Develop a high dynamic range camera prototype to measure the LIGO laser beam profile

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Abstract

Interferometric gravitational detectors use laser beams, which produce images with a very high dynamic range at the viewports. These images carry a significant amount of information, therefore their full reconstruction is of prime importance. In this report, we present an interesting optical setup to ensure the high dynamic range for the digital CMOS camera. We developed the basic software to analyze the image produced by this novel setup. We will also highlight potential future improvements and application of this device.

1 Introduction

Gravitational waves are emitted by accelerating masses as electromagnetic waves are produced by accelerating charges with the difference that gravitational waves ripple the space-time itself. It means that gravitational waves cause weak perturbation our local flat space and hold a huge amount of information about the strong-field regions where they started up. For the astrophysicist, the observation of this phenomena will open up a new and very different window onto the universe. However, the formulas of the gravitational waves were calculated in general relativity by Albert Einstein in 1916, gravitational signs are so small that no one has detected gravitational waves directly as yet. We have already known indirectly the existence of gravitational radiation from the 1974 discovery and observations, by radio astronomers Russell Hulse and Joseph Taylor, of the first binary pulsar. Hulse and Taylor have measured the orbital decay to the emission of gravitational waves which caused by the orbiting of the two neutron stars in the binary pulsar. Their precise measurements agree with the predictions of general relativity therefore we have great evidence that gravitational wave exist. However it could be very important to observe gravitational waves directly because by the help of gravitational waves we win information about extremely strong changing gravitational field for example black holes collision which has a lots of references in astrophysics. But this observations also can test the theory of general relativity and the properties of the graviton which is the fundamental particle of the gravitation.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States is one of the various detectors in the world which have been developed to detect gravitational waves directly. LIGO is a joint Caltech-MIT project, supported by the National Science Foundation. The LIGO facilities are contained a pair of L-shaped laser interferometers: one in Hanford, Washington, and the other in Livingston, Louisiana. All of these interferometers and also the 40 Meter Prototype Interferometer at Caltech, which is being upgraded to prototype the Advanced LIGO optical configuration and controls use infrared laser beams. The interferometer requires the beam to has an extremely high stability in intensity, launch position and angle, and transverse profile. The images of the beam profile carry a significant amount of information for adjusting the beam to the best setting, and the full reconstruction is of prime importance. The beam produces these images with a very high dynamic range at the viewports, therefore to analyze the beam we need expensive devices, otherwise we get saturated pixels on the images, that means we lose information. LIGO needs a lot of this hardware and software, which can execute the function above, therefore our goal is to find a simple, fine and cheep solution. Concretely, we would like to multiply the dynamic range of a common camera. In this report, we present and test an interesting optical setup, which is appropriate, and we review all of its properties. We use a CMOS camera to our measurements and we developed the basic software to analyze the image produced by this novel setup. We will also highlight potential future improvements and application of this device.

2 Primary requirements

First, let us collect our primary requirements.

- High dynamic range.

  We would like to produce better dynamic range, than 10-12 bits, which is the common specification of a beam analyzer device.

- Relatively cheep solution.

  We would like to find a cheeper solution, than buying a complete beam analyzer device, because LIGO needs a lot of them. Therefore we do not use expensive material and components. For example, a plausible solution is to use electrooptic shutter in front of the camera to get images from different intensity ranges. Consequently, utilizing some frame we can construct a frame, which contains the whole information about the beam profile. That means, decreasing the frame rate we can raise the dynamic range. But we have disapproved this solution, because electrooptic shutters are very expensive.

- Relatively simple setup.

  As stated above, LIGO needs a lot of these device, so it is very advantageous, if we can reproduce the setup easily.

- Real-time analyzing, acceptable frame rate.

  We would like to use the device with beam, which is changing in time, therefore we need acceptable frame rate. However we just would like frame per second, which is good enough for our eyes.

- Modular, customizable and easy to enhance software.

  It speaks for itself. We just note, that it is also decreasing the charge, because you do not have to buy the analyzing software with every single hardware.

