Status of the Advanced Virgo Gravitational Wave Detector

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Advanced Virgo is the French-Italian second generation laser gravitational wave detector, successor of the Initial Virgo. This new interferometer keeps only the infrastructure of its predecessor and aims to be 10 times more sensitive, with its first science run planned for 2017. This article gives an overview of the Advanced Virgo design and the technical choices behind it. Finally, the up-to-date progresses and the planned upgrade for the following years are detailed.

Keywords: Gravitational wave; Virgo; laser interferometer.

1. Introduction

The year 2016 will be remembered as the beginning of the gravitational wave astronomy with the announcement by the LIGO and Virgo collaborations of the first direct detection on Earth of the coalescence of two massive black holes. This remarkable achievement was possible thanks to the unprecedented sensitivity of the so-called second generation of gravitational wave detectors. The first gravitational wave signal was recorded by the two Advanced LIGO detectors, first interferometers to be online for this new generation. In 2017, the LIGO detectors will be joined by the Advanced Virgo interferometer, the French-Italian detector which is the topic of this article.

2. The Importance of Advanced Virgo

As mentioned in the introduction, the year 2017 will see the creation of the first network of three gravitational wave detectors: the 2 LIGO detectors and the Virgo one. That is a crucial step for the development of the new astronomy with gravitational waves. More detectors in the network means better redundancy and so longer cumulated observational time, as the typical duty cycle of a detector is around 60%[1]. More important, a tremendous improvement in the sky localisation of the source is expected by adding a third detector to the LIGO network. An accurate sky localisation is essential to enable the multi-messenger astronomy which includes also observations with electromagnetic and neutrino telescopes.

Simulations have shown that even an early version of Advanced Virgo, with a range only 25% of the one from LIGO can reduce the 90% confidence angular area on the sky of the source by a 60%[2].

3. The Advanced Virgo Interferometer

In this section more historical and technical details will be given about the Advanced Virgo interferometer.

Fig. 1. Aerial view of Virgo detector with the two perpendicular 3-km long arm across the Tuscanian countryside. Credit: The Virgo Collaboration.

3.1. *Background*

Advanced Virgo has been built and operated by the Virgo collaboration. The Virgo collaboration is not a new comer in the field since it has been created in 1994 combining the forces from French CNRS and Italian INFN laboratories. At that time, the common goal was to build a laser interferometer gravitational wave detector in the area of Pisa in Italy. This construction of this first generation detector called Virgo was completed in 2003 (see figure 1) and took scientific data intermittently for several years from 2007 to 2011 conjointly with other detectors. This period marks the birth of the global collaboration with exchange of scientific data and technical knowledge between the different continents[3].

In parallel of running the initial Virgo detector, a research effort was started as early as 2005 (with the Advanced Virgo White paper[4]) for a new detector 10 times more sensitive. The Advanced Virgo detector was approved by the French-Italian institutions in 2009 and the major upgrade started on site at the end 2011 after the end of the last science run of the Initial Virgo.

Today the Virgo collaboration, it is 250 people, 20 laboratories spread over 6 European countries, despite its increase in size, the majority of the collaboration still comes from French and Italy institutions.

3.2. *Optical setup and expected sensitivity*

The optical setup of Advanced Virgo is a dual recycled Michelson interferometer with 3 km long Fabry-Perot arm cavities as shown in figure 2. From the point of view of the optical functionality, the interferometer could be decomposed in

