Development of optical imaging system for LIGO test mass contamination and beam position monitoring

Chen Jie Xin *
Mentors: Keita Kawabe, Dan Moraru, Rick Savage †

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Motivation for Camera System

The LIGO interferometer is a modified Michelson interferometer with two orthogonal, 4-kilometer long "arms" [1]. For each arm there are two test masses—both 40 kg mirrors; one is at the end of the arm (the end test mass) and the other (the input test mass) is at the corner station, where the two arms meet [1]. This forms a 4 km long Fabry-Pérot cavity, within which the input laser light travels back and forth multiple times [2].

The circulation of light in the cavity multiplies the power of the input beam and the distance travelled by the beam to achieve the sensitivity necessary to detect the small length fluctuations due to gravitational waves [2]. Therefore, it is desirable to maintain low optical losses in these resonators [3].

Understanding the optical performance of the test mass mirrors in the operating interferometer could provide the basis for improvements in the performance of the optics and, consequently, the sensitivity of the interferometer [4]. Observing the light scattered from test masses with a camera system can contribute to understanding their performance.

Background of Camera System

Presently, cameras for observing the end test masses have already been installed and are operational. These cameras are part of the photon calibrator (PCAL) beam localisation camera systems and are used to determine the location of the PCAL beams on the ETM surfaces [5].

However, in addition to monitoring PCAL beam positions on the test masses, the camera system can also be used to capture images of the test masses when either 532 nm or 1064 nm laser light is resonating in the arms of the interferometer. These images provide a qualitative picture of light scattered from the test masses, but a quantitative estimate of the power loss due to the scattering yet to be made. Since the scattering is thought to most likely be due to the combination of the internal imperfections of the reflective coating, as well as particulate contamination of the test masses surfaces, obtaining a quantitative estimate can help in understanding the amount of the additional optical losses introduced by the contamination at the end test masses. To do so, the camera system needs to be calibrated.

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†LIGO Hanford Observatory

Moreover, as the camera system was originally intended for PCAL beam localisation at the end test masses, they have yet to be installed at the input test masses. However, unlike the end test mass camera system, the input test mass camera system uses a Celestron 8" EdgeHD Schmidt-Cassgrain telescope instead of a Nikon telephoto zoom lens. This is because the viewports for the input test masses are several times further away—at a distance of 32.756 m [6]—from the test mass surface than those for the end test masses.

While the focus and zoom of the Nikon zoom lens at the end test mass camera system can be controlled directly through the same Nikon Camera Control Pro 2 software used for capturing the images, the Celestron telescope requires an external controller connected to a focuser to adjust zoom and focus. For integration into the existing slow controls systems, a Beckhoff EP7041-2002 fieldbus module is used, in conjunction with a MoonLite high resolution stepper motor and focuser. A user interface for operators in the control to adjust the focus of the camera also needs to be developed.

Work on Camera System Calibration

The first step in calibrating the camera system is to determine how the power incident on the camera sensor relates to the pixel values of the resulting images. This is accomplished by shining a monochromatic laser light of known power and wavelength (1064 nm) directly on the camera sensor (camera lens is removed from the camera) and capturing images of the beam with different exposure times and ISO speeds.

The camera was calibrated for power between 81 nW and 370 nW; The power of the incident laser light was measured with a power meter before and after images at various camera settings were taken. At each camera setting, three "dark" images were taken with the laser beam being blocked and three "bright" images were taken with the laser beam shining on the camera sensor. ISO speeds between 100 and 200 were used as higher ISO speeds tend to make the images noisier, and a shutter speed of 1/2000 s was used to such that the images are not saturated.

The images captured by Nikon D7100 camera are stored in 14-bit lossless NEF format, an image format which contains the raw sensor data at each pixel of the CMOS image sensor in the camera [7]. Moreover, the NEF format also contains metadata about the colour of each pixel, which is the colour of the RGB Bayer colour filter array laid over the image sensor at that particular pixel. The raw sensor data and the colour filter array information from each image were extracted as 4020×6023 integer arrays with `rawpy`, a Python library for decoding raw image formats. As the transmissivities of the red, green, and blue filters with respect to the monochromatic infrared laser light used are different, the pixel values for each colour are treated separately.

For each image, the pixel values of each colour are summed over the entire image. At each camera setting, the total pixel values for each colour of the three "dark" and three "bright" images are averaged; the average "dark" pixel values are then subtracted from the "bright' pixel values to account for the effects of ambient light and counts due to the dark current of the image sensor. The total pixel values for each colour are then plotted against the number photons N incident on the camera sensor, which is given by

$$N = \frac{E_{\text{total}}}{E_{\text{perphoton}}} = \frac{Pt}{hc/\lambda}$$

where P is the measure power, t is the exposure time (i.e. shutter speed), and $\lambda = 1064$ nm is the wavelength of the laser light.

