

Test of an 18-m-long suspended modecleaner cavity

K. D. Skeldon, K. A. Strain, A. I. Grant, and J. Hough
Department of Physics and Astronomy, University of Glasgow, G12 8QQ, Scotland

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Fluctuations in laser beam geometry such as lateral beam movement and beam width variation can produce perturbations in the output signal of a laser interferometer through various coupling mechanisms. In order to avoid this type of laser noise from degrading the sensitivity of interferometers designed to detect gravitational radiation, currently planned long-base-line detectors will employ resonant optical filters called modecleaners to suppress beam geometry noise. Here we describe a prototype modecleaner cavity constructed at Glasgow having an optical path length of 18 m and containing four suspended mirrors. We present results detailing various aspects of its performance. © 1996 American Institute of Physics. [S0034-6748(96)05107-6]

I. INTRODUCTION

There are now several projects around the world constructing laser-based gravitational wave detectors of long base line. In the USA the LIGO team is building two 4 km detectors to be sited in the states of Louisiana and Washington, respectively.¹ The French-Italian VIRGO team is currently developing a 3 km detector in Italy.² The Japanese have begun construction of a 300 m base-line detector—TAMA300 in Tokyo.³ Meanwhile, in Germany work has commenced in constructing the 600 m arm length German-British detector—GEO 600.⁴ It is projected that all of these detectors will come on line during the year 2000 or soon after.

During their first phase of operation the above detectors are expected to achieve a strain sensitivity of the order of $10^{-22}/\sqrt{\text{Hz}}$ at 100 Hz. There are various types of noise that have to be dealt with before this level of performance can be realized in practice. In the case of geometry fluctuations associated with the illuminating laser beam, suppression of several orders of magnitude is required. This can be achieved either with the use of a single-mode optical fiber or a resonant Fabry-Perot optical cavity placed between the laser and the input of the interferometer. The latter of these forms the basis of a modecleaner scheme and is the system that all of the long-base-line detectors will implement in one form or another. Experience with prototypes has shown that optical fibers have rather poor laser power handling capabilities making it difficult to achieve power throughput values of more than about 50%. The proposed modecleaner schemes should be able to achieve much higher throughputs while providing large suppression factors for beam geometry noise.

All the long-base-line interferometers will use infrared Nd:YAG lasers ($\lambda=1064 \text{ nm}$). This contrasts with prototype interferometers which have used argon-ion lasers. The use of Nd:YAG lasers is driven primarily by their much better efficiency and generally quieter characteristics with regard to practically all types of laser noise. In the case of beam geometry noise, measurements show that Nd:YAG lasers are about an order of magnitude quieter than argon-ion lasers, having beam jitter and width fluctuation noise levels of $\delta x/w \approx 2 \times 10^{-6}/\sqrt{\text{Hz}}$ and $\delta w/w \approx 10^{-6}/\sqrt{\text{Hz}}$, respectively, at 100 Hz.⁵ Thus, the requirements imposed on a mode-

cleaner system to suppress beam geometry noise are made somewhat less stringent by the use of Nd:YAG lasers.

II. BEAM GEOMETRY NOISE IN INTERFEROMETERS

To assess the beam geometry noise suppression that will be necessary for an interferometer to achieve a strain sensitivity of $10^{-22}/\sqrt{\text{Hz}}$, we must have a good knowledge of the noise performance of the illuminating laser and the strength of the potential coupling mechanisms that exist. An estimate of the beam geometry noise associated with the illuminating laser can be based upon existing measurements such as those given above. The coupling mechanisms are a more complex issue and two particular cases are considered here. First, there is coupling of lateral beam movement due to beam splitter misalignment from a perfectly symmetric interferometer system. Second, there can be coupling of beam width fluctuation because of a lack of symmetry in the interferometer introduced by a mirror curvature mismatch in the arms, for example. Both of these are considered for the case of a simple Michelson interferometer where the driving laser has a beam waist at the beam splitter.

