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Superattenuator seismic isolation measurements by Virgo interferometer: a comparison with the future generation antenna requirements

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Abstract

Each mirror of the interferometric gravitational wave antenna *Virgo* is attached to a *Superattenuator*, a chain of mechanical filters designed to suppress by many orders of magnitude the seismic vibrations, starting from a few Hz. The total attenuation was estimated on a prototype combining the mechanical transfer functions measured on the single filters. The filter chain attenuation is here measured directly on the antenna, exciting its suspension point with sinuisodal forces and using the interferometer as sensor. At almost all the excitation frequencies no peak was distinguished from the interferometer noise floor and thus only upper limits of the vibration transmission were provided. The measured attenuations turn out to be compliant with the next generation antenna *Advanced Virgo*. In the third generation detector *Einstein Telescope* modifications to the present Superattenuator will be necessary only if the detection band will be extended below 3 Hz.

Key words: Gravitational Wave Detectors, Suspensions, Seismic Isolation

1 Introduction

Virgo [1] is a suspended recycled Michelson interferometer with two orthogonal arms along which 3 km long Fabry-Perot cavities are accommodated. The detector is located at the European Gravitational Wave Observatory (EGO), close to Cascina (Pisa), and it is designed to detect gravitational waves emitted by astrophysical sources between a few Hz and a few kHz. A gravitational wave impinging on the plane of a suspended interferometer is expected to stretch one arm and to shrink the other alternatively in each half-period. In the detection band, the deformation ΔL is in a good approximation proportional to the arm length L and to the gravitational wave dimensionless amplitude ($h(t)$), in accordance with the relationship $\Delta L \simeq h(t)L/2$. Even considering km-long arms, the most promising signals do not induce differential arm length variations larger than 10^{-20} - 10^{-18} m. In order to detect a so weak signal the interferometer has to be characterized by an extremely high sensitivity. In the tens of Hz spectral region and below ground seismic vibrations are very large, billions of times larger than the small deformation of the arms to be detected. For this reason each *VIRGO* mirror was attached to a suspension system (*Superattenuator - SA*) designed to filter the vibrations by more than ten orders of magnitude in all the degrees of freedom, starting from a few Hz.
The antenna sensitivity is usually expressed by the linear spectral density of the dimensionless amplitude h ($Hz^{-1/2}$ units) of the equivalent gravitational signal that would produce the measured noise spectrum at the interferometer output (the photodiode where the interference takes place). The antenna sensitivity to a differential arm displacement (typically expressed in $m \cdot Hz^{-1/2}$

units) can be obtained multiplying the h sensitivity curve by the arm length. The *Virgo* second scientific run started on July 2009 in coincidence with two gravitational interferometric antennas of the US LIGO project [2], forming a network for the Universe observation. A typical *Virgo* sensitivity curve (obtained a few months after the run start) is plotted in Fig.1.

2 The Superattenuator

The *SA* (Fig.2), described in [3], is essentially a five-stage pendulum supported by a three legs elastic structure. In an N-stage pendulum the horizontal displacement of the suspension point, at a frequency f much higher than its normal modes, is transmitted to the last stage attenuated by a factor proportional to f^{2N}. Designing a long pendulum chain (about 8 m) all the normal modes were displaced below 2.5 Hz so to have a remarkable attenuation of the ground horizontal seismic noise (by more than 10 orders of magnitude) starting from a few Hz. The vertical seismic vibrations are not attenuated by the pendulum chain. On the other hand the vertical vibrations of the mirror are partially transferred to the laser beam horizontal direction because of unavoidable mechanical couplings (estimated to be well below one per cent) and of the Earth curvature.[1] For this reason each mass of the multi-stage pendulum is replaced by a cylindrical mechanical filter [4] with a set of concentric cantilever blade springs having low stiffness. The blades work in parallel with a magnetic anti-spring system assembled on each filter and designed to reduce its main vertical oscillation from about 1.5 Hz down below 0.5 Hz. The blades support, through an about 1 m long steel wire, the next mechanical filter forming in this way a chain of low frequency oscillators also in the vertical direction. Thanks to the anti-springs the chain modes are all below 2.5 Hz and the mirror is thus well isolated also from the vertical seismic noise starting from a few Hz.
The *Optical Payload* [5] is suspended by a steel wire from the last filter of the chain and it is composed by three elements: the *Marionette*, the mirror and its *Reference Mass*. Two pairs of thin metallic wires arranged in cradle configuration start from the Marionette to suspend in parallel the Reference Mass and the mirror, with a pendulum mode frequency around 600 mHz. The Marionette exhibits four arms at the end of which a permanent magnet is screwed. They are faced to four coils attached at the end of four 1 m long cylinders

