ABSTRACT

DESIGN AND IMPLEMENTATION OF AN INEXPENSIVE FAST IMAGING SYSTEM FOR COLD ATOM EXPERIMENTS

by Matthew C Gillette

A home built system for imaging optical lattices is presented. Our imaging system uses a repurposed astronomy camera - the complete system costs less than $5,000 while rivaling the performance of a commercially available system which costs $40-50k. The camera must have an extremely low dark current, high quantum efficiency, as well as the ability to take precisely timed millisecond exposures. Using LabVIEW a sequence of precise electronic pulses is created to control the laser beams in order to load the lattice structure with cold atoms. When running a LabVIEW VI at millisecond timescales Windows introduces inaccuracies in pulse timing. A master slave computer setup, called a real time target (RTT) is created in order to keep accuracy to the microsecond level.
DESIGN AND CONSTRUCTION OF A FAST IMAGING SYSTEM FOR DETECTION AND ANALYSIS OF OPTICAL LATTICES

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Dedication

To my amazing family, without whom I would literally not exist
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CHAPTER 1 - INTRODUCTION

This chapter will discuss the motivation behind the construction of the inexpensive camera system as well as previous works. Then the outline of the thesis will be presented.

I.1. Motivation

The most common and straightforward way of quantitatively evaluating cold atom dynamics is the use of a CCD to image them. There are many cold atom experiments that use CCDs. The temperature of a cold atom cloud can be measured using expansion imaging techniques [1]. Observation of optical ratchets is also possible by tracking the center of mass of a cold atom cloud [2]. There are very specific requirements for these CCDs and they must be very strictly controlled in sync with the experiment at hand. There have been significant advancements in cold atom physics in recent years, yet the technology to image cold atoms using a CCD has progressed very little. All cold atom experiments using CCDs track either the center of mass of the atoms or the FWHM, which requires precision of both timing and high resolution. The cost is prohibitively expensive at costs of up to $50,000 for a camera marketed for cold atom imaging. The cameras cost is due to their high signal to noise ratio, their cooling capabilities such that they can image a BEC [3] and their excellent accompanying software.
I.2. – Previous Works

To the best of our knowledge there has only been one group who has attempted to build their own imaging system. In 2006 D. Whitaker et al.[1] attempted to repurpose an astronomy camera for imaging cold atoms for reasons explained in Chapter II.2. However their technology at this point is outdated. The camera had a resolution of 0.4 MP, which is too small (the atomic cloud moves <1 pixel per millisecond) for current applications such as center of mass and FWHM tracking of the atomic cloud. The timing jitter or uncertainty between when the camera is told to take an image and when an image was actually taken is 250ms. This is unusable for many of cold atom experiments because most experiments take place in timescales an order of magnitude less than that. Due to an outdated USB connection the readout time of the camera took 20s, this makes experimental cycles inconveniently long. The lasers used in cold atom experiments can lose lock over time. A mechanical shutter to fix the timing jitter [1] but this is not ideal because unwanted vibrations by the shutter can also break the lock of the experiment’s lasers. Vast improvements can be made by updating hardware (e.g. camera, Data Acquisition Cards), redesigning the software (e.g. Drivers and control software) and connections between LabVIEW and Windows. This thesis discusses and implements these improvements.

I.3. Organization of Thesis

The thesis is organized as follows. Chapter 2 gives an overview of the different components of the imaging system, the requirements and choice of camera, lens and labVIEW cards. In chapter 3 the LabVIEW timing system is discussed and its connection with Windows described. A detailed user-manual like description of the user interface is given followed by an explanation of the timing accuracies of the system. Chapter 4 discusses the various imaging techniques that can be used with the system for data taking. Chapter 5 discusses the role of sources of noise, specifically readout noise and dark current. Chapter 6 discusses the basics of optical lattices, and how the camera system is utilized to
for lattice detection. Chapter 7 discusses future experiments planned with the system for investigating optical ratchets and Levy motion.
CHAPTER 2 –OVERVIEW OF COMPONENTS

Traditionally, in order to purchase a camera with experiment ready software, choices are limited. One option, a cheap security camera and lens system with no timing capabilities, for detecting the presence of cold atom clouds. The other options are camera systems with experiment ready software from companies such as Princeton Instruments and ANDOR, which cost $40,000-$50,000. These systems offer single photon resolution and can easily interface with LabVIEW for implementation of multiple timing sequences. Below we describe the components necessary to custom build an imaging system that rivals the Princeton/ANDOR systems in performance for 1/10th the cost. In addition the spatial resolution of the expensive camera systems is low each pixel 16µm x 16µm which can be a limiting factor when imaging the tiny movements of the atoms and is improved upon in our design.

II.1. Choice of Camera

Taking a cue from ref [1], we decided to use an astronomy camera repurposed for our experiment. Astronomy cameras were found to have similar characteristics as the more expensive cameras due to their intended use with very weak light signals. However they are meant for extremely long exposure times and hence their timing capabilities are not developed, leading to large jitter in the time at which the image is actually taken. We show that this can be corrected. The features necessary for a cold atom imaging camera will all be discussed in detail in further sections but will be mentioned briefly here. Figure 1 shows the camera purchased for our experiment for less than $3,000.
Figure 1 shows the ATIK 460ex

The ATIK 460ex was chosen because it can cool to 25° below ambient, has a quantum efficiency of 60% at 780nm and low exposure times. Considering the excited state lifetime of Rb and the timescales involved in the experiments a short exposure time is necessary (e.g., our lattice detection experiment lasts around 30ms total). The camera chosen has a minimum exposure time of 1ms. This allows us to take images without motion blur due to the motion of the atoms on such a small timescale (on the order of a tenth of a millimeter per millisecond).

