Measurements of the Vibration Stability of the NSLS-II Storage Ring[1]

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Abstract – Unexpectedly large vibration levels and lack of correlation between girder-to-girder motions were discovered during recent vibration stability measurements of the NSLS-II magnet-girder assemblies. A comprehensive ambient site vibration study was undertaken to investigate several vibration issues, namely, night-to-day vibration amplitude ratio of about 4, several high vibration spikes during night time, vibration levels during adverse weather, and vibration correlation versus distance. In this paper we present the results of these studies and describe a vibration mitigation scheme under development.

1. Introduction

Modern light sources, such as the NSLS-II at Brookhaven National Laboratory, are designed to generate an electron beam with very low emittance and small beam size which requires a high degree of mechanical stability of the girder assembly as well as a low ground vibration level. For NSLS-II, the vibration stability specification for the uncorrelated motion integrated between 4 Hz and 50 Hz is 25 nm for magnets on the same girder, and 75 nm for magnets on adjacent girders. The ground motion below 4 Hz is assumed to be correlated over the length of the storage ring cell (25 m), and motion above 50 Hz is expected to be negligible.

2. Correlation study

Correlation between motion of magnets separated by different distances was studied using two Sercel L4C seismometers of 1 Hz resonance frequency (Web-1). The seismometers were placed on the top of different quadrupoles on the same girder, as well as on another girder nearby. Measurements were also made with both seismometers placed very close to each other on the same magnet ("zero" separation) to ensure that the measurements are well correlated in this case. Similar measurements were made on the storage ring floor also.

The real part of correlation as a function of frequency is shown in Fig. 1 for various distances measured on the storage ring floor. It is seen that there is a noticeable drop in the correlation at above a few Hz for distances as small as ~3 m. At a distance of 11.4 m, a good correlation (real part > 0.95) is seen only below ~2 Hz. (See Fig 1). Similar correlation results were obtained at all times of the day, even though the absolute motion varied by about a factor of 4-5 (see Sec. 4). There was practically no difference between the correlation curves measured on the top of the magnets and on the storage ring floor. Thus, the floor, as well as magnet motion over the length of a cell (~25 m) is not expected to be well correlated below 4 Hz, contrary to what was previously assumed.

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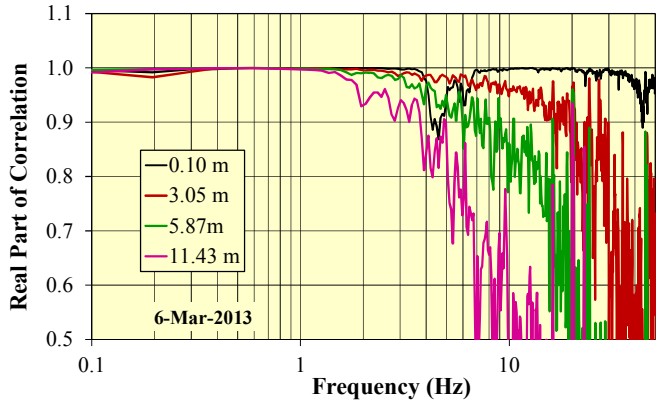


Fig. 1 Real part of correlation as a function of distance

3. Mechanical stability of NSLS-II girder

The measured natural frequency of the NSLS-II magnet-girder system is 30 Hz for the lowest (rocking) mode and 50 Hz for the next higher (twisting) mode (Ravindranath et al. 2012). A comprehensive set of measurements to verify the vibrational stability of the NSLS-II girder assembly was performed. Measurements were made simultaneously on the floor, and either the girder, or a magnet, or the vacuum chamber using Sercel L4C seismometers to obtain the transfer function. In view of the correlation study results presented in the previous section, we studied integrated motion between 2-50 Hz instead of NSLS-II specification of 4-50 Hz. The analysis showed the vertical transfer ratio from the floor to the girder assembly and magnets was close to 1, ranging from 1.0 to 1.16. These results are summarized in Table 1.

