A SIMULATION PROGRAM FOR THE VIRGO EXPERIMENT
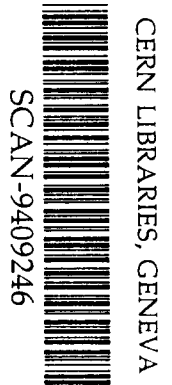
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Abstract

Within the VIRGO experiment we are developing a simulation program providing an accurate description of the interferometric antenna behaviour, taking into account all sources of noise. Besides its future use as a tool for data analysis and for the commissioning of the apparatus, the simulation helps finalizing the design of the detector. Emphasis is put at the present time on the study of the stability of optical components implied in the global feedback control system of the interferometer.

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1   Introduction

The goal and the detector layout of the VIRGO experiment have been described in detail elsewhere[1, 2, 3]. We remind briefly that the experiment aims at detecting gravitational wave (GW) signals from astronomic sources by the means of a large Michelson interferometer, to be fully operational by the end of 1999. The construction of the apparatus has now started and the role of a detailed simulation of the detector should keep growing from now on. Such a simulation has a variety of applications.

In the long term, it should be a necessary tool for data analysis, allowing to develop offline search algorithms as well as online preselection algorithms[4].

Closer from now – the first tests of the experimental setup should start in 1997 – the simulation facility should play a crucial role in understanding the apparatus behaviour at the beginning of its operation.

At present, simulated data are used to exercize the online software developed for VIRGO, and studies done with the simulation contribute in the final choices of the detector design. As an example, the global feedback control system will be described in more details here, showing how the optical components stability can be evaluated with the simulation for a given configuration.

Numerical computations have been used before in the collaboration. They were dedicated to specific issues such as the definition of the optical specifications or the design of the laser source[3]. A more general purpose program[5] has been developed for a few years in order to take into account all correlations between mechanical and optical aspects. Various levels of accuracy should however be made available for the description of the different aspects, allowing thus to stress any of them according to the issue under investigation. This program, named SIESTA, is able to simulate dynamically the behaviour of the interferometer as a function of time, therefore including features related to metrics (GW signal), optics and mechanics.

2   Principles of the simulation

Mechanical motion:

SIESTA computes the positions of all mirrors of the interferometer as a function of time, under the influence of seismic and thermal noises. Seismic motion of the mirror originates from random ground motion, of known amplitude, transmitted (with attenuation) through the suspension. Among all sources of thermal noise, only the dominant one, the pendular thermal noise of the mirror, is accounted for in the simulation, so far.

The simulation of the mirror suspension requires the description of a complex setup including the mirror, its positioning device ('marionetta') and its suspension ('super attenuator'), consisting in a cascade of seven oscillators[3]. A simple solution to simulate the system is to describe the suspension with a digital filter reproducing the transfer function of the super attenuator and to solve mechanical equations only for the marionetta and the mirror. A more detailed method to compute the motion of the system relies on the resolution of pendulum equations for all nine stages. However the complexity of this method makes it practicable only for one degree of freedom.

Figure 1 shows the spectrum of a mirror position, obtained as the Fourier transform of its simulated time dependence. The spectrum is dominated by seismic noise at low frequency whereas thermal noise dominates above a few hertz.
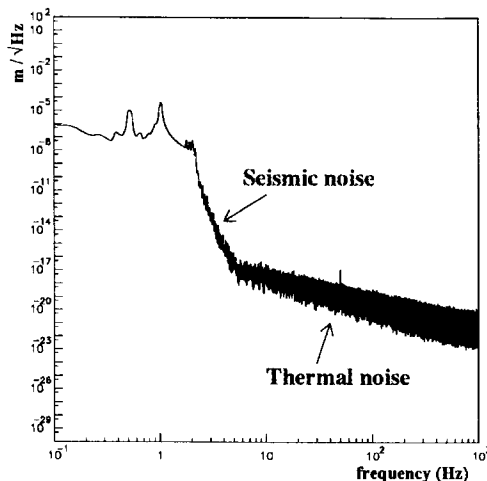
Figure 1: Position spectrum of a suspended mirror, obtained as the Fourier transform of its simulated time dependence.

Gravitational wave signal:

Once the positions of all mirrors are known, the current arm lengths of the Michelson interferometer can be computed. At this level, the distances between mirrors can also be modified according to metric fluctuations expected from a GW signal. The shape of those metric fluctuations depends on the type of GW source. Generation of GW signals from binary coalescences and from pulsars is implemented in the simulation.

