Ground based gravitational wave interferometric detectors of 1st and 2nd generation: an overview

Giovanni Losurdo

Istituto Nazionale di Fisica Nucleare - Sez. di Firenze - Via G. Sansone 1 - 50019 - Sesto F. (Firenze)

E-mail: losurdo@fi.infn.it

Abstract. The era of first generation of interferometric detectors of gravitational waves is ending. No detection has been done so far. However, remarkable results have been achieved: the design sensitivity has been approached (and in some cases even exceeded) together with good robustness and reliability. A world wide network of detectors has been realized. The data collected so far have allowed to put upper limits on several sources. Some second generation technologies have been tested on the first generation detectors. The scenario for the next years is very exciting. The projects to upgrade LIGO and Virgo to second generation interferometers, capable to increase the detection rate by a factor ∼1000 have been funded recently. The construction of Advanced LIGO and Advanced Virgo has started. GEO600 has started the upgrade to GEO HF, introducing squeezing for the first time on a large detector. LCGT has been partly funded and construction of the vacuum system is underway. There might be a chance that the third Advanced LIGO interferometer be moved to Australia or India. So, a powerful world wide network could be in operation by the end of the decade. In this paper we review the results achieved so far and the perspectives of the advanced detectors.

1. Introduction

After a decade of commissioning, data taking and soft upgrading, the interferometric detectors of gravitational waves (GW) are now being shut down to start their upgrade to *second generation*. This is possible thanks to the research and development activity that has been carried out in parallel with the operation of LIGO [1], Virgo [2] and GEO600 [3], which has allowed to engineer the needed technologies. We are at a turning point: the era of the first generation kilometer-scale interferometers ends leaving a remarkably rich heritage. Such richness is being invested in a new generation of detectors that finally promise to open a new window on the universe.

2. The legacy of the first generation detectors

At the beginning of the 2000s the large interferometer construction was being completed. In ten years enormous progress has been done. It is the right moment to discuss what are the main achievements of the first generation detectors and what is their legacy to the second generation.

- **Infrastructures:** The investments for the first generation leave us important infrastructures that will host the advanced interferometers: the LIGO facilities (Hanford, WA and Livingston, LA), the Virgo site (Cascina, Italy) and the GEO600 one (Hannover, Germany) (see fig. 1,2). More facilities will be realized: the construction of the underground



Figure 1. The LIGO-Livingston facility



Figure 2. The Virgo facility

3km detector LCGT has been funded in japan [4] and the possibility to move one of the three Advanced LIGOs to India is being explored.

- **A long commissioning:** all the detectors went through a commissioning phase that lasted years, improving the sensitivity progressively (see fig. 3). The interferometers were new instruments, never tested before in such extreme configurations. The commissioning teams had to learn how to operate controls, to cope with optical configurations of increasing complexity, to cope with thermal effects and scattered light, to identify unknown sources of noise and fix the detectors as unexpected problems showed up. Eventually, the inspiral range for binary neutron star of the LIGO Hanford detector was as good as 20 Mpc.
- **Noise and sensitivity:** LIGO and Virgo have closely approached their design sensitivities. The noise sources have been mostly understood (see fig.4).
- **Robustness:** all detectors finally achieved a very good robustness. Between November 2007 and June 2009 GEO600 was in science mode for 86% of the time. Virgo and LIGO have achieved duty cycles of $\sim 80\%$.
- **Network:** a major step forward has been walked when the LIGO Scientific Collaboration and Virgo have signed an MoU for joint data taking, data analysis and publication of the science results. A world wide network of GW observatory has been founded and this is the cornerstone for the start of the GW astronomy.
- **Multi-messenger:** beside establishing a network, the GW community has moved forward in starting a multi-messenger approach. Some GW events are likely to have an electromagnetic or particle counterpart. A detection of a GW chirp and a GRB from the same source, for instance, would widen enormously the investigation capability and the depth of the understanding. Therefore, the LSC and Virgo have signed MoU for joint observation with optical and radio telescopes, gamma and X-ray satellites, neutrino detectors.
- **Science:** Extensive science runs have been performed. No detection has been claimed so far. However, science results have started to flow and relevant upper limits have been set (some examples: [6], [7], [8], [9]).
- **Preparing the near future:** some technologies suitable for the second generation or useful to prepare it have been tested in the recent years:
  - the isolation from vibrations of the Virgo superattenuator is compliant with the advanced detectors sensitivities [17]. Virgo could already struggle with the

