The role of the Thermal Compensation System in Gravitational Waves' detectors

M. Ianni(1)(2)(*), L. Aiello(1)(2), E. Cesarini(1), M. Cifaldi(1), L. A. Corubolo(1)(2), V. Fafone(1)(2), M. Lorenzini(1)(2), D. Lumaca(1), Y. Minenkov(1), I. Nardecchia(1), A. Rocchi(1)and V. Scacco(1)(2)

(1) *INFN, Sezione di Roma 2 - Roma, Italy*
(2) *Università di Roma "Tor Vergata" - Roma, Italy*

Summary. — The global network of gravitational wave detectors has revolutionized astrophysics, offering new opportunities to study some of the most energetic phenomena in the universe. The increasing number of events detected by the LIGO and Virgo interferometers during the various scientific runs has demonstrated the effectiveness of the improvements made to these instruments over the years. Enhancing the sensitivity of these detectors poses a significant challenge, as it requires their proper operation at increasingly higher powers. However, increasing the circulating power in the Fabry-Perot optical cavities leads to greater thermal effects and the onset of wavefront aberrations which, if not properly compensated, compromise the performance of the instrument. For this reason, the implementation and continuous improvement of a Thermal Compensation System have proven essential. The experience gained from the development of LIGO and Virgo will be crucial for the transition to third-generation detectors, such as the Einstein Telescope in Europe and the Cosmic Explorer in the United States.

1. – Introduction

Einstein's theory of General Relativity [1] predicts the existence of gravitational waves (GWs) - ripples in spacetime that propagate at the speed of light and weakly interact with ordinary baryonic matter. While indirect evidence was first observed in the 1970s through the orbital decay of a binary pulsar [2], the first direct detection occurred in 2015, when the LIGO and Virgo collaborations recorded the merger of two stellar-mass black holes [3]. This discovery marked the beginning of gravitational wave astronomy, confirming a century-old prediction. GWs are generated by energetic cosmic events such as black hole and neutron star mergers and core-collapse supernovae, and they carry

(*) Author to whom any correspondence should be addressed.

unique information about the nature of gravity and the behavior of matter under extreme conditions. The produced strain is extremely small - on the order of 10^{-21} - requiring highly sensitive instruments to detect them.
To further improve sensitivity and expand the astrophysical reach of current detectors, next-generation observatories like the Einstein Telescope (ET)[4] and Cosmic Explorer[5] are under development.

2. – Gravitational Waves Detector's Sensitivity

The third observing run (O3) of the LIGO and Virgo detectors, conducted from April 2019 to March 2020, yielded several groundbreaking discoveries. Among the most remarkable was the detection of GW190521, a merger involving a black hole with an unexpectedly large mass that challenged existing models of stellar evolution [6]. These observations have provided invaluable insights into the population, formation mechanisms, and evolution of compact objects in the universe.
Detector upgrades have continued steadily and these improvements have led to a higher detection rate and enabled the observation of more distant gravitational events (Fig. 1). Despite significant progress, further enhancements in detector sensitivity are crucial

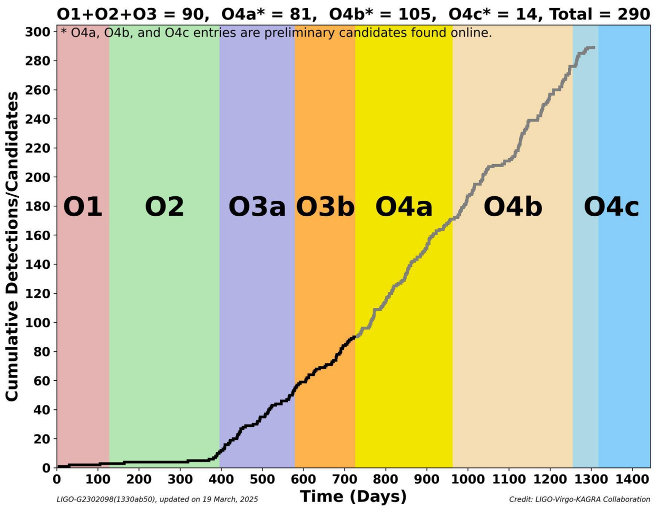

Fig. 1. – The number of gravitational wave alerts detected by interferometers (left vertical axis) and the cumulative observed volume per unit time (right vertical axis) are shown as a function of time. The trend highlights the impact of the upgrades implemented between the different observing runs.

to detect fainter and more distant signals and to deepen the understanding of General Relativity under extreme gravitational conditions.
Although an analytical description of noise behavior is not feasible, the limiting factors for gravitational wave interferometer sensitivity can be characterized using statistical quantities summarized into two categories:

- **Fundamental noises**: fluctuations due to the intrinsic properties of matter that, in principle, cannot be completely removed: spontaneous fluctuations (thermal noise) or due to a flux of quantized objects (shot noise).
- **Disturbances**: signals of external origin with respect to the investigated system (RF interferences, power lines, seismic noise...), that can be reduced by using ad hoc filters or specific shielding techniques [7].

