Seismic Measurements on the LMA Fizeau Interferometer Optical Bench

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June 27, 2010

Introduction

The CNRS Laboratoire des Materiaux Avancés (LMA) at Villeurbanne, Lyon (France) uses one Fizeau interferometer apparatus [a] for the high-precision measurement of mirror flatness maps.
This apparatus setup has been used for Virgo mirrors. The repeatability of the current setup is 0.4 nm RMS [b]. LMA is considering how to improve the apparatus to comply with the requirements for AdV mirrors (flatness better than 0.5 nm RMS on a diameter of 150 mm).
The Fizeau is placed on one optical bench which is currently located inside the clean room at the first floor of the LMA building. Figure 1 shows a picture of the apparatus. The bench sits on a seismic isolation system consisting of four pneumatic legs [c]. In order to further reduce the residual vibration of the Fizeau, LMA is evaluating the possibility to move the bench and Fizeau setup to the underneath clean room, which is at the building ground-zero level and it is presumably seismically quieter.
LMA asked us to perform a comparative measurement of seismic vibration of the present bench support floor (FLO1) and of the building ground-zero floor (FLOZERO). These measurements are described and discussed in Section 3. We have performed additional measurements to evaluate: (A) the performance of the pneumatic isolation stage described and discussed in Section 4; (B) the relative motion of the support structures of the Fizeau reference and test mirror, described and discussed in Section 5.
In Section 1 we describe the measuring equipment, while in Section 2 we describe the measurement locations and the experimental setup. The full measurement set was done on Tuesday May 11, 2010 between 9:00 and 15:00 UTC (10:00 to 16:00 LT).

Figure 1: The Fizeau apparatus setup in the LMA clean room.

1. Measuring equipment

The measuring tools consist of (see Table 1 for specs.): one **Guralp** tri-axial velocimeter, one **Episensor** tri-axial accelerometer, and two **PCB** single axis accelerometers.

Name	Model	SN	Flat response range	Sensitivity
Guralp	CGM-3TD	T35788/A1479	0.1 – 100Hz	1.6e-9 m/s/count
Episensor	FBA ES-T	3669	0.1 – 200Hz	80V/g
PCB 1	393B12	3409	1 – 1000Hz	10V/g
PCB 2	393B12	26991	1 – 1000Hz	10V/g

Table 1: Specifications of the seismic sensors used.

The Guralp sensor has a built-in digitizer and it is connected to a storage memory, it thus allows continuous and standalone readout. The Episensor, or in turn, the PCBs is read with one ONO-SOKKI CF3600 spectrum analyzer [d].
The sensors cross calibration was checked at EGO. The sensors have been placed side by side on the same floor which was excited with a sequence of short seismic pulses. Results are shown in Figures 2, 3 and 4. As for the Episensor and Guralp (Figure 2) the measurement was meaningful in the 1 to 20 Hz range, where the two sensors measured equal spectral noise within 10%. Outside of this range it was not possible to achieve a sufficient coherence of the sensors signal (a longer record would be necessary, which is not possible with the limited memory size of the ONO-SOKKI instrument). However, since both instruments have flat certified spectral response between 0.1 and 100 Hz, it is reasonable to assume that cross calibration result can be extended to the 0.1 to 100 Hz range.

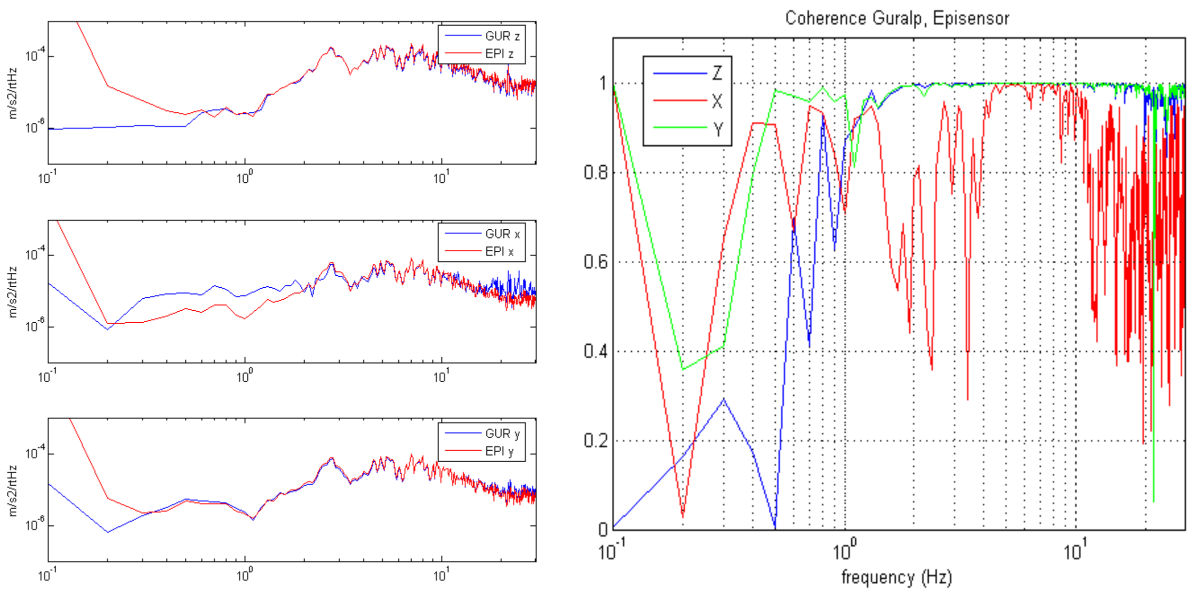

Figure 2: Cross calibration of the Guralp and Episensor seismometers. (left) amplitude spectra; (Right) coherence spectra.