A. Beam splitter misalignment

If the beam splitter is aligned so that the interferometer system is perfectly symmetric then lateral displacements of the beam at the input produce no signal at the interferometer output. However, if the beam splitter is misaligned from this ideal situation by a small angle α then a simple geometrical argument shows that a lateral movement δx of the input beam causes an effective differential displacement signal δs given by

$$\delta s = 4\alpha \delta x. \quad (1)$$

For the case of the GEO 600 detector which contains a folded delay line in each arm, the optical arm length is effectively 1200 m and the lateral beam jitter noise for a Nd:YAG laser stated above yields an effective strain sensitivity limit of

$$h_{\text{min}} \approx 7 \times 10^{-11} \alpha / \sqrt{\text{Hz}}, \quad (2)$$

measured at 100 Hz. The precise value of the misalignment angle will depend on the precision of auto-alignment systems⁶ among other factors. Experience with prototype in-

terferometers suggests that a value of $\alpha \approx 10^{-7}$ is maintainable leading to a strain sensitivity limit of $h_{\min} \approx 7 \times 10^{-18} / \sqrt{\text{Hz}}$. Thus, we require a suppression factor of almost five orders of magnitude to achieve the target sensitivity in this case.

B. Mirror curvature mismatch

In a simple Michelson interferometer illuminated with a Gaussian laser beam, the recombining beams have a definite Guoy phase relationship at the recombination point. The Guoy phase characterizes the difference between the wave front of a propagating Gaussian beam and an ordinary spherical wave front.⁷ For the interferometer application here, this phase is dependent on a number of factors including the distance traveled in the arms, the size of the beam waist at the beam splitter, and the curvature of the mirrors at the end of each arm. Alteration of some or all of these parameters will affect the phase relationship of the recombining beams which may lead to an effective displacement noise. Of particular interest here is the case where the beam waist size at the beam splitter is fluctuating. In a perfectly symmetric interferometer this will have no effect on the relative phase of the beams at the recombination point. However, if the mirror curvatures are mismatched by a fractional amount $\delta R/R$ then a waist size fluctuation δw_0 will produce an effective differential displacement noise δs . For the GEO 600 detector with its 1200 m arm length, computation of the propagation of the Guoy phase along each arm yields a value for δs given by⁸

$$\delta s \approx 10^{-6} \frac{\delta R}{R} \frac{\delta w_0}{w_0}, \quad (3)$$

which can be used with the value of beam width fluctuation given above to give a sensitivity limit of

$$h_{\min} \approx 8 \times 10^{-16} \frac{\delta R}{R} / \sqrt{\text{Hz}} \quad (4)$$

at 100 Hz. It is generally accepted that large curvature mirrors can be matched to around 1% giving rise to a strain sensitivity limit of $\sim 8 \times 10^{-18} / \sqrt{\text{Hz}}$ at 100 Hz. Consequently, we require beam width fluctuation suppression of almost five orders of magnitude.

III. MODECLEANER FILTER FOR BEAM GEOMETRY NOISE

As illustrated above it appears that for a simple Michelson interferometer system, beam geometry noise suppression of up to five orders of magnitude is required to allow a target strain sensitivity of $10^{-22} / \sqrt{\text{Hz}}$ at 100 Hz to be reached. A more realistic detector system will involve power recycling cavities and possibly Fabry-Perot cavities in the interferometer arms which will have properties that differ from the simple Michelson arrangement. However, the above figures can be considered as upper bound estimates of the suppression required since the more complex systems usually provide some extra degree of suppression for the coupling of beam geometry noise.