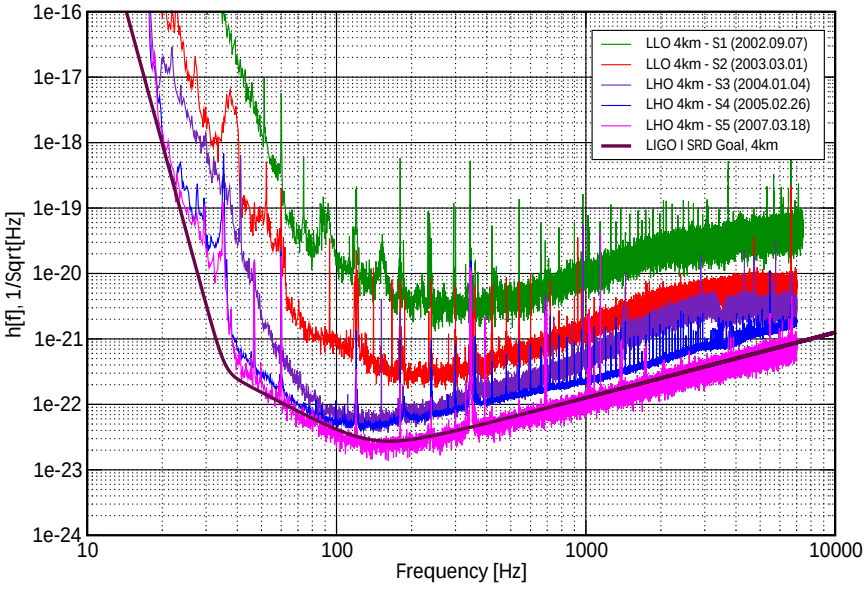


Figure 3. LIGO sensitivity in the science runs from S1 (2002) to S5 (2007) [5]. The brown solid line is the design sensitivity.

commissioning problems typical of the low frequency range, and this experience will be precious in the next years.
- GEO600 pioneered several technologies that will be used in advanced detectors: signal recycling with DC readout, monolithic suspensions, electrostatic actuators. Moreover, that have injected first squeezed light in the interferometer (fig. 5). 3.5 dB of squeezing have been achieved on a real detector [11].
- Virgo has installed and tested monolithic payloads in advanced configuration (thin fibers, large mirrors) [12], allowing for the first time to beat the "first generation" suspension thermal noise limit.
- LIGO has used DC readout for routine operations and it is performing a squeezing test [13]
- GEO, LIGO and Virgo have used thermal compensation systems.

3. Second generation: technology challenges

We have today the technology to improve the detection rate of a factor of ~ 1000 with respect to the first generation (see fig. 6,7). LIGO and Virgo are being upgraded to Advanced LIGO [14] and Advanced Virgo [15]. With such an improvement the detection of tens of events per year is expected [19] at the design sensitivity of Advanced LIGO. This should be achieved by means of advanced technologies, able to improve the sensitivity in different frequency ranges.

3.1. Optical configuration

The optical configuration will be improved in several aspects:

- Advanced Virgo/LIGO will have signal recycling cavity, allowing to tune quantum noise, thus enhancing the sensitivity in some frequencies at the expenses of others. Such handle,

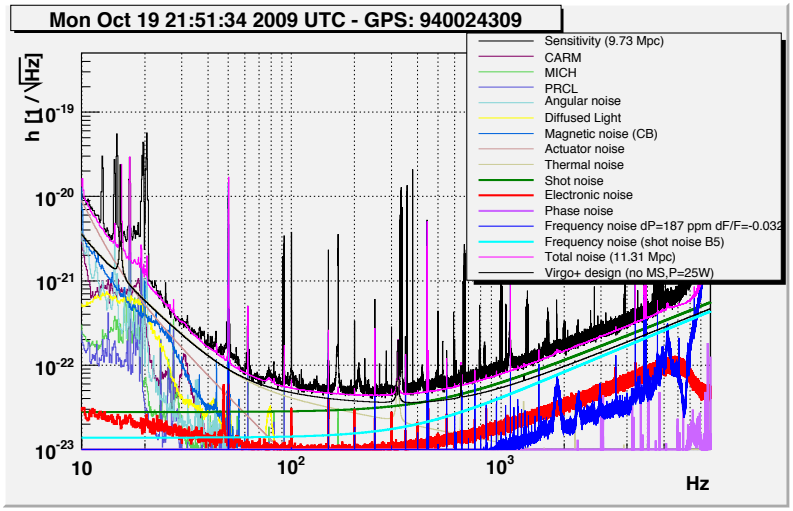


Figure 4. Virgo noise budget [10]. The measured sensitivity is compared with the combination of the modeled noise (magenta line) and the design sensitivity (black solid line).