[1] The Earth curvature makes 3 km far plumb lines not parallel to each other, with a misalignment of about $3 \cdot 10^{-4}$ rad. At least one of the two suspended cavity mirrors has thus to be inclined with respect to the other to keep the parallelism. This implies a misalignment of the mirror with respect to the local plumb line and a consequent transmission by $3 \cdot 10^{-4}$ of the mirror vertical motion to the beam direction.

bolted to the bottom part of the *SA* last filter body. This coil-magnet system steers the payload in three degrees of freedom (the translation along the beam and the rotations around the other two orthogonal axes). A fine mirror position control along these degrees of freedom is obtained also by using four coil-magnet pairs, with the first element screwed on the Reference Mass and the second one glued on the mirror back side.

Below the detection band, between 200 mHz and 2.5 Hz, the seismic excitation is amplified by the filter chain normal modes, making the mirror swinging by several microns along the beam. This displacement has to be actively controlled at the level of the optical payload to maintain the interferometer in the longitudinal working position with a large accuracy. [2] On the other hand a too large compensation force applied close to the mirror is not acceptable, because any electro-mechanical actuation system has a finite dynamics and thus induces a white noise force (affecting the entire detection band) proportional to the maximum required compensation amplitude. With the present dynamics of the DAC board used for the payload control (a noise floor of 300 $nV \cdot Hz^{-1/2}$ over a range of $\pm$ 10 V [11]), the maximum adjustable horizontal displacement by using the payload actuators (without affecting the detector sensitivity) is of a few tenths of micron. A preliminary reduction of the mirror swing induced by the chain resonances is thus necessary. This is made at the chain top stage, where a mechanical filter named *Filter Zero*, is suspended by means of three short metallic wires from the three leg elastic structure visible in Fig.2, called *Inverted Pendulum* [6]. Its elasticity is obtained by a flexural joint made of Maraging steel through which each single leg is anchored on the ground based bottom ring. Tuning the main oscillation frequencies of the Inverted Pendulum along the two horizontal directions at about 30-40 mHz a remarkable pre-attenuation is achieved also in the range where the chain resonances are located. An inertial control system (*Inertial Damping*) acting on the suspension top stage is used to further decrease the mirror swing [7]. It is based on three high sensitivity accelerometers [8] developed for the purpose and assembled on the Inverted Pendulum top stage in a pinwheel configuration. They are used to monitor the suspension point acceleration in the horizontal plane (two translations and one rotation about the vertical axis) with high accuracy. Three coil-magnet actuators are used in feed-back to keep the position of the top stage locked to an inertial frame. An effective damping of the *SA* mechanical resonances was obtained in this way. A similar approach is adopted to damp the vertical resonances. Two accelerometers and two coil-magnet actuators are used in feedback on the Filter Zero blades at which the chain suspension point is attached.

A hierarchical control strategy is adopted to further reduce the mirror swing and thus the control noise. The ultra-low frequency mirror displacements (below 10 mHz), induced by drifts and Earth tides, are very large (hundreds

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[2] Accuracies of 10^{-12}-10^{-10} m are necessary to keep the cavities at resonance and an acceptable destructive interference condition at the antenna output).

of microns). They are compensated using the interferometer as sensor and the three coil-magnet pairs of the horizontal Inertial Damping as feedback actuators [9]. In this case, the huge electro-mechanical floor induced by the necessity to operate large actuations is suppressed by the strong filtering of the entire pendulum chain below. The residual payload displacement along the beam (around a fraction of micron after the action of the Inertial Damping and tidal control) is compensated up to a few Hz from the Marionette. The induced electro-mechanical floor is suppressed down to an acceptable level by the mirror pendulum below. The Reference Mass actuators, pushing directly on the mirror, are used only to compensate few nm residual mirror displacements, above a few Hz. The actuation noise measurements performed on the interferometer (to be presented in a forthcoming paper), demonstrated that even the main contribution, coming from the Marionette actuation point, does not affect the *Virgo* sensitivity as well as that one of the next generation interferometer *Advanced Virgo* [10].