Table 1. Transfer Function Results

	Vertical (2-100 Hz)		**Horizontal (2-100 Hz)**	
	RMS (nm)	**Ratio**	**RMS (nm)**	**Ratio**
Floor	75.0	1.00	57.6	1.00
Girder	73.4	0.98	60.5	1.05
Magnet	81.2	1.08	61.8	1.07
Chamber	79.9	1.07	66.6	1.16

4. Variation of floor motion with time of the day

Vibration data taken every 30 minutes on the storage ring floor for a number of days in October 2012 had shown that the daytime floor motion was considerably higher than the night-time floor motion (Ravindranath et al. 2012). The RMS vertical motion integrated over 2-100 Hz varied from ~ 15-20 nm at night time to ~50 nm during day time on weekends, and as much as over 120 nm during mid-day on weekdays. The night time motion was about the same on a weekend and a weekday. Numerous sets of data were taken over the next few months, some for as long as a week, over the weekend, and during varying weather conditions. These new measurements also captured the effect of high winds during otherwise relatively quiet night times. It was seen that high winds caused significant motion at about 1 Hz (Cheng, et al. 2013). The RMS motion integrated between 0.5 and 2 Hz increased from ~175 nm to ~320 nm on windy days. The normal vibration levels are very repeatable from day to day and week to week. Preliminary investigation had shown that the time profile of vibration level is similar to the traffic pattern on the nearby Long Island Expressway (LIE), although there seemed to be a phase lag of about 2 hours between the two profiles. Subsequent work done to understand this difference is presented in Sec. 6.

The diurnal variation results are consistent with results from a vibration study carried out by a group from DESY, Germany, at many accelerator sites around the world, including BNL and the Advanced Photon Source (APS) at Argonne (Bialowons et al. 2006). The maximum vibration levels seen on the APS storage ring floor was ~10 nm, and it did not vary much from night to day. We have also performed vibration studies at APS and verified the conclusion from the DESY study. The vibration levels at APS varied from 10 nm at night to 12 nm during the daytime ignoring any outliers due to known local activities at the measurement site. APS is approximately the same distance away from a major interstate highway (I-55) as BNL is from the Long Island Expressway, yet the vibration levels at APS do not seem to be affected by traffic. The adverse traffic response for NSLS-II is probably related to the much higher (by a factor of 4) stiffness of the compacted sand.

In view of the differences between the APS and NSLS-II floor vibration patterns, we have also measured correlation as a function of distance at APS storage ring floor in sector 28. This study showed that unlike the NSLS-II storage ring, the relative motion at APS is well correlated up to a frequency as high as ~8 Hz for the length of a cell (see Fig 2).

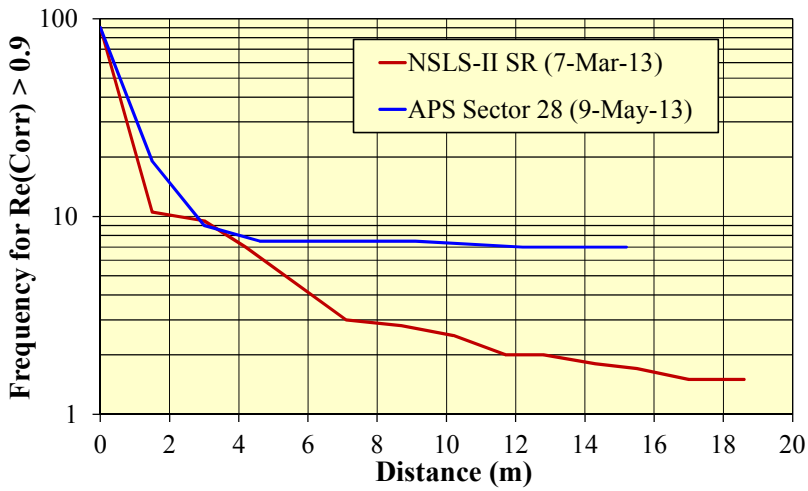


Fig. 2 Comparison of the NSLS-II and APS correlation results. The vertical axis shows frequency below which the real part of correlation is greater than 0.9.

5. Green field measurements

The larger than expected vibration levels and poor correlation above just 2 Hz seen on the storage ring floor brought up a number of questions. Was the poor correlation due to the structure of the building? Was the building amplifying the ground vibration levels? 'Green Field' measurements were carried out on the BNL site at a number of locations. (see Fig. 3) to answer these questions. The time variation of the ground motion on the storage ring floor suggested vehicular traffic as the likely cause of these variations. The Long Island Expressway (LIE) is located 1.3 Km away from the NSLS-II building, on the southern border of the BNL site (Fig 3). The displacement amplitude as well as its short term time variation decreased with increasing distance from the LIE (Fig. 4), pointing to the traffic on the LIE as a likely source of the large vibrations seen on the storage ring floor.

Correlation data were taken near the LIE and near the northern-most boundary of the BNL site (marked North-East in Fig. 3). The real part of correlation is plotted as a function of frequency in Fig. 5 for a distance of 5.5 m on the storage ring floor and near the northern-most boundary of the BNL site. It is seen that the correlation is similar at both locations for frequencies below 5 Hz. In fact, the NSLS-II storage ring floor shows a better correlation at higher frequencies than the green field site.

