# Vision document beyond the Advanced Virgo project

**VIR-0136A-16**

*The VIRGO collaboration*
*September 2016*

# Contents


**1 Introduction** **3**

**2 Advanced Virgo and beyond** **4**
2.1 The future of Advanced Virgo . . . . . . . . . . . . . . . . . . . . . 5
2.2 From Advanced Virgo to Einstein Telescope . . . . . . . . . . . . 8

**3 Newtonian noise cancellation** **10**
3.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10
3.2 Part 1: Site characterisation and noise modelling . . . . . . . . . 10
3.3 Part 2: Coherent detection of Newtonian noise . . . . . . . . . . 11
3.4 Part 3: Development of Newtonian-noise cancellation system . . 12
3.5 Timeline . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 13

**4 Lowering the thermal noise** **15**
4.1 Scientific case . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15
4.2 Larger beam profile . . . . . . . . . . . . . . . . . . . . . . . . . . 16
4.2.1 Increasing the mirror substrate size . . . . . . . . . . . . . . 16
4.2.2 Coating development on large mirrors . . . . . . . . . . . . 17
4.3 New coating materials . . . . . . . . . . . . . . . . . . . . . . . . 18

**5 Larger beams and thermal noise limit** **21**
5.1 Cost and man power . . . . . . . . . . . . . . . . . . . . . . . . . 22

**6 Squeezing** **23**
6.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23
6.2 Implementation Plan . . . . . . . . . . . . . . . . . . . . . . . . . 24
6.3 Cost Estimate . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 25

**7 The improvement of the detector robustness** **27**
7.1 Anthropogenic noise reduction . . . . . . . . . . . . . . . . . . . 27
7.2 Low frequency robustness . . . . . . . . . . . . . . . . . . . . . . 27
7.3 The optical stability of the recycling cavities: the long cavity solution . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 29
7.4 The upgrades of thermal compensation system . . . . . . . . . . 30

**8 Extending the arm length of Virgo** **33**
8.1 Motivation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 33
8.2 Discussion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 33
8.3 Implementation Plan . . . . . . . . . . . . . . . . . . . . . . . . . 33
8.4 Cost and man power . . . . . . . . . . . . . . . . . . . . . . . . . 34

**9 Conclusion** **35**

# 1 Introduction

The scope of this document is to trace a first path of the evolution of Advanced Virgo toward the third generation of detectors. The sensitivity of Advanced Virgo can be improved further by adding new sub-systems as a vacuum squeezer, or increasing further the mirror dimensions and the quality of their coating. Moreover, after the first detection it becomes more and more important to increase the reliability of the international network for increasing the overall observational time. This implies to improve the robustness of each detector . In this document our goal is mainly to give a coherent picture of the main actions to be pursued in the short and middle terms for achieving these goals. Then , we will try to draw a potential scenario for the longer term improvements. In this context, for completeness, we studied also a hypothetic change of the Virgo infrastructure to increase the Virgo arm length. However, we are conscious of the strong impact on the territory around Virgo ( the channels to control the river flooding and the streets) and potentially in contrast with the need to have in the future long periods of data collections of the GW network.

The major detectors currently operative are enhanced versions of the first generation (Virgo+ and eLIGO), with higher laser power and some technological improvements. They are based on technologies currently available, sometimes tested in reduced scale prototypes and then implemented in full scale. Despite the big progress made, the current detectors are not fully exploiting the potentiality if the infrastructures hosting them.Therefore, there is room for further enhancement of the 2nd generation targets. The R&D carried out within the GW community in the last years already makes possible to walk steps forward: for instance, the technology to produce and inject squeezed states in large interferometers has been already demonstrated and a relevant progress has been done on the way to realise a frequency dependent squeezing. We analyse in the following sections the open options for the AdV enhancement and highlight the most likely path that Virgo plans to follow.

The starting point of the following discussion is the final design sensitivity curve of Advanced Virgo.

The figure shows clearly that in oder to improve the sensitivity above 10 Hz, two main actions must be pursued: the reduction of the mirror thermal noise and the quantum noise. The last requires an experimental effort for implementing a vacuum squeezer, while for the mirror thermal noise the multiple approach of improving the dissipations associated to the mirror coating and enlarging the beams impinging on the mirrors Below 10 Hz the curve reported in the figure 1, which contributes mainly to the final sensitivity is the Newtonia Noise followed by the suspension thermal noise. However, the experience learned with Virgo and VIrgo+ tells us that in this frequency range other noise sources, with no stationary characteristics and difficult to model, can contribute. We will call them technical noise sources and we will discuss how to deal with these limitation in the section devoted the improvements of the detector robustness.

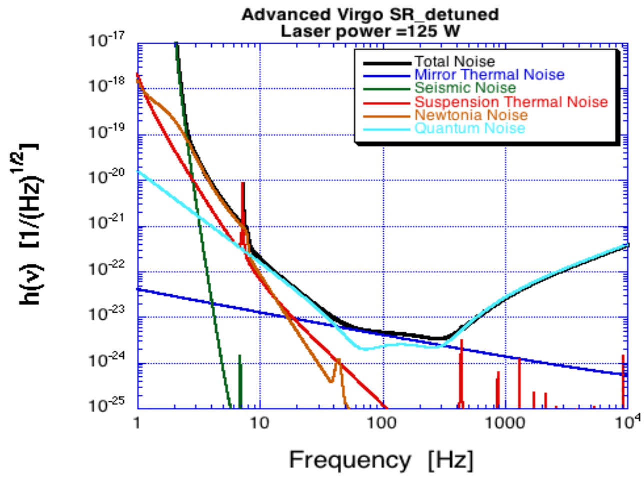



Figure 1: Sensitivity of the Virgo gravitational wave detector present in the Technical Design Report of Advanced Virgo. In the plot the curves of the various noise contributions are shown.

## 2 Advanced Virgo and beyond

With the first direct detection of gravitational waves, a new chapter of physics and astronomy has been opened. More discoveries are in front of us and Virgo is committed to be part of this enterprise. Beside the detection of other BH-BH events, new phenomena have to be observed, as the coalescence of binary neutron systems, stellar collapses and continuous signal from pulsars and the gravitational background noise of astrophysical origin. Thus, we need to ensure the optimisation of the interferometer as well as long take data periods.

As a consequence, in the next years the Virgo collaboration will have to accomplish a challenging mission:

- commissioning the detector in order to achieve the nominal sensitivity;
- performing science runs together with Advanced LIGO;
- completing the gradual integration of all the AdV components (including the phase 2 ones, like the signal recycling, the high power laser and the frequency independent squeezing).

In this sense we present a vision about the future of Virgo by classifying the various steps in the three following phases:

- Phase 1 (2017-2021): achieve the design sensitivity
- Phase 2 (2021-2025): the best we can do in the current infrastructure
- Phase 3 (>2025): attempts for a further increase of the AdV sensitivity and useful in view of a new available infrastructure

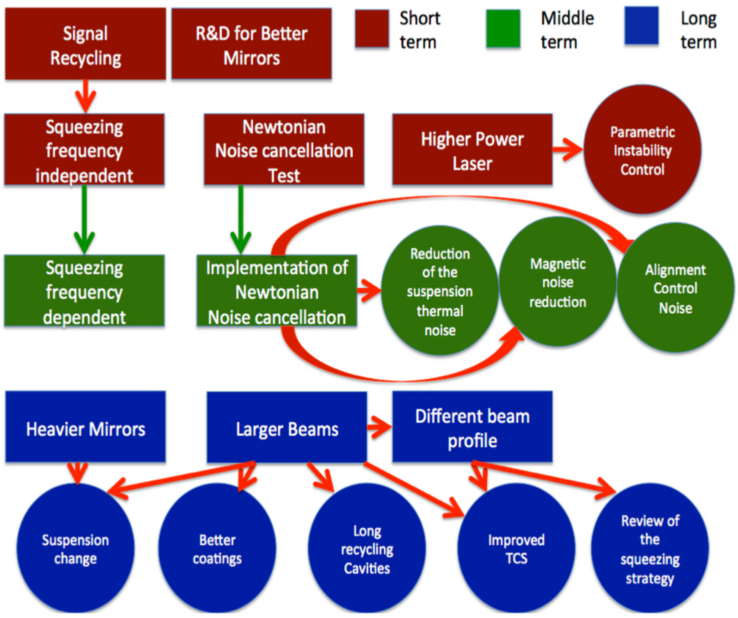



Figure 2: *Main actions to achieve the promised final sensitivity of Advanced Virgo and beyond.*

In the figure 2 we report a pictorial view of the main actions to be pursued for achieving the promised final sensitivity of Advanced Virgo and beyond. Here the colors of the rectangular boxes are related to the timelines of the foreseen actions. The brown corresponds to the short term, while the green and the blue to the middle and long terms respectively.

The installation of the signal recycling, the new laser and the external bench of the squeezed vacuum are the first steps for improving of the Virgo sensitivity. At the end of the Virgo science run in the advanced configuration the plan is to have ready for the installation the corresponding hardware, which includes also the new monolithic suspensions for the test masses. At this level, the brown circle of the parametric instability is connected to the higher power laser: it is drawn here to recall that it is urgent also to study this effect in Virgo, that it could prevent us to increase the power in the interferometer. In the rest of the figure rectangles and boxes are connected by arrows following a similar logic approach. The green line is a list of predict actions that we need to prepare for the era following the second scientific run for Virgo. The blue boxes are hypothesis requiring R&D to confirm their feasibility.

