Sensitivity enhancement via vacuum squeezed injection in Advanced Virgo

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Abstract. Modern gravitational-wave astronomy is based on the Michelson interferometer design, for which a key towards enhancement of the sensitivity is to reduce the noise which arises from different sources. As it was first proposed by Caves, injected squeezed states can be used to reduce the measurement shot noise, thus improving the sensitivity in the high-frequency band. This result was achieved with the German-British interferometer GEO600 in Hannover, and Advanced Virgo joined the third observational run on April 2019 with its operating source of squeezed vacuum producing an improvement in the high-frequency sensitivity up to 3 dB (the horizon for a Binary-Neutron Star detection increases by 2-4 Mpc).

1. Introduction: gravitational waves and detection

In recent years, the interest in Gravitational Waves (GWs) detection has grown significantly, mostly thanks to the development of fine-tuned interferometers (namely the two LIGO and the Virgo experiments), capable of reaching very high sensitivities.

GWs are ripples in the fabric of the spacetime that travel at the speed of light, and are produced when the mass distribution of a body becomes inhomogeneous (as deviations from spherical symmetry). More precisely, a quadrupole asymmetry of an isolated system must be present in order for it to emit GWs. This happens in many astrophysical scenarios, including supernova explosions or gravitational interactions between black holes or neutron stars. They travel through spacetime, deforming it, making the bodies strained and the distances alternatively stretched and squeezed.

In spite of being produced by extremely violent events in the Universe, GWs are difficult to detect: spreading out in all directions and having an extremely low interaction with the surrounding spacetime, they get weaker while travelling from distant sources, so that the signal results to be quite faint once it gets to the Earth.

Virgo is an interferometric detector located near Cascina (PI). It has been designed and built by collaboration between the Italian Istituto Nazionale di Fisica Nucleare (INFN) and the French Centre National de la Recherche Scientifique (CNRS). Virgo is now operating on the site of the European Gravitational Observatory (EGO), by an international collaboration of scientists from France, Italy, the Netherlands, Poland, Germany, Belgium, Spain, and Hungary. The construction started in 1994, and since 2007 Virgo and LIGO have shared and jointly analyzed the data taken by all the interferometers of the network.
Figure 1. Noise sources as upper limits to the sensitivity of the interferometer. Quantum noise dominates the high-frequency range, while in the low-frequency range it is covered by other noises such as gravity gradient and suspension thermal noise.

When a GW crosses Virgo, the 3-km arms of the detector are stretched/squeezed by a billionth of a billionth of a meter, i.e. less than a thousandth of the diameter of a proton. Therefore, in order to detect the strain signal, the Virgo interferometer is based on modern technologies in different areas, including ultra-high vacuum, optics, electronics and mechanics.

The task of a GW detection is challenging because of both the considerable small strain signal and the fact that all measurements are affected by a variety of noises. For this reason, the development of a second generation of detectors has been a necessary but profitable activity and led to the first detection of a GW signal on September 14th, 2015 [3]. The discovery was made by the LIGO Scientific Collaboration and the Virgo Collaboration using data from the two LIGO detectors.

After a multi-year upgrade program and several months of commissioning, the Advanced Virgo (AdV) detector joined the second observation run (O2) on August 1, 2017, and shortly after it managed to detect its first GW signal: a coalescence of two stellar mass black holes (GW170814 [4]). For the first time, there was a network of three second-generation detectors, capable of localizing the source of a GW signal by means of triangulation techniques.

At the end of O2, Advanced Virgo underwent a further upgrade of the experimental apparatus, which affected every subsystem, from the infrastructure to the electronics of the control. The primary goal was to improve the detector performance in terms of sensitivity.

2. Sensitivity and Noise

The sensitivity of the interferometer is limited by noises arising from fundamental physical processes such as counting statistics of individual photons, as well as other contributions coming from the detector construction and the environment.

Fig. 1 shows the noise sources that mostly affect the sensitivity of the interferometer. In the low frequency range, major contributions to the noise come from thermal, gravity gradient and radiation pressure noise. On the other hand, the high-frequency band is dominated by shot noise. Quantum noise (radiation pressure and shot noise) is expected to dominate the detector sensitivity in the whole frequency band at the final target laser input power (125 W [5]).
Quantum noise stems from the quantum nature of light, and is driven by vacuum fluctuations of the optical field entering from the unused port of the interferometer. The effect of quantum noise is twofold: shot noise, generating phase fluctuations of the optical field is the main sensitivity limit at high frequencies, and radiation pressure noise, generating position fluctuations of the suspended masses, contributes to the noise at low frequencies.

It was first proposed by Caves [6] that injected squeezed states can be used to reduce the shot noise contribution, and thus to improve the sensitivity in the high frequency band. This result was achieved with the German-British interferometer GEO600 [7] and was replicated in 2013 with the LIGO interferometer at Livingston [8].

