STEP

SUBTITLE

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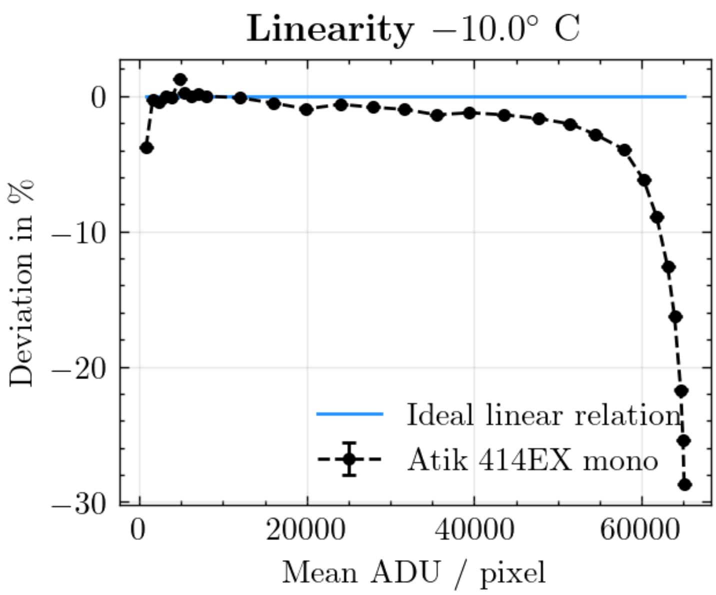
NOVEMBER 22, 2021



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Theory

3.1 Charged-coupled devices (CCDs)

A charge-coupled device (CCD), is a solid state image sensor used to detect light. It is an integrated circuit that is essentially an array of metal-oxide semiconductor (MOS) capacitors (MOSCAP) representing the pixels, forming a photoactive region of silicon. In addition the CCD also consists of a shift register to transfer the accumulated charge, that will be interpreted as an image.

3.1.1 Semiconductors

Silicon is a semiconductor. A semiconductor is a type of solid state material, which is neither a conductor or an insulator. This distinction between insulators and conductors is defined from the difference in the density of states at the chemical potential at a temperature of $0K$[2]. For metals we have a finite density of states, and otherwise it is an insulator or a semiconductor. A semiconductor is, in addition to the former, a material for which the band gap between the highest occupied states in the valence band, and the lowest unoccupied states in the conduction band, is sufficiently small to thermally excite electrons across the gap. This gap is usually in the order of magnitude of a few electron volts.

A semiconductor is by definition a solid for which the chemical potential at absolute zero is placed at an energy such that the density of states is zero. This is around the center of the band gap. At finite temperature, some of the electrons from the valence band are thermally excited into the conduction band. This leaves behind so called holes in the valence band. Holes are simply a convenient way to describe the absence of electrons, allowing for us to treat them as positively charged quasiparticles. The movement of electrons through the valence band is permitted by the presence of holes, which in turn can be seen oppositely, as the movement of a hole in the opposite direction. Holes are hence chrage carriers in the valence band allowing conduction. We call electrons and holes 'carriers', and the concentration of carriers are in part what determines the conduction properties of a material.

The concentration of carriers in an intrinsic semiconductor, that is one which is pure, is too low to give an appreciable contribution to conduction properties. A way to circumvent this problem is by doping the semiconductor. This is a process in which we introduce impurities in the solid. These impurities, also called dopants, can either function as donors, also called **n doping**, in which they are able to donate electrons to the solid, or as acceptors, also called **p doping**, in which they take electrons in turn producing a hole. N dopants are chosen such that, at not too high temperatures, the states lie just below the conduction band minimum (CBM), while the p dopant states are just above the valence band maximum (VBM).

3.1.2 The pn-junction

The MOSCAP is an example of a practical technological application of semiconductor physics that is based on the working principles of the pn-junction. The pn-junction is the boundary between regions of a p- and n-doped semiconductor, and is achieved by doping inhomogenously. In the n-doped region most donors are ionized, and the majority carriers are electrons, while in the p-doped region, acceptors are negatively charged, and the majority carriers are holes.

As the two regions are joined, electrons diffuse into the p-region and holes into the n-region. This leads to recombination of electron-hole pairs as they meet. This gives rise to a region at the boundary, of immobile acceptors and donors, whose charge is not compensated by mobile charged carriers. We call this site the **depletion layer**. The thickness of this layer is around 0.1 to 1μm [2]. An electric field is formed due to the presence of the immobile ionized donors and acceptors. The electric field points from the, now net-positively charged n-region into the negatively charged p-region, presenting as an obstacle for holes to move from the p-region to the n-region. The depletion layer widens, and the field increases, until an equilibrium between the electromagnetic and diffusion forces is reached. There is hence a **diffusion current** across the region for those carriers with enoguh energy to overcome the opposing eletric field, and a **drift current** due to the presence of the same field. The chemical potential in the p-doped region lies close to the VBM, and in the n-doped region is close to the CBM, as can be seen via an argument on charge neutrality. However, if we apply a voltage across the depletion layer the equillibrium between these currents is broken such that a net current[2] is produced

$$I = I_{\text{diffusion}} - I_{\text{drift}} = I_0 \left(e^{eV/k_B T} - 1 \right) \tag{1}$$

Where V is the so-called **bias voltage**. This bias voltage is essentially what lets the diode function as a valve for the current.

3.1.3 The MOS capacitor

The MOSCAP is a part of the so-called MOSFET structure. A MOSFET is a type of transistor made from the principle of the pn-junction, and is usually constructed from silicon. A MOSCAP is constructed by forming a layer of silicon-dioxide on top of a p-doped semiconductor. On top of this metal or polycrystalline silicon is deposited functioning as an electrode, aslo called the gate, which is the source of the bias voltage. Silicon dioxide is a dielectric insulator, so this construction is akin to a planar capacitor. See figure 1.

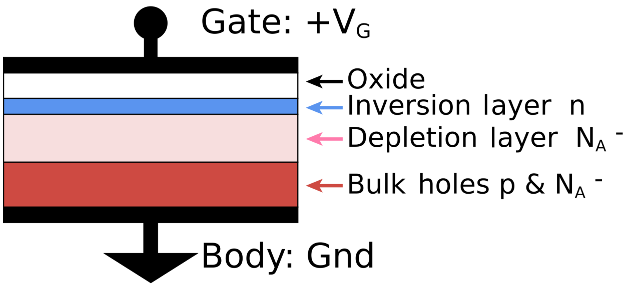

Figure 1: A MOS capacitor (MOSCAP). Image by Brews ohare Own work. Licensed under CC BY-SA 4.0, via Wikimedia Commons.