## 2.1 The future of Advanced Virgo

The timeline of science runs, shown in figure 3 is defined until O3. Observation periods are alternated to the time intervals devoted to the implementation of the new components and the related commissioning. After O3 new plans will be defined in a coordinated way with LIGO and, hopefully, KAGRA.

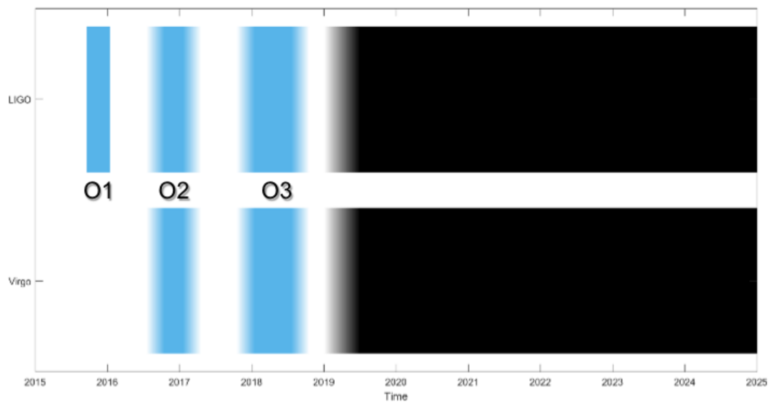



Figure 3: *Planned timeline of the scientific data taking of the advanced detectors.*

The data taking plan for the advanced detectors is described in the LIGO–Virgo paper [**?** ] and the main scheme is reproduced hereafter for completeness:

- **2016 - 2017 (O2)** A six-months run with H1-L1-V;
- **2017 - 2018 (O3)** A nine-months run with H1-L1-V;
- **2019+** Runs including H1-L1-V and KAGRA.

The Japanese interferometer KAGRA, expected to be completed in 2018, will hopefully join the network.

We recall also that, after the discovery announcement, the Indian government announced the approval of the IndIGO project, the LIGO-India detector that should become operative in 2024-2025. The complete network will permit a full overage of the sky and a better pointing capability to locate the transient GW source.

In this scenario we have to plan actions for a progressive improvement in the detector sensitivity with the goal to increase the BNS horizon by a factor of the order of 50 % with respect to that of the AdV design sensitivity. These steps forward are needed to have a precise characterisation of the sources complemented by the EM follow up observations: these will open new scenarios in the understanding of phenomena as the GRBs and contribute to scientific debate on cosmology. The sensitivity increase must be obtained to develop new technologies to be implemented on the advanced detectors, while we will prepare a new infrastructure for hosting third generation of GW interferometers.

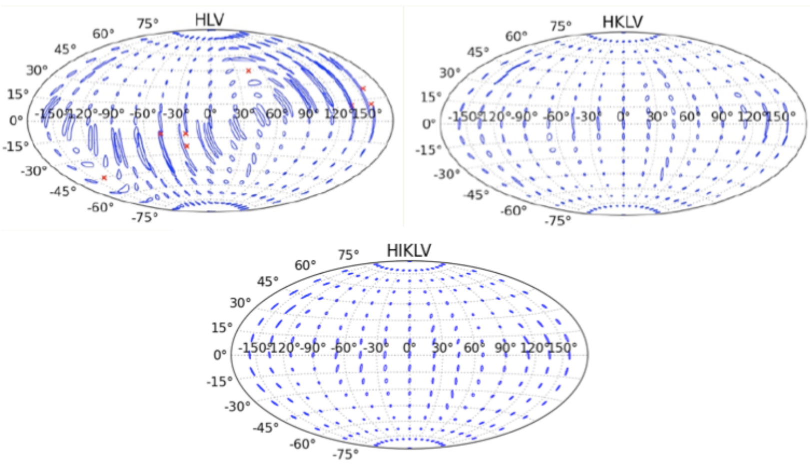



Figure 4: *Pointing capabilities of the network of advanced detectors (H =Hanford, L=Livingston, V= Virgo, K=KAGRA, I= INDIGO, - credits to S. Fairhrust). The ellipses show* 90% *confidence localisation areas based upon timing triangulation alone. The third panel shows the role of the addition of the KAGRA and the INDIGO detectors.*

## 2.2 From Advanced Virgo to Einstein Telescope

The roadmap from the 2nd to the 3rd generation of GW observatories is based on the following key points:

- Achieving the nominal sensitivity minimising the down–times due to heavy installations and performing a long data taking at the beginning of the next decade;
- Enhancing the sensitivity of the Advanced detectors by adopting new technologies as the frequency dependent squeezing, larger and better coated mirrors, newtonian noise subtraction, . . . to fully exploit the available infrastructure;
- Starting the realisation of a 3rd generation infrastructure, the Einstein Telescope.

In order to continue to play a co–leadership role in the global network of GW facilities it will important to have a 3G level observatory in Europe for the end of the next decade. Hence it is expected to have the ET infrastructure completed in 2030. Already at beginning of its life, the interferometer installed the new infrastructure could permit to jump ten times better in the sensitivity of the advanced detectors.

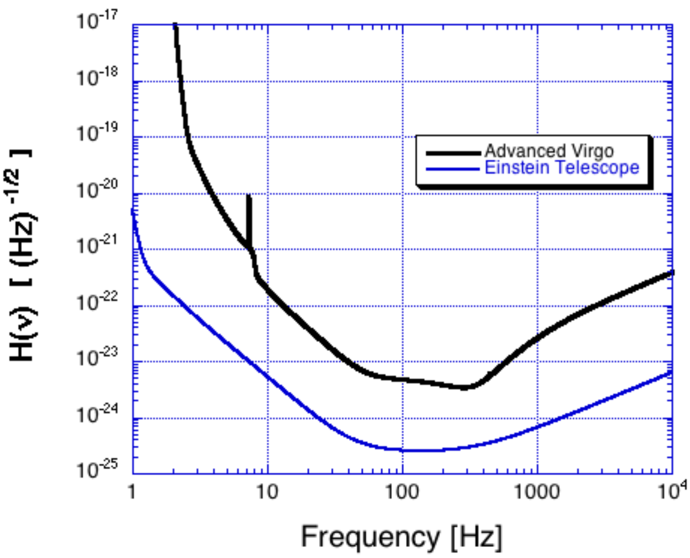



Figure 5: *The sensitivity curve of the Advanced Virgo compared with the first phase of ET.*

It is worth noting that the time elapsed between the delivering of the conceptual design report and the realisation of the infrastructure has been about 15 years both for Virgo, LIGO, Advanced LIGO, about 10 years for Advanced Virgo; it is realistic a similar time for the Einstein Telescope and this implies that the whole process should start soon. All these points are summarised in Fig. 6, where the parallel plans for Virgo,LIGO and KAGRA are drafted.

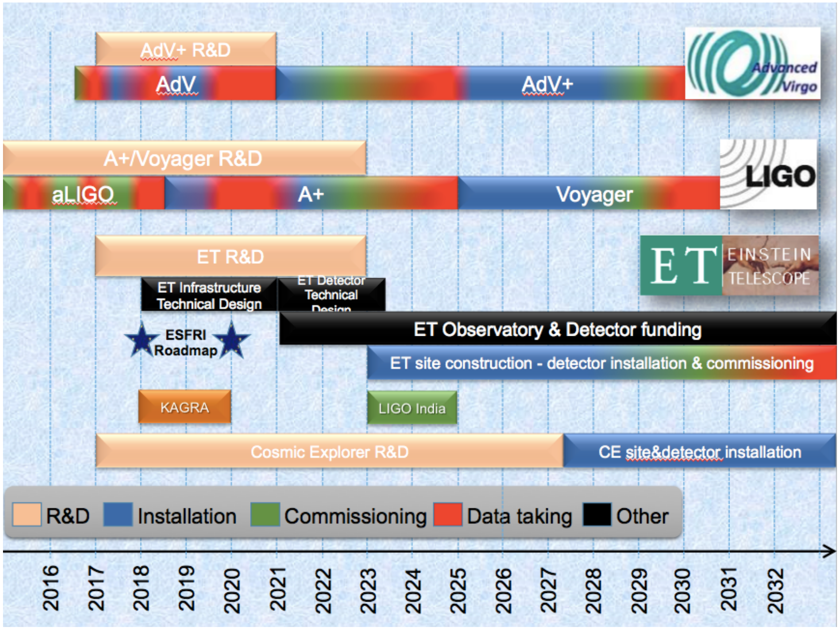



Figure 6: *Roadmap of the GW detectors in the next 15 years. The first two lines represent the evolution of the Advanced Virgo and Advanced LIGO detectors in the current infrastructures. The last two lines represent the evolution of the 3G level infrastructures, ET and LIGO 3G. The color code is specified in the figure.*

To realise this scenario few conditions must be verified. The science produced by the network of advanced detectors should push an increased interest of the whole physics and astronomic community. To be more attractive and credible , it is compulsory that advanced detectors produce excellent scientific results. On the short term for Virgo we need as first to maintain, renew and expand our competences. The main tool for stimulating an expansion process is be the transition of the French-Italian EGO organisation into an European Research Infrastructure Consortium (ERIC). It will embed other European nations and it will strengthen our capability to attract European funds.

On the other hand, we are conscious that also in the future the gravitational physics requires the coordinated operation of detectors of higher sensitivity. This will push for strengthening our partnership with LIGO, the LIGO Scientific Community and KAGRA. This implies today to increase the effort on the R&D activities in a sinergic way with the international partners that it will pave the way for converging toward a world wide coordinated action for the construction of the new infrastructures hosting the 3G detectors. An adequate funding for R&D is needed and we wish to focus the attention of the EGO council on this issue. In parallel the VIRGO collaboration is committed to act in a way coherent with the picture reported in this document and take advantage of additional support got at national and international level.

