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Coping with anomalous power absorptions in the Advanced Virgo core optics

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Summary. — For the next observational run (O4), the gravitational wave interferometer, Advanced Virgo Plus (AdV+), will increase the injected power with respect to the past in order to improve its sensitivity at high frequency, the detection volume and the number of candidate sources. In these conditions, the thermal distortions, induced by absorption in optics, will become more relevant, with the risk to degrade the interferometer performance reducing the quality of the control signals and the duty cycle of the instrument. The correction of optical aberrations through adaptive optical systems is crucial to reach design performance. During the third observing run (O3), highly absorbing spots on the surfaces of the main optics have been observed. The analysis and the mitigation of this point-like aberrations has a central role for the interferometer operation, requiring the installation of a new dedicated actuator.

1. – Introduction

Virgo is a dual-recycled Michelson interferometer with Fabry-Perot arm cavities located in Cascina, near Pisa, on the site of the European Gravitational Observatory (EGO) [1], with a detection range from 10 Hz to 10 kHz. It is one of the largest and most sensitive detectors currently in operation, together with the two LIGO interferometric detectors, located in the United States, one in Hanford and one in Livingston [2]. The detection principle of an interferometer is based on the measurement of the phase shift induced by the gravitational wave at the output of the instrument. The Virgo optical layout comprises four resonant optical cavities: Fabry-Perot cavities in the arms (FPC), the power recycling cavity (PRC) and the signal recycling one (SRC). The PRC is designed to recycle the power reflected back towards the symmetric port of the interferometer and the SRC to "recycle" the gravitational signal and shape the sensitivity curve. They are marginally stable and more sensitive to defects [3].

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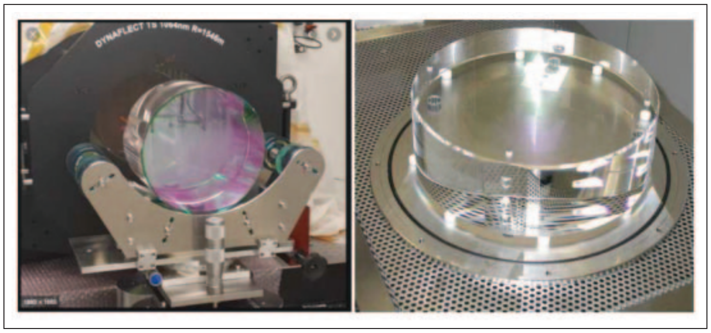


Fig. 1. – Examples of the Advanced Virgo mirrors([1]). (Credits: M. Perciballi/EGO & The Virgo Collaboration.)

2. – Advanced Virgo core optics and the Point Absorbers

2·1. *Advanced Virgo test masses.* – A fundamental role in the interferometer performance is played by the the core optics inside the Fabry Perot cavities (of the order of 100 kW). They must have excellent optical quality and must exhibit very low absorptions because of the high power circulating in the cavities [4]. Advanced Virgo test masses are spherical mirrors with Radius of Curvature RoC ≈ 1.5 km suspended by four fused silica fibers. Examples are shown in fig. 1. They have high-purity fused silica substrates, with a diameter of 35 cm, a mass of 42 kg, and a multi-layer coating made of amorphous oxides. The High Reflectivity (HR) surface has 99.998% reflectivity. Its average power absorption is about 0.5 ppm [5].

2·2. *The Point Absorbers.* – One of the methods used to improve the detection volume and the number of possible gravitational wave source candidates concerns the increase of the input power [3]. In the third scientific run O3, the power was a factor of 2 higher than in the previous observing run. This led to the discovery of highly absorbing spots on the coatings of the core optics which appeared both in LIGO [6] and Virgo: these spots are called Point Absorbers (PA). They are highly detrimental to the performance of the interferometer as they cause scattering of power from the fundamental mode to the higher order modes, with a consequent increase of the round-trip losses inside the FPC, leading to a reduction of the detector's sensitivity. From a spectroscopic analysis, they are caused by a high concentration of Aluminium that polluted coating during their deposition on the mirror and, thus, they can not be cleaned. PAs cause a thermo-elastic deformation of the HR surface and a thermal lensing effect in the optic substrate. Thanks to the information provided by the thermal lensing, it was possible to put in evidence the presence of Point Absorbers on both the Virgo North and West input test masses, as shown in fig. 2. The parameters recovered by the analysis of these data are listed in table I.

The closer a point absorber is to the center, the more harmful it is for the stability of the interferometer. Thanks to the evaluation of these parameters, it was possible to evaluate the thermo-elastic deformation due to the points and the corresponding correction to be applied to mitigate it.

([1]) https://www.virgo-gw.eu/.