To assess the performance of a modecleaner as a filter for beam geometry noise, it is useful to consider such noise in the transverse mode frame of the laser light. In rectangular coordinates the laser modes of propagation can be described to a good approximation by the Hermite-Gaussian functions.⁷ For a cavity with optic axis aligned with the z axis of a Cartesian coordinate system, the spatial part of the amplitude field describing the TEM_{nm} mode is given by

$$E_n(x, z) = \left(\frac{2}{\pi}\right)^{1/4} \left(\frac{1}{2^n n! w}\right)^{1/2} e^{j(n + \frac{1}{2})\tan^{-1}(\lambda z / \pi w_0^2)} \\ \times H_n\left(\frac{\sqrt{2}}{w(z)} x\right) e^{-jkx^2/2q}, \quad (5)$$

with an equivalent expression for the amplitude field along the y axis. It is useful to state the expressions for the fundamental, first-, and second-order modes. These can be deduced by setting $n=0, 1, 2$, respectively, in Eq. (5) to yield

$$E_0(x, z) = \left(\frac{2}{\pi}\right)^{1/4} \left(\frac{1}{w}\right)^{1/2} e^{j\frac{1}{2}\tan^{-1}(\lambda z / \pi w_0^2)} e^{-jkx^2/2q}, \quad (6)$$

$$E_1(x, z) = \left(\frac{2}{\pi}\right)^{1/4} \left(\frac{1}{w}\right)^{3/2} 2x e^{j\frac{3}{2}\tan^{-1}(\lambda z / \pi w_0^2)} e^{-jkx^2/2q}, \quad (7)$$

$$E_2(x, z) = \left(\frac{2}{\pi}\right)^{1/4} \left(\frac{1}{w}\right)^{5/2} (4x^2 - 1) \\ \times e^{j\frac{5}{2}\tan^{-1}(\lambda z / \pi w_0^2)} e^{-jkx^2/2q}. \quad (8)$$

If a laser beam containing only the fundamental mode translates sideways by a small amount δx then it is equivalent to adding to Eq. (6) a small amount of first-order mode $E_1(x, z)$. The new light field $E_{\delta x}(x, z)$ can be expressed⁹

$$E_{\delta x}(x, z) = E_0(x, z) + \frac{\delta x}{w_0} E_1(x, z). \quad (9)$$

If a laser beam containing only the fundamental mode undergoes a fluctuation δw_0 in the size of its waist w_0 then the light field near the waist $E_{\delta w_0}(x, z)$ is equivalent to Eq. (6) added to a small amount of $E_2(x, z)$ and can be written as

$$E_{\delta w_0}(x, z) = E_0(x, z) + \frac{1}{\sqrt{2}} \frac{\delta w_0}{w_0} E_2(x, z). \quad (10)$$

The coupling coefficients of the higher-order mode in each case are seen to be directly related to the value of the beam geometry fluctuations. This modeling of beam geometry noise as contaminations to the fundamental mode with higher-order transverse modes simplifies the analysis regarding the role of a Fabry-Perot cavity as a filter for such noise. A modecleaner is such a cavity used in transmission, whose geometry is chosen such that when the fundamental mode is resonant the higher-order modes, which have different cavity eigenfrequencies from the fundamental, are strongly off-resonant and are suppressed.¹⁰

For a two-mirror Fabry-Perot cavity on resonance with the fundamental laser mode, the amplitude throughput of a general transverse mode A_{nm} can be expressed in terms of the fundamental amplitude A_{00} by the formula

$$\frac{A_{nm}}{A_{00}} = \frac{\sqrt{t_1 t_2}}{1 - \sqrt{r_1 r_2} \{1 + 4[\sqrt{r_1 r_2} / (1 - \sqrt{r_1 r_2})^2] \sin^2[(n+m) \cos^{-1}(\sqrt{1 - L/R_1} \sqrt{1 - L/R_2})]\}^{1/2}} \quad (11)$$

where t_i , r_i and R_i are the power transmittance, reflectance, and curvature of the i th mirror, respectively, and L is the mirror separation. The leading term on the right-hand side of Eq. (11) is an amplitude transmission factor common to all modes. The light power throughput when the cavity is on resonance with the fundamental mode can be expressed in terms of this factor as

$$\frac{P_{out}}{P_{in}} = \frac{t_1 t_2}{(1 - \sqrt{r_1 r_2})^2} \quad (12)$$

The term in curly brackets in the denominator of Eq. (11) contains the dependency of the higher-order mode throughput on the cavity geometry and can be considered as the suppression factor S_{nm} afforded to a general TEM_{nm} mode by a cavity locked to the TEM_{00} mode. In terms of the cavity finesse \mathcal{F} this suppression factor can be written

$$S_{nm} = \left(1 + \frac{4\mathcal{F}^2}{\pi^2} \times \sin^2 \left\{ (n+m) \cos^{-1} \left[\left(1 - \frac{L}{R_1}\right)^{1/2} \left(1 - \frac{L}{R_2}\right)^{1/2} \right] \right\} \right)^{-1} \quad (13)$$