- And we do not want to introduce noise into the LIGO measurement, so we would like to avoid mechanical motions.

  We mention this, because a possible good solution is to rotate a circular variable density filter in front of the camera by a motor, and use an optical encoder to tell to the analyzer software the angle position of the filter to calculate the transmissivity at that time. The point is the very same as using an electrooptic shutter: decreasing the frame rate the dynamic range increases. We note, the solution with the circular variable density filter could be better than the electrooptic shutter, because very high quality density filters are produced. You can get filter with optical density[1] from 0.04 to 4.0.

3 Description of the optical setup

In this section, we introduce our optical setup, what we have done and tested after all. The tentative optical setup has built on an optical table and contains the following instruments. The top view of the setup is shown on the following figure.

- 1 mW laser diode module with the wavelength of 670 nm.

  We do not want to use a high intensity infrared laser module, we would just like to demonstrate that our optical setup is appropriate and works. The diameter of the beam is about 0.15 in.

- Polarizer.

  We use a polarizer to construct the beam similar to the LIGO beam.

- Iris diaphraghm.

  The iris diaphraghm is just used because our laser diode produces some extra beam near the main beam, and we want to filter them out.

- Precision parallel, flat window with the thickness of 0.38 in.

  The window multiplies the number of the beams because of the reflection and transmission. It is shown on the figure, but we will also discuss it fully later. Now we just note, that beams must not overlap one another, so that is the reason why we use thick window.

- 2 precision optical flat mirrors[2].

  The angular offset of the mirrors is adjustable and we tilt the mirrors with a small angle in the opposite direction. Therefore the spots on

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[1] Optical density equals the log to the base 10 of the reciprocal of the transmittance.

[2] We note, that it is easy to get high quality mirrors at a low price.

the screen are graded in two different lines and the beams coming from the left side do not overlap the beams coming from the right side.

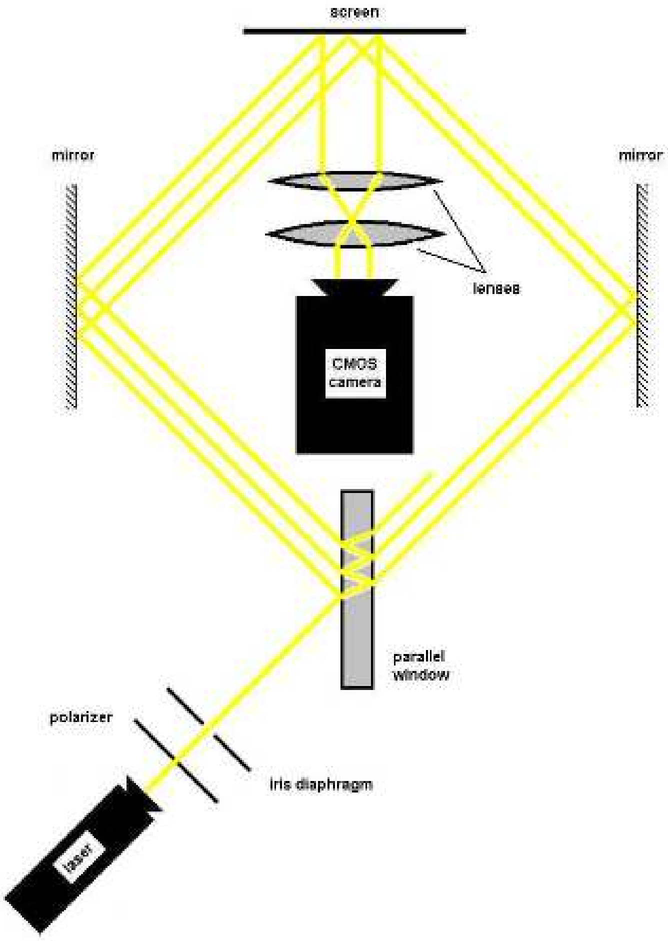

Figure 1: Top view of the optical setup.