When deciding on a camera careful consideration must be taken as to the signal to noise ratio. The amount of noise from a CCD is extremely important to consider and is discussed in much more detail in chapter 5.

In addition to how the signal to noise ratio, what wavelength of light must also be considered. The quantum efficiency of the camera is important to get a large signal. For the ATIK 460EX the quantum efficiency at 780nm is ~36%. The quantum efficiency will be discussed in detail in chapter 5. A CCD alone is not enough, a lens system is also needed and is discussed in the next section.
II.2. Lens and filter system

In order to image the atoms the light must be focused onto the CCD. A standard 4f lens system, shown in figure 2, which works for both fluorescence and absorption imaging, was built in order to do this. The lens system uses a focal length 120 mm lens to capture the light and a 60 mm lens to focus the light onto the CCD. The chamber housing the atoms is fairly large, a 12 cm radius (R) with 1.5” (2r) windows. A 2” lens is positioned just after the window to capture all light that escapes it. Inside the chamber light is emitted in all directions, it can be calculated that only .6% of light emitted exits the window.

\[ \text{Fraction of light collected} = \frac{\pi r^2}{4 \pi R^2} \]  
(1)

The lens system can be seen below in figure 2.

Figure 2 shows the 4f lens system and light tight box
The light then passes through an infrared filter that blocks most of the ambient light from entering; this is placed directly against the camera so as to also provide a first layer of light tightening. In addition to the filter a black box was built around the lens system to further prevent stray light from entering. With both of these light tightening methods we are able to perform experiments with room lights on and see no noticeable difference in the images produced.

II.3. LabVIEW components

In addition to controlling the camera timing for when and how the camera takes an image, we need a way to control the laser pulses and magnetic gradient. In order to do this a LabVIEW Data Aquisition (DAQ) card is needed. These cards allow signals to be read as well as sent out in real time from a computer. Thus allowing us to time our experiment in sync with the camera system. Due to the time scales of interest (the entire experiment lasting only 30ms and sometimes 10 different pulses are sent out during that time) the timing of the laser pulses both when they occur and their width must have sub-millisecond accuracy. A DAQ card with a 1MHz clock pulse is chosen giving us 1 microsecond precision on the timing pulses. This card is the NI PCIe-6320, XSeries Multifunction DAQ card. A much more detailed explanation of the LabVIEW system will be presented in the next chapter. Note that while there is 1 us precision in the laser and magnetic field timings, the camera has a +/- .5ms precision with a determined delay that can be accounted for. Please see chapter 3 for more information.
Chapter 3 - LabVIEW Timing System

In this chapter the LabVIEW system will be discussed in detail, including the necessity of a Real Time Target system and how that system interfaces with our windows computer. A detailed user-manual style discussion of the user interface will be presented and finally an discussion of the camera timing accuracy is presented.

III.1. Real Time Target System

Imaging of the cold atoms becomes impossible if the triggering of the camera is not properly aligned with the triggering of other events in the experiment. Previously the timing for events in our experiment (such as magnetic field on/off, laser on/off, frequency modulation of laser beams, etc) had been accomplished using a combination of home-built digital timing circuits and function generators. This was acceptable for some applications [4, 5] but severely limited the versatility of the system. In addition the camera is not capable of being triggered off of an external TTL pulse, meaning that syncing the camera to the digital TTL system is difficult and potentially not well determined. A new solution was needed.

The first attempt at a solution was very simple involving a single computer with a NI PCI-6014 PCI card and BNC block. The system was able to create 8 channels of signals and output TTL pulses in a timing sequence. During testing it was quickly realized that the computer was unable to handle near-millisecond precision of the pulses. The system would work for a fraction of a second before flat lining (sending out all low signals).

This limitation of Windows is due to the fact that Windows 7 is not a real-time operating system (RTOS). A RTOS system is an operating system that is created in order to provide real time operations [6]. The OS must have a predictable delay (e.g., in an air bag deployment system the results are catastrophic if strict timing requirements are not met) [7]. Inside of a non-RTOS there exists a problem when dealing with small timescales. Any command sent to
the OS will be fulfilled but only at some point few hundred milliseconds in the future. This delay is not fixed and varies from shot-to-shot, this is illustrated in figure 3. To the typical user this difference is unnoticeable (timescales of milliseconds) but in a system that needs pulses at microsecond precision this unstable delay is unacceptable. RTOSs allow for a high degree of control over prioritization enabling the most important applications to be run in a well determined manner.

![Figure 3: Shows an example of the timing differences between a standard OS and a RTOS with a simple pulse request](image)

In order to combat the unwanted effects of a standard operating system a RTOS needed to be used. This presented another problem, how to interface the camera with the RTOS. The camera was not capable of taking commands from any RTOS so a new system needed to be devised as described in the next section.
III.2. Connection between LabVIEW and Windows

A master-slave configuration of two computers was created that allows the camera to interface with a windows computer while still providing the microsecond precision of a real-time system.

Figure 4 shows the master-slave computer configuration

The system consists of two labVIEW VIs running in unison, one on the master computer, one on the slave. The two computers communicate back and forth over a crossover cable connected through their Ethernet ports as shown in figure 4. An additional connection between two DAQ cards was added which is discussed in III.3. The communication between the computers consists of a series of checkups and notifications, shown in figure 5, that enable the two to stay in phase with each other.