The conclusion was that the vibrations were originating from outside the NSLS-II building, and that the building itself was not the reason for the poor correlation seen on the storage ring floor. The reason for this poor correlation, and the striking contrast with the APS floor, is not clear.

Fig. 3 BNL site map showing locations of vibration measurements.

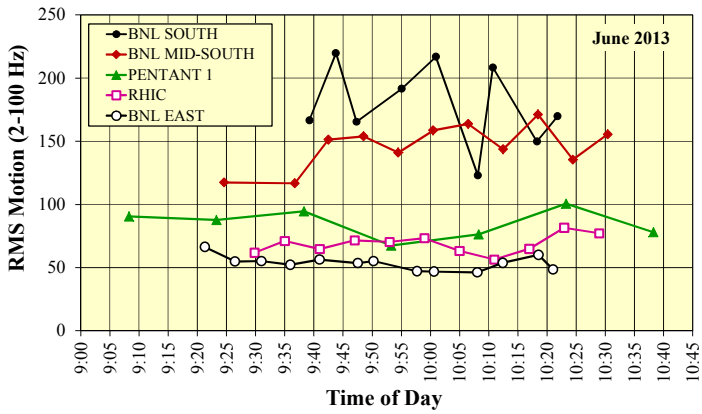


Fig. 4 Vibration levels at various "Green Field" locations and on the NSLS-II storage ring floor.

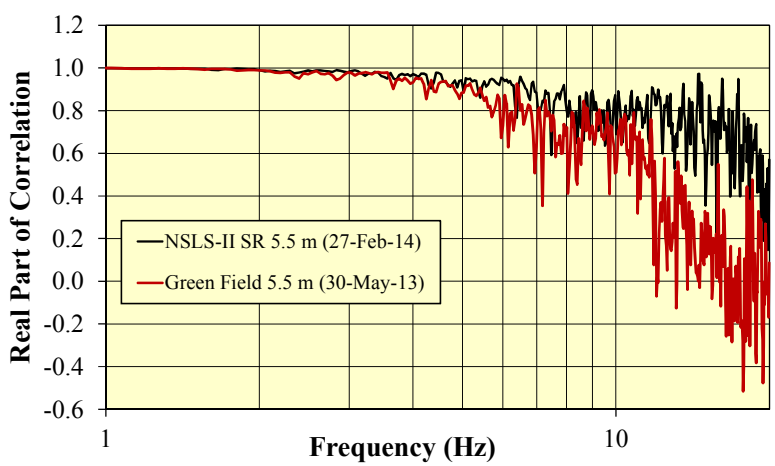


Fig. 5 Real part of correlation as a function of frequency for 5.5 m separation on the NSLS-II storage ring floor, and at a green field location farthest from the Long Island Expressway (BNL North-east in Fig. 4).

6. Direct comparison with LIE traffic counts

The NSLS-II site lies about 1.3 Km north of the LIE between exits 68 and 69. Historic total traffic count data between these exits were obtained from the New York State Department of Transportation (NYDOT) and compared to the vibration data measured on the storage ring floor. Although the traffic count showed a diurnal variation similar to the vibration data, there appeared to be a lag of about 2 hours between the two sets of data that was puzzling. Although the traffic data were not collected at the same time as the vibration data, they were both taken during summer months. So, seasonal differences were perhaps not the cause of the discrepancy. It was plausible that the vibrations could be related only to the flow of heavier traffic on the expressway which could have a time profile different from the total traffic. The NYDOT traffic counts for this stretch of the LIE do not distinguish between cars, light trucks, heavy trucks, etc. so this could not be readily verified from the available data.

A preliminary investigation was carried out by setting up a video camera very close to the expressway to record the LIE traffic over a few days. Unfortunately, manual analysis of the video footage proved too time consuming to pursue. Also, the headlights of vehicles at night made it impossible to count any traffic past 6 PM. Instead, BNL personnel, armed with digital counters, performed a manual traffic count of the eastbound and westbound truck traffic on the LIE in September 2013 for a period of 12 hours, from 6 AM until 6 PM. Vibration data taken during the same period was not useful because it was marred by intense local activities on the storage ring floor. Instead, data taken a few months earlier was compared to the traffic count. These data did show that there is a difference between the heavy vehicles and total traffic time profiles and a more comprehensive study needed to be made.

In June 2014, a private firm Tri-State Traffic Data, Inc. (Web 2) was contracted to record and analyze via software the east and west bound traffic on the LIE between exits 68 and 69. The traffic in each direction was further separated into 3 categories – motorcycles, cars or light trucks, and large trucks. Vibration measurements were carried out in parallel with these traffic count studies to facilitate a direct comparison of the vibration and traffic time profiles. The vibration measurements were carried out at two locations in NSLS-II – on the experimental floor, and on the storage ring floor in Cell 3. The time profiles of RMS vibration amplitudes at these two locations were very similar.

