Environmental noise studies in Virgo

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Abstract. The study of the external influences from environmental disturbances is a fundamental issue in interferometric detection of gravitational wave, both in locking and in normal operation.

Virgo is continuously monitored by a large number of environmental sensors, ranging from seismometers to microphones to electromagnetic probes, up to a weather station. Using data collected during the engineering runs, we have studied the features of the main external noise sources, and the way they interfere with Virgo operation and expected sensitivity. In this paper we present the preliminary results obtained.

The study of external influences on interferometer dark fringe signal is of fundamental importance in gravitational wave detectors, to improve the sensitivity, reduce false alarms, and understand locking problems.

This paper will present a review of the status of environmental noise studies, focused on seismic, acoustic and magnetic disturbances.

The data presented here have been collected during the first phase of Virgo commissioning run C5 , when the interferometer was operated in recombined mode with a sensitivity of $10^{-15}/\sqrt{Hz}$ at 10 Hz and $10^{-20}/\sqrt{Hz}$ around 200 Hz(see [1]), while more recent data are used for the analysis of the effect of wind and lightning.

1. The Virgo environmental monitoring system

Virgo is continuously monitored by several environmental sensors placed in key points inside the central and the terminal buildings.

Data collected by the monitoring system are recorded, together with the interferometer output,and stored by the data acquisition system.

Slow varying quantities, like temperature, pressure and humidity are acquired once per second, while quickly varying ones are recorded with varying sampling rate according to the sensor bandwidth.

The slow monitoring system consists of more than 150 temperature probes (placed inside and outside the vacuum region, at different heigths along the suspensions), 11 pressure and humidity sensors, one weather station and one lightning detector.

The fast monitoring system is more complex: the seismic activity and the mechanical vibrations are monitored by 13 piezo vertical accelerometers, 5 triaxial low frequency accelerometers, and one very low frequency triaxial velocimeter. In addition, the accelerometers and LVDT's placed on top of each inverted pendulum, used for the inertial damping control, can provide additional information in the sub-Hz range.

Acoustic noise is monitored with six microphones, placed inside the building (near the beam splitter and North input towers, and inside the laser injection room), the mode cleaner and the terminal buildings.

Finally, nine magnetometers, three for each direction, are placed inside the building and the terminal towers.
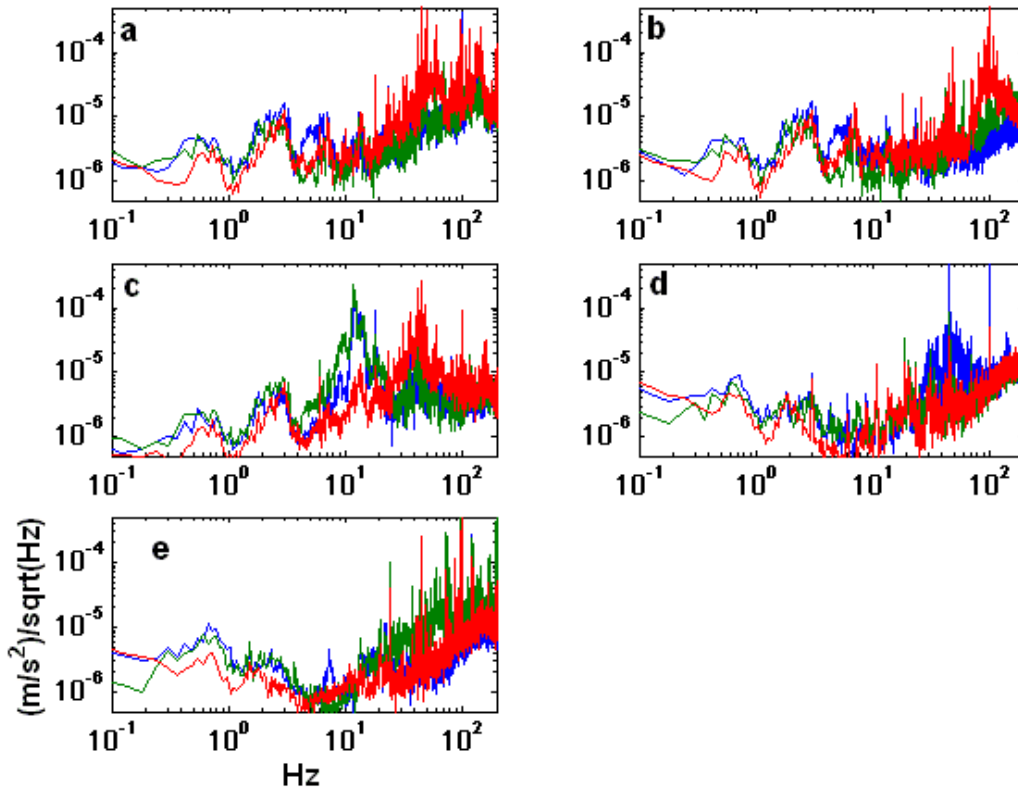
2. Seismic noise