Figure 5 shows the timing sequence between the two computer systems
The windows computer builds the pulse cycle from user inputs as described in the next section. The Real Time Target or RTT computer takes this built waveform and starts a cycle in unison with the windows computer. The windows computer sits and waits for a command from the RTT while the RTT starts sending out pulses to the experiment until the time that a command is sent from the RTT to the Windows computer to initiate taking an image. In response from this command from the RTT the windows computer sends a command to the camera to take an image. There is delay in this communication which can be accounted for as discussed in section III.4. Once the image is taken and saved, the Windows computer sends a command to the RTT computer and the cycle repeats after a user-determined delay. A user-manual like description of the system is given in the next section.
III.3. User Interface and Usage

The LabVIEW system has a relatively simple user interface considering the complexity of the system. Below we will discuss features and usage of the camera system.

Main Screen

In Figure 6 below you can see the main screen of the camera system.

Figure 6 shows the main screen of the camera UI

The large black box displays image information from the previous data run. Along the top of the screen you can see 5 tabs each linked to a different section of the windows system – these tabs and their function will be discussed in detail. The camera function controls give you control of several important features
of the system. It is important to note that when changing “noise correction” or “exposure length” the LabVIEW VI must be reset afterwards.

“Bin Level”

The bin level lets you bin together boxes of pixels in order to reduce download time of the image. This bin is locked to an X by X format so each binned pixel must be a square. For example if binning is set to 1, each pixel is used individually, but if binning is set to 4, 16 pixels are used as one in a 4x4 array. In general this value is set to 8, allowing for the quickest download time, but it can easily be changed.

“Noise Correction”

The “noise correction” sets the total area that is being sampled on the CCD, and compensates for the use of binning. The total number of pixels seen in any image can be determined by the simple equation.

\[
\frac{\text{Noise Correction}}{\text{Binning}} = \text{Imaged Pixels}
\]  (2)

In most cases this value is set to 1600, allowing for a quick image to be taken while still having a large field of view.

“Exposure Length”

This value simply lets you change the exposure length of the system in terms of seconds. This value can be used to compensate for any jitter in the image timing to ensure that an image is taken at the appropriate time. For example the final jitter of our camera image time is +/- 500 µs, if the event of interest is less than that time the exposure time can be increased to increase the chances of exposing during the event.

“Camera Connected” and “Enable Diagnostic Camera” Mode

The “Camera connected” toggle can be used to let the program run without the camera connected. This can be useful for diagnostics of the timing
system where the camera is not needed. If the camera is not connected and this is toggled On the program will return errors. The “Enable Diagnostic” toggle is used for developmental diagnostics and should not be touched on a daily basis.

“Experiment Data Files”

This is simply the location of the saved data and can be chosen at any time by clicking on the small file icon on the right hand side of the bar. It is recommended that the save location is a fast drive, either an SSD or a RAMdisk to improve write times.
“Camera Timing Data” Tab

The “camera timing data” tab, as seen below in figure 7 has no settings and is only used for diagnostic purposes. There are various timing readouts but the most important readout is the list of recent exposure timings. This gives a readout of the time between when the windows computer sends a command to take an image and the time that the image was returned. This gives the delay or jitter in the timing of the image due to the camera itself. Most of the time this value is returned as a constant small value. But if there are settings mismatches or mistakes the jitter can be huge and this can be instantly seen in this list of recent exposure timings and corrected.

Figure 7 shows the Camera timing data tab of the windows computer
“Camera Temperature Control”

The “camera temperature control” tab has one input that lets you control the temperature of the camera. In most cases the camera should be set to just below 0°C (-2°C works perfectly). This suppresses thermal fluctuations in the CCD removing most dark current fluctuations. The two displays on (see figure 8) this tab show the workload on the TEC cooler as well as the temperature of the CCD over time. This graph only updates once a minute so it can seem to be frozen at times. **It is important to note that the CCD must be allowed to return return to ambient temperature before being unplugged or the CCD risks being damaged.**

![Camera Temperature Control System for CCD](image)

Figure 8 shows the temperature control system for the CCD
“Real Time System Configuration”

The “Real time system configuration” file allows for the saving of experimental settings and can be seen in figure 9. In order to do this it is necessary to go to the system configuration tab in the RTT while the experiment in interest is still set up and click the POST button. This will send that configuration to the “Shared variable engine” which is a cloud between the two computers that data can be uploaded to and downloaded from at any time. Then click RETRIEVE on the Windows system configuration page. The configuration file will now be saved in the location noted in the bar to the left. In order to upload a file follow the same procedure but using the windows side first.

Figure 9 shows the System configuration tab of the windows system
“Real Time Front” Tab

The front page of the RTT VI contains several important functions and displays. The main feature is the display of the 8 channel outputs. When built properly the display will change to show the current experimental settings. In the lower left corner there is the “build digital waveforms” button as shown in figure 10. This builds the waveforms for the experimental cycle with the data input from the other tabs. It is necessary to click this button after any changes are made or they will not be reflected in the actual experiment. In addition there are three “LEDs” on the page that show the status of the system and can be used to troubleshoot.

Figure 10 shows the main tab of the Real-Time system.
“Wave input” tabs

These eight tabs are relatively simple and can be seen in figure 11, they consist of 4 numeric inputs that signify the time (in microseconds) of each transition. In addition there is a switch that controls the starting state of the tab’s channel. It is important to note that for a channel to work properly each subsequent transition must start at least 1 microsecond after the previous. If another transition is not desired all remaining transitions can be set to one value which will stop the transition all together.

