

Fast Time-Resolved Imaging Photometry for Gamma-Ray Burst Studies

by

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Abstract

Charge Coupled Devices (CCDs) revolutionized modern astronomy, playing critical parts in modern cosmology surveys and the discovery of dark energy. However, they have a read noise penalty that makes them unsuitable for exploring short time domain phenomenon. EMCCDs are a relatively new technology that allows photometric measurements with high time resolution essentially free of read noise, an ideal tool for transient sources. Multiple, simultaneously operating EMCCD cameras in different filter bands also allow time-resolved broad-band spectral shape measurements. These measurements of the broad-band spectral shape are critical in determining the emission mechanism of GRBs (Shen Zhang, 2009). Measuring the optical slope would help identify emission mechanism definitely. In addition, electron multiplying CCDs have rarely been used in astronomy, especially in the 0.1 - 1s regime. In this thesis, performance predictions for EMCCD cameras along with the comparisons to conventional CCD performance will be made and compared to measured performance of the cameras on the sky, including observations made with the Zeiss 1000 W telescope at Tien Shan Astrophysical Observatory.

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Chapter 1

Gamma-Ray Burst Telescope

Experiment at NU

Gamma-ray bursts (GRBs) were discovered in the late 1960s in data from the Vela satellites [20]. Over the years of study it is now known that GRB is a bright phenomena (about several photons $cm^{-2}s^{-1}$ flux in the 50 - 300 keV band). [24] Most gamma-ray bursts (GRB) have duration 10-60 seconds from tens to hundreds keV. As it can be seen from figure 1-2, the optical emission drops rapidly from prompt to afterglow. From looking at figure 1-1 it can be noted that it is crucial to start making observations within 10 seconds after the bursts are detected. [26] Due to the lack of the data at the optical band at the beginning of the bursts, there are several models that describe the origin of the emission. [11] Multiple, simultaneously operating EM-CCD cameras in different filter bands allow time-resolved broad-band spectral shape measurements. These measurements of the broad-band spectral shape are critical in determining the emission mechanism of GRBs [30]. Measuring the optical slope would help identify emission mechanism definitely.

After 1997, when optical radiation from gamma-ray bursts was first discovered, we learned that we are dealing with the most powerful explosions in the universe. [14] This radiation, observed a few hours after the burst, is in fact, an afterglow that is generated after a giant explosion in a shock wave passing through the interstellar medium surrounding the central machine [3]. The afterglow depends little on the

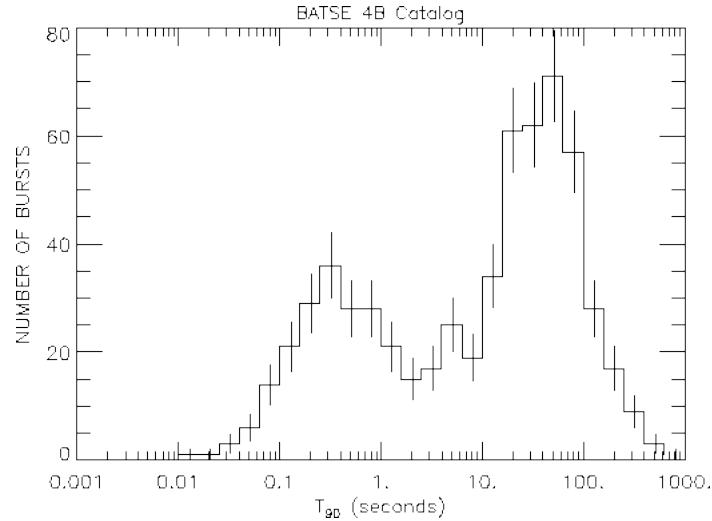


Figure 1-1: Histogram of detected numbers of GRBs. Figure is taken directly from P. R. Wozniak et. al. [27]

nature of the explosion and is mainly determined by the energy of the explosion and the properties of the surrounding matter. Although many researchers agree that gamma-ray bursts are the result of the formation (collapse) of special fast-rotating black holes. [22] To understand the details of this process, it is necessary to register the process itself, that is, to carry out observations in all ranges of the spectrum (especially in optical) at the time when the gamma-ray burst has not yet ended. For the first time among few, prompt optical radiation from the gamma-ray burst GRB990123 was observed in 1999 by the ROTSE-I observatory. [12]

However, observing prompt radiation emission is much more difficult than afterglow, because the gamma-ray burst itself, as a rule, lasts no more than a few seconds. Therefore, there are two ways to observe the phenomena:

Constantly observe large areas of the sky, expecting that the gamma-ray burst will fall into the field of view accidentally (a brilliant example here is the observations of the TORTORA apparatus of the brightest burst GRB080319B [24]

Or to use special robotic telescopes that are ready to start making observations at any time depending on the signal from the space observatory (i.e. SWIFT) - the alert mode.

The main difficulty with the second method is to quickly make 4 steps, while the

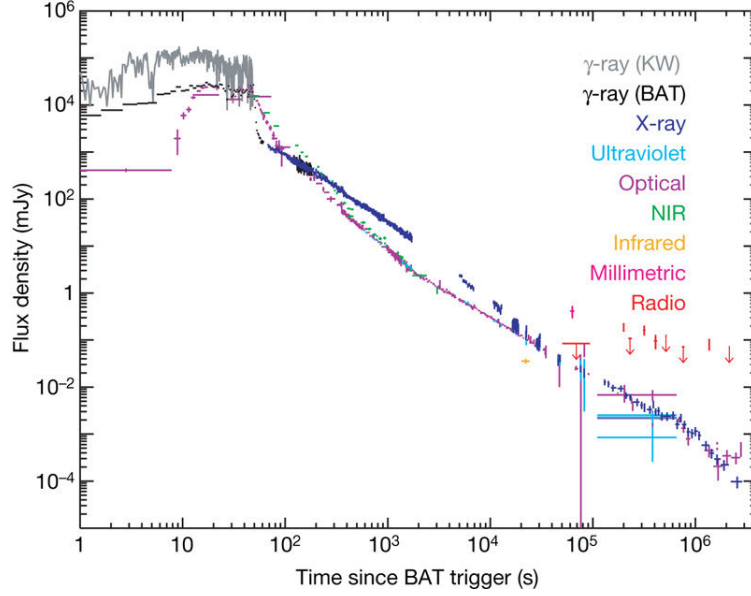


Figure 1-2: Optical light curve of GRB 080319B, "The Naked Eye Burst" is considered the brightest optical burst ever observed. As it can be seen, the flux density in optical range drops rapidly in about 100 seconds after the beginning of observation (optical emission drops rapidly from prompt to afterglow).[10] See details in the text. Figure is taken from Racusin et. al. 2008

gamma-ray burst is still "online" (also see figure 1-3).

1. Gamma-ray bursts are detected by cosmic gamma-ray telescopes (Swift, Fermi, INTEGRAL etc.)
2. After processing the data (within 10 seconds), the spike coordinates are sent to the Center of the International Network for the Study of Gamma-ray Bursts located on the NASA website (GCN). [24]
3. The received coordinates are sent over the Internet to all ground-based telescopes, 0.5 sec
4. Telescopes are setup and guided by the received coordinates and start observing in according spectrum. (it takes about 7 to 40 seconds for small telescopes to locate and start observing).

The "Naked Eye Burst 080319B" is the only of a kind ever observed (from the very beginning) burst by the SWIFT satellite in the last 14 years, [9] with the peak brightness in a visual magnitude of 5.3 (see figure 1-2) at a redshift of $z = 0.937$ [10]. As it was stated in the paper by Racusin "GRB 080319B was the brightest optical

burst ever observed.” Looking at the data in optical observation in figure 1-2, we can see, that the data is missing at the first 10 seconds after the burst. Meanwhile, the majority of GRBs are 10 magnitude fainter (around 16 mag). So how do we get the best time resolution with the field 10 magnitude fainter?

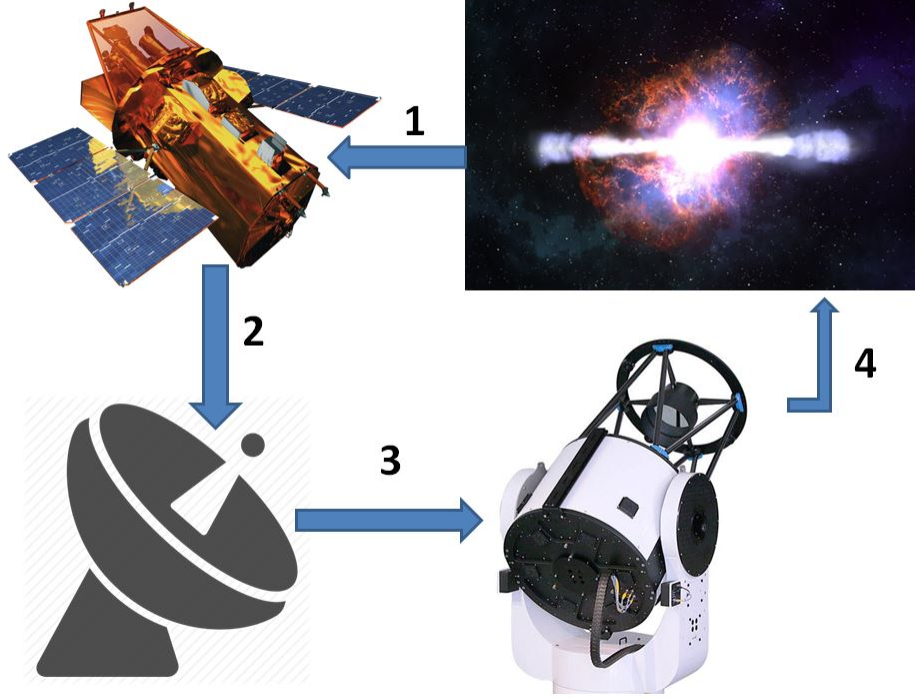


Figure 1-3: Graphical illustration of the working principle of the GRB Telescope mission at the Nazarbayev University presented by Dr. Grossan. After the GRB is detected by the SWIFT, the coordinates are sent to the ground by GCN and then via internet to the observatory. It takes then about 10 seconds to start making observations with the telescope after the burst is detected. [11] This would allow us to get data for majority of bursts in several bins of time resolution for correlation. Images are taken from the web.

As a part of the of the experiment devoted to the study of GRBs, Energetic Cosmos Laboratory at Nazabayev University conducts an observational research. The idea of the research is well described in presentation paper [11]. Using fast-moving telescope with aperture diameter of 700 mm, we should be able to point anywhere on the observable sky in less than 9 seconds. This would allows us to start making observation of the active GRB at the prompt emission phase. In addition, the images will be taken by two electron-multiplying charge-coupled device (EMCCD) operating

at high-time resolution in B and V filters. So far, we ran experiment at the Tian-Shan Astronomical Observatory in November 2017, where we tested the experimental camera performance (Andor EMCCD) at various electron multiplication gain and exposure time settings. On the basis of the results obtained from that test, we came with the best optimal performance recommendations.

Chapter 2

Introduction to Astronomical Imaging

2.1 Charge-Coupled Device - CCD

For the first time, the Charge-Coupled Device (CCD) principle with the idea of storing and then reading electronic charges was developed by two BELL engineers in the late 60s in the search for new types of computer memory. [23] This idea turned out to be unpromising, but the ability of silicon to respond to the visible spectrum of radiation was noticed and the idea of using this principle for image processing was developed.

What distinguishes the CCD receiver from a conventional semiconductor photodiode then? First, light-sensitive areas - pixels (elements that absorb electromagnetic radiation and convert it into electric charges) in the CCD receiver are great in numbers: from several thousands to several millions. The dimensions of the individual pixels are assumed to be the same and in the order of microns. Pixels can be aligned in rows and columns and receiver is called a CCD matrix.[6]

Secondly, in a CCD receiver, there are not many numbers of electrical contacts for outputting electrical signals that would seem to come from each light receiving element. Yet, an electronic circuit is connected to the CCD receiver, which allows to extract an electrical signal from each photosensitive element proportional to its illumination. Electrons appear in pixels under the influence of light coming from a

source. Within a given interval of time, each pixel is gradually filled with electrons in proportion to the amount of light that has entered it. By the end of the exposure time, the electric charges accumulated by each pixel are transferred to the device output and measured by the register. After exposure of the chip, the electronic control circuit of the instrument supplies a complex set of impulse voltages, which begin to shift the columns with the electrons accumulated in pixels to the edge of the matrix. The charges are shifted in perpendicular direction and fall on the measuring element, creating signals proportional to the individual charges. Thus, for each subsequent moment of time, we can get the value of the accumulated charge and figure out which pixel on the matrix (row number and column number) it corresponds to.

The charge-coupled device (CCD) uses a silicon photo sensor (pixel) connected to a charge storage area, which in turn is connected to an amplifier that reads the amount of accumulated charge. Detected photons generate electronic charges that accumulate in the charge storage area. If the incident photons have sufficient energy and are absorbed in the depleted region of the semiconductor, then an electron is released which then can be measured as a charge [33]. In CCD sensors, usually only one amplifier is used, located in the corner of the entire matrix. The accumulated charge is sequentially transferred through parallel registers to a linear serial register, and then to the output node adjacent to the reading amplifier. The performance of the CCD sensors widened the limits in the efficiency of recording light and reducing the noise from both the weak signal and the reading amplifier. One of the disadvantages of CCD sensors is the fact that the array is essentially a sequential readout device, that leads to the noise generation due to slow reading rate (charge transfer).

2.1.1 Electron Multiplying Charge-Coupled Devices (EMCCDs)

The EMCCD camera has essentially the same structure as a CCD with the addition of a very important feature. The accumulated charge is transferred through parallel registers to a linear register, as before, but now, before the charge is read, it is

amplified through the multiplication register, reducing the effective readout noise to levels smaller than one electron rms. [7] The signal gets amplification above the read noise, which leads to a higher sensitivity compared to the CCDs. EMCCD cameras use similar structures, like CCD cameras, and are also limited in obtaining the minimum exposure time [5].

EMCCDs have great advantage over the old micro-channel plates with bi-alkali photo-detectors that were used as imaging photo-detectors before the CCD technology came. The Swift UVOT instrument was equipped with one of those detectors and has quantum efficiency peak of 24% in the UV band. [26] Meanwhile, EMCCDs and CCDs have QE of about 95%. [33]. So the main advantage of the EMCCD cameras is the fact that, EMCCDs do not have read noise penalty as much as CCDs. The details are given in the following chapter.

2.2 Reduction of CCD and EMCCD images

The accuracy of measuring parameters above, largely depends on the signal-to-noise ratio of the objects under the observation. The statistics of the photons incident on the radiation receiver in the first approximation are described by the Poisson distribution. The CCD matrix creates an additional noise, determined mainly by the so-called read noise. The determination of the accumulated charge (reading out) in each element (pixel) of the CCD matrix is burdened with an error. On average, the reading noise of CCD systems used today in astrophysical observations is in the range of 5-10 electron per receiver element, the minimum achieved value is about 1 electron per pixel. [6] For bright light signals, the noise of the CCD readout can be neglected, however, the read noise has a significant effect in cases where a small number of electrons accumulate in the pixels (weak signal of a source). In addition to random errors that affect the statistics of samples in the image, the CCD array has a number of instrumental (systematic) effects that significantly reduce the accuracy of spectral measurements, including: the heterogeneity of the sensitivity of the matrix and the discontinuity in the bias current both large-scale and small-scale, dark current,

nonlinearity of the pixel response, positional instability of the receiver, sensitivity of the matrix to high-energy "cosmic rays" etc.[15] In general case, all these instrumental effects change with time, which must be taken into account in the observation process. Let us dwell in more detail on the description of the basic instrumental effects of the CCD array.

In the absence of any exposure of the matrix during image reading, we will receive on average a non-zero value of the samples, this initial level of the signal is called the bias current, and in each element of the matrix the value of the zero current is different.[29] Typically, the amount of bias current can be varied, usually the initial signal level is selected such that, it reaches the linear portion of the characteristic curve of the receiver in the region of small samples. For correct subtraction of the bias, several series of images without exposure (or with the so-called zero time exposure) are obtained during the observation process, each series consists of several images that are averaged among themselves to reduce the effect of receiver read noise. The number of series and images in each series is determined by the instability of the bias current and the necessary photometric accuracy. It is common to make two series of bias frames (at the beginning and end of observations). [7] [8]

With short and long exposures, with the closed (dark) cover of the CCD we get a signal different from the bias current during reading the arrays. Elements of the receiver can spontaneously generate electrons with the passage of time at any temperature other than absolute zero. The signal read from the CCD array in the absence of illumination that is proportional to the exposure time is called the dark current. This effect depends mainly on temperature, therefore CCD matrices used in astrophysical observations are cooled to low temperatures up to $-100C^0$ and even lower with the help of liquid nitrogen. [31] The procedure for subtraction of the dark current from the sample images is similar to subtraction of the bias current. However, in order to take into account this instrumental effect correctly, the time to acquire a dark-current frame should be equal to the acquisition time of the object image and, as in the case of subtracting the bias current, several frames with dark current must be obtained to reduce the effect of receiver read noise.

$$Flux = \frac{N(e^-)}{QE} = \frac{gain * DN}{QE} \quad (2.1)$$

Here, Flux is number of photons detected, QE is quantum efficiency of the detector, DN is acronym of Data Number that represents proper transformation of analog signal to digital units (ADU). Analog-to-Digital Converter uses 16-bits to represent the DN, the dynamic range is therefore: $(2^{16} - 1) = 65,535$. Let's call PW - full well capacity of pixel, then the gain is defined as

$$G = \frac{PW}{ADC_{saturation}} \quad [\frac{e^-}{DN}] \quad (2.2)$$

As an example of a CCD performance:

"For LRIS, the CCD pixels "fill up" at around 300,000 e^- , the highest data number is 65,535 so a sensible inverse-gain is $4.58e^-/DN$. Using the inverse-gain of around 2 that is available, the ADC saturates long before the pixels well have filled, giving up a factor of 2.3 in dynamic range per exposure". [1]

The following figures will be used in the next equations and calculations

Table 2.1: Meaning of variables used in the calculations.