3 Seismic Noise Attenuation Requirements

As shown in Fig.1, *Virgo* is operating close to its design sensitivity also in the low frequency range and it is presently not limited by the mirror seismic noise passing through the *SA*. The goal of our measurements is to check if the present *SA* attenuation is compliant with the higher sensitivity of the next generation antennas. The mechanical transfer function requirements for isolation systems in future detectors can be obtained starting from their design sensitivity curve, expressed in displacement (Fig.3). The curves refer to *Advanced Virgo* [12], the next generation 3 km long interferometer expected to enter in action in 2014 at the Virgo site, and to the two reference configurations of the third generation underground antenna (*Einstein Telescope*), presently in the design study phase [13]. The goal of the 10 km arm interferometer, to be located underground, is the improvement of the sensitivity reachable by second generation detectors by about a factor ten in the whole detection band (between 10 Hz and a few kHz). An additional improvement is the extension of the detection band low frequency threshold from 10 Hz down to a few Hz. The maximum acceptable transfer function amplitude of the ground seismic vibrations for the mirror isolation system is plotted as a function of the frequency in Fig.4. This is given by the ratio between the detector displacement sensitivity curves of Fig.3 and the input seismic noise linear spectral density measured on the ground. At the *Advanced Virgo* site (the same of *Virgo*) the linear spectral density of the ground seismic displacement was measured to be roughly isotropic and approximable, between a fraction of Hz and a few tens of Hz, by the frequency f function $10^{-7}/f^2\ m{\cdot}Hz^{-1/2}$ [14]. A conservative value of $5{\cdot}10^{-7}/f^2\ m{\cdot}Hz^{-1/2}$ was considered to take into account enhancements and possible fluctuations in some spectral regions and the fact that the residual seismic noise displacement affects all the four mirrors of the two Fabry-Perot cavities. [3]

The *Einstein Telescope* site has not yet been chosen. The seismic noise floor of $5\cdot 10^{-9}/f^2\ m\cdot Hz^{-1/2}$ measured in the Kamioka mine, where the new cryogenic Japanese interferometric detector is planned to be installed [15], is taken as a reference. The recent progresses by the *Einstein Telescope* working group in the selection of less noisy underground sites are promising. This makes the chosen reference seismic floor conservative for our goals. It is important to stress that the transfer function requirements are valid both for the vertical and horizontal seismic noise that, as mentioned above, have a similar magnitude. While in horizontal the argument is straightforward, in the vertical case the plot represents the maximum fraction of ground vertical seismic noise that can be transferred to the mirror along the beam direction without affecting the antenna sensitivity. It is evident that the vertical to horizontal coupling factor mentioned in the previous section (in any case less than one) helps to reach the required filtering.

4 Previous Superattenuator Attenuation Measurements

The residual displacement at the mirror level is extremely small even if strong excitations are applied to the *SA* top stage. This makes a direct measurement of the total transfer function impossible with commercial instrumentation. An experimental evaluation of the *SA* filter chain attenuation has been made on a prototype by exciting one by one all the mechanical filters [3]. The 6x6 transfer function matrices, connecting the displacements in all the degrees of freedom of each couple of consecutive filters, were measured by commercial accelerometers and combined together to estimate the filter chain total attenuation. The measured isolation for vertical and horizontal seismic noise (see Fig.10 of [3]), in excellent agreement with the Lagrangian simulation, turned out to be enough to suppress seismic noise below the *Virgo* sensitivity curve starting from about 3 Hz. An attempt to measure directly the total attenuation of the *SA* filter chain was made a few years ago at the frequency of 4.1 Hz [16]. A sinusoidal force was applied at this frequency along the beam direction to the chain suspension point (i.e. to the Inverted Pendulum top stage) by injecting a current in the Inertial Damping coil-magnet actuators. The *Virgo* test interferometer (*Central Interferometer - CITF* [17]) was used as sensor of the mirror residual displacement. Thanks to the softness of the Inverted Pendulum a wide displacement of the suspension point (fractions of

[3] At the frequencies of our interest, the residual seismic noise on different mirrors sum incoherently. This means that four mirrors with the same displacement noise provide, in terms of linear spectral density, a double contribution with respect to a single one.

micron) can be induced by an acceptable coil current, not exceeding 1 A. Despite the good sensitivity of the *CITF* (in any case a few orders of magnitude worst than the *Virgo* one) and the long measurement time (hours), [4] no peak at 4.1 Hz was distinguished at the mirror level from the interferometer noise floor (around $2 \cdot 10^{-12}\ m \cdot Hz^{-1/2}$). As a consequence only an upper limit of vibration transfer function by a few 10^{-8} was given for this specific frequency. Multiplying this upper limit by the seismic noise measured on the top stage at the same frequency when no excitation is applied, one can evaluate the upper limit of the mirror residual seismic displacement during *Virgo* operations. The conclusion was that already at 4.1 Hz (i.e. below the *Virgo* detection band, starting from 10 Hz) the residual displacement is smaller than the one induced by the mirror thermal noise, limiting the antenna sensitivity in the low frequency range. The same conclusion (at the frequency of 4.15 Hz) was reached for the vertical seismic noise, by applying the sinusoidal current to the Inertial Damping coil-magnet actuators controlling the vertical position of the chain suspension point.
The *Virgo* interferometer is now working very close to its low frequency design sensitivity, offering a very sensitive apparatus for this kind of tests. The mirror displacement, indeed, can be now monitored with a much better accuracy (about four orders of magnitude around 10 Hz with respect to *CITF* and one-two orders of magnitude in the Hz frequency range).

