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Assessment of Spatially Varying Ground Motion Coherence based on Micro-seismic Field Measurements and Numerical Analyses

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ABSTRACT

The influence of the subsurface soil structure and in particular its fundamental frequency on the evolution of the spatial coherence of ground motion, a measure of importance in high sensitivity accelerator facilities such as synchrotrons and linear colliders, is studied based on extensive field measurements of micro-seismic activity and numerical analysis of wave propagation in layered media.

Specifically, the evolution of the micro-seismic activity at the surface of the NSLS II site consisting of ~600m deep formation of silt, clay, sand and sandy gravels over bedrock with a water table interface near the surface has been assessed over an extensive period of daily and seasonal variations. Along with the micro-seismic amplitudes and spectra, coherence measurements were made both at the said site and other sites around the world where stability sensitive synchrotrons were being constructed.

Observed characteristic behavior of the spatial coherence was explored using two- and three-dimensional, numerical models representing the site were field measurements were conducted. The field data indicated loss of coherence even at small separation distances attributed to the resonant frequency of the deposit. This elaborate study was conducted in an effort to understand the impact of the soil layer (s) as well as the spatial variation of soil properties on coherence and help explain the observed behavior. Results of the field study on micro-seismic background which includes natural and cultural noise (ocean wave action and man-made sources) and of the analytical/numerical effort aiming to predict the coherence spatial evolution will be presented.

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1. Introduction

Next generation synchrotrons and liner colliders require extreme stability of the accelerator lattice to minimize beam jitter and emittance growth. Stability goals for these accelerators of a few nanometers for synchrotrons [1] and sub-nanometer for next generation linear colliders require a full understanding of the ground vibration, its dominant contributing sources and their frequency range and most importantly the spatial variation of ground motion over the footprint of the accelerator measured in terms of coherence.

The influence of the subsurface soil structure and in particular its resonant frequency on the evolution of the spatial coherence of ground motion has been studied extensively for a synchrotron accelerator based on extensive field measurements of micro-seismic activity and novel numerical analysis of wave propagation in layered media. Specifically, the evolution of the micro-seismic activity at the ground surface of the site of the National Synchrotron Light Source II (NSLS II) consisting of ~600m deep formation of silt, clay, sand and sandy gravels over bedrock with a water table interface near the surface has been assessed over an extensive period of daily and seasonal variations.

Observed loss of spatial coherence even at short distances, a feature attributed to the resonant frequency of the soil layer, was explored using two- and three-dimensional, numerical models representing the site were field measurements were conducted. This comprehensive study was conducted in an effort to understand the impact of the soil layer (s) as well as the spatial variation of soil properties on coherence and help explain the observed behavior. Results of the field study on micro-seismic background which includes natural and cultural noise (ocean wave action and man-made sources) and of the analytical/numerical effort aiming to predict the coherence spatial evolution will be presented.

Takeda et al [7] studied power spectral densities and coherence functions for ground motions are studied for the next generation electron-positron linear collider to assess the impact of incoherent ground motion on the spatially varying movement of the lattice elements leading to beam jitter, destruction of the straight trajectory and emittance growth of the two colliding electron beams. Observed in [7] is that the spectrum of the ground motion can characteristically be divided into two frequency ranges, the high frequency range (>1 Hz) dominated by cultural (man-made) noises and low frequency range (< 1 Hz) linked to natural ground motion which in turn has strong dependence on the given site.

C. Collette et al [8] analyzed a set of micro-seismic measurements at the LHC tunnel at CERN in an effort to develop a numerical model that will adapt to the accelerator lattice for machine alignment and potentially the mechanical stabilization of the quadrupoles.

Subsurface characteristics based on H/V spectra of ambient vibrations have been deduced by models developed by Nakamura [4]. Hobiger et al. [5] employed a random decrement technique to determine Rayleigh wave Ellipticity using a single station recordings of ambient noise and over a wide frequency range on the premise that the Rayleigh wave ellipticity is linked to dynamic properties of the substructure such as shear wave velocity or fundamental frequency. While information around the resonant frequency of the substructure can be deduced from the H/V spectra (Nakamura, 1989) in [5] ellipticity is deduced by eliminating all wave types, except for Rayleigh waves,

The significance of stochasticity in the characteristics of the surface layers of a given site to the resulting spatial variation of seismic ground motions and the seismic ground strains has been investigated by Zerva & Harada [6]. Their study revealed that the spatial coherence of the motions on the ground surface is similar to that of the incident motion at the bedrock-layer interface except at the predominant frequency of the layer, where it decreases considerably. The present study focuses primarily on the effects of the layer predominant frequency on the loss of coherence.

Kanda [9] analyzed spatial coherency and amplitude characteristics of ground motions using a two-dimensional finite element model while considering a layered medium with irregular interfaces. The analytical results showed that the interface irregularities between layers spatially change the frequency characteristics of ground motions on the soil surface.

Reported in this paper are (a) the results of the multi-year NSLS II site microseismic activity characterization, including the layer structure, (b) the experience from other similar sites using measurements made by the team as well as results of other independent studies, (c) relevant theoretical studies that provide confirmation to the field observations made through the campaign and in particular the spatial coherence and finally (e) the results of a novel numerical model developed to address wave propagation at the NSLS II site and the ability of the model to predict coherence loss.

2. Primary Study Site Description

Detailed descriptions of the geologic units comprising Long Island are provided in Williams (1976); Figure 3 shows that Paleozoic-age crystalline bedrock underlies Long Island at depths to several hundred meters. Consolidated sedimentary strata overlie the bedrock surface. The depth of the soil overburden at the site is approximately 1550 feet beneath the NSLS II site and consists of relatively dense gravels and sands interspersed with stiff clays and sandy clays. Based on the approximately 1 on 55 southeast slope of the bedrock, it is safe to assume that the local site consists of horizontal deposits overlaying the bedrock. Shear wave velocity measurements made [4] indicate a uniform to slightly increasing shear wave velocity with depth. Velocities varied from 860 feet per second (fps) to 1,180 fps. The average shear wave velocity from 34 tests was 975 fps [3]. Depths to water table from vary between 28 and37 feet below ground surface.

Figure 1: Geographical location of the site studied (left) and NSLS II synchrotron requiring extreme stability and spatial coherence (right)

An extensive monitoring of the NSLS II site spanning over several years had been undertaken. The microseismic activity at the site and its implications to the extreme stability required by the synchrotron begun prior to its construction and during the conceptual design of the project in an effort to assess the appropriateness of the particular site to host such a critical facility. The site microseismic activity monitoring continued through the construction and commission of the synchrotron now in full operation. A pair of GÜRALP CMG-3TDE seismometers interfaced with the SCREAM system, a set of Wilcoxon high sensitivity accelerometers interfaced with a data recording/FFT analyzer RION-S78 were used in the field study.