ϕ_p	incident photon flux	photons/sec/pix
B	background count rate	$e^-/sec/pixel$
t	exposure time	seconds
r	radius of an aperture	pixels
n_{pix}	number of pixels in aperture	πr^2
G	gain	e^-/DN
D	dark current	$e^-/pixel/sec$
σ_r	read noise	e^-/pix
η	Quantum Efficiency	%

Let's now discuss types of noise in the measurements. Due to the fact that photons arrive in a randomly to the surface of the detector, there is always uncertainty linked to it.[18] It turns out that the 68% confidence interval for a Poisson distribution, in

the limit that the mean is large, is the same as that for a Gaussian. Since the number of photons we measure is usually large [32], we can safely make this assumption. Thus the fractional error on the flux represented will be [4]:

$$\sigma = \sqrt{\eta \phi_p t} \quad [e^-] \quad (2.3)$$

$$\sigma = \sqrt{\eta \phi_p t} / G \quad [DN] \quad (2.4)$$

Noting that if several frames of the same fields were averaged the effective gain would be $n * G$.

Next type of noise as it was defined at the beginning of the chapter is a read noise. Note here we take the read noise to be the measured noise not associated with dark current or exposure (i.e. not changing in time). This is not exclusively the noise associated with the read stage of the electronics, it includes noise from EM and related noise of the electronics and signal processing; please note our nomenclature here. Since read noise occurs after EM gain, it is not affected by EM gain:

$$\sigma_r = \sqrt{\frac{\sum_{i=1}^N (B_i - B_{mean})^2}{2(N-1)}} \quad [e^-/pix] \quad (2.5)$$

Where B_i and B_{mean} stand for single bias frame and averaged bias frame respectively. N is the number of frames. In other words, we calculate the standard deviation of the difference between frames. Ideally, the difference should be zero. Yet, due to the noise in charge reading process, and photon nature, there is always non-zero value for the σ_r . Using EMCCD can decrease the influence of this noise in our measurement, so the shot noise will dominate over the read noise.

If n frames were averaged and combined, then the RN would decrease by $\sqrt{n}$. [1]

Depending on the type of detector dark noise might play different role. From the Noise performance comparison of the CCD and EMCCD cameras done by David Dussalut and Paul Hoess [4], in any CCD sensor, dark current noise (σ_{dark}) is given by the square root of the dark current signal:

$$\sigma_{dark} = \sqrt{2.55 \cdot 10^{15} \cdot D \cdot t \cdot d_{pix}^2 \cdot T^{3/2} e^{\frac{-E_g}{2kT}}} \quad [e^-/pix] \quad (2.6)$$

D is the dark current in nA/cm^2 at 300K; d_{pix} is the pixel size in cm, T is the CCD camera operating temperature in Kelvins, k is the Boltzmann's constant ($k = 8.62 \cdot 10^{-2} eV/K$), E_g is the bandgap energy:

$$E_g = 1.557 - \frac{7.021 \cdot 10^{-4} T^2}{1108 + T} \quad [eV] \quad (2.7)$$

"Cooling a CCD greatly reduces the dark current. For example, a non cooled CCD might generate a dark current of 300e/s/pixel at 20°C, but only 1e/s/pixel at -40°C." [4]

On the other hand, working with CCD images, we can calculate the dark noise experimentally from the images we took by the following formula

$$\sigma_{dark} = \sqrt{\frac{\sum_{i=1}^N (D_i - D_{mean})^2}{2(N-1)}} \quad [e^-/pix] \quad (2.8)$$

Where D_i and D_{mean} stand for single dark frame and averaged dark frame respectively. N is the number of frames. The units of the dark noise is given in e^-/pix , so that later we can compare the noise for different exposure times (tables 4.1, 4.2 and 4.3))

The noise in the background measured in counts of electrons per pixel is given by

$$\sigma_B = \sqrt{\pi r^2 \cdot B \cdot t} = \sqrt{n_{pix} B \cdot t} \quad (2.9)$$

Value for the B is calculated by estimating the median of the image in the area free of stars (details are in the next chapter).

Another important variable we we will be suing in our calculation is SCALE of the detector. Scale can also represent the area of one pixel. Let's call L - angular distance, then

$$SCALE = \frac{L}{A} \quad [\frac{arcsec}{pixel}] \quad (2.10)$$

It can also be expressed in the form of the ratio of signal counts in a pixel to the flux

in a square arcsecond:

$$m_{pixel} = m_{v2} - 2.5 \log(SCALE^2) \quad (2.11)$$

So the empirical expression for the total noise of the measurement would be:

$$\sigma_{tot} = \sqrt{\sigma^2 + \sigma_B^2 + \sigma_r^2 + \sigma_{dark}^2} \quad (2.12)$$

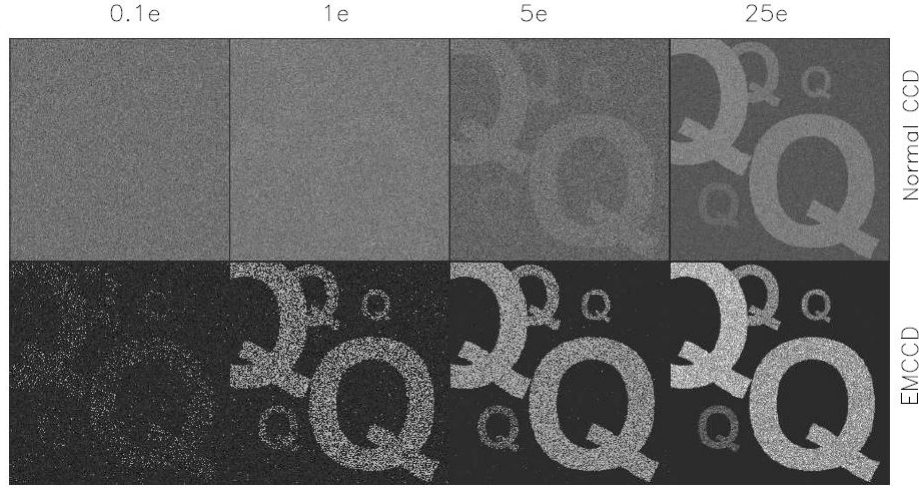


Figure 2-1: Comparison of an EMCCD and a normal CCD of $5e^-$ read-noise. Signal increases to the right. At low signal levels the EMCCD is greatly superior. at higher signal levels the conventional detector produces less-noisy images. Image is taken directly from Simon Tulloch

As it can be seen from figure 2-1, the signal-to-noise ration (SNR) of the CCD can not be increased to a higher value without increasing the signal level, since the read noise cannot be any less. Meanwhile for an EMCCD this limit can be changed depending on the EM gain settings and exposure time of the frame. For $\phi_p \gg 10$ photons, we can see that the $\sigma_B \sim \sqrt{\phi_p} = \sqrt{B \cdot t}$ where t is exposure time, B is background rate, number of photons per unit time.

Now considering a long exposure time, $B \cdot t \gg \sigma_r$. So $\sigma_B^2 + \sigma_r^2 \sim \sigma_B^2$. If $\phi_p < B$, ϕ_p is photons from the source, then $\sigma_{\phi_p}^2 + \sigma_B^2 \sim \sigma_B^2$. Consequently,

$$SNR \sim \frac{\phi_p \cdot t}{\sqrt{B \cdot t}} \sim \sqrt{t} \quad (2.13)$$

The EM gain is actually a complex function of the probability of secondary-electron generation and the number of pixels in the multiplication register. The signal-to-noise ratio for a single frame exposure is more specific from for a EMCCD is given by [18].

$$SNR = G \frac{\eta \phi_p t}{(\sigma^2 + \sigma_B^2 + \sigma_{dark}^2 + \sigma_r^2)^{1/2}} \quad (2.14)$$

From the equation (2.15) [4] it can be noted that the main advantage of the EMCCD over CCD is the fact that EMCCDs can generate high electron multiplication (EM) gain, and by doing that they can cause the shot noise σ to overwhelm the noise generated by the camera electronics. On the other hand, at low EM gain settings, the SNR will be limited by the detector's noise. As the EM gain starts to increase the SNR continues to increase till it reaches the limit of the shot noise limit and then it stays the same. [4]

These is a trade-off between long time single frame exposure and short time frame-added exposures. As it can be seen from equation (2.13) SNR can be increased by increasing the time we expose the camera. Also, SNR can be improved by adding successive single frames with short exposure times and creating one co-added image frame with long exposure time. When SNR is increased by taking longer exposure time frames:

$$SNR_{long} = \frac{n_l G \eta \phi_p t}{\sqrt{(\sigma^2 + \sigma_B^2 + \sigma_{dark}^2) n_l + \sigma_r^2}} \quad (2.15)$$

$$SNR_{long} = \sqrt{n_l} \frac{G \eta \phi_p t}{\sqrt{\sigma^2 + \sigma_B^2 + \sigma_{dark}^2 + \sigma_r^2/n_l}} \quad (2.16)$$

Where n_l is the number by which the exposure time is increased. Meanwhile, the SNR for the co-added frames can be found by the following formula:

$$SNR_{co-add} = \frac{n_{ca} G \eta \phi_p t}{\sqrt{(\sigma^2 + \sigma_B^2 + \sigma_{dark}^2 + \sigma_r^2) n_l}} \quad (2.17)$$

$$SNR_{co-add} = \sqrt{n_{ca}} \frac{G \eta \phi_p t}{\sqrt{\sigma^2 + \sigma_B^2 + \sigma_{dark}^2 + \sigma_r^2}} \quad (2.18)$$

Where n_{ca} is the number of co-added frames used to calculate the given SNR. Comparing equations (2.14) and (2.16), we see that the n_l used in the single long time exposure frame SNR affect only time dependent quantities (i.e. shot noise, dark noise, sky noise). The SNR for the image of co-added frames on the other hand, the n_{ca} term applies not only to the time dependent quantities, but also to the readout noise term. This leads to a SNR improvement of $\sqrt{n_{ca}}$ over the unit frame and approaches the long frame SNR. [4] The results of the simulation done by David Dussault and Paul Hoess are displayed in Figures 2-2. The figure presents data for long time frame integration and frame co-adding for the given flux and exposure time required to achieve SNR of 1. The graphs were plotted by using equations 2.16 and 2.18. As it is stated in the paper, the values of n_a (for frame adding) and n_l (for long frame) that are necessary to maintain an unity SNR were calculated. These values were then multiplied by the single frame integration time in order to obtain the total observation time.

2.3 Noise Analysis

Yet it is not all about the CCD image reduction process. As it was stated in chapter 1, besides obtaining data frames, one needs to gather information about the CCD performance by taking dark, bias and flat frames. [29] Proper reduction of the frames is described later in this chapter, for now the reduction of the raw image is presented symbolically as:

$$ReducedImage = \frac{(RawImage) - (BiasFrame) - (DarkFrame)}{NormalizedFlatFrame} \quad (2.19)$$

From the expression above it follows that, before reducing the raw data, first we need to reduce dark, bias and flat images (i.e. bias and dark frames should be subtracted from the flat frames. Since the flat frames gives information only about the surface distortion of the CCD, the output signal they provide is arbitrary, and we have to normalize the average signal in each pixel to 1.0 by dividing the flat frames

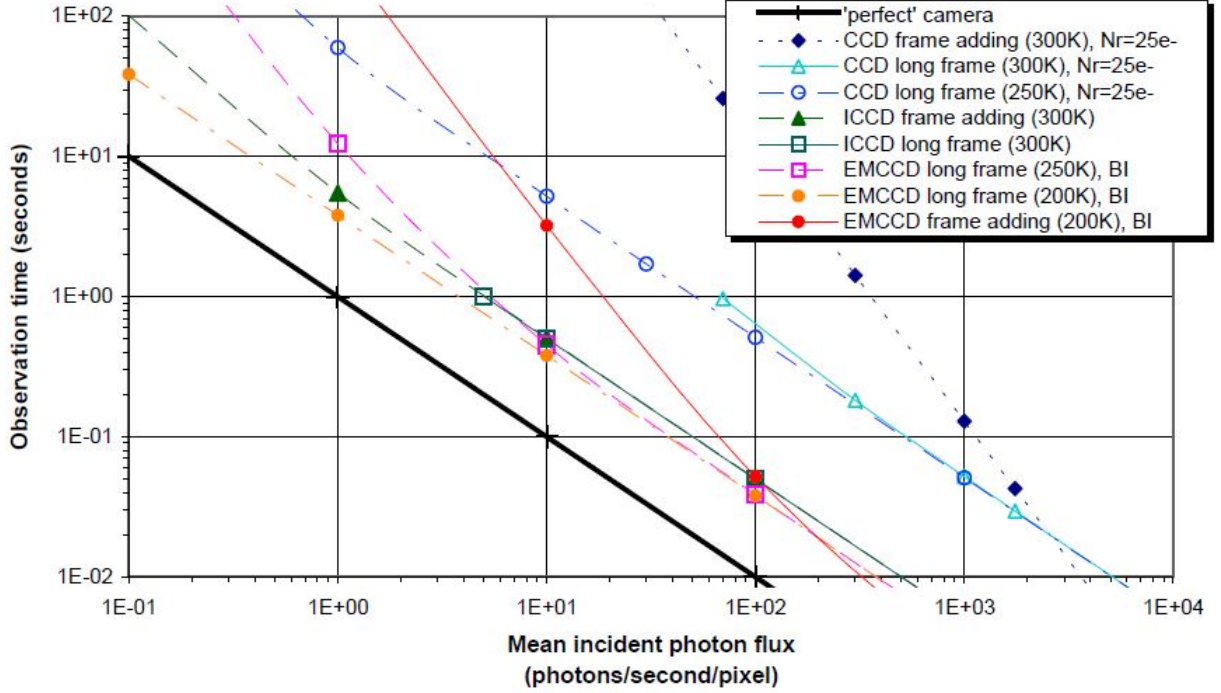


Figure 2-2: Observation time for frame adding and long frame as a function of mean incident photon flux with low camera noise. It shows the observation time needed to obtain an unity SNR at a given photon flux ϕ_p when performing long time frame integration or frame adding with CCD, ICCD and EMCCD systems. Image taken directly from David Dussault and Paul Hoess. [4]

by the average signal.

Then we estimate the average of dark frames with the same EM gain settings and exposure times. [8]

$$Dark_{average} = \frac{dark_1 + dark_2 + dark_3 + ...dark_m}{m} \quad (2.20)$$

First we find the average of all flat frames for the corresponding electron multiplication (EM) gain setting:

$$Flat_{average} = \frac{flat_1 + flat_2 + flat_3 + ...flat_n}{n} \quad (2.21)$$

Then, so called master-image is created by subtracting the averaged dark image

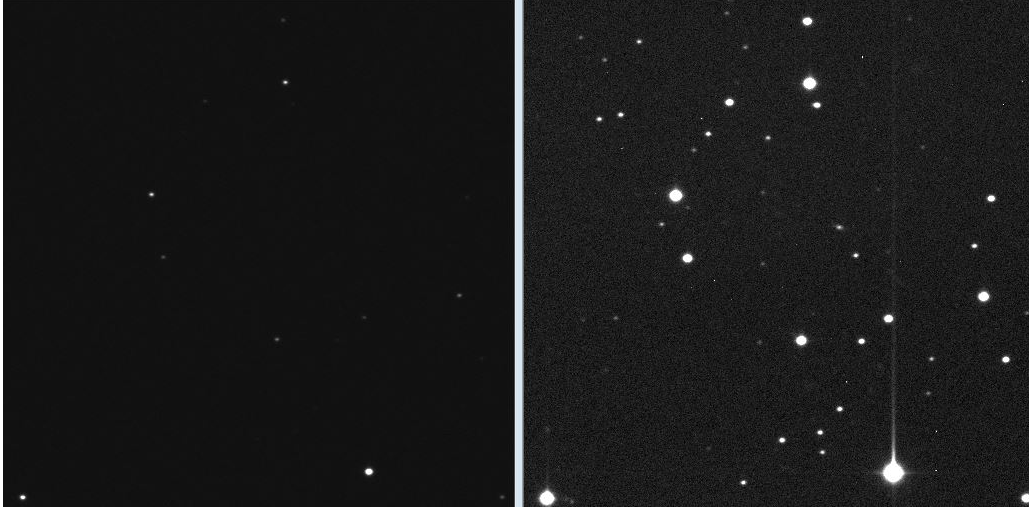


Figure 2-3: The image on the left is 100 co-added frames exposed for 5 seconds each, at EM gain = 1. The image on the right is 100 co-added frames exposed for 5 seconds each, at EM gain = 100. Both images were taken at the same night and at the same sky field. As we can observe, we can see more stars in the right image comparing to the image on the left. Some stars that can be seen in the right image, cannot be observed in the left image. As we can see, by co-adding many 5 seconds exposures with an EMCCD, is more beneficial than with a CCD. Both images were taken at the Tian-Shian Astronomical Observatory on 12th of November 2017.

from the averaged flat image.

$$Flat_{master} = Flat_{average} - Dark_{average} \quad (2.22)$$

Calculate the normalized flat frame F_{norm} by

$$F_{norm} = \frac{F_{master}}{F_{scalarmean}} \quad (2.23)$$

Then, raw image can be reduced by the following expression:

$$Image = \frac{Image_{raw} - Dark_{average}}{F_{norm}} \quad (2.24)$$

Looking at Figure 2-3, we can note that the co-added image looks more noisy. However, noise in the co-added images increases with square root of numbers of frames added, and the signal increases linearly proportional to the number of frames

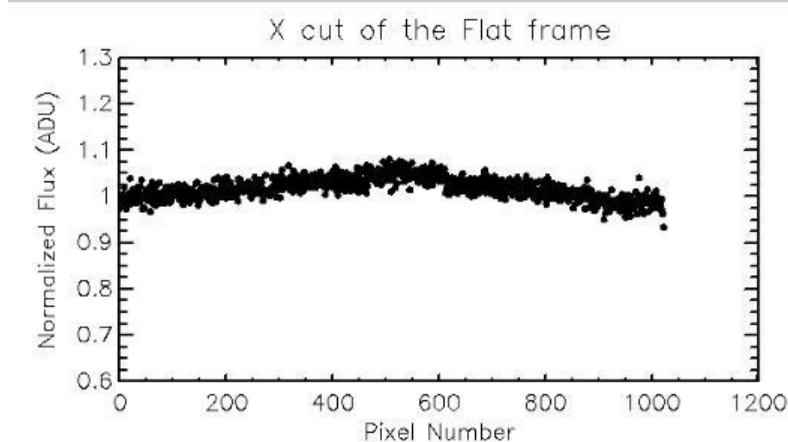


Figure 2-4: X-cut through the normalized flat frame. Sample flat frame obtained with the EM gain of 100 and average normalized to 1. Y-cut looks similar to X-cut. There is a higher pixel response on the center of the EMCCD chip to the incoming photons. To account the unevenness of the chip we divide the image by the normalized flat frame. Eq. 2.23

co-added. Thus, we can see how drastically image is improved just by adding frames together. The image on the left is less noisy, but the signal is also weak. So it can be noted that numbers of objects observed in the right image, cannot be seen in the image on the left.