Timing:

Table 1: Timeline for ta 3G infrastructure and detector

| Action | Timeline |
|---|---|
| Infrastructure design | ESFRI roadmap timeline |
| Site selection | 2021-2022 |
| Construction starts | 2023 |
| Detector design | end-2022 /mid-2023 |
| First data of the first 3G ITF | 2030 |

# 3 The Newtonian Noise Cancellation

## 3.1 Introduction

Newtonian noise (NN) is predicted to become a sensitivity limiting noise source in Advanced Virgo at frequencies below 20 Hz. Potentially relevant sources of gravity perturbations include seismic waves, atmospheric perturbations, and vibrating structures near test masses. Coherent noise cancellation is currently being investigated as most promising noise-mitigation technique with minimal impact on the infrastructure of the existing detectors. The cancellation scheme envisions the deployment of environmental sensors near all test masses of the GW detectors to retrieve information about mass-density fluctuations, which then serves to produce a coherent estimate of NN. The effectiveness of this scheme was demonstrated in numerical simulations based on realistic compositions of the seismic field, and has been applied successfully in the past to cancel other types of noise in GW detectors. Site characterisation, analytical studies, and numerical simulations have all been identified as quintessential for the development of NN cancellation systems. The goal of this project is to work towards NN suppression by more than a factor 10 over the next 5 to 10 years.

## 3.2 Part 1: Site characterisation and noise modelling

A detailed characterisation of the Virgo site needs to be carried out with initial focus on understanding the seismic field in terms of its spectra and two-point spatial correlation. These quantities are fundamental to the design of the seismic arrays for the purpose of noise cancellation. With improving cancellation performance, other contributions to NN will become relevant, which calls for more detailed site characterization with respect to atmospheric perturbations, and vibration of detector infrastructure. The various site characterization tasks, ordered according to when they are expected to become relevant, are the following:

1. Temporary installations of seismic arrays (about 50 sensors) to obtain detailed knowledge of seismic two-point correlations in the vicinity of all test masses.
2. Calculate improved NN prediction using acquired array data based on detailed models of laboratory buildings, and using numerical simulations, e. g. SPECFEM3D, which runs on clusters. Numerical simulations should also investigate response of building to individual seismic sources.
3. Deploy few seismometers (2 – 5) at each station for long-term (at least one year) studies of variability of seismic spectra and correlation, due to seasonal changes and human activity.
4. Use accelerometers to measure vibrations of important infrastructural components near test masses, e. g. handles used for installation of payloads, vacuum chambers.
5. Carry out geoseismic surveys with large seismic arrays (about 50 sensors) to study local geology.
6. Deploy microphone arrays (about 10 sensors) to measure sound spectra and correlations inside and outside Virgo buildings.

| | |
|---|---|
| People | 2 postdocs |
| Equipment | 50 seismometers (50 k€)<br>cabling, DAQ, synchronization (50 k€)<br>10 microphones + preamps + cabling (3 k€) |

## 3.3 Part 2: Coherent detection of Newtonian noise

Temporary installations of seismic arrays at an advanced stage of the Advanced Virgo commissioning will be used to attempt a first coherent detection of NN in the GW channel. The method that will be applied here is very similar to what will later be used for the noise cancellation. Seismic arrays monitoring seismic displacement in the vicinity of the test masses will provide a coherent estimate of NN, which can then be correlated with the GW channel. Once an effective cancellation of the dominant seismic NN is achieved (as a result of activities in Part 3), a similar investigation needs to be carried out for weaker forms of NN such as sound NN or NN from vibrating infrastructure. Advanced filtering technology needs to be developed in preparation of NN detection.

It should be emphasised that NN will be most relevant during intermediate stages of the detector commissioning when the laser power has not yet reached its final value, and when a signal-extraction mirror is not yet installed, or if the signal-extraction cavity is maintained in broadband mode. This means that a first detection of NN can be attempted relatively early, potentially already in late 2016 depending on the commissioning progress, which means that this project is well timed with respect to the Advanced Virgo commissioning plan. The tasks of Part 2 are:

1. Develop modified Wiener filters to be effective with non-stationary NN.
2. Analyze alternative environmental couplings (scattered light, residual seismic noise,...) to allow distinction between them and NN.
3. Deploy seismic arrays (about 10 − 20 sensors) with initial design informed by previous site characterization.
4. Deploy microphone arrays (10 − 20 sensors) with initial design informed by previous site characterization.

| People | 2 postdocs |
|---|---|
| Equipment | 20 seismometers (20 k€) + cabling, DAQ, synchronization (20 k€)<br>10 microphones (in addition to the purchase in Part 1) + preamps + cabling (3 k€) |

## 3.4 Part 3: Development of Newtonian-noise cancellation system

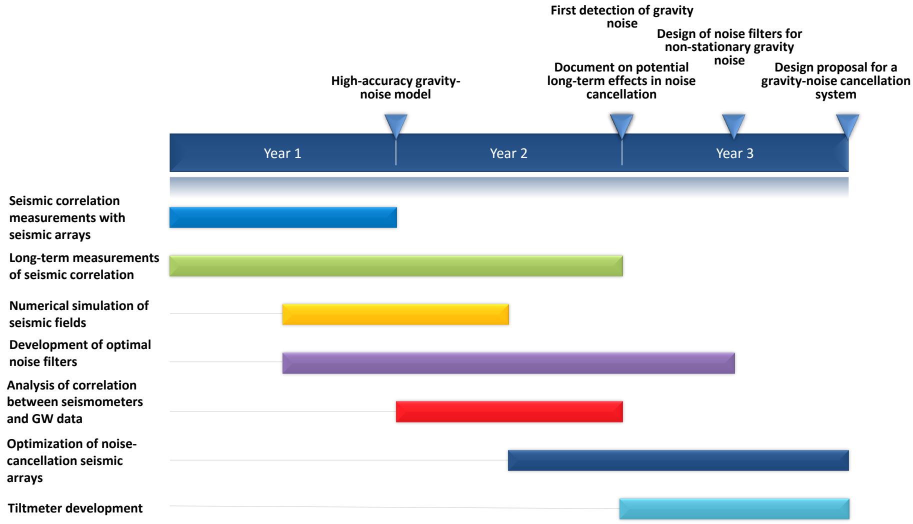
In the third step, the goal is to develop a NN cancellation system to be implemented as possible upgrade of the Advanced Virgo detector. The main result of this part will be a design proposal for seismic arrays for NN cancellation. An accurate prediction of how many seismometers and microphones are ultimately needed cannot be made, but initial analytical and numerical work suggests that 4 seismometers per test mass are sufficient for simple realizations of the seismic field at locations with near flat surfaces. Since such conditions do not hold at the Virgo site, it is difficult to estimate the required number of sensors, but it is highly unlikely that more than 20 sensors per test mass are required for a NN suppression factor of 10. Projecting predictions into the more distant future with correspondingly higher NN suppression goals is not possible, since it is not even known what type of effects become significant at this level.

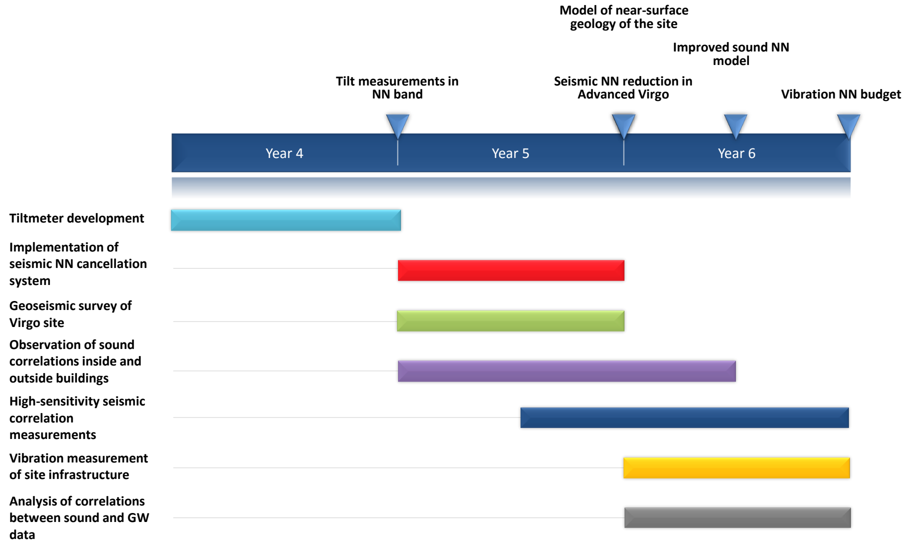
This part also includes sensor development, especially tiltmeters sensitive in the NN, which can potentially enhance NN cancellation performance. In summary, the tasks of Part 3 are:

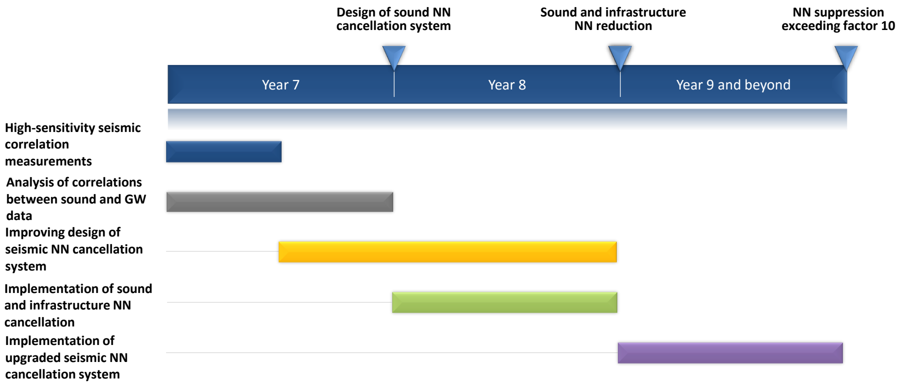
1. Use results from Parts 1&2 to deploy optimal seismometer arrays with the goal to suppress seismic NN by a factor of about 10.
2. Sensor development including tiltmeters for the NN band.
3. Deploy accelerometers to monitor vibrations of infrastructure and cancel NN.
4. Use results from Parts 1&2 to deploy optimal microphone arrays with the goal to suppress sound NN by a factor of about 3.
5. Improve efficiency of seismic NN cancellation by deploying further sensors, potentially installed in boreholes, and achieve NN suppression factors higher than 10.

| | |
|---|---|
| People | 4 postdocs |
| Equipment | Tiltmeter development (30 k€)<br>Prize per unit: seismometer (1 k€–15 k€) + cabling, DAQ, synchronization (1 k€–5 k€)<br>Each microphone + preamps + cabling (300 €)<br>Each borehole 50 k€ – 200 k€ |

## 3.5 Timeline




Design of sound NN cancellation system
Sound and infrastructure NN reduction
NN suppression exceeding factor 10
Year 7
Year 8
Year 9 and beyond
High-sensitivity seismic correlation measurements
Analysis of correlations between sound and GW data
Improving design of seismic NN cancellation system
Implementation of sound and infrastructure NN cancellation
Implementation of upgraded seismic NN cancellation system

# 4 Lowering the thermal noise

## 4.1 Scientific case

In the frequency band were Advanced Virgo is more sensitive, the dominant limiting noise is the thermal noise of coatings. Any reduction factor of coating thermal noise level will determine an increment of the same factor either of the maximum detection distance or of the signal-to-noise-ratio. Moreover, reducing the thermal noise will allow the interferometer to be quantum limited over most of its frequencies, enabling the fully benefit of using squeezed light.

The dependence of coating thermal noise level on the different detector parameters will be given below and in the next sections the upgrades plan will be outlined.

It has been demonstrated experimentally that thermal noise spectral density $S_{xx}$ in coatings is related to the different parameters of the laser beam and mirror by the following expression:

$$S_{xx}^{coat} = 2\,k_B\,T \cdot \frac{1-\sigma_s}{\sqrt{\pi^3}\,w\,Y_s} \cdot \frac{\phi_{eff}}{f} \cdot C_{FTM}^2 \tag{1}$$

where $k_B$ is the Boltzmann constant, $T$ is the temperature, $\sigma_s$ and $Y_s$ the Poisson ratio and the Young's modulus of the substrate, $w$ the laser spot size on the mirror ($w$ is the radius at which the field amplitude drops down to $1/e$, $f$ the frequency, $C_{FTM}^2$ is a correction term that takes into account the finite dimensions of the substrate and the effective loss angle of the material $\phi_{eff}$ is

$$\phi_{eff} = \frac{h}{\sqrt{\pi}\,w}\left(\frac{Y_s}{Y_\perp}\phi_\perp + \frac{Y_\parallel}{Y_s}\phi_\parallel\right) \tag{2}$$

where $h$ and $\phi$ is the coating thickness and loss angle respectively. The symbols $\perp$ and $\parallel$ indicate the directions perpendicular and orthogonal with respect to the surface of the coatings.

At room temperature there is not any other material for the mirror substrate like Suprasil®(a special synthetic fused silica made by Heraus GmbH) in terms of absorption, homogeneity and stress release. Therefore for all the room temperature upgrades of Advanced Virgo the substrate material will remain the same.

The only possible reduction of coating thermal noise has to come from the increase of the beam radius $w$ and the reduction of mechanical loss angle $\phi$.

The beam radius is the parameter that gives the strongest dependence of thermal noise above of all the others. The beam size on the mirrors is limited by the maximum allowable clipping losses and by the stability parameter $g$ of the cavities.
Changing the optical mode from simple Gaussian into one of the higher modes

like the Laguerre-Gauss 33 (LG33) give an increment of a factor 1.7 of the effective beam size $w$ but at the same time the compatibility of higher order modes with squeezing of light has to be demonstrated yet. For Advanced Virgo three types of upgrades are possible having different benefit and impact on the detector as explained synthetically in the next table.

| Upgrade | Benefit | Changes |
|---|---|---|
| No change on substrate dimensions<br><br>Little increase of beam size | Thermal noise reduction relies on new coating material | Cavity mirrors + input and output optics |
| Larger mirrors but same mass | Significant reduction of thermal noise based on larger $w$ and lower $\phi$ | as above + beam splitter and payload design |
| Larger mirrors with same aspect ratio | Largest reduction of thermal noise | as above + upper suspensions design |

Production of coatings for larger mirrors and development of a new low loss materials are the two R&D programs necessary for the upgrades od Advanced Virgo. A description of these two programs, their implementation plan and cost will be given in the next sections.

## 4.2 Larger beam profile

Increasing the beam profile could be done in two complimentary ways: increasing the diameter of the mirror substrate and using higher-order mode. Another advantage of using larger beams is the reduction of the thermal lensing magnitude, thanks to the reduction in the power density.

### 4.2.1 Increasing the mirror substrate size

One solution to have larger beams on the arm cavity mirrors is simply to have larger diameter substrates to keep the clipping losses at a negligeable value (in the order of few ppm). So what could be the maximum diameter for the mirror ? To limit the risk and the development time, one can choose to have the arm cavity mirrors of the same size as the current Advanced Virgo beamsplitter, the largest optic of the interferometer. The current beamsplitter is 550 mm in diameter, 65 mm thick and weighting 40 kg (the same weight as the actual test masses). We already know that such piece could be handled, cleaned, coated and caracterized at LMA (see section 4.2.2). Moreover, a suspension for such a large piece has already been developed and installed, albeit not a monolithic one.

So using a 550 mm diameter miroir, one can expect a possible increase of 60% of the size of the beam on the mirrors, compared to Advanced Virgo. That means a reduction of a factor 1.6 for the amplitude of the coating thermal noise and a reduction of 2.6 for the magnitude of thermal lensing. The beam radius will be 80 mm on the input mirror and 95 mm on the end mirror. Since we keep the arm cavities the same length, we will be closer to the instability region with a g-factor of 0.98. That leads to more stringent specifications on the mirror radius of curvature as well as the alignment system.

Even with a beam of 80 mm radius at the level of the input mirrors, it is possible to keep similar size of optics (PR, POP, SR, BS and CP) in the central part of the interferometer at the price of higher clipping loss, and hence more light on the baffles. For example, a beam of 80 mm passing through a 330 mm diameter optic will loose 200 ppm of its power, this value must be compared to the current 1500 ppm loss in the power recycling cavity. It should be noted that the reduction of the recycling gain due that additional loss, could be compensated by reducing the transmission of the power recycling mirror.

It is possible to have the same beam size on the power and signal recycling mirrors as presently, if the input mirrors could be equivalent to a converging lens by having a curved anti-reflection side. That will come to the price of having no etalon effect in the input mirror, which in any case could not be present due to the very good anti-reflective coating which can be achieved now (AR $<$ 100 ppm routinely achieved).

#### 4.2.2 Coating development on large mirrors

We suppose in this section a mirror diameter larger than 40 cm. The coating deposition technology developed at LMA is ready to treat two mirrors at a time in planetary motion. Although the required coating uniformity is the same as the one achieved for Advanced Virgo, an improvement of that uniformity at distances larger than 10 cm from the mirror centre has already started.

The proposed plan is for developing the deposition technology for mirrors with dimensions twice that of Advanced Virgo mirrors, i.e. a diameter as large as 70 cm, thickness 40 cm and mass of 300 kg. These dimensions are close to the maximum possible for the Grand Coater at LMA. The cleaning facility developed with the fundings for Advanced Virgo is instead limited to a diameter of 55 cm.

The following tasks will form the research plan that will deliver the technology for future upgrades of Advanced Virgo.

i) **New planetary motion.** A new rotary system able to hold and spin a 300 kg mirror at sufficiently high speed to have the maximum uniformity on nanometric layers will be developed. The system will have a precise control of deposition temperature over a wide range depending on the results of the research on new materials.

ii) **Dynamic control of sputtered material.** Developed as an alternative to the use of masks to make uniform the coating thickness, this technique is based on changing the geometry of the targets with respect to the ion beams so that the direction of sputtered material will be controlled. This task is developed in two stages: at first there is the conception and realization of the mechanics of the new system; later, there will be the optimization of the different parameters. This significant change of the Gran Coater will make it unavailable for any production of large mirrors for a considerably long time.

iii) **Post deposition correction.** This technique is based on applying a layer of silica after the deposition of the full stack of coatings in order to correct the wave front of the reflected light. The design of the coating stack has to be conceived specifically for the possible further correction. The deposition can be realized with the robot already developed with the Advanced Virgo fundings for the correction of the substrate or with the new system based on the sputtering lobe control of point ii).

iv) **Study of aberrations.** The development of coatings for Advanced Virgo has not answered to a question: what are the wavefront aberrations that more than others contribute to the loss of the cavities? Apparently the ordinary development on Zernike polynomial is not the most suited to this purpose and a new base has to be found. The outcome of this activity will indicate which type of post-deposition correction is necessary to apply to the stack.

Several new technologies for mirrors and suspensions are going to be developed for the upgrades of Advanced Virgo. At the end of the project a demonstrator, a pathfinder, is proposed based on a mirror of 550 mm diameter.