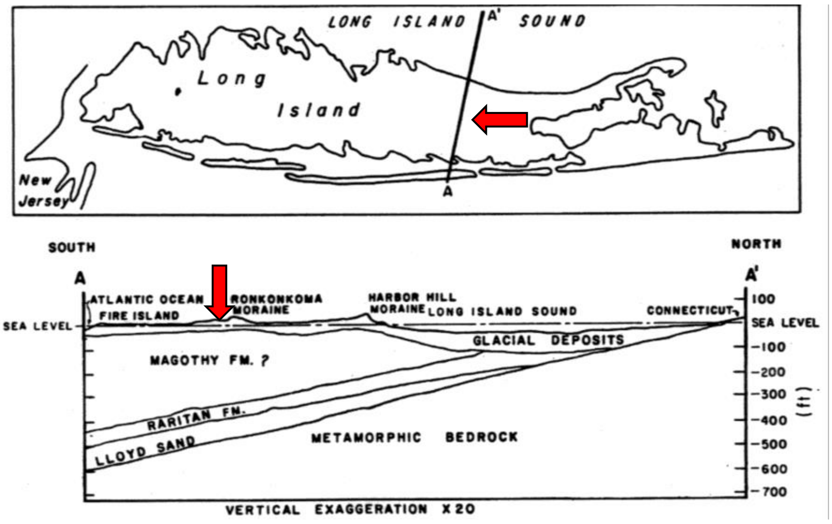

Figure 2: Transverse sections showing detailed stratigraphy beneath the NSLS II Synchrotron [after 2]

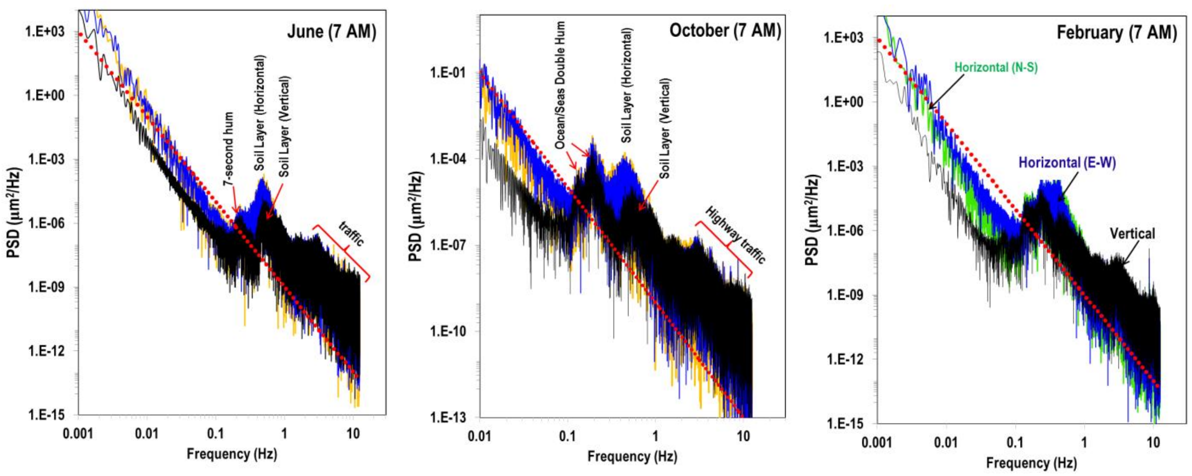

Figure 3: Power spectral densities of microseismic activity (natural and cultural noise) recorded at the NSLS II site

Power spectral densities of the microseismic (ambient) vibration as well as coherence measurements were performed during the multi-year campaign. The relations below define correlation and coherence. By defining the cross-spectral density as

$$xy(\omega) = \int_{-\infty}^{\infty} \boldsymbol{R}xy(\tau)\, e^{-i\omega t}\, d\tau$$

The normalized power spectral density is defined as

$$\boldsymbol{C}xy(\omega) = \frac{xy\ (\omega)}{\sqrt{\boldsymbol{\Phi}xx(\omega)\quad yy(\omega)}}$$

The real part of $\boldsymbol{C}xy(\omega)$ represents the correlation and the module the coherence.

Shown in Figure 3 are excerpt power spectral densities recorded at the NSLS II site delineating the effects of ocean wave activity, the response of the site soil layer (vertical and horizontal resonances) and the highway traffic. It should be noted that the multi-layered structure above the bedrock works as a wave guide with limited attenuation of ground motion.

Using Ellipticity to unravel NSLS II site substrate characteristics

It is important in this effort to identify the resonant frequency of the ~600m layer beneath the site and quantify its impact on the spatial variability of the motion at the surface (i.e. coherence) which in turn is paramount importance to the optimal performance of the synchrotron. We relied on the extensive data collected at the site to deduce the soil layer characteristics and in particular the relation between the horizontal and vertical components of the motion at any given monitoring station. Specifically, the spectral ration *H/V*, according to (Nakamura, [4]) calculates the ratio between the horizontal and the vertical spectrum of ambient vibrations recorded on a single three-component seismic sensor by:

$$H/V(f) = \sqrt{(|EW(f)|^2 + |NS(f)|^2)} /(\sqrt{2}|ZZ(f)|)$$

where $EW(f)$, $NS(f)$ and $ZZ(f)$ are the spectra of the east–west, north–south and vertical displacements of the sensor. In the above relation both Rayleigh and Love waves contribute to the H/V spectrum.