For CCDs the read noise penalty increases with the numbers of added frames need to construct the image. For the EMCCDs however, we can bypass this issue by applying electron multiplication gain. So the read noise of the electronics would become negligible comparing to the other values. It can be noted from Figure 2-5 how SNR of the image increased drastically in the co-added image with the EM gain of 500.

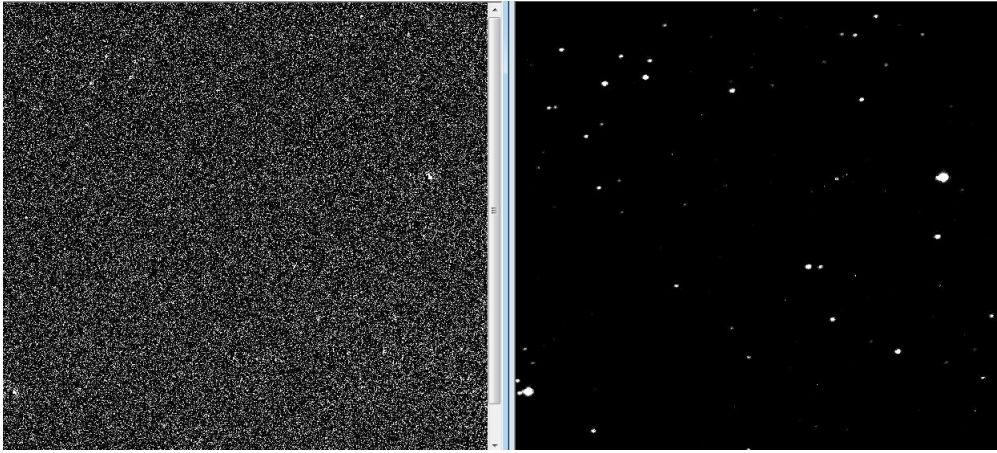


Figure 2-5: Comparison of the single frame image (left, 0.1 seconds exposure time) to the 200 frames of co-added image (right, 20 seconds of total exposure time). The EM gain of the EMCCD was set to 500 and individual frames were taken with 0.1 seconds exposure. Image on the left is dominated by the noise as the exposure time is short. EM gain is the important part of reducing the effective read noise and by co-adding frames we can decrease the effect of read noise and achieve higher signal to noise ratio in our image (right). The images are taken in the field of Fast-Radio Burst 121102 at the Tian-Shian Astronomical Observatory on 13th of November 2017.

Chapter 3

Astronomical Photometry

3.1 Aperture Photometry and PSF

The principle of aperture photometry is in the summation of the pixel intensity values within a certain region. Usually a circle of some radius is used, although in some cases it is a ring or an ellipse.

Aperture photometry can be summed up into the following steps:

1. Define the center of the aperture.
2. Estimate the background in the aperture.
3. Set the aperture size for the photometry.
4. Apply the aperture correction
5. Calibration of the measurement for intensity.
6. Convert the results into the UBVRI standard magnitude system.

3.1.1 Background estimation.

Background estimation is made in the annular region around the star, the inner radius, which is usually chosen as several times of FWHM (Full width at half maximum - the width of the star image profile by half the maximum brightness) [29] in order to correct for the influence of distant wings of the star image profile. The radius of the annulus is put far away from the center of the aperture, so the fluctuation of the

background in the region is small.

A lot of information about the background around the star can be obtained from the brightness histogram of pixels - the pixel brightness distribution function. Usually, a region is chosen in the form of a ring around each star, so that the outer boundary is outside the wings of the star profile. In the case of an ideal detector and an isolated star, this background brightness histogram must coincide with the Gaussian distribution. The most reliable estimate of the background in this case, is the average value of the distribution; the average value coincides with the median and mode of distribution. The median can be defined as the brightness value that divides the histogram into two equal parts. The mode of distribution is the brightness at the maximum of the histogram, i.e. the most common pixel intensity.

In the case of a real image, there is a noise present in the area of the background assessment and the whole image due to the wings of bright stars, weak unresolved stars, galaxies, cosmic particles and defective pixels. This disturbance and imperfection of the measurements lead to the appearance of an asymmetry in the histogram. As the consequence, the median, the mode and the mean do not coincide anymore. The value of the mean is the most sensitive to such interference, then goes the median and the mode is the least sensitive. Thus, the mode should in principle give the best estimate of the background. [16] But, it is necessary to take into account that in a crowded stellar fields we are forced to have a very limited number of pixels to estimate the background around the stars. Therefore, with a small statistical sample and large noises, secondary peaks may appear on the histogram. They mostly will affect the mode. In this case, the median is the most stable characteristic of the background. In the Midas Users Guide, for example, the value of "three medians minus two averages" is used as the background estimate. In our further calculations we used median of the pixel values in the regions far away from any stars in the image to estimate the background.

For the tables 3.1-3.3 we used median as a value of the background. To choose the region for the background estimation, special regions on the sky image were chosen in such a way, that the region does not contain any stars in it. The area of regions

were 25x25 pixels. Three of different regions were observed and the background was calculated by taking the average value of medians from three regions. Due to the fact that, the image contains bright stars and non-linear pixels, median calculated from the whole image was higher than the median calculated from the average of three regions.

Other important issues to take into account in the background estimation is the conditions on which images were taken. Such conditions are air glow of the upper level of atmosphere, zodiacal light, moon phase, location of the moon on the sky, light pollution from city or observatory, wind, clouds, time of observation etc.

3.1.2 Aperture size for the photometry.

Point spread function (PSF) - is two-dimensional intensity profile of a star. Due to diffraction limit in the optics, a star cannot be resolved as the point source, and instead, the profile of a star in 2 dimensional array is an Airy disk. Thus, the size of the aperture should be considerably large, so the signal from the source still dominates the background. To reason the statement above let's say that the radius of a chosen aperture is R and signal intensity is I_{st} . Corresponding output of the CCD is I_{CCD} in ADU units. Then number of generated photo-electrons is $I_{st} * I_{CCD}$. The standard deviation of the number of measured photons corresponding to the incoming $I_{st} * I_{CCD}$ signal is $\sqrt{(I_{st} * I_{CCD})}$ in photo-electrons, or $\sqrt{\frac{I_{st}}{I_{CCD}}}$. Then, the noise in the measurement in magnitude scale

$$m \pm \sigma m_1 = -2.5 \log(I_{st} \pm \sigma(I_{st})) \quad (3.1)$$

or

$$\sigma m_1 = -2.5 \log\left(\frac{I_{st} + \sigma(I_{st})}{I_{st}}\right) = -2.5 \log\left(1 + \frac{\sigma I_{st}}{I_{st}}\right) = 1.09 \frac{\sigma I_{st}}{I_{st}} \quad (3.2)$$

$$\sigma m_1 = \frac{1.09}{I_{st} * I_{CCD}} \sqrt{I_{st} * I_{CCD} + r^2 * npix} \quad (3.3)$$

where r - is readout noise in electrons, $npix$ - number of pixels inside the chosen aperture.

The equation 2.3 demonstrates the fact that when readout-noise is negligible, the uncertainty in magnitude scale decreases as the aperture radius increases. We can see it from I_{st} and aperture radius relation in figure 3-1. As the aperture radius increases, the intensity also increases (figure 3-1). Yet, this statement is true only for a certain limit of increasing aperture radius. As soon as the aperture radius gets to its limit, the I_{st} would not increase anymore as the area under the curve stays the same. Then, the σm will stay the same and even increase as a square root of number of pixels inside the aperture. Thus, it is important to set the limit of the aperture radius, so we will not lose information about the full intensity of a source and yet keep the uncertainty within the acceptable range. As it was described above, there is another

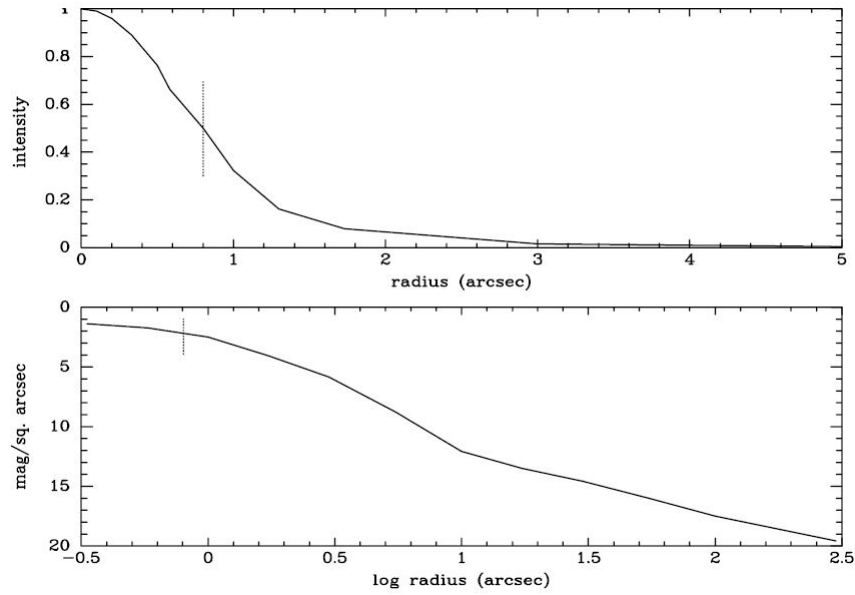


Figure 3-1: Radial intensity of light (normalized to center= 1.0) (Image courtesy of W. Romanishin)

great source of uncertainty in the measurements. It is noise in the background or the sky noise. The sky noise is also treated with Poisson statistics. The value of the sky background around the aperture of a star is considered to be defined when it is calculated using enough number of pixels to get more accurate results (i.e. several hundreds of pixels). The noise in the sky background is then,

$$\sigma m_2 = \frac{1.09}{I_{st}} \sqrt{\frac{npix * I_{sky}}{I_{CCD}}} \quad (3.4)$$

Consequently, the expression for the total noise is

$$\sigma m = \frac{1.09}{I_{st} * I_{CCD}} \sqrt{I_{st} * I_{CCD} + npix(r^2 + I_{sky} I_{CCD})} \quad (3.5)$$

from equation (3.5) we can conclude 2 cases:

1. Bright stars with $I_{st} * I_{CCD} \gg npix(r^2 + I_{st} * I_{CCD})$. In this case, aperture with large radii are allowed.
2. Faint stars with $I_{st} * I_{CCD} \geq npix(r^2 + I_{st} * I_{CCD})$. In this case, small radius apertures are preferred.

It is important to note that I_{st} and I_{sky} are proportional to the exposure time, meanwhile r^2 is fixed. Thus, in order to minimize the effect of readout-noise it is preferred to take long time exposures over the sum of short time ones. Yet with a proper EMCCD camera the effect of a readout-noise can be minimized as it will be shown in chapter 4.

3.1.3 Applying the Aperture Correction

The size of the aperture is set in such a way that on one side it reduces the influence of neighboring objects and sky background on the image, and on the other side it measures accurately the brightness of the star. It is necessary to estimate the contribution of the trimmed part to the real brightness of the star. This procedure is called aperture correction. To estimate this correction, we need to construct the dependence of the brightness of the star on the radius of the aperture as is shown in figure 2-1.

The aperture correction depends on the quality of the star images. On a telescope with a long focal distance and with a good quality optics, the blurring of the image is mainly determined by the distortions of the air caused by atmospheric turbulence. It can vary greatly from one image to another.

The fundamental principle that underlies the application of the aperture correction

to all other image stars is the linear response of a CCD array. In the absence of distortion, the point-spread function is the same for all stars independently of their brightness and location on the image. Thus, images of weak and bright stars differ only by scale. Therefore, it is necessary to determine the aperture correction for the each image studied. The aperture correction curve is based on several bright and sufficiently isolated stars. It's dependence on the increasing aperture radius tends to some asymptote, which should give an estimate of the total brightness (flux) of the star.

In other words, PSF is the distribution of intensity on the receiver produced by the unresolved point source - star. Thus, image of bright and faint stars are differ only by scale. The difference between the magnitudes of bright measured with large and small aperture radii is called aperture correction. This correction is then added to the magnitude of the faint stars measured with a small aperture size. This method works for isolated stars and does not work for the crowded fields. It is due to the fact, that the wings of a stars contain photons coming from another star or galaxy for example. That is why Gaussian statistics is helpful at this point to solve for an aperture correction.

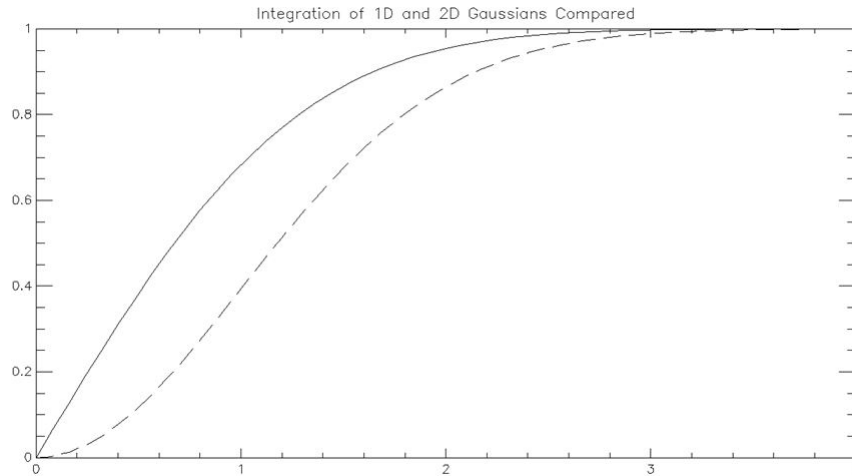


Figure 3-2: Comparison of 1D and 2D integrated Gaussian.

To describe such a function, we will use the mathematical description of the object and the image in the form of functions $I(x, y)$ and $I_0(x_0, y_0)$. These functions describe

the dependence of the intensity distribution on the spatial coordinates.

$$I_0(x_0, y_0) = \int \int I(x, y) F(x, y) dx dy \quad (3.6)$$

Where $I_0(x_0, y_0)$ is the observed intensity of a source, $I(x, y)$ is the true intensity of the source and $F(x, y)$ is the point spread function. Normalized 2-D Gaussian integral in radial distance units (pix) is then be

$$G'(r) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{r^2}{2}\right] \quad (3.7)$$

Where r is radius of aperture in HWHM units. The formula we used in our calculation in GDL

$$G(r) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-r^2/2\sigma^2) \quad (3.8)$$

i.e. this means the sigma enters into the normalization, and the maximum of the function is not one.

Then combining equations 2.8 and 2.10 we get the true intensity of our measured source

Equation 2.11 estimates the true apparent intensity of a source and gives us information in unit of photo-electrons/sec, ADU/sec, counts/sec or just in counts in ADU. Using this information we can convert the flux of a source into the standard magnitude scale.

$$I(x, y) = I_0(x_0, y_0) \frac{1}{1 - \frac{\exp(-r^2/(2\sigma^2))}{\sigma\sqrt{2\pi}}} \quad (3.9)$$

3.1.4 Calibrated measurement of intensity

The measured number of photo-electrons are then converted to ADU and counted by our measuring system. The strength of a star signal measured by our instruments can be expressed in terms of magnitude as follows:

The instrumental stellar magnitude of a star is assumed by a simple formula as

$m = -2.5 \log I$ [from CCD Photometry PDF]:

$$I = \sum_{ij} (I_{ij} - n_{pix} * I_{sky}) \quad (3.10)$$

$$m_I = -2.5 \log \left(\frac{I_{ap} - A_{ap} I_{sky}}{t_{exp}} \right) \quad (3.11)$$

Where I_{ap} is defined as integrated number of counts under the aperture, A_{ap} is the aperture area in pixels, I_{sky} is number of counts from the sky background and t_{exp} is exposure time in seconds. [2]

3.1.5 Standard Magnitude System

In order to calibrate our system and make our data readable to others, we need to adjust the results to the commonly accepted data form. To do that, the instrumental magnitude was added to the apparent magnitude of the standard star measured by Landolt [21]

$$m_{cor} = m_{apparent} + m_I \quad (3.12)$$

To transfer the data into magnitude scale, so called standard stars are need to be measured. Standard stars are the stars with known brightness, color, temperature, distance, coordinates and etc. In addition, it is important to measure those stars in different CCD filters, so we can construct the color slope of our measured object and define not only its brightness, but also color.[3] During the transformation to the standard system it is necessary to take into account atmospheric extinction, a coefficient that describes the amount of light absorbed by the atmosphere for a certain wavelength. The extinction coefficient can be measured by observing the same object at the different time of the night of observation, so the object changes its location on the night sky. The variation of the coefficient due to the different zenith location of an object, allows us to measure the light absorbed by the atmosphere. As path

length increases, the optical depth also linearly increases with distance.

$$\chi = \frac{\tau}{l} \quad (3.13)$$

Where χ is the absorption coefficient per unit length, l is the length of the path and τ is optical depth.

