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2015 J. Phys.: Conf. Ser. 610 012015

(http://iopscience.iop.org/1742-6596/610/1/012015)

10th International LISA Symposium (LISAX) IOP Publishing
Journal of Physics: Conference Series **610** (2015) 012015 doi:10.1088/1742-6596/610/1/012015

Status of GEO 600

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Abstract. The German-British laser-interferometric gravitational wave detector GEO 600 is in its 13th year of operation since its first lock in 2001. After participating in science runs with other first generation detectors, GEO 600 has continued collecting data as an astrowatch instrument with a duty cycle of 62% during the time when the other detectors have gone offline to undergo substantial upgrades. Less invasive upgrades to demonstrate advanced technologies and improve the GEO 600 sensitivity at high frequencies as part of the GEO-HF program have additionally been carried out in parallel to data taking. We report briefly on the status of GEO 600.

1. Background

GEO 600 [1] is the German-British laser-interferometric gravitational wave (GW) detector that was built in the late 1990s and started operation in the early 2000s [2, 3] in conjunction with other first generation GW detectors. GEO 600 uses a dual-recycled Michelson configuration with 1200 m long arms folded inside 600 m long beam tubes. From the start, the project focused on researching, incorporating, and demonstrating riskier technologies compared to the designs of its longer-arm counterparts, Virgo (3 km) [4] and LIGO (4 km) [5]. Early design features that were unique to GEO 600 included multi-chain suspensions with a monolithic final stage and a reaction mass chain, electro-static actuators, and signal recycling [6].

Following the era of first generation detector science runs when the other observatories began going offline for substantial upgrades [7, 8], GEO 600 opted to serve the role of being the sole detector continuing to collect data through a program called *Astrowatch*. Simultaneously, starting in 2009, GEO 600 began a program called *GEO-HF* [9] which has the aim of carrying out a set of upgrades to improve the detector's high frequency sensitivity above approximately 600 Hz where quantum shot noise is the limiting noise source. The primary techniques implemented include the injection of squeezed vacuum, a change in signal recycling bandwidth and operating point, DC readout with an output mode cleaner, and higher laser power combined with a thermal compensation system.

2. GEO-HF status

Figure 1 shows the results to date of how the GEO-HF upgrades have affected the GEO 600 strain sensitivity. The most notable effect is above 600 Hz where as much as a factor of 4 improvement in sensitivity is achieved. The dominant contributing factor to this improvement

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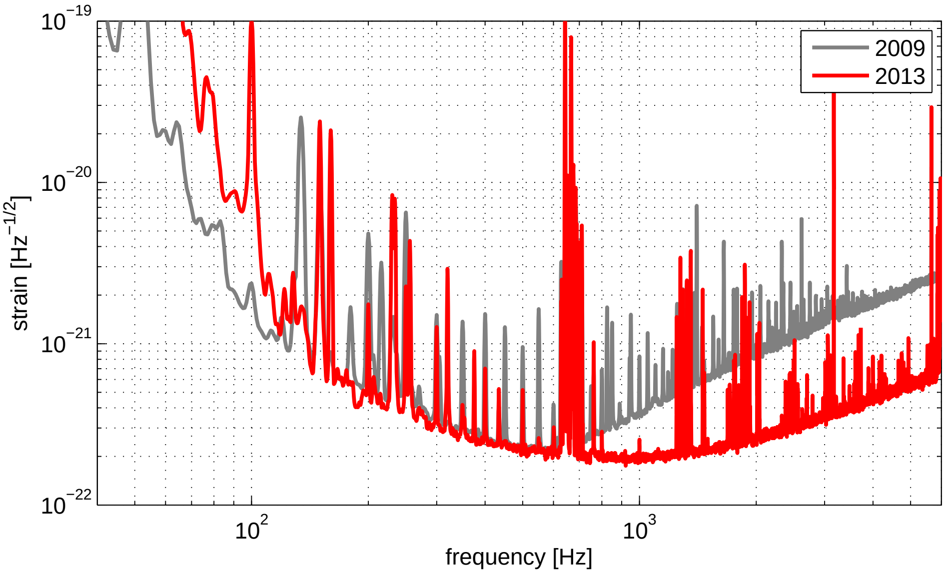

Figure 1. Strain sensitivity of GEO 600 today compared to the sensitivity at the start of the GEO-HF upgrade [3]. A new signal recycling mirror, squeezed vacuum injection, and DC readout contribute to the substantial improvement in high-frequency sensitivity. An effort to increase the laser power is ongoing. The large cluster of lines centered around 650 Hz are the violin modes of the suspension fibers.

is the decrease in the finesse of the signal recycling cavity (SRC). This was accomplished in 2010 by exchanging the signal recycling mirror from one with reflectivity of $R = 98\%$ to one with $R = 90\%$, thus reducing the storage time of the GW signal in the interferometer and therefore altering the detector's frequency response. The next most significant factor is squeezing, which creates (in its current state) a factor 1.5 improvement in sensitivity above approximately 1 kHz and was first demonstrated in 2010 [10]. Finally, a change in 2009 from heterodyne to homodyne (DC) readout of the GW signal [11] renders a fundamental factor $\sqrt{3/2}$ improvement in signal-to-noise ratio (SNR) [12]. An increase in laser power is not reflected in the 2013 sensitivity curve and is a topic of ongoing work.

