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Status of the GEO600 Gravitational Wave Detector

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ABSTRACT

The GEO600 laser interferometric gravitational wave detector is approaching the end of its commissioning phase which started in 1995. During a test run in January 2002 the detector was operated for 15 days in a power-recycled michelson configuration. The detector and environmental data which were acquired during this test run were used to test the data analysis code.

This paper describes the subsystems of GEO 600, the status of the detector by August 2002 and the plans towards the first science run.

Keywords: Gravitational Wave Detector, GEO600

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Figure 1. The buildings of GEO 600 are split into three regions with different cleanroom classes: The so-called gallery were people can work with normal clothes, the inner section which has a cleanroom class of 1000 and a movable cleanroom tent installed over open tanks with a class 100 cleanroom. The convolute beam tube has a diameter of 60 cm and a wall thickness of 0.8 mm. The tanks are 2 m tall and accommodate the triple-pendulum suspensions of the interferometer mirrors.

1. INTRODUCTION

The GEO 600 laser interferometer with 600 m armlength is part of a worldwide network of gravitational wave detectors. These detectors will be searching for gravitational waves from a number of different astrophysical sources like supernovae explosions, non-symmetric pulsars, inspiralling binary systems of neutron stars or black-holes and remnants of the big bang. A summary of the current understanding of astrophysical sources for gravitational waves and of predicted event rates is given in a paper by Schutz.[1] Furthermore unknown sources may produce gravitational waves of detectable strength.

Six detectors are currently under construction: Three interferometers of the LIGO project[2] in the USA (two interferometers with 4 km baseline and one interferometer with 2 km baseline), one detector of the French-Italian VIRGO project[3] in Italy with 3 km baseline, the TAMA detector[4] in Japan with a baseline of 300 m and the British-German GEO 600 detector[5] with 600 m armlength in Germany. A prototype interferometer with the option to extend it to a large-scale detector is under construction by the ACIGA project in Australia.

The GEO 600 detector was designed based on the experience with two prototypes: the 10 m interferometer at the Glasgow University and the 30 m interferometer at the Max-Planck-Institute for Quantum Optics in Garching, near Munich. The construction of GEO 600 started in 1995 as a German/British collaboration on a site near Hannover in Germany and will be completed in 2002. Based on the constraint that the length of the vacuum pipes could not exceed 600 m an advanced optical layout including signal recycling and novel techniques for the seismic isolation systems were included in the detector design. In parallel to the commissioning of the detector methods for data analysis as well as simulations of possible sources were developed at the University of Cardiff and at the Albert-Einstein-Institute of the Max-Planck-Gesellschaft in Potsdam.

The infrastructure of the GEO 600 detector including the buildings and the vacuum system is ready since 1998. One central building (13 m by 8 m in size) and two end buildings (6 m by 3 m) accommodate the vacuum