Seismic noise isolation is achieved in Virgo through a multi-stage suspension (the so called superattenuator)[2, 3] , whose performance is enhanced through the active inertial damping of the horizontal movements of the supension point of the first stage. Seismic movements are thus attenuated by 10 orders of magnitude already at 4 Hz.

The most useful informations for seismic studies comes from the triaxial accelerometers, (Episensor ES-T from Kinemetrics), since their useful bandwidth, from 0.1 to 200 Hz, coincides with

Figure 1. ground acceleration spectra as measured in different places: the blue line is North-South direction, the green one is East-West and the red one is vertical.
a) Central building, near beam splitter
b) Central building, near North input tower
c) Central building, inside the laser injection room
d) North end building
e) West end building

the greatest sensitivity of the interferometer to external vibrations. Three of them are placed inside the building (near the beam splitter and North input towers, and inside the laser injection room), while one is placed inside each of the terminal towers. The sensors are mounted on the same concrete slab were suspension towers are placed.

The properties of the seismic activity of the Virgo site are described in detail in[6].

The seismic spectra measured by the five Episensors in the three Virgo buildings are shown in fig.1: they show different shapes, while their order of magnitude is similar.

Checking the daily and weekly variations of the spectral densities and the correlation with weather condition[6], one can identify four bands:

- For 0.1 Hz to 1 Hz the main contribution is due to sea microseism.
- From 1 Hz to about 4 Hz we have the contribution from the traffic on the nearby highway bridges

- From 4 Hz to 10 Hz the local human activity dominates.
- From 10 to 200 Hz we can see lines due to motors and electronic equipment inside the buildings.

The coherence among the sensors in far buildings is quite negligible, except for a small but significative correlation in the microseism and traffic bands.

The signals from Episensors show a clear correlation with the dark fringe signal at very low frequency, from 0.1 Hz (were sensor noise dominates) to about 1.2 Hz (see fig.2).

Moreover, the correlation with horizontal ground acceleration dominates up to 0.5 Hz, while from 0.5 H to 1.2 Hz the vertical resonances of the superattenuator are clearly visible.

The future implementation of inertial damping also for the vertical degree of freedom should thus substantialy reduce the rms of the dark fringe signal.

For higher frequency, the coherence is negligible, expect for some very narrow lines in the region between 20 and 100 Hz, clearly correlated with lines seen by the building seismoters. This region, however, will be better studied using acoustic detectors (see next section).

3. Acoustic noise

The coherence of the dark fringe signal with the microphones placed in North End and West end buildings shows no correlation among these quantities.

However, significant coherence is present in narrow lines up to 400 Hz between the dark fringe and the microphones placed inside the central building, as can be seen in fig.3.

The coherence is larger with the microphone placed inside the clean room which hosts the laser stabilization system (the so-called *laser lab*). Moreover, some of these lines have been succesfully identified as produced by pumps, motors and other electronic equipment placed in the same room by switching them off in turn.

To study the path tracked by the noise inside the injection system, some dedicated tests have been performed, placing a loudspeaker inside the laboratory, and driving it with a known and reproducible signal, like pseudo-random white noise or a frequency sweep.

The test performed during the C4 run is described in [7] and suggested the presence of a non linear coupling among the acoustic noise and the dark fringe.

To check that possibility, a new test during C5 has been performed using a frequency sweep as a test signal.

The input signal frequency varied from 20 Hz to 1700 Hz with a rate of 1.2 Hz/s. The sound level was about 40 dB over the normal level.

The injected line was clearly visible in the dark fringe, as can be seen in figure 4, but also a second harmonic appears: one can also see that its amplitude increases when the fundamental crosses a resonance.