When a voltage is applied to the gate, holes in the body, the p-type substrate, will be repelled, and minority electrons will be attracted, generating a depletion layer unerneath the oxide layer. If the voltage is great enough, enough electrons will be attracted, and electrons become the majority carriers, forming an n-type region. We call this layer an **inversion layer**. The threshold voltage at which this happens is an important parameter. It is defined as that voltage, at which the density of the electrons in the inversion layer is the same as that of the density of holes in the p-type substrate.

If in addition, two so-called **terminals** are included on either side of the body, consisting of n-doped regions (opposite type compared to the body type), the source and the drain, we call the structure a **MOSFET**. In the case of a p-type (n-type) body, and two n-type (p-type) terminals, we denote it an nMOSFET (pMOSFET) or n-channel MOSFET. This makes up two pn-junctions. As voltage is applied to the gate and the inversion layer forms, a channel is formed that will allow current flow. The higher the voltage the greater the electron carrier density, and hence the greater the current flow between the two terminals. Transistors either amplify or switch electronic signals, and are essential building blocks in electronics.

3.1.4 CCD charge generation

Before exposure of the CCD the MOSCAPs in the array are biased into the depletion region, thus having not formed the inversion layer at this point. The gate is then biased positively (in n-channel MOSCAPS) above the threshold for inversion, creating an n-channel below the gate, just as in the MOSFET structure. Holes are pushed far into the body substrate, and no mobile electrons remain; the CCD is in a non-equillibrium state called **deep depletion**. As photons strike the depletion region, an electron-hole pair is formed and separated by the electric field. Charge is hence accumulated at the surface. Electron-hole pairs may also be created by thermal excitations anywhere in the array. These pairs generate noise. This effect is linear with time and follows a poisson distribution, since they are rarely occuring stochastic incidents. We call this effect **Dark current**. Dark current adds noise to an image, that may be corrected for. This charge generation process can occur untiol a new thermal equillibrium is reached, a state which we call **full well**.

3.1.5 CCD charge transfer and image readout

After the phase of charge generation, usually called **exposure**, the accumulated charge must be read. This is done by transfering the charge from the array, and sending the resulting electrical signal through an **analogue-to-digital converter (ADC)** which will convert the nalogue signal of charges into a digitized signal that can be interpreted by a computer. This stage is called readout, and happens on a line-by-line basis [1]. Rows are shifted down one at a time, until they reach the **readout register** (the final row). Within each row, each pixel is read out sequentially.

Generally, during readout the chip is exposed to light, and hence the shift process should be very fast, in order to avoid smear in the image. This however poses another problem, as a faster readout process results in a higher noise level.

[1] Here a line denotes a row in the CCD MOSCAP array

This issue is solved in a **frame transfer CCD** by a shielded area of the chip, equal in size to the photosensitive area. The shielded area typically consists of a highly reflective material, such as aluminium. After exposure the rows are rapidly shited into the shielded area, after which the necessary time to read out the measurements is available. In many cameras, this can also be achieved via a **mechanical shutter**.

3.2 Characterization of CCDs

3.2.1 Gain

The relationship between the number of electrons generated at the chip, and the actual pixel value in the image, is called **gain**[3]. This value is dependent on the software used to read out as well as the chip itself. As electrons are transferred out from the chip, they pass through an amplification stage, where a capacitor is charged. The voltage from this capacitor is passed through an **Analogue-to-digital converter (ADC)** which transforms the voltage signal into one that can be interpreted as a string of binary digits. This conversion is done by the software, and the resultant units are **Analogue-to-digital units (ADUs)**, which is ultimately the pixel value. At the ADC and software conversion levels we can scale the signal by an arbitrary factor, preservin gthe relative pixel values. This arbitrary scaling factor is exactly the gain. It can be expressed as

$$\text{gain} = \frac{\text{Number of electrons per pixel}}{\text{Number of counts per pixel}} \tag{2}$$

In each pixel bin on the chip, there is a maximum number of electrons that can be store. This number is known as the **ful well capacity** of the chip. In addition, there is a maximum number that can be represented in the digitized signal, that depends on the number of available bits in the ADC. For a 16bit ADC, this number is $\text{ADU}_{\text{max, 16 bit}} = 2^{16} = 65563$. It is hence natural to choose the gain factor such that the full well capacity corresponds to the maximum digital value that we can store.

3.2.2 Dark frames

A dark frame is an image acquired while the chip is not exposed to incoming photons. Such a frame may be used to study dark current and readout noise effects in a CCD detector, and is also used to construct the master bias frame discussed below.

3.2.3 Bias

In order to avoid negative counts in an image that consists entirely of noise, an offset voltage is applied to the CCD. This is because read out noise in the chip folows a gaussian distribution (see section 3.2.4.1) centered on zero, and hence includes negative values in some of the pixels. This voltage offset level is called **bias**.

In general bias is roughly constant across a chip, but it is common for the bias frame to show some level of structure in the chip. These structures can either be form the mechanical construction of the chip surface, from bad columns that may hve a significantly higher offset than the rest of the chip, or resultant from the chip being made up of different sections that were constructed independently, and then later joined together.

Bad columns and sectors in the bias image is generally stable over a long time, and bias does not vary with time, and hence is independent of exposure time.

In order to study the bias level in the CCD, one may acquire an image with effectively zero exposure time[2]. In addition this exposure should be a so-called **dark frame**. Such a frame is acquired in a dark setting such that no light reaches the chip during exposure or readout. Since the chip is initially discharged right before exposure, and then read out seqentially after the exposure has been completed, it is important to ensure that as few photons as possible reaches the chip.

A master bias frame may be constructed by averaging many repeats of a dark frame taken at (effectively) zero exposure (0.001s for the test procedure camera). Such a frame may be seen in

3.2.4 Noise

For a CCD there are three main types of important noise. These are **Readout noise (RON)**, **Photonic noise** and thermal noise also called **dark current**. These three kinds of noise will be discussed in turn below.