Various cavity geometries provide different degrees of suppression for a given mode. In practice it is desirable to suppress those modes to which beam geometry fluctuations couple most strongly, particularly TEM_{10} and TEM_{20} to which beam jitter and beam curvature variation are most strongly related. The cavity geometry $R_1 = R_2 = R$ with $R/L = 0.6$ is a popular choice, giving $S_{10} \approx 0.58F$ and $S_{20} \approx 0.47F$ (compared with a maximum possible suppression of $\sim 0.64F$). In principle, the required suppression can then be achieved by choosing an appropriate value for the mode-cleaner cavity finesse. With currently available supermirrors it is relatively straightforward to construct a cavity having a finesse of up to a few thousand that can cope with incident light powers of many watts;¹¹ however, to achieve suppression factors of order 10^5 requires an unreasonably high fi-

nesse. The solution for GEO 600 is to use two modecleaners placed in series each having a finesse of ~ 1000 . Together these should provide $>10^5$ suppression of beam jitter and width fluctuation, which should more than satisfy the target sensitivity requirements, while still affording a satisfactory level of power throughput.

IV. DESIGN OF A PROTOTYPE SUSPENDED MODECLEANER

The modecleaner developed in the laboratory at Glasgow contains four suspended mirrors arranged in a figure-eight cavity geometry as shown in Fig. 1. A ring cavity design avoids problems caused by light directly reflected back to the laser. The mirrors used were all 25-mm-diam superpolished substrates with coatings manufactured by British Aerospace. The mirrors were attached to fused-silica masses by the use of small amounts of cyanoacrylate adhesive. The input and output coupling mirrors are both flat and have transmittance 0.5% while the other mirrors have 15 m radius of curvature and maximum reflectance. The total optical round trip path is 18 m providing a free spectral range of 8.3 MHz which is sufficiently low to permit the passing of modulation frequency sidebands, should that be required at some later stage of system development. This cavity geometry is equivalent to two mirrors of 15 m curvature placed 9 m apart, and so meets the $R/L = 0.6$ criterion. Each mirror is suspended as a single pendulum by a single loop of steel wire and locally damped by the use of four shadow sensor coil-magnet assemblies as illustrated in Fig. 2. Three assemblies are mounted at the rear of the mass and one at the side. Together they damp all degrees of freedom of motion associated with the mass and also allow control over its position by feeding dc signals to the control coils. The laser used was a highly modified Spectra-Physics 171 argon-ion type run-

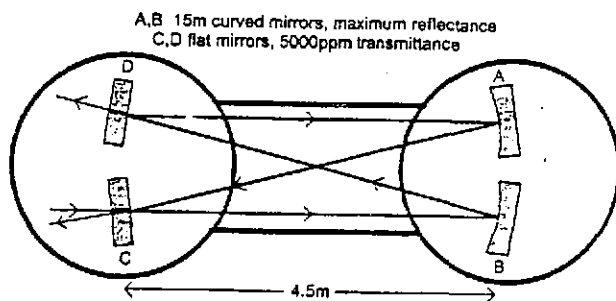


FIG. 1. The geometry of the four-mirror modecleaner cavity developed at Glasgow. The figure-eight configuration allows a large optical path length to be obtained in a relatively short physical space.