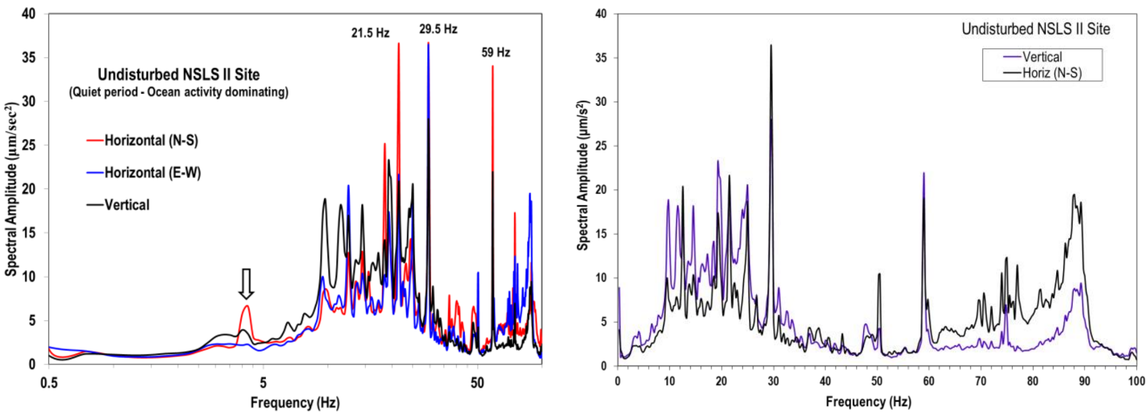

Figure 4: Average Fourier spectra of surface ground motion recorded on the undisturbed site. Quiet period (left) and noisy period (right)

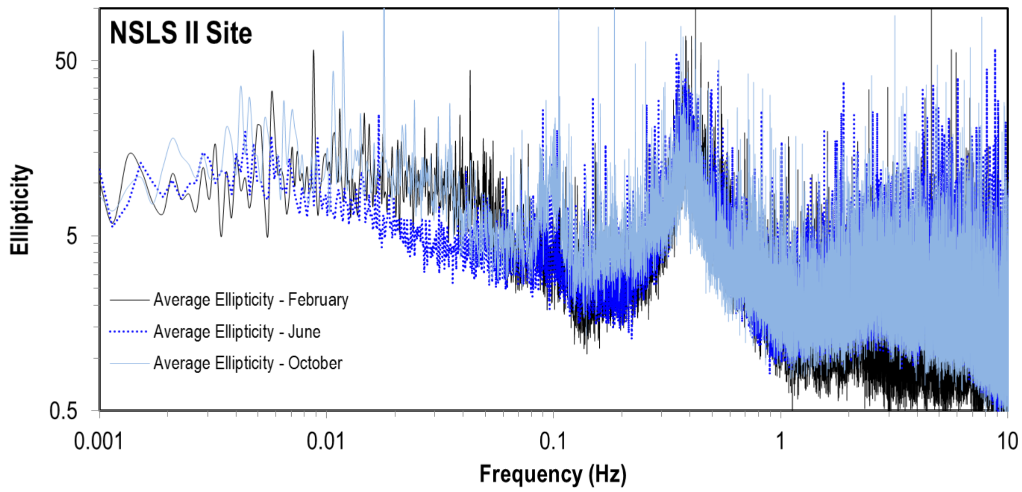

Figure 5: Ellipticity generated using averaging of 3600s record segments of recorded surface ground displacements using a single station recording system. The invariant location of the characteristic ellipticity peak over long periods reveals the resonant frequency of the substrate layer.

Figure 4 depicts Fourier spectra (average) recorded at the un-disturbed NSLS II site showing the effect of cultural noise. Figure 5 plots the ellipticity deduced from measurements made at single stations over long periods. The characteristic peak at ~0.4 Hz defines the resonant frequency of the soil deposit. Coherence and correlation functions governing the undisturbed NSLS II site are depicted in Figures 6-10. Important to note is the characteristic loss of coherence near the resonant frequency of the soil layer even at short distances. This observation is explored further both in terms of experience from other studies (including theoretical studies [6]) as well as simulations of wave propagation and attenuation at the NSLS II site.

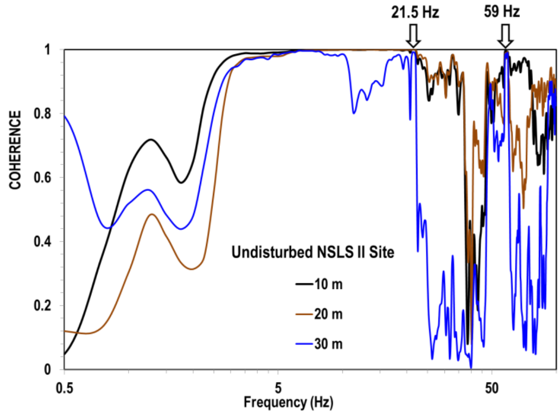

Figure 6: Recorded coherence on the undisturbed site and identification of site-wide ambient frequencies.

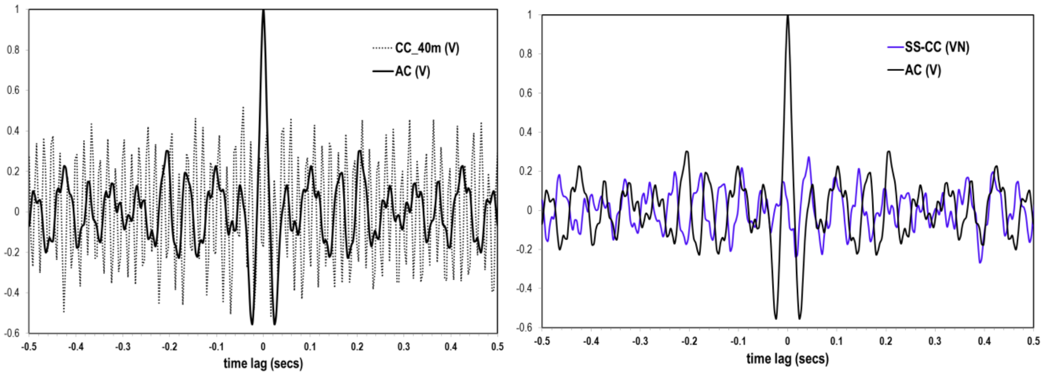

Figure 7: Auto and cross-correlation of recordings on the undisturbed site (station separation 40m)

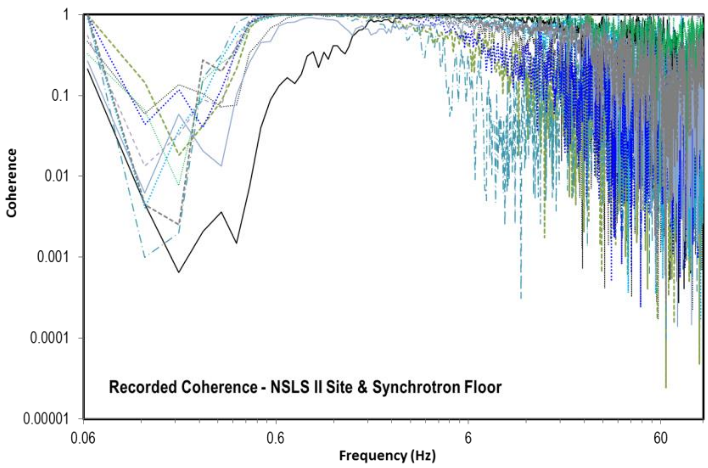

Figure 8: Coherence measurements made in the undisturbed site (quiet period and prior to the construction of the NSLS II synchrotron.