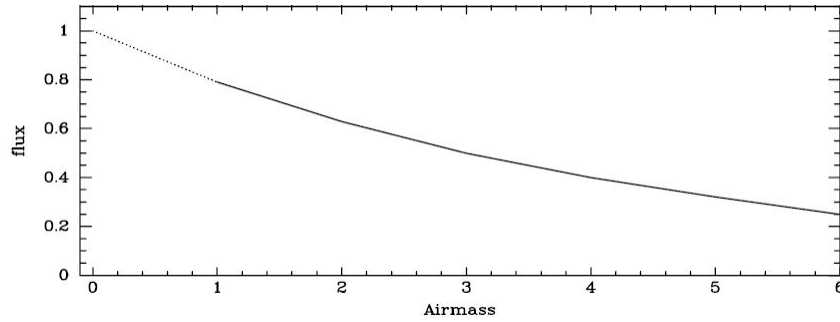


Figure 3-3: A star flux versus the airmass above the observatory. Image was taken directly from W. Romanishin

Multiplication of the coefficient by so called airmass gives us the value of the atmospheric extinction coefficient. Airmass is the length that light travels through the atmosphere before falling into the aperture of the telescope. At the zenith (minimum possible path length through the atmosphere for a given altitude of observatory) the airmass is equal to 1, and increases as the object moves away from the zenith. The following formula is used to convert the star magnitude to standard system:

$$m_{std} = m_{inst} + a_0(B - V)_{std} + a_1X + a_2X(B - V)_{std} + \dots, \quad (3.14)$$

Where, m_{inst} instrumental magnitude corrected for the exposure time, X - observed airmass $X = \sec Z$, $m_{std}, (B - V)_{std}$ - magnitude and color of a standard star. a_0 is the color coefficient, a_1 - extinction coefficient of the first order.[17]

3.2 Fast and Slow Photometry

As it was stated above, GRBs are phenomena of a relatively short duration. In a few seconds radiation with a tremendous energy is emitted. This energy is in the form of electromagnetic radiation of various wavelength. Our research only considers observation of the phenomena in optical spectra. Knowing that, special charge-coupled devices (CCD) and electron multiplied charge-coupled devices (EMCCD) are used to make observation. Although, no GRBs were captured during the research project, we learned how to setup, control and read the equipment properly. Also, EMCCD performance were tested on the field of standard stars with different EM gain and exposure times. Having said that, let's hold the EM gain and consider the exposure time first.

$$t = \frac{SNR^2(N + pS) + SNR\sqrt{SNR^2(N + pS)^2 + 4N^2pR^2}}{2N^2} \quad (3.15)$$

Here, SNR is a signal to noise ratio in the general definition of it, N is the number of electrons per second per image, R is the CCD pixel readout noise in number of electrons this can be taken to be 4 e- for all practical purposes (see CCD Characteristics cooled with liquid nitrogen), p is number of pixels in stellar image and S is the sky count rate in electrons per second per pixel (background). [1]

As it can be seen from the eq. 4.1. SNR increases under the square root of exposure time. So to get the twice higher SNR we need to expose the shutter 4 times longer. This leads us to the problem of accumulation random electrons in our image (as N increases proportional to exposure time). In order to reduce the noise and obtain higher SNR different exposure times can be applied along with the various numbers of frames. I.e. one can take 100 frames of the same object with 5 seconds exposure time. As noise in the image increases with the square root of the number of images, while the signal increases linearly proportional to it, one can get better SNR (see Figure 3-4) [13]

Also, short exposure times with several number of frames are used to avoid the saturation of the pixel value. If we expose the camera on a certain star field for long

period of time, the image of stars would probably be saturated and data would be useless. However, not only exposure time is the key to make proper images.

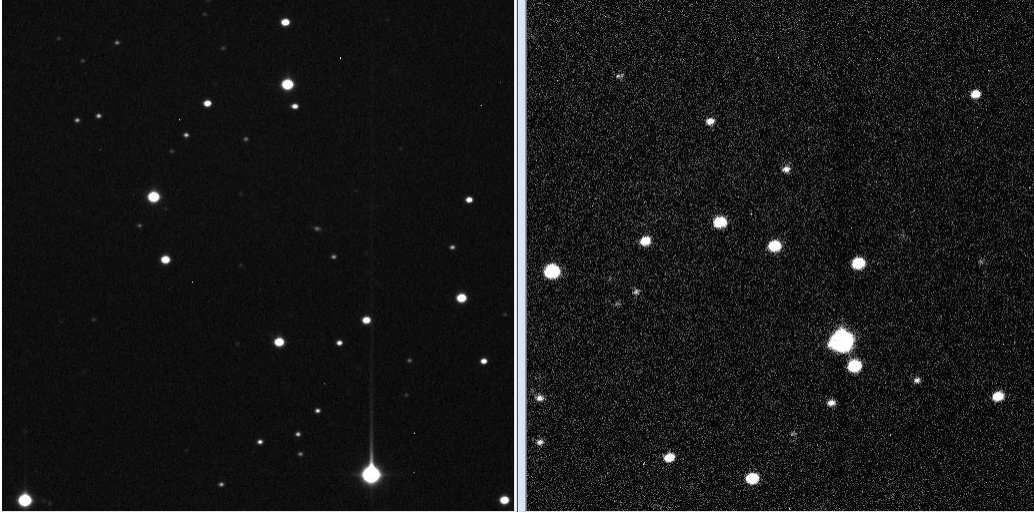


Figure 3-4: Image on the left was created by reducing the noise in each 5 second frame and then averaging them (five-sigma sensitivity for the images was found to be 21.67 mag.). Image on the right was created by reducing the noise in single 500 seconds exposure time frame (five-sigma sensitivity for the images was found to be 20.7 mag.). Both images were captured at EM gain of 100.

Using the methods described in chapter 2, we can now estimate the quantities for the images taken during the observational experiment at TSHAO on November 2017. Image on the left in Figure 3-4 was created by reducing the noise in each 5 second frame and then averaged. So the pixel value now is presented in electrons/pixel. The image of the right obtained by reducing the noise in the single 500 seconds frame. Numerical comparison is presented in next chapter.

Chapter 4

Astronomical Camera Performance

4.1 A comparison of results for different EM Gain

Since bias frames are shot with zero second exposure times, we subtract 2 bias frames from each other to estimate the readout noise (σ_r) of the camera at the certain EM gain settings. An ideal camera should give zero ADU in each element of the 1024x1024 array. Yet, due to imperfection of the detector, the difference of the matrix elements are not zero. The histogram of the subtracted bias frames were plotted to "clip" the edges of the extension of the wings of the distribution. By doing that, we excluded "sensitive" pixels from our estimates. Then the readout noise of the camera was found by taking the standard deviation of all those pixels. However, to estimate the readout noise we also need to include the noise in the difference between two frames. To do that we divide the resulting value of the differences by $\sqrt{2}$. [25]

$$\sigma^2(x - y) = \left(\frac{\partial}{\partial x}(x - y)\right)^2 \sigma_x^2 + \left(\frac{\partial}{\partial y}(x - y)\right)^2 \sigma_y^2 \quad (4.1)$$

$$\sigma^2(x - y) = \sigma_x^2 + \sigma_y^2 \quad (4.2)$$

When σ_x equals to σ_y :

$$\sigma(x - y) = \sigma_x \sqrt{2} \quad (4.3)$$

Using equations 4.1-4.3 we derived values of the read noise for three EM gain regimes. For the EM gain of 1 the σ_r is $8.81 \pm 0.02e-$, for EM 100 the σ_r is $13.03 \pm 0.01e-$, for the EM 500 the σ_r is $12.81 \pm 0.01e-$. As we can see the read noise slightly increases with increasing EM gain. However, looking at the values for EM 1, EM 100 and EM 500 we see, that the increment of the read noise comparing to the increment of the EM gain is negligibly small.

Estimation of the dark current and the dark noise is done by first subtracting the bias frame from the dark frames. Since the Bias is present in all our measurements, first we need to subtract it from the frame studied. If the image was captured with electron multiplier gain, then the studied frames need to be divided by the EM gain. Then, dark current for the given temperature and given EM gain setting is the bias-subtracted-dark frame (BSD). Dark noise on the other hand, is the value of the standard deviation of the difference between two BSD frames. [19]

As it was explained in the second chapter, the sky background and sky noise can only be estimated after the EMCCD image reduction process. Particularly, we took the image with a certain exposure time and subtracted the dark frame with the same exposure time and divide it by the electron multiplier gain value. Then, resulting image was divided by the flat frame captured with the same EM gain settings as the star field image and the dark frames. Then, the sky background value was found by taking the median in certain aperture that does not contain bright spots and any stars in it. Three different regions were chosen for each image frame with square area of 25x25 pixel. The averages of the medians of those areas are presented in the tables below as the sky background of the image studied. The noise in the sky measurements were calculated by estimating the standard deviation of the of those fields. Units are presented in electrons per pixel per corresponding exposure time. The data in the tables were calculated by the code written in IDL software and can be found in the Appendix A.

From data displayed in Table 4.1, we see that the dark current is negligibly small even for the long exposure times (i.e. 180-500 seconds). The noise or the uncertainty of the dark current (dark noise) however, seems not to change much for different

Table 4.1: Exposure time dependence of the characteristics of the Andor EMCCD with corresponding EM of 1. The readout noise of the camera for EM gain of 1 is 8.81 e-/pix/readout

t_{exp} [sec]	Dark $[\frac{e^-}{pixel}]$	$\sigma_{dark}[\frac{e^-}{pixel}]$	Sky $[\frac{e^-}{pixel}]$	$\sigma_{sky}[\frac{e^-}{pixel}]$
1	0.00	6.23	0.00	8.80
5	2.4	6.25	0.00	9.32
10	0.00	6.28	9.53	8.67
12	0.00	6.27	7.14	9.02
35	7.2	7.25	N/A	N/A
60	2.4	6.33	55.91	9.83
180	4.79	6.5	209.65	12.07
360	7.2	6.93	304.76	13.77
500	0.00	6.23	474.32	17.88

exposure time settings. As it was stated in chapter 2, sky background and sky noise get mostly influenced by the exposure time variations. As we can see sky background almost increases linearly proportional to the exposure time. Meanwhile the change in the noise of the background is negligibly small. Comparing the data in the table 4.1 we can see that the read noise is in the same order as the dark noise and the sky noise. Thus, we can witness the prediction we have made before stating that for the conventional CCD operation mode, there is a read noise penalty in measurements.

Table 4.2: Exposure time dependence of the characteristics of the Andor EMCCD with corresponding EM of 100. The readout noise of the camera for EM gain of 100 is 13.03 e-/pix/readout

t_{exp} [sec]	Dark $[\frac{e^-}{pixel}]$	$\sigma_{dark}[\frac{e^-}{pixel}]$	Sky $[\frac{e^-}{pixel}]$	$\sigma_{sky}[\frac{e^-}{pixel}]$
0.1	0.00	0.22	0.03	0.37
1	0.02	0.26	0.71	0.82
5	0.09	0.41	3.55	1.66
12	0.36	1.21	10.23	2.80
20	0.67	1.33	N/A	N/A
35	1.30	1.69	32.21	4.96
60	2.30	1.76	55.06	6.76
500	19.10	5.88	569.47	31.98

For the EM gain of 100 the dark current data in Table 4.2 slightly differs from

table 4.1. Comparing both, we can note that the dark current is negligibly small for the shorter exposure times, and increases slightly with the exposure time (i.e. 500 seconds exposure time dark current value is $19.1e^-$ and $0.36e^-$ for 12 second exposure time). Noise in the dark current is also negligible for the observations made with EM 100. Yet, now we can see small increase in the dark noise. In table 4.1, the dark noise stayed almost the same (around $6.5e^-$), but for the EM 100 we can see how σ_{dark} increases with exposed time. The background of the sky increase increases almost linearly proportional to the exposure time and σ_{sky} also increases with the square root of time as in the data for EM 1. However, noise in the sky is slightly higher for the EM 100. This is due to the fact that EMCCDs have a low probability of producing gain. When electron moves from one element to the next one in the EM register, it has approximately 1% chance of creating an additional electron. [33] This noise in the gain experienced by a photo-electron creates an additional noise source in an EMCCD and is known as multiplication noise. [28]. That is why we have slightly higher background noise values for the EM gain of 100. As we can see from the table 4.2, sky noise starts to dominate the with the EM gain of 100 for the long exposure times.

Table 4.3: Exposure time dependence of the characteristics of the Andor EMCCD with corresponding EM of 500. The readout noise of the camera for EM gain of 500 is 12.81 e-/pix/readout

t_{exp} [sec]	Dark $[\frac{e^-}{pixel}]$	$\sigma_{dark}[\frac{e^-}{pixel}]$	Sky $[\frac{e^-}{pixel}]$	$\sigma_{sky}[\frac{e^-}{pixel}]$
0.1	0.00	0.26	0.00	0.35
5	0.14	0.83	4.15	1.77
20	1.05	1.00	16.87	3.60
200	10.23	2.89	N/A	N/A

There are not much data for the EM 500 was gathered during the observational experiment held on November 2017. However, we still can construct general trend-line and show the change of noises (dark and sky) and changes in dark current along with the value of the background in our measurements. From the data presented in table 4.3, we can note that the increase in the dark noise value is not negligible,

same as the increase in the sky noise. As it was predicted, the background increases linearly proportional to the exposure time, meanwhile the noise of the background goes as the square root of time. Comparing read noise for EM gain of 1 and EM gain of 500 (see Figure 4-1), we see that the increase in the read noise with increasing EM gain is negligibly small (EM gain was increased 500 times, while read noise increased 1.5 times).

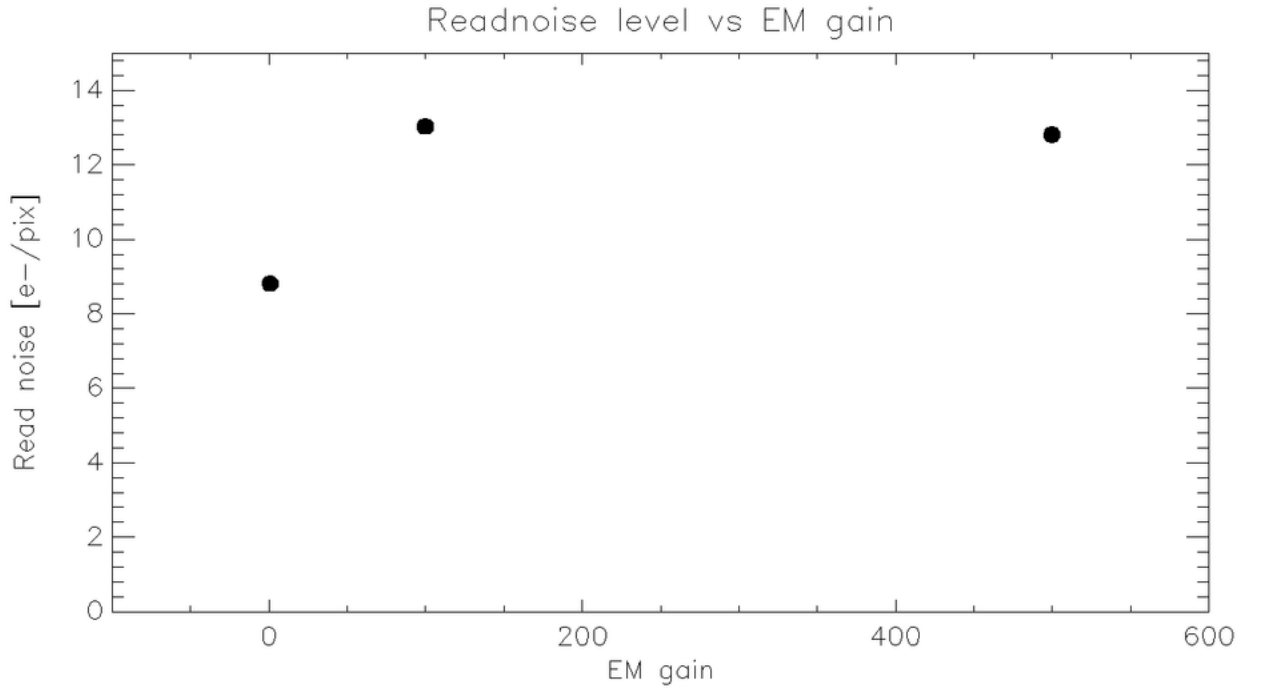


Figure 4-1: Readout noise of the EMCCD as a function of EM gain. Read noise at EM 1 is $8.81 \pm 0.02e^-$, EM 100 is $13.03 \pm 0.01e^-$, EM 500 is $12.81 \pm 0.01e^-$. As we can see in the plot, the variance of the bias changes only very slightly with huge changes in gain. This is due to the EM process and any associated electronics and signal processing. However, this increase in bias variance is very small compared to the signal increase due to the EM Gain. As we will see in later plots, the increase in signal is much larger than the read noise, plus any excess factor due to EM Gain or anything else; the EM gain therefore allows us to take short exposures without any significant noise penalty.

Figure 4-2 shows that the dark current estimated at EM gain of 1 mainly dominated by the system electronics (noise) rather than its actual value (cross sign). Looking at the data points (disks and rhombus) we see negligible increase in dark current for the EM gain of 100 and 500 respectively. However, looking at the figure

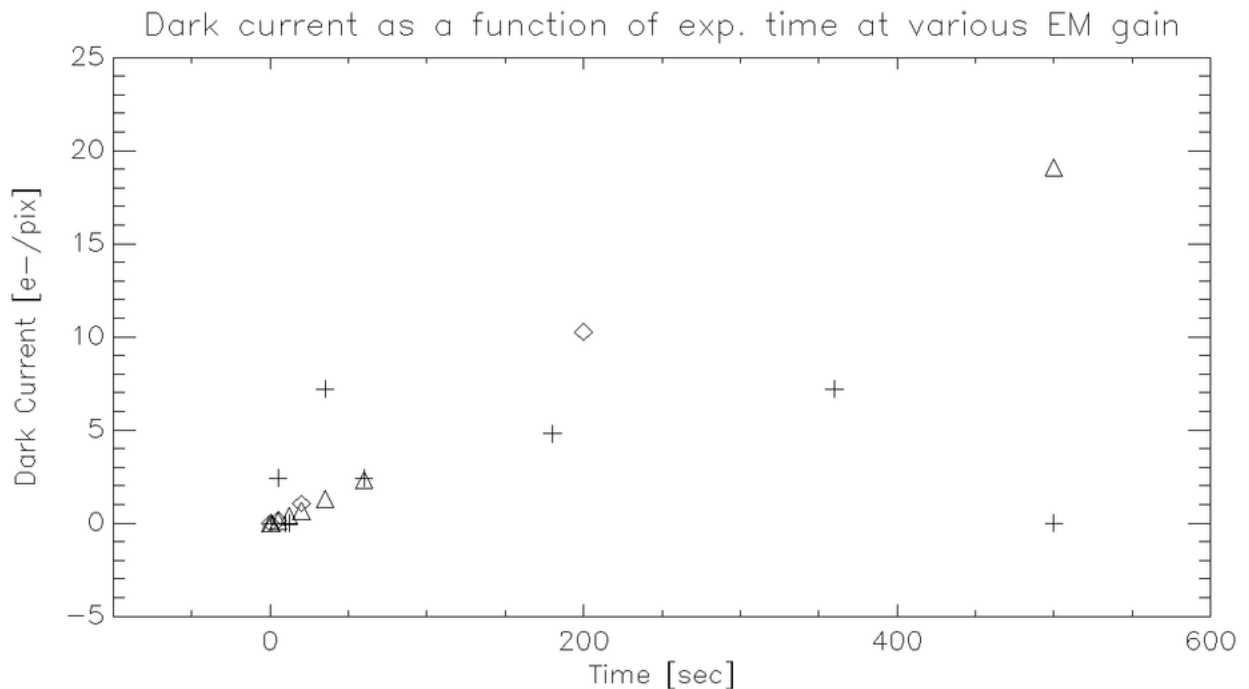


Figure 4-2: Dark current dependence upon the exposure time at EM gain of 1, 100 and 500. Data for EM 1 is cross sign, for EM 100 is a triangle and rhombus for EM 500. See text for details.