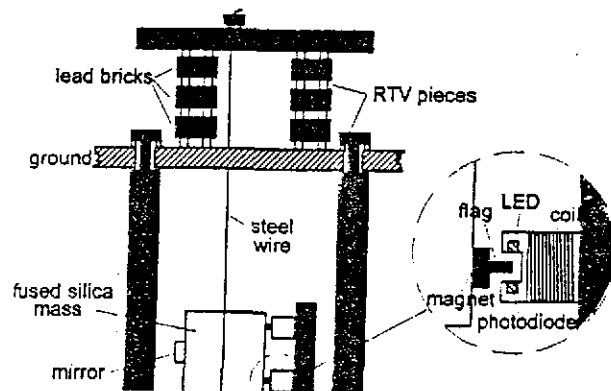


FIG. 2. The suspension assembly with the damping coil arrangement for one of the suspended masses. The mass contains four magnets each attached to a small flag. Each shadow sensor coil-magnet unit converts the position of the flag into a signal which is filtered and fed back to the control coil. The coil produces a local damping force by acting on the magnet.

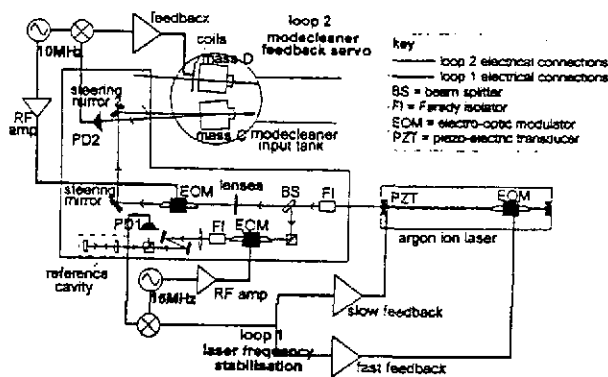


FIG. 3. The experimental configuration of the modecleaner system showing the two feedback loops. The first loop frequency stabilizes the laser allowing the second loop to lock the modecleaner cavity to the light.

ning in a single longitudinal and transverse mode at $\lambda=514$ nm. The laser provided about 200 mW at the input to the modecleaner cavity. The experimental configuration contains a dual loop feedback system shown schematically in Fig. 3. The first loop is a laser stabilization system that contains a rf reflection locking scheme¹² (modulation frequency 16 MHz) and a rigid reference cavity of finesse ~ 1000 . This system significantly reduces the frequency excursions of the argon-ion laser down to about $3 \times 10^{-1} \text{ Hz}/\sqrt{\text{Hz}}$ above a few Hz. The second loop also contains a rf reflection locking scheme (modulation frequency 10 MHz) deriving its signal from the modecleaner cavity and providing a feedback signal that locks the cavity to the stabilized light. This is achieved by applying the feedback signal to three of the coils mounted at the back of the output modecleaner mass, providing a longitudinal feedback force. In operation, the first loop would be manually closed and then the second loop would find a fringe and lock to it almost immediately. Acquisition of lock was found to be straightforward while the losing of lock was almost always caused by the first loop failing, because of a mode transition in the argon-ion laser, for example.

V. PERFORMANCE OF THE PROTOTYPE MODECLEANER

Apart from the beam geometry noise suppression afforded by the modecleaner, there are several other aspects of the system that are interesting to test. The achievable power throughput, the spacial mode cleaning imposed on the beam, and the long-term cavity alignment stability are three other properties that could be important for gravitational wave interferometers. These are now considered briefly in turn.

A. Power throughput

The best power throughput of the modecleaner cavity, assuming each of the four mirrors to have a nominal loss of ~ 50 ppm, can be calculated to be 96%. However, there are various factors such as imperfect mode matching and the power channeled into modulation sidebands that will produce a lower power throughput in practice. In the absence of mirror losses, the cavity finesse should be around 600; however, ring down measurements showed the finesse of the cavity to be around 550, implying a mirror loss of over 300 ppm