Fig. 6 shows a comparison of the vibration levels (RMS motion integrated over 2-100 Hz) and the total traffic count, including light and heavy vehicles, and traveling in either direction. It is obvious that the total traffic is not well correlated with the vibration pattern. In particular, the vibration levels decrease significantly over the weekend, whereas the total traffic remains about the same as on a weekday. Also, if one concentrates on the evening and night time data only, a phase difference between the traffic and

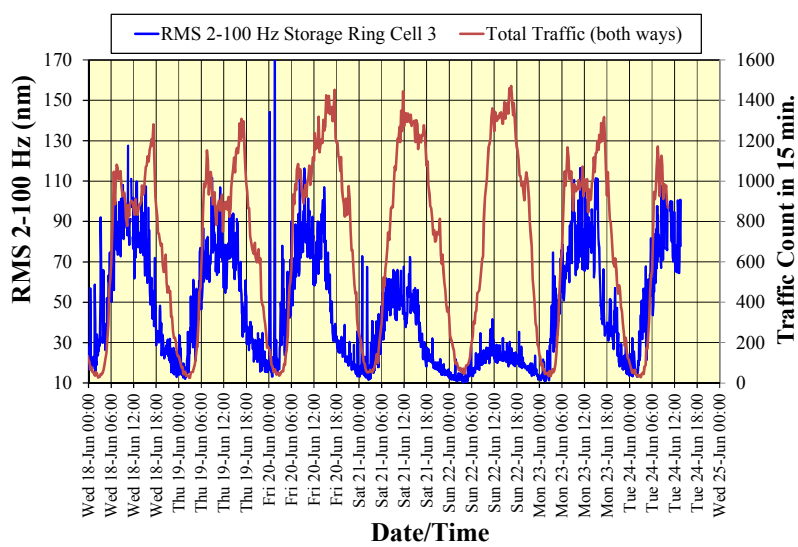


Fig. 6 Time variation of vibration levels and the total traffic on the Long Island Expressway.

vibration data is apparent. A similar discrepancy is seen if one looks at either the eastbound or the westbound total traffic.

The day time vibration levels typically show two peaks (seen most clearly in the data taken on June 20, 2014 in Fig. 6). One peak occurs early in the morning around 9 AM, whereas the other peak occurs in the afternoon around 3 PM. The count of eastbound trucks also showed a peak in the morning, consistent with the vibration pattern, but these eastbound truck counts taper off rapidly and do not explain the second vibration peak in the day (see Fig. 7). The westbound truck traffic, on the other hand, does have a peak around 3 PM that matches the vibration pattern in the afternoon (see Fig. 8). The only observation here is that the westbound truck traffic tends to persist in the afternoon and evening hours well beyond the time when the vibration levels have already reduced significantly. This discrepancy is seen very clearly in the data on Saturday, June 21 in Fig. 8. It is possible that these westbound trucks late in the day are returning empty and do not contribute significantly to the vibration levels. The same may apply also to some early morning (~7 AM) peaks in the eastbound truck traffic.

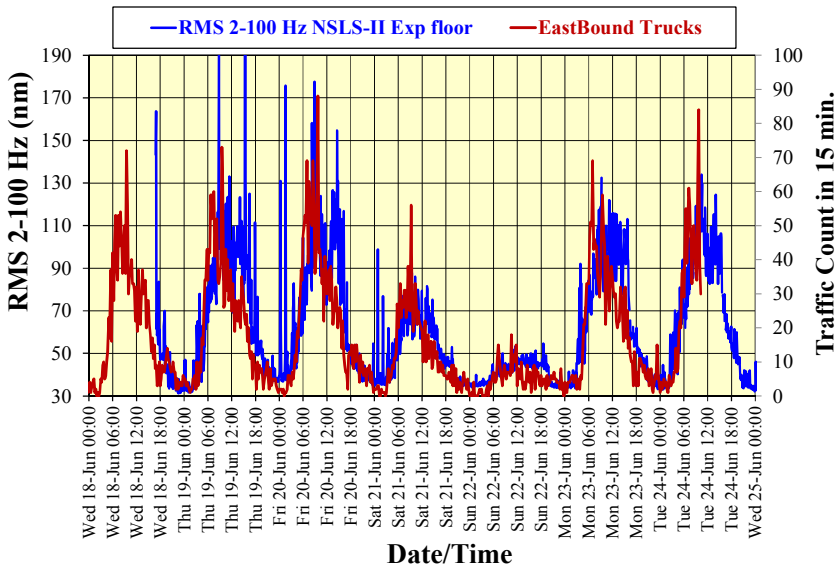


Fig. 7 Time variation of vibration levels and the eastbound truck traffic on the Long Island Expressway.