4-3 we see that the dark current is no longer dominated by the system's electronics and slightly increases with exposure time.

4.2 Time resolved Photometry

To do the photometry several images with various numbers of frame will be used (different EM gain, exposure time, numbers of frames etc.). First, taking the images from figure 3-4 we can compare photometry results for the single frame long time exposed image with the frames co-added short time exposed image. Before going up to the observatory we made a list of star that we want to observe and later calibrate our results, so they would make sense by the method described in chapter 3. The short frames were captured in the field of 2 standard stars: GD2 and GD2C. Both stars property can be found in the paper by Arlo U. Landolt. [21] A list of standard stars seen around the sky at +50 degree declination is given in the paper. Coordinates

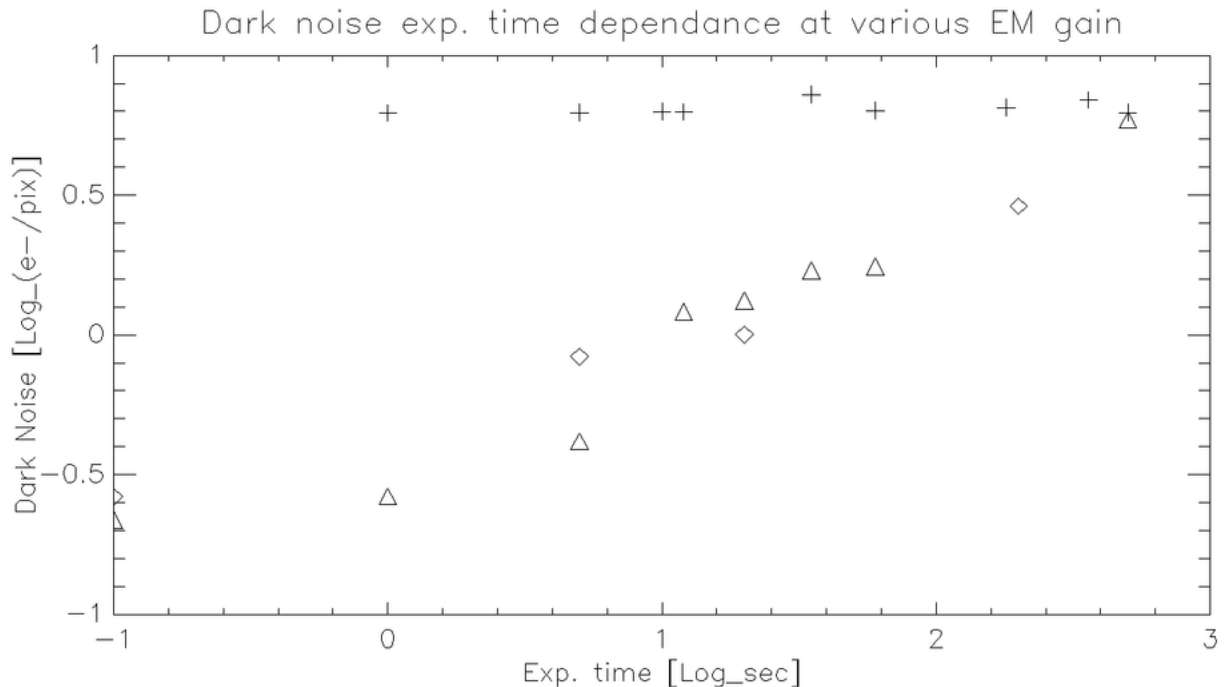


Figure 4-3: Dark noise dependence upon the exposure time at EM gain of 1, 100 and 500. Data for EM 1 is cross sign, for EM 100 is a triangle and rhombus for EM 500.

of the Tien Shan Astronomical Observatory are: 43:03:27N and 76:58:17E. Knowing that, we chose the best optimal stars that pass through the zenith during the night so we would get as low airmass as possible. The seeing during the observations were about 1.8 arc seconds. From the catalog by Landolt, apparent magnitude of GD2 in R filter is 13.944. Apparent magnitude of GD2C in R filter is 12.95.

After the image frames were reduced by the methods explained above, we chose the center of standard stars in the pixel coordinates (i.e. center of the GD2 in the image used is [555,687]). Then setting the photometric aperture to be equal to r in units of HWHM of the star profile (r is the radius of the aperture is equal to 1.4 HWHM), we integrate the pixel values that fall inside the circular aperture. The result of the integration is the signal from the star under the observation. Yet, it is not true flux of the star, as to calculate the flux, we need to subtract the background from the star signal.

$$\phi_{star} = \phi_{star+sky} - \phi_{sky} \quad (4.4)$$

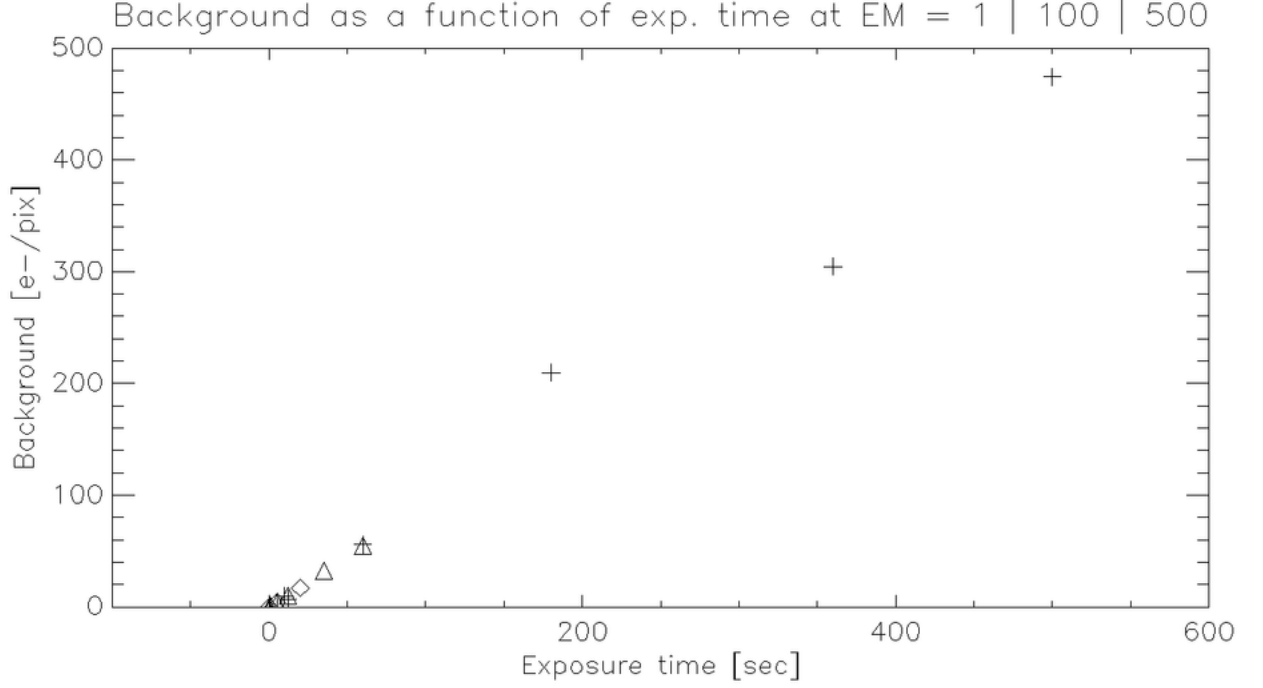


Figure 4-4: Sky background vs the exposure time at EM gain of 1, 100 and 500. Data for EM 1 is cross sign, for EM 100 is a triangle and rhombus for EM 500. As we read the data, we can see how background increases proportional to the exposure time for all EM gain regimes.

The units of ϕ_{star} is in electrons per pixel now. After calculation of the flux, next we apply aperture correction to our estimation.

$$\phi_{ap-cor} = \frac{\phi_{star}}{1 - \exp(-r^2) \ln(2)} \quad (4.5)$$

So after the estimation the flux of the star, we now can estimate the uncertainty in our measurements. Using equations 2.3, 2.5, 2.8, and 2.9 the total noise is

$$\sigma_{tot} = \sqrt{\sigma^2 + \sigma_{sky}^2 + \sigma_r^2 + \sigma_{dark}^2} \quad (4.6)$$

From equation 4.6 we can derive the flux of the star and compare that value to the value given in the catalog by Landolt [21]. To do that, we need to convert the flux of a star to the magnitude scale using the following equation (This is simple form of the equation 3.11). That is why we need to have data for the standard stars, so

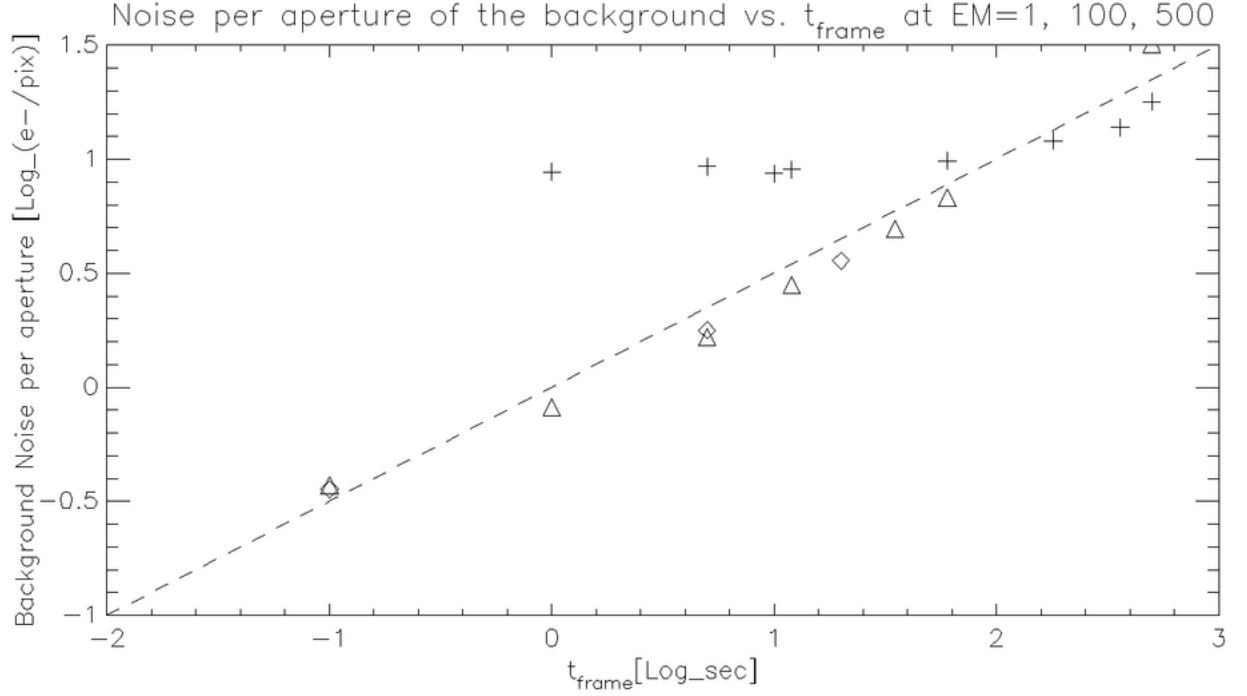


Figure 4-5: Sky noise vs the exposure time at EM gain of 1, 100 and 500. Data for EM 1 is cross sign, for EM 100 is a triangle and rhombus for EM 500. Dashed line is a slope of 1/2. As it was predicted in chapter 2, the noise in the background does indeed increase as a square root of time. In log-log scale we can see that by taking the slope of the trend-line for EM gain 100 and 500. The data for EM gain of 1 does not change with time due to the fact, that the measurements are dominated by the read noise. But for the EM 100 and 500 we can distinguished slope of close to 1/2. Also, at low exposure time ($t < 100 \text{ sec}$) we can't see that slope for EM 1 because our data is dominated by read noise. The data tends to align the slope of 1/2 only after around 120 seconds of exposure. And it also can be noted that as we turn up the gain, the results are get better.

we can calibrate our data and convert it to the standard system.

$$m_{inst.} = -2.5 \cdot \log_{10}(\phi_{ap-cor}) \quad (4.7)$$

Where $m_{inst.}$ is the instrumental magnitude of the observed star. Then comparing instrumental magnitude to the apparent magnitude of the observed standard star, we can find the calibration factor "cf":

$$cf = m_{std.star} + m_{inst.} \quad (4.8)$$

Then using GD2 standard star we found the calibration factor to be 22.46 mag (100 images were taken at 100 EM gain with 5 seconds exposure). Using the calibration factor, now we can apply it to all other objects in our images. So all our data is now can be converted to the standard system and compared with works of the others.

Five sigma limit (fsl) can also be found by using equation below:

$$m_{fsl} = cf - 2.5 \cdot \log_{10}(5 \cdot \sigma_{sky}) \quad (4.9)$$

To check the work, we re-run the image reduction process for the same images yet now for the different standard star - GD2C, which has apparent magnitude of 12.954 by Landolt catalog. Then after running the code and applying the cf of 22.46 our estimate of the magnitude of GD2C

$$m = cf - m_{inst} = 12.959 \quad (4.10)$$

It is also important to note that the results presented in figure 4-7 and figure 4-6 were estimated with assumption that the calibration factor does not change much with time and sky conditions. Several images and standard star fields were used to derive the value of calibration factor and the average of all values measured was used in the calculations. From this result, we can say that our photometry results are correct and the method can be used to compare the values for different standard stars, fields obtained at different EM gain and exposure times.

Single image of 500 seconds exposure time taken with EM gain of 100 will be analyzed next. We can visually compare them by looking at the figure 3-4. From that we see that the long exposure image is more nosy than the co-added one.

4.3 Sensitivity limit and best performance of the EMCCD

Using equation 2.9 we estimated the background noise σ_{sky} for each images studied. Units of σ_{sky} is in electrons per aperture. Then, applying calibration factor to equation 4.10 and using the estimated noise of the background, we find five-sigma-sensitivity for each EM gain regime and exposure time. Figure 4-6 is the presentation of the data for three electron-multiplication gain regimes operated at various exposure times. Sensitivity limit is shown for the single frame exposure time, meaning that images were not co-added or averaged. As we can see from the figure, the sensitivity of EM100 and EM500 increases rapidly with increasing exposure time. Meanwhile, the sensitivity obtained by operating EMCCD at EM1 gain lies below the higher EM gain data. Another important point to note, is the fact that at fast exposures, images taken at higher EM gains show higher sensitivity limit than EMCCD operating at no EM gain.

The results shown in figure 4-6 perfectly coincide with the expectations we have made before. As the EM gain of the EMCCD increases, we start getting better results. For single frames taken at low exposure times, the sensitivity of EM of 1 in 1 second exposure frame is 14.85 mag, EM 100 in 0.1 seconds is 15.79 mag and EM 500 in 0.1 seconds is 15.83 mag. Comparing all EM gains data taken in 5 seconds exposure each, EM1 is 16.54 mag, EM100 is 17.43 mag, EM500 is 18.34 mag. Also, looking at figure 4-6 we can see that at fast exposures the sensitivity of EM1 regime increases slowly comparing to EM 100 or EM 500 regimes. Thus, using higher EM gain settings for short exposure times would not only make our image less noisy, but also provides better sensitivity limit in the measurements.

Gamma-Ray Bursts are phenomena of limited observable time and most of GRBs have duration of a hundred seconds. Thus, it is crucial to introduce the best operational mode for the EMCCD to have the highest sensitivity limit in the photometry. After experimentally proving that the EMCCDs operate better than the CCDs we can now estimate the suggested performance of the EMCCD and CCD. To do that,

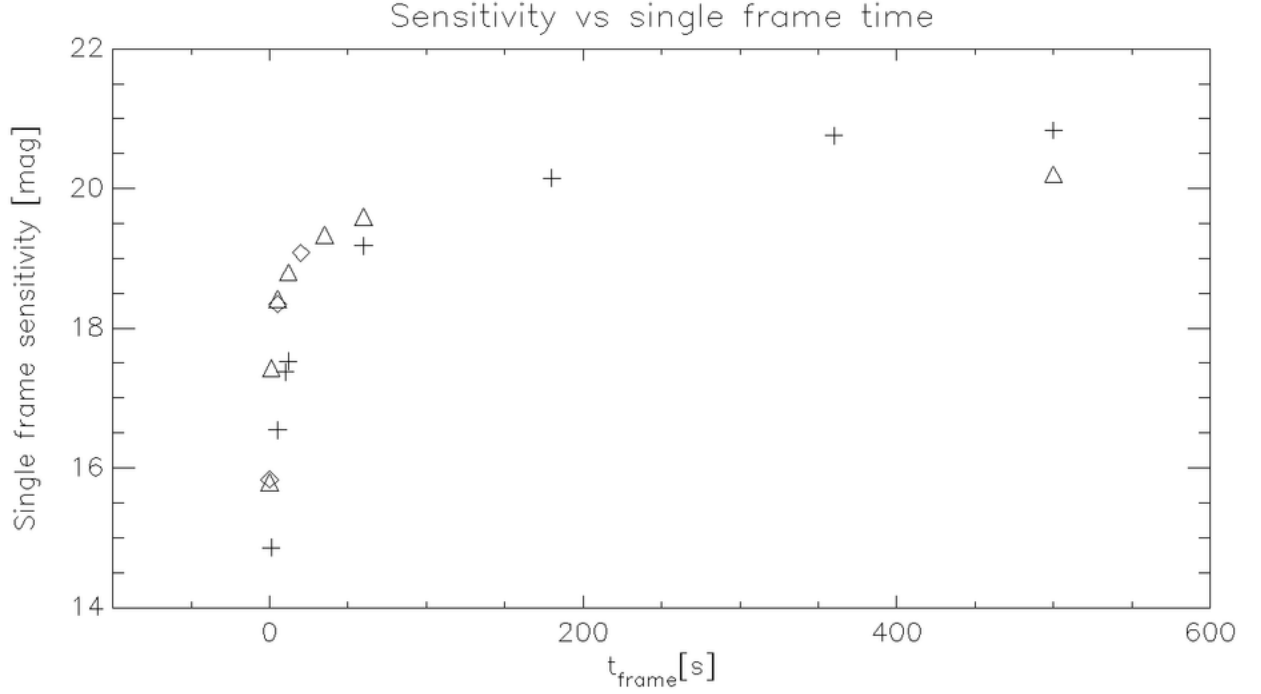


Figure 4-6: Five-sigma-limit of the measurements taken at different exposure times and EM gain settings. Data for EM 1 is cross sign, for EM 100 is a triangle and rhombus for EM 500. See details in the text.

first we chose the total exposure time to be fixed to value of 120 seconds (let's say that the burst last 120 seconds). Then we estimated the five-sigma-sensitivity for different exposure time frames. For example, we used 120 individual frames of 1 second exposure time frames to construct 120 seconds single image. The same technique used to add 24 frames of 5 seconds exposures, 4 frames for 30 seconds exposure etc. Then estimating the sensitivity limit for each constructed image we came with the figure 4-7. This figure show the five-sigma-limit for different exposure time and EM gain regimes. Data for EM1 is shown as a cross sign and data for EM100 is shown as a triangle sign. Also, we can see some deviation of the data on the figure. This is due to the fact that the sky conditions were changing in the nights of observation on November 2017. Some images were captured when light clouds were passing above the observatory and some were captured on windy conditions. Thus, it is also important to take into account the uncertainty in the estimations.