## 4.3 New coating materials

The coating stack used for Advanced Virgo was made by alternating layers of silica ($SiO_2$) and titania doped tantala ($TiO_2$:$Ta_2O_5$) having mechanical losses of $(0.45 \pm 0.03) \times 10^{-4}$ and $(2.4 \pm 0.3) \times 10^{-4}$ respectively as measured on monolayers deposited on cantilevers. The stack design was optimized in order to reduce the fraction of the lossier titania doped tantala but the gain was reduced by an excess loss supposedly related to the interfaces that brought the total loss angle of the ETM HR stack at $(2.3 \pm 0.1) \times 10^{-4}$, close to that of $TiO_2$:$Ta_2O_5$. The mixing of titania and tantala gave the lowest loss angle among all the high index materials tested at that time.

It is impossible to aim at a fixed reduction factor of coating loss angle because there is not yet a theory that explain the level of losses and relates it to the structural parameters at molecular level. Most of the amorphous materials have losses in the range $10^{-4} - 10^{-3}$. Recently films of amorphous silicon deposited at 400°C have shown losses as low as $10^{-6}$ but the material is not transparent at 1064 nm.

The research plan for the development of the new materials for the future upgrades of Advanced Virgo follows.

i) **New amorphous materials.** Selection of few oxides and nitrides, optimization of the deposition parameters for optical and mechanical properties. At first the work will be focused on the high index materials because they contribute the most to the overall loss of the stack.

ii) **Investigation on new mixing.** Following the experience with the titania and tantala in this task different mixtures of high index oxides are tested with the double purpose of lowering the mechanical losses or increasing the crystallization temperature.

iii) **Investigation on the high temperature deposition.** Results published in the literature have shown that mechanical losses and absorption coefficient of amorphous semiconductors deposited at high temperature are reduced more than what is achieved with a post-deposition annealing done at the same temperature. This task aims to investigate the effect of the deposition temperature on oxides and nitrates.

iv) **Origin of structural relaxations.** The previous lines of research can be conducted in an empirical way, finding the best set of materials and deposition parameters that minimize the mechanical losses. In this task light will be shed on the structural explanation at the molecular level of the origin of relaxations and on the different effect of mixing and temperature deposition. Analyzing tools are the Raman and Brillouin scattering and the different types of X-rays diffraction.

Not only the production of samples is an important activity in terms of manpower and equipment but also and even more the characterization of samples. Optical and mechanical characterization will be assured by several of the Virgo laboratories, as long as their demand of manpower will be fulfilled. Structural characterization will be done in collaboration with research groups that are non part of the Virgo collaboration but that have an already established collaboration with them.

# Required resources

For the two main R&D activities presented above the requested budget will be presented separately. The execution time is meant to be three years.

| Coatings for large mirrors | | |
|---|---|---|
| Personnel | 1 Post-doc | 200 k€ |
| Equipment | Large mirror mechanics | 30 k€ |
| | Temperature control | 20 k€ |
| | Dynamic control of scattering lobes | 50 k€ |
| | Metrology on large plates | 20 k€ |
| Consumables | Large plates for uniformity test | 50 k€ |
| | Polishing of one Virgo old substrates | 100 k€ |
| Pathfinder | Substrate and polishing | 200 k€ |
| TOTAL | | **570 k€** |

| New low loss materials | | |
|---|---|---|
| Personnel | 4 Post-doc | 792 k€ |
| | 3 PhD | 300 k€ |
| Equipment | Upgrade of existing facilities | 200 k€ |
| Consumables | Targets for deposition of new materials | 200 k€ |
| | Small substrates | 80 k€ |
| | Structural analysis | 30 k€ |
| TOTAL | | **1602 k€** |

# 5 Larger beams

As it was discussed in a previous section, the mirror Internal Thermal Noise is the dominant noise source in Advanced LIGOÕs maximum frequency range. Coating Thermal Noise dominates over Substrate Thermal Noise. to reduce thermal noise by a factor of the order of 2. By systematically optimising the laser intensity profile, we can decrease thermal noise compared to the use of Gaussian beams. In particular it has been proposed to use Laguerre-Gauss modes [**?** ], A. Allocca, A. Gatto, M. Tacca, R. A. Day, M. Barsuglia, G. Pillant, C. Buy and G. Vajente, *Higher-order Laguerre-Gauss interferometry for gravitational-wave detectors with in situ mirror defects compensation*, Physical Review D 92, 102002 (2015), known in the literature for their low diffraction loss. In fact, it has been analytically demonstrated that the thermal noise of the mirrors can be reduced by a factor which depends on the spatial order $N = 2p + l$ of the ${LG^l}_p$ mode resonant in the interferometer: higher $N$ values lead to larger beams and lower thermal noise. For example, the thermal noise level could be decreased by nearly a factor of 2 by using an ${LG^3}_3$ beam. Furthermore, the interferometric GW detectors are strongly affected by thermal issues, caused by laser power absorption in the optics (either in the bulk or on the coating): the absorbed power gives rise to a temperature gradient in the material, which results in a refractive index change and in a thermal deformation of the mirror surface. The resulting aberrations in the beam wavefront cause a loss of detector sensitivity. Thermal effects related to higher-order ${LG^l}_p$ beams should be in general lower than those given by the Gaussian intensity pattern.

To be used in GW detectors, higher-order ${LG^l}_p$ beams must be generated with very high purity and stability. The mode purity is crucial for having far-field propagation in kilometer-scale interferometers with no degradation of the propagating beam shape, and for optimal coupling of the mode to the Fabry-Perot cavities of the detector. Moreover, since high-power laser beams of hundreds of Watts will be used, higher-order ${LG^l}_p$ modes must be generated with high efficiency and low losses. To explore this approach for reducing the mirror thermal noise requires a dedicated R&D study is required.

Like the fundamental Gaussian beam, those modes are still compatible with spherical mirrors and hence are compatible with current mirror technologies. Although, it has already been demonstrated the successful generation and control of such modes [1, 2], two obstacles remain:

- By definition, one higher order mode is degenerated with all the optical modes with the same order. In order to guarantee the purity of the mode in the arm cavity with limited coupling to other modes, outstanding mirror surface quality is essential which is currently beyond the current polishing technology. One solution to relax the polishing requirement would be to use in-situ thermal figuring of the mirror surface [3]. This attractive solution has been explored theoretically but only demonstrated experimentally in the a simple case[4].
- The compatibility of the higher order modes with squeezing of light still has to be demonstrated. There is no fundamental problem, but many technical challenges should be expected.

### 5.1 Cost and man power

The following cost estimate, which includes VAT, is a rough estimate based on numbers from AdV construction for some parts. A detailed project is required for an accurate costing.

For the two main R&D activities presented above the requested budget will be presented separately. The execution time is meant to be three years.

| R&D on larger beams | | |
|---|---|---|
| Personnel | 1 Post-doc | 200 k€ |
| Equipment | Mirror mechanics | 30 k€ |
| | Optical table | 20 k€ |
| | Instrumentation for LG production | 50 k€ |
| Consumables | Electronic components and photodiodes | 50 k€ |
| TOTAL | | **300 k€** |

# 6 Squeezing

## 6.1 Introduction

Quantum noise limits the sensitivity of AdV above 30 Hz. Therefore a significant sensitivity enhancement can be achieved through reducing the quantum noise contribution. This can be accomplished by injecting a frequency-dependent squeezed vacuum field (FDS) into the interferometer's dark port.

Figure 7 shows two scenarios to improve Virgo sensitivity by using squeezing: the blue curve show the case of frequency-independent squeezing (FIS) injection, achievable using current state-of-the-art technology (12 dB squeezing produced by the squeezer before injection, 22% injection losses and 20 mrad phase jitter), while the red curve shows the case of FDS using an improved setup based on experimental parameters that should become realistic by 2020 when the FDS shall be employed. In particular for the red curve, 15% injection losses and 15 mrad phase jitter are considered. Other relevant parameters used for simulating the sensitivity curves are described in the following.

This figure also displays the sensitivities without squeezing, including the detuned signal recycling configuration that is another way to shape the sensitivity and change the impact of quantum noise. The BNS range could be improved a bit with the detuned setting, doing even better than both the tuned and FIS cases, but at the price of significant sensitivity reduction at high frequencies. The injection of frequency-dependent squeezing provides the best result for both simultaneously improving BNS range and high-frequency sensitivity.