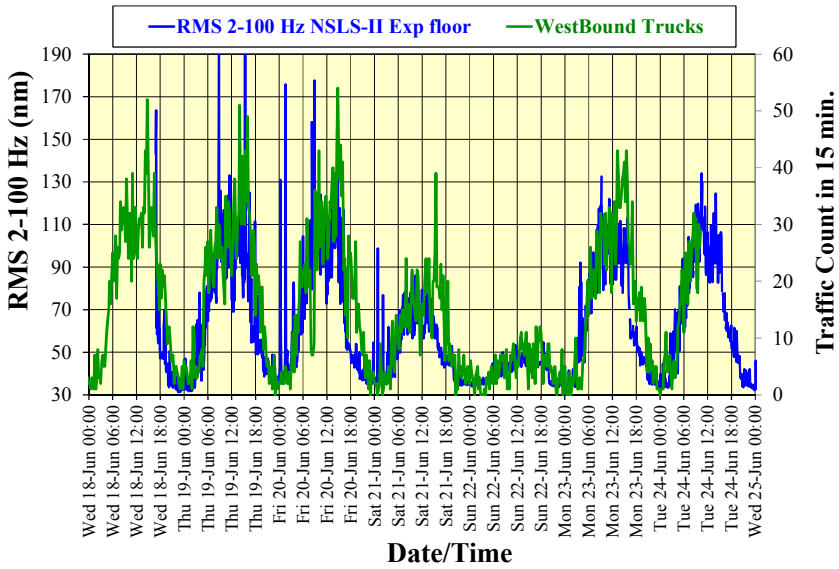


Fig. 8 Time variation of vibration levels and the westbound truck traffic on the Long Island Expressway.

7. Anomalous large vibrations

During the acquisition of vibration data in the NSLS-II complex and on the BNL site, a number of intermittent large spikes in the vibration levels were captured in the data (see, for example, Figs. 6-8). This was attributed earlier to either hardware glitches or local disturbances because the NSLS-II was still under construction with significant local activity. However, as can be seen from Figs. 6-8, these large spikes also occurred in the middle of the night during otherwise quiet period, and when no activity was known to be underway in the storage ring. These anomalous spikes could be as high as 275 nm in the middle of the night when the normal vibration level is one order of magnitude lower.

For routine studies, a typical vibration measurement consists of data taken for a period of 143.5 s at 1600 Hz and the measurements are repeated every 5-30 min. In order to fully capture the time evolution of these spikes, which seemed to occur at random times, the sampling time was extended to as much as 1 hour, with data acquisition restarted almost immediately to cover the entire night time period with negligible interruptions. Several periods of large vibration were captured from around midnight to 4 AM. The signal output from a L4C seismometer as a function of time is shown in Fig. 9 for one such data set showing one instance of large vibrations.