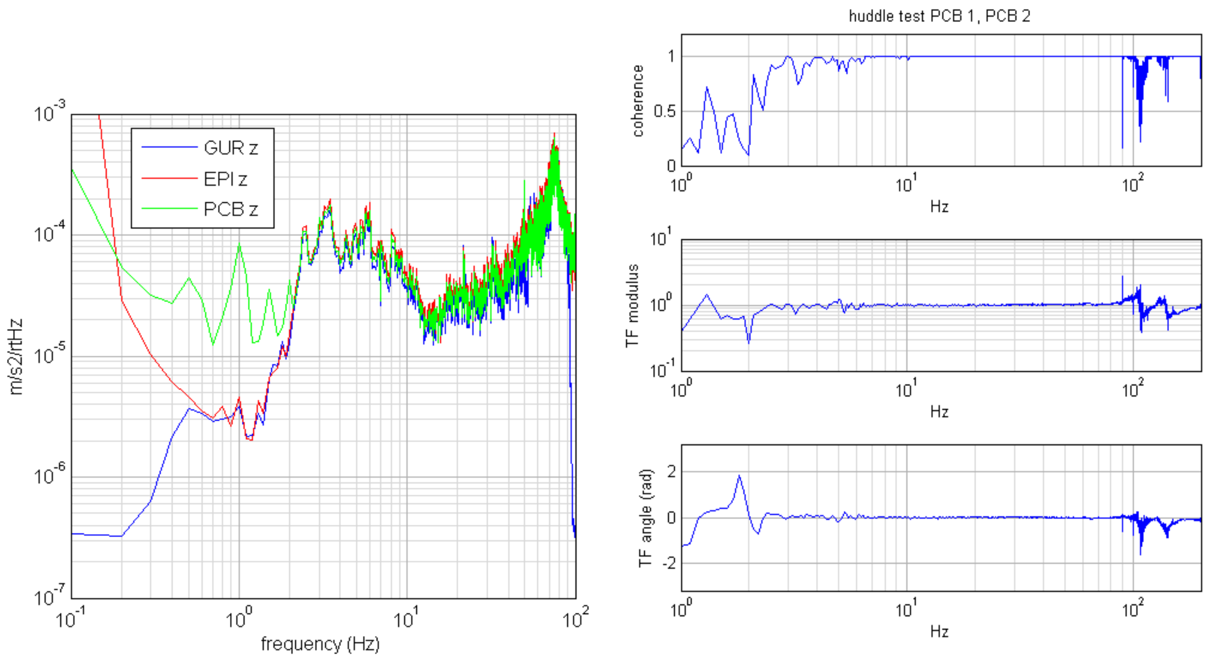

Figure 3: (Left) Cross calibration of the PCB1, Episensor and Guralp seismometers; (Right) huddle test of the PCB1 and PCB2 seismometers.

2. Measurement locations

We adopted the reference system which has the horizontal "X" axis along the optical axis of the Fizeau, the "Y" axis is along the orthogonal horizontal direction, and "Z" is along the vertical direction. Table 2 below describes the various experimental setups. Experiments A1 to A3 concern the clean room and ground zero floors. Experiment B1 concerns the bench isolation system. Experiments C1 to C4 concern the Fizeau setup. The following sections give more details and discuss results.

Experiment	Sensors position	Special conditions	TIME (start, duration)
A1	Guralp on ground zero floor, its "NS axis" along "X".		10:00 LT, 6 hours
A2	Episensor on Clean Room floor, its "X axis" along "X".		14:05 LT, 32s
A3	Episensor on Clean Room floor, its "X axis" along "X".	Vacuum pumps off	14:00 LT, 32s
B1	Episensor on Bench, its "X axis" along "X"		FFT record
C1	Episensor on test mirror frame base		FFT record
C2	Episensor on base of test mirror frame, PCB1 on mirror frame along X, PCB2 on Fizeau support along X.		FFT record
C3	Same as C2	Exciting floor	32s
C4	Same as C2	Fizeau ON measuring	32s

Table 2: Description of experimental setups. Experiments A1 to A3 concern the clean room and ground-zero floors. Experiment B1 concerns the bench isolation system. Experiments C1 to C4 concern the Fizeau setup.

3. Seismic noise of the two floors

The noise of the ground zero floor (*FLOZERO*) has been monitored for a continuous period of 6 hours from 10:00 to 16:00 Local time. Figure 4 shows the Guralp installation (experiment A0, Table 2). Figure 5 is the time frequency plot of the time record. Figure 6 shows the evolution of RMS noise during the observation time. The seismic record is characterized by three periods (approximately 10:00 to 10:45, 11:50-12:10 and 12:40 to 13:00 LT) when noise increased of about 3 times the RMS value in the 10-100Hz. The origin of this noise is not known. An intense tonal noise is present in the 20-25Hz and 45-50 Hz regions, shown in the zoomed spectrogram of Figure 5. These are typical noise emissions of 4-pole and 2-pole asynchronous engines. Sources have not been searched for, although possible culprits are pumps (likely ones are the two heat exchangers on the scaffolding visible in Figure 4) or air conditioning. The typical FLOZERO noise displacement is shown in Figure 7, for the three spatial components. The horizontal noise is roughly isotropic. The vertical noise differs because of a quieter “saddle” around 1Hz. The 45-50Hz tonal noise is most intense along the horizontal directions while the 20-25Hz tones are mostly heard along the vertical (this effect might be attributed to amplification characteristics of the floor).

Figure 4: The Guralp installation at LMA building ground zero. The Guralp “North arrow” is perpendicular to and points towards the end wall located on the left when entering the room.

