MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Progress with the Garching 30-meter prototype for a gravitational wave detector

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Abstract

The experimental work with the Garching 30-meter prototype (started in 1983) is mainly aimed at isolating, identifying, and then suppressing noise contributions in excess of the fundamental limit of shot noise.

Mechanical noise, thermally or seismically driven, was considerably reduced through the use of separate (extremely simple) suspensions for the two near mirrors and the beam splitter. Fluctuations in laser beam geometry were efficiently reduced by using a single-mode fiber that ends in the vacuum on a (separately suspended) beam-steering block. The laser frequency stabilization was considerably improved in a second control loop, using the total optical path in the interferometer as reference.

The interferometer was operated with 50 and later, 110 beams in the delay line (optical paths of 1.5 and 3.3 km, respectively). Inside the frequency range of interest, from 500 Hz to 6 kHz, the noise measured is close to the shot noise for the 100 mW of available light power. With $L = 3.3$ km, the noise expressed as strain (linear spectral density) amounts to $\tilde{h} = 2 \times 10^{-19}/\sqrt{\text{Hz}}$.

Resonance peaks around 10 kHz were recently identified as being due to the Pockels cell mounting. From 1 kHz downward, a gradual increase in noise is observed, the origin of which is not yet known. Anticipated improvements in the isolation from ground noise and increases in the available light power will help to identify the sources of the remaining excess noise.

1. Introduction

This short paper discusses recent experiences of the Garching group with some familiar noise sources: frequency noise, laser beam jitter, seismic noise, and thermal noise. But first a general introduction to the instrument at Garching, in Max-Planck-Institut für Quantenoptik, is in order.

The literature contains a number of descriptions of the principles and techniques underlying the interferometric method of gravitational wave detection[1] and so only a few of the relevant details for the 30 m apparatus will be given here. A schematic diagram of the instrument is shown in figure 1.