- White screen.

  White screen disperses the light very good. However we also need the surface of the screen to be very flat to have good quality pictures. Therefore we use painted metal surface.

- Objective.

  We use an objective to exploit the whole CMOS pixel array, so we bring the interesting area of our screen into focus.

- BASLER A602f CMOS camera.

  The whole specifications of our tentative camera is in the appendix. We use only an 8 bits/pixel mono camera to our demonstration.

The whole setup lays inside a dark box.

4 Working of the setup

In this section, we introduce the working of the setup. Our solution is based on the fact, that decreasing the resolution we can increase the dynamic range. And in our respects, this is a better solution than increasing the dynamic range at the expense of decreasing the frame rate, because in this latter case we have to buy a camera with better frame rate, which is far more expensive.

Let us follow the path of the beam. First, the beam passes trough the polarizer and becomes vertically polarized. Then it leaves the iris diaphraghm and gets to the window. At the front surface of the window, one part of the the beam reflects off and the other part passes through the surface. And the transmitted beam also reflects off and passes trough the other side of the window, etc. Finally we can see some reflected and some transmitted beams, as it is shown on the firs figure, which are shifted to each other, and its intensity decrease more and more. The number of the visible beams depends on the initial intensity and the angle of incidence. Increasing the angle of incidence, the transmitted intensity decreases, so we have fewer visible beams. However, decreasing the angle of incidence, shifted beams go closer to the others and can overlap one another. We definitely do not want the beams to overlap one another, because we would like to collect all the information about the profile of each beam. Therefore, there is one special angle of incidence for the optimal reconstruction of the beam profile. In our setup, this special angle is about 29.5 degrees.

So, leaving the window we have beams look like beam, which has passed through an optical density filter. That means, these beams produce images of the same initial beam profile in different intensity range. We would like to record these pictures on the same frame, therefore we use mirrors to guide our beams to the suitable area of the screen. In our measurement, we have 3 reflected and 2 transmitted visible beams, and tilting the mirrors, we can adjust them in two lines on the screen as it is shown on the figure 2.

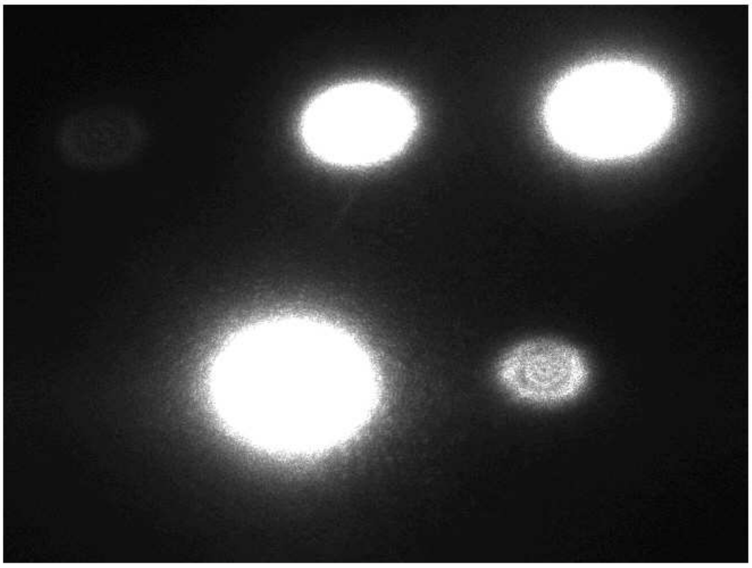

Figure 2: A typical frame with the camera.

We note, that our camera does not videotape directly the beams, because it only can be carried out with at least 3 mirrors. So, the camera gets the scattered light from the screen, therefore everything is black except the screen.

5 Transformations of the spots on the screen

On figure 3, we have highlighted the saturated pixels. The figure shows, that you do not get all the information from one spot. We have to utilize all the spots to have the best image from the beam profile. However, the spots on the figure are in different location and position, and have different intensity etc. Therefore, to superpose them, and produce the image of the beam profile, we need to know all the geometrical and non geometrical transformation that the spots have been suffered.

