
- V9 – Thomas Street between Westlake Avenue North and 9th Avenue North
- V11 – Allen Institute on 9th Avenue North at Mercer Street
- V12 – Cascade Public Media (KCTS 9 Television) on 4th Avenue North at Mercer Street

The result of the vibration propagation measurements is the L.S.T.M. The L.S.T.M. data from the above four measurement sites were averaged together for inclusion in the UW Medicine South Lake Union campus prediction model. Best-fit coefficients were calculated from the averaged L.S.T.M. data; these coefficients were used to estimate the L.S.T.M. at the distances between the track and the sensitive buildings. The best-fit coefficients are shown in Table 3-2. The L.S.T.M. at a particular distance can be calculated using the equation:

$$L.S.T.M. = A + B * \log(dist) + C * \log\,(dist)^2$$

Table 3-2. Line Source Transfer Mobility Coefficients for South Lake Union

Coefficient	6.3 Hz	8 Hz	10 Hz	12.5 Hz	16 Hz	20 Hz	25 Hz	31.5 Hz	40 Hz	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz
A	21.7	14.2	28.9	33.9	38.4	22.7	19.6	86.3	141.9	120.3	109.4	108.6	158.6	128.7	180.0	186.3
B	-9.6	-6.1	-14.3	-16.9	-16.7	-11.1	-10.0	-38.0	-61.9	-53.1	-49.9	-48.9	-72.6	-61.5	-84.5	-86.5
C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Hz = hertz

Vibration propagation measurements inside the buildings were used to characterize building coupling loss and any floor resonances in a "building adjustment" applied in the prediction model at the most highly vibration-sensitive (Category 1) land uses. Because no site-specific data are available, the vibration predictions for the UW Medicine South Lake Union campus are presented as a range of values assuming a building vibration adjustment of 0 to minus 5. Many of the large buildings along the alignment showed greater vibration attenuation than minus 5 decibels, so the building adjustment is likely a conservative estimate.

Because site-specific vibration propagation and building adjustment data could not be measured at the UW Medicine South Lake Union campus, a safety factor of +2 decibels is included in the prediction model. There is also a 3-decibel safety factor incorporated into the force density level used in the prediction model.

3.3 Predicted Vibration Levels

The predicted levels for Preferred Alternative DT-1 are presented in Table 3-3, and the predicted levels for Alternative DT-2 are presented in Table 3-4. The range in predicted vibration levels represents a range in building attenuation from 0 to -5 decibels. The results show there is no predicted impact for Preferred Alternative DT-1, where the closest buildings on the campus are over 400 feet away.

For Alternative DT-2, the predicted levels for the most sensitive equipment in Buildings D and B closest to the project alignment exceeds the criteria by 4 decibels to 11 decibels. Figures 3-3 and 3-4 show the spectra of the predicted levels and the relevant criteria. The predicted levels exceed the impact threshold in the 40-hertz to 80-hertz range for the M.R.I. and N.M.R. The following mitigation measures are proposed for different levels of exceedance:

- If the measured building adjustment results in predicted levels that exceed the limit by more than 5 decibels at 40 hertz and above, a continuous mat floating slab should be installed near Buildings B and D. The resonant frequency and insertion loss of the continuous mat floating slab should be designed based on site-specific measured data. If no measured data are available, the continuous mat floating slab should be designed to achieve at least 12 decibels of reduction at 40 hertz and above, which assumes a building adjustment of 0 decibels.

- If the measured building adjustment results in predicted levels that exceed the limit by less than 5 decibels at 40 hertz and above, high-resilience fasteners should be installed near Buildings B and D. Based on a prior study, high-resilience fasteners are expected to provide 5 decibels of reduction at 40 hertz and up to 8 decibels of reduction at 80 hertz. A figure of the expected vibration reduction from the high-resilience fasteners is provided in Section 7.4.

In a future design phase, vibration propagation data into the buildings and existing vibration levels should be measured to finalize the proposed mitigation measures.

Table 3-3. Predicted Vibration and Groundborne Noise Levels at UW Medicine South Lake Union Campus with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Basement research area (Building D)	735	35	23-28	66	>0	Noise Abatement Criteria 45	Does not exceed
Basement research area (Building E)	449	35	25-30	66	>0	Noise Abatement Criteria 45	Does not exceed
3T M.R.I. (Building D)/ **N.M.R.** mass spectrometer	735	35	23-28	48	Not applicable	Not applicable	Does not exceed
14T M.R.I. (Building B)	695	35	24-29	48	Not applicable	Not applicable	Does not exceed
mass spectrometer (Building S)	483	35	24-29	48	Not applicable	Not applicable	Does not exceed

[a.] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 3-4. Predicted Vibration and Groundborne Noise Levels at UW Medicine South Lake Union Campus with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Basement research area (Building D)	87	45	54-59	66	43	Noise Abatement Criteria 45	Does not exceed
Basement research area (Building E)	256	45	34-39	66	10	Noise Abatement Criteria 45	Does not exceed
3T M.R.I. and N.M.R. mass spectrometer (Building D)	87	45	54-59	48	Not applicable	Not applicable	6-11
14T M.R.I. (Building B)	94	45	52-57	48	Not applicable	Not applicable	4-9
Mass spectrometer (Building S)	254	45	34-39	48	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 3-3. Predicted Vibration Level for 6th Avenue/Mercer Street Alternative (DT-2) at M.R.I. at UW Medicine South Lake Union Campus

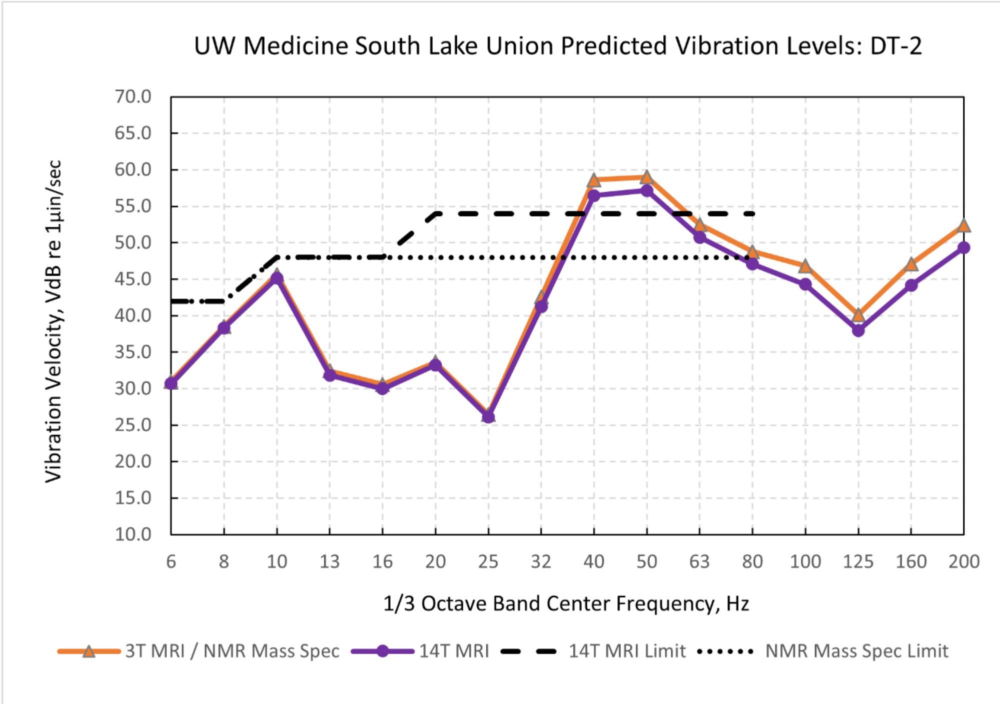
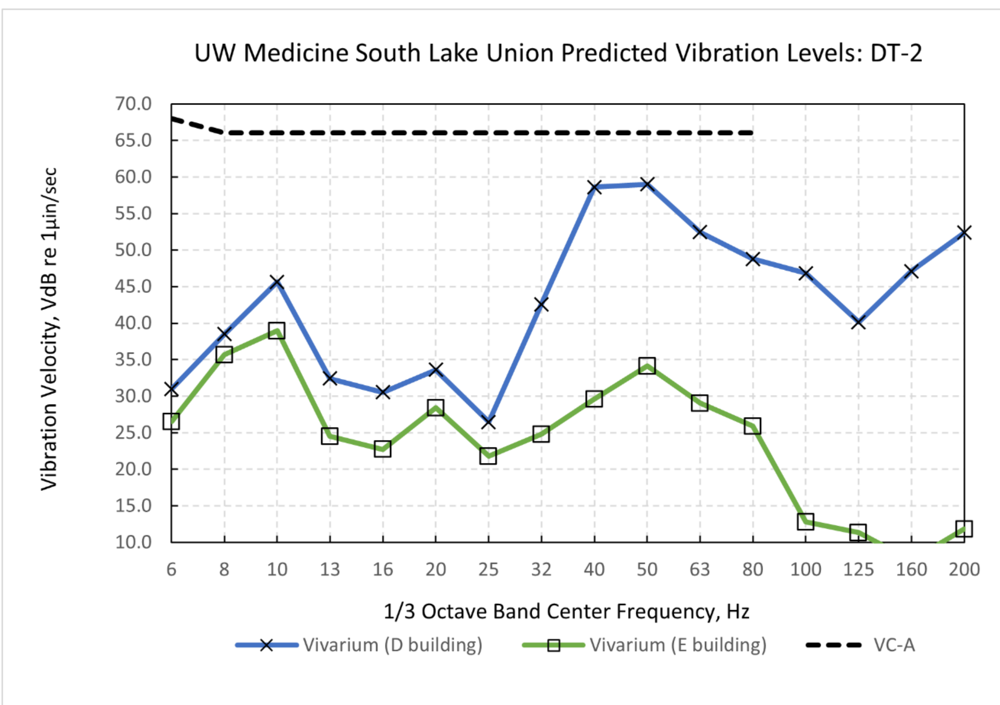


Figure 3-4. Predicted Vibration Level for 6th Avenue/Mercer Street Alternative (DT-2) at Basement Research Areas at UW Medicine South Lake Union Campus



4 ALLEN INSTITUTE FOR BRAIN SCIENCE

4.1 Description of Sensitive Space

The Allen Institute for Brain Science is a non-profit organization that focuses on bioscience research. Their research facility is at 615 Westlake Avenue, at the intersection of Mercer Street and Westlake Avenue in the Downtown Segment of the Ballard Link Extension. The building was purpose-built for the institute and designed to accommodate sensitive research equipment and laboratories.

The vibration-sensitive spaces at the Allen Institute for Brain Science are on floors one through five, with conference and meeting spaces on the sixth floor. There are four levels of parking below-grade level. Each floor with research space has three wings: a West Wing, North Wing, and South Wing.

Table 4-1 lists the vibration-sensitive research equipment within the Allen Institute by floor and wing based on information gathered during a site visit on August 21, 2019. Most of the vibration-sensitive equipment or activities are located or performed on vibration-isolated tables or platforms, except in the West Wing. The most vibration-sensitive space in the facility is the Electron Microscope Suite. The microscopes in this suite are installed on custom-built isolation mounts, and the floor slab for that space is thicker compared to the rest of the building to minimize ambient vibrations.

Table 4-1 presents the vibration limit applied to each of the sensitive spaces. The vibration limits are based on the FTA *Transit Noise and Vibration Impact Assessment Manual*, which uses the industry-standard vibration criteria (V.C.) curves and on the National Institutes of Health Design Requirement Manual Table 5.2.2. The National Institutes of Health recommends a limit of 60 VdB for optical equipment on isolation tables, which is applied to the upper floor laboratories where all sensitive equipment observed during a site visit was placed on isolation tables. A more stringent limit of 48 VdB was applied to the Electron Microscope Suite on the ground floor. The least stringent limit of 72 VdB was applied to the research space in the West Wing upper floors, based on the National Institutes of Health guidance. The National Institutes of Health guidance for ductwork and fan control provides a recommended noise limit of noise criteria of NC-45 for the research area on the West Wing ground floor. This limit is adopted as the groundborne noise criteria. The NC, or noise criteria, curves are defined by Beranek in *Revised Criteria for Noise Control in Buildings* (1957).

Table 4-1. List of Vibration-Sensitive Equipment or Spaces in Allen Institute for Brain Science

Location	Vibration-Sensitive Space	Description	Vibration Limit
West Wing, first floor	Laboratory and holding rooms	Research space without isolated tables	66 VdB/V.C.-A
West Wing, second floor	Laboratory	Research space without isolated tables	72 VdB
South Wing, first floor	Electron Microscope Suite	Most sensitive equipment in building, on custom-built isolation mounts, 6 electron microscopes	48 VdB/V.C.-D
South Wing, second floor	Electron microscopy	Scanning Electron Microscope (2nanometer resolution), Ultramicrotome	60 VdB/V.C.-B

Location	Vibration-Sensitive Space	Description	Vibration Limit
North Wing, second floor	Electrophysiology	Patch clamp rig (>1 micron displacement allowable)	60 VdB/V.C.-B
South Wing, third floor	Optical/laser-based imaging	Three photon system on two isolation tables mounted together, neuropiezo probe	60 VdB/V.C.-B
South Wing, fourth floor	Imaging lab	Two photon excitation microscopes, custom system on largest air tables in building	60 VdB/V.C.-B
North Wing, fourth floor	Scanning lab	Many microscopes all located on isolation tables, acquisitions can last several hours	60 VdB/V.C.-B
South Wing, fifth floor	Microscopy and Assay Development	Ten super resolution microscopes (120 nm resolution), fluorescence correlation spectroscopy, Hamilton robot	60 VdB/V.C.-B

4.2 Existing Noise and Vibration Levels

Existing vibration levels were measured over a 1-hour period throughout the Allen Institute for Brain Science. A 1-hour noise measurement was completed inside the ground floor West Wing research area in the hallway between rooms 158 and 159. The 1-hour equivalent noise level was 48 dBA. Figure 4-1 shows the 1-second noise levels. The high noise levels at the beginning and end of the measurement were excluded from the 1-hour noise level.

The 1-hour vibration measurements are presented in Table 4-2. Figures 4-2 through 4-9 show plots of the 1-second vibration levels. Figures 4-10 and 4-11 show spectra of the measured vibration levels. The measured vibration levels show the following:

- With the exception of the parking structure, vibration levels are lowest in the Electron Microscope Suite. This is expected based on descriptions of a thicker floor slab in this space to minimize background vibration. The ambient levels on the Electron Microscope Suite ground are lower than the proposed vibration limit of V.C.-D (48 VdB).

- The right plot in Figure 4-11 shows the spectra of the vibration measured on and off the isolation tables in Suites 240 and 440. Vibration levels are much lower on the isolation tables, as expected. The data also show that the recommended limit of V.C.-B (60 VdB) is appropriate for the space, because existing ground vibration is equal to the V.C.-B limit at 12.5 hertz.

- The left plot in Figure 4-11 shows the spectra of the vibration measured on the ground for floors 2 to 5 in the South Wing and in the parking structure. The vibration levels in the South Wing are fairly consistent across all floors and are lower than the proposed vibration limit of V.C.-B.

Table 4-2. Ambient Vibration Levels at Allen Institute for Brain Science

Monitoring Location	Vibration Level (1 hr Leq)
Parking structure bottom level	43 VdB
Electron Microscope Suite, on ground	47 VdB
Electron Microscope Suite, on springs	54 VdB
220 Suite, South Wing	51 VdB
320 Suite, South Wing	58 VdB
420 Suite, South Wing	58 VdB
520 Suite, South Wing	57 VdB
West Wing, first floor	54 VdB
West Wing, second floor	59 VdB
270 Suite, West Wing	54 VdB
240 Suite, North Wing on ground	63 VdB
240 Suite, North Wing on isolation table	55 VdB
440 Suite, North Wing on ground	64 VdB
440 Suite, North Wing on isolation table	58 VdB

Figure 4-1. Measured 1-second Noise Levels in Allen Institute for Brain Science West Wing First Floor

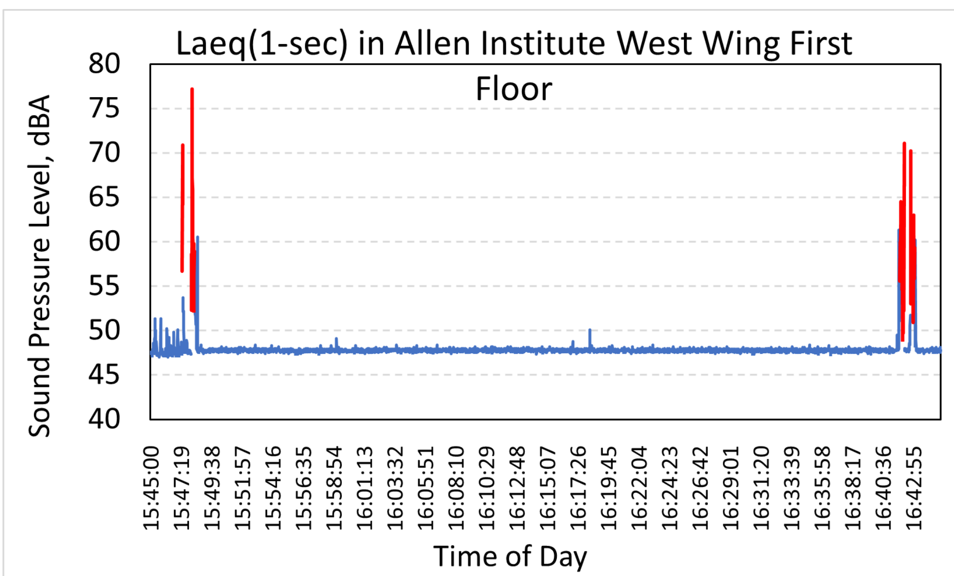


Figure 4-2. Measured 1-second Vibration Levels in Allen Institute for Brain Science Parking Garage

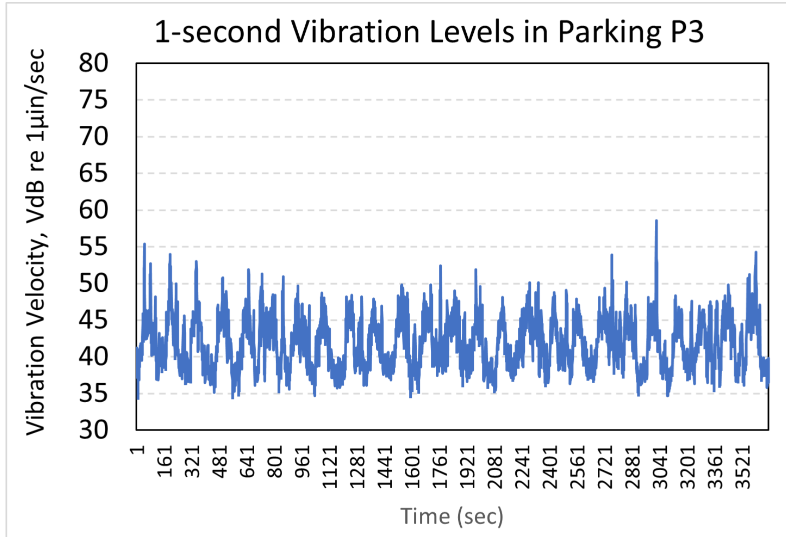
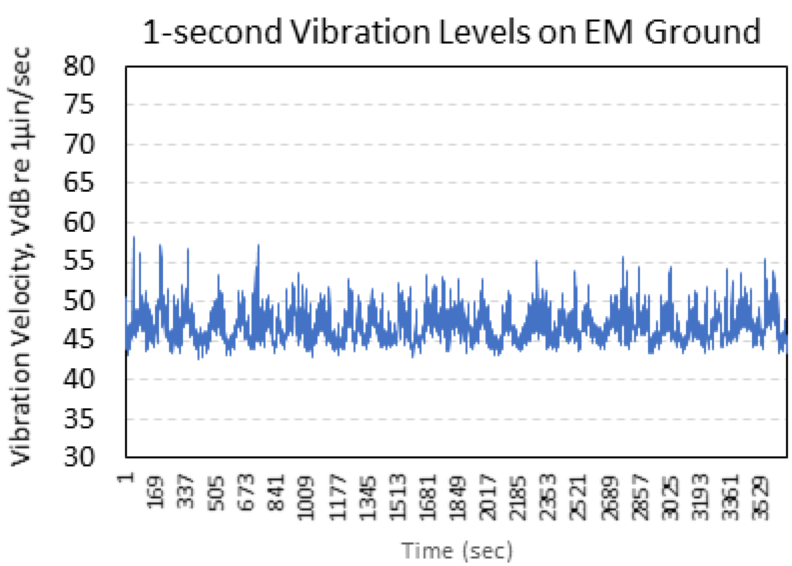


Figure 4-3. Measured 1-second Vibration Levels in Allen Institute for Brain Science Electron Microscope Suite



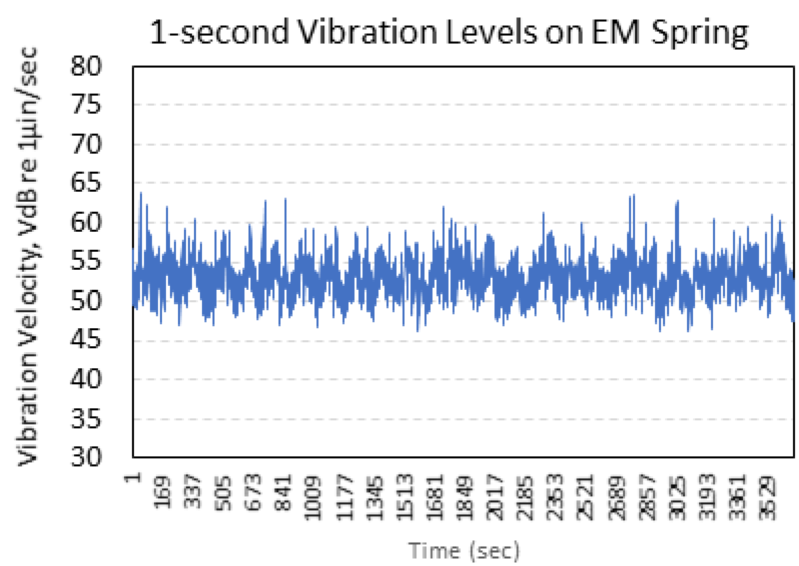


Figure 4-4. Measured 1-second Vibration Levels in Allen Institute for Brain Science Suites 220 and 320

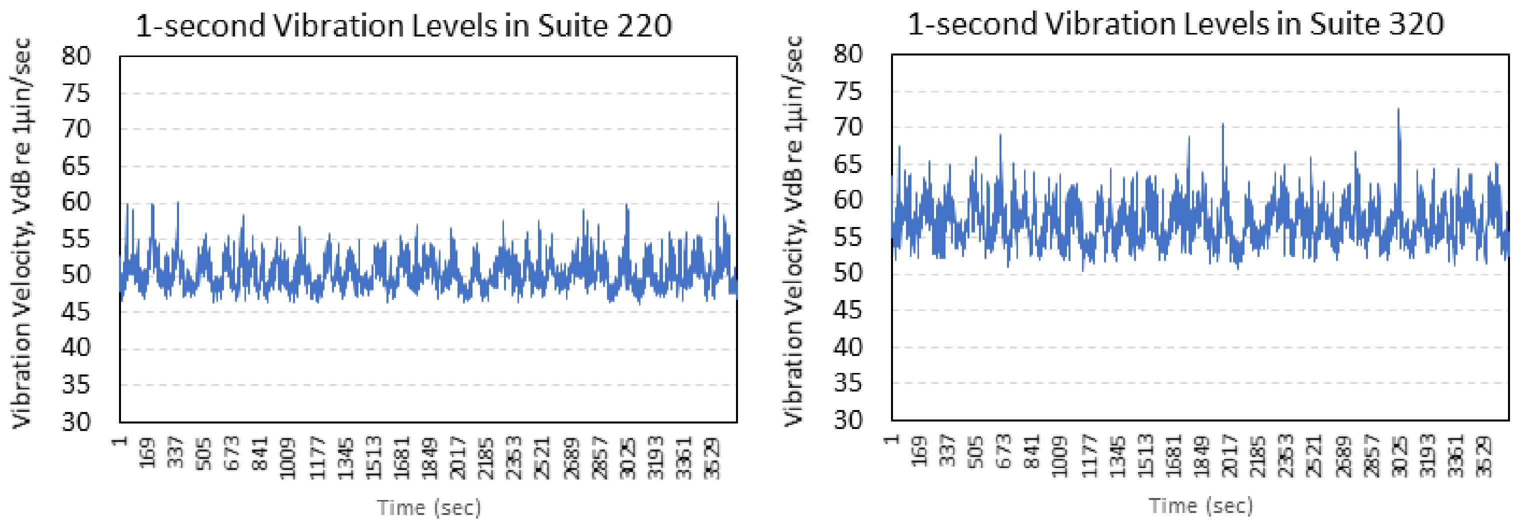


Figure 4-5. Measured 1-second Vibration Levels in Allen Institute for Brain Science Suites 420 and 520

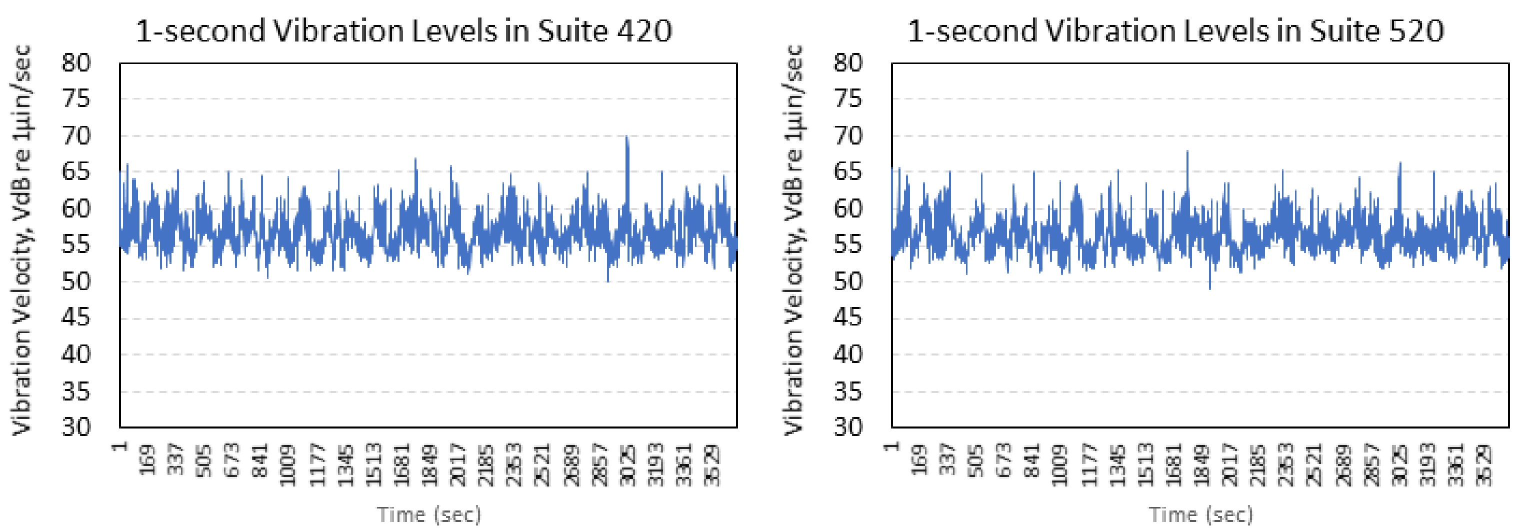
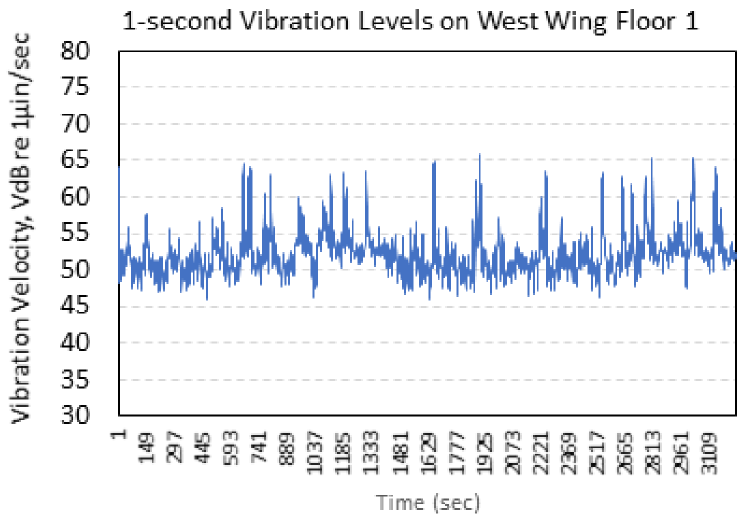


Figure 4-6. Measured 1-second Vibration Levels in Allen Institute for Brain Science West Wing



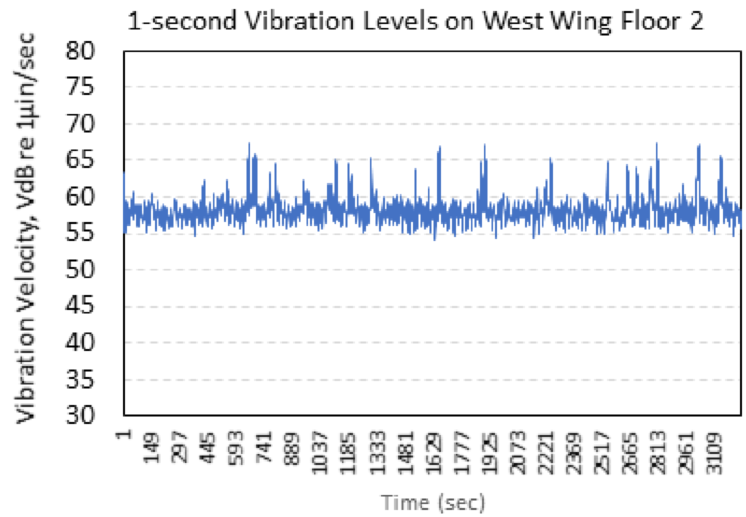


Figure 4-7. Measured 1-second Vibration Levels in Allen Institute for Brain Science Suite 270

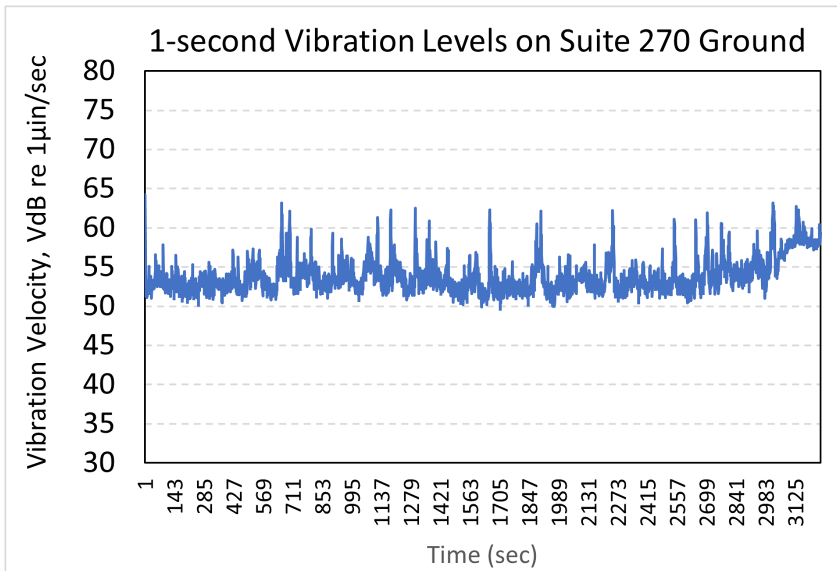


Figure 4-8. Measured 1-second Vibration Levels in Allen Institute for Brain Science Suite 240 On and Off Isolation Table

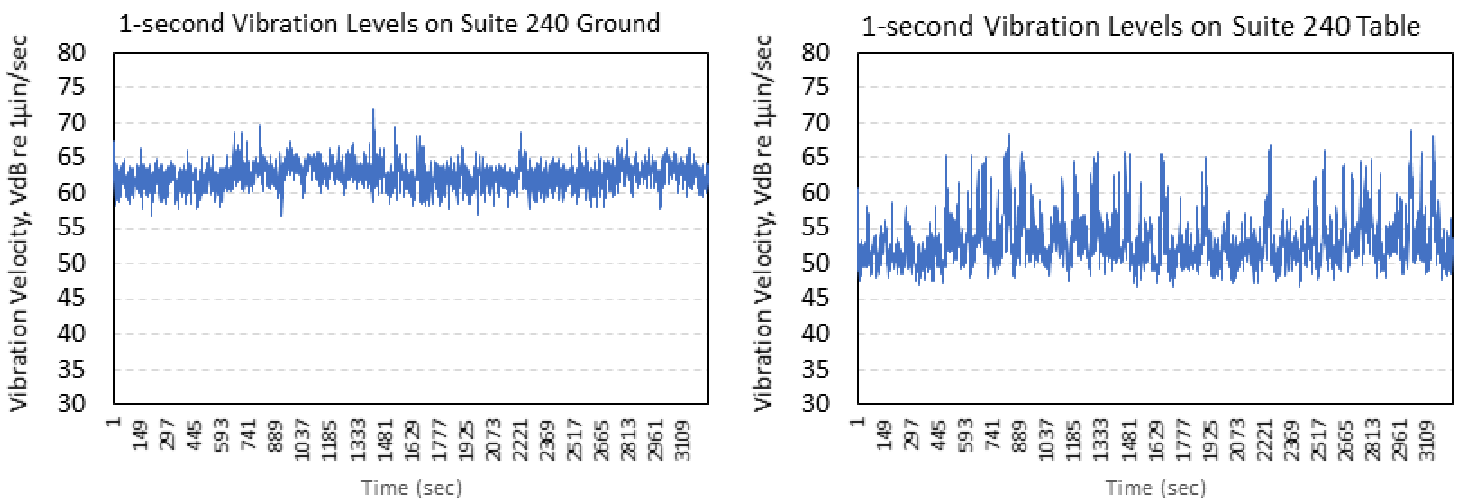


Figure 4-9. Measured 1-second Vibration Levels in Allen Institute for Brain Science Suite 440 On and Off Isolation Table

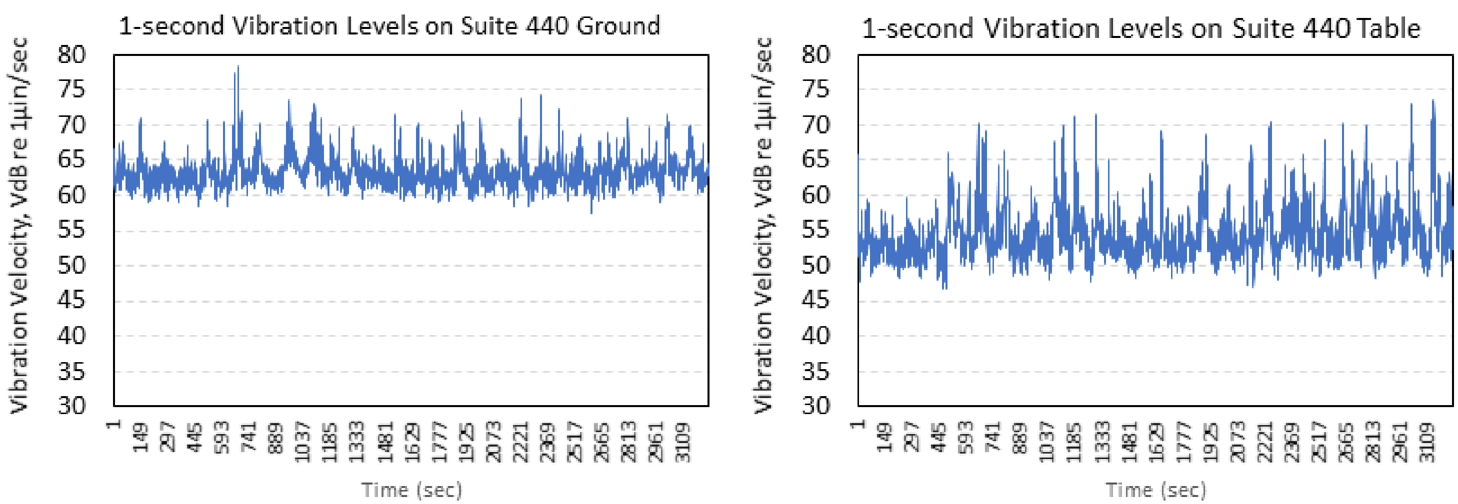
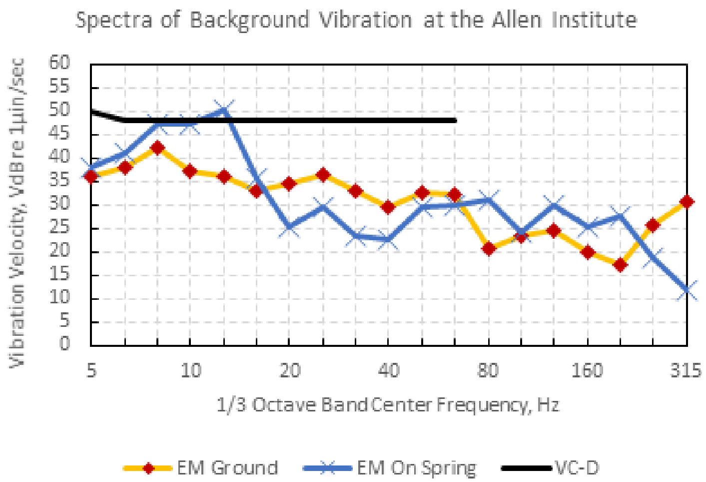


Figure 4-10. Spectra of Ambient Vibration Levels at Allen Institute for Brain Science Electron Microscope Suite and West Wing



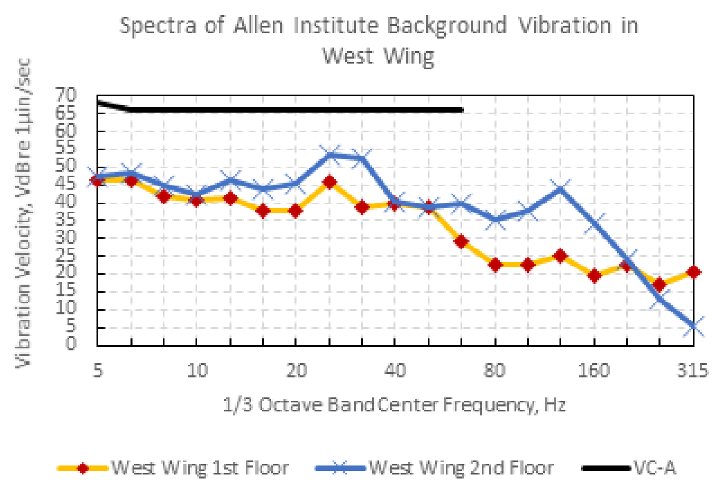
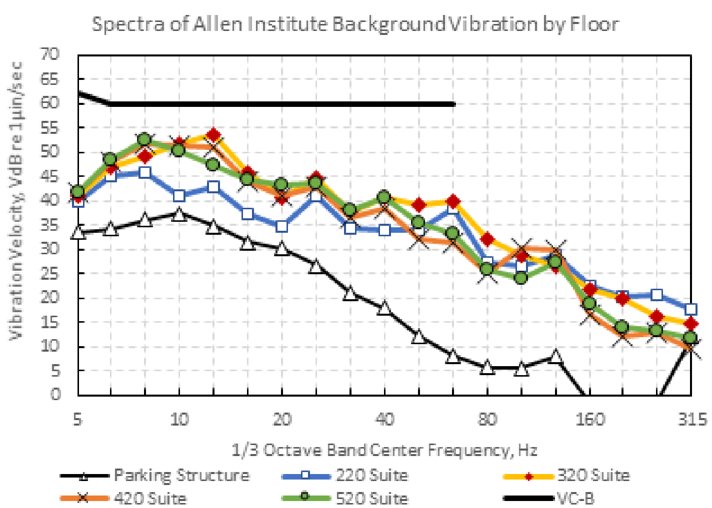
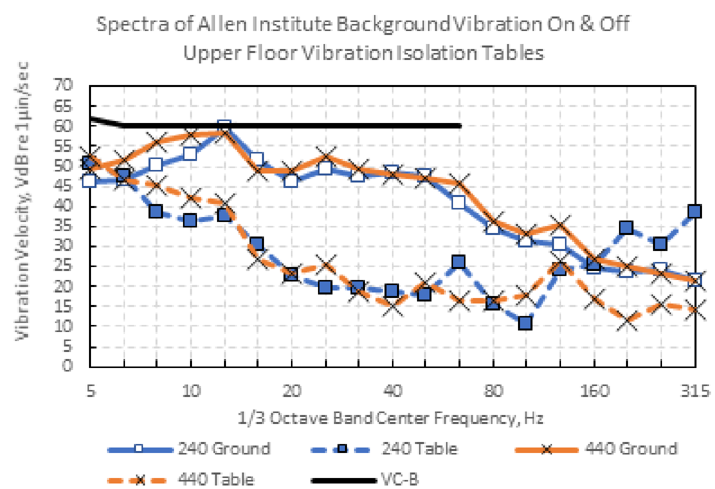


Figure 4-11. Spectra of Ambient Vibration Levels at Allen Institute for Brain Science Electron Microscope Upper Floor Suites





4.3 Vibration Propagation Measurement Description

A borehole vibration propagation test was completed at the Allen Institute for Brain Science to determine how efficiently vibration propagates from the approximate depth of the tunnel into the sensitive spaces. The borehole was located in the northbound lane of 9th Avenue North, along the west façade of the building. Data were collected from five borehole depths: 90 feet, 95 feet, 100 feet, 105 feet, and 110 feet.

In total, propagation data were measured at 7 outdoor locations and 14 indoor locations. Eleven channels of data were collected for the first three depths, and another ten channels of data were collected for the last two depths. The outdoor measurement locations were used to quantify the decrease in vibration levels as a function of distance from the impact force. The outdoor vibration measurements were also used as a reference to examine how levels change as the vibration travels from the soil into the building structure.

The indoor measurement locations are the same locations where ambient vibration data were collected as listed in Table 4-1. The measurement positions were selected to get representative data in sensitive locations throughout the building.

Figure 4-12 shows the ground level floor plan of the Allen Institute for Brain Science, and Figure 4-13 shows the second level floor plan with the approximate sensor locations labeled. Approximate location of the outdoor sensors and borehole position are also indicated in Figure 4-12. Photographs of the borehole measurement site are provided in Attachment N.3B, Vibration Measurement Site Photographs.

Figure 4-12. Allen Institute for Brain Science Ground Floor Plan

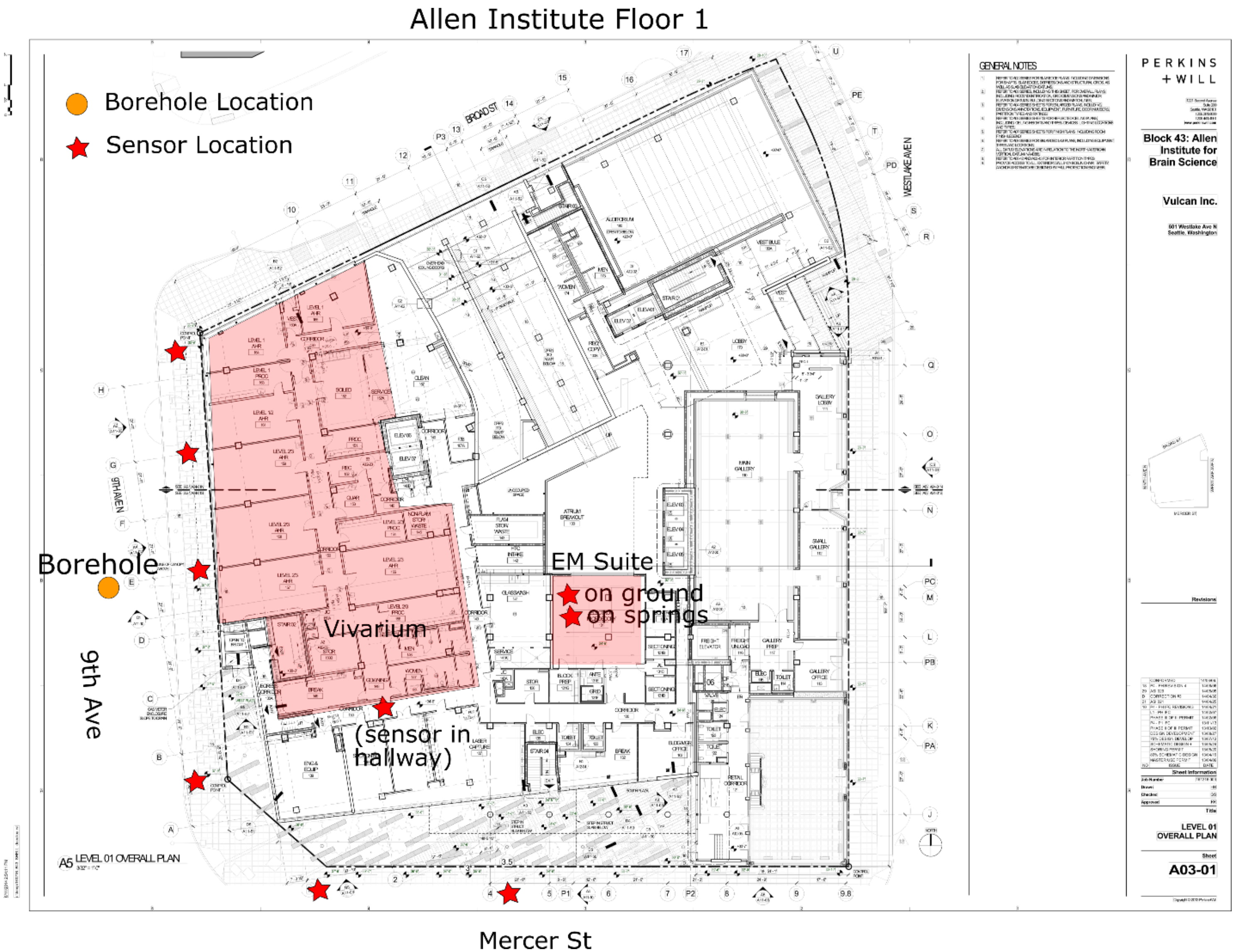
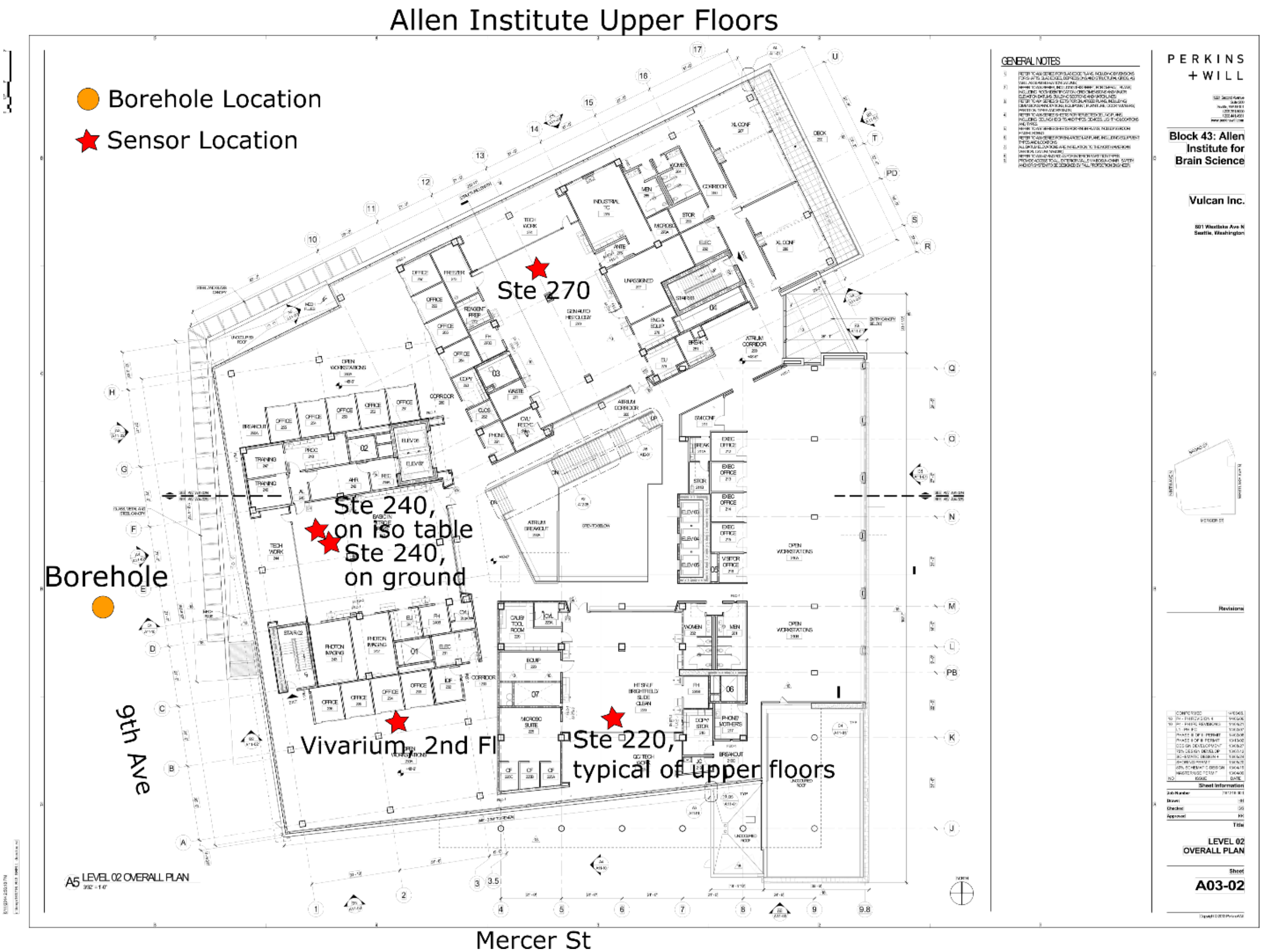


Figure 4-13. Allen Institute for Brain Science Second Floor Plan



4.4 Vibration Propagation Measurement Results and Predicted Levels

The borehole vibration propagation tests measure the point source transfer mobility (P.S.T.M.), a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the P.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The P.S.T.M. and coherence results for the indoor measurement positions and the closest outdoor measurement position are shown in Figures 4-14 through 4-21. Data at half of the measurement positions were collected at three borehole depths (90 feet, 95 feet, and 100 feet), and data at the other half of the measurement positions were collected at two borehole depths (105 feet and 110 feet). The data for each sensor were plotted with the same color and marker, with dashed lines indicating the data at different depths for a particular sensor. Observations from the P.S.T.M. and coherence results are as follows:

- There is high coherence in the parking garage, likely due to very low ambient vibration levels there. The P.S.T.M. levels in the parking garage are very low compared to the outdoor P.S.T.M. levels, which indicates the significant attenuation in vibration levels as vibration travels from the soil into the building.
- All aboveground indoor spaces had much lower coherence levels compared to the parking garage. This might be due to a combination of higher ambient vibration levels and lower vibration levels from the propagation test at higher floors in the building.
- The data collected at the Electron Microscope Suite isolation springs and the Suite 440 isolation table show the isolation systems are effectively attenuating vibration. The low coherence indicates it is likely that the results are underestimating the effect of the isolation tables. Data from the Suite 220 isolation table are anomalously high and therefore are not included in the prediction model.
- The second floor West Wing is the only indoor location that shows amplification, with very high P.S.T.M. levels in the 125-hertz 1/3-octave band. This 1/3-octave band corresponds with high levels of ambient vibration.

Figure 4-14. P.S.T.M. and Coherence in Allen Institute for Brain Science Parking Garage

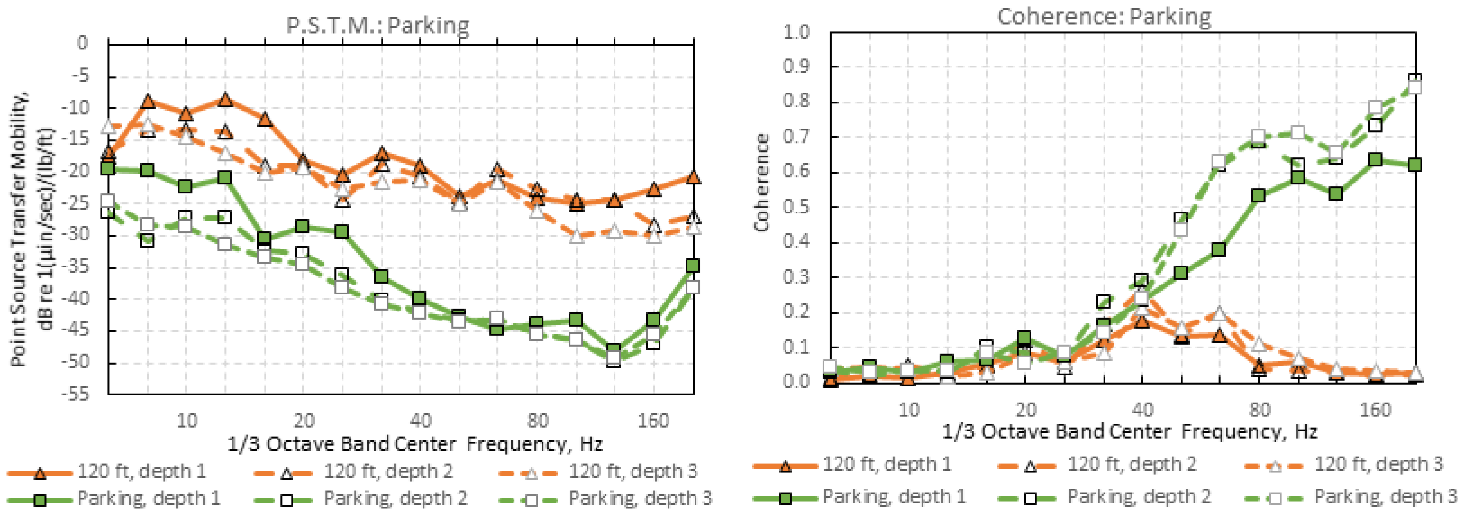


Figure 4-15. P.S.T.M. and Coherence in Allen Institute for Brain Science, Electron Microscope Suite

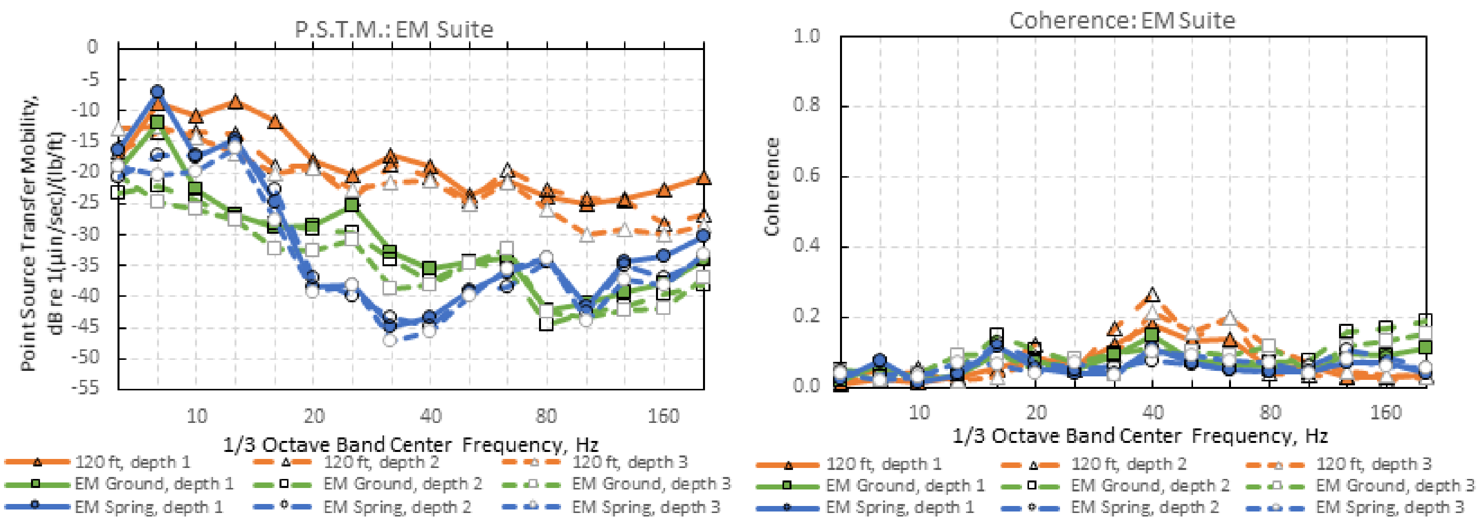


Figure 4-16. P.S.T.M. and Coherence in Allen Institute for Brain Science Suites 220 and 320

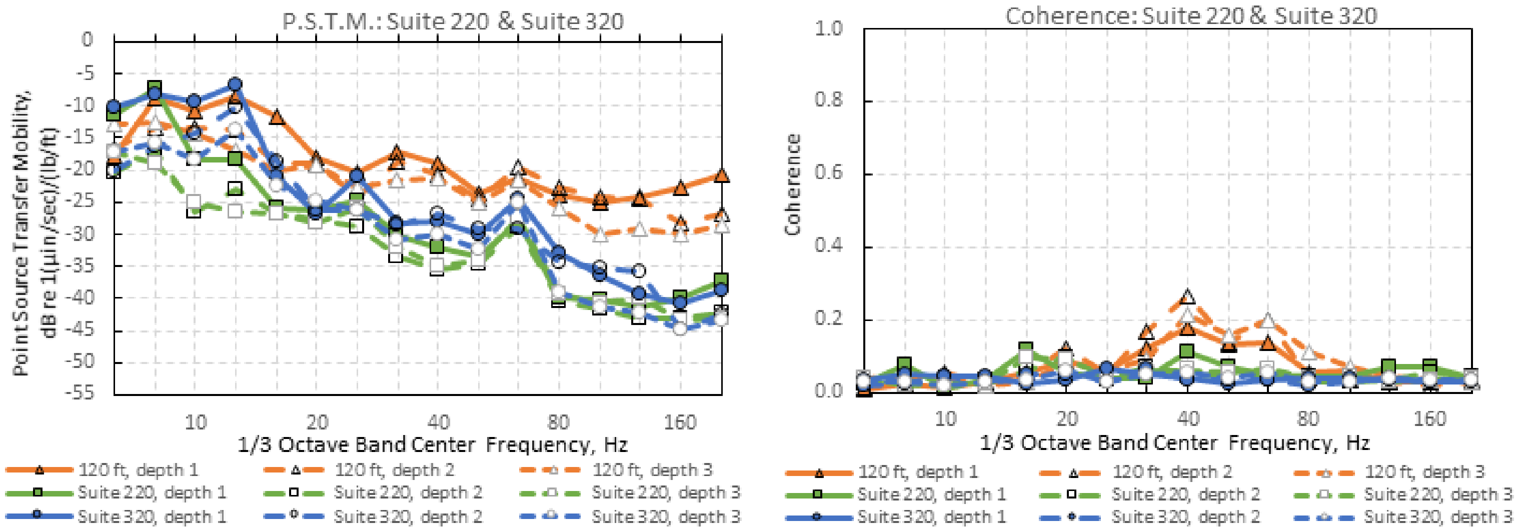


Figure 4-17. P.S.T.M. and Coherence in Allen Institute, for Brain Science Suites 420 and 520

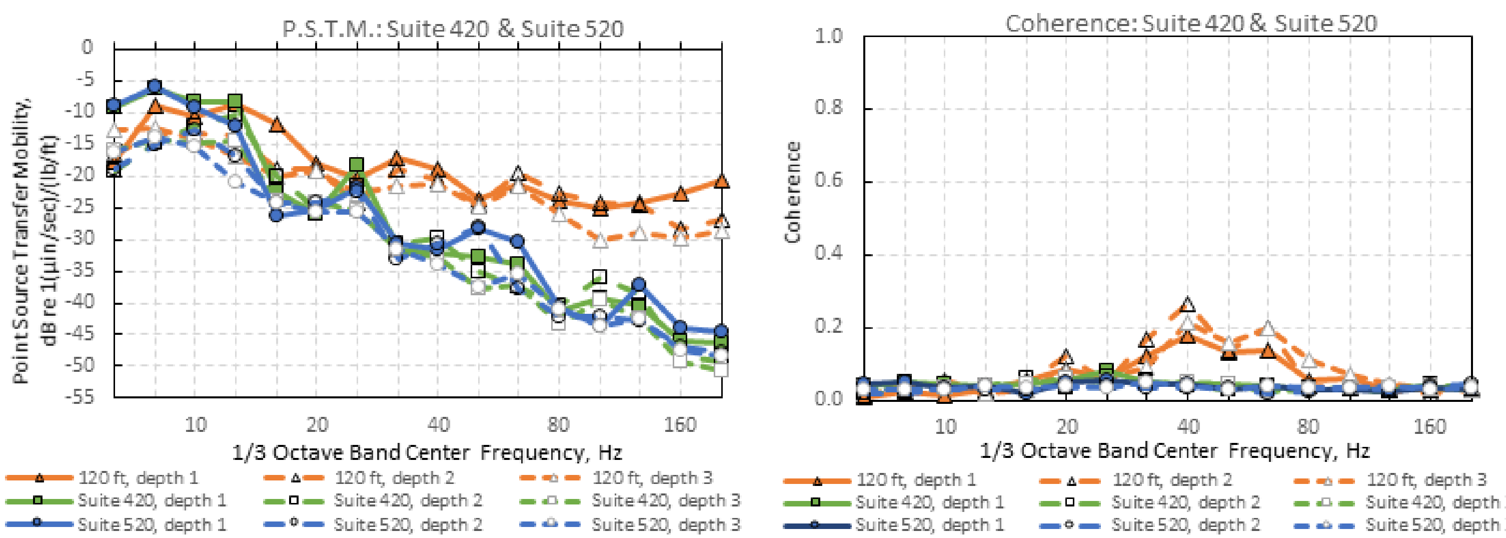


Figure 4-18. P.S.T.M. and Coherence in Allen Institute for Brain Science Electron Microscope Suite and Suite 270

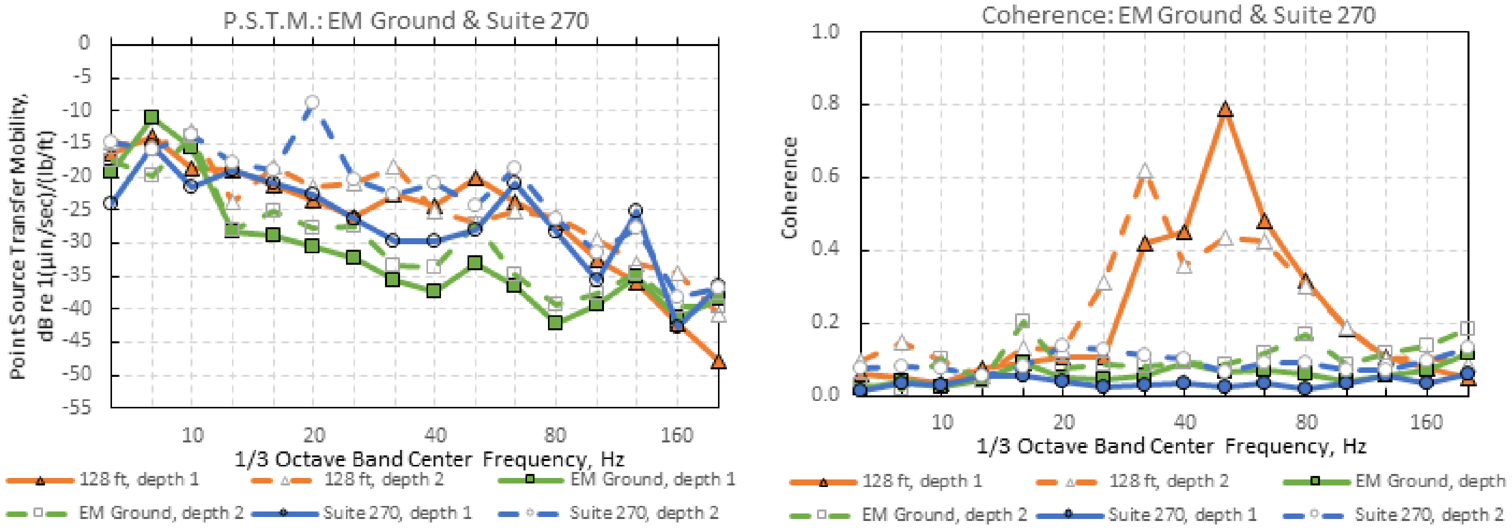


Figure 4-19. P.S.T.M. and Coherence in Allen Institute for Brain Science West Wing Floors 1 and 2

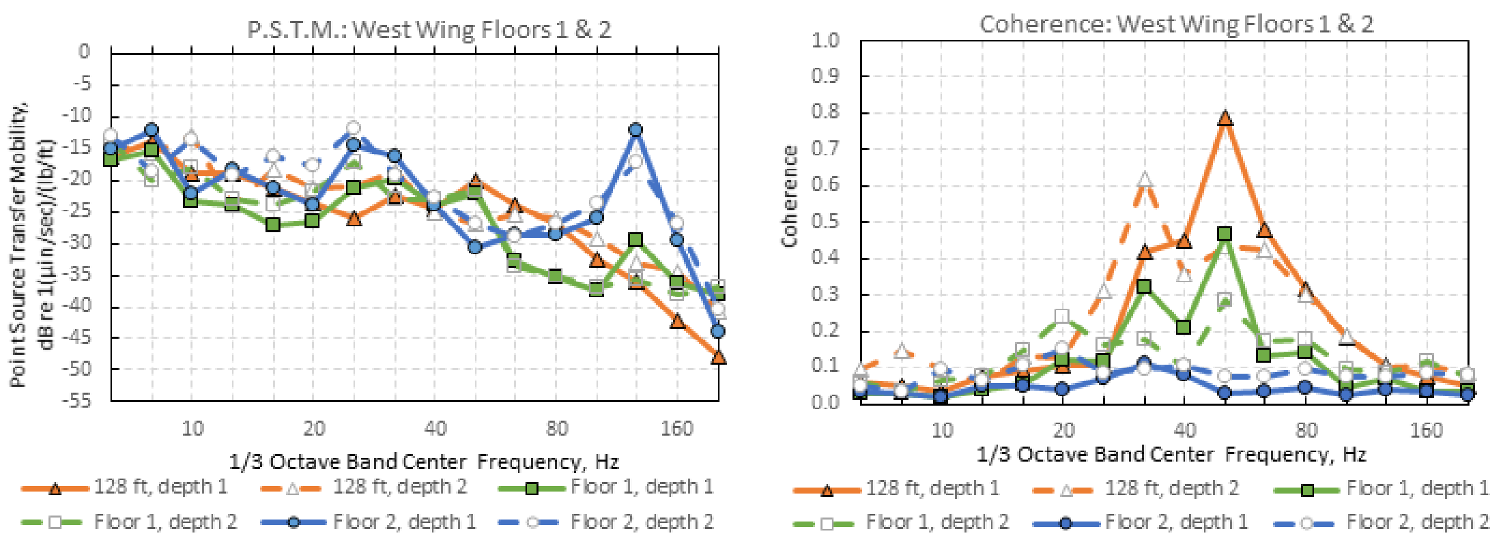
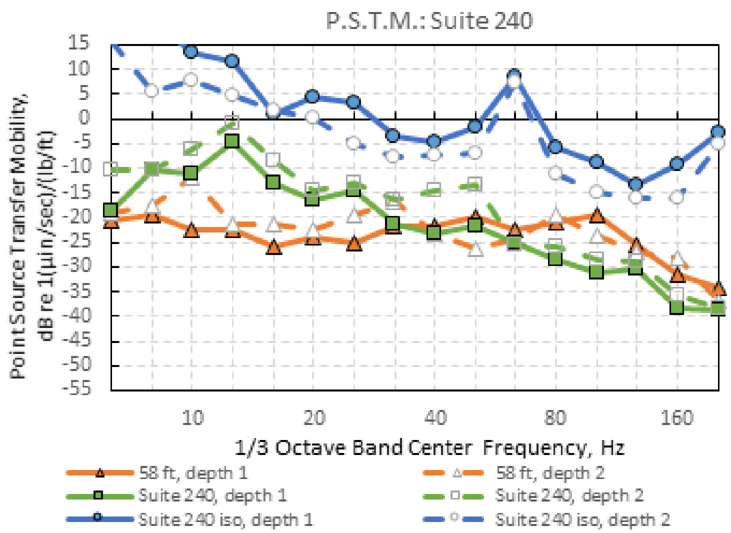


Figure 4-20. P.S.T.M. and Coherence in Allen Institute for Brain Science Suite 240 On and Off Isolation Table



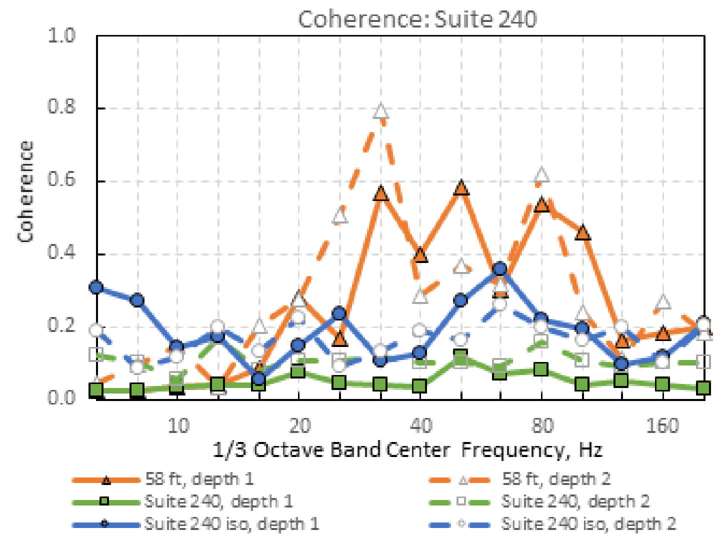
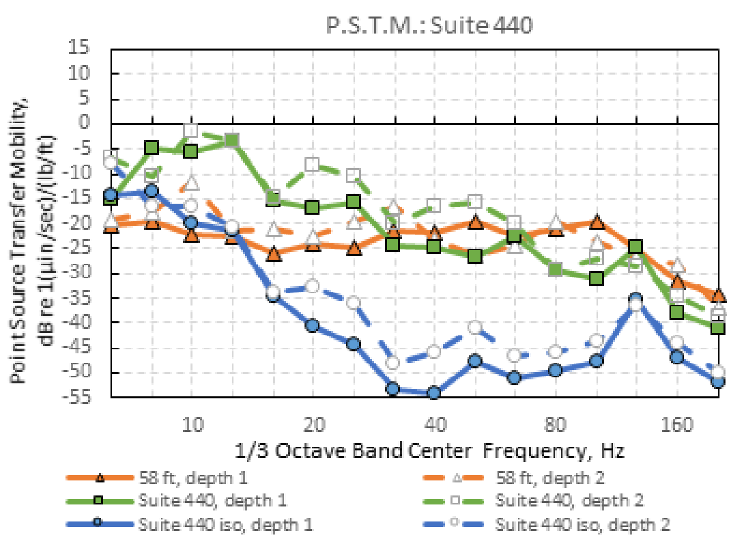
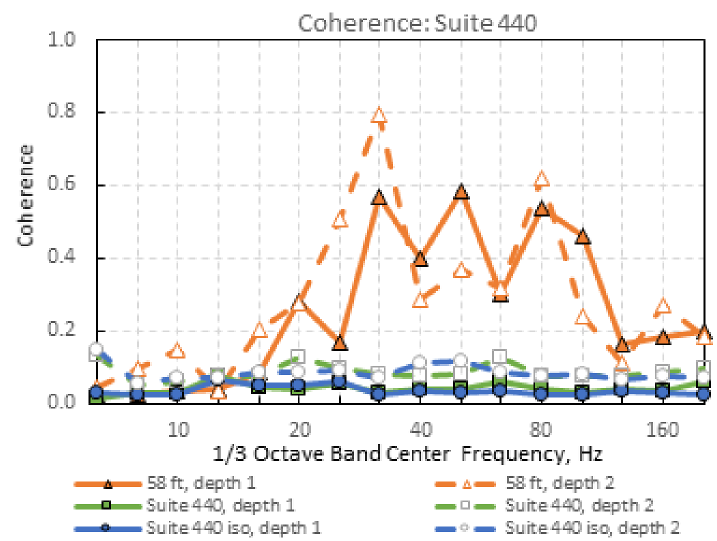


Figure 4-21. P.S.T.M. and Coherence in Allen Institute for Brain Science Suite 440 On and Off Isolation Table





A building adjustment was applied in the prediction model to account for the building coupling loss and any floor resonances. This adjustment was calculated by taking the difference between the outdoor P.S.T.M. at an equivalent setback distance and the indoor P.S.T.M. The building adjustment for the Allen Institute for Brain Science sites is computed from an average of the results collected at different depths. The measured building adjustments are shown in Figures 4-22 through 4-24. The building adjustment for upper floors was based on data collected in the South Wing (Suites 220 to 520) because of better coherence compared to the results measured in Suites 240, 270, or 440. Following are observations for the resulting building adjustment:

- The building adjustment is assumed to be 0 decibel at frequencies below 25 hertz for all spaces. The coherence is below 0.2 for all spaces in this frequency range, including the parking garage. This indicates poor signal-to-noise and low confidence in the results; therefore, to be conservative, the assessments assume there is no coupling loss in this frequency range.

- The parking garage shows attenuation of 10 decibels or greater at all frequencies above 20 hertz. This indicates that the substantial mass of the building is successfully attenuating vibration as vibration travels from the soil into the building. There was relatively good coherence in the parking garage, likely due to very low background levels, which provide good confidence in the results.

