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Introduction to gravitational wave detection and Advanced Virgo Status and perspectives

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Abstract

The present year has seen the announcement by the LIGO-Virgo collaboration of the discovery of gravitational waves with the confirmation of more than one event detected. These detections are a success after half a century of experimental investigations and represent the starting point of a new astronomy era, where a network of gravitational waves observatory are expected to be capable of pointing the source and trigger the so-called multi-messenger astronomy for the searches of electromagnetic or other radiation counterparts. The signal detection has been done by the two ADV-LIGO detectors [1, 2] while the Virgo detector was ultimating the construction of the ADV-Virgo detector; once that also ADV-Virgo will be operative the network for pointing the source will be completed. In this paper we report briefly on the history of gravitational wave detection and we will focus on the Adv-Virgo apparatus, describing the optical scheme, the critical experimental points and the expected sensitivity.

1. Introduction

Gravitational waves (GW) are a perturbation of the metric propagating in a Minkowsky space-time, generated by the rapid motion of large, compact masses. The effect of GWs is to modify the distance between two free falling masses, the induced displacement being proportional to the gravitational wave amplitude, usually indicate with h, and to the initial distance between them.

The induced strain tensor $h_{\mu\nu}$ can be expressed in terms of the quadrupolar moment tensor $Q_{\mu\nu}$ of the GW emitting source as

$$h_{\mu\nu} = \frac{2G}{rC^4}\ddot{Q}_{\mu\nu} \tag{1}$$

where r is the source distance, G is the gravitational constant, and c is the speed of light. The amplitude of expected GW signals above $f \approx 10$ Hz from known astrophysical sources is typically $h < 10^{-21}$. The first experimental efforts towards direct GW detection consisted in the observation of mechanical resonances in rigid structures. For a few decades starting from 1960 several resonant bars were operated, providing narrowband detectors in the kHz range with peak sensitivity of the order of $h \approx 10^{-19} \div 10^{-21}$. In spite of a great and deep experimental effort the resonant bars did not succeeded in detecting the GWs. Hence, during the 80s the idea of using interferometers became more and more realistic. The main characteristic of the interferometer is that the masses can be placed several kms apart: being the gravitational wave effect proportional to the distance this a great gain with respect to mechanical resonators that are typically confined in few meters of length. The other great gain in using interferometeric detection was the enlarging of the bandwidth from tens of Hz around the mechanica resonance to few KHz, in particular extending the lower limit of detection towards low frequency. In this framework great importance is due to the

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Virgo collaboration that pioneer pushed the research towards seismic noise suppression having 10 Hz as a goal for the bandwidth lower limit. Now that the sources discovered are coalescence of massive black holes, that are detected and understood thanks to the lower sensitivity limit around 30 Hz, that choice appears of remarkable importance.

In the interferometer masses (mirrors) of few tens of kg are suspended to pendulums and behave as free falling in the frequency range above the pendulum oscillation mode. A GW will induce a differential elongation $\Delta L = hL$ between the two equal arms of length L in a symmetric Michelson interferometer. The phase shift induced at the interferometer output by a low frequency GW is

$$\Delta\phi = \frac{4\pi}{\lambda}\Delta L \tag{2}$$

where λ is the wavelength of the circulating light. The sensitivity can be further improved by increasing the effective length of the interferometer by means of Fabry-Perot arm cavities. A first generation of optical interferometry detectors, i.e. Virgo [3], LIGO [4] and GEO600 [5] operated from 2005 to 2011, with peak strain sensitivity down to $\tilde{h} \approx 10^{-22} \frac{1}{\sqrt{Hz}}$ and bandwidth of about two decades around a few hundred Hz. Although no GW detection occurred at the time, such interferometers represented a cornerstone in the technology for advanced detectors. They reached or approached their design sensitivity all over the detection band, with high reliability and robustness providing a duty cycle of 80% or larger. Based on these results, a second generation of GW detectors was started with the aim to improve the sensitivity by one order of magnitude over the fist generation. Since the GW amplitude scales with the inverse distance r of the source, this corresponds to an increase in the observed volume, and thus of the detection rate, by about three orders of magnitude. The general approach was to reduce fundamental noise sources with a proper design, and to benefit of the acquired experience in operating the first generation instruments in order to control all technical noise sources. The LIGO detectors were shutted-down in 2010 and ADV-LIGO both in Hanford, WA and Livingstone, LA restarted operation in 2015; the Virgo detector was de-commissioned starting from end 2011, the integration of Adv-Virgo detector was completed during 2016 and it is presently (fall 2016) under commissioning phase. The Advanced LIGO detectors [6] on September 14th 2015 at 09:50:45 UTC, reported the coincident observation of a signal, initially detected by a low-latency search for generic gravitational-wave transients [7].

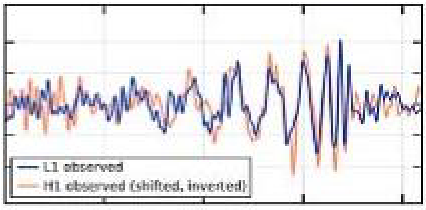

Figure 1: Signals at LIGO detectors: the strain measured in Livingstone detector (blue) and for comparison the strain meaured in Hanford detector (red) shifted in time by the arrival time difference and inverted to account for relative detector orientation. Figure from [1]

The signal has been then analyzed with a matched-filter, constructed from relativistic models of compact binary objects [8] and found to be the most significant event in each detector in the first part of the observing run, with a combined signal- to-noise ratio (SNR) of 24 [9]. The time evolution of the signal, named GW150914, shown in figure 1, suggests that this signal has been produced by the coalescence of a binary black hole system with the expected phases of inspiral, merger, and subsequent final black hole ringdown. In about eight cycles, lasting 0.2 seconds, the frequency increases from 35 to 150 Hz, where also the amplitude is maximum. The low frequency evolution, the phase of the two inspiralling masses, m1 and m2, is characterized by the chirp mass M_c [10]:

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5} \tag{3}$$

where G and c are the gravitational constant and the speed of light; f and $\dot{f}$ are the observed frequency and its time derivative and can be both estimated from the data. To evaluate the source parameters, general relativity-based models [11, 12, 13, 14] have been used, in some cases including also spin precession, and, for each model, a coherent Bayesian analysis has been performed to derive the distributions of the source parameters [15], discussed in detail in [16]. The uncertainties include statistical and systematic errors deriving from the average of the results of different waveform models. Using the fits to numerical simulations of binary black hole mergers provided in [17, 18], the mass and spin of the final black hole, the total energy radiated in gravitational waves, and the peak gravitational-wave luminosity [16] have been computed. The masses at the source of the primary black holes is estimated in $M_1 = 36{+}5{-}4$ solar masses, the secondary is $M_2 = 29 \pm 4$ solar masses, the mass of the final black hole $M_f = 62 \pm 4$ solar