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Abstract

As indicated in several papers [1,2] a suitable small number of tilt-meters can account for a complete recovery of Newtonian Noise and allows performing an efficient noise subtraction from the detector signal to obtain a better extraction of the Gravitational Wave signal from the noise. In order to obtain the main specifications on the tilt-meter as starting point, it is useful to constrain the level of sensitivity required to the tilt-meter. As already stated in the previous papers, the needed sensitivity is of the order of $\tilde{\vartheta}_n \le 10^{-12}\, rad \big/ \sqrt{Hz}$ in the region of frequencies spanning from about 4 to 20 Hz.

To reach this extremely low level of sensitivity, it is required to overcome several experimental limits. The first one is the read-out sensitivity of the instrument. Standard optical levers systems [3] cannot reach such sensitivity and this forces to choose interferometric systems. Also, the tilt-meter must not couple the various degrees of freedom, in order to supply exactly the angular movement of the ground and not, let's say, its horizontal or vertical accelerations.

Finally, the system must be designed in order to be mechanically robust and capable of taking data for at least one week without human intervention.

To fulfill these constraints and check their needs, a prototype tilt-meter has been designed and realized. The test of this prototype has allowed to study the major experimentally critical points and set the specification for the final instruments.

MECHANICAL DESIGN

The mechanical design is the core for a mandatory robust instrument. The mechanics is illustrated in Figure1: the tilt-meter is composed by an arm that can rotate around an horizontal axis defined by two flexible joints. Each joint is excavated from a single piece of Be-Cu alloy and the thin part is a strip 100 μm thick, 500 μm large and 6 mm high, as shown in the scheme of Figure 2. These dimensions have been chosen, considering that the momentum of inertia is 1.3×10^{-2} kgm^2, to maintain the resonance frequency of the arm oscillation within few tens of mHz. The arm is made of aluminum, is 0.5 m long and has a mass of 0.150 kg. Counterweights of 0.200 kg of brass have been mounted at the ends of the arms to obtain the above mentioned value of the momentum of inertia.

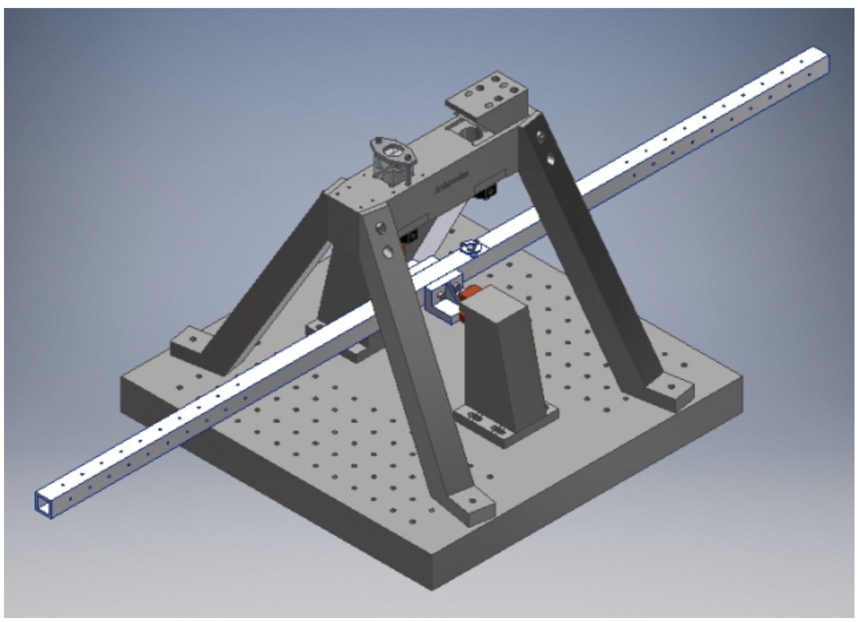

Figure 1: The mechanical scheme of the tilt-meter.