- The average of the attenuation for the upper floor suites in the South Wing (220 to 520) shows attenuation at 16 hertz and above. There is not as much attenuation measured in these upper floor suites as compared to the parking garage. This might be due to a combination of higher ambient vibration levels (poor signal-to-noise ratio) and vibration levels increasing on suspended floors.

- The West Wing on the first floor shows little to no attenuation, and the West Wing on the second floor show some amplification at 25 hertz and higher frequencies. Based on the results in the parking garage and the South Wing suites, it may be the case that there is no amplification. The high L.S.T.M. results could be due to high ambient vibration levels and poor signal-to-noise ratio. However, the measured building adjustment results are included in the prediction model as a conservative assumption.

- Figure 4-23 shows the data for on and off the isolation table for Suite 440. The data show that the isolation table is significantly reducing vibration levels above 16 hertz. The table may also be reducing vibration at lower frequencies, but there was not enough signal-to-noise ratio to measure a reduction at those frequencies. The vibration limit for the upper floor suites is for the ground vibration level, assuming isolation tables will be in place for more sensitive equipment. Therefore, the building adjustment to the top of the isolation table is not applied in the predictions.

- Figure 4-24 shows the data in the Electron Microscope Suite off the springs and on the ground. The data show the springs provide some reduction in the 20-hertz to 63-hertz range. The springs are also likely very effective at lower and higher frequencies, but there was not enough signal-to-noise ratio to measure a reduction at those frequencies.

Figure 4-22. Measured Building Adjustment at Allen Institute for Brain Science West Wing and Upper Floor Suites

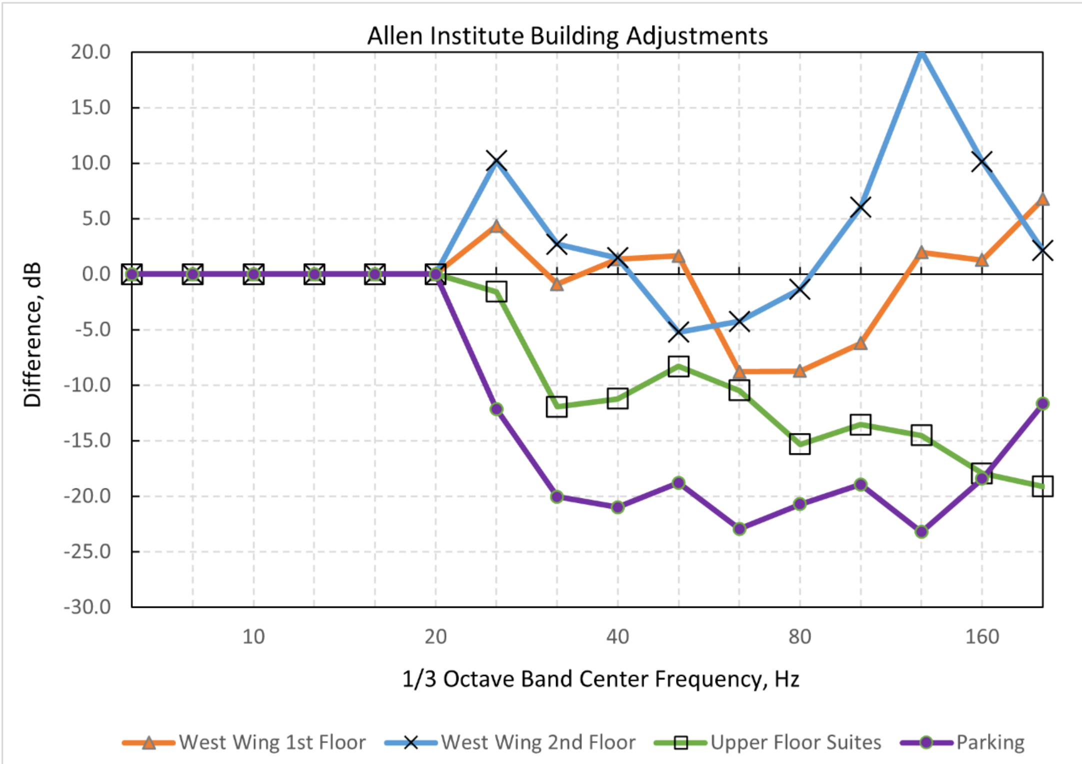


Figure 4-23. Measured Building Adjustment at Allen Institute for Brain Science Suite 440 On and Off Isolation Table

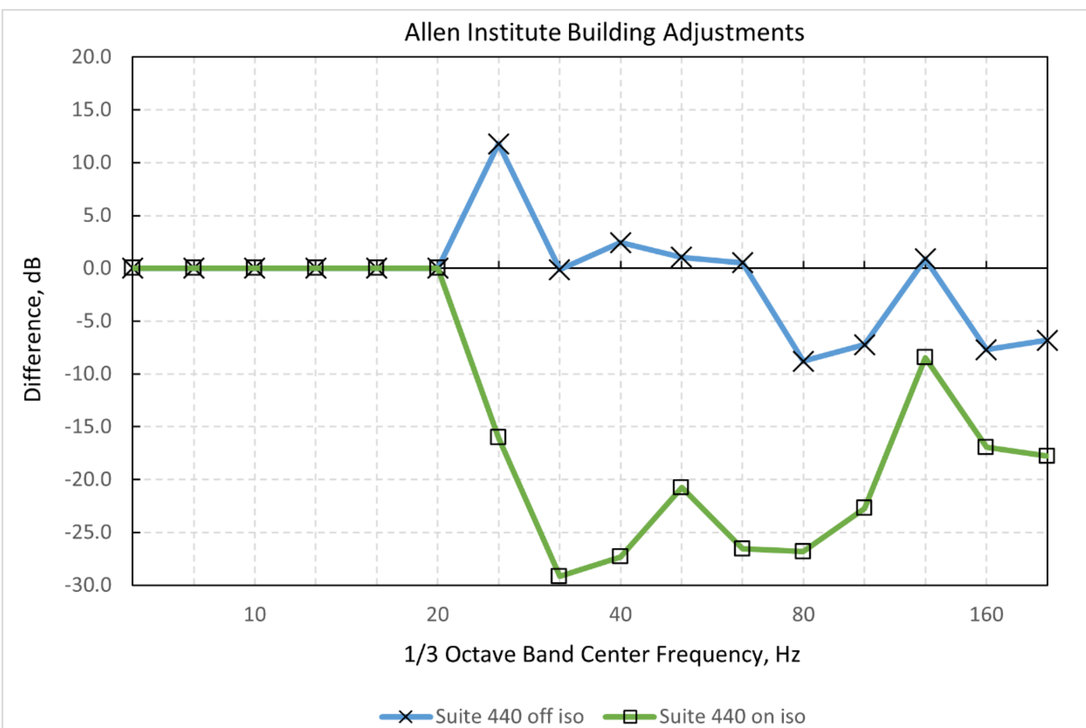
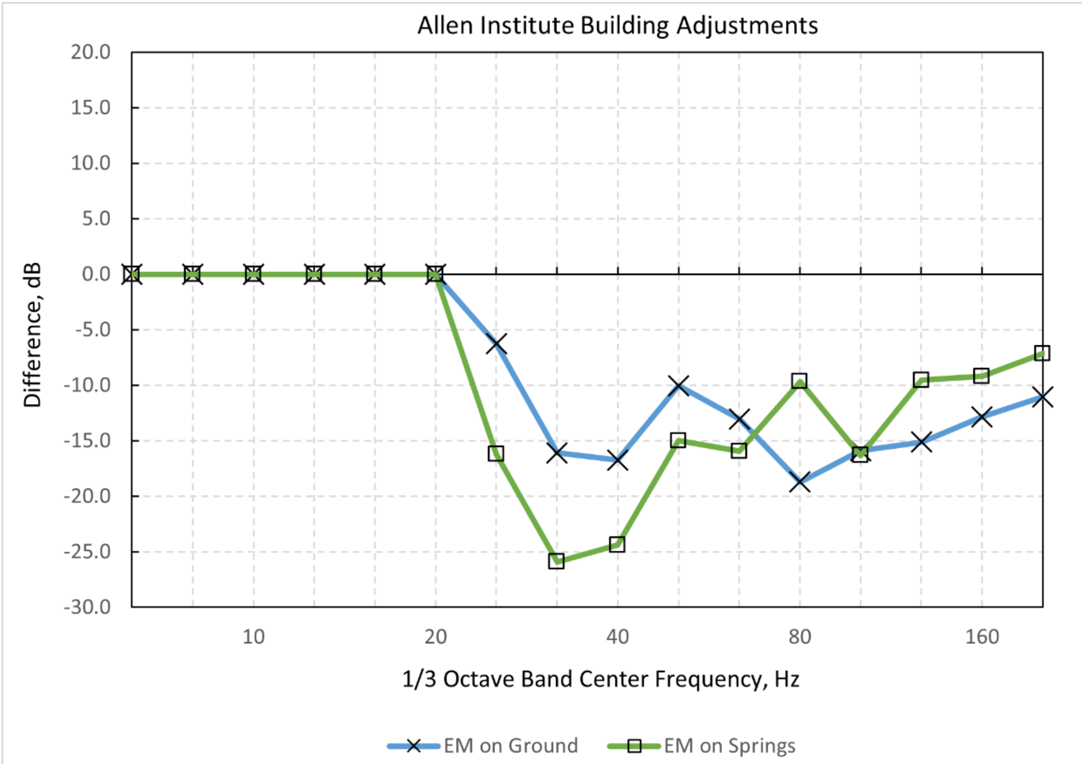


Figure 4-24. Measured Building Adjustment at Allen Institute for Brain Science Electron Microscope Suite On and Off Isolation Springs



The predicted levels for Preferred Alternative DT-1 are presented in Table 4-3, and the predicted levels for Alternative DT-2 are presented in Table 4-4. The predicted levels used the L.S.T.M. coefficients for site V-11 measured outside the Allen Institute for Brain Science and the building adjustments presented in Figures 4-22 to 4-24. The spectra for the predicted levels for Alternative DT-2 is presented in Figure 4-25. The results show there is no predicted impact for either Downtown Segment alternative. The low predicted vibration levels are the result of the following:

- The building is over 200 feet from the closest alignment.
- The construction of the building provides attenuation as the vibration travels from the soil into the building.
- Most of the sensitive equipment are equipped with vibration isolation tables.

Table 4-3. Predicted Vibration and Groundborne Noise Levels at Allen Institute for Brain Science with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Electron microscope on ground	1129	35	35	48	Not applicable	Not applicable	Does not exceed
Electron microscope on springs	1129	35	35	48	Not applicable	Not applicable	Does not exceed
West Wing, first floor	1129	35	35	66	4	Noise Abatement Criteria 45	Does not exceed
West Wing, second floor	1129	35	35	66	Not applicable	Not applicable	Does not exceed
Upper floor suites	1129	35	35	60	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 4-4. Predicted Vibration and Groundborne Noise Levels at Allen Institute for Brain Science, with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

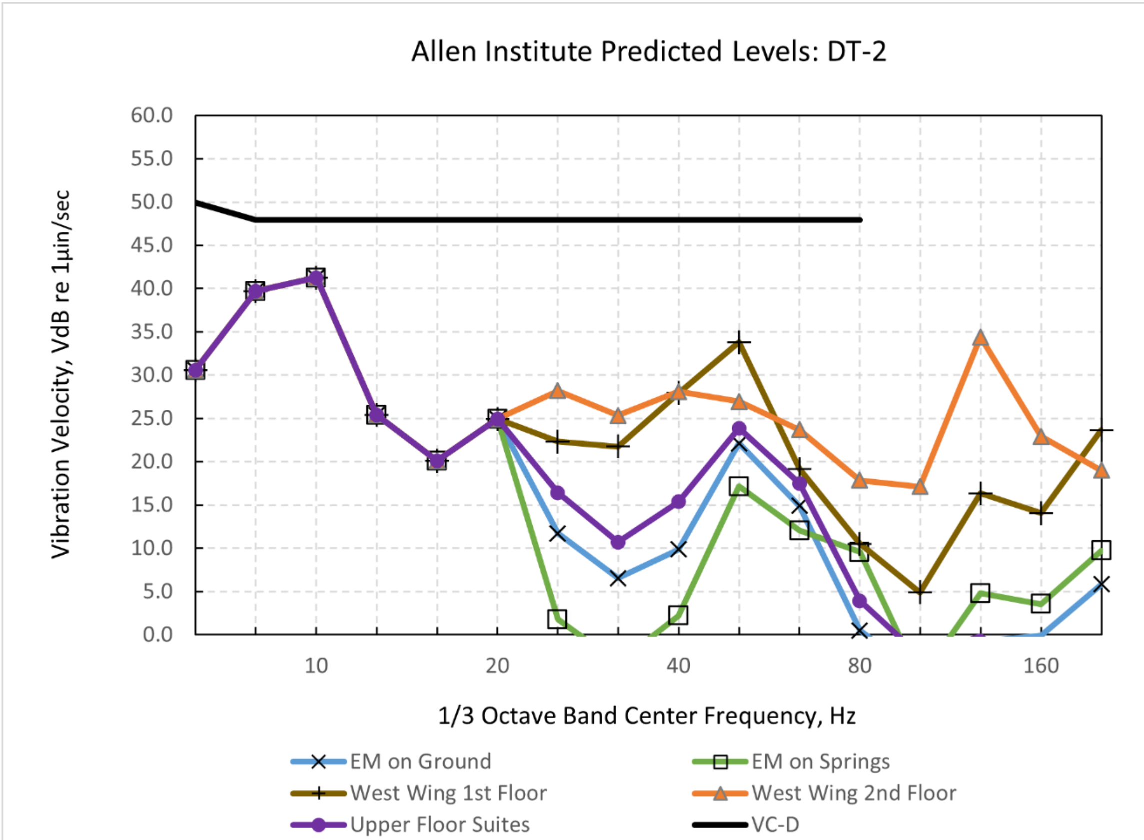
Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Electron microscope on ground	221	45	41	48	Not applicable	Not applicable	Does not exceed
Electron microscope on ground	221	45	41	48	Not applicable	Not applicable	Does not exceed
West Wing, first floor	221	45	41	66	14	Noise Abatement Criteria 45	Does not exceed
West Wing, second floor	221	45	41	66	Not applicable	Not applicable	Does not exceed
Upper floor suites	221	45	41	60	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 4-25. Predicted Vibration Level for 6th Avenue/Mercer Street Alternative (DT-2) at Allen Institute for Brain Science



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5 SEATTLE CENTER – CASCADE PUBLIC MEDIA (KCTS 9 TELEVISION)

5.1 Description of Sensitive Space

Cascade Public Media (KCTS 9 Television) is a public broadcasting service located at 401 Mercer Street in the Seattle Center in the Ballard Link Extension's Downtown Segment. The building houses a large studio, editing suites, and office space. The space most sensitive to groundborne noise and vibration is the main studio, which was designed to be isolated from the rest of the building to maintain low noise and vibration levels. Figure 5-1 is a photograph of the main studio.

Recording occurs occasionally near the office area on the second floor; however, this area is not purposefully built for low noise and vibration levels. Other noise- and vibration-sensitive spaces are the edit suites and audio sweetening room, where critical listening takes place. Photographs of the audio sweetening room and second floor office recording area are presented in Figure 5-2.

The FTA criteria for television studios was applied to the main studio space. The FTA *Transit Noise and Vibration Impact Assessment Manual* does not specifically address the sensitivity of editing suites or mixed-use office recording areas. The FTA criteria for auditoriums were applied to the audio sweetening rooms and office recording area because critical listening and occasional recording takes place there. These spaces are not as sensitive as the main studio, and the criteria for auditoriums are the next-most restrictive in the FTA *Transit Noise and Vibration Impact Assessment Manual* after the criteria for television studios.

Figure 5-1. Photograph of Cascade Public Media (KCTS 9 Television) Main Studio

Figure 5-2. Photographs of Cascade Public Media (KCTS 9 Television) Audio Sweetening Room and Second Floor Office Recording Area

5.2 Existing Noise and Vibration Levels

Existing noise and vibration levels were measured over a 1-hour period between 4:00 p.m. and 5:00 p.m. in the Cascade Public Media main studio, audio sweetening room, and the office recording area. Due to COVID-19, there were few staff present in the building. Staff were mostly in the second floor office area, which may have resulted in below normal existing noise and vibration levels for a typical work day. The large doors to the main studio space were closed during the ambient measurement to simulate the environment during filming. The door to the audio sweetening room was left open, but there was little activity in the building.

The measured 1-hr Leq noise and vibration levels are shown in Table 5-1. The 1-second noise levels are plotted in Figures 5-3 and 5-4. The 1-second vibration levels are plotted in Figures 5-5 and 5-6, and the spectra of the vibration levels are plotted in Figure 5-7. The measured data show the following:

- The main studio has the lowest noise levels. This is consistent with the quality of the doors and acoustic design of the space.
- The second-floor office recording area has higher noise levels compared to the other two spaces. This space is on a landing adjacent to open-plan office space and is not closed off from the general office activities. Also, higher vibration levels are typical of upper floor spaces.

Table 5-1. Background Noise and Vibration Levels Cascade Public Media (KCTS 9 Television)

Monitoring Location	Noise level (1 hr Leq)	Vibration level (1-hr Leq)
Cascade Public Media Main Studio	22 dBA	44 VdB
Cascade Public Media Audio Sweetening Room	30 dBA	42 VdB
Cascade Public Media Second Floor Office Recording Area	38 dBA	57 VdB

Figure 5-3. Measured 1-second Noise Levels in Cascade Public Media (KCTS 9 Television) Main Studio

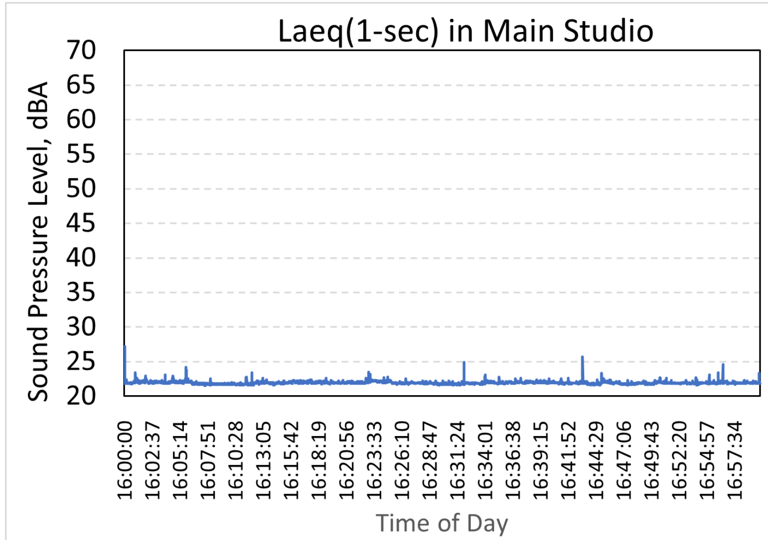


Figure 5-4. Measured 1-second Noise Levels in Cascade Public Media (KCTS 9 Television) Audio Sweetening Room and Second Floor Office Recording Area

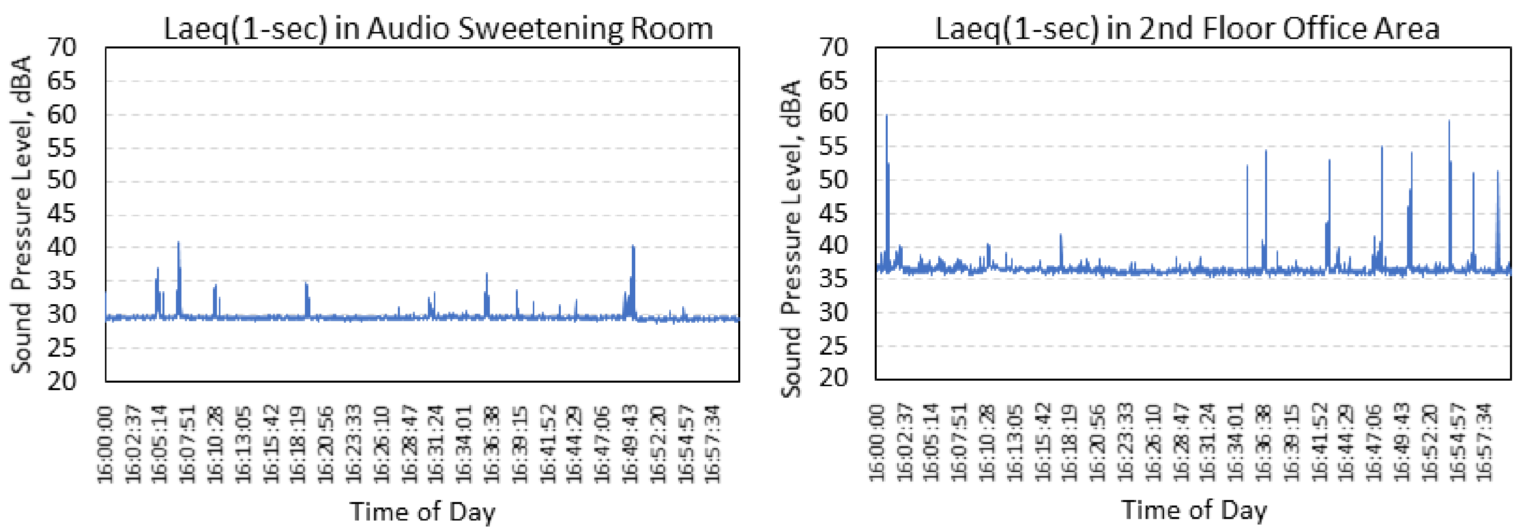


Figure 5-5. Measured 1-second Vibration Levels in Cascade Public Media (KCTS 9 Television) Main Studio

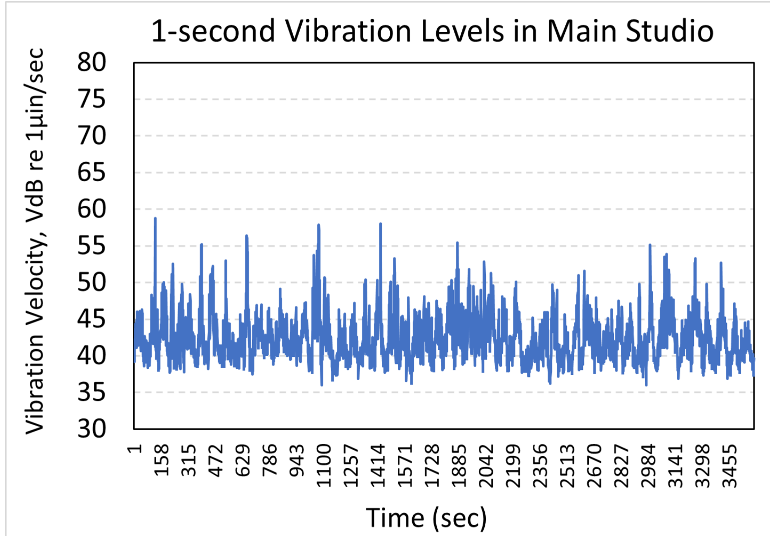
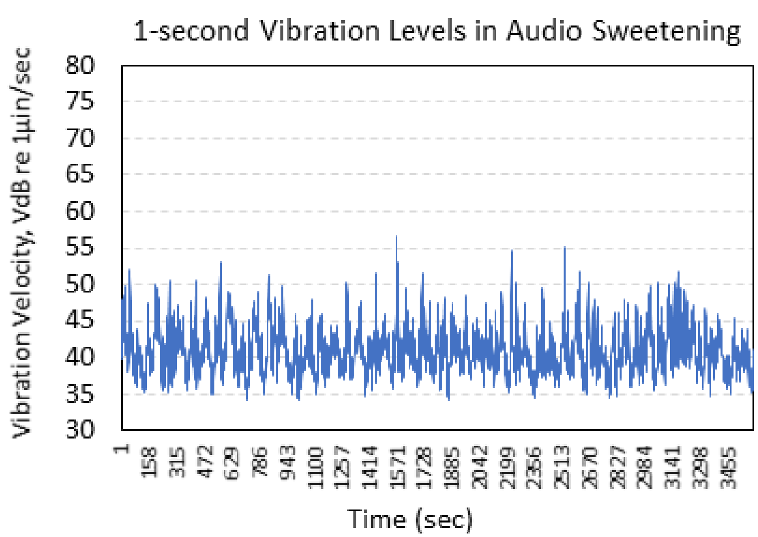


Figure 5-6. Measured 1-second Vibration Levels in Cascade Public Media (KCTS 9 Television) Audio Sweetening Room and Second Office Recording Area



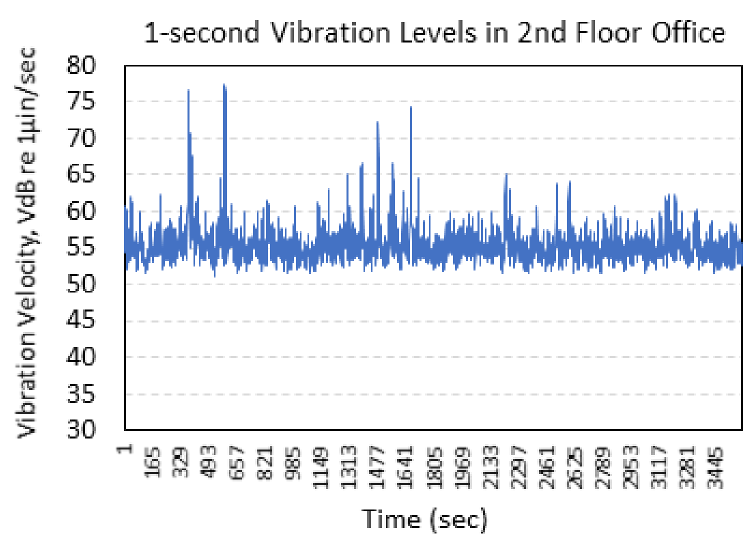
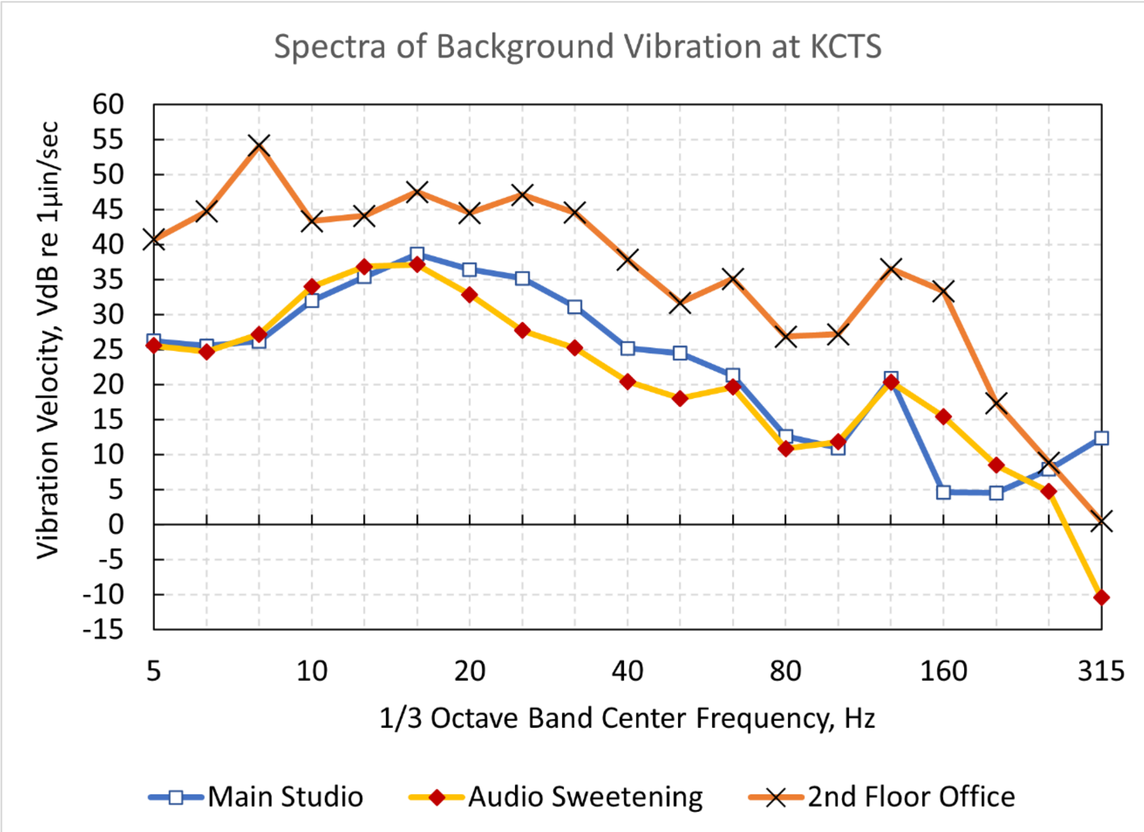


Figure 5-7. Spectra of Background Vibration Levels at Cascade Public Media (KCTS 9 Television)



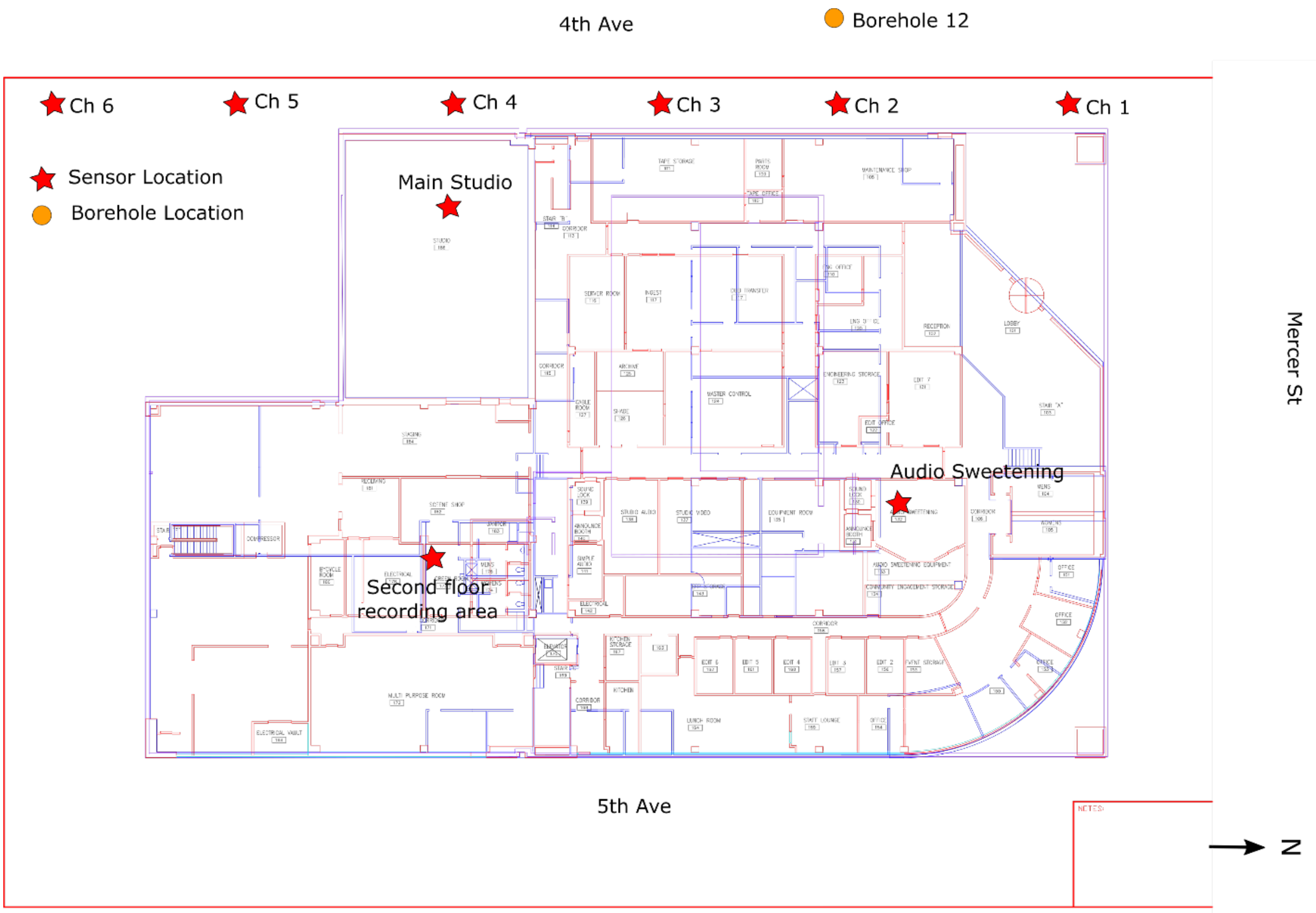
5.3 Vibration Propagation Measurement Description

A borehole vibration propagation test was completed at Cascade Public Media to determine how efficiently vibration propagates from the depth of the tunnel into the sensitive spaces. The borehole was west of the Cascade Public Media building on 4th Avenue North. Data were collected at three borehole depths, but due to equipment failure down the borehole, only data from the 120-foot depth were available for the assessment.

The vibration levels were measured at three indoor and six outdoor locations. The outdoor measurement locations were used to quantify how vibration levels decrease with distance from the impact force. The outdoor measurements were also used as a reference to examine how levels change as the vibration travels from the soil into the building structure. The three indoor measurement locations are the same as the ambient measurement locations: (1) the main studio, (2) the audio sweetening room, and (3) the second floor office recording area.

Figure 5-8 shows the ground level floor plan of Cascade Public Media with the approximate sensor locations labeled. Approximate location of the borehole position and outdoor sensor locations are also indicated in the figure. Photos of the borehole measurement site are provided in Attachment N.3B, Vibration Measurement Site Photographs.

Figure 5-8. Cascade Public Media (KCTS 9 Television) Floor Plan with Sensor Locations



5.4 Vibration Propagation Measurement Results and Predicted Levels

The borehole vibration propagation tests measure the P.S.T.M., a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the P.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The P.S.T.M. and coherence results for the K.C.T.S indoor measurement positions and their closest outdoor measurement position are shown in Figures 5-9 to 5-11. Observations from the P.S.T.M and coherence results are as follows:

- There is relatively good coherence in the main studio above 16 hertz. The main studio has lower P.S.T.M. levels compared to the outdoor location at frequencies above 63 hertz, which is typical of large masonry buildings.
- There is relatively good coherence in the audio sweetening room above 16 hertz. Similar to the main studio, there are lower P.S.T.M. levels compared to the outdoor location at frequencies above 63 hertz.
- There is relatively poor coherence in the second floor office recording area at all frequencies. Which is likely due to higher ambient vibration levels. The P.S.T.M. data show higher levels indoors between 20 hertz and 40 hertz and above 100 hertz; however, this is likely due to higher ambient vibration levels and not efficient propagation from the borehole into the space.

Figure 5-9. P.S.T.M. and Coherence in Cascade Public Media (KCTS 9 Television) Main Studio

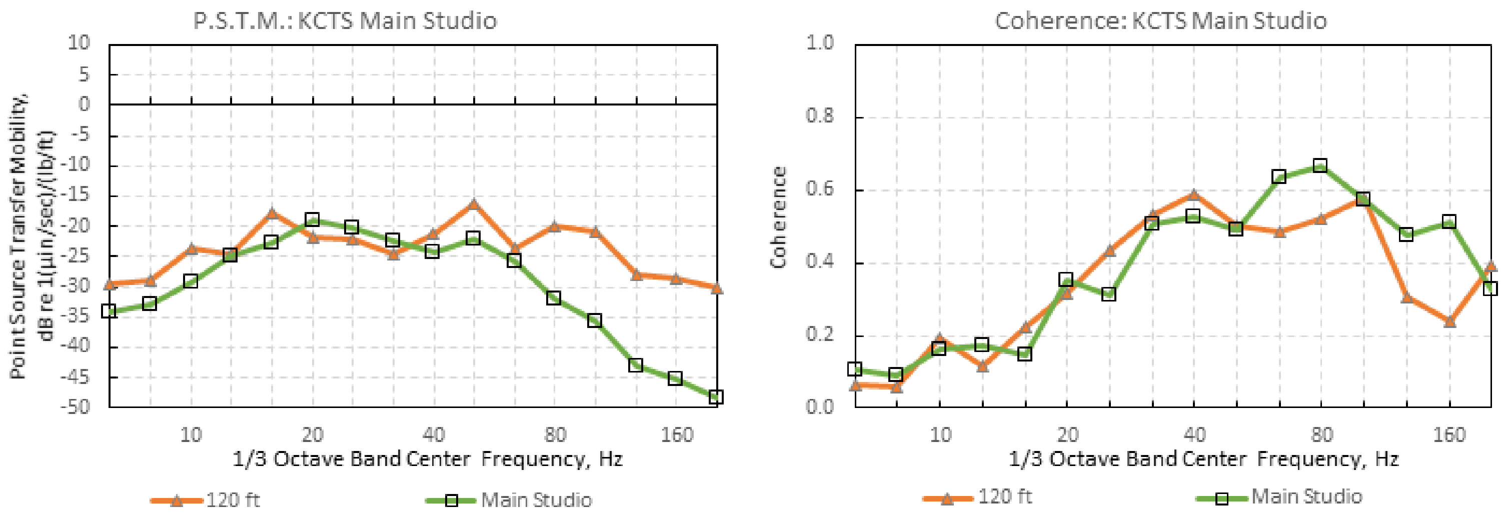


Figure 5-10. P.S.T.M. and Coherence in Cascade Public Media (KCTS 9 Television) Audio Sweetening

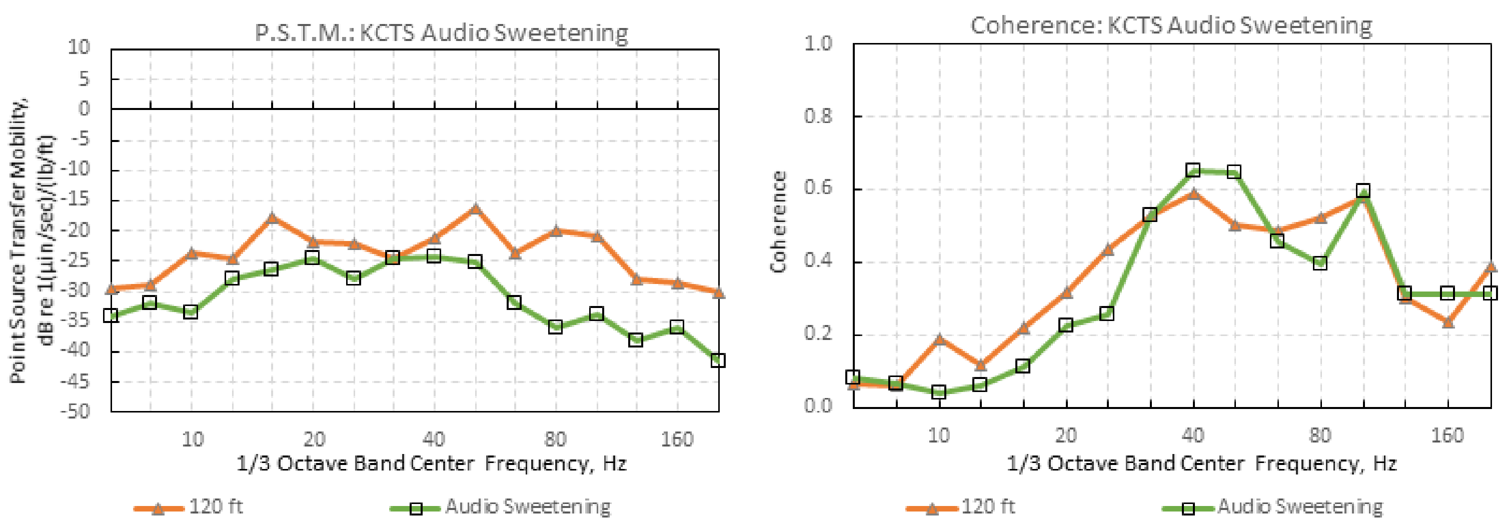
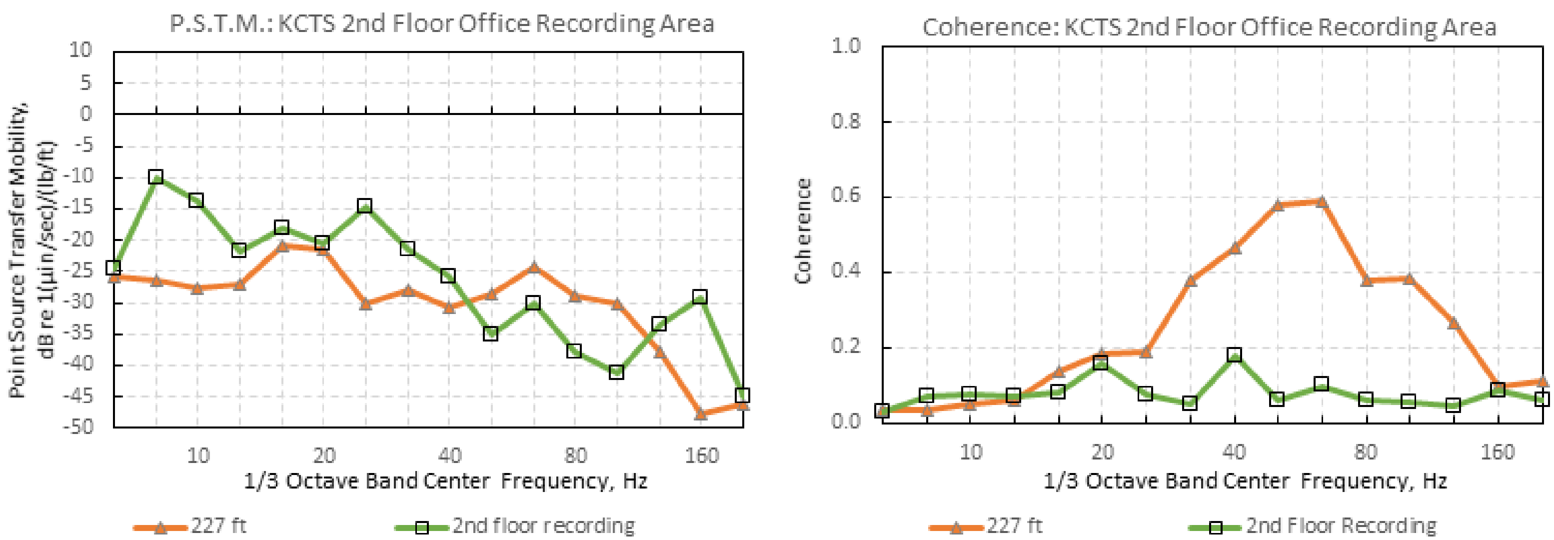


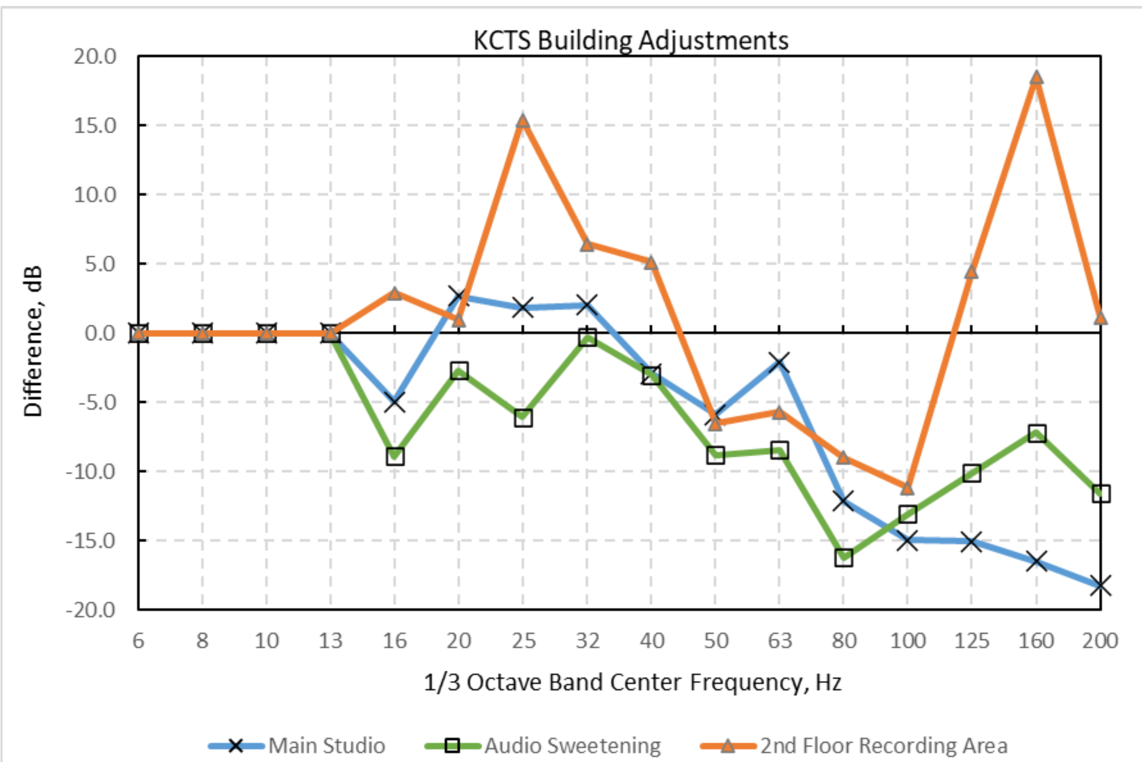
Figure 5-11. P.S.T.M. and Coherence in Cascade Public Media (KCTS 9 Television) Second Floor Office Recording Area



A building adjustment was applied in the prediction model to account for the building coupling loss and any floor resonances. This adjustment was calculated by taking the difference between the outdoor P.S.T.M. at an equivalent setback distance and the indoor P.S.T.M. The building adjustment for the three sensitive spaces where data were collected is shown in Figure 5-12. The building adjustment is assumed to be zero at frequencies 12.5 hertz and below because of low coherence values indoors and outdoors at low frequencies and because it is unlikely that there are floor resonances at these low frequencies. Following are observations for the resulting building adjustment:

- The building adjustment at the Cascade Public Media main studio and audio sweetening room range between plus and minus 5 decibels up to 31.5 hertz band, with increasing attenuation at higher frequencies. This is typical of large masonry buildings.
- The second floor office recording area shows high amplification at 25 hertz and 160 hertz. There are often resonances on suspended upper floors; however, the magnitude of the amplification may be overestimated because of the high existing vibration levels and the distance between the borehole and the sensitive space. High existing levels and a relatively far distance between the force and sensor result in poor signal-to-noise ratio.

Figure 5-12. Measured Building Adjustments at Cascade Public Media (KCTS 9 Television)



The predicted levels for the Preferred Alternative DT-1 are presented in Table 5-2, and the predicted levels for Alternative DT-2 are presented in Table 5-3. The predictions for both alternatives use the L.S.T.M. coefficients from site V-12 located on 4th Street adjacent to Cascade Public Media, positioned between the two Downtown Segment alternatives. The predicted levels for both alternatives use the building adjustments in Figure 5-12. No safety factor is included in the predictions because the predictions use site-specific L.S.T.M. levels and there is a 3-decibel safety factor incorporated into the force density level. The spectra of the predicted levels for the two alternatives are presented in Figures 5-13 and 5-14.

Tables 5-2 and 5-3 show there is no predicted impact for K.C.T.S for either Downtown Segment alternative. Compared to the Northwest Rooms and the theatres in the Seattle Center, the Cascade Public Media building is farther from the proposed alignment. No vibration mitigation is proposed for Cascade Public Media.

Table 5-2. Predicted Vibration and Groundborne Noise Levels at Cascade Public Media with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Cascade Public Media Main Studio	354	45	38	65	1	25	Does not exceed
Cascade Public Media Audio Sweetening	354	45	37	72	1	30	Does not exceed
Cascade Public Media Second Floor Office Recording Area	354	45	39	72	2	30	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 5-3. Predicted Vibration and Groundborne Noise Levels at Cascade Public Media for 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Cascade Public Media Main Studio	213	45	40	65	3	25	Does not exceed
Cascade Public Media Audio Sweetening	213	45	38	72	2	30	Does not exceed
Cascade Public Media Second Floor Office Recording Area	213	45	41	72	6	30	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 5-13. Predicted Vibration Level for Preferred 5th Avenue/Harrison Street Alternative (DT-1) at Cascade Public Media (KCTS 9 Television)

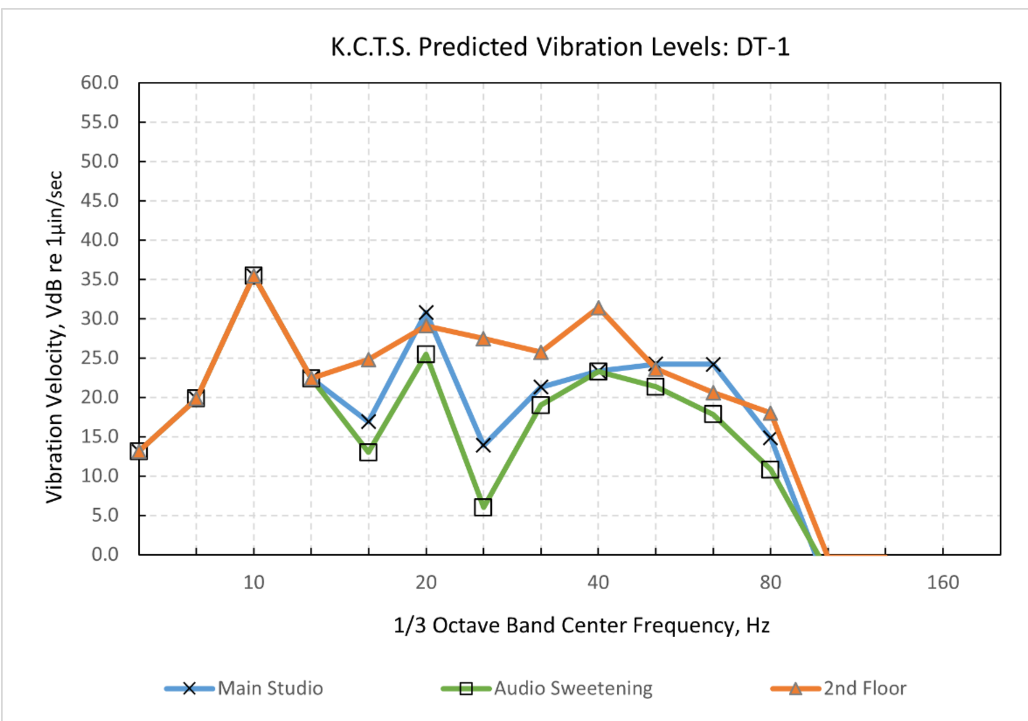
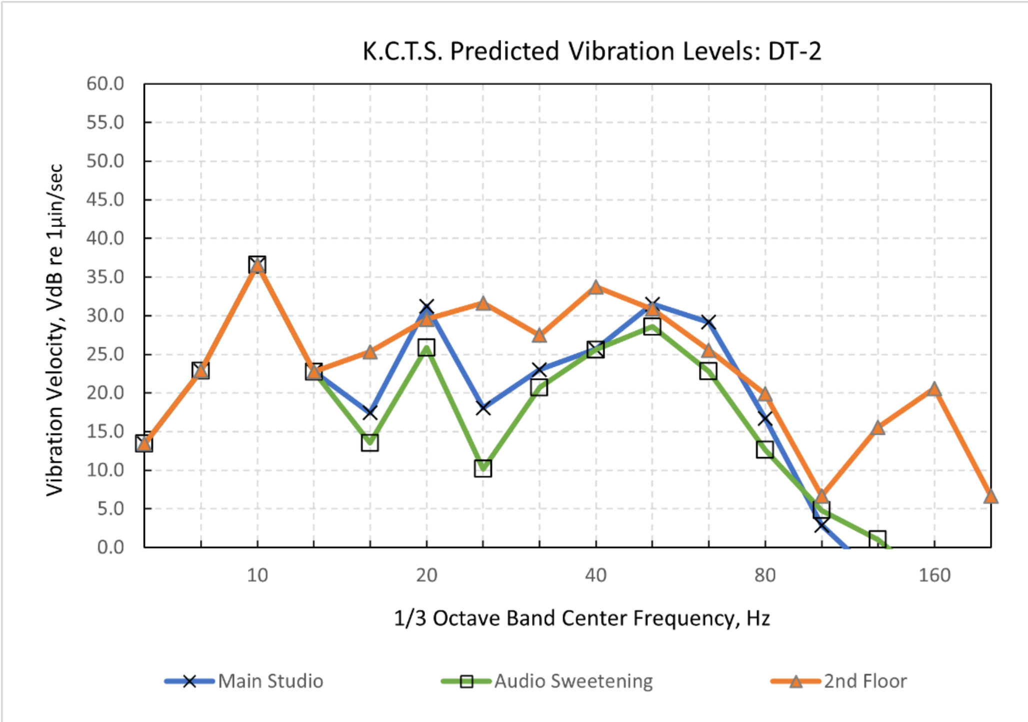


Figure 5-14. Predicted Vibration Level for 6th Avenue/Mercer Street Alternative (DT-2) at Cascade Public Media (KCTS 9 Television)



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6 SEATTLE CENTER – MCCAW HALL, SEATTLE OPERA, AND PACIFIC NORTHWEST BALLET

6.1 Description of Sensitive Space

McCaw Hall is a concert hall at 321 Mercer Street in the Seattle Center, which is along the Ballard Link Extension’s Downtown Segment. To the west, it is connected via underground tunnel to the Exhibition Hall in the Pacific Northwest Ballet building at 301 Mercer Street. The Pacific Northwest Ballet facilities are on the above-ground floors above the Exhibition Hall. To the east, McCaw Hall is connected to the Seattle Opera Center. The Seattle Opera Center is a purpose built addition to McCaw Hall and opened in 2018.

The groundborne noise- and vibration-sensitive spaces at McCaw Hall are the main hall, where Seattle Opera and Pacific Northwest Ballet performances take place, and a smaller lecture hall on the Mercer Street side of the building. Figure 6-1 shows a photograph of the main McCaw Hall and smaller lecture hall. The FTA criteria for concert halls were applied to the main hall, and the FTA criteria for an auditorium were applied to the lecture hall. The concert hall criteria are the most stringent criteria for performance venues in the FTA *Transit Noise and Vibration Impact Assessment Manual*. The Seattle Center Studios also use the McCaw Hall main hall area for recording. The FTA criteria for recording studios are the same as for concert halls, so the assessment results for the McCaw Hall main hall also apply to the Seattle Center studios.

The Seattle Opera Center to the east of McCaw Hall houses rehearsal space, a community performance hall (concert hall), the King FM classical radio station broadcast booths, and other support services for the Seattle Opera. Figure 6-2 shows a photograph of the concert and rehearsal halls, and Figure 6-3 is a photograph of one of the broadcast booths. The FTA criteria for auditoriums are applied to the rehearsal space, the FTA criteria for concert halls are applied to the community performance hall, and the FTA criteria for recording studios are applied to the radio station broadcast booth.

In the adjacent building to the west, the groundborne noise- and vibration-sensitive spaces are the Exhibition Hall and the Pacific Northwest Ballet practice studios. The Exhibition Hall holds a variety of different events such as craft fairs, expos, or events during festivals, including music festivals. The FTA criteria for auditoriums were applied to the Exhibition Hall because of the multipurpose use of the space.

The Pacific Northwest Ballet’s practice studios are not used for formal performances but are used regularly for classes and practice. Small audiences may be invited to the larger studios for less formal performances. Figure 6-4 is a photograph of Pacific Northwest Ballet’s Studio G. The FTA criteria for theatres were applied to the Pacific Northwest Ballet’s practice studios. The criteria for theaters, which are the least stringent criteria for performance venues in the FTA *Transit Noise and Vibration Impact Assessment Manual*, were applied to the Pacific Northwest Ballet studios because the studios may be used to host informal performances.

Figure 6-1. Photographs of McCaw Hall Main Hall (left) and Lecture Hall (right)

Figure 6-2. Photographs of Seattle Opera Concert Hall (left) and Rehearsal Hall (right)

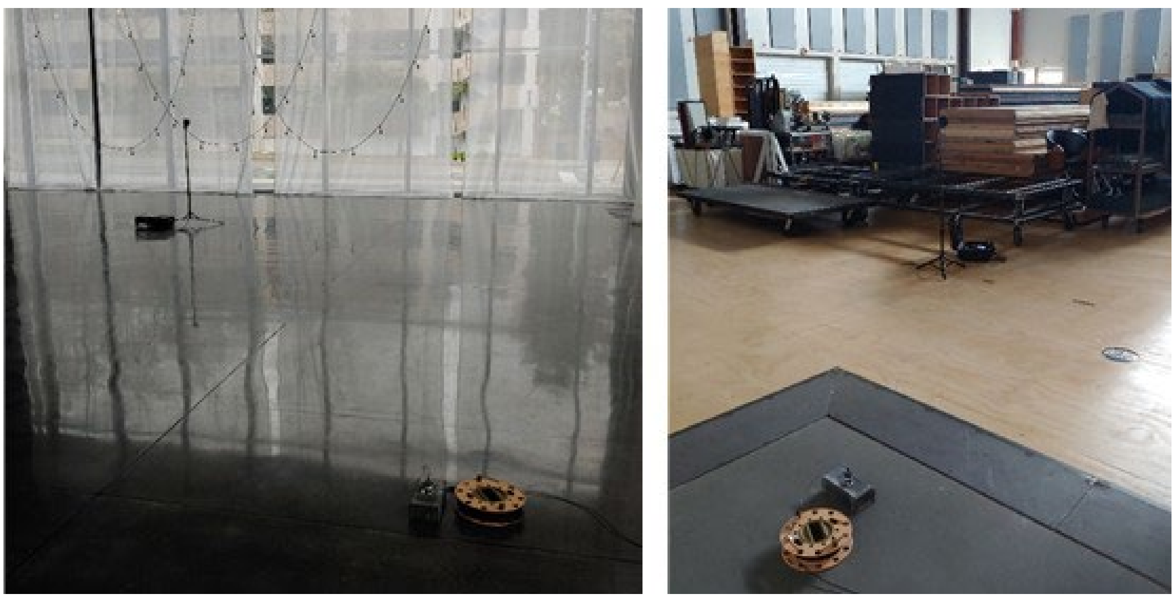
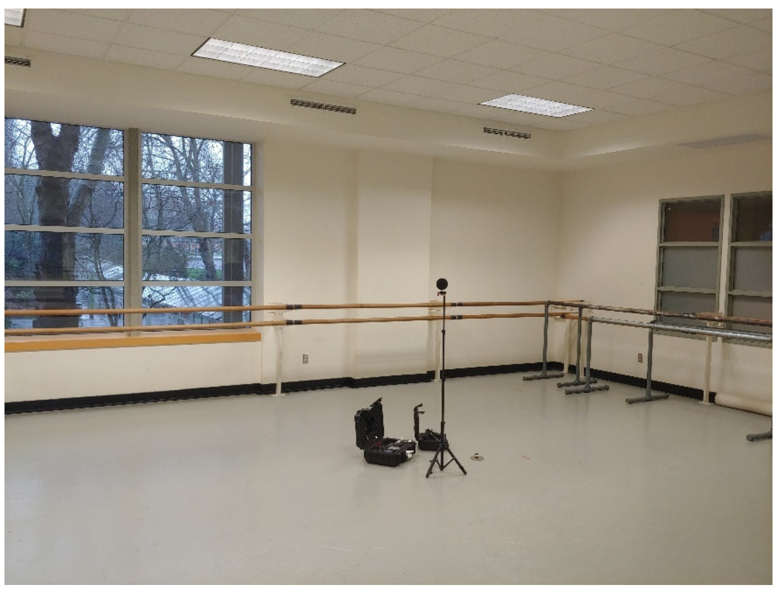


Figure 6-3. Photograph of Seattle Opera Broadcast Booth

Figure 6-4. Photograph of Pacific Northwest Ballet Studio G



6.2 Existing Noise and Vibration Levels

Existing noise and vibration levels were measured over a 1-hour period in the McCaw Hall main hall, lecture hall, and Pacific Northwest Ballet Studio G. The measurements were completed between 8:15 a.m. and 9:15 a.m. but on different days at McCaw Hall and Pacific Northwest Ballet. At McCaw Hall, there were very few staff present in the building, but there were some backstage activities in the main hall that interfered with the noise measurement. At Pacific Northwest Ballet, the measurement was completed between 8:15 a.m. and 9:15 a.m., with active rehearsals and classes in other studios but no activity in Studio G.

On a separate date, existing noise and vibration levels were measured in the Seattle Opera concert hall, rehearsal hall, and King FM broadcast booth. In the rehearsal hall and the concert hall, the measurements were completed between 3:10 p.m. and 4:10 p.m. In the broadcast booth, measurement was completed between 2:35 p.m. and 2:55 p.m.

The measured 1-hr Leq noise and vibration levels are shown in Table 6-1. The 1-second noise levels are plotted in Figures 6-5 through 6-8. The 1-second vibration levels are plotted in Figures 6-9 through 6-12, and the spectra of the vibration levels are plotted in Figures 6-13 and 6-14. The measured data show the following:

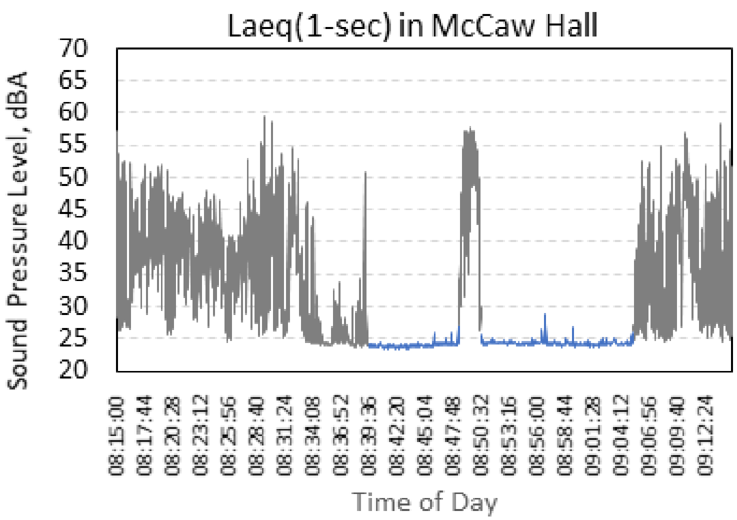
- The McCaw Hall main hall has the lowest noise levels when no activity is taking place. The high noise levels plotted in gray were removed from the 1-hour Leq presented in Table 6-1.
- The vibration levels in the McCaw Hall main hall are higher than the levels in the lecture hall. The floor of the lecture hall is slab-on-grade, but the floor of the main hall is suspended with ducts and vents beneath the floor, likely resulting in higher ambient vibration levels.
- The noise levels in Pacific Northwest Ballet Studio G are relatively low, even though there were active rehearsals in nearby studios with piano and other music playing, which indicates relatively good sound insulation of the studios.
- The noise levels in the Seattle Opera broadcast booth were lower than the concert and rehearsal halls, indicating good sound insulation in the booths. The elevated noise levels in the concert hall are likely due to the large windows fronting Mercer Street and Fourth Avenue.
- Vibration levels in the Seattle Opera broadcast booth are lower than measured elsewhere, indicating good isolation from ambient vibration sources.

Table 6-1. Background Noise and Vibration Levels at McCaw Hall and Pacific Northwest Ballet

Monitoring Location	Noise level (1-hr Leq)	Vibration level (1-hr Leq)
McCaw Hall Main Hall	24 dBA [a]	58 VdB
McCaw Hall Lecture Hall	30 dBA	50 VdB
Pacific Northwest Ballet Studio G	29 dBA	60 VdB
Seattle Opera Concert Hall	45 dBA	47 VdB
Seattle Opera Rehearsal Hall	33 dBA	54 VdB
Seattle Opera Broadcast Booth	30 dBA [a]	37 VdB

[a.] Less than one hour of measurement data.