3.2.4.1 Readout noise

Readout noise is as stochastic process associated with the amplkification of the signal at the amplifier during readout of the charge from the chip. It is usually quoted in terms of the number of a RMS number of electrons introduced per pixel upon readout [3]. Read noise cannot be eliminated completely, but it can be minimized.

[2]By 'effectively zero' we mean, as short an exposure time, as is permitted by the camera at hand. Typically this value is in the range of about 0.001s.

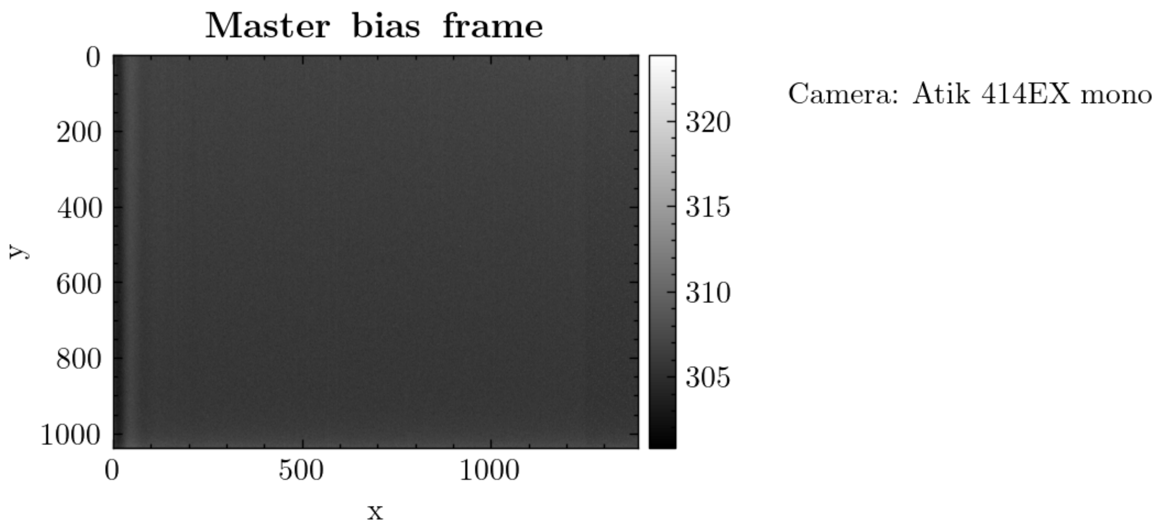

Figure 2: A master bias frame constructed by averaging many repeats of a dark frame taken at (effectively) zero exposure ($0.001s$ for the test procedure camera). The scale denotes the number of ADUs in a given pixel.

There are two components to the phenomena. The first one is an introduction of uncertainty at the ADC level. The process of converting the analogue signal to a digital one is not perfectly repeatable, but is a distribution of possible answers centered on a mena value. The second component is extra electrons introduced by the electronics at work during readout. The width of the resultant additive distribution is interpreted as the readout noise, as a number of introduced electrons per pixel. The size and temperature of the amplifier contribute to this noise. Especially the temperature introduces as significant contribution due to thermal fluctuations.

Read out noise follows a gaussian distribution, and the width, that is the standard deviation of the distribution, is the read noise (in electrons) divided by the gain (in electrons per count). This can be seen by producing a histogram of the values in the master bias frame. It is seen that this distribution is gaussian with a mean value of the mean bias level offset, and a width corresponding to the readout noise. See figure 3.

Generally a slower read out speed, will reduce the read out noise [3]. This however poses another complication, as a slower readout speed will

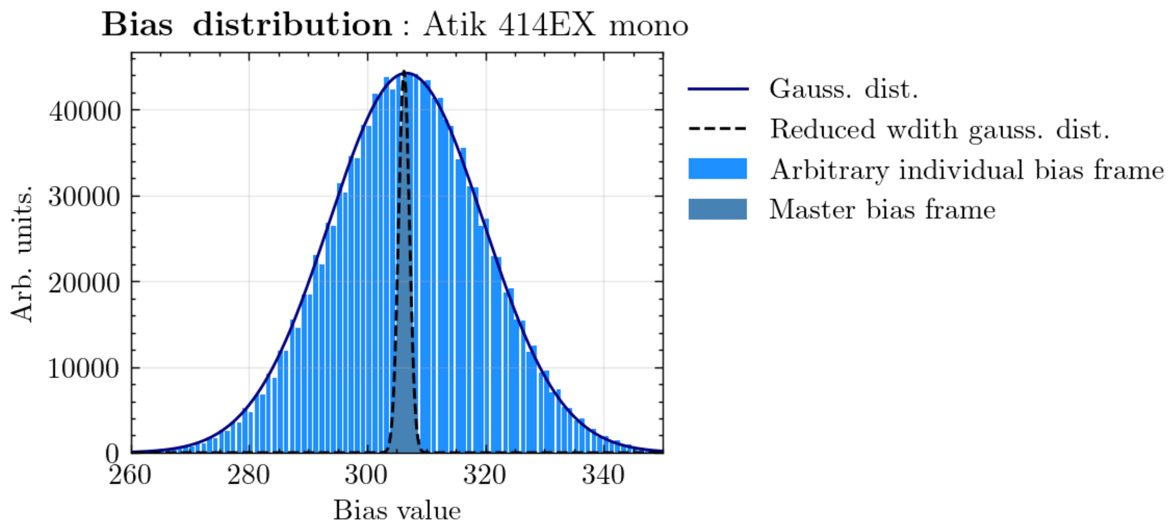

Figure 3:

3.2.4.2 Photonic noise

Photon noise is the natural variation, or in other words statistical fluctuation, of the photonic flux detected by the CCD. Photons detected follow a poisson distribution, since each photon is a discrete quanta, and the probability of the detection of the photon is independent of the other photons detected. A poisson distribution tends to that of normal distribution for large numbers, and hence the photon noise depends on the number of photons detected. We may hence reduce this photonic noise by observing bright objects that emit many photons, or by using longer exposure times.

