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# Experimental Demonstration of an Automatic Alignment System for Optical Interferometers

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## Abstract

An automatic alignment system, based on a differential phase sensing technique described in an earlier paper [1], has been experimentally demonstrated on the 10 m prototype laser interferometric gravitational wave detector in Glasgow. The alignment system developed was used to control the relative orientation of two mirrors in a 10 m long suspended Fabry-Perot cavity with respect to the direction defined by the input laser beam. The results of the test and a discussion of the performance of the system is given.

Key words: Alignment, interferometry, Fabry-Perot, gravitational wave detectors.

## 1. Introduction

In high precision interferometers, such as those currently being developed as gravitational wave detectors (see *e.g.* [2], [3], [4]), differential phase modulation is normally applied to allow the relative phase of two interfering beams at the output of the interferometer to be determined. A feedback system is then often used to maintain a null fringe at the output of the interferometer. In an earlier paper [1] we demonstrated that in any interferometer locked using a differential phase modulation technique, information about the mismatch in overlap of the two beams at the output can also be obtained.

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*Deceased 14/1/92.

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A purely angular misalignment of the two beams at the output of the interferometer results in a differential phase gradient across the interference pattern. This can be detected using a split photodiode (with the split centered on the interference pattern). In 1 we showed that it is possible to use a further split photodiode to obtain information also about any lateral offsets which may be present. The technique can also be extended, using annularly split photodiodes, to detect any difference in radius of curvature of the phase fronts or beam size mismatches; this was not demonstrated in the experiments discussed here.

Initial tests of such an alignment technique had already been made earlier by one of us (HW) using a 40 m long suspended mirror cavity at the California Institute of Technology, but full development of the system and evaluation of its performance had not been possible at that time. More recently the technique has been implemented on one of the 10 m optical cavities which forms part of the prototype gravitational wave detector in Glasgow. The cavity is locked using the standard *rf* reflection locking technique 5, and in such a situation, the two interfering beams may be thought of as the directly reflected light from the input mirror and the light which leaks out of the cavity on resonance. Differential modulation is achieved by phase modulating the light directed towards the cavity. The component which is directly reflected off the input mirror retains the modulation, whereas the light leaking out of the cavity on resonance has negligible phase modulation, provided the modulation sidebands do not resonate in the cavity. Adjustment of the pointing directions of the suspended mirrors can cause both relative angular and lateral misalignments of these two beams.

## 2. Experimental set-up

The 10 m cavity used to demonstrate the automatic alignment system consists of two high quality dielectric supermirrors suspended as pendulums to give some isolation from seismic noise and situated inside a vacuum system. The mirrors are coated directly onto cylindrical fused silica masses, 4 inches in diameter, 5 inches long and having a mass of about 3 kg. The input mirror has a transmission of 500 ppm in intensity and is plane. The end mirror, which is of maximum reflectivity, has a radius of curvature of 15 m. The cavity is illuminated by laser light from a *cw* argon ion laser of wavelength 514 nm. The beam waist of the cavity is situated at the surface of the input mirror and has a radius of $\sim$ 1 mm. During the tests of the automatic alignment system the fringe visibility[1] with optimum alignment was quite poor – about 30%, limited by excess losses due to (temporarily) contaminated mirrors. The finesse of the cavity was about 3000.

As illustrated in figure 1 the plane/curved nature of the cavity causes tilts and rotations of the curved mirror to couple exclusively to relative lateral offsets of the interfering beams. Misalignments of the plane mirror produce relative beam tilts that appear to originate from a point at the centre of the cavity.

Plane polarised light is phase modulated at 12 MHz using a Pockels cell and directed towards the cavity through a polarising beamsplitter and a quarter wave plate which form an optical diode. The light beams returning from the cavity are therefore rejected from the polarising beamsplitter and can be detected using one or more photodiodes. Coherent demodulation of the signal from a single photodiode looking at the whole interference pattern yields a signal that is a measure of the offset from resonance of the cavity. A suitable signal may then be developed to control either the axial position of the mirrors which form the cavity or, as was done during these tests, to control the frequency of the laser light; this servo system thus locks the cavity on resonance.