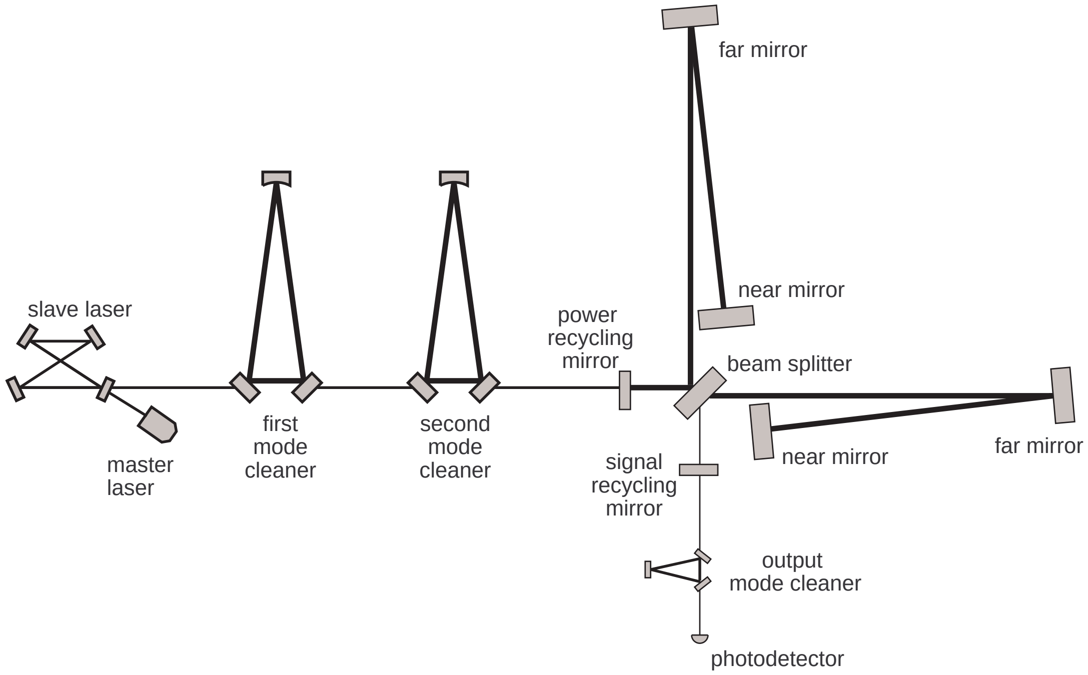

Figure 2. Optical layout of GEO 600: A 12 W injection locked laser system is filtered by two sequential modecleaners and injected into the dual-recycled interferometer. A folded light path is used to increase the round-trip length of the interferometer arms to 2400 m. An output modecleaner will be used to spatially clean the laser mode before it reaches the photodetector.

tanks (2 m tall) in which the optical components are suspended. Figure 1 show a picture of the interior of the central building and a picture of the vacuum tubes in the 600 m long trenches. A novel convoluted-tube design which allows a wall thickness of only 0.8 mm was used to reduce weight and cost of the 600 m long stainless-steel vacuum tube. Baffles are installed inside the tube to avoid stray-light reflections by the shiny tube wall. Each tube was baked for two days in air at 200°C and for one week under vacuum at 250°C. The whole vacuum system, except for the modecleaner section, is pumped by four magnetically-levitated turbo pumps with a pumping speed of 1000 l/s, each backed by a Scroll pump ($25\,\mathrm{m}^3/\mathrm{h}$). Additional dedicated pumping systems are used for the modecleaner and the signal-recycling section. Currently the pressure in the beam tubes is in the upper 10^{-9} mbar region.

Figure 2 shows the optical layout of the GEO 600 detector. The light of an injection locked laser system is filtered by two sequential modecleaner in the spatial and time domain and injected into a power recycled Michelson interferometer. In contrast to the other long baseline interferometric gravitational wave detectors no Fabry Perot cavities are used in the interferometer arms. A signal recycling mirror will be placed at the interferometer output port to increase the storage time for the gravitational wave signal sideband.

The following sections will review the status of the different detector subsystem as in August 2002 and will end with an outline of the future steps towards the first long data run.

2. LASER AND MODECLEANERS

The GEO 600 laser system, a detailed description of which can be found in,[6] is based on an injection-locked laser-diode pumped Nd:YAG system with an output power of 12 W. A non-planar ring-oscillator (NPRO) with an output power of 0.8 W is used as the master laser. Two Nd:YAG crystals, each pumped by a fiber-coupled laser-diode with a power of 17 W, are used as the active medium in the four-mirror slave ring-cavity. Three of these mirrors and a piezo-electric transducer (PZT) carrying the fourth mirrors are mounted on a rigid invar spacer to increase the mechanical stability of the slave-laser cavity.

The light from the laser system is currently attenuated to 2 W and injected into the two modecleaners, each with 8 m round-trip length. The main purpose of the two sequential modecleaners is the spatial filtering of the laser beam.[7] All modecleaner mirrors are suspended as double pendulums to isolate them from seismic ground motion.

