Hartmann Wavefront Sensors for Advanced LIGO

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Abstract: The operation and sensitivity of the Advanced LIGO gravitational wave detector are degraded by absorption-induced wavefront distortion. We describe the use of ultra-sensitive Hartmann wavefront sensors to tune detector operation and optimize sensitivity.
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1. Introduction

The detection of gravitational waves from the coalescence of binary black hole [1] and binary neutron star [2] systems has been widely acclaimed and launched the field of multi-messenger gravitational astronomy. However, the quest has only just begun. Improving the sensitivity of the Advanced LIGO (aLIGO) and Advanced Virgo (AdV) detectors will increase the detection rate and produce unparalleled insight into the dark and violent side of the universe.

Advanced-generation gravitational wave detectors, such as aLIGO [3], are signal and power recycled, Michelson interferometers with 4 km Fabry-Perot (FP) cavities in each of the Michelson arms, each of which would be required to store 750 kW to reach design sensitivity. The cavity mirrors have a figure of $\lambda/600$ to enable the required mode-matching at the Michelson beam-splitter, thereby reducing shot noise and the coupling of laser technical noise into the readout and maintaining adequate stability of the control systems. However, since residual optical absorption in the mirror substrates and coatings produces excessive power-dependent wavefront distortion, an adaptive optics (AO) system was also required [4].

The AO system design specified independent wavefront sensors that could measure changes in wavefront with a sensitivity of 1.35 nm_{RMS}, a transverse spatial resolution better than 10 mm and be able to provide this sensitivity with a bandwidth > 0.25 Hz [4]. Additionally, to prevent degradation of the detector sensitivity due to reflection of scattered light back into the interferometer, the wavefront sensor could not use the 1064 nm interferometer beam or require additional optics within that beam.

2. Hartmann wavefront sensors

Hartmann wavefront sensors (HWS) sample the wavefront using an array of apertures in an otherwise opaque plate, often referred to as a Hartmann Plate (HP). The beam of light created by each aperture propagates perpendicularly to the local wavefront, creating an array of spots at a pixelated sensor. Changes in the incident wavefront result in transverse displacements of the spots, proportional to the change in local slopes of the wavefront and the "lever arm" distance between the HP and the active surface of the sensor. This gradient field is integrated to produce the wavefront change [5].

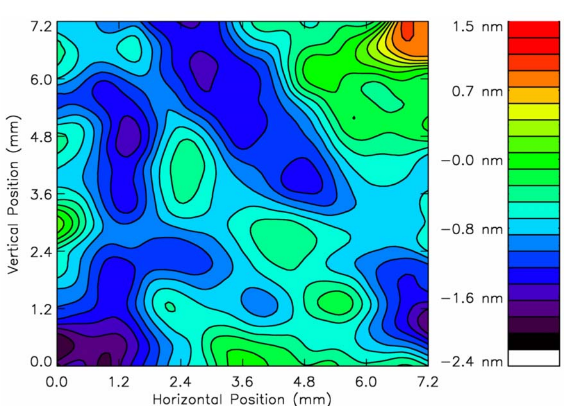

Fig. 1. A map of the HWS noise floor, calculated using two nominally identical spot patterns.

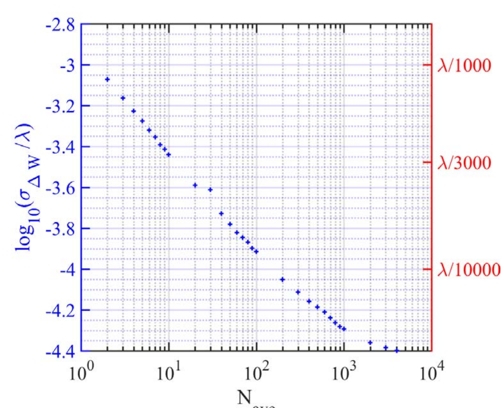

Fig. 2. Plot of improvement in wavefront sensitivity due to averaging N_{ave} spot patterns (N_{ref} = 1000). The CCD was sampled at ca. 60 Hz.

