Characterization of Charge Coupled Devices

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Abstract

The Large Synoptic Survey Telescope (LSST) will require a camera that is very fast, while still having great detail and contrast for imaging the night sky. The research group at UC Davis will test multiple Charge Coupled Devices (CCDs) in order to determine their ability to meet the requirements of this camera. Because of the uniqueness of the LSST, previous CCD testing has been unable to confirm the behavior of CCDs in this environment. For our tests, we will create a realistic illumination identical to the LSST f/1.2 camera beam. This will allow us to confirm that the CCDs that are installed in the LSST will be able to provide the data that is necessary for the LSST project. As a result, we will be able to observe a much larger section of the night sky, in great detail, much more frequently, than has ever been done before.

Introduction

What is dark matter? This is one of the biggest questions facing modern physicists, and it is one the many questions which the Large Synoptic Survey Telescope (LSST) will attempt to answer. The LSST will allow the entire sky to be imaged with incredible frequency and detail. This will allow techniques such as gravitational lensing to be used in order to map the dark matter distribution in the universe, potentially giving physicists new insight into the nature of dark matter. This new telescope is going to be constructed in Chile. Upon completion it will record images of the entire sky through six different filters every four nights. It will have an 8.4 meter primary mirror, 3.5° field of view, 340 m^2 deg^2 etendue, and an f-ratio of f/1.234. LSST will require a camera which conforms to very strict standards to take advantage of this telescope's properties, and it will be subjected to an environment in which Charge Coupled Devices (CCDs) are currently relatively unproven. The research group at UC Davis will develop experimental tests to determine CCDs' viability for this application.

Background

In the 1970s, CCDs were first used to record astronomical images. It was immediately clear that CCDs provided a dramatic improvement over the photographic plates that were commonly used at the time. This is largely because of the linear response and large dynamic range of a CCD. In addition, typically 70% of the light that is incident on a CCD produces a response, which is far better than the 2% response common to photographic film.

A CCD is primarily made of a single piece of a semiconducting material, typically silicon, on the order of 10 – 100 mm across and 100 µm thick. The semiconductor is doped in such a way that it acts as a two dimensional grid of photodiodes, and each of these photodiodes is called a pixel. During the image exposure, an image is formed on the surface of the CCD. Each of the pixels absorbs photons during the exposure, and for each photon an electron is excited to the conduction band and is trapped within its pixel.

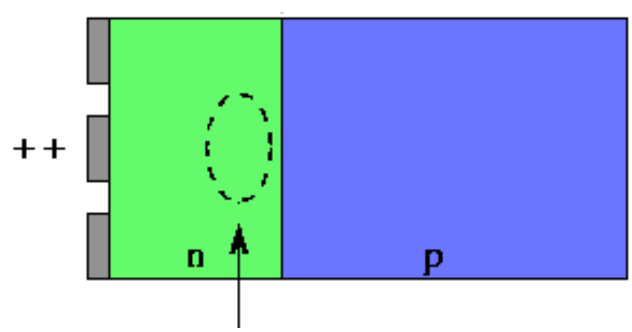

Figure 1. This shows the n- and p-doped regions of the semiconductor which form the photodiode. The arrow shows where electrons will be stored.

After the exposure is complete, the number of electrons in each pixel must be recorded. This is accomplished by sequentially transferring the electrons from each pixel to a single amplifier. The electrons in each row of pixels are sequentially transferred to the shift register, which sequentially transferred the electrons from each pixel to the amplifier. The amplifier produces a voltage which is proportional to the number of electrons which were stored. This process can be used to accurately count 10-300,000 electrons in a typical CCD. Since the number of photons incident on the CCD is directly proportional to the intensity of light, this is a huge dynamic range. This allows a CCD to accurately record the light from objects of vastly different brightnesses simultaneously.