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[1] The fringe visibility, $V$, is calculated from the intensity of the light reflected from the cavity in the unlocked state, $I_0$, and the reflected intensity with the cavity locked, $I_l$, using the equation

$$V = \frac{I_0 - I_l}{I_0} .$$

## 3. Optical arrangement of the automatic alignment system

The optical arrangement of the system and some of the sensing and mixing electronics is shown schematically in figure 2. Two quadrant diodes were used to provide alignment information in each of two orthogonal directions. A schematic diagram of the front-end electronics for a single dimension of a quadrant diode is shown in figure 3. Each opposite pair of diode segments was resonated in a tuned circuit to enhance sensitivity at the 12 MHz modulation frequency, with the tuned transformer conveniently providing the required difference signal.

One diode was placed close to the beam waist at the cavity input mirror to sense any angular misalignments of the beams. The resulting signals could depend only on misalignments of the input mirror and were thus used to provide control signals that were fed back after suitable filtering to control the orientation of this mirror.

As discussed in our previous paper 1, lateral offsets could be sensed by a second photodiode either positioned a large distance away from the beam waist, or alternatively placed close to the focal point of a suitable lens. However with the cavity used in these tests neither solution was convenient as a method of introducing a phase shift between the first order and fundamental mode large enough to allow efficient signal detection. With no lens the photodiode would have to be placed several meters away from the beam waist. If a single lens was to be used it would have to have a reasonably short focal length ($\sim 1$ m) in order to keep the physical size of the optical system manageable. Even for a focal length of 1 m, the waist formed by the lens would be $\sim 170\,\mu$m for an input waist of 1 mm. Typically the gap between segments of the quadrant diodes is $\sim 200\,\mu$m; the spot size would thus be too small for satisfactory use. Even if the loss of light in the gaps was to be tolerated, a servo system would almost certainly have to be used to keep the interference spot centred on the photodiode.

In practice the multiple lens system shown in figure 2 was used. This was relatively compact in size ($\sim 1$ m in length) and gave a sufficient phase shift between the first order and fundamental modes to allow detection of any misalignment of the curved mirror, whilst maintaining a beam size of about 1 mm on the second quadrant photodiode.

The signal detected using the second quadrant photodiode was also sensitive to misalignment of the plane mirror in the cavity. As discussed in 1, it is in principle possible to null out completely the dependence of this signal on misalignments of the plane mirror by carefully choosing the powers and positions of the lenses in front of the second quadrant photodiode. In practice however, it is more convenient simply to ensure that the signal detected using the second quadrant photodiode has some reasonable dependence on the misalignment of the curved mirror and then to electronically subtract out (using the signals from the first quadrant photodiode) any component due to misalignment of the plane mirror. The system was set up by dithering the alignment of the input mirror at a few hertz and observing the resulting signal in the output of the mixing circuit. This component could then be nulled out by suitable adjustment of the mixing ratio, resulting in a signal that was proportional solely to misalignment of the curved mirror.

Coil/magnet actuators were used to control the orientation of the suspended mirrors. Each mirror is suspended by two loops of wire from a suspended control block. By driving current through coils, forces are applied to magnets attached to the control blocks, thereby allowing the tilt and rotation of the mirrors to be adjusted. These actuators are also used together with locally acting optical sensors to damp the high $Q$ pendulum resonances, preventing excessive motion of the mirrors at these frequencies. Each automatic alignment servo was designed with suitable electronic filtering in order to give a bandwidth of about 10 Hz and an open loop gain of about 20 dB below the pendulum resonances ($\sim$ 1 Hz).

## 4. Performance

The performance of the system could be judged by observing the visibility of the interference fringe viewed in reflection when the laser was stabilised to be on resonance with the cavity. Any misalignment of the cavity axis with respect to the input beam direction results in a coupling of the input light into higher order modes. The amount of light in the fundamental mode is therefore decreased, resulting in a decrease in the observed visibility.

As a test of the alignment system, each mirror was deliberately misaligned by a small amount in each of its two degrees of freedom. The servo systems were then switched on one at a time resulting in the stepwise improvement in the visibility shown in figure 4.

The visibility was improved from about 20% to the optimum value of 30%, equal to the best that could be obtained by manually steering the mirrors using electronic offsets applied to the locally acting orientation servo controls.

It is also interesting to note that the fluctuations in the visibility were reduced when the cavity was optimally aligned. This is due to the fact that static offsets in the alignment of the cavity mirrors increase the coupling of large low frequency motions of the suspended mirrors into the light intensity in the interference pattern.

The error points of the servos were also measured and calibrated in order to give estimates of the angular fluctuations as viewed by the automatic alignment systems. The error point of the servo used to control the tilt of the curved mirror is shown in figure 5.