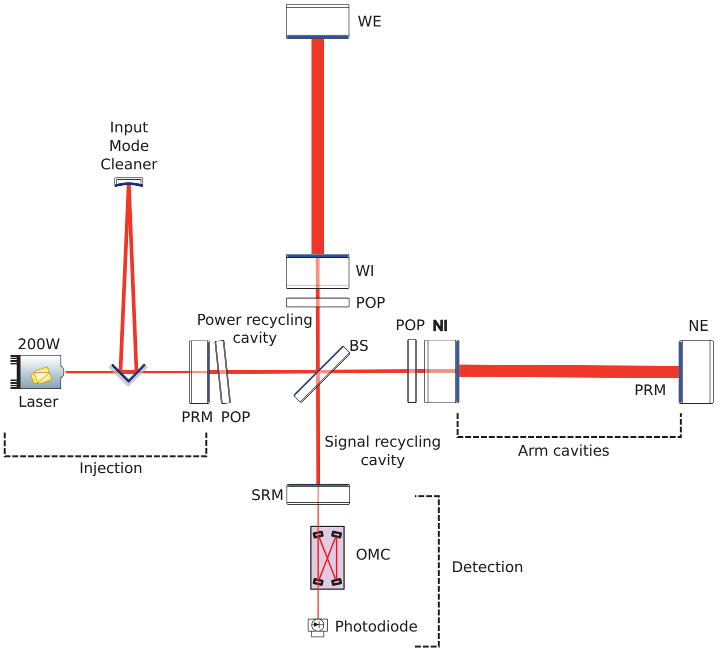

Fig. 2. Schematics of the Advanced Virgo optical setup.

four blocks:

The injection. It is composed by the input light source: a laser at 1064 nm and with a power up to 200 W for the final configuration of the detector and all the components to modulate, to stabilize in amplitude and frequency and also to shape the laser beam. Before the laser and the interferometer, there is also a 3 mirrors 150 m long linear optical cavity to filter the beam and also a 40 times enlarging telescope to achieve the proper beam size on the power recycling mirror.

The detection. This part converts the gravitational signal imprinted in the optical phase of the light to a voltage which can be recorded. Moreover most of the signals used to control the interferometer are derived from the detection side of the interferometer.

The arm cavities. The two perpendicular 3 km long Fabry-Perot cavities are formed by the input and end mirrors. Those mirrors are the most critical optics of the interferometer. Any light lost in the arm cavities is directly synonymous of a degradation of the detector sensitivity.

The recycling cavities. Two additional cavities are formed with the arm cavities and the power recycling mirror (on the injection side) as well as the signal recycling mirror (detection side). The former is called the power recycling cavities and is used to enhance the power circulating in the arm cavities by nearly a factor 40. The latter, the signal recycling cavity, can change the optical response of the interferometer and hence modify the frequency dependent sensitivity curve of the detector.

The goal of Advanced Virgo is to be 10 times more sensitive than the initial Virgo interferometer, enabling a potential volume of detection 1000 times larger than the first generation. Advanced Virgo has kept the same overall infrastructure of the Virgo detector but the core of the interferometer has been largely upgraded.

To ease the commissioning of the detector, it has been decided to have a two steps approach before reaching the final sensitivity of Advanced Virgo[5]:

(1) first, the interferometer will work with a low input power (below 40 W) and without signal recycling mirror. In this configuration, the interferometer is very similar to initial Virgo and so the strategy to handle the interferometer is well known and already experienced. Even with this reduced setup, the astrophysical range for the detection is already more than 80% of the final configuration.
(2) second, in this final step (planned for 2018), the full power of the 200 W laser will be used and the signal recycling mirror will be installed. That will enable the detection full range of Advanced Virgo with recording of black hole merger up to 1 Gpc, with tens of detection per year.

3.3. *Selected key technologies*

To achieve its design sensitivity, Advanced Virgo uses state of the art technologies. It would be too long to detail all the impressive technological aspects of the interferometer, so the author has (arbitrarily) decided to develop only few of them. A more exhaustive view of the various subsystems can be found in Advanced Virgo Technical Design Report[6].

3.3.1. *The large mirrors*

The four mirrors forming the two arm cavities (called NI, WI for the input ones and NE and WE for the end ones as shown in 2) are the most critical optics of the interferometer. Those mirrors have a cylindrical shape with a diameter of 350 mm and a thickness of 200 mm, weighting around 40 kg.