5 Attenuation Measurements in the Virgo Interferometer

Several sinusoidal excitations have been applied to the *SA* top stage (both in vertical and horizontal) in the Hz and tens of Hz range. Each measurement required the interferometer locked for several hours close to its design sensitivity. Moreover only a single frequency was injected in each experiment to the top stage so to maximize the excitation at the investigated frequency without saturating the coil-magnet actuator range. Even if a few tests were performed in parallel on the four *SA*s of the two Fabry-Perot cavities, the entire set of measurement required a long commissioning time. It is important to stress that in our experiments it is the filter chain suspension point, connected with the Filter Zero blade tip, to be excited. As a consequence, the transfer function is measured from this point to the mirror. An additional attenuation of ground seismic noise, excluded in our measurement, is provided by the pre-isolator stages working both in horizontal and vertical (Inverted Pendulum and Filter Zero). The result of a typical experiment (with the specific excitation at 32.3 Hz along the beam) is reported in Fig.5. Since no peak is distinguished from the noise at the mirror level, the ratio between the floor and the top stage

[4] We remind that the ratio between the peak amplitude and the incoherent floor scales with the square root of the integration time.

peak amplitude gives the transfer function upper limit of the filter chain at this frequency. The *Virgo* calibration to pass from the photodiode signal (in W) and the differential mirror displacement (in m) exhibits an uncertainty around 10 %. A similar accuracy can be considered for the Inertial Damping accelerometers used to measure the top stage displacement. In almost all the experiments no peak was detected at the level of the interferometer. For three cases only around 30 Hz, a corresponding peak was distinguished from the interferometer noise floor (see Fig.6). However, also in these experiments, the transfer function was measured to be a few 10^{-11}, and thus within the requirements displayed in Fig.4. The possibility that other mechanisms could cause the very thin mirror motion, by-passing the extremely high mechanical attenuation, has to be considered when a so accurate measurement is performed. The measured weak transmission between the top stage actuation coils and the mirror could be induced by spurious couplings between cables and/or electronic boards, or to antenna effects between the top stage coil excitation signal and the coil used in the payload control. In order to better investigate this point the measurements around 30 Hz were repeated at the same frequencies exciting the top stage along the horizontal direction perpendicular to the beam. While the electromechanical excitation amplitude, and thus the source of possible spurious effects, is similar to the previous case, the mechanical transmission should not produce a measurable mirror displacement along the interferometer if the mechanical transfer function (with the excitation along the beam) has the value previously measured. The separation of the degrees of freedom in the suspension chain and the accuracy in providing the excitation force along the orthogonal direction should guarantee that the mirror displacement along the beam cannot exceed a few percents of the previous one (when the same excitation amplitude is applied). Vice versa, in each of the three experiments, a peak was again visible above the noise floor, with transfer function measurements comparable to the previous cases. Even if this is not a formal demonstration that a by-pass effect takes place, this evidence prevents us to state that in the three cases around 30 Hz a direct measurement of the total *SA* transfer function was performed. The vertical experiments, made at the same frequencies, did not provide a distinguishable peak at the mirror level. However, it is important to stress that the vertical coil-magnet actuators have a complete different geometry and that the used coils are much smaller than the horizontal ones.

The results of the measurement campaign are summarized in *Table 1* (when the excitation is along the beam) and in *Table 2* (for vertical excitation experiments). In the different columns: a) Superattenuator under test (*CITF* refers to the old measurements performed on the *Virgo* Central Interferometer, already published in [16], 'W' and 'N' indicate the cavity of the Superattenuator under test, West or North, while 'I' and 'E' its position in the cavity, Input or End); b) Measurement time length; c) Excitation frequency; d) Peak amplitude of the top stage displacement linear spectral density at the excitation frequency measured by the Inertial Damping accelerometers; e) Linear spectral density of the mirror displacement along the beam at the excitation frequency, as detected by the interferometer; f) Transfer function amplitude (ratio between columns e and column d); g) Note on the measurement outcome (the symbol "$<$" denotes that only an upper limit was given, while the two stars indicate that a peak was detected at the mirror level).

