Observation of Quantum Radiation Pressure Noise in a Suspended Interferometer: the QURAG Experiment

Ph.D. Research Project

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The existence of gravitational waves (GW’s) is one of the most interesting predictions of Einstein’s theory of General Relativity [1]. The experimental discovery of GW’s would therefore be an important test of the theory itself. Moreover, since gravitational waves interact weakly with matter, they can travel through very dense regions without undergoing significant changes, contrary to what happens to electromagnetic waves [1]. The detection of gravitational waves would therefore open a new window of investigation especially in regions of the Universe inaccessible to electromagnetic observation. Interferometric detectors, such as Virgo [2, 3], are currently the most promising devices for the detection of GW’s originated from astrophysical sources. Virgo is a Michelson interferometer (ITF) for the detection of GW’s that works in the range of frequencies 10 Hz - 6 kHz, trying to detect signals from massive astrophysical sources, such as supernovae and coalescing binaries present in clusters of galaxies, like the Virgo Cluster, from which the interferometer was named after. Currently, the sensitivity of GW detectors (GWd) is not yet sufficient to observe signals with the rate of a few events per year, so there is underway an experimental program to improve it [3]. In particular the next generations of GWd, at low frequencies (10 Hz-50 Hz), will be limited by the quantum radiation pressure effect on the suspended mirrors [3, 4]. This phenomenon, not yet experimentally observed, is the subject of one of the most active research field at the time. Rich of the experience acquired with Virgo, this work aims at building a detector for Quantum Radiation Pressure Noise: the QURAG experiment. It will consist of a suspended Michelson interferometer in which the geometry is optimized in order to detect the quantum radiation pressure noise. Each arm of the interferometer will be a high finesse Fabry Pérot cavity in which only the end mirrors will be suspended and then sensitive to the quantum radiation pressure noise. This phenomenon is due to the quantum fluctuations of the laser within the cavity which generates a pressure effect responsible for movements of the suspended mirrors of order of a few $10^{-17}m/\sqrt{Hz}$ at 100 Hz. This effect can be modeled as [4]

$$X_{RP}(\omega) = 4 \frac{F}{m\omega^2} \sqrt{\frac{h}{(2\pi)^2}} \frac{P_{las}}{\lambda c}$$  \hspace{1cm} (1)

where $F$ is the finesse of the cavity, $h$ is the Planck’s constant and $c$ the speed of light. The laser used is a Nd:YAG of wavelength $\lambda = 1.064\mu m$ and $P_{las}$ is the power of the laser. The values for the cavity finesse and the laser’s input power that will be used are probably $F = few10^4$ and $P_{las} = few\ mW$. And high
finesse implies that the mirrors will be more sensitive to what happens inside the cavity respect to what comes from the outer part. It naturally follows that all the parameters involved should be optimized in order that the displacement of the suspended mirror induced by the radiation pressure noise (eq.1) will be $10^2 - 10^3$ times greater than the displacements due to all the other effects in the range of frequency of interest (10 Hz 1 kHz). Therefore, it is necessary to reduce all the other noises that limit the sensitivity of this ITF. Hence all the ITF will be under vacuum, it will be suspended to reduce seismic noise and the ITF elements will be made of silica to reduce thermal noise losses [4]. Moreover the internal thermal noise of the mirrors will be reduced using Hermite-Gauss (HG) mode [5] of higher order [6, 7, 8]. These modes will be generated by diffraction optics by a Space Light Modulator (SLM) with electric addressing. Therefore, a software which communicates with the SLM has been developed in order to generate high order HG modes by monitoring all its degrees of freedom.

Before working with the final model of interferometer it is necessary to conceive and develop all the subsystems involved, as the generation and optimization of HG modes, the suspension system and the electrostatic control of the mirrors. Within this aim the first months of this PhD research work has been devoted to the generation of high order HG modes and optimization of their coupling with a mode cleaner triangular cavity. In this period has been developed a standard procedure for the choice of the optimal “input” parameters for the software. Moreover, for each combination of parameters has been necessary to collect many sets of data hence to do a large amount of analysis. It has been possible to generate square HG mode till the order 25,25. In particular the best results obtained are a coupling of 90% for the modes 1,1 and 2,2, percentage that decreases to 80% for a mode 5,5 and to 70% for a mode 10,10. Nevertheless, the mechanics of the mode cleaner triangular cavity [4] that has been used, prevents the free propagation of the modes of order higher than 4,4. Therefore, it has been built a new triangular cavity with bigger 2” mirrors, that is now under test.

The following step has been working on the electrostatic control of a suspended mirror in a small Michelson interferometer (of about 10cm arm length), in which the second mirror is fixed on a piezoelectric ceramic bar (PZT). A signal is sent to the two electrodes placed behind the suspended mirror and thus a capacitor is created between them and the mirror’s dielectric. The electrodes are placed on a moving slit that allows to change the distance between them and the suspended mirror hence to vary the force that they apply on it. The interference condition is provided by the analog locking acting on the PZT. The measures aimed at the estimation of how much (order of nanometers) this system is able to displace the mirror by sending a signal to the electrodes. This value can be inferred by measuring the lengthen of the PZT bar deduced from the correction signal. A maximum displacement of 800nm has been obtained with a square signal of 100V. The electronics is under study in order to increase the maximum signal up to 300V. Preliminary results shown that the displacement of the mirror will increase of a factor 10. At the same time a large effort has been done on the mirror suspension system. Several configurations and materials have been tested. Hence, the standard method that should be used to suspend the mirrors of the final interferometer is also under conception. All the first year research has been developed at the laboratories of ARTEMIS at the Observatoire de la Cote d’Azur, Nice. The evaluation of the contribution of the whole interferometer to the thermal noise [9, 10, 11, 12] is necessary to obtain the ITF sensitivity curve and then to establish constraints on the design and assemblage. In fact, the thermal noise internal to the mirrors is likely to limit the measure of the radiation pressure noise. The dissipations are mainly due to the coatings [13] of the mirror and to the bonding layer between the mirror and the wires [11, 13]. With this aim this part of the work is developing in collaboration with the expertise of the Virgo group at La Sapienza University in Rome. Several simulation on thermal noise have been done with the software ANSYS (which operates the finite elements analysis). Various suspensions configuration have been investigated and still need to be analyzed. Then the sensitivity curve with thermal and radiation pressure noise have been estimated for all the configurations. All these analysis are showing that the work is evolving in the right direction. Moreover, it has been confirmed that the suspension system should be monolithic, as in Virgo+, (that means that wires and mirror are made with the same material) in order to reduce the clamping losses and the material used should have very low internal losses. Therefore, the suprasil, widely applied on GWd,
or sapphire are good candidates [13].

References