The laser frequency is stabilized to the resonant frequency of the first modecleaner MC1 by feeding back to the master-lasers temperature and PZT actuator. A phase correcting Pockels cell is used to enhance the bandwidth of this first control loop to approximately 100 kHz. In a second feed-back control loop the length of the first modecleaner is then changed to make the laser frequency resonant in the second modecleaner MC2. The paper of Freise *et al*[8] gives a detailed overview of the laser frequency control scheme.

The rms length changes of the modecleaners in time intervals of 10 s is below 1 μm which allows a lock acquisition of the modecleaners within typically 10 s. An automatic alignment and drift control system is used to maintain the alignment of the modecleaner cavities.[9] With this automatic alignment system installed the modecleaners work reliable and continuous lock periods for both modecleaners of more than 48 hours could be achieved.

3. MICHELSON INTERFEROMETER WITH POWER RECYCLING

The main interferometer is designed as a dual-recycled folded-arm Michelson interferometer. Dual recycling on a suspended interferometer was first demonstrated by Heinzel *et al*.[10] The anticipated power buildup in GEO 600 is 2000 which leads to a power of about 10 kW at the beam splitter. Any phase change of the light in the interferometer arms caused by a gravitational wave or by noise will lead to light leaking out of the output port of the interferometer. The signal recycling mirror will reflect this light back into the interferometer and the light power representing the signal at specific Fourier frequencies is enhanced. This effect reduces the shot-noise-equivalent apparent displacement noise of the detector for these Fourier frequencies. The reflectivity of the signal recycling mirrors allows to tune the bandwidth for which this reduction takes place and the microscopic position of the mirror determines the center frequency of this sensitivity enhancement. Even though signal recycling improves the interferometer contrast due to the mode-healing effect[10] an output modecleaner will be implemented in GEO 600 to reduce the higher-order-mode content of the light reaching the photodetector. The photodector consists of 16 InGaAs photodiodes of 2 mm diameter, each of which can operate up to 50 mA of photocurrent . The AC part of the photocurrent of these diodes will be combined and demodulated at the modulation frequency of the heterodyne readout scheme.

Figure 3 shows the seismic isolation system used to isolate the beam splitter and the mirrors of the Michelson interferometer. Three legs with active and passive seismic isolation support the so-called stack stabilizer and the rotational stage. The mirror is the lowest mass of a triple pendulum with two blade-spring stages for vertical isolation which is mounted to the rotational stage.

The triple pendulum has three masses: An upper mass made of stainless steel, a fused-silica intermediate mass and the mirror which is 18 cm in diameter (the beam splitter diameter is 26 cm). Co-located feedback systems are used to damp all six degrees of freedom of the upper mass. Due to the specific design of the triple pendulum this damping extracts energy from all pendulum modes below Fourier frequencies of 10 Hz. The reaction pendulums for length control of the Michelson interferometer consist of similar triple pendulums suspended 3 mm behind the corresponding mirror. The intermediate mass of the reaction pendulum carries coils which act on magnets glued to the intermediate mass of the mirror triple pendulum. To keep the internal quality factor of the mirrors as high as possible no magnets are glued to the mirror itself but electrostatic feedback between the mirror and the lowest mass of the reaction pendulum is used to apply feedback forces in the high Fourier-frequency range. A detailed description of the seismic isolation system can be found in the paper of Plissi *et al*[11] .