Let us collect these transformations and their root causes.

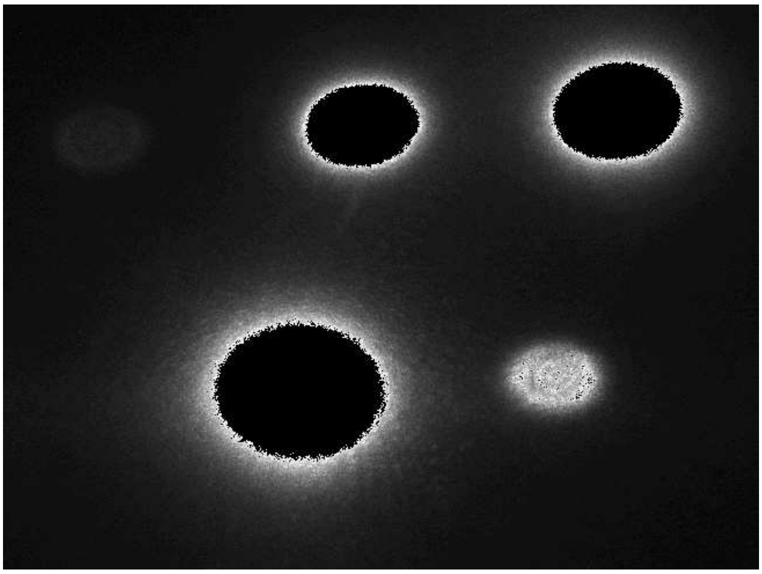

Figure 3: A typical frame with saturated pixels. We have highlighted saturated pixels with black

- Translation.

  The centers of the spots are translated to each other due to the thickness of the window and the tilted mirrors.

- Horizontal flip.

  The two transmitted beams, which are reflected odd times, are suffered horizontal flip on the screen.

- Rotation.

  Spots are rotated with a small angle due to the tilted mirrors. If the mirrors are parallel to the window, than the angle of the rotation is equal to the angle of the tilting. However, it is sure, that the 3 top spots and the 2 bottom spots on the screen are rotated separately with the same angle.

- Expansion.

  The nearly circular beam profile becomes to an elliptic profile on the screen, because the screen is not perpendicular to the beam.

- Intensity changing.

  The intensity of the several beams is not equal to each other, because their path in the air and in the glass has different length, and the reflectivity and transmissivity are also differ from each other. The power reflectivity and transmissivity depend on the angle of incidence and the polarization. The equations, which determine these coefficients, are called Fresnel's formulas and they are given in the appendix.

6 Calibration

To superpose the images of the spots, we need to know exactly the parameters of the transformation listed in the previous section. Moreover, it is necessary to know precisely.

There are two kind of transformation: geometrical and non geometrical, however this latter is only the intensity changing. The parameters of the geometrical transformations can be allocate with the help of the following patterns.

Figure 4: Patterns for the calibration.

If we put one of these patterns in front of the iris diaphraghm, the beam produces well defined pictures on the place of the spots on the screen. Some example are shown on the figure 5. After that, we can find easily the geometrical transformations and their parameters, because we just need to move and transform these well defined images, produced by the patterns, onto each other. These images have to be exactly the same, except the intensity, after using the right transformations.

We note, that our special tentative beam profile contains some concentric rings, therefore we can calibrate our system without any patterns, but it is not a generalizable method.