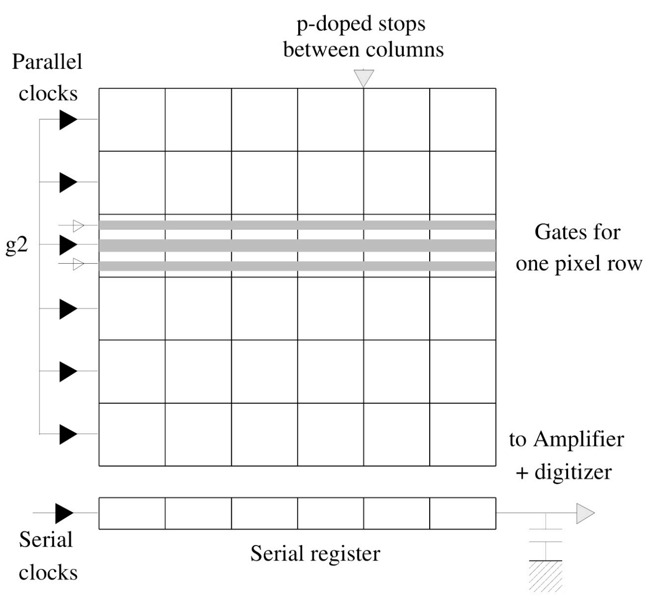

Figure 2. Many of the basic components of a CCD are shown. Thin regions of p-doped material electrons moving right/left, while a series of gates prevents motion up/down during the exposure and control motion during readout.

LSST will use the largest digital camera which has ever been built: 3.2 gigapixels. This will be accomplished by arranging 189 CCDs, each with 16 megapixels, into a grid. Because the camera is made up of numerous CCDs, it is called a mosaic CCD camera. In addition, LSST has an f-ratio (the ratio of the effective focal length to the diameter of the aperture) of f/1.234. This means that the distance light would travel from the center of the primary mirror to the CCD is greater than the diameter of the aperture by only a factor of 1.2. Because these dimensions are so similar, the light arrives at the CCD through a wide angular range.

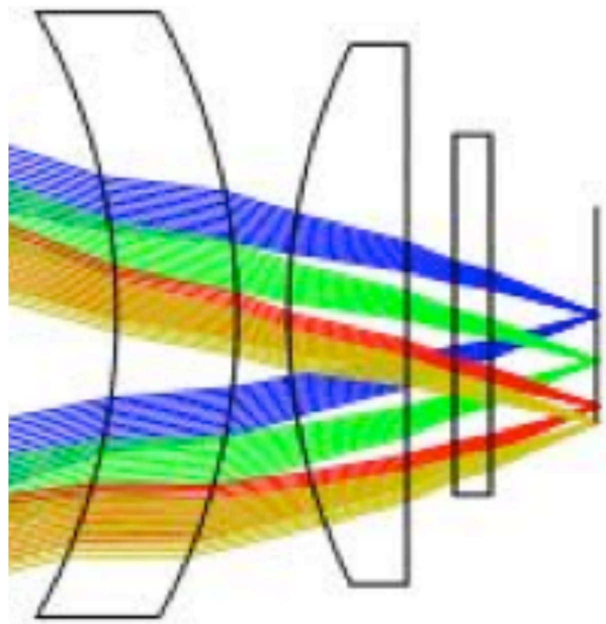

Figure 3. This diagram accurately shows that path which light will travel before arriving at the CCD. Note the wide angle from which light converges as it is incident with the CCD.

The low f-ratio of the LSST also means that it can record images very quickly. The aperture is very wide relative to the focal length, and this means that each pixel receives a large number of photons. This is crucial to the LSST's ability to capture detailed images with a very short exposure. The exposure time will be only fifteen seconds, which is necessary to reach the goal of imaging the entire sky through six filter bands every four nights.

Experimental Setup

To ensure the CCDs used in the LSST satisfy all of the requirements, we must perform numerous tests. Our goal is to prepare a laboratory in such a way that tests we currently intend to perform can be efficiently accomplished, while also having the ability to quickly develop and perform tests which have not yet been considered. Some current tests as well as the laboratory setup are discussed.

Flatness

The wide angle of light incident with the CCD produces an environment in which slight changes to the distance between the primary mirror and the CCD cause the image to move out of focus very easily. According to our simulations, the entire image will be in focus if each CCD is flat to within 5 μm peak-to-valley. In order to test this we create an image of an artificial star, and the CCD will record ~100 exposures of this star throughout a range which extends in front of and behind the focal plane. This process will be repeated with the star centered on numerous different pixels. By analyzing these images the height variation of the CCD can be determined, and then the process is repeated again with an image of multiple artificial stars. These images will provide the necessary data to determine if the images will be in focus across the entire CCD.

Edge-scan

The response of a CCD to light is well understood because of the understanding of the material properties of semiconductors. However, it has been shown that near the edge of a crystalline solid the structure changes, and this in turn changes the material properties. In previous applications the pixels near the edge of a CCD represent a sufficiently small quantity of data that the behavior of these pixels has not been studied in great detail. In the LSST, with 189 CCDs forming the mosaic, these pixels will produce a sufficiently large quantity of data that we must study their behavior. One way we will test their behavior is by placing the image of an artificial star on a pixel near the edge (~10 pixels away) and repeatedly imaging the star between movements on the order of one pixel width that will bring the star to the edge of the CCD. There are theoretical predictions that this type of edge-scan will cause the image to become distorted, but this has not yet been experimentally proven.