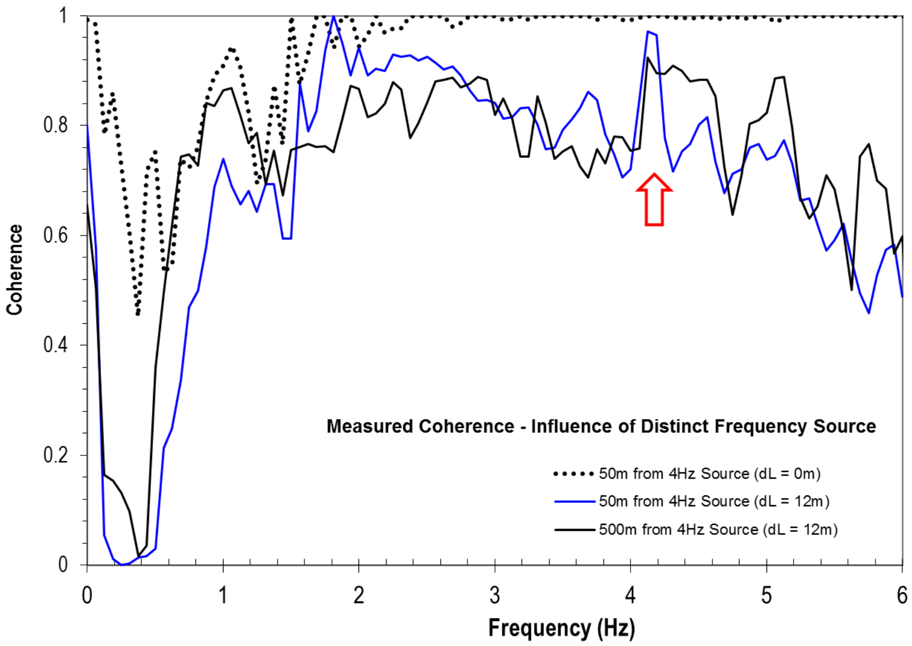

Figure 9: Coherence measurements made as a function of distance from a distinct large source operating on the proximity of NSLS II with 4.25 Hz dominant frequency

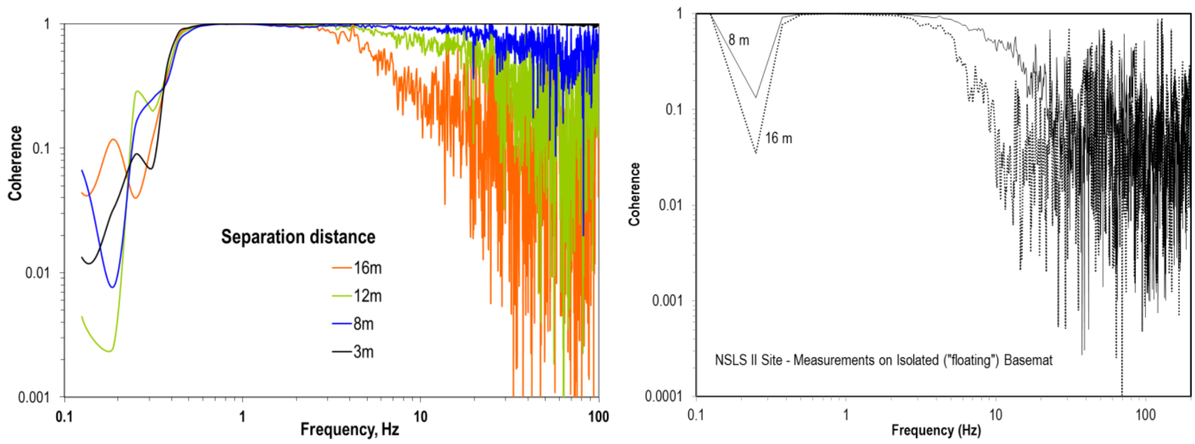

Figure 10: Filtering effects on recorded coherence by floating slabs on the NSLS II site. On the experimental floor of the NSLS II ring (left) and at the high-sensitivity Nanoprobe beamline (right)

Coherence/Substrate Resonant Frequency Relation at SIRIUS Synchrotron site, Brazil

Extensive site measurements at the undisturbed site of the LNLS Laboratory in Campinas, Brazil considered for the currently under construction SIRIUS synchrotron (Figure 11a) were performed in 2009. Free-field measurements of coherence are depicted in Figure 11b indicating a loss of coherence above 1 Hz (~2.7 Hz) in contrast to similar coherence loss which in turned occurred below 1 Hz and at the resonant frequency of the soil layer at NSLS II site. Ellipticity deduced from single station ground motion recordings at the undisturbed SIRIUS site (Simos, 2009) were deduced based on H/V technique and are shown in Figure 12a. The ellipticity trace reveals the resonant frequency of the SIRIUS site at ~2.7 Hz (along with the existence of a second peak at ~90 Hz attributed to a surface layer effect at the measurement location). Figure 12b depicts the correlation between the measured coherence and ellipticity at the undisturbed SIRIUS site. Measurements conducted at the prepared site for the SIRIUS synchrotron construction via a geophysical study in 2015 by an independent group [ ] confirmed the H/V relation as seen in Figure 13. It should be pointed out that measurements made in 2009 on the undisturbed site were at different locations than those of the 2015 campaign o the prepared site.

The filtering effect of a “floating” slab supporting a high sensitivity transmission electron microscope (TEM) at the LNLS facility is shown in Figure 14 clearly showing minimal impact on coherence at short distances due to the small geometrical size of the slab. As in the case of the NSLS II site the recorded data summarized in Figures 11-14 confirm the effect of soil column resonance on the coherence recorded at the surface.