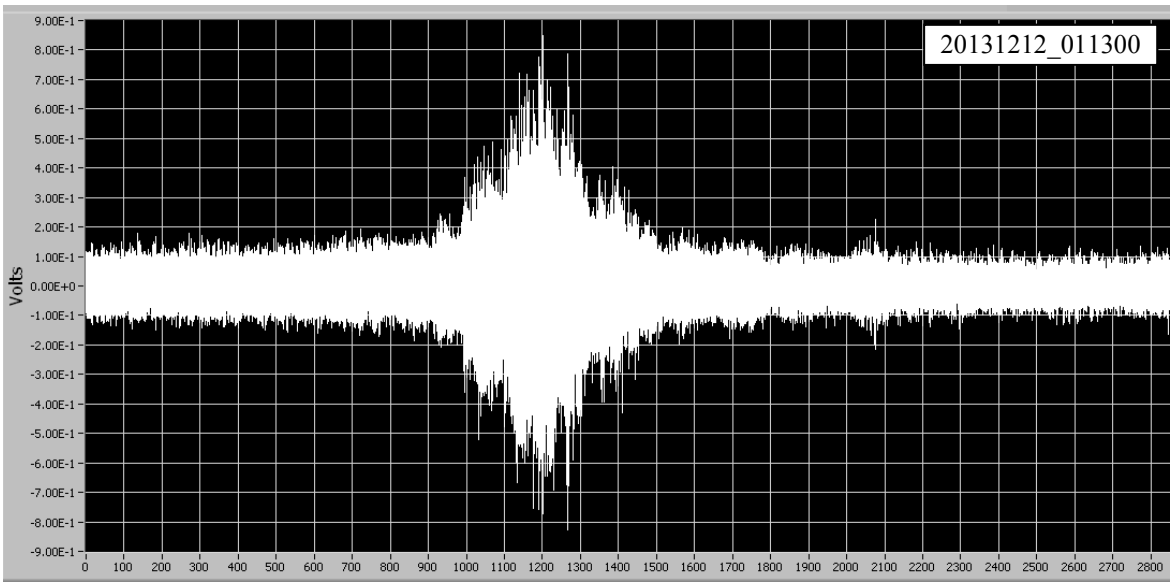


Fig. 9 Portion of a signal output from a L4C seismometer (amplified 200X) recorded for one hour containing one instance of large vibrations. The horizontal axis shows time in seconds since the start of data acquisition.

Two aspects of the waveform shown in Fig. 9 are noteworthy. One is that the enhancement in vibration level is not momentary, but is enhanced for and extended period of ~10 min (as in Fig. 9), and could be as much as over 20 min in some cases. The other aspect is that the vibration level gradually increases over a period of several minutes, and then gradually decreases in almost a symmetric fashion. This indicates that the source of these enhanced vibrations may be approaching slowly from a faraway distance, and then receding away from the NSLS-II site. Such a profile could be indicative of vibrations caused by any trains passing nearby.

Two Long Island Railroad (LIRR) lines run in the vicinity of BNL, one just south of BNL bordering the property line (see Fig. 3), the other about 12 Km south of BNL. Passenger trains were ruled out for these night time spikes because no passenger trains run at those hours. This left freight trains as the potential source of these vibrations.

After some research, it was discovered that the New York and Atlantic Rail (NY&A, see Web-3) operated a freight service using the LIRR tracks at night. Communications with NY&A confirmed that freight trains did run on the tracks adjacent to the BNL site but at irregular intervals from 11:30 PM to 4:00 AM when the tracks were not in use for passenger service. It was verified that the times of large

vibrations did match the Yaphank-Riverhead freight train schedule for those days. The tracks that run from Yaphank to Riverhead are only about 10 m away from the BNL property line.

Due to the way the freight train service is administered and scheduled, it was difficult to obtain a well-defined schedule, or even the times when a train service actually operated. An Infrared (IR) video camera was therefore setup to record the passage of all trains just south of the BNL property. The camera was setup to run continuously and vibration data were taken simultaneously on the experimental floor. It was found that three different types of trains operate on these tracks. The *passenger trains* are of length such that they passed the IR video camera location in about 6-9 seconds. The *short freight trains* also passed the camera location in about the same time as the passenger trains, whereas the long freight trains took as much as 20-40 seconds to pass. It is conceivable that the onset of increase in vibrations occurs well before the train arrives at the BNL location, and higher vibration levels last well after the train has passed through the BNL location. The total travel time from Yaphank to Riverhead is 26 min for the passenger trains, and is assumed to be the same for the freight trains. The increased vibrations could thus last potentially for as long as 26 min, consistent with observations from data taken in one hour chunks. It appears that the effect from smaller freight trains and passenger trains is felt only when the trains are about 5 min away from the BNL site, whereas the effect from the larger freight trains lasts for almost the entire travel time. The timings of the longer freight trains seen by the IR camera matched those of the significantly enhanced vibration levels seen on the experimental floor, confirming the freight trains as the source of these anomalous vibrations. (see Fig. 10, red arrows). The short freight trains also operate during the normally quiet periods and their effect can also be seen (Fig. 10, green arrows), although it is not as severe as the longer freight trains. The effect from the passenger trains is not so clear. Most of the passenger trains operate during day time when the vibration levels are already high due to traffic effect (see Sec. 6) and there may be other local activities going on. Although some small spikes in the vibration level seem to match passenger train times, a few trains that run in the late evening and night hours did not seem to have much effect (Fig. 10, blue arrows).