To minimize the internal thermal noise of the mirror and the pendulum thermal noise the lowest pendulum stage is made completely from fused silica. The Q factor of fused-silica suspensions comparable in size has been

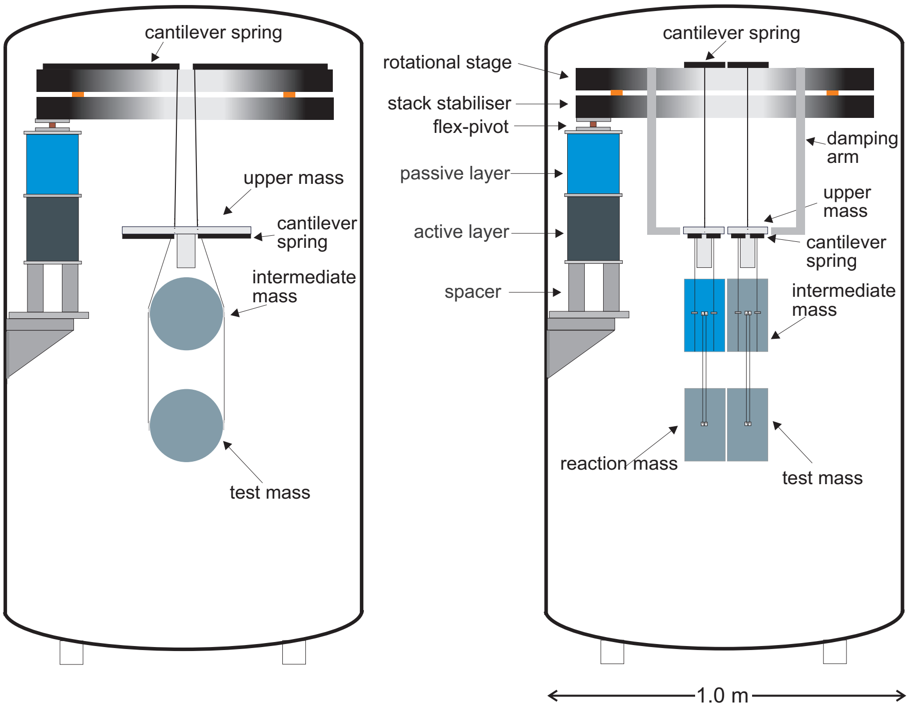

Figure 3. The GEO 600 main suspension system. Two stack layers (one active, one passive), a rotational flexure, two vertical cantilever stages and a triple horizontal pendulum is used to isolate the test mass from seismic noise. The lower pendulum stage is a monolithic fused-silica design to minimize thermal noise.

demonstrated[12] to be as high as 1×10^7. Small fused-silica pieces are attached to the intermediate mass and to the mirror itself by a technique called hydroxide-catalysis bonding.[13] This technique provides high-strength bonds and allows to keep the quality factors high and therefore the thermal noise low. Four fused-silica fibers with 270 μm diameter are welded to these fused-silica pieces and support the mirrors.

4. DETECTOR CONTROL AND DATA ACQUISITION

GEO 600 has four suspended cavities and the suspended Michelson interferometer which need length and alignment control systems. 25 pendulums need local damping of at least 4 degrees of freedom, 8 vacuum tanks have active seismic isolation control (in three supporting legs each) and additional feedback-control systems are needed for the laser stabilization. Most of these control loops are implemented with analog electronic controllers with some guidance by a LabView computer-control environment.[14] Only the active seismic isolation and some slow alignment-drift-control systems are implemented as digital control loops. The LabView computer control has authority to allow pre-alignment, guide lock acquisition, monitor the detector status and compensate for long-term drifts. Typical response times of this system are 100 ms.

Although only the $h(t)$ channel includes a possible gravitational-wave signal a multi-channel data acquisition system is needed to detect environmental and detector disturbances and exclude false detections. Two different sampling rates (16384 Hz and 512 Hz) are used in the data-collecting units of GEO 600. In the central building 32 fast channels and 64 slow channels are available, and in each of the end buildings we can use 16 fast channels. Most of these channels will be used for detector characterization only. A selection of those channels together with information coming from the LabView control program and the detector status database is combined to a data stream with a data rate of aproximately 0.7 Mbyte/s and stored in a raw data format at the detector site. These raw data files are send via a radio link from the site to Hannover where the data is stored in the so-called frame format, a common data format for all laser interferometric gravitational wave detectors. From