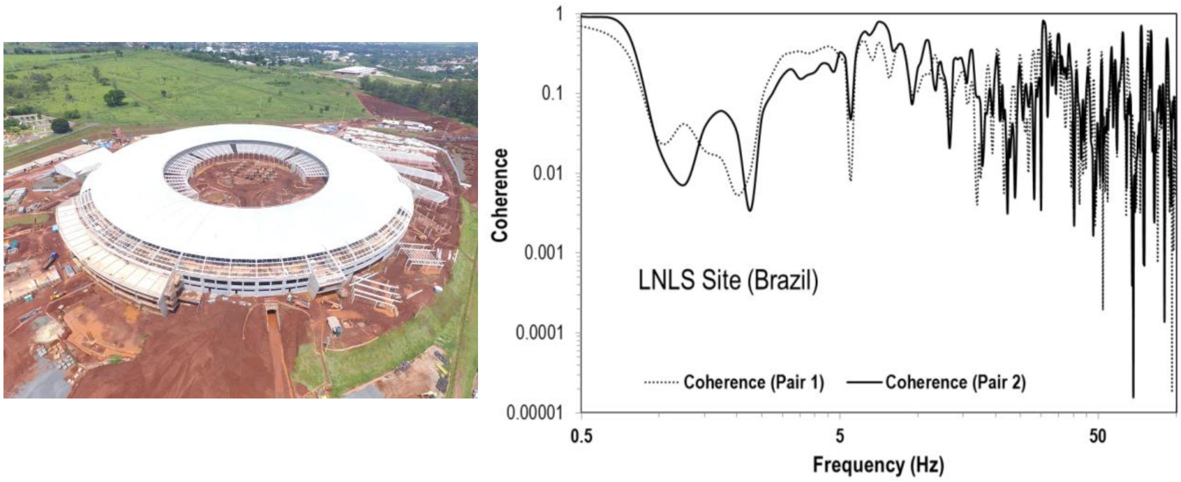

Figure 11: Overview of the SIRIUS Synchrotron (left) and coherence measurements (Simos et al., 2009) on the undisturbed site

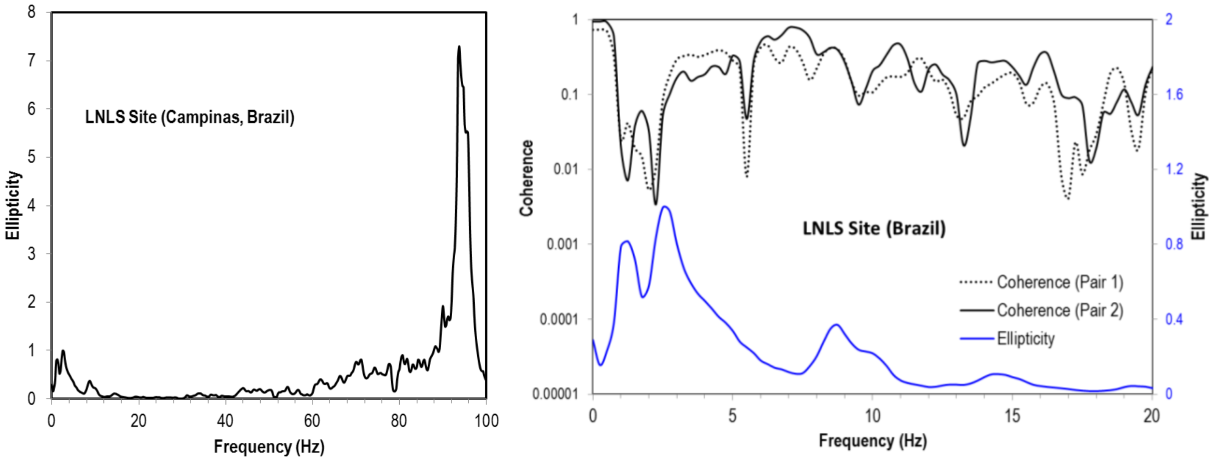

Figure 12: Measured ellipticity at left (Simos, 2009) and correlation with recorded coherence at Sirius Synchrotron

Figure 15 depicts coherence spectra measured at the PETRA ring and HERA tunnel at DESY facility (Germany). The loss of coherence at the HERA accelerator tunnel at relatively short distances (0m and most prominently at 40m) further confirms the effect the local site characteristics have on spatial coherence.

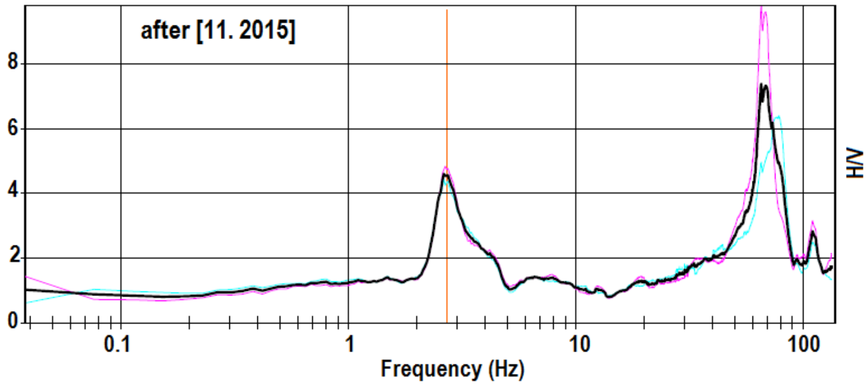

Figure 13: H/V measurements (SIRIUS Geophysical Study, 2015 [11]) of the prepared site in agreement with the recorded ellipticity of Figure 12 (Simos, 2009)

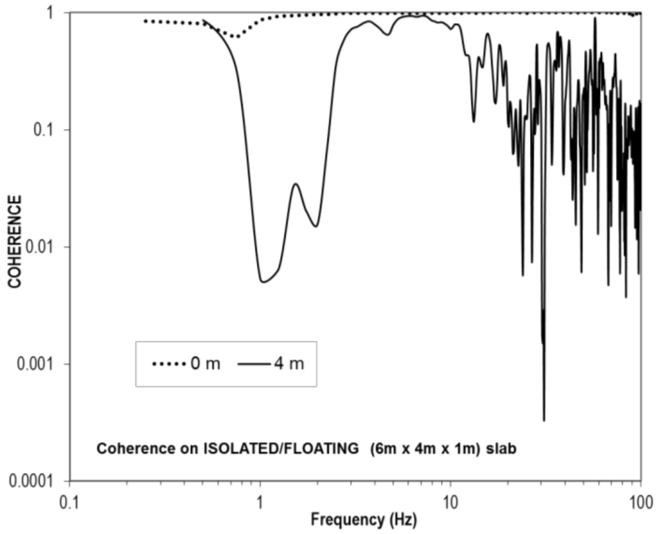

Figure 14: Filtering effects on coherence by a fully isolated (floating) slab on the LNLS site, Brazil (Simos, 2009)