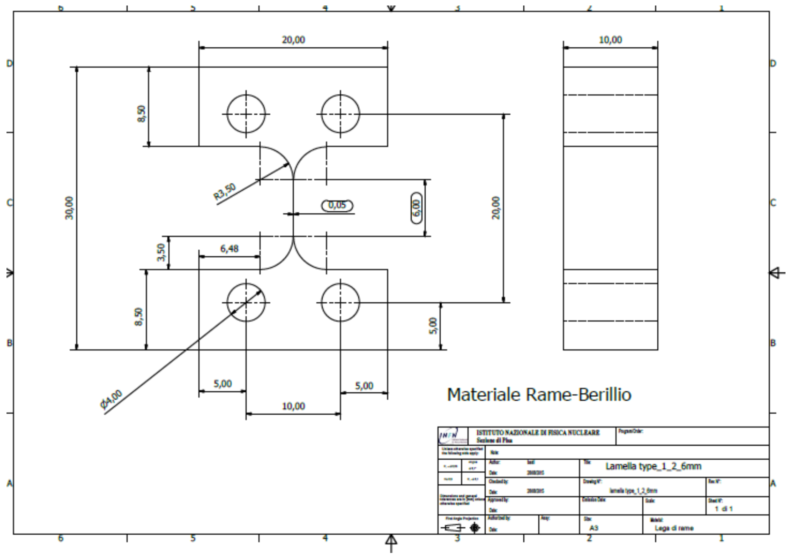

Figure 2: The technical drawing of the joints.

The whole tilt-meter is realized in steel, in order to maintain robustness and high resonance frequencies for the modes not of interest. The major source of mechanical coupling is with the longitudinal acceleration of the ground, i.e. the acceleration along the direction of the arm. As it is well known [4] this coupling can be minimized by having the rotational axis of the arm being coincident with the center of mass of the arm itself. Indeed the ground longitudinal acceleration $\ddot{z}$ produces the torque $\tau = m\ddot{z}\delta$ where m is the mass of the arm and δ is the distance of the rotation axis from the center of mass. If, as it is in our case, the rotational resonance frequency is few tens of mHz, the transfer function from the applied torque τ to tilt θ for frequencies of the order or above few Hz is simply $\vartheta = -\frac{\tau}{I\omega^2} = \frac{m\ddot{z}\delta}{I\omega^2}$, where I is the momentum of Inertia. This equation sets the first specification on the tilt-meter: the ratio m/I is of the order of L^{-2}, where L is the arm length, typically of the order of 0.5 m; the longitudinal acceleration of ground depends greatly on the site. In sites located on the earth surface (not underground) a typical value is shown in Figure 3, where in red we have reported the ground acceleration at the Virgo site, while other colors refer to underground sites.

