

Thermal compensation system in advanced and third generation gravitational wave interferometric detectors

L Aiello^{1,2}, E Cesarini³, V Fafone^{1,4,5}, M Lorenzini^{1,2}, Y Minenkov⁵, I Nardecchia^{1,2}, A Rocchi⁵ and V Sequino^{4,5}

¹ Gran Sasso Science Institute, Viale Francesco Crispi 7, I-67100, L'Aquila, Italy

² INFN - Laboratori Nazionali del Gran Sasso, Via Giovanni Acitelli 22, I-67100 Assergi, Italy

³ Centro studi e ricerche Enrico Fermi, Piazza del Viminale 1, I-00184, Roma, Italy

⁴ Dipartimento di Fisica, Università di Roma Tor Vergata, Via della Ricerca Scientifica 1, I-00133, Roma, Italy

⁵ INFN - Roma Tor Vergata, Via della Ricerca Scientifica 1, I-00133, Roma, Italy

E-mail: lorenzo.aiello@gssi.infn.it

Abstract. On September 14th 2015 the first gravitational wave signal has been detected by the Advanced LIGO interferometers, opening the era of the gravitational astronomy and giving new opportunities to investigate the universe. The Advanced LIGO and Advanced Virgo interferometers are now back in a commissioning phase in order to improve their sensitivity for the next observing run, which will start in the first months of 2019.

In the high-frequencies region of their sensitivity band, the detectors are shot-noise limited: the sensitivity in this frequency window could be improved increasing the laser input power, but this increases also the optical aberrations due to the thermal effects. The optical power absorptions in the substrate and coatings of the optics induce both an increase of the optical path length in the substrates of the mirrors (thermal lensing) and a thermal expansion of the optic itself along the optical axis (thermo-elastic deformation). Both these aberrations reduce the sensitivity of the detector, limiting its performances. In order to face and minimize them, an adaptive Thermal Compensation System is required in order to guarantee the proper operation of the interferometer.

An overview of the present Thermal Compensation System system installed on Advanced Virgo, with also a focus on the possible improvements of the actual actuators for the next generation of detectors, is presented here.

1. Introduction

One century after their prediction by General Relativity, Gravitational Waves have been detected: after the first detection ever made in 2015 [1] other events followed [2–5], among which the famous GW170817 signal [6, 7] emitted by the merger of two neutron stars, that marked the begin of the the multi-messenger astronomy. After the end of the O2 observing run in August 2017, the Advanced LIGO and Advanced Virgo detectors are back in a commissioning phase with the installation of new upgrades in order to further improve their sensitivity.

In order to reduce the shot noise contribution in the high frequency window of the detector band, an increase of the interferometer input power is planned for the next observing run O3. However,



the higher power circulating inside the detector will increase also the optical aberrations due to thermal effects. These aberrations are originated by the optical power absorbed in the substrate and in the coatings of the mirrors, that induce both an increase of the optical path length in the substrates of the mirrors (*thermal lensing*) and a thermal expansion of the optic itself along the optical axis (*thermo-elastic deformation*). As a consequence, some light is scattered from the fundamental mode to higher-order ones: the error signals to maintain the cavities at resonance become fainter, resulting in a loss of robustness and sensitivity that reduces the performances of the detector. In order to face and minimize the optical aberrations, an adaptive Thermal Compensation System (TCS) to guarantee the proper operation of the interferometer is required.

2. The Thermal Compensation System

The TCS has been designed [8, 9] to reduce the thermal effects arising from the high power circulating in the detector. The subsystem is composed by sensors to detect the aberrations and by actuators to compensate them. The scheme of the different TCS components integrated in Advanced Virgo is shown in Figure 1. As it is possible to see from it, TCS is made up of:

- Hartmann Wavefront Sensors (HWSs) dedicated to the measurement of the thermal lensing (HWS-RC) and of the thermo-elastic deformation (HWS-HR), see section 2.1;
- CO₂ laser projector and Ring Heater (RHs) for the correction of the above-mentioned optical aberration, see section 2.2.