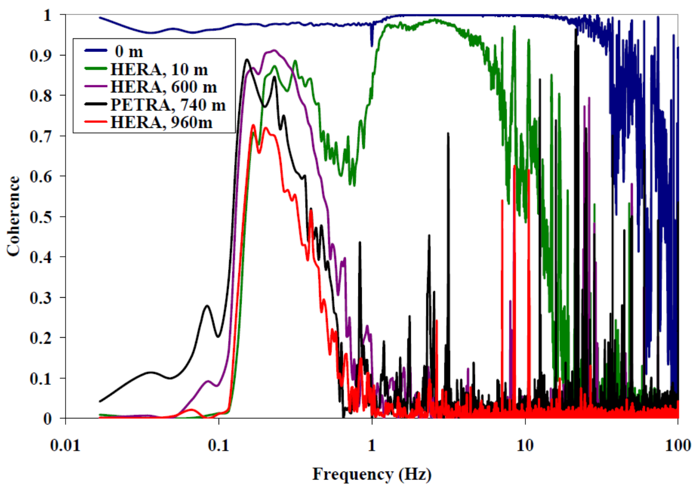

Figure 15: Coherence spectra measured at the PETRA ring and HERA tunnel at DESY [11]

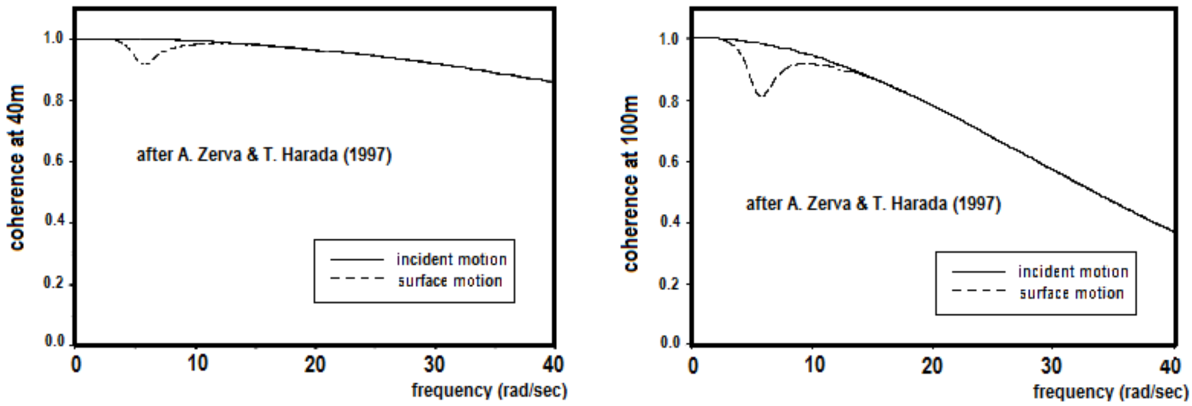

Figure 16: Variation of the total spatial coherence (incident motion and layer stochasticity) with frequency at separation distances of 40 and 100m (after Zerva & Harada [6])

The overall coherence (incident motion coherence and layer stochasticity) in the spatial variation of the surface motions discussed in [6] is presented in Fig. 16 for two separating distances (40m and 100m). As noted in [6] the overall shape of the total coherence is controlled by that of the incident motion (solid line); the layer stochasticity results in a decrease in the correlation *close to the mean value of the natural frequency of the layer*. The latter statement is of paramount importance to the present study which aims to evaluate the influence of the site on spatial coherence both through a multi-year field campaign and state-of-the-art numerical analyses.

4. Numerical Studies at NSLS II Site

Using the capabilities of the LS-DYNA computer code [14] a three-dimensional finite element model discretized into several million finite elements capable of propagating waves through its mesh with frequencies up to 100 Hz was formulated and used in (a) an eigen analysis that confirmed the resonant frequencies of the site and (b) a wave propagation analysis that accounted for both distinct and random sources. The subsurface for this reported analysis phase accounted for the water table interface at 30 feet depth beneath the ground surface. Stochastic treatment of the soil in the distinct layers from the surface to the bedrock is not included/reported in this paper (on-going). The spatial variability of the soil properties generated via the latest geotechnical study for the top 100 feet is accounted for in a stochastic model and its impact on the ground surface microseismic motion will be reported in the future. In addition to the 3-D model an effectively 2-D model with finer discretization than the 3-D counterpart was also generated and used to deduce the layer resonant frequencies.

In the 3-D model the presence of the nearby highway was modeled and accounted for by introducing pavement excitations based on actual measurements of random heavy traffic. Figure 17 depicts Fourier spectra of actual recordings made at the edge of the highway pavement. A large source (Chilled Water Facility) operating currently in the vicinity of the NSLS II accelerator with dominant forcing frequency at 4.25 Hz felt throughout the site also accounted for as deterministic noise source.

Given that the ultimate objective was to predict the response of the accelerator ring which has been designed to be a “floating” slab in the form of a disk on the ground surface (~300m diameter) and fully detached from the superstructure, the detailed FE model of the accelerator structure was included in the model. The RC concrete ring structure was assumed to be bonded to the engineered sand being supported on. The NSLS II ring structure along with the highway and the deterministic 4.25 Hz source are shown in the top view of the 3-D model in Figure 18.

The eigen analyses based on both the 3-D and 2-D models deduced a vertical resonant frequency of the soil layer between 0.39-0.44 Hz depending on the assumption of shear wave velocities in the distinct layers. This finding is in agreement with the resonant frequency of the site deduced based on extensive ellipticity measurements (Figure 5) thus providing a good benchmark for the models and the subsequent analyses.

Shown in Figure 18 is the top view of the 3D model that includes the NSLS II “floating” ring structure, the on-site deterministic large source with a 4.25 Hz dominant frequency and the proxime heavy traffic highway (~1 mile from the NSLS II ring). Figure 19 depicts snapshots of the propagation of the waves from the two sources (random and deterministic). Clearly shown in Fig. 19 is the interaction of the waves with the NSLS II ring and the filtering that is expected to take place (frequencies >1 Hz with 1 Hz representing the threshold of ring interaction based on its geometrical parameters).

Most relevant to this study numerical results are depicted in Figures 22-24 which present model generated coherence values at the NSLS II site and the NSLS II ring structure. The coherence in the numerical studies was computed using an assemble of time histories from the ground response assuming that the process is stationary and based on the relations reported earlier and the use of a specially designed .processing code

Specifically, Figure 22 shows predicted coherence in the free field which captures the basic characteristics of recorded coherence especially near the resonant frequency of the subsurface which is captured by the numerical model. Similar prediction is shown in Figure 23 where the numerically evaluated coherence is in the experimental floor of the NSLS II ring structure and subject to ground motion filtering by the structure. Comparison of the predicted coherence by the model in the vicinity of the large deterministic source is shown in Figure 24 where it is observed that the model captures the main coherence features.