Optical response:

This part of the simulation converts distances between optical elements into the corresponding photodiode signals at the output of the interferometer. The most detailed method – and also the most CPU time consuming – computes the full wavefront of the beam using a grid representation and the fast Fourier technique for the propagation through the interferometer. Field equations are solved by iterations. This method allows to take into account many different effects, including those coming from optical surface defects. An intermediate method, very useful for mirror misalignment studies, is based on a modal expansion of the beam structure. But the fastest simulation of the interferometer optical response is obtained by using the matrix relationship existing in the linear regime between longitudinal displacements of mirrors and detected signals. Photon counting noise, or shot noise, is also taken into account at this level of the simulation.

3 Simulation of the feedback control system

Introduction :

The VIRGO interferometer is more complex than a simple Michelson interferometer because of the Fabry-Perot cavities present in its arms and of the recycling mirror (see for example figure 2). Automatic control is needed on the optical elements for the detector to be operational.

The interferometer is said to be locked when the two Fabry-Perot cavities as well as the

recycling cavity are in resonance with the laser source, and when the output signal of the interferometer is minimum (dark fringe condition). To reach and maintain this state, four independent lengths have to be controlled. Refering to figure 2, these are the lengths L_1, L_2 of the Fabry-Perot cavities, the length of the recycling cavity $d_0 + (d_1 + d_2)/2$ and the length difference between the two arms of the short Michelson interferometer $d_1 - d_2$.

The control of these four independent lengths requires associated error signals. The extraction of error signals uses a modulation technique: The incident laser beam is phase modulated with an electro-optic device. Photodiode signals collected at strategic points of the interferometer are synchronously demodulated, in phase and/or in quadrature. They carry information about variations of the important lengths and provide the error signals used in the feedback control system. Various schemes are possible for the control system. We restrict ourselves here to one of them, sketched on figure 2. In this scheme, error signals are digitally processed to get correction signals used to modify accordingly the positions of four mirrors, namely the two end mirrors of the interferometer arms, the beam-splitter and the recycling mirror.

The feedback system should meet two requirements. On the one hand it should have a high gain (about 10^5 or 10^6) at low frequency (below 1 hertz) to stabilize the mirrors, starting from their natural motion under the influence of seismic and thermal noises. On the other hand, it should not introduce noise in the operating frequency range of VIRGO (10 Hz - 1kHz).
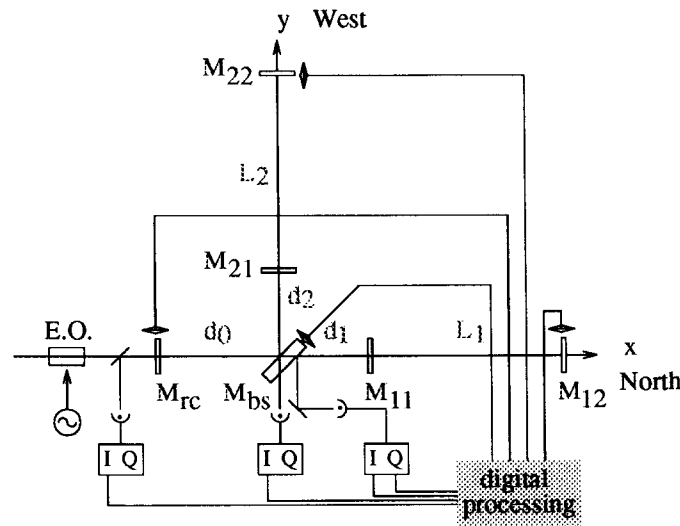

Figure 2: Sketch of a possible configuration for the feedback control system. The different optical signals used are shown, as well as the mirrors which undergo automatic control.

Simulation:

The simulation of the feedback system resumes most of the points mentioned above. The mechanical behaviour of the suspended mirrors is simulated under the influence of seismic and thermal noises. The optical response of the interferometer is then computed, providing a global measurement of mirror displacements. The resulting error signals are filtered to produce correction signals used in the computation of mirror motion, thus closing the loop.