The same harmonic can be seen in the spectrogram of the power intensity of the laser light coming out from the Mode Cleaner.

The most likely non linear mechanism which could produce such effect is a transverse vibration of the laser beam before entering the mode cleaner; the trasmitted amplitude will thus receive contribution from the square of the angular beam jitter with respect to the mode cleaner axis, as described in [7].

Laser amplitude stabilization is expected to reduce the amount of noise introduced in the dark fringe; for a real cure of the problem, however, a better acoustic isolation could be essential.

Figure 2. Top: coherence among ground acceleration and dark fringe signal. Color code is the same as fig.1
a) Beam splitter
b) North End
c) West End
Bottom: seismic noise contribution to the dark fringe, calculated from the coherence, taking into acocunt the correlations among sensors:
blue: dark fringe spectrum;
red: contribution from horizontal acceleration;
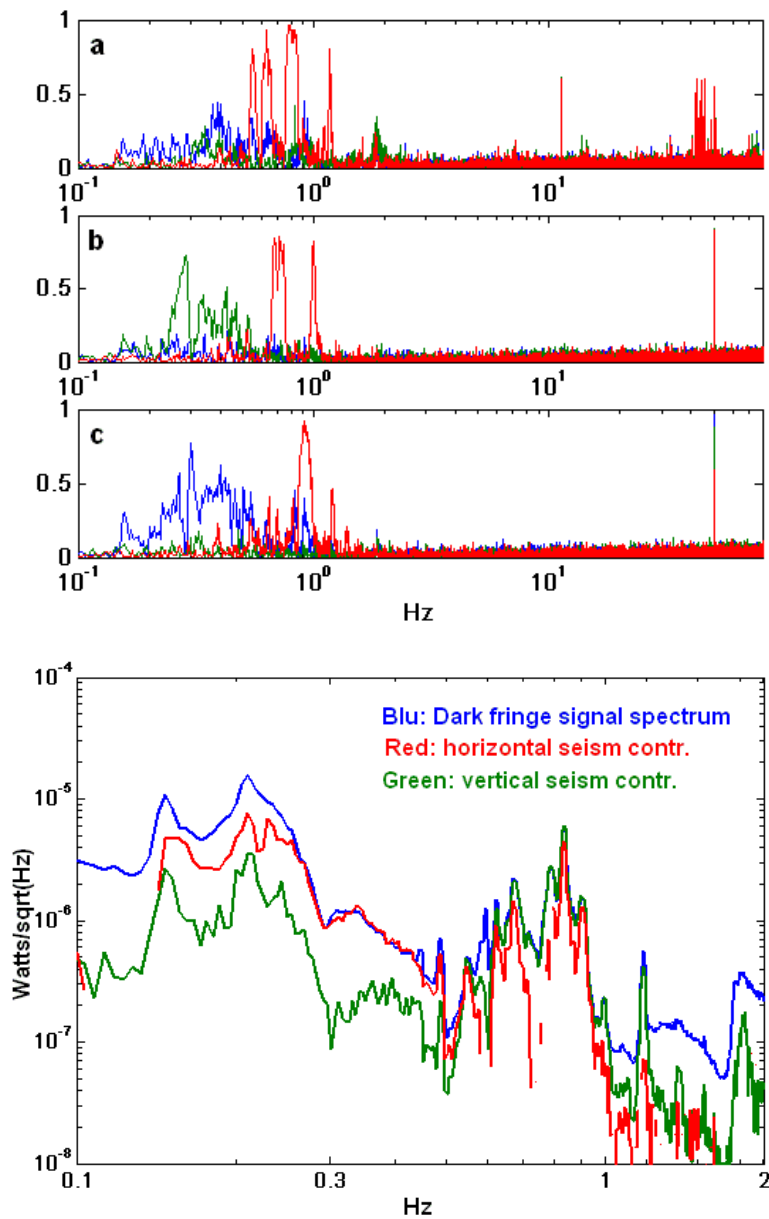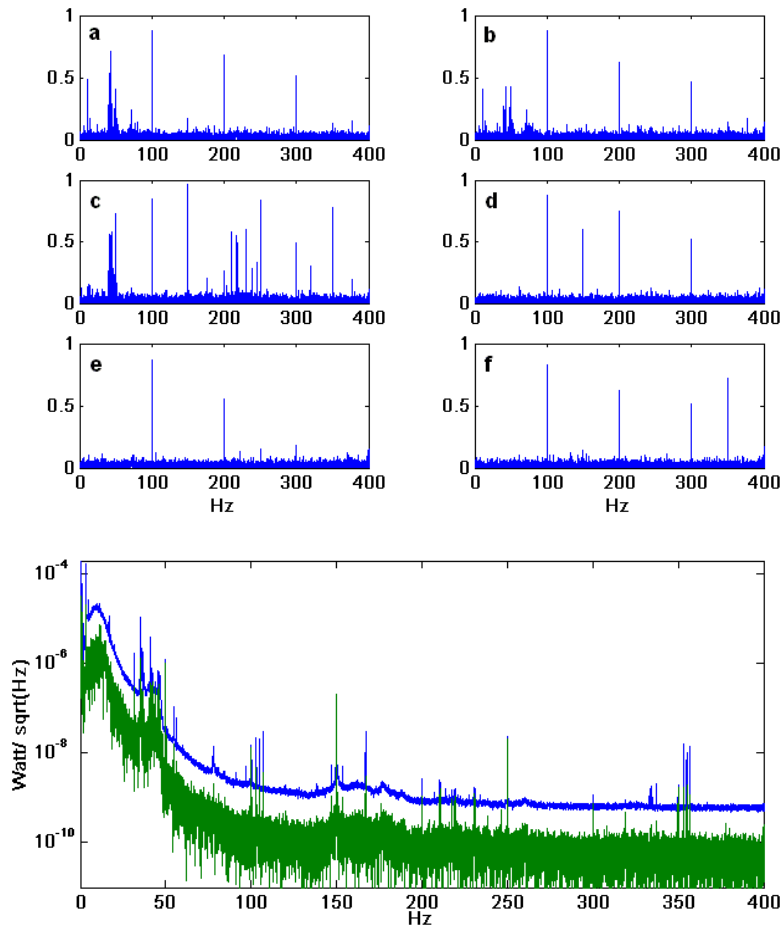green: contribution from vertical acceleration.