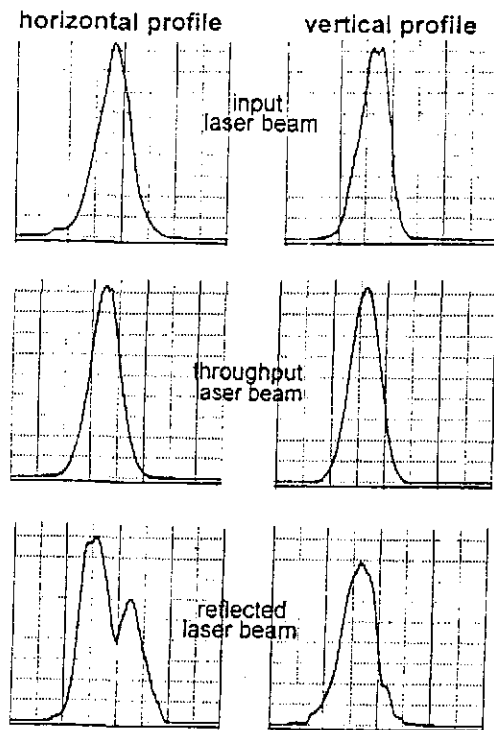


FIG. 4. A qualitative comparison of the profiles of the incident, reflected, and transmitted laser beams. The light powers in each case are different and the vertical axes are not drawn to a common scale.

per mirror. This loss is much higher than expected and was attributed to the cleanliness conditions in the laboratory and the fact that the mirrors used were not new. The measured throughput was 70% which, given the observed cavity visibility of 90% and the measured cavity losses, is consistent with theory.

B. Spatial filtering action

The modecleaner should act as a spatial filter for the incident laser beam, supporting a fundamental cavity mode whose Gaussian integrity is determined by the geometrical quality of the cavity mirrors, rather than the nature of the incident beam profile. This property of the system can be regarded as the cavity mode suppression considered at zero frequency. The traces shown in Fig. 4 were taken by a scanning-slit beam profiler. The distorted profile of the reflected beam contrasts sharply with the purity of the transmitted beam. There are slight imperfections on the transmitted beams but these are due to the fact that the beam exiting from the cavity passes through an untreated glass viewport.

C. Long-term stability

The long-term drift of the cavity alignment was monitored by measuring the cavity visibility over a period of several weeks. The system was initially aligned and a visibility of 90% was achieved. The visibility dropped to 20% over a 2 month period. There was no auto-alignment scheme installed on the system and so this change in visibility is due entirely to settling of stacks, or drifts in the position of the incident laser beam. This degree of misalignment over such a time

scale implies minimal maintenance to keep the system locked as part of a detector system. Auto-alignment systems should be able to maintain good modecleaner cavity visibility requiring infrequent manual adjustments.

D. Beam jitter suppression

The primary objective of a modecleaner system is to reduce the levels of geometry noise present in the laser beam. This was checked for lateral beam movements by applying an artificial beam jitter to the light incident to the modecleaner. The jitter was applied by replacing one of the main beam steering mirrors in the modecleaner injection optics chain with a mirror mounted on a loudspeaker cone. The motion of the loudspeaker cone when energized from a signal generator was longitudinal, giving rise to a purely lateral translation of the beam. The levels of beam jitter noise for the incident and exiting beams were then measured by directing each beam in turn to the centre of a split photodiode and measuring the difference signal with a spectrum analyzer. A common problem when making beam jitter measurements is the sensitivity of the measurement process to fluctuations in laser power. In principle this problem can be minimized by maintaining exactly equal amounts of power on each half of the split photodiode, for then the difference signal is insensitive to laser power noise. In practice, slow beam drift makes this condition impossible to maintain without constant manual attention. To avoid the need for such manual adjustments, the two segments of the split photodiode were connected to voltage-controlled load resistors that formed part of a feedback system to help maintain symmetry automatically in the presence of slow beam drifts.⁵ The issue of laser power noise is especially important for measurements made at the output of the modecleaner. Here there is laser power noise that is transmitted through the modecleaner cavity below its corner frequency. In addition, there is new power noise due to the modecleaner action of converting beam jitter of the input light to laser power noise on the output light. To achieve the necessary level of laser power noise suppression at the output of the modecleaner, a light power stabilizer was constructed. For the purposes of the measurements being made here, it was sufficient to mount this system locally at the modecleaner output, so that the active component alters the light exiting the cavity. In a real detector system, such a servo would probably take its sample beam from after the modecleaner but act on the light before the modecleaner so that any beam jitter introduced by the active component, usually an electro-optic modulator (EOM), would then be suppressed. The active component used here was an acousto-optic modulator (AOM) driven from a 40 MHz rf source with adjustable drive power. Carefully designed systems using AOMs can provide many orders of magnitude suppression of laser power noise.¹³ The decision to use an AOM rather than an EOM was driven primarily by the tendency of the latter to introduce asymmetric beam geometry noise. A simplified diagram of the measurement system is shown in Fig. 5. The signal from the reference photodiode was amplified and applied with negative feedback to the AOM drive. Also applied to the AOM drive was a manually adjustable dc bias to allow the operating point of the intensity servo to be