Figure 5. The squeezer installed on the GEO600 detector.

together with the possibility of tuning the power, gives the advanced detectors the chance to be optimized for chosen astrophysical sources.

- To reduce the impact of coating thermal noise the Fabry-Perot cavities will be co-focal, so to maximize the spot size on the test masses.
- To reduce the sensitivity to thermal aberrations the Advanced LIGO will be provided with stable recycling cavities.

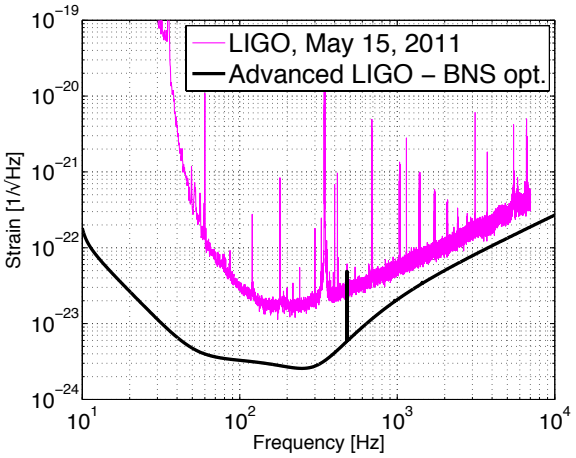


Figure 6. The LIGO sensitivity compared with the Advanced LIGO target (in BNS-optimized configuration). Measured spectrum from [18]

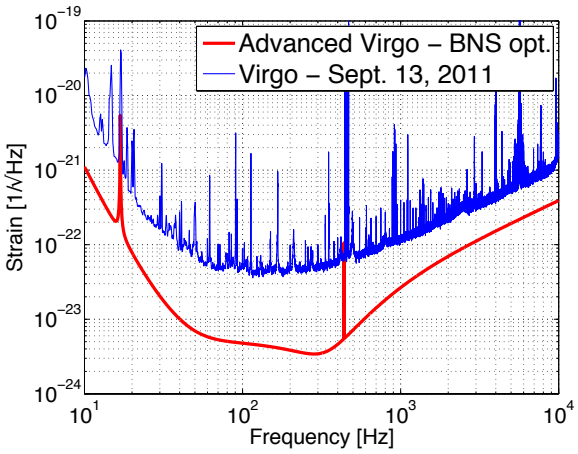


Figure 7. The Virgo sensitivity compared with the Advanced Virgo target (in BNS-optimized configuration). Measured spectrum courtesy of the Virgo Collaboration.

3.2. Mirrors

The quality of the mirrors will be a crucial aspect for the advanced detectors.

- Due to the increased power in the interferometer, the mirror weight must be increased to avoid that radiation pressure noise limits the low frequency sensitivity. The test masses for Advanced LIGO/Virgo will weigh about 40 kg.
- The absorption of the high-reflective coating must be kept as low as possible to reduce thermal lensing (better than 0.5 ppm).
- The coating thermal noise limits the sensitivity of the advanced detectors in the mid-frequency range. Progress has been done in reducing the coating losses by doping the high index layer of Ta_2O_5 with Titanium [20].
- The surface figure and the micro-roughness of the mirrors are important to keep the optical losses low (the target for Advanced LIGO/Virgo is 75 ppm round-trip losses). Superb polishing figures have been achieved by ion-beam milling the Advanced LIGO test masses ($\sim$ 0.2 nm rms).

3.3. Laser and thermal compensation systems

The available laser power will be increased by one order of magnitude with respect to the current detectors. A solid state laser able to provide 200 W of output power has been realized by the Lazer Zentrum Hannover and Albert Einstein Institute [21]. For Advanced Virgo a different technology has been chosen (a rod amplifier).