3.2.4.3 Thermal noise and Dark current

Thermal noise, also called **dark current** is the resulting current within the chip, due to thermic motion of the electrons in the solid state material. This effect can be studied using so-called **dark-frames** described above, in which the chip is not exposed to incoming photons, and hence no photo-electrons should be produced (in the ideal case of a perfectly dark room). Dark current depends on time, and is usually given as electrons per second. We thus obtain the following relation for the dark current in the chip

$$\text{dark current} = \frac{\text{ADU} \cdot \text{gain}}{\text{exposure time}} \tag{3}$$

where the ADU value refers to the mean ADU / pixel in a dark frame. Gain is the detector gain described above. Since dark current results from thermic motion of electrons in the chip, it is strongly temperature dependent, and can be practically eliminated by cooling the chip. A well designed testing procedure should characterize the dark current levels as a function of temperature of the chip. Readout noise levels are usually significantly greater than dark current levels, so dark frames must be taken at exposure times that are long, in order to yield an appreciably large dark current effect that can be practically isolated from that of the readout noise. This can also be achieved by averaging over a large number of dark frames. It should also be noted that a master bias frame should be subtracted from the dark fame in order to isolate dark currents.

A master dark current frame can be constructed by averaging over many dark frames at a given exposure, subtracting the master bias frame, and then computing the dark current in each pixel according to equation 3. Such a frame can be seen in 4

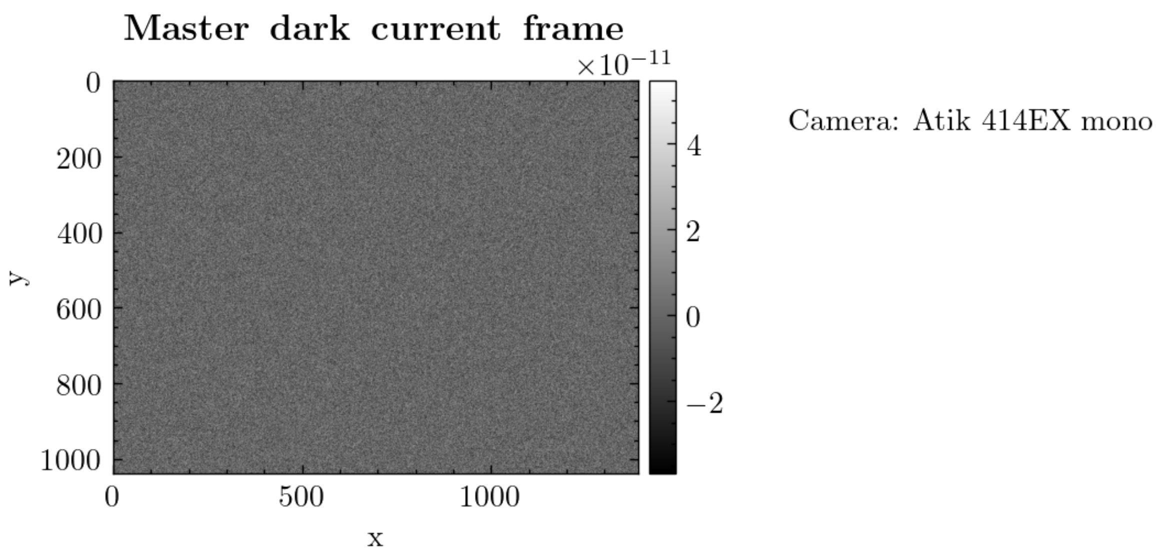

Figure 4: A master dark current frame constructed by averaging over many dark frames at a given exposure, subtracting the master bias frame, and then computing the dark current in each pixel according to equation 3.

3.2.5 Flat fielding

A CCD may not have a perfectly flat response to incoming light. By an ideal flat CCD detector we mean a detector that uniformly detects photons with the same efficiency, sensitivity, gain etc, across the entire light-sensitive area of the chip. This ideal situation is seldom realized in practice due to faults in the chip or various manufacturing processes. Some CCDs may be constructed by joining several photo sensitive pieces of silicon, or may be constructed by grinding off layers of a block of silicon to get achieve a thin detector. This grinding process may leave circular or straight lines through the chip that can be either more or less sensitive to light. There may also be specks of dust or fingerprints on the camera window causing blocking of light and diffraction patterns in the image.

In order to overcome this difficulty and to reconstruct the desired image from detector data in a non-flat CCD (which is usually the case at hand), we can utilize flat field frames. Such frames are acquired by imging a flat field, such as a white flat screen. Any non-uniformities in the resulting image, should, in the ideal experimental design, be due to non-flatness of the chip, or obstructing objects on the camera window. This flat field frame then represents the relative light sensitivity between pixels in the chip. Construction of a master flat field frame, by averaging over many such flat exposures, can then be used as a correction frame after the frame has been normalized to unity. This is done by finding the greatest pixel ADU-value, and dividing the rest of the pixels in the frame by this value. This should be done after a hot pixel correction. Now the master flat contains values in the interval (0, 1], the left end of the interval representing pixels that receive the most light. This frame can now be used for flat field corrections. This is done by dividing an image in question with the master flat on a pixel-by-pixel basis [3]. An example of such a master flat frame can be seen in figure 5

3.2.6 Hot pixels

A hot pixel is a pixel which after an arbitrary exposure time, has an ADU value that is significantly greater than the mean value in the image. Such an effect can occur either because that pixel has a higher sensitivity to incoming photons, due to the detector being struck by cosmic rays, or because the dark current in that pixel is higher and/or not proportional to time in a linear way. For cameras in space, cosmic rays are of great importance, since the rate of incidence is much higher than at the surface of earth.

3.2.7 Linearity

Linearity is the measure of response between measured ADUs and exposure time. In other words, if one doubles the exposure time, we expect to also double the number of measured ADUs. We may study this effect by acquiring frames at different exposure times, and comparing the mean ADU/pixel across exposure times. A detector is seldom

[3]Division by zero will not be a problem in practice, since generally there will always be a non-zero value in each pixel, for an arbitrary exposure time greater than bias, even after bias correction.