Table 1 - Excitation along the beam

SA	$time(s)$	$f(Hz)$	$top(mHz^{-1/2})$	$mir(mHz^{-1/2})$	TF	$Note$
CITF	10485	2.25	4.8e-5	2.5e-10	5.2e-6	**
CITF	10485	4.10	3.3e-5	2.0e-12	6.1e-8	$<$
WI	20971	4.30	4.3e-6	3.6e-14	8.4e-9	$<$
WI	20971	6.30	6.0e-6	5.4e-14	9.0e-9	$<$
WI	20971	10.30	3.0e-6	1.8e-16	6.0e-11	$<$
WI	20971	18.30	2.8e-6	4.8e-17	1.7e-11	$<$
NI	41943	29.30	3.0e-6	1.5e-17	5.1e-12	**
WI	41943	30.30	9.4e-7	6.0e-17	6.4e-11	**
NE	41943	31.30	1.4e-6	1.8e-17	1.3e-11	**
WE	41943	32.30	1.2e-6	2.0e-18	1.7e-12	$<$

Table 2 - Vertical Excitation

SA	$time(s)$	$f(Hz)$	$top(mHz^{-1/2})$	$mir(mHz^{-1/2})$	TF	$Note$
CITF	2620	2.25	1.7e-4	2.6e-10	1.5e-6	**
CITF	2620	4.10	3.0e-4	3.0e-12	1.0e-8	$<$
NI	25165	29.30	1.2e-6	3.0e-18	2.5e-12	$<$
WI	25165	30.30	3.9e-6	3.0e-18	7.7e-13	$<$
NE	25165	31.30	4.1e-6	3.0e-18	7.2e-13	$<$
WE	25165	32.30	4.4e-6	3.0e-18	6.8e-13	$<$

The upper limits achieved (and the "direct measurements") of the transfer function are reported in Fig.7 and compared with the next generation antenna requirements already displayed in Fig.4. One can notice that the transfer function of the filter chain for the investigated frequencies above 10 Hz turns out to be below the transfer function requirements for all the planned future detectors. The additional attenuation by the pre-isolator stages in both directions increases the safety margin. The measured upper limits below 10 Hz are not

enough to state that at the investigated frequencies the filter chain alone is enough to suppress the seismic noise below the *Einstein Telescope* sensitivity. It is important to stress again that in this region only upper limits were set and that the expected transfer function will be likely remarkably smaller, in agreement with the indirect stage by stage measurement [3]. Moreover, the few tens of dB distance between the measured upper limits around 4 and 6 Hz and the transfer function requirement curves (reduceable by longer and more sensitive measurements) can be assumed to be already well covered by the future antenna pre-isolator stages.
As shown in [3], going below 4 Hz, approaching to the resonance range, the transfer function exhibits a steep increase. As shown in *Table 1* and *Table 2* the unique direct measurement in the ultra-low frequency range was performed on the *Central Interferometer* at 2.25 Hz both in vertical and in horizontal. A direct measurement of the filter chain transfer function by a few parts per million was achieved in both cases [16].[5] The gap with the requirements is thus very wide and could just be barely covered by upgraded pre-isolator stages. Moreover the last chain resonant frequency around 2.5 Hz (in both directions) would make the attenuation small at this frequency and thus the seismic noise dominant in the antenna. One can thus conclude that at 2-2.5 Hz the present *SA* is likely not compliant with *Einstein Telescope*. Looking at the steep behavior of the indirect transfer function measurement (Fig.10 in [3]) one can infer that the crossing between the mirror residual seismic noise and the *Einstein Telescope* sensitivity should take place around 3 Hz. We remind that the *Einstein Telescope* low frequency detection threshold is still not fixed, since the present *Newtonian noise* estimates turns out to be high, making difficult a sensitive detection below a few Hz. This noise mechanism, described in [18], is induced by the gravitational coupling of the mirror with the ground mass distribution, varying because of seismic waves.

6 Conclusions

The suspension points of the *Virgo* Superattenuator filter chains have been excited several times both in horizontal and in vertical injecting sinusoidal signals at different frequencies in the top stage coil-magnet actuators. In almost all the experiments, the mirror residual motion at the excitation frequency was too small to be distinguished from the interferometer noise floor and only transfer function upper limits were provided. In only three tests, around 30 Hz, with the suspension point excitation along the beam a peak above the interferometer floor was detected putting in evidence a noise transmission. An

[5] In this case, where the measured transfer function is remarkable, there was no doubt that the measured mirror displacement was driven by residual mechanical excitation.

indication that the detected small residual signal could be induced by other mechanisms, by-passing the strong Superattenuator mechanical attenuation, was given by additional measurements. In any case, at all the investigated frequencies, the transfer function of the filter chain (measured directly or by upper limits) turns out within the requirements of *Advanced Virgo*, whose detection band starts from 10 Hz. Above this frequency the measured attenuations are compliant also with the third generation detector *Einstein Telescope* that is, at frequency above 10-15 Hz, less demanding in terms of attenuation because of the underground lower seismic noise. The additional attenuation by the pre-isolator stages, from which the filter chain is suspended, provides an additional the safety margin.
The upper limits of the filter chain transfer function measured at lower frequencies, around 4 and 6 Hz, are larger than the required values but the few tens of dB gap can be nulled by longer and more sensitive measurements and it is in any case small enough to be covered by the additional attenuation coming from the pre-isolator stages. This argument, together with the indirect measurement of attenuation valid at all frequencies [3], allows concluding that modifications to the Superattenuator (such as a lengthening of the chain) will be necessary in *Einstein Telescope* only if the detection threshold frequency will be displaced below 3 Hz.