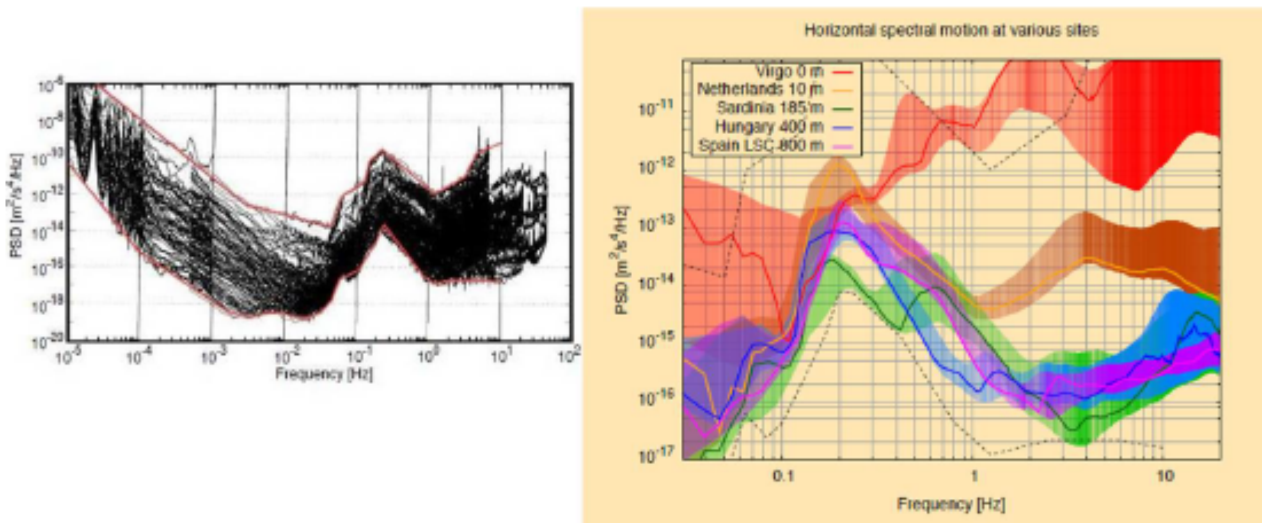

Figure 3: left) The power spectral density of acceleration in different sites of the world, with red curves indicating the maximum and minimum values. Right) The value at different European sites, Virgo being the red curve, showing a value of few 10^{-11} $m^2/s^4/Hz$ for the power spectral density, corresponding to about 6 x 10^{-6} $m/s^2/Hz^{-1/2}$ for the usual square root.

Considering the conservative value of $\ddot{z}$ = 6 x 10^{-6} $m/s^2/Hz^{-1/2}$, to not reintroduce a noise in θ higher than the specification, the constraint for the distance δ is $\delta < 25\ \mu m$. This specification implies that the tilt-meter center of mass must be regulated possibly with a remote system.

OPTICAL READ-OUT AND CONTROL SYSTEM

The final sensitivity required to the tilt-meter cannot be achieved with the usual optical lever systems. Indeed even the presently best optical levers reach few $10^{-11}\, rad/\sqrt{Hz}$ which is more than one order of magnitude worse than specifications [4,5]. An interferometric system is thus required. But considering that in typical conditions the arms will fluctuate around its equilibrium position, due to seismic noise excitations, particularly at the resonance frequency, a control system that maintains the interferometer on the working point is required as well [6].

As it is well known, since the interferometric signal is not linear for fluctuations that span more than a wavelength in the differential path of the interferometric arms, it is questionable if only an interferometric read-out may be sufficient or if it is better to have an auxiliary, high range system, to be used to bring the interferometer to its working point and hence switch the error signal of the loop on the interferometer.

This strategy is used for example in several suspended apparatus, even in Virgo itself, and it is the strategy that we have followed in designing and realizing a prototype to test and obtain the specifications for the final tilt-meter. In our case the proposed system is composed by an optical lever that constitutes the auxiliary system. Thanks to the error signal provided by the optical lever, the system is brought around the interferometric working point. Hence the loop is switched on the interferometric signal and the optical lever read out is no more used. The actual scheme of the prototype optical lever system is reported in Figure 4.