The 8\textsuperscript{th} wave tab (Wave #7) controls the camera trigger. The camera trigger must be set to start HIGH and the first transition LOW will be the trigger for the camera. There exists a delay between the trigger and the actual image process usually around 235ms. This delay however is repeatable, only having a jitter of +/-5ms. It is necessary to check this delay at least once a week as it can drift over time by 1-2ms - this can be done using an LED placed in front of the lens system triggered off of another wave input from another channel. The trigger time can be adjusted until the LED flash is caught by the camera reliably.

Figure 11 shows the wave tabs for each channel
The last tab in the Real-time system is used for various settings. The first four settings (Digital I/O, Digital Output Rate, Line grouping and Timing source) should not be touched on a regular basis and adjust the card target. They should be left at the defaults as displayed in figure below. The “Single cycle length time” input allows the user to set the total time for each cycle (in microseconds) typically our experimental cycle will be set to 2e6 (i.e. 2 seconds). Finally the 8 inputs at the bottom allow the channel names to be changed for ease of use as seen in figure 12.

Figure 12 shows the settings tab for the RTT
III.4. Jitter and Improvements

Jitter in the image timing was a significant problem throughout the development of the system. The first iteration of the system had a jitter of +/- 500ms making the system incapable of imaging cold atoms experiments since the length of the entire experiment is on the order of 30ms. With the implementation of the master/slave configuration this jitter was reduced to +/-250 ms, still unusable in the experiment. Through careful consideration it was decided that the write time of the camera could be causing issues and a RAMdisk was installed. A RAMdisk is made by portioning out a section of a computers ram to be used for storage, but the speeds are over 100 times faster than that of a traditional hard drive. This addition reduced the jitter to just +/-8ms. This was a huge improvement but still made the experiment difficult without the use of an electronic shutter. A new solution was needed. The problem remained with the communication between the RT and the windows computer. The time it took windows to read the signal from the crossover cable was not repeatable. In order to improve on this shot-to-shot variation nature a new communication method was devised that is contained completely within labVIEW. This method is shown in figure 13.

Figure 13 shows the current system setup including the new DAQ connection.
A National Instruments DAQ card (NI PCIe-6320, XSeries Multifunction DAQ) was added to the windows computer that can receive digital pulses and one of the channels from the RTT was tied to a wire sent between the two DAQ cards. This signal was then processed on the Windows side all within LabVIEW reducing the jitter in the image timing to just +/- 500 µs, an order of magnitude improvement over the +/-8 ms jitter (and an improvement of 1000 over the original jitter), finally bringing the jitter down to usable levels without a needing to introduce a vibration inducing mechanical shutter as was the case in ref [1].
CHAPTER 4 – IMAGING TECHNIQUES

There are a number of ways to use a CCD camera to image cold atoms. We will discuss three widely used methods here.

IV.1. Non-destructive Fluorescence imaging

The first method, non-destructive fluorescence imaging involves using the fluorescence from the lattice to image the lattice. A typical timing sequence is shown in figure 14.

Figure 14 shows a typical experimental cycle for non-destructive fluorescence imaging. A standard experimental cycle starts with the B-field turning off, 2ms allows for the B-field to dissipate and an additional 1ms is allowed such that the atoms can thermalize. The MOT beams turn off and the lattice beams turn on simultaneously and the atoms can fall into the lattice sites for 10ms before an image is taken. For the rest of two seconds the experiment returns to its starting point allowing for the MOT to build up.

The light that scatters out of the lattice is collected by the 4f lens system described in chapter II.2. This technique is straightforward, easy to implement and non-destructive to the lattice but there is one drawback. Image intensity is meant to be an indicator of atom number but lattice images for different lattice intensities cannot be compared since the fluorescence depends on the excitation intensity.
Special care must be taken in interpreting the data when using this imaging method.

**IV.2. Fluorescence imaging**

A more robust method is to use a separate fluorescence beam to illuminate and image the lattice. This beam is a low power (around 100µW) resonant beam that is controlled by the camera system and is pulsed ON for a time ranging from 50 µs to 1 ms or beyond depending on user settings. This allows for a consistent power for the imaging beam thus removing the drawback from the previous section. In addition, this technique allows for a shorter effective exposure time since a 50 µs imaging pulse effectively lowers the exposure to just 50 µs even if the camera is limited to its specified minimum exposure of 1ms. A typical experimental cycle can be seen in figure 15.

![Figure 15](image)

Figure 15 shows a typical experimental cycle for Fluorescence imaging. The process is the same as that of non-destructive fluorescence imaging except a resonant beam is turned on at the same time an image is taken.

The drawback for this technique is that it is destructive.
IV.3. Absorption Imaging

In both the fluorescence techniques only a small percentage of light is captured (.6% as seen in II.2.) A method of imaging the atoms with increased sensitivity is needed. Absorption imaging fills this need. In this system the cold atoms are hit with a resonant laser beam. A portion of these photons are absorbed by the atoms and reemitted in a random direction. This creates a shadow in the beam that can then be imaged through the 4f lens system into the CCD. This imaging technique is significantly more sensitive than fluorescence imaging. This is due to the fact that in the fluorescence technique only a small amount of the emitted photons are detected while in the absorption technique case all photons that were absorbed are not detected. Absorption imaging measures the optical density (OD) of the atom cloud or lattice by use of Beer’s law where I is the intensity of light after the sample and \(I_0\) is the intensity before the sample.

\[ I = I_0e^{-\text{OD}} \]  

(3)

Without the 4f lens system the image is a diffracted mess. Past the atoms the image has three components (as shown in figure 16): the imaging beam (shown in blue) is focused and recollimated as expected onto the CCD, the shadow (shown in green) and fluorescence (shown in red) from the atoms are collimated and then focused back onto the CCD [8].