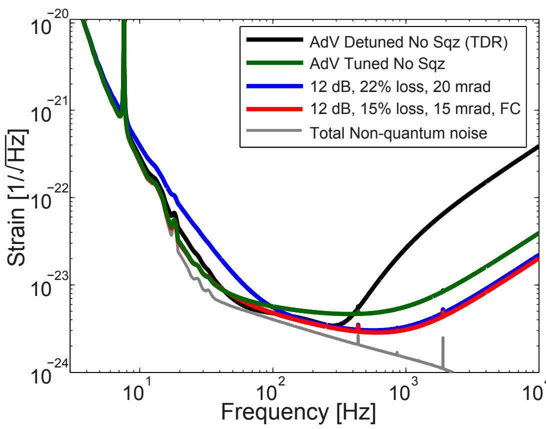



Figure 7: *Sensitivity curves with and without squeezing. The total non-quantum noise curve is the contribution of the various nominal non-quantum noises as given by the AdV TDR. The BNS/BBH ranges go from 134/1197 Mpc (tuned signal recycling) and 146/1165 (detuned signal recycling) with no squeezing, to 124/601 Mpc with FIS and 158/1212 Mpc with FDS injection respectively. At 1 kHz, compared to the AdV tuned case, the sensitivity improves by a factor of 1.7 with FIS and 1.8 with FDS, while the detuned case reduces the sensitivity by a factor of 5.*

So far, the most robust and efficient method to produce FDS is by rotating the squeezing produced by a FIS system, by means of reflection from a filter cavity (FC) offset from the carrier. Recently this technique has been demonstrated experimentally in the audio frequency band and thus could also be used in enhancing Advanced Virgo. It demands some further R&D with respect to what is already available. In detail:

- Development of a vacuum state of light, with 12 dB squeezing being produced/available in the acoustic frequency band: the source should operate in vacuum and be equipped with seismic isolation. An in-air source has already been developed by a few groups and prototypes are also under development by Virgo collaborators. The next step (suspended source in a vacuum environment) has not been fully developed yet and requires specific R&D. The Virgo collaboration is considering the possibility to put the optical bench of the squeezing source within a minitower in the detection area. The laser sources used in the generation of the squeezed state would instead be housed on a standard bench close to the minitower.
- Development of a low loss system to inject the squeezed state. The minimal requirement is injection losses at the level of 22%: this can only be achieved by reducing the losses of the detection path, with especially the development of custom Faraday isolators (3 on the squeezer bench and 1 on the detection bench) having losses lower than 2% each in vacuum. Other parts, including the OMC, are expected to require some improvement. Optical losses are one of the most critical issues for taking advantage of the squeezed state of light and has not yet been fully solved. Thus it has high priority and should be addressed as soon as possible.
- Development of a single linear filter cavity: this geometry is motivated by the requirement of minimizing optical losses to lower than 1ppm/m. A 100 to 300 m long cavity with state-of-the-art mirror quality is estimated to satisfy the loss requirement, having losses at the level of 0.2 ppm/m. The FC can be housed in the north-input arm, in a dedicated vacuum enclosure with mirrors suspended by "microtowers" (reduced version of the minitowers hosting mSAS and just a mirror or a very small optical table).

## 6.2 Implementation Plan

The squeezed light sensitivity enhancement for AdV will be implemented in two main phases:

1. Development of the **frequency-independent, in-vacuum, suspended squeezed light source** and integration on AdV by 2018-20. The integration of the squeezer should be made in the same time window required for the installation of the other AdV upgrades.

   The squeezing source will be used in the first years of the AdV operation as a FIS source to mitigate the risk related to high input optical power. Figure 1.4 of the AdV squeezing TDR shows that using FIS, the full power

(125 W) sensitivity could be approached at much lower input power (25 W).

To meet the short term integration plan, development of the in-vacuum squeezer with all the related and necessary optical, electronic and mechanical systems (auto-alignment systems, low loss ITF injection optics, in-vacuum electronics etc.) should start as soon as possible. *Possibly these activities should start in early 2017 and be completed by 2018.*

2. **Filter cavity for frequency dependent squeezed light**. Integration on AdV in 2020 or after the deployment of the full input laser power.

   To convert FIS to FDS will require the FC after the in-vacuum squeezed source. An early installation of its main infrastructures during the first planned upgrade of AdV in 2018-19 is highly recommended. The target improvements in injection losses and phase jitter will require R&D and could be tested on the detector as enhancements of the FIS subsystem.

## 6.3 Cost Estimate

The following cost estimate is a rough estimate based on numbers from some parts of AdV construction (including VAT). These estimates do not include manpower. A detailed project costing is required for greater accuracy.

Table 2: Cost of in-vacuum suspended squeezer

| | |
|---|---|
| Minitower | 125 kEuro |
| in-vacuum susp. bench | 285 kEuro |
| optics+electronics+mechanics | 300 kEuro |
| mSAS isolation system | 130 kEuro |
| mSAS control electronics and DAQs | 40 kEuro |
| extra clean areas | 40 kEuro |
| Low loss Faraday Isolators (1 on SDB1 + 3 on SQZB) | 90 kEuro |
| Low-loss OMC | 90 kEuro |
| Optics on SDB1 | 20 kEuro |

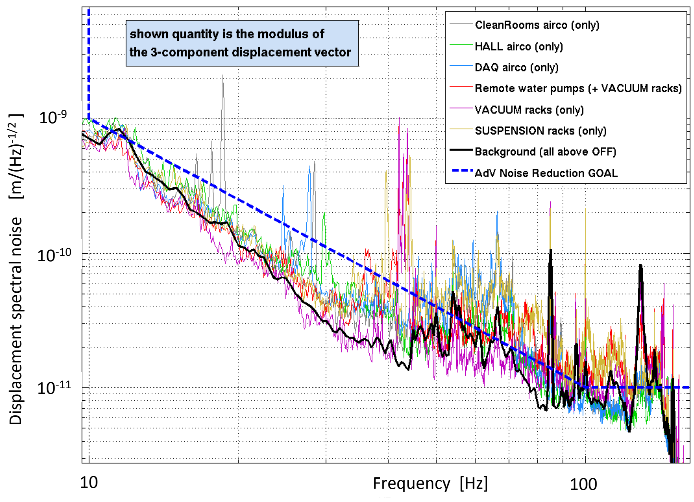
This sums up to 1120 kEuro, on which we need to add some contingency (180 kEuro). Probably two third of this budget would need to be committed in 2017.

Table 3: Filter Cavity Cost

| | |
|---|---|
| Beam tube, 300 m lenght, 250 mm diameter | 180 kEuro |
| 2 vacuum enclosures for mirrors (“microtowers” ) | 2x80 kEuro |
| mSAS isolation systems | 2x130 kEuro |
| cavity mirrors | 150 kEuro |
| auxiliary optics and control electronics | 100 kEuro |

This sums up to 750 kEuro, on which we need to add some contingency (150 kEuro). Probably one third of this budget would need to be committed in 2017.

In total, the overall project sums up to 2300 kEuro, with roughly half of that to be committed in 2017.




# 7 The Improvement of the detector robustness

## 7.1 Anthropogenic noise reduction

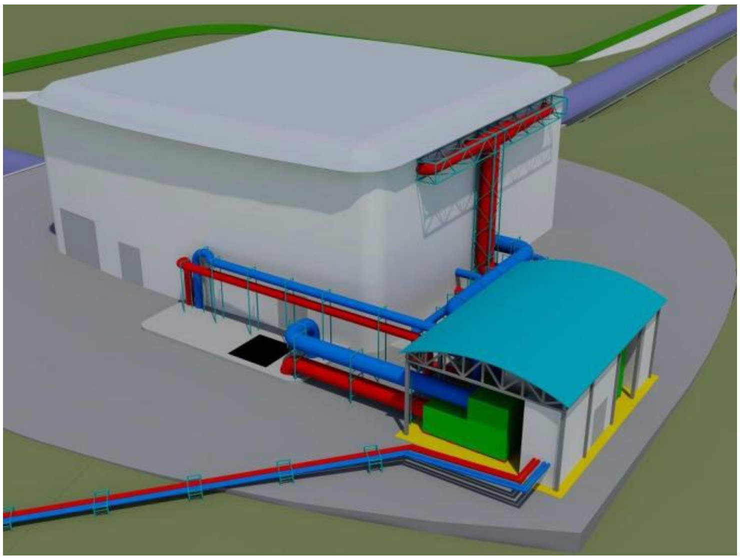
In the figure 7.1 we report the measurements of the displacement noise performed using a high sentivitive seismometer Guralp CMG-40T during the commissioning phase data taking of Virgo+. On the base of these spectra we proposed for advanced Virgo to move all the machineries still present in the central area out of the experimental buildings. It implies mainly to displace part of the auxiliary ultra high vacuum equipments and the rough pumps and to improve the acoustic insulation of the duct paths.

This proposal was abandoned mainly for lower the budget cost of advanced Virgo, but it could happen that, to beat the barrier of the design AdV , we need to relaunch this proposal. As it is sketched in the 3D scheme shown in the figure 7.1, it require to build an other hangar to host the machinery and few tens of meters of isolated extra ducts. The cost of this project is evaluate around 500 k€.

## 7.2 Low frequency robustness

As any other complex detector, Virgo can be assumed to be known only with a given approximation. In fact, many intrinsic and environmental parameters affect detector status and performances and three detectors observing simultaneously need a duty cycle greater than 80% to get an overall duty cycle equal to 50%.

For example, we know that large remote earthquakes can cause a stop of operations for several minutes while large sea waves can make cavities lock acquisition and lock keeping difficult for few days each month. We also know that

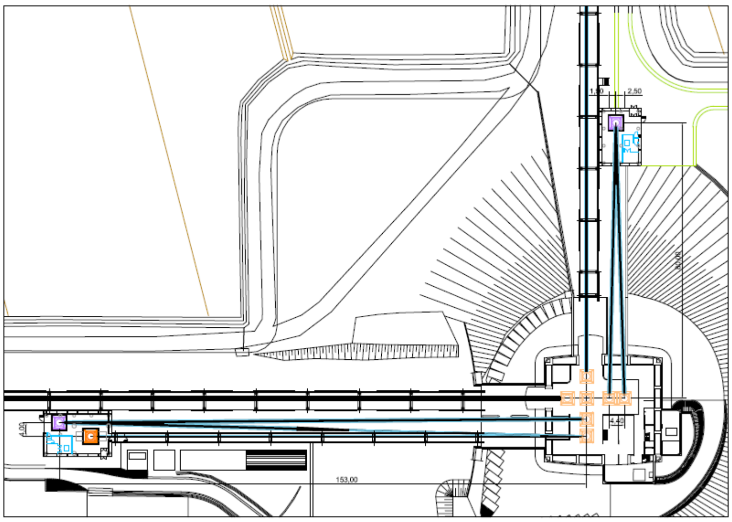


small changes in temperature can cause suspensions length to vary significantly. Similarly, small changes in power stored in Virgo cavities can affect mirrors curvature. All these parameters variations can produce a significative drop in observing time penalising detector duty cycle. Moreover, most of our control loops operate in small neighbourhood of n-dimensional working point, where we can assume systems to be linear. In most cases, changing working point produce very large variation of system parameters and therefore variation of control loops performances that can produce a degradation of stability margins.