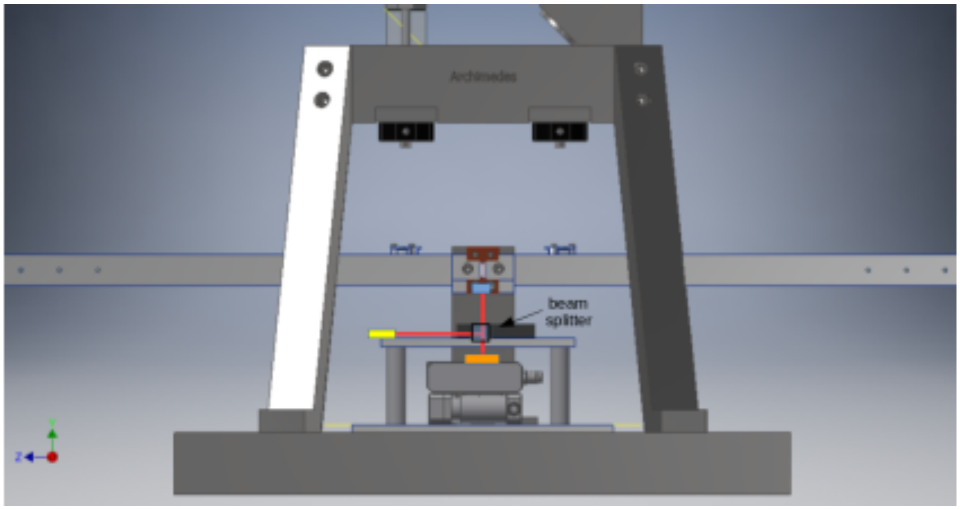

Figure 4: The optical lever system. A beam (in red) exiting from an optical fiber collimator (yellow) is sent to a beam splitter. The light reflected by the beam splitter is sent towards the tilt-meter arm, imping perpendicularly to the arm. One mirror is fixed at the center of the arm. It reflects the beam back to the beam splitter and the light transmitted by the beam splitter is read by a motorized quadrant photodiode (in orange). A tilt of the arm results in a displacement of the beam on the quadrant.

The optical lever configuration, particularly the perpendicularity to the arm, has been chosen to minimize the couplings with other degrees of freedom. The arm of the optical lever is about 6 cm. As previously said, this system is auxiliary to the interferometric read out. A scheme of the interferometer is reported in Figure 5.

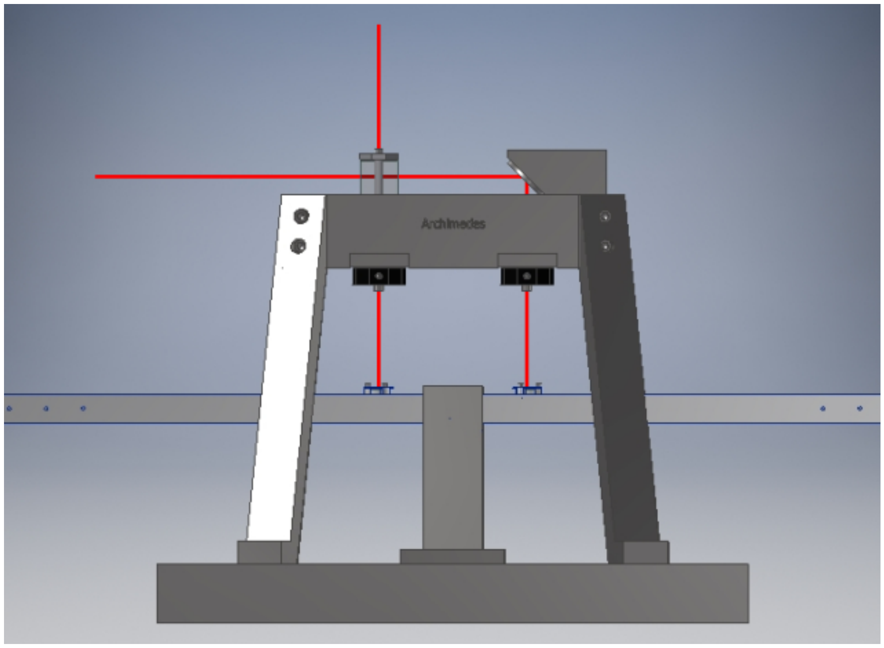

Figure 5: The scheme of the interferometer. The interferometer is a Michelson interferometer with un-equal arms. The optical components placed in the upper part of the figure are all fixed. The only moving part of the interferometer is the tilt-meter arm. The light comes from the left side of the figure (red beam) and impinges in the cubic beam splitter. The first path is given by the light reflected by the beam splitter, which is sent to the first mirror of the arm and it is reflected back towards the beam splitter. The second path is determined by the light transmitted by the beam splitter. It impinges on a mirror placed at 45 degrees and it is sent to the second mirror of the tilt-meter arm. The beam reflected by this second mirror comes back to the beam splitter were it recombines with the beam of the first path to exit from the output port. The read-out port (the vertical beam exiting the beam splitter) is read with a DC photodiode.

Figure 5 also shows two lenses (in black). These lenses have equal focal length to the distance to the arm. This makes the interferometer contrast insensitive to the tilt of arm (at the first order), so that even for arm rotations at mrad level, the interferometer maintains a good performance. This feature makes the interferometer far more robust with respect to earthquakes, allowing long data taking without intervention.