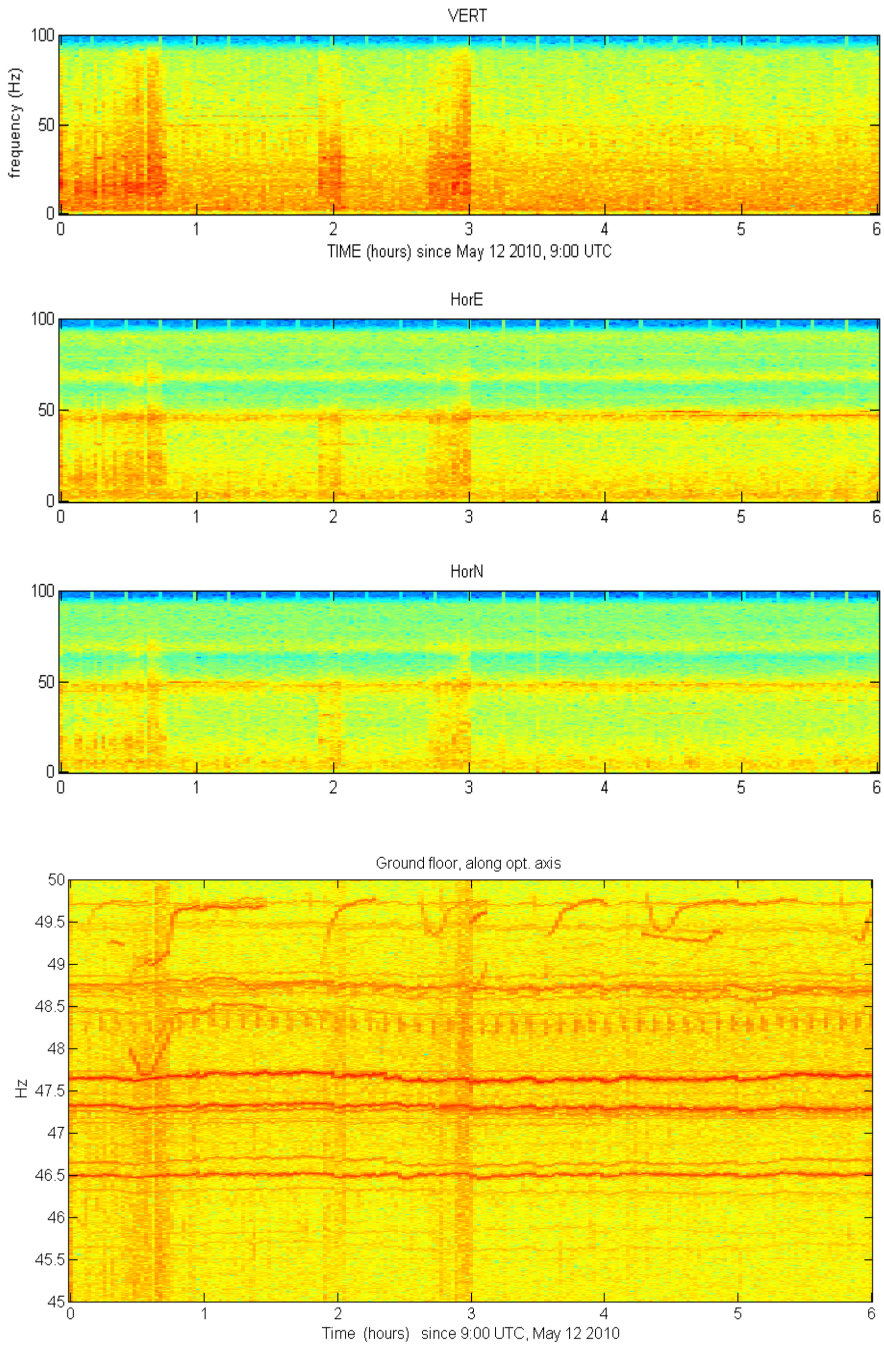

Figure 5: Time-frequency plot of seismic displacement of FLOZERO. Top: three components. Bottom: zoom-in 45 to 50 Hz.

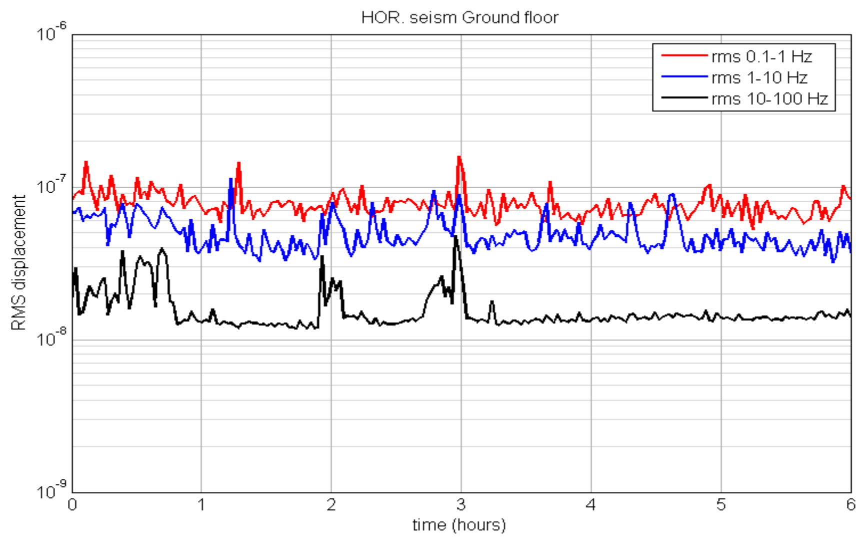

Figure 6: Evolution of RMS noise of FLOZERO in three frequency bands: 0.1-1Hz, 1-10Hz, 10-100Hz.

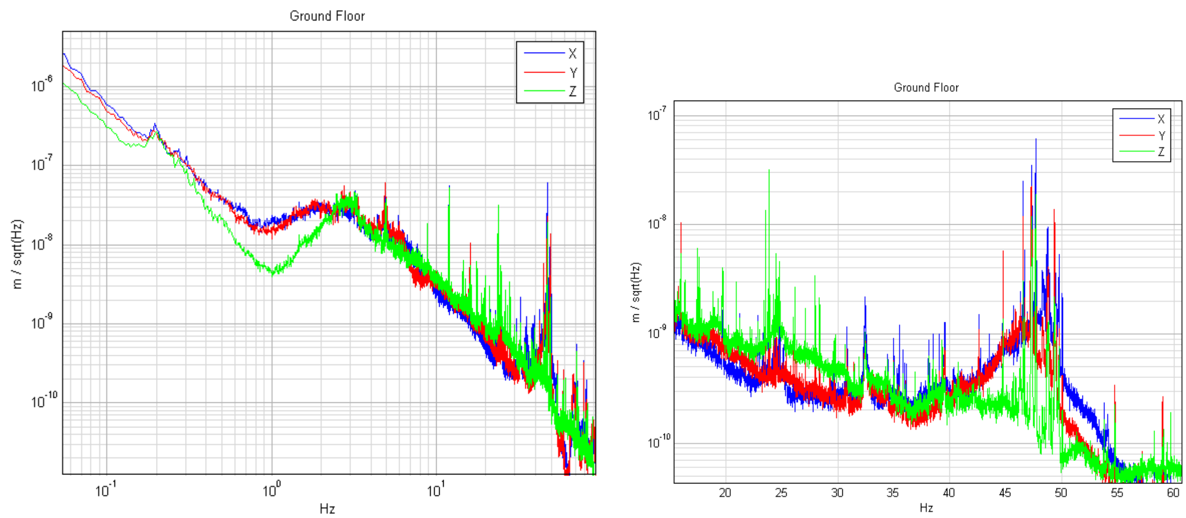

Figure 7: (Left) FLOZERO displacement noise, 3 components. The peak at 0.2Hz might be attributed to microseism. Data seems dominated by sensor noise below 0.2Hz, possibly due to a not complete thermal stabilization of the Guralp. (Right) Zoom on tonal noise.

The clean room at LMA 1st floor (FLO1) is a floating floor. It consists of tiles resting on the false ceiling support beams, tiles have holes to permit the clean air to flux in laminar way to the underneath ground zero room. The Episensor was rigidly attached to one tile and aligned with the Guralp axes. Figure 8 shows a picture of the Episensor setup. Figure 9 shows the three component displacement of FLO1. The measure is taken when no people are walking on the false ceiling. The noise is quite isotropic, except for the region 10-30Hz. We had the impression that the noise in this region was subject to fluctuations. One of such fluctuations is caught in Figure 10. We do not have a long continuous monitor of FLO1.
With the Episensor in this position we took one record during a period when the vacuum primary pumps serving the ion beam sputtering system were switched off. Figure 10 illustrates the result. Pumps contribute to noise floor above 100Hz.

To conclude, the horizontal displacement noise of FLO1 and FLOZERO floors is compared in Figure 11. The two spectra are not synchronous. However, the time offset is presumably less than a minute, the 32s record at FLO1 was taken in a controlled quiet period and the FLOZERO associated 32s time stretch was part of a quite stationary time period, thus we are confident that no major transient perturbation was affecting one of the two signals. The measured FLO1 spectral noise below 1Hz might be affected by Episensor instrumental noise, while above 1Hz the spectral noise comparison is robust. Starting from 10Hz, the FLOZERO moves significantly less than FLO1. As figure of merit we quote the cumulated RMS above 10Hz, which is 8E-8m (FLO1) versus 1.7E-8m (FLOZERO). To be noted that FLOZERO noise is significantly contributed by the 45-50Hz ("engines") noise, which explain about 1.4E-8m out of the 1.7E-8m RMS above 10Hz.