With the servo switched off (upper trace), it can be seen that the low frequency angular fluctuations correspond to a level of a few times $10^{-6}\,\mathrm{rads}/\sqrt{\mathrm{Hz}}$ and fall off into the background measurement noise level at around 10 Hz. This spectrum was similar for all of the servo systems used to control the orientation of the two mirrors in the cavity. The low frequency fluctuations are probably due to seismic noise which propagates through the suspension system with little attenuation at these frequencies. The background noise is not shot noise but excess intensity noise on the light at the *rf* modulation frequency caused by a lack of optical isolation in the system. The shot noise level was around $10^{-10}\mathrm{rad}/\sqrt{\mathrm{Hz}}$.

Switching on the alignment system (lower trace) results in a reduction of the angular fluctuations at low frequencies by at least 20 dB. This was as expected, given the design of the servo.

## 5. Problems and limitations

With systems operating at very low frequencies the main problems to be expected are in stability of operation. Good DC stability in the feedback electronics is essential. While offset voltages which can arise at the inputs to the various amplifiers used can in principle be nulled out when initially setting up the system, any drifting of these voltages will cause misalignment of the cavity mirrors.

Similar problems can be caused by *rf* pickup in the electronics before the mixers which can also produce DC offsets in the servos. Although these effects can also be dealt with by nulling out the offsets using suitable correction voltages, the amount of pickup in the front end electronics can be surprisingly variable unless very good shielding is employed.

The main optical limitation to the sensitivity of the technique was the 'excess light noise' caused by a lack of optical isolation in the system. This set a limit of around $10^{-7}$ rads/$\sqrt{\mathrm{Hz}}$ on the angular stability that could be achieved at low frequencies. It is expected that additional optical isolation should significantly reduce this noise source.

## 6. Summary and Conclusions

The automatic alignment technique outlined in 1 has been successfully applied to align the mirrors in one of the 10 m long suspended optical cavities in the Glasgow prototype gravitational wave detector. In this test it was possible to reduce the angular fluctuations of the cavity mirrors by more than 20 dB at frequencies below 10 Hz.

## ACKNOWLEDGMENTS

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# FIGURES

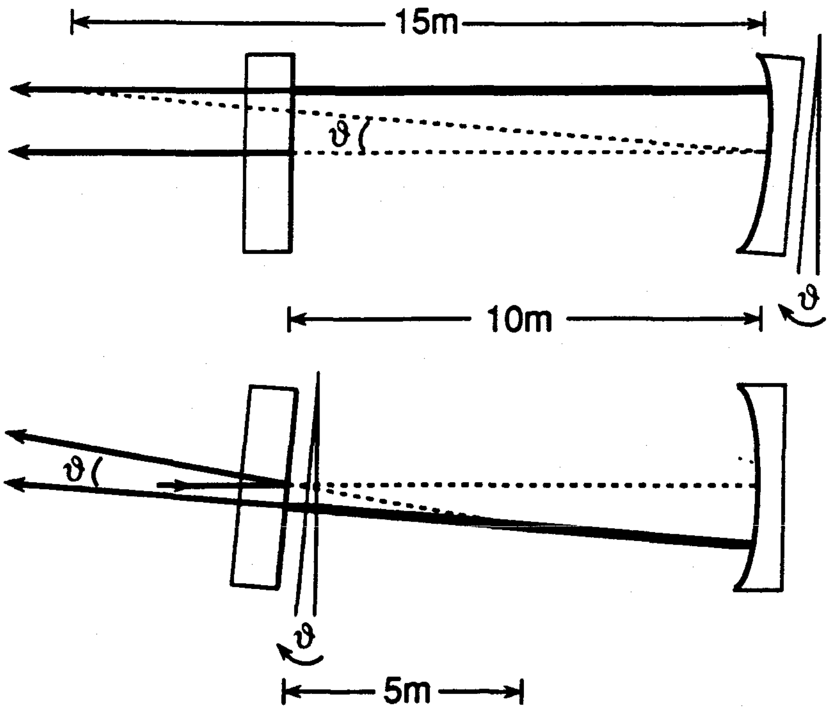
Fig. 1. The effects of misalignment of the two mirrors in the plane/curved cavity used for the tests. The directly reflected and cavity leakage beams are indicated schematically by the arrowed lines. (The incident beam in each case is propagating horizontally and strikes the plane mirror at its midpoint.) Note that the path followed by the superposition of the two components depends on their relative magnitudes.