Figure 6-5. Measured 1-second Noise Levels in McCaw Hall Main Hall and Lecture Hall



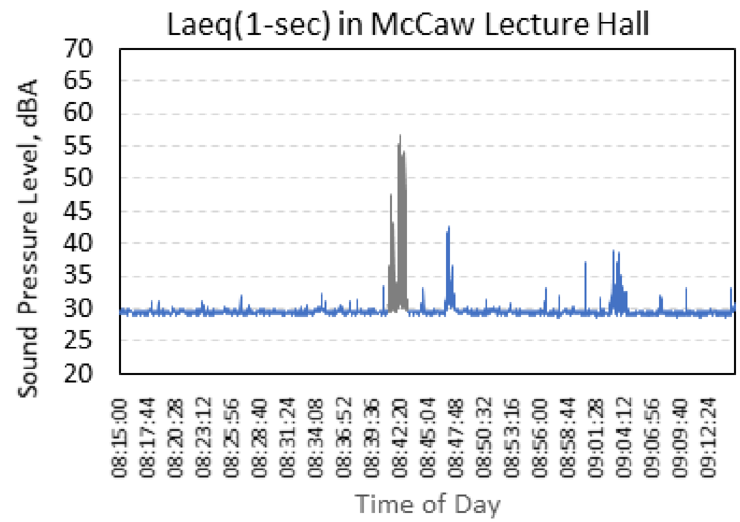


Figure 6-6. Measured 1-second Noise Levels in Pacific Northwest Ballet Studio G

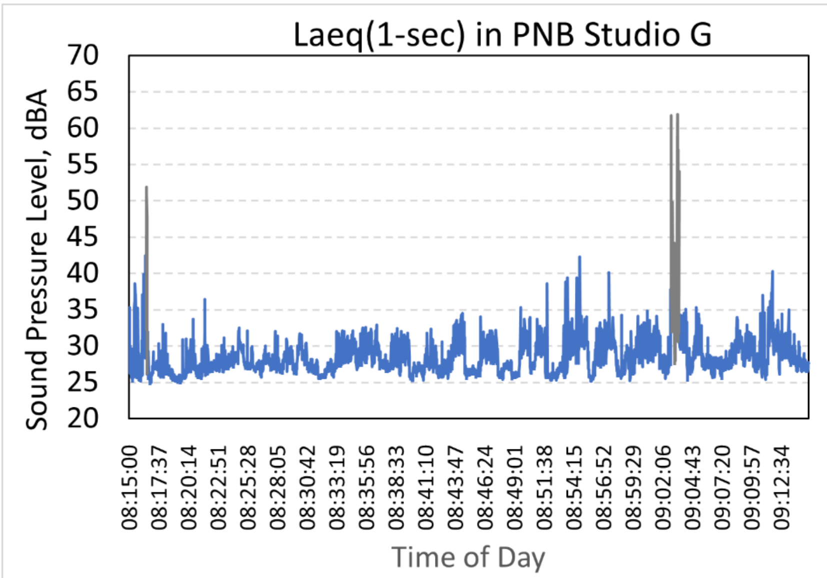


Figure 6-7. Measured 1-second Noise Levels in Seattle Opera Concert Hall and Rehearsal Hall

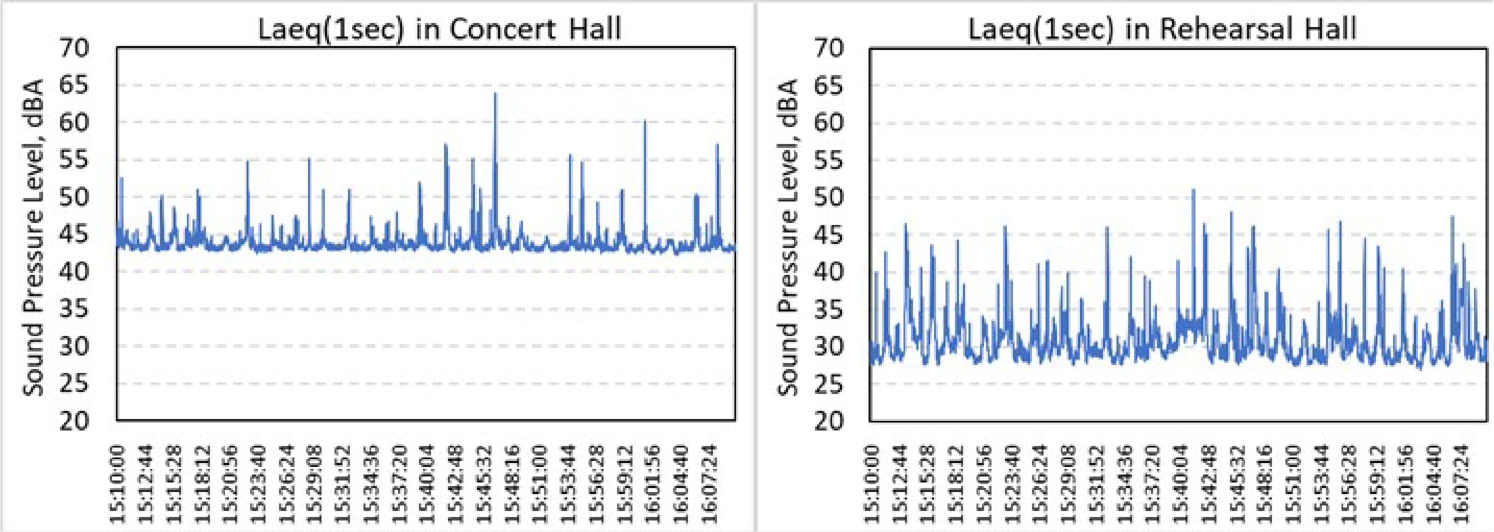


Figure 6-8. Measured 1-second Noise Levels in Seattle Opera Broadcast Booth

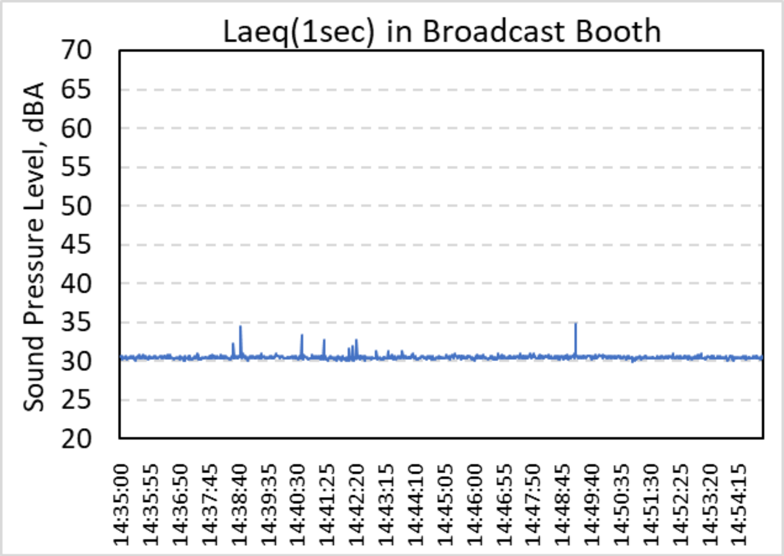
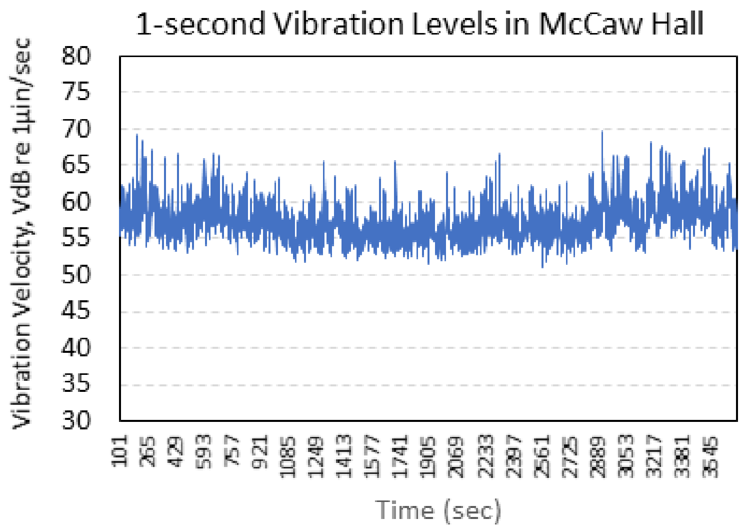


Figure 6-9. Measured 1-second Vibration Levels in McCaw Hall Main Hall and Lecture Hall



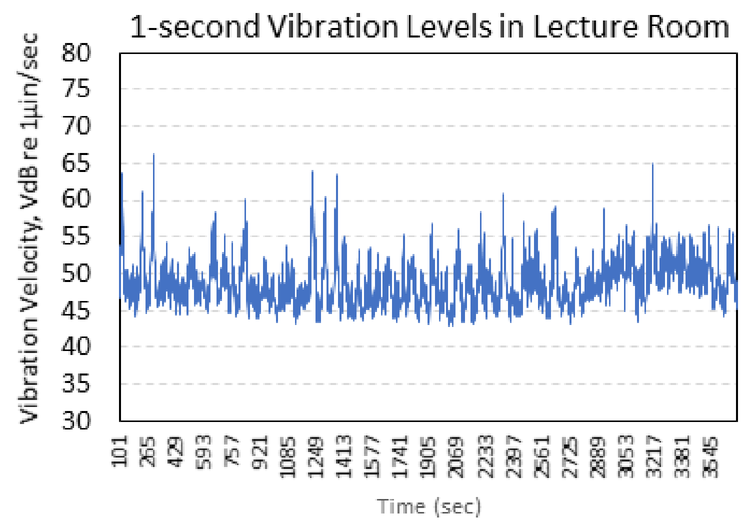


Figure 6-10. Measured 1-second Vibration Levels in Pacific Northwest Ballet Studio G

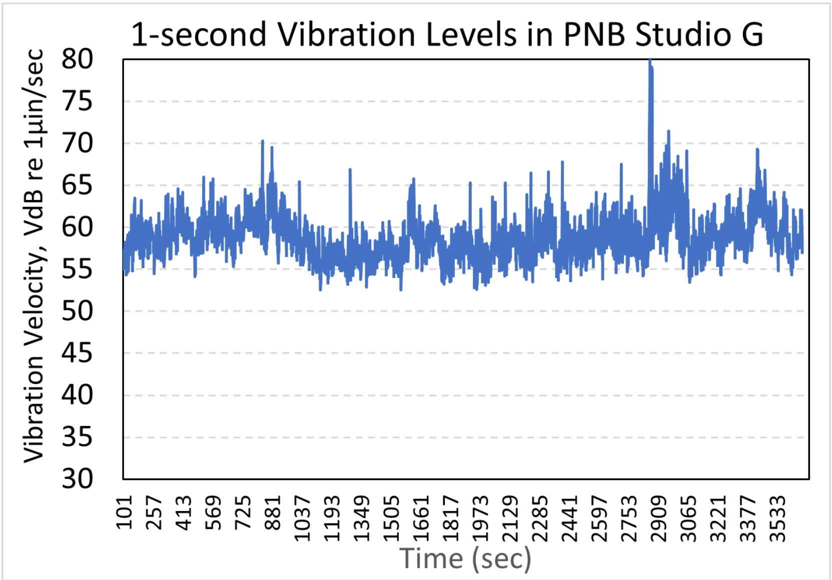


Figure 6-11. Measured 1-second Vibration Levels in the Seattle Opera Concert and Rehearsal Halls

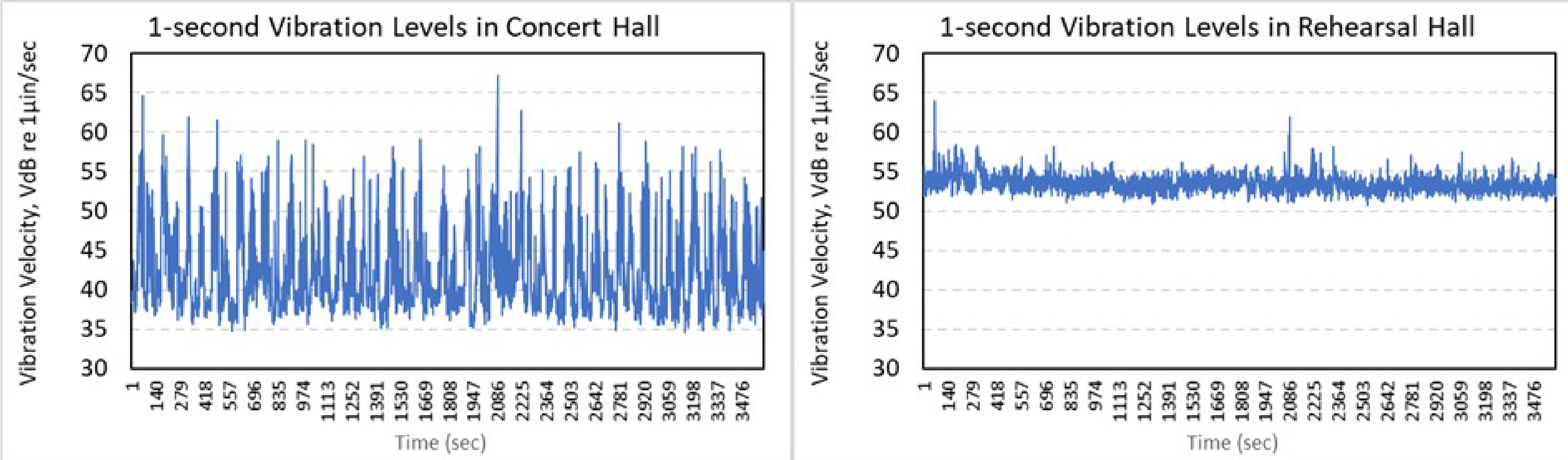


Figure 6-12. Measured 1-second Vibration Levels in the Seattle Opera Broadcast Booth

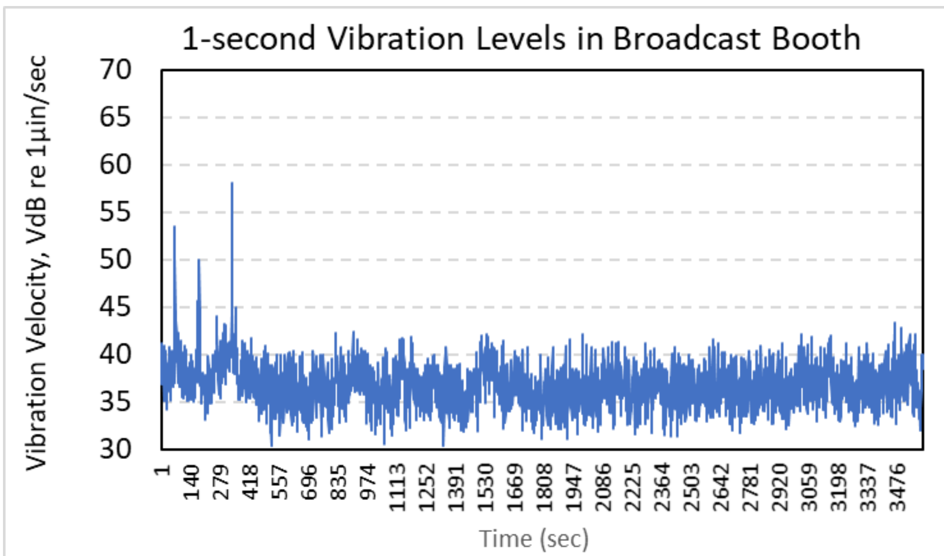


Figure 6-13. Spectra of Background Vibration Levels at McCaw Hall and Pacific Northwest Ballet

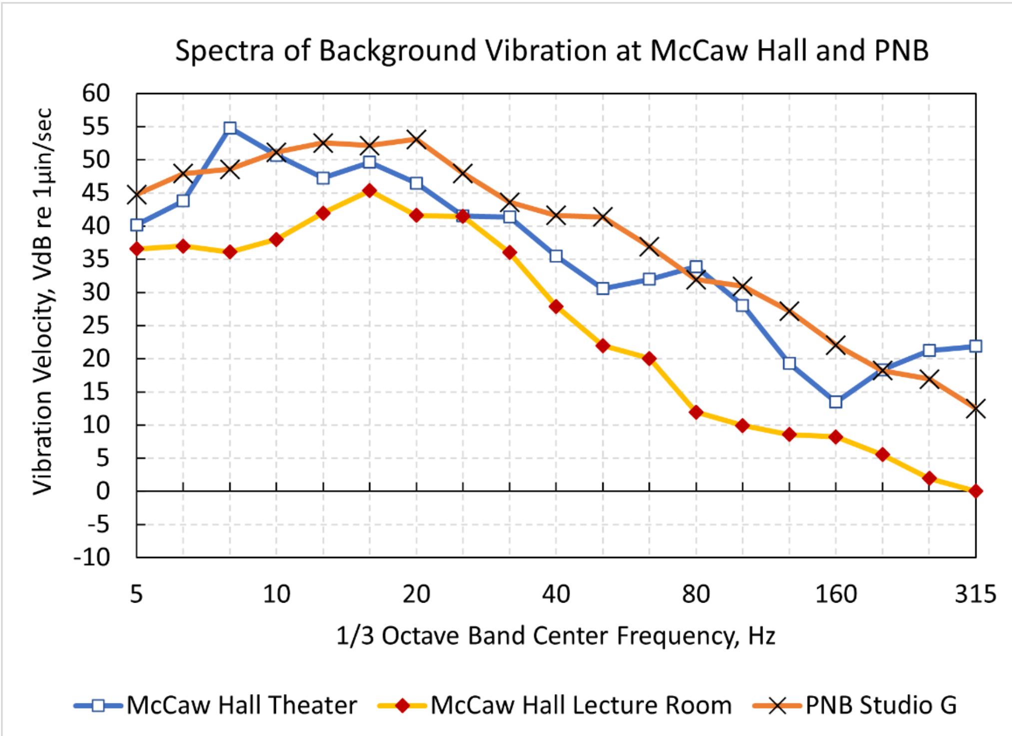
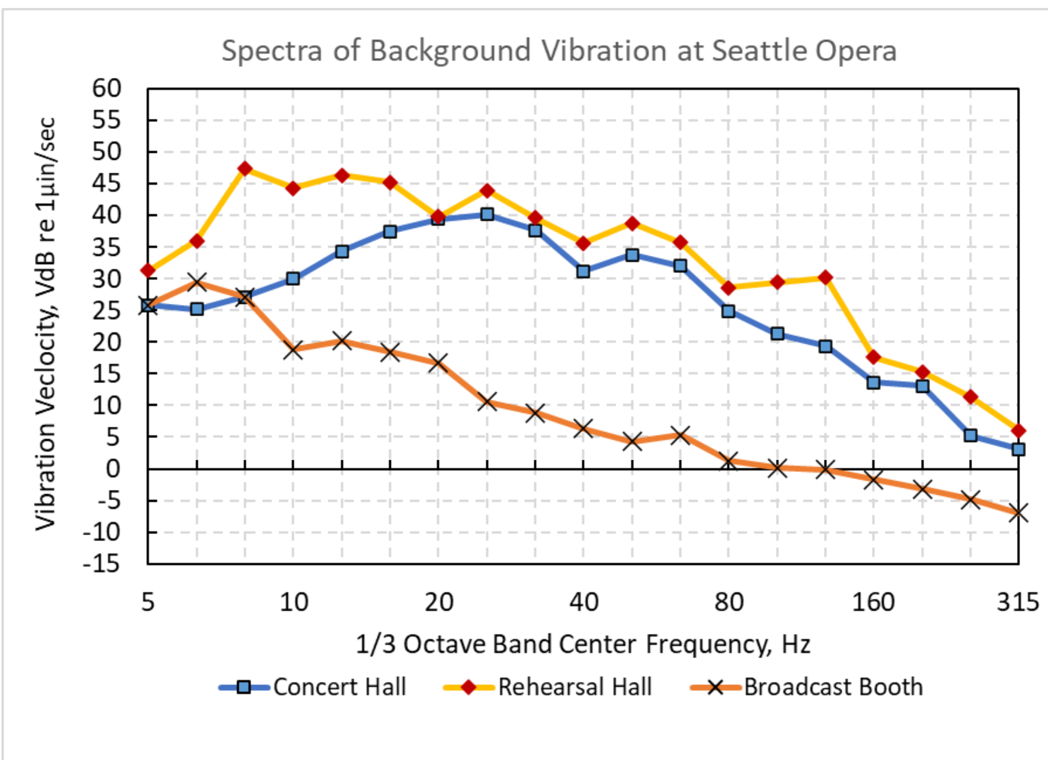


Figure 6-14. Spectra of Background Vibration Levels at Seattle Opera Center



6.3 Vibration Propagation Measurement Description

A borehole vibration propagation test was completed at McCaw Hall and the Pacific Northwest Ballet building to determine how efficiently vibration propagates from the approximate depth of the tunnel into the sensitive spaces. The borehole was on the edge of the August Wilson Way pedestrian walkway, in front of the Pacific Northwest Ballet building. Data were collected from three borehole depths: 80 feet, 90 feet, and 100 feet.

The vibration levels were measured at five indoor and five outdoor locations. The outdoor measurement locations were used to quantify how vibration levels decrease with distance from the impact force. The outdoor vibration measurements were also used as a reference to examine how levels change as the vibration travels from the soil into the building structure.

The five indoor measurement locations are: (1) McCaw Hall mechanical room, (2) McCaw Hall main hall, (3) McCaw Hall lecture hall, (4) Exhibition Hall in the basement of the Pacific Northwest Ballet building, and (5) Pacific Northwest Ballet hallway next to Studio G. The measurement positions were selected to get representative data in sensitive locations from McCaw Hall and the Pacific Northwest Ballet building.

Figure 6-15 shows the mezzanine level and lower level floor plans of McCaw Hall, with the sensor locations labeled. Figure 6-16 shows the Exhibition Hall and Pacific Northwest Ballet studio level floor plans for the Pacific Northwest Ballet building, with the sensor locations labeled. Approximate location of the outdoor sensors closest to the buildings and the borehole position are also indicated in the figures.

A separate, surface vibration propagation test was completed for the Seattle Opera Center to determine how efficiently vibration propagates from the soil into the sensitive spaces. A drop-hammer was used to impart a force along the Fourth Avenue sidewalk, and the resulting vibration was measured outside and inside the building. Data were collected from four impact points spaced 15 feet apart near the concert hall and three impact points spaced 15 feet apart near the broadcast booth.

The three indoor Seattle Opera Center measurement locations are: (1) concert hall, (2) rehearsal hall, and (3) broadcast booth. Figure 6-17 shows the Seattle Opera Center floor plan with the sensor location. The approximate locations of the outdoor sensors closest to the building and the impact locations for the drop-hammer are also indicated in the figure. Photos and a schematic of the vibration propagation site are provided in Attachment N.3B, Vibration Measurement Site Photographs.

Figure 6-15. McCaw Hall Mezzanine (top) and Lower Level (bottom) Floor Plans

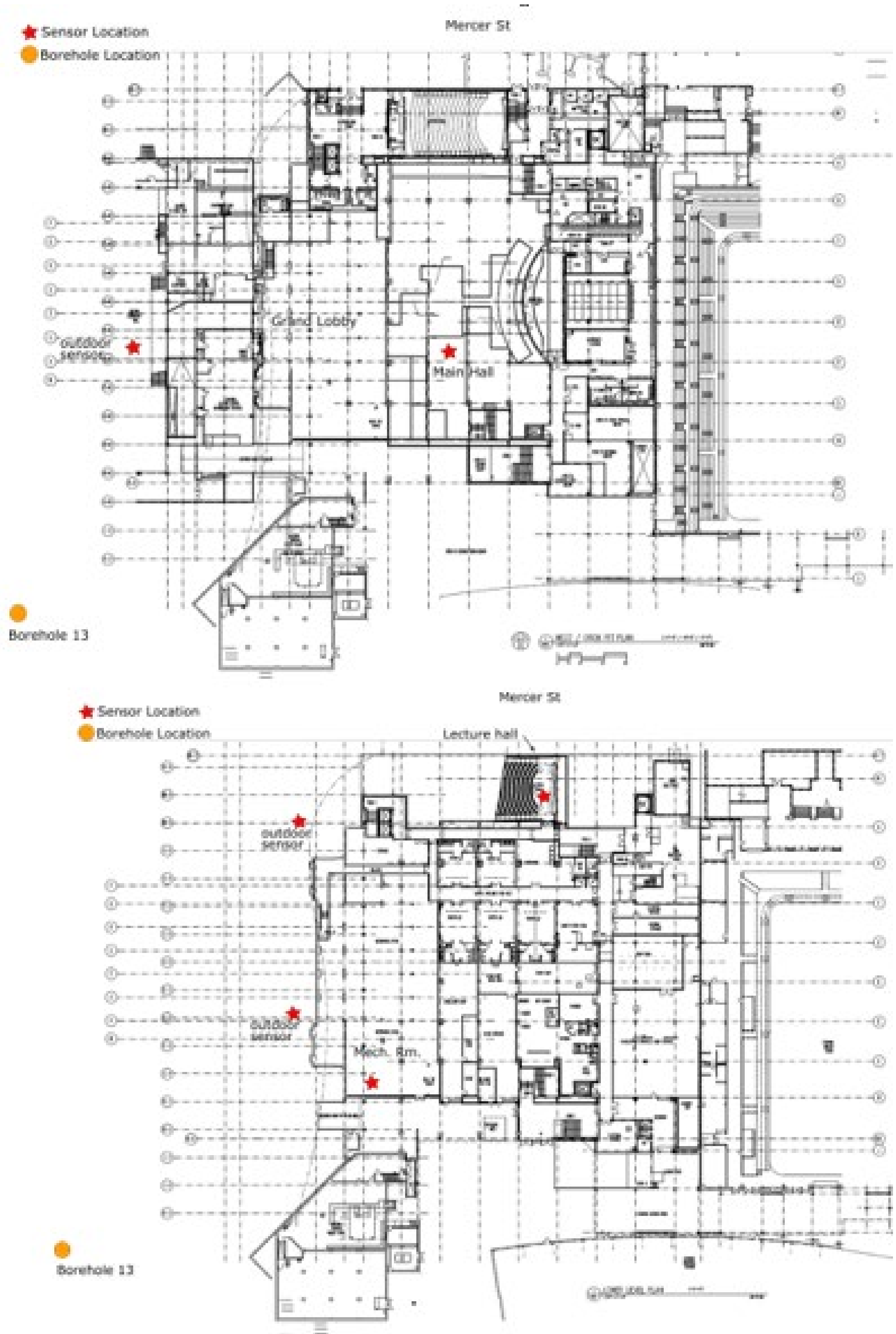
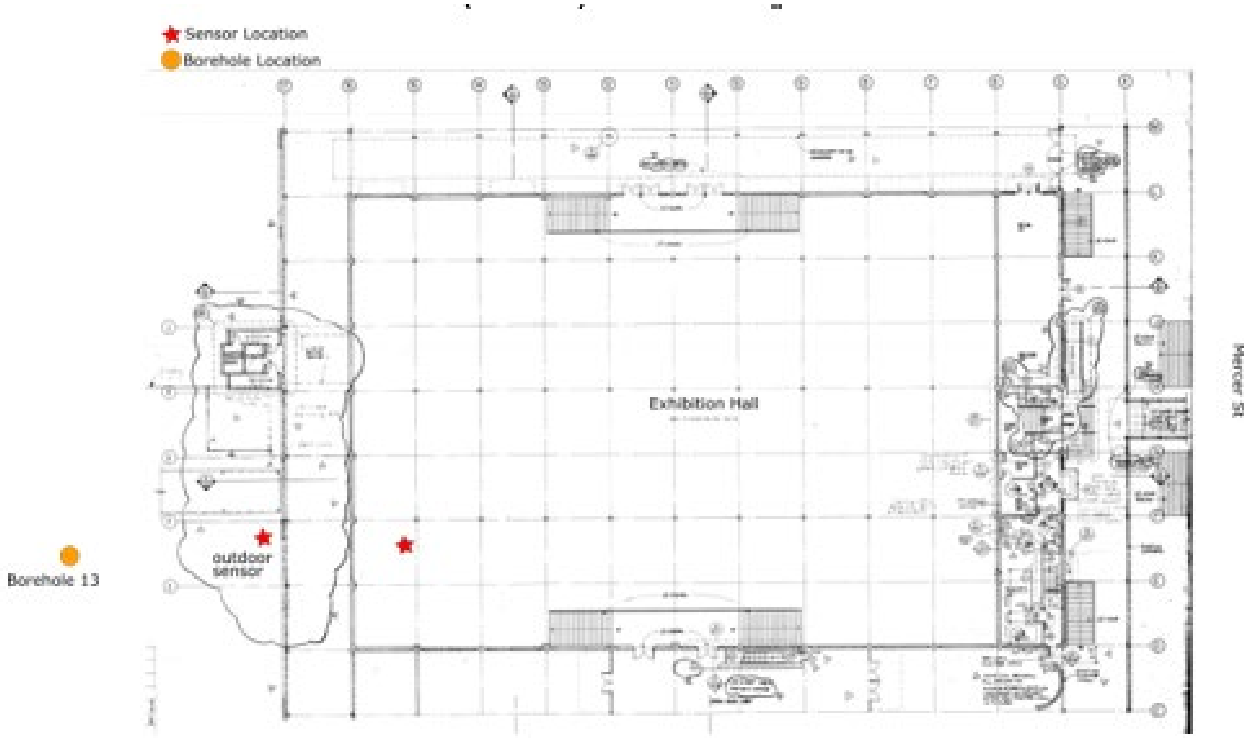


Figure 6-16. Pacific Northwest Ballet Exhibition Hall (top) and Studio Level (bottom) Floor Plans



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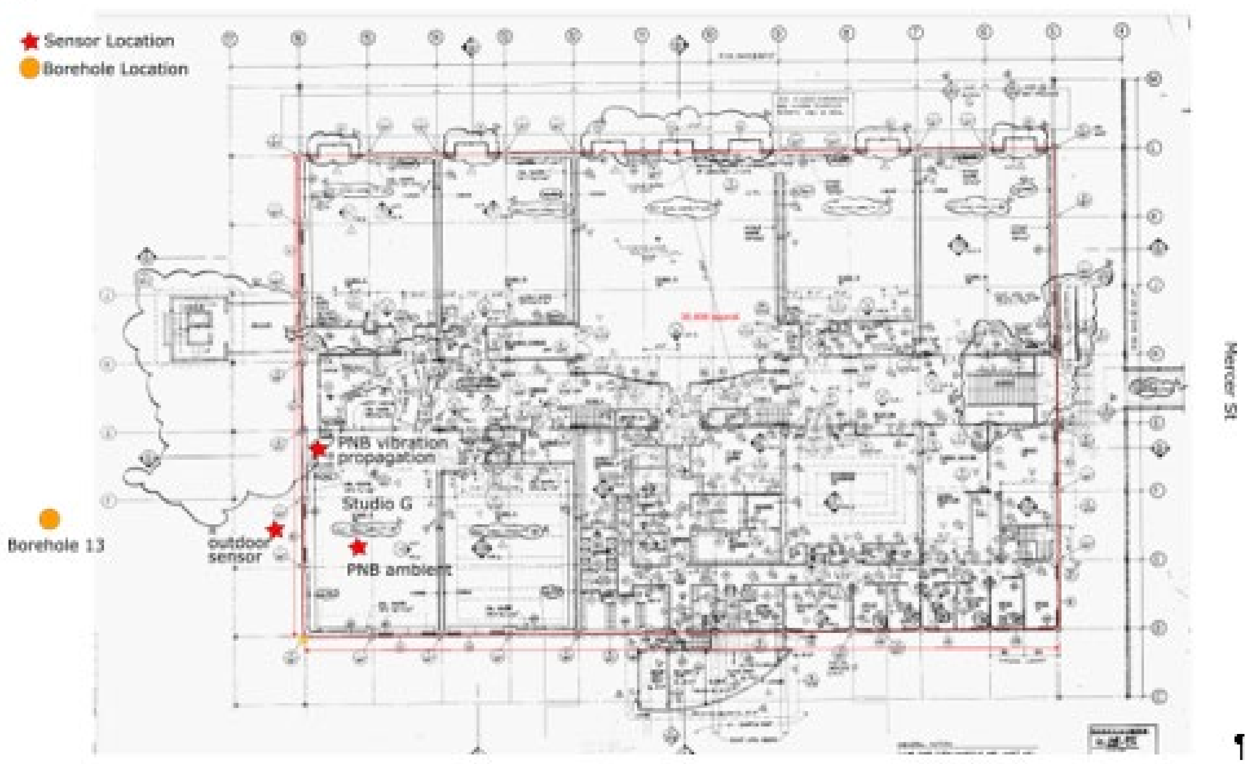

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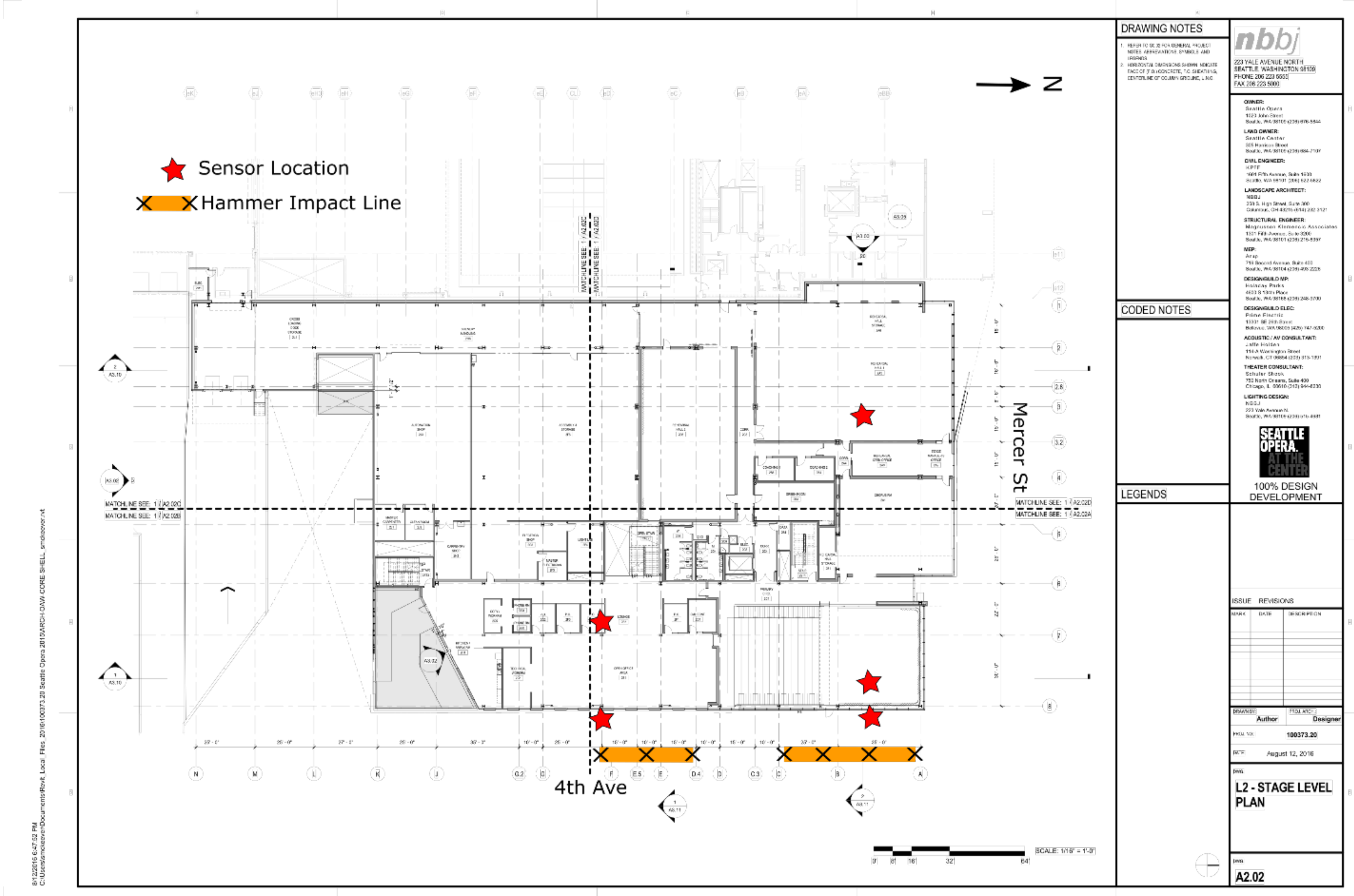
Figure 6-17. Seattle Opera Center Floor Plan



6.4 Vibration Propagation Measurement Results and Predicted Levels

The borehole and surface vibration propagation tests measure the P.S.T.M., a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the P.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The P.S.T.M. and coherence results for the indoor measurement positions and their closest outdoor measurement position are shown in Figures 6-18 through 6-24. For the borehole measurement, data were collected at three depths: 80 feet, 90 feet, and 100 feet. The data for each sensor are plotted with the same color and marker, with dashes indicating the data from different depths. For the surface measurements, data were collected at multiple hammer impact positions, and the data are indicated similar to the different borehole depths. Observations from the P.S.T.M. and coherence results are as follows:

- The McCaw Hall main hall has lower coherence compared to the lecture hall, even though the lecture hall is farther from the borehole. This might be because the lecture hall has lower ambient vibration levels. Low coherence due to high ambient vibration levels indicates the P.S.T.M. in the main hall is likely overestimated.
- The Exhibition Hall, which is in the basement level of the Pacific Northwest Ballet building, has good coherence, indicating confidence in the results.
- The Pacific Northwest Ballet P.S.T.M. has low coherence but relatively low P.S.T.M. levels, which indicates that there is poor vibration transmission into the space.
- The Seattle Opera concert hall P.S.T.M. has high coherence, but much lower P.S.T.M. levels compared to the outdoor sensor, which gives high confidence that the building is effectively attenuating the vibration.
- The Seattle Opera rehearsal hall has low coherence, which indicates the vibration is not effectively transmitted from the ground level (where the concert hall is) up to the second level rehearsal spaces.
- The broadcast booth has low coherence, which indicates good vibration isolation of the booth.

Figure 6-18. P.S.T.M. and Coherence in McCaw Hall Main Hall

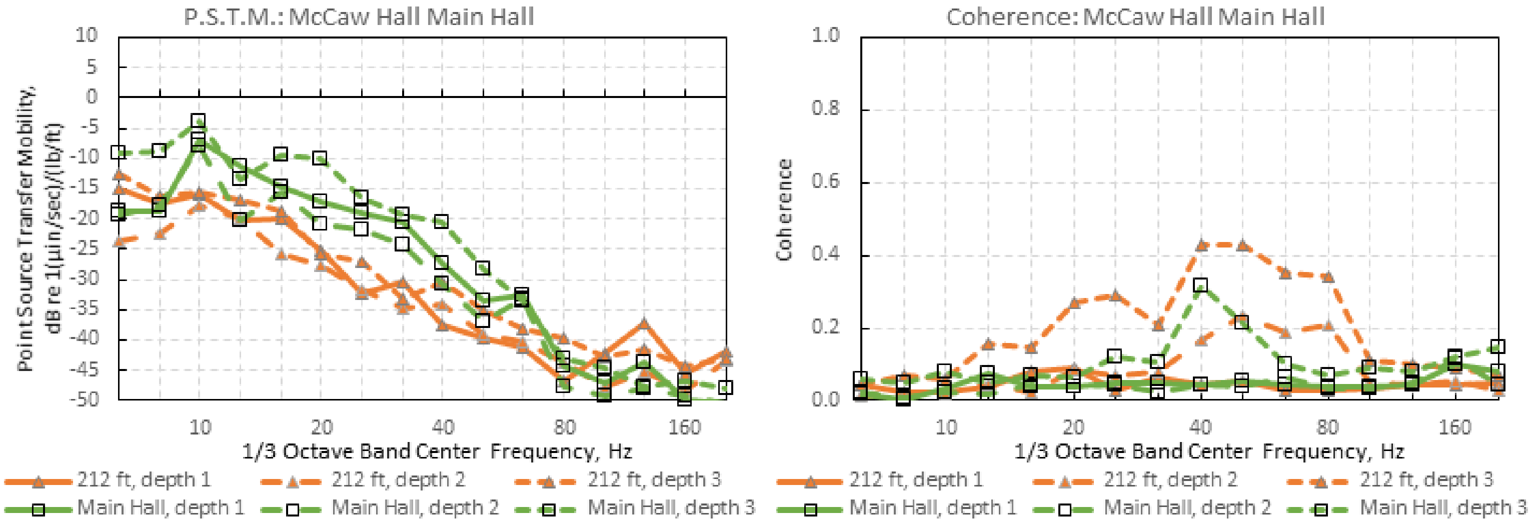


Figure 6-19. P.S.T.M. and Coherence in McCaw Hall Lecture Hall

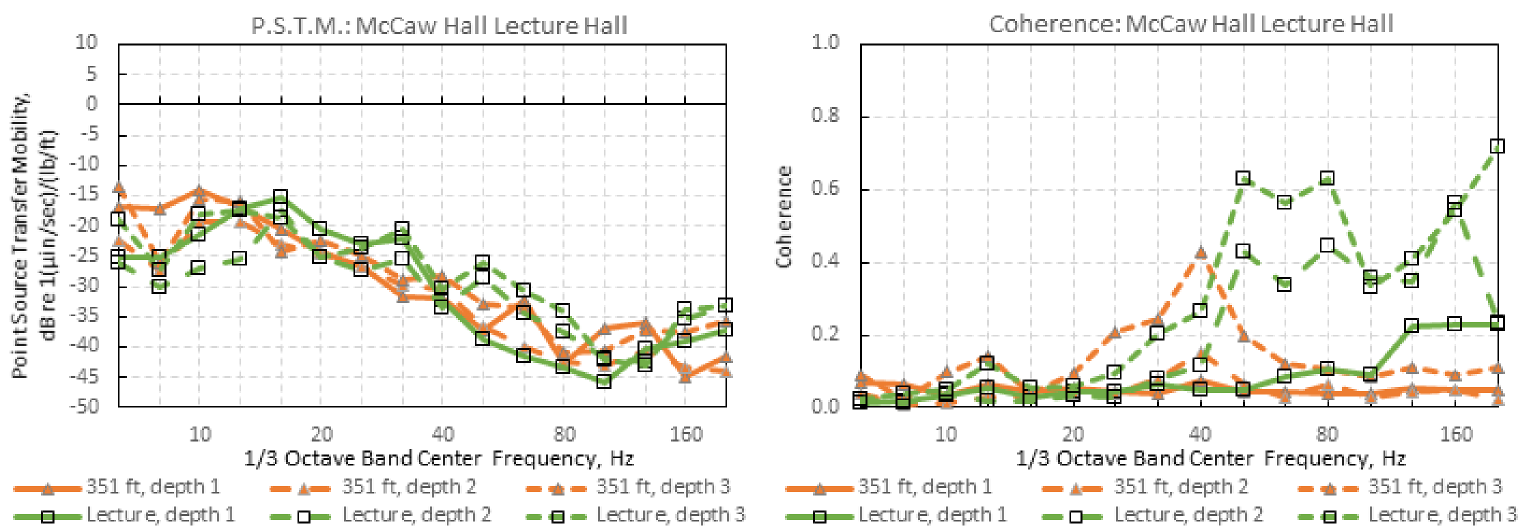


Figure 6-20. P.S.T.M. and Coherence in Exhibition Hall

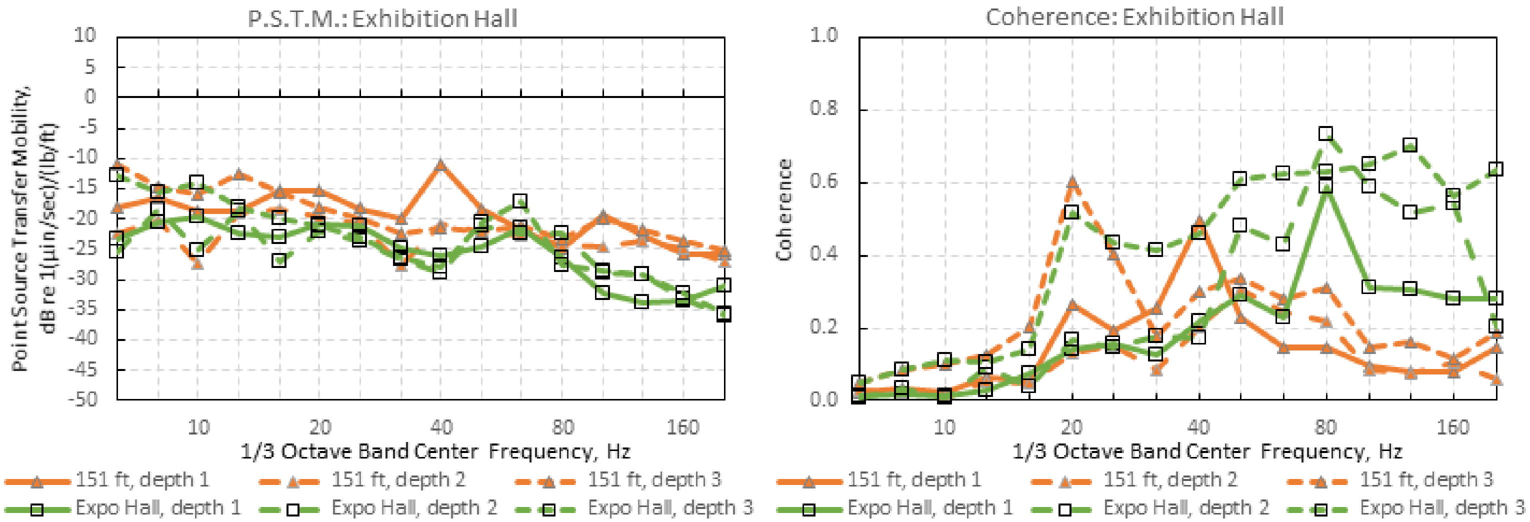


Figure 6-21. P.S.T.M. and Coherence in Pacific Northwest Ballet Studio G

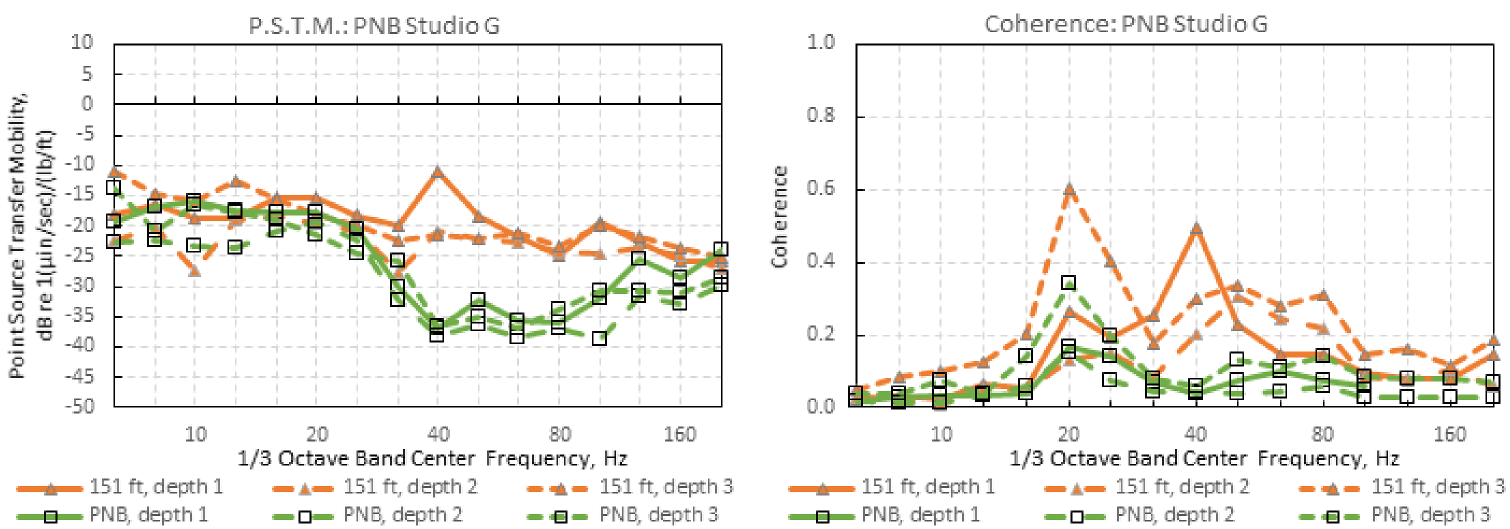


Figure 6-22. P.S.T.M. and Coherence in Seattle Opera Concert Hall

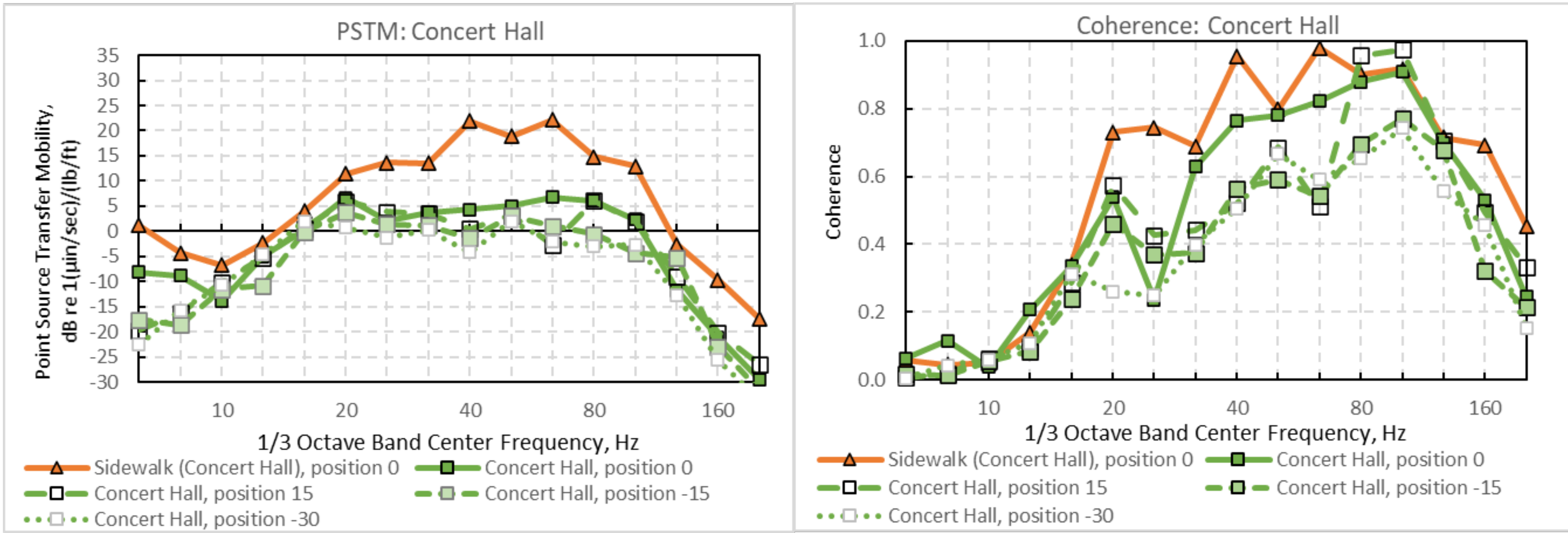


Figure 6-23. P.S.T.M. and Coherence in Seattle Opera Rehearsal Hall

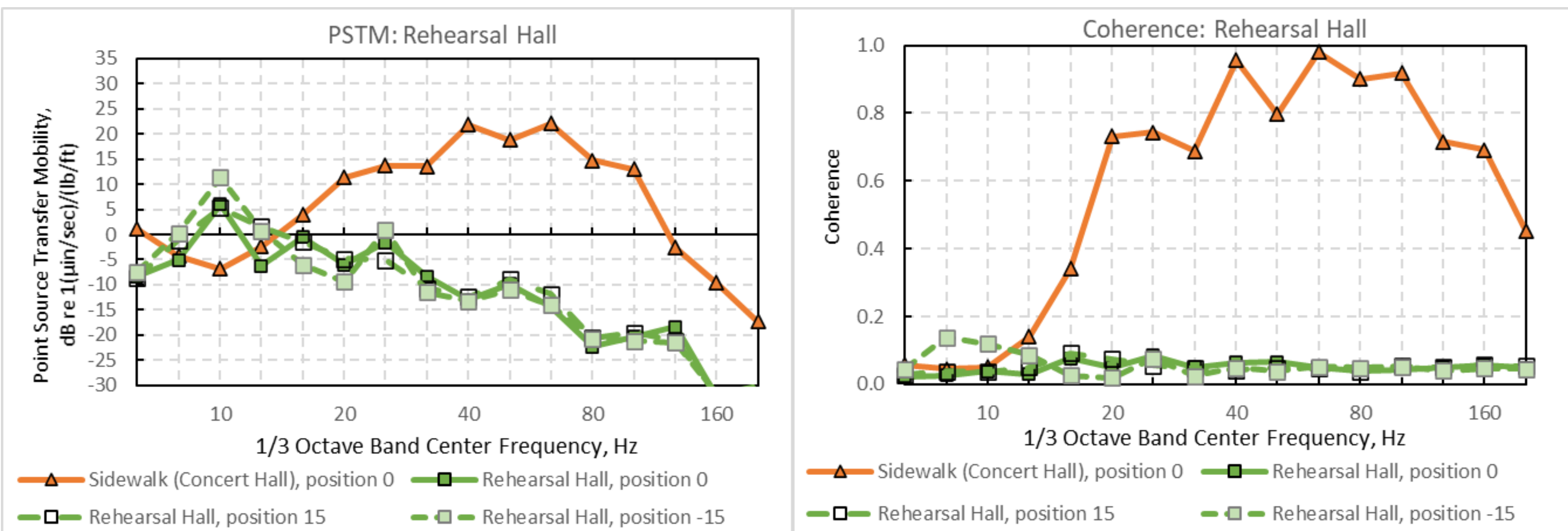
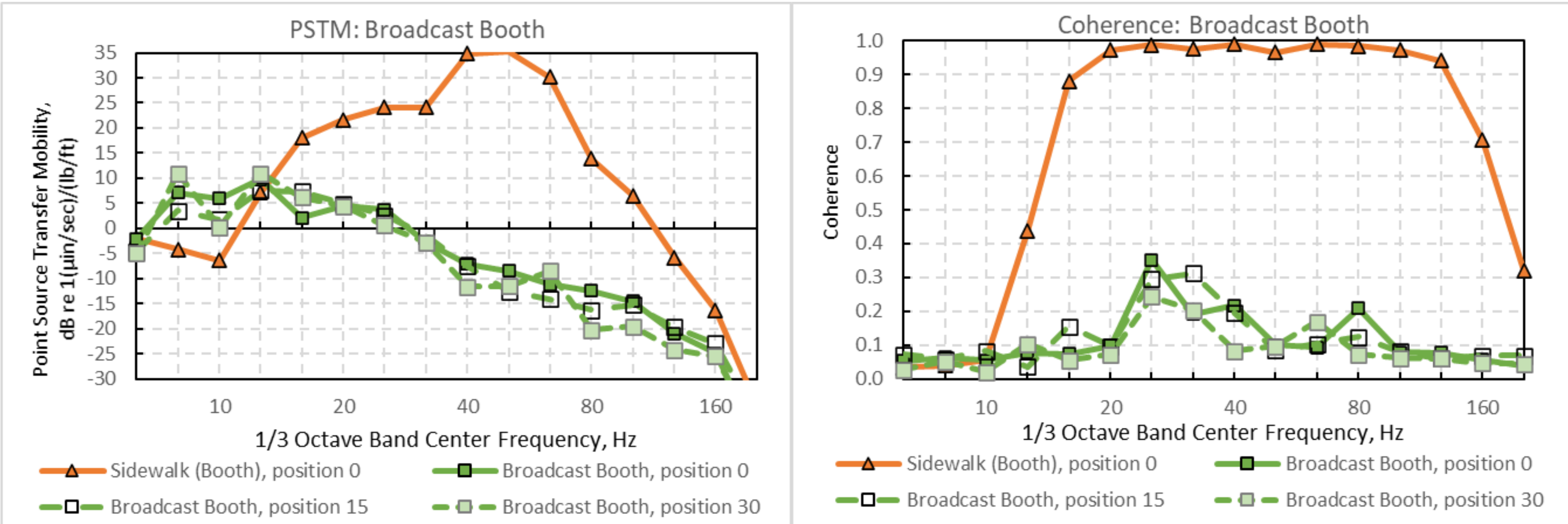


Figure 6-24. P.S.T.M. and Coherence in Seattle Opera Broadcast Booth



The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances is the difference between the outdoor P.S.T.M. at an equivalent setback distance and the indoor P.S.T.M. The building adjustment for the McCaw Hall and Pacific Northwest Ballet measurement sites is an average of the data collected at the 90-foot and 100-foot borehole depths. The data from the 80-foot borehole depth were not included because of unrepresentative results at that depth; the unrepresentative results were likely caused by movement of the borehole force sensor in soft soil, which generated unreliable force signals. The building adjustment applied for the Seattle Opera Center indoor measurement positions is an average of three surface impact points.

The measured building adjustments are shown in Figure 6-25 and Figure 6-26. Following are observations from the building adjustment:

- The McCaw Hall main hall has a higher building adjustment than the lecture hall. This is expected because the lecture hall floor is slab-on-grade, but the main hall is a suspended floor with ducts and vents underneath. However, the building adjustment for the main hall might also be an overestimate due to higher ambient vibration levels in that space.
- The Exhibition Hall building adjustment is generally between 0 decibel and -5 decibel. This is typical of slab-on-grade construction.
- The Pacific Northwest Ballet studio building adjustment is showing vibration reduction at frequencies 40 hertz and above. The data show significant vibration reduction as vibration travels from the Exhibition Hall on the basement level up to the studio level. The high reduction may be the result of retrofits completed to convert the space used by Pacific Northwest Ballet.
- The Seattle Opera rehearsal hall and broadcast booth show similar results with some amplification below 15 Hertz and high attenuation at higher frequencies, indicating good vibration attenuation.
- The Seattle Opera concert hall building adjustment is generally between -5 decibels and -15 decibels, and shows a spectral shape similar to many large slab-on-grade buildings.

Figure 6-25. Measured Building Adjustment at McCaw Hall and Pacific Northwest Ballet

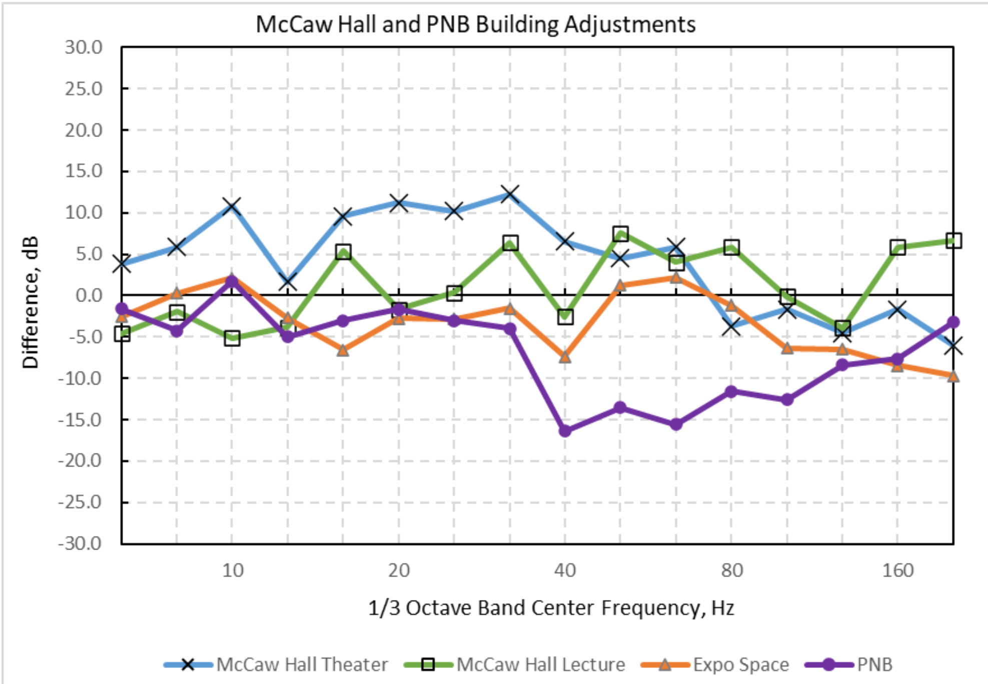
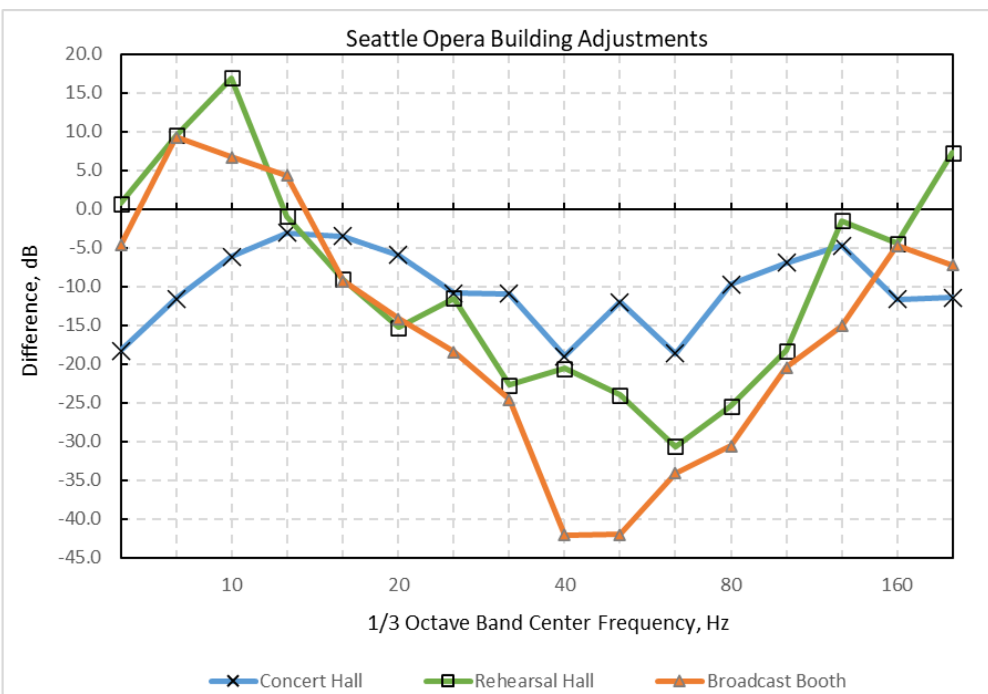


Figure 6-26. Measured Building Adjustment at Seattle Opera Center



For McCaw Hall and Pacific Northwest Ballet, the predicted levels for the Downtown Segment's Preferred Alternative DT-1 use the L.S.T.M. coefficients from site V-13 near McCaw Hall and Pacific Northwest Ballet on August Wilson Way. The predicted levels for Alternative DT-2 use the L.S.T.M. coefficients for site V-14 near the Cornish Playhouse adjacent to Mercer Street.

Different coefficients were used for Alternative DT-2 because that borehole was closer to the Mercer Street alignment. The L.S.T.M. levels were higher for site V-14 compared to site V-13.

For Seattle Opera Center, the predicted levels for both alternatives use the L.S.T.M. coefficients from site V-12 adjacent to the Seattle Opera Center on 4th Avenue, which was located between the two alternative alignments.

The prediction model applies the building adjustments shown in Figures 6-25 and Figure 6-26 to each individual space. No safety factor is included in the predictions because the predictions use site-specific L.S.T.M. levels and there is a 3-decibel safety factor incorporated into the force density level. Tables 6-2 and 6-3 present the predicted levels for Preferred Alternative DT-1 and Alternative DT-2, respectively. The spectra of the predicted vibration levels for Preferred Alternative DT-1 are presented in Figures 6-27 and 6-28. The spectra of the predicted levels for Alternative DT-2 are presented in Figure 6-29 and 6-30.

Tables 6-2 and 6-3 show there is no predicted impact for either Downtown Segment alternative. Compared to the Northwest Rooms and Theatres in the Seattle Center, the McCaw Hall, Seattle Opera Center and Pacific Northwest Ballet building are farther from the proposed alignments and did not show significant building amplification. No vibration mitigation is proposed for McCaw Hall, Seattle Opera Center, or the Pacific Northwest Ballet building.

Table 6-2. Predicted Vibration and Groundborne Noise Levels at McCaw Hall, Pacific Northwest Ballet, and Seattle Opera Center with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
McCaw Hall Main Hall	278	45	55	65	0	25	Does not exceed
McCaw Hall Lecture Hall	278	45	41	72	5	30	Does not exceed
Exhibition Hall in Pacific Northwest Ballet Basement	205	45	48	72	2	30	Does not exceed
Pacific Northwest Ballet Studios	205	45	47	72	<0	35	Does not exceed
Seattle Opera Concert Hall	347	45	31	65	1	25	Does not exceed
Seattle Opera Rehearsal Hall	347	45	52	72	0	30	Does not exceed
Seattle Opera Broadcast Booth	347	45	43	65	0	25	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 6-3. Predicted Vibration and Groundborne Noise Levels at McCaw Hall, Pacific Northwest Ballet, and Seattle Opera Center for 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
McCaw Hall Main Hall	171	45	56	65	15	25	Does not exceed
McCaw Hall Lecture Hall	171	45	49	72	22	30	Does not exceed
Exhibition Hall in Pacific Northwest Ballet Basement	177	45	48	72	11	30	Does not exceed
Pacific Northwest Ballet Studios	177	45	46	72	11	35	Does not exceed
Seattle Opera Concert Hall	152	45	31	65	3	25	Does not exceed
Seattle Opera Rehearsal Hall	152	45	54	72	4	30	Does not exceed
Seattle Opera Broadcast Booth	152	45	44	72	2	25	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 6-27. Predicted Vibration Level for Preferred 5th Avenue/Harrison Street Alternative (DT-1) at McCaw Hall and Pacific Northwest Ballet

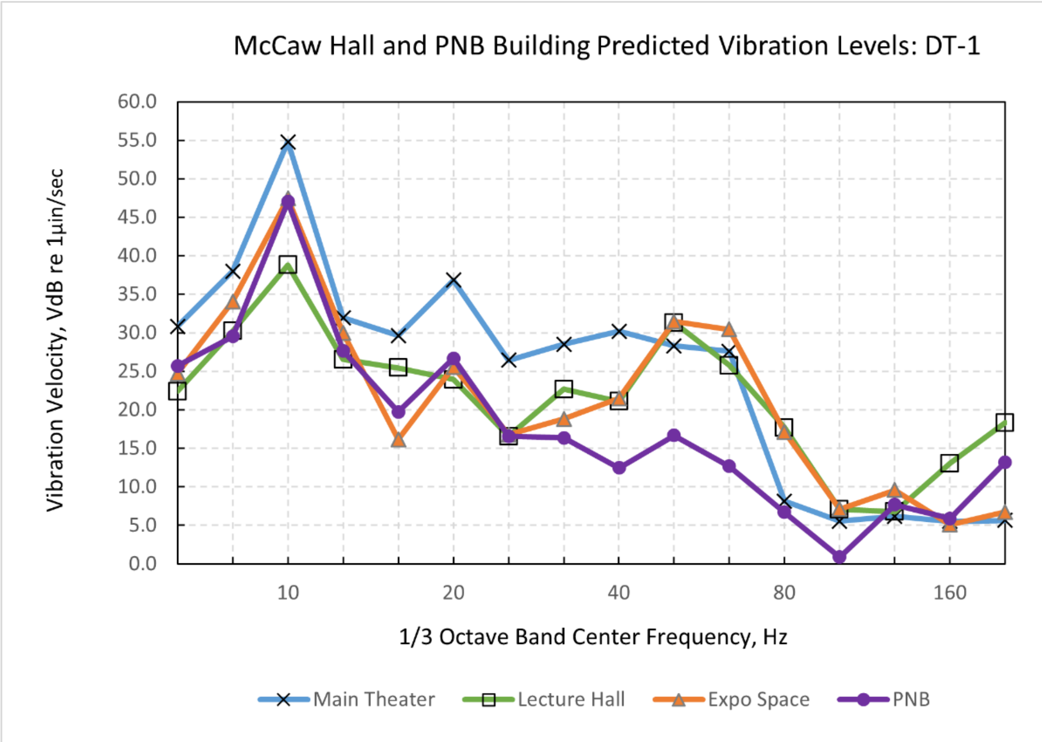


Figure 6-28. Predicted Vibration Level for Preferred 5th Avenue/Harrison Street Alternative (DT-1) at Seattle Opera Center

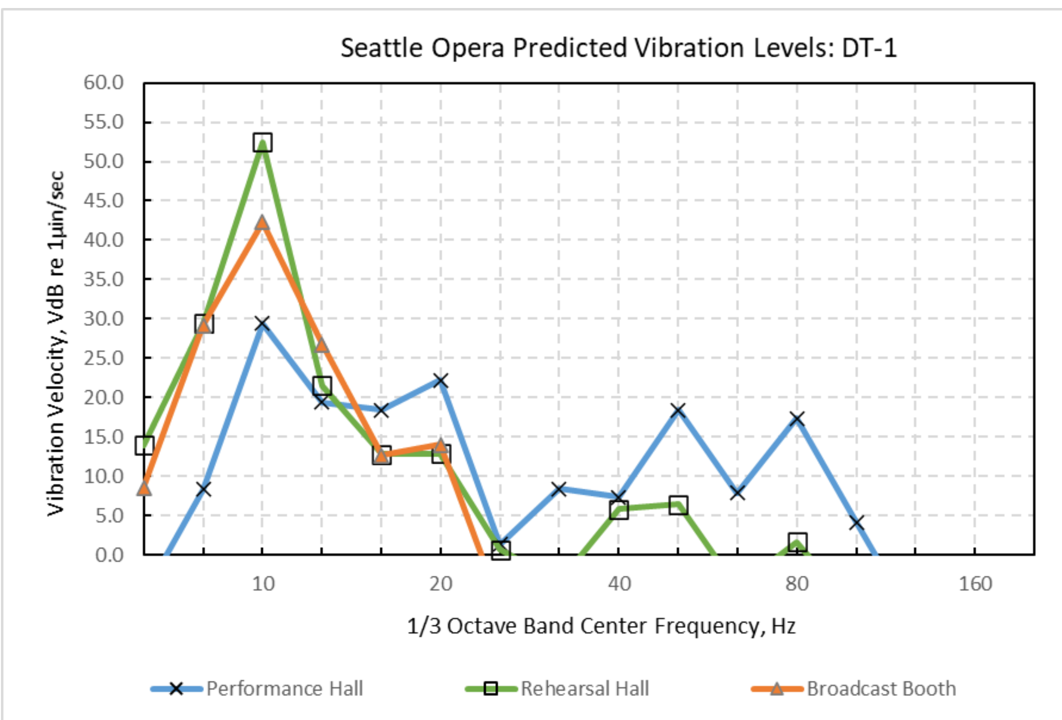


Figure 6-29. Predicted Vibration Level for 6th Avenue/Mercer Street Alternative (DT-2) at McCaw Hall and Pacific Northwest Ballet

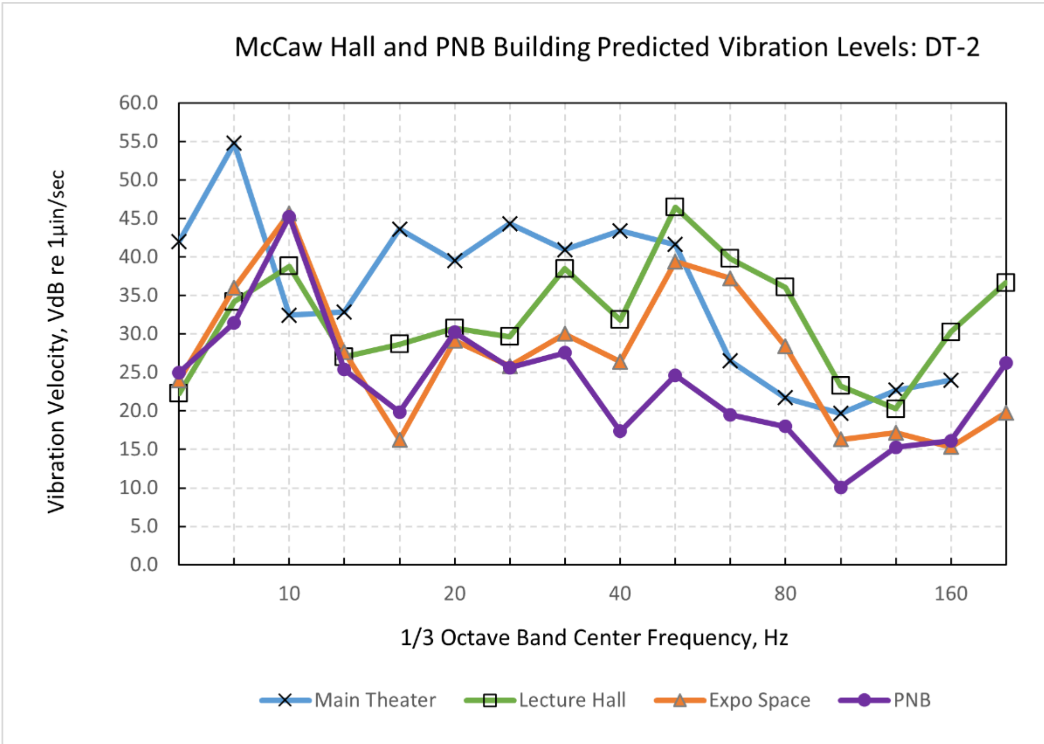
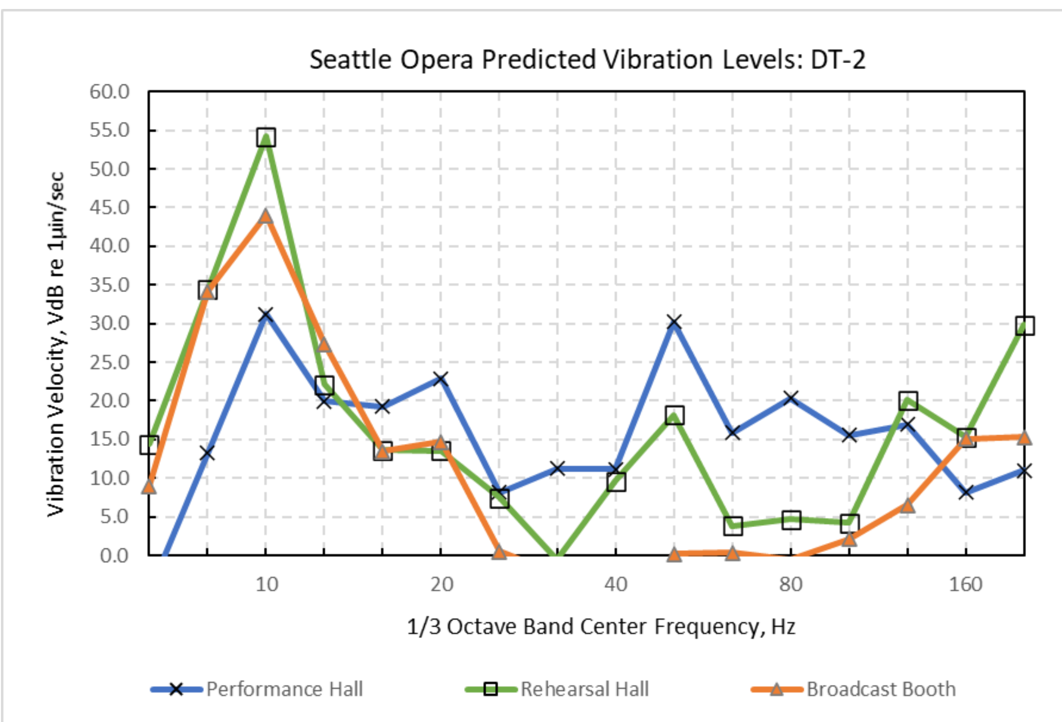


Figure 6-30. Predicted Vibration Level for 6th Avenue/Mercer Street Alternative (DT-2) at Seattle Opera Center



7 SEATTLE CENTER THEATRES – SEATTLE REPERTORY THEATRE AND CORNISH PLAYHOUSE

7.1 Description of Sensitive Space

The Seattle Repertory Theatre (Seattle Rep) and the Cornish Playhouse are in the Seattle Center on Mercer Street on either side of 2nd Avenue along the Ballard Link Extension’s Downtown Segment. The Seattle Rep is at 155 Mercer Street, and the Cornish Playhouse is at 201 Mercer Street. The Seattle Rep building has two theaters: the original Bagley Wright Theater and the Leo K. Theater, which was built as an addition that opened in 1996. The Cornish Playhouse, associated with the Cornish School of the Arts, has one main theater and a smaller rehearsal space behind the main building. Figures 7-1 and 7-2 are photographs of the theater spaces. The FTA “special building” criteria for theaters were applied to the Seattle Rep and Cornish Playhouse theaters.

Figure 7-1. Photographs of Bagley Wright Theater (left) and Bagley Wright Pit (right) at Seattle Rep

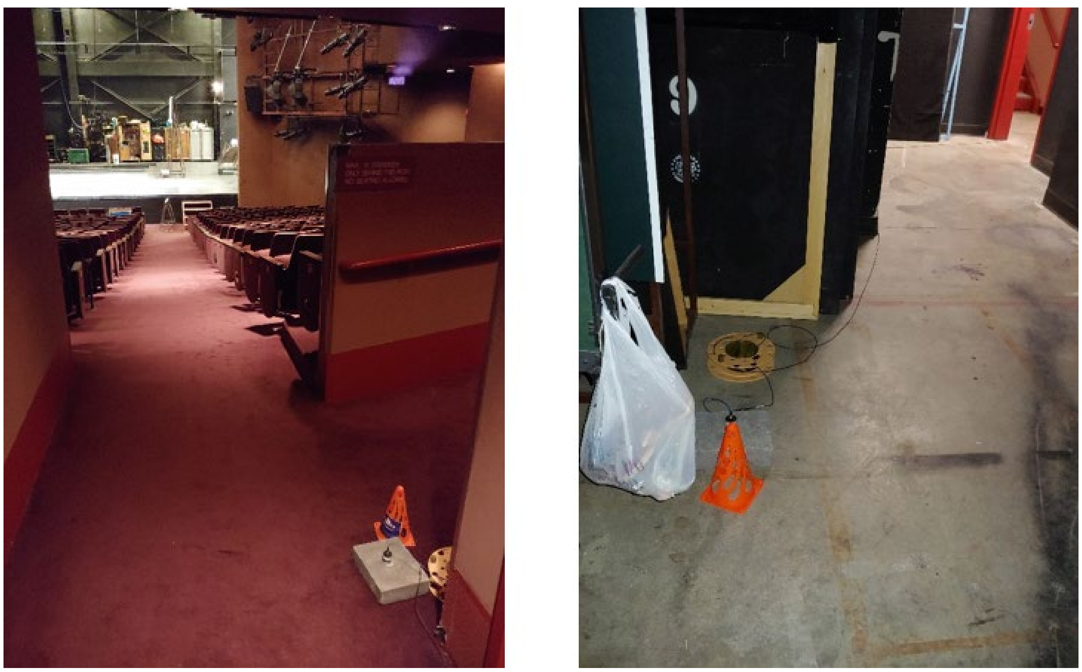
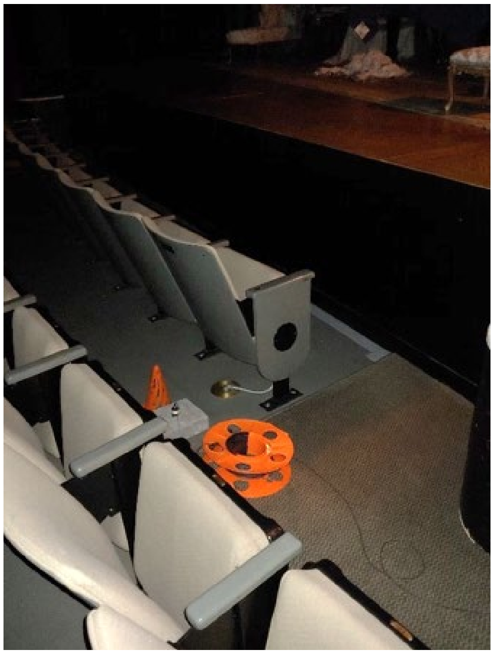
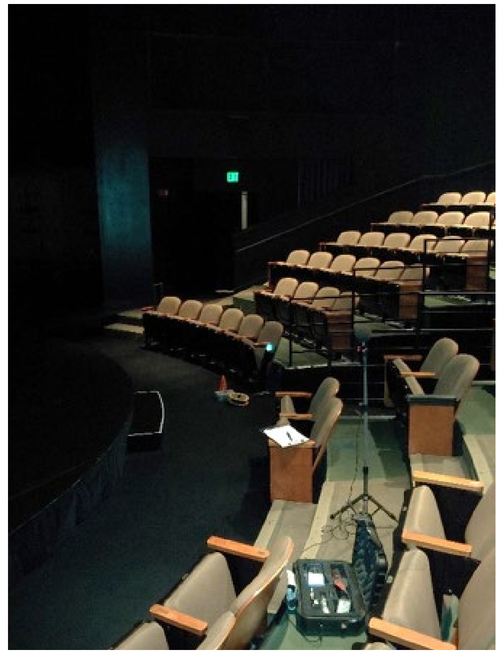


Figure 7-2. Photographs of Leo K. Theater at Seattle Rep (left) and the Cornish Playhouse Theatre (right)





7.2 Existing Noise and Vibration Levels

Existing noise and vibration levels were measured over a 1-hour period in the Seattle Rep and Cornish Playhouse theaters. The measurements at Bagley Wright and the Cornish Playhouse were completed between 5:00 p.m. and 6:00 pm while there was limited activity in the theaters. Staff were told to stay out of the theaters for the duration of the measurement. The measurement at Leo K. Theater was completed the following day, from 12:00 to 1:00 pm. Elevated levels from what was likely staff entering the spaces during the measurement are plotted in gray and are not included in the 1-hour Leq calculations.

The measured 1-hour Leq noise and vibration levels are shown in Table 7-1. The 1-second noise levels are plotted in Figures 7-3 and 7-4. The 1-second vibration levels are plotted in Figures 7-5 and 7-6, and the spectra of the vibration levels are plotted in Figure 7-7. Unrepresentative high levels plotted in gray were removed from the Leq calculations. The measured data show the following:

- The Leo K. Theater has the highest existing vibration levels, with relatively low noise levels.
- The Bagley Wright Theater shows a peak in the vibration levels at 40 hertz, which may be from a floor resonance. None of the other spaces show strong spectral peaks, although the Leo K. Theater has higher levels at 80 hertz compared to the other spaces.
- The Cornish Playhouse has lower noise and vibration levels compared to the Seattle Rep spaces.