Figure 8: The Episensor installation at FLO1 (floor of the first floor clean room).

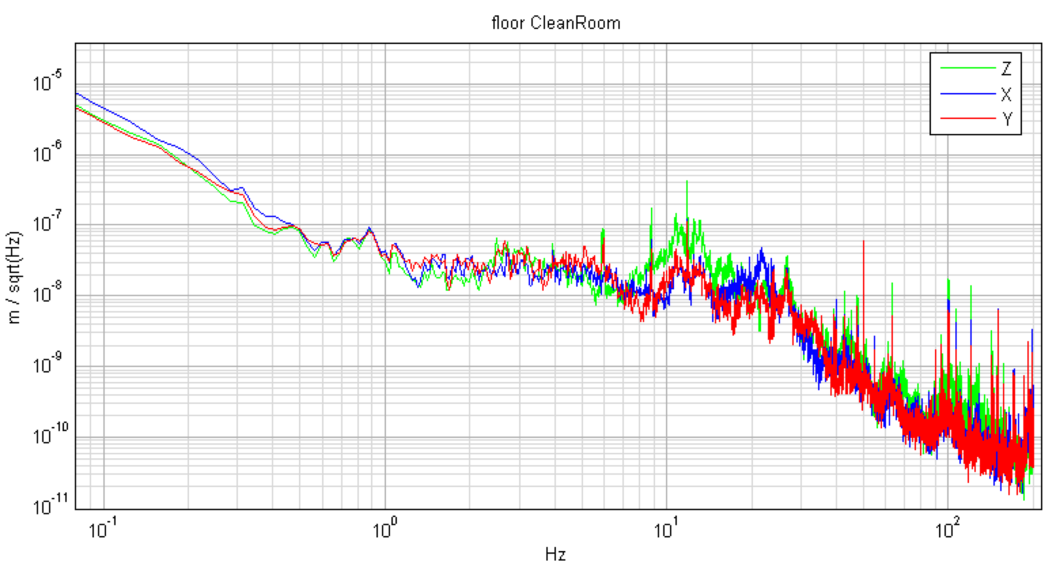

Figure 9: Three components of FLO1 displacement.

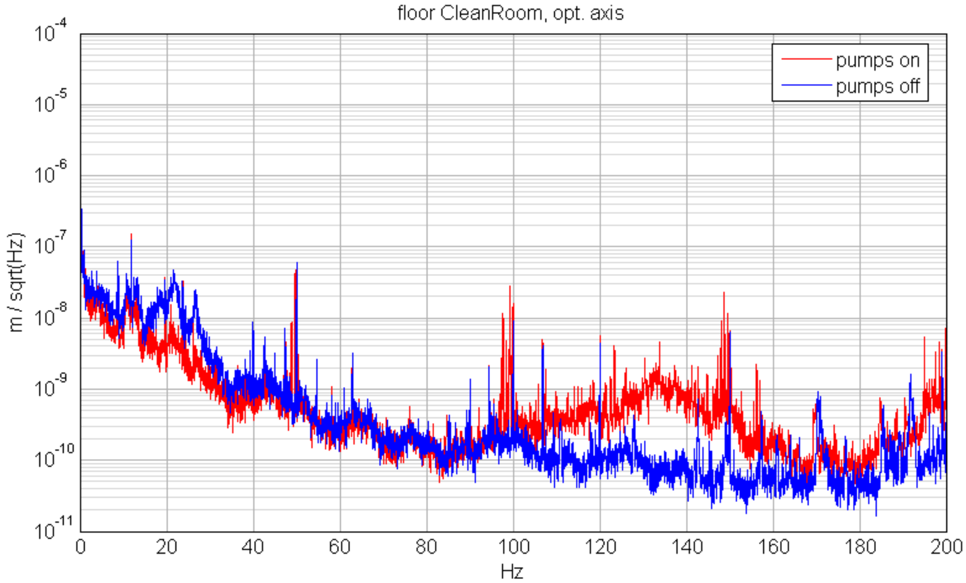

Figure 10: Seism of FLO1, along X, corresponding to the switch off of vacuum pumps: BLUE is with pumps off.

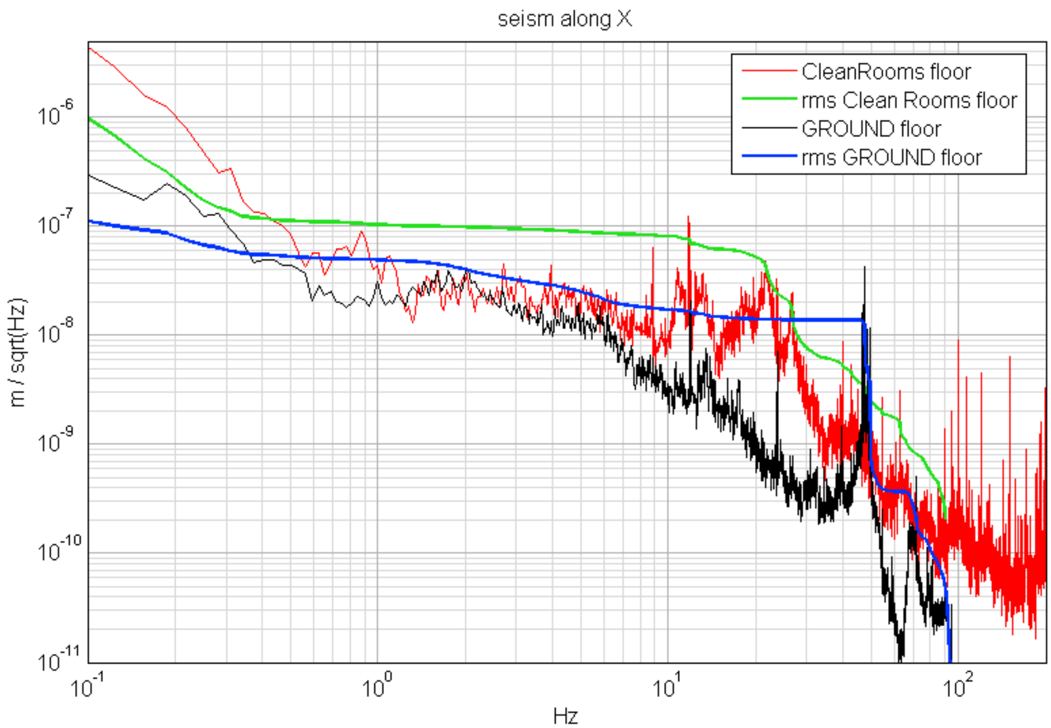

Figure 11: Comparison of FLO1 (red) and FLOZERO (black) displacement noise, along X. Cumulative RMS are shown for FLO1 (green) and FLOZERO (blue). Pumps were powered on.