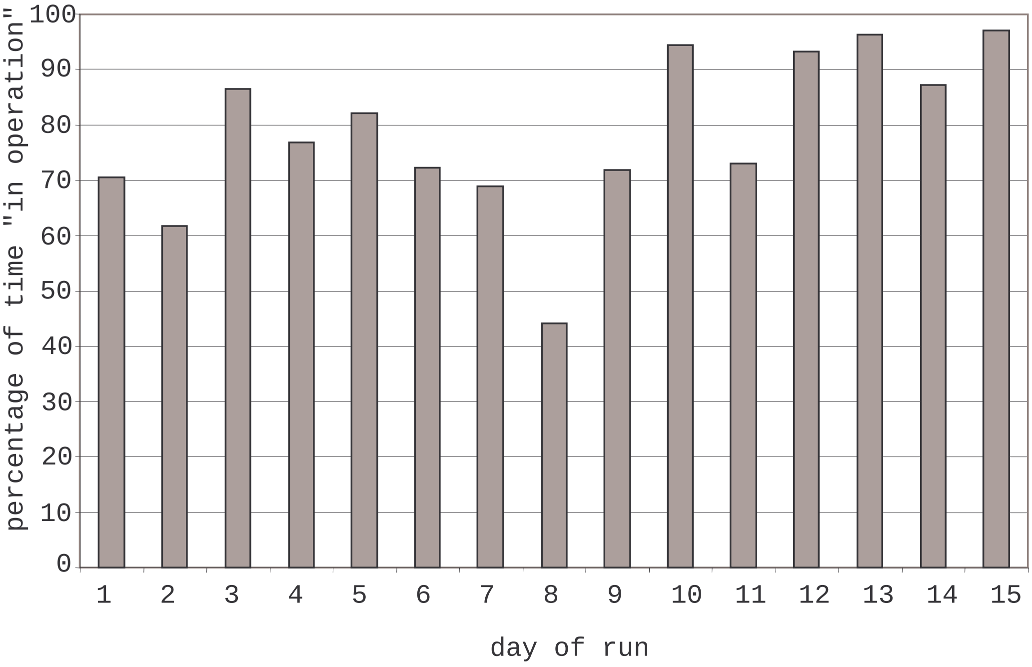

Figure 4. Duty cycle of the GEO 600 detector during the January 2002 test run. Shown is the percentage of time for which the detector was in operation. A maintenance period on the detector reduced the duty cycle on day 8 to less than 50% but improved the detector up-time for the second half of the test run.

here the data is distributed to the data-analysis groups whereas the time-critical data analysis will be performed in Hannover.

Due to the small signal-to-noise ratio of expected gravitational-wave signals a very good understanding of the detector noise is needed to perform an adequate data analysis. Furthermore an extensive detector characterization effort[15] during the commissioning phase can help to identify noise sources and improve the sensitivity. Based on the understanding of the detectors noise sources a so-called detector characterization robot (DCR) is under development [16] to condition the data and provide false-alarm vetos for the data analysis.

5. CURRENT STATUS AND OUTLOOK

The GEO 600 detector was operated in the power-recycled Michelson configuration for a test run from December 28th 2001 until January 14th 2002. During this test run the lock acquisition of the laser system, modecleaners and interferometer was automated and the automatic alignment control for the modecleaner was implemented. The alignment and drift control of the Michelson interferometer was not installed and operator interaction was needed to keep the 600 m long arms aligned with respect to each other. The main goal of this test run was to try to run the detector for many hours and acquire long stretches of data. This data was used to analyze the behavior of the different subsystems, and to provide data with real detector noise on which the data analysis codes could be tested. An overall duty cycle better than 70% was achieved and the longest lock was for 3 hours and 38 minutes. Figure 4 shows the duty cycle over the days of the test run. The data acquisition system worked reliably and a total of 0.9 Tera bytes of data was acquired. An analysis of the interferometer behavior close to the occasions when the Michelson interferometer lost lock provided useful insights into the reasons for the interruption of operation. Due to the fact that the full data analysis computing power is not available yet, only segments of data were analyzed with the binary inspiral code. Matched filtering of the data with an inspiral