Table 7-1. Background Noise and Vibration Levels at Seattle Rep and Cornish Playhouse

Monitoring Location	Noise level (1-hour Leq)	Vibration level (1-hour Leq)
Bagley Wright Theater, Seattle Rep	35 dBA	45 VdB
Bagley Wright Pit, Seattle Rep	Not measured	43 VdB
Leo K. Theater, Seattle Rep	30 dBA	49 VdB
Cornish Playhouse Theatre	25 dBA	39 VdB

Figure 7-3. Measured 1-second Noise Levels in Bagley Wright Theater and Leo K. Theater at Seattle Rep

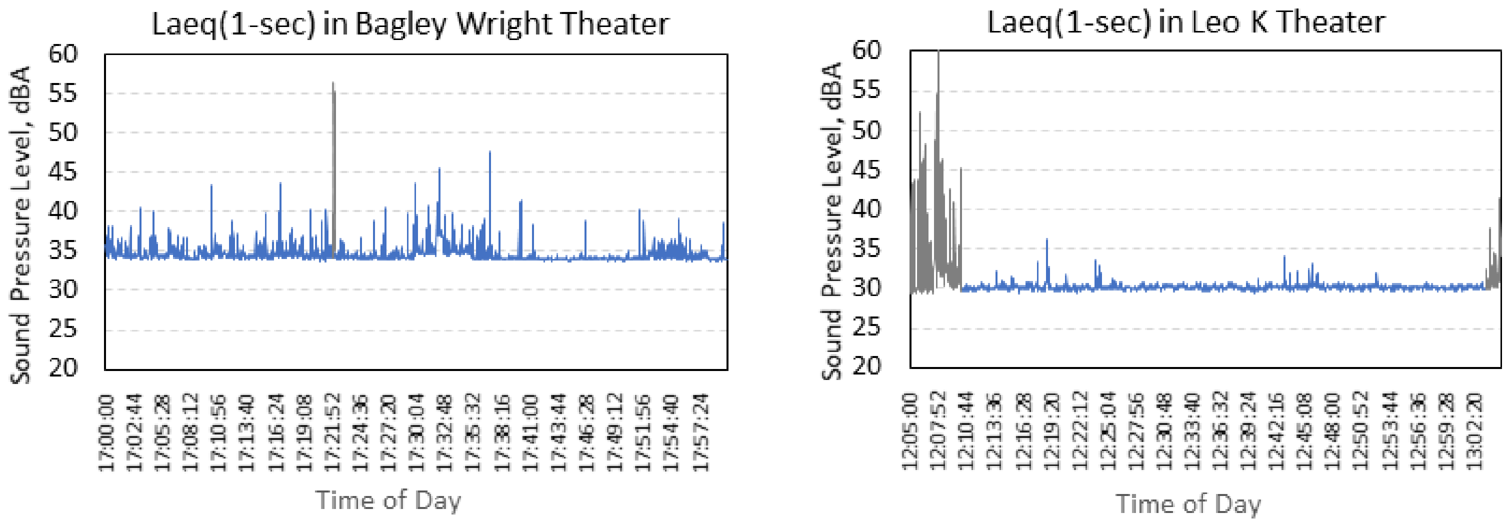


Figure 7-4. Measured 1-second Noise Levels in the Cornish Playhouse Theatre

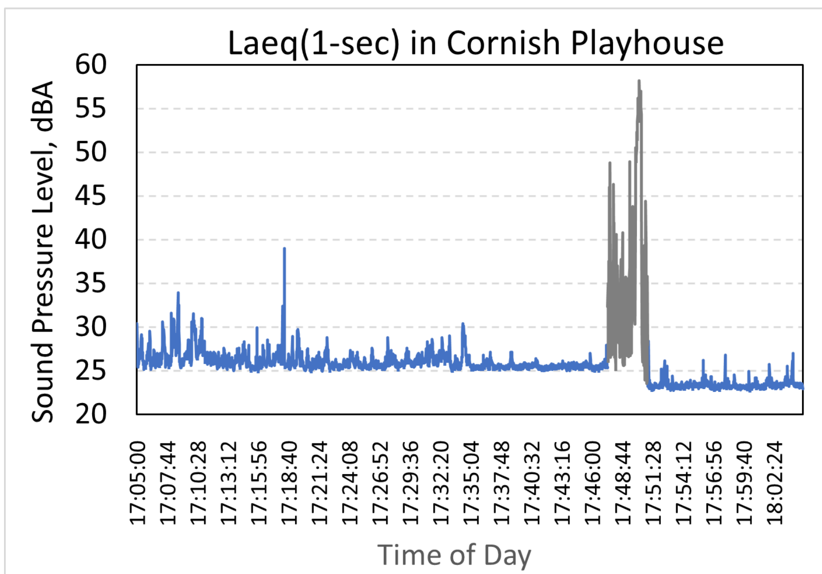


Figure 7-5. Measured 1-second Vibration Levels in Bagley Wright Theater and Pit at Seattle Rep

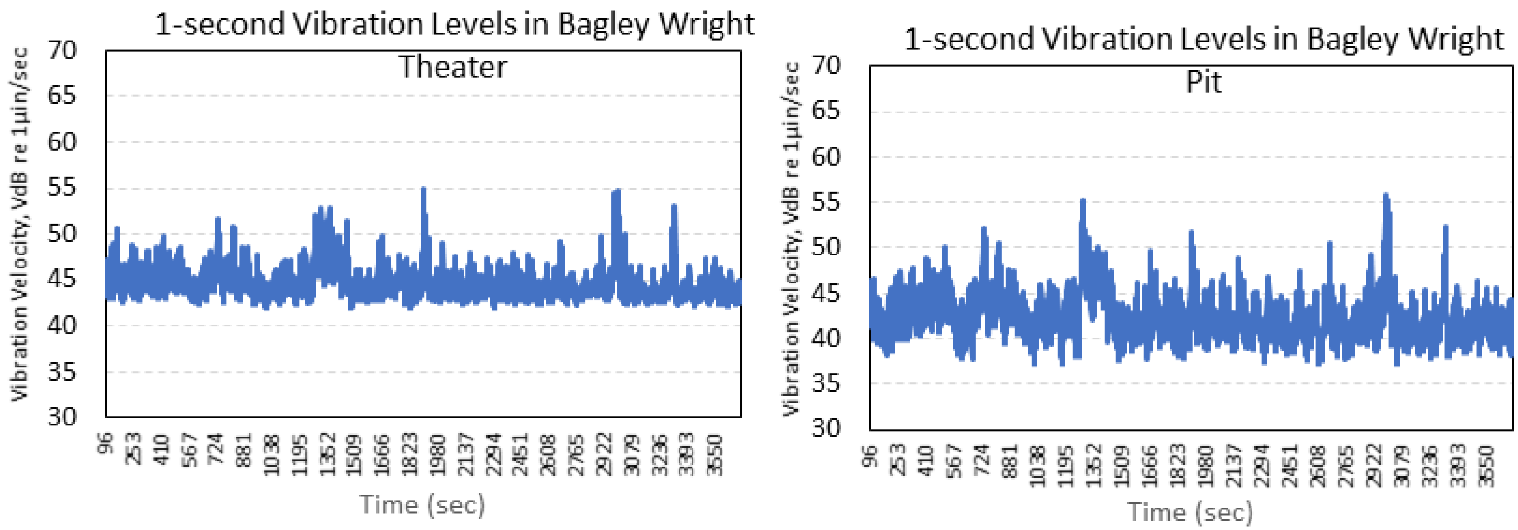


Figure 7-6. Measured 1-second Vibration Levels in Leo K. Theater at Seattle Rep and Cornish Playhouse Theatre

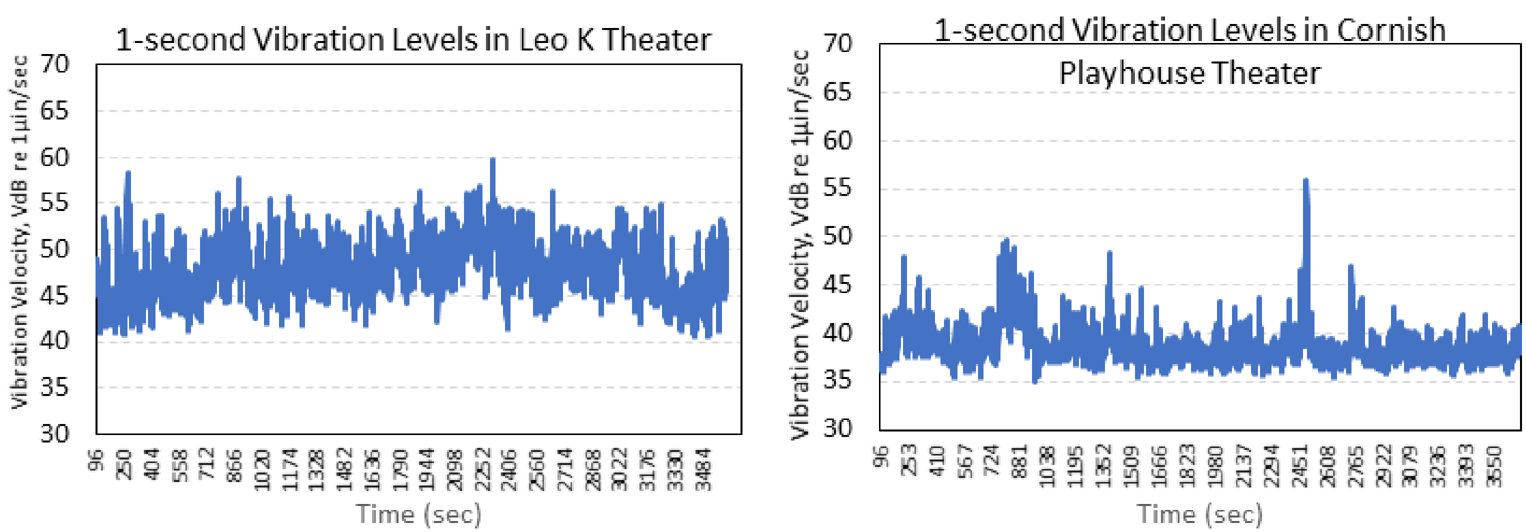
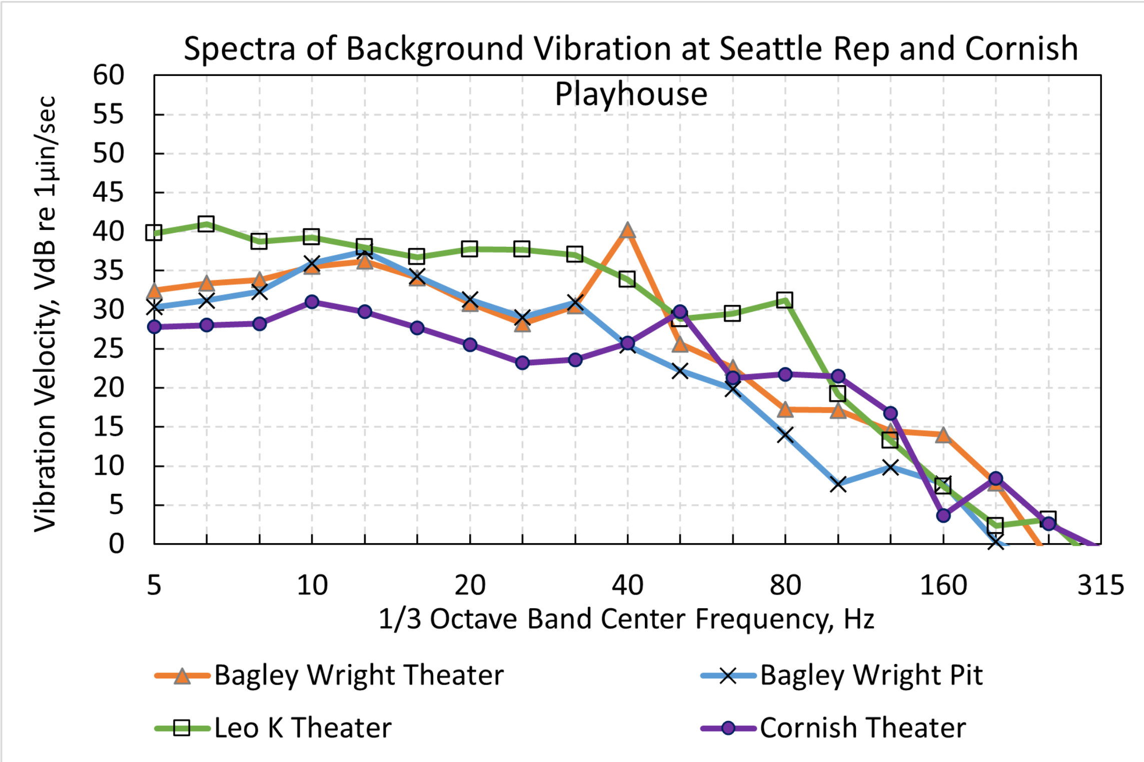


Figure 7-7. Spectra of Background Vibration Levels at Seattle Rep and Cornish Playhouse



7.3 Vibration Propagation Measurement Description

A borehole vibration propagation test was completed at the Seattle Center between the Seattle Rep and Cornish Playhouse buildings near Mercer Street to determine how efficiently vibration would propagate from the approximate depth of the light rail tunnel into the sensitive spaces. The borehole was in the pedestrian walkway on 2nd Avenue close to the Cornish Playhouse, about 40 feet south of Mercer Street. Data were collected from three borehole depths: 90 feet, 100 feet, and 110 feet.

The vibration levels were measured at five indoor locations and six outdoor locations. The outdoor measurement locations were used to quantify how vibration levels decrease with distance from the impact force. The outdoor vibration measurements were also used as a reference to examine how levels change as the vibration travels from the soil into the building structure. The indoor measurements at Seattle Rep and Cornish Playhouse are: (1) Bagley Wright Pit, (2) Bagley Wright Theater, (3) Leo K. Theater, (4) Cornish Playhouse lobby, and (5) Cornish Playhouse theater.

Figures 7-8 and 7-9 show the floor plans of Seattle Rep and Cornish Playhouse with the sensor locations. Approximate locations of the outdoor sensors closest to the building and the borehole position are also indicated.

Figure 7-8. Seattle Rep Floor Plan with Sensor Locations

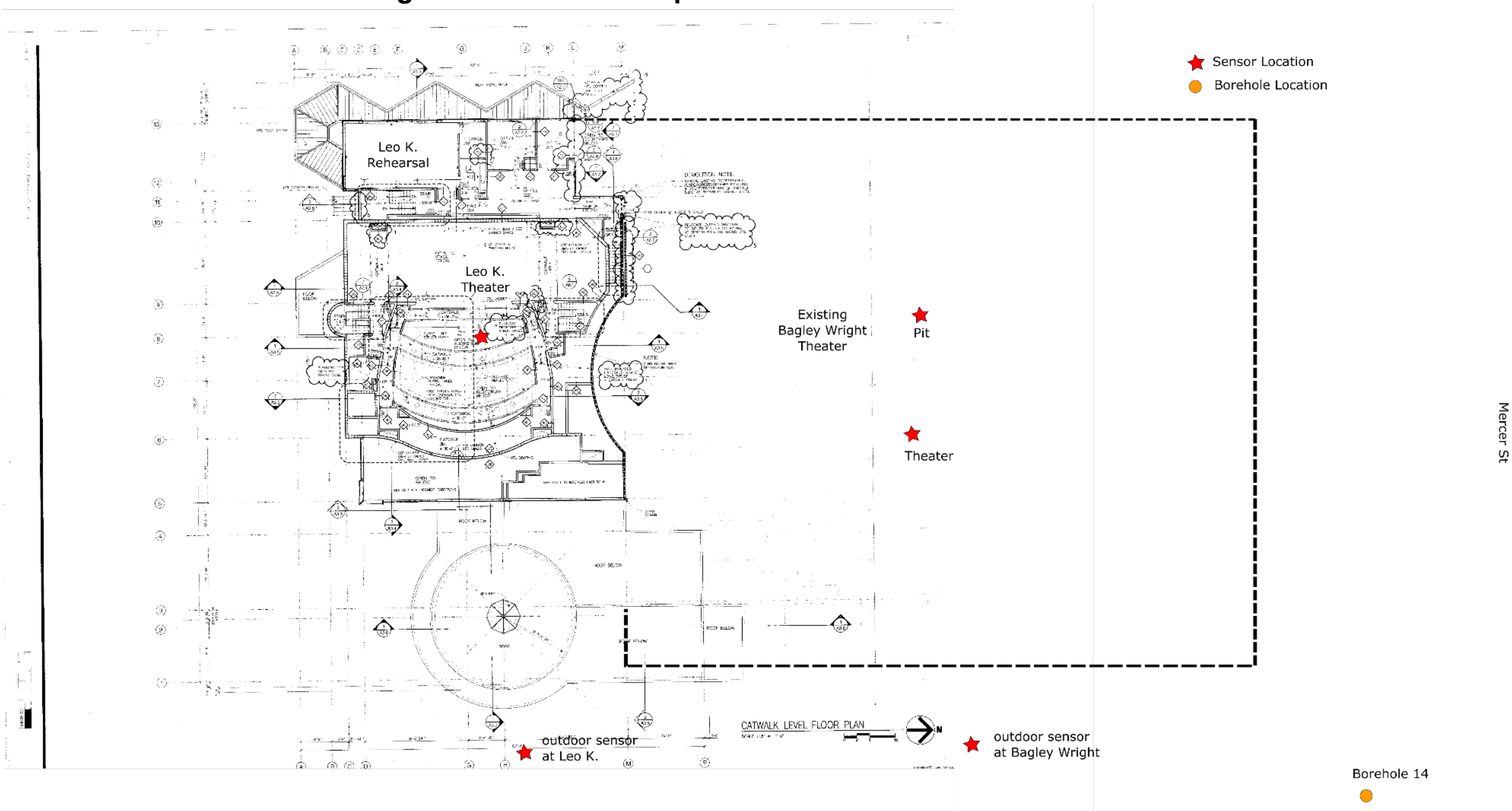
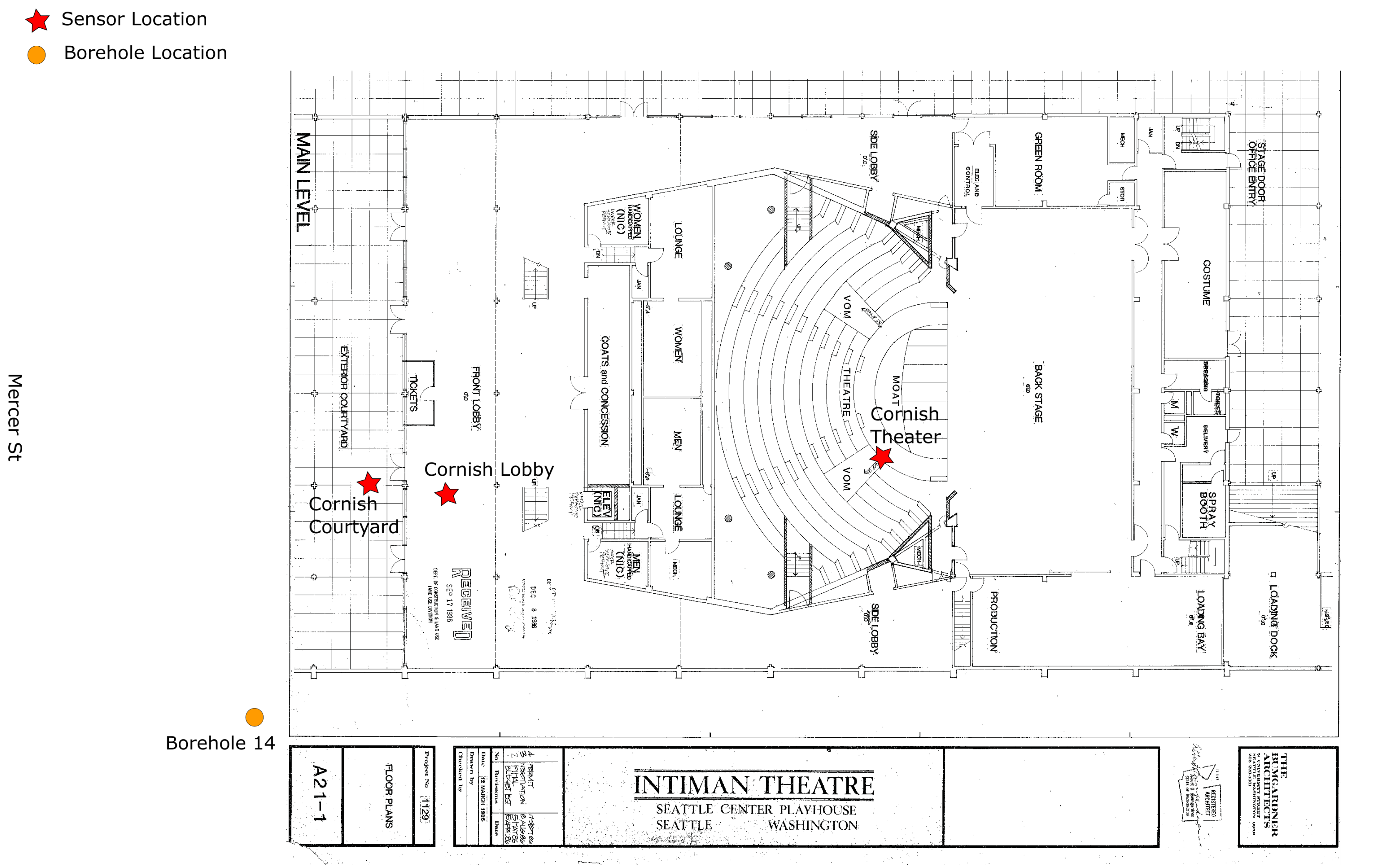


Figure 7-9. Cornish Playhouse Floor Plan with Sensor Locations



7.4 Vibration Propagation Measurement Results and Predicted Levels

The borehole vibration propagation tests measure the P.S.T.M. Coherence is a measure of the quality of the L.S.T.M. results and varies between 0 and 1. A coherence of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The P.S.T.M. and coherence results for the indoor measurement positions and their closest outdoor measurement position are shown in Figures 7-10 through 7-13. Data collected from one sensor at multiple depths are shown in the same color with dashed lines. Following are observations from the P.S.T.M. and coherence results:

- Coherence results are above 0.2 for frequencies above 20 hertz for both the indoor and outdoor measurement positions. This indicates good quality data.
- The P.S.T.M. levels are very similar for the three measurement depths (90 feet, 100 feet, and 110 feet).
- The P.S.T.M. levels for the Leo K. Theater at Seattle Rep show higher levels compared to the outdoor sensor location and the other indoor locations. The high coherence levels at the Leo K. Theater is unusual for a measurement location more than 300 feet from the borehole, but this indicates the high P.S.T.M. levels represent valid data, rather than artificially high levels from a poor signal-to-noise ratio.

Figure 7-10. P.S.T.M. and Coherence in Cornish Playhouse

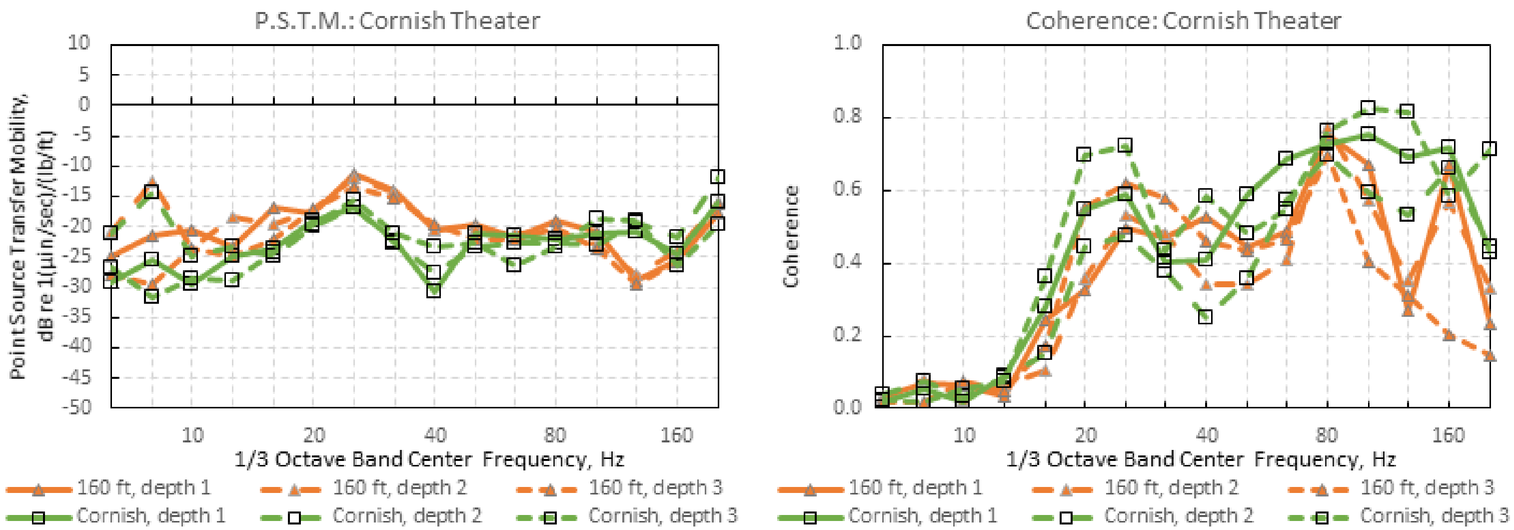


Figure 7-11. P.S.T.M. and Coherence in Seattle Rep Bagley Wright Pit

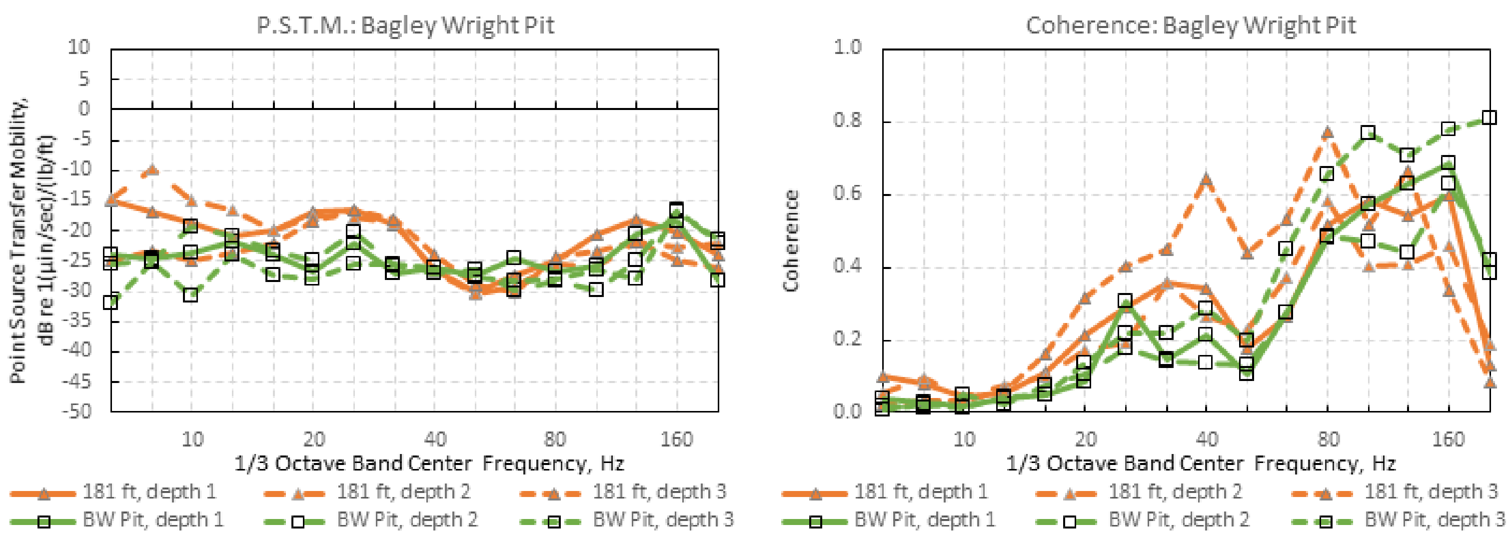


Figure 7-12. P.S.T.M. and Coherence in Seattle Rep Bagley Wright Theater

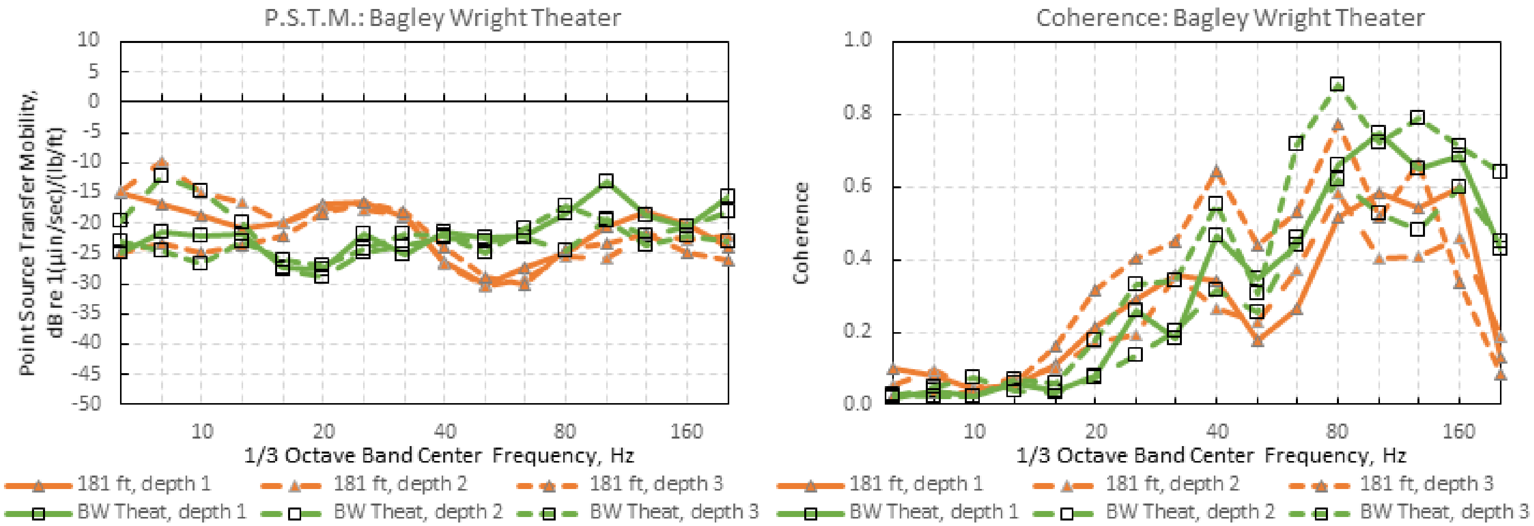
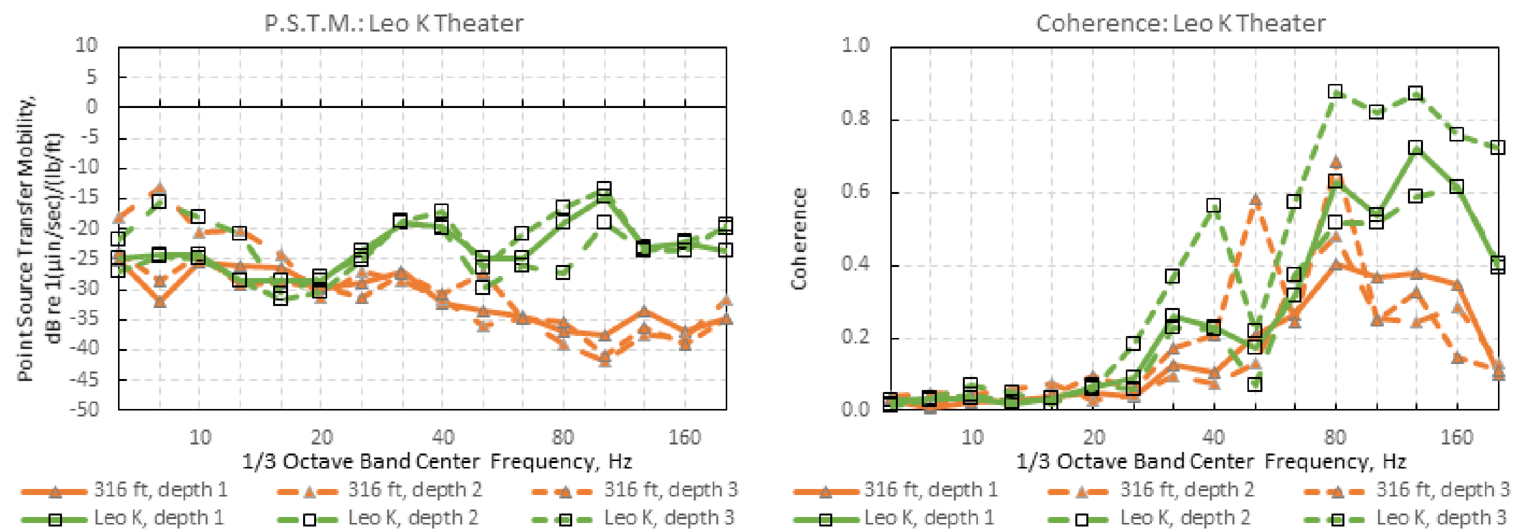


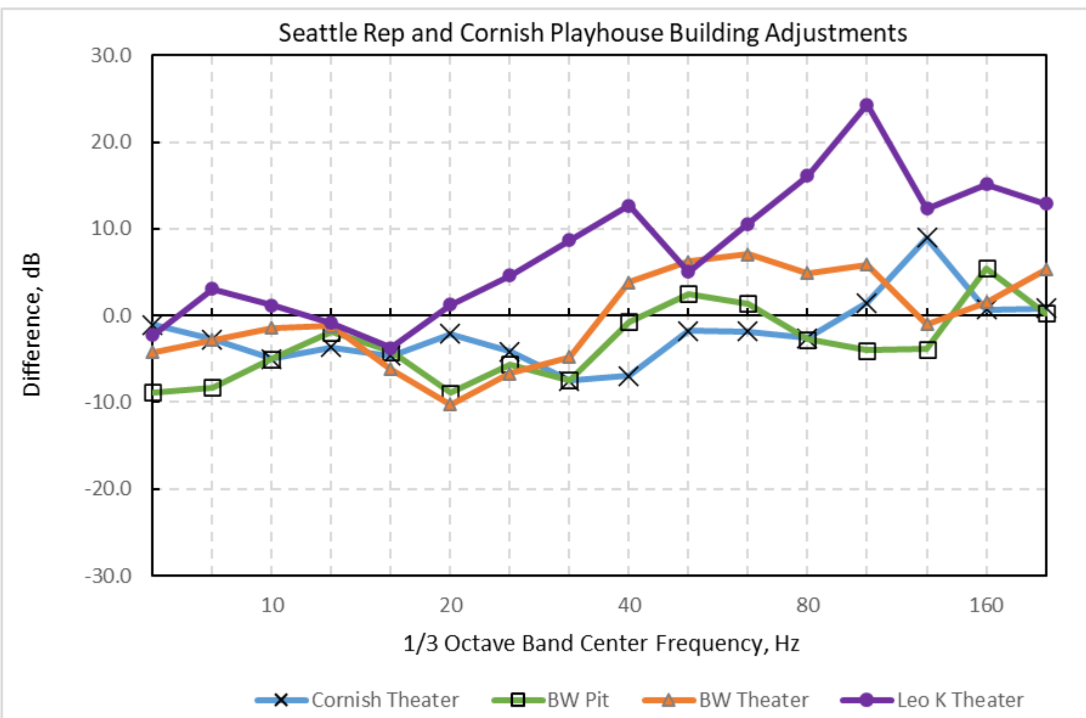
Figure 7-13. P.S.T.M. and Coherence in Seattle Rep Leo K. Theater



The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances is the difference between the outdoor P.S.T.M. at an equivalent setback distance and the indoor P.S.T.M. Where data were collected at multiple depths, the building adjustment from multiple depths was averaged. The building adjustment for the sensitive spaces where measurements were completed at the Cornish Playhouse and Seattle Rep are shown in Figure 7-14. Following are observations from the building adjustment:

- The Cornish Playhouse theater shows the building structure is attenuating vibration levels at mid-frequencies and 10 decibels of amplification in the 125 hertz 1/3-octave band.
- The Bagley Wright Pit and Theater show similar trends, but the theater shows amplification about 5 decibels higher than the Pit, from 40 hertz to 100 hertz. This is expected because the Pit floor is slab-on-grade, the theater is suspended over the Pit, and suspended floors are more likely to show resonances.
- The Leo K. Theater shows high levels of amplification above 20 hertz. The high levels of amplification might be related to the theater being constructed as an addition to the original Bagley Wright Theater structure.

Figure 7-14. Measured Building Adjustment at Seattle Rep and Cornish Playhouse



The predicted levels for Preferred Alternative DT-1 are presented in Table 7-2 and use the L.S.T.M. coefficients from site V-15 near the Seattle Center Northwest Rooms on Republican Street. The predicted levels for Alternative DT-2 are presented in Table 7-3 and use the L.S.T.M. coefficients for site V-14 near the Cornish Playhouse adjacent to Mercer Street. The L.S.T.M. levels are higher for site V-15 compared to site V-14. The building adjustment presented in Figure 7-14 was used in the predictions for both Downtown Segment alternatives. The spectra of predicted levels are presented in Figures 7-15 and 7-16.

Table 7-2. Predicted Vibration and Groundborne Noise Levels at Seattle Rep and Cornish Playhouse with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Cornish Playhouse Theatre	167	45	54	72	28	35	Does not exceed
Seattle Rep Bagley Wright Theater	121	30	63	72	37	35	2
Seattle Rep Leo K. Theater	121	30	70	72	48	35	13

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 7-3. Predicted Vibration and Groundborne Noise Levels at Seattle Rep and Cornish Playhouse with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Cornish Playhouse Theatre	175	45	44	72	17	35	Does not exceed
Seattle Rep Bagley Wright Theater	191	45	47	72	19	35	Does not exceed
Seattle Rep Leo K. Theater	191	45	53	72	28	35	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 7-15. Spectra of Predicted Vibration Levels at Cornish Playhouse and Seattle Rep with Preferred 5th Avenue/Harrison Street Alternative (DT-1)

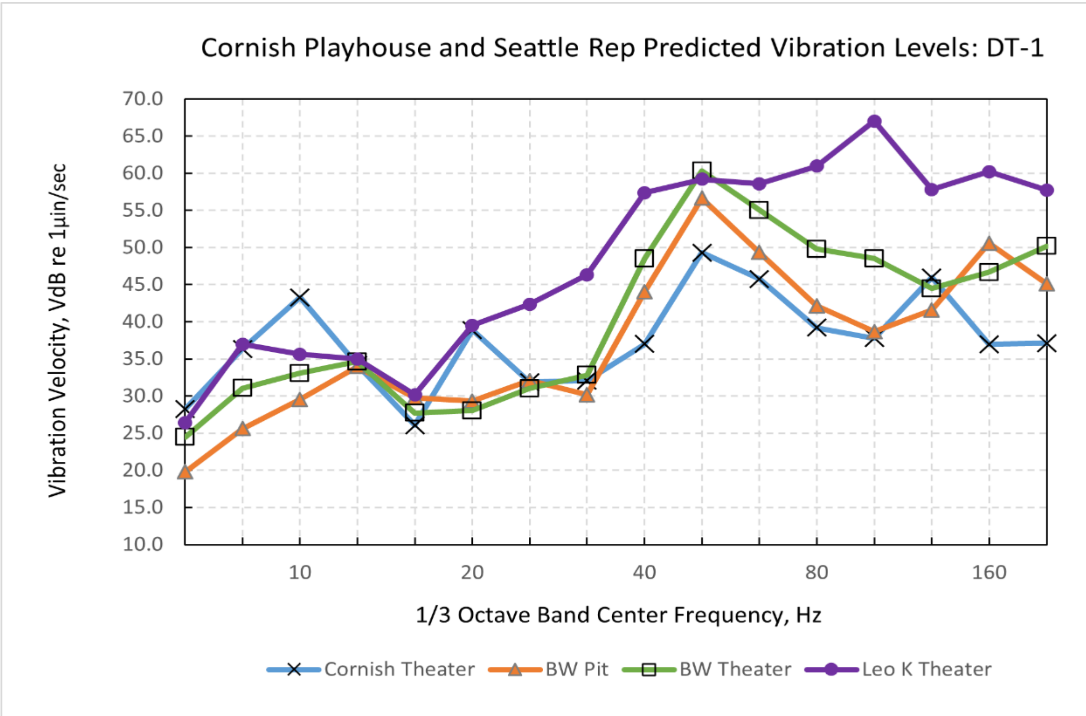
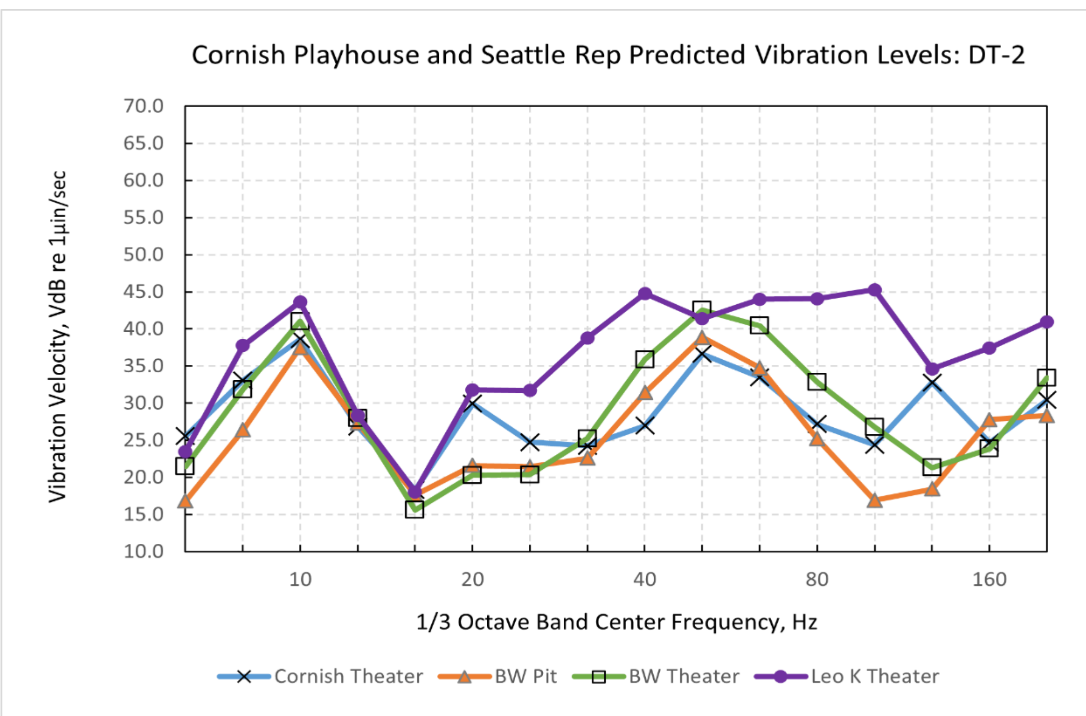


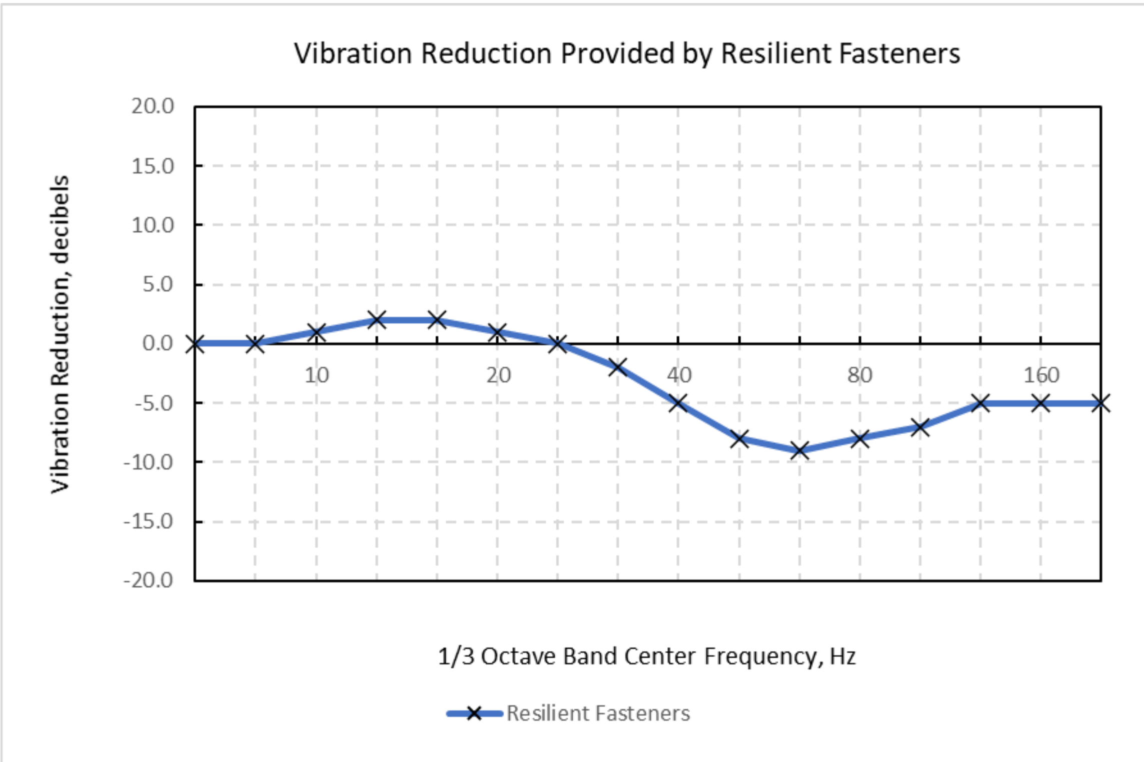
Figure 7-16. Spectra of Predicted Vibration Levels at Cornish Playhouse and Seattle Rep with 6th Avenue/Mercer Street Alternative (DT-2)



Groundborne noise is predicted to impact Preferred Alternative DT-1 in the Bagley Wright Theater and Leo K. theaters at Seattle Rep. There is no predicted impact for Alternative DT-2 because the alternative alignment would be farther away from the sensitive spaces and because there is less efficient vibration propagation from Mercer Street compared to Republican Street.

The proposed mitigation measure for Preferred Alternative DT-1 is high-resilience fasteners, which are an effective mitigation measure at frequencies 40 hertz and above. Figure 7-17 shows the spectra of the change in vibration provided by the high-resilience fasteners[1]. High-resilience fasteners would reduce the predicted groundborne noise levels to below the impact threshold for the Bagley Wright Theater at Seattle Rep.

Figure 7-17. Spectra of Vibration Reduction Provided by High-Resilience Fasteners



The predicted vibration level with high-resilience fasteners at the Leo K Theater at Seattle Rep is 42 dBA, which is seven decibels above the impact threshold of 35 dBA. However, there are several conservative assumptions in the prediction model at higher frequencies that contribute to over-predicting groundborne noise levels:

- The predicted level does not consider the vibration reduction provided by the light rail tunnel structure. A tunnel structure with no invert is likely to provide 3 decibels to 5 decibels of attenuation, and a tunnel structure with a 1-meter-thick invert might provide up to 10

[1] The vibration reduction from high-resilience fasteners is based on a study completed for the Northgate Link Extension under the University of Washington campus.

decibels of attenuation at the same frequencies (McKenna and Layman 2018; Saurenman et al. 1982).

- The assumed insertion loss for high-resilience fasteners is likely underestimating the reduction at frequencies above 80 hertz. The insertion loss is based on measurements that show 8 decibels to 9 decibels of reduction at 50 hertz to 80 hertz, and only 5 decibels of reduction at frequencies above 100 hertz. The measured decrease in performance at higher frequencies is likely due to lower signal-to-noise ratio at the high frequencies during measurements, and it would be likely that the fasteners achieve equivalent or higher reduction at high frequencies compared to the mid-frequencies.
- The Krad is the radiation factor used to convert the predicted groundborne vibration level to groundborne noise. A Krad value of -5 is used in the prediction model, which is described as a typical value for residences in the FTA *Transit Noise and Vibration Impact Assessment Manual*. However, this is likely an underestimate for a theater, which would have higher noise absorption than a typical residence.
- The L.S.T.M. values are likely overestimated. The Seattle Rep buildings sit between measurement sites V-15 and V-14 but use the outdoor propagation data collected at site V-15. Using the vibration propagation measurements from site V-14, there would be no residual impact after high-resilience fasteners are applied.

The predicted groundborne noise level at the Leo K. Theater is one decibel below the impact threshold, assuming a vibration reduction of 5 decibels from the tunnel structure at 100 hertz and above and a vibration reduction of 9 decibels from high-resilience fasteners at 100 hertz and above. Considering that a -5 decibel reduction in vibration from the light rail tunnel structure, the Krad value, and the L.S.T.M. values are likely conservative estimates at high frequencies, no additional mitigation measures are proposed. However, the insertion loss of the light rail tunnel structure and the expected attenuation of the high-resilience fasteners should be confirmed with modeling during final design when the thickness of the tunnel invert and the stiffness of the high-resilience fasteners are selected.

8 NORTHWEST ROOMS AT SEATTLE CENTER – K.E.X.P., THE VERA PROJECT, AND SEATTLE INTERNATIONAL FILM FESTIVAL FILM CENTER

8.1 Description of Sensitive Space

The Northwest Rooms at the Seattle Center are at the intersection of 1st Avenue North and Republican Street in the northwest corner of the Seattle Center, in the Downtown Segment of the Ballard Link Extension. The facility houses three sensitive land uses that qualify as “special buildings”: K.E.X.P., The Vera Project, and the Seattle International Film Festival (SIFF) Film Center.

8.1.1 K.E.X.P.

K.E.X.P. is a local radio broadcaster at 472 1st Avenue North. The noise- and vibration-sensitive spaces at K.E.X.P. are D.J. booths, edit rooms, a mastering suite, and a large studio with control room where live performances are recorded. The large studio and D.J. booths have floated floors to isolate the spaces from vibration. Non-sensitive spaces at K.E.X.P. include offices and a café. Figures 8-1 and 8-2 show photographs of the sensitive spaces where measurements were completed in K.E.X.P.

The FTA criteria for recording studios were applied to spaces where recording takes place: the large studio and the D.J. booths. The FTA *Transit Noise and Vibration Impact Assessment Manual* does not address the sensitivity of editing or mastering suites. The FTA criteria for auditoriums were applied to the editing rooms, control rooms, and mastering suite because critical listening takes place there. These spaces are not as sensitive as the rooms where recording takes place, and the criteria for auditoriums are the next-most restrictive in the FTA *Transit Noise and Vibration Impact Assessment Manual* after the criteria for recording studios.

Figure 8-1. Photograph of K.E.X.P. D.J. Booth 2 (left) and Audio Edit 2 (right)

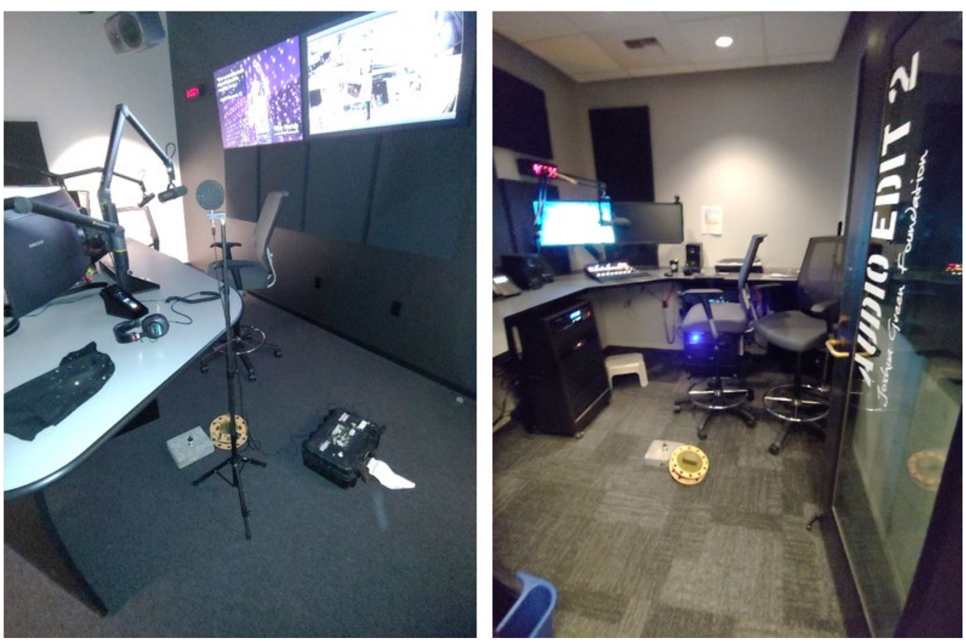
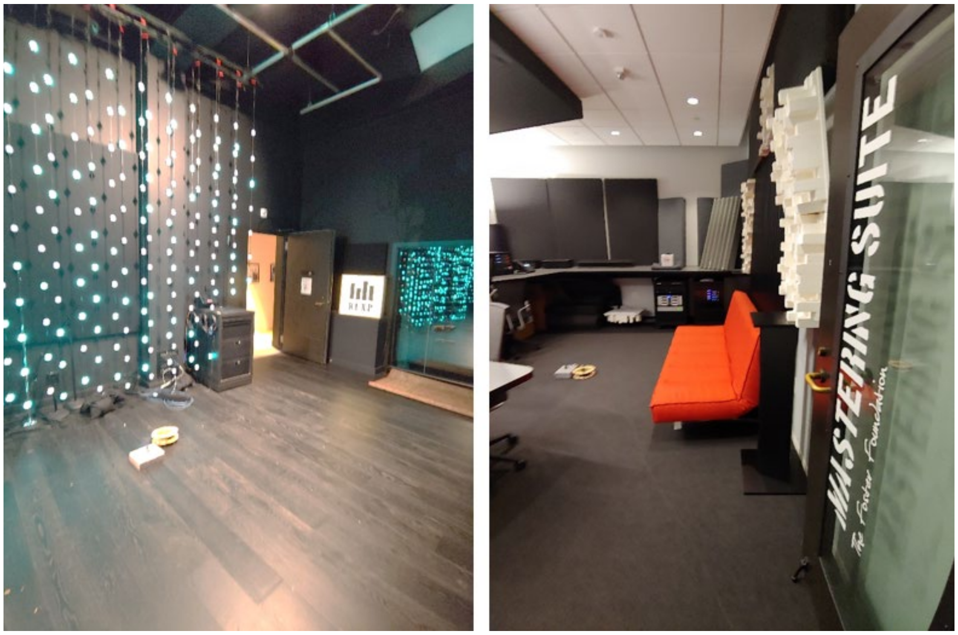


Figure 8-2. Photograph of K.E.X.P. Studio (left) and Mastering Suite (right)



8.1.2 The Vera Project

The Vera Project is a community non-profit, all-ages music and arts venue at 305 Harrison Street. The noise- and vibration-sensitive spaces in the building are a recording area with a sound-isolated booth and a performance space that hosts live concerts. Non-vibration-sensitive spaces include offices and art rooms. Figure 8-3 shows photographs of the noise- and vibration-sensitive spaces at The Vera Project.

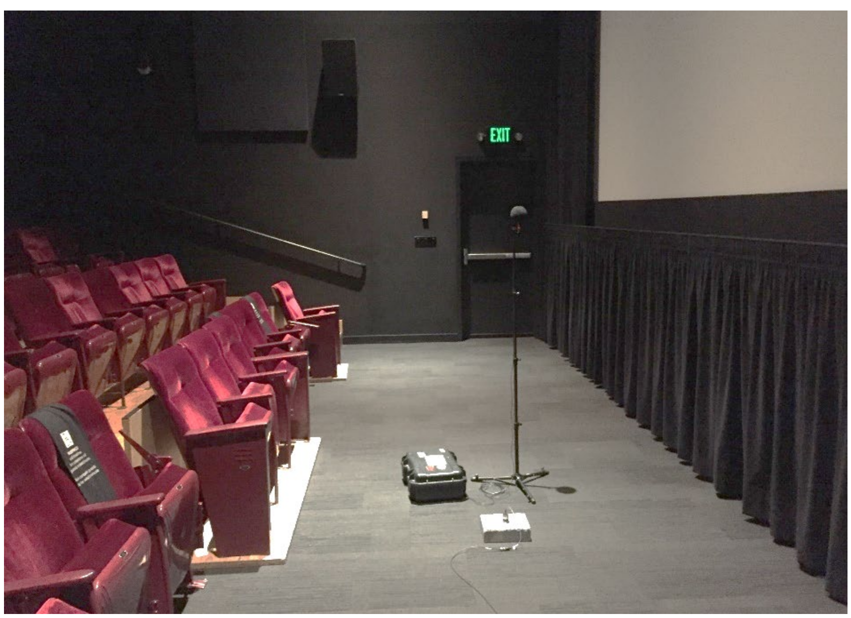
The FTA criteria for theaters were applied to the performance space. The FTA criteria for auditoriums were applied to the recording space. These criteria are consistent with the criteria applied for editing suites or control rooms in professional studios, such as K.E.X.P. and Victory Studios. The isolated recording space is typically used as the control room and editing space, while the musicians and microphones are in the open loft area outside of the booth. The measured existing vibration levels in the recording space (shown in Figure 8-11 later in this section) often exceed the 65 VdB limit for recording studios.

Figure 8-3. Photograph of The Vera Project Performance Space (left) and Recording Space (right)

8.1.3 SIFF Film Center

The SIFF Film Center is at 305 Harrison Street. The noise- and vibration-sensitive space at the Film Center is a jewelbox theater where films are screened. Non-sensitive spaces in the building include offices and lobby space. Figure 8-4 shows a photograph of the theater. The FTA criteria for theaters were applied to the theater.

Figure 8-4. Photograph of the SIFF Theater



8.2 Existing Noise and Vibration Levels

Existing noise and vibration levels were measured over a 1-hour period at representative sensitive spaces at K.E.X.P., The Vera Project, and the theater at the SIFF Film Center. At The Vera Project and SIFF Theater, the measurements were completed outside of normal operating hours and there was limited activity in the building. At K.E.X.P., the measurements were completed during working hours and staff were instructed to stay out of the instrumented spaces. Elevated levels from staff entering the spaces were removed from the measured data.

The measured 1-hour Leq noise and vibration levels are shown in Table 8-1. The 1-second noise levels are plotted in Figures 8-5 through 8-8. The 1-second vibration levels are plotted in Figures 8-9 through 8-12, and the spectra of the vibration levels are plotted in Figures 8-13 and 8-14.

Table 8-1. Background Noise and Vibration Levels at the Seattle Center Northwest Room: K.E.X.P., The Vera Project, and SIFF Theater

Monitoring Location	Noise level (1-hour Leq)	Vibration level (1-hour Leq)
D.J. Booth	33 dBA	55 VdB
Studio	28 dBA	5 VdB
Mastering	Not available	56 VdB
Edit booth	29 dBA	Not available
Vera Performance Space	35 dBA	52 VdB
Vera Recording Space	24 dBA	64 VdB
SIFF Theater	31 dBA	54 VdB

At K.E.X.P., the measured data show the following:

- The large studio has very low vibration levels. The floating floor is effectively isolating the vibration, even at very low frequencies.
- The D.J. booth has lower levels compared to the mastering suite at frequencies above about 20 hertz. This indicates that the floating floor in the D.J. booth is effective at frequencies above about 20 hertz.
- The noise levels are relatively low for all spaces.
- Where data showed K.E.X.P. staff entered the space during measurements, the data were removed from the 1-hour Leq calculation. The removed data are plotted in gray.

At The Vera Project and SIFF Theater, the measured data show the following:

- The Vera performance space has the lowest vibration levels. It is on the bottom floor, while the Vera recording space and SIFF Theater are on upper floors.
- The Vera recording space is well-insulated for noise but has relatively high existing vibration levels. The recording space is on a lofted second level that likely has a resonance at about 40 hertz. Because the 1-second vibration levels in the Vera recording space exceed the FTA criteria for recording studios of 65 VdB throughout the 1-hour measurement duration and because the space is typically used as a control room, the FTA criteria for auditorium were applied. These criteria are consistent with that applied in other critical listening areas, such as the editing and mastering suites at K.E.X.P.

Figure 8-5. Measured 1-second Noise Levels in the K.E.X.P. D.J. Booth and Editing Room

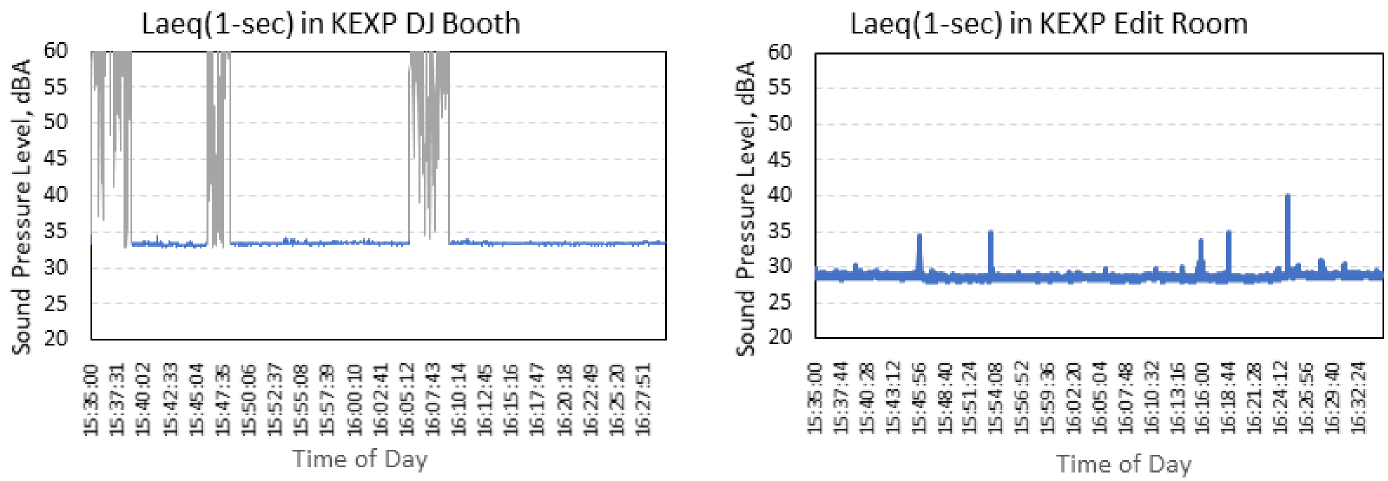


Figure 8-6. Measured 1-second Noise Levels in the K.E.X.P. Studio

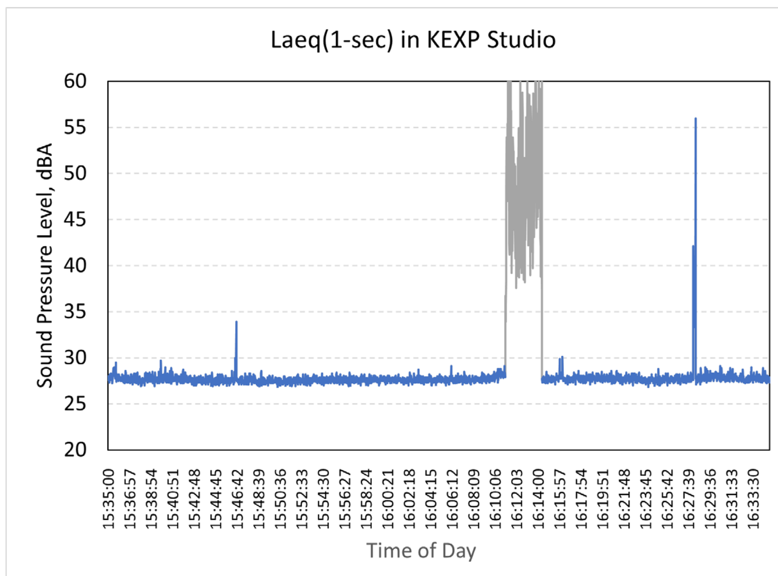
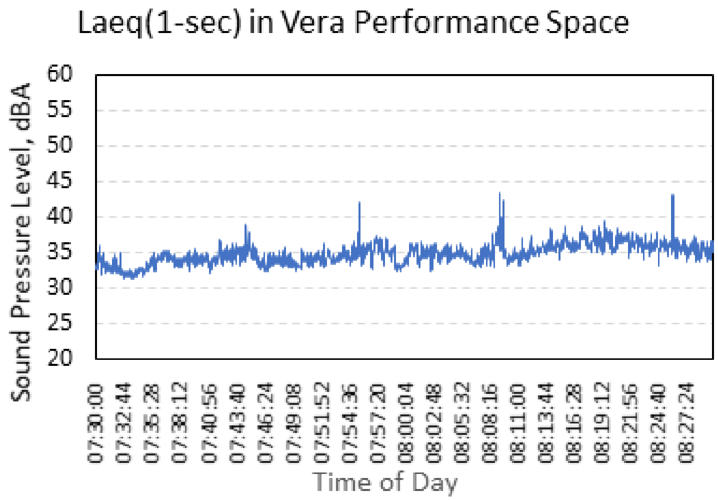


Figure 8-7. Measured 1-second Noise Levels in Vera Performance Space and Recording Space



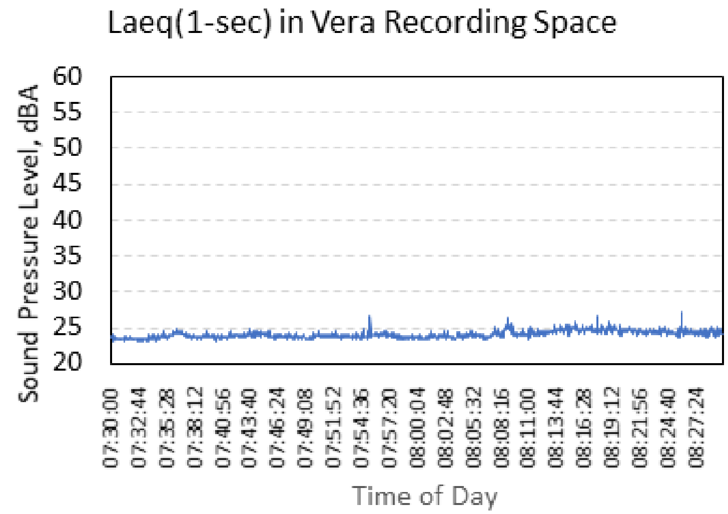


Figure 8-8. Measured 1-second Noise Levels in SIFF Theater

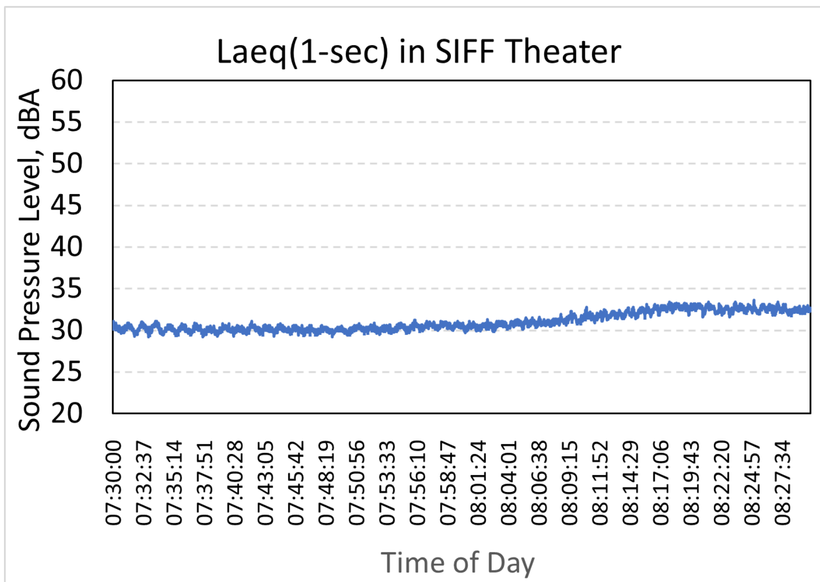


Figure 8-9. Measured 1-second Vibration Levels in K.E.X.P. D.J. Booth and Studio

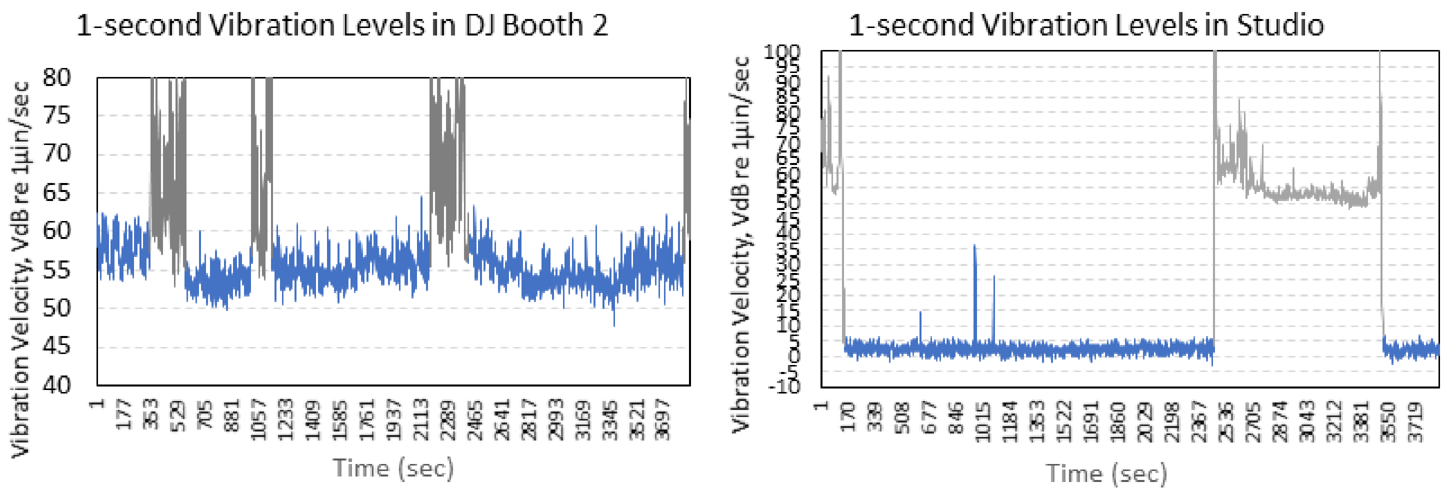


Figure 8-10. Measured 1-second Vibration Levels in K.E.X.P. Mastering Suite

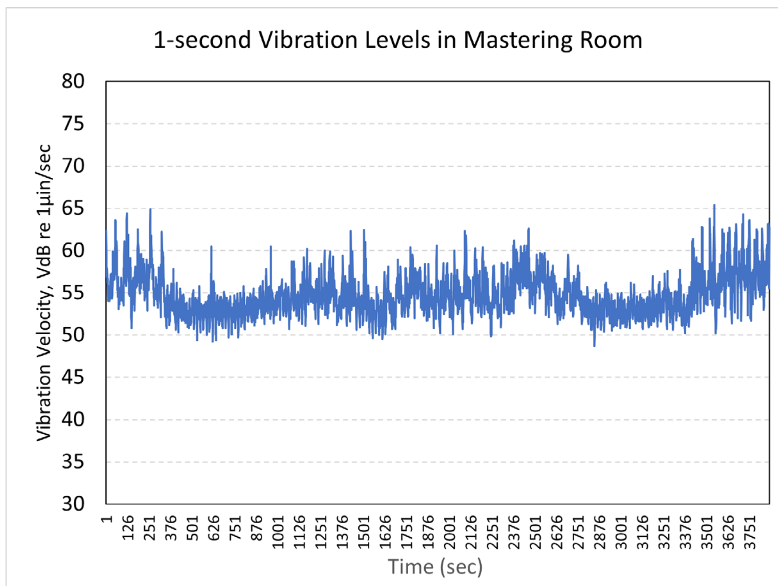
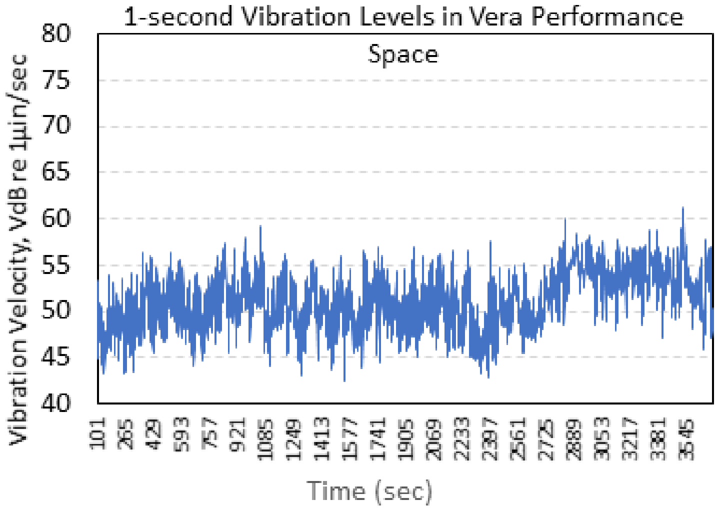


Figure 8-11. Measured 1-second Vibration Levels in Vera Performance Space and Recording Space



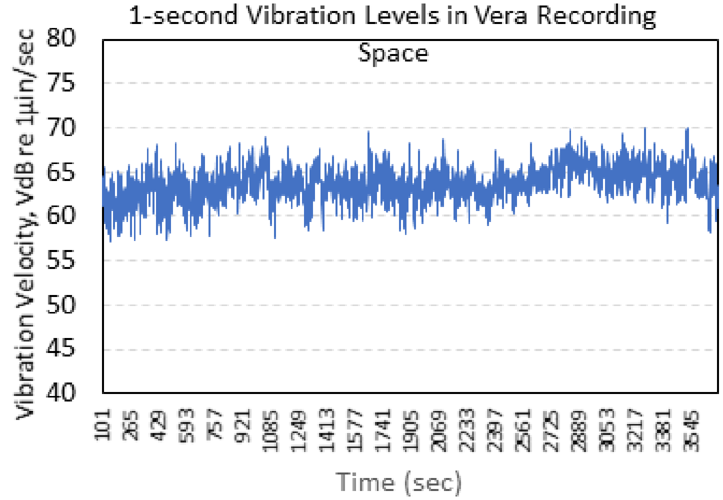


Figure 8-12. Measured 1-second Vibration Levels in SIFF Theater

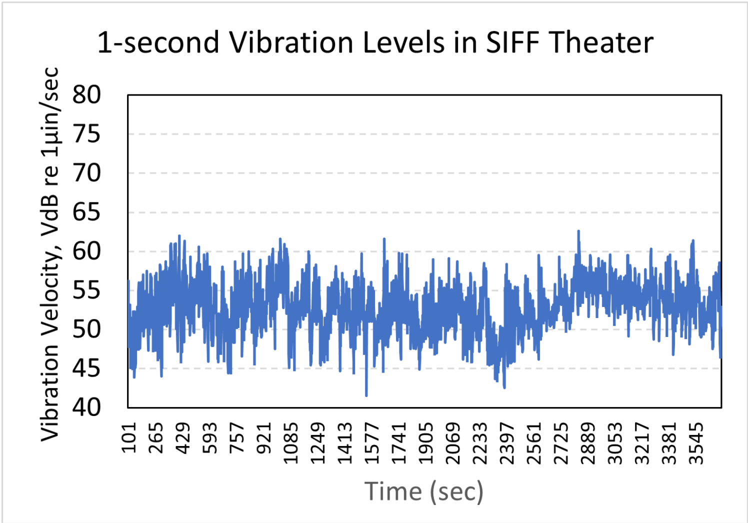


Figure 8-13. Spectra of Background Vibration Levels at K.E.X.P.