The design of the servo-loop filters may benefit a lot from these simulations. Comparison between mirror motions obtained with different configurations will determine the configuration closest to the specifications. As an example, figure 3 shows the amplitude spectrum of the main
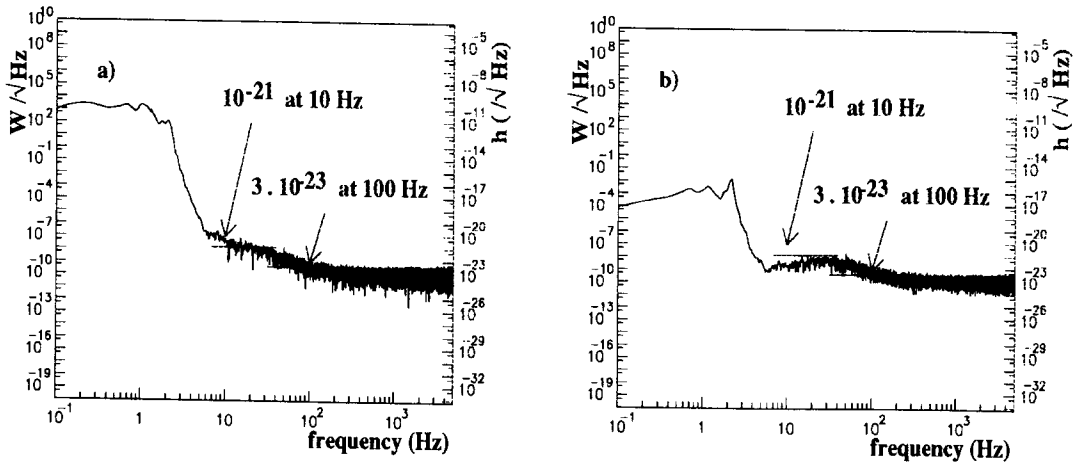
Figure 3: Spectrum of the dark fringe signal a) without feedback, b) with a tentative feedback system operating at 10 kHz.

output signal of VIRGO, the dark fringe one, in the case when no feedback is applied and in the case when a tentative feedback system, operating at 10 kHz, is applied. In the latter case, there is an important attenuation of low frequency fluctuations, whereas the higher frequency range where GW signals are expected is not affected (also shown is the designed sensitivty of VIRGO at 10 and 100 Hz).

Simulation is also very convenient to quantify the effects of fluctuations in the electronics used in the amplification-demodulation operation. Digitization effects induced by the limited precision of the ADC's used in the servo-loop have been simulated as well. Figure 4 shows the spectrum of the dark fringe signal, in this particular example of feedback system, when error signals are digitized simulating 12 bit or 14 bit ADC's, compared with the spectrum obtained neglecting digitization effects. The figure shows clearly the degradation in the signal spectrum at high frequency due to the introduction of digitization noise in the servo-loops. The spectrum obtained when simulating 16 bit ADC's – not shown on the figure for sake of visibility – is nearly identical to that obtained without digitization, showing that in this particular example, the use of 16 bit ADC's would be appropriate.
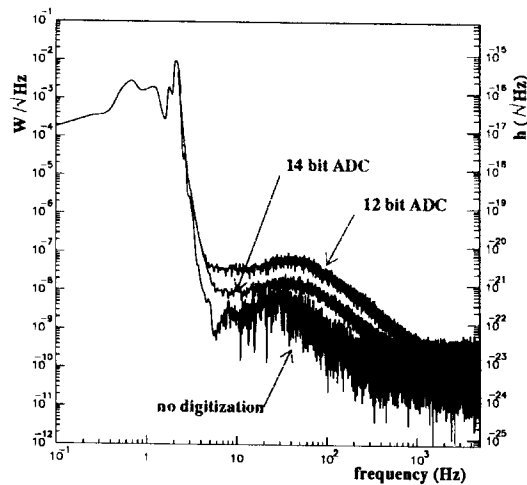

Figure 4: Spectrum of the dark fringe signal, according to wether the finite precision of the ADC's used in the feedback system to sample the errror signals is taken into account or not.

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4 Conclusion

We are developing a simulation program in order to describe accurately the VIRGO interferometric antenna. A current application is the final definition of the design of the detector, we have shown how the simulation can test any particular configuration of the feedback control system. In the long term, the experience gained in the accurate modelling of the VIRGO antenna will turn into a major tool for data analysis.

Acknowledgements

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References

[1] M. Yvert, 'Status of the VIRGO Experiment', these proceedings and preprint LAPP-EXP-94.15

[2] VIRGO Coll., Proposal for the construction of a large interferometric detector of Gravitational Waves (1990)

[3] VIRGO Coll., Final Conceptual Design (1992)

[4] R. Flaminio et al., Preprint LAPP-EXP-93.13, submitted to *Astropart. Phys.* (1993)

[5] B. Mours, I. Wingerter-Seez, Proc. of the sixth Marcel Grossmann Meeting on General Relativity, Kyoto, June 1991, ed. Humitaka S. and Nakamura T., 1576 (1992)