During last few years several techniques where studied and tested in Virgo to improve control loops robustness to system uncertainties and perturbation. Some of these techniques were already operative in Virgo+, for example a method to improve robustness to tele-seism. Other techniques were simply studied like for example predictive control of tidal strain. Adaptive algorithms were also studied to improve, for example, lock time during windy days processing data produced by the detector itself together with environmental data. In parallel with algorithms we keep on investigating inertial sensors technologies with a special attention to angular acceleration sensors and angular velocity sensors. Adding ground tilt sensing capabilities to the Virgo detector will improve ground noise rejection.

Robust and adaptive control can significantly increase observing time and improve detector knowledge. Furthermore, detector performances will benefit from a reduction of noise injected into the system by non-optimal control loop design or non-optimally tuned sensors and actuators. At the same time, system designer will eventually have a clear view of specifications to be changed to obtain further improvements in the overall system performance.

In particular, the global control of the auxiliary degrees of freedom, along the longitudinal and angular directions, are implemented in order to ensure high duty cycle and long period of data taking, but any noise in the associated auxiliary degrees of freedom will couple to the gravitational wave channel at



some level.

The control noise of the auxiliary dofs is indeed a strong critical limiting factor at low frequency, below few tens of Hz, as it has been experienced in Virgo and Virgo+ [5] and in Advanced LIGO [6].

Several actions can be foreseen to mitigate and reduce the noise re-introduction in the gravitational wave signal such as using a real-time feed-forward cancellation techniques, improve the error signal SNR increasing the amount of power on the photo-diodes and reduce the environmental and diffuse light noise.

## 7.3 The optical stability of the recycling cavities: the long cavity solution

The present optical configuration of Advanced Virgo is based on the use of recycling optical cavities, that are marginally stable. This solution can make more difficult the operation of the interferometer with higher power of the light stored in the cavities. The alternative solution is to use non degenerate recycling cavities that should make simpler to achieve the optical stability. At the time of the approval of the advanced Vigo project this approach has been excluded mainly for financial reasons. The scheme was based on the installation of long cavities implying the construction of two smaller buildings and two vacuum tubes more than 100 m long. as it is shown in the figure 7.3. A rough cost estimate of the infrastructures and vacuum system has been performed, considering a redundant approach, that means to provide building, infrastructures and system of the same level of the ones presently used in Virgo, and the maximum possible length solution (180 m-long cavity for Power Recycling, and 80 m for Signal Recycling cavity).

The result of the cost analysis is reported in the table 4.

Table 4: *Rough evaluation of the the long recycling cavities*

| | |
|---|---|
| Civil Infrastructures | 6600 kE |
| Vacuum Tube | 4000 kE |
| Equipment | 400 kE |

### 7.4 The upgrades of thermal compensation system

The Thermal Compensation System (TCS) needs to correct all wave-front aberrations in the optics of the interferometer that can prevent the detector to operate at design sensitivity. Besides thermal aberrations, due to the absorption of a fraction of the power circulating in the interferometer, there are sources of optical defects arising from imperfections in the production and polishing of the glass used for the various substrates in the recycling cavity. Surface figure errors on reflective and transmissive surfaces do contribute to the aberrations as well as spatial variations in the index of refraction of the substrates.

The TCS installed in Advanced Virgo [7–9] has been designed to allow for maximum flexibility, comprising sensors and actuators to control the radii of curvature of all test masses and to compensate for wave-front aberrations in the recycling cavities. However, some upgrades are necessary to cope with a new possible optical design of AdV+.

**Enlarged beams** If the beam circulating in the recycling cavity is made bigger, the sensitivity to wave-front distortions will increase. Thus, it will be necessary to upgrade the $CO_2$ projector in order to flatten the optical path length over a larger portion of the optics. A new optical layout of the $CO_2$ benches will be needed, while the core concept of the correction system (the so called Double Axicon System [10]) could still be used. The upgrade of the bench would take place in 2020.

**Non-axysimmetric defects** The strategy envisaged and installed in Advanced Virgo to correct for non-symmetric defects [11] makes use of a $CO_2$ laser scanning system [12], driven by a pair of galvo mirrors. This technique, while being effective in reproducing the desired heating pattern [13], 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 $CO_2$ laser beam: one of the most promising makes use of Micro-Electro-Mechanical-System (MEMS) deformable mirrors [9], which imprint a phase modulation to the wave-front of the incoming Gaussian beam that converts the beam's intensity distribution into the desired one holographically. The R&D activity should begin as soon as 2017, the installation would take place in 2020.

**Hartmann Wave-front Sensors** In Advanced Virgo, each optic with a significant thermal load is independently monitored [7, 8]. The HR face of each test mass is monitored in reflection off-axis for deformation. The input test mass/compensation plate phase profile is monitored on reflection on-axis from the recycling cavity side.

The TCS sensors, dedicated to the measurement of thermally induced distortions, consist of a Hartmann Wave-front Sensor (HWS), and a probe beam (at a different wavelength than the ITF beam) whose wave-front contains the thermal aberration information to be sensed.

The Hartmann sensor selected for Advanced Virgo is that already developed and characterized on test bench experiments and in the Gingin High Optical Power Test Facility for the measurement of wave-front distortion [14]. This sensor has been demonstrated to have a shot-to-shot reproducibility of $\lambda/1450$ at 820 nm, which improves to $\lambda/15500$ with averaging, and with an overall accuracy of $\lambda/6800$ [15].

Recently, the DALSA Teledyne Company has put out of production the Pantera 1M60 CCD, which is the core of the present HWS. Thus, it is absolutely necessary to start an R&D activity to find another CCD with good performances in terms of noise, fill factor, frame rate and saturation power and to design a new Hartmann plate and spacers in order to maximize the performances of the wave-front sensors, by optimizing the parameters over the new CCD, and guarantee or overcome the sensitivity of the present device.

Moreover, it has been demonstrated [16] that the HWS is sensitive to fluctuations of the environmental temperature. While a control loop has been developed and implemented, capable of stabilizing the sensor's temperature within 5 mK [16], it would be desirable to minimize such sensitivity by a clever design of the Hartmann plate and spacers.

This R&D should start in 2017, in order to install the new sensors in 2020.

**Laguerre-Gauss beams** If the use of higher order Laguerre-Gauss modes ($LG_{33}$) is considered to reduce the coating thermal noise, the $CO_2$ projector needs to be completely re-designed and re-built and an R&D activity should start as soon as possible (already in 2017). This would allow to conclude the relevant procurements in 2019 and proceed with the installation on the detector in 2020.

**Adaptive optics for squeezing** One of the main parameters that affect the amount of squeezing injected in the detector is the mode matching between the interferometer beam and the squeezed beam. From the side of the interferometer, TCS has the task to keep the ITF beam as Gaussian as possible. However, the level of compensation that can be achieved cannot guarantee perfect Gaussianity. For this reason, it is advisable to start an R&D activity to develop an adaptive optical system that, acting on the squeezed beam itself, would further improve the mode matching, without introducing additional losses along the squeezed beam path. This task should start in 2017, in order to match the timeline of the squeezer development.

The following cost estimate, which includes VAT, is a rough evaluation based on expenses for AdV construction. A detailed project is required for an accurate costing. The above mentioned upgrades require:

- *$CO_2$ laser projector*: to cope with enlarged beams, 100 kEuro for the installation;

- *Development of a $CO_2$ laser beam shaper*: procurement of MEMS deformable mirrors and related electronics. About 70 kEuro for the R&D and 130 kEuro for the installation on site;
- *Development of a HWS*: for the development of the new sensor, about 50 kEuro are estimated, while for the installation, considering that there are currently six sensors installed on Advanced Virgo, the total estimated cost is about 150 kEuro;
- *TCS for Laguerre-Gauss modes*: around 350 kEuro are estimated for the installation of completely new $CO_2$ laser projectors, including some R&D on proper laser beam shaping ($\sim$60 kEuro);
- *Adaptive optics for squeezing*: the estimated cost for the R&D activity is about 50 kEuro; for the integration of the system in the squeezer, 70 kEuro have been considered.

Some of these items partially overlap, so the total cost is not the sum of the single tasks, but it will be defined according to the design choices for AdV+.

Minimum required manpower: one post-doc fellow for three years. The costs for the three different scenarios are summarized in tables 5, 6 and 7.