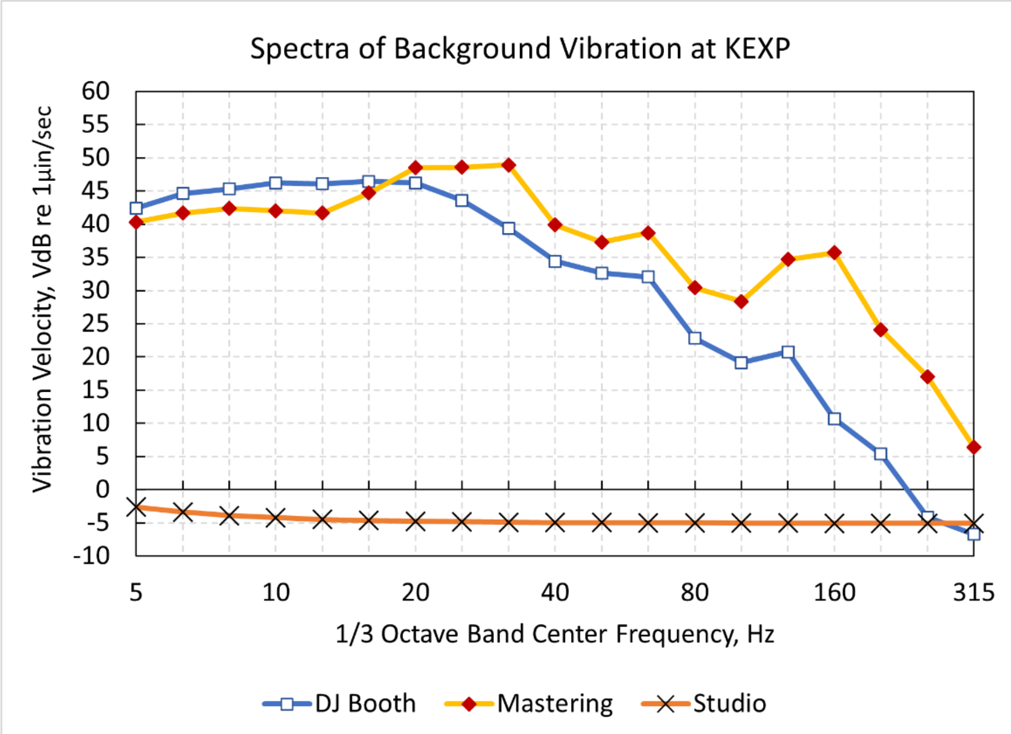
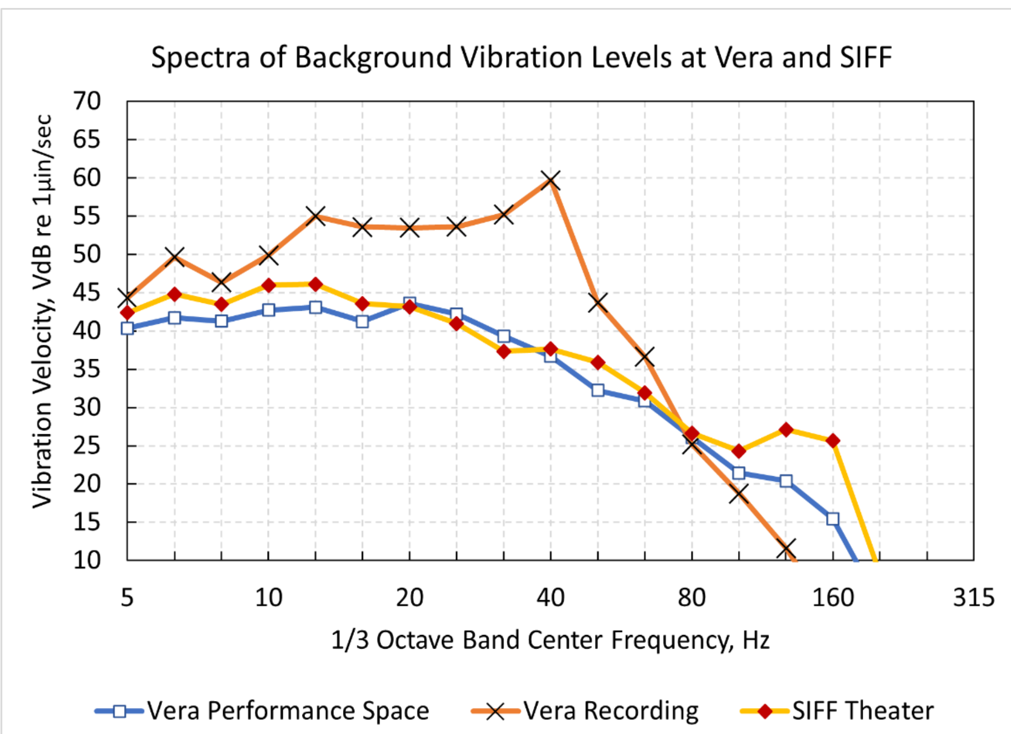


Figure 8-14. Spectra of Background Vibration Levels at The Vera Project and SIFF Theater



8.3 Vibration Propagation Measurement Description

A borehole vibration propagation test was completed at the Seattle Center Northwest Rooms to determine how efficiently vibration propagates from the approximate depth of the light rail tunnel into the sensitive spaces. The borehole was in the parking lane on the south side of Republican Street, outside of K.E.X.P. Data were collected from three borehole depths: 93 feet, 110 feet, and 120 feet. The data were collected over 2 days. On the first day, data were collected at a depth of 93 feet, with measurement positions in K.E.X.P., The Vera Project, and SIFF Theater. Data could not be collected at 100 feet due to heaving soils backfilling the borehole.

On the second day of data collection, the sensors from The Vera Project and SIFF Theater were placed outdoors due to lack of access into those spaces during measurements. Additional vibration propagation data at The Vera Project and SIFF Theater were collected using a surface impact hammer. The data collected with the surface impact hammer were used to determine the outdoor-to-indoor building adjustment. Data at Cascade Public Media showed that the outdoor-to-indoor building adjustment is about the same for a borehole vibration propagation test or a surface vibration propagation test.

The vibration levels were measured at six indoor locations and seven outdoor locations. The outdoor measurement locations were used to quantify how vibration levels decrease with distance from the impact force. The outdoor vibration measurements were also used as a reference to examine how levels change as the vibration travels from the soil into the building structure.

The six indoor measurement locations are: (1) K.E.X.P. D.J. booth 2, (2) K.E.X.P. studio, (3) K.E.X.P. mastering room, (4) Vera performance space, (5) Vera recording space, and (6) SIFF Theater. The measurement positions were selected to get representative data in sensitive locations from K.E.X.P., The Vera Project, and SIFF Theater. Data were collected in The Vera Project and SIFF Theater only at the first depth because access could not be arranged for the second day of data collection. Those sensors were relocated outdoors for data collection at the second and third depths.

Figures 8-15 through 8-17 show the floor plans of K.E.X.P., The Vera Project, and SIFF Film Center, with the sensor locations labeled. Approximate location of the outdoor sensors closest to the buildings and the borehole position are also indicated.

Figure 8-15. K.E.X.P. Floor Plan with Sensor Locations

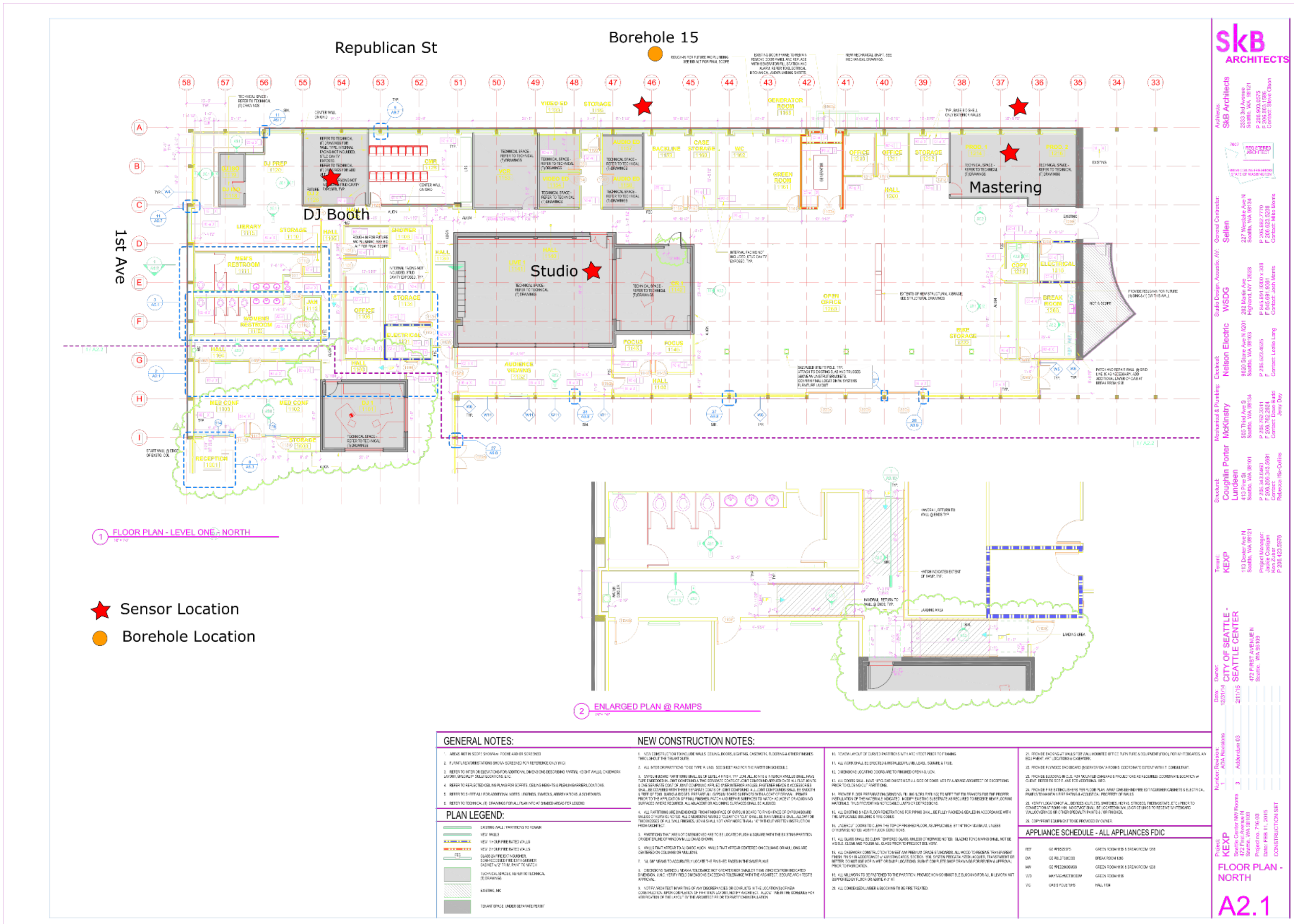


Figure 8-16. The Vera Project Floor Plan with Sensor Locations

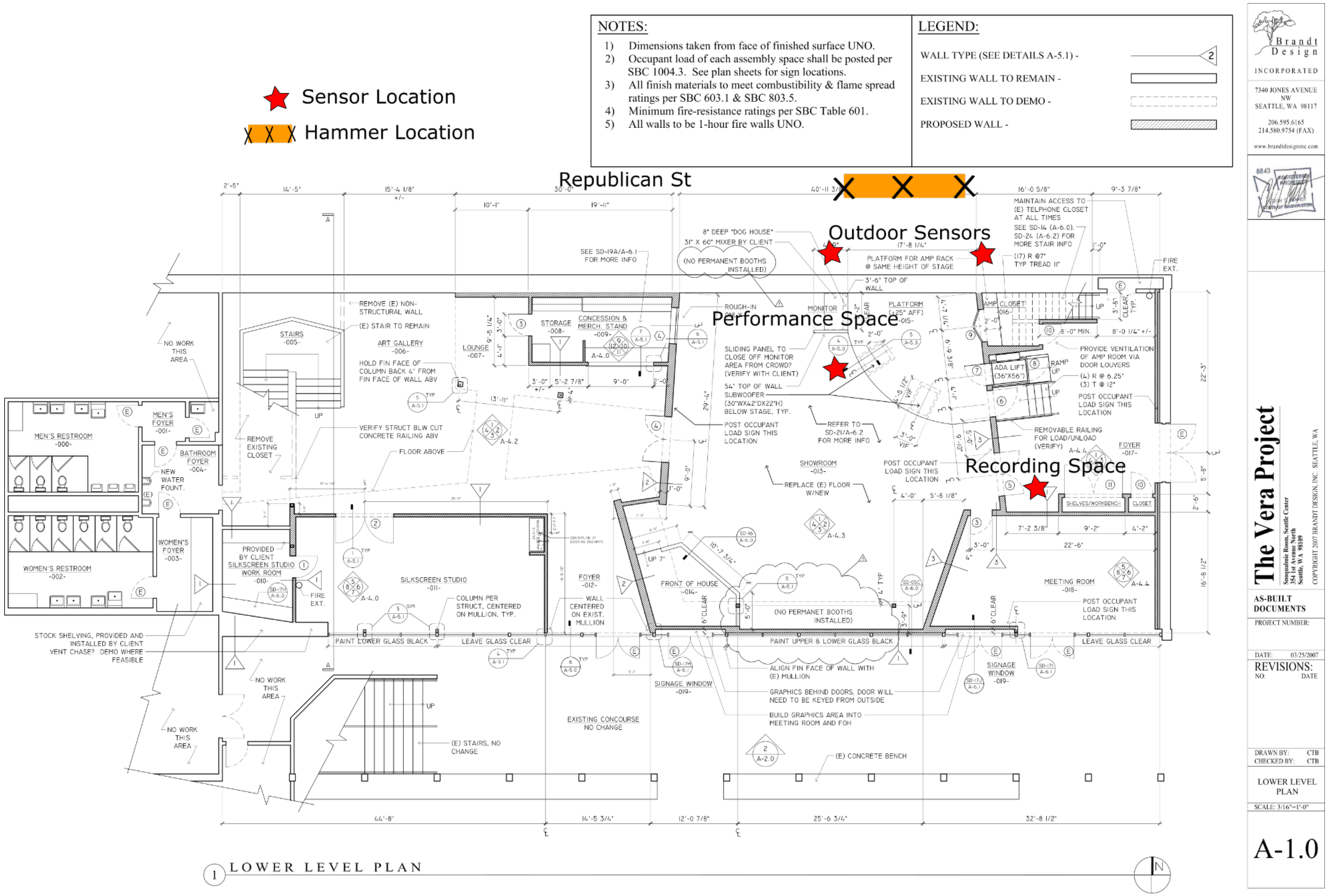
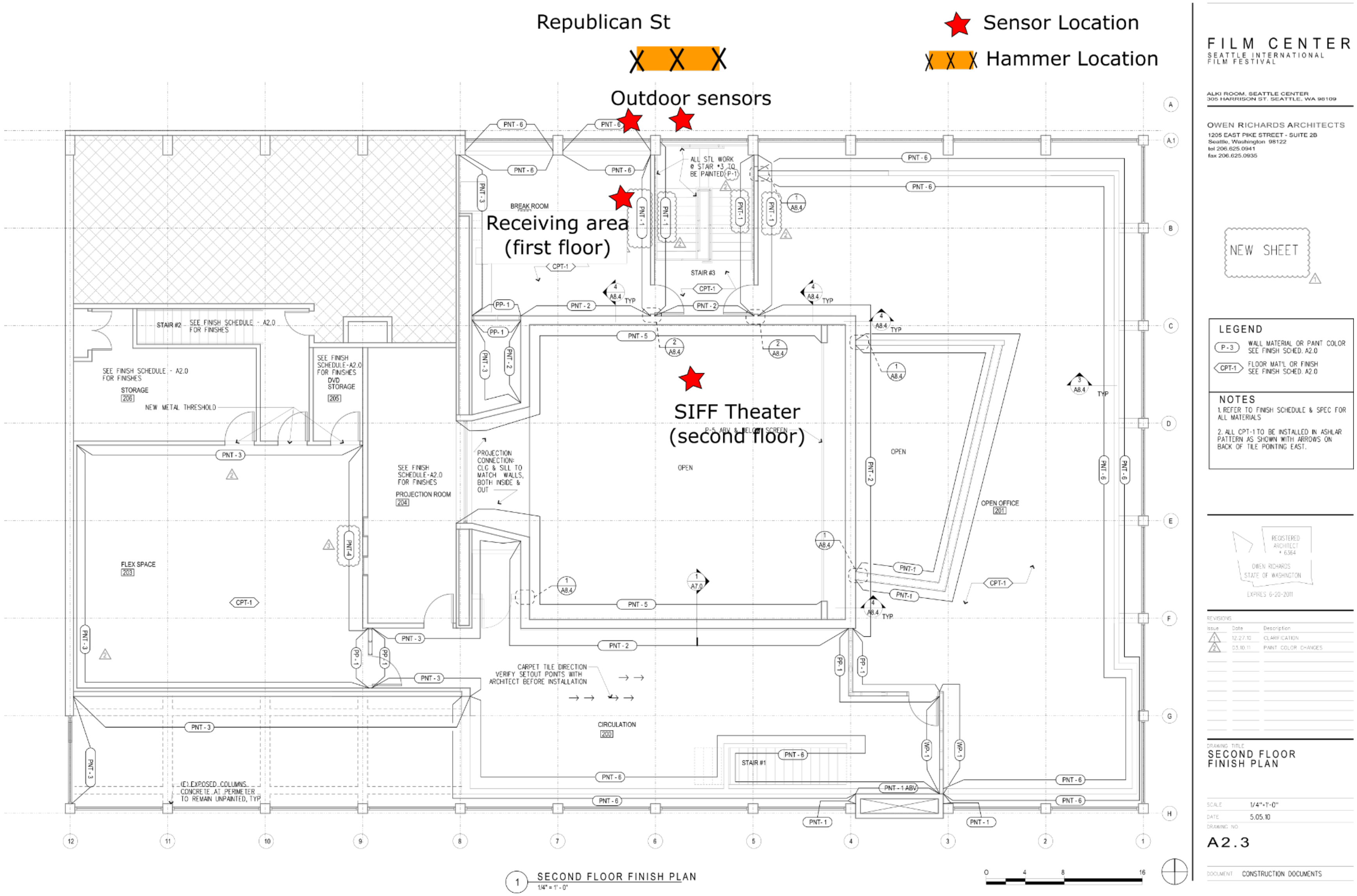


Figure 8-17. SIFF Film Center Floor Plan with Sensor Locations

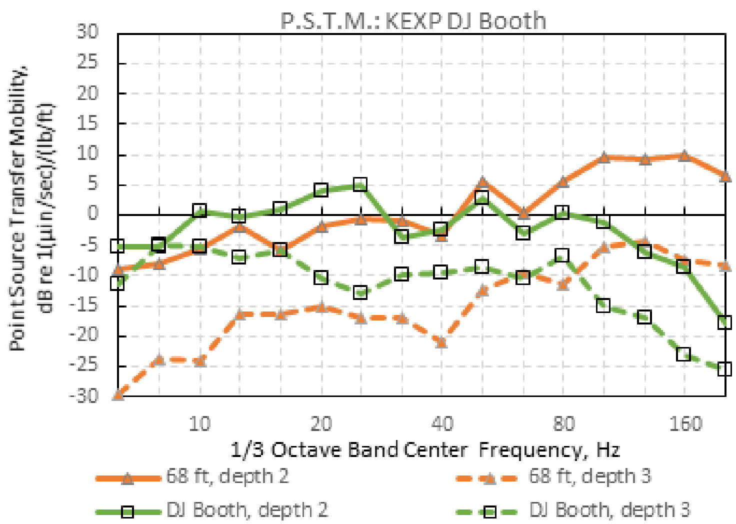


8.4 Vibration Propagation Measurement Results and Predicted Levels

The borehole or surface vibration propagation tests measure the P.S.T.M., a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the P.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The P.S.T.M. and coherence results for the indoor measurement positions near the impact line and their closest outdoor measurement position are shown in Figures 8-18 through 8-22. For indoor measurement positions where data were collected at multiple depths, the results from additional depths are shown with dashed lines. For The Vera Project and the SIFF Theater, data from the surface vibration propagation measurement are shown and used in the analysis because of improved coherence values. Following are observations from the L.S.T.M. and coherence results:

- Coherence results for both indoor and outdoor locations from the borehole vibration propagation test are fairly low below frequencies of about 40 hertz. This indicates that the soil is likely more effective at transmitting vibration at higher frequencies compared to low frequencies.
- The coherence results for the K.E.X.P. studio is low at all frequencies, which is an indication that the floating floor is effectively isolating vibration as intended. The outdoor measurement position at 10 feet from the borehole also has low coherence at all frequencies, which might be due to interference from the vibration generated by the drill rig. At most borehole propagation sites, there were generally low coherence levels for the measurement positions closest to the drill rig. There was also more activity from traffic and pedestrians at the sensor closest to the rig.
- The coherence results for The Vera Project and SIFF Theater borehole vibration propagation measurement were very low because the spaces are more than 250 feet from the borehole. The data from the surface vibration propagation measurement, where the hammer was placed 30 feet from the buildings, were used instead. The coherence for the surface vibration propagation test is relatively high above 20 hertz.
- The P.S.T.M. for the Vera recording space is about 10 decibels higher than for the performing space at frequencies from 31.5 hertz to 63 hertz. This is likely due to amplification from the lofted floor.

Figure 8-18. P.S.T.M. and Coherence in K.E.X.P. D.J. Booth



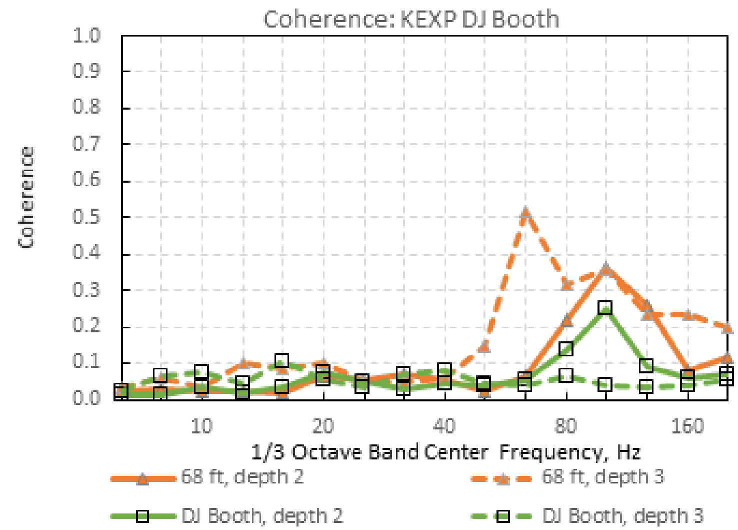
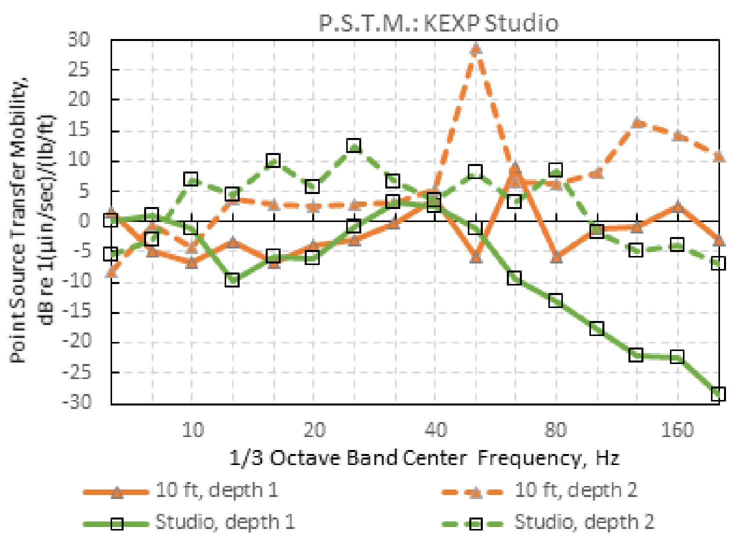


Figure 8-19. P.S.T.M. and Coherence in K.E.X.P. Studio



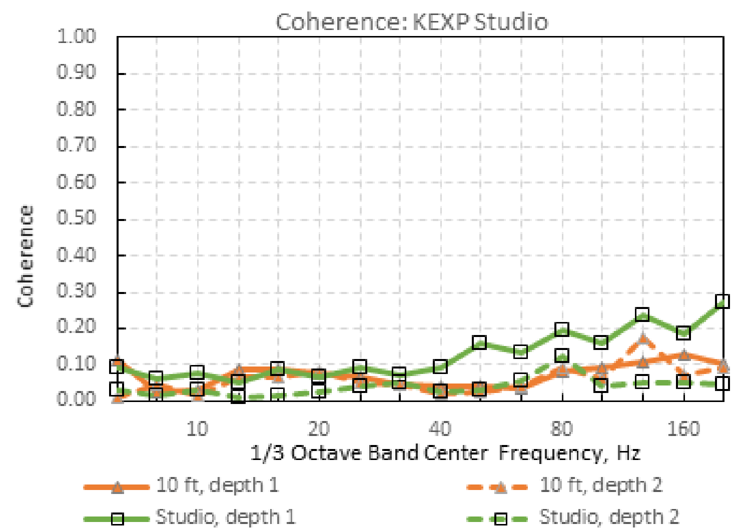


Figure 8-20. P.S.T.M. and Coherence in K.E.X.P. Mastering Suite

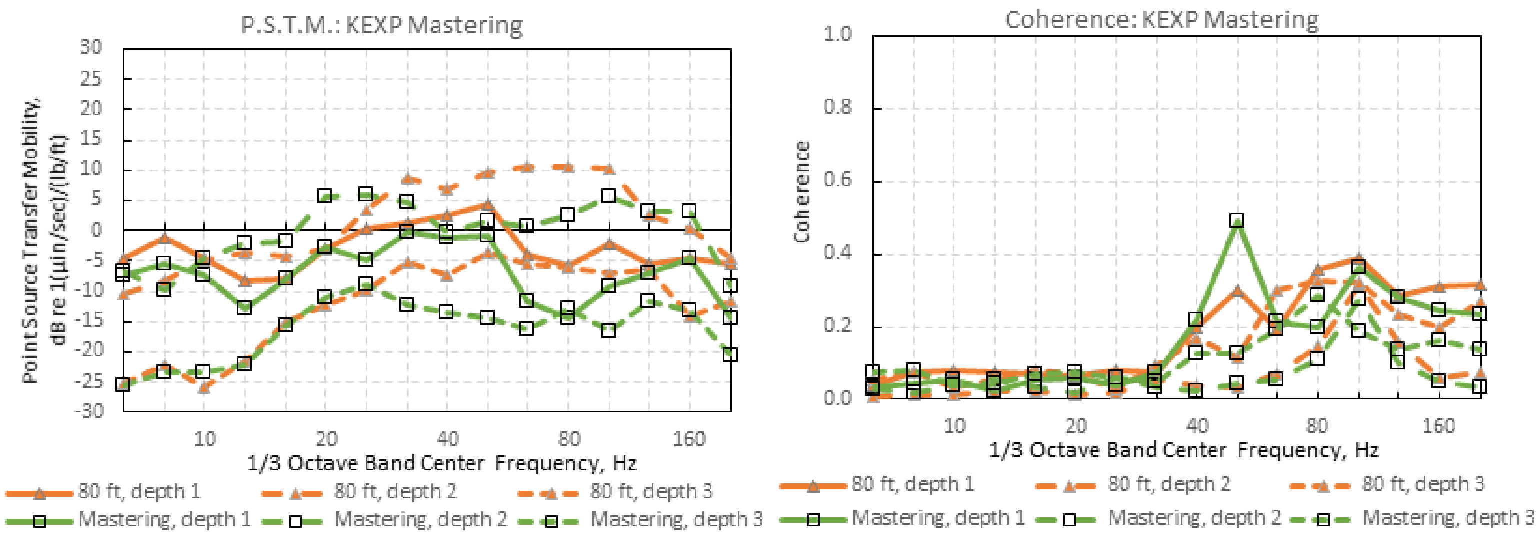


Figure 8-21. P.S.T.M. and Coherence at The Vera Project

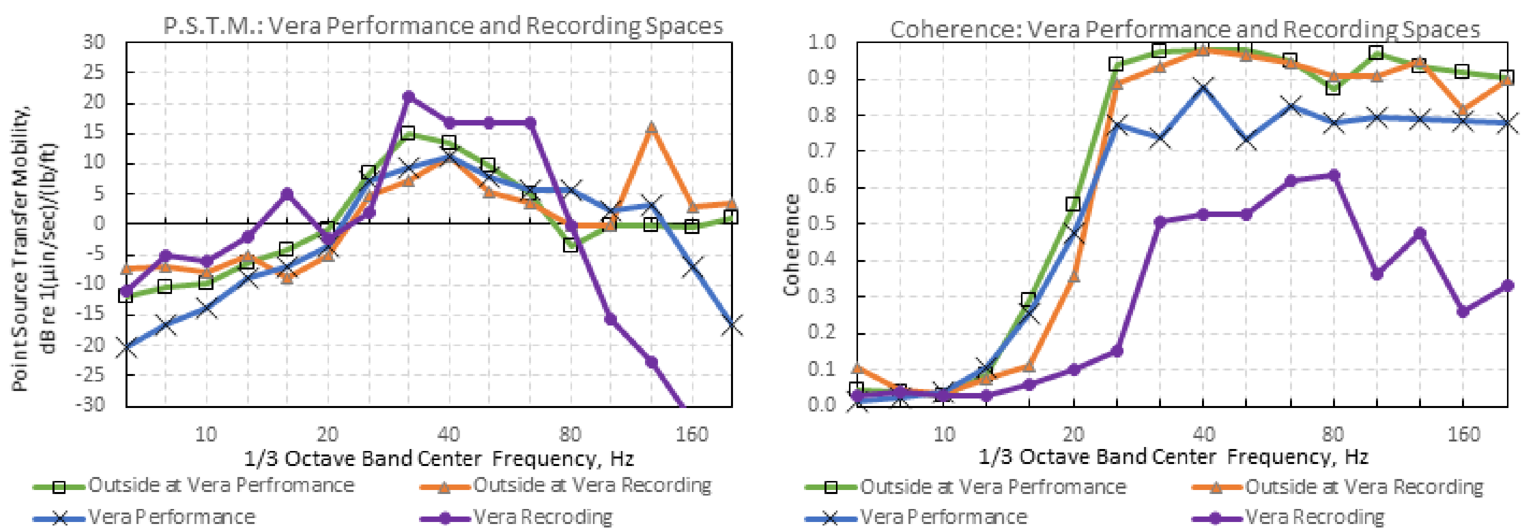
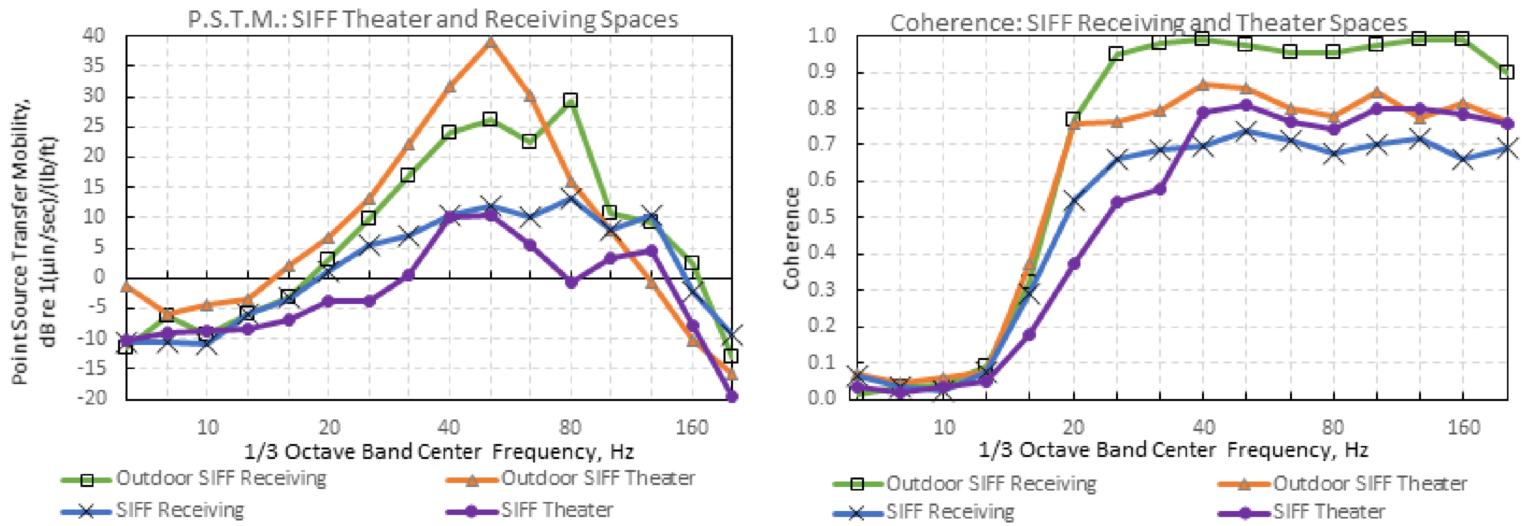


Figure 8-22. P.S.T.M. and Coherence at SIFF Theater



The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances is the difference between the outdoor P.S.T.M. at an equivalent setback distance and the indoor P.S.T.M. Where data were collected at multiple depths, the results from the multiple depths were averaged. The building adjustment for the sensitive spaces where measurements were completed in K.E.X.P., The Vera Project, and SIFF Theater are shown in Figures 8-23 and 8-24. The building adjustment is assumed to be zero at frequencies 20 hertz and below because of low coherence values indoors and outdoors at low frequencies and because it is unlikely that there are floor resonances at these low frequencies. Following are observations from the building adjustment:

- The building adjustments for the K.E.X.P. D.J. booth and studio show increasing vibration attenuation with increasing frequency, which are consistent with floating floors.
- The building adjustment for the K.E.X.P. mastering suite is consistent with a slab-on-grade masonry building, with vibration attenuation between 0 decibel and 10 decibels at mid-frequencies from about 30 hertz to 100 hertz.
- The building adjustment for the Vera recording space shows high vibration amplification. Amplification from a floor resonance in the recording space is expected because it is on a lofted second level floor.
- The building adjustment for SIFF Theater shows some amplification at higher frequencies, which are the same frequencies where higher existing vibration levels were measured compared to The Vera Project spaces.

Figure 8-23. Measured Building Adjustment at K.E.X.P.

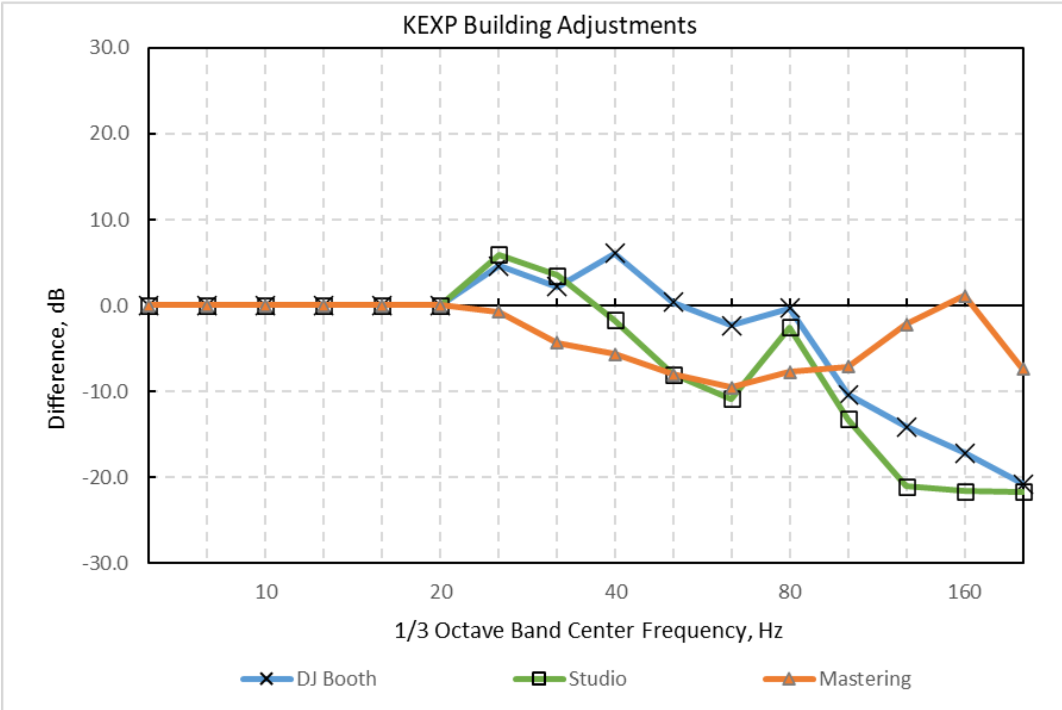
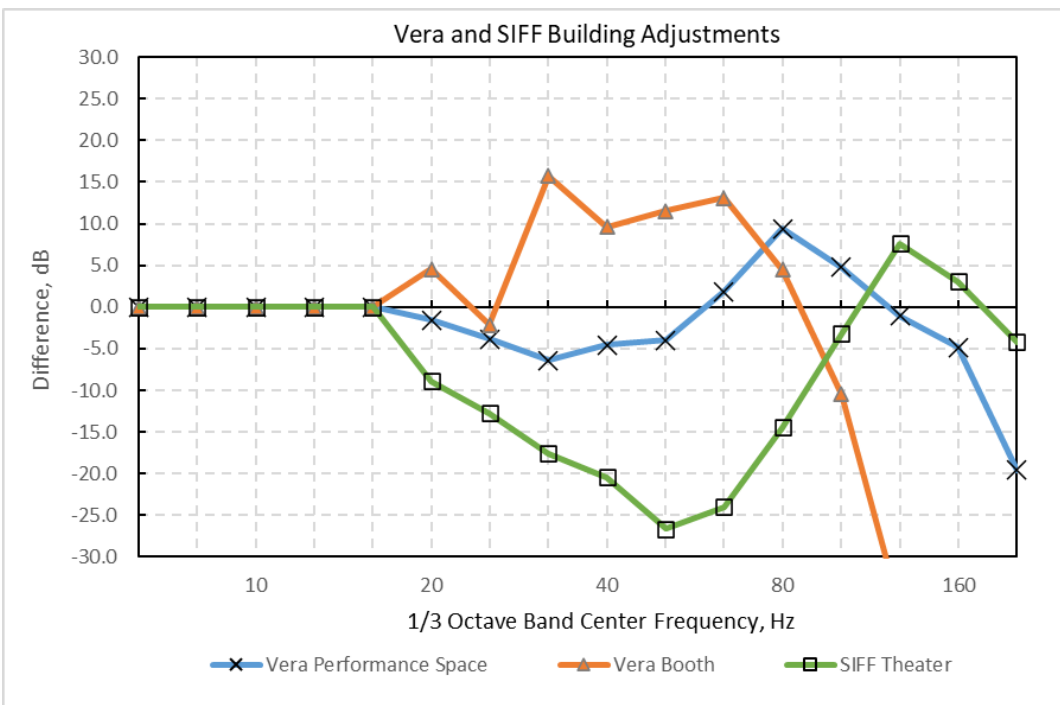


Figure 8-24. Measured Building Adjustment at The Vera Project and SIFF Theater



The predicted levels for Preferred Alternative DT-1 are presented in Table 8-2 and use the L.S.T.M. coefficients from site V-15 near the Seattle Center Northwest Rooms on Republican Street. The predicted levels for Alternative DT-2 are presented in Table 8-3 and use the

L.S.T.M. coefficients for site V-14 near the Cornish Playhouse adjacent to Mercer Street. The L.S.T.M. levels are higher for site V-15 compared to site V-14. The building adjustments presented in Figures 8-23 and 8-24 were used in the predictions for both Downtown Segment alternatives. The spectra of predicted levels for Preferred Alternative DT-1 are presented on Figures 8-25 and 8-26.

Sensitive spaces in K.E.X.P., The Vera Project, and SIFF Film Center are predicted to be impacted by Preferred Alternative DT-1. There would be no predicted impact for Alternative DT-2 because the alignment is much farther away from these sensitive spaces.

The proposed mitigation measure for Preferred Alternative DT-1 is high-resilience fasteners, which are an effective mitigation measure at frequencies 40 hertz and above. High-resilience fasteners would reduce the predicted vibration level to below the impact level for the K.E.X.P. spaces and the Vera performance and recording spaces. The change in vibration provided by high-resilience fasteners is shown above in Section 7-4 on Figure 7-17.

The predicted groundborne noise level with high-resilience fasteners at the SIFF Theater would be 37 dBA, two decibels above the limit. This residual exceedance would be due to measured building amplification at high frequencies. There are several conservative assumptions at higher frequencies, as discussed for the predicted levels for the Seattle Rep in Section 7.4.

Additional study on the vibration reduction provided by the light rail tunnel structure and a more accurate prediction of the vibration reduction provided by the high-resilience fasteners is likely to show that no additional mitigation measures would be necessary. As with the Seattle Rep, the insertion loss of the tunnel structure and the expected attenuation of the high-resilience fasteners should be confirmed with modeling during final design when the thickness of the tunnel invert and the stiffness of the high-resilience fasteners would be selected. Because Sound Transit expects at least 5 decibels of reduction from the tunnel structure that is not included in the prediction model, no additional mitigation measures beyond high-resilience fasteners are proposed.

Table 8-2. Predicted Vibration and Groundborne Noise Levels at The Vera Project, SIFF Theater, and K.E.X.P. with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Vera Performance Space	102	30	62	72	35	35	0
Vera Recording Space	102	30	72	72	38	30	8
SIFF Theater	94	45	65	72	45	35	10
K.E.X.P. D.J. Booth	111	55	66	65	32	25	7
K.E.X.P. Studio	111	55	59	65	26	25	1
K.E.X.P. Mastering Suite	111	55	60	72	35	30	5

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 8-3. Predicted Vibration and Groundborne Noise Levels at The Vera Project, SIFF Theater, and K.E.X.P. Studios with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibels) [c]
Vera Performance Space	508	45	33	72	<0	35	Does not exceed
Vera Recording Space	508	45	36	72	<0	30	Does not exceed
SIFF Theater	512	45	32	72	<0	35	Does not exceed
K.E.X.P. D.J. Booth	508	30	22	65	<0	25	Does not exceed
K.E.X.P. Studio	508	30	22	65	<0	25	Does not exceed
K.E.X.P. Mastering Suite	508	30	21	72	<0	30	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 8-25. Predicted Vibration Levels at The Vera Project and SIFF Theater with Preferred 5th Avenue/Harrison Street Alternative (DT-1)

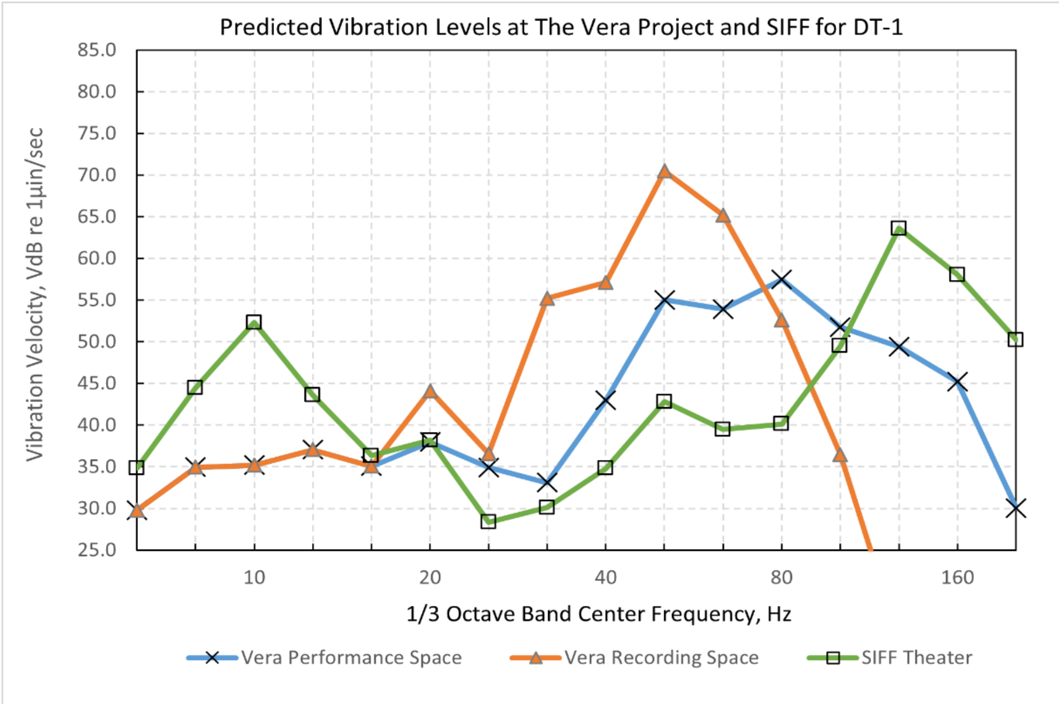
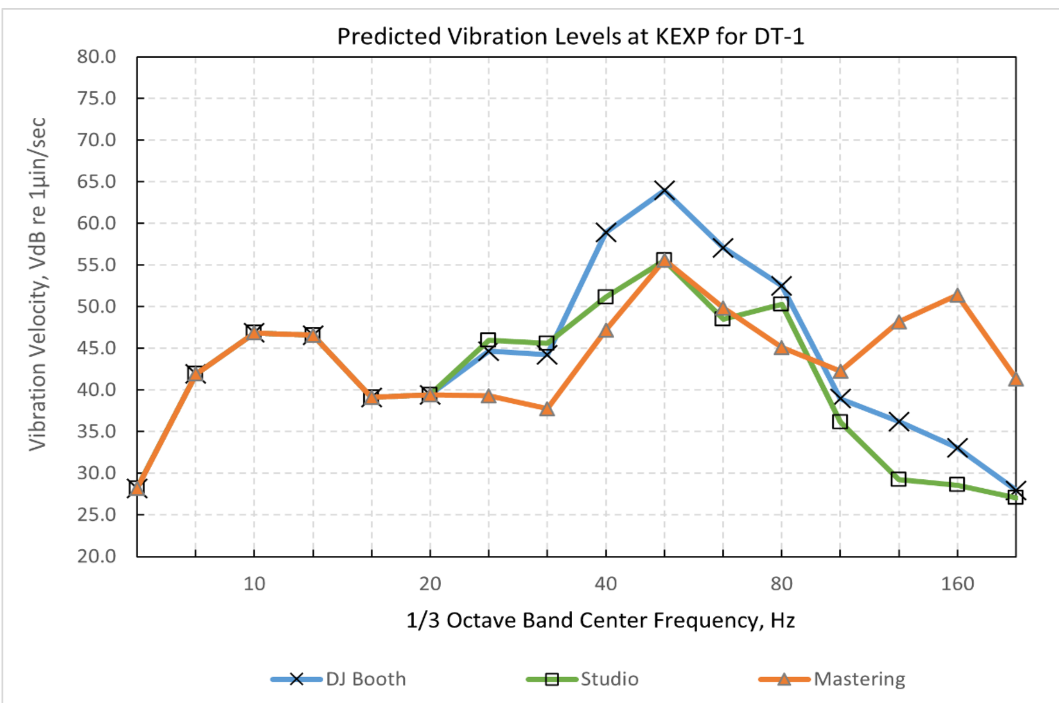


Figure 8-26. Predicted Vibration Levels at K.E.X.P. with Preferred 5th Avenue/Harrison Street Alternative (DT-1)



9 219 TERRY AVENUE NORTH: KINETA, BIODESIX, AND GENEWIZ

9.1 Description of Sensitive Space

219 Terry Avenue North is a building in South Lake Union owned by Alexandria Real Estate. This building provides office and laboratory space for research facilities. At the time of this vibration assessment, the building housed three tenants with vibration-sensitive research areas: Biodesix on the first floor; Genewiz on the second floor; and Kineta on the second and third floors and basement. Based on information gathered during a site visit in Fall 2019, the most sensitive equipment in the building is a mass spectrometer on the second level.

The vibration limits are based on the FTA *Transit Noise and Vibration Impact Assessment Manual*, which uses the industry-standard V.C. curves (e.g., V.C.-A), and on the National Institutes of Health *Design Requirements Manual* Table 5.2.2. The National Institutes of Health guidance for mass spectrometers is a limit of 48 VdB. The National Institutes of Health guidance for “General Laboratory” is 66 VdB. The FTA *Transit Noise and Vibration Impact Assessment Manual* describes the 66 VdB limit as appropriate for medium-to-high power optical microscopes (400x), microbalances, optical balances, and similar specialized equipment. During a site visit to the building in Fall 2019, no additional pieces of equipment beyond the mass spectrometers were called out as being particularly sensitive. Therefore, the General Laboratory limit of 66 VdB is considered appropriate for the other spaces in the building.

Figure 9-1 shows photographs of a microphone set up in the basement near Kineta and an accelerometer near the open Biodesix door on the first floor. Figure 9-2 shows photographs of sensors near Genewiz on the second floor and Kineta on the third floor.

Figure 9-1. Photographs of the 219 Terry Avenue North Basement and First Floor

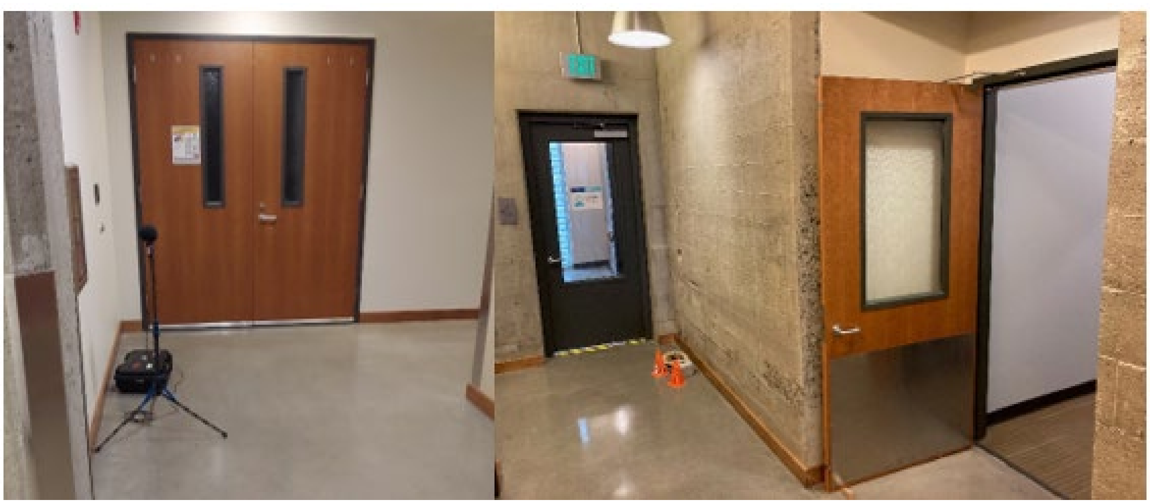


Figure 9-2. Photographs of the 219 Terry Avenue North Second and Third Floors

9.2 Existing Noise and Vibration Levels

Existing vibration levels were measured over a 1-hour period on each floor of the building. The measurement was conducted from 10:30 a.m. to 11:30 a.m. on a Friday morning. Staff were present at the building during the measurements. Existing noise levels were also measured over a 1-hour period in the basement hallway.

The measured 1-hour Leq noise and vibration levels are shown in Table 9-1. The 1-second noise levels are plotted in Figure 9-3. The 1-second vibration levels are plotted in Figures 9-4 and 9-5, and the spectra of the vibration levels are plotted in Figure 9-6. The measured data show the following:

- Ambient vibration levels increase with higher floor levels.
- Ambient vibration spectra show that vibration levels on the basement floor drop off significantly above 63 hertz but are similar for all floors at lower frequencies. Slab-on-grade floors, such as the basement, typically have lower vibration levels than upper story floors.

Table 9-1. Background Noise and Vibration Levels at 219 Terry Avenue North

Monitoring Location	Noise level (1-hr Leq)	Vibration level (1-hr Leq)
Basement – Kineta	58 dBA	51 VdB
1st Floor – Biodesix	Not applicable	52 VdB
2nd Floor – Genewiz	Not applicable	54 VdB
3rd Floor – Kineta	Not applicable	58 VdB

Figure 9-3. Measured 1-Second Noise Levels in the 219 Terry Avenue North Basement

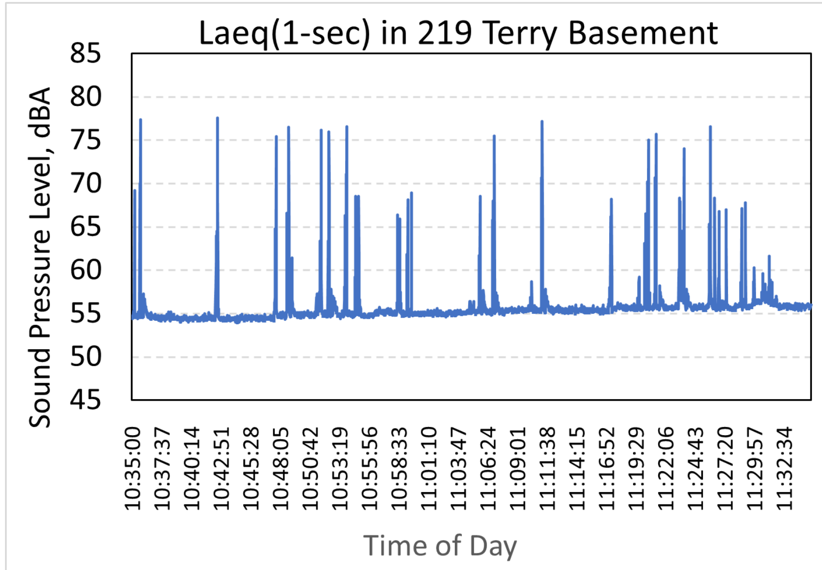


Figure 9-4. Measured 1-second Vibration Levels in 219 Terry Avenue North Basement and First Floor

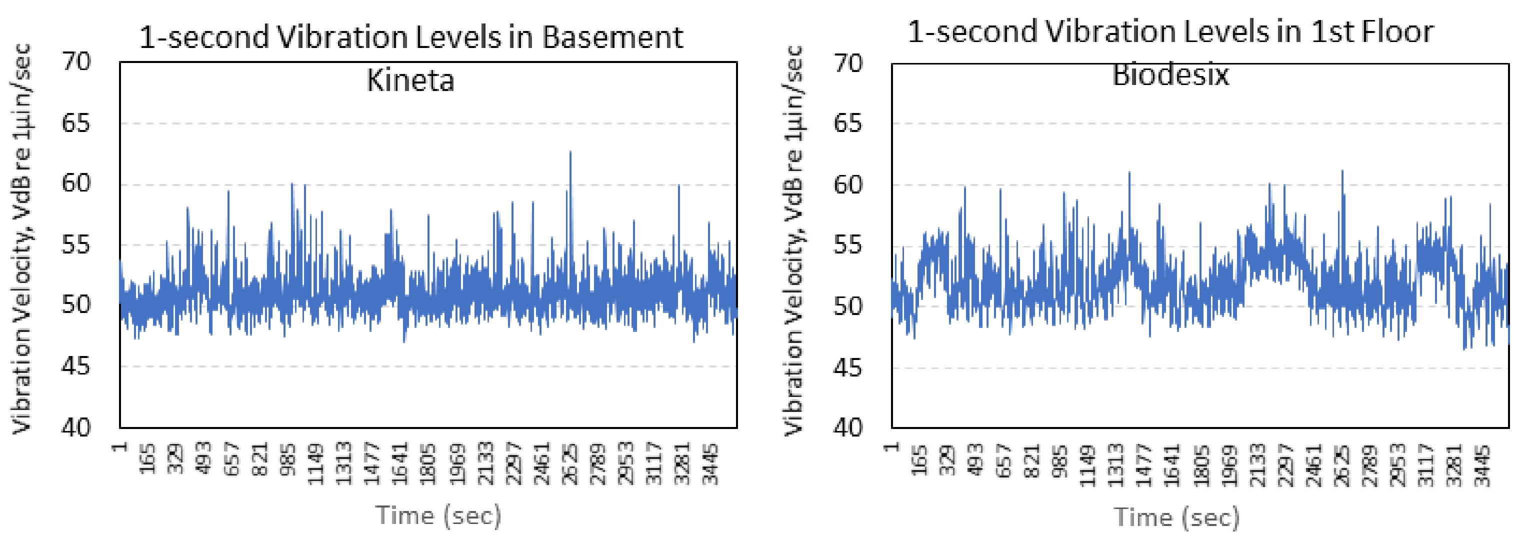


Figure 9-5. Measured 1-Second Vibration Levels in 219 Terry Avenue North Second and Third Floors

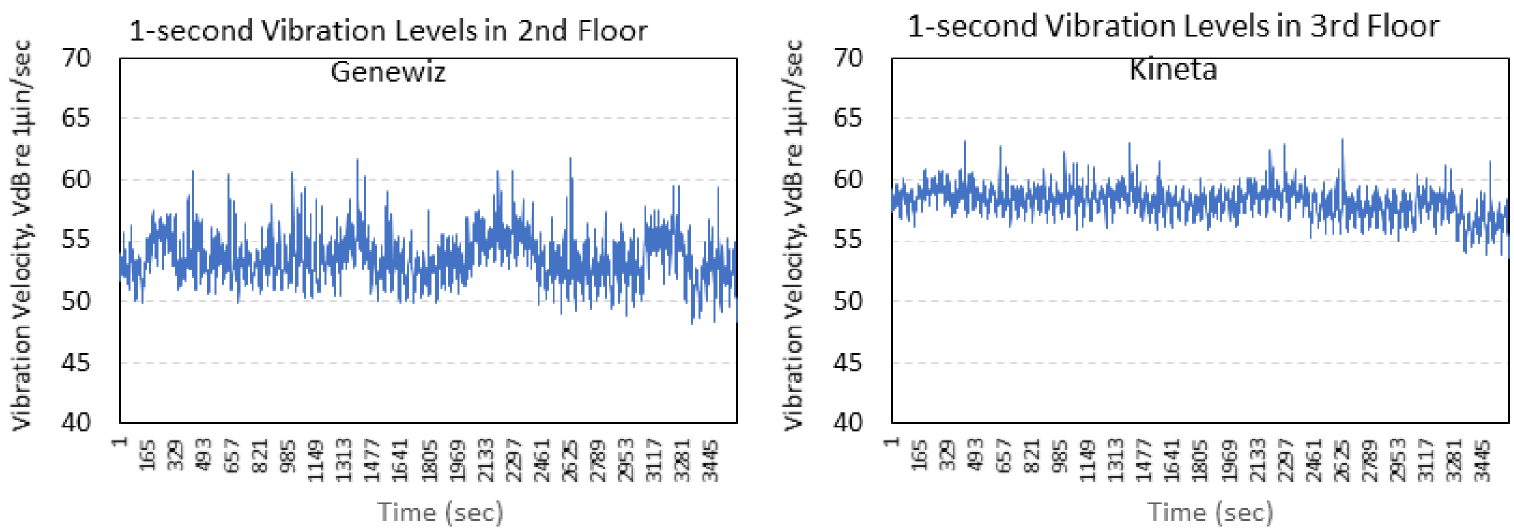
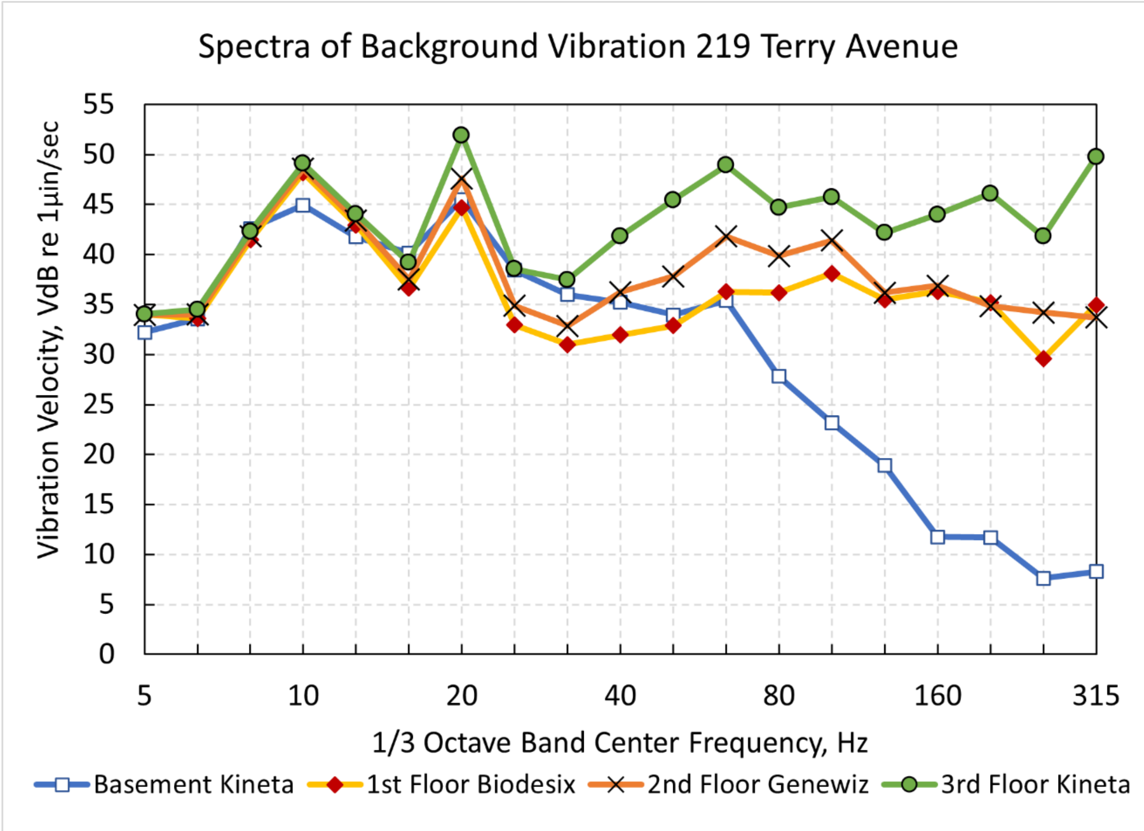


Figure 9-6. Spectra of Background Vibration Levels at 219 Terry Avenue North



9.3 Vibration Propagation Measurement Description

A surface vibration propagation test was completed at 219 Terry Avenue North to determine how efficiently vibration propagates form the soil into the building. A drop-hammer was used to impart a force in the alleyway behind the building, and the resulting vibration was measured outside and inside the building. Data were collected from five impact points spaced 15 feet apart in the alley. Photos and a schematic of the vibration propagation site are provided in Attachment N.3B, Vibration Measurement Site Photographs.

The vibration levels were measured at three outdoor locations and four indoor locations. The outdoor measurement locations were used as a reference to examine how levels change as the vibration travels from the soil into the building structure.

The four indoor measurement locations were the basement hallway, first floor hallway, second floor hallway, and third floor hallway. The measurement locations were selected to get representative data on each floor of the building.

Figure 9-7 shows the basement level floor plan, and Figure 9-8 shows the first level floor plan of 219 Terry Avenue North with the sensor locations labeled. The approximate location of the outdoor sensors and the drop-hammer impact locations are also indicated on the basement level floor plan. The relative location of the sensors on the second and third levels are the same as the first level.

Figure 9-7. Basement Level Floor Plan for 219 Terry Avenue North

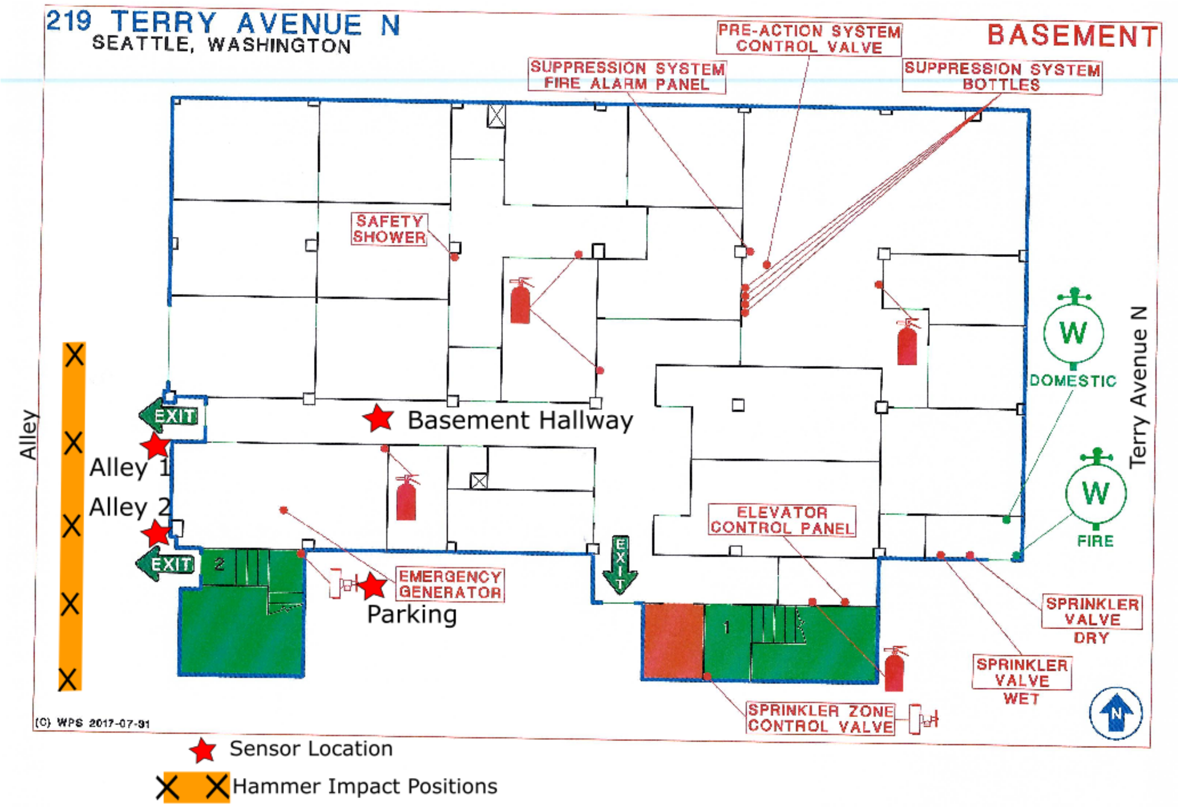
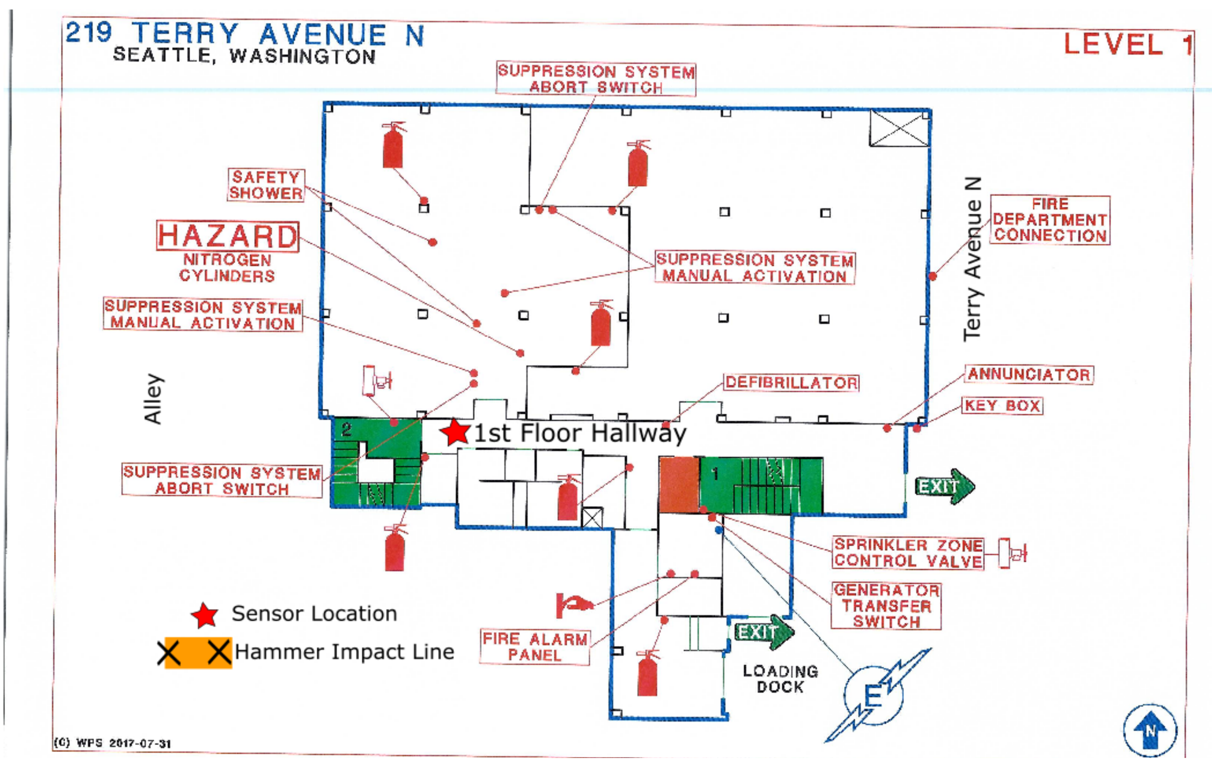


Figure 9-8. First Level Floor Plan for 219 Terry Avenue North



9.4 Vibration Propagation Measurement Results and Predictions

The result of the vibration propagation test is the P.S.T.M., a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the P.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The P.S.T.M. and coherence results for the indoor measurement positions and their reference outdoor measurement position are shown in Figures 9-9 through 9-12. The reference outdoor measurement position was chosen to have approximately the same distance between the drop-hammer and the outdoor accelerometer as the distance from the drop-hammer to the indoor accelerometer (not accounting for vertical distance to higher floors).

Data were collected at five impact positions. Following are observations from the P.S.T.M. and coherence results:

- The coherence at the outdoor measurement positions in the alley and the indoor basement measurement position are very high at 20 hertz and above. The coherence for the indoor measurement positions on floors 1, 2, and 3 is relatively low at 50 hertz and above. The low coherence is likely due to the higher existing vibration levels at 50 hertz and above for the upper floors.

- All indoor measurement locations show lower P.S.T.M. levels compared to the outdoor position, thus indicating the building structure is effectively attenuating the vibration. For floors 1, 2, and 3, there is particularly effective attenuation at 50 hertz and above.