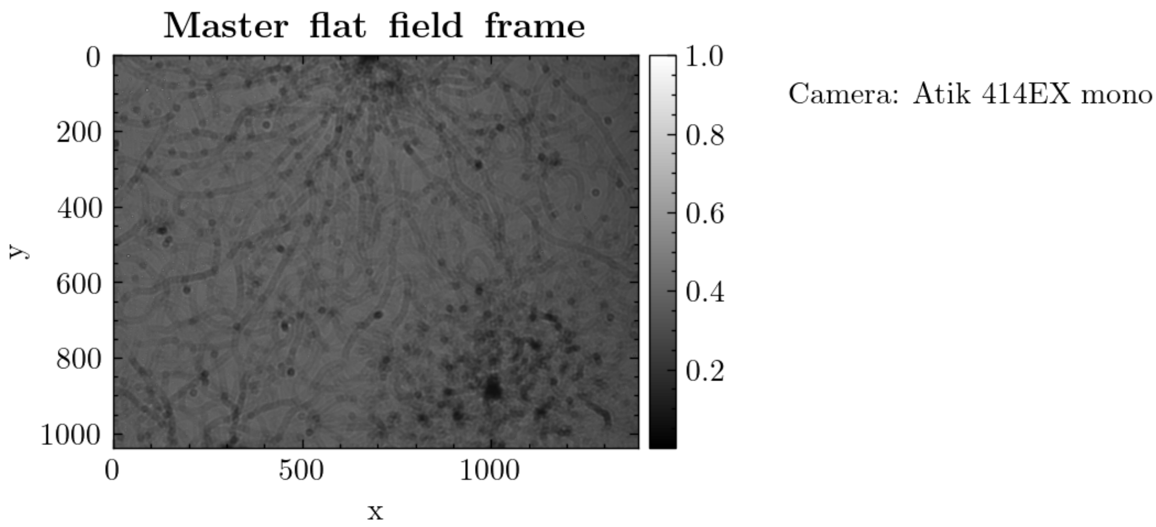

Figure 5: A master flat frame constructed by averaging over a given number of light exposures of a flat field, with 10s exposure times, subtrcting the bias and dark current master frames, and then normalizing to unity as described in section 3.2.5.

perfectly linear, and thus we wish to determine the unlinearity, so we can correct for it. The measure of the unlinearity of the detector can be defined as the deviation of a given measurement from the perfect linear case.

3.2.8 Charge diffusion and charge transfer efficiency

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Methods

4.1 Developing the characterization procedure

One of the aims of this project is to develop an experimental procedure that enables us to characterize the camera that may be flown on the STEP mission. This characterization is crucial in order to test the validity of the scientific goals for the mission. Such a procedure should be exactly reproducible, such that we can ensure its correctness.

4.1.1 Preliminary thoughts and considerations

4.1.1.1 Acquiring data and reducing noise

Characterization of a CCD chip involves acquiring image frames in a variety of way to study several effects. We study effects by acquiring frames while varying a parameter like temperature (thermal noise) or exposure time (linearity). For each value of this varied parameter, say temperature for thermal noise (dark current), we wish to associate a functional value, here electrons per second in the example at hand. This is done by considering the frame taken at that value of the variable (temperature), and computing the mean value of the experimental metric (dark current, electrons per second) across all pixels in the image. For any measurement, we should take steps to reduce the noise in the image. Dark current can be reduced by cooling the chip before acquiring data frames. Readout noise is **gaussian** and the noise in the distribution is reduced by a factor of $1/\sqrt{N}$ for N measurements. Hence, for each datapoint, before computing the desired variable, like dark currrent for a specific temperature, we should, at that temperature,

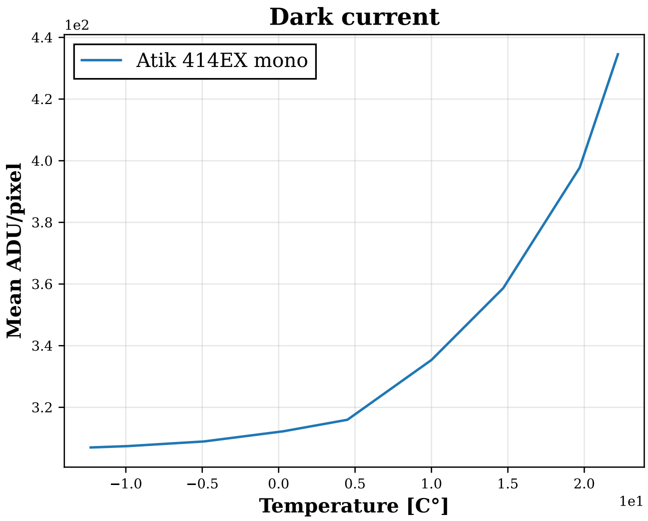

Figure 6: Preliminary dark current measurement, performed at the office in sub-optimal settings, to get a first glimpse of the behaviour of this variable.

acquire N frames, and construct a mean image from these N frames. Typically N is chosen to be as large as is practically feasible. The value of the experimental metric is then computed from that average frame.

4.1.1.2 Background noise and Dark current

In order to find a good starting point for the development of the testing procedure, a preliminary investigation of the noise levels of the chip was carried out. This was done at a desktop in an office, using a very primitive experimental setup. This preliminary test confirms that dark current is strongly dependent on temperature. See figure 6. Since the camera cooler is only able to cool to a temperature gradient of $\Delta T = 30°\text{C}$, the temperature $T = -10°$ C was chosen since we cannot be sure that we can feasibly stay at a lower temperature, if room temperature varies. This should ensure that we can minimize dark current and read-out noise.

4.1.1.3 Master bias and flat field frames

300 images are acquired at exposure times of 0.001 seconds. From these a **master bias** frame can be constructed. This frame should be subtracted from all other data points, and represents a bias voltage applied to the chip, in order to avoid negative values in the

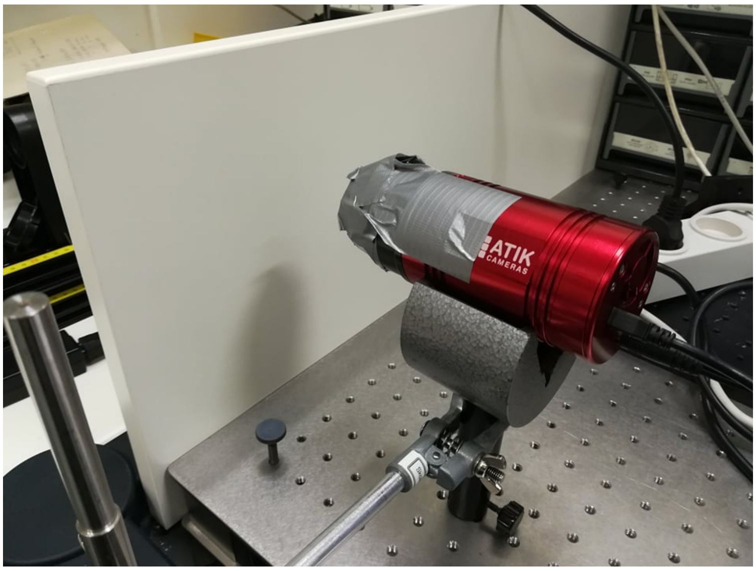

Figure 7: Initial experimental setup, which was used both for the light and dark exposures.