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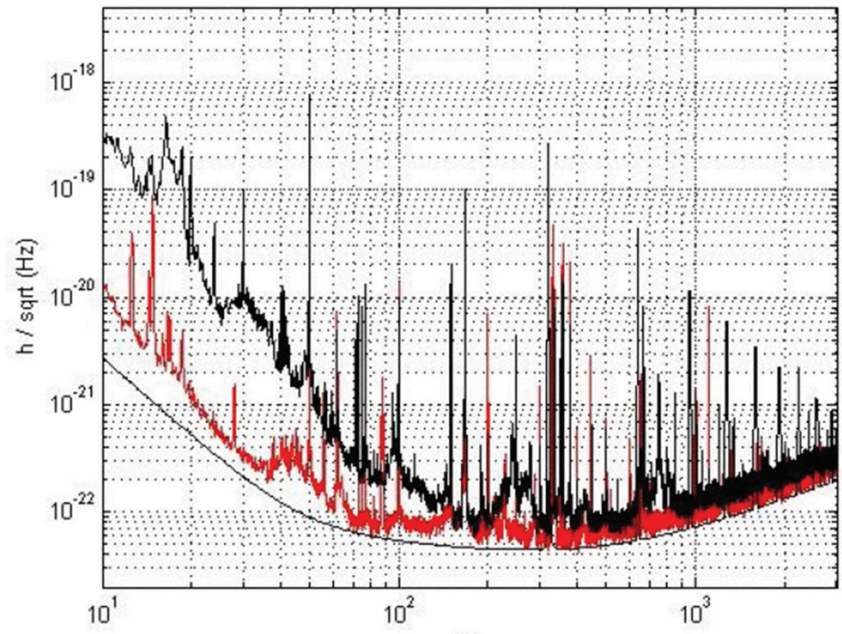

Fig. 1. The typical *Virgo* sensitivity achieved after a few months of the second scientific run (red curve), just slightly better (a factor 2-3 in the tens of Hz region) than the ones achievable during our test period. The continuous curve represents the design sensitivity (discussed in [1] - section *Sensitivity Curves*), while the black one is the sensitivity reached in 2007, during the first scientific run.

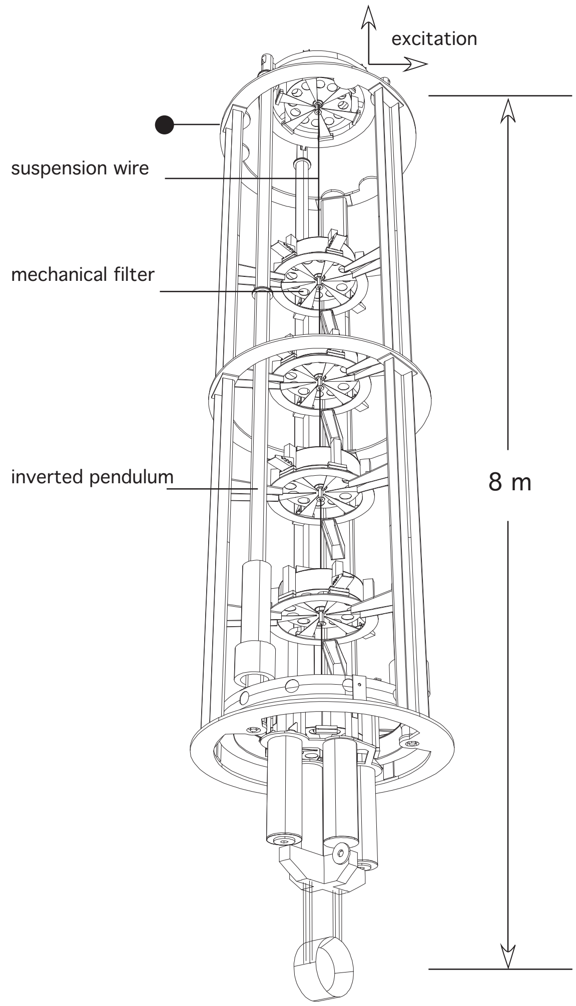

Fig. 2. The *Virgo* Superattenuator to suppress the transmission of ground seismic vibrations to the suspended mirror. One can notice the mechanical filter chain and the three legs of the inverted pendulum resting on the bottom ring connected to the ground based external safety structure, surrounding the entire system. In our attenuation measurements the excitation is applied to the filter chain suspension point.