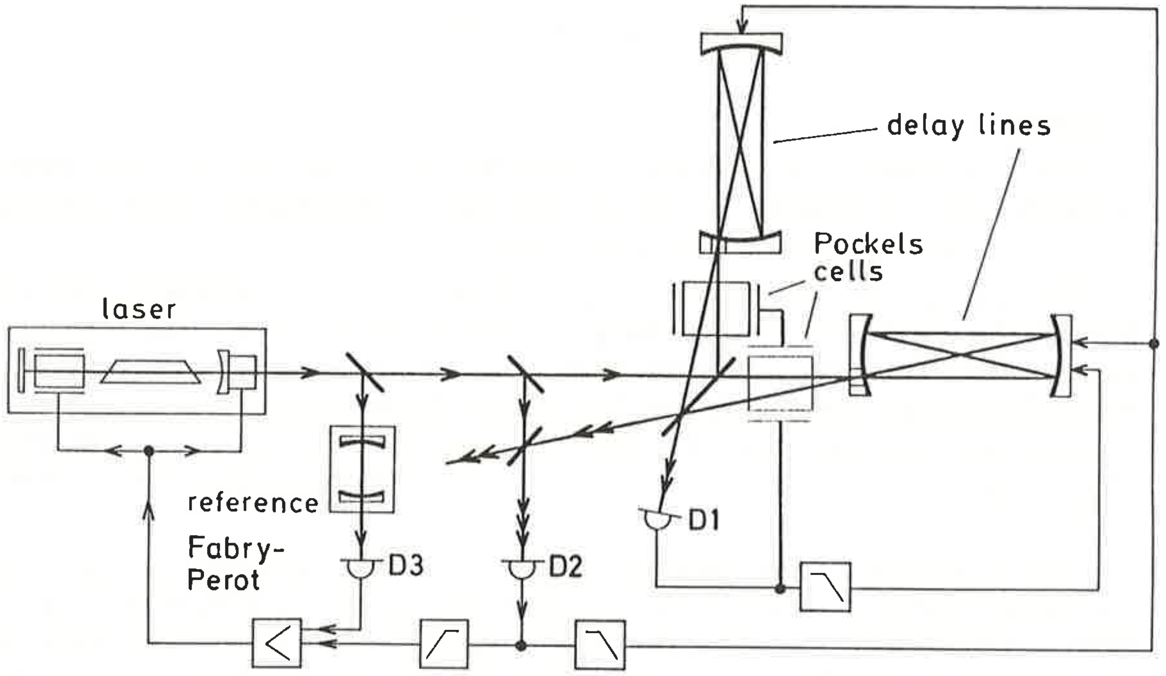

Fig. 1 : Schematic diagram of the laser interferometer. The illumination is provided by an argon laser (1 Watt, 514 nm), shown at the left. The two arms of the Michelson interferometer, with 4 beam delay lines indicated, are at the right. Frequency stabilization and interferometer servo-systems are shown at the bottom.

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[1] See, for instance, A. Rüdiger et al: *Gravitational wave detection by laser interferometry,* in: *Lasers and Applications,* Eds. I. Ursu, A.M. Prokhorov, CIPPress Bucharest (1983) 155-179; or R. Schilling et al: *Improved sensitivities in laser interferometers for the detection of gravitational waves,* in: *Gravitation, Geometry, and Relativistic Physics,* Lecture Notes in Physics **212** (1984), Springer-Verlag Heidelberg. These articles describe a similar 3 m interferometer.

The separation of the mirrors is 30 m; the optical path in the interferometer arms is increased by the use of optical delay lines, typically with 50 or 110 beams. The resulting storage times are 5 and 11 μs respectively. The light returning from the two arms is brought to interference, and the output of the interferometer that falls on photodiode D1 is kept at a minimum of intensity by a servo-system using a modulation technique: Electro-optical (Pockels) cells in the light paths impress a 10 MHz modulation on the light and maintain the 'lock' at high frequencies (above 30 Hz), and drivers for the mirrors take care of large low-frequency excursions (utilizing fixed air-core electromagnets exerting forces on permanent magnets attached to the mirrors). This 'differential' fringe-locking system keeps the difference of the arm lengths constant, and the correction signal of this servo-system would contain the gravitational wave signal.

All of the optical components are isolated from ground motion by hanging them as pendulums. The electromagnets and permanent magnets mentioned above also serve as part of an electronic damping system to keep the motion at the resonant frequency of the pendulums small, while not compromising the quality factor Q at measurement frequencies.