The control loop is closed with the use of electrostatic actuators. These are simply 30 cm^2 metallic plates, placed in front of the tilt-meter arm. They are parallel to the arm, in both sides and both ends. They are only partially superimposed to the arm, so that when a voltage is applied to a couple of plates they exert a force, and hence a torque, to maximize the facing area.

A picture of the actual tilt-meter is reported in Figure 6.

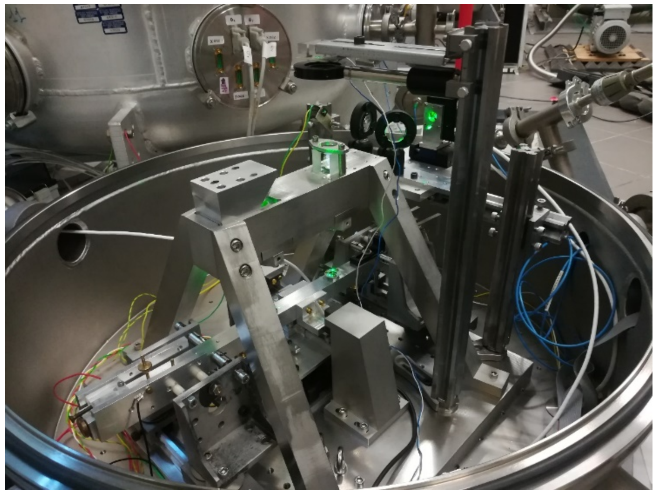

Figure 6: A picture of the tilt-meter. The green light is the interferometer light.

To test in laboratory the performances of the tilt-meter, it has been placed on a commercial seismic isolation platform. The results are shown in Figure 7. In this working condition the loop is closed on the interferometric signal and the optical lever signal is still read as an auxiliary channel.

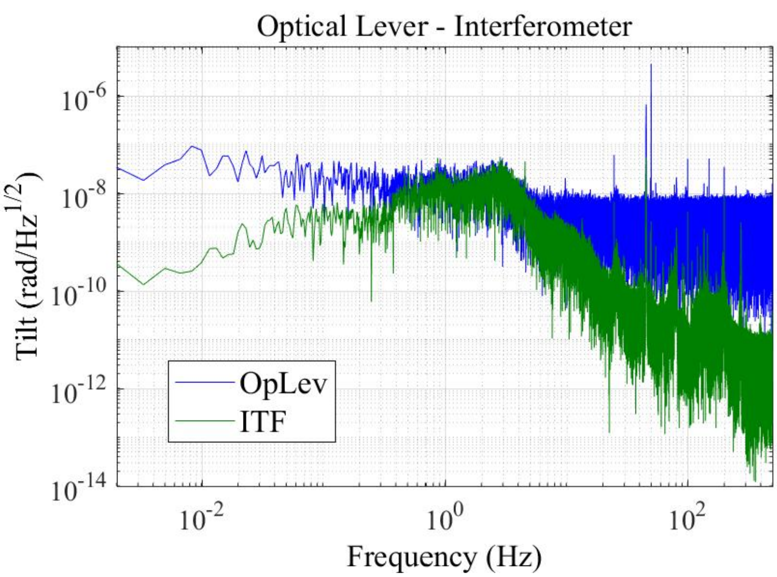

Figure 7: Sensitivity from low to high frequency. The optical lever is at its electronic noise. The interferometer is reading the residual seismic noise.

Figure 7 shows the sensitivity of the system. At the present the signal read corresponds to seismic noise. Indeed our lab is very noisy, since it is located in an in-a-town academic building. New measurements will be conducted in better environmental conditions. Several days of measurement have been taken, to test the robustness of the system.

The results are reported in Figures 8 and 9 and correspond to two periods in which an earthquake has happened. The case of Figure 8 is an earthquake in the northern of Italy, (epicenter near Castel del Rio (BO) 29-12-2018 – 19:56) of Magnitude 2.7, at a distance from our lab of about 700 km. Our system has been disturbed for few minutes and then the interferometer has recovered its working point.

Remarkably, as shown by the signal A_y, which is the optical lever system, the arm does not recover its initial position, because the interferometer gets locked in a different fringe. As previously stated, this turns out to be not a problem thanks to the optical scheme of the interferometer, using the two lenses with suitable focal length.