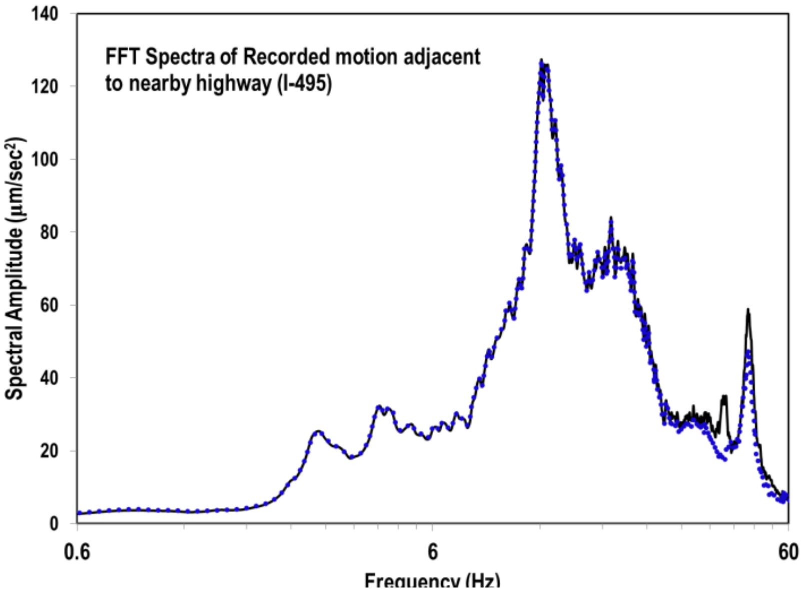

Figure 17: Fourier spectra of recorded highway pavement motion used as input to emulate random excitation

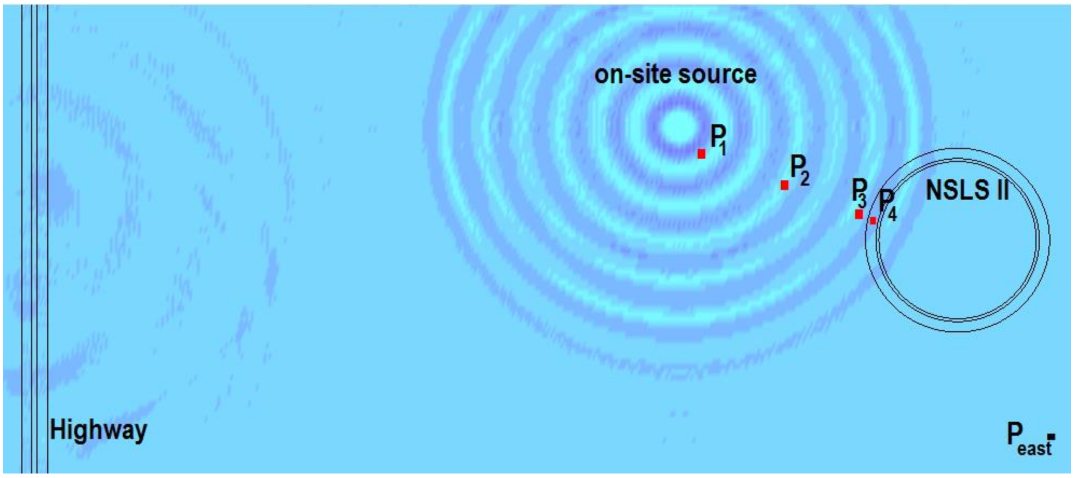

Figure 18: Top view of the 3-D FE model used in the NSLS II ground vibration study including the NSLS II ring structure, the nearby (~1 mile) heavy traffic highway and the 4.25 Hz on-site source

Figure 19: Snapshots of wave propagation and their interaction with the NSLS II ring structure

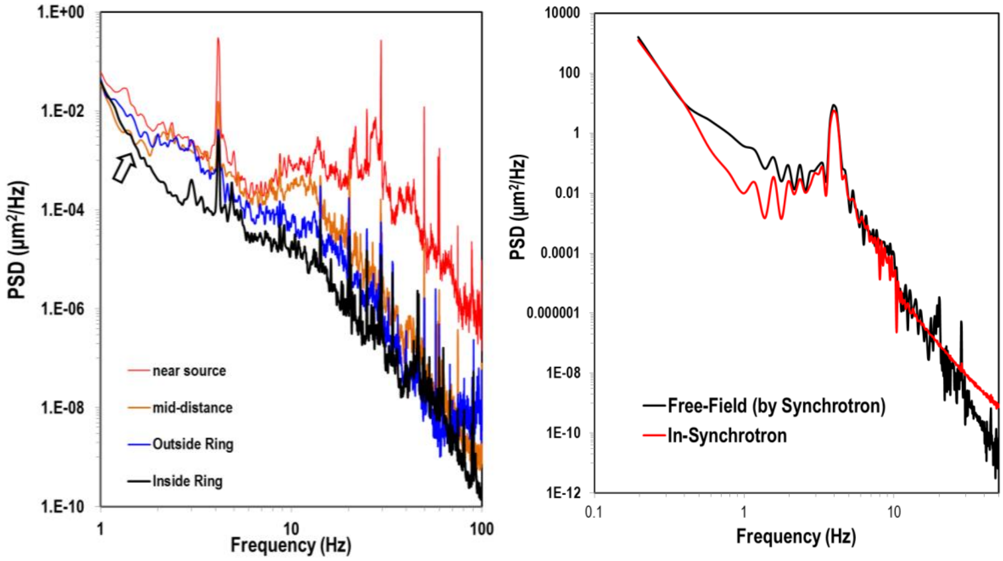

Figure 20: Filtering of ground motion by the NSLS II ring structure. Measurements (left) and model prediction (right)

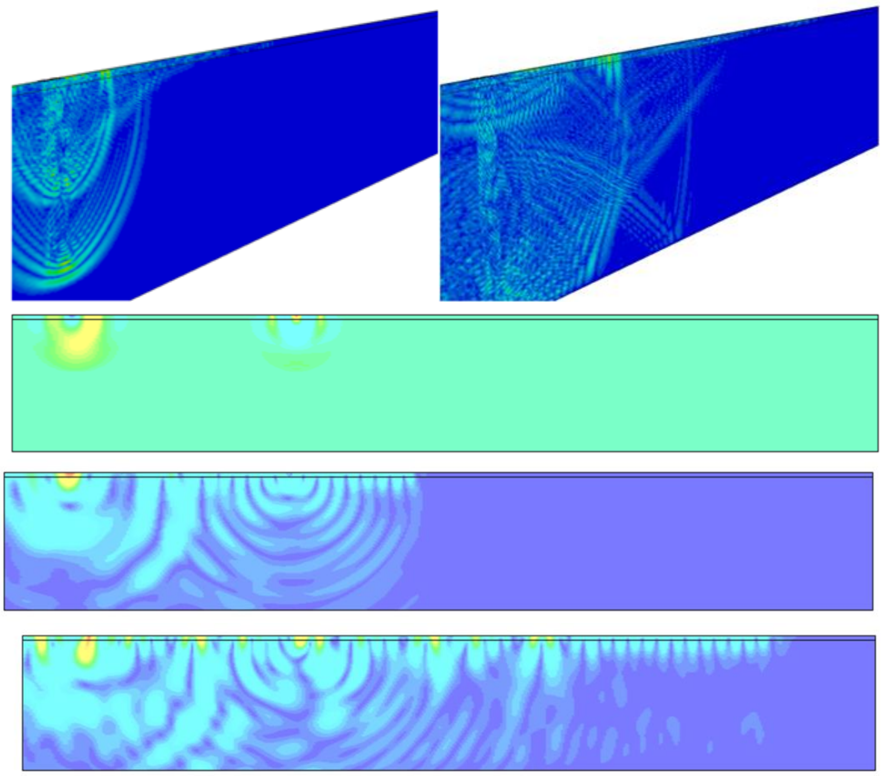

Figure 21: NSLS II site cross section and wave propagation and reflection from the bedrock.

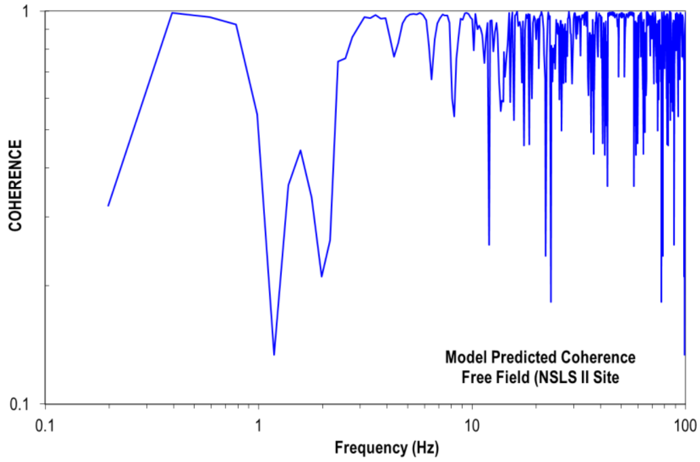

Figure 22: Predicted coherence by the 3D model generated for the NSLS II site under the action of random (highway) and deterministic sources (coherence in free field)

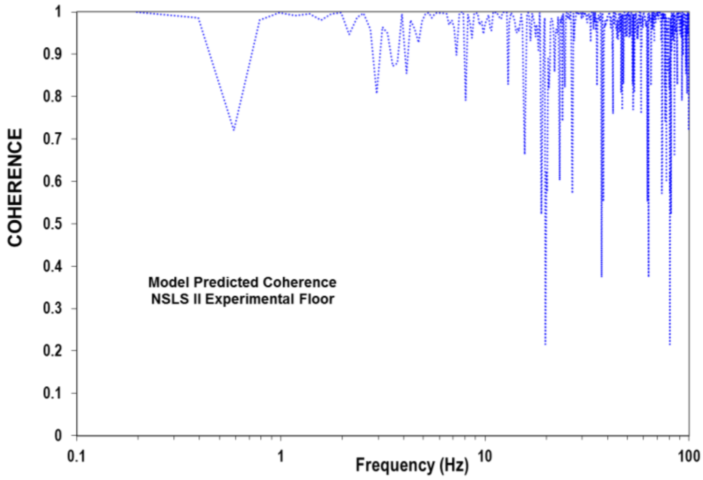

Figure 23: Predicted coherence by the 3D model generated for the NSLS II site under the action of random (highway) and deterministic sources (NSLS II experimental floor)

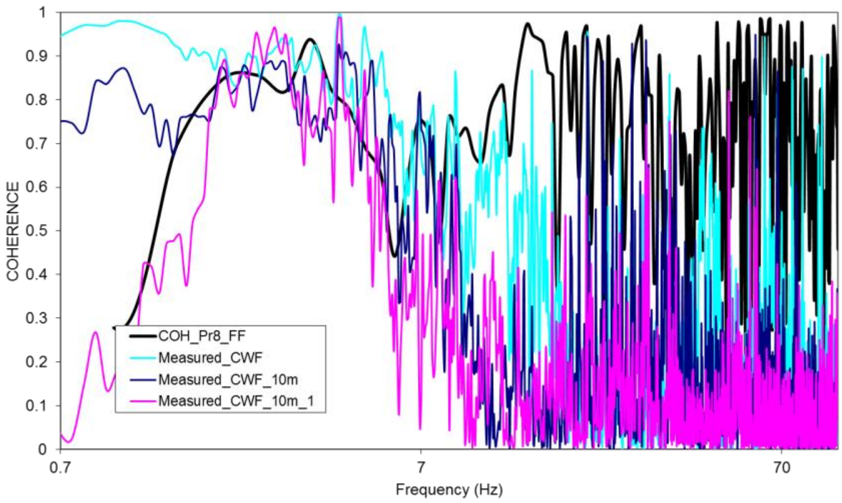

Figure 24: Comparison of predicted and measured coherence in the NSLS II site free field near the large deterministic source

SUMMARY

In an effort to design the next generation NSLS II synchrotron so that the stringent stability criteria required by such sensitive facility can be met, a multi-year microseismic activity campaign had been undertaken. The field study was complemented by a novel numerical simulation of wave propagation and attenuation. This study focusses primarily on the coherence of ground motion exhibited by the NSLS II site which represents a key parameter in the performance of the synchrotron operation where the electron beam jitter and subsequently the emittance growth must remain extremely low. Incoherent ground motion at the lattice supports in the ring will inevitably cause growth of the beam emittance.

The results of the multi-faceted, multi-year campaign revealed loss of coherence in the vicinity of the resonant frequency of the soil layer where the NSLS II synchrotron is supported. The findings, which were also confirmed with measurements at other similar synchrotron facilities around the world, are in full agreement with coherence behavior predicted by theoretical studies.

A large scale numerical model generated to study wave propagation and attenuation at the NSLS II site as well as the response of the synchrotron ring structure also revealed the characteristic behavior of coherence loss near the resonant layer frequency.

ACKNOWLEDGMENTS

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