Because of the large separation between the mirrors, only the central optical elements (beam splitter and near delay line mirrors) are in the laboratory itself; the vacuum system penetrates the outside wall of the building, and the far mirrors are in separate end houses. The vacuum tubing is supported by a concrete bed and steel guides, and is first protected by a semi-circular concrete cover and then by an earth berm about one meter thick. The installation is kept at a vacuum of 10^{-1} to 10^{-2} mbar by pumping once per day. This is low enough to avoid arcing across the Pockels cell terminals, and to keep the influence of index fluctuations in the remaining gas on the observed optical path below the limit due to the present photon shot noise (corresponding to roughly 100 mW of light power).

A simplified configuration of the interferometer has proved invaluable for troubleshooting noise sources; it can be realized by turning around the near delay line mirrors, so that the light no longer falls through their entrance holes. The light path then extends from the beamsplitter to the near mirrors and back (a total distance of 40 cm); this has the effect of removing the delay lines from the optical circuit, which both simplifies the optics and reduces the sensitivity to mirror (and ground) motion.

2. Frequency Noise

The first noise source that will be discussed is frequency jitter of the illuminating laser light. There are two basic ways in which this can cause noise in the output of the interferometer: through a static path length difference or through scatter from optical surfaces in the instrument. In both cases, the problem is that light leaving the laser at different times is being compared. The solution that is being pursued at Garching is to stabilize the frequency of the laser so that the new and old light have a fixed phase relationship. The extent to which this can be achieved depends on the stability of the frequency reference, and on the gain possible in the servo-loop which holds the laser frequency to this reference. As can be seen in figure 1, two references are used. The first is a 25 cm Fabry-Perot cavity; deviations in the laser frequency result in changes in the transmission of the cavity, and this error signal (from diode D3) is sent to an intracavity Pockels cell and to a piezoelectric transducer controlling one laser mirror.