In order to distinguish the noise source from the GW signal, the **amplitude of the spectral density** $h(f)$ for each noise is defined as:

$$h(f) = \frac{\sqrt{\tilde{x}^2(f)}}{L_0}\,, \tag{1}$$

where L_0 is the arm length and $\tilde{x}^2(f)$ is the **power spectral density** of the displacement due to the noise source. The quantity $h(f)$, which has dimension $\frac{1}{\sqrt{Hz}}$, indicates the amplitude of the gravitational wave signal that would produce the displacement caused by the noise per unit frequency [8]. The sensitivity of a GW detector is expressed in terms of the strain sensitivity obtained by summing quadratically the amplitude spectral densities of the noises affecting the detector:

$$h(f) = \sqrt{\sum_{i=1}^{n} h_i^2(f)}\,, \tag{2}$$

where i runs on the total number of noises. Through the evaluation of the noise contribution, it is possible to evaluate the sensitivity curve, representing the minimum intensity of the gravitational signal detectable by an interferometer.

As illustrated in Fig. 2, which shows the design sensitivity curve of Advanced Virgo +, different noise sources dominate across various frequency ranges. At low frequencies, the main contributors are quantum radiation pressure noise, Newtonian noise, suspension thermal noise, and coating Brownian noise, which also dominates in the mid-frequency range. In contrast, at higher frequencies, shot noise becomes the primary limiting factor.

3. – Thermal Effects and Wavefront Distortion

To reduce high-frequency shot noise, interferometric gravitational wave detectors must operate with higher circulating optical power. However, this enhancement introduces thermal effects that induces variation in the optical path and degrade the detector's performance. Deviations from the ideal optical configuration could arise from static imperfections of the optics originating from manufacturing processes - the so-called *Cold Defets* - but are primarily caused by thermally induced wavefront distortions (**WD**) in the main laser beam. Even minimal absorption - just a few parts per million - leads to mirrors heating and the resulting temperature gradients cause thermal expansion in the optics, producing two main effects:

- The thermo-elastic deformation - which alters the mirror's radius of curvature **RoC** - is described by:

$$\Delta OPL(r,\theta) \approx 2\alpha \int_0^h \Delta T(r,\theta,z)\,dz\,. \tag{3}$$

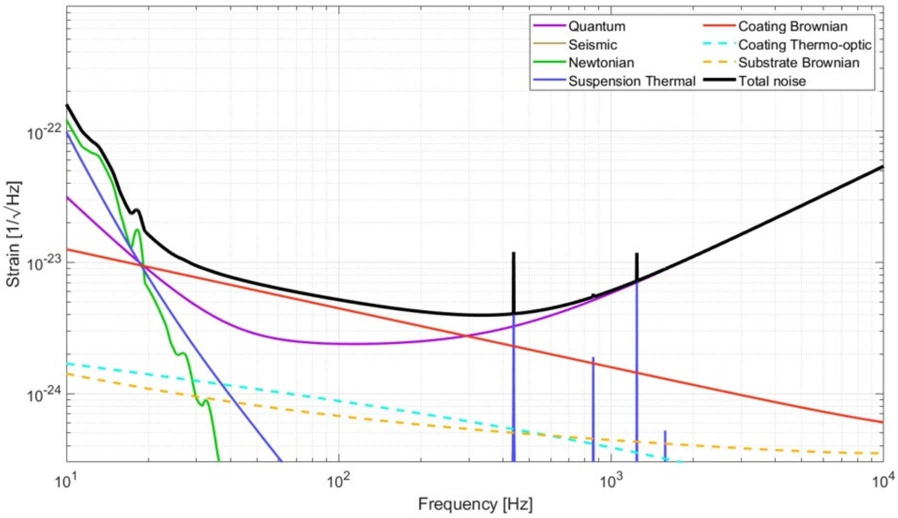

Fig. 2. – AdV+ design sensitivity curve. The coloured lines represent the different contribution of the noise components.

- The Thermal lensing - resulting from the temperature-dependent refractive index - is described by:

$$\Delta OPL(r,\theta) \approx dn/dt \int_S \Delta T(r,\theta,z)dz\,. \tag{4}$$

Where α is the thermal expansion coefficient, h is the optic thickness, n the refractive index, r is the radial distance, θ is the angular position and z is the depth within the material.

4. – The Termal Compensation System

Featuring both wavefront sensors and actuators, the Thermal Compensation System (**TCS**) was designed to address wavefront distortions caused by both thermally-induced effects and cold defects in order to restore the interferometer's optimal optical configuration [9]. As a reference, a scheme of the TCS parts integrated in the Advanced Virgo layout is shown in Fig. 3.