4. About the isolation of the bench pneumatic legs

We perform a rough evaluation. Seismic spectra were acquired with the Episensor on the floor (experiment A2) and then on the bench (experiment B1). Figure 12 shows the Episensor installation on the bench. Figure 13 compares the displacement noise spectra of the floor and the bench.

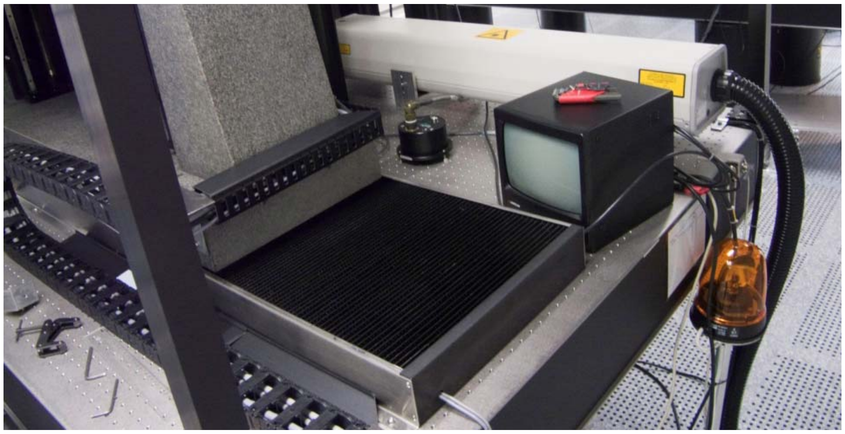

Figure 12: Episensor on bench (exp.B1).

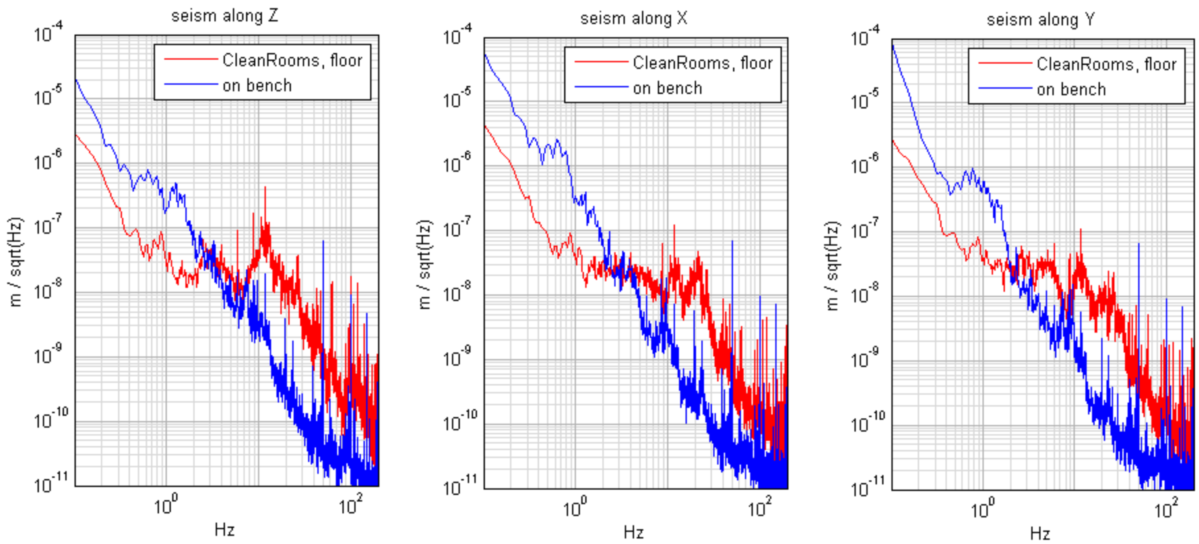

Figure 13: Displacement noise of clean room floor (red) and bench (blue), three components, "X" is along the Fizeau axis, that is the short bench side.

Seismic noise is suppressed starting from about 3Hz. A factor 5 to 20 reduction is achieved between 10 and 100Hz. Conversely, below 2Hz we observe an amplification of the floor noise by a rough factor 10. Although measurements are not coincidence, we observed these noise characteristics to not change during repeated measurements. We suspect this might be an effect of the pneumatic isolation system, to be possibly investigated with the manufacturer company.

5. About the motion of the Fizeau support structures

The Fizeau apparatus in the current setup is meant to perform high precision maps of the flatness of the surface of a test mirror (repeatability of 0.4 nm RMS) over a diameter of 330 mm (diameter of the Virgo mirror coatings). In the future setup, in order to map the AdV mirrors, the repeatability must be enhanced to about 0.1 nm RMS. A laser beam (wavelength ≈ 1μm) illuminates the test mirror and a reference mirror. The reflected beams recombine forming a 2D interference figure of black and white fringes which is recorded. One Fizeau measuring cycle lasts about 20 seconds, during which the reference mirror is moved back and forth by lambda/2 along "X" driven by a piezoelectric actuator. Figures 1 and 14 illustrate the Fizeau setup: (1) the test mirror is mounted on a support structure (“gimbal”) made by different parts to allow alignment and vertical positioning of the mirror, the gimbal is fixed to a granite base, the granite base rests on a slid which allows for horizontal translations of the base; (2) the Fizeau, with its reference mirror, is fixed on top of a four-leg table whose legs are fixed on the bench.

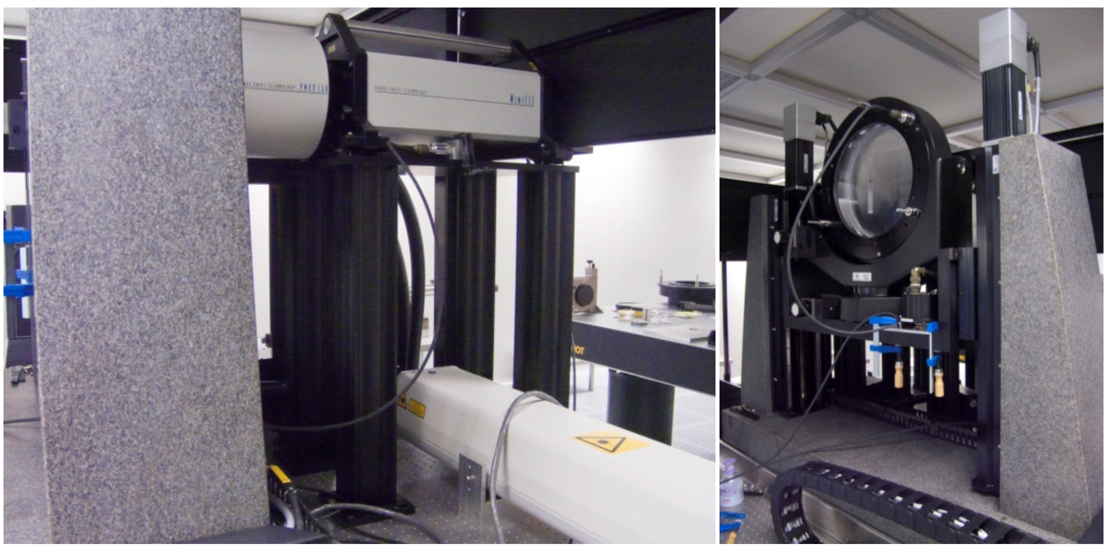

Figure 14: (Left) the Fizeau (and reference mirror) support structure, and the PCB2 installation (exp. C2 to C4). (Right) the Test mirror frame. The picture shows the Episensor installation on its base and the PCB1 accelerometer on the mirror holder (exp. C1 to C4).

