Virgo upgrade investigations

F. Acernese\(^6\), P. Amico\(^10\), M. Alshhourbagy\(^{11}\), S. Aoudia\(^7\), S. Avino\(^6\), D. Babusci\(^4\), G. Ballardin\(^2\), F. Barone\(^6\), L. Barsotti\(^{11}\), M. Barsuglia\(^8\), F. Beaulieu\(^1\), S. Birindelli\(^{11}\), M.A. Bizouard\(^8\), C. Boccara\(^9\), F. Bondu\(^7\), L. Bosi\(^{10}\), C. Bradaschia\(^{11}\), S. Braccini\(^{11}\), A. Brillet\(^7\), V. Brisson\(^8\), L. Brocco\(^{12}\), D. Buskulic\(^1\), E. Calloni\(^6\), E. Campagna\(^3\), F. Cavalieri\(^8\), R. Cavalieri\(^2\), G. Cella\(^{11}\), E. Chassande-Mottin\(^7\), C. Corda\(^{11}\), A.-C. Clapson\(^8\), F. Cleva\(^7\), J.-P. Coulon\(^8\), E. Cuoco\(^2\), V. Dattilo\(^2\), M. Davier\(^8\), R. De Rosa\(^6\), L. Di Fiore\(^6\), A. Di Virgilio\(^{11}\), B. Dujardin\(^7\), A. Eleuteri\(^9\), D. Enard\(^2\), I. Ferrante\(^{11}\), F. Fidecaro\(^{11}\), I. Fiori\(^{11}\), R. Flaminio\(^{1,2}\), J.-D. Fournier\(^7\), O. Francois\(^2\), S. Frasca\(^12\), F. Frasconi\(^{2,11}\), A. Freise\(^2\), L. Gammaitoni\(^{10}\), A. Gennai\(^{11}\), A. Giazotto\(^{11}\), G. Giordano\(^4\), L. Giordano\(^6\), R. Gouaty\(^1\), D. Grosjean\(^1\), G. Guidi\(^1\), S. Hebri\(^2\), H. Heitmann\(^7\), P. Hello\(^8\), L. Holloway\(^2\), S. Karkar\(^4\), S. Kreckelbergh\(^8\), P. La Penna\(^2\), N. Letendre\(^1\), M. Lorenzini\(^5\), V. Loriette\(^9\), M. Loupias\(^2\), G. Losurdo\(^3\), J.-M. Mackowski\(^5\), E. Majorana\(^{12}\), C. N. Man\(^7\), M. Mantovani\(^{11}\), F. Marchesoni\(^{10}\), F. Marion\(^1\), J. Marque\(^2\), F. Martelli\(^3\), A. Masserot\(^1\), M. Mazzoni\(^3\), L. Milano\(^6\), C. Moins\(^2\), J. Moreau\(^9\), N. Morgado\(^5\), B. Mours\(^1\), A. Pai\(^{12}\), C. Palomba\(^{12}\), F. Paoletti\(^{2,11}\), S. Pardi\(^3\), A. Pasqualetti\(^2\), R. Passaquieti\(^{11}\), D. Passuello\(^{11}\), B. Perniola\(^3\), F. Piergiovanni\(^2\), L. Pinaud\(^3\), R. Poggiani\(^{11}\), M. Punturo\(^{10}\), P. Puppo\(^{12}\), K. Qipiani\(^6\), P. Rapagnani\(^{12}\), V. Reita\(^9\), A. Remillieux\(^3\), F. Ricci\(^{12}\), I. Ricciardi\(^6\), P. Ruggi\(^2\), G. Russo\(^6\), S. Solimeno\(^6\), A. Spallicci\(^7\), R. Stanga\(^3\), R. Tedde\(^2\), M. Tonelli\(^{11}\), A. Toncelli\(^{11}\), E. Tournefier\(^1\), F. Travasso\(^{10}\), G. Vajente\(^{11}\), D. Verkindt\(^1\), F. Vetrano\(^3\), A. Viceré\(^3\), J.-Y. Vinet\(^7\), H. Vocca\(^{10}\), M. Yvert\(^1\), Z. Zhang\(^2\)