From figure 4-7, we see that at EM1 the sensitivity limit is very low at fast

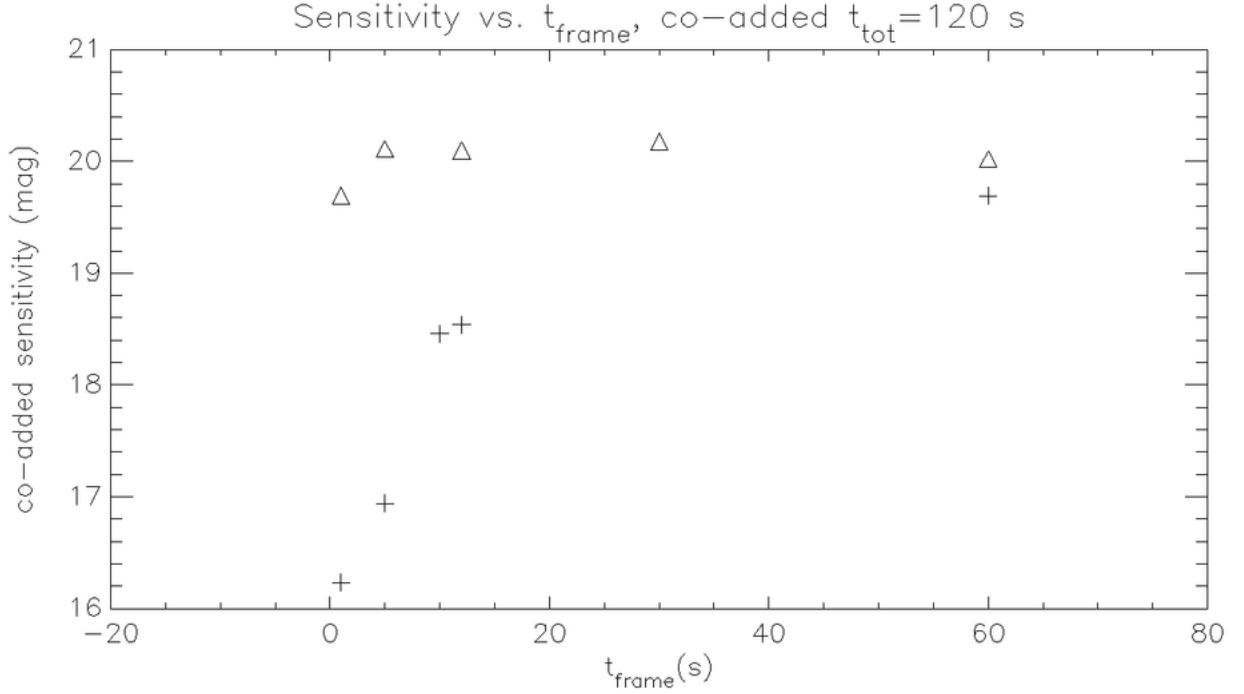


Figure 4-7: Plot shows the data for the sensitivity limit obtained at EM1 and EM100 at co-added exposures. The total, fixed exposure time was chosen to be 120 seconds, and individual exposure times were co-added to construct 120 seconds image. Data for EM 1 is cross sign, for EM 100 is a triangle. See details in the text.

exposures and starts to show higher value only at 60 seconds. Meanwhile, the data for EM100, shows considerably adequate results starting from as low as 1 second exposures. From observations and measurements we come to the conclusion that at total fixed time of 120 seconds, the best sensitivity of the photometry can be reached by the taking images at 5 seconds exposures.

4.4 Conclusion

Currently, astronomy that measures phenomena like GRBs requires short time exposure measurements in optical band with high sensitivity and time resolution [30]. The results of the thesis work demonstrates the frontier opened by the new technology such as EMCCDs. The read noise that is considered to be main ballast in doing photometry with conventional CCD is now, can be overwhelmed by the effect of electron multiplication gain. This, allowed us to achieve higher signal-to-noise ratios and

deeper sensitivity limit in our images (see figure 2-1. Also, we witnessed the fact that read noise does not depend on EM gain, and varies negligibly with EM gain variation (figure 4-1). The relative plots for dark current and dark noise showed us that at the no EM gain regime, the dark current is negligibly small and can be as low as 20 e- per pixel per 500 seconds exposure (figure 4-2. Looking at the figure 4-4 we see that the background indeed increases almost linearly proportional to the exposure time. From figure 4-5, we know that the noise of the background goes as the square root of exposure time and in log-log scale, we can show it by comparing the data points with the slope of the $1/2$ trend-line. EM1 gain starts to align the slope of $1/2$ only after about 100 seconds of exposure time. EM 100 and EM 500 data however, shows more linear results even at low as 0.1 seconds exposure time.

Since the observation of GRBs are limited by the duration of bursts, exposing images for 0.1-10 seconds frames would allow us to obtain the highest time resolution possible, in a fixed burst time. In addition, using EMCCD and co-adding frames we can increase the sensitivity of the photometry. As the results shown in figure 4-7 , the best sensitivity we can achieve with the given method, Andor EMCCD, Telescope and weather conditions is 20.11 mag. Thus, the concluding the thesis, we can say that we achieved amazing results of the EMCCD performance and developed deep understanding of the fast time-resolved photometry with high sensitivity limit.

Appendix A

Code

```
Pro single_frames

print, ' NOW LETS ANALYZE BIAS FRAMES'

; BIAS FRAMES AT EM GAIN 1

e1bb1=fltarr(1024,1024)
e1bb2=fltarr(1024,1024)
e1bb1=readfits('BIAS-0010_G24E1.fit',header)*2.4
e1bb2=readfits('BIAS-0003_G24E1.fit',header)*2.4
e1rnoisex=(e1bb1-e1bb2)
e1rnoise=where(e1rnoisex le 30. and e1rnoisex ge -30., count)
plohist,e1rnoisex[e1rnoise], xRANGE = [MIN(-30), MAX(30)],
title='Histogram of the difference biasframes at EM1',xtitle='pixel values [ADU]',
ytitle='number of pixels'
b1FWHM=9. ; FWHM of the histogram of the averaged bias frame
readnoise1=(b1fwhm/2.) * sqrt(1./(2.*alog(2.)))

; BIAS FRAMES AT EM GAIN 100
e100bb1=fltarr(1024,1024)
e100bb2=fltarr(1024,1024)
e100rnoise=fltarr(1024,1024)
e100bb1=readfits('BIAS121117-0011_G24_E100.fit',header)*2.4
e100bb2=readfits('BIAS121117-0002_G24_E100.fit',header)*2.4
e100rnoisex=(e100bb1-e100bb2)
e100rnoise=where(e100rnoisex le 40. and e100rnoisex ge -40., count)

b100FWHM=9. ; FWHM of the histogram of the averaged bias frame
readnoise100=(b100fwhm/2.) * sqrt(1./(2.*alog(2.)))
```

```

; BIAS FRAMES AT EM GAIN 500
e500bb1=fltarr(1024,1024)
e500bb2=fltarr(1024,1024)
e500bb1=readfits('BIAS141117-0011_G24E500.fit',header)*2.4
e500bb2=readfits('BIAS141117-0005_G24E500.fit',header)*2.4
e500rnoisex=(e500bb1-e500bb2)
e500rnoise=where(e500rnoisex le 80. and e500rnoisex ge -80., count)

b500FWHM=9. ; FWHM of the histogram of the averaged bias frame
readnoise500=(b500fwhm/2.) * sqrt(1./(2.*alog(2.)))

readnoise=[stdev(e1rnoisex[e1rnoise]), stdev(e100rnoisex[e100rnoise]),
stdev(e500rnoisex[e500rnoise])]/sqrt(2.)
emgain=[1.,100.,500.]
plot, emgain, readnoise, xtitle='EM gain', ytitle='Read noise [e-/pix]',
title='Readnoise level vs EM gain', psym=8, xrange=[-1,510], charsize=1.5
print, 'STDEV of difference frames of EM1, EM100, EM500 respectively = '
print, readnoise
print, 'Read noise calculated by the width of the histogram image is =', readnoise1
medbias=[median(e1bb1),median(e100bb1),median(e500bb1)]
rnlog=alog10(readnoise)
emlog=alog10(emgain)
berror=sqrt(readnoise)
ploterror, emgain, readnoise, BACKGROUND = 255, COLOR = 0, berror,
xtitle='EM gain', ytitle='Read noise [e-/pix]', title='Readnoise level vs EM gain',
psym=8, xrange=[-1,510], charsize=1.5, symsize=1.5
stop

; BELOW ARE CALCULATIONS FOR THE DARK NOISE OF EM 1
; Variable name meaning example: d1d1e1= first "d1" means 1 dark frame,
;second "d1" means exposure time in seconds (1 sec), e1 means EM gain of 1
; 1 second exposure time
d1d1e1=fltarr(1024,1024)
d2d1e1=fltarr(1024,1024)
d1d1e1=readfits('DARK131117-0002_G24E1_1s.fit',header)*2.4-e1bb1
d2d1e1=readfits('DARK131117-0003_G24E1_1s.fit',header)*2.4-e1bb1
dnoise1e1x=(d2d1e1-d1d1e1)
dnoise1e1=where(dnoise1e1x le 40. and dnoise1e1x ge -40., count)*1.0
print, stdev(dnoise1e1x[dnoise1e1])/sqrt(2.)
plohist,dnoise1e1x[dnoise1e1], title='Histogram of the difference of 1 seconds darkframes',
xRANGE = [MIN(-10), MAX(10)], xtitle='pixel values [ADU]',ytitle='number of pixels'

; 5 second exposure time
d1d5e1=fltarr(1024,1024)
d2d5e1=fltarr(1024,1024)
d1d5e1=readfits('DARK121117-0001_G24E1_5s.fit',header)*2.4-e1bb1

```

```

d2d5e1=readfits('DARK121117-0004_G24E1_5s.fit',header)*2.4-e1bb1
dnoise5e1x=(d2d5e1-d1d5e1)
dnoise5e1=where(dnoise5e1x le 40. and dnoise5e1x ge -40., count)*1.0
plothist,dnoise5e1x[dnoise5e1], title='Histogram ofthe difference of 5 seconds darkframes',
  xRANGE = [MIN(-10), MAX(10)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 10 second exposure time
d1d10e1=fltarr(1024,1024)
d2d10e1=fltarr(1024,1024)
d1d10e1=readfits('DARK131117-0001_G24E1_10s.fit',header)*2.4-e1bb1
d2d10e1=readfits('DARK131117-0005_G24E1_10s.fit',header)*2.4-e1bb1
dnoise10e1x=(d2d10e1-d1d10e1)
dnoise10e1=where(dnoise10e1x le 40. and dnoise10e1x ge -40., count)*1.0
plothist,dnoise10e1x[dnoise10e1], title='Histogram ofthe difference of 10 seconds darkframes',
  xRANGE = [MIN(-10), MAX(10)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 12 second exposure time
d1d12e11=fltarr(1024,1024)
d2d12e11=fltarr(1024,1024)
d1d12e11=readfits('DARK121117-0005_G24E1_12s.fit',header)*2.4-e1bb1
d2d12e11=readfits('DARK121117-0004_G24E1_12s.fit',header)*2.4-e1bb1
dnoise12e1x=(d2d12e11-d1d12e11)
dnoise12e1=where(dnoise12e1x le 40. and dnoise12e1x ge -40., count)*1.0
plothist,dnoise12e1x[dnoise12e1], title='Histogram ofthe difference of 12 seconds darkframes',
  xRANGE = [MIN(-10), MAX(10)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 35 second exposure time
d1d35e1=fltarr(1024,1024)
d2d35e1=fltarr(1024,1024)
d1d35e1=readfits('DARK121117-0002_G24E1_35s.fit',header)*2.4-e1bb1
d2d35e1=readfits('DARK121117-0003_G24E1_35s.fit',header)*2.4-e1bb1
dnoise35e1x=(d2d35e1-d1d35e1)
dnoise35e1=where(dnoise35e1x le 40. and dnoise35e1x ge -40., count)*1.0
plothist,dnoise35e1x[dnoise35e1], title='Histogram ofthe difference of 35 seconds darkframes',
  xRANGE = [MIN(-15), MAX(15)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 60 second exposure time
d1d12e1=fltarr(1024,1024)
d2d12e1=fltarr(1024,1024)
d1d60e1=readfits('DARK121117-0002_G24E1_60s.fit',header)*2.4-e1bb1
d2d60e1=readfits('DARK121117-0003_G24E1_60s.fit',header)*2.4-e1bb1
dnoise60e1x=(d2d60e1-d1d60e1)
dnoise60e1=where(dnoise60e1x le 40. and dnoise60e1x ge -40., count)*1.0
plothist,dnoise60e1x[dnoise60e1], title='Histogram ofthe difference of 60 seconds darkframes',
  xRANGE = [MIN(-20), MAX(20)], xtitle='pixel values [ADU]', ytitle='number of pixels'

```

```

; 180 second exposure time
d1d180e1=fltarr(1024,1024)
d2d180e1=fltarr(1024,1024)
d1d180e1=readfits('DARK131117-0002_G24E1_180s.fit',header)*2.4-e1bb1
d2d180e1=readfits('DARK131117-0003_G24E1_180s.fit',header)*2.4-e1bb1
dnoise180e1x=(d2d180e1-d1d180e1)
dnoise180e1=where(dnoise180e1x le 40. and dnoise180e1x ge -40., count)*1.0
plothist,dnoise180e1x[dnoise180e1], title='Histogram ofthe difference of 180 seconds darkframes',
xRANGE = [MIN(-20), MAX(20)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 360 second exposure time
d1d360e1=fltarr(1024,1024)
d2d360e1=fltarr(1024,1024)
d1d360e1=readfits('DARK131117-0002_G24E1_360s.fit',header)*2.4-e1bb1
d2d360e1=readfits('DARK131117-0003_G24E1_360s.fit',header)*2.4-e1bb1
dnoise360e1x=(d2d360e1-d1d360e1)
dnoise360e1=where(dnoise360e1x le 40. and dnoise360e1x ge -40., count)*1.0
plothist,dnoise360e1x[dnoise360e1], title='Histogram ofthe difference of 360 seconds darkframes',
xRANGE = [MIN(-15), MAX(15)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 500 second exposure time
d1d500e1=fltarr(1024,1024)
d2d500e1=fltarr(1024,1024)
d1d500e1=readfits('DARK131117-0001_G24E1_500s.fit',header)*2.4-e1bb1
d2d500e1=readfits('DARK131117-0002_G24E1_500s.fit',header)*2.4-e1bb1
dnoise500e1x=(d2d500e1-d1d500e1)
dnoise500e1=where(dnoise500e1x le 40. and dnoise500e1x ge -40., count)*1.0
plothist,dnoise500e1x[dnoise500e1], title='Histogram ofthe difference of 500 seconds darkframes',
xRANGE = [MIN(-15), MAX(15)], xtitle='pixel values [ADU]', ytitle='number of pixels'

exptime1gain=[1.,5.,10.,12.,35.,60.,180.,360.,500.]

darknoise1gain=[stdev(dnoise1e1x),stdev(dnoise5e1x),stdev(dnoise10e1x),stdev(dnoise12e1x),
stdev(dnoise35e1x),stdev(dnoise60e1x),stdev(dnoise180e1x),stdev(dnoise360e1x),stdev(dnoise500e1x)]
/sqrt(2.)

medians=[median(d1d1e1),median(d1d5e1),median(d1d10e1),median(d1d12e1),median(d2d35e1),
median(d1d60e1),median(d1d180e1),median(d1d360e1),median(d2d500e1)]

gain1=log10(darknoise1gain)
dlogtime1=log10(exptime1gain)
plot, exptime1gain, medians, title='Dark current exposure time dependance at EM gain of 1',
psym=8, xtitle='Exp. time [sec]', ytitle='Dark Noise [e-]'

Print, 'DONE WITH EM 1 DARKS'