Figure 9-9. P.S.T.M. and Coherence on Basement Level at 219 Terry Avenue North

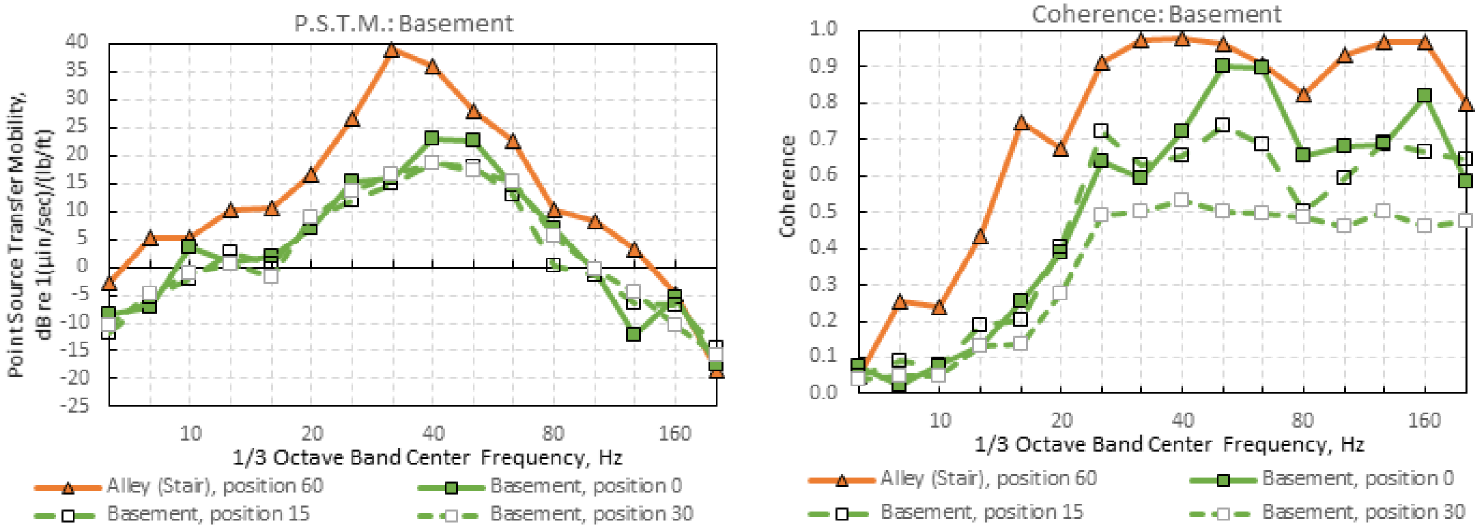


Figure 9-10. P.S.T.M. and Coherence on Floor 1 at 219 Terry Avenue North

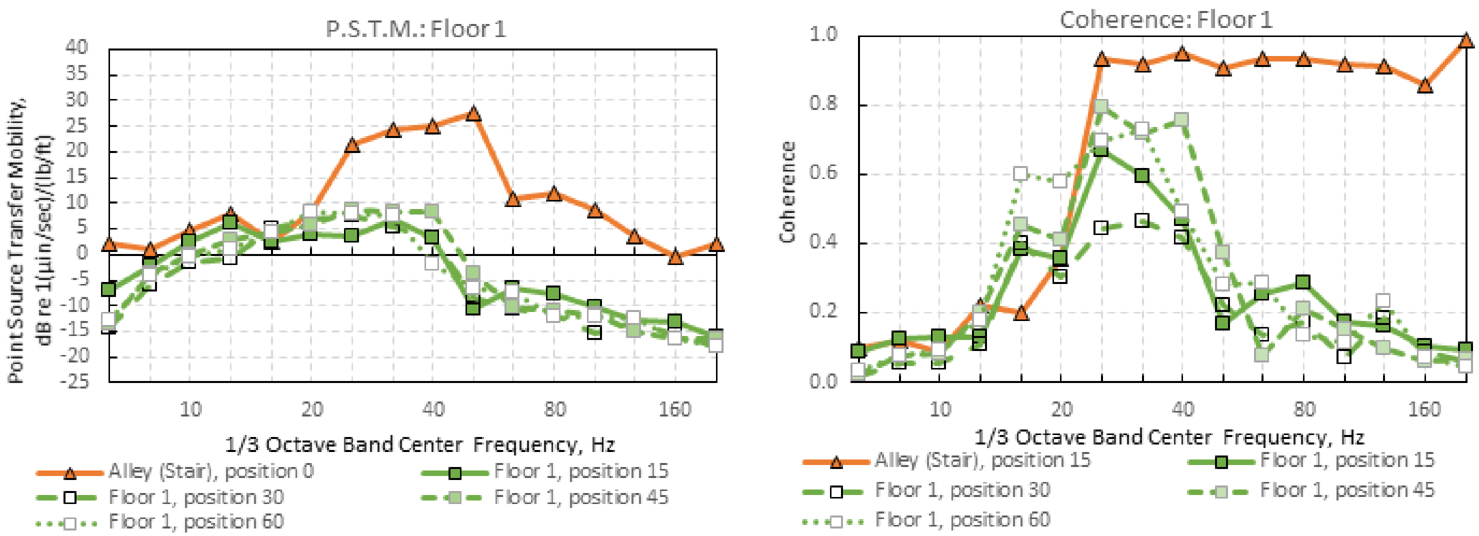


Figure 9-11. P.S.T.M. and Coherence on Floor 2 at 219 Terry Avenue North

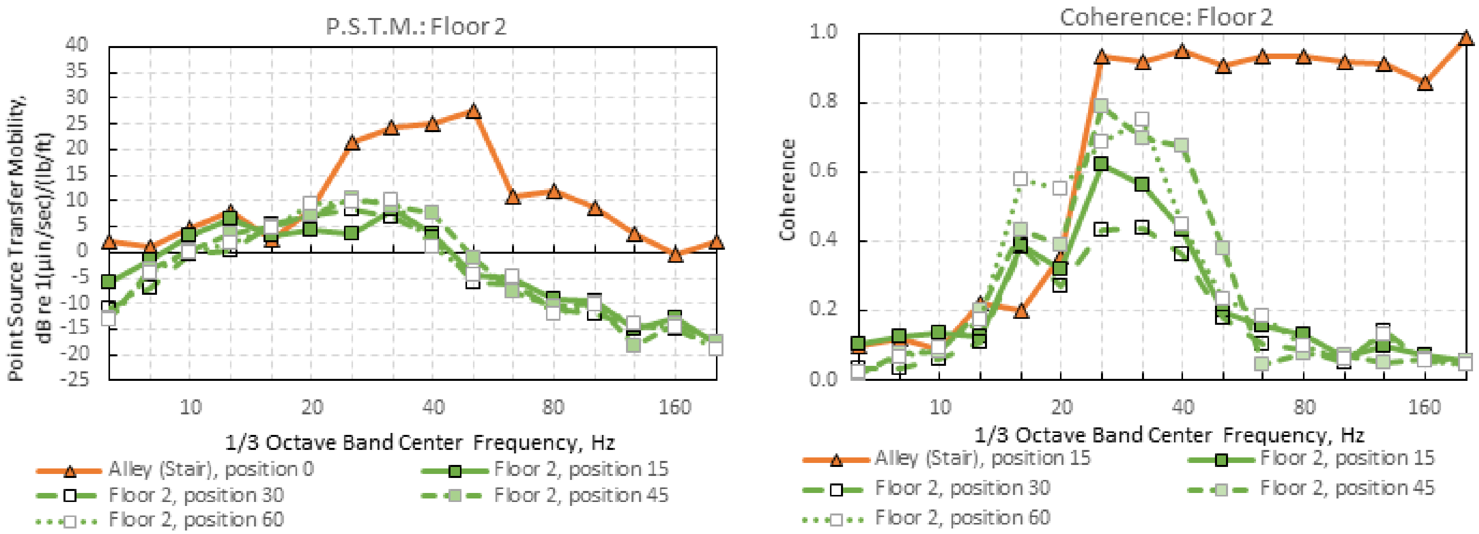
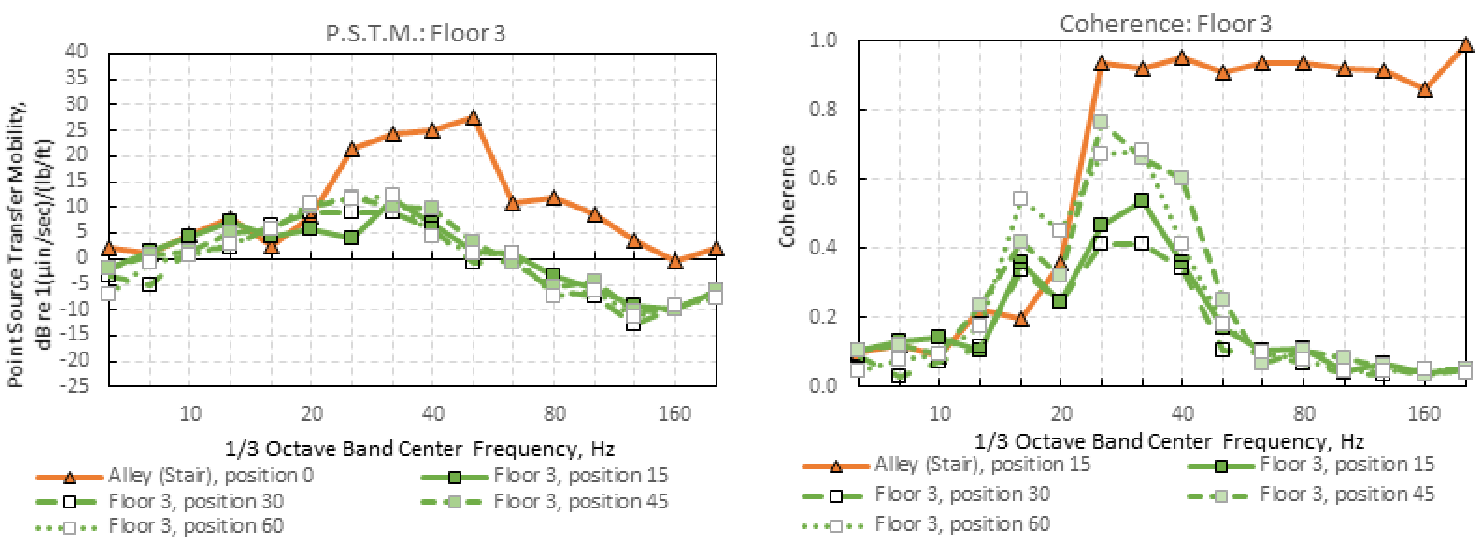


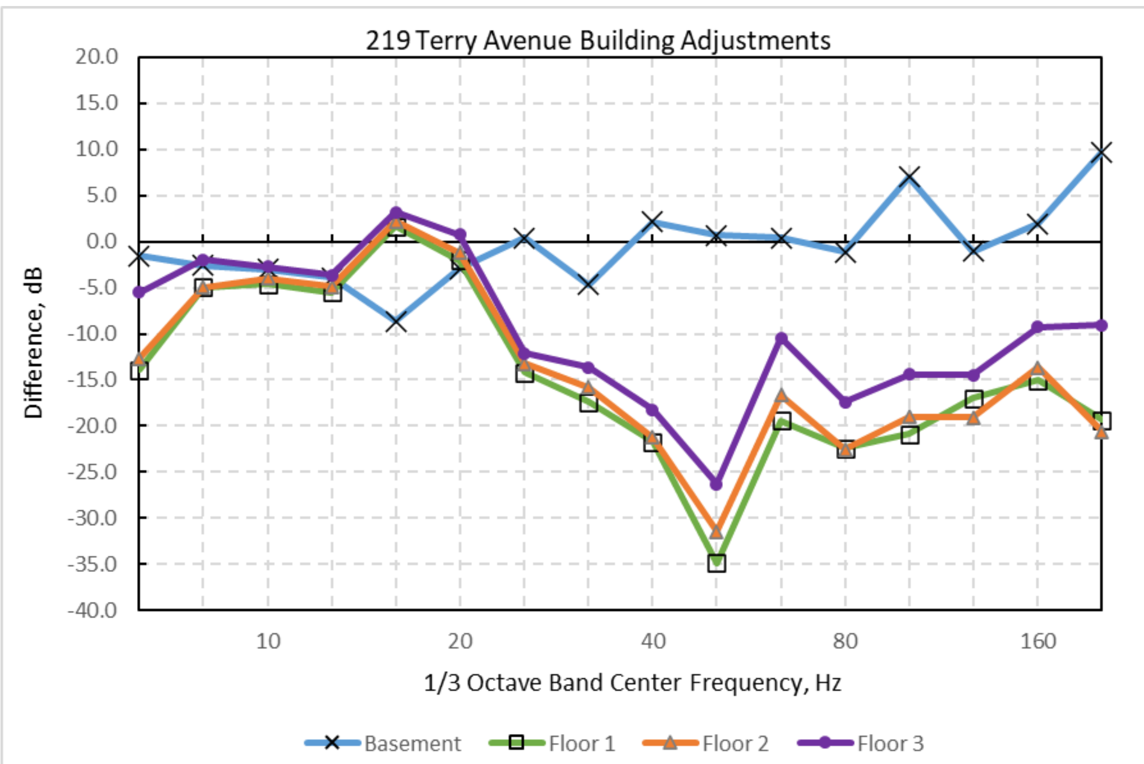
Figure 9-12. P.S.T.M. and Coherence on Floor 3 at 219 Terry Avenue North



The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances are the difference between the outdoor P.S.T.M. at an equivalent setback distance and the indoor P.S.T.M. The building adjustment for the 219 Terry Avenue North measurement sites is an average of the data collected over several of the outdoor impact positions. The measured building adjustments are shown in Figure 9-13. Following are observations from the building adjustments:

- The basement level shows little to no attenuation across the frequency spectrum. This is consistent with some slab-on-grade structures, although larger buildings may show some reduction.
- The upper floors show consistently high attenuation above 20 hertz. This indicates vibration does not propagate efficiently to the higher floors.

Figure 9-13. Measured Building Adjustment at 219 Terry Avenue North



The predicted levels for Preferred Alternative DT-1 are presented in Table 9-2. The predicted levels for Alternative DT-2 are presented in Table 9-3. The predicted levels use the building adjustment shown in Figure 9-13 and L.S.T.M. coefficients averaged from the four closest measurement sites in the South Lake Union area, discussed in Section 3.2, because there is not site-specific borehole vibration propagation data available. The prediction for Preferred Alternative DT-1 includes a +3-decibel adjustment for a curve and for Alternative DT-2 includes a +10-decibel adjustment for a crossover. No safety factor is included in the predictions because the predictions use site-specific building adjustments and there is a 3-decibel safety factor incorporated into the force density level. The spectra of the predicted levels for Alternative DT-2 are shown in Figure 9-14. The spectra of the octave band levels and the Noise Abatement Criteria 45 groundborne noise criteria are shown in Figure 9-15. The prediction assumes the unweighted groundborne noise is equal to the vibration (groundborne vibration to ground noise radiation factor, Krad, equal to 0). The predicted groundborne noise is below the Noise Abatement Criteria 45 criteria in all octave bands.

Tables 9-2 and 9-3 show there is no predicted impact for either Downtown Segment alternative. The highest vibration levels are predicted on the basement level, where the building attenuation is low. The most stringent criteria apply on the second level, where a mass spectrometer is located. For Alternative DT-2, the predicted vibration level at the mass spectrometer on the second level is within 3 decibels of the limit. Although the predicted level does not exceed the limit, Sound Transit recommends a low-impact frog for the crossover (such as a monoblock frog) to ensure vibration from the crossover does not negatively interfere with operations in the sensitive spaces.

Table 9-2. Predicted Vibration and Groundborne Noise Levels at 219 Terry Avenue North with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibel) [c]
Basement	364	35	26	66	<0	Noise Abatement Criteria 45	Does not exceed
1st Floor (general lab space)	364	35	23	66	Not applicable	Not applicable	Does not exceed
2nd Floor (mass spectrometer)	364	35	23	48	Not applicable	Not applicable	Does not exceed
3rd Floor (general lab space)	364	35	26	66	Not applicable	Not applicable	Does not exceed

Table 9-3. Predicted Vibration and Groundborne Noise Levels at 219 Terry Avenue North with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibel) [c]
Basement	118	45	58	66	46	Noise Abatement Criteria 45	Does not exceed
1st Floor (general lab space)	118	45	45	66	Not applicable	Not applicable	Does not exceed
2nd Floor (mass spectrometer)	118	45	45	48	Not applicable	Not applicable	Does not exceed
3rd Floor (general lab space)	118	45	46	66	Not applicable	Not applicable	Does not exceed

Figure 9-14. Predicted Vibration Level for 6th Avenue/Mercer Street Alternative (DT-2) at 219 Terry Avenue North

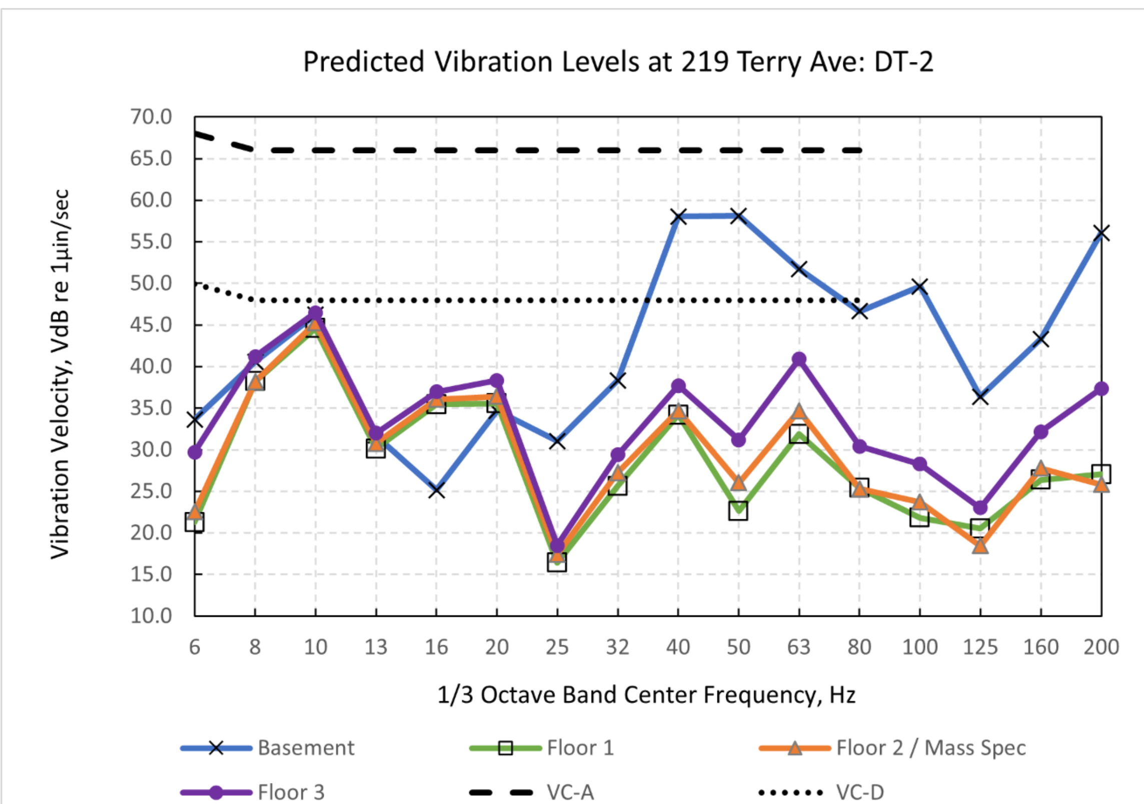
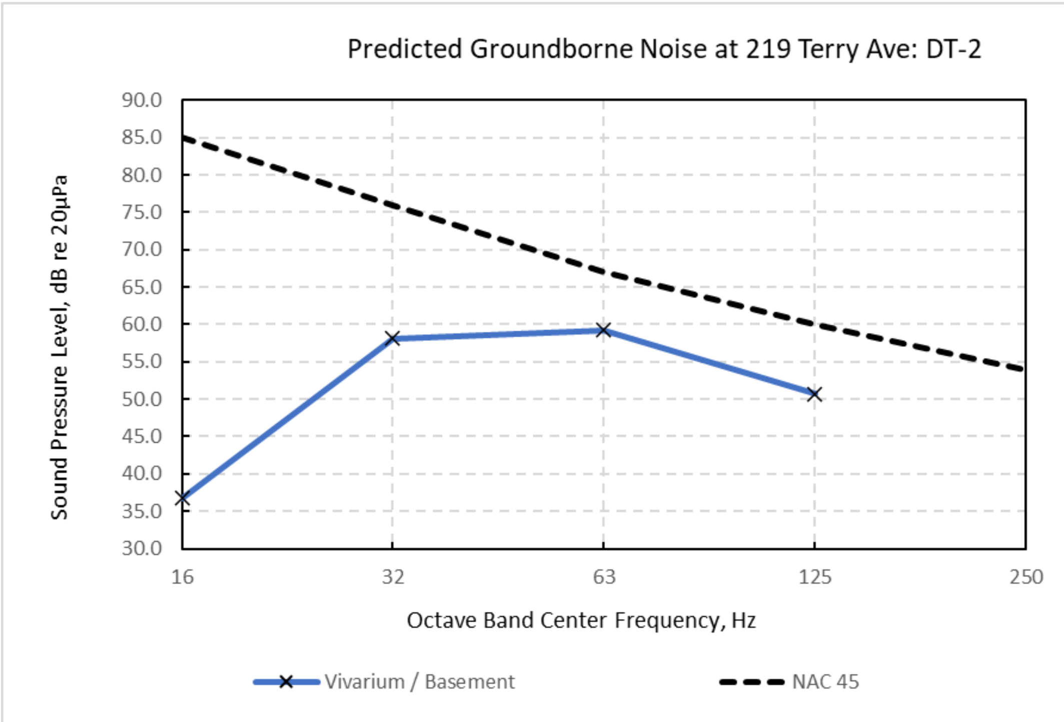


Figure 9-15. Predicted Groundborne Noise Level for 6th Avenue/Mercer Street Alternative (DT-2) at 219 Terry Avenue North



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10 401 TERRY AVENUE NORTH: INSTITUTE FOR SYSTEMS BIOLOGY AND JUST BIOTHERAPEUTICS

10.1 Description of Sensitive Space

The building at 401 Terry Avenue North is located along the Ballard Link Extension Downtown Segment and houses two tenants with vibration-sensitive research areas: the Institute for Systems Biology on floors three and four and Just Biotherapeutics on floor two. The vibration-sensitive equipment for both tenants is summarized in Table 10-1. The sensitive equipment was identified during a site visit in August 2019.

The vibration-sensitive equipment identified at the Institute for Systems Biology are mass spectrometers, microscopes, and the Labcyte Echo, which is a pipetting machine that uses ultrasonic acoustic energy to eject small droplets. No information on vibration limits for the Labcyte Echo was received from the manufacturer. This analysis applies a limit of V.C.-C, which the FTA *Transit Noise and Vibration Impact Assessment Manual* notes is a good standard for most inspection equipment to a detail size of 1 micron. Vibration limits for the mass spectrometer was received from the manufacturer, Thermo Fisher; that criteria are presented in Table 10-2. However, there was no information on whether the manufacturer criteria apply to peak-particle velocity or R.M.S. velocity, and over what time interval or frequency bandwidth the criteria should apply. Because of the difficulty in interpreting the manufacturer's criteria, the existing vibration levels in the building were also used in determining an appropriate vibration threshold. The vibration limit of 54 VdB (V.C.-C) is applied to the mass spectrometers. The limit of 54 VdB corresponds to a level of 0.013 millimeters/second, which is a conservative limit compared to the manufacturer's recommendations in Table 10-2. The limits applied for microscopes is V.C.-A, based on FTA *Transit Noise and Vibration Impact Assessment Manual* guidance for optical microscopes up to 400x magnification, microbalances, optical balances, and other similar specialized equipment.

The vibration-sensitive equipment identified at Just Biotherapeutics are mass spectrometers and cell imagers. The vibration limit adopted for the cell imagers is 54 VdB (V.C.-C), which is appropriate for detail size down to 1 micron. The vibration limit for mass spectrometers is 54 VdB (V.C.-D), the same as that adopted for the mass spectrometer at the Institute of Systems Biology.

Table 10-1. List of Vibration-Sensitive Equipment at 401 Terry Avenue North

Location	Vibration-Sensitive Equipment	Description	Vibration Limit
Institute of Systems Biology	Mass Spectrometers	Criteria provided by manufacturer without sufficient information to interpret accurately	54 VdB (V.C.-C)
Institute of Systems Biology	Labcyte Echo	Pipetting machine that uses ultrasonic acoustic energy to eject small droplets	54 VdB (V.C.-C)
Institute of Systems Biology	Microscopes	Assuming microscopes more sensitive than 400x are on an isolation table	66 VdB (V.C.-A)
Just Biotherapeutics	Mass Spectrometers	Assumes similar sensitivity to Institute of Systems Biology mass spectrometer	54 VdB (V.C.-C)
Just Biotherapeutics	Cell Imagers	Assuming cell size down to 1 micron	54 VdB (V.C.-C)

Table 10-2. Vibration Criteria for Thermo Fisher Mass Spectrometer

Frequency	Velocity (millimeters/second)
48.3 hertz	0.09
25.25 hertz	0.07
11.0 hertz	0.05
10.8 hertz	0.06
6.5 hertz	0.02
2.5 hertz	0.02

Figure 10-1 shows photographs of accelerometers set up in a hallway near the Just Biotherapeutics mass spectrometers on the left, and in an Institute for Systems Biology laboratory on the right.

Figure 10-1. Photographs of the 401 Terry Avenue North Second Floor (left) and Fourth Floor (right)

10.2 Existing Vibration Levels

Existing vibration levels were measured over a 1-hour period at measurement locations on the north end and in the middle of the building on the second and fourth floors from 10:10 a.m. to 11:10 a.m. on a Friday morning. Vibration levels were measured on the south end of the building over a 10-minute period on the same day from 12:10 p.m. to 12:20 p.m. Staff were present at the building during the measurements.

The measured 1-hour or 10-minute Leq vibration levels are shown in Table 10-3. The 1-second vibration levels are plotted on Figures 10-2 through 10-4, and the spectra of the vibration levels are plotted on Figure 10-5. The measured data show the following:

- Ambient vibration levels generally increase with higher floor levels.
- Ambient vibration differs on the north and south ends of the building:
    - Vibration levels are higher on the north end of the building compared to the south end. In the north part of the building, vibration levels are roughly 10 VdB higher in the 8-, 31.5-, and 63-Hertz 1/3-octave bands.

  - Vibration levels on the south end of the building show a peak roughly 15 VdB higher than the northern end at 200 Hertz.

- The 4th floor north measurement position is the only location that exceeds the V.C.-C (54 VdB) vibration criteria curve. The exceedance is in the 8-Hertz 1/3-octave band. The other measurement positions, with the exception of the 2nd floor south measurement position, exceed the V.C.-D vibration criterion curve, indicating the V.C.-C is an appropriate limit for the building.

During the 1-hour vibration measurement, two streetcars passed the building on Terry Avenue. It was not possible to identify the vibration from the streetcar above the ambient levels in the building.

Table 10-3. Ambient Vibration Levels at 401 Terry Avenue North

Monitoring Location	Vibration level (Leq)
2nd Floor North – Just Biotherapeutics	57 VdB [a]
4th Floor Mid-Building – Institute for Systems Biology	56 VdB [a]
4th Floor North – Institute for Systems Biology	63 VdB [a]
2nd Floor South – Just Biotherapeutics	51 VdB [b]
3rd Floor South – Institute for Systems Biology	54 VdB [b]

a. 1-hour Leq.

b. 10-minute Leq.

Figure 10-2. Measured 1-second Noise Levels in 401 Terry Avenue North Second Floor

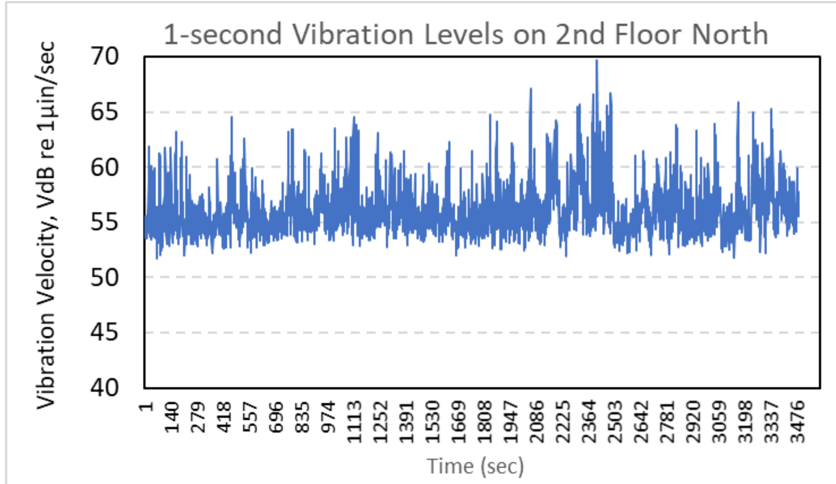


Figure 10-3. Measured 1-second Vibration Levels in 401 Terry Avenue North Fourth Floor

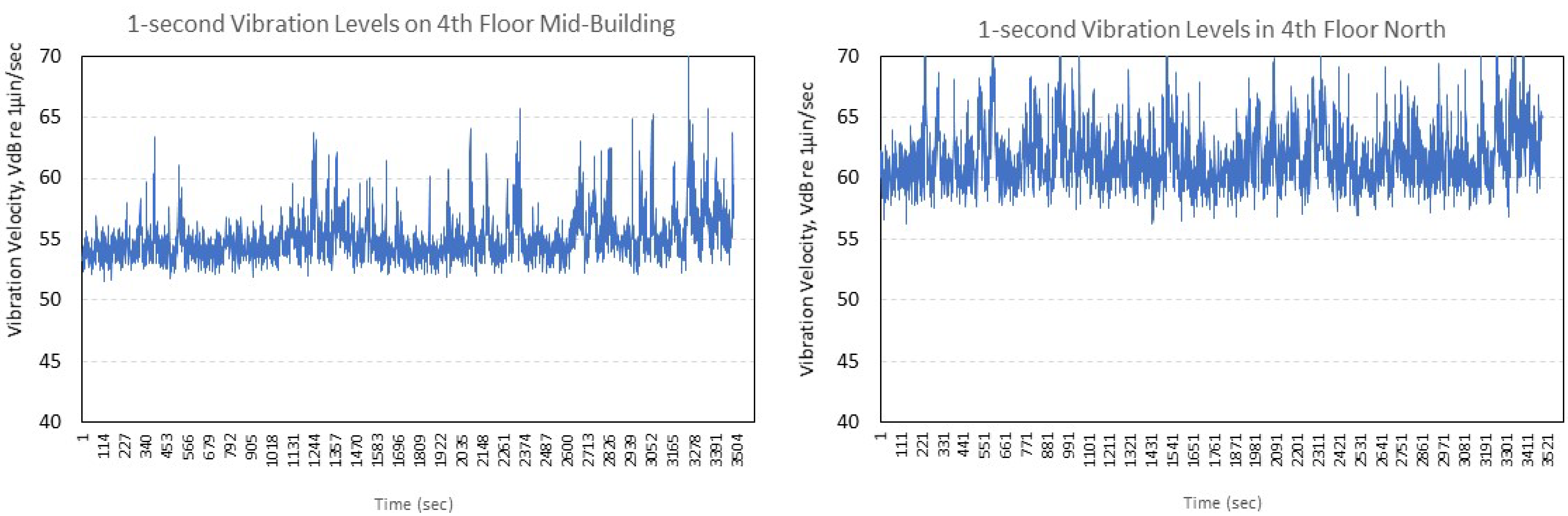
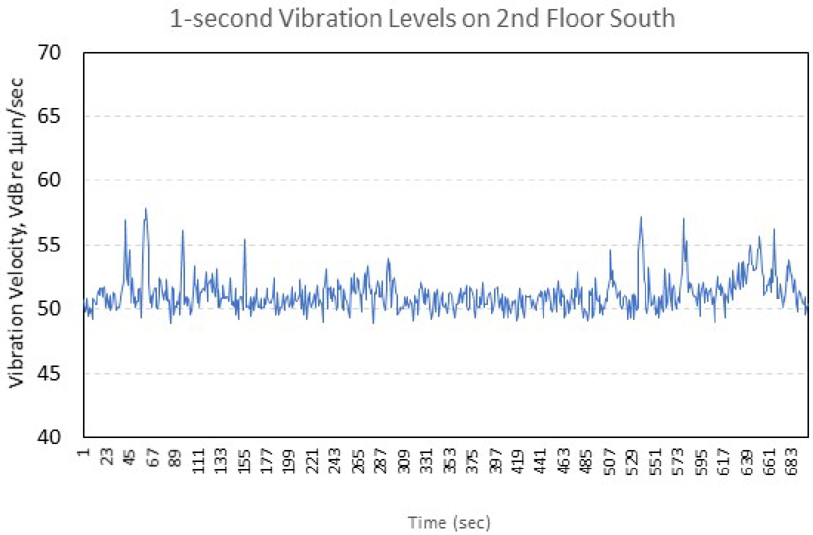


Figure 10-4. Measured 1-second Vibration Levels in 401 Terry Avenue North Second and Third Floors (South)



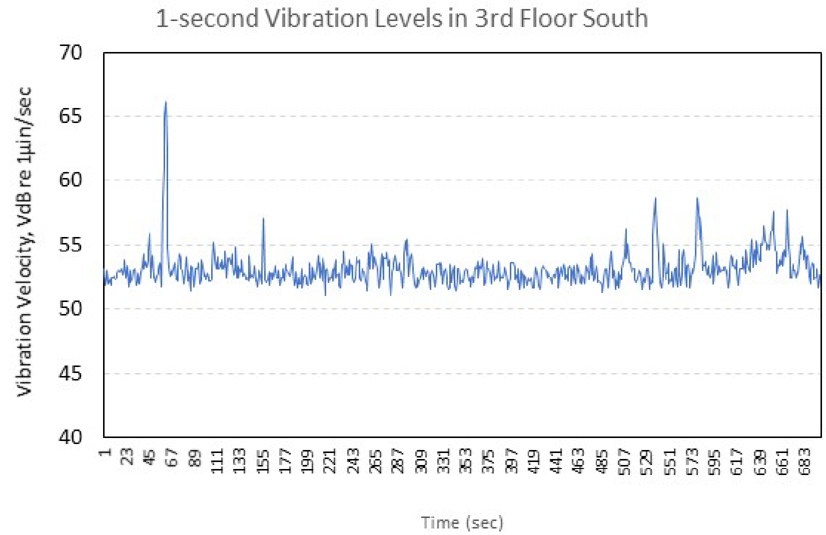
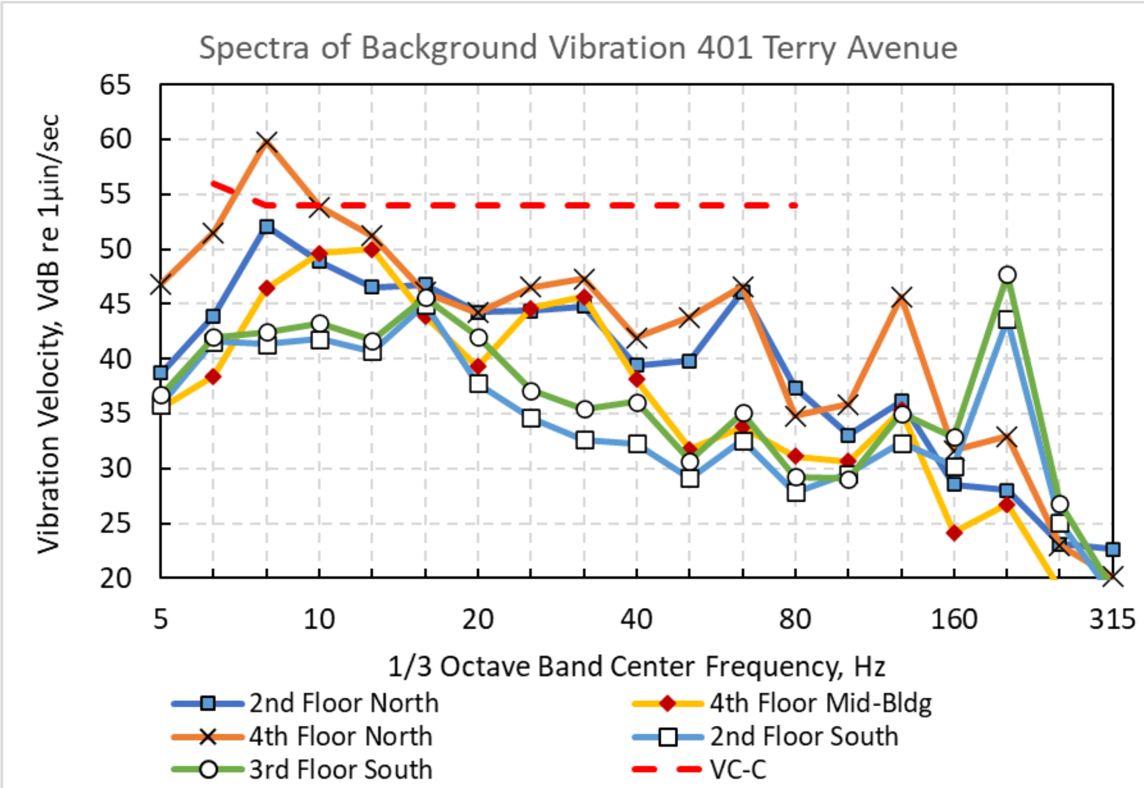


Figure 10-5. Spectra of Background Vibration Levels at 401 Terry Avenue North



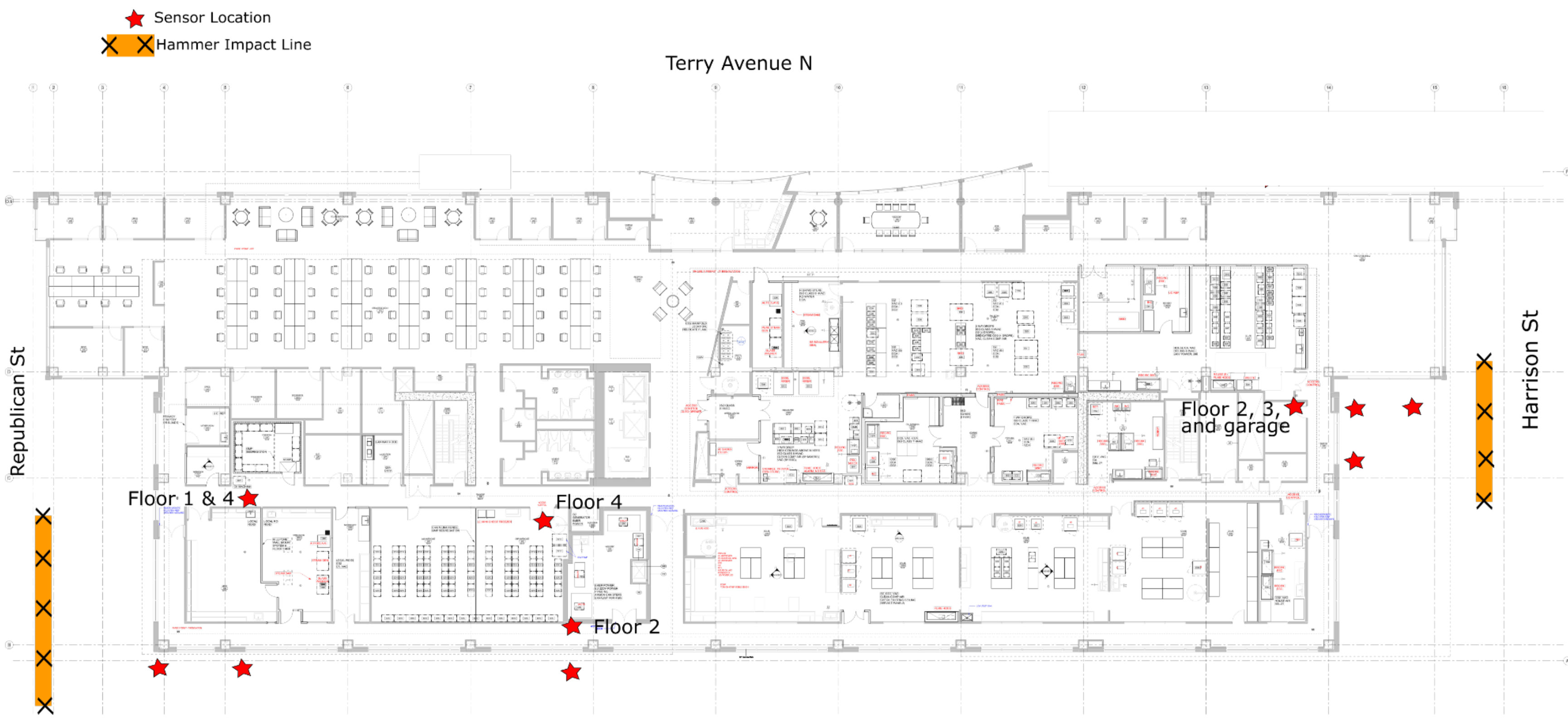
10.3 Vibration Propagation Measurement Description

A surface vibration propagation test was completed at 401 Terry Avenue North to determine how efficiently vibration propagates form the soil into the building. A drop-hammer was used to impart a force along the Republican Street and Harrison Street sidewalks, and the resulting vibrations were measured outside and inside the building. Data were collected from five impact points spaced 15 feet apart along Republican Street and four impact points spaced 15 feet apart along Harrison Street. Photos and a schematic of the vibration propagation site are provided in Attachment N.3B, Vibration Measurement Site Photographs.

The vibration levels were measured at three outdoor locations on Republican Street and three outdoor locations on Harrison Street, which were used as a reference to examine how levels change as the vibration travels from the soil into the building structure. For the impact points on Republican Street, the indoor measurement locations were the receiving room on the ground level, second floor hallway mid-building, fourth floor at north facade, and fourth floor mid-building. For impacts along Harrison Street, the indoor measurement locations were the parking garage, second floor south facade, and third floor south facade. The measurement locations were selected to collect representative data on each floor of the building.

Figure 10-6 shows the second-level floor plan of 401 Terry Avenue North with the sensor locations labeled. The approximate location of the outdoor sensors and the drop-hammer impact locations are also indicated.

Figure 10-6. Second Level Floor Plan at 401 Terry Avenue North



10.4 Vibration Propagation Measurement Results and Predictions

The result of the vibration propagation test is the P.S.T.M., a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the P.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The P.S.T.M. and coherence results for the indoor measurement positions and their reference outdoor measurement position are shown in Figures 10-7 through 10-11. The reference outdoor measurement position was chosen to have approximately the same distance between the drop-hammer and the outdoor accelerometer as the distance from the drop-hammer to the indoor accelerometer (not accounting for vertical distance to higher floors).

Data were collected at five drop-hammer impact positions on Republican Street along the north façade of the building and four impact positions on Harrison Street along the south façade of the building. Following are observations from the P.S.T.M. and coherence results:

- The coherence from indoor measurement positions at the north end of the building are very low (mostly below 0.2) and should therefore be used with caution. The outdoor position at 109 feet in the alley also has mostly poor coherence. Ambient measurements showed higher existing levels at the north end of the building, which contribute to a poor signal-to-noise ratio.
- The coherence from indoor measurement positions at the south end of the building is high at 20 Hertz and above. These indoor measurement locations show lower P.S.T.M. levels compared to the reference outdoor position, indicating the building structure is effectively attenuating the vibration. There is particularly effective attenuation at 31.5 Hertz and above at the south end of the building.

Figure 10-7. P.S.T.M. and Coherence on 401 Terry Avenue North Second Floor (North)

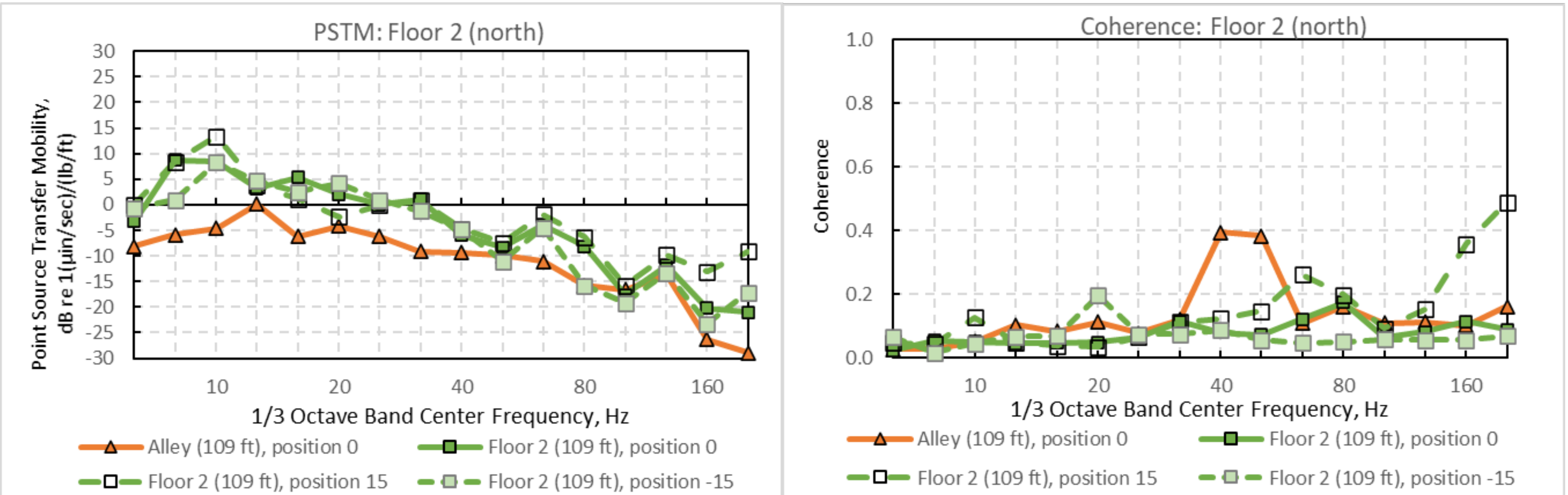


Figure 10-8. P.S.T.M. and Coherence on 401 Terry Avenue North Fourth Floor (North)

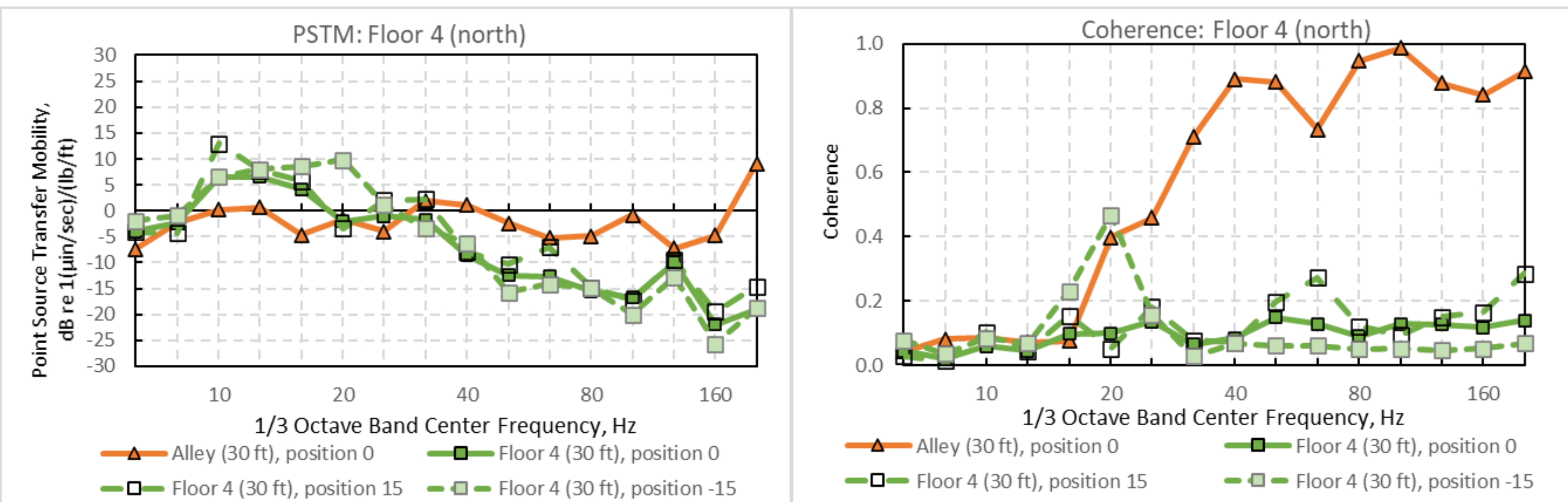


Figure 10-9. P.S.T.M. and Coherence on 401 Terry Avenue North Fourth Floor (Mid-building)

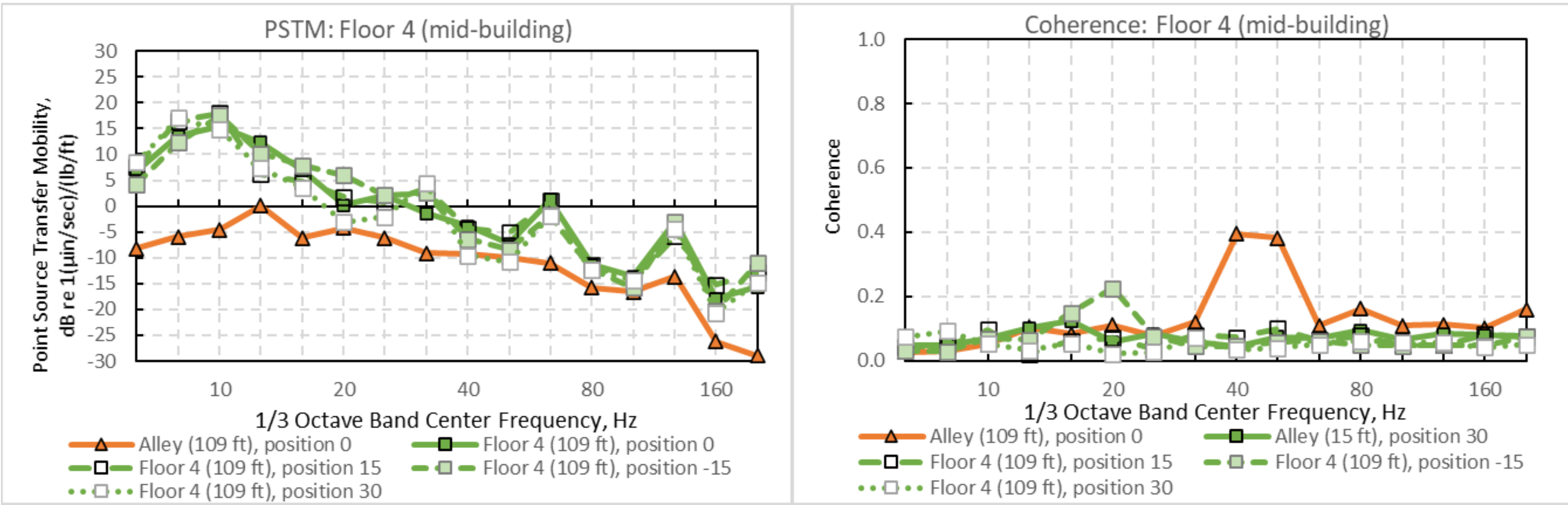


Figure 10-10. P.S.T.M. and Coherence on 401 Terry Avenue North Second Floor (South)

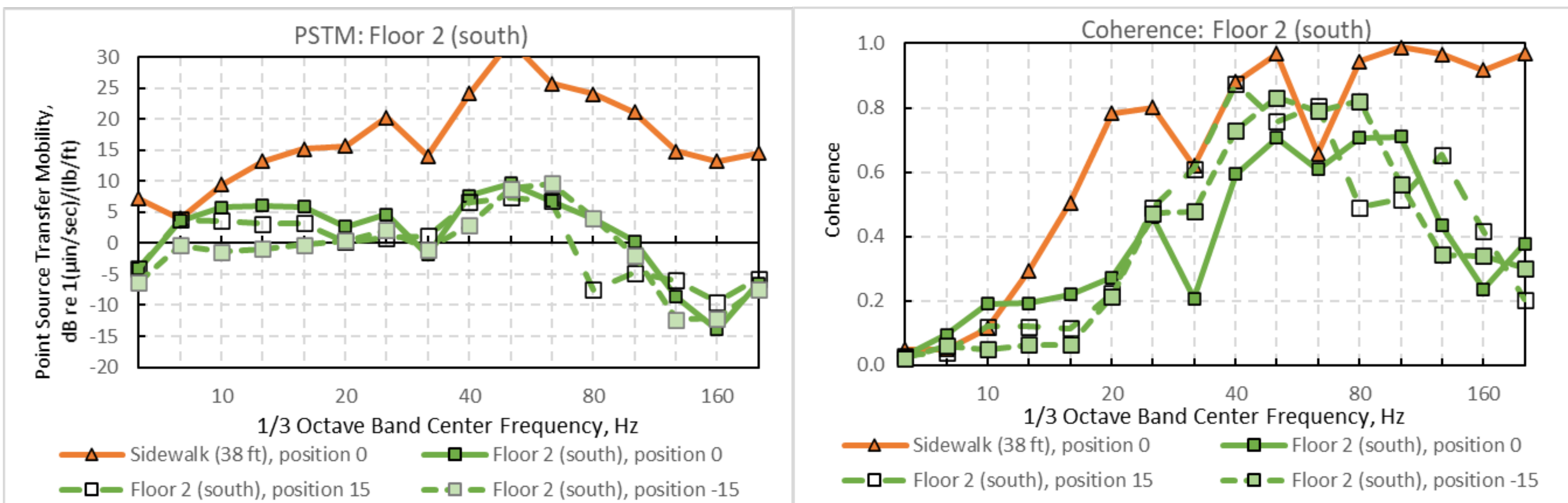
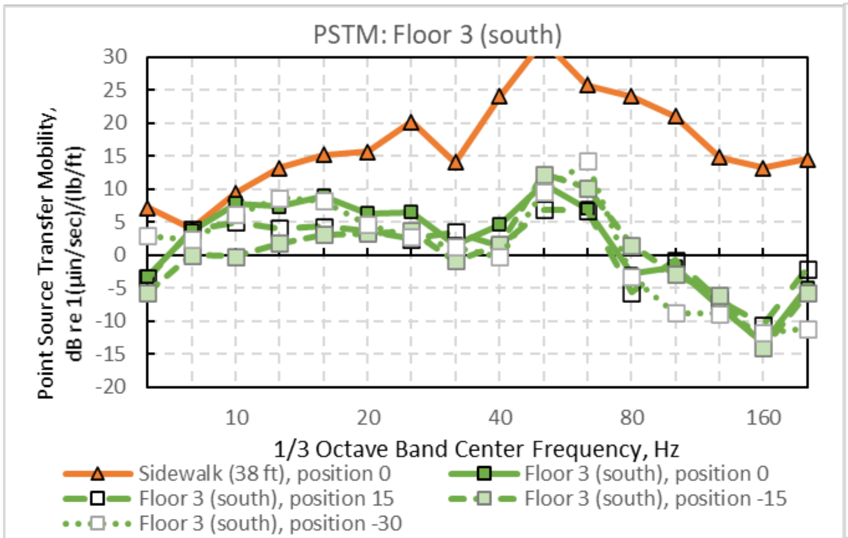
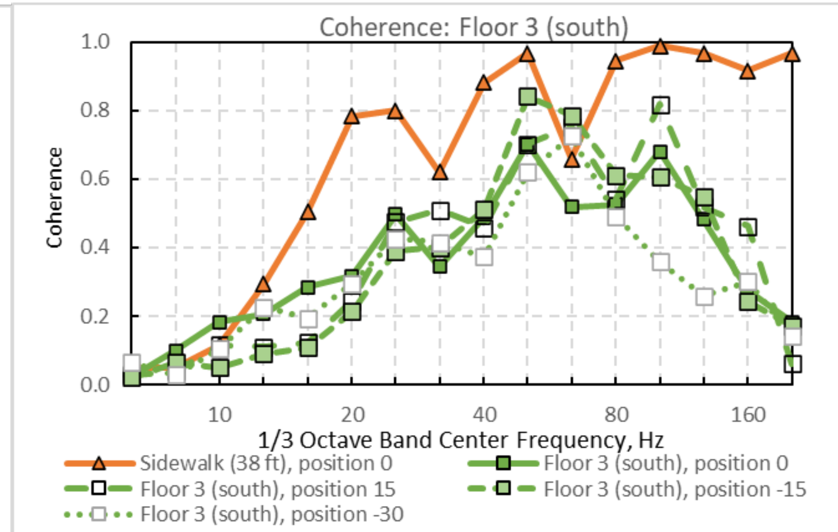


Figure 10-11. P.S.T.M. and Coherence on 401 Terry Avenue North Third Floor (South)





The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances is the difference between the outdoor P.S.T.M. at an equivalent setback distance and the indoor P.S.T.M. The building adjustments are shown in Figure 10-12. As discussed above, the low coherence for the north end of the building indicates the results should be interpreted with caution, particularly for the mid-building locations. It is very unlikely that the building is amplifying vibration at the north end of the building and attenuating vibration at the south end of the building. It is more likely that the higher ambient vibration levels in the north end of the building and relatively inefficient vibration propagation result in a poor signal-to-noise ratio, which leads to an over-estimate of the transfer mobility levels inside the building.

To account for the uncertainty in the results, multiple building adjustments are applied in the prediction model, which results in a range of predicted levels. The following building adjustments are applied:

- For the Institute of Systems Biology, the 4th floor north building adjustment and a 0-dB building adjustment are applied.
- For Just Biotherapeutics, the 2nd floor south building adjustment and a 0-dB building adjustment are applied.

The 0-dB building adjustment assumes the building provides no attenuation or amplification, and is a very conservative assumption based on the data collected on the south end of the building. The mid-building results, which show the potential for amplification, are not applied due to the low coherence values and the poor confidence in the results.

In addition to the building adjustment, the predicted vibration levels include a 3-decibel adjustment to account for track curvature and a 3-decibel safety factor incorporated into the force density level.

The predicted vibration levels for Preferred Alternative DT-1 are presented in Table 10-4, and the predicted vibration levels for Alternative DT-2 are presented in Table 10-5. The results show there is no predicted impact for Preferred Alternative DT-1 where the building is over 600 feet from the light rail alignment.

Figure 10-13 shows the spectra of the predicted levels for Alternative DT-2. For Alternative DT-2, the predicted levels with no building adjustment are one decibel below the impact threshold for the most sensitive equipment. Applying the building adjustments measured near the north façade on the fourth floor or near the south façade on the second floor, the predicted level is at least 10 decibels below the impact threshold for the most sensitive equipment. No mitigation measures are proposed because the predicted levels are below the impact thresholds.

Figure 10-12. Measured Building Adjustment at 401 Terry Avenue North

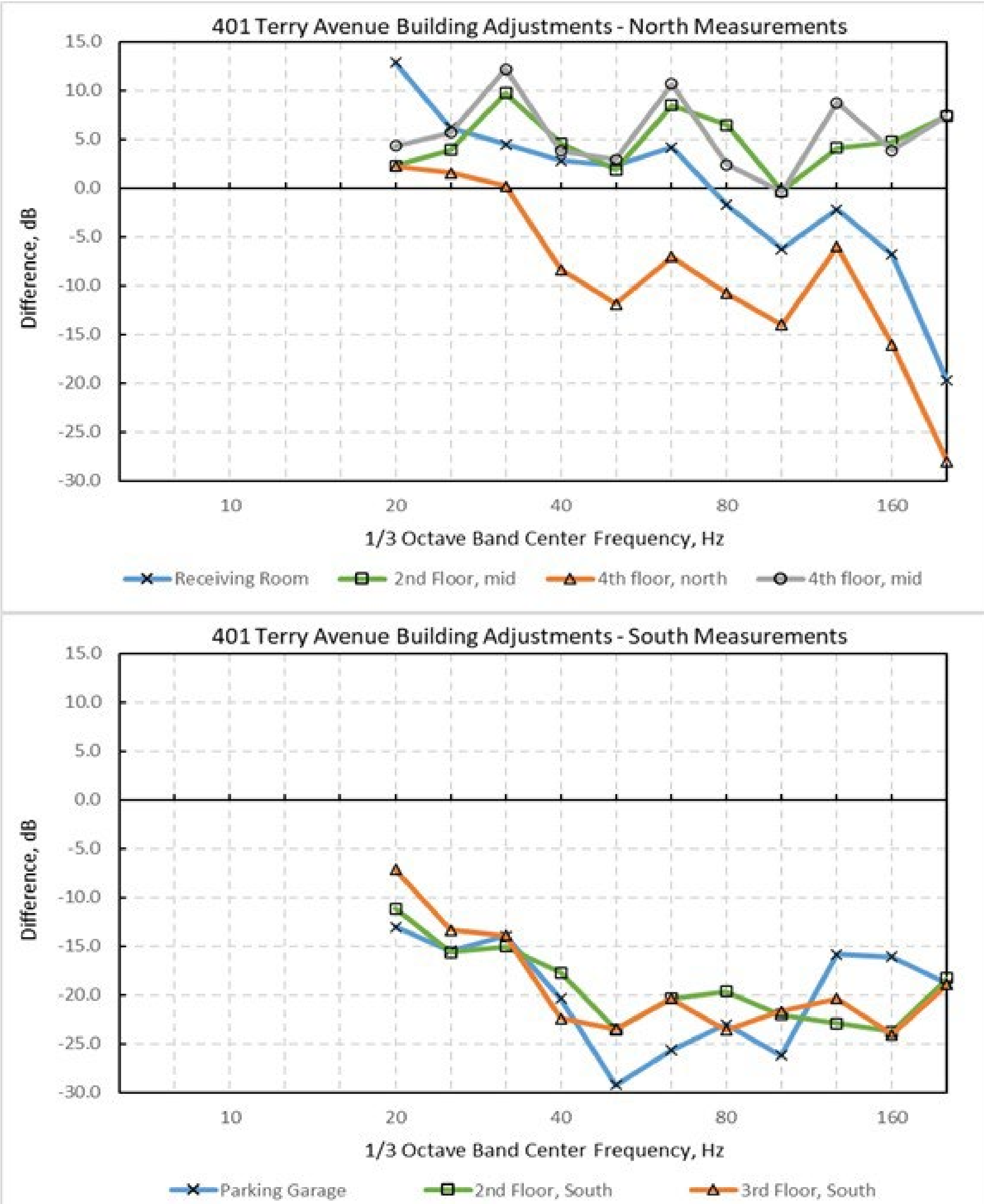


Table 10-4. Predicted Vibration and Groundborne Noise Levels at 401 Terry Avenue with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibel) [c]
I.S.B. Labcyte Echo	685	35	27	54	Not applicable	Not applicable	Does not exceed
I.S.B. Mass Spectrometer	685	35	27	54	Not applicable	Not applicable	Does not exceed
I.S.B. Microscopes	685	35	27	66	Not applicable	Not applicable	Does not exceed
Just Biotherapeutics Cell Imagers	685	35	27	54	Not applicable	Not applicable	Does not exceed
Just Biotherapeutics Mass Spectrometer	685	35	27	54	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 10-5. Predicted Vibration and Groundborne Noise Levels at 401 Terry Avenue North with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

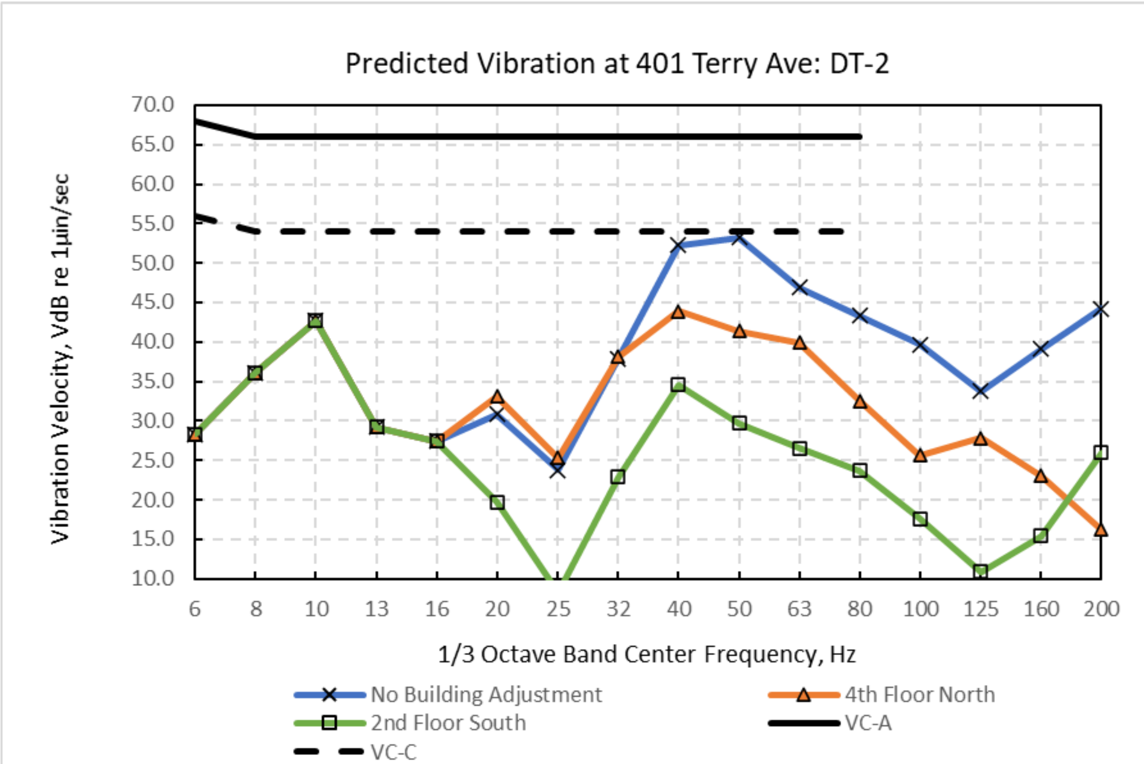
Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibel) [c]
I.S.B. Labcyte Echo	102	45	44 to 53	54	Not applicable	Not applicable	Does not exceed
I.S.B. Mass Spectrometer	102	45	44 to 53	54	Not applicable	Not applicable	Does not exceed
I.S.B. Microscopes	102	45	44 to 53	66	Not applicable	Not applicable	Does not exceed
Just Biotherapeutics Cell Imagers	102	45	44 to 53	54	Not applicable	Not applicable	Does not exceed
Just Biotherapeutics Mass Spectrometer	102	45	44 to 53	54	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second. Range of predicted levels reflects different building adjustments.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 10-13. Predicted Vibration Level for 6th Avenue/Mercer Street Alternative (DT-2) at 401 Terry Avenue North



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11 400 DEXTER AVENUE NORTH: JUNO THERAPEUTICS

11.1 Description of Sensitive Space

The building at 400 Dexter Avenue North along the Ballard Link Extension Downtown Segment in South Lake Union is owned by Alexandria Real Estate, an organization that specializes in providing office and laboratory space for research facilities. At the time of this vibration assessment, most of the building was occupied by Bristol Myers Squibb, with lab space on the second floor and the fifth through ninth floors. On floors 5 through 9, lab space is typically found along the east half of the building and office space located along the west half of the building. On floor 2, there is a smaller lab space located at the north end of the building. The sensitive equipment in the building was identified during a site visit in October 2019.

The vibration-sensitive equipment and the applicable vibration limits are summarized in Table 11-1. The vibration limits are based on the FTA *Transit Noise and Vibration Impact Assessment Manual*, which uses the industry-standard vibration-criteria curves and on the National Institutes of Health *Design Requirement Manual* Table 5.2.2. The most sensitive piece of equipment at Juno Therapeutics is the mass spectrometer. The FTA *Transit Noise and Vibration Impact Assessment Manual* does not have specific criteria for mass spectrometers, so the National Institutes of Health recommended limit of 48 VdB (V.C.-D) is applied. The FTA *Transit Noise and Vibration Impact Assessment Manual* describes V.C.-D as suitable in most instances for the most demanding equipment.

The laboratory spaces throughout the building have various cell imagers and microscopes. A limit of 54 VdB (V.C.-C) is adopted for this equipment, which the FTA *Transit Noise and Vibration Impact Assessment Manual* describes as appropriate to 1-micron detail size. The same limit is applied to the Xuri wave reactors, which use a rocking technology to provide an environment to grow cell cultures. The manufacturer did not respond to a request for vibration limits, so the same V.C.-C criteria are applied assuming that the 1-micron detail size acceptable for cell imaging is also suitable for growing cell cultures.

The laboratory spaces also have various pipetting and centrifuge equipment. A limit of 78 VdB is applied to this type of instrumentation, which is appropriate for probe test equipment.

Table 11-1. List of Vibration-Sensitive Equipment at 400 Dexter Avenue North

Vibration-Sensitive Equipment	Description	Vibration Limit
Mass spectrometers	Used to determine the masses of particles or molecules to determine the chemical structure of compounds	48 VdB/V.C.-D
Cell imagers and microscopes	Some on isolation platforms, assuming anything more sensitive than 1000x magnification or 1 micron detail size is on an isolation platform	54 VdB V.C.-C
Xuri Wave Reactors	Uses a rocking technology to provide an environment to grow cell cultures	54 VdB/V.C.-C
Pipetting and centrifuge equipment	Assumed to be equivalent in sensitivity to probe test equipment	78 VdB

Figure 11-1 shows photographs of accelerometers set up in a hallway near ninth floor labs on the southern end of the building on the left, and near second floor labs on the northern end of the building on the right.

Figure 11-1. Photographs of 400 Dexter Avenue North Ninth Floor (left) and Second Floor (right)

11.2 Existing Vibration Levels

Existing vibration levels were measured over a 1-hour period on the southern end of the building on the fifth, sixth, and ninth floors from 10:00 a.m. to 11:00 a.m. on a Saturday morning. Vibration levels were measured on the northern end of the building over a 15-minute period on the same day from 1:00 p.m. to 1:15 p.m. No Bristol Myers Squibb staff were present at the building during the measurements due to the weekend hours.

The measured 1-hour (or 15-minute) Leq vibration levels are shown in Table 11-2. The 1-second vibration levels are plotted in Figures 11-2 through 11-4, and the spectra of the vibration levels are plotted in Figure 11-5.

Table 11-2. Ambient Vibration Levels at 401 Terry Avenue North

Monitoring Location	Vibration level (1-hr Leq)
5th Floor South	45 VdB
6th Floor South	45 VdB
9th Floor South	47 VdB
2nd Floor North	45 VdB [a.]

[a.] 15-minute Leq measurement.

Figure 11-2. Measured 1-second Vibration Levels in 400 Dexter Avenue North Fifth and Sixth Floors

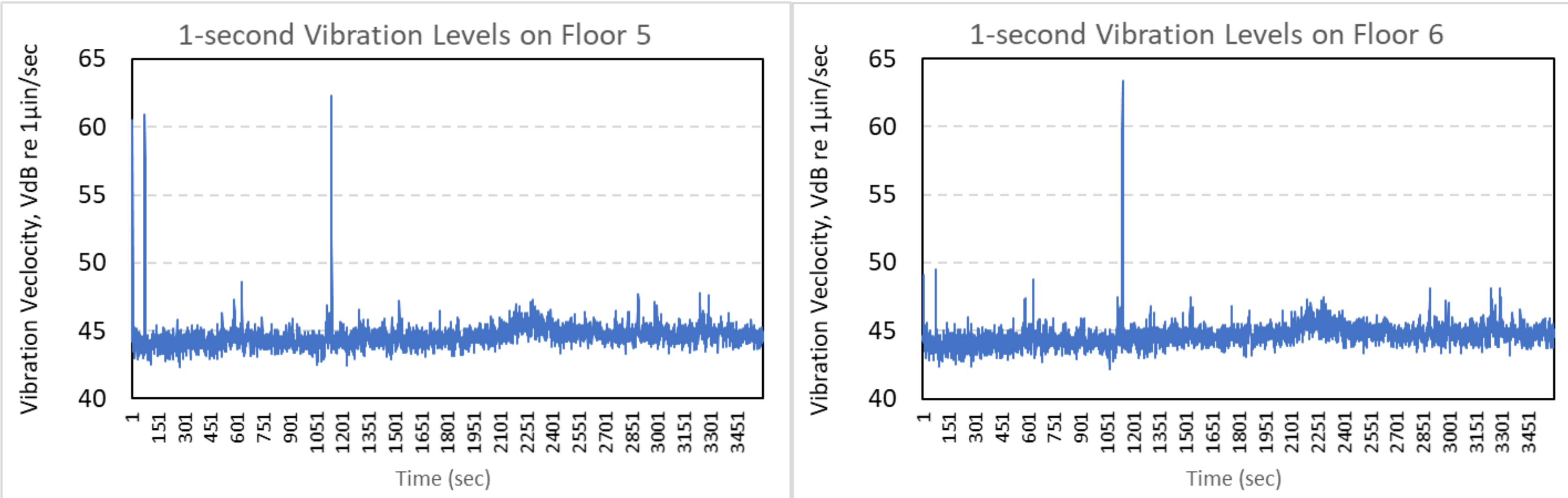


Figure 11-3. Measured 1-Second Vibration Levels in 400 Dexter Avenue North Ninth Floor

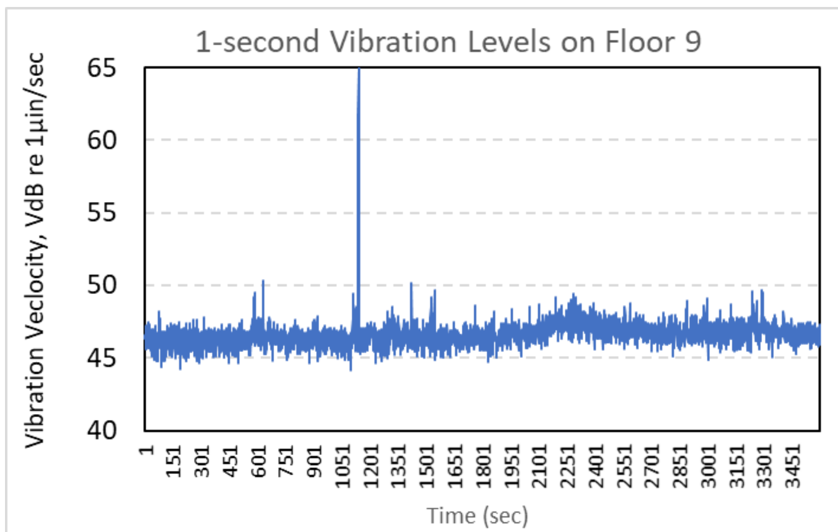


Figure 11-4. Measured 1-second Vibration Levels in 400 Dexter Avenue North Second Floor

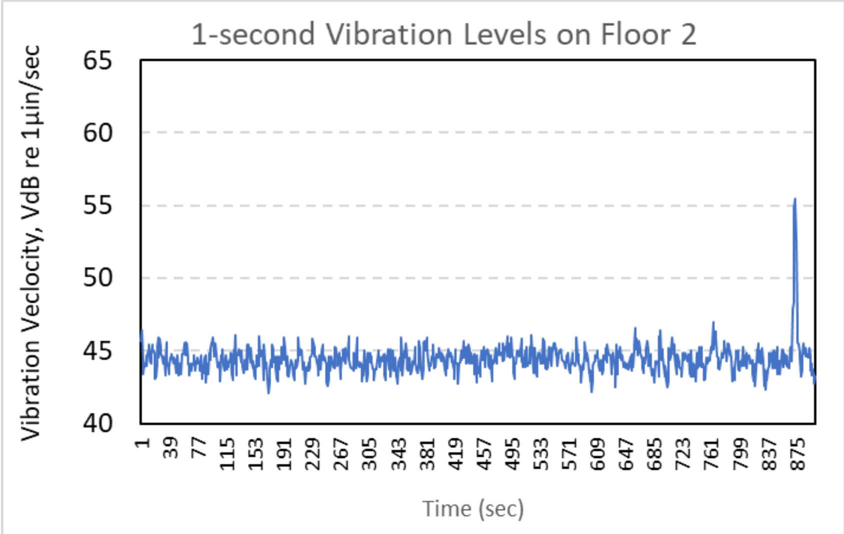
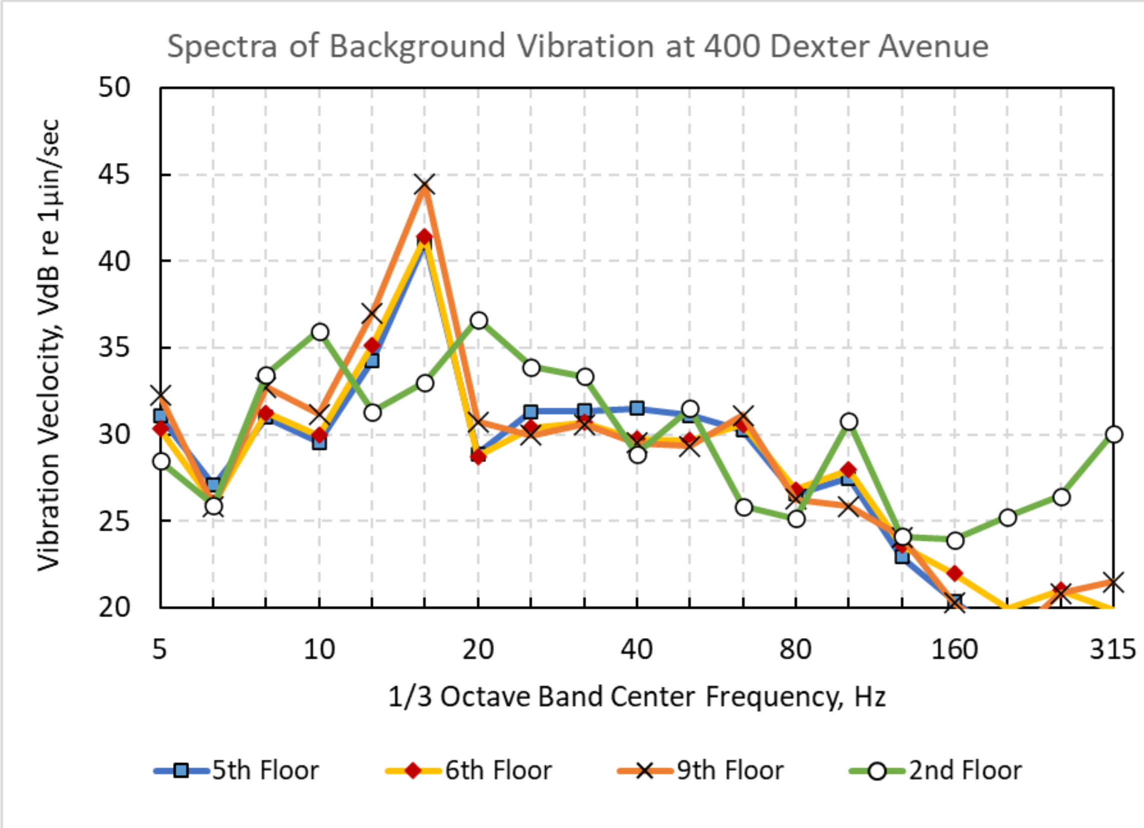


Figure 11-5. Spectra of Background Vibration Levels at 400 Dexter Avenue North



The measured data show the following:

- The 5th, 6th, and 9th floor ambient vibration levels are very consistent. Vibration levels are highest in the 16-Hertz 1/3-octave band. There was a vibration event that occurred simultaneously on all three floors with levels exceeding 60 VdB.
- The Leq measured on floor 2 at the north end of the building is similar to the levels measured on the higher floors towards the south end of the building. However, the levels on floor 2 have a different spectral shape, with a much lower amplitude at 16 Hertz.