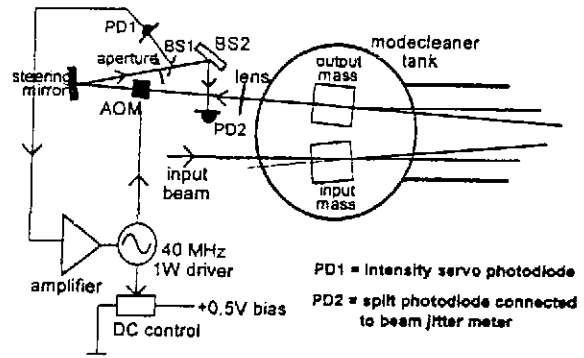


FIG. 5. The experimental configuration for comparing the beam jitter levels associated with the light at the input and output of the modecleaner cavity. A beam splitter is used to direct either the incident or exiting beam onto the center of the split photodiode.

set. The feedback signal produces a variation of the light power diffracted by the AOM, which in turn controls the intensity of the undeflected beam. The undeflected beam was then directed to the split photodiode where the beam jitter measurements were made. This system could afford up to 30 dB of intensity noise suppression although only about 20 dB was found to be required.

The traces in Fig. 6 show various backgrounds of beam jitter measured before and after the modecleaner with a jitter peak applied at 125 Hz. The overall suppression factor afforded to the applied peak can be measured between the top and bottom traces to be ~48 dB (factor of ~250). Given the measured modecleaner finesse of 550, the expected suppression for TEM₁₀ should be 51 dB (factor of 319). This result is in reasonable agreement with theory.

It should be noted that the background level of the bottom trace in Fig. 6 is comparable with the magnitude of seismic noise associated with the guiding mirrors, laser power stabilizer, and photodiode unit, as measured with an accelerometer. The true level of beam jitter noise at the modecleaner output is likely to be lower, determined mainly by the residual motion of the modecleaner mirrors.

In summary, the modecleaner cavity developed at Glas-

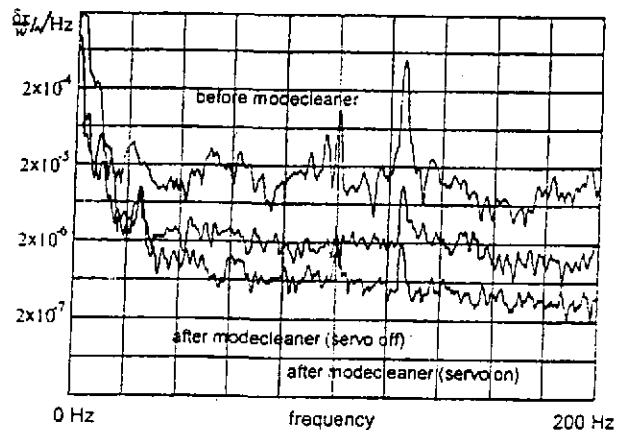


FIG. 6. Comparison of beam jitter noise level associated with the beam entering the modecleaner and the beam exiting the modecleaner with the intensity servo switched off and then on. The peak of 125 Hz is an artificially applied lateral beam jitter.