Figure 3. Coherence among dark fringe and microphones. Microphone placed:
a) in central building near North input tower
b) in central building near Beam splitter
c) in central building, inside the laser injection lab
d) inside the mode cleaner building
e) inside the North end tower
f) inside the West End tower.
Bottom: contribution of acoustic noise (green) to dark fringe spectrum (blue).
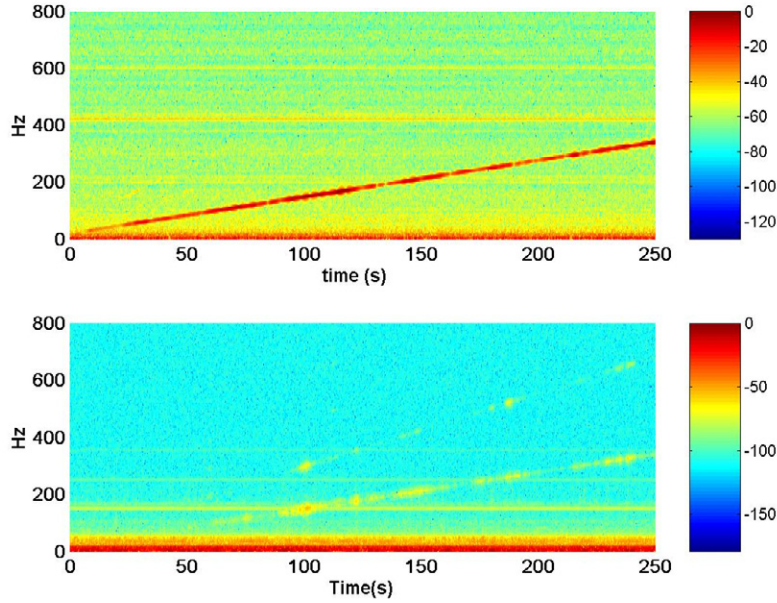

3.1. Wind

A meteo station is placed on the roof of the central building: it records atmospheric temperature, pressure and humidity, plus wind velocity and direction.

To study the effect of the wind, two days of no wind and high wind (about 40 km/h) have been selected in April 2005.