The marked degradation in strain sensitivity below 100 Hz arises from technical side effects of both DC readout and the new signal recycling mirror. The limiting noise sources at these frequencies are alignment feedback noise and signal recycling length feedback noise. First, the dark-fringe offset required for DC readout creates a TEM$_{00}$ carrier field on the Michelson alignment sensors. Jitter of this field caused by output optics creates an alignment sensing offset which is impressed on the mirrors. Second, the new signal recycling cavity's lower finesse decreased the SNR of the SRC length signal, creating higher feedback noise.

3. Ongoing research

Ongoing research at GEO 600 has several fronts. For one, there are still some technical challenges and open research questions related to realizing the full potential of DC readout and squeezing. Second, the GEO-HF goal of increasing the laser power by a factor of $4-6$ must still be achieved and requires the design and commissioning of a new thermal compensation subsystem.

3.1. Squeezed vacuum integration

Injection of squeezed vacuum to the interferometer's output port is a novel technique employed to suppress quantum noise [13]. For nearly the last 3 years, GEO 600 has demonstrated the first long-term application of squeezed vacuum in a gravitational wave detector, achieving a 90% duty cycle during science times and improving the shot-noise-limited strain sensitivity up to a factor of 1.5 (3.7 dB) [10, 14]. In order to achieve even more stable and better squeezing levels, recent work at GEO 600 has focused on the development and commissioning of squeezer alignment and phase control systems [6]. Ongoing work includes the commissioning of a new wavefront sensing scheme in reflection of the OMC to ensure maximum overlap of the squeezed field with the interferometer output field to achieve higher squeezing levels. In addition, a new error signal for sensing the relative phase of the squeezed field with the interferometer output is being studied in order to eliminate lock point offsets and create more stable squeezing [15].

3.2. Higher laser power

One unique feature of GEO 600 is that it does not have Fabry-Perot arm cavities. Instead, a signal recycling mirror alone is used together with the power recycling mirror to amplify the GW signal. A side effect is that *all* of the stored power in the interferometer is transmitted through the substrate of the beam splitter (BS). The current operation of GEO 600 uses 2–3 kW at the BS, which leads to thermal lensing problems of the same magnitude that will be faced by advanced detectors when operated at full design power. GEO 600 currently does not have any thermal compensation at the BS and this limits the ability to operate with higher laser power. During commissioning periods, stable operation with as much as 7 kW can be achieved, but there is excess noise below 600 Hz in this high power state. Design of an array of heating elements to project optimized patterns of radiation onto the BS to compensate the lens represents ongoing work. Other challenges related to higher power which have already been addressed are the correction of astigmatism at one of the end mirrors using segmented thermal compensation [16] and the elimination of stray light coupling to shadow sensors on each of the mirrors through a modulation-demodulation technique [17].

3.3. Alternative OMC alignment techniques

The upgrade from RF to DC readout involved the installation of an output mode cleaner (OMC) in the interferometer's output port directly before the GW readout photodiode. Its purpose is to filter out all light that does not contribute to the GW signal. Higher order modes make it challenging to develop an alignment scheme with sufficient bandwidth that maximizes the SNR of the light transmitted through the OMC without introducing beam jitter coupling. Ongoing work at GEO 600 is the commissioning of a new alignment technique which uses wavefront sensors in reflection of the OMC. The wavefront sensors sense the relative alignment between fields representing the GW mode and the OMC eigenmode. The fields used are the radio frequency sidebands which are resonant in the interferometer and audio sidebands which are generated from a length dither of the OMC [6]. This scheme both eliminates low frequency dithering of the output steering optics and facilitates an increase in the alignment control bandwidth up to several Hz.

4. Astrowatch

Starting in 2007, GEO 600 has served as the community's Astrowatch detector. Astrowatch mode is a science run from the standpoint of detector operations such that GEO 600 is maintained at its highest possible sensitivity in a full interferometer lock and no experiments are allowed which could reduce its sensitivity. Furthermore, a realtime system with interferometer parameter tracking assures valid strain calibration [6]. A search in the Astrowatch data is triggered by an external event such as a gamma ray burst [18], neutrino detection, or an optical detection of a supernova. Upon operating in science mode mostly on nights and weekends, GEO 600 has maintained an average science time duty cycle of 62% over the last several years. Active commissioning and upgrade activities are carried out during the remainder of the time.

5. Summary and outlook

GEO 600 continues to actively pursue the goals of the GEO-HF upgrade program and to dedicate significant time to collecting Astrowatch data during the time when the other GW detectors are being upgraded. The techniques of signal recycling, homodyne (DC) readout, and squeezed vacuum injection have been demonstrated to the benefit of the GEO 600 high frequency sensitivity. Research into better integration of squeezed vacuum and improved OMC alignment schemes are active areas of continued work on these topics. At the same time, a new thermal compensation system for the BS is being developed which will enable the use of higher laser powers. GEO 600 will continue to collect Astrowatch data and research advanced techniques in conjuction with furthering the improvement of its high-frequency sensitivity.

Acknowledgements

The authors are grateful for support from the Science and Technology Facilities Council (STFC), the University of Glasgow in the UK, the Bundesministerium für Bildung und Forschung (BMBF), and the state of Lower Saxony in Germany. This work was partly supported by DFG grant SFB/Transregio 7 Gravitational Wave Astronomy. This document has been assigned LIGO document number P1400172.

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