Interferometer signal detection system for the VIRGO experiment

VIRGO collaboration

presented by

Raffaele Flaminio

L.A.P.P., Chemin de Bellevue, Annecy-le-Vieux F-74941, France

Abstract

VIRGO is a laser interferometer aiming at the first detection of gravitational waves emitted by astrophysical sources. The signal detection system consists of all the output optics and the electronics necessary for the measurement of the interferometer output signal. An output mode-cleaner has been developed in this context. The system has been installed at the detector site and is now being used for the central interferometer, the first step in the construction of VIRGO. The first results obtained so far are shown hereafter.

1 Introduction

VIRGO is a gravitational wave detector based on a Michelson interferometer with arms length L = 3Km. The goal is to detect gravitational waves emitted by astrophysical sources like supernovae, pulsars, coalescing binaries and other compact objects in the frequency range between 10 Hz and a few kHz. The best strain sensitivity of the detector will be of the order of $h=10^{-23}$ $Hz^{-1/2}$ at 100 Hz. The detector is being built by a French - Italian collaboration in Cascina, near Pisa (Italy) [1], [2].

As a gravitational wave travel across the detector one arm of the interferometer get longer by a tiny amount ($= hL/2 \sim 10^{-19}$ m) while the other get shorter by the same amount. As a consequence the phase difference between the light travelling in one of the arm and the light travelling in the other changes and the light power transmitted at the Michelson anti symmetric port also changes.

The detection system is the part of the detector which measures this tiny power change and convert it into a digital signal [3], [4].

2 Detection system design

In order to achieve the best sensitivity the Michelson interferometer is kept locked on the destructive interference state (the so-called dark fringe). The laser light is phase modulated at high frequency and the signal is detected using a synchronous detection technique. The demodulated signal is proportional to the change in the length difference between the interferometer arms [5].

To detect a change in length of the order of 10^{-19} m the detection system should be able to detect changes in the RF power of the order of 1 nW. The main difficulty consists in detecting these tiny power changes over the quite large backgrounds due to the interferometer contrast defect and to the relatively large signals produced by the mirrors residual motion at very low frequency.

In order to reduce the effect of the interferometer contrast defect an output mode-cleaner has been built [3], [6] and installed at Cascina. Since this device is quite sensitive to external vibrations it is installed on an optical bench suspended to a seismic isolator and placed in vacuum. This same bench contains all the optics required to match the light beam into the output mode-cleaner and keep it aligned. A second bench outside the vacuum chambers contains all the photodiodes and the cameras required to control the interferometer and to detect the main output signal.

3 Suspended bench position control

In order to keep the output mode-cleaner aligned with the interferometer output beam the suspended bench position should be controlled in all the degrees of freedom with a precision of the order of few10^{-6} m in translation and of few 10^{-7} rad in angle.

The control system is based on a CCD camera [7] placed outside the vacuum chamber. The camera looks at the images of four different clusters of LED's, attached to the vacuum chamber, and reflected by four mirrors placed on the bench. Using the image positions of the four clusters the bench position in all its six degrees of freedom is deduced. Each cluster of LED's is composed by a matrix of 10x10 LED's. This allows increasing the sensitivity of the measurement by about a factor of 10 [3].

The spectra of the bench motion in the 6 degrees of freedom are shown in figure 1. The dashed line are the spectra measured before the vacuum chamber is pumped while the continuos one are the same spectra once the vacuum chamber has been evacuated. The white noise above a few Hz is the camera noise, which allows measuring displacements of the order of few 10^{-8} $\mathrm{mHz}^{-1/2}$ and misalignments of few 10^{-7} rad $\mathrm{Hz}^{-1/2}$. At lower frequencies the sensitivity is limited by acoustic noise as far as the bench is in air and by seismic noise once the vacuum is performed (the camera is attached to the ground). The peaks due to the suspensions residual motions are well above this noise.

The bench position measured by the camera is used as error signal for a feedback performed using a DSP board [8] and eight DAC channels driving eight electro-magnetic actuators. Once the feedback is closed all the suspension peaks are dumped and the bench position is controlled with a precision better than 1 μm (rms) in translations and a few tenths of μrad (rms) in angle.