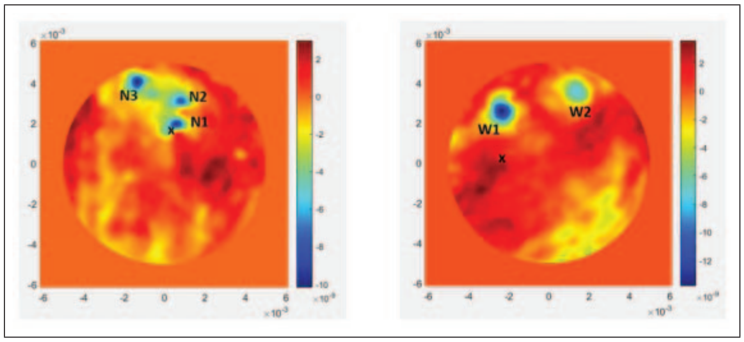
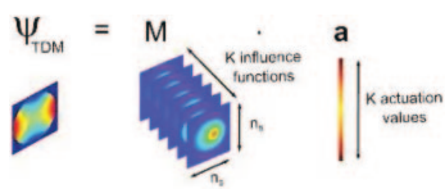


Fig. 2. – Wavefront (WF) maps measured by the Hartmann Wavefront Sensors (HWS) probing the test masses: the North input on the left and the West input on the right. WF has been acquired after the ITF is locked at dark fringe when the power stored in the arm cavities is at maximum.

Table I. – *Point Absorbers characteristics on the Advanced Virgo North (N) and West (W) test masses.*

#point	Distance from the centre [cm]	OPL increase [cm]	Absorption [ppm]	P absorbed [mW]
N1	0.09	0.97	4.3	12.1
N2	1.55	1.19	3.2	11
N3	3.77	0.94	13.9	11.3
W1	3.57	1.18	8.5	10.6
W2	5.35	1.44	19	9.6

To reproduce the corrective target, the influence matrix formalism has been applied [7, 8]:



The idea is to use a matrix of independent actuators. By representing the action of each actuator on the mirror as an influence function, the target will be given by the product of the influence matrix and an actuation vector. The influence matrix collects the influence functions of all the actuators and the actuation vector says which actuator must work at which value.

2˙3. *Actuator design.* – The corrective map is produced by imaging on the test mass surface the heating pattern, defined by the actuation vector. The heating pattern will be generated by illuminating a binary mask (so the allowed actuation coefficients can only take values 0 or 1) with the radiation produced by a ceramic heater. A preliminary evaluation of the correction pattern produced by the actuator is shown in fig. 3.

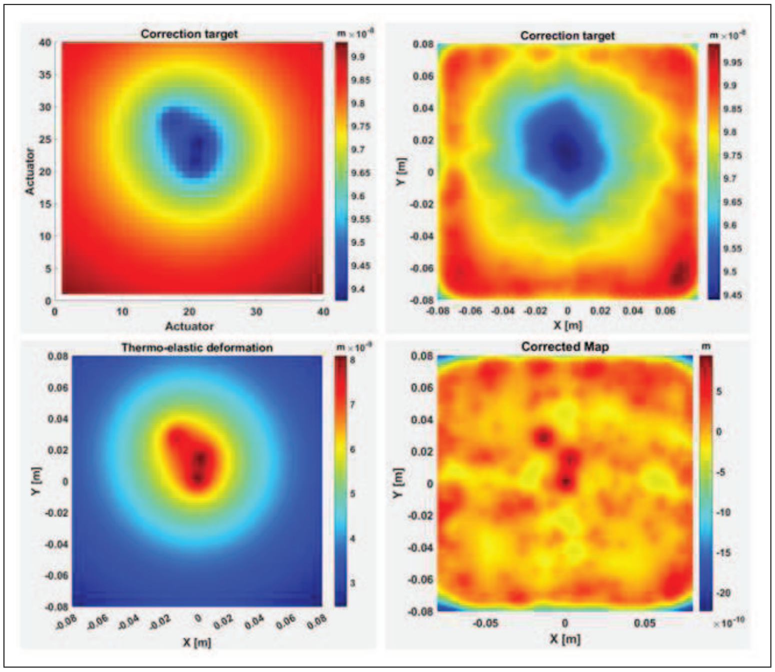


Fig. 3. – Simulated maps with Ansys and MATLAB. Example of the procedure for the North input test mass with 40×40 actuators. Top: (left) the desired correction target; (right) the target reproduced with the influence matrix. Bottom: (left) the original thermo-elastic deformation; (right) the corrected map. The actuation area is smaller than the effective dimensions of the mirror as the effect of the PA is considered relevant within the region of the laser spot size (circular area of about 50 mm of radius).

3. – Conclusions

Point Absorbers investigation is a big challenge in view of the next observational run of ground based interferometers, scheduled for the end of 2022. The design of the system has been finalized and testing and installation on the interferometer will be performed in the forthcoming months.

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