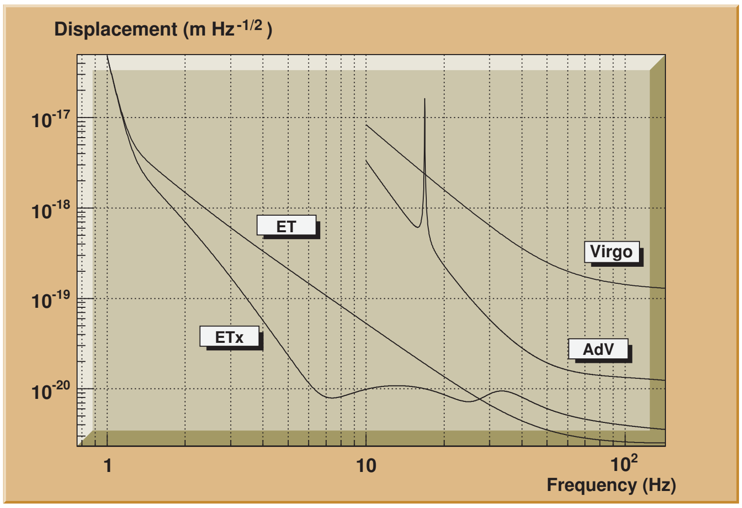

Fig. 3. Design displacement sensitivities of *Virgo* and of the future antennas: *Advanced Virgo* (*AdV*) and the two reference configurations of *Einstein Telescope*, the standard set-up (*ET*) and the 'Xylophone' design (*ETx*), optimized for the low frequency detection. While *Virgo* and the *AdV* detection band starts from 10 Hz, *Einstein Telescope* aims to reduce the lower frequency threshold down to a few Hz.

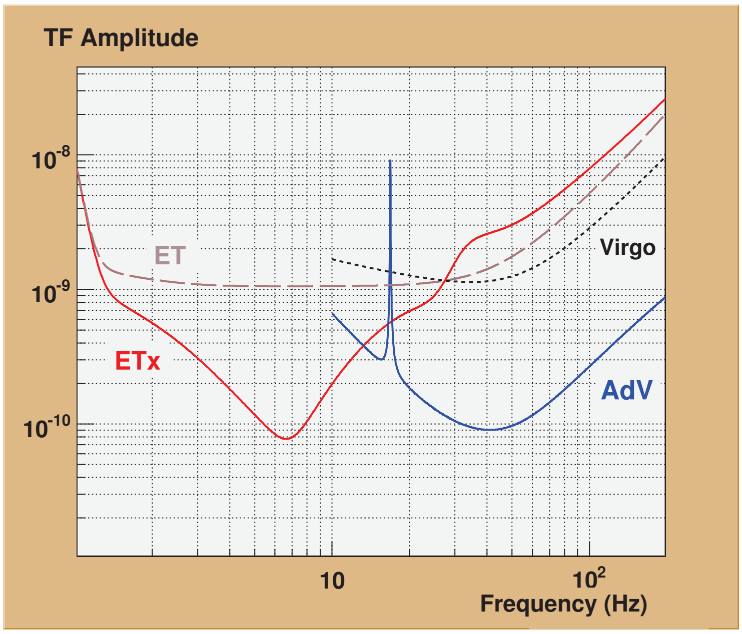

Fig. 4. Seismic vibration transfer function requirements for the different antennas. The curves are obtained dividing the displacement sensitivities displayed in Fig.3 by the conservative linear spectral density of the seismic noise at the ground level. Since the seismic noise will be at least a couple of orders of magnitude smaller operating underground, *Einstein Telescope*, despite its better sensitivity, is less demanding in terms of seismic attenuation at high frequency.