```

```

;BELOW IS EM 100 NOISE ANALYSIS PROCEDURE
; Here we read the DARK files with exposure time of 01 sec.
; the variable name ends with the exposure time in seconds,
; i.e. d1d01 - means 1 dark frame with 0.1 exp. time.
; 0.1 second exposure time
d1d01=fltarr(1024,1024)
d2d01=fltarr(1024,1024)
d1d01=(readfits('DARK121117-0001_G24E100_01s.fit',header)*2.4-e100bb1)/100.
d2d01=(readfits('DARK121117-0002_G24E100_01s.fit',header)*2.4-e100bb1)/100.
imd1d01=readfits('DARK121117-0002_G24E100_01s.fit',header)*2.4
dnoise01x=(d2d01-d1d01)
dnoise01=where(dnoise01x le 100. and dnoise01x ge -100., count)
plothist,dnoise01x[dnoise01], title='Histogram ofthe difference of 0.1 seconds darkframes',
xRANGE = [MIN(-100), MAX(100)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 1 second exposure time
d1d1=fltarr(1024,1024)
d2d1=fltarr(1024,1024)
d1d1=(readfits('DARK121117-0001_G24E100_1s.fit',header)*2.4-e100bb1)/100.
d2d1=(readfits('DARK121117-0002_G24E100_1s.fit',header)*2.4-e100bb1)/100.
imd1d1=readfits('DARK121117-0001_G24E100_1s.fit',header)*2.4
dnoise1x=(d2d1-d1d1)
dnoise1=where(dnoise1x le 50. and dnoise1x ge -50., count)
plothist,dnoise1x[dnoise1], title='Histogram ofthe difference of 1 seconds darkframes',
xRANGE = [MIN(-50), MAX(50)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 5 second exposure time
d1d5=fltarr(1024,1024)
d2d5=fltarr(1024,1024)
d1d5=(readfits('DARK121117-0001_G24E100_5s.fit',header)*2.4-e100bb1)/100.
d2d5=(readfits('DARK121117-0002_G24E100_5s.fit',header)*2.4-e100bb1)/100.
imd1d5=readfits('DARK121117-0001_G24E100_5s.fit',header)*2.4
dnoise5x=(d2d5-d1d5)
dnoise5=where(dnoise5x le 100. and dnoise5x ge -100., count)
plothist,dnoise5x[dnoise5], title='Histogram ofthe difference of 5 seconds darkframes',
xRANGE = [MIN(-100), MAX(100)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 12 second exposure time
d1d12=fltarr(1024,1024)
d2d12=fltarr(1024,1024)
d1d12=(readfits('DARK121117-0001_G24E100_12s.fit',header)*2.4-e100bb1)/100.
d2d12=(readfits('DARK121117-0002_G24E100_12s.fit',header)*2.4-e100bb1)/100.
imd1d12=readfits('DARK121117-0001_G24E100_12s.fit',header)*2.4
dnoise12x=(d2d12-d1d12)
dnoise12=where(dnoise12x le 100. and dnoise12x ge -100., count)

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plothist,dnoise12x[dnoise12], title='Histogram ofthe difference of 12 seconds darkframes',
xRANGE = [MIN(-100), MAX(100)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 20 second exposure time
d1d20=fltarr(1024,1024)
d2d20=fltarr(1024,1024)
d1d20=(readfits('DARK121117-0002_G24E100_20s.fit',header)*2.4-e100bb1)/100.
d2d20=(readfits('DARK121117-0001_G24E100_20s.fit',header)*2.4-e100bb1)/100.
imd1d20=readfits('DARK121117-0002_G24E100_20s.fit',header)*2.4
dnoise20x=(d2d20-d1d20)
dnoise20=where(dnoise20x le 100. and dnoise20x ge -100., count)
plothist,dnoise12x[dnoise12], title='Histogram ofthe difference of 20 seconds darkframes',
xRANGE = [MIN(-100), MAX(100)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 35 second exposure time
d1d35=fltarr(1024,1024)
d2d35=fltarr(1024,1024)
d1d35=(readfits('DARK121117-0001_G24E100_35s.fit',header)*2.4-e100bb1)/100.
d2d35=(readfits('DARK121117-0002_G24E100_35s.fit',header)*2.4-e100bb1)/100.
imd1d35=readfits('DARK121117-0001_G24E100_35s.fit',header)*2.4 ; -----
;--- This dark images will be used in image subtraction from the star image
dnoise35x=(d2d35-d1d35)
dnoise35=where(dnoise35x le 200. and dnoise35x ge -200., count)
plothist,dnoise35x[dnoise35], title='Histogram ofthe difference of 35 seconds darkframes',
xRANGE = [MIN(-200), MAX(200)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 60 second exposure time
d1d60=fltarr(1024,1024)
d2d60=fltarr(1024,1024)
d1d60=(readfits('DARK121117-0001_G24E100_60s.fit',header)*2.4-e100bb1)/100.
d2d60=(readfits('DARK121117-0002_G24E100_60s.fit',header)*2.4-e100bb1)/100.
imd1d60=readfits('DARK121117-0001_G24E100_60s.fit',header)*2.4
dnoise60x=(d2d60-d1d60)
dnoise60=where(dnoise60x le 300. and dnoise60x ge -300., count)
plothist,dnoise60x[dnoise60], title='Histogram ofthe difference of 60 seconds darkframes',
xRANGE = [MIN(-300), MAX(300)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 500 second exposure time
d1d500=fltarr(1024,1024)
d2d500=fltarr(1024,1024)
d1d500=(readfits('DARK121117-0001_G24E100_500s.fit',header)*2.4-e100bb1)/100.
d2d500=(readfits('DARK121117-0002_G24E100_500s.fit',header)*2.4-e100bb1)/100.
imd1d500=readfits('DARK121117-0001_G24E100_500s.fit',header)*2.4
dnoise500x=(d2d500-d1d500)
dnoise500=where(dnoise500x le 750. and dnoise500x ge -750., count)

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plothist,dnoise500x[dnoise500], title='Histogram ofthe difference of 500 seconds darkframes',
xRANGE = [MIN(-750), MAX(750)], xtitle='pixel values [ADU]', ytitle='number of pixels'

darknoise=[stdev(dnoise01x),stdev(dnoise1x),stdev(dnoise5x),stdev(dnoise12x),stdev(dnoise20x),
stdev(dnoise35x),stdev(dnoise60x),stdev(dnoise500x)]/sqrt(2.)
exptime=[0.1,1.,5.,12.,20.,35.,60.,500.]
median100=[median(d1d01),median(d1d1),median(d1d5),median(d1d12),median(d1d20),median(d1d35),
median(d1d60),median(d1d500)]

gain100=log10(darknoise)
dlogtime100=log10(exptime)
plot, exptime, median100, title='Dark current exposure time dependance at EM gain of 100',psym=8,
xtitle='Exp. time [sec]', ytitle='Dark Current [e-/pix]';,yrange=[1,2.5], xrange=[0,510]
; BELOW ARE CALCULATIONS FOR THE DARK NOISE OF EM 500
; Variable name measning example: d1d1e1= first "d1" means 1 dark frame, second "d1" means
; exposure time in seconds (1 sec), e1 means EM gain of 1
; 0.1 second exposure time
d1d01e500=fltarr(1024,1024)
d2d01e500=fltarr(1024,1024)
d1d01e500=(readfits('DARK131117-0002_G24E500_01s.fit',header)*2.4-e500bb1)/500.
d2d01e500=(readfits('DARK131117-0003_G24E500_01s.fit',header)*2.4-e500bb1)/500.
imd1d01e500=readfits('DARK131117-0002_G24E500_01s.fit',header)*2.4
dnoise01e500x=(d2d01e500-d1d01e500)
dnoise01e500=where(dnoise01e500x le 200. and dnoise01e500x ge -200., count)
plothist,dnoise01e500x[dnoise01e500], title='Histogram ofthe difference of 0.1 seconds darkframes
at EM 500', xRANGE = [MIN(-200), MAX(200)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 5 second exposure time
d1d5e500=fltarr(1024,1024)
d2d5e500=fltarr(1024,1024)
d1d5e500=(readfits('DARK141117-0002_G24E500_5s.fit',header)*2.4-e500bb1)/500.
d2d5e500=(readfits('DARK141117-0003_G24E500_5s.fit',header)*2.4-e500bb1)/500.
imd1d5e500=readfits('DARK141117-0002_G24E500_5s.fit',header)*2.4
dnoise5e500x=(d2d5e500-d1d5e500)
dnoise5e500=where(dnoise5e500x le 500. and dnoise5e500x ge -500., count)
plothist,dnoise5e500x[dnoise5e500], title='Histogram ofthe difference of 5 seconds darkframes
at EM500', xRANGE = [MIN(-500), MAX(500)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 20 second exposure time
d1d20e500=fltarr(1024,1024)
d2d20e500=fltarr(1024,1024)
d1d20e500=(readfits('DARK141117-0002_G24E500_20s.fit',header)*2.4-e500bb1)/500.
d2d20e500=(readfits('DARK141117-0003_G24E500_20s.fit',header)*2.4-e500bb1)/500.
imd1d20e500=readfits('DARK141117-0002_G24E500_20s.fit',header)*2.4
dnoise20e500x=(d2d20e500-d1d20e500)

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dnoise20e500=where(dnoise20e500x le 800. and dnoise20e500x ge -800., count)
plothist,dnoise20e500x[dnoise20e500], title='Histogram ofthe difference of 20 seconds darkframes
at EM500', xrange = [MIN(-800), MAX(800)], xtitle='pixel values [ADU]', ytitle='number of pixels'

; 200 second exposure time
d1d200e500=fltarr(1024,1024)
d2d200e500=fltarr(1024,1024)
d1d200e500=(readfits('DARK131117-0002_G24E500_200s.fit',header)*2.4-e500bb1)/500.
d2d200e500=(readfits('DARK131117-0003_G24E500_200s.fit',header)*2.4-e500bb1)/500.
imd1d200e500=readfits('DARK131117-0002_G24E500_200s.fit',header)*2.4
dnoise200e500x=(d2d200e500-d1d200e500)
dnoise200e500=where(dnoise200e500x le 2100. and dnoise200e500x ge -2100., count)
plothist,dnoise200e500x[dnoise200e500], title='Histogram ofthe difference of 200 seconds
darkframes ate EM500'

median500=[median(d1d01e500),median(d1d5e500),median(d1d20e500),median(d1d200e500)]
darknoise500gain=[stdev(dnoise01e500x),stdev(dnoise5e500x),stdev(dnoise20e500x),
stdev(dnoise200e500x)]/sqrt(2.)
exptime500gain=[0.1,5.,20.,200.]
plot, exptime500gain, median500, title='Dependance of the dark current upon the exposure
time at EM gain 500', xtitle='Exposure time [seconds]', ytitle='Dark noise [ADU]',psym=6

print, 'Dark Noise with EM 1:'
print, darknoise1gain
print, 'Dark Noise with EM 100:'
print, darknoise
print, 'Dark Noise with EM 500:'
print, darknoise500gain

derror1=sqrt(medians)
derror100=sqrt(median100)
derror500=sqrt(median500)

plot, exptime1gain, medians, BACKGROUND = 255, COLOR = 0, title='Dark current as a
function of exp. time at various EM gain', xtitle='Time [sec]', ytitle='Dark Current [e-/pix]',
charsize=1.5, xrange=[-1,501],yrange=[-1,22], psym=1,symsize=1.5
oplot, exptime, median100, COLOR = 0, psym=5 ,symsize=1.5
oplot, exptime500gain, median500, COLOR = 0, psym=4 ,symsize=1.5
gain500=log10(darknoise500gain)
dlogtime500=log10(exptime500gain)
stop

plot, dlogtime100, gain100, BACKGROUND = 255, COLOR = 0, title='Dark noise exp. time dependance
at various EM gain',psym=5, xtitle='Exp. time [Log_sec]', ytitle='Dark Noise [Log_(e-/pix)]',
charsize=1.5 ,symsize=1.5 ;,yrange=[0,3];, xrange=[-1,510]
oplot, dlogtime1, gain1, COLOR = 0, psym=1 ,symsize=1.5

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oplot, dlogtime500, gain500,COLOR = 0, psym=4 ,symsize=1.5
stop
print, 'Define FLATS for different EM gain settings'
f1=fltarr(1024,1024)
f1=readfits('FLAT121117-0021_G24E1_35s.fit', header)*2.4-e1bb1 ; in units of e-
flat1=f1/mean(f1)
f100=fltarr(1024,1024)
f100=readfits('FLAT131117-0044_G24E100_1s_R.fit', header)*2.4-e100bb1
;f100=readfits('FLAT161117-0004_G24E100_Rs.fit', header)*1.0-e100bb1 ; 1 sec of exp time flat
flat100=f100/mean(f100)
f500=fltarr(1024,1024)
f500=readfits('FLAT161117-0004_G24E500_Rs.fit', header)*2.4-e500bb1
flat500=f500/mean(f500)
print, ' NOW WORK WITH IMAGES'
;Below are images with EM 1 captured ad various exp. time

;For the sake of convenience we take the numbers of pixels in the aperture to be equal to 625

npix=625.
cr=22.46
em1time1=fltarr(1024,1024)
em1time1=readfits('FRB121102-0200_G24E1_1s_R.fit',header)*2.4
im1time1=(em1time1-e1bb1-d1d1e1)/flat1
aaa1=median(im1time1[200:225,205:230]) ; - sky valuse
bbb1=stdev(im1time1[200:225,205:230]) ; noise in the sky
aaa2=median(im1time1[90:115,585:610])
bbb2=stdev(im1time1[90:115,585:610])
aaa3=median(im1time1[595:620,120:145])
bbb3=stdev(im1time1[595:620,120:145])
aveb1=(aaa1+aaa2+aaa3)/3. ; mean sky value
aven1=(bbb1+bbb2+bbb3)/3./1. ; mean noise in the sky in e-/sec
sigmals1em=aven1*sqrt(npix)
fsl1s1em=cr-2.5*log10(5.*sigmals1em)
print, fsl1s1em

em1time5=fltarr(1024,1024)
em1time5=readfits('GD2_GD2C-0080_G24E1_5s_R.fit',header)*2.4
im1time5=(em1time5-e1bb1-d1d5e1)/flat1
aa51=median(im1time5[180:205,270:295]) ; - sky valuse
bb51=stdev(im1time5[180:205,270:295]) ; noise in the sky
aa52=median(im1time5[185:210,660:685])
bb52=stdev(im1time5[185:210,660:685])
aa53=median(im1time5[815:840,110:135])
bb53=stdev(im1time5[815:840,110:135])
aveb5=(aa51+aa52+aa53)/3. ; mean sky value

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aven5=(bb51+bb52+bb53)/3. ; mean noise in the sky
sigma5s1em=aven5*sqrt(npix)
fsl5s1em=cr-2.5*log10(5.*sigma5s1em/5.)

em1time10=fltarr(1024,1024)
em1time10=readfits('FRB121102-0100_G24E1_10s_R.fit',header)*2.4
im1time10=(em1time10-e1bb1-d1d10e1)/flat1
aa101=median(im1time10[295:320,220:245]) ; - sky valuse
bb101=stdev(im1time10[295:320,220:245]) ; noise in the sky
aa102=median(im1time10[325:340,30:55])
bb102=stdev(im1time10[325:340,30:55])
aa103=median(im1time10[420:425,600:625])
bb103=stdev(im1time10[420:425,600:625])
aveb10=(aa101+aa102+aa103)/3. ; mean sky value
aven10=(bb101+bb102+bb103)/3. ; mean noise in the sky
sigma10s1em=aven10*sqrt(npix)
fsl10s1em=cr-2.5*log10(5.*sigma10s1em/10.)

em1time12=fltarr(1024,1024)
em1time12=readfits('GD2_GD2C-0008_G24E1_12s_R.fit',header)*2.4
im1time12=(em1time12-e1bb1-d2d12e11)/flat1
aa121=median(im1time12[745:770,80:105]) ; - sky valuse
bb121=stdev(im1time12[745:770,80:105]) ; noise in the sky
aa122=median(im1time12[100:125,735:760])
bb122=stdev(im1time12[100:125,735:760])
aa123=median(im1time12[430:455,305:330])
bb123=stdev(im1time12[430:455,305:330])
aveb12=(aa121+aa122+aa123)/3. ; mean sky value
aven12=(bb121+bb122+bb123)/3. ; mean noise in the sky
sigma12s1em=aven12*sqrt(npix)
fsl12s1em=cr-2.5*log10(5.*sigma12s1em/12.)

em1time60=fltarr(1024,1024)
em1time60=readfits('GD61_OABC-0005_G24E1_60s_R.fit',header)*2.4
im1time60=(em1time60-e1bb1-d1d60e1)/flat1
aa601=median(im1time60[650:675,50:75]) ; - sky valuse
bb601=stdev(im1time60[650:675,50:75]) ; noise in the sky
aa602=median(im1time60[435:460,130:155])
bb602=stdev(im1time60[435:460,130:155])
aa603=median(im1time60[200:225,90:115])
bb603=stdev(im1time60[200:225,90:115])
aveb60=(aa601+aa602+aa603)/3. ; mean sky value
aven60=(bb601+bb602+bb603)/3. ; mean noise in the sky
sigma60s1em=aven60*sqrt(npix)
fsl60s1em=cr-2.5*log10(5.*sigma60s1em/60.)

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em1time180=fltarr(1024,1024)
em1time180=readfits('GD61_0ABC_after-0003_G24E1_180s_R.fit',header)*2.4
im1time180=(em1time180-e1bb1-d1d180e1)/flat1
aa1801=median(im1time180[180:205,70:95]) ; - sky valuse
bb1801=stdev(im1time180[180:205,70:95]) ; noise in the sky
aa1802=median(im1time180[705:730,495:520])
bb1802=stdev(im1time180[705:730,495:520])
aa1803=median(im1time180[205:230,590:615])
bb1803=stdev(im1time180[205:230,590:615])
aveb180=(aa1801+aa1802+aa1803)/3. ; mean sky value
aven180=(bb1801+bb1802+bb1803)/3. ; mean noise in the sky
sigma180s1em=aven180*sqrt(npix)
fsl180s1em=cr-2.5*aalog10(5.*sigma180s1em/180.)

em1time360=fltarr(1024,1024)
em1time360=readfits('GD61_0ABC-0001_G24E1_360s_R.fit',header)*2.4
im1time360=(em1time360-e1bb1-d1d360e1)/flat1
aa3601=median(im1time360[400:425,880:905]) ; - sky valuse
bb3601=stdev(im1time360[400:425,880:905]) ; noise in the sky
aa3602=median(im1time360[420:445,140:165])
bb3602=stdev(im1time360[420:445,140:165])
aa3603=median(im1time360[760:785,565:590])
bb3603=stdev(im1time360[760:785,565:590])
aveb360=(aa3601+aa3602+aa3603)/3. ; mean sky value
aven360=(bb3601+bb3602+bb3603)/3. ; mean noise in the sky
sigma360s1em=aven360*sqrt(npix)
fsl360s1em=cr-2.5*aalog10(5.*sigma360s1em/360.)

em1time500=fltarr(1024,1024)
em1time500=readfits('GD2_GD2C-0001_G24E1_500s_R.fit',header)*2.4
im1time500=(em1time500-e1bb1-d1d500e1)/flat1
aa5001=median(im1time500[230:255,730:755]) ; - sky valuse
bb5001=stdev(im1time500[230:255,730:755]) ; noise in the sky
aa5002=median(im1time500[260:285,125:150])
bb5002=stdev(im1time500[260:285,125:150])
aa5003=median(im1time500[815:840,60:85])
bb5003=stdev(im1time500[815:840,60:85])
aveb500=(aa5001+aa5002+aa5003)/3. ; mean sky value
aven500=(bb5001+bb5002+bb5003)/3. ; mean noise in the sky
sigma500s1em=aven500*sqrt(npix)
fsl500s1em=cr-2.5*aalog10(5.*sigma500s1em/500.)

fives11em=[fsl1s1em,fsl5s1em,fsl10s1em,fsl12s1em,fsl60s1em,fsl180s1em,fsl360s1em,fsl500s1em]
skyem1=[aveb1,aveb5,aveb10,aveb12,aveb60,aveb180,aveb360,aveb500]
noiseem1=[aven1,aven5,aven10,aven12,aven60,aven180,aven360,aven500]