4˙1. *Wavefront Sensors*. – Two primary types of sensors are employed in current gravitational wave detectors:

- The Hartmann Wavefront Sensor (**HWS**, a differential sensor capable of directly measuring wavefront distortions [10].

- Phase Cameras, global sensors that measures the amplitude and phase of the electromagnetic fields in the interferometer [11].

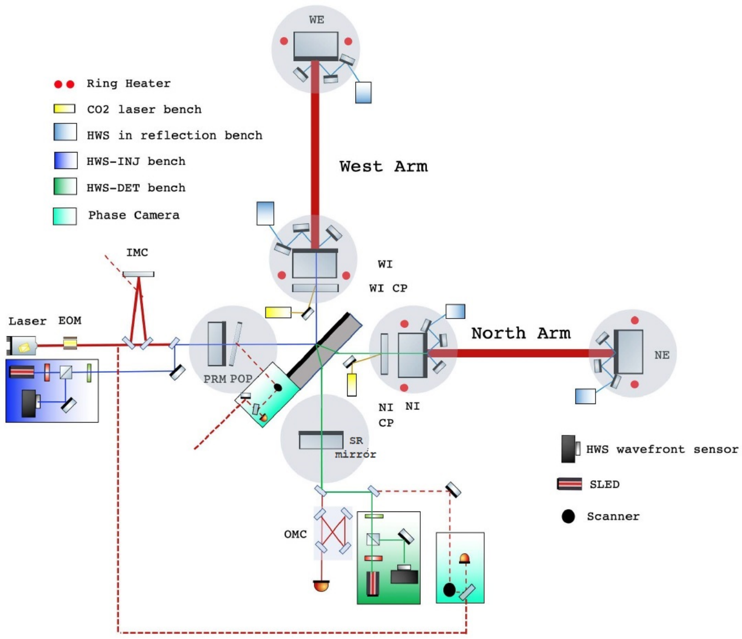

Fig. 3. – Schematic view of the Thermal Compensation System of Advanced Virgo superimposed on the optical layout of the detector.

4˙2. *Actuators*. – TCS employs several actuators to apply corrective heating patterns directly to optical components:

- Ring Heaters (**RHs**): used to adjust the RoC of the mirror by heating its barrel.
- CO_2 Laser Projectors: correct thermal lensing by delivering a properly shaped heating pattern to the optics. Two typical patterns are used: an annular one to compensate for lensing effects and a central one to reduce thermal transients during the interferometer's downtime.
- CHRoCC (Central Heating RoC Correction): compensates for thermally induced curvature changes on the mirror's high-reflectivity surface through controlled surface heating.

5. – Conclusions

The increase in circulating power in gravitational wave interferometers requires ever more precise control of optical aberrations to ensure system stability and optimal performance. To meet the demands of upcoming science runs and next-generation detectors such as the Einstein Telescope, ongoing improvements to the TCS are essential. The expertise gained over years of operation with current detectors now guides the development of advanced TCS solutions for third-generation observatories. While axisymmetric aberrations have been effectively corrected in previous runs, non-axisymmetric distortions remain a significant challenge, calling for innovative technologies. Addressing these issues is crucial to building robust thermal compensation systems that meet the stringent requirements of future high-power interferometers.

REFERENCES

[1] Einstein, A.,*Die Grundlage der allgemeinen Relativitätstheorie*, *Annalen der Physik*, **354** (769) 1916

[2] Hulse, R. A. and Taylor, J. H., *Discovery of a pulsar in a binary system. apjl*, **195** (L51) 1975

[3] Abbott et al., *Observation of Gravitational Waves from a Binary Black Hole Merger Phys. Rev. Lett.*, **116** (241103) 2016

[4] the ET science team, *Einstein Gravitational Wave Telescope Conceptual Design Study: ET-0106C-10, 2020*

[5] Hall, Evan D., *Cosmic Explorer: A Next-Generation Ground-Based Gravitational-Wave Observatory Galaxies*, **90** (4) 2022

[6] Abbott et al., *GW190521: A Binary Black Hole Merger with a Total Mass of 150 Solar Masses, Physical Review Letters 125, 2020.*

[7] M. Maggiore, *Gravitational Waves, Volume 1, Theory and Experiments, Oxford University Press, 2008.*

[8] I. Nardecchia et al., *Detecting Gravitational Waves with Advanced Virgo, Galaxies, 10, 2022.*

[9] A. Rocchi , E. Coccia, V. Fafone, V. Malvezzi, Y. Minenkov, L. Sperandio., *Thermal effects and their compensation in Advanced Virgo Journal of Physics*, **363** (012016) 2012

[10] Brooks, A. F., *Hartmann Wavefront Sensors for Advanced Gravitational Wave Interferometers, Ph.D. Thesis (2007).*

[11] K. Agatsuma et al., *High-performance phase camera as a frequency selective laser wavefront sensor for gravitational wave detectors, Optics Express 27(13) (18533) 2019*