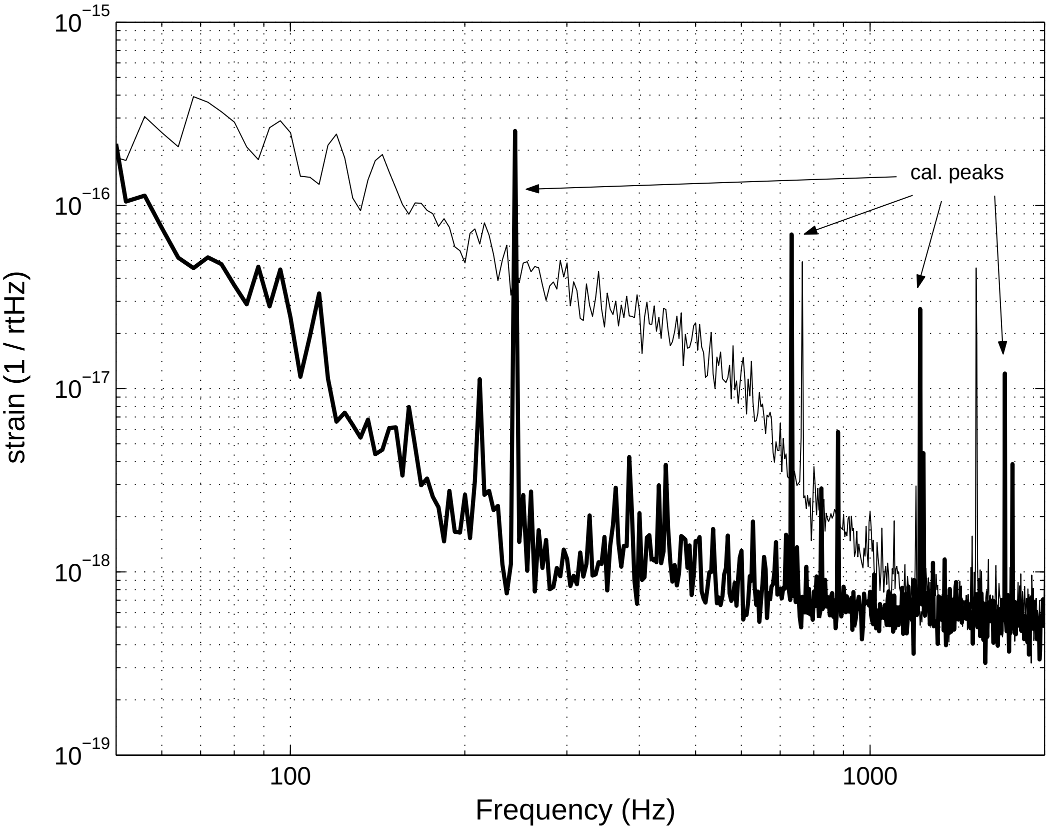

Figure 5. Strain sensitivity of GEO 600 in January and Juli 2002: A key point in improving the sensitivity was the reduction of stray light reflected back into the interferometer by optical components placed in the detector output port. The background noise level above 1 kHz corresponds to the shotnoise on the output photodetector.

binary template bank gave some huge signal-to-noise ratio false alarms. Work needs to be done on reducing transient events in the detector, implementing a chi-square analysis of candidate events and on a veto concept to reduce the false alarm rate of the detector. The full data set was used to search for gravitational waves from the pulsar J1939+2134. We expect that an upper limit based on this analysis can be published soon.