4 Output mode-cleaner

Due to various defects such as mirrors surface deformation, radii of curvature mismatching and interferometer misalignments, the fringe contrast will not be perfect and a large fraction of the light is expected to be transmitted at the anti-symmetric port. The exact fraction of light depends on the importance of these effects when compared to other defects such as light absorption in the substrates and light scattering by the coatings. Some simulations show that this fraction can be as high as 50% of the light injected into the interferometer and that the contrast defect can be of the order of 1%. This spoil the optimum shot-noise sensitivity by about a factor of 2-3 [3, 4]. In order to recover the best sensitivity VIRGO decided to use an output mode-cleaner [1].

The adopted solution is to use a short monolithic cavity (l=2.5 cm) made of silica [3]. The small piece of silica is machined, polished and coated in order to get a short triangular cavity with a finesse of 50. The large cavity bandwidth (~75MHz) allows to transmits both the carrier and the side bands in the same Airy peak. Due to this choice a small change in the mode-cleaner length can induce a change in the carrier/side-bands relative phase and simulate a gravitational wave signal. To avoid this problem the cavity is suspended to a seismic isolator inside the vacuum chamber. The output mode-cleaner was tested on a small tabletop Michelson interferometer and a contrast defect improvement by a factor of 30 was achieved. The output mode-cleaner is now installed on the detector at Cascina and has been tested using the Central Interferometer [2]

The main difficulty consists in locking the cavity on the right mode (TEM_{00}) since this mode is only a small fraction of the total light transmitted at the interferometer output port. To this purpose the cavity length is modulated at 30kHz with a small piezoelectric and the error signal is synchronously detected by a photodiode looking at the transmitted beam. In order to distinguish the TEM_{00} mode a CCD camera also looks at this same beam and compare the image to the expected mode shape. If the χ^2 of this fit is below a given threshold and the transmitted power is above a given threshold the feedback is automatically started by acting on the cavity temperature using two Peltier cells. All the signals processing is performed digitally and runs at 10Hz.

The evolution of the transmitted power and of the χ^2 signal while the cavity temperature is scanned are shown in figure 2. The χ^2 identifies clearly the TEM00 mode. Once the feedback is started the cavity takes about 10 minutes to get locked. The feedback is rather slow (as all thermal feedback) but is quite robust: the cavity remains locked even if the interferometer gets unlocked for a few tens of seconds. If the interferometer lock is lost for a longer period the control system automatically maintains the cavity at the actual temperature. This allows keeping the cavity near the resonance for half an hour or more.

The beam profiles before and after the output mode-cleaner, when both the interferometer and the mode-cleaner are locked, are shown in figure 3. The filtering of higher order mode is evident. A detail study of the contrast improvement is on going.

5 Light detection

Once the interferometer output beam has been filtered by the output mode-cleaner the light has to be efficiently detected by the photodiodes. Since the shot noise limit decreases as the square root of the detection efficiency, very high quantum efficiency photodiodes have been selected for VIRGO.

These are 3-mm diameter InAsGa photodiodes that, thanks to an anti-reflecting coating, have quantum efficiency larger than 90% [3]. The diameter is the maximum imposed by the junction capacitance, which may limit the electronics bandwidth.

Since each photodiodes can deal with a maximum power of the order of 100mW several photodiodes in parallel will be used (from 8 to 16). The use of the output mode-cleaner allows reducing the number of photodiodes required.

6 Signal amplification and digitisation

Once the interferometer is locked on the dark fringe the mirror residual motion at very low frequency (less than 1 Hz) will be of the order of 10^{-12} m. Even if small, this is still much larger than the displacement produced by the gravitational wave and puts severe constraints on the electronics dynamic range [4] (of the order of 10^9). The use of 16 photodiodes in parallel, each with its own electronics, allows to reduce the constraints on the dynamical range down to 2-3 10^8.

This is still quite large when compared to the ADC dynamical range. Using 18 bits ADC sampled at 20 kHz it was possible to achieve a range of about 10^7 (10 V peak over a noise of 1 μV $\mathrm{Hz}^{-1/2}$). In order to fit the signal range into the ADC range the low frequency part of the signal is filtered with a low noise analogue filter before the digitisation.

The overall electronics noise due to the photodiodes plus the analogue electronics and the ADC's was measured at the site. The result of the measurement is shown in figure 4 and compared to the expected VIRGO sensitivity in $h/\sqrt{\mathrm{Hz}}$ units. The plot on the right shows the same measurement once the 50 Hz and its harmonics, due to the power supply, are removed.

References

[1] Virgo collaboration, VIRGO Final Design (1997).