Already in the first generation detector the capability to cope with thermally induced aberrations (due to the absorption in coatings and substrates) with a proper compensating system has been crucial to increase the input power at a level close to 20 W. In the advanced detectors, the possibility of exploiting the higher available power relies on the higher performance of the thermal compensation systems. Advanced LIGO/Virgo will use a system based on a CO2 laser to project annulus-shaped beams on "compensation plates" facing the input test masses but contained in the recycling cavities: in this way the noise of the CO2 laser does not spoil the sensitivity. Optimized beam profiles can be produced using a "Double Axicon System". Ring heaters around the test mass barrels are used to correct for the deformations of the radius

of curvature. In the case of Advanced Virgo, which uses marginally stable recycling cavities and so it is more sensitive to thermal aberrations and cold defects of the mirrors, a system for compensation of non-axisymmetric defects must be also used. Proper sensing will be needed: Hartmann sensors and phase cameras will be used.

3.4. Vibration isolation and suspensions

The Virgo superattenuators will still be used for Advanced Virgo since they were already conceived as second generation isolators and demonstrated a compliant performance. Advanced LIGO will install a totally new vibration isolator system to extend the detector bandwidth down to 10 Hz [16]. It is based on platforms that are seismically isolated in 6 d.o.f. by active controls. Test masses and other optics are suspended by the platform through triple/quadruple pendulums. In both detectors the test masses will be suspended by fused silica fibers.

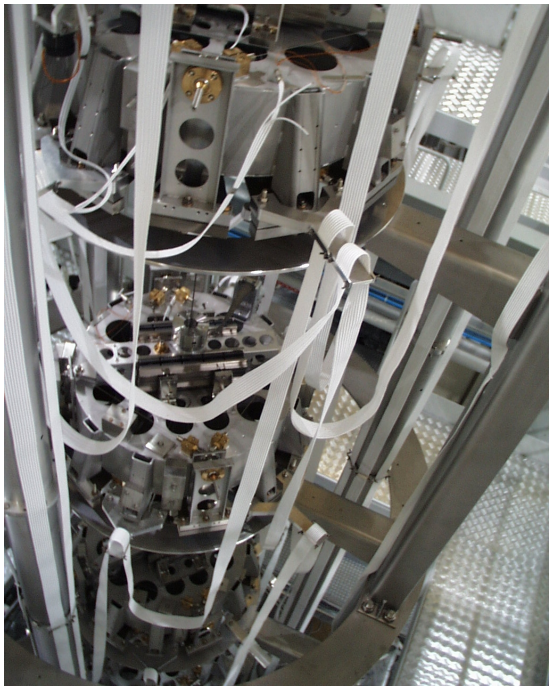


Figure 8. The Virgo superattenuator.

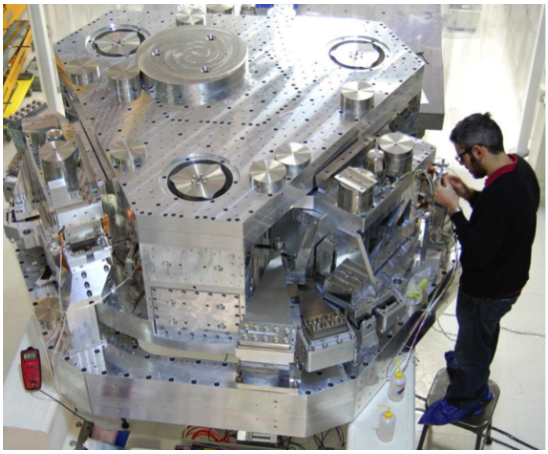


Figure 9. The active vibration isolator for Advanced LIGO.

4. The decade scenario

2015 is the time when a first science run of the advanced detectors could be possible. Advanced LIGO has been funded by NSF in April 2008 and its installation is now about 50% complete. Already next year a "single cavity" test will be performed at Hanford: this will be useful to learn how to operate a high finesse cavity suspended from the new active isolation system. Advanced Virgo has been funded by INFN and CNRS, with a contribution by the Dutch laboratory NIKHEF, at the end of 2009. The installation has started in November 2011 and it is expected to be completed in 2014. GEO600 is undergoing a phase of incremental upgrades (GEO-HF) aimed to reach a competitive sensitivity in the high frequency range. Beside the upgrades of the existing detectors, a 3km underground detector (LCGT) has been funded in Japan. The schedule is quite ambitious: the goal is being part of the second generation network as soon as 2017 [4]. A further novelty might be the realization of a new detector in the southern hemisphere, which would improve considerably the accuracy in the reconstruction of the source angular position.