In Figure 15 we compare the displacement noise of the bench (experiment B1) and the noise on the base of the test mirror frame (Figure 14, left). The two measurements are not synchronous, however are done in similar quiet conditions. The two parts seem to move almost rigidly together.

Figure 16, similarly compares the displacement motion along the optical axis (X), of the mirror frame base, the test mirror, and the Fizeau support. In the 20 to 60 Hz region these parts do not appear rigidly connected. The test mirror and the Fizeau motion is amplified at some well defined frequencies which are possibly associated to mechanical resonances of the mirror frame (27Hz and 30Hz) and the Fizeau table (59Hz, 37Hz and 42Hz). Note that (see Figure 14 middle and right) the accelerometers are a bit mis-centered with respect to the optical axis, consequently they are sensitive to possible rotation modes of the two structures and see them amplified.

The natural vibration of the mirror frame and the Fizeau table does not appear to increase when the apparatus is in operation. This is shown in Figure 17 (experiment C4).

Figure 18 reports the result of experiment C3: mechanical resonances of the legs, bench, and Fizeau structures are seismically excited by repeated shocks on the floor. We identify resonant mode frequencies at 7.5Hz, 27Hz, 30Hz, 37Hz, 42Hz, 59Hz and 72Hz.

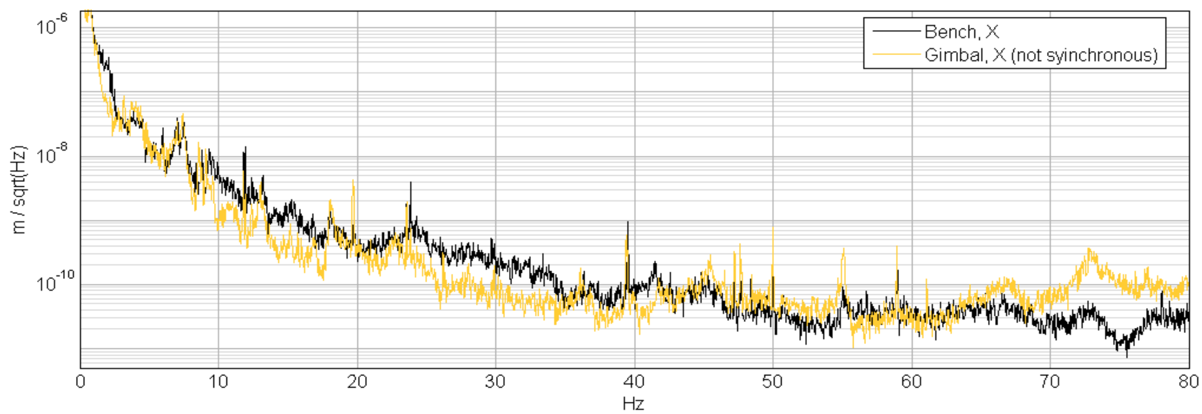

Figure 15: displacement noise of bench (black) and the base of the Gimbal mount (yellow), along the Fizeau optical axis. The two measurements are NOT synchronous.

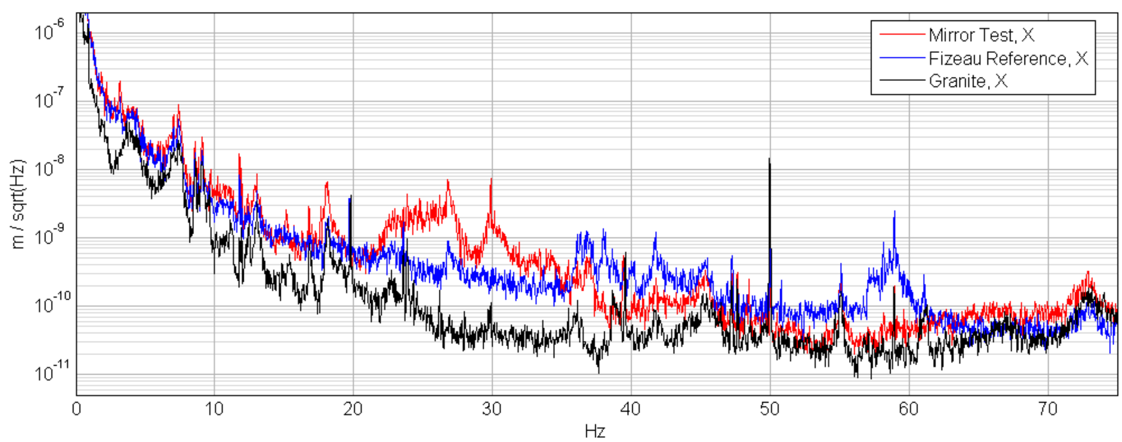

Figure 16: displacement noise of bench (black), the Mirror test mass (red) and the Fizeau laser (blue) along the Fizeau optical axis. Measurements are synchronous.

The relative displacement noise of the test mirror and the reference mirror seems an interesting quantity, its RMS value during the Fizeau measuring period sets the accuracy of the test mirror flatness measurement. Each single Fizeau measurement lasts about 1s, seismic noise above 1Hz is integrated during the measurement. Figure 19 shows the relative displacement noise of the two parts (test mirror and reference mirrors (i.e. Fizeau)) as measured by our accelerometers. This is computed taking the difference of the two accelerometer signals, and then converting it into displacement values. The actual relative motion tends to be overestimated by this measurement: below 3 Hz it seems dominated by the intrinsic noise of the probes; above 3Hz it possibly accounts for an amplified relative angular motion because of the off-axis position of the probes. Also shown in Figure 19 is the cumulative RMS value of the relative displacement. We read that about 20nm RMS is cumulated at 6Hz (at frequencies of 6Hz or less the relative motion measurement is not significant being comparable to the instrumental noise).