[2] L.DiFiore et al., “Present status of the VIRGO central interferometer” to be published on this same volume

[3] D.Buskulic et al., Proceedings of the 2nd TAMA workshop on Gravitational Wave Detection, UAP, Tokyo (2000)

R.Flaminio et al., Nucl. Instrum. Methods A, 409 (1998) 477-479

[4] D.Buskulic et al., ‘Gravitational waves and Experimental gravity’, Proceedings of ‘XXXIV Rencontres de Moriond’ Ed. J.Tran Thanh Van (2000) 165-170

[5] B.J.Meers and K.A.Strain, Phys. Rev. A 44 (1991) 4693-4703

[6] A.Dominjon, These de Doctorat, Univesite de Savoie (1996)

[7] F.Bellachia et al.; Nuclear Instruments & Methods in Phys. Res.A 413 (1998) 151

[8] R.Taddei, Tesi di Laurea, Universita di Pisa (1999)

Captions

Figure 1

Spectra of the suspended bench motion in the six degrees of freedom as measured by the camera before the vacuum chamber is evacuated (dashed line) and after (continuos line).

Figure 2

The power transmitted by the mode-cleaner (top) and the $\chi 2$ signal (bottom) as a function of time while the temperature (on the left) is scanned. The interferometer is locked on the dark fringe.

Figure 3

The dark fringe beam profile seen before (on the left) and after (on the right) the output mode-cleaner.

Figure 4

The electronics noise expressed in units of strain as a function of frequency before and after the 50 Hz harmonics are removed. For comparison the planned VIRGO sensitivity is also shown.

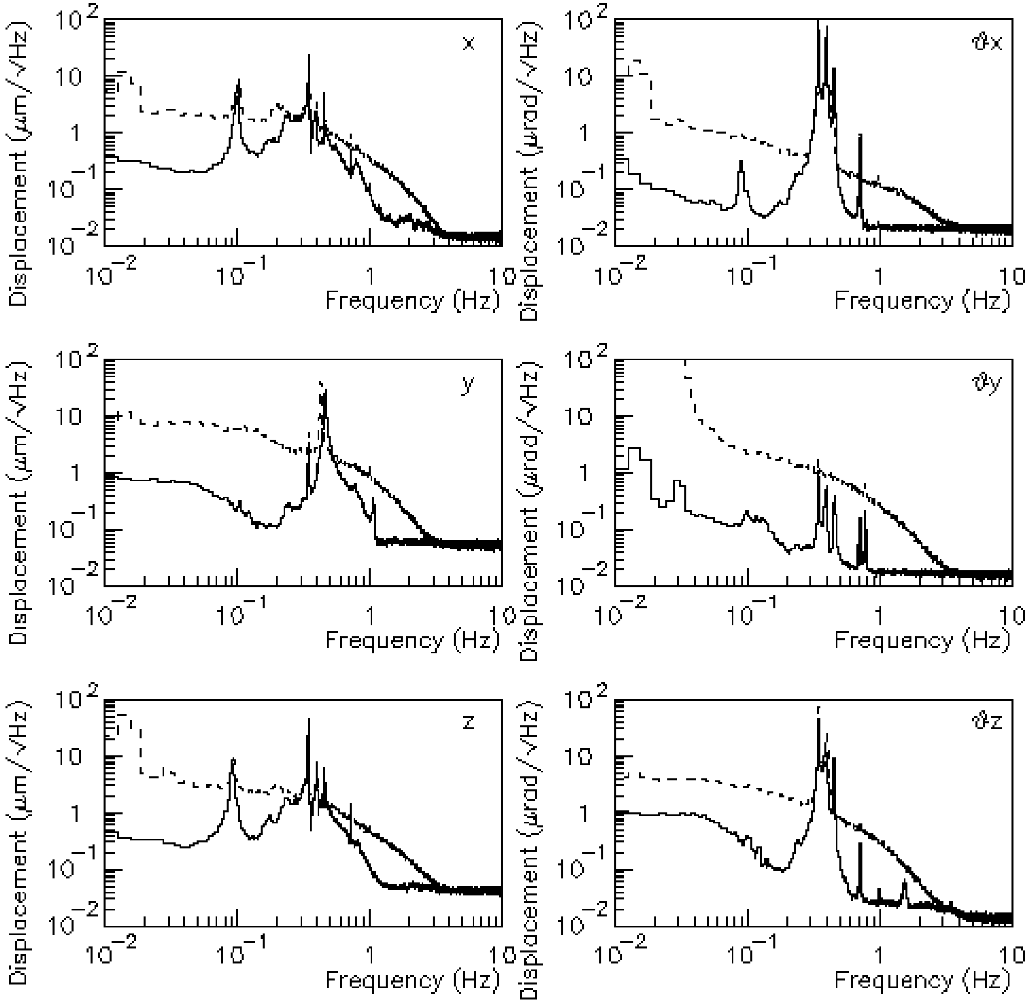
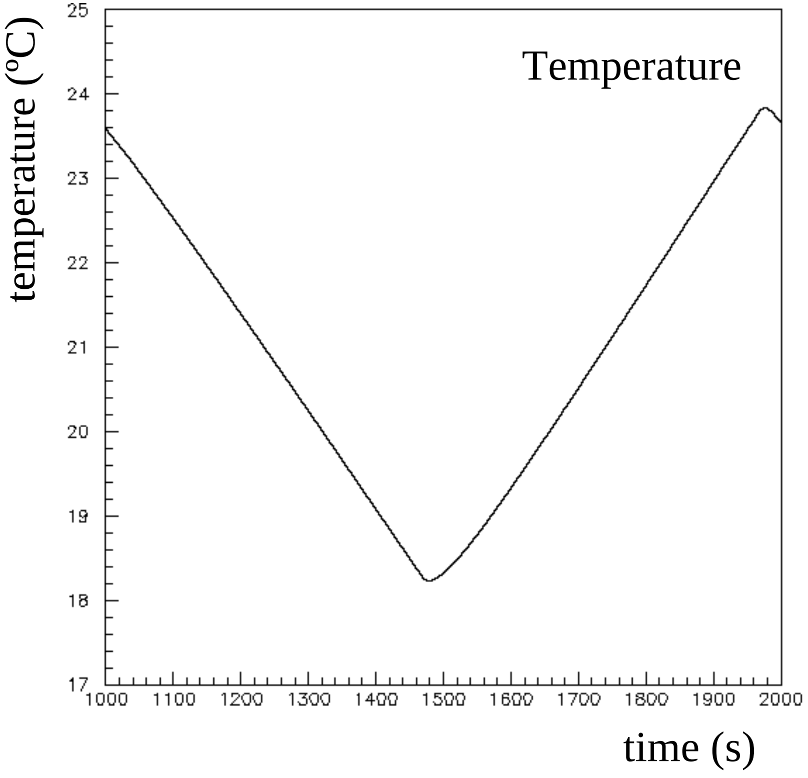