The wind produces a wideband increase of the acoustic and seismic noise up to 100 Hz.

The largest increase (two orders of magnitude) can be seen in the microphone placed in the mode cleaner, which is the lightest building, at a frequency of about 0.8 Hz.

Figure 4. Spectrograms of microphone (top) and dark fringe (bottom), for the first 250 seconds of frequency sweep. The second harmonic is clearly visible.

However, thanks to the good performance of the seismic attenuation, the increase in r.m.s. of the mirror angular displacement (measured by local controls [8]) remains moderate.

4. Magnetic noise

The magnetometers installed inside the Virgo buildings are MFS-06 from Metronix.

The sensor noise is $10^{-2} nT/\sqrt{Hz}$ at 0.01 Hz, and $10^{-7} nT/\sqrt{Hz}$ at 10 kHz. The nominal working range extends up to 10 kHz.

External magnetic field can interact with the mirrors through the magnets attached on their surface which are part of the actuator system used in the locking. Two coupling mechanism are equally likely: through the magnetic field magnitude, which exerts a torque on the mirror magnets, or through field gradient, which exert a net force. In both case, however, the expected contribution to the dark fringe will depende linearly both on the total magnetic momentum of the mirrors (at maximum 0.12 Am^2 in the North input mirror) and on the field strength.
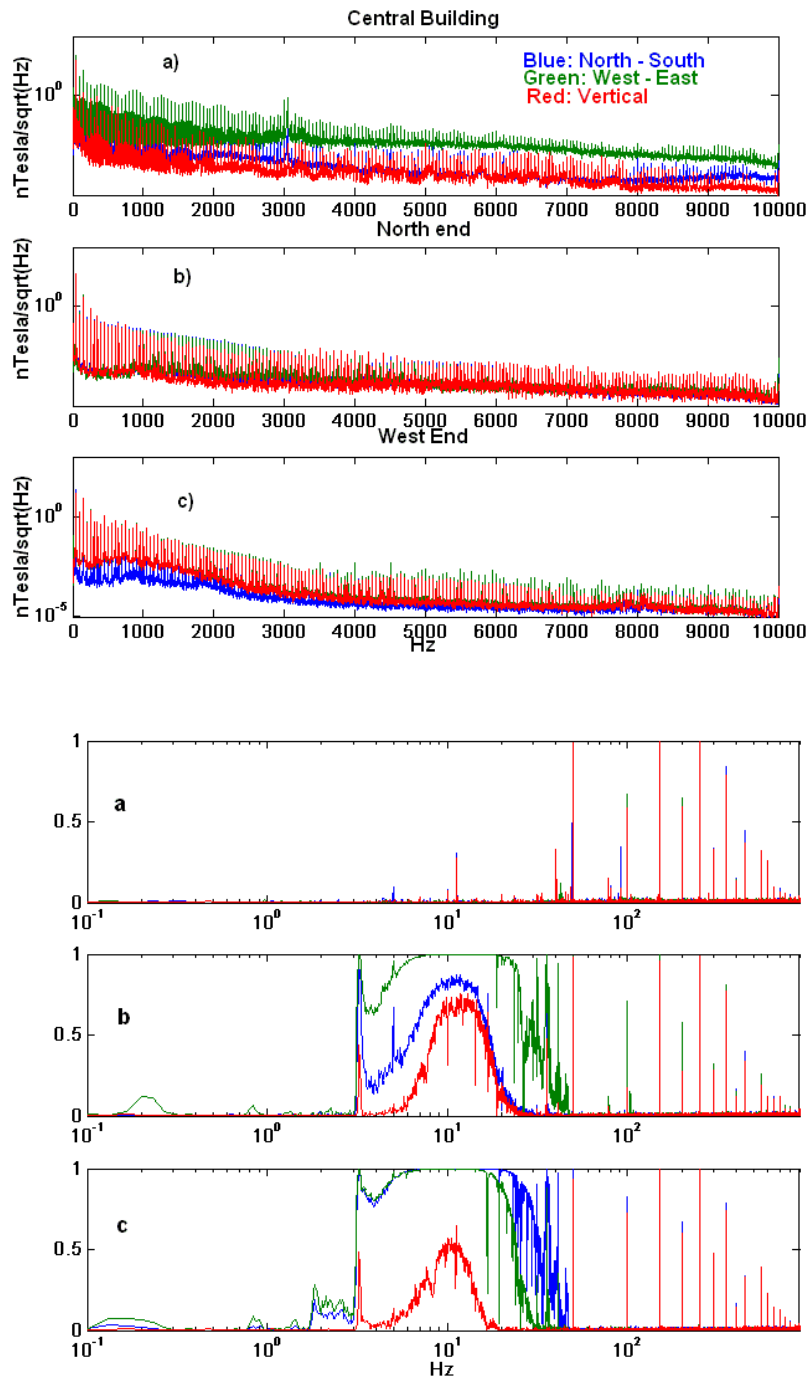
As can be seen in fig.5 no structure can be seen in the noise spectrum, which is dominated by the harmonics of the 50 Hz power line: the background falls smoothly from about $10^{-2} nT/\sqrt{Hz}$ at low frequency (comparable to the sensor noise) to less than $10^{-4} nT/\sqrt{Hz}$ at 10 kHz.

