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GEO 600: building a gravitational wave observatory

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An international network of laser-interferometric gravitational wave detectors is nearing the end of the main commissioning phase and will soon enter into an extended observational period, collecting data for a duration of order one year. This article outlines the construction, design and commissioning of the GEO 600 gravitational wave observatory. GEO 600 is a laser-interferometric gravitational wave detector which has 600 m long arms and uses advanced optical and suspension techniques to achieve a sensitivity comparable to the longer base-line detectors currently operating in the U.S.A and Europe.

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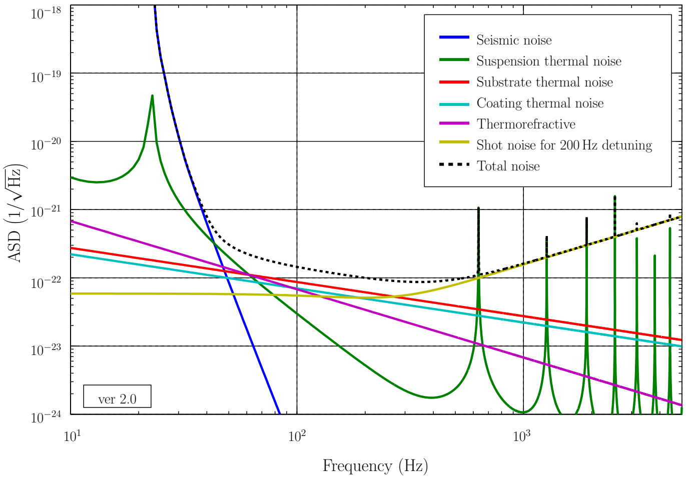

Figure 1: Theoretical noise curves for GEO 600 for a signal recycling cavity detuned to 200 Hz.

1. Introduction

For the last few decades, the world-wide effort to make a direct detection of gravitational waves has steadily increased. This effort began with the construction of various resonant mass detectors (see [1, 2, 3] for examples) and has continued in the last decade or so with the construction of a number of large-scale laser-interferometric gravitational wave detectors. These interferometers are currently in the final stages of commissioning before beginning extended data taking periods. They are: the three LIGO detectors located at two separate observatory sites in the USA [4]; the VIRGO detector in Italy [5], the TAMA detector in Japan [6], and the GEO 600 detector in Hannover, Germany [7].

GEO 600 is a joint British-German project. The interferometer has 600 m arms and employs complex interferometric techniques and advanced suspension systems to give a design peak sensitivity that is comparable to the longer base-line interferometers of the LIGO and VIRGO projects. In particular, the techniques of power and signal recycling (together, termed dual-recycling) are used to enhance the intra-cavity power and signal sidebands respectively.

The core of the instrument is a Michelson interferometer that is held at a dark fringe condition using a Schnupp modulation scheme [8]. Control sidebands are imposed on the light that is injected into the interferometer and are detected at the output (south) port, giving an error signal that can be used to feedback to the main mirrors of the Michelson to keep the detector at a dark fringe. When held at this operating point, practically all of the laser light that is injected into the interferometer is reflected by the interference condition at the beamsplitter, back towards the input (west) port. Another mirror, the power-recycling mirror, is placed at the input port to reflect the light coming from the beamsplitter. By doing this, we create a resonant cavity for the carrier light between the power recycling mirror and the Michelson. Any differential arm-length changes (for example, from gravitational waves) impose signal sidebands on the light which exit the interferometer at the output port. By placing a further mirror, the signal-recycling mirror, at the output port, we create a second resonant cavity, this time resonant for signal sidebands, to improve the shot-noise limited

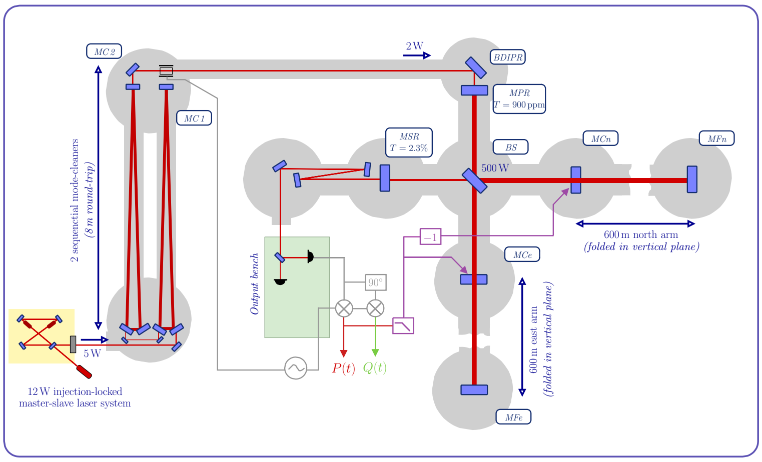

Figure 2: A schematic of the optical layout of GEO 600. The arms of GEO 600 are folded in vertical plane to give an optical path length of 2400 m in each arm. A highly simplified schematic of the Michelson differential length-control servo is shown.

sensitivity of the instrument (see Figure 1). A schematic of the GEO 600 optical layout is given in Figure 2. In order to keep GEO 600 at its operating point and both the power-recycling and signal-recycling cavities on resonance, a large number (~ 200) of control servos is used. These servos range from high bandwidth ($\sim$ 20 kHz) loops for frequency and power stabilisation of the laser, through intermediate bandwidth loops ($\sim$ 100 Hz) to control the differential arm-length degree of freedom of the Michelson, to slow, low bandwidth servos that correct slow drifts of the mirror alignment due to tides and temperature variations. A mixture of analog and digital servos is used to achieve the required performance and degree of control.