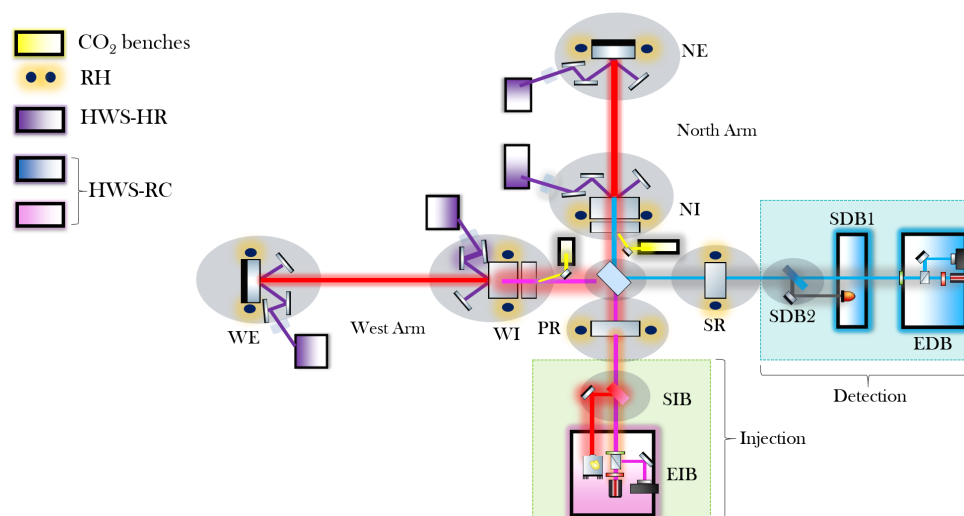


Figure 1. Scheme of the Thermal Compensation System of Advanced Virgo, superimposed on the optical layout of the detector.

2.1. Sensing: Hartmann Wavefront Sensor

The sensing part of the TCS is based on HWSs [10]. HWS is a differential sensor, that measures the change of a live wavefront with respect to a reference one through an incoherent probe beam. The latter is generated using a fiber-coupled SLED (Superluminescent Diode) source: it has been demonstrated that its low spatial coherence improves the noise performance of the HWS, because eliminates interference between stray beams and reduces the cross-talk between neighboring spots [9, 10]. HWS consists of an holed plate (Hartmann plate) placed at a distance

L from a CCD camera. When the wavefront has no aberration, the SLED beam crosses the holed plate straight resulting in a series of equally distributed light spots on the CCD. The presence of aberration in the analyzed wavefront is identified from the displacement of the light spots on the CCD from the reference position. The wavefront reconstruction is then obtained by integration of the gradient field by the HWS.

In order to monitor the thermal lensing effect and the thermoelastic deformation, two different setup are used, as shown in Figure 2.

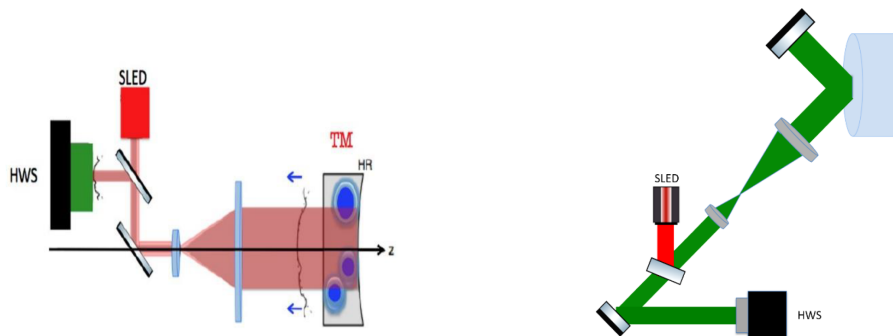


Figure 2. HWS setup for the estimation of the thermal lensing (left, on-axis measurement) and of the thermoelastic deformation (right, off-axis measurement).

For the thermal lensing estimation on the mirrors at the input of the cavities (Input Test Masses, ITMs) the SLED, superimposed on the main laser, arrives on the ITMs, pass through them and then it is reflected back toward the HWS along the same path. These are called *on-axis measurements*. Regarding the thermoelastic deformation (*off-axis measurements*), the probe beam impinges on the mirrors with an angle of 45° , then propagates up to an optics that reflects it back on the High Reflectivity surface and then toward the sensor.

Both in the on-axis and the off-axis measurements the probe beam passes on the interested area twice, making these measurements double-pass with a consequent increase of the signal-to-noise ratio.

2.2. Actuation: Ring Heater and CO_2 Laser Projector

One of the possible way to correct the thermoelastic deformation of the mirrors is to engage the RHs [11, 12]. The heaters are made of two rings of pyrex surrounded by a polished copper shield, heated by Joule effect with a wrapping of NiCr flat wire. In each RH, equipped with a pair of pyrex rings, the current in one ring flows in the opposite direction with respect to the other one: this allows to make the coupling of the stray magnetic field along the mirrors axis with actuation magnets negligible.

At the maximum power (24 W for each ring) the RH is able to reduce the radius of curvature of the mirror of 100 m over a nominal value of around 1.5 km.

Another type of actuators engaged to contrast thermal effects are 50 W CO_2 lasers. Their actuation is performed not directly on the mirrors, as it was done in the first generation of detectors: this is due to the fact that the intensity fluctuations of the CO_2 lasers could inject displacement noise into the interferometer. In the initial detectors intensity stabilization servos have been implemented and they have been able to reduce the laser fluctuations [13] but, unfortunately, the present technology is not enough developed to reduce the displacement noise up to a value below than the advanced interferometers sensitivity requirements [14]. To solve this problem the CO_2 beam, properly shaped, is shined on an additional transmissive optic, the Compensation Plate

(CP), made by fused silica and placed immediately before the ITMs. The choice of these lasers is because they emit at $\lambda=10.6 \mu\text{m}$, a wavelength which is strongly absorbed in the immediate surfaces of this material [15].