The existing vibration levels on all floors meet the VC-D vibration criteria curve, indicating it is an appropriate threshold to apply for the most sensitive equipment in the building.

11.3 Vibration Propagation Measurement Description

A surface vibration propagation test was completed at 400 Dexter Avenue North to determine how efficiently vibration propagates form the soil into the building. A drop-hammer was used to impart a force along the Republican Street and Harrison Street sidewalks, and the resulting vibrations were measured outside and inside the building. Data were collected from five drop-hammer impact points spaced 20 feet apart along Harrison Street and five impact points spaced 15 feet apart along Republican Street. Photos and a schematic of the vibration propagation site are provided in Attachment N.3B, Vibration Measurement Site Photographs.

The vibration levels were measured at two outdoor locations for both impact sites, which was used as a reference to examine how levels change as the vibration travels from the soil into the building structure. For impacts along Harrison Street, the indoor measurement locations were the parking garage level 5, ground floor, fifth floor, sixth floor, and ninth floor. For the impacts on Republican Street, the indoor measurement locations were the ground floor and second floor. The measurement locations were selected to collect representative data on each floor of the building with sensitive use.

Figures 11-6 and 11-7 show floor plans of 400 Dexter Avenue North with the sensor locations labeled. The approximate locations of the outdoor sensors and the drop-hammer impact locations are also indicated.

11.4 Vibration Propagation Measurement Results and Predictions

The result of the vibration propagation test is the P.S.T.M., a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the P.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The P.S.T.M. and coherence results for the indoor measurement positions and their reference outdoor measurement position are shown in Figures 11-8 through 11-13. The reference outdoor measurement position was chosen to have approximately the same distance between the drop-hammer and the outdoor accelerometer as the distance from the drop-hammer to the indoor accelerometer (not accounting for vertical distance to higher floors).

Data were collected at five impact positions along both Harrison Street and Republican Street. Following are observations from the P.S.T.M. and coherence results:

- The parking garage is the only indoor location with coherence above 0.2 decibel. The low coherence indoors is likely due to inefficient vibration transmission, because the existing vibration levels are relatively low.
- The outdoor P.S.T.M. levels are much greater than the indoor P.S.T.M. levels above 20 Hertz, indicating the building structure is effectively attenuating the vibration.

The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances are the difference between the outdoor P.S.T.M. at an equivalent setback distance and the indoor P.S.T.M. The building adjustments for 400 Dexter Avenue North measurement sites are shown in Figure 11-14. Following are observations from the building adjustments:

- The parking garage, the only indoor location with coherence above 0.2, shows building attenuation greater than 20 dB at frequencies 31.5 Hertz and above.
- The upper floors show high attenuation in the 40 to 80 Hertz frequency range, and lower attenuation above 80 Hertz.
- The second floor shows attenuation greater than 5 dB at frequencies 40 Hertz and above.

Figure 11-6. Second Level Floor Plan at 400 Dexter Avenue North

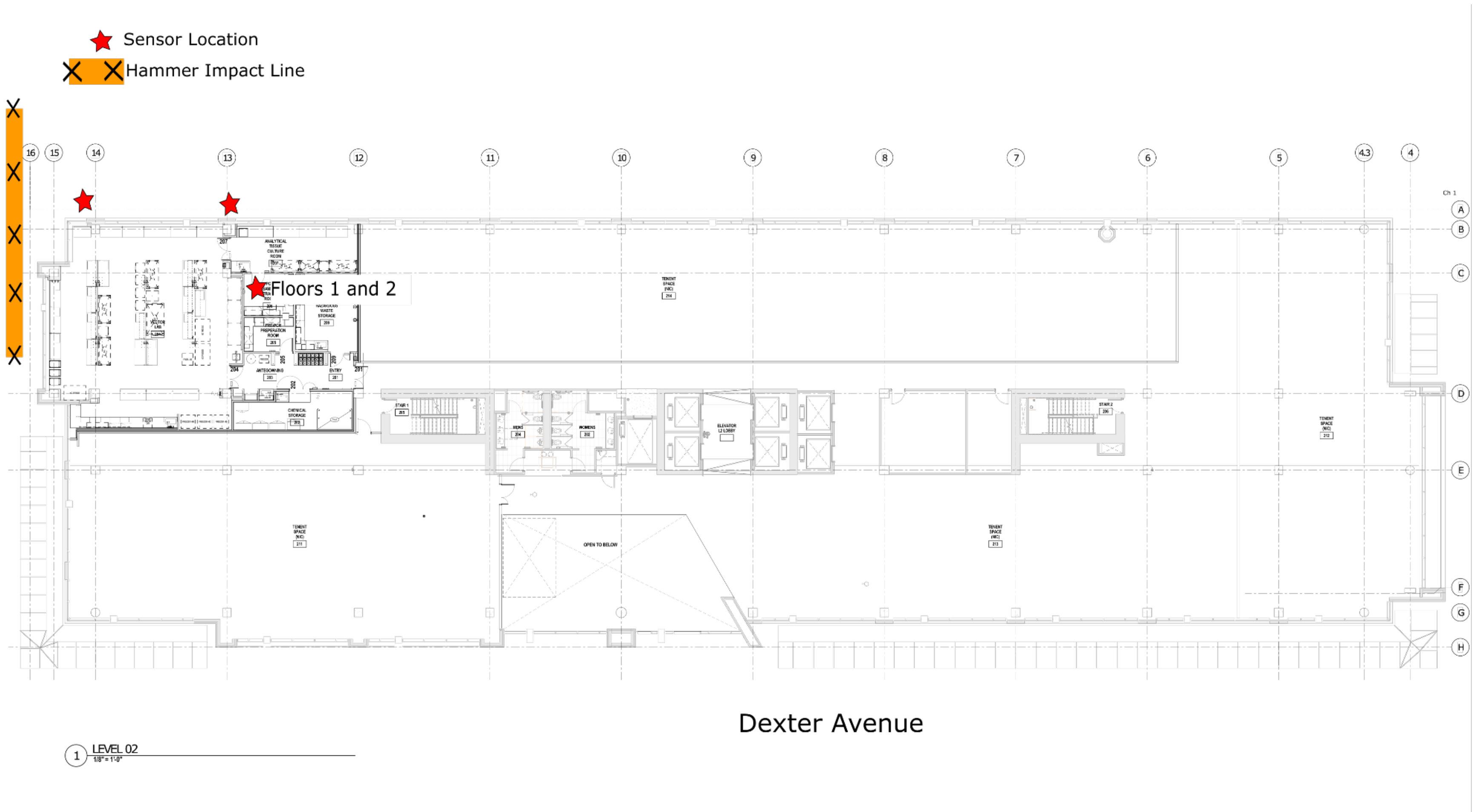


Figure 11-7. Fifth Level Floor Plan at 400 Dexter Avenue North

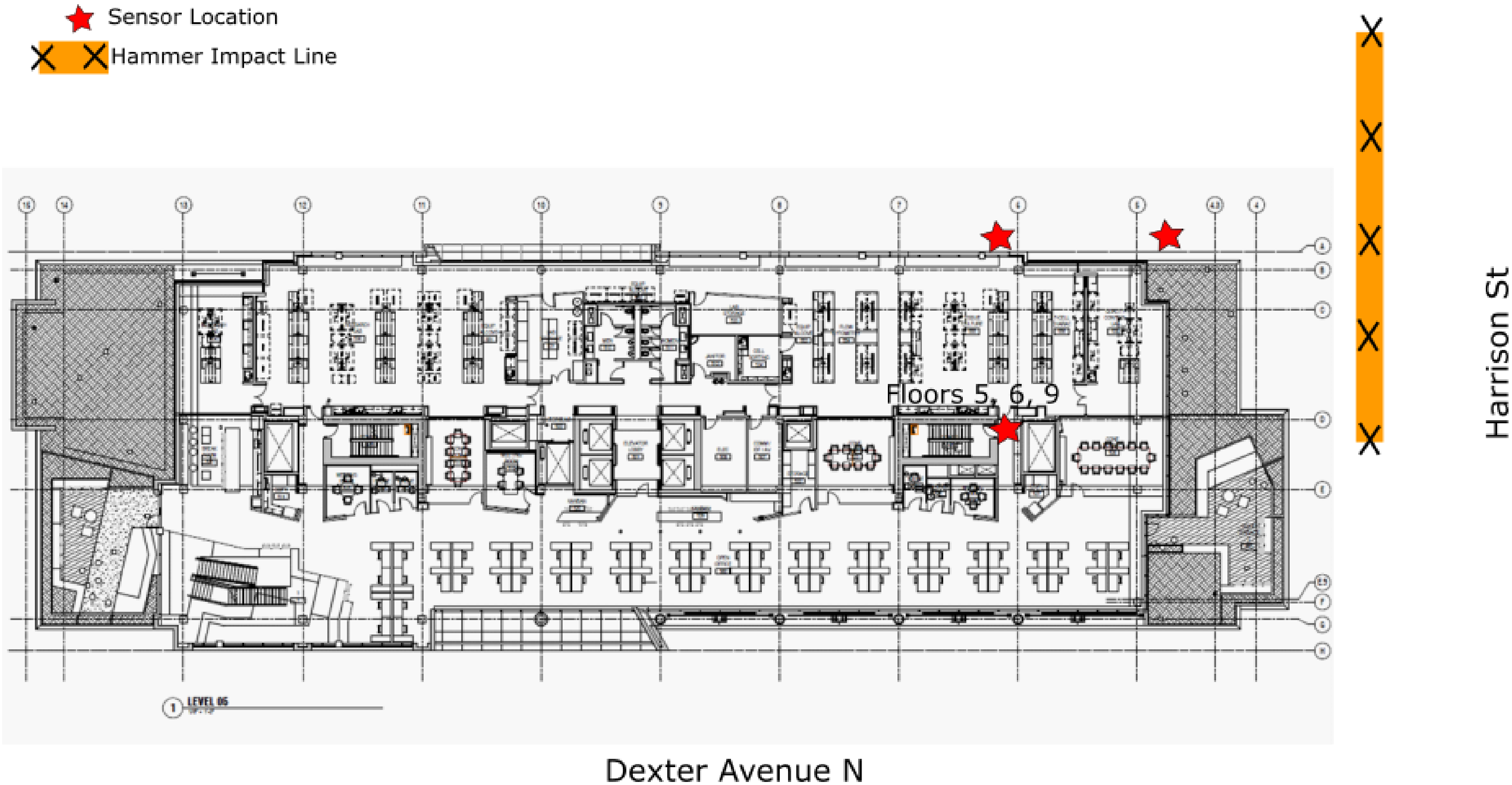


Figure 11-8. P.S.T.M. and Coherence on 400 Dexter Avenue North Parking Garage

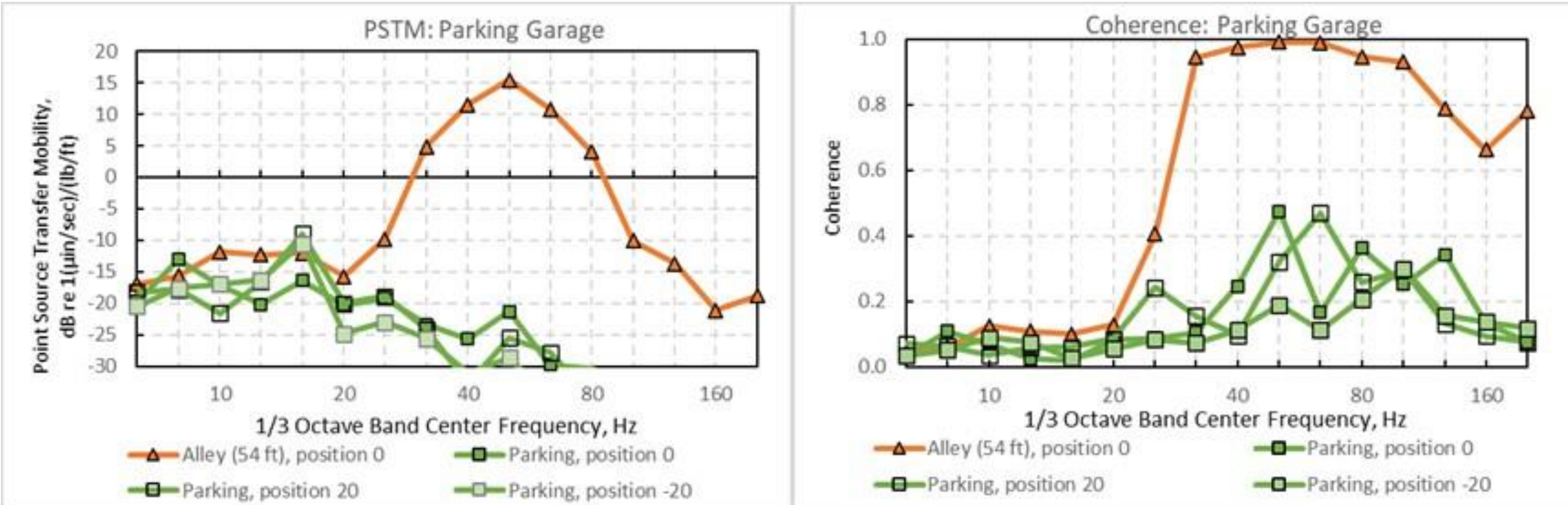


Figure 11-9. P.S.T.M. and Coherence on 400 Dexter Avenue North Fifth Floor

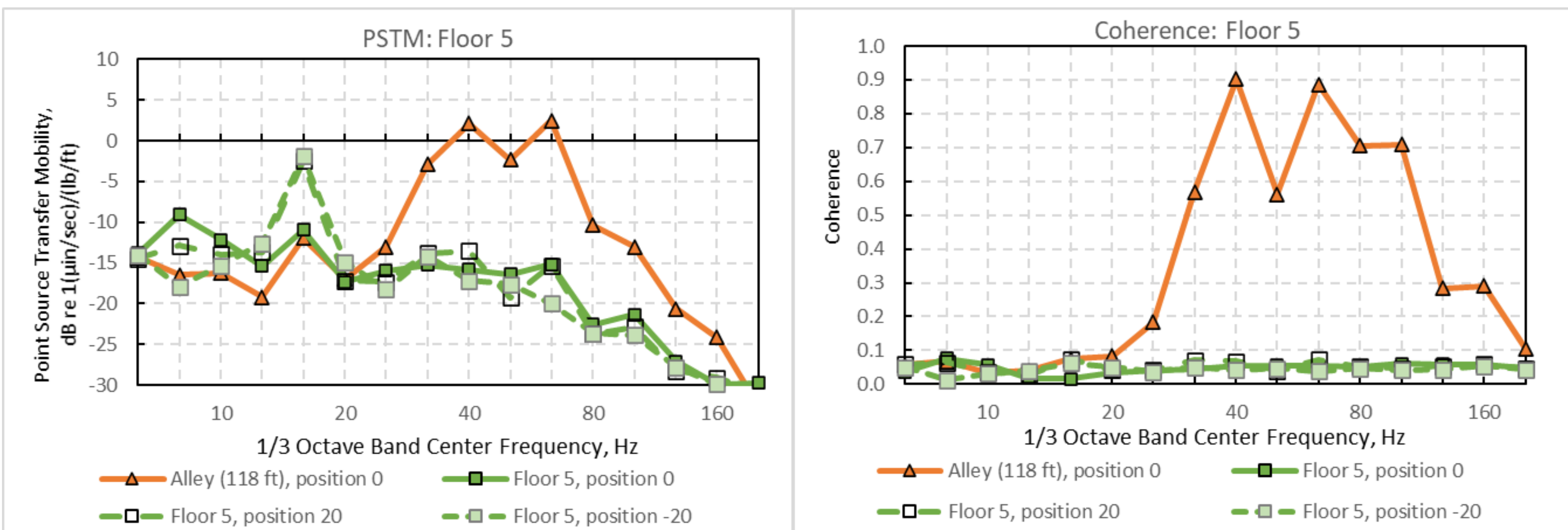


Figure 11-10. P.S.T.M. and Coherence on 400 Dexter Avenue North Sixth Floor

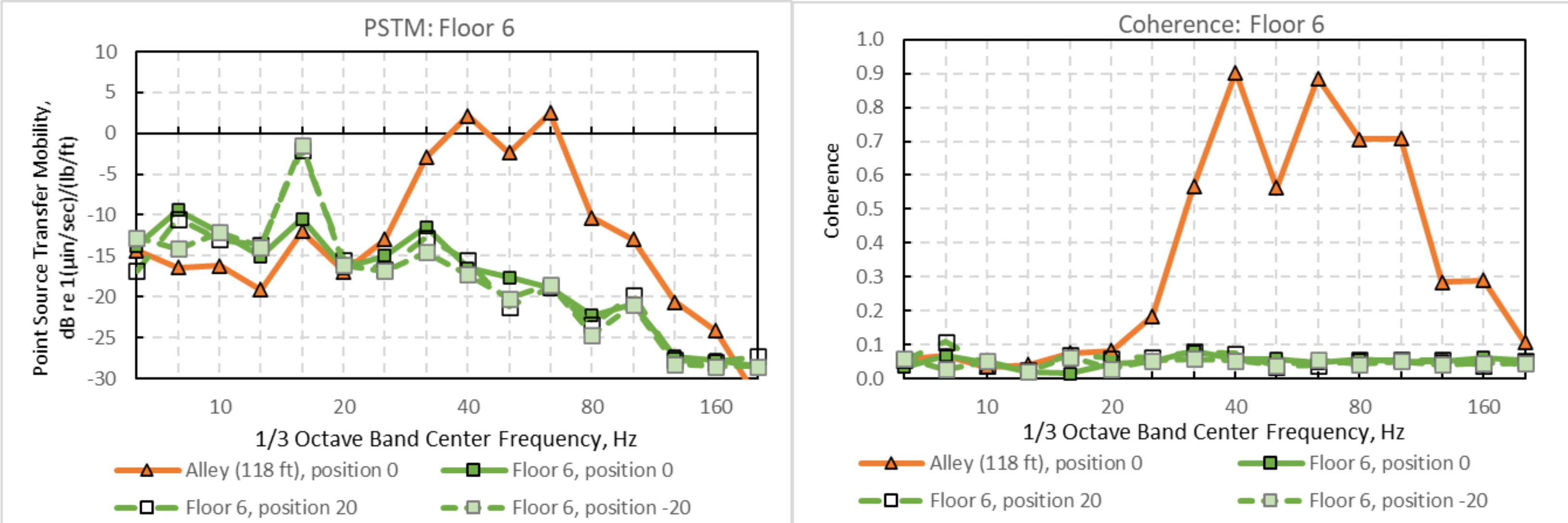


Figure 11-11. P.S.T.M. and Coherence on 400 Dexter Avenue North Ninth Floor

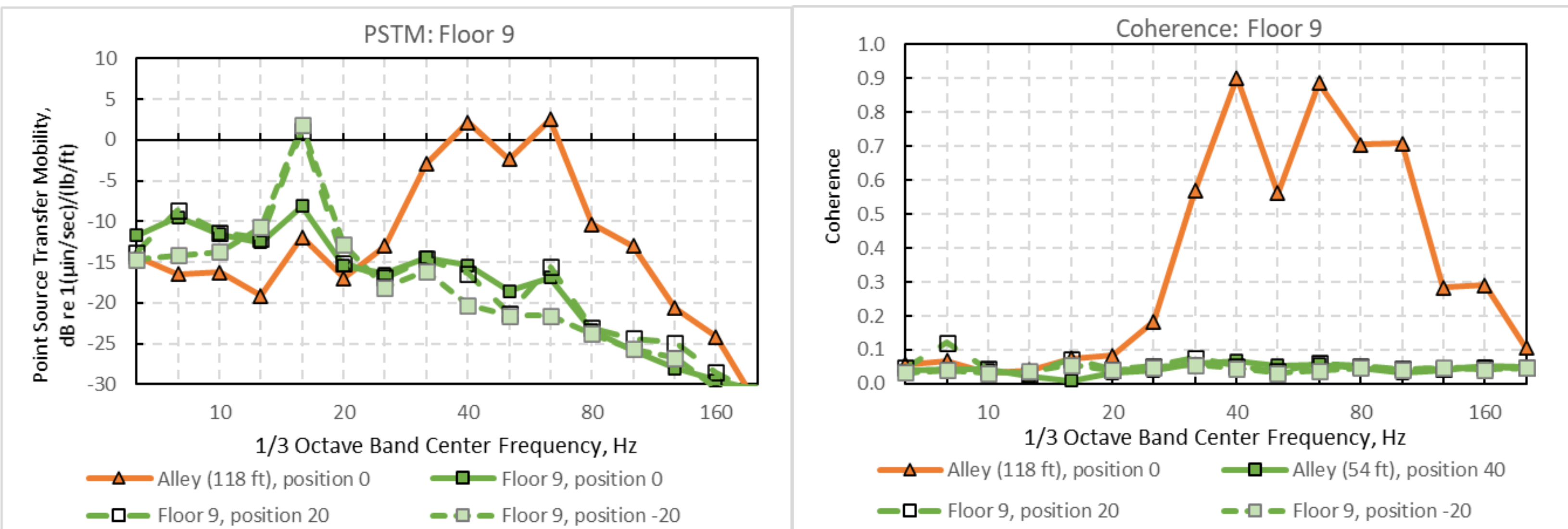


Figure 11-12. P.S.T.M. and Coherence on 400 Dexter Avenue North First Floor (North)

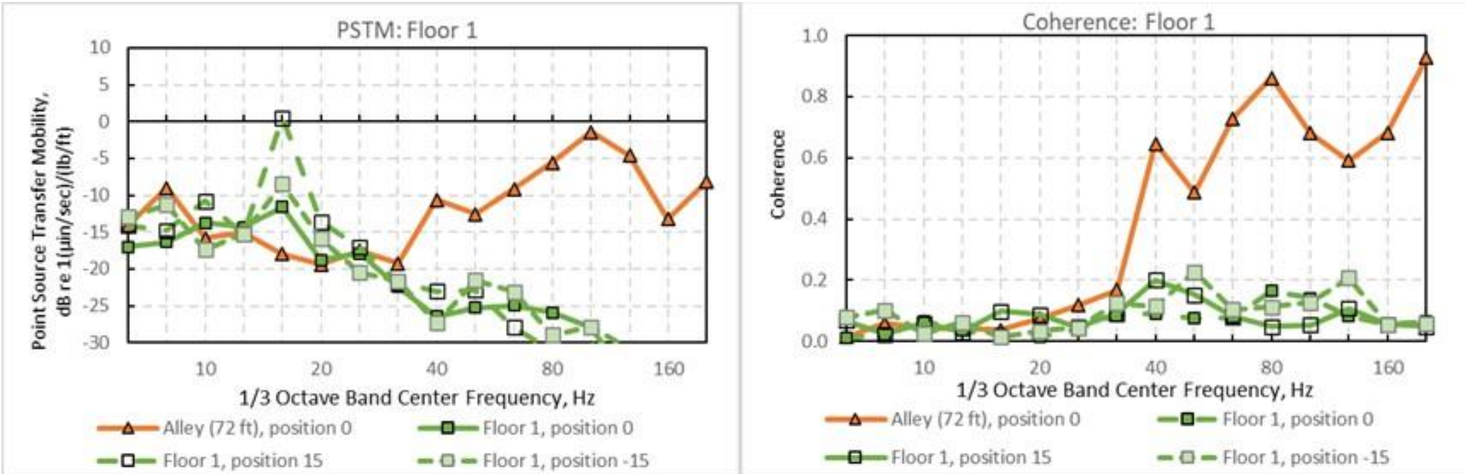


Figure 11-13. P.S.T.M. and Coherence on 400 Dexter Avenue North Second Floor (North)

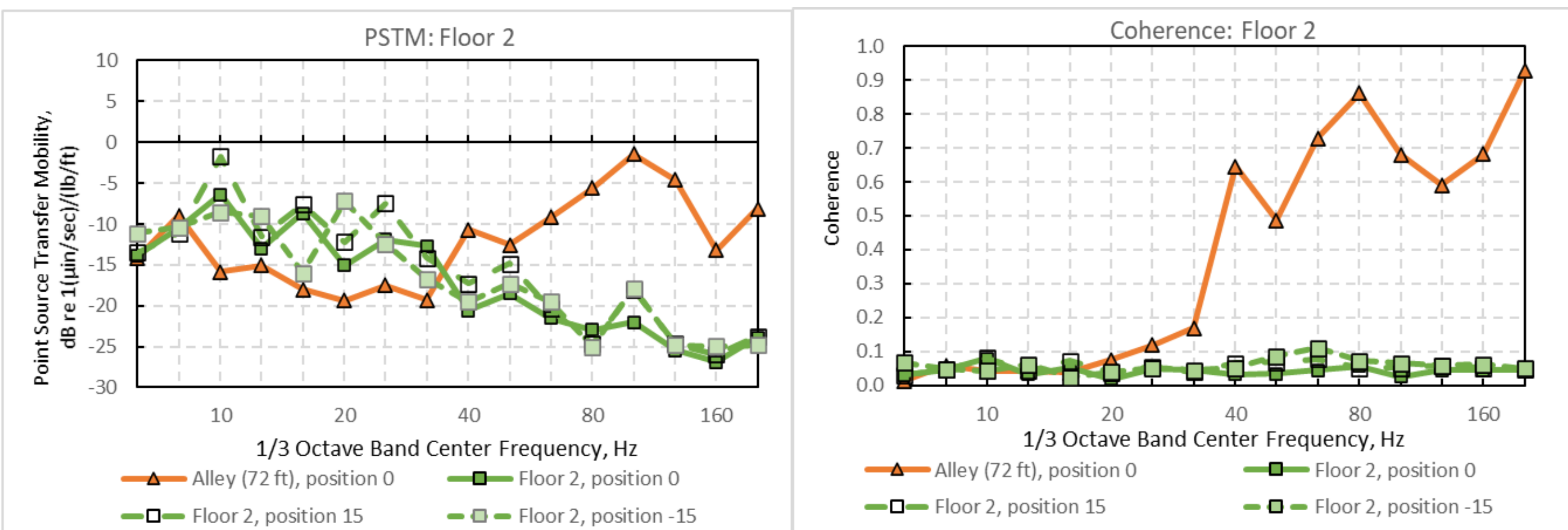
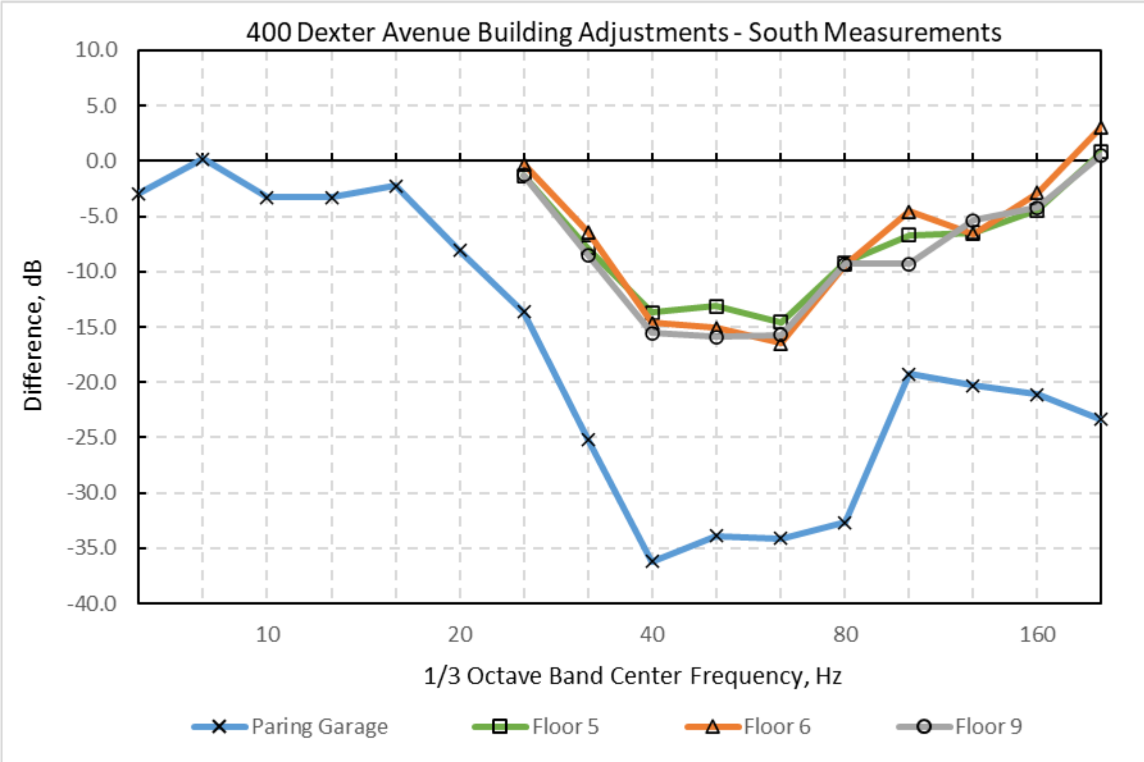
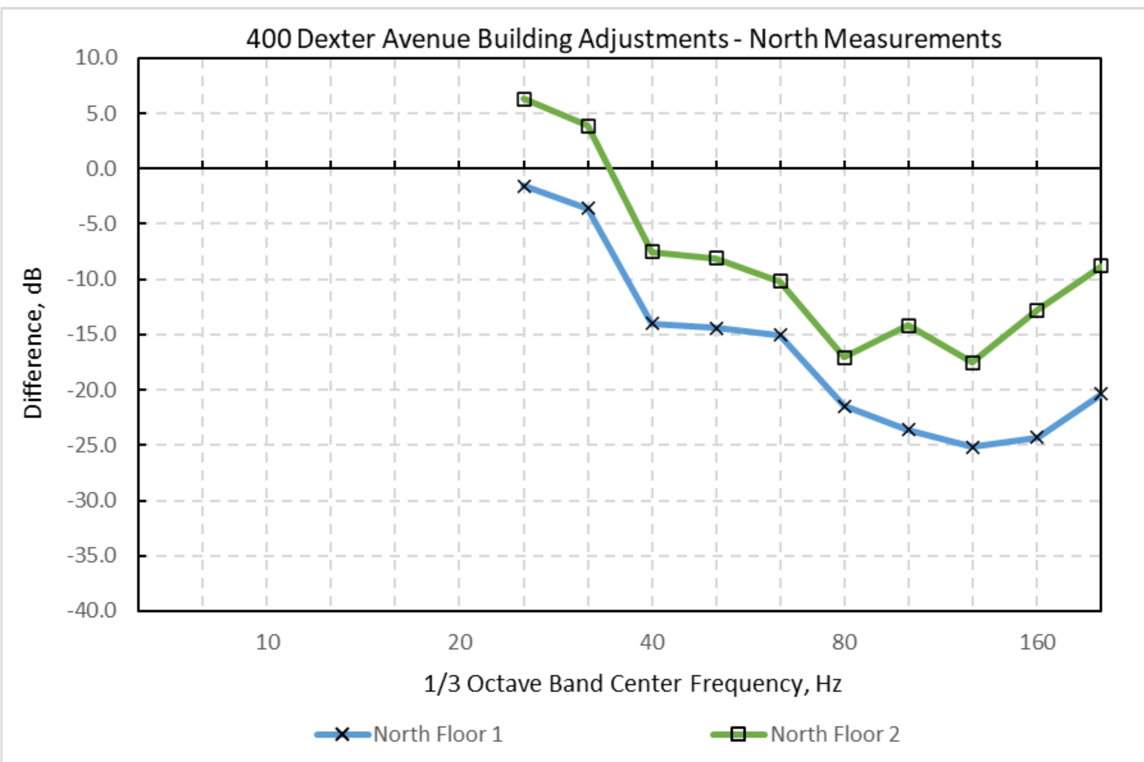


Figure 11-14. Measured Building Adjustment at 400 Dexter Avenue North





In the prediction model, the building adjustment measured on the second floor is applied for the sensitive equipment located in the second floor laboratory. For the remainder of the building, an average of the measured building adjustment from floors 5, 6, and 9 is applied. Based on the building adjustment measured in the parking garage, which showed much greater attenuation, the building adjustment values applied in the prediction model are likely conservative. The building adjustments for the parking garage and first floor are shown for context only; there is no sensitive equipment located in those spaces.

In addition to the building adjustment, the prediction model also includes a 3-decibel adjustment to account for curvature in the track and a 3-decibel safety factor incorporated into the force density level used in the prediction model.

The predicted vibration levels for Preferred Alternative DT-1 are presented in Table 11-2, and the predicted levels for Alternative DT-2 are presented in Table 11-3. The results show there is no predicted impact for either Downtown Segment alternative. For Alternative DT-2, the building is over 800 feet from the light rail alignment. For Preferred Alternative DT-1, the building is 152 feet from the alignment, but the speed would be relatively low at 35 miles per hour. The spectra of the predicted levels and the relevant criteria for Preferred Alternative DT-1 are presented in Figure 11-15. No vibration mitigation measures are proposed.

Table 11-2. Predicted Vibration and Groundborne Noise Levels at 400 Dexter Avenue North with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibel) [c]
Mass Spectrometer	152	35	31	48	Not applicable	Not applicable	Does not exceed
Cell imagers/ microscopes	152	35	31	54	Not applicable	Not applicable	Does not exceed
Xuri Wave Reactor	152	35	31	54	Not applicable	Not applicable	Does not exceed
Pipetting and Centrifuge	152	35	31	78	Not applicable	Not applicable	Does not exceed
Floor 2 Laboratory	152	35	34	54	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 11-3. Predicted Vibration and Groundborne Noise Levels at 400 Dexter Avenue North with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

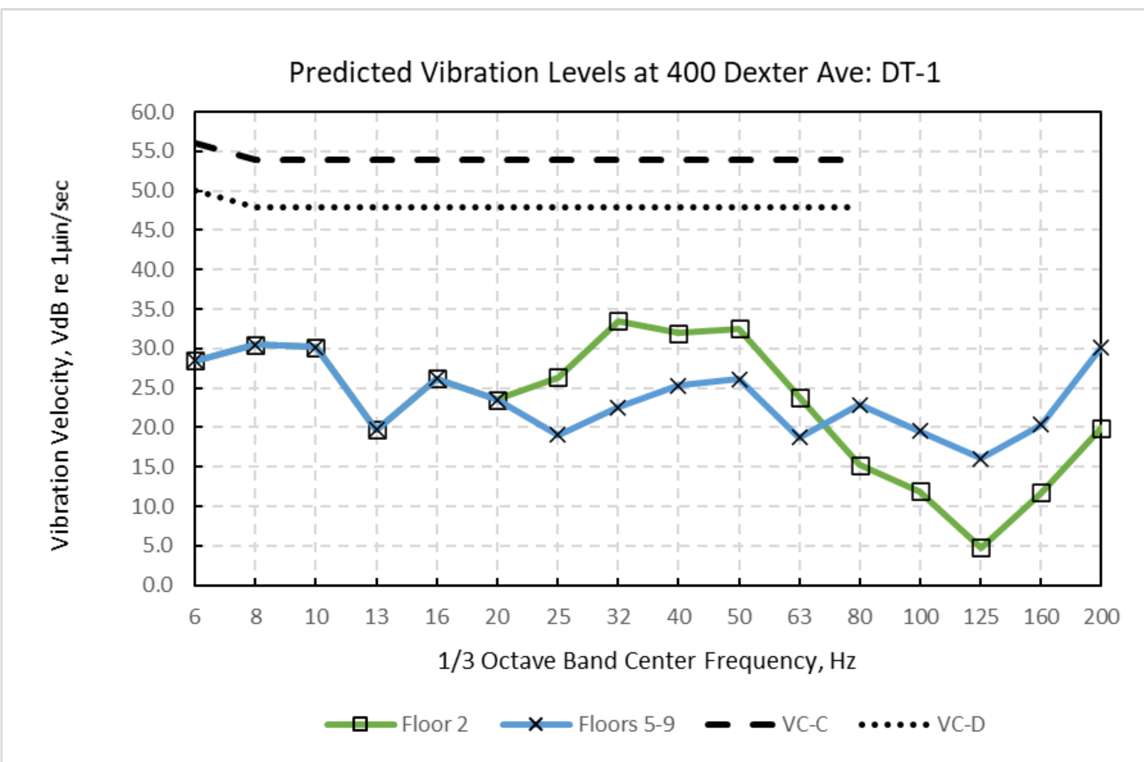
Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibel) [c]
Mass Spectrometer	857	45	31	48	Not applicable	Not applicable	Does not exceed
Cell imagers/ microscopes	857	45	31	54	Not applicable	Not applicable	Does not exceed
Xuri Wave Reactor	857	45	31	54	Not applicable	Not applicable	Does not exceed
Pipetting and Centrifuge	857	45	31	78	Not applicable	Not applicable	Does not exceed
Floor 2 Laboratory	857	45	31	54	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 11-15. Predicted Vibration Level for Preferred 5th Avenue/Harrison Street Alternative (DT-1) at 400 Dexter Avenue North



12 307 WESTLAKE AVENUE NORTH: SEATTLE CHILDREN'S RESEARCH INSTITUTE CENTER FOR GLOBAL INFECTIOUS DISEASE RESEARCH

12.1 Description of Sensitive Space

The Seattle Children's Research Institute Center for Global Infectious Disease Research is in the South Lake Union area at 307 Westlake Avenue North in the Downtown Segment of the Ballard Link Extension. The research institute is home to many research laboratories that work on prevention, treatment, and cures of infectious diseases impacting children and families. One of the facilities at the 307 Westlake Avenue North building is an imaging core, which provides tools for capturing and analyzing images that look at cell changes and functions. The imaging core equipment listed on the Seattle Children's Research Institute Center for Global Infectious Disease Research website is listed in Table 12-1, along with applicable vibration limits.

The owner of the research institute's building denied permission for a site visit or measurements on the property of the building. No information on existing vibration levels or whether the equipment listed in Table 12-1 is located on vibration isolation tables was provided. The limits in Table 12-1 should be confirmed with existing vibration measurements during a future project phase. A site visit is also recommended to confirm whether there is additional vibration-sensitive equipment at this location and to confirm the magnification of the Nikon TI-E inverted microscope to determine the appropriate vibration limit.

Table 12-1. List of Vibration-Sensitive Equipment at Seattle Children's Research Institute Center for Global Infectious Disease Research

Vibration-Sensitive Equipment	Description	Vibration Limit
GE Healthcare DeltaVision Elite Microscope	Focus control within 50 nanometers	48 VdB/V.C.-D
Leica Stellaris 8 Confocal Microscope	Similar to a scanning electron microscope	48 VdB/V.C.-D
Nikon Eclipse E600 Upright Microscope	Up to 100x objective plus 10x eyepiece	54 VdB/V.C.-C
IVIS Lumina II Imaging System	Up to 50 micron pixel resolution	72 VdB
Nikon TI-E Inverted Microscope	Insufficient information on website to determine appropriate vibration limit	More information needed

12.2 Predicted Vibration Levels

The vibration prediction model quantifies how efficiently vibration propagates through the soil and into buildings using data collected from vibration propagation tests. A vibration propagation measurement was performed outside the Seattle Children's Research Institute Center for Global Infectious Disease Research building on Thomas Street (site V-9). Photographs of the site are included in Attachment N.3B, Vibration Measurement Site Photographs, and the results of the vibration propagation measurement are included in Attachment N.3C, Vibration Propagation Measurement Results.

At most highly vibration-sensitive (Category 1) land uses, vibration propagation measurements inside the building were used to characterize the building coupling loss and any floor resonances in a "building adjustment" applied in the prediction model. Because the building owner denied the project team right-of-entry to the property, no measured building adjustment data are available. The building adjustment in the prediction model is assumed to be between 0 decibel and -5 decibel. Many of the large buildings along the light rail alignment showed greater vibration attenuation than -5 decibel, so the building adjustment is likely a conservative estimate.

Because measured building adjustment data are not available for Seattle Children's Research Institute Center for Global Infectious Disease Research building, a safety factor of +2 decibels is included in the prediction model. There is also a 3-decibel curve adjustment and a 3-decibel safety factor incorporated into the force density level used in the prediction model.

The predicted vibration levels for Preferred Alternative DT-1 and Alternative DT-2 are presented in Tables 12-2 and 12-3, respectively. The results show there is no predicted impact for either alternative. Both light rail alignments are over 250 feet from the building. The spectra of the predicted level and the relevant criteria are presented in Figure 12-1. No vibration mitigation measures are proposed.

Although no impact is predicted, a site visit and existing vibration measurements during a future phase of the project are recommended for the building to confirm the limits identified are appropriate. If either alternative alignment is shifted closer to the building, vibration propagation measurements into the building should also be considered.

Table 12-2. Predicted Vibration and Groundborne Noise Levels at Seattle Children's Research Institute Center for Global Infectious Disease Research with Preferred 5th Avenue/Harrison Street Alternative (DT-1), Downtown Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibel) [c]
GE Healthcare DeltaVision Elite Microscope	112	35	42	48	Not applicable	Not applicable	Does not exceed
Leica Stellaris 8 Confocal Microscope	112	35	42	48	Not applicable	Not applicable	Does not exceed
Nikon Eclipse E600 Upright Microscope	112	35	42	54	Not applicable	Not applicable	Does not exceed
IVIS Lumina II Imaging System	112	35	42	72	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 12-3. Predicted Vibration and Groundborne Noise Levels at Seattle Children's Research Institute Center for Global Infectious Disease Research with 6th Avenue/Mercer Street Alternative (DT-2), Downtown Segment

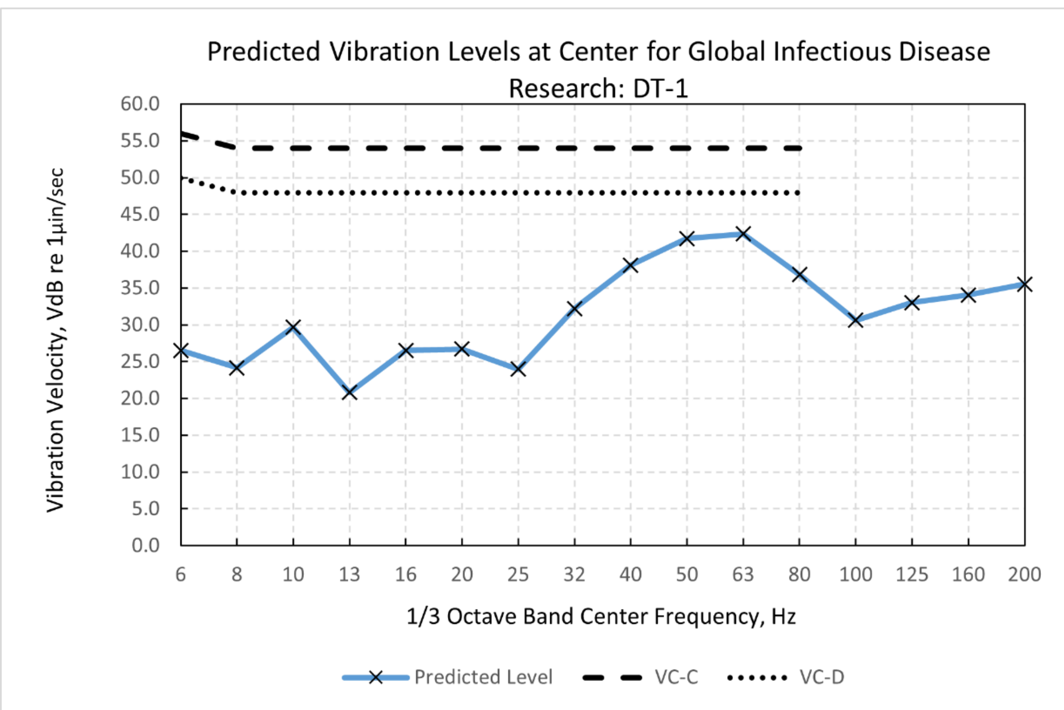
Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit (dBA)	Amount Exceeds (decibel) [c]
GE Healthcare DeltaVision Elite Microscope	364	45	32	48	Not applicable	Not applicable	Does not exceed
Leica Stellaris 8 Confocal Microscope	364	45	32	48	Not applicable	Not applicable	Does not exceed
Nikon Eclipse E600 Upright Microscope	364	45	32	54	Not applicable	Not applicable	Does not exceed
IVIS Lumina II Imaging System	364	45	32	72	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 12-1. Predicted Vibration Level for Preferred 5th Avenue/Harrison Street Alternative (DT-1) at Seattle Children's Research Institute Center for Global Infectious Disease Research



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13 VICTORY STUDIOS

13.1 Description of Sensitive Space

Victory Studios is a recording and production facility at 2247 15th Avenue West in the South Interbay Segment of the Ballard Link Extension. Victory Studios is a two-level masonry building. There are isolated recording booths with control rooms on both the upper and lower levels. There are two large video shoot rooms on the lower level. Figure 13-1 shows a photograph of a recording booth from within the control room. Figure 13-2 shows a photograph of a large video shoot room.

The FTA criteria for recording studios were applied to the isolated recording booth spaces. The FTA *Transit Noise and Vibration Impact Assessment Manual* does not address the sensitivity of control rooms. The FTA criteria for auditoriums were applied to the control rooms because they are areas where critical listening takes place. These spaces are not as sensitive as the recording booths, and the criteria for auditoriums were the next most restrictive in the FTA *Transit Noise and Vibration Impact Assessment Manual* for special buildings after the criteria for recording studios. The same auditorium criteria were applied to the video shoot rooms because they are also sensitive to noise but tend to be tolerant of higher background noise levels than an isolated recording booth. The existing background noise levels in the control room and large shoot room are 8 decibels and 11 decibels higher, respectively, than the background noise levels in the isolated recording booth.

Figure 13-1. Photograph of the Bad Animals Recording Booth and Control Room

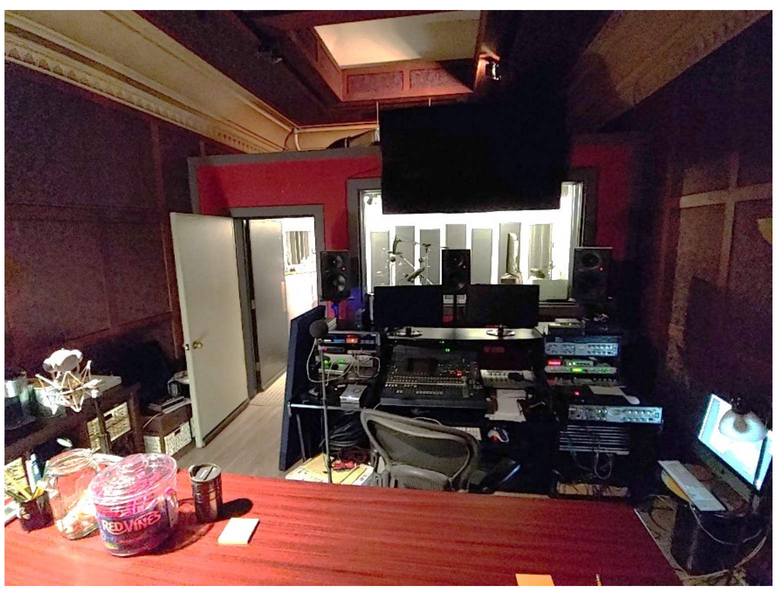


Figure 13-2. Photograph of the Large Shoot Room at Victory Studios

13.2 Existing Noise and Vibration Levels

Existing noise levels were measured over a 1-hour period in the Bad Animals Red recording booth and control room on the upper level and in the large shoot room on the lower level. During the noise measurement, the doors of the recording booth, control room, and shoot room were closed and no one entered or exited the spaces. The measurement was conducted on a Sunday afternoon when there were very few people in the building.

The measured 1-hour Leq noise levels and 10-minute Leq vibration levels are shown in Table 13-1. The 1-second noise levels are plotted in Figures 13-3 and 13-4. The 1-second vibration levels are plotted in Figures 13-5 and 13-6, and the spectra of the vibration levels are plotted in Figure 13-7. Ambient vibration levels were measured over 1-hour. However, electrical noise from a poor connection corrupted much of the data from the control room, and there were high vibration levels from an unknown source for part of the measurement in the large shoot room. The 10 minutes of data presented in the table and figures represents the background vibration levels under clean, controlled conditions.

The measured data show that noise levels are lowest in the isolated recording booth and vibration levels are lowest in the large shoot room on the lower level. The spectral data show that the isolated recording booth is effectively isolating ambient vibration at frequencies above 100 hertz.

Table 13-1. Background Noise and Vibration Levels at Victory Studios

Monitoring Location	Noise level (1-hr Leq)	Vibration level (10 -min Leq)
Large Shoot Room	30 dBA	39 VdB
Bad Animals Recording Booth	22 dBA	51 VdB
Bad Animals Control Room	33 dBA	52 VdB

Figure 13-3. Measured 1-second Noise Levels in Large Shoot Room at Victory Studios

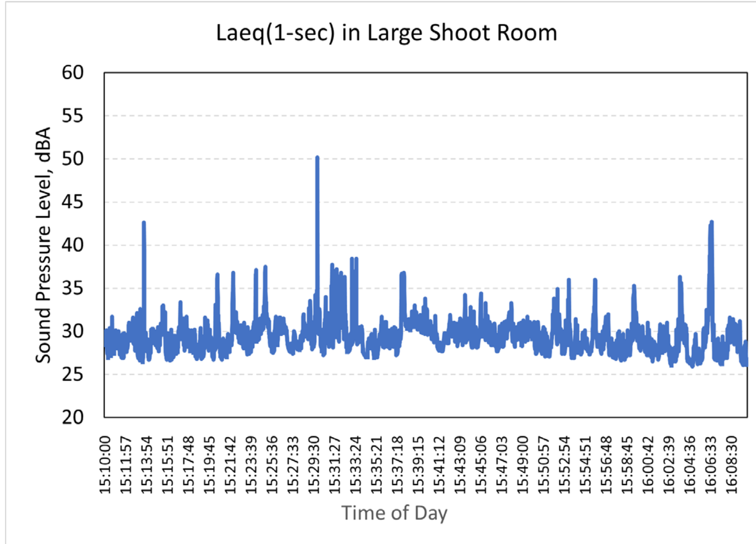


Figure 13-4. Measured 1-second Noise Levels in Bad Animals Recording Booth and Control Room at Victory Studios

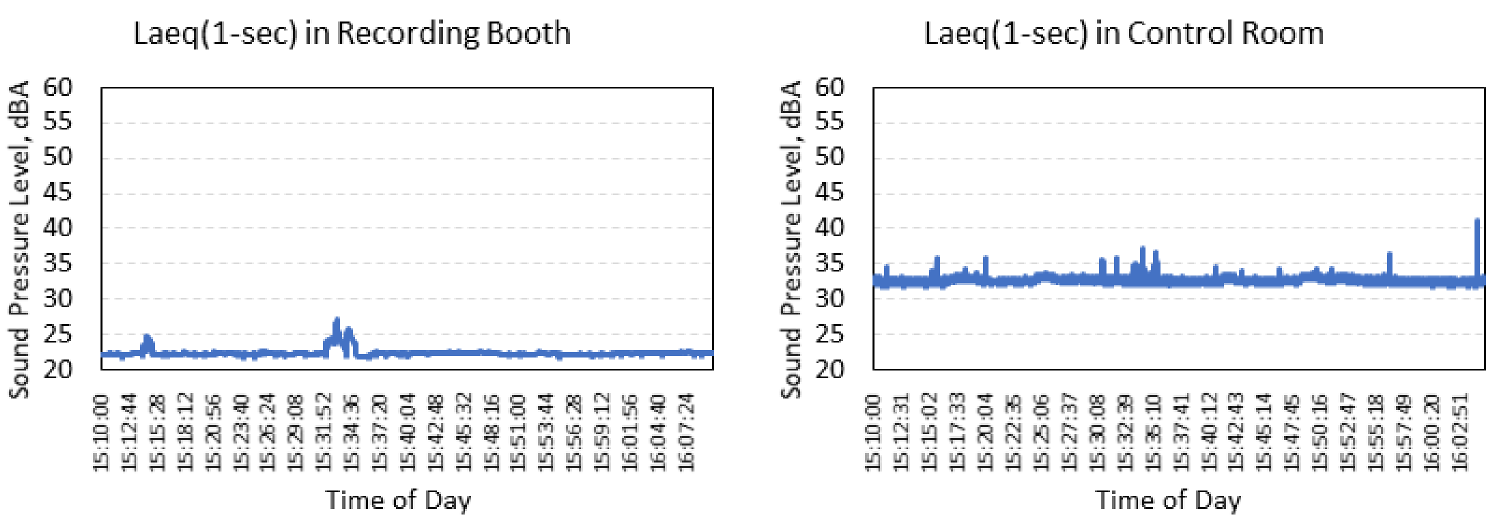


Figure 13-5. Measured 1-second Vibration Levels in the Large Shoot Room at Victory Studios

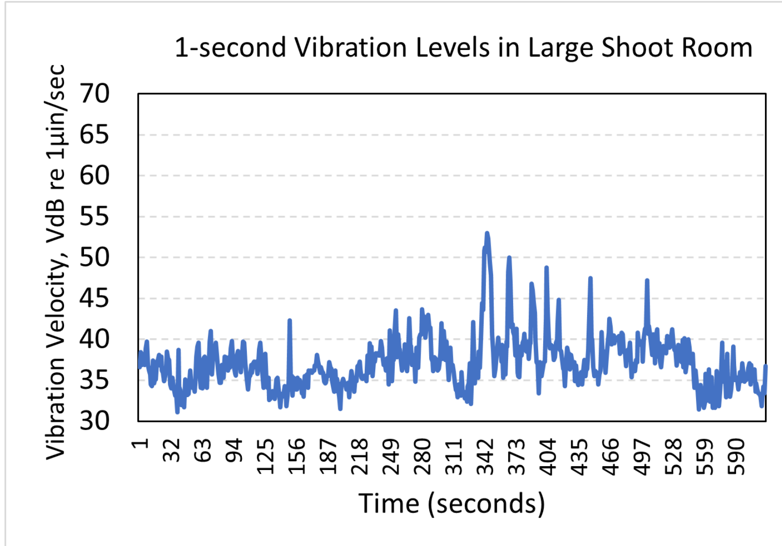


Figure 13-6. Measured 1-second Vibration Levels in Bad Animals Recording Booth and Control Room at Victory Studios

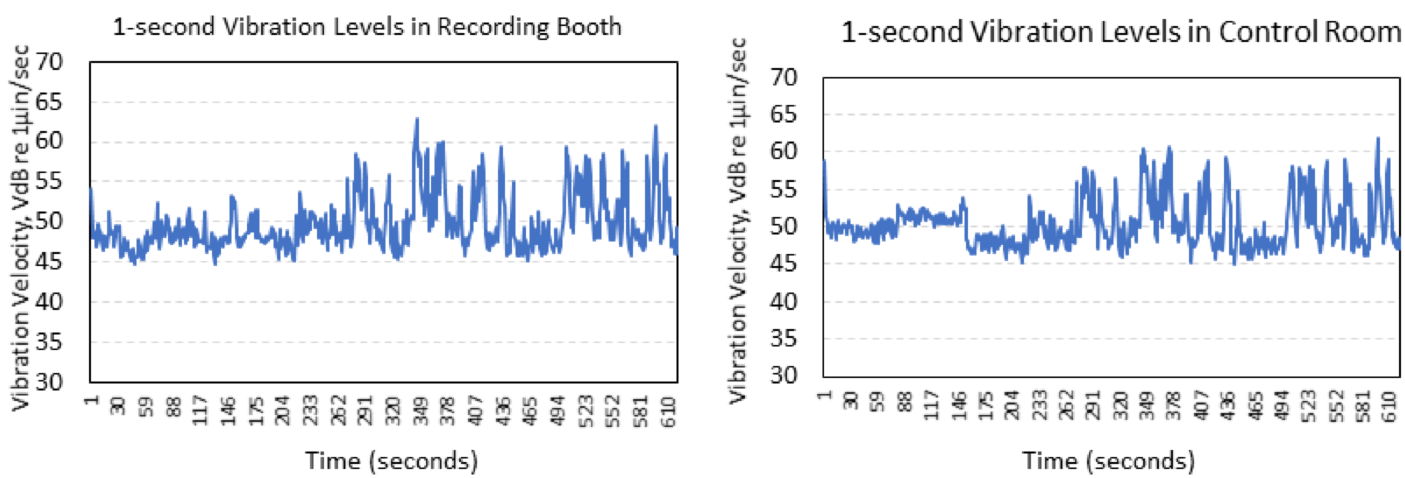
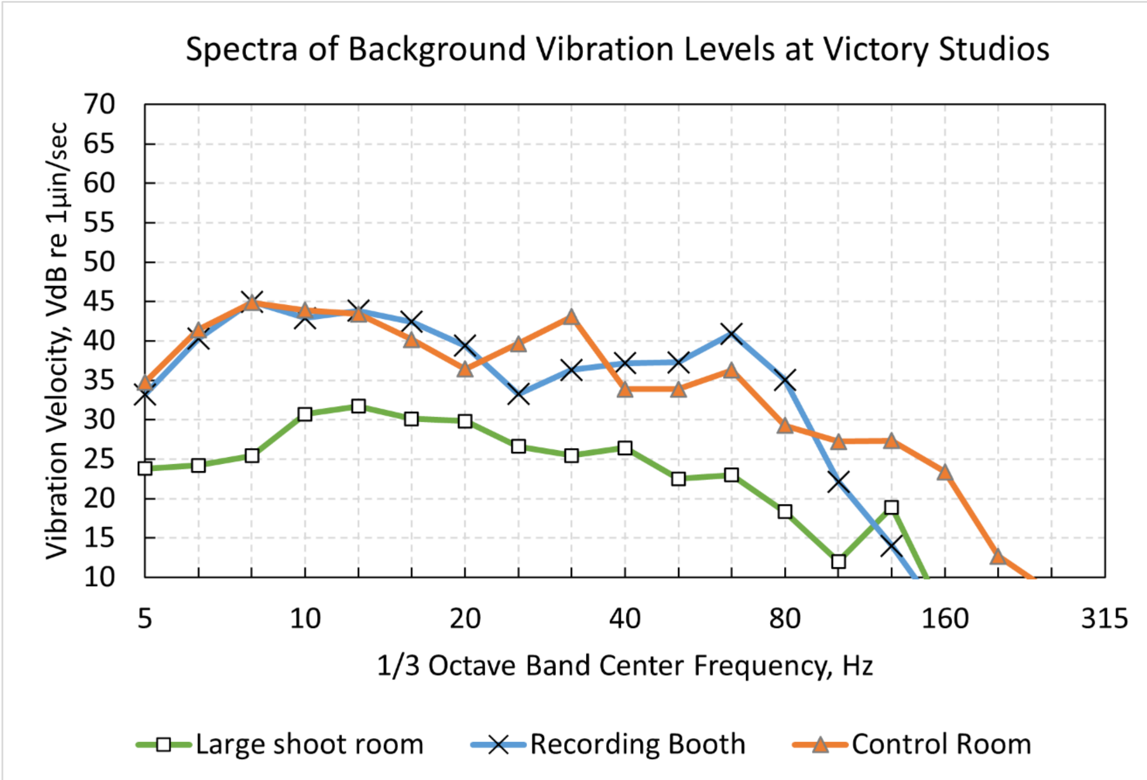


Figure 13-7. Spectra of Background Vibration Levels at Victory Studios



13.3 Vibration Propagation Measurement Description

In the vibration propagation measurement, an impact hammer is used near the proposed location of the light rail tracks to generate a force, and the vibration response is measured at representative locations. At Victory Studios, the impact hammer was positioned on the sidewalk of 15th Avenue West. The hammer was operated at 11 positions spaced 15 feet apart to simulate the length of a light rail train.

The vibration levels were measured at five outdoor positions and six indoor positions. The outdoor measurement locations are used to quantify how vibration levels decrease with distance from the impact force. The outdoor vibration measurements are also used as a reference to examine how levels change as the vibration travels from the soil into the building structure.

The six indoor measurement locations are (1) the large shoot room on the lower level, (2) the office area above the large shoot room, (3) the recording booth and (4) control room of Bad Animals Red studio on the upper level, and the (5) recording booth and (6) control room of the Freshmade studios on the lower level. The measurement positions were selected to get representative data in control rooms, edit booths, and production rooms on both the upper and lower level of the building. Where a sensor was placed in a recording booth, a corresponding sensor was placed in the adjacent control room to evaluate the effectiveness of the isolated floors of the recording booths.

Figures 13-8 and 13-9 show the floor plans of the upper and lower level of Victory Studios with the sensor locations labeled. Approximate location of the outdoor sensors closest to the building and the hammer impact positions are also indicated.

Figure 13-8. Victory Studios Lower Level Floor Plan with Sensor Locations

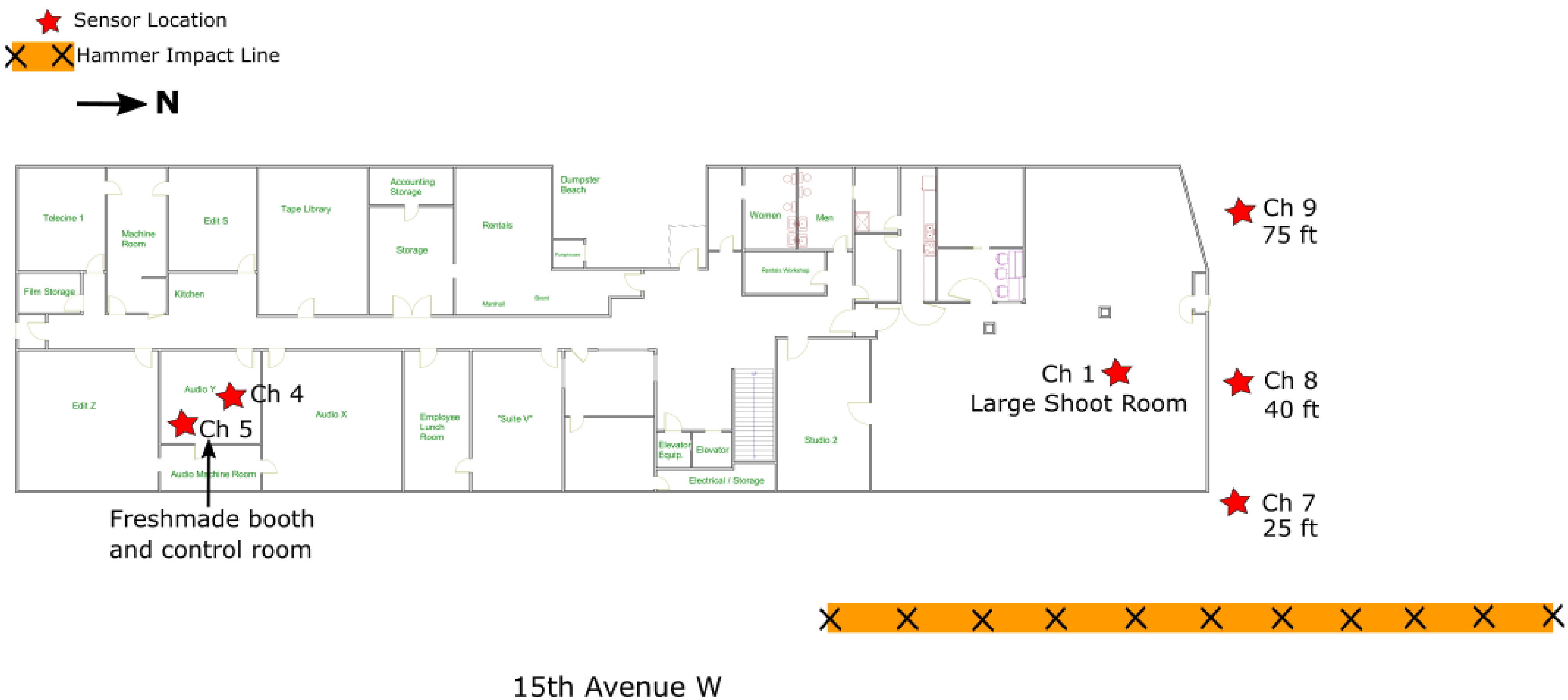
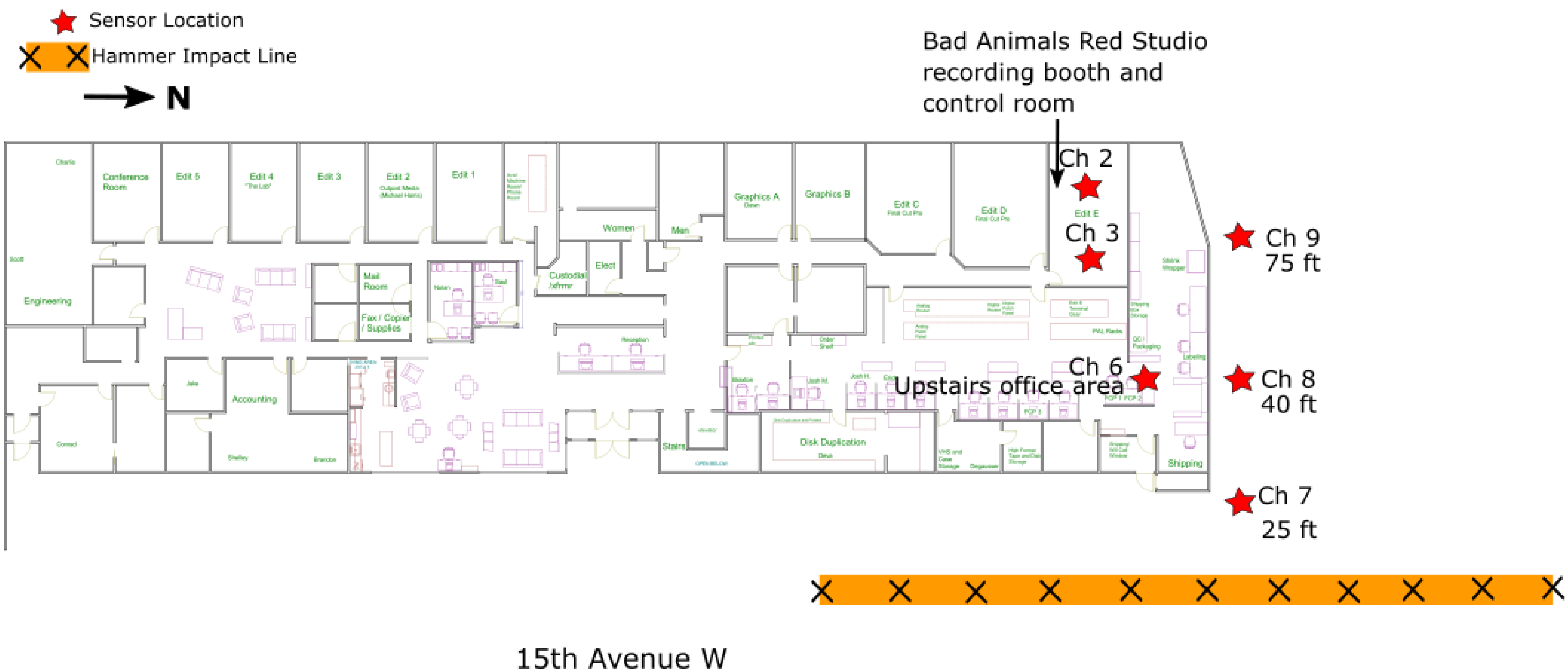


Figure 13-9. Victory Studios Upper Level Floor Plan with Sensor Locations

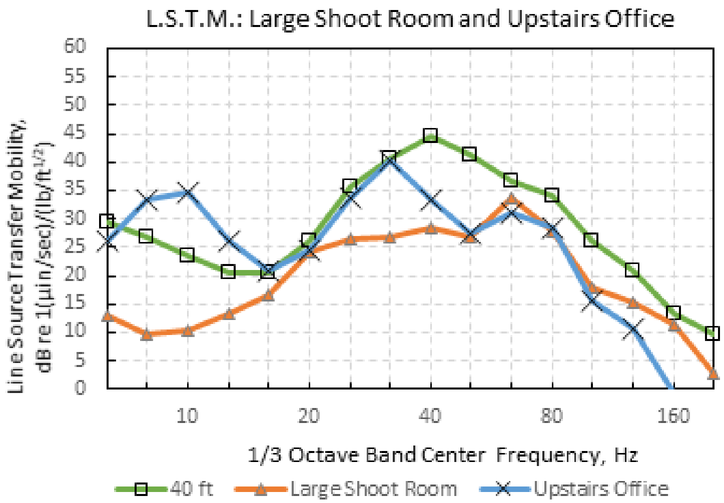


13.4 Vibration Propagation Measurement Results and Predicted Levels

The result of the surface vibration propagation tests is the L.S.T.M., a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the L.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates that the vibration response and the force generated by the dropped weight are closely related. The L.S.T.M. and coherence results for the indoor measurement positions near the impact line and the closest outdoor measurement position for Victory Studios are shown in Figures 13-10 through 13-12. For the Freshmade studio, the P.S.T.M. results for an impact point outside the studio is used instead of the data from the line of impacts farther from the studio. Following are observations from the transfer mobility and coherence results:

- There is low coherence below 20 hertz for both the indoor and outdoor positions. The L.S.T.M. for measurement positions on the upper level are higher than the outdoor positions at low frequencies, but the low coherence indicates this is likely due to higher background vibration levels indoors and not more efficient vibration propagation at the lower frequencies.
- The large shoot room has lower L.S.T.M. levels compared to the 40-foot outdoor measurement position. This indicates there is a coupling loss as vibration travels from the soil into the building foundation.
- The upstairs office space has higher L.S.T.M. levels compared to the large shoot room in the 25 hertz to 40 hertz range. These higher levels are likely due to floor resonances.
- The Bad Animals recording booth has high L.S.T.M. levels at 63 hertz and 80 hertz compared to the control room and outdoor position at 75 feet. This indicates the resonance of the floating floor for the isolated recording booth is in this frequency range.
- The Freshmade recording booth has high L.S.T.M. levels at 20 hertz, which indicates the resonance of the Freshmade recording booth may be at a lower frequency than the Bad Animals recording booth.