The second reference is the interferometer itself. While the interferometer output falling on diode D1 is kept at a minimum of intensity, the other output is at a maximum and has suffered a time delay and hence phase delay which is the average of the phase delays in the two arms. This light is brought to interference with part of the light coming directly from the laser, and the intensity of this interference (observed at diode D2) is then a very sensitive measure of the frequency of the laser, the length of the delay lines being used as a reference. This is exactly the right criterion for frequency stability, since what must be held constant to suppress this noise source is the number of wavelengths of light in the delay lines.

Suitably high-pass filtered, this error signal is used to further control the laser frequency; the resulting frequency jitter is below the level where it can cause excess noise in the interferometer output. Figure 2 shows the efficacy of these frequency control systems.

The other very important feature of this second reference is that it prevents common-mode motion of the interferometer mirrors. Notice that the differential fringe-locking system does not object to a simultaneous lengthening of the two delay lines. If not controlled, this motion is usually at the pendulum frequency of the mirrors and has an amplitude of many wavelengths of light (in terms of optical path). In this case, the phase of scattered light trapped in the delay lines rapidly moves against the main beams, and through the non-linearity of the addition of phases it can create spurious noise signals in the kilohertz range. The interference fringe on D2 is sensitive to this 'breathing' of the mirrors, and if this low-pass-filtered signal is properly applied to the delay line mirrors, it can prevent this common-mode motion.

It appears that these measures taken against noise signals due to frequency jitter and scattering from the mirror surfaces are sufficient to eliminate their influence on the noise spectrum.

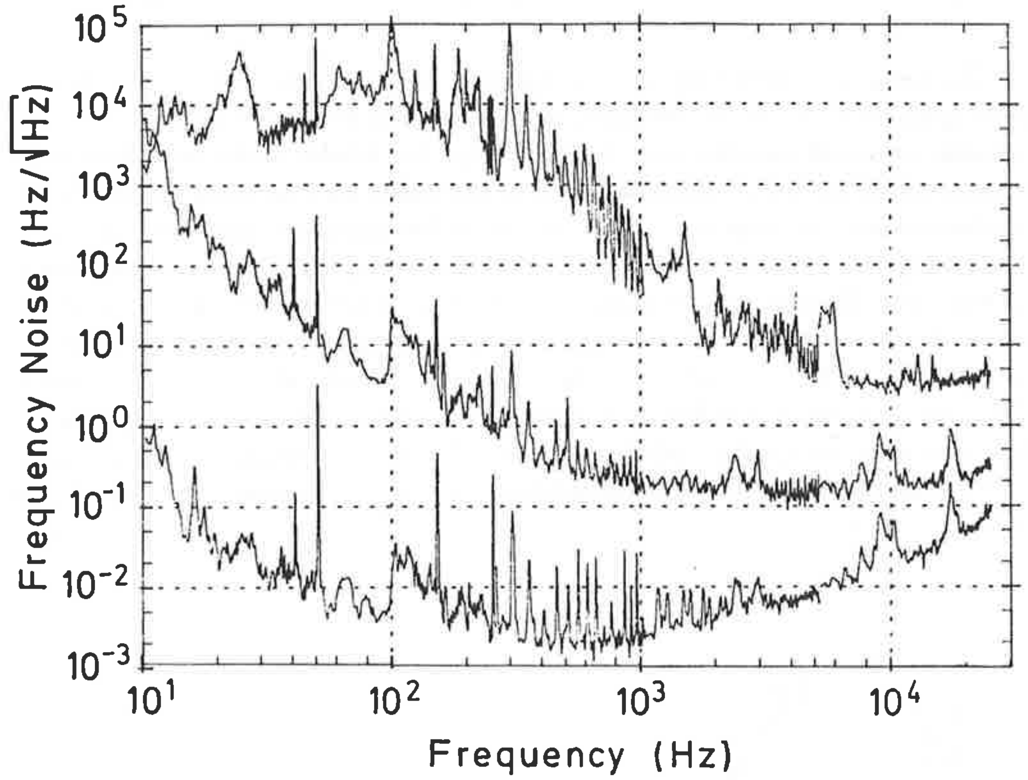

Fig. 2 : Frequency noise in the illuminating laser beam. The vertical scale is in Hz/$\sqrt{Hz}$, the noise present in a 1 Hz bandwidth. The top curve is the frequency noise present in the uncontrolled laser output, the middle curve is the noise level when the Fabry-Perot cavity is used as the reference, and the bottom curve is the error signal for the system including the interferometer as the 'second reference'.