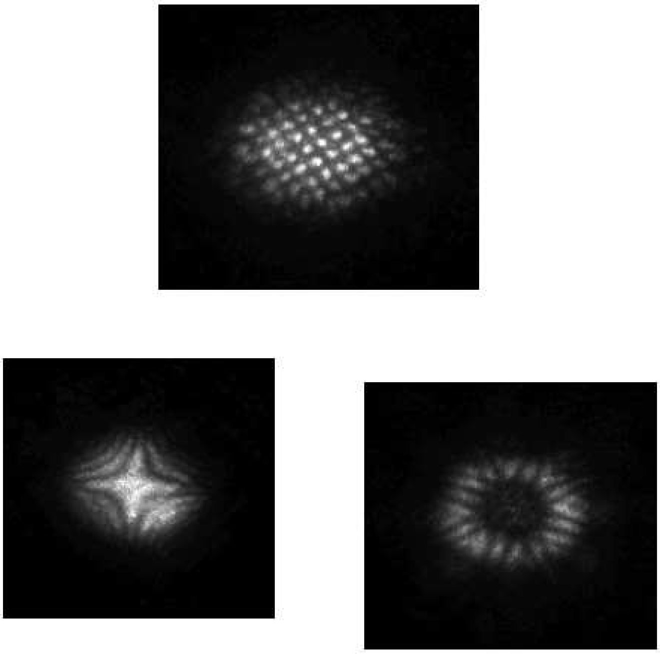

Figure 5: Images, which are produced by some of the patterns above.

Now, let us see, how can we calibrate the non geometrical parameter, which is the loss of intensity. The shutter speed of the camera is adjustable. First, we have checked the linear characteristic of the shutter. We changed the shutter speed, and regarded the value of a selected pixel[3]. We observed that the shutter value-pixel value function is a linear function, which goes across the origin. After that, we can change the shutter speed, and note the shutter value when the average intensity of a spot[4] is equal to a reference level. The relation of the noted shutter values will give the relation of the loss of intensity, what we have wanted. We use this method only for calibration before the running, because changing the shutter value decreasing very much the frame per second.

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[3] In truth, we regarded the environment of a selected pixel, and averaged the pixel values. In this way, the error has decreased.

[4] We always calculate the average intensity on a fixed size area around the spot.

7 The results

We have written a software in Visual C++.net which calculates the whole beam profile in real-time if you specify all of the parameters of the transformation. We have also calibrated our system manually and transmit the parameters to the software. A typical frame from the reconstructed image is on the figure 6. The range of colors is logarithmic on the figure. Unfortunately, we have used a bad objective, and the spots in the corners are distorted, therefore our final beam profile has the quality as it is shown. But it is obvious, that this setup work very well if the optical components have good quality.

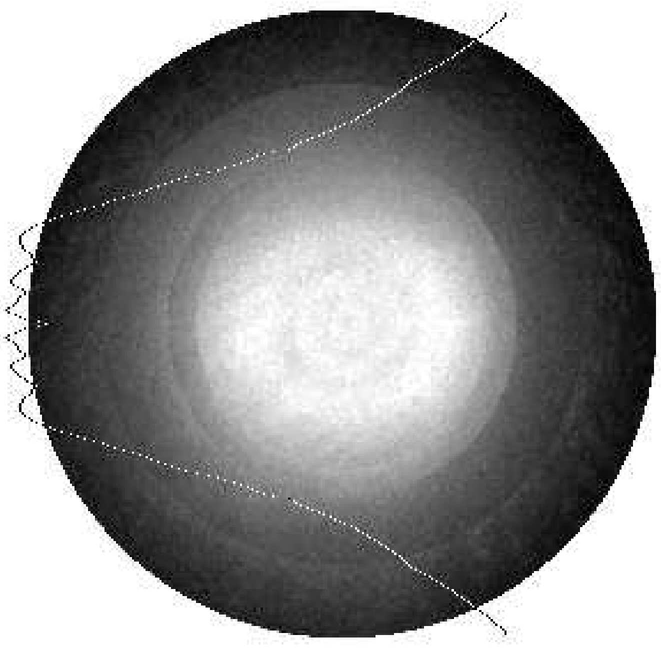

Figure 6: The reconstructed image and its radial intensity histogram.

We note that the dynamic range used to be measure in bits, but in this case we have far higher dynamic range, because our scale is logarithmic.