The total pixel values—regardless of pixel colour—were found to have a linear relation to the the number of photons incident on the camera sensor. A typical plot with a linear least-squares fit is shown in Figure 1. The value of the slope indicates the total pixel values per unit power, which

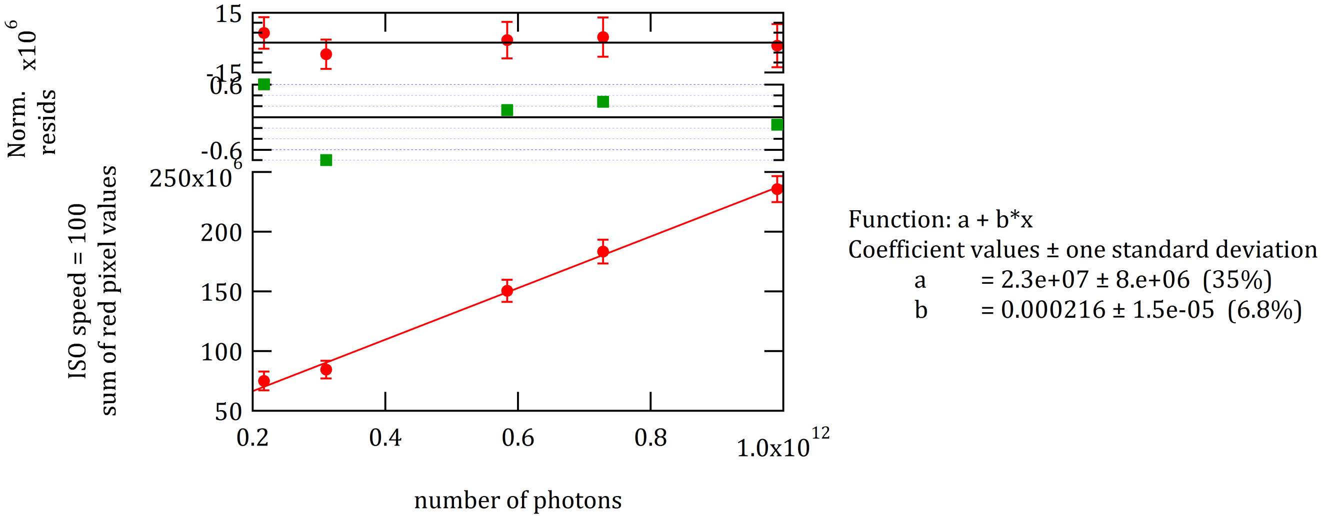

Figure 1: Plot of total red pixel values against number of photons incident on camera sensor with camera settings of ISO speed = 100 and shutter speed = 1/2000 s.

is a function of the number of pixels of the particular colour, the transmissivity of the filter of the particular colour, and the response of the pixel on the CMOS sensor—essentially a photodiode.

However, one notes that the y-intercept of the linear fits is a positive value regardless of ISO speed and pixel colour, which suggests non-zero pixel values even when no photons are incident on the camera sensor. Given that sensor values from ambient light and sensor dark current ought to have been accounted for when the pixel values of the "dark" images were subtracted from the "bright" images, the source of the positive intercepts warrants further investigation. A possible cause for the positive intercepts could be a systematic error in the shutter speed—i.e. it is consistently slower than the value stated by the manufacturer. Attempting to quantify the error Δt needed to produce the intercepts is part of the further work to be conducted in this part of the project.

Work on Input Test Mass Camera System

Work thus far on the input test mass camera system has consisted of attempting to figure out the cabling for the stepper motor of the MoonLite focuser to the Beckhoff controller. As documentation for both pieces of hardware were somewhat ambiguous, there were initially some problems with determining the cabling for the 12 V power supply for the stepper motor. The pin-out for the stepper motor called for 12 V to be supplied directly to it via pin 5 with no apparent ground, and the Beckhoff controller had a socket for "Motor Supply"[8], it was not apparent whether it was supposed to be for power input to the controller, or for power supply to the motor.

As it was unclear how the Beckhoff controller supplied 12 V to the motor in the case of the former, a first attempt was made to connect the motor and the Beckhoff controller assuming that the "Motor Supply" socket provided a 12 V output to the motor. The attempt was unsuccessful as the motor failed to power up. However, the Ethernet link between the Beckhoff controller and the computer was established successfully.

A second attempt, in which the "Motor Supply" socket was given a 12 V input, yielded positive results. The motor could be enabled from the computer through the TwinCAT software for the Beckhoff system, and motion control was achieved through the velocity control interface in TwinCAT.

However, as it was still unclear where the ground for the stepper motor was, further investigation was carried out using a multimeter and oscilloscope. The conclusion reached was that the stepper motor controller contains an H-bridge and provided the ground internally [9].

In summary, despite a number of detours, the links between the Beckhoff controller and the motor, as well as the controller and the computer were successfully established such that the motor can be controlled from the computer.

Plans for Further Work on Camera System Calibration

Further work on calibrating the camera system consists of analysing the existing images with a revised model taking into account possible systematic errors in shutter speed and attempting to quantify the amount of error introduced by the dark current, shutter speed, etc. We also hope to determine how pixel values when the same amount of power is incident on the camera sensor varies with ISO setting. This can be done with existing data, and should be complete within this week (week of 4 July, 2016).

After the camera itself is calibrated, we hope to determine the amount of additional optical losses introduced by the zoom lens and the telescope used in the end test mass and input test mass camera systems respectively. Following that, if time permits, we hope to determine how the viewport itself, as well as the viewing angle at the viewport affects the light scattered from the test masses masses.

Plans for Further Work on Input Test Mass Camera System

As of now, the stepper motor can now only be controlled through TwinCAT 2. Moreover, so far, we have only been able to use the velocity control interface from TwinCAT to move the motor; the position control interface would likely better serve our purposes. Therefore, the goal for the upcoming weeks is to determine how to use (and calibrate, if necessary) the position control interface for the stepper motor in TwinCAT 2. This should be complete by the end of next week (week of 11 July, 2016).

Subsequently, the goal is the develop an I/O interface in MEDM, and determine how to import values to from EPICs to TwinCAT so that the focuser can be controlled from the control room without having to directly access TwinCAT, which is not available on the control room computers. This is expected to take about two to three weeks, and is expected to be complete by the first week of August 2016. It is hoped that actual installation and debugging of the camera system at the corner station can take place concurrently with the user interface development.

References

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