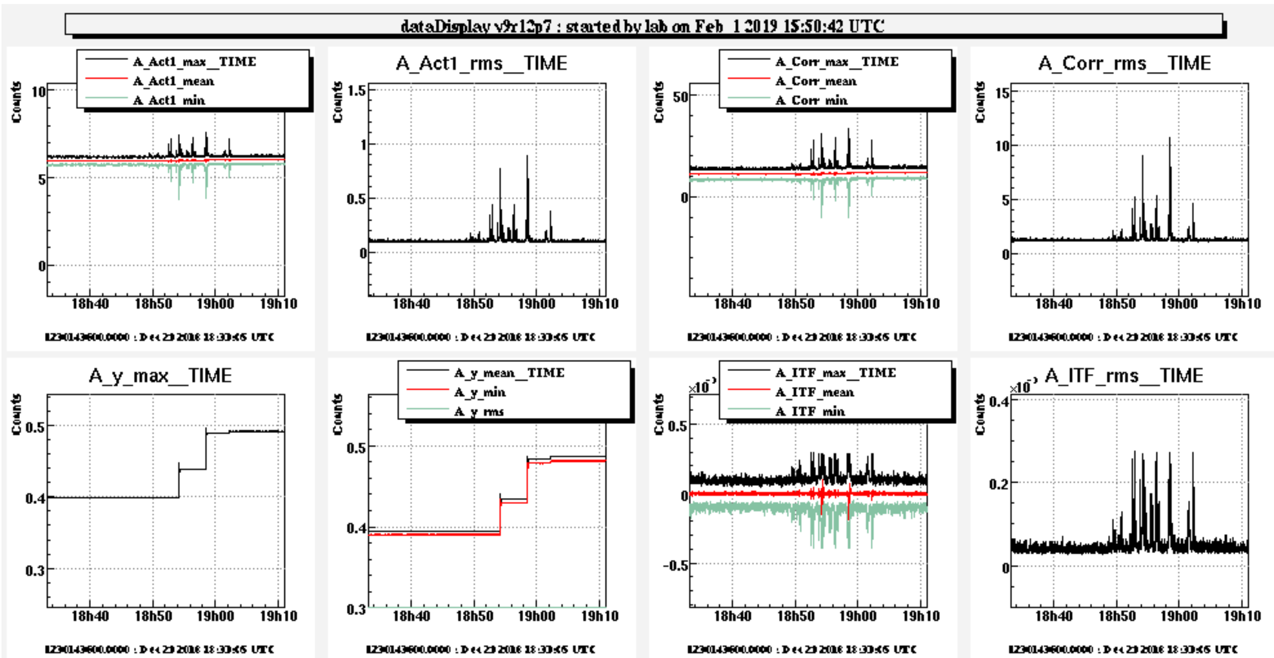

Figure 8: The signals during a far and feeble earthquake (Above, first and second from the left: signals and RMS of the signal sent to actuators; third and fourth: control signal and RMS of the loop. Bottom line, first and second plot: tilt as read from optical lever; third and fourth: the interferometer signal and its RMS).

Figure 9 shows the same plot for a nearer and stronger earthquake. In this case the magnitude is 4.1 and the distance from the lab is about 300 km. Again the interferometer loses its working point for few minutes, hence it gets locked again, in a different fringe. In this case all the signals are much more disturbed and in fact the interferometer finds its final lock on a position quite different from the initial one. Nonetheless the contrast remains very good and data taking can continue.