Out of these, about 7nm are cumulated below 10Hz apparently in correspondence of structural modes of the supports, the residual 13nm seems cumulated in correspondence of one peak at about 7.5Hz. The interpretation is that the test mirror and the Fizeau do not move rigidly at this frequency.
We do not know the origin of this peak. We only note that it seems present on the frame base, and on the bench as well (see Figure 15) but not on the floor (Figure 13). We suspect it is a resonant mode of the bench on the support legs.

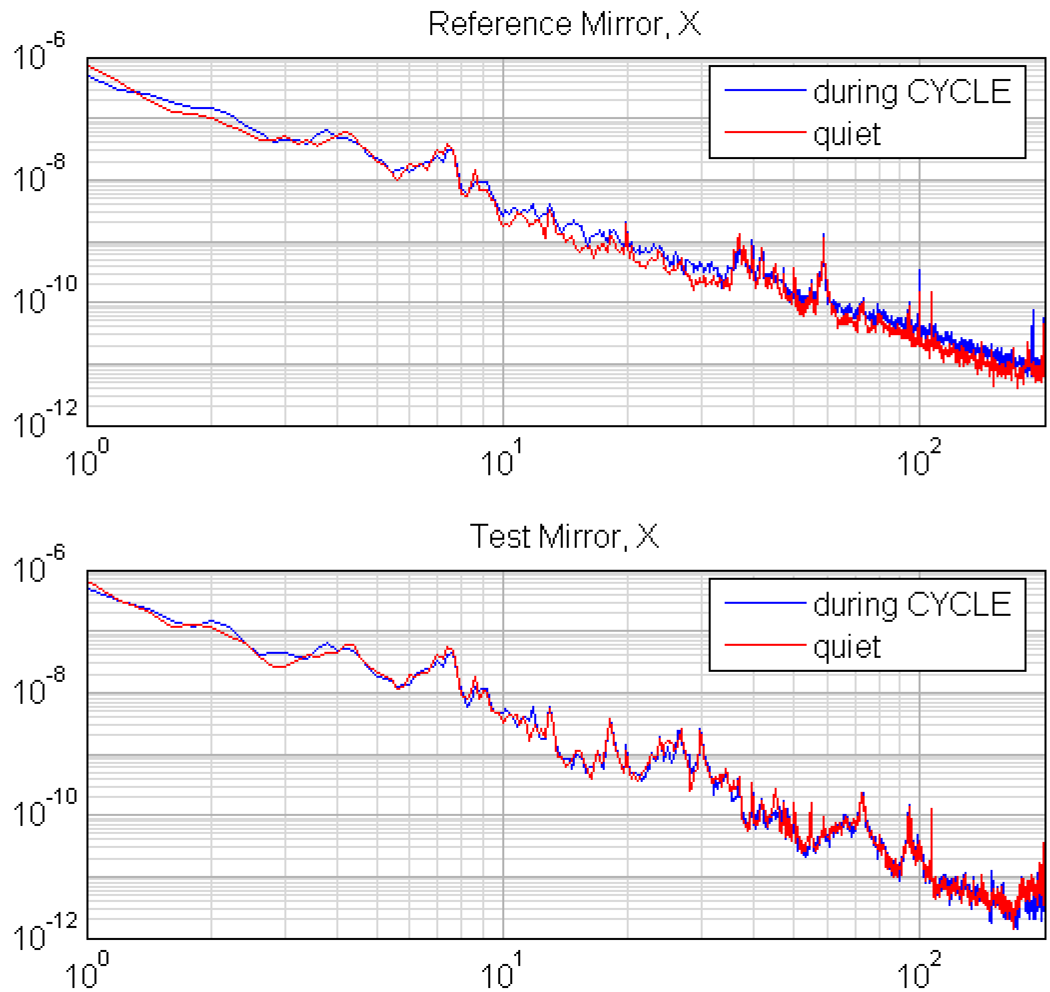

Figure 17: displacement noise of the Fizeau reference Mirror (Top) and of the test Mirror (Bottom), while the apparatus is OFF (red) and while the apparatus is performing a measurement cycle (blue). Experiment C4. Frequency (Hz) is reported in the horizontal axis.