To maximise the interaction between the light and the gravitational wave signal, the various optical losses such as scattering or absorption have to be an kept at an unprecedented low level. In that purpose, the substrate of the mirrors is made of the purest fused silica glass available. The polishing which gives the shape of the surface is done at the atomic level with on the central part, a peak to valley of the height of the mirror surface consistently less than 2 nm. Finally, the very uniform multi-layer coating[7] on the surface allows a reflection of more than 99.999% of the light while absorbing less than 1 part per million[8].

3.3.2. *The mirror payload*

The payload represents the system between the mirrors and the suspension chain. Each arm cavity mirror is suspended using 4 glass fibers of diameter 0.4 mm. The fibers itself are attached to mirror using two glued glassed ears on either side of the mirror barrel. This all glass system is called a monolithic suspension and is a key feature to minimize the mirror displacement induced by thermal noise[9]. Only the arm cavity mirrors are suspended with glass fibers, the other large optics such as the beamsplitter or recycling mirrors are using steel wires.

Compared to Initial Virgo, the payload has been completely redesigned and is now much more complex. For Advanced Virgo, not only the mirror has to be attached though the payload but also additional optics and parts. As an example on the arm cavity input mirror payload, a second large optic is also suspended: the compensation plate, a heating ring (both parts are described in section 3.3.4) and light baffles (see section 3.3.5) are also present.

3.3.3. *The seismic isolation*

The isolation of the mirror from the ground motion is ensured by the super attenuator[10]. The core of the system is a long series of cascaded pendula (8 m high, in vacuum) installed for the Initial Virgo interferometer and was already compliant with the specifications for Advanced Virgo. Thanks to this suspension system, the seismic noise is attenuated by 10 order of magnitude above few Hertz in the six degrees of freedom.

3.3.4. *The thermal compensation*

The combination of very high circulating power (up to 600 kW of light in the arm cavities) and optical absorption (albeit very low, in the order of part per million), leads to the heating of the main optics of the interferometer. The presence of those thermal gradient induces optical aberration jeopardizing the control and sensitivity of the detector. Those negative effects already experienced by the first generation of detector, are much stronger in advanced interferometers. As a result, specific diagnostic tools and actuators are required to mitigate the effect of the absorbed optical power[11].

The distortions induced by the laser beam are monitored in real time by two dedicated light beams probing the input mirror substrates and analyzed through an Hartmann sensor. In parallel, the magnitude and the shape of the interferometer control sidebands (light beams frequency shifted from the main beam) are also been analyzed with phase cameras. Those sidebands are well suited figures of merit about the state of the interferometer since they are extremely sensitive to any defects from the polishing tolerances of the optics, to misalignment or thermal aberrations.

Thanks to those monitoring techniques, error signals can be derived and send to thermal actuators for active aberration control. For example, heating rings have been inserted around the main mirrors to change in-situ their radii of curvature. Controlled heating pattern can also be sent on the Compensation Plates (CP in figure 2) using CO_2 laser beams for near arbitrary correction.

3.3.5. *The diffused light mitigation*

The importance of managing the diffused light has been a hard lesson learned from the first generation of detectors. As some point in time, each detector had their sensitivity limited by diffused light.

All the optics, even the outstanding ones as for Advanced Virgo, always scatter a small amount of the incident light at small and large angles. This light may reach a part of the detector not isolated from the ground, be partially reflected and then recombine to the main laser beam, inducing extra phase noise. Several extensive actions has been taken in Advanced Virgo to mitigate the effect of the diffused light: use of superpolished optics, custom light traps (called baffles) around the optics and all the critical optics for the detection are installed on suspended bench inside vacuum chambers.

4. The Rise of Advanced Virgo

4.1. *A brief timeline*

The installation of Advanced Virgo has started at the end of 2011, right after the last data taking run of the Initial Virgo. After the decommissioning of the previous interferometer, infrastructure works such as the creation of new clean rooms or modification of vacuum pipes have begun. The first subsystem to be ready was the injection which includes the laser and a milestone was achieved with the locking of the Input Mode Cleaner cavity in the middle of 2014. As the large optics of the interferometer were being installed and a stable input beam was available, the first 3 km arm cavity was locked in the middle of 2016. At the beginning of 2017, the final configuration of the first phase of Advanced Virgo was reached with the all the cavities locked at their operating points.