The test run was followed by a maintenance period in which a number of sub-systems were repaired. For example an undamped resonance in the beamsplitter suspension was found to be due to some structure touching one suspension wire and effectively reducing the wire length.

Figure 5 shows the result of an noise optimization phase which followed the maintenance period. Due to a number of changes in different subsystems we were able to improve the sensitivity between 100 Hz and 1 kHz by more than an order of magnitude. The noise spectral density above 1 kHz corresponds to the shot noise level on the photodetector at the detector output.

Furthermore the automatic alignment system for the Michelson interferometer and for the power-recycling cavity[9] was installed. With this system in place the detector stayed in lock for more than 15 hours without operator intervention. Figure 6 shows the noise spectral density of the angular misalignment of the two Michelson arms in rotation with and without the automatic alignment system turned on.

In the near future we will implement a high power photodetector at the output port to improve the sensitivity and to prepare the detector for the enhancement of the circulating power. With the high power detector but no additional optics installed we will perform a data run in late August in coincidence with the LIGO detectors.

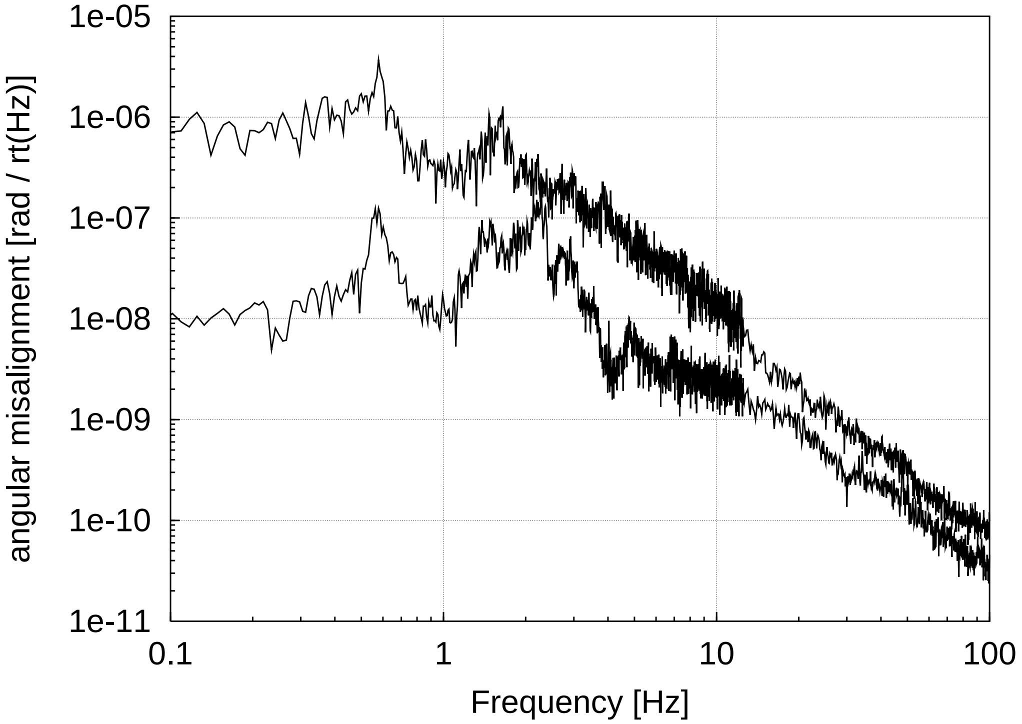

Figure 6. Angular misalignment of the Michelson interferometer with and without automatic alignment.

After this data run we will install the signal recycling mirror. Once the dual recycled detector is understood we plan to increase the circulation power in the interferometer, install the output modecleaner and change the remaining test mirrors to the final mirrors suspended from fused silica fibers.

In parallel to these hardware installations we will work to understand the noise performance and the sources for transients in the detector. Based on this knowledge we will optimize the detector, implement a vetoing system and start a long data taking period early next year.

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