The optical benches on which the CO₂ lasers are installed have been designed in order to allow the lasers to shine on the CPs three different (and independent) types of actuation pattern. The first of these patterns is the *Central Heating* (CH), consisting in a CO₂ Gaussian beam shined in the CP center. As the RHs, its aim is to correct the thermo-elastic deformation but acting in the opposite way. Indeed while the RHs, heating the peripheral of the mirrors, decrease their radius of curvature, the CH is able to rise it.

The second actuation pattern is used to correct the thermal lensing due to coating absorption in the ITMs and consist in an axi-symmetric heat distribution. It is provided by two annuli-shaped intensity patterns, each of them obtained with an axicon¹ lens. The power in the two annuli can be separately regulated with dedicated waveplates, one for each annulus, and a lens placed before each axicon is used to modify the annulus thickness. This setup is called *Double Axicon System* (DAS).

The last pattern that could be engaged is the *Scanning System* (SS), that provides a correction for the residual not axi-symmetric aberrations. It consist of a CO₂ beam that arrives on two galvanometer mirrors, that move the laser beam on the surface of the CP scanning it along a 25x25 raster pattern. Power on the SS is regulated through an Acusto-Optic Modulator (AOM), and the needed intensity pattern is obtained as the sum of all the spots.

3. Improving the actuation

3.1. Mode cleaner cavity for CO₂ lasers

In order to have a good compensation, the actuators should be able to modify with high precision the shape of the laser beam: this could result quite difficult when the CO₂ lasers exhibit a not so good beam shape. To improve their actuation power, the higher-order modes must be removed from the laser beam. This could be done with a spatial beam filtering, but the efficiency of this type of system is not enough for the next generation of detectors: a mode cleaner cavity for CO₂ lasers is then needed. A design of a prototype cavity has been developed and a triangular configuration has been adopted, as shown in Figure 3.

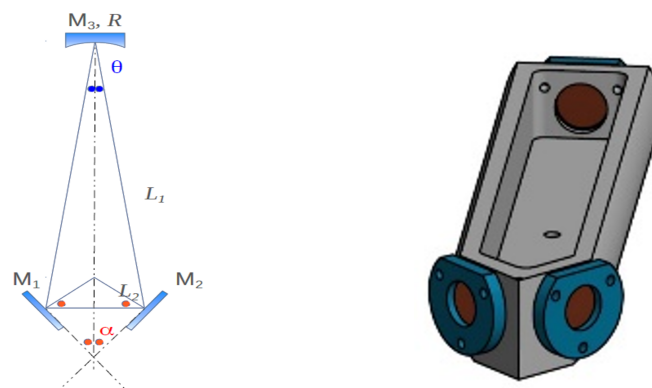


Figure 3. Conceptual layout of a three-mirror triangular mode cleaner cavity (left) and preliminary design of the studied cavity (right).

¹ The axicon is a particular type of lens with a conical surface that transform a Gaussian laser beam in an annular one.

The factor that quantifies the selectivity of the mode cleaner is the so-called *Finesse* \mathcal{F} , defined as its free spectral range divided by the (full width at half-maximum) bandwidth of its resonances. However, higher is the finesse, more complicated is to keep the cavity at resonance. In order to make a trade-off between the improvement of the laser beam quality and the difficulty to make the cavity work, after some calculations a reasonable value of $\mathcal{F} \sim 100$ has been chosen. Moreover, in order to allow an easy installation and integration in the actual TCS setup on Advanced Virgo, the cavity has been designed also to be compact: the total round trip of the laser inside it is less than one meter.

The common way to keep a cavity at resonance is the Pound-Drever-Hall technique [16], based on the modulation of the laser beam with an Electro-Optic Modulator (EOM). However, because of the EOM crystals for the CO₂ lasers wavelength from usual companies are too much expensive, an investigation to keep the cavity resonant with an AOM frequency shifter is in progress.

3.2. Deformable mirror

The scan and step frequency of the SS are within the sensitivity band of Advanced Virgo, then it can introduce displacement noise in the detector at the frequency of the pattern repetition rate. For this reason, it is necessary to develop new methods to shape the CO₂ laser beam: one of the most promising makes use of Micro-Electro Mechanical-System (MEMS) deformable mirrors (DM), which imprint a phase modulation to the wavefront of the incoming Gaussian beam that converts the beams intensity distribution into the desired one holographically [17]. Currently a DM [18] is under test in Tor Vergata University: the goal of the ongoing tests is to evaluate the influence functions of its actuators, i.e. how much the displacement of a single actuator changes the observed wavefront.

4. Conclusions

Thermal Compensation System is fundamental to contrast optical aberration arising from thermal effects when the input power in the detector increases. Its sensing system is able to identify and quantify the amount of aberrations, while their actuators can act in different and versatile ways to minimize the noise arising from thermal effects.

Looking at the next generation of the detectors, in order to further improve the efficiency of the actuation, an enhancement of the present actuators is under investigation with the design of a Mode Cleaner cavity for the CO₂ lasers and the characterization of the performances of a DM to improve the present SS actuator.

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