Fig. 2. Schematic layout of 10 m suspended optical cavity and the main elements of the control system used for auto alignment in one dimension.

Fig. 3. Schematic diagram showing a tuned photodiode front-end for one dimension.

Fig. 4. Effect of the automatic alignment system on the fringe visibility of the 10 m cavity.

Fig. 5. Angular fluctuations as viewed by the sensing system used to control the tilt of the curved mirror in the 10 m cavity.



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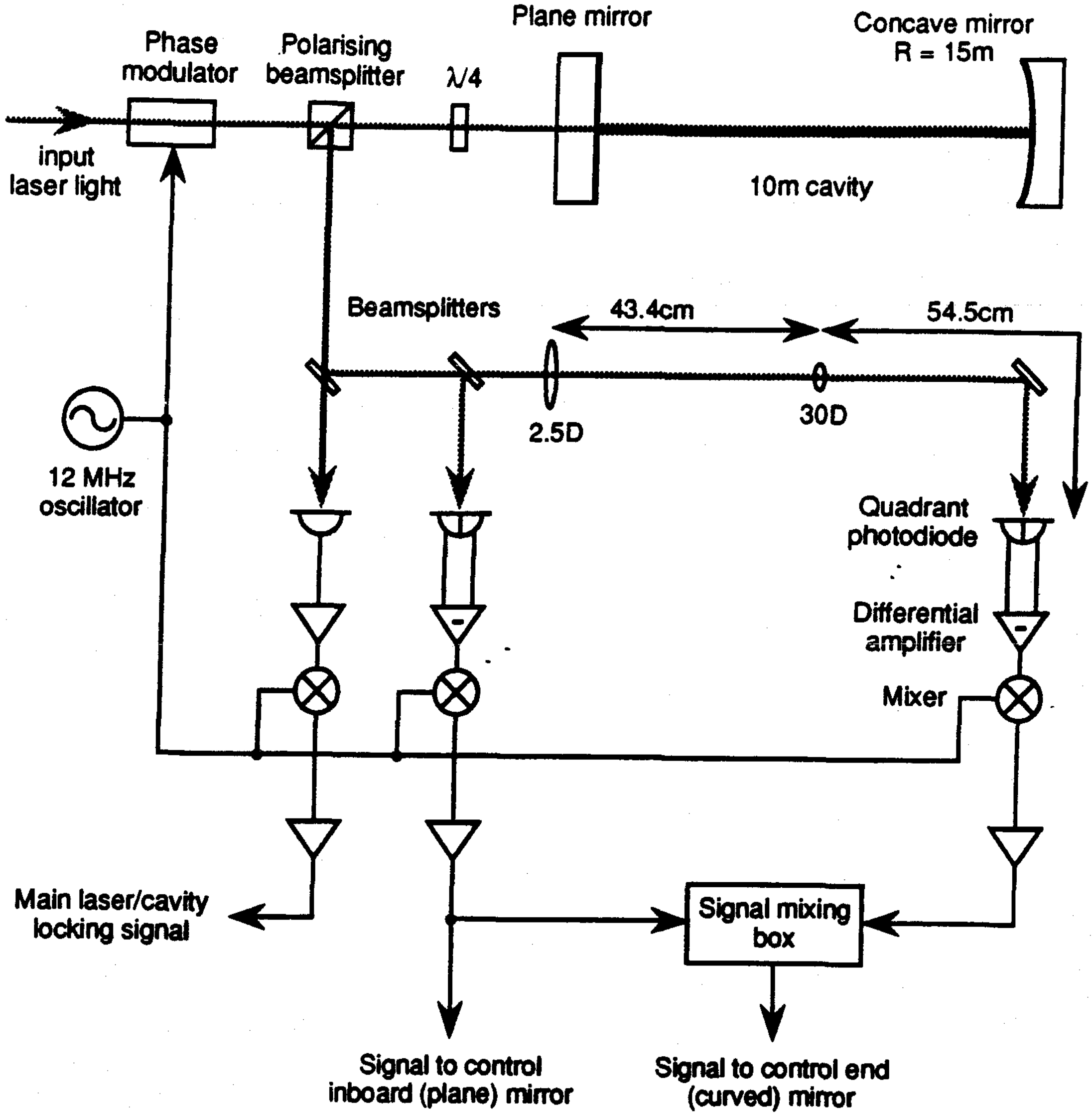

Figure 2: Schematic layout of 10 m suspended optical cavity and the main elements of the control system used for auto alignment in one dimension.