```

```

time=[1.,5.,10.,12.,60.,180.,360.,500.]
ratio=skyem1/noiseem1
print, skyem1

skylog1=log10(skyem1)
plot, time,skyem1, psym=1, title='Background as a function of exp. time at EM 1',
xtitle='Exposure time [sec]', ytitle='Background [e-]'

logtime1=log10(time)
noiselog1=log10(noiseem1)
plot, logtime1,noiselog1, psym=1, title='Noise of the background as a function of
exp. time at EM 1', xtitle='Exposure time [Log_sec]', ytitle='Background [Log_Ne-]'
print, 'DONE WITH IMAGES AT EM GAIN 1'
;Below are images with EM 100 captured at various exp. time
em100time01=filtarr(1024,1024)
em100time01=readfits('FRB121102-0198_G24E100_01s_R.fit',header)*2.4
im100time01=(em100time01-imd1d01)/100./flat100
cc011=median(im100time01[380:405,85:110]) ; - sky valuse
dd011=stdev(im100time01[380:405,85:110]) ; noise in the sky
cc012=median(im100time01[350:375,240:265])
dd012=stdev(im100time01[350:375,240:265])
cc013=median(im100time01[790:815,130:155])
dd013=stdev(im100time01[790:815,130:155])
avee100b01=(cc011+cc012+cc013)/3. ; mean sky value
avee100ne01=(dd011+dd012+dd013)/3. ; mean noise in the sky
sigma01s100em=avee100ne01*sqrt(npix)
fsl01s100em=cr-2.5*log10(5.*sigma01s100em/0.1)

em100time1=filtarr(1024,1024)
em100time1=readfits('FRB121102-0197_G24E100_1s_R.fit',header)*2.4
im100time1=(em100time1-imd1d1)/100./flat100
cc11=median(im100time1[315:340,240:265]) ; - sky valuse
dd11=stdev(im100time1[315:340,240:265]) ; noise in the sky
cc12=median(im100time1[290:315,390:415])
dd12=stdev(im100time1[290:315,390:415])
cc13=median(im100time1[810:835,820:845])
dd13=stdev(im100time1[810:835,820:845])
avee100b1=(cc11+cc12+cc13)/3. ; mean sky value
avee100ne1=(dd11+dd12+dd13)/3. ; mean noise in the sky
sigma1s100em=avee100ne1*sqrt(npix)
fsl1s100em=cr-2.5*log10(5.*sigma1s100em/1.)

em100time5=filtarr(1024,1024)
em100time5=readfits('GD2_GD2C-0073_G24E100_5s_R.fit',header)*2.4
im100time5=(em100time5-imd1d5)/100./flat100

```

```

cc51=median(im100time5[750:775,90:115]) ; - sky valuse
dd51=stdev(im100time5[750:775,90:115]) ; noise in the sky
cc52=median(im100time5[135:160,680:705])
dd52=stdev(im100time5[135:160,680:705])
cc53=median(im100time5[400:425,360:385])
dd53=stdev(im100time5[400:425,360:385])
avee100b5=(cc51+cc52+cc53)/3. ; mean sky value
avee100ne5=(dd51+dd52+dd53)/3. ; mean noise in the sky
sigma5s100em=avee100ne5*sqrt(npix)
fsl5s100em=cr-2.5*alog10(5.*sigma5s100em/5.)

em100time12=fltarr(1024,1024)
;em100time12=readfits('GD2C_GD2_12s-0003_G24E100.fit',header)*1.0
em100time12=readfits('GD2_GD2C-0003_G24E100_12s_R.fit',header)*2.4
im100time12=(em100time12-imd1d12)/100./flat100
cc121=median(im100time12[620:645,40:65]) ; - sky valuse
dd121=stdev(im100time12[620:645,40:65]) ; noise in the sky
cc122=median(im100time12[130:155,835:860])
dd122=stdev(im100time12[130:155,835:860])
cc123=median(im100time12[55:80,60:85])
dd123=stdev(im100time12[55:80,60:85])
avee100b12=(cc121+cc122+cc123)/3. ; mean sky value
avee100ne12=(dd121+dd122+dd123)/3. ; mean noise in the sky
sigma12s100em=avee100ne12*sqrt(npix)
fsl12s100em=cr-2.5*alog10(5.*sigma12s100em/12.)

em100time35=fltarr(1024,1024)
;em100time35=readfits('GD61_OABC_35s-0004_G24E100.fit',header)*1.0
em100time35=readfits('GD61_OABC_after_35s-0005_G24E100.fit',header)*2.4
im100time35=(em100time35-imd1d35)/100./flat100
cc351=median(im100time35[90:105,90:105]) ; - sky valuse
dd351=stdev(im100time35[90:105,90:105]) ; noise in the sky
cc352=median(im100time35[345:370,755:780])
dd352=stdev(im100time35[345:370,755:780])
cc353=median(im100time35[915:940,135:160])
dd353=stdev(im100time35[915:940,135:160])
avee100b35=(cc351+cc352+cc353)/3. ; mean sky value
avee100ne35=(dd351+dd352+dd353)/3. ; mean noise in the sky
sigma35s100em=avee100ne35*sqrt(npix)
fsl35s100em=cr-2.5*alog10(5.*sigma35s100em/35.)

em100time60=fltarr(1024,1024)
;em100time60=readfits('GD61_OABC-0005_G24E1_60s_R.fit',header)*1.0
em100time60=readfits('FRB121102_60s-0002_G24E100.fit',header)*2.4
im100time60=(em100time60-imd1d60)/100./flat100

```

```

cc601=median(im100time60[405:430,130:155]) ; - sky valuse
dd601=stdev(im100time60[405:430,130:155]) ; noise in the sky
cc602=median(im100time60[300:325,630:655])
dd602=stdev(im100time60[300:325,630:655])
cc603=median(im100time60[885:910,630:655])
dd603=stdev(im100time60[885:910,630:655])
avee100b60=(cc601+cc602+cc603)/3. ; mean sky value
avee100ne60=(dd601+dd602+dd603)/3. ; mean noise in the sky
sigma60s100em=avee100ne60*sqrt(npix)
fsl60s100em=cr-2.5*alog10(5.*sigma60s100em/60.)

em100time500=fltarr(1024,1024)
em100time500=readfits('GRB783479_500s-0003_G24E100.fit',header)*2.4
im100time500=(em100time500-imd1d500)/100./flat100
cc5001=median(im100time500[145:170,660:685]) ; - sky value
dd5001=stdev(im100time500[145:170,660:685]) ; noise in the sky
cc5002=median(im100time500[285:310,135:160])
dd5002=stdev(im100time500[285:310,135:160])
cc5003=median(im100time500[815:840,60:85])
dd5003=stdev(im100time500[815:840,60:85])
avee100b500=(cc5001+cc5002+cc5003)/3. ; mean sky value
avee100ne500=(dd5001+dd5002+dd5003)/3. ; mean noise in the sky
sigma500s100em=avee100ne500*sqrt(npix)
fsl500s100em=cr-2.5*alog10(5.*sigma500s100em/500.)
fivesl100em=[fsl101s100em,fsl11s100em,fsl15s100em,fsl12s100em,fsl135s100em,fsl60s100em,fsl500s100em]
skyem100=[avee100b01,avee100b1,avee100b5,avee100b12,avee100b35,avee100b60,avee100b500]
noiseem100=[avee100ne01,avee100ne1,avee100ne5,avee100ne12,avee100ne35,avee100ne60,avee100ne500]
time100=[0.1,1.,5.,12.,35.,60.,500.]
ratio100=skyem100/noiseem100
print, skyem100

logtime100=alog10(time100)
skylog100=alog10(skyem100)
plot, time100,skyem100, psym=8, title='Background as a function of exp. time at EM 100',
  xtitle='Exposure time [sec]', ytitle='Background [e-]', xrange=[-1,501], charsize=1.5

noiselog100=alog10(noiseem100)
plot, logtime100,noiselog100, psym=8, title='Noise of the background as a function of exp.
time at EM 100', xtitle='Exposure time [Log_sec]', ytitle='Background Noise [Log_Ne-]',charsize=2
print, 'DONE WITH IMAGES AT EM GAIN 100'
;Below are images with EM 500 captured ad various exp. time
em500time01=fltarr(1024,1024)
;em500time01=readfits('FRB121102_01s-0153_G24E500.fit',header)*1.0
em500time01=readfits('FRB121102-0128_G24E500_01s_R.fit',header)*2.4
im500time01=(em500time01-imd1d01e500)/500./flat500

```

```

ff011=median(im500time01[425:450,245:270]) ; - sky valuse
gg011=stdev(im500time01[425:450,245:270]) ; noise in the sky
ff012=median(im500time01[255:280,525:550])
gg012=stdev(im500time01[255:280,525:550])
ff013=median(im500time01[625:650,190:215])
gg013=stdev(im500time01[625:650,190:215])
avee500b01=(ff011+ff012+ff013)/3. ; mean sky value
avee500ne01=(gg011+gg012+gg013)/3. ; mean noise in the sky
sigma01s500em=avee500ne01*sqrt(npix)
fsl01s500em=cr-2.5*log10(5.*sigma01s500em/0.1)

em500time5=fltarr(1024,1024)
em500time5=readfits('FRB121102_5s-0007_G24E500.fit',header)*2.4
im500time5=(em500time5-imd1d5e500)/500./flat500
ff51=median(im500time5[280:305,330:355]) ; - sky valuse
gg51=stdev(im500time5[280:305,330:355]) ; noise in the sky
ff52=median(im500time5[215:240,790:815])
gg52=stdev(im500time5[215:240,790:815])
ff53=median(im500time5[740:765,320:345])
gg53=stdev(im500time5[740:765,320:345])
avee500b5=(ff51+ff52+ff53)/3. ; mean sky value
avee500ne5=(gg51+gg52+gg53)/3. ; mean noise in the sky
sigma5s500em=avee500ne5*sqrt(npix)
fsl5s500em=cr-2.5*log10(5.*sigma5s500em/5.)

em500time20=fltarr(1024,1024)
em500time20=readfits('FRB121102_20s-0006_G24E500.fit',header)*2.4
im500time20=(em500time20-imd1d20e500)/500./flat500
ff201=median(im500time20[170:195,50:75]) ; - sky valuse
gg201=stdev(im500time20[170:195,50:75]) ; noise in the sky
ff202=median(im500time20[430:455,260:285])
gg202=stdev(im500time20[430:455,260:285])
ff203=median(im500time20[250:275,810:835])
gg203=stdev(im500time20[250:275,810:835])
avee500b20=(ff201+ff202+ff203)/3. ; mean sky value
avee500ne20=(gg201+gg202+gg203)/3. ; mean noise in the sky
sigma20s500em=avee500ne20*sqrt(npix)
fsl20s500em=cr-2.5*log10(5.*sigma20s500em/20.)

skyem500=[avee500b01,avee500b5,avee500b20]
noiseem500=[avee500ne01,avee500ne5,avee500ne20]
time500=[0.1,5.,20.]
ratio500=skyem500/noiseem500
print, skyem500
logtime500=log10(time500)

```

```

skylog500=log10(skyem500)
fivesl500em=[fsl01s500em,fsl15s500em,fsl20s500em]
noiselog500=log10(noiseem500)
plot, time, fivesl1em, BACKGROUND = 255, COLOR = 0, psym=1, title='Sensitivity vs single
frame time', xtitle='t!Dframe!N[s]', ytitle='Single frame sensitivity [mag]',
symsize=1.5, yrange=[14,21], xrange=[-1,520], charsize=1.5
oplot, time100, fivesl100em,COLOR = 0, psym=5, symsize=1.5
oplot, time500,fivesl500em,COLOR = 0, psym=4, symsize=1.5
stop

plot, time,skyem1, BACKGROUND = 255, COLOR = 0, psym=1, title='Background as a function
of exp. time at EM = 1 | 100 | 500', xtitle='Exposure time [sec]', ytitle='Background [e-/pix]',
charsize=1.5, xrange=[-1,550] ,symsize=1.5;, yrange=[0,7]
oplot, time100,skyem100,COLOR = 0, psym=5 ,symsize=1.5
oplot, time500, skyem500, COLOR = 0,psym=4 ,symsize=1.5
stop

plot, logtime1,noiselog1, BACKGROUND = 255, COLOR = 0, psym=1, title='Noise per aperture of
the background vs. t!Dframe!N at EM=1, 100, 500', xtitle='t!Dframe!N[Log_sec]', ytitle='Background
Noise per aperture [Log_(e-/pix)]', charsize=1.4, yrange=[-1,1.5], xrange=[-2,3] ,symsize=1.5
xslope=[-2,-1,0,2,3]
yslope=[-1,-0.5,0,1,1.5]
oplot, logtime100,noiselog100,COLOR = 0, psym=5 ,symsize=1.5
oplot, logtime500,noiselog500,COLOR = 0, psym=4 ,symsize=1.5
oplot, xslope, yslope, color =1, linestyle=2
print, 'DONE WITH IMAGES AT EM GAIN 500'
print, 'DONE'
stop

end

```

Appendix B

Figures

Bibliography

- [1] Mike Bolte. Modern observational techniques: Fall 2015. Lecture slides of AY 257 at the University of California, Santa Cruz, August, December 2015.
- [2] Taylor S. Chonis and C. Martin Gaskell. Setting ubvri photometric zero-points using sloan digital sky survey ugriz magnitudes. *The Astronomical Journal Journal*, 135:264–267, January 2008.
- [3] James L. Clem and Arlo U. Landolt. Faint ubvri standard star fields. *The Astronomical Journal Journal*, 146:88–107, September 2013.
- [4] P. Hoess D. Dussaulta. *Noise performance comparison of ICCD with CCD and EMCCD cameras*. Stanford Computer Optics.
- [5] ANJUM S. MUKADAM et al. High-speed time-series ccd photometry with agile. *PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC Journal*, 123:1423–1433, December 2011.
- [6] Jan W T Heemskerk et al. Experimental comparison of high-density scintillators for emccd-based gamma ray imaging. *Physics in Medicine Biology Journal*, 57:4545–4554, June 2012.
- [7] Lijian Zhang et al. A characterization of the single-photon sensitivity of an electron multiplying charge-coupled device. *Phys. B: At. Mol. Opt. Phys. Journal*, 42:114011, June 2009.
- [8] OLIVIER DAIGLE et. al. Extreme faint flux imaging with an emccd. *PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC Journal*, 121:866–884, August 2004.
- [9] A J Levan et.al. A new population of ultra-long duration gamma-ray bursts. *The Astrophysical Journal Journal*, 781:22, January 2014.
- [10] Racusin J.L. et.al. Broadband observations of the naked-eye -ray burst grb 080319b. *Nature Journal*, 455:183–188, September 2008.
- [11] B. Grossan M. Kistaubayev G. Smoot, L. Scherr. Measurement of the shape of the optical-ir spectrum of prompt emission from gamma-ray bursts. *American Astronomical Society AAS Meeting*, 230:314.06, June 2017.

- [12] Carl W. Akerlof et. al. Galen Gisler. The rotse detection of early optical light from grb990123. *AIP Conference Proceedings Journal*, 499:pp. 8, November 1999.
- [13] RONALD L. GILLILAND and TIMOTHY M. BROWN. Time-resolved ccd photometry of an ensemble of stars. *Publications of the Astronomical Society of the Pacific Journal*, 100:754–765, June 1988.
- [14] B. Grossan. Prompt optical grb observations, the missing science. *Energetic Cosmos Laboratory Conference Presentation*, August 2017.
- [15] G R Hopkinson and D H Lumb. Noise reduction techniques for ccd image sensors. *Journal of Physics E: Scientific Instruments Journal*, 15:1214–1222, June 1982.
- [16] STEVE B. HOWELL. Two-dimensional aperture photometry: Signal-to-noise ratio of point-source observations and optimal data-extraction techniques. *Publications of the Astronomical Society of the Pacific Journal*, 101:616–622, June 1989.
- [17] STEVE B. HOWELL and GEORGE H. JACOBY. Time-resolved photometry using a ccd. *Publications of the Astronomical Society of the Pacific Journal*, 98:802–808, August 1986.
- [18] J. Hyneczek and T. Nishiwaki. Excess noise and other important characteristics of low light level imaging using charge multiplying ccds. *IEEE Trans. Electron Devices Journal*, 50:239–245, January 2003.
- [19] Hans Kjeldsen and Soren Frandsen. High-precision time-resolved ccd photometry. *Publications of the Astronomical Society of the Pacific Journal*, 104:413–434, March 1992.
- [20] Strong I. B. Olson R. A Klebesadel, R. W. Observations of gamma-ray bursts of cosmic origin. *Astrophysical Journal Journal*, 182:L85, June 1973.
- [21] Arlo U. Landolt. Ubvri photometric standard stars around the sky at +50 deg declination. *The Astronomical Journal Journal*, 146:131–172, November 2013.
- [22] En-Wei Liang et.al. Liang Li. A comprehensive study of gamma-ray burst optical emission. i. flares and early shallow-decay component. *The Astrophysical Journal Journal*, 758:27–45, October 2012.
- [23] David Morton. Charge-coupled device.
- [24] P. Giommi N. Gehrels, G. Chincarini. The swift gamma-ray burst mission. *The Astrophysical Journal Journal*, 611:1005–1020, August 2004.
- [25] MICHAEL V. NEWBERRY. Signal-to-noise considerations for sky-subtracted ccd data. *Publications of the Astronomical Society of the Pacific Journal*, 103, 1991.

- [26] B. Grossan P. Kumar, D. Perley and G. F. Smoot. A small, rapid optical-