3. Beam Jitter

Another property of the illuminating laser beam which can lead to unwanted effects is its motion in angle or position at the input of the interferometer. In a simple Michelson interferometer, a misalignment of the beam splitter will lead to a conversion from the input beam position to a path length difference; and a difference in length between the two arms will lead to a conversion of angle fluctuations of the input beam to fluctuations of the path length difference. Small imperfections in the optical components (e.g., mirror irregularities or internal strains in the Pockels cells) can also allow these beam motions to introduce noise terms.

Two different approaches to solving this problem have been implemented. Previously, a Fabry-Perot cavity in resonance was used to suppress the transmission of all but its fundamental mode (turning position fluctuations into amplitude fluctuations from which the differential fringe-locking system gives us great immunity). However, the extent of suppression was limited by the quality of mirrors available and by the fact that the cavity itself was not sufficiently isolated from ground noise.

The solution currently used, suggested by R. Weiss of MIT, is to use a single mode glass fiber to lead the light from the laser to the interferometer. The fiber will only support one (nearly Gaussian) spatial mode, and also allows for a simple decoupling of the mechanical motion of the laser and its associated noise from the interferometer. In practice, the light must be matched into and out of the fiber, which supports a mode diameter of a few microns; microscope objectives are used. Because the fiber does not hold a particular polarization, a $\lambda/2$ plate is placed before the fiber input and a linear polarizer is placed at the output to select and hold the correct polarization. The resulting optical efficiency is about one half. The fiber output assembly is isolated from ground noise by suspending it on a electronically damped pendulum mass; this is neccessary to obtain a jitter-free beam, and allows convenient adjustment of the input beam angle and position as well.

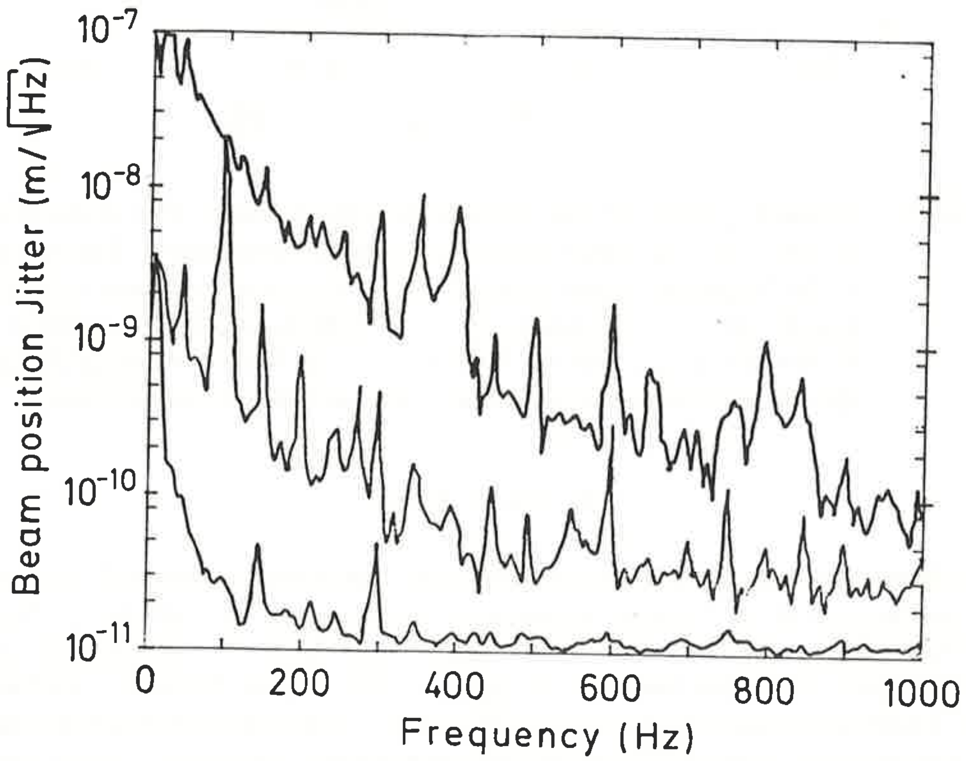

Fig. 3 : Laser beam jitter, as measured with a position sensitive diode. Top curve: beam directly from the laser. Middle: as suppressed by the Fabry-Perot mode cleaner. Bottom: as suppressed by the single mode fiber.