\(^{1}\) Laboratoire d’Annecy-le-Vieux de Physique des Particules, Annecy-le-Vieux, France
\(^{2}\)European Gravitational Observatory (EGO), Cascina (Pi), Italy
\(^{3}\)INFN, Sezione di Firenze-Urbino, Sesto Fiorentino, and/or Università di Firenze, and/or Università di Urbino, Italy
\(^{4}\)INFN, Laboratori Nazionali di Frascati, Frascati (Rm), Italy
\(^{5}\)LMA, Villeurbanne, Lyon, France
\(^{6}\)INFN, sezione di Napoli and/or Università di Napoli "Federico II" Complesso Universitario di Monte S.Angelo, and/or Università di Salerno, Fisciano (Sa), Italy
\(^{7}\)Departement Artemis – Observatoire de la Côte d’Azur, BP 42209 06304 Nice, Cedex 4, France
\(^{8}\)ESPCI, Paris, France
\(^{9}\)INFN, Sezione di Perugia and/or Università di Perugia, Perugia, Italy
\(^{10}\)INFN, Sezione di Roma and/or Università di Roma "La Sapienza", Roma, Italy
\(^{11}\)INFN, Sezione di Pisa and/or Università di Pisa, Pisa, Italy
\(^{12}\)INFN, Sezione di Perugia and/or Università di Perugia, Perugia, Italy
Abstract. While the current interferometric gravitational wave detectors are approaching their nominal sensitivity, the new generation of detectors is in an advanced design phase. The Virgo collaboration is defining now the path to arrive to a complete design of the advanced version of the detector within about two years. The upgrades needed to obtain a detector with improved sensitivity in a relatively short time are here discussed.

1. Introduction
The commissioning of the Virgo detector started in September 2003 and in less than two years the sensitivity gained many orders of magnitude, approaching the nominal one (see [1]). When the technical noises, that are still dominating the sensitivity of the detector (mainly control and electronic noises), will reach their design level, the detector noise performances will be described in terms of three fundamental noises: seismic noise at very low frequency, thermal noise between few hertz and few hundred hertz and shot noise from few hundred hertz to 10 kHz. Obviously, the realization of an advanced version of the current detector passes through the reduction of these noises; this will be attained replacing many of the detector components (mirrors, lasers, suspension wires, . . .), upgrading the control system electronics and strategy and designing more advanced interferometer topologies (signal recycling). Some of these upgrades are compatible with the current optics and mechanics or require a relatively short implementation time; for this reason an intermediate upgrade step of the Virgo interferometer can be foreseen (Virgo +), replacing only few components, but obtaining a competitive detector sensitivity.

2. Noises limiting the expected Virgo sensitivity and medium term upgrades
2.1. Seismic noise
In the Virgo detector, the main interferometer mirrors are suspended through a chain of seismic filters named Super–Attenuator (SA) [2]. The filtering performance of the SA is already compliant with the noise requirements of a second generation detector; in fact, above 4 Hz the expected suspension thermal noise is larger than the measured residual seismic noise. For this reason, a major upgrade of the SA system is not foreseen. It must be noted that another noise related to the seismic vibration is the Newtonian or gravity gradient noise [3], due to the direct coupling of the suspended mirrors with the neighboring masses, that is not limiting the sensitivity of current detectors but will play a large role in the next generation interferometers.