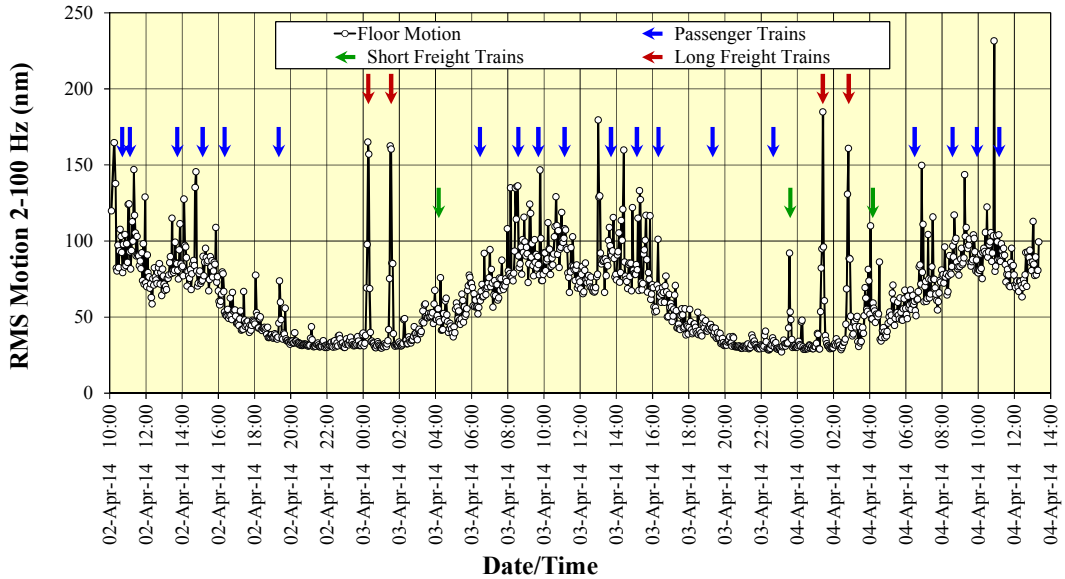


Fig. 10 Vibration levels measured on the experimental floor and timings of various types of trains passing close to the BNL site.

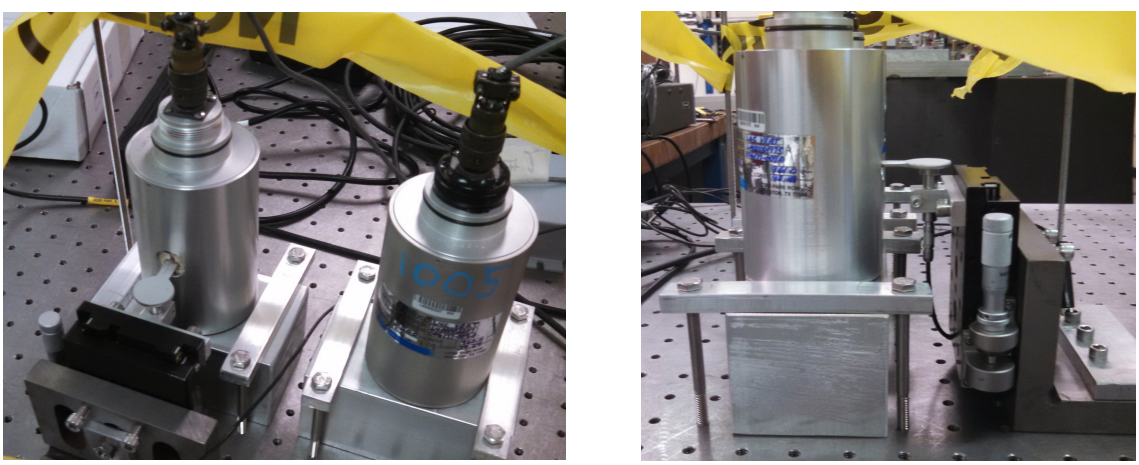
8. Minimizing impact of high vibration levels

Work is currently in progress to devise means to minimize the impact of the large vibration levels on the operation of the machine and the experiments. Despite the lack of correlation in the 2-4 Hz range for long distances, it is anticipated that the relative motion of magnets on the same girder will still meet the

requirement of uncorrelated motion below 25 nm. However, the BPM stands will see the large vibration levels and may affect machine operation. One option to mitigate this is to develop a displacement sensor that can feed the BPM motion information to the control system in real time.

The Sercel L4C seismometer provides a velocity signal which could be integrated to obtain a displacement signal. However, such hardware integration usually results in a drift due to voltage offsets. Capacitive displacement sensors, on the other hand, require a reference surface which itself should be very stable. The idea is to create such a reference surface by the suspended mass of a low resonant frequency (~0.5 Hz or so) pendulum. Since the pendulum will attenuate any floor motion above the resonant frequency, the mass may be considered to have negligible motion above ~2 Hz. A capacitive displacement sensor mounted to the floor could then be used to measure motion with respect to this mass, which can be considered at rest, effectively giving directly the floor motion for ~2 Hz and above.