Figure 16 reproduced from [8] shows the typical setup for absorption imaging. The blue represents the absorption beam, the green represents the shadow of the atoms and the red represents the fluorescence of the atoms.
At this point a background image of the resonant beam without atoms present is recorded and subtracted away from the previous image to produce an inverted image of the cold atom cloud. This image, unlike the previous two methods will have a dip, or a negative peak instead of a positive peak at the location of the atoms. A typical experimental cycle for absorption imaging looks the same as that of fluorescence imaging. Absorption imaging typically has around a factor 100 improvements in signal to noise ratio over fluorescence imaging when done properly. This can be difficult as the absorption beam needs to have a very low intensity such that almost all of the light is absorbed by the atoms.

The advantage of absorption imaging is that short exposure times with consistent power and a signal increased by a factor 100 than fluorescence images. The drawback is that it is a destructive imaging technique; furthermore we found the diffracted images can be hard to read or analyze. For this reason we chose to use fluorescence imaging for our experiments even though it has more noise than the absorption imaging, in the next chapter we will discuss the sources of noise.
CHAPTER 5 – SOURCES OF NOISE

CCDs work by receiving a photon and converting it into a number of electrons which are then stored in the pixel that it hit. Each pixel can only hold a certain number of electrons. The number of electrons in each well can then be read out and converted to a contrast based on the number of electrons in the well compared to the maximum number that the wells can hold.

The photon to electron conversion is not 1:1. There are CCDs capable of reaching single photon counting levels but these can cost upwards of $50,000. There are several factors that contribute to the number of electrons that end up in each well, the first being quantum efficiency. Each CCD has different quantum efficiencies for different wavelengths, for example, the ATIK 460EX that we use in our lab has a quantum efficiency of ~60% for a wavelength of 780nm. This means that only 60% of the photons that hit the CCD will actually be registered. In addition to quantum efficiency there is an amplification associated with each CCD. This amplification, called the Analog to Digital Converter (ADC) converts the voltage from each pixel to a digital pixel value. The ADC will also introduce random noise into the system, in fact two identical cameras taking the exact same image can have drastically different images due to noise. A detailed look at two major sources of CCD noise will be examined in the next two sections.

VI.1. Readout Noise

CCD readout noise is a fundamental feature of all CCDs that limits the signal to noise ratio of a camera. There are several sources of noise in each image taken by a CCD takes no matter how long or short the exposure is. These sources are usually lumped together into one number called the “readout noise”. This value is measured in the average number of noise electrons per pixel or e-. This value can range from one to hundreds of electrons per pixel. In our case the ATIK has a readout noise of 5 e-. The readout noise is caused by a few factors and for the whole array will be on average the same in every image however each pixel
can fluctuate wildly from shot to shot. The noise is caused on the CCD itself and by the ADC in the signal to image conversion.

Figure 1 shows a typical image of only readout noise.

VI.2. Dark Current

Dark current is caused by thermal fluctuations in a CCD even if it is not being exposed to light at the time. With a long enough exposure time the dark current will fill each pixel completely and saturate the image. Thus the dark current is measured in electrons per pixel per second. This can be combated by controlling the temperature of the CCD. For example the dark current noise of the ATIK CCD at room temperature is around 10e⁻/p/s but when the CCD internally cooled down to -10°C the dark current is reduced to just 0.001e⁻/p/s, a factor 10000 improvement. Below in figures 17 and 18 is a graph showing the readout and dark current noise as a function of time at two temperatures, room temperature and -5°C. In our experiments the camera is typically run at -5° because we have found the camera struggles to stay at -10° depending on ambient conditions.
Figures 17 shows the typical camera noise as a function of exposure time for the ATIK camera at two different temperatures.

VI.3. Signal to Noise Ratio

A low signal to noise ratio is critical to taking clear images with a CCD. It is calculated simply by taking the total number of electrons that each pixel can hold, in our case 20000e⁻ and dividing it by the average noise of the image, in our case 5e⁻.

\[
S - N \text{ ratio} = \frac{\text{Pixel well depth}}{\text{readout noise}}
\]  

(4)

This gives us a theatrically maximum ratio of 4000 to 1. Reducing the noise by half to 2.5e⁻ would double that value to 8000 to 1, meaning even tiny changes to the noise can help immensely when it comes to producing clear images.
CHAPTER 6 – OPTICAL LATTICES

An optical lattice consists of a system of two or more laser beams that intersect in space. A periodic modulation of potential energy wells is created in the intersection region due to the polarizations and intensities of the lasers interfering with one another. The beams can have many configurations, and the lattice can be 1, 2 or 3 dimensional. In order to achieve a 1-D lattice, two beams are needed, 2-D needs 3, and 3-D needs 4. There are many different beam configurations that can be used depending on the number of beams and the intent of the experiment but in our case we use a standard 1D LinLin configuration which consists of 2 counter-propagating linearly polarized laser beams of equal intensity. In the intersection region of these 2 beams the net intensity is uniform, but there exists a spatial polarization gradient as shown in figure 19 [9]. This leads to spatially varying light-shifts [8,9] in the energy-levels of atoms that happen to traverse this gradient, leading to the creation of energy crests and troughs – an array of potential wells, or in other words, an optical lattice – for these atoms. A brief discussion of light shifts is presented in the next section.