2.2. Suspension thermal noise
The displacement power spectrum due to suspension thermal noise can be written as:

\[ \langle x^2(\omega) \rangle = \frac{4k_BT}{\omega} M_m \left[ \frac{1}{\omega_0^2 \phi_T(\omega)} + \frac{\omega_0 Q_{visc}^{-1}}{\omega \omega_0^2 g} \right] |H_{pend}(\omega)|^2 \]  

(1)

where \( k_B \) is the Boltzmann constant, \( T \) is the temperature, \( 1/Q_{visc} \) is the sum of all the viscous losses, \( H(\omega) \) is the force–to–displacement transfer function for the pendulum mode:

\[ H_{pend}(\omega) = \frac{1}{M_m} \left( \frac{1}{\omega_0^2 - \omega^2} + \frac{1}{\omega_0^2 \phi_T(\omega) + \omega_0 Q_{visc}^{-1}} \right) \]  

(2)

and \( \omega_0^2 = g/L_w \), \( M_m \) is the mirror mass, and, for a four wire suspension is

\[ \omega_{0w}^2 = \frac{k_{elastic}}{M_m} = \left( \frac{4 \cdot 2 \cdot \sqrt{\Lambda E_w I_2}}{2L_w^2} \right) \cdot \frac{1}{M_m} ; \quad \Lambda = \frac{M_m g}{4} ; \quad I_2 = \frac{\pi}{4} r_w^4 \]  

(3)
\( L_w, r_w \) and \( E_w \) are respectively the length, the radius and the Young’s modulus of the suspension wire. The loss angle \( \phi_T(\omega) \) should take into account several contributions: structural losses \( \phi_s \), excess losses \( \phi_e \) and the thermoelastic effect \( \phi_{te} \). The structural loss angle is intrinsic to the suspension material. The excess loss angle is due to several sources: clamping, friction with the mirror, surface effects.

Although the last stage of the mirror suspension [4] in Virgo is a traditional metallic double wire suspension, a large effort has been dedicated to minimize the dissipation due both to the wire material [5] and to the clamping system [6]. This permits to obtain a mechanical quality factor \( Q \) of the pendulum mode of about \( 8 \cdot 10^5 \); hence, the expected thermal noise due to the suspension is given by the curve (c) in figure 1. Another effect can reduce the pendulum \( Q \) in Virgo, limiting the detector sensitivity in the low frequency range: the dissipation due to the eddy currents generated in the reference masses by the steering magnets attached to the Virgo mirrors. The eddy current effect has been evaluated in [7, 8]; this kind of dissipation causes a viscous damping of the pendulum mode and, since the damping due to the residual gas in the Virgo tower is negligible, in the equations (1) and (2) can be set \( Q_{\text{visc}} \approx Q_{\text{eddy}} \). In the current implementation of the Virgo suspension, this dissipation should be comparable with the pendulum mechanical \( Q \) and some adjustment will be necessary in order to reach the nominal Virgo noise.

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**Figure 1.** Fundamental noises limiting the expected (a) Virgo sensitivity: (b) Seismic noise; (c) Thermal noise of the pendulum mode of the last stage suspension; (d) Mirror thermal noise; (e) Optical read–out noise (Shot + radiation pressure noises); (f) Newtonian Noise [3]

**Figure 2.** Comparison between the model (continuous line) of the force exerted on a suspended mass by an comb capacitor actuator and the data measured in the prototype

2.2.1. Monolithic fused silica suspension: Thanks to the pioneering work [9] of the Braginsky group in Moscow, to the studies for the realization of the GEO600 suspension of the Glasgow group [10] and to the R&D activity of the Virgo Perugia group [11], the reduction of the suspension thermal noise can be obtained adopting a monolithic fused silica fiber design for the last stage of the mirror suspension. The thermo–mechanical characteristics of the fused silica permit to reduce both the structural loss \( \phi_s \) and the thermo–elastic effect \( \phi_{te} \); the monolithic design reduces the excess losses \( \phi_e \). The realization of a monolithic fused silica suspension in Virgo requires a severe engineering activity; a full scale prototype must be realized and the
compatibility with the Virgo cleanliness and robustness must be verified; the Virgo control systems must be upgraded to ensure the safety of the suspension. For this reason, in the framework of the EGO R & D programme, the realization of two fiber production facilities has been supported and an innovative CO\textsubscript{2} laser fiber production machine and a completely automatized O\textsubscript{2}–H\textsubscript{2} flames facility are under construction respectively by the Glasgow GEO600 and Perugia Virgo groups.