Figure 13-10. L.S.T.M. and Coherence in Large Shoot Room and Upstairs Office at Victory Studios



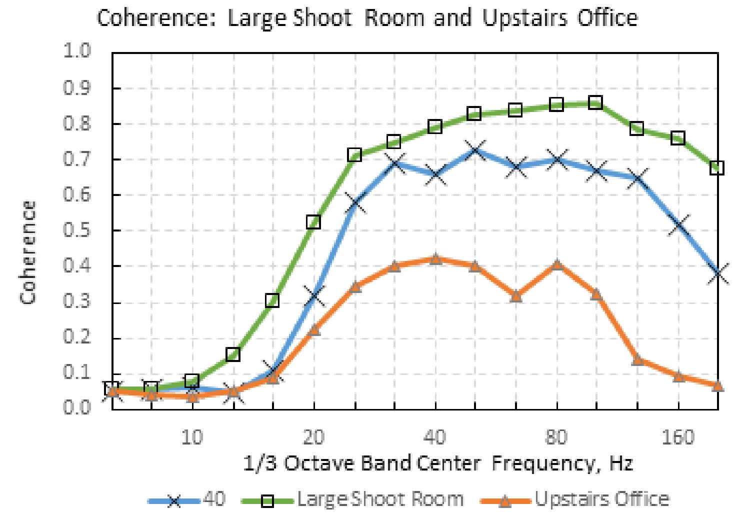
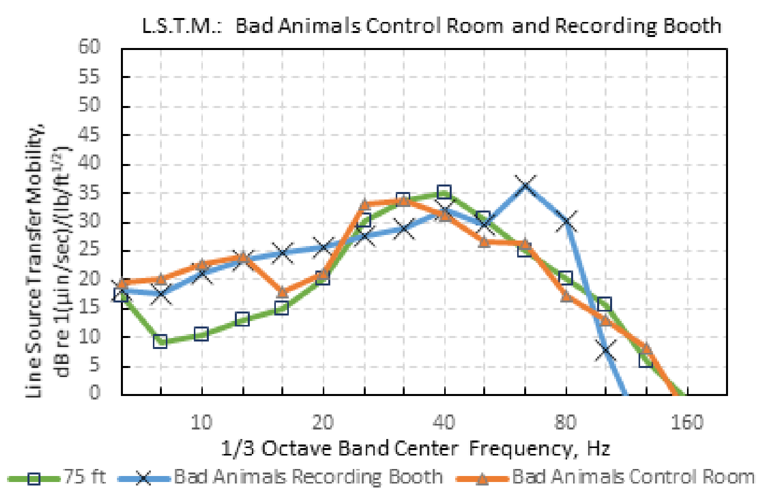


Figure 13-11. L.S.T.M. and Coherence in Bad Animals Red Recording Booth and Control Room at Victory Studios



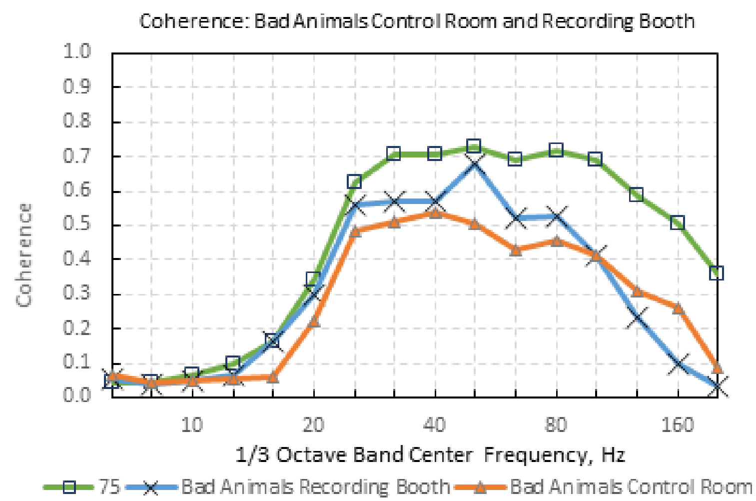
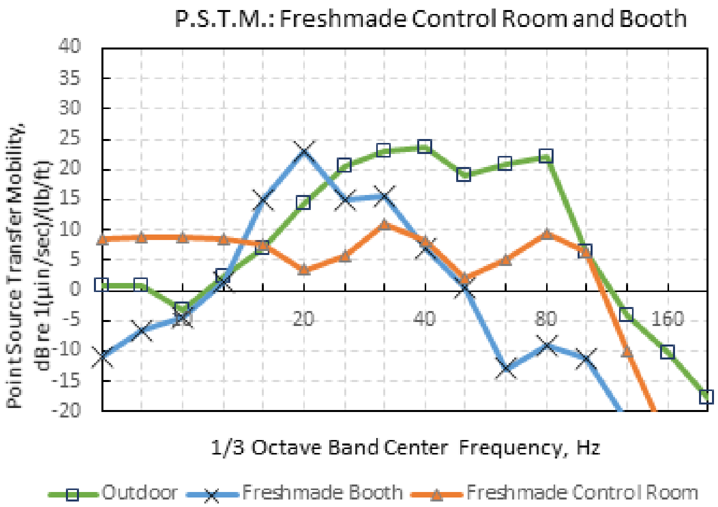
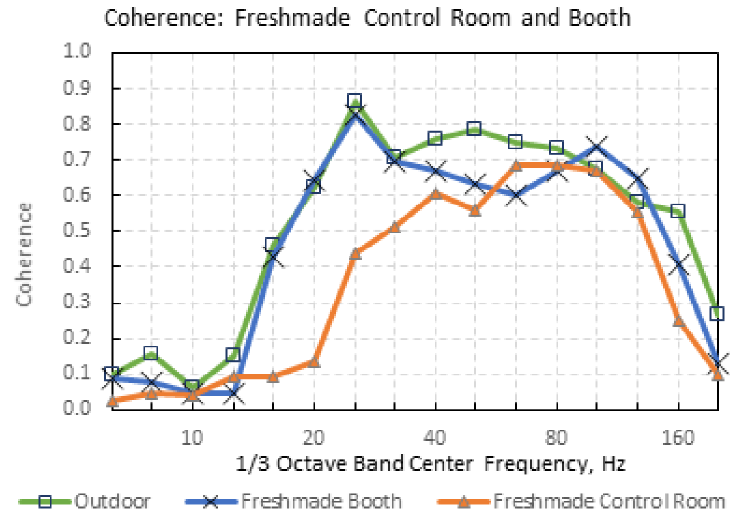


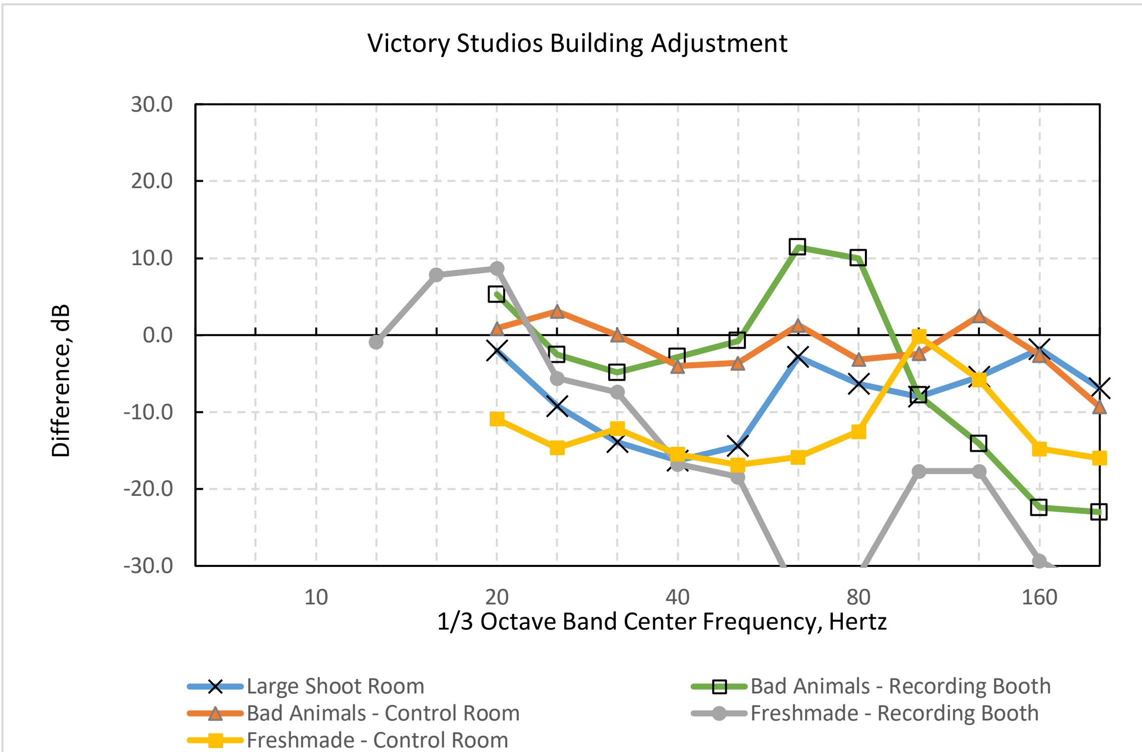
Figure 13-12. P.S.T.M. and Coherence in Freshmade Control Room and Recording Booth at Victory Studios





The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances is the difference in the between the indoor L.S.T.M. and the outdoor L.S.T.M. at an equivalent setback distance. The building adjustment for the sensitive spaces in Victory Studios is shown in Figure 13-13. No building adjustment is applied for frequencies below 20 hertz except in the Freshmade recording booth because the L.S.T.M. and coherence data indicate there is a poor relationship between the force and the measured vibration response. The Bad Animals and Freshmade recording booths show high vibration reduction at frequencies above 100 hertz, as expected for floating floors. However, the data for the Bad Animals booth shows a resonance at a higher frequency compared to the Freshmade recording booth. The large shoot room shows attenuation at all frequencies, which is likely due to the building coupling loss and the lack of any floor resonances on the lower level of the building.

Figure 13-13. Measured Building Adjustment at Victory Studios



The predicted levels using the L.S.T.M. coefficients for site V-G (Victory Studios) and the building adjustment in Figure 13-13 are presented in Tables 13-2 through 13-4. No safety factor was added to the predicted levels because the predictions use site-specific L.S.T.M. levels and there is a 3-decibel safety factor built-in to the force density level. The predicted vibration levels for the closest alternative, Alternative SIB-2, are presented in Figure 13-14.

With Alternative SIB-2, the predicted level for groundborne noise in the Bad Animals recording booth would exceed the criteria by 8 decibels. There are no predicted impacts for the other alternatives in the South Interbay Segment. The proposed mitigation measure is high-resilience fasteners, which are an effective mitigation measure at 63 hertz, the 1/3-octave band with the highest levels of predicted vibration and groundborne noise. An alternative mitigation measure would be to retrofit any isolated recording booths on the upper level so the recording booths provide isolation at 50 hertz and above.

Table 13-2. Predicted Vibration and Groundborne Noise Levels at Victory Studios with Preferred Galer Street Station/Central Interbay Alternative (SIB-1), South Interbay Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Large Shoot Room	831	55	32	72	<0	30	Does not exceed
Bad Animals Recording Booth	831	55	32	65	<0	25	Does not exceed
Bad Animals Control Room	831	55	32	72	<0	30	Does not exceed
Freshmade Recording Booth	831	55	32	65	<0	25	Does not exceed
Freshmade Control Room	831	55	32	72	<0	30	Does not exceed

[a] The slant distance between the near track and the façade of the sensitive receiver, in feet.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 13-3. Predicted Vibration and Groundborne Noise Levels at Victory Studios with Prospect Street Station/15th Avenue Alternative (SIB-2), South Interbay Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Large Shoot Room	68	55	51	72	18	30	Does not exceed
Bad Animals Recording Booth	68	55	62	65	33	25	8
Bad Animals Control Room	68	55	55	72	25	30	Does not exceed
Freshmade Recording Booth	68	55	51	65	8	25	Does not exceed
Freshmade Control Room	68	55	51	72	12	30	Does not exceed

[a] The slant distance between the near track and the façade of the sensitive receiver, in feet.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[d] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 13-4. Predicted Vibration and Groundborne Noise Levels at Victory Studios with Prospect Street Station/Central Interbay Alternative (SIB-3), South Interbay Segment

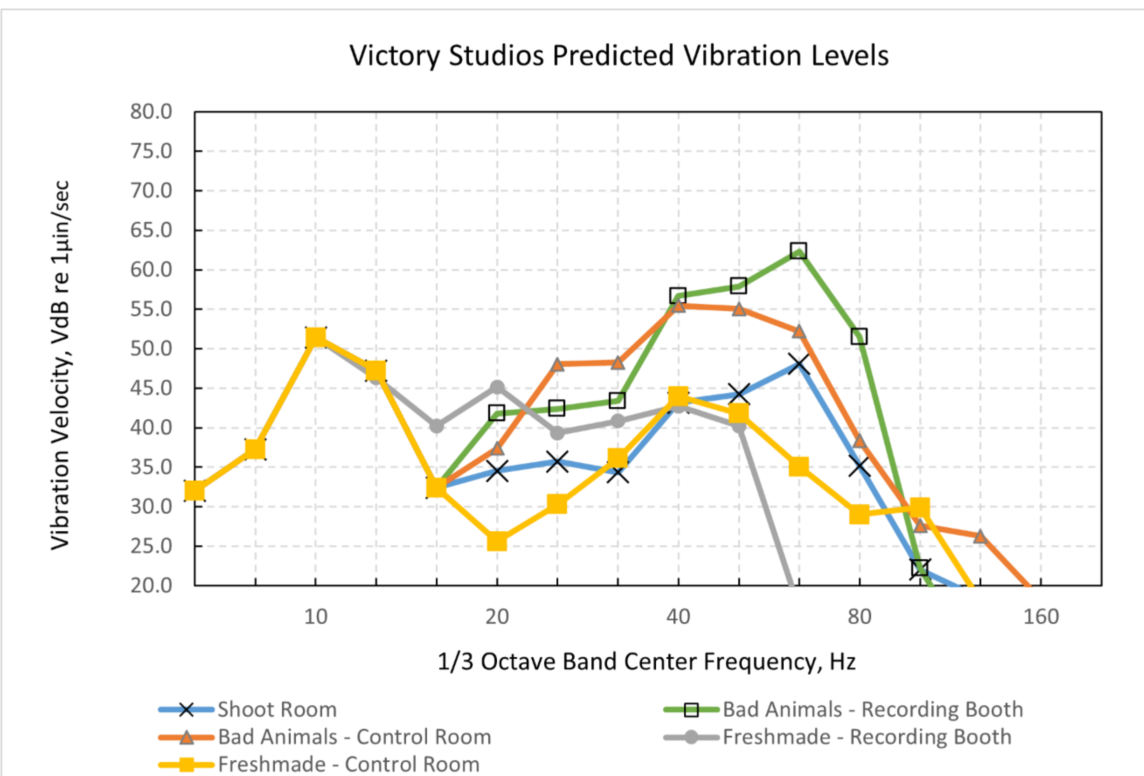
Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Large Shoot Room	512	55	36	72	<0	30	Does not exceed
Bad Animals Recording Booth	512	55	36	65	<0	25	Does not exceed
Bad Animals Control Room	512	55	36	72	<0	30	Does not exceed
Freshmade Recording Booth	512	55	36	65	<0	25	Does not exceed
Freshmade Control Room	512	55	36	72	<0	30	Does not exceed

[a] The slant distance between the near track and the façade of the sensitive receiver, in feet.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 13-14. Predicted Vibration Levels at Victory Studios



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14 645 ELLIOTT AVENUE WEST: IHEART MEDIA, NEXELIS, AND LUMINEX

14.1 Description of Sensitive Space

The building at 645 Elliott Avenue West in South Interbay Segment of the Ballard Link Extension currently houses three tenants with vibration-sensitive operations: iHeartMedia, Nexelis, and Luminex. iHeartMedia is on the fourth floor and contains a live radio broadcast studios with booths that incorporate noise and vibration isolation. Nexelis and Luminex are on the third and first floors, respectively, and have vibration-sensitive lab space. Nexelis is a contract research organization with expertise in the fields of vaccines, large molecules, immunotherapies, and biomarkers. Luminex is a biotechnology company that develops and manufactures biological testing technologies.

The owner of the 645 Elliott Avenue West building denied permission for measurements on the property of the building. A site visit was completed in Fall 2019, during which the property manager noted the building was constructed to attenuate vibration from the adjacent existing freight track. Table 14-1 presents the sensitive spaces and recommended limits based on the information gathered during the site visit. Information from the tenants on any specific vibration-sensitive equipment was not provided during the site visit. The vibration limit recommended for these spaces is 66 VdB (V.C.-A), which the FTA *Transit Noise and Vibration Impact Assessment Manual* recommends for medium-to high-power optical microscopes, microbalances, optical balances, and similar specialized equipment. During a future project phase, the type of equipment at use in Nexelis and Luminex should be confirmed and existing vibration levels should be measured to verify the vibration limits recommended in Table 14-1.

Table 14-1. List of Vibration-Sensitive Equipment at 400 Dexter Avenue North

Vibration-Sensitive Space	Description	Vibration Limit
iHeartMedia broadcast booths	Used for live radio broadcasts, are noise- and vibration-isolated	65 VdB
iHeartMedia editing suites	Used as a critical listening space, are not noise- and vibration-isolated	72 VdB
Nexelis lab space	Contract research organization	66 VdB (V.C.-A)
Luminex lab/assembly space	Develops and manufactures testing technologies	66 VdB (V.C.-A)

14.2 Predicted Vibration Levels

The vibration prediction model quantifies how efficiently vibration propagates through the soil and into buildings using data collected from vibration propagation tests. At most highly vibration-sensitive (Category 1) land uses, site-specific vibration propagation measurements, including measurements inside the building, are used in the prediction model. Because the building owner did not grant right-of-entry to the project team, site-specific measurements were not completed.

In place of using site-specific vibration propagation data, the average of the South Interbay and Interbay/Ballard segments surface measurement sites was applied. These are the same data applied for the residential and institutional land uses in the South Interbay and Interbay/Ballard segments, which are discussed in Section 5.3.2 of the Noise and Vibration Technical Report.

The building adjustment, which characterizes the building coupling loss and any floor resonances, was assumed to be -5 decibel because the building manager noted that the building was constructed to attenuate vibration from the existing freight line. Many of the large buildings along the light rail alignment showed greater vibration attenuation than -5 decibel, so the building adjustment is likely a conservative estimate.

Because site-specific vibration propagation and building adjustment data were not measured at 645 Elliott Avenue West, a safety factor of +2 decibels is included in the prediction model. There is also a 3-decibel curve adjustment and a 3-decibel safety factor incorporated into the force density level used in the prediction model.

The predicted vibration levels for the three South Interbay Segment alternatives are presented in Tables 14-2 through 14-4. The results show there is no predicted impact for any of the alternatives. No vibration mitigation measures are proposed.

Although no impact from operational vibration is predicted, existing vibration measurements and more information on the equipment in use by the tenants during a future phase of the project are recommended to confirm the recommended vibration limits are appropriate. As discussed in Section 6.4.2 of the Noise and Vibration Technical Report, construction vibration impacts are predicted. Establishing appropriate vibration limits for construction is necessary to identify the most practical construction mitigation measures.

Table 14-2. Predicted Vibration and Groundborne Noise Levels at 645 Elliott Avenue West with Preferred Galer Street Station/Central Interbay Alternative (SIB-1), South Interbay Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
iHeartMedia recording booth	90	55	60	65	22	25	Does not exceed
iHeartMedia editing suite	90	55	60	72	22	35	Does not exceed
Nexelis lab space	90	55	60	66	Not applicable	Not applicable	Does not exceed
Luminex lab space	90	55	60	66	Not applicable	Not applicable	Does not exceed

[a] The slant distance between the near track and the façade of the sensitive receiver, in feet.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 14-3. Predicted Vibration and Groundborne Noise Levels at 645 Elliott Avenue West with Prospect Street Station/15th Avenue Alternative (SIB-2), South Interbay Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
iHeartMedia recording booth	91	55	60	65	21	25	Does not exceed
iHeartMedia editing suite	91	55	60	72	21	35	Does not exceed
Nexelis lab space	91	55	60	66	Not applicable	Not applicable	Does not exceed
Luminex lab space	91	55	60	66	Not applicable	Not applicable	Does not exceed

[a] The slant distance between the near track and the façade of the sensitive receiver, in feet.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[d] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 14-4. Predicted Vibration and Groundborne Noise Levels at 645 Elliott Avenue West with Prospect Street Station/Central Interbay Alternative (SIB-3), South Interbay Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
iHeartMedia recording booth	299	55	55	65	4	25	Does not exceed
iHeartMedia editing suite	299	55	55	72	4	35	Does not exceed
Nexelis lab space	299	55	55	66	Not applicable	Not applicable	Does not exceed
Luminex lab space	299	55	55	66	Not applicable	Not applicable	Does not exceed

[a] The slant distance between the near track and the façade of the sensitive receiver, in feet.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

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15 SEATTLE FILM INSTITUTE

15.1 Description of Sensitive Space

The Seattle Film Institute is a private film school at 3210 16th Avenue West in the Interbay/Ballard Segment of the Ballard Link Extension just north of West Dravus Street. It is housed in a two-level masonry building. In addition to classroom space, there is an isolated edit booth in one of the classrooms, a theater room for viewing movies, and a mixing room as well as other production and storage rooms. Figure 15-1 shows a photograph of the edit booth inside the classroom; Figure 15-2 shows a photograph of the mixing room; and Figure 15-3 shows a picture of the theatre room.

Schools are considered Category 3 (institutional) land uses in the FTA impact assessment methodology. Based on their use and existing noise and vibration levels, the Category 3 criteria are appropriate for all spaces in the building except the isolated edit booth, which has very low existing noise and vibration levels. The FTA threshold for auditorium is applied to the edit booth Because it is a place where critical listening takes place. This impact threshold is consistent with the threshold applied to editing suites at other sensitive receivers near the project. The theater room has existing noise and vibration levels consistent with the Category 3 FTA thresholds, and higher than the FTA thresholds for theaters. The existing noise and vibration levels are presented below.

Figure 15-1. Photograph of Edit Booth at Seattle Film Institute

Figure 15-2. Photograph of Mixing Room at Seattle Film Institute

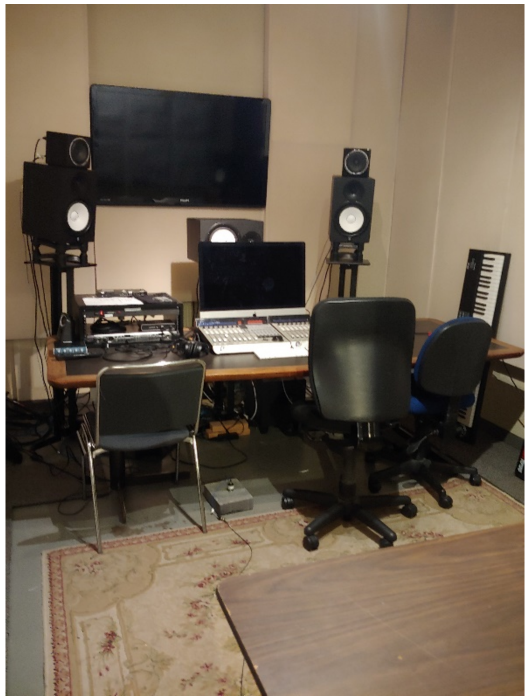
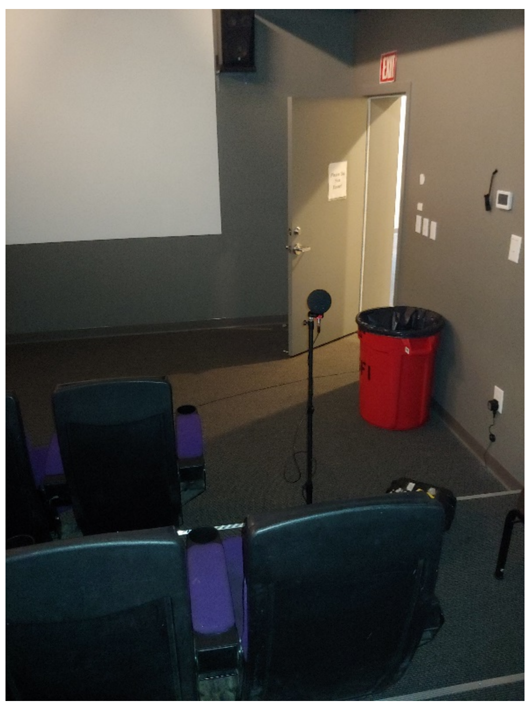


Figure 15-3. Photograph of Theatre Room at Seattle Film Institute



15.2 Existing Noise and Vibration Levels

Existing noise levels were measured over a 1-hour period in the Seattle Film Institute edit booth and theater room. During the noise measurement, the doors of the spaces were closed and signs were posted for no one to enter or exit. The measurements were conducted on a Friday morning at 9:00 am when there were relatively few students in the building.

The measured 1-hour Leq noise and vibration levels are shown in Table 15-1. The 1-second noise levels are plotted in Figure 15-4. The 1-second vibration levels are plotted in Figures 15-5 and 15-6, and the spectra of the vibration levels are plotted in Figure 15-7.

The measured data show that the noise and vibration levels are much lower in the isolated edit booth compared to the theater room. The theater room had relatively high levels of heating, ventilation, and air conditioning noise and is on the second floor. Second floor spaces often have higher vibration levels than first floor spaces. The mixing room and edit booth have a similar spectra for vibration levels, which indicates that the edit booth is primarily isolating noise and not vibration.

Table 15-1. Background Noise and Vibration Levels at Seattle Film Institute

Monitoring Location	Noise level (1-hour Leq)	Vibration level (1-hour Leq)
Theatre Room	42 dBA	73 VdB
Mixing Room	Not measured	55 VdB
Edit booth	22 dBA	55 VdB

Figure 15-4. Measured 1-second Noise Levels in Seattle Film Institute Edit Booth and Theatre Room

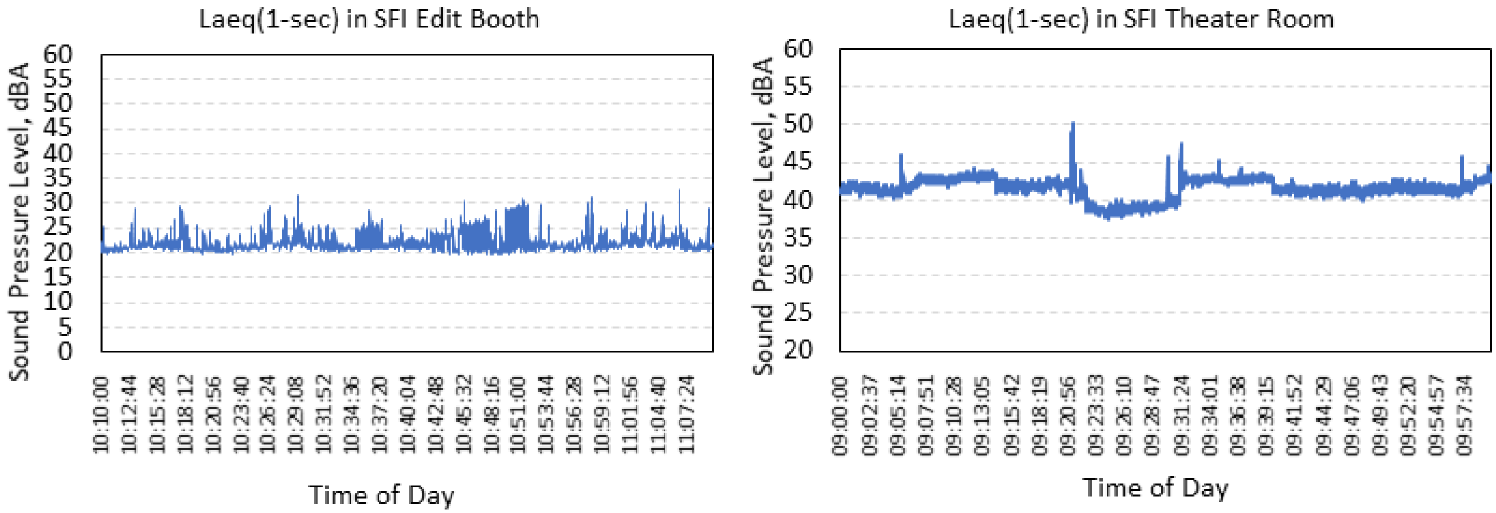


Figure 15-5. Measured 1-second Vibration Levels in Seattle Film Institute Edit Booth

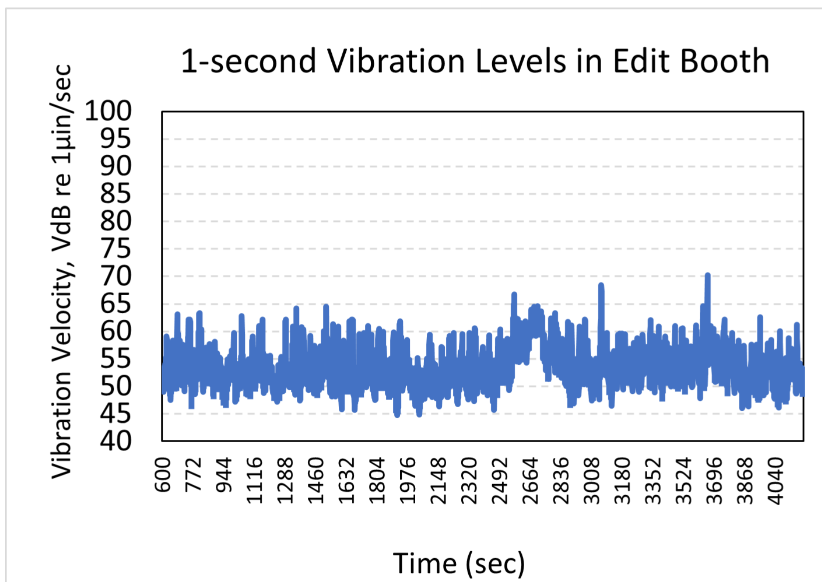


Figure 15-6. Measured 1-second Vibration Levels in Seattle Film Institute Mixing Room and Theatre Room

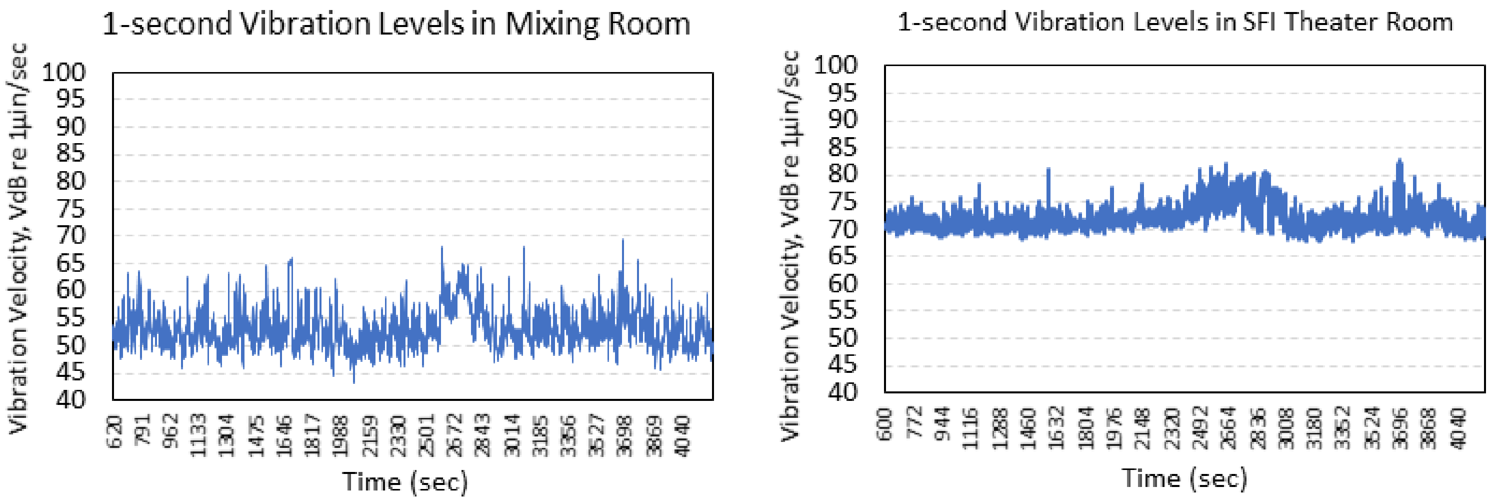
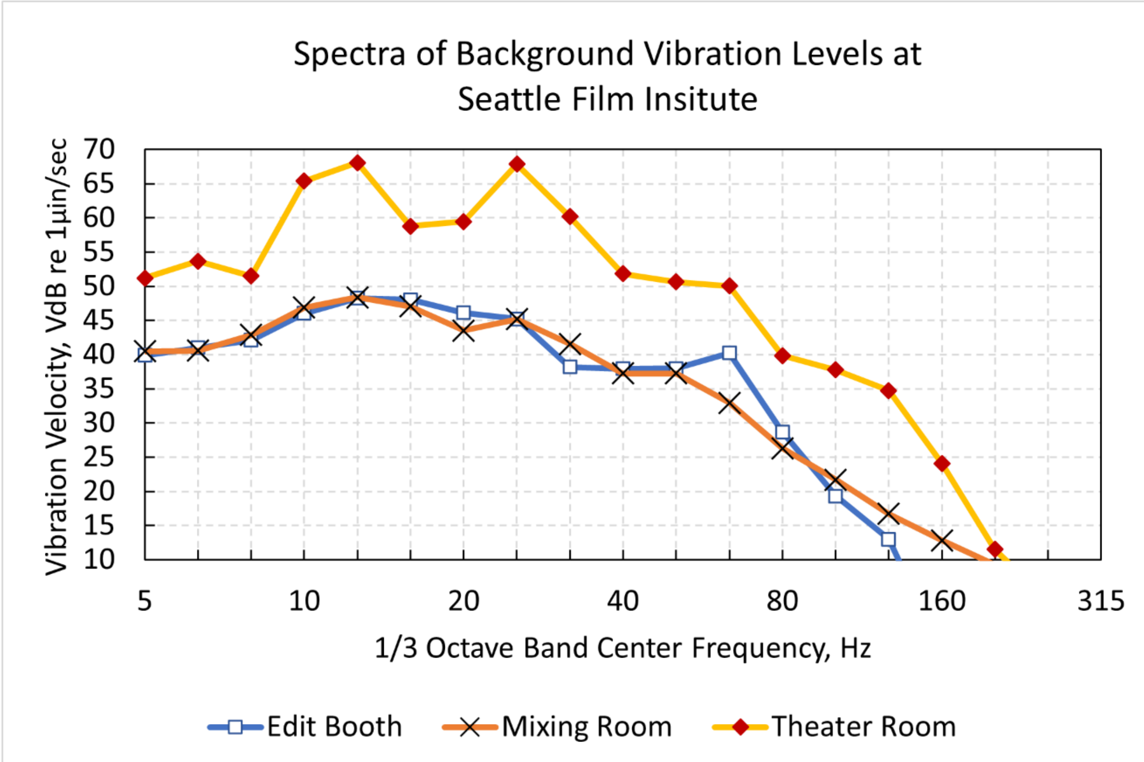


Figure 15-7. Spectra of Background Vibration Levels at Seattle Film Institute



15.3 Vibration Propagation Measurement Description

In the vibration propagation measurement, an impact hammer was used near the proposed location of the light rail trackway to generate a force, and the vibration response was measured at representative locations. At Seattle Film Institute, the impact hammer was on the sidewalk of 15th Avenue West. The hammer was operated at 11 positions spaced 15 feet apart to simulate the length of a light rail train.

The vibration levels were measured at six outdoor positions and three indoor positions. The outdoor measurement positions were used to quantify how vibration levels decrease with distance from the impact force. The outdoor vibration measurements were also used as a reference to examine how levels change as the vibration travels from the soil into the building structure.

The three indoor measurement locations were (1) the theater room, (2) the mixing room, and (3) the edit booth. The measurement positions were selected to get representative data in sensitive spaces on the first floor (mixing room) and second floor (theater room), and to measure any vibration isolation provided by the edit booth.

Figure 15-8 shows an aerial photograph of the measurement location that indicates the hammer impact line on the sidewalk and the approximate locations of the outdoor accelerometer positions in the alley north of the Seattle Film Institute building and the indoor locations of the accelerometers. The proposed light rail alignment is in the middle of 15th Avenue West. No floor plans of the Seattle Film Institute were available to indicate where indoor sensors were placed.

Figure 15-8. Aerial Photograph of Seattle Film Institute Vibration Propagation Measurement

15.4 Vibration Propagation Measurement Results and Predicted Levels

The result of the surface vibration propagation test is the L.S.T.M., a measure of how efficiently vibration propagates through the soil. Coherence is a measure of the quality of the L.S.T.M. results and varies between 0 and 1. A coherence value of 1 indicates the vibration response and the force generated by the dropped weight are closely related. The L.S.T.M. and coherence results for the indoor measurement positions and the closest outdoor measurement positions at the Seattle Film Institute are shown in Figures 15-9 through 15-11. Following are observations from the L.S.T.M. and coherence results:

- There is low coherence for all indoor and outdoor measurement positions below 20 hertz. The L.S.T.M. for the theater room shows high levels at frequencies lower than 20 hertz compared to the outdoor position, but the low coherence indicates the high levels are likely due to higher background vibration indoors and not more efficient vibration propagation at the lower frequencies.

- The mixing room and edit booth show similar L.S.T.M. levels to the outdoor positions, except at 31.5 hertz and 40 hertz, where the L.S.T.M. measured inside is lower than the L.S.T.M. measured outside.

Figure 15-9. L.S.T.M. and Coherence in Seattle Film Institute Theatre Room

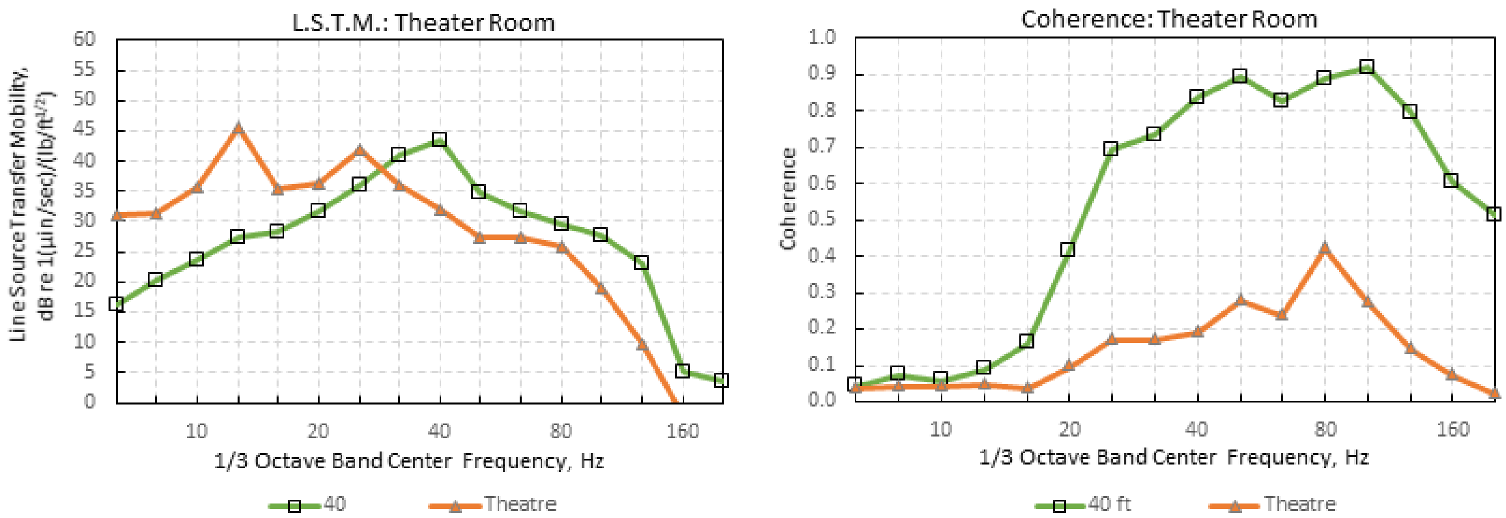


Figure 15-10. L.S.T.M. and Coherence in Seattle Film Institute Mixing Room

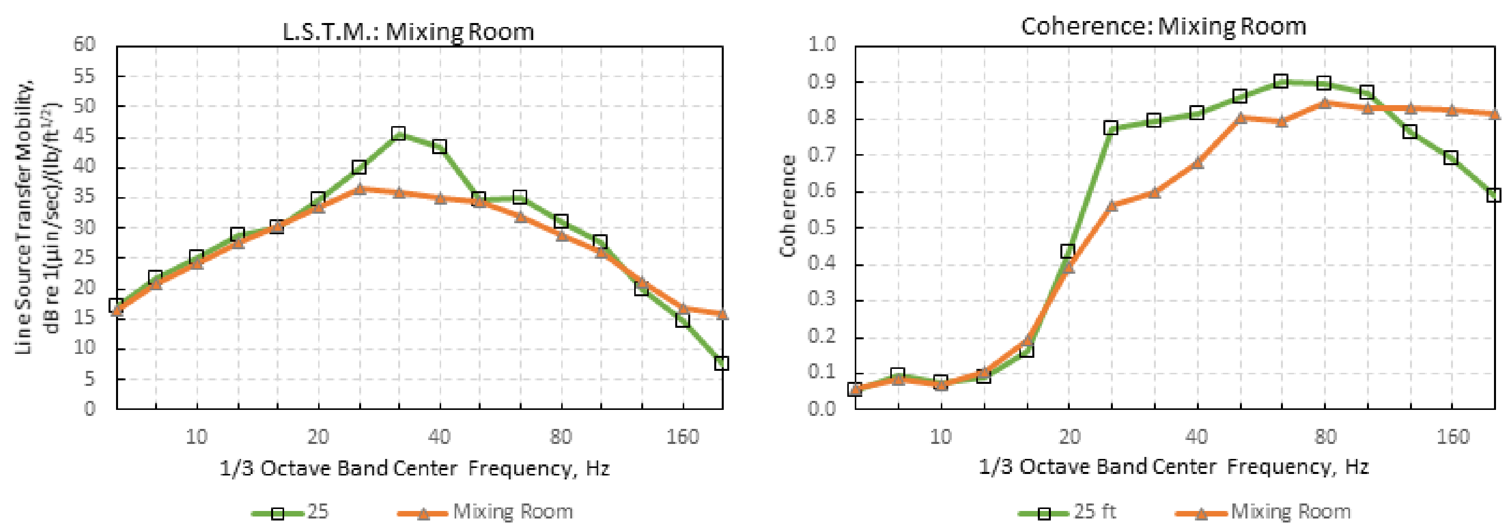
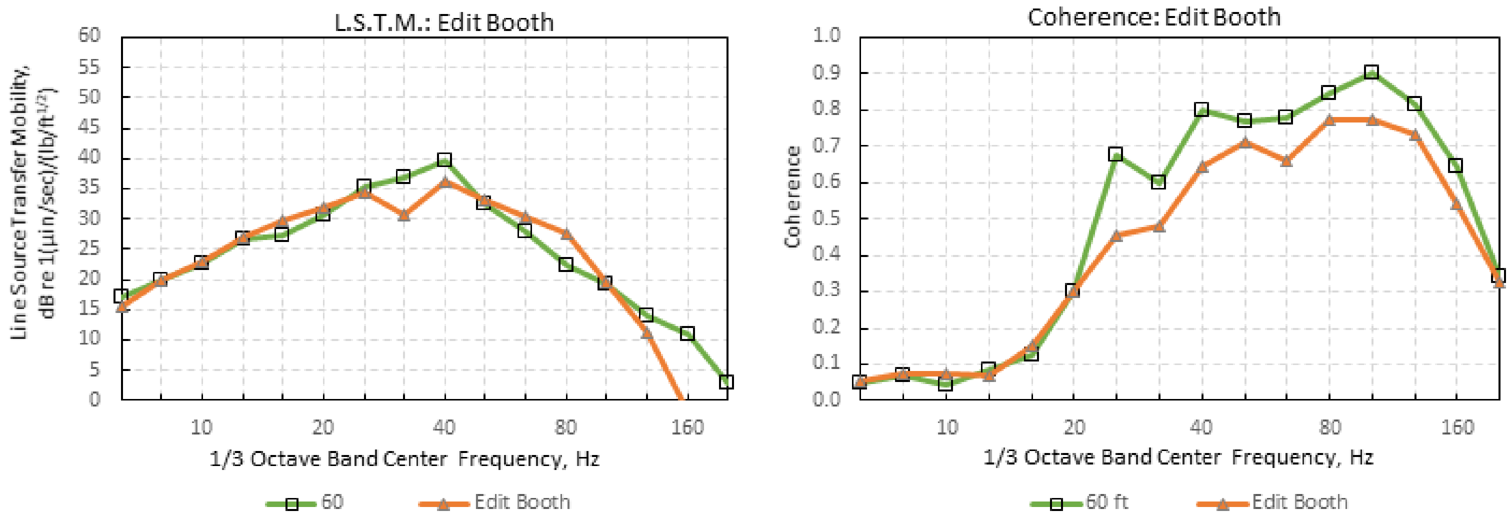
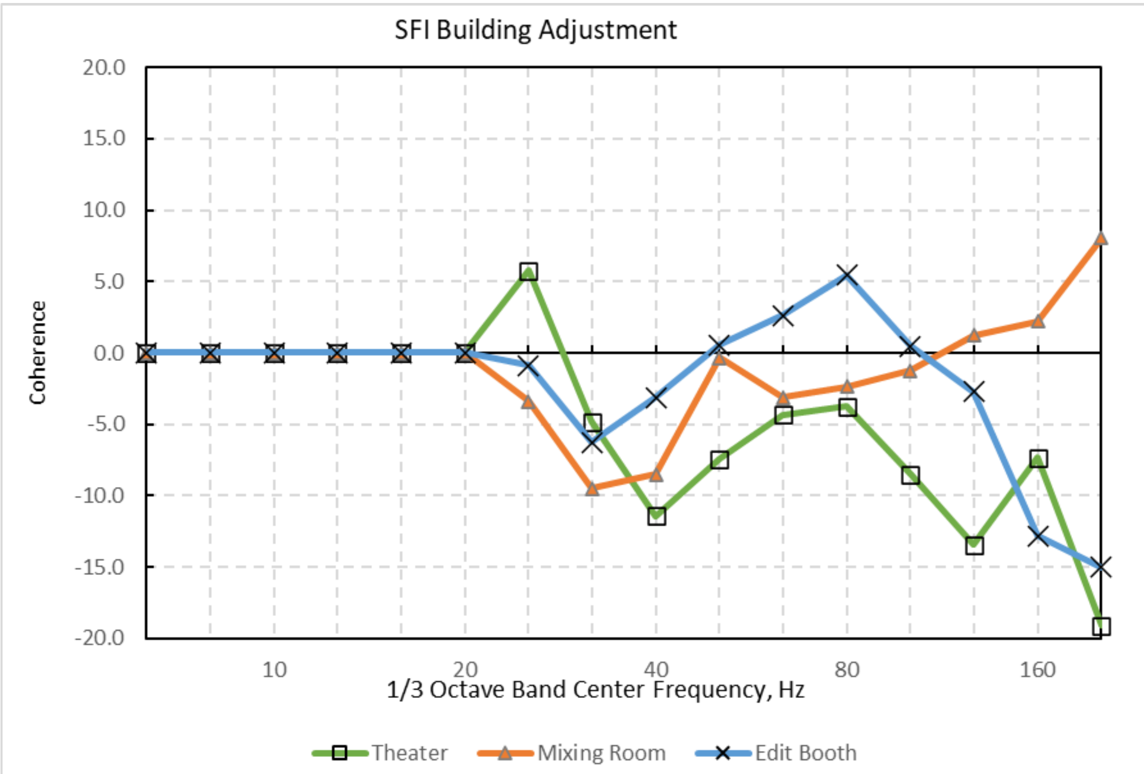


Figure 15-11. L.S.T.M. and Coherence in Seattle Film Institute Edit Booth



The building adjustment applied in the prediction model to account for the building coupling loss and any floor resonances is the difference between the indoor L.S.T.M. and the outdoor L.S.T.M. at an equivalent setback distance. The building adjustments for the measurement positions in the Seattle Film Institute are shown in Figure 15-12. No building adjustment was applied for frequencies below 20 hertz because the L.S.T.M. and coherence data indicate there is a poor relationship between the force and the measured vibration response and it is unlikely there are floor resonances at low frequencies.

Figure 15-12. Measured Building Adjustment at Seattle Film Institute



The predicted levels using the L.S.T.M. coefficients for site V-H (Seattle Film Institute) and the building adjustment in Figure 15-12 are presented in Tables 15-2 and 15-3. Predictions are provided for alternatives that are within the 450-foot screening distance for Category 1 sensitive receivers. No safety factor was added to the predicted levels because the predictions used site-specific L.S.T.M. levels and there is a 3-decibel safety factor built into the force density level. The predicted levels for Alternative IBB-3, which is the closest alternative in the Interbay/Ballard Segment, include a +5-decibel adjustment for a crossover within 100 feet to 200 feet from the Seattle Film Institute. The predicted vibration levels for this alternative are presented in Figure 15-13.

The predicted vibration level for the edit booth is 1 decibel below the impact threshold for Alternative IBB-3 and 3 decibels below the impact threshold for Option IBB-1b. No vibration mitigation is proposed because the predicted levels are below the impact threshold; however, a low-impact frog for the crossover near Seattle Film Institute for Alternative IBB-3 could be considered to provide a greater margin of safety. Alternatively, mitigation could be applied at the edit booth if vibration is shown to exceed the FTA criteria.

Table 15-2. Predicted Vibration and Groundborne Noise Levels at Seattle Film Institute with Elevated 14th Avenue Alignment Option (from Prospect Street Station/15th Avenue) (IBB-1b), Interbay/Ballard Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Theatre	117	45	62	78	9	40	Does not exceed
Mixing Room	117	45	62	78	14	40	Does not exceed
Edit Booth	117	45	62	65	16	25	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 15-3. Predicted Vibration and Groundborne Noise Levels at Seattle Film Institute with Elevated 15th Avenue Alternative (IBB-3), Interbay/Ballard Segment

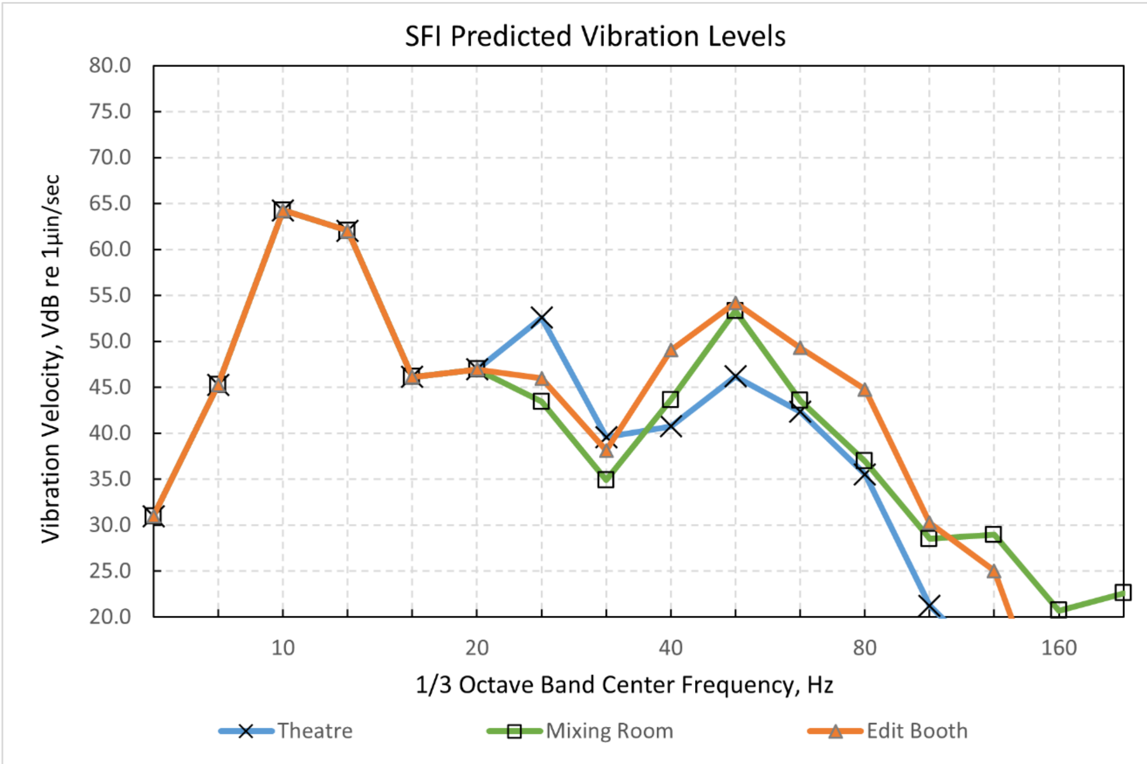
Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Theatre	114	55	64	78	16	40	Does not exceed
Mixing Room	114	55	64	78	20	40	Does not exceed
Edit Booth	114	55	64	65	23	25	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Figure 15-13. Predicted Vibration Levels at Seattle Film Institute for Elevated 15th Avenue Alternative (IBB-3)



16 FRIEDMAN & BRUYA AND BARDAHL MANUFACTURING

16.1 Description of Sensitive Spaces

Friedman & Bruya is an accredited analytical laboratory that specializes in organic and inorganic analyses of soil, water, product, and vapor samples using United States Environmental Protection Agency- and state-approved testing methods. The Friedman & Bruya laboratory is at 3012 16th Avenue West in the Interbay/Ballard Segment of the Ballard Link Extension near Option IBB-1b and Alternative IBB-3. When contacted, Friedman & Bruya identified their most vibration-sensitive equipment as 12 turbomolecular pumps located on the top floor of their facility. A vibration limit of 72 VdB is applied to Friedman & Bruya; this is generally suitable for microscopes to 100 times magnification and other equipment of low sensitivity.

Bardahl Manufacturing produces lubricants, oils, and additives for the automobile industry. Bardahl did not respond to outreach attempts to gather more information on their manufacturing plant or any laboratories that may be located in their facility near the light rail alignment. A vibration limit of 72 VdB is applied to the facility based on the information on their website. Their website indicates they develop new products at the facility, which would imply they have general laboratory space. However, the actual activities in the facility should be confirmed during future project design phases, particularly if vibration limits during construction are adopted.

16.2 Predicted Vibration Levels

The vibration prediction model quantifies how efficiently vibration propagates through the soil and into buildings using vibration propagation tests. At most highly vibration-sensitive (Category 1) land uses, site-specific vibration propagation measurements including measurements inside the building were used in the prediction model. Because neither Friedman & Bruya nor Bardahl Manufacturing identified equipment sensitive enough to qualify for vibration criteria V.C.-A or lower, site-specific measurements were not completed.

In place of using site-specific vibration propagation data, the average of the South Interbay and Interbay/Ballard segments surface measurement sites was applied. These are the same data applied for the residential and institutional land uses in the South Interbay and Interbay/Ballard segments and are discussed in Section 5.3.2 of the Noise and Vibration Technical Report. The building adjustment, which characterizes the building coupling loss and any floor resonances, was assumed to be 0 decibel. Many of the large buildings along the light rail alignment showed greater vibration attenuation than -5 decibel, so the building adjustment is likely a conservative estimate.

Because site-specific vibration propagation and building adjustment data were not measured at Friedman & Bruya and Bardahl Manufacturing, a safety factor of +2 decibels is included in the prediction model. There is also a 3-decibel curve adjustment and a 3-decibel safety factor incorporated into the force density level used in the prediction model.

The predicted levels are presented in Tables 16-1 through 16-5. The results show there is no predicted impact for any of the Interbay/Ballard Segment alternatives. No vibration mitigation is proposed.

Table 16-1. Predicted Vibration and Groundborne Noise Levels at Friedman & Bruya and Bardahl Manufacturing with Preferred Elevated 14th Avenue Alternative (IBB-1a), Interbay/Ballard Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Friedman and Bruya	898	55	51	72	Not applicable	Not applicable	Does not exceed
Bardahl Manufacturing	192	55	55	72	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria.

Table 16-2. Predicted Vibration and Groundborne Noise Levels at Friedman and Bruya and Bardahl Manufacturing with Elevated 14th Avenue Alignment Option (from Prospect Street Station/15th Avenue) (IBB-1b), Interbay/Ballard Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Friedman and Bruya	133	35	50	72	Not applicable	Not applicable	Does not exceed
Bardahl Manufacturing	177	55	55	72	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria

Table 16-3. Predicted Vibration and Groundborne Noise Levels at Friedman and Bruya and Bardahl Manufacturing with Preferred Tunnel 14th Avenue Alternative (IBB-2a) *, Interbay/Ballard Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Friedman & Bruya	913	30	46	72	Not applicable	Not applicable	Does not exceed
Bardahl Manufacturing	168	55	65	72	Not applicable	Not applicable	Does not exceed

* As described in the introduction to Chapter 2, Alternatives Considered, of the Draft Environmental Impact Statement, at the time the Sound Transit Board identified alternatives for study in the Draft Environmental Impact Statement some alternatives were anticipated to require third-party funding based on early cost estimates. The asterisk identifies these alternatives and the alternatives that would only connect to these alternatives in adjacent segments.

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria

Table 16-4. Predicted Vibration and Groundborne Noise Levels at Friedman and Bruya and Bardahl Manufacturing with Preferred Tunnel 15th Avenue Station Option (IBB-2b)*, Interbay/Ballard Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Friedman & Bruya	913	30	46	72	Not applicable	Not applicable	Does not exceed
Bardahl Manufacturing	257	55	56	72	Not applicable	Not applicable	Does not exceed

* As described in the introduction to Chapter 2, Alternatives Considered, of the Draft Environmental Impact Statement, at the time the Sound Transit Board identified alternatives for study in the Draft Environmental Impact Statement some alternatives were anticipated to require third-party funding based on early cost estimates. The asterisk identifies these alternatives and the alternatives that would only connect to these alternatives in adjacent segments.

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria

Table 16-5. Predicted Vibration and Groundborne Noise Levels at Friedman and Bruya and Bardahl Manufacturing with Elevated 15th Avenue Alternative (IBB-3), Interbay/Ballard Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Friedman & Bruya	134	35	49	72	Not applicable	Not applicable	Does not exceed
Bardahl Manufacturing	333	30	43	72	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria

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17 SPECIALTY VETPATH

17.1 Description of Sensitive Space

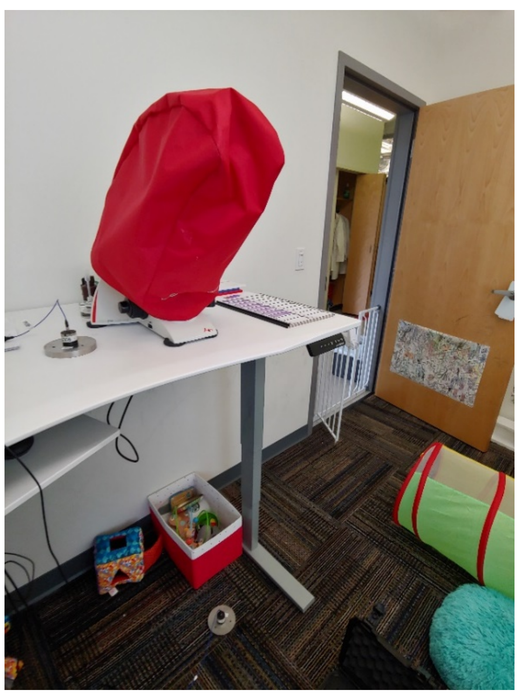
Specialty VETPATH provides veterinary diagnostic services. They have offices and a laboratory in their location at 3450 16th Avenue West, Suite 303, in the Interbay/Ballard Segment of the Ballard Link Extension. The vibration-sensitive equipment identified by Specialty VETPATH at their office and laboratory are microscopes and balance scales. The microscopes have magnification of 100x, with an additional 10x provided by the lens in the eyepiece. The balance scale can measure to 1/10 of a milligram. In the future, they plan to acquire equipment for extracting antibodies form egg yolks. This equipment might also be sensitive to vibration, but they do not yet have information from the manufacturer.

Specialty VETPATH has reported issues related to vibration from machinery used by another tenant in the building. The bottom level of the building is occupied by Dusty Strings Harps and Hammered Dulcimers, and the space is used as a workshop to actively construct musical instruments. To reduce interference from the vibration, Specialty VETPATH has installed foam pads at the base of their microscopes.

Figure 17-1 shows a photograph of the covered microscope in an office. There are foam pads under the mount, but the microscope is not placed on a purpose-made vibration isolation pad. The microscope is placed on a convertible standing desk.

The vibration criteria curve V.C.-A were applied to the Specialty VETPATH office. These criteria are adequate in most instances for optical microscopes with magnification up to 400x and for microbalances. The criteria for optical microscopes to 1,000x were not applied to the Specialty VETPATH office because existing vibration levels exceed those criteria. The existing vibration levels at Specialty VETPATH is presented in the next subsection.

Figure 17-1. Photograph of Microscope in Specialty VETPATH Office



17.2 Existing Noise and Vibration Levels

Existing vibration levels were measured over a 1-hour period in the Specialty VETPATH office pictured in Figure 17-1. Accelerometers were placed on the floor under the desk and on top of the desk. The measurement was conducted during normal working hours, but the office was empty for the 1-hour measurement duration. No high-vibration events from the Dusty Springs tenant were observed during the measurement.

The measured 1-hour Leq is shown in Table 17-1. The 1-second vibration levels are plotted in Figures 17-2 and 17-3. The spectra of the vibration levels are plotted in Figure 17-4. The measured data show that vibration levels are lower on the floor compared to on the desk. The background vibration levels measured on the floor were used to determine the appropriate vibration criteria for Specialty VETPATH because the desks might be replaced in the future. However, the data show vibration interference for the microscopes could be addressed by choosing desks that do not amplify the floor vibration.

The spectra of the vibration levels in Figure 17-4 show that the existing vibration level measured on the floor exceeds 60 VdB in the 31.5 hertz 1/3-octave band. The V.C.-B vibration criteria curve is recommended for optical microscopes with magnification up to 1,000X and limits vibration to 60 VdB in 1/3-octave bands from 8 hertz to 80 hertz. The next most stringent criteria, the V.C.-A vibration criteria curve, are recommended for the Specialty VETPATH office. The V.C.-A criteria curve limit vibration to 66 VdB in 1/3-octave bands from 8 hertz to 80 hertz and are considered adequate for optical microscopes up to 400X and for microbalances. This recommended limit is below the vibration level measured on the Specialty VETPATH desk.

Table 17-1. Background Noise and Vibration Levels at Specialty VETPATH

Monitoring Location	Vibration Level (1-hour Leq)
Specialty VETPATH Office Floor	66 VdB
Specialty VETPATH Office Desk	75 VdB

Figure 17-2. Measured 1-second Vibration Levels in Specialty VETPATH on Floor

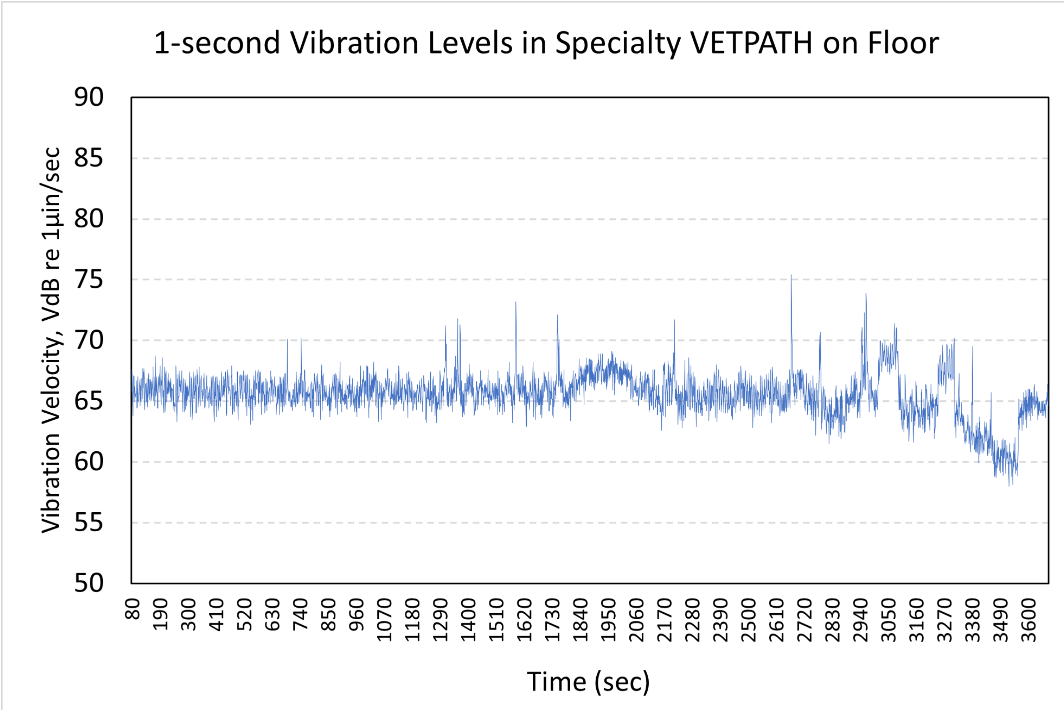


Figure 17-3. Measured 1-second Vibration Levels in Specialty VETPATH on Desk

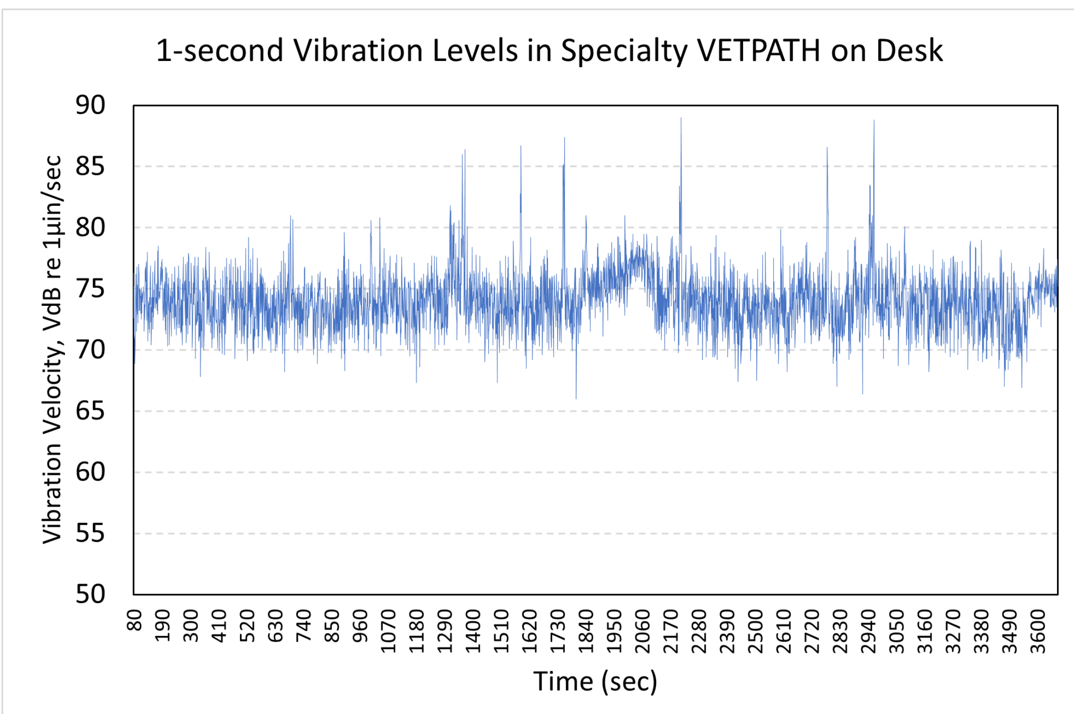
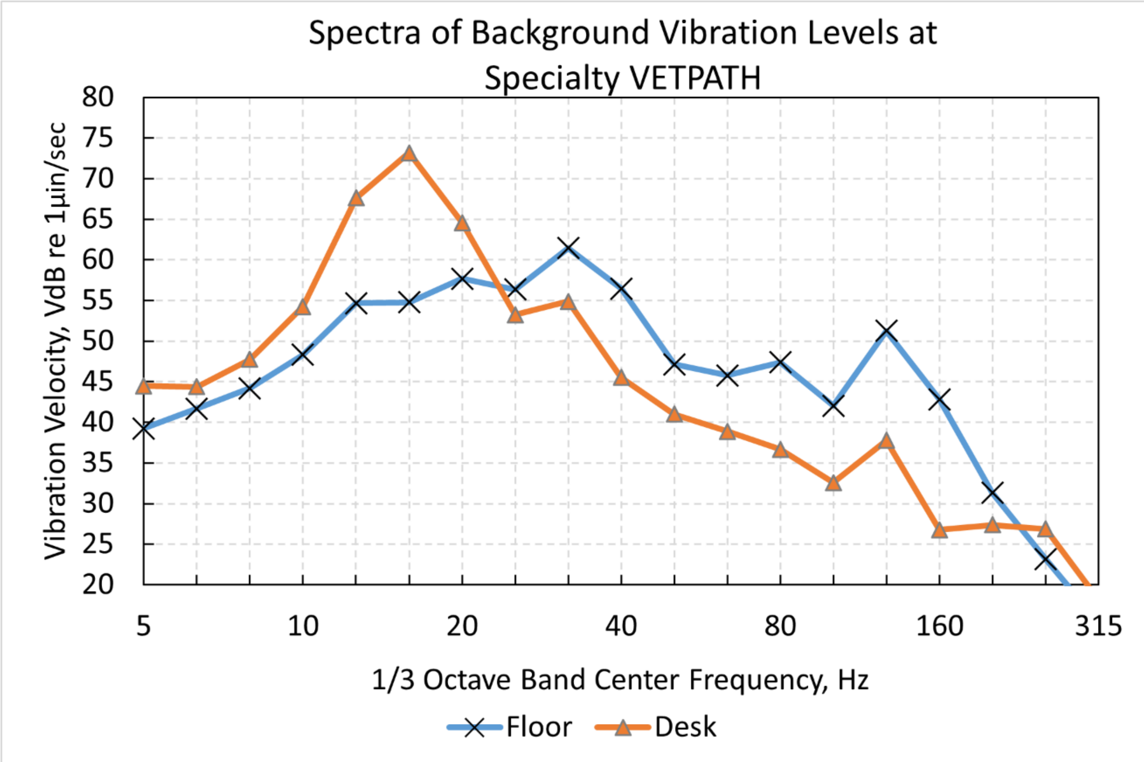


Figure 17-4. Spectra of Background Vibration Levels at Specialty VETPATH



17.3 Predicted Vibration Levels

The vibration prediction model quantifies how efficiently vibration propagates through the soil and into buildings using vibration propagation tests. At most highly vibration-sensitive (Category 1) land uses, site-specific vibration propagation measurements, including measurements inside the building, were used in the prediction model. However, site-specific measurements were not completed at Specialty VETPATH because the existing vibration measurement confirmed relatively high existing vibration levels, which indicates that Specialty VETPATH is less sensitive than many of the other laboratory spaces throughout the light rail alignment. Additionally, the proposed alignment near Specialty VETPATH is elevated structure, which would result in vibration levels about 10 decibels lower compared to at-grade or below-grade track.

In place of using site-specific vibration propagation data, the average of the South Interbay and Interbay/Ballard segments surface measurement sites was applied. These are the same data applied for the residential and institutional land uses in the South Interbay and Interbay/Ballard Segments and are discussed in Section 5.3.2 of the Noise and Vibration Technical Report. The building adjustment, which characterizes the building coupling loss and any floor resonances, was assumed to be 0 decibel. Many of the large buildings along the alignment showed greater vibration attenuation than -5 decibel, so the building adjustment is likely a conservative estimate.

Because site-specific vibration propagation and building adjustment data were not measured at Specialty VETPATH, a safety factor of +2 decibels is included in the prediction model. There is also a 3-decibel safety factor incorporated into the force density level used in the prediction model and a 2-decibel curve adjustment applied to the prediction model for Option IBB-1b.

The predicted levels are presented in Tables 17-2 and 17-3. No predicted levels are presented for Preferred Alternative IBB-1a, Preferred Alternative IBB-2a*, and Preferred Option IBB-2b* because the building would be a full take for those alternatives. The results show there is no predicted impact. No vibration mitigation is proposed.

Table 17-2. Predicted Vibration and Groundborne Noise Levels Specialty VETPATH with Elevated 14th Avenue Alignment Option (from Prospect Street Station/15th Avenue) (IBB-1b), Interbay/Ballard Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Specialty VETPATH	304	55	59	66	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria

Table 17-3. Predicted Vibration and Groundborne Noise Levels at Specialty VETPATH with Elevated 15th Avenue Alternative (IBB-3), Interbay/Ballard Segment

Sensitive Receiver	Distance (feet) [a]	Speed (miles per hour)	Predicted Vibration (VdB) [b]	Vibration Limit (VdB)	Predicted Groundborne Noise (dBA)	Groundborne Noise Limit, (dBA)	Amount Exceeds (decibels) [c]
Specialty VETPATH	144	55	59	66	Not applicable	Not applicable	Does not exceed

[a] Slant distance between the receiver and the near track centerline.

[b] Predicted maximum 1/3-octave band vibration level; decibels referenced to 1 micro inch per second.

[c] The decibel amount that the vibration (VdB) or groundborne noise (dBA) exceeds the applicable criteria

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18 REFERENCES

Beranek, L.L. 1957. *Revised Criteria for Noise Control in Buildings*, Noise Control, vol. 3, 1957, pp. 19-27.

McKenna, S., and C. Layman. 2018. *Predicting light-rail groundborne noise and vibration from tunnels*. Proceedings of Inter-Noise 2018.

Saurenman, H.J., Nelson, J.T., and G.P. Wilson. 1982. *Handbook of Urban Rail Noise and Vibration Control*. Urban Mass Transportation Administration Report No. UMTA-MA-06-0099-82-1, October.

The 5th Avenue Theatre. 2019. The Historic Theatre:From Vaudeville to Movies to Musicals. https://www.5thavenue.org/about/about-the-5th/the-historic-5th/.

National Institutes of Health. 2019. *Design Requirements Manual.* Division of Technical Resources, Office of Research Facilities. Issuance Notice December 12, 2016, Revision 1.4: 4/24/2019.

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