As a first approximation to such a pendulum, we have modified a Sercel L4C seismometer to attach an aluminum flag to its pendulum mass. The modified seismometer is mounted on aluminum block ridigly attached to a steel table (see Fig. 11). A capacitive probe is then mounted to the steel table using the flag as a reference surface. Assuming that the flag is at rest, the capacitive probe then directly measures the motion of the steel table. The resonant frequency of the pendulum in L4C is 1 Hz and there is a significant mechanical as well as electrodynamic damping in the system, so the approximation is not strictly valid below several Hz, but this experiment was carried out as a proof of principle. Collette et al. (2014) have also built a displacement sensor by fitting a geophone with a capacitive sensor and have obtained good results. The difference is that we plan on using the pendulum mass as an inertial reference, whereas Collette et al. have used the actual dynamic characteristics of the mass to obtain precise measurements of absolute motion. Although approximate, our approach allows for a displacement signal in real time, without requiring use of Fourier analysis and response compensation. The idea here is not to make precise measurements of the motion, but to provide a real time signal adequate for compensation within tolerable limits. In our setup we have also placed an unmodified Sercel L4C adjacent to the modified L4C to serve as a reference measurement of the motion of the steel table, against which the signal from the capacitive sensor can be compared.



(a) (b)

Fig. 11 (a) A modified Sercel L4C seismometer (left) with a flag attached to its pendulum to serve as reference surface, along with an unmodified L4C (right). (b) A capacitive displacement sensor mounted on the table to be measured. The micrometer is used to adjust the position of the displacement sensor to bring the gap within the measurement range of the sensor.

The power spectra measured by the reference L4C and the capacitive sensor are shown in Fig. 12. It is seen that there is a very good agreement between the two spectra for frequencies of ~1.5 Hz and above. The difference spectrum shown in Fig. 12 takes into account also the phase information, and shows that the capacitive sensor in this case can be used for compensating ground motion at frequencies above a

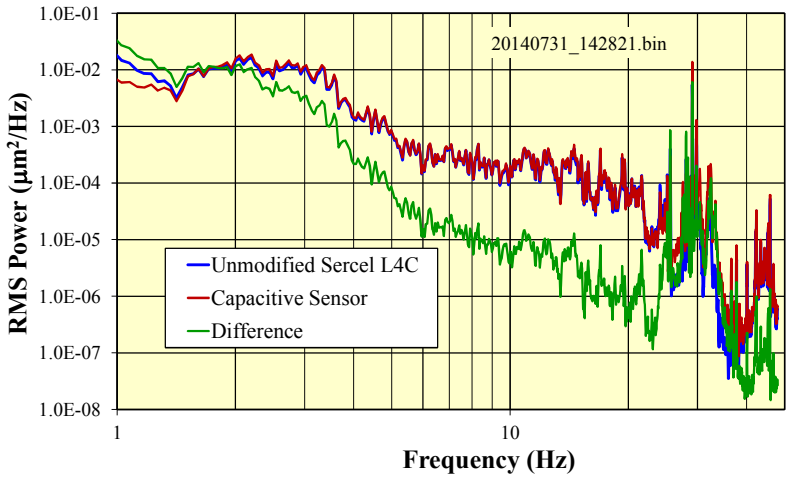


Fig. 12 Power spectra measured by the unmodified Sercel L4C geophone and the capacitive sensor.

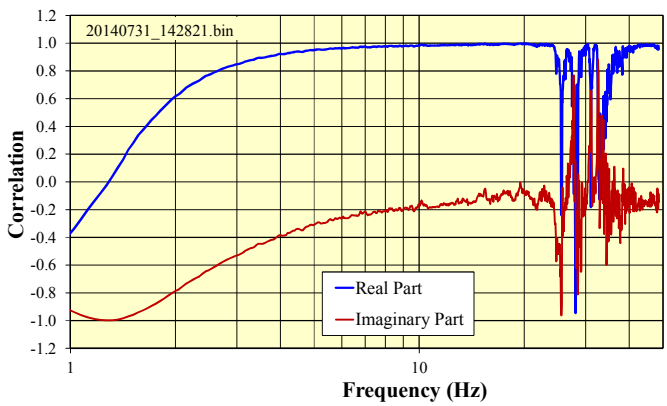


Fig. 13 Correlation between the unmodified Sercel L4C geophone and the capacitive sensor.

few Hz. Fig. 13 shows the correlation between the two signals. The drop in real part at frequencies below ~8 Hz is a consequence of significant mechanical and electrodynamic damping in the system, leading to a phase shift. Thus at 2 Hz, for example, only a partial compensation is possible with this system, although it may be enough to bring down the resulting error to within tolerable limits. A weakly damped system, on the other hand, would amplify motion at its resonant frequency. These drawbacks of this approach will need to be addressed for a system that could be useful in practice.

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