2.2.2. Electrostatic actuators: Using a monolithic fused silica fiber design for the Virgo suspension a Q of about 10\textsuperscript{9} can be obtained for the pendulum mode (evaluated with fibers of 500\textmu m of diameter); obviously this requires a dramatic reduction of the eddy current dissipation. This can be reached either simply using a dielectric reference mass or adopting an electrostatic actuation system to control the mirror position and movement. Although the latter option is the most complex, it could permit to obtain some improvement in the mirror thermal noise, because of the reduction of the excess dissipation due to the magnets attached on the mirror surface. For this reason an electrostatic control system is under study in the Virgo–Napoli laboratory. An electrostatic actuation system is already working in the GEO600 interferometer [12], but further information are needed to understand if such a system is compatible with the noise requirements of an advanced version of Virgo; a refined model of the force field generated by a comb capacitor actuator has been studied and compared with the data recorded in a prototype developed in Napoli. A comb capacitor actuator has been used to exert a displacing force on a small cylindric test mass (7 cm radius, 7 cm thickness) suspended in a double wire configuration; the displacement has been measured through an optical lever system. The preliminary results on the agreement between the force model and the measured data are reported in figure 2.

**Figure 3.** Mirror thermal noise evaluated in Virgo: curve (a) is the incoherent sum of all the mirror dissipation contributions; (b) is the bulk Brownian noise; (c) is the coating Brownian noise \((\phi_{\text{coat}} = 4 \cdot 10^{-4})\); (d) is the bulk thermo-dynamical noise; (e) is the coating thermo-dynamical noise and (f) is the thermo-refractive noise.

**Figure 4.** Mirror thermal noise evaluation: curve (b) shows the new bulk dissipation evaluation based on the model in equation (5); (c) is the Brownian noise due to the coating \((\phi_{\text{coat}} = 1.6 \cdot 10^{-4})\); (a) is the new mirror total thermal noise evaluation; (d) is the mirror thermal noise evaluation based on a frequency independent bulk dissipation model.
2.3. Mirror thermal noise

The mirror thermal noise in the sensitivity curve can be seen as the incoherent sum of four different noise sources: Classical Brownian motion of the mirror (bulk+coating), Thermo–Dynamical fluctuation of the mirror bulk, Thermo–Dynamical fluctuation of the mirror coating and Thermo–refractive fluctuation of the mirror coating.

It has been shown by Levin [14] that the Brownian noise of the mirror bulk can be evaluated by the direct application of the Fluctuation–Dissipation theorem; the displacement power spectrum can be written, at low frequency, as:

\[
\langle x_{\text{Brown}}(\omega) \rangle^2 = \frac{4k_BT}{\omega} \phi_{\text{mirr}} \cdot U
\]

where \(\phi_{\text{mirr}}\) is the loss angle of the mirror, taking in account also the contribution of the coating Brownian dissipation [13], and \(U\) the the elastic energy stored in the mirror under a normalized gaussian pressure having the shape of the laser beam. The energy \(U\) has been evaluated by Levin in the approximation of an infinite size mirror and by Vinet [15] for a finite size mirror and it is related to the waist of the beam impinging into the mirror. The thermo–dynamical and thermo–refractive noises are due [16] to the coupling of the temperature variance \(\delta T\) to the displacement fluctuation through, respectively, the thermal expansion coefficient \(\alpha\) and the thermal gradient of the refraction index \(\partial n/\partial T\) of the coating and bulk materials. Thanks to the measurement of the \(T_{\text{aqO}_5}\) coating dissipation [17] and to the evaluation of the bulk dissipation of the Virgo mirror at the drum mode resonance [18], it is possible to evaluate the four dissipation contributions to the mirror thermal noise, as reported in figure (3). It must be noted that, for sake of completeness, in figure (3) and (4), the thermal peak of the first drum mode of the Virgo mirrors is reported, although the equation (4) cannot describe it.