8 Future plans

We have tested the optical setup, but we have not use utter components, which will be necessary to a real high power infrared laser beam. Therefore, the setup should be tested with a higher power infrared laser beam, for example it could be tested in the 40 Meter Prototype Interferometer. The calibration of the setup has been processed, but this manual method could be easily developed to an automatic procedure. The software can be improved with an automatic calibration module.

9 Appendix A Specifications of the tentative CMOS camera[2]

Sensor size (H × V pixels)	659 × 493
Sensor type	Progressive scan CMOS
Pixel size	$9.9\,\mu\mathrm{m} \times 9.9\,\mu\mathrm{m}$
Max frame rate	100 frames/s
Color / mono	Mono
Video output type	IEEE 1394
Video output format	8 bits/pixel
Synchronization	Via external trigger or the 1394 bus
Exposure control	Programmable via the 1394 bus
Power requirements	+8 to +30 VDC (12 VDC nominal)
Lens mount	C-mount
Housing size (L × W × H)	65.7 mm × 44 mm × 29 mm
Weight	max. 100 g
Conformity	CE, FCC

10 Appendix B Fresnel's formulas[1]

Fresnel's equations relate the amplitudes for reflection and transmission to the incident field amplitude at a dielectric interface. From these equations, the power reflectivity and transmissivity can be calculated, as well as the phase shifts for reflected and transmitted wave. Below, we assume that all optical properties in the two media are governed by real indices of refraction and neglect inhomogenities at the surface and in the bulk, thus ignoring scattering losses.

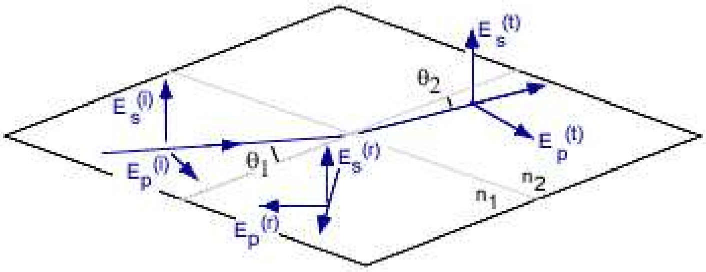

Figure 7: Illustration of the plane of incidence.

The plane of incidence contains the normal vector of the interface and the propagation vector of the incident. The electric field perpendicular to the plane of incidence is called the S-polarized component. The electric field parallel to the plane of incidence is called the P-polarized component.

- P-polarized field transmittivity.

$$t_P = \frac{E_P^{(t)}}{E_P^{(i)}} = \frac{2n_1 \cos\Theta_1}{n_2 \cos\Theta_1 + n_1 \cos\Theta_2}$$

- S-polarized field transmittivity.

$$t_S = \frac{E_S^{(t)}}{E_S^{(i)}} = \frac{2n_1 \cos\Theta_1}{n_1 \cos\Theta_1 + n_2 \cos\Theta_2}$$

- P-polarized field reflectivity.

$$r_P = \frac{E_P^{(r)}}{E_P^{(i)}} = \frac{n_2 \cos\Theta_1 - n_1 \cos\Theta_2}{n_2 \cos\Theta_1 + n_1 \cos\Theta_2}$$

- S-polarized field reflectivity.

$$r_S = \frac{E_S^{(r)}}{E_S^{(i)}} = \frac{n_1 \cos\Theta_1 - n_2 \cos\Theta_2}{n_1 \cos\Theta_1 + n_2 \cos\Theta_2}$$

- P-polarized power reflectivity.

$$R_P = \frac{\tan^2(\Theta_1 - \Theta_2)}{\tan^2(\Theta_1 + \Theta_2)}$$

- S-polarized power reflectivity.

$$R_S = \frac{\sin^2(\Theta_1 - \Theta_2)}{\sin^2(\Theta_1 + \Theta_2)}$$

In Fresnel's equations, Θ_2 is calculated from Snell's Law:

$$n_1 \sin\Theta_1 = n_2 \sin\Theta_2$$

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