Figure 3 illustrates the effectiveness of these two solutions. The measurement in the case of the single mode fiber is limited above 200 Hz by shot noise in the position sensitive (PIN) photodiode; other measurements using the 40 cm troubleshooting interferometer put a slightly more stringent limit of $3 \times 10^{-12}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ on the position jitter, again limited by the measurement shot noise. Using the PIN diode and an optical lever arm of 30 m, an upper limit of $3 \times 10^{-12}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ can be given for the angle jitter.

4. Seismic Noise

As mentioned in the introduction, the optical components of the interferometer are isolated from ground noise by hanging them as pendulums so that motion of the suspension point will be filtered by the pendulum resonance. An ideal pendulum would be expected to give a filter characteristic of $(f_0/f)^2$ at frequencies above the resonance f_0 of .6 Hz until a transition frequency of $f_0 \times Q$ (which in our case is on the order of 10^4 Hz), where the filter characteristic becomes $f_0/(f \times Q)$.

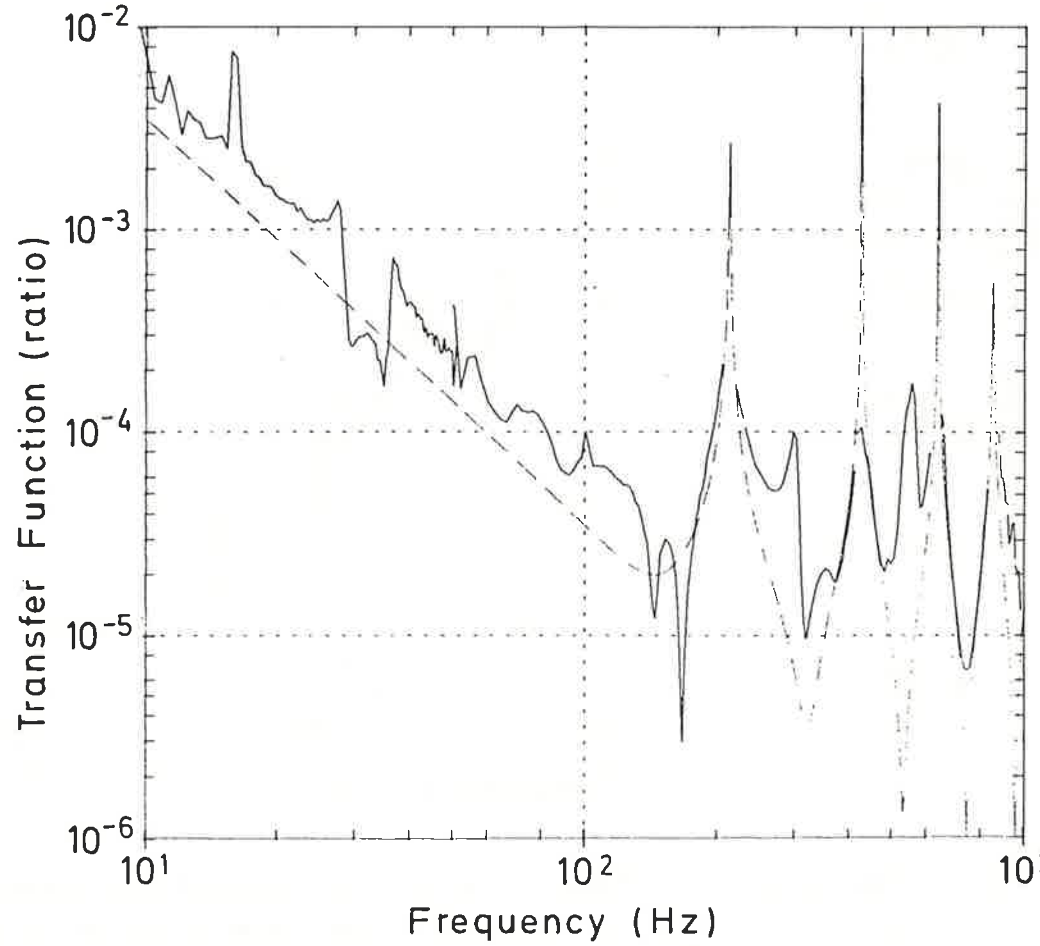

Fig. 4 : Pendulum transfer function for motion at the suspension point to motion at the mirror. Solid curve: measured. Dashed curve: calculated.

However, the wires which connect the mass (in this case just the mirror) to its suspension point also play a role. One can make a transmission line model in which the system is viewed in terms of the frequency-dependent complex impedances of the suspension point, wire, and mirror mass; the resulting expression for transmission is similar to that for a Fabry-Perot. The prediction of the model is that at frequencies comparable to one-half of the first string mode of the wires, the filter characteristic no longer falls monotonically but oscillates around a fixed value of suppression. The level at which this transition occurs depends on the relative impedances of the support, string, and mirror; in the case of the Garching system it is at a level of suppression of about 10^{-4} and at a corner frequency of roughly 100 Hz. As shown in figure 4, the measured transfer function of the pendulum suspension system agrees reasonably well with this model.

If one takes the filter function of the pendulums and applies it to the measured ground noise at the pendulum suspension points, a prediction of the low-frequency response of the interferometer can be made. Such a prediction can be seen, plotted with the actual interferometer output, in Figure 5. The agreement is good. Also plotted is the expected motion of the pendulum due to thermal noise forces, as described in the next section.