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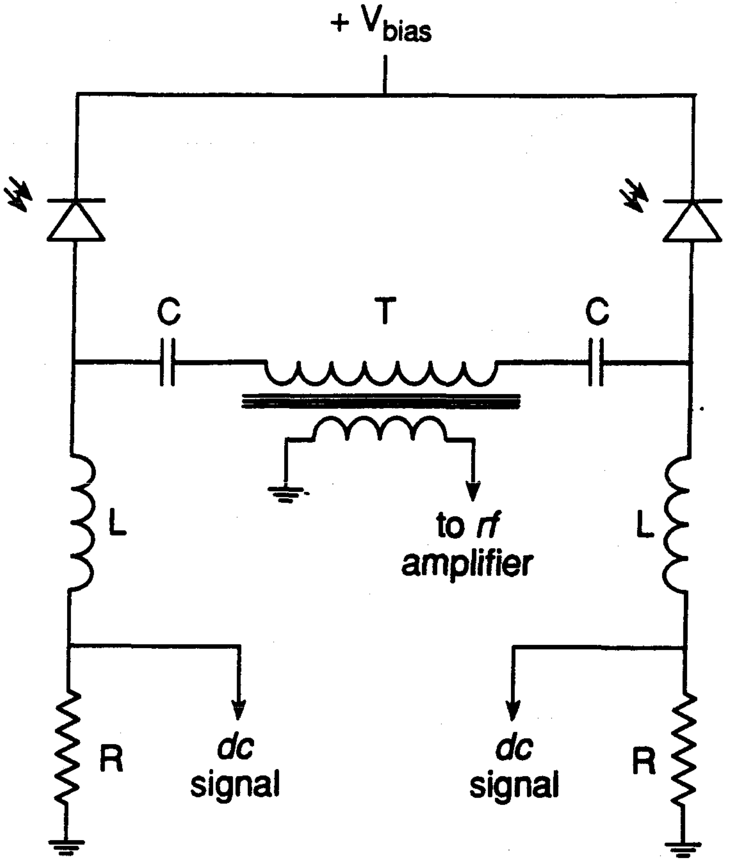

Figure 3: Schematic diagram showing a tuned photodiode front-end for one dimension.

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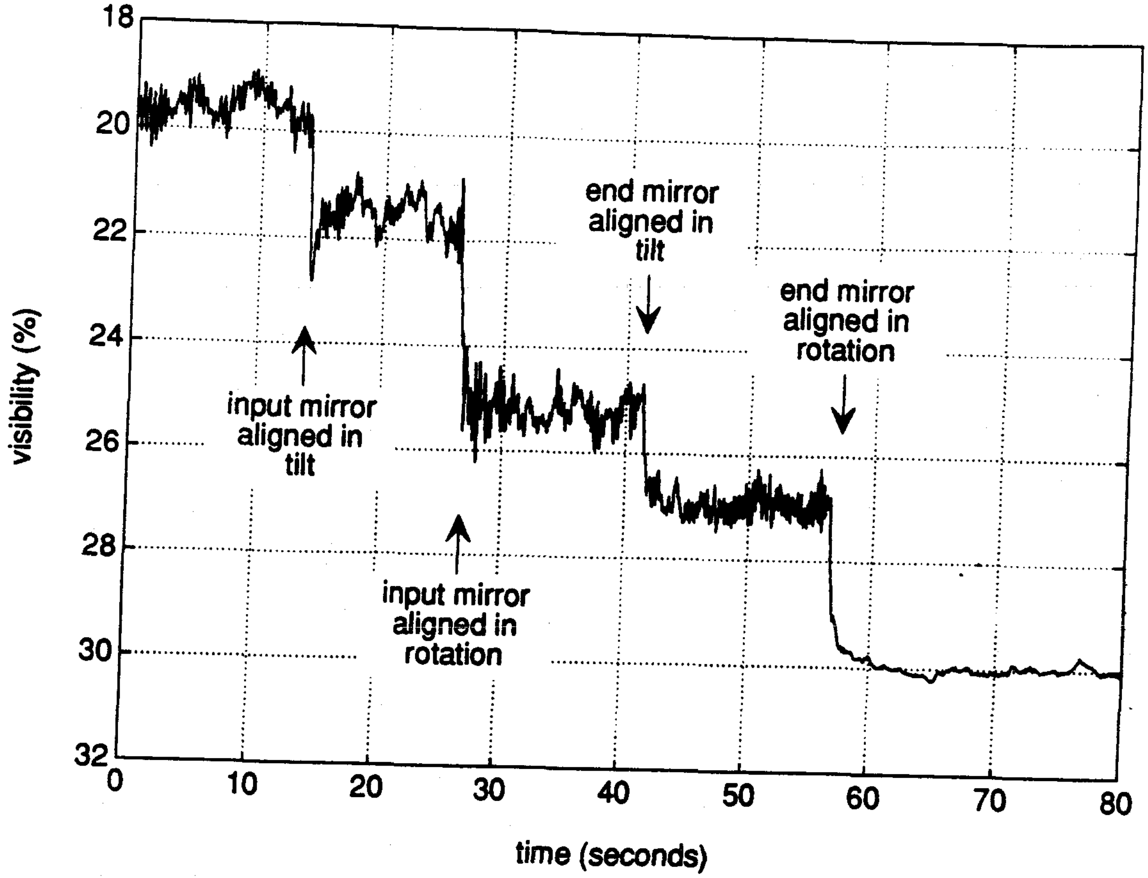