ADC. This effect is also studied as a function of temperature via the readout noise (RON) effect. In addition flat field frames (300 frames) are acquired as well, and meaned over, subtracting the master bias. All of these frames are acquired at the $T = -10^{\circ}$ temperature setpoint chosen above.

4.1.1.4 The initial experimental setup

The initial setup used with this camera, to carry out the testing and characterization procedure, can be seen in figure 7.

The setup consists of the aforementioned camera in question, which is resting on a stand, pointed into a white lacquered wooden screen. The camera is connected via USB2 to the lab-computer, and is additionally connected to a power supply. Since the setup for dark frames simply require a sufficiently dark room, an in house dark-room is used. For all light exposures the ambient room lighting was used, and the camera (with a pinhole mounted with tape, constructed from heavy black cardboard) was pointed into the screen. For all dark frames, the same configuration was used, but with no ambient light, and computer screens turned off.

4.1.1.5 Exposure times for linearity

The linearity measurement consists of acquiring exposures of the white screen, as a function of exposure time, in order to study the linearity of the response in measured photons by the detector. Hence we should first determine which exposure time interval to use. At first a 100s exposure acquisition was carried out, in which considerable saturation was observed. From this it was concluded that an exposure time of 100 seconds was a good 'datapoint' to use for the last acquisition. The choice of exposure times relies on trial and error, to decide what range of exposure times we should use, at a given light source intensity. At first frames at exposures between $0.001s$ and $110s$ in $5s$ intervals was acquired. It was found that the light source stability varies significantly, resulting in greater uncertainty in short exposure measurements, and hence it was chosen to omit 0 seconds, and instead acquire frames in the interval $1s$ to $10s$ in 1 second intervals, in addition to the data sequence described just above.

4.1.1.6 Noise as a function of temperature

Readout noise and dark current are expected to be temperature dependent, and hence, in the entire cooling range of the camera, it is interesting to acquire images of dark frames in order to study the behaviour of these physical effects. Exposure times are chosen such that the minimal exposure time is chosen for the readout noise images, since no photon should have been detected, and since dark current is time dependent, and hence should be negligible in this regime. For dark current frames, it is crucial to pick an exposure time such that the dark current contribution is greater (by a considerable amount, higher orders of magnitude) than the readout noise contribution. Dark current follows a **poissonian** distribution, and to recover this underlying distribution we should pick long exposure times. Since this require **very** long times of exposure, it is more practical to pick an exposure time of $10s$, and then mean over 100 acquired images at this temperature, to reduce the noise contribution, since readout noise should be gaussian with a zero-centered mean value.

4.1.1.7 Hot pixel treatment

It is crucial to treat hot pixels. One way to do this, is to realize that hot pixels, are those pixels in which dark current does not show a linear temporal behaviour. Acquiring a *very* long exposure, and a medium long (considerably shorter than the former) exposure, we can study the dark current in each pixel, and determine if there is a linear relationship between the two frames. This is done by scatterplotting the pixels, and findin (qualitatively) the range within which the data points seem to follow a linear relationship. The remainder are considered hot in this sense, and from this information a mask can be constructed. These pixels can then be omitted in mean values used in the other analyses.

4.1.1.8 Testing of ground assumptions

In our experimental setup, assumptions have been made that need to be tested. The two most important ones, which enable the testing of linearity are that

- The camera has a well-calibrated zero point temporally. That is to say that a 10 second exposure is actually physically the frame resulting from light being able to enter the chip for exactly 10 seconds.
- The ambient light source in the room is stable during exposure, so we can accurately compare ADU intensities between different frames.

The latter assumption can be tested by analyzing the many exposures taken during the linearity sequence, by plotting the percentage deviation, from the mean ADU (mean across all 100 exposures at a given exposure time) as a function of exposure number.

4.1.2 Stability of the lightsource

That the light source used for the light exposures, is stable is one of two ground assumptions that went into the experimental setup. This assumption should be tested, since we can generally not expect a flourescent light bulb, connected to the main relay, to be stable to a high precision. At first, this was tested by utilizing the wealth of data acquired during the linearity measurement sequence. At each exposure interval, 100 consecutive frames were acquired. This enables us to plot the intensity as a function of time. This was done by considering the series of images, say the series of images taken at a $30s$ exposure time. From this series a mean image was constructed. The mean ADU/pixel in this image is our reference value. The percentage deviation in the mean ADU/pixel, in each of the individual frames, was then plotted as a function of time (repeat numbers, properly speaking). This way it was possible to qualitatively judge the stability of the lightsource as a function of time. Such a plot can be seen in figure 8. It is clear that, save for a few of the exposure times, the lighting is only stable to a few percentage points deviation. This gives us a first estimate of the instability, indicating that we should attempt to correct for this source of systematic error.

These deviations from perfect stability can not be used as a correction, since this does not include the correlation of instability between exposure times. Instead it is proposed that a reference exposure is utilized. Within a given repeat sequence,