Table 5: *Rough cost evaluation for the TCS Upgrade and R&D*

| | | |
|---|---|---|
| Personnel | 1 Post-doc fellow for three years | 150 k€ |
| Equipment | $CO_2$ laser beam shaper | 200 k€ |
| | New Hartmann sensors | 200 k€ |
| | Adaptive optics for squeezing | 120 k€ |
| TOTAL | | **670 k€** |

Table 6: *Rough cost evaluation for the TCS Upgrade and R&D with enlarged beams*

| | | |
|---|---|---|
| Personnel | 1 Post-doc fellow for three years | 150 k€ |
| Equipment | $CO_2$ laser projector | 100 k€ |
| | $CO_2$ laser beam shaper | 200 k€ |
| | New Hartmann sensors | 200 k€ |
| | Adaptive optics for squeezing | 120 k€ |
| TOTAL | | **770 k€** |

Table 7: *Rough cost evaluation for the TCS Upgrade and R&D with LG modes*

| | | |
|---|---|---|
| Personnel | 1 Post-doc fellow for three years | 150 k€ |
| Equipment | TCS for Laguerre-Gauss modes | 350 k€ |
| | $CO_2$ laser beam shaper | 200 k€ |
| | New Hartmann sensors | 200 k€ |
| | Adaptive optics for squeezing | 120 k€ |
| TOTAL | | **1020 k€** |

# 8 Extending the arm length

## 8.1 Motivation

The sensitivity is directly related to the arm length, since the strain is the displacement divided by the arm length. Most of the displacement noises, like the thermal noise, or sensing noise are almost independent of the arm length. Therefore, increasing the arm length to 4 km like aLIGO would provide a 33% increase almost independently of the frequency and therefore a 2.4 event rate increase for all sources.

This is an increase that would be on top of any other proposed improvement. The required change of mirrors could also be the opportunity to increase a bit the beam diameter which is the other reason why the aLIGO sensitivity is better than that AdV one (by about 11%).

## 8.2 Discussion

The following image is showing the area at the end of both arms. The first houses along the arm axis are around 4.5 km from the central building. Therefore, the possibility for the arm extension is limited to about 4km, which would match the LIGO arms length.

However, the north arm would have to cross a road and a channel. Building a bridge for a road might be possible and a preliminary investigation indicates that the arm would be above the channel. But this is not based on a real study that should include the various legal or engineering constrains.

This example is showing that today, we don't know if the arm extension is feasible or not. This upgrade is listed in this document, not yet as a proposition of upgrade, but as a proposition of study at this stage.

## 8.3 Implementation Plan

Given the unknown highlighted in the previous section, it is too early to write a realistic implementation plan. The first step is to do a realistic evaluation of the project, investigating the technical and legal issues, land acquisition feasibility, establishing a timeline for the construction and a budget. This would be mostly a task for the infrastructure group of EGO, with help for vacuum experts, and various subsystems once the possibility of this extension become more plausible.

One could expect that such an evaluation take of the order of one year. Then we would be in a position to make a choice, taking into account the cost, planning and long-term role of the Virgo infrastructure in the international network of gravitational waves detectors.

The construction itself will likely take several years, ending maybe at the time of LIGO-India commissioning, a key parameter for the long term role of the Virgo infrastructure. However, most of the construction, like the new end buildings, could be done in parallel with data taking of AdV, leading to a down time for

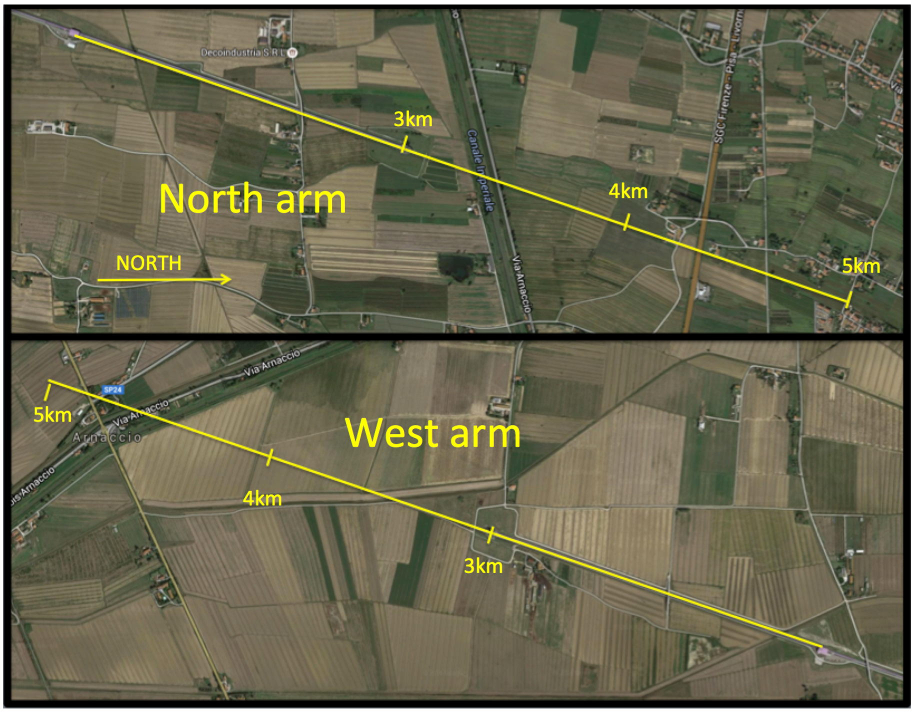



Figure 8: *Aerial view of the north and west arms (from Google map) with the projection of the extension to 4 or 5 km long arms.*

connecting the arm extension and moving the terminal towers and suspension to maybe a year. Such a down time has to be compared to the 2.4 event rate increase meaning that 1 year of data collected with AdV 4km would be equivalent to 2.4 year of data with AdV 3 km.

### 8.4 Cost and man power

It is obviously too early to give a robust estimate of the cost. Nevertheless, an order of magnitude could be derived from the Virgo construction cost (investment) that was 78 ME, including 18 MEuros for the tunnels. In first approximation, we can take one quarter of this cost for 1 km of arm plus the terminal buildings since we can reuse the vacuum chambers, suspensions and the central building contains more hardware. Then, adding 35% inflation from 1995 to 2016 plus 15% contingency, we get 30 MEuros as very rough estimate. This is significant but the payoff expressed in Mpc/MEuros might be competitive compared to other upgrades.

# 9 Conclusion

The future evolution is summarised in a three-phase scenario:

- *Short term ( 2017-2019)* ■ Achieving the AdV design sensitivity, integrating the mature new technologies and starting a new R&D program aimed to enhance the 2nd generation and preparing the 3rd generation. Starting the infrastructure design to get included in the ESFRI roadmap;

- *Medium term ( 2025)* ■The R&D is finalised and the new systems are integrated in the existing infrastructure. Construction of the new infrastructure is progressing;

- *Long term (>2025)* The construction of the new detector is started.

In this document we have described a number of open technical options for the enhancement of AdV. Among those we expect that squeezing and subtraction of newtonian noise will be certainly implemented. The total investment for integrating these mature technologies is expected to be of the order of 5M€.

R&D for the other options is strongly encouraged and their implementation will be considered on the basis of the R&D outcomes and a tradeoff analysis evaluating the scientific payoff, the impact on the data taking plans, the budget an schedule aspects.

The new 3 G detector will require a total investment ranging around 1B€. Seen the scale of investment, a coordinated effort of several countries is needed. It should also cover dedicated R&D program with an expected cost in the range around 10 - 20 % of the total investment (for comparison, the cost of the R&D program for aLIGO was about 30% of the project budget).

## References


[1] M. Granata, C. Buy, R. Ward, and M. Barsuglia. Higher-order laguerre-gauss mode generation and interferometry for gravitational wave detectors. *Phys. Rev. Lett.*, 105(23):231102, Nov 2010. 21

[2] Paul Fulda, Keiko Kokeyama, Simon Chelkowski, and Andreas Freise. Experimental demonstration of higher-order laguerre-gauss mode interferometry. *Physical Review D*, 82(1):012002, 2010. 21

[3] RA Day, G Vajente, M Kasprzack, and J Marque. Reduction of higher order mode generation in large scale gravitational wave interferometers by central heating residual aberration correction. *Physical Review D*, 87(8):082003, 2013. 21

[4] A Allocca, A Gatto, M Tacca, RA Day, M Barsuglia, G Pillant, C Buy, and G Vajente. Higher-order laguerre-gauss interferometry for gravitational-wave detectors with in situ mirror defects compensation. *Physical Review D*, 92(10):102002, 2015. 21

[5] F. Acerne and et al. Automatic alignment system during the second science run of the virgo interferometer. *Astroparticle Physics*, 34(6):327–332, 2011. 29

[6] LIGO collaboration. The sensitivity of the advanced ligo detectors at the beginning of gravitational wave astronomy. *http://arxiv.org/abs/1604.00439*. 29

[7] Alessio Rocchi. Thermal effects and their compensation in the interferometric gravitational wave detector advanced virgo. *Proceedings of the 46th Rencontres de Moriond, ed E Auge, J Dumarchez and J T T Van*, 2011. 30

[8] Alessio Rocchi and et al. *J. P. Conf. Series*, 363:012016, 2012. 30

[9] Alessio Rocchi. Thermal effects and other wave-front aberrations in recycling cavities. *Advanced interferometers and the searches for gravitational waves*, ISBN: 978-3-319-03791-2:404, 2014. 30

[10] Viviana Fafone and et al. Tcs: R&d progress. *VIR-0090A-11*, 2011. 30

[11] Viviana Fafone and Alessio Rocchi. Adv tcs: Considerations on actuation and sensing for the correction of high order aberrations in msrc. *VIR-0373A-11*, 2011. 30

[12] R. C. Lawrence. *Ph.D. thesis, MIT, LIGO-P030001-00-R*, 2003. 30

[13] Matteo Lorenzini and et al. Tcs status update - virgo week. *VIR-0575A-14*, 2014. 30

[14] Y. Fan and et al. *Rev. Sci. Instrum.*, 79:104501, 2008. 31

[15] A. F. Brook and et al. *Optic Express*, 15(16):10451, 2008. 31

[16] Ilaria Nardecchia and et al. Tcs test facility: Tetis-status report. *VIR-0499A-15*, 2015. 31