x
y
z
ϑx
ϑy
ϑz
Displacement (μm/√Hz)
Displacement (μrad/√Hz)
Frequency (Hz)
10^{-2}
10^{-1}
1
10
10^{2}

Figure 1


Temperature
temperature (ºC)
25
24
23
22
21
20
19
18
17
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
time (s)

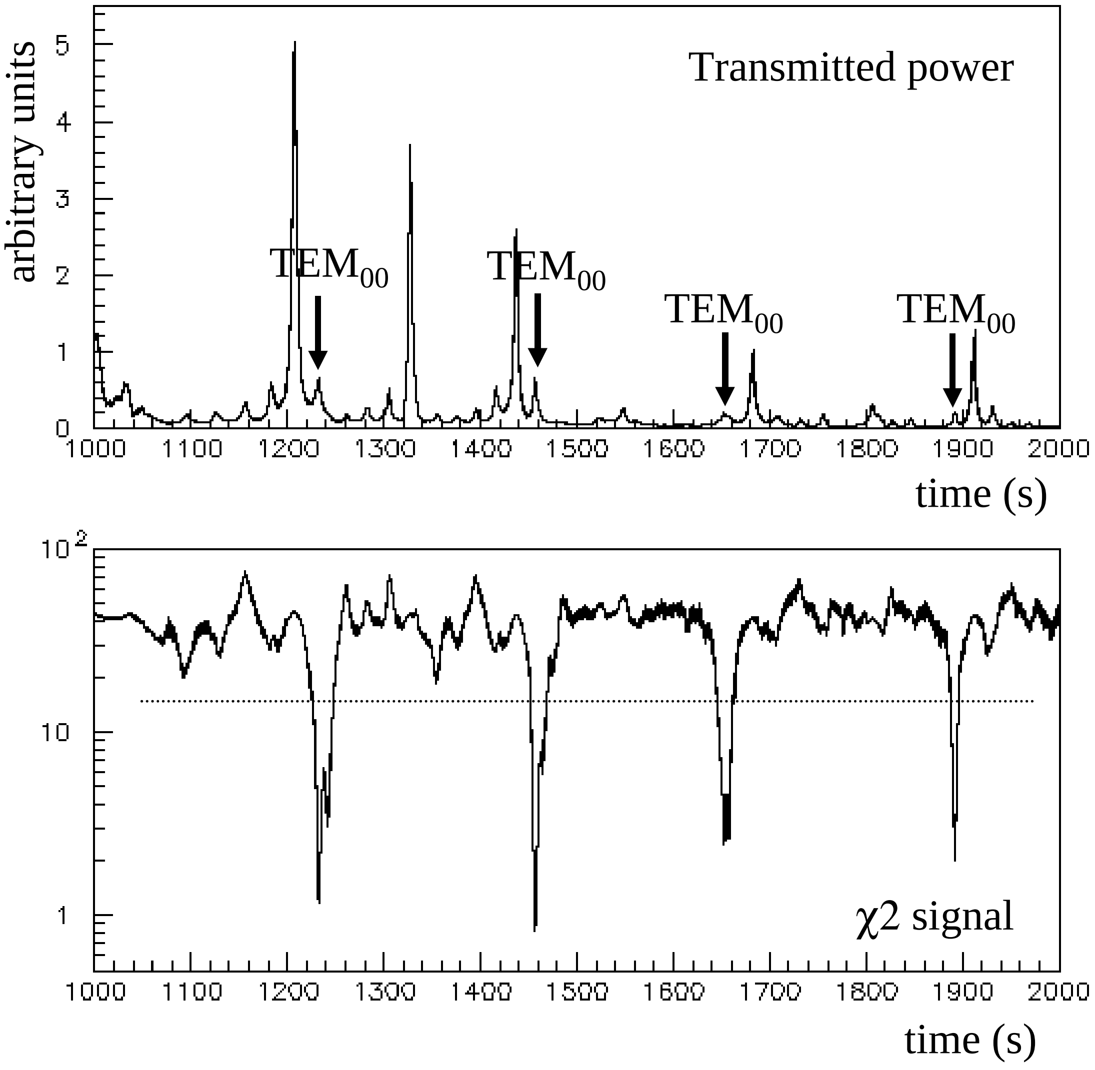

Transmitted power
arbitrary units
5
4
3
2
1
0
TEM$_{00}$
TEM$_{00}$
TEM$_{00}$
TEM$_{00}$
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
time (s)
10^2
10
1
χ2 signal
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
time (s)