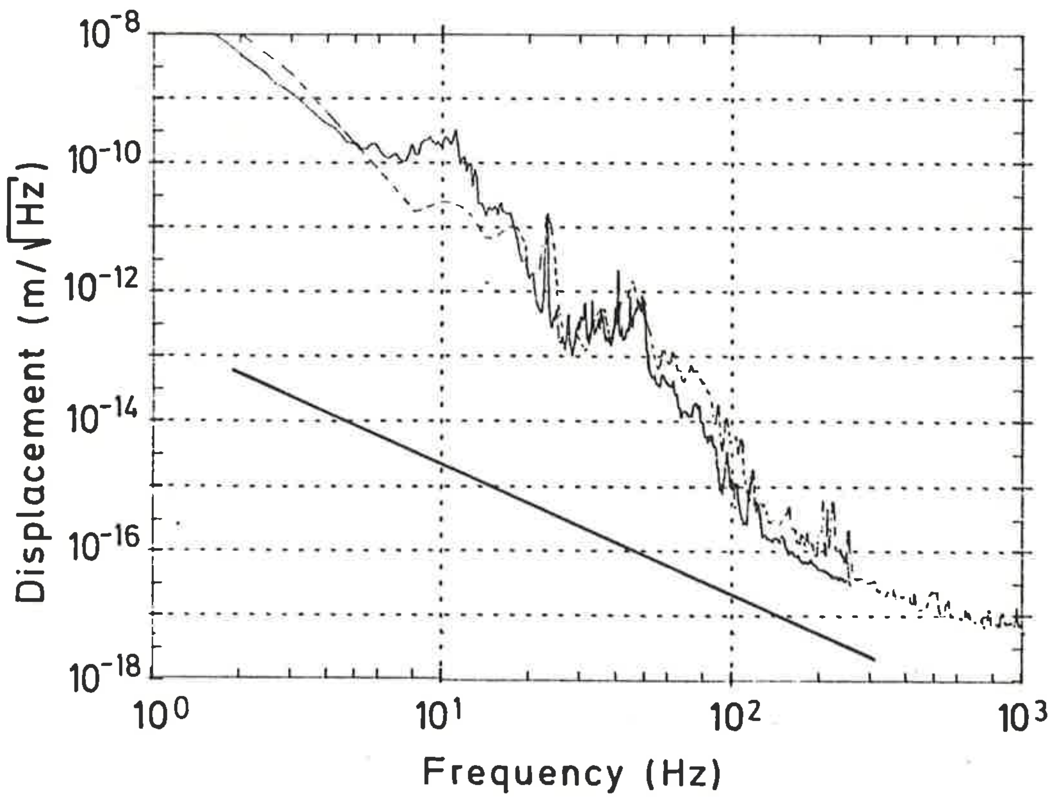

Fig. 5 : Interferometer low frequency output, predicted (solid line) and measured (dotted line). The straight line with a slope of $1/f^2$ is the calculated thermally driven motion of the mirrors.

5. Thermal Noise

The last noise source that will be discussed is that due to thermal driving forces. Lossy systems have a driving force that is determined by the properties of the system and will cause the resonances of the mechanical system to be excited. It is convenient to divide the frequency spectrum of this noise into three regimes. Above the resonant frequency, the displacement falls as $1/f^2$:

$$\tilde{x} = \sqrt{4kT\omega_0/MQ\omega^4} \qquad \omega \gg \omega_0$$

At resonance, the peak has the value

$$\tilde{x} = \sqrt{4kTQ/M\omega_0^3} \qquad \omega = \omega_0$$

and below the resonance, the noise has a flat frequency characteristic:

$$\tilde{x} = \sqrt{4kT/MQ\omega_0^3} \qquad \omega \ll \omega_0$$

where $\tilde{x}$ is a spectral density (for instance, in units of $m/\sqrt{\mathrm{Hz}}$), ω is the angular frequency, ω_0 is the resonant angular frequency, k Boltzmann's constant, T temperature, M mass, and Q the quality factor. Notice that in this low frequency plateau the level is $1/Q$ times the peak value at resonance.

The thermal motion of the optical elements can result in noise in the interferometer output. The pendula, which act as ground isolation, have a low resonant frequency (about 0.6 Hz) and a high quality factor (about 10^4); this results in thermally driven motions which in the high-frequency limit (the $(\omega_0/\omega)^2$ regime) as yet lie below the filtered ground noise (shown in the bottom curve in figure 5). The mirror substrates themselves have resonances at about 6 kHz, and the peaks due to this thermally driven motion (illustrating the resonance regime) can be clearly seen in the spectra from the interferometer (see Figure 6). In the case of the mirror substrates, the Q is so large that the low-frequency plateau lies well below the more fundamental limit of the photon shot noise.

However, a series of resonances in our spectra near 10 kHz have a Q sufficiently small that their low-frequency motion can influence the interferometer spectrum – not seriously at the current level of the light intensity, but already measurably. The source of these resonances was recently identified (with the help of the 40 cm troubleshooting interferometer) as the way in which the Pockels cells in the interferometer were mounted, and a new mounting technique without these resonances has been developed. It is at first difficult to see how motions of the Pockels cells could affect the light path, except as a second-order effect; one possibility lies in the fact that ADP, the electro-optical material used, has a large photoelastic coefficient (resulting in a change in index of refraction when the material is stressed). Spectra have not yet been taken with the full instrument and new Pockels cells.

In general, it appears that it is very important to keep the mechanical systems associated with the optical elements as simple as possible, both to reduce the number of resonances and to keep the quality factor Q large. This philosophy has led to hanging each of the optical elements separately; and to making the hanging system a simple wire 'sling' in which the optical component is balanced. As a consequence, many resonances have been eliminated from the spectrum.

6. Present Results

Figure 6 shows the current performance of the Garching 30-meter interferometer for the case of 110 beams in the delay lines, with the vertical scale calibrated in terms of mirror displacement. In the low-frequency regime from 50 to 250 Hz there is a sharply falling spectrum due to the remaining filtered ground motion at the interferometer mirrors. The mirror fundamental resonance at 6.3 kHz can be seen, as well as the aforementioned Pockels cell resonances around 10 kHz.