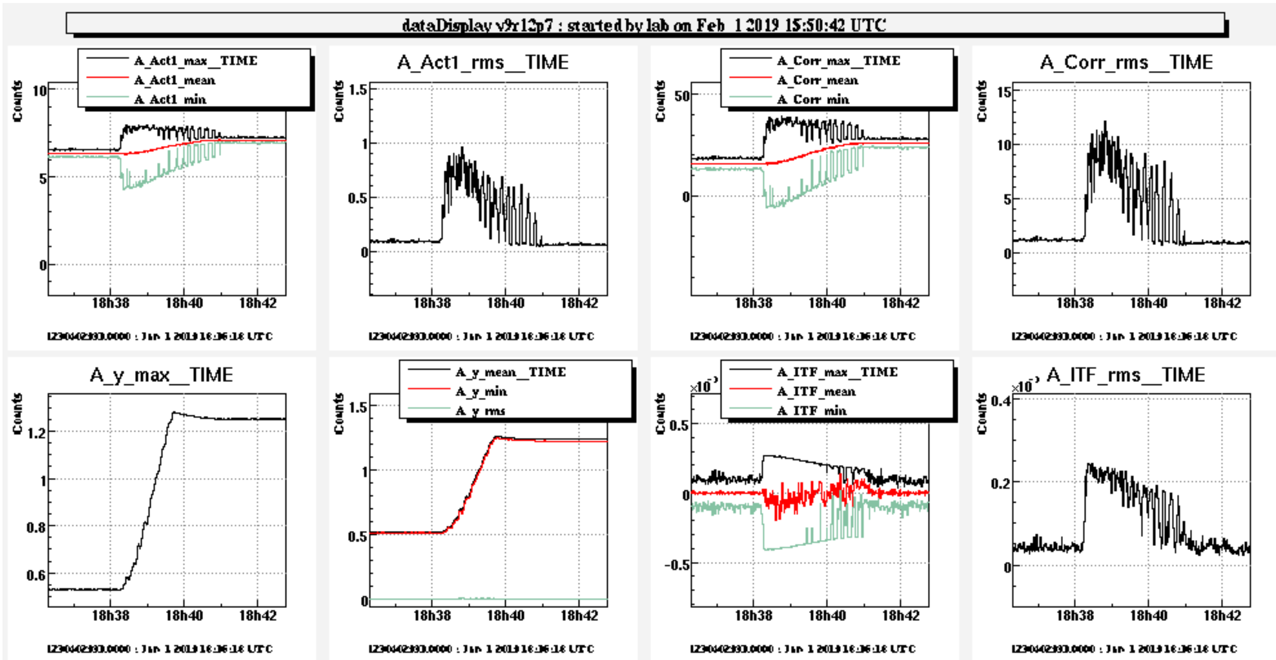

Figure 9: The signals in case of a not far and not feeble earthquake (the meaning of each plot is the same of figure 8).

OPERATION ON SITE

The tilt-meter is presently operating at the Virgo site. Installation on site has shown the need of several specifications not scientific but technical, mainly regarding not generation of seismic or electromagnetic noise and specifications on integration of the system with the whole Virgo data acquisition.

Seismic noise can well be introduced by the tilt-meter vacuum pumps. Here the specifications are given the seism at the site: the noise produced by the pumping system must be lower than the present seismic noise as measured on the Virgo tower basement. Similar considerations apply for the electromagnetic noise.

Specifications on system integration regard mainly the integration with the data acquisition system. The tilt-meter system should not be seen as a stand-alone system. The main motivation is that a stand-alone system can hardly be acquired by the Virgo system and thus the signals become not real-time. This slows down the commissioning of the systems, the tests on noise generation and prevent from executing coherence tests with the other sensors present in the building. The preparation of the system for integration requires that both the control system (if any) and the data acquisition system will be performed directly by the Virgo system. Thus the control system must be accessible to the general Virgo control system at least for feed-back loop parameters settings. For the data acquisition, clearly an analog read-out signal should be provided.

The tilt-meter has been installed at the North-END building, aligned with the Virgo North arm, since several weeks. The tilt-meter has continuously acquired data without major problems being locked on the interferometer signal, as expected.

First signals have been acquired to test the integration, the control and the acquisition systems and all the results are positive.