2.3.1. New substrate thermal noise evaluation

The previous mirror thermal noise evaluation has been computed considering a frequency independent bulk loss angle and performing the direct measurement of the mechanical Q of the mirror drum mode (about 5580 Hz) through the evaluation of the characteristic ring–down time. The typical measured value is of the order of \(10^7\). Recently, a new model [19] for the frequency dependence of the mechanical losses in fused silica has been proposed; the loss angle shows the behavior:

\[
\phi(f, S/V) = C_1 S/V + C_2 \left( \frac{f}{1Hz} \right)^{C_3} + C_4 \phi_{\text{te}}
\]

where \(S/V\) is the ratio between the surface and volume of the mirror. Penn and coll. [19] evaluated the coefficients \(C_i\) for the Haraeus Suprasil 312 fused silica, finding \(C_1 = 6.5 \cdot 10^{-12} \text{ m}\), \(C_2 = 7.6 \cdot 10^{-12}\), \(C_3 = 0.77\), neglecting the thermo–dynamical contribution \(\phi_{\text{te}}\) of the substrate. The Virgo input mirrors are made by Haraeus Suprasil 311 SV fused silica and we could expect a similar behavior; implementing \(\phi(f, S/V)\) in the equation (4) the curve (b) in figure (4) is obtained for the bulk Brownian noise in a Virgo mirror.

2.3.2. Low mechanical dissipation coatings

The reduction of the computed contribution of the bulk dissipation to the mirror thermal noise budget enhances the role of the coating dissipation. The Virgo–LMA group in Lyon started several R&D activities in collaboration with LIGO, in the EGO R&D and ILIAS frameworks. It has been measured, in thin coated slabs, that doping the coating with Titanium, increases the mechanical Q by a factor 2. In recent measurements [19] it has been obtained \(\phi_{\text{coat}} = 1.6 \cdot 10^{-4}\); using this value the coating Brownian noise contribution to the mirror thermal noise, in the Virgo geometry, has been evaluated in the curve (c) of figure (4).
2.4. High power lasers
The high frequency range of the nominal Virgo sensitivity is dominated by the laser shot noise; obviously the reduction of this noise passes through the use of high power lasers in Virgo. Although high power lasers, based on different technologies (disk lasers, fiber lasers, . . .), are already available, very promising is the development of a low noise, hundred(s) Watt power laser by the GEO600–Hannover [20] group; the implementation in Virgo of such as laser requires the upgrade of many components in the interferometer. In a shorter term scenario it seems already possible to insert a 50 W laser with minor changes in the injection and main optics.

2.5. Controls upgrade
It should not be neglected that the sensitivity of the current detectors is still dominated, in a large fraction of their frequency range, by the electronic and control noises. In Virgo the controls are managed by custom DSP boards and by CPU’s; the complexity of the implemented control loops pushed these systems to the limit. For this reason a new DSP board generation, hosting 6 DSP, is under development [21] as well as new communication and timing boards. New actuation electronics (DACs with larger dynamic range and coil drivers with lower noise) is under realization, while new ADCs are under evaluation.

3. Conclusions
Considering the previous list of upgrades, a new sensitivity curve can be drawn for the detector, as shown in figure 5. This noise level could permit to reach a detection range for NS/NS of about 56 Mpc (SNR 6.5) to be compared to the 14 Mpc of Virgo. Obviously this Virgo + scenario is only the first step toward a complete upgrade of the Virgo detector, pointing to the realization of a second generation (advanced) interferometric detector. In the latter, higher power lasers, a new topology of the interferometer (signal recycling) and new beam geometries (i.e. flat beams) are probably necessary and this will be studied in a longer R&D program in Virgo.

Figure 5. A possible scenario for Virgo + sensitivity: (a) Virgo + sensitivity using the mirror thermal noise evaluated in figure 4 and the Newtonian noise [3]; (a1) Virgo + sensitivity without Newtonian noise; (a2) Virgo sensitivity; (c) Virgo + pendulum thermal noise; (d) mirror thermal noise evaluated in figure 4; (e) optical read–out noise (shot noise + radiation pressure noise); (f) Newtonian noise.

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