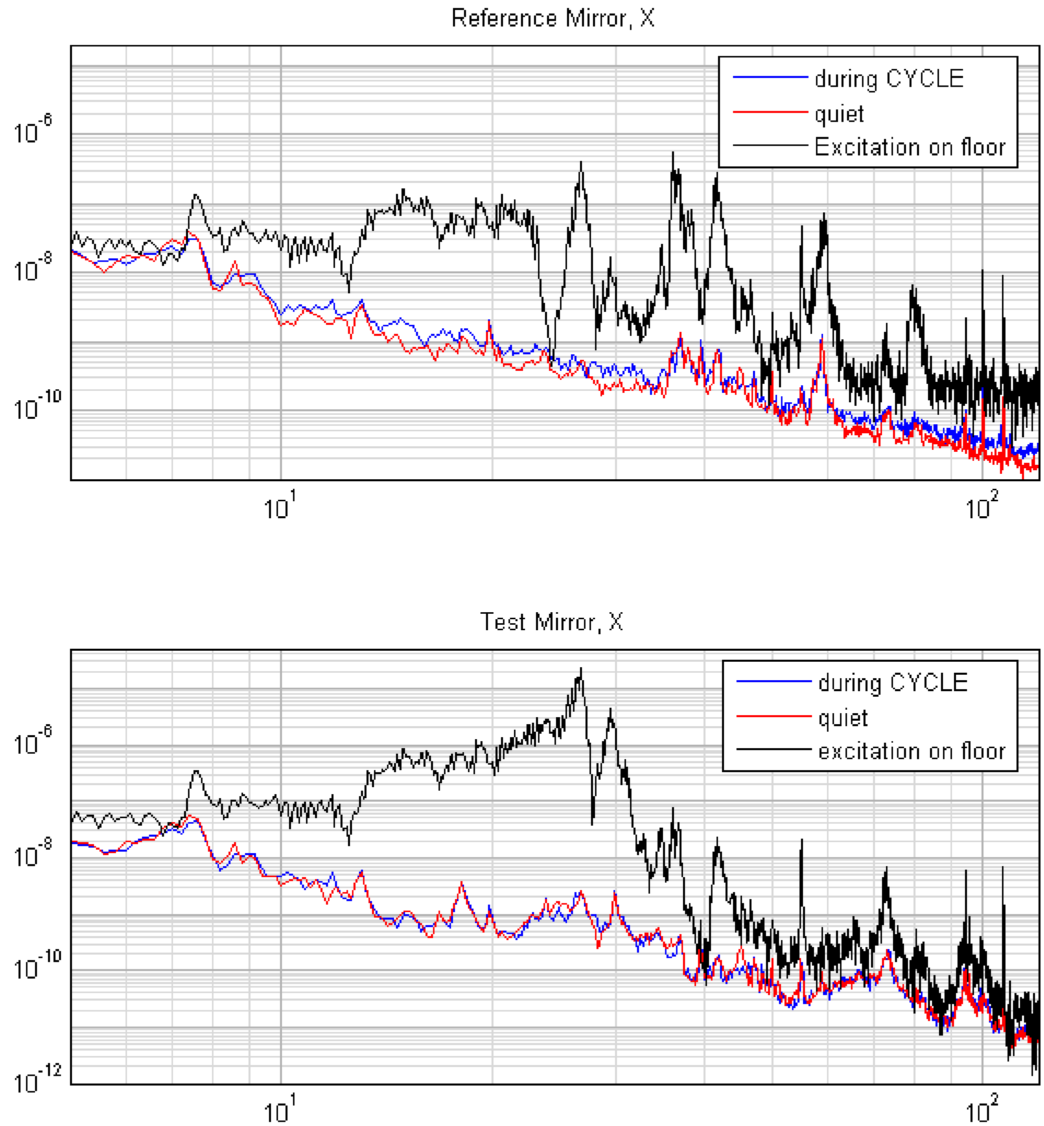

Figure 18: BLACK curves show the amplified displacement noise of the test Mirror and the Fizeau reference Mirror when the floor is excited with some repeated shocks noise (experiment C3). For reference also the quiet noise (same as Figure 17) is reported (blue and red). Frequency (Hz) is reported in the horizontal axis. Frequency of peaks is: 7.5Hz, 27Hz, 30Hz, 37Hz, 42Hz, 59H and, 72Hz.

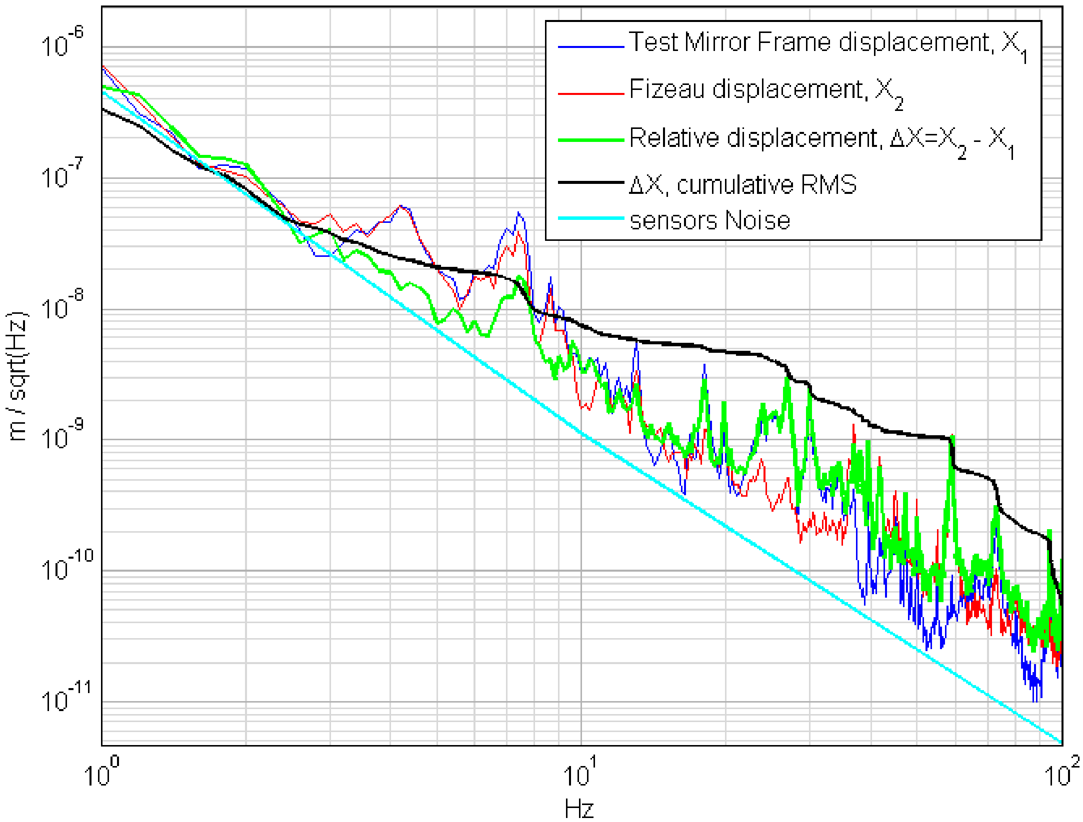

Figure 19: relative displacement of the test mirror mount and the Fizeau (green). Superimposed is the cumulative RMS (black). Also shown are: the reference mirror (blue) and test mirror (red) as measured by the two PCB accelerometers, the uncorrelated intrinsic noise of the two PCB sensors which is estimated as the nominal sensor noise times a square root of two.

6. Conclusions

Concerning the comparison of noise of the two floors, our conclusions are the following:

- In the region between 10 Hz and 100Hz, the floor beneath the optical lab is quieter than the floating floor where the Fizeau measuring system is presently located. As a figure of merit, we quote the integrated RMS above 10Hz, which is 8e-8 m (FLO1) versus 1.7e-8 m (FLOZERO).

- The Floor Zero RMS value integrated above 10Hz is dominated by structures around 48Hz that are presumably due to some asynchronous motors. This noise accounts for 1.4e-8 m out of the 1.7e-8 m RMS above 10Hz. If these noise sources are mitigated, the gain in terms of RMS ratio will be further increased.

Concerning the bench pneumatic isolation system, we conclude that:

- The seismic isolation system of the optical bench is effective above 3Hz in both horizontal and vertical directions.

- Below 3Hz, the isolation system appears to cause a not negligible amplification of the bench motion.

Concerning our study of the seismic noise of the Fizeau support structures, the evidence points towards the provisional conclusions reported below:

- The support structures of the test and the reference mirrors have mechanical resonances in the bandwidth going from 20 to 80 Hz. More specifically, these are: 27 Hz, 30 Hz, 37 Hz, 42 Hz, 59 Hz and 72 Hz.
- One resonant mode around 7.5Hz is possibly associated to the bench itself.

- The “gimbal” base (Figure 14, Left) seems to move rigidly enough with respect to the bench itself.

- No increase in seismic noise occurs when the apparatus is in operation; this means that if the apparatus does introduce seismic noise at all, it is below the seismic noise that due to the environment (floor).

- Because of resonances mentioned, a relative displacement of the two Fizeau parts (test and reference mirror) exists, as illustrated in Figure 19.

- We measure a differential displacement of about 6nm RMS at 10Hz, and 20nm RMS at 3 Hz. These values are to be intended as upper limit (as explained).

References

[a] www.zygo.com/library/papers/proc_5921_73.pdf

[b] https://pub3.ego-gw.it/itf/tds/file.php?callFile=VIR-0300A-10.pdf

[c] http://www.cvimellesgriot.com/Products/SuperDamp-Self-Leveling-Vibration-Isolators.aspx

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