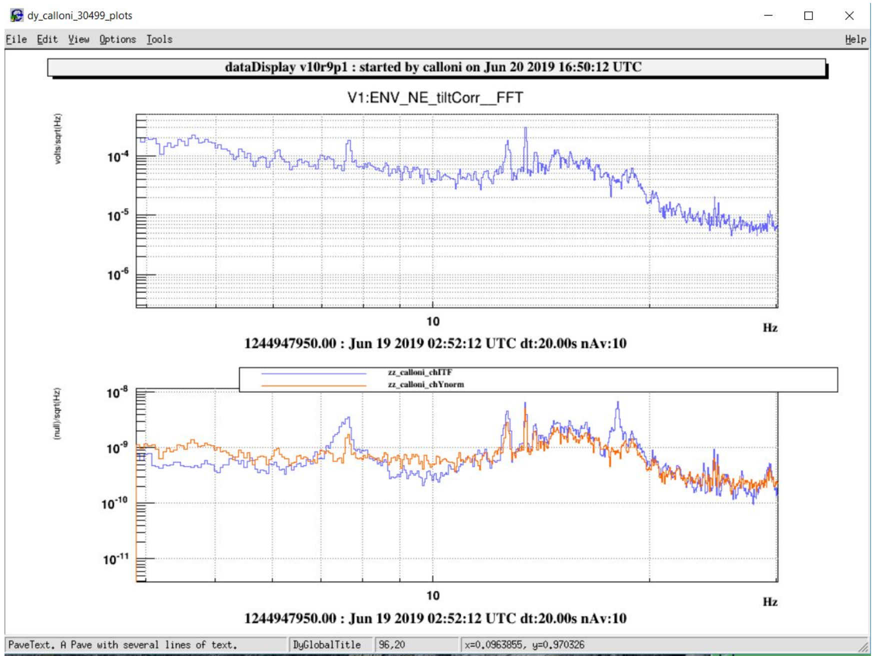

Figure 10: Correction spectrum (above) and tilt spectra form optical lever (bottom orange curve) and interferometer (bottom blue curve). In the region of interest the optical lever is near its sensitivity limit of about 5x10^{-10} rad/sqrt(Hz) while the interferometer, as expected, is not limited by its sensitivity but is reading a tilt signal. These signals have been compared with other environmental signals acquired in the building, particularly the accelerometers.

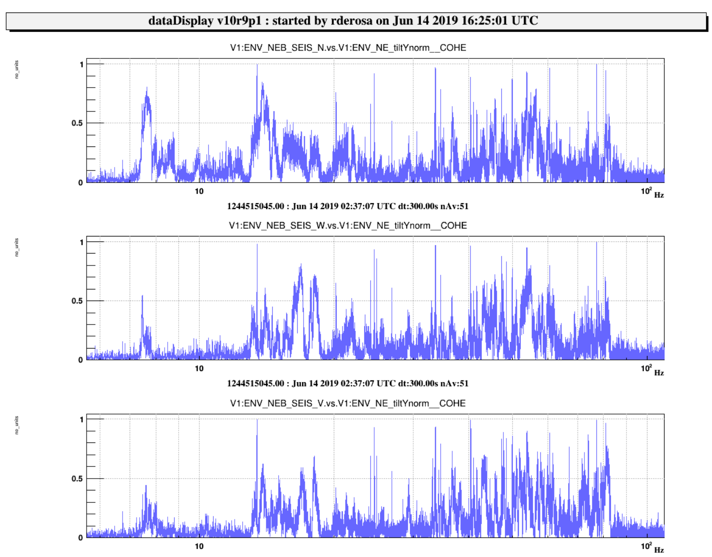

Figure 11: The tilt-meter signal shows coherence with accelerometer signals. This is to be expected both because the accelerometers read a tilt η of the ground as an acceleration gxη and for the coupling of tilts and accelerations due to building structure.

CONCLUSIONS

Following all the above tests and considerations we can set the following specifications for the tilt-meter:

1) Sensitivity in rad/ sqrt(Hz): 10^{-12} rad/sqrt(Hz) in the]4 : 20 [Hz measurement band;

2) Interferometric read-out system combined with an auxiliary high range control system;

3) Mechanical robustness: it is recommended to not have moving optical parts on the interferometer arm or on the reference arm;

4) Optical Robustness: it is recommended an optical scheme capable of maintaining the interferometer correctly working even if large static (order of hundreds μrad) arm tilts are present;

5) Electronic compatibility with Virgo control and acquisition system.

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