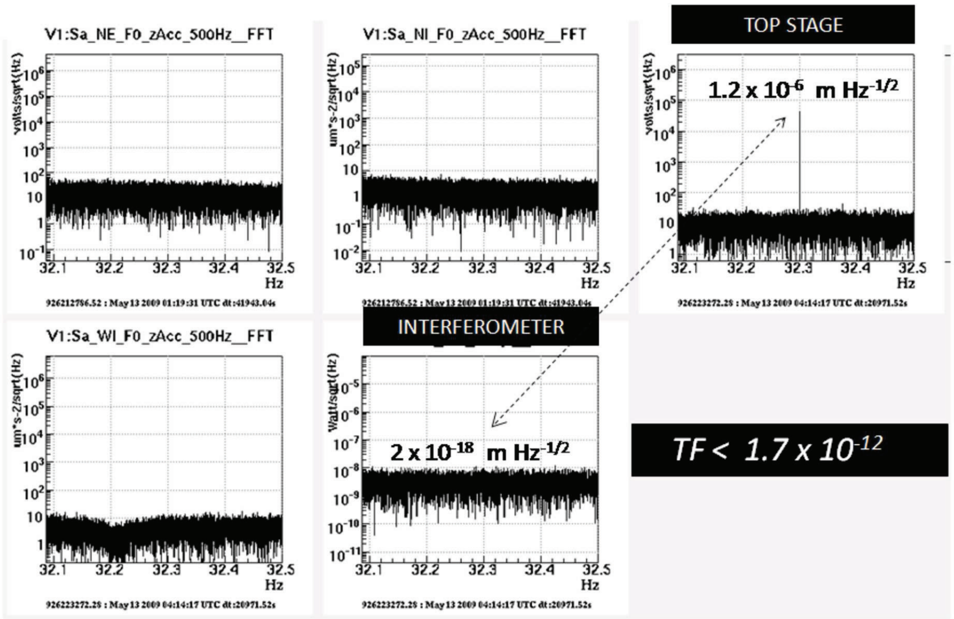

Fig. 5. The top stage of the *Virgo* West cavity terminal Superattenuator is shaked along the beam direction at 32.3 Hz. The top stage displacement linear spectral density measured by the accelerometers is compared with the mirror displacement one detected by the interferometer, dominated by the antenna noise. While in terms of linear spectral density an incoherent floor is independent of the measurement time, the peak amplitude on the top stage scales with its square root. The integration time of all the experiments is reported in *Table 1* and *Table 2*. The other plots concern the top stage horizontal displacements of the Superattenuators not involved in the measurement.

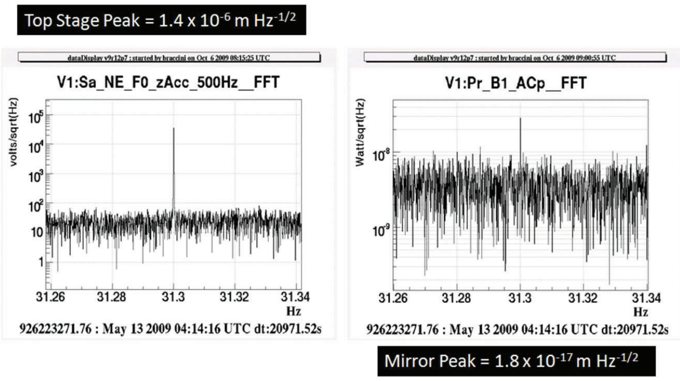

Fig. 6. When a sinusoidal excitation is applied along the beam at 31.3 Hz to the top stage of the terminal Superattenuator of the North Fabry-Perot cavity a residual peak was detected at the mirror level and a transfer function around $1.3{\cdot}10^{-11}$ was measured.

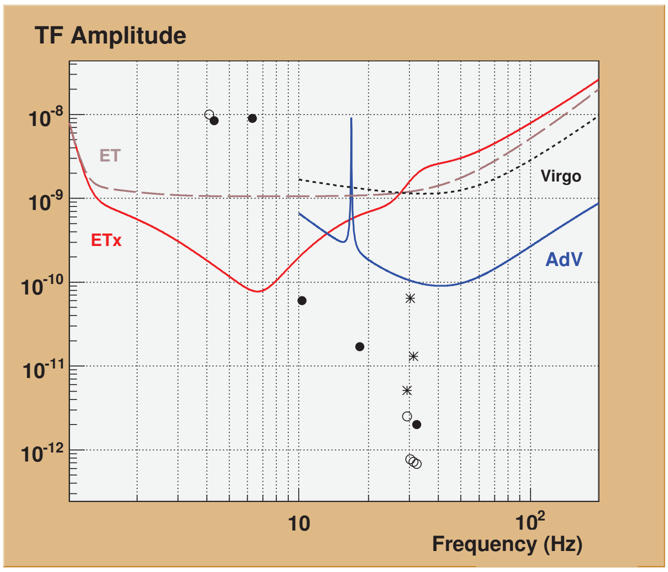

Fig. 7. The transfer functions measured in the various experiments (see *Table 1* and *Table 2*) compared to the requirements of Fig.4. The dots indicate the upper limits (full dots: excitations along the beam, empty dots: vertical excitations). The three stars denotes the "direct measurements", when a peak was detected at the mirror level with top stage beam direction excitation.