Figure 2

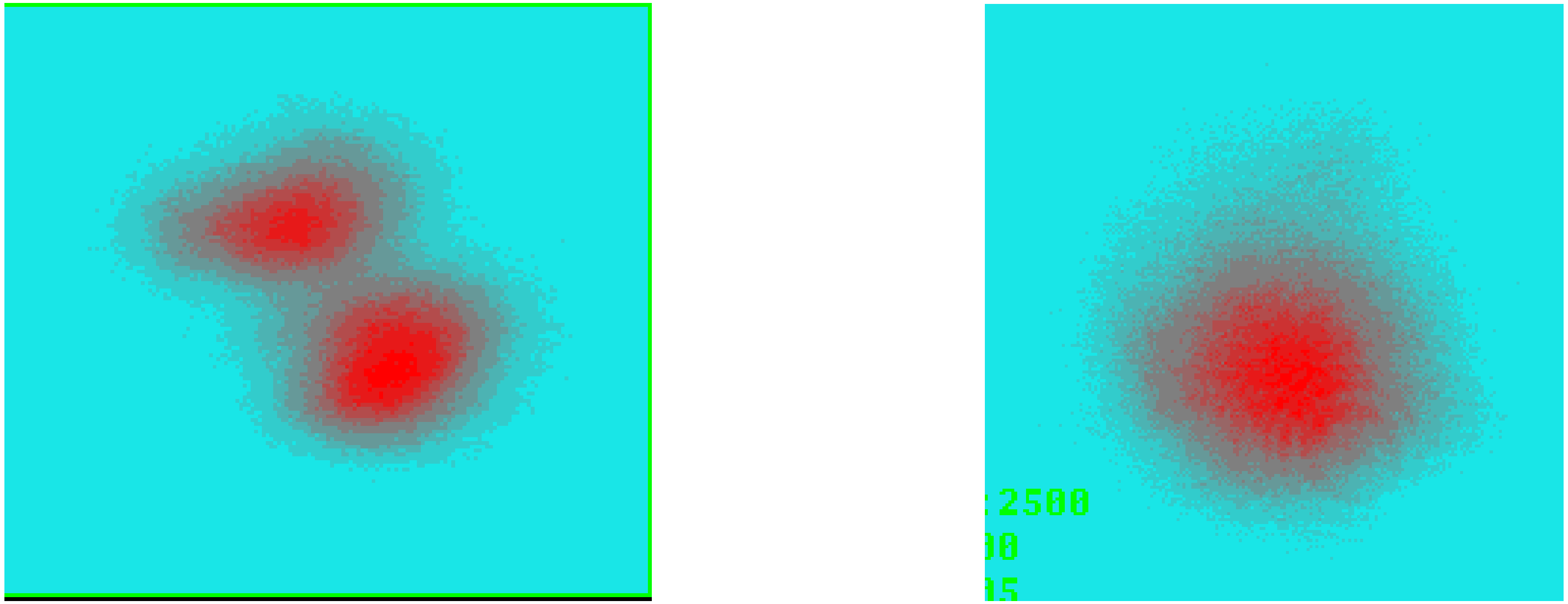


Figure 3

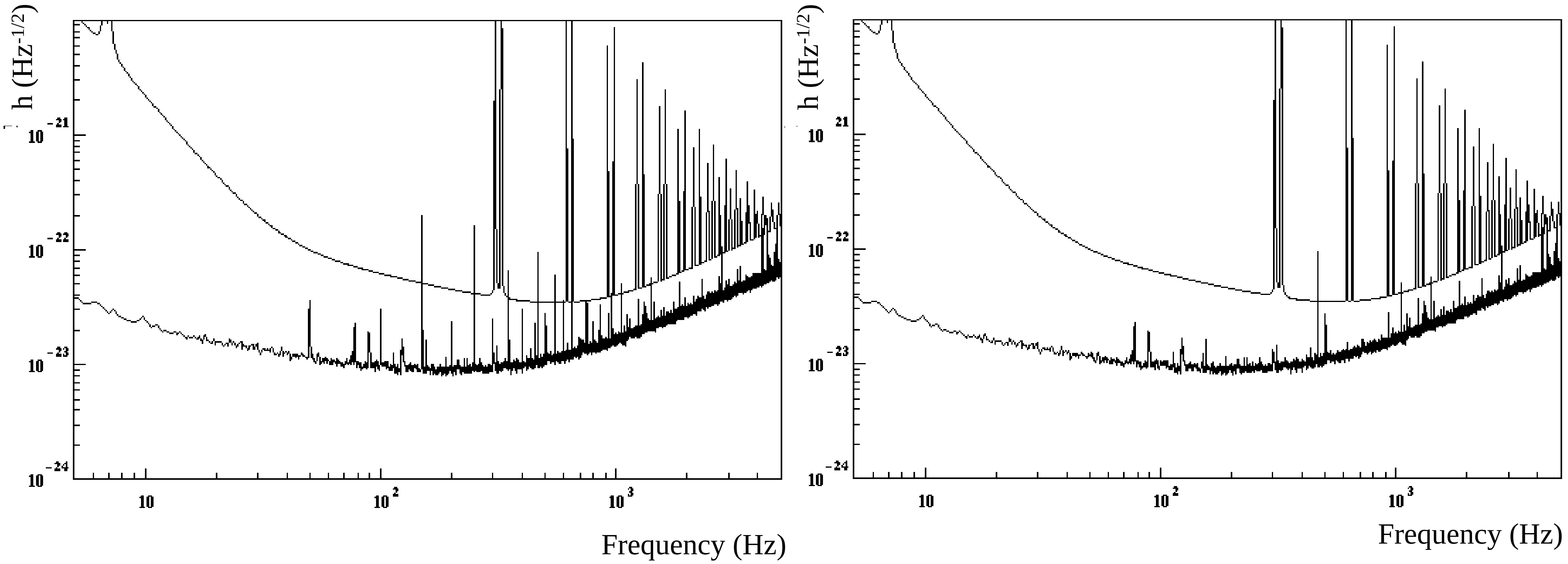

h (Hz-1/2)
10-21
10-22
10-23
10-24
10
10 2
10 3
Frequency (Hz)
h (Hz-1/2)
10 21
10-22
10-23
10-24
10
10 2
10 3
Frequency (Hz)

Figure 4