The Hartmann sensors installed in aLIGO use invar HPs that have ca. 850 holes, each of 150 μm diameter, in a hexagonal-closed-packed array with a pitch of 430 μm. They are mounted on Dalsa 1M60 CCD cameras using invar spacers, and have a nominal lever arm of 10 mm. The mirror surfaces are imaged onto the HP using a 17.5x demagnification telescope, yielding a spatial resolution of 7.5 mm.

The sensitivity of the HWS was determined by uniformly illuminating the HP with a light from single-mode-fiber-coupled super-luminescent-LED (SLED) and analyzing the reproducibility of the spot patterns [5]. A typical map of the wavefront sensitivity, determined using two spot patterns separated in time by 15 s, is plotted in Fig. 1. This map yields a sensitivity of ca. 1.0 nm_{RMS}, which is consistent with that expected from shot-noise in the pixel photoelectron counts. The sensitivity can be further improved by using averaged spot patterns, as shown in Fig. 2.

3. HWS in aLIGO

The HWS installed in aLIGO are used to calibrate and align the AO actuators, tune the operation of the detector, and monitor changes in the thermally-induced wavefront distortion for each of the FP mirrors. They measure on-axis distortion using probe beams that have wavelengths different to that of the interferometer beam and without introducing additional optics within the interferometer beam.

The absorption-induced distortion and actuation for the mirrors at the end of the FP arms is measured using coherent 532 nm beams that pass through the substrate and retro-reflect from the high-reflectivity (HR) surfaces. A numerical model is used to estimate the thermo-elastic distortion of the HR surfaces.

The HWS for the FP input-couplers use probe beams from SLED sources to minimize stray interference fringes that would degrade the sensitivity of the HWS. The wavelength is chosen so that the probe beams can be transmitted through or reflected from existing interferometer optics.

An example of the evolution of the uncompensated quadratic component of the wavefront distortion in a FP input coupler as power is stored in the FP cavity is plotted in Fig. 3. The AO is used to mode-match the beams from the two arms at the Michelson beam-splitter. The HWS can also reveal non-quadratic distortion, as shown in Fig. 4. This distortion could not be compensated and is believed responsible for the reduced sensitivity of LIGO Hanford during Observing Run 2.

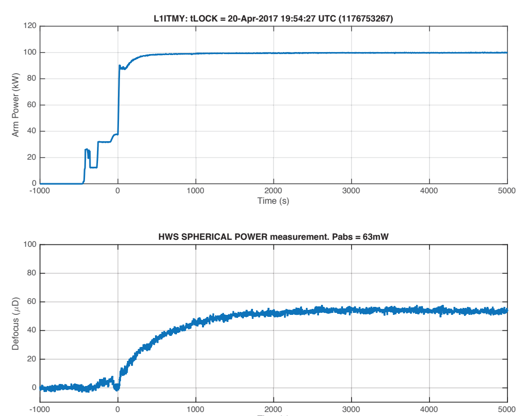

Fig. 3. Evolution of the uncompensated thermal lens within a F-P input coupler.

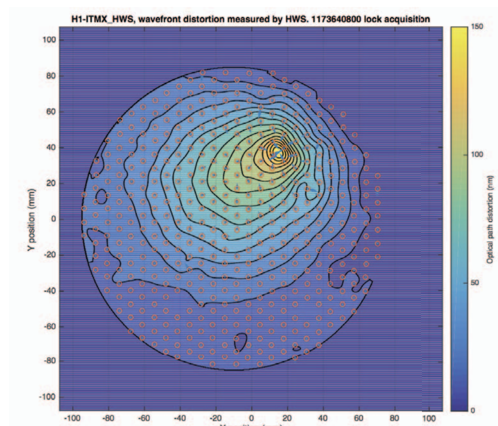

Fig. 4. Non-quadratic wavefront distortion due to a point absorber on the surface of an FP input coupler. The red circles represent the apparent location of the HP apertures.

4. References

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