VI.1. Sisyphus Cooling

At this point we have only given a simple view of what is actually going on inside of the lattice and now we will go into more detail. To do that we will consider a one dimensional lattice, which consists of two counter propagating beams with polarizations set orthogonally to each other. These polarizations interfere to create a periodic structure of polarizations of areas of circular polarization next to areas of linear polarization [9] as shown in figure 18.
Figure 18 shows the polarization gradients created by the lin$_{1}$lin 1D lattice.

Continuing with our simple model let’s consider what would happen if we put a fictitious two level atom with ground state angular momentum $J_g = 1/2$ into the spatially varying polarization field. First, the degenerate ground state of that atom is split into two hyperfine sublevels $-1/2$ and $+1/2$ because of the presence of the small magnetic field created by the orbiting electrons – this is the hyperfine structure. Next, these ground states are light-shifted. The shift is based on the polarization of the light at the location of the atom. As seen from Fig. 20 the light polarization varies periodically in space, and so does the light shift for each sublevel. But the lightshift for the +1/2 sublevel oscillates out-of-phase with the lightshift for the -1/2 sublevel – this is because of the Clebsch-Gordan coefficients which describe the transition strengths between hyperfine atomic levels for light of a specific polarization. Consider an atom placed into this structure. The atom or atoms are supplied from a magneto optical trap created before the lattice is built using a tapered amplifier previously built in our lab [10]. The atom moves in one of the ground states, climbing up a well towards position 1, as illustrated in Figure 19.
Figure 19 shows the workings of the Sisyphus cooling mechanism

As the atom climbs its energy is reduced. The higher in the well the atom rises the closer it is in resonance with the excited state – this is because the light is red-detuned. At the top of the well, near position 1 in figure 19, the atom is most likely to be pumped up to the excited state (position 2). From there the atom has the option of either falling back to the same level, i.e., at the top of the hill (in which case this process repeats), or falling to the bottom (position 3) of the other light-shifted level that co-exists at the same location with the peak of the first light-shifted level. If it falls to the lower ground state the atom finds itself again climbing a well. This process repeats, meaning the atom finds itself perpetually climbing hills and losing energy, until the atom no longer has enough energy to climb the walls of the well and the atom becomes trapped. This process is called Sisyphus cooling. Because the lattice beams in this case are perfectly collinear they confine the atoms in one dimension while allowing them to move more freely in the two orthogonal dimensions. The confinement is illustrated in figure 20.
Figure 20 shows the confinement of a 1d lattice of collinear beams where the blue disks represent the areas of high potential and a separated by a length of $\lambda/4$.

In a typical lattice we expect to see the atoms expand faster in the non confined directions than the atoms in the direction of the lattice axis. This along with other data can be used as evidence for the creation of an optical lattice.

**VI.2. Lattice Detection**

To begin taking a typical data set (seen in figure 21) the atoms are trapped in a magneto-optical trap (MOT) and allowed to load for approximately two seconds.

Figure 21 shows the timing sequence of a typical lattice image

Once the MOT is fully loaded the magnetic trap is turned off and the atoms enter a molasses state. This process takes 3.5ms of which 2.5 ms is the time taken for the magnetic gradient to completely turn off and the remaining 1 ms is time taken by the molasses to thermalize [11]. The resonant laser is then turned off and
simultaneously the lattice beams are turned on. The atoms at this point start to deposit themselves into the lattice wells via Sisyphus cooling. Again the atoms are allowed to remain inside the lattice for a predetermined time, in our case anywhere from 2-25 ms. We find that beyond 25 ms the 1-D lattice is no longer able to confine the atoms. For our subsequent measurements we keep the lattice confinement time fixed at 10 ms [11]. At the end of 10 ms the lattice beams are again turned off and simultaneously a resonant beam is turned back on. At this point all atoms trapped inside the lattice will be released and will fluoresce in the presence of a resonant beam. An image of the lattice with a 1ms exposure time is taken. A timing diagram can be seen in figure 21. Again it is important to note that the timing on the diagram is not representative of the start pulse sent to the camera and that the delay described in Section III.3 under heading *Wave Input Tab* needs to be taken into account.