Figure 4: Effect of the automatic alignment system on the fringe visibility of the 10 m cavity.

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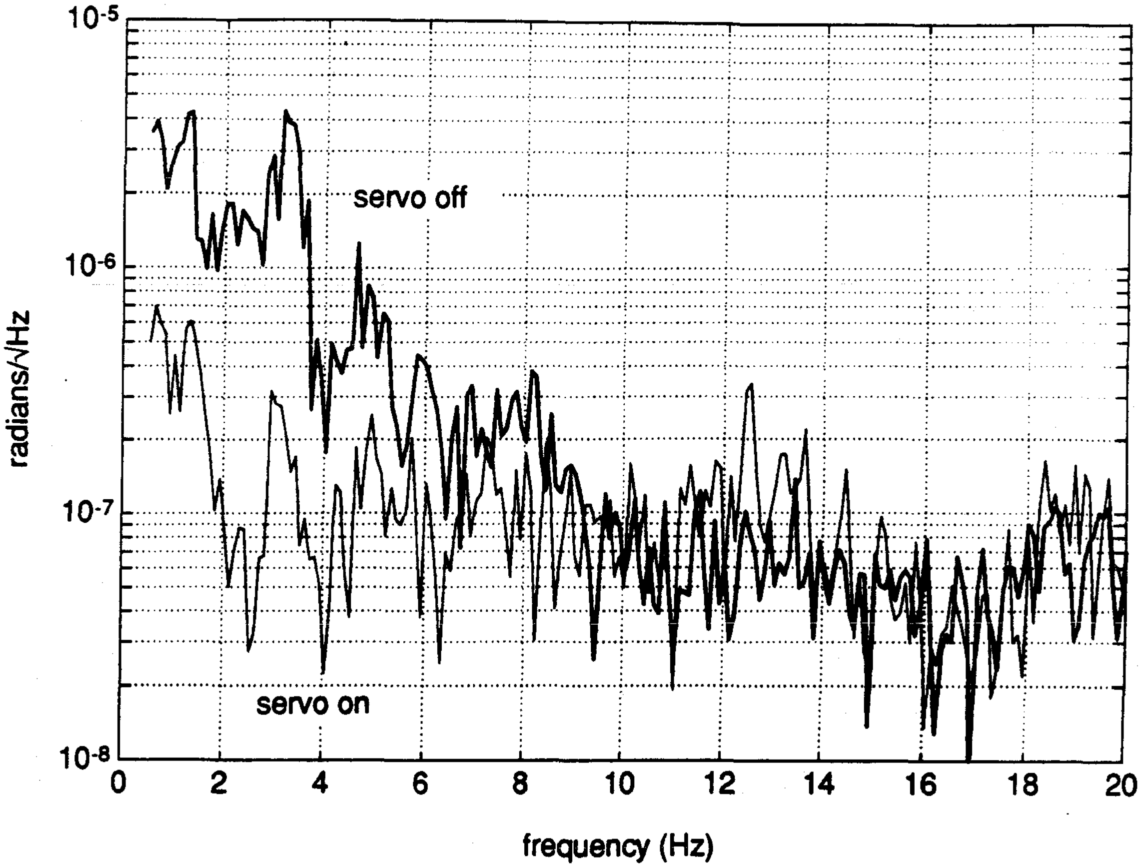

Figure 5: Angular fluctuations as viewed by the sensing system used to control the tilt of the curved mirror in the 10 m cavity.

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