Hardware

In order to develop and perform many different tests in one laboratory, we require hardware which is highly modular and adjustable. In addition, we need to produce images exactly the way LSST will produce them. We designed the LSST Beam Simulator (a series of lenses, mirrors, and baffles) to produce such images.

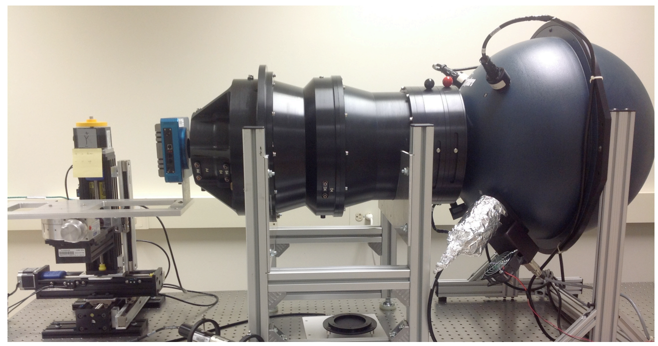

Figure 4. The primary hardware is shown. On the left the stepper motors and their tracks are visible. Mounted on their platform is the stand-in camera. The black object in the center is the LSST Beam Simulator. The blue sphere on the right is the light source.

The light source we use is a LabSphere. It is a hollow sphere with a rough, white interior so that light emitted through the exit aperture is completely diffuse (ie, each photon has random polarization, phase, and direction of propagation). There are four independent lights for variable light intensity, and one of the four has a variable shutter to allow more fine adjustment of intensity.

The LSST Beam Simulator produces images exactly the way the LSST will; the light arrives from the same direction. Also, there are provisions for mounting plates with various pinhole arrangements to create our artificial stars.

We use three Vexta P266 stepper motors controlled by a Velmex VXM-3 stepper controller. These motors are mounted together such that we have a platform which can be moved in three dimensions independently. The step size for our assembly is 2.5 μm. In order to accurately measure the position of the platform, we use

Acu-rite Senc 150 linear encoders with 1 μm resolution for each direction.

LabVIEW

All of the hardware is controlled using National Instruments' LabVIEW. A program has been written which allows numerous exposures to be taken from a specified collection of positions. The user must supply positions to start and stop, as well as the distance to travel between images and the order in which to travel (eg, along the z-axis, then along the x-axis, and finally along the y-axis). To obtain this level of automation, the program was completely rebuilt making use of the state-machine architecture. This allows the program to determine which action must be taken next based on the previous action as well as the condition of various indicators. Also, it allows the program to wait to respond to user-input until necessary tasks are completed. The typical process is as follows: take an image, save the image with the relevant information (position, CCD temperature, exposure time, light intensity, etc.), check which direction of motion was specified, check if the platform has reached the stop position, move, repeat.

Python

Once a collection of images has been recorded, they must be analyzed. This is primarily done using Python. Scripts have been written for use with the single artificial star setup. They can find the pixel the star is centered on as well as the full width at half of the maximum amplitude (FWHM) of the point spread function (PSF). The PSF describes the image of a point source, so the FWHM of the PSF quantifies the amount to which the light from the artificial star spreads out. This quantity is minimized when the CCD is perfectly aligned with the focal plane. By analyzing the single star images from a flatness test, it is possible to map the surface of the CCD.

Conclusion and Future Work

The LSST will provide a means of observing the universe that is unprecedented, but this requires an understanding of CCD behavior in optical environments in which they have not yet been well documented. This can be obtained by performing experiments using the laboratory setup that has been developed at UC Davis, once the CCDs arrive. There are other laboratories in which similar tests could be performed, but at present they do not possess the same capability for developing new tests. Few other laboratories currently have the ability to control CCD motion to the extent that it can be controlled in our laboratory.

Moving forward, members of this project will perform the tests previously outlined on CCDs which will be provided by multiple vendors. Once those CCDs arrive, the LabVIEW program will need to be modified to control them. In addition, Python scripts that can analyze images containing multiple artificial stars need to be completed. If a vendor proves able to produce a CCD that conforms to the necessary standards, they will begin production of the full mosaic, and ten to twenty percent of them will be subjected to the same tests as the initial CCDs. While this takes place construction of the LSST will begin, and it is scheduled to be operational in 2023.