2. Commissioning

The commissioning of GEO 600 will continue until all planned subsystems are installed, and until the sensitivity of the instrument reaches the anticipated sensitivity (sometimes called *design* sensitivity). Recently, the last major installation work was carried out. Here, the power-recycling mirror was changed to one with higher reflectivity, so as to increase the stored power in the cavity, and thus improve the shot-noise limited sensitivity. The original power-recycling mirror had a transmission of 1.35%, whereas the new mirror has a transmission of 0.1%. With this new mirror, an increase in circulation power of roughly a factor 3 was observed, which means, when fully operational, there is around 1.5 kW in the cavity.

After the installation of the many subsystems, the whole detector enters a commissioning phase where the various noise sources and their couplings to the main detector output are investigated. Whenever possible, these are reduced in a process termed ‘noise hunting’. Any remaining couplings are studied and characterised to serve as veto channels in any analysis of the data. The identification of these technical noises and their contribution to the main output signal is done using ‘noise projections’. Noise is injected into a subsystem at a point prior to a measurement point of that system and the transfer function between the measurement point and the main detector output is measured. This transfer function can then be used to *project* the nominal noise at the measurement point to the main detector output. Noise projections typically aid the commissioning process by highlighting the limiting noise sources and helping prioritise the commissioning steps.

3. Data flow, characterisation, and calibration

GEO 600 is a highly complex instrument that comprises many subsystems. In order to properly interpret the main output signal(s), we need to monitor many signals throughout the entire detector. Typically of order 50 or more signals are recorded at a high sample rate of 16384 Hz, with another 100 or so recorded at a sample rate of 512 Hz. In addition, of order 1000 channels are recorded at 1 Hz sample rate; these are slow varying parameters of the system (gains, switch states, *etc*). The overall data rate is of order 40 Gbytes per day. Since the anticipated running time of the detector is of the order a few years, and since we are looking for rare and potentially short-lived signals, we require a data acquisition system that is extremely reliable and robust. The current system [9, 10] has a duty cycle of well over 99%, typically losing only a few hours of data per year. Once the data set is recorded, it is permanently archived to allow the analysis efforts to continue independently from the data taking.

In order to properly interpret the main output data streams of GEO 600, a calibration must be performed. Due to the complexity of the optical layout of GEO 600, any detected gravitational wave signal will appear in two output signals. Therefore, it is desirable that the calibration is performed before any analysis is undertaken. At GEO 600 a time-domain calibration method was developed that takes the main output data streams and, with the aid of injected calibration signals, determines, and corrects for, the detector response function in quasi-real-time. This means that a single data stream is produced (in real-time with a few second latency) that contains the optimal amount of gravitational wave information compared to the output noise of the detector. Full details of the calibration process are given in [11, 12]. Figure 3 shows the result of the calibration. Three traces are shown: $h_{\mathrm{P}}(f)$ and $h_{\mathrm{Q}}(f)$ are spectral density estimates of the two calibrated output signals (termed $P(t)$ and $Q(t)$ in Figure 2); the third trace is the optimal combination of these two signals that maximises the signal-to-noise ratio of potential gravitational wave signals for all frequencies across the detection band.

4. Future prospects

The near future involves another increase in the power circulating in the power-recycling cavity. This will be achieved by increasing the amount of laser light that enters the first mode-cleaner. After this, a further period of intense noise hunting and commissioning will start, leading up to an extended data taking period, planned to be done in coincidence with the LIGO detectors.

After an extended data taking period ($\sim$ 1 year), a program of incremental upgrades will be started which will greatly improve the high frequency sensitivity of the instrument. This program (called GEOHF [13]), will involve even higher cavity power (from a new laser system) to increase the high-frequency shot-noise-limited sensitivity, more use of digital control systems, and the injection of squeezed light.

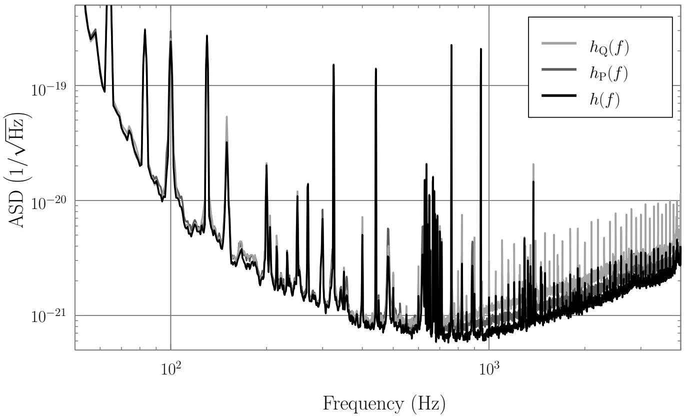

Figure 3: Amplitude spectral density estimates of the two calibrated outputs of GEO 600, together with the optimal combination of these.

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