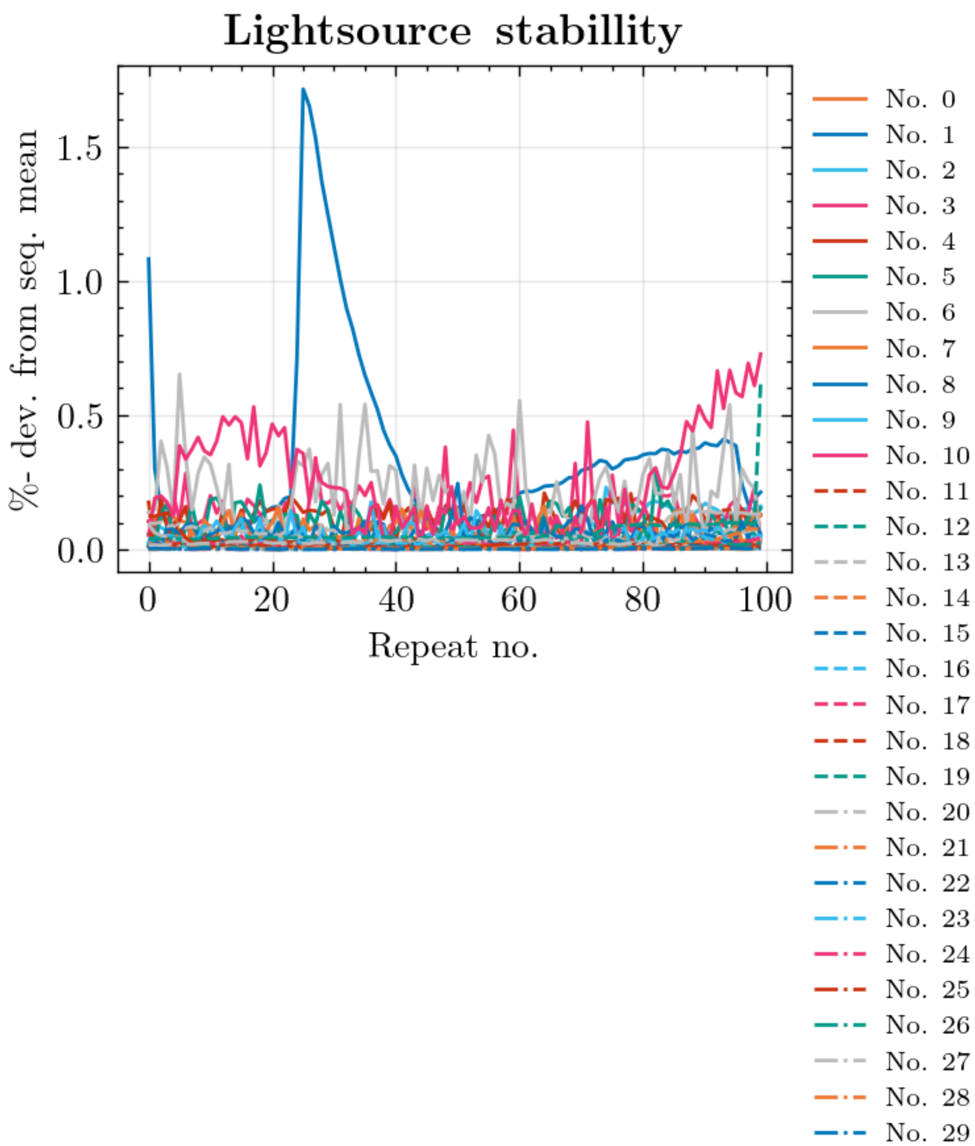

Figure 8: A plot of the temporal dependence in the lightsource intensity (flux) across each of the different exposure times. Numbering is ordered according to the preliminary series of exposure times as described in the text.

one may use a reference of $10s$ exposure by alternating between the chosen reference exposure, and the actual desired exposure. Such an exposure series is akin to $[10s, 1s, 10s, 1s, 10s, \ldots 10s, 2s, 10s, 2s, \ldots]$ covering the entire range. For each actual frame we then have a 10 second exposure just before and right after. For the test procedure camera, the software designed for the camera, only enables the user to set up a sequence of 10 data points to be acquired automatically, but allows for that sequence to be repeat. hence it was most practical for the analysis to acquire data in the series $[10s, 1s, 10s, 2s, 10s, 3s, 10s, \ldots 10s, 9s, 10s]$, repeat that N times ($N = 10$ was chosen due to time constraints), and then repeat until the desired exposure time range has been covered. The two reference measurements to use in correction of a given frame will then be the two taken at adjacent times.

The flux of the light source at the time of our desired frame then lies somewhere in between, assuming no wild fluctuations or drifts, and a linear change in the time in between acquisition of the two reference frames. These assumptions of local monotonicity of the light source flux are justified by considering figure 8. Let $\boldsymbol{F}(x[s]) = \text{mean}\left(\text{Image}([s])\right)$ be interpreted as the mean flux in an image of exposure time s in seconds, that is, the mean ADU value of an arbitrary image of exposure time s. Hence we may correct for the instability, using a 10 second reference exposure, for a given frame via the computation

$$\boldsymbol{F}(x[s])_{\text{corrected}} = \frac{\boldsymbol{F}(x[s])}{\frac{1}{2}\left[\boldsymbol{F}(10s)_{\text{before}} + \boldsymbol{F}(10s)_{\text{after}}\right]} \cdot 10 \tag{4}$$

Where the last factor of 10 is to account for the relation between the 10 second and 1 second exposure times, in the ideal case where there is no time offset.

4.1.3 Time calibration

Another assumption is one that pertains to the camera itself, the time calibration of the measurements. A series of measurements was constructed in order to study whether or not the zero point of the camera imaging was actually at $0s$ and to what precision. A preliminary estimate can be studied by acquiring eight frames, by noting that, under the assumption that our detector is linear, it should be true that for a given frame Image(Exposure time), we must expect for a perfect time calibration that

$$\frac{\text{Image}(21s) - \text{Image}(1s)}{\text{Image}(11s) - \text{Image}(1s)} = \frac{\text{Image}(10s) - \text{Bias}}{\text{Image}(20s) - \text{Bias}} \tag{5}$$

Or that

$$\frac{\textbf{mean}(\text{Image}(21s) - \text{Image}(1s))}{\textbf{mean}(\text{Image}(11s) - \text{Image}(1s))} - \frac{\textbf{mean}(\text{Image}(10s) - \text{Bias})}{\textbf{mean}(\text{Image}(20s) - \text{Bias})} = 0 \tag{6}$$

where **mean**() refers to the mean ADU/pixel within an image. The result of this, for the test procedure camera, being 0.0063 indicates a time offset which must be determined properly, and applied as a correction. The test procedure camera does not have a shutter, and the data sheet [1], specifies a $1/15s$ readout time. Hence an exposure time of $1s$ should correctly be interpreted as an exposure time of $1s + \Delta t$, where Δt should be deduced experimentally. Via a seperate linearity measurement series with greater precision (more datapoints) in the uncertain interval of $1s - 10s$ in which this readout time would actually be able to significantly impact exposure times, we can get a first estimate of Δt by fitting a linear function to the data points, and determining the roots of polynomium. If there is a time offset, the line will intersect the first axis at a point different from the origin. The intersection point on the first axis should be subtracted. For a negative value of the intersect point on the first axis, a subtraction physically corresponds to a longer exposure time. We should then correct for this time offset by adjusting the equation 4, and achieving a the same time the true measure of unlinearity, δ as

$$\delta = \left(\frac{\boldsymbol{F}(x[s])}{\frac{1}{2}\left[\boldsymbol{F}(10s)_{\text{before}} + \boldsymbol{F}(10s)_{\text{after}}\right]} \frac{10s + \Delta t}{x[s] + \Delta t} - 1 \right) \cdot 100\% \tag{7}$$