The magnetometer placed along the East-West direction in the building is far away from the others, near a metallic platform, and shows an higher noise level.

While no coherence can be seen between the central building magnetometers and the dark fringe, the terminal building sensors show very high correlation with the dark fringe signal in the region from 2 up to about 20 Hz: however, this is not noise going from the environment to the interferometer, but rather due to the detection of the magnetic field from marionetta control coils. This can be easily verified by looking to the magnetic noise spectrum when control coils are switched off.

Figure 5. Upper three plots: spectrum of magnetometers signal. Lower three plots: coherence of magnetometers signal with dark fringe. The blune line is NS direction, the green one is EW and the red one is vertical.
a) Magnetometers in central building
b) Magnetometers in North End
c) Magnetometers in West En

Using this data we performed a preliminary measurement of the frequency dependence of the magnetic field attenuation from the vacuum tube walls: a preliminary study shows that the transfer function is almost flat up to about 20 Hz, and then falls with a single pole slope.

To study the effect of an external magnetic field on the mirrors, a dedicated test is being performed: a big air-wound coil winded on air has been placed near the external wall of the vacuum vessel housing the North input mirror suspension. The field produced by this arrangement on the mirror, in absence of any shielding from the tower walls, was estimated to be 100 nT at a frequency of 61 Hz, strong enough to be seen on the dark fringe . The test is still in progress.

4.1. Lightning detector

A Boltek LD-250 lightning detector is placed on top of the building. It provides a rough estimate of the azimuth and distance of lightning up to about 450 km, within a timing precision of about 1s.

Signals coincident with magnetometer outputs show that our instruments are able to reveal nearby lightning (some km). No effect has been seen so far on the dark fringe.

5. Conclusions

The main environmental disturbance which affect the Virgo dark fringe signal are monitored and well characterized.

Study is in progress to understand the coupling mechanism, and to further reduce their contribution to the detector noise.

[1] F.Acernese et. al, (Virgo Collaboration) *Status of Virgo*, these proceedings.

[2] F. Acernese et al. (Virgo Collaboration) *The commissioning of the interferometer of the Virgo gravitational wave detector*, Astroparticle Physics 21 (2004) 1-22

[3] A. Bozzi et al. (Virgo Collaboration), *Last stage control and mechanical transfer function measurement of the Virgo suspensions*, Rev. Sci. Inst., 73 (2002), 2143-2149

[4] G.Ballardin et al. (Virgo Collaboration), *Measurement of the Virgo superattenuator performance for seismic noise suppression*, Rev. Sci. Inst, 72 (2001), 3643-3652

[5] G. Losurdo et al. (Virgo Collaboration), *Inertial control of the mirror suspensions of the Virgo interferometer for gravitational wave detector* Rev. Sci. Inst., 72 (2001) 3653-3661

[6] F. Acernese et al. (Virgo Collaboration), *Properties of seismic noise at the Virgo site*, Class. Quantum Grav. 21 (2004) S433-S440

[7] F. Acernese et al. (Virgo Collaboration), *A first study of environmental noise coupling to the Virgo interferometer*, Proceedings of GWDAW-9 workshop. to be published on Class. Quantum Grav. 22 (2005)

[8] F. Acernese et al. (Virgo Collaboration), *A local control system for the test masses of the Virgo gravitational wave detector*, Astroparticle physics 20 (2004) 617-628