LIGO had planned to move the third interferometer (the second Hanford detector) to Australia. This was eventually impossible. Now, the Indigo consortium [22] is exploring the viability of hosting it in India.

5. Conclusive remarks

What should we expect from the next years? The schedule and sensitivity goals of the advanced detectors, together with the expectations on the event rates suggest that a discovery could be done in the second half of this decade. The plans for LCGT and LIGO-India suggest that a global world GW rudimentary telescope , covering the entire sky, might be up at the end of the decade. However, the experience with the first generation suggests to be careful and patient: the sensitivity progress could be slower than planned.

The early plans for the interferometric detectors started more that a quarter of century ago. After many years of design, R&D, construction, commissioning, upgrading, the GW community was able to demonstrate the interferometer technology and approach the design sensitivities. Extended science runs have been performed and the former skepticism of the scientific community is today much less diffused. Today we are confident that interferometers are the right instruments for such a challenge, but also aware of the complexity of the commissioning of such machines (the commissioning of the 1st generation machines lasted about 5 years). The commissioning of the advanced detectors will certainly benefit of the former experience. However, some new challenges have to be faced: new technologies are being employed and the sensitivity goals are more ambitious.

On the other hand, a large GW community has grown and is now firmly established. The existence of a collaborative network will ease the exchange of information and the upcoming challenges will be faced in a more efficient way. If the plans for the realization of the advanced detectors go on smoothly and the nature is friendly we could hope to celebrate the centennial of general relativity with the discovery of gravitational waves.

6. References

[1] Abbott B P *et al.* (The LIGO Scientific Collaboration), 2009, *Rep. Prog. Phys.* **72** 076901
[2] Acernese F *et al.* (The Virgo Collaboration), 2008, *Class. Quantum Grav.* **25** 114045
[3] Grote H *et al.* (The GEO600 Collaboration), 2008, *Class. Quantum Grav.* **25** 114043
[4] Kuroda K *et al.* (The LCGT Collaboration), 2006, *Class. Quantum Grav.* **23** S215
[5] Frey R E (for the LIGO Scientific Collaboration), 2007, *AIP Conf. Proc.* **928** 11
[6] LIGO Scientific Collaboration and Virgo Collaboration, 2009, *Nature* **460** 990
[7] Abadie J *et al.* (The LIGO Scientific Collaboration and The Virgo Collaboration), 2010 *Phys Rev.* **D82** 102001
[8] Abadie J *et al.* (The LIGO Scientific Collaboration and The Virgo Collaboration), 2010 *Phys Rev.* **D81** 102001
[9] Abadie J *et al.* (The LIGO Scientific Collaboration and The Virgo Collaboration), 2011 *Ap. J.* **737** 93
[10] Accadia T *et al.* (The Virgo Collaboration), 2010 *Class. Quantum Grav.* **27** 084002
[11] LIGO Scientific Collaboration, 2011, *Nature Physics doi: 10.1038/nphys2083*
[12] Lorenzini M for The Virgo Collaboration, 2010, *Class. Quantum Grav.* **27** 084021
[13] Barsotti L, these proceedings
[14] Harry G (for the LIGO Scientific Collaboration), 2010, *Class. Quantum Grav.* **27** 084006
[15] Accadia T *et al.* (The Virgo Collaboration), to appear in *Proceedings of the Rencontres de Moriond COnference 2011*
[16] Abbott B P *et al.*, 2002, *Class. Quantum Grav.* **19** 1591
[17] Acernese F *et al.* (The Virgo Collaboration), 2010, *Astroparticle Phys.* **33** 182
[18] http://www.ligo.caltech.edu/∼jzweizig/distribution/LSC_Data/
[19] Abadie J *et al.* (The LIGO Scientific Collaboration and The Virgo Collaboration), 2010 *Class. Quantum Grav.* **27** 173001
[20] Cimma B *et al.*, 2006, *Appl. Opt.* 45 1436
[21] Willke B *et al.* 2008 *Class. Quantum Grav.* **25** 114040
[22] Souradeep T, these proceedings