4.1.4 Shutter test

4.2 Measurement plan

4.2.1 Linearity

For each exposure time in the series $[1, 2, \ldots 9, 10, 15, 20, \ldots 100, 105, 110]$, all in units of seconds, with a 10 second reference frame as described above, was acquired, with $N = 10$ repeats which are then meaned over in order to reduce readout noise levels. The unlinearity is computed according to equation 7 for each exposure time after meaning across N frames. This produces a plot like figure 9

4.2.2 Temperature dependence of noise

For each temperature in the series $[-10, -8, -6, -4, -2, 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20]$ all in °C, 100 bias frames at 0.001s, and 100 dark frames at $10.0s$ for each temperature was acquired. The former was used to compute the readout noise as a function of temperature. Each temperature sequence was considered. As an example consider the one for -8°C. For this series, each repeat image was considered in turn, and the mean ADU/pixel was computed and subtracted form every pixel in the image. This resultant image was

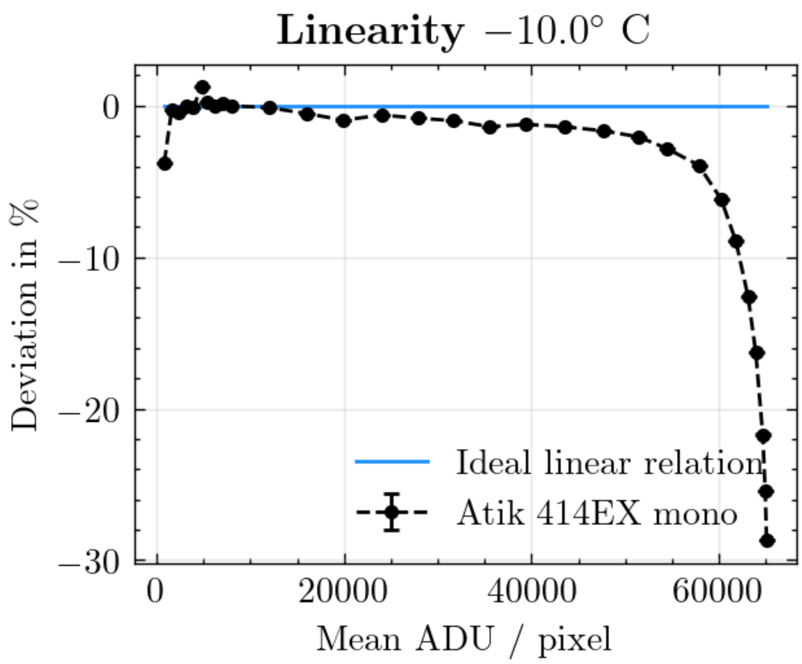

Figure 9: A plot of the percentage deviation from ideal linearity, computed according to equation 7 for each exposure time after meaning across N frames.

a stochastic distribution around zero. We expect this to be a gaussian distribution. By multiplying with the camera gain factor in each pixel, we can interpret the width of this distribution as the readout noise, in units of electrons. The standard deviation was computed from the flattened array of pixels to obtain the width. This yielded, for a temperature sequence, 100 standard deviations. From this a RMS value was computed. These values can then be plotted as a function of temperature.

The dark current data was treated in much the same way. For each temperature sequence, a mean image was constructed in order to reduce the readout noise contamination in the image. This picture was then multiplied with the camera gain factor, and divided by the exposure time according to equation 3, and from this the mean ADU/pixel was computed. This is plotted as a function of temperature.

The result of these two anlysis may be seen plotted in figure 10

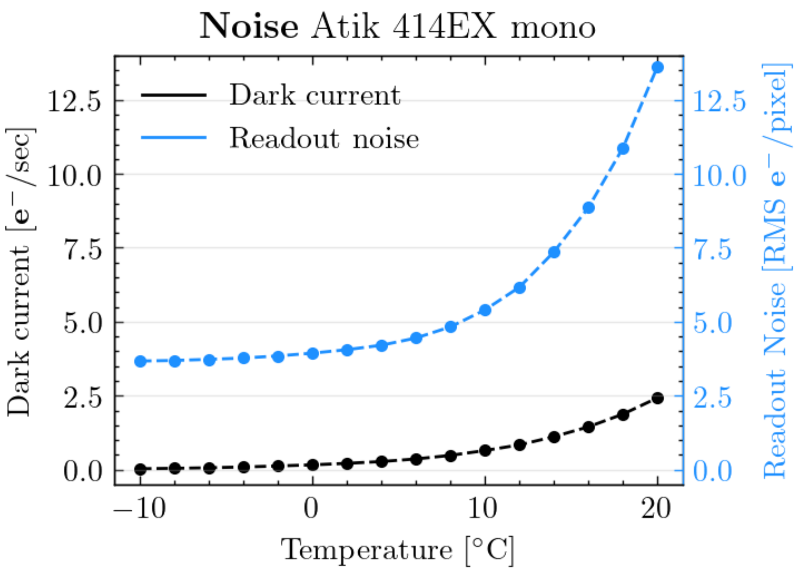

Figure 10: Dark current and readout noise as a function of temperature. The datapoints have been constructed by acquiring 100 dark frames at exposure times 0.001 s for readout noise, and 10s for dark current, at each temperature. Readout noise is computed according to section 4.2.2, and dark current according to equation 3.

5

Results

6

Discussion

7

Conclusion

Bibliography

[1] Atik cameras spec sheets. https://www.atik-cameras.com/specification-tables/. Accessed: 8th October 2021.

[2] Philip Hoffmann. *Solid State Physics. An Introduction 2nd ed.* Wiley-VCH Berlin, 2015.

[3] S. Howell. *Handbook of CCD Astronomy*. Cambridge: Cambridge University Press, 2nd edition, 2006.