During the installation, several failures of the monolithic suspension occurred with the breaking of the thing glass fibers supporting the arm cavity mirrors. To not delay the commissioning, it has been decided to suspend temporary the mirror with steel wires while the problem was investigated. The decision was not an easy one as using steel wires increases the suspension thermal noise, degrading the interferometer sensitivity at low frequency.

4.2. *Current status*

In this section, we detailed the status of the detector in April 2017. At this date, the interferometer is routinely on the dark fringe with all the cavities reliably locked for several hours. Special care was taken to automate the locking sequence and the interferometer can consistently go to its operating point without any human intervention.

A new phase of the commissioning has started with the first noise budget detailing the noise sources currently limiting the sensitivity. So current effort are dedicated to implement low noise actuators and to engage the auto-alignment loops to close all the degrees of freedom. However, no official sensitivity curve has yet been publicly released.

It was worth noting that the thermal compensation system, a key technology of Advanced Virgo to ensure stability of the recycling cavities and correct the optical aberration is currently being tested and tuned. However, so far, the locking and stability have been achieved without the use of TCS, which is particularly encouraging and simplify the early commissioning.

The short term priority is to be able to join the two LIGO detectors for the second observation run (O2) around the summer of 2017.

In parallel to the progress on the interferometer, a dedicated task force has been created to understand the failure of the monolithic suspension. Extensive investigations has been carried out within and outside the Virgo collaboration to find the origin of the breaking. These investigations were successful and the cause of the failure was found to be linked to the vacuum implementation. The suspending fibers were broken (or deadly fragilized) at the time of venting the tower when exposed to high speed particles coming with the entering flux of air[12].

4.3. *Improvement following O2*

After the second observational run (O2) planned to be completed at the end of August of 2017, a period of around one year, is planned to allow invasive improvements before the next data taking run (O3). This dedicated period of installation and commissioning will be common to the LIGO and Virgo interferometers.

For Advanced Virgo, the priority is to reinstall the monolithic suspension for the arm cavities mirrors to reach the design sensitivity in the low frequency range. This work will also include installation of guards around the fibers and upgrades on the vacuum infrastructure to greatly reduce the amount of projected dust. At this occasion, cleaning of the mirrors and of the vacuum tanks will also be done. This activity is likely to last almost half a year.

A second major work also planned during that period is the installation of a squeezed vacuum light source at the output of the detector[13]. This special light source, provided by the Albert Einstein Institute in Germany, allows to reduce the sensitivity in the high frequency range where the detector is limited by the light shot noise, noise inherent to the quantum nature of light.

Following these two main works, once the state of the interferometer is recovered, commissioning time for several months is required to ensure optimal stability and sensitivity of the detector before considering the next data taking period (O3).

Beyond O3, the final high power laser is expected to be installed as well as the signal recycling mirror with the high reflective coating.

5. The Upgrade Path

For the horizon 2020, large upgrades for Advanced Virgo are also been investigated in the laboratories of the collaboration. The main goal is to contribute in the best way to the international network of detectors both in term of reliability and sensitivity. For that, we must go beyond the design sensitivity of Advanced Virgo while keeping the same infrastructure[14].

Among the promising leads to explore one can quote: new squeezed light source to further reduce the quantum noise at low and high frequencies (called frequency dependent squeezer[15]), cancellation of the Newton noise at very low frequency[16] or even new larger mirrors with advanced coating to reduce the thermal noise[17].

6. Conclusion

Advanced Virgo is a second generation interferometer complementary to the Advanced LIGO detectors. Currently, the detector is in the state of active commissioning and the highest priority is to be able to take data conjointly with the Advanced LIGO interferometers during the summer 2017. After this first observational run, a series of upgrade is already planned to further increase the sensitivity and reliability of the detector promising a bright future for the gravitational wave astronomy.

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