Note that the lattice is difficult image directly because each lattice site is only a quarter of a wavelength apart. The three false-color images (red = highest atomic density) below provide indirect but compelling evidence of the existence of a one-dimensional optical lattice. If atoms are confined in the 1-D lattice then we expect to see a cigar shape signal from the camera with the short axis co-aligned with the lattice beams. In order to protect against false positives we take a second image of the background where no atoms have been trapped and subtract it away using MATLAB. TO confirm that confinement was not being confused with an optical lattice the polarizations of the two lattice beams were set to parallel to each other, this would result in the creation of no lattice well but would still allow for confinement due to counter-propagating off resonant beams. Below in figure 22 are some of the images taken of the lattice showing an image with lattice beams present and not present.
Figure 22 shows three false-color images (red = highest atomic density) that provide indirect but compelling evidence for the existence of a one-dimensional optical lattice. Fig. (A) is a snapshot of uniformly expanding optical molasses. To create the optical molasses, first the magnetic gradient of the MOT is turned off at $t = 0$. The picture is taken at $t = 4$ ms. For the first 3 ms of the expansion the optical molasses beams were ON allowing the atoms to thermalize in the molasses, but for the last 1 ms all laser beams were turned off and the atoms were allowed to expand ballistically. The snapshot in A is taken by flashing an independent resonant beam and recording the fluorescence. Clearly, the molasses expansion is rather uniform in all directions. (B) is a snapshot of the optical lattice. Just as in Fig. A the magnetic gradient of the MOT is turned off at $t = 0$. The atoms are allowed to thermalize in the molasses for 1 ms and simultaneously a pair of counter-propagating laser beams (called the lattice beams, indicated by red arrows) are turned on instead. The atoms are allowed to expand through the lattice for 10 ms and then an image is taken using the fluorescence from these lattice beams. We clearly see slower expansion along the axis of the lattice beams owing to Sisyphus cooling, yielding indirect evidence for the existence of potential wells along this direction. No such wells exist in the orthogonal direction. Fig (C) is the exact same experiment as in (B) except that the polarizations of the counter-propagating lattice beams are no longer orthogonal, preventing the creation of the light-polarization gradient appropriate for lattice formation, leaving the atoms to expand completely ballistically and leave the imaging volume. This is convincing evidence that the spatial confinement seen in Fig. (B) along the lattice axis is not due to some radiation pressure forces by the lattice beams, but is indeed due to the formation of a lattice structure.
CHAPTER 7 – FUTURE OUTLOOK

There are two main projects that we are progressing towards. They will be discussed in detail here.

VII.1. Optical Ratchets

Brownian optical ratchets are optical lattices that have been modulated such that they can generate a current of particles out of fluctuations that create no mean force in any direction. There are many types of ratchets, some more simple than others but in our case we will consider the Brownian rocking ratchet. In a rocking ratchet, a periodic (asymmetric in time) potential is created using a biharmonic drive [2]. This drive modulates the phase of the two laser beams and creates the asymmetry in time due to harmonic mixing. The phase modulation for the two beams is created using an AOM system where a FM modulation $f$ is being applied to their driving frequency at around 10kHz and takes the form of two cosine waves.

$$f(t) = A \cos(\omega t) + B \cos \left(2\omega t + \frac{\pi}{2}\right)$$

In order to create an optical ratchet a few things are needed in addition to the typical optical lattice components. In order to create the phase modulated yet frequency locked laser beams needed to create the lattice additional control is needed over the AOMs that are used. Most commercial drivers for these crystals are not able to provide these characteristics so an alternate method is needed. Our typical AOM crystal runs most efficiently at 80MHz, meaning both the driving frequency of the crystal and the frequency shift of the light passing through it is 80MHz. In order to create this signal a driver is needed. We chose a RIGOL signal generator (RIGOL DG4102) for this purpose. It has two channels which can be phase-locked to each other while also having the ability to individually modulate: frequency, amplitude or phase. This allows for the input of two independent secondary signals (the biharmonic drive).
Once the signal is created it needs to be amplified. The AOMs in our lab require 1Watt of power to operate at peak efficiency, but the RIGOL signal generator cannot create a signal at this strength. In our lab we use RF amplifiers (RF bay Inc. MPA-12-30 amplifiers). These can amplify a signal of 30-1200MHz with a gain of 30dB. This gain varies as a function of frequency as shown below in figure 23.

![Gain vs Frequency](image)

Figure 23 shows the gain of the RF bay amplifiers as a function of input frequency.

The required input signal cannot be calculated and must be measured. In order to do this we measured the amplitude of the output of the AOM commercial drivers (that came with the AOM) to the crystal on an oscilloscope. A 50Ω terminator was used on the oscilloscope to present the same input impedance to the driver as the crystal. Using a two channel scope we simultaneously displayed the signal from the RIGOL+Amplifier combination and the signal from the commercial driver. The RIGOL’s output amplitude was adjusted until the signal out of the amplifier matched the height of the commercial driver – we find that the matching occurs when the RIGOL amplitude is -2.08dBm. This is a unit often used for RF power (P) measurements and the relation between Watts and dBm is given by
\[ P(dBm) = 10 \log_{10}(P(Watts)) + 30 \] (6)

It is important to note that the amplifiers can distort the signal if the input signal has too high of an amplitude. Around 0dBm or 1mW the output signal starts to distort laterally. It is very important to avoid this as the biharmonic drive would be lost completely. At the previously mentioned power of -2.08dBm there is no measurable distortion in the signal. Figure 24 shows the signal of the RIGOL/amplifier combo next to the AOM’s original driver.

![Figure 24](image)

Figure 24 shows the signal from the commercial driver (green) compared to that of the Rigol/Amplifier system (white)

As can be seen above each amplifier creates a unique phase lag. The lag is deterministic and does not seem to drift even over long periods of time. The two channels need to be set with a phase difference of 87° in order for them to be the same phase at all times. The AOMs have been tested thoroughly and function at levels equal to that of the commercial drivers.

Once control is obtained over the AOM crystals the biharmonic driving needs to be created. This is done using a function generator’s (HP MODEL
arbitrary waveform inputs. Using a GPIB cord and a waveform easily created in excel a waveform can be created that can be used as the modulation input to the RIGOL. There are a few problems with this technique, first the HP has a limit of resolution on the amplitude and the time that can cause problems when building a 10ms signal at 100kHz. Second triggering the scope is not straightforward. It can be hard to trigger it at the correct time to get the whole 10ms signal from the RTT system. Figure 25 shows the RF system.