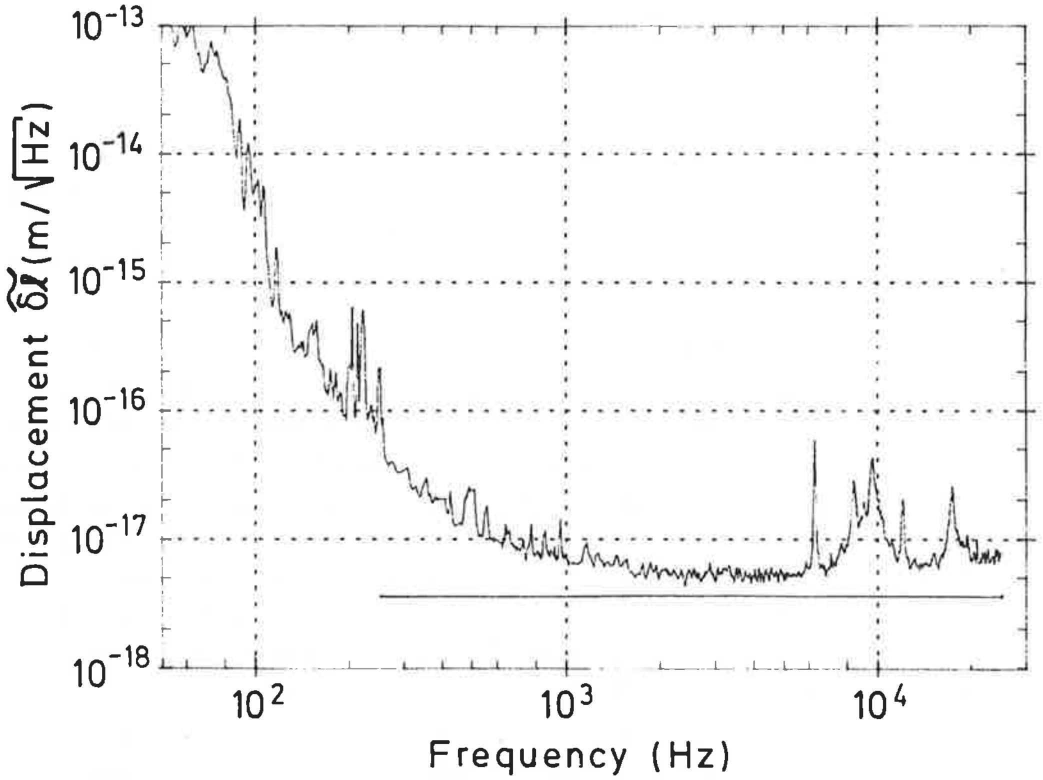

Fig. 6 : Noise spectrum of the 30 m Garching interferometer for an optical path length of 3.3 km; the vertical axis is calibrated in equivalent mirror motion $\widetilde{\delta\ell}$. The horizontal line indicates the calculated shot noise.

The horizontal line at a level of 3.2×10^{-17} m/$\sqrt{\mathrm{Hz}}$ represents the sensitivity which one would obtain if the only limit in detecting the light were the shot noise; it can be seen that our measured curve lies a factor of about two above this fundamental limit in the frequency range from 500 Hz to 5 kHz. This excess noise in the 'flat' region has not been fully understood. It is not yet certain (although very likely) that the relatively large excess from 250 to 500 Hz is due to insufficiently filtered ground noise. Current efforts in the laboratory are aimed at improving the ground isolation and its measurement, and at increasing the available light power. It is hoped that these steps will lead to answers to these unknowns.

The interferometer output can also be interpreted in terms of the equivalent strain in the linear spectral density $\widetilde{\delta\ell}/\ell = \tilde{h}$. The lowest levels achieved, $2 \times 10^{-19}/\sqrt{\mathrm{Hz}}$, are the best yet obtained with interferometric antennae, but are a long way from the levels required to observe predicted events. The success with this prototype interferometer has encouraged plans for a full-scale gravitational wave detector[2], in which the 30 m instrument will continue to play the role of a test bed for new ideas.

[2] See W. Winkler et al, *Plans for a large gravitational wave antenna in Germany*, Proc. Fourth Marcel Grossmann Meeting on Recent Developments in General Relativity, Rome, 1985, to be published; preprints available as Internal Report MPQ 101, July, 1985