A squeezed state $|\alpha, \zeta\rangle$ is in general represented by an error ellipse in the complex amplitude plane whose axes are the two quadratures $X_1$ e $X_2$: its center is located at $\alpha = \langle X_1 + iX_2 \rangle$, and the radii $\Delta X_1$ and $\Delta X_2$ indicate the uncertainties on $X_1$ e $X_2$.

The complex amplitude $\alpha$ of a squeezed state is the same as the corresponding coherent state $|\alpha\rangle$ (a “displaced” vacuum state); moreover it’s a minimum uncertainty state. The difference lies in the unequal uncertainties for the two quadratures: the error circle of the coherent state is “squeezed” into an ellipse of the same area (Fig. 2).

3. Squeezed vacuum generation

A squeezed states generator (squeezer), like the ones used in modern interferometers, exploits the nonlinear properties of some crystal to manipulate the two vacuum quadratures.

The response of a medium to an external electromagnetic field is analysed in terms of the electric polarization $\vec{P}$, which is defined as the electric dipole moment per unit volume.

In such a medium, the electrons are excited by the passage of an electromagnetic wave $\vec{E}(t) = E_0 \cos(\omega pt)$ and they begin to oscillate. These oscillations can be described by:

$$\vec{P} = \epsilon_0 \chi^{(1)} \vec{E} + \epsilon_0 \chi^{(2)} \vec{E}^2 + \epsilon_0 \chi^{(3)} \vec{E}^3 + \ldots \Rightarrow P^{(n)} = \epsilon_0 \chi^{(n)} \vec{E}^n,$$

where $\epsilon_0$ is the electric permittivity of free space and $\chi$ is the electric susceptibility of the medium.

This relation is a general form of the linear response (first term of the above equation), which is a good approximation given the usually small amplitudes of the input field.
The nonlinear wave equation is an inhomogeneous differential equation, and it can be demonstrated (see e.g. [9]) that the general solution comprises a homogeneous part and an inhomogeneous term, acting as a driver/source of the electromagnetic waves. As a consequence, the energy is mixed between different frequencies by the nonlinear process.

The nonlinear process of interest is a second order one, termed parametric generation: this is characterized by an intense laser beam at angular frequency \( \omega_p = 2\omega \) (pump beam), which interacts with the ever-present vacuum modes (signal beam). The nonlinear crystal mixes the signal with the pump and produces an idler beam; in this case, signal and idler are identical in both polarization and frequency, and thus indistinguishable:

\[
\omega_i = \omega_p - \omega_s = 2\omega - \omega = \omega.
\]

The generated idler photons then mix again with the pump to produce more signal photons, and so on. Since these photons are generated in the very same process, they show quantum correlations in their phase operators [10], and thus the uncertainty circle of the vacuum is squeezed into an ellipse of the same area: the phase fluctuations are reduced, while the amplitude fluctuations are enhanced due to the Heisenberg’s uncertainty principle (anti-squeezing).

The squeezer now operating in Advanced Virgo was developed at the Albert Einstein Institute (AEI) in Hannover and delivered in Cascina on January 2018 (see Fig. 3).

![Figure 3. The picture and the scheme of the squeezer built in Hannover at the Albert Einstein Institute (AEI).](image)

4. Towards O4: Frequency-dependent squeezing

With both quantum noise sources present, the squeezing ellipse needs to be rotated as a function of Fourier frequency, so as to not increase noise from the presence of anti-squeezing affecting the other noise quadrature. Therefore, frequency-dependent squeezing is needed, although it’s not a piece of cake to be produced. Kimble et al. [11] proposed two detuned cavities off which the squeezed states are reflected to achieve the optimal squeeze angle for all frequencies, and later Khalili [12] proposed one optical resonator (called filter cavity) being suitable. Spectral components of the squeezed vacuum lying within the linewidth of the cavity experience a change in their phase upon reflection; those outside the linewidth do not. By operating the cavity in a detuned configuration, differential phase can be imparted upon the upper and lower squeezed vacuum sidebands, leading to frequency-dependent quadrature rotation [13].
Figure 4. Sensitivity curve of Virgo with squeezing injection (red) and no squeezing injection (blue). These data were taken on March 30, 2019, two days before the beginning of O3.

Conclusions

Advanced Virgo joined the third observational run (O3) with an operating source of squeezed vacuum developed at the AEI (Albert Einstein Institute) of Hannover: the average squeezing level is 3.1 dB in the high-frequency bandwidth (over 100 Hz). The injection of the squeezed vacuum field produces an improvement in the high-frequency sensitivity and the horizon for a Binary-Neutron Star detection increases by 2-4 Mpc (see Fig. 4).

Injecting phase-squeezed vacuum improves the sensitivity at high frequencies where the interferometer is dominated by shot noise; at the same time, the corresponding amplitude anti-squeezing makes radiation pressure noise at low frequencies increase.

Further increases in the injected squeezing level degrade the horizon due to the radiation pressure [14].

Frequency-dependent squeezing with the filter cavity is now under development in Advanced Virgo.

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