Figure 25 shows an illustration of the RF AOM control system

An alternate and easier to use method would be the use of an analog LabVIEW card (In our case the NI PCIe-6323. Use of this card allows for an analog output that can be fed directly into the modulated function generator. The card had an analog sample rate of 900kS/s and 16-bit resolution over a range of +/-10V. This would allow us to program the biharmonic signal into the LabVIEW program directly and have total control of when the signal is turned on.

Simply turning on the biharmonic drive is not enough. It needs to be turned on slowly. Typically our biharmoic would be on for 10ms and 1ms of that time would be allocated to an adiabatic turn on of the signal [12]. This is necessary because turning the modulation on too suddenly can jolt the atoms out
of the optical lattice destroying all chances of creating the optical ratchet. A simplified version of the adiabatic turn on can be seen in figure 27.

![Figure 27](image-url)

Figure 27 shows the adiabatic turn of the biharmonic driving signal (Frequency not to scale for illustrative purposes).

With this signal applied to the RF generator and then a single lattice beam modulated a ratchet can be created. This ratchet can then be imaged at various times throughout the biharmonic drive or after a period of ballistic expansion. The center of mass can be tracked as a function of time to give evidence of the optical ratchet. This is easily achieved with the above described camera system and a simple program built in MATLAB to calculate the center of mass of an atom cloud. The MATLAB program can calculate the center of mass to an accuracy of .4 pixels or 9.5 µm in real space.
VII.2. – Levy Flights

Once the lattice is detected there are a number of experiments that can be performed. One interesting experiment for our current setup is examining Levy flights of atoms between lattice sites - an example can be seen in figure 28. Once the atoms have thermalized and settled down in the bottom of the wells they still exhibit random motion between adjacent wells. Every now and then, though, they may embark on a large excursion spanning multiple wells – this large excursion is known as a Levy flight. Levy flights have been recently studied extensively in many other fields from biology to political science in addition to physics. Multiple groups have measured the anomalous diffusion in 1-D optical lattices as a function of lattice well depth \[12, 13\] and recently a group has tracked the anomalous diffusion of a single ion in an optical lattice \[14,15\] although their measurements had a spatial resolution of over 30 well widths.

Figure 28 shows a 3D model of Levy Motion

Levy flights consist of small random jumps interspersed with less frequent large jumps. This motion comes from Sisyphus-like mechanisms. The small motion comes from the motion of the atoms between local lattice sites and can be seen in figure 29. As discussed previously the atoms move around in the wells and as they move up a well from position 1 to position 2, they can be optically pumped into the
excited state. Once in the excited state the atoms can emit back to their original state (position 2) or emit to the other ground state (position 3). Similar considerations apply if the atom is at position 3 when it gets pumped to the excited state and subsequently drops to position 2. No matter what the original or final ground state may be (excluding the null case where the atom ends up in the same ground state as it started) the atom will always end up in an adjacent well. This constitutes the usual process for diffusion of an atom through the optical lattice.

Figure 29 shows the process of optical pumping that can result in Levy Flights if repeated multiple times.
What constitutes the process for large jumps leading to Levy flights is more interesting. We have previously discussed Sisyphus cooling but what happens if the process happens in reverse? As before the atom starts in position 1 and moves around inside the well. While climbing the well (and losing kinetic energy) it is optically pumped from position 2 (when it still had some “hill left to climb”) into the excited state, and subsequently dropped into position 3. The atom now finds itself, instead of climbing a hill and losing energy, in a situation where it rolls down a hill gaining energy. This has the net effect of giving the atom energy. This itself does not cause the Levy jumps but if this happens multiple times the atom can build up enough energy be able to run up and down multiple wells before it is Sisyphus-cooled and eventually captured again. These large jumps become less likely as the well depths of the lattice get deeper. Ref. [16] shows that Levy flights are observable at well-depths of \( \sim 65 \ E_R \) and below (where \( E_R \) is the recoil energy, and is 0.37 \( \mu \)K for \(^{85}\text{Rb}\)) for the 1D case.

In order to measure the Levy motion we need to look at the motion of the atoms as they diffuse through the lattice. With our new camera system we are able to take pictures of the expanding atomic cloud at different intervals as the atoms diffuse. If they are confined in the lattice potentials and Levy flights are absent the atoms will diffuse in a Gaussian distribution. However if confined in the lattice and undergoing Levy flights we expect the FWHM of the diffusing atoms to scale as a power law \( t^{1/\alpha} \) where \( \alpha \) depends on the well depth of the lattice sites and \( t \) is the time after the lattice was released. An \( \alpha \) value of 2 will make a Gaussian distribution while any other number will produce anomalous diffusion. A measurement of the atomic distribution of the lattice while it diffuses reproduced from Ref. [16], can be seen in figure 30. We hope to be able to produce similar plots in the near future.
Chapter 8 – Conclusions

In conclusion we have presented a home built camera system for imaging optical lattices. Our imaging system uses a repurposed astronomy camera - the complete system costs less than $5,000 while rivaling the performance of a commercially available system which costs $40-50k. Using LabVIEW a sequence of precise electronic pulses is created to control the laser beams in order to load the lattice structure with cold atoms. A master slave computer setup, called a real time target (RTT) is created in order to keep accuracy to the microsecond level. Signatures of the lattice were detected and we will now be moving towards detecting optical Brownian ratchets by tracking the center of mass of the atom cloud and Levy flights by tracking the FWHM of the cloud
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PRESENTATIONS:

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