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Results of Phase 1 Newtonian Noise Measurements at the LIGO Sites, February-March 2011

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1 Phase 1 Measurements

In February and March 2011, Jan Harms, Jenne Driggers, Robert Schofield and Anamaria Effler performed a series of measurements at both the Hanford and Livingston LIGO sites with the goal to produce a more accurate prediction of Newtonian noise (NN) from various potential sources (JH, RS at LHO, and JH, JD, AE at LLO).

In T1100004, we outlined a research program for Newtonian-noise experiments at the sites. The program was divided into three phases. Experiments of the first phase are finished. The data, plots and a few details of the experiments can also be found at:

https://awiki.ligo-wa.caltech.edu/aLIGO/Newtonian%20Noise

Newtonian noise has already been calculated for a few sources (seismic, atmospheric, chambers, people) and published in papers, but estimates do not exist for many other sources like fans, building vibrations and tilts, and water pipes. The goal of the phase-1 experiments was to identify all sources of NN and complete previous analyses.

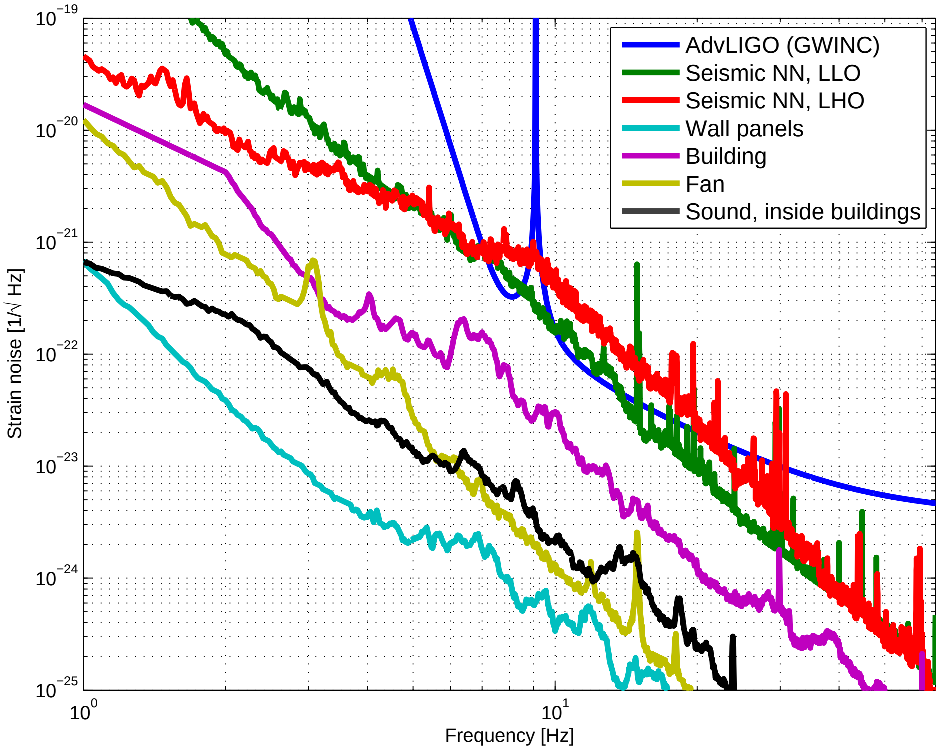

Figure 1: Predicted strain noise from several candidate Newtonian noise sources. The aLIGO strain curve is a reference sensitivity produced by GWINC. Phase-1 experiments identified the seismic NN and NN from motion of the buildings as dominant contributions. Noise from motion of the chambers was simulated previously and results reported in T070192.

Figure 1 shows our estimate of the strain noise due to several candidate Newtonian noise sources. We note that seismic NN is likely to be the dominant source that we will see in aLIGO, with the tilt of the end station buildings the next most important source. We expect that other sources such as vibrations of the wall panels and the air handler fans will be less important. In addition to the sources considered for this plot, estimates of NN from the chambers should be included as presented in T070192.

The following subsections will describe the measurements that we have done to obtain more information about each of these sources, as well as how we arrive at the estimate of the NN contribution for each. Section 2 describes our plans for Phase 2 measurements, based on the results of the Phase 1 results discussed here.

1.1 Seismic Noise

We currently anticipate that surface seismic noise will be the dominant NN source in aLIGO. We measured seismic noise both inside and outside of buildings at both LHO and LLO using Streckeisen STS-2 and Güralp CMG-40T seismometers.

To estimate the strain noise due to the seismic motion, we use the simple model of evanescent waves propagating on the surface of a homogeneous medium. The NN acceleration of the test mass in horizontal direction can be written as

$$a_{\mathrm{NN}}(\Omega) = (Numerical\ Factor) 2\pi\mathrm{i}G\rho_0\xi(\Omega)\exp(-hk) \tag{1}$$

where ξ is the vertical surface displacement at the test mass, k denotes the (horizontal) wavenumber of the field at frequency Ω, G is Newton's constant, ρ_0 is the average or unperturbed density of the ground, and h is the height of the test mass above ground. The value of the numerical factor depends on the mode content of the seismic field. Density changes due to vertical displacement of the surface produced by Rayleigh waves is partially cancelled by density changes inside the ground due to compressional components of the field. In this case, the numerical factor is about 0.8 depending on the Poisson's ratio of the ground.

To convert to strain noise, we divide by $\Omega^2 = (2\pi f)^2$ and multiply by $2/L$ where $L = 4\,\mathrm{km}$ is the length of the arms. The latter factor is based on the assumption that all four test masses feel incoherent Newtonian noise with the same spectral density. The numerical estimate of the seismic NN uses $\rho_0 = 2500\,\mathrm{kg/m^3}$ and the 90th percentile of the two histograms shown in figure 2.

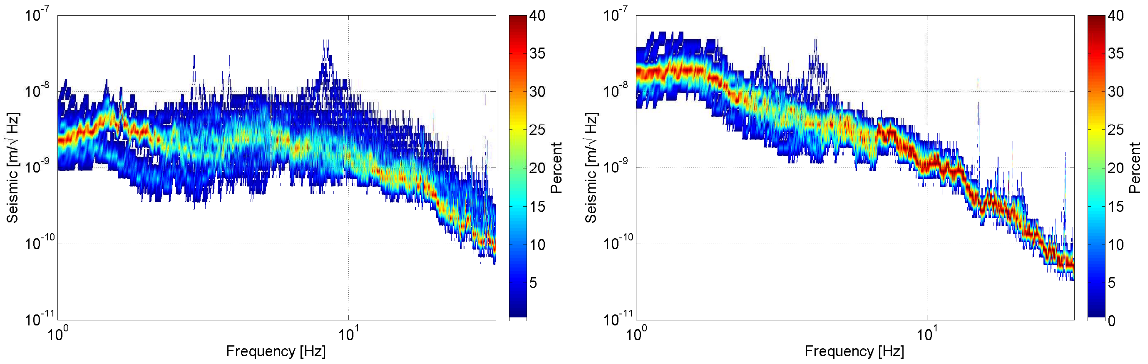

Figure 2: Histogram of spectra of vertical displacement measured inside the LVEAs at Hanford (left plot) and Livingston (right plot).

1.2 Vibration of Panels on Outside Walls of Buildings

The LIGO buildings are constructed such that they have double walls, the inner of which is a structural wall, while the outer wall is made of thin sheet metal, with an approximately 1 meter gap between the two walls. The outer wall panels are attached in small sections — about 2 m wide — to a metal beam framework. To calculate the NN, we assume that the vibrations of wall panels can be described as an incoherent sum over contributions from individual panel sections with coherence length equal to 2 m along both directions of the wall, each panel section vibrating in normal direction to the wall like a drumhead.

We calculate the contribution for a single wall panel that is very near the beam axis, and assume that if we include all of the sections on the front and back walls they will add to give some amount of cancellation, in addition to not vibrating in the same direction as the beam axis, so they will add to about the order of one single section. When considering both the front and back walls, we need to multiply by $\sqrt{2}$ if they add incoherently.

We choose to keep the model of the panel NN simple since, as shown in Figure 1, the wall panel vibrations are not close to being a limiting source. We are confident that the estimated strain noise shown in Figure 1 is an overestimate of the wall vibration NN, since it is calculated assuming that the entire wall panel vibrates with the maximum amplitude, however the edges of each panel are bolted to the wall structure, which has displacement that is weaker by an order of magnitude than the maximum displacement of the center of a panel.

Since we have supposedly an overestimate of the noise, and this estimate is so far from being a limiting source, we will likely not look into more detailed measurements and simulations of wall panel vibrations in Phase 2.

To calculate the strain noise, we start as usual with the dipole approximation of NN test-mass acceleration

$$\vec{a}_{NN} = G \int dV \rho \frac{1}{r^3} \Big(\vec{\xi} - 3 \big(\vec{e}_r \cdot \vec{\xi} \big) \vec{e}_r \Big) \tag{2}$$

We assume that, for the panels close to the beam axis, $\vec{e}_r \parallel \vec{\xi}$, so $\Big(\vec{e}_r \cdot \vec{\xi} \Big) \vec{e}_r \sim \vec{\xi}$, and $\Big(\vec{\xi} - 3 \big(\vec{e}_r \cdot \vec{\xi} \big) \vec{e}_r \Big) \sim -2\vec{\xi}$. Just as with the seismic NN contributions, we change from acceleration to displacement by dividing the NN amplitude by Ω^2. We then multiply by $\sqrt{2}/L$ to get strain assuming that the wall panels are much closer to the test masses at the end stations, so we only include noise from the end stations. We also approximate the integral over volume as giving us the mass of a single wall panel being uniformly displaced. So we have

$$h_{NN} = G(Mass\ of\ panel) \frac{4\xi}{D^3} \frac{1}{(2\pi f)^2} \frac{1}{L} \tag{3}$$

where D is the distance between the wall(s) and the test mass at the end stations along the direction of the arm, ξ is the measured wall displacement, and L is the length of the LIGO arms.

Assume an individual wall panel has an area of 4m^2, a thickness of 3 mm, and a density of 7000 $\mathrm{kg/m^3}$. These values are only estimates, but they are sufficiently accurate to allow us to rule out the NN from vibrating panels as being important. Figure 3 shows representative spectra of the wall panel vibrations, measured with a Wilcoxon 731-207 accelerometer.

1.3 Tilt of Buildings

From all possible types of motion of the end-station buildings, the tilt or rocking mode along the direction of the arms would produce the strongest NN since the walls move in phase and NN adds up from the two walls ”in front of” and ”behind” the test masses. So the conservative NN estimate

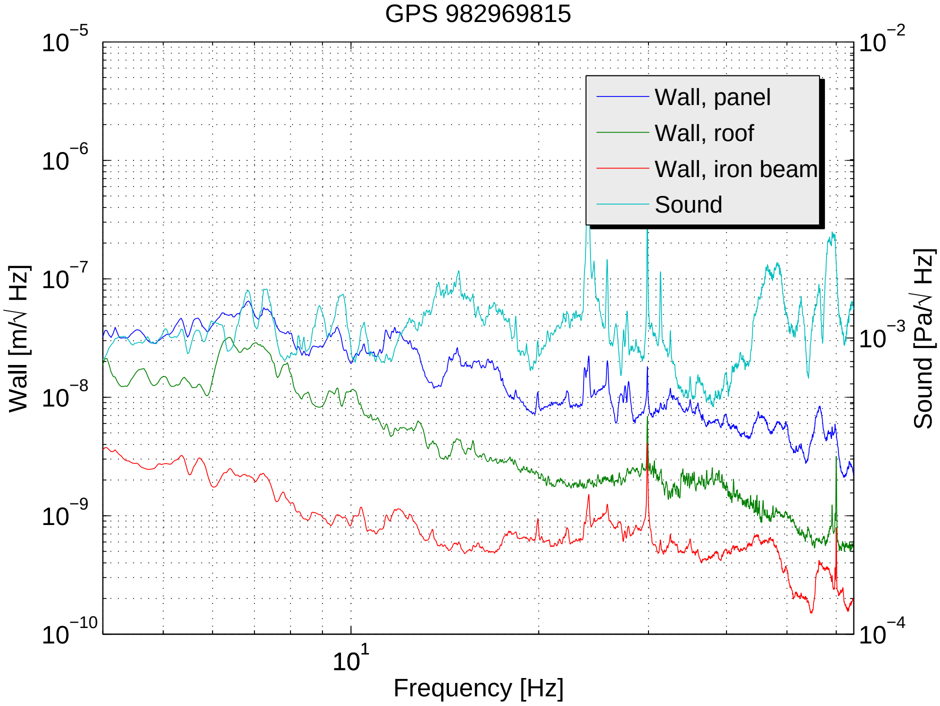

Figure 3: Various measurements of wall displacement at Livingston Y end station. ’Wall, panel’ displacement is an accelerometer directly mounted to the outer wall sheet metal, near the ground. ’Wall, roof’ is an accelerometer mounted to the outer wall (not panel), a few inches below the roof of the building. ’Wall, iron beam’ is an accelerometer mounted to the iron beam structure of the outer wall to which the sheet metal panels are mounted.

will take the total mass of the two walls and assume coherent displacement. NN contribution of the tilt of the buildings is calculated in much the same way as the wall panels.

The coherent motion yields a factor of 2 in NN from back and front wall. We also assume that the displacement of the walls increases linearly from 0 displacement at the ground to maximum displacement at the roof. This is based on the accelerometer spectra measured at the base and roof of the buildings, which show that displacement at the roof is much stronger. So to obtain an effective uniform displacement of the walls, we divide the spectra measured at the roof by 2. Finally, we make the additional assumption that this type of NN is significantly weaker at the corner station since the buildings are larger and walls in the direction of the arms are further away from the test masses.

Then strain due to tilt of the buildings is

$$h_{NN} = \sqrt{2}G(Mass\ of\ wall)\frac{2\xi}{D^3}\frac{1}{(2\pi f)^2}\frac{1}{L} \tag{4}$$

Figure 3 shows spectra of accelerometer data, where the stronger motion measured by the roof accelerometer indicates that tilt could indeed be the dominant mode of the building. We use 25 tons (2.5e4 kg) as the mass of a single wall of the end stations, and we use 5 meters as the distance between the walls and the end test masses. This estimated total mass of each wall is a potentially bad guess, and since NN from buildings is sufficiently close to aLIGO sensitivity, a more detailed phase-2 calculation should be carried out based on a better estimate of the total mass of the wall.

1.4 Air Pressure Fluctuations

Perhaps one of the previously most concerning NN candidates is air pressure fluctuations (since it is very difficult to subtract them if significant). According to our measurements, it appears that sound and air pressure fluctuations are not going to be a limiting NN source for aLIGO.

We start with the same NN acceleration as calculated for seismic compressional body waves, since the physics is the same:

$$a_{NN} = \frac{8\pi}{3}G\rho\xi \tag{5}$$

We then convert to strain amplitude using the same $1/\Omega^2$ and $2/L$ terms considering incoherent contributions from both ends of each arm. Since sound data are pressures and not displacements, we need to convert:

$$\delta\rho = -\rho_0\big(\vec{\nabla}\cdot\vec{\xi}\big) \tag{6}$$

$$\delta\rho = -\rho_0\big(\vec{k}\cdot\vec{\xi}\big) \tag{7}$$

$$\delta\rho = -\rho_0\big(k\xi\big) \tag{8}$$

So

$$\xi = \frac{\delta\rho}{\rho_0}\frac{1}{k} = \frac{\delta\rho}{\rho_0}\frac{c}{2\pi f} \tag{9}$$

where the density change is linked to the measured pressure change via

$$\frac{\delta\rho}{\rho_0} = \frac{1}{\gamma}\frac{\delta p}{p_0} \tag{10}$$

where $\gamma = 1.4$ is the adiabatic constant of air. We finally obtain the strain noise

$$h_{NN} = \frac{8\pi}{3} G\rho_0 \frac{\delta\rho}{\rho_0} \frac{c}{2\pi f} \frac{1}{(2\pi f)^2} \frac{2}{L} \tag{11}$$

We use 100 kPa as the average air pressure p_0, and air mass density $\rho_0 = 1.3\,\mathrm{kg/m^3}$. The speed of sound is $c = 330\,\mathrm{m/s}$.

Since the sound inside and outside of the buildings have comparable spectral densities, we will integrate NN all the way to the chambers in contrast to the calculation in Teviet Creighton's paper (CQG, 25 (2008) 125011) where NN is only integrated outside of the buildings leading to a larger NN suppression (although suppression is not significant at 10 Hz). Integrating NN from sound waves over large volumes is certainly simplistic since sound waves do not propagate freely due to building walls, trees, chambers, etc, but this is ok since it leads to an overestimation of NN.

Figure 4 shows representative spectra from inside the EX building at the Hanford site. Note that the LIGO microphones (in this plot represented by "Microphone, BSC9") are sufficiently sensitive down to $\sim$ 3Hz, however below 3-4Hz, the response of the LIGO microphones decreases.

The strain curve shown in Figure 1 is calculated using microphone data, and so cannot be trusted below 3-4Hz. At very low frequencies we will need to utilize infrasound sensors, however these are unnecessary for the ~10Hz regime where the NN contributions are likely to limit future LIGO detectors.

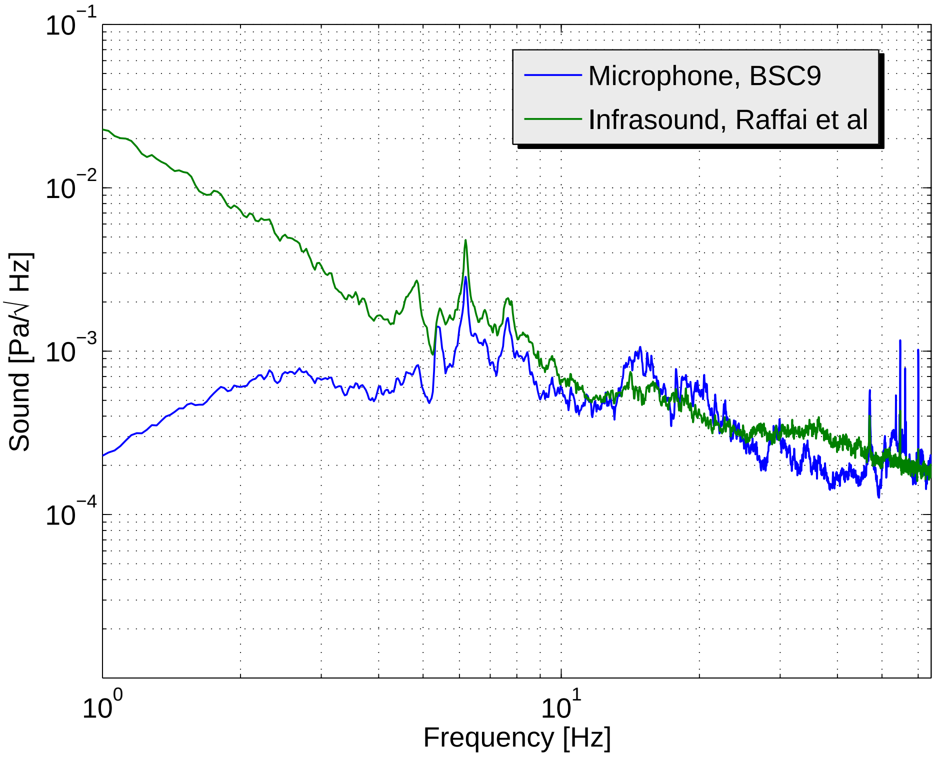

Figure 4: Sound spectra taken at the X end station at Hanford.

1.5 Air Handler Fans

The air handler fans are large fans used in the air conditioning of the LVEA and VEA areas at the sites. The fans are very large, and have strong vibrations, and could be a potential NN source. The main problem with the NN calculation for the fans is that in principle we need to consider macroscopic motion of fan parts instead of microscopic vibrations. The proper way to calculate this is to expand the NN into contributions from the different mass moments of the fan that oscillate at multiples of the rotation frequency Ω. The lowest oscillating orders are the dipole and quadrupole moments. Now, we already know that the dipole moment gives rise to NN that decreases with distance r between test mass and source as $1/r^3$. One can show that the NN from the quadrupole moment falls as $1/r^5$, and so on for the higher moments. Now, the simple model that we will use in the following is that ideally, all low order mass moments of the fan should vanish by design (assuming that there is a high symmetry of the rotating parts). Then the dominant contribution to NN would come from the residual oscillating mass dipole moment, which certainly exists since the fan is vibrating. In fact, we will assume that the vibrations measured at the fan are due to the residual mass dipole moment alone, which is a reasonable assumption since a changing dipole moment requires that a second body attached to the fan (the ground) compensates the associated oscillating momentum. So we will use the dipole formula (2) to calculate NN from fans using the vibration spectra. The link between residual dipole moment and vibrations certainly needs to be investigated in more detail, but it shall serve as starting point for a simplified model.

To calculate the fans' NN contribution we use

$$h_{NN} = G(Mass\ of\ Fan)\frac{\xi}{D^3}\frac{2}{L}\frac{1}{(2\pi f)^2} \tag{12}$$

The distance D is 12 m between the fans at the end stations and the end test masses. The distance between the corner station fans and the input test masses is about 27 m. We assume that the vibrating mass is 1000 kg.

We show in figure 5 spectra of an accelerometer epoxied near the base of one of the fans at the Livingston site. The fan's vibration is so strong that we were not able to directly measure it on the fan. So if our NN model is correct, then the NN from fans would be much stronger than indicated in figure 1. Further measurements need to be taken on these fans. Note that in the vibration spectral histogram there is a 'quiet time' and a 'loud time'. Periodically, the Livingston fans increase their vibration significantly. The Hanford site does not have this bimodal vibration, and more closely resembles the 'quiet' times.

2 Phase 2 Plans

Even though we tried to be conservative and to pick models such that NN is rather overestimated than underestimated, this attempt may well have failed in some cases. The conclusion from phase-1 measurements is that we need further simulations and experiments targeting the sources that produce the strongest NN.

Given phase-1 results, we identify the seismic NN, the NN from the building and the chamber NN as main candidates. As explained in the previous section, NN from fans could not be estimated well and may be stronger than shown in our results. Phase-2 experiments and simulations should target these four sources to further improve estimates. To get a more accurate value of the seismic NN, measurements at the sites with seismic arrays are required. Improving the estimate of chamber

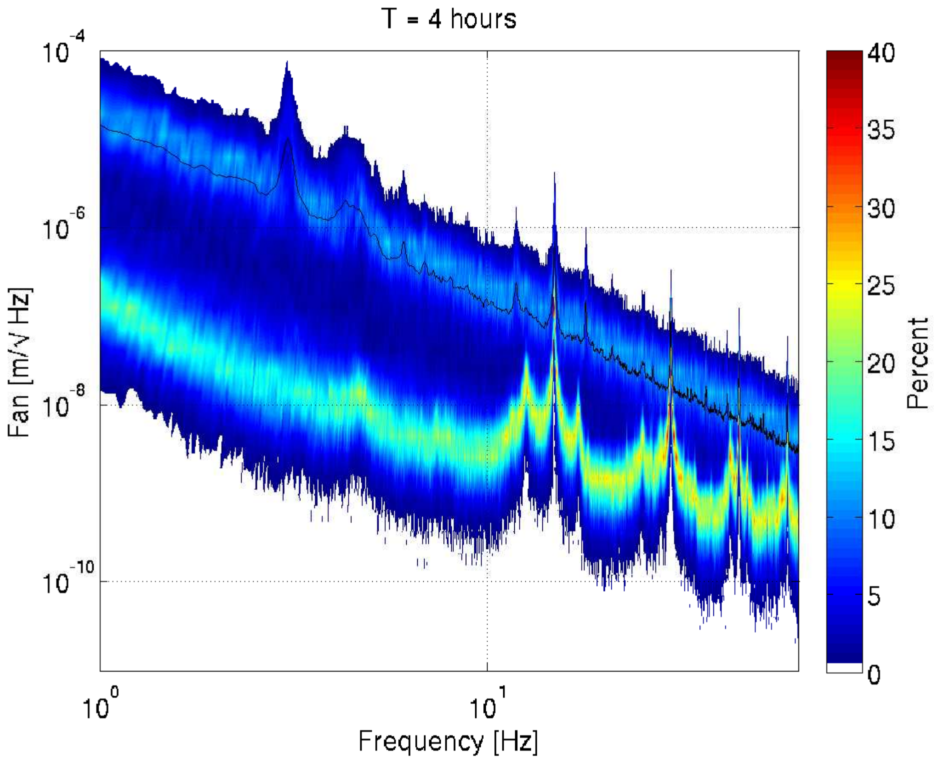

Figure 5: Spectral histogram showing displacement due to fan motion, measured near the base of the fan. Measuring the fan directly was not possible as the accelerometers were completely saturated.

NN, we need a more accurate simulation that also includes tilts. The building NN can be improved by using better estimates of the mass of the walls, and by studying in detail how walls move to check if the simple uniform tilt motion is a valid assumption. The following list of tasks summarizes what should be done for the second phase of NN investigations:

a) Improve numerical simulation of NN from chambers (including near chamber mechanical structures)

b) Calculate/simulate NN from suspension cage near test mass

c) Measure building motion at end stations. For this, four or more accelerometers should be attached near roof height at all building walls (monitoring displacement normal to the wall).

d) Seismic array measurement inside LVEA and end stations. One should check first if accelerometers have sufficient SNR. Monitoring vertical displacement is most important, so for a phase-2 measurement, it would be ok to work with single-axis instruments.

e) Measure vibrations on large fans in mechanical rooms with strong motion sensor.

f) Construct theoretical model of fan NN from rotating parts (in terms of mass multipoles).

The next question is when these experiments should be finished. It is very likely that NN will be seen in aLIGO and that we should use seismometer data for NN subtraction. Since only a small subtraction is required, it may well be that no extra seismometers need to be purchased, but we cannot be sure until we have learned more about the seismic field at the sites. The purpose of the phase-2 seismic array experiment is to acquire all the information to design the phase-3 array properly. The phase-3 experiment is more complicated, needs 3-axes seismometers and potentially more seismometers than available. So in case we need to borrow seismometers, say from PASSCAL, then any time lost with phase 2 would increase the risk that the phase-3 measurement will not be done in time. As geophysics experiments usually have priority, it can take some time before instrument requests to PASSCAL are fulfilled. Also, construction of seismic faults for phase-3 instruments (no indication so far that we need them), would require extra time. I suggest that phase-2 array measurements at corner and end stations should be finished next year.

All other phase-2 work is not very urgent and can be finished any time before aLIGO reaches good low-frequency sensitivity. If these analyzes show that NN has been underestimated significantly, then it will be easy to adapt the NN subtraction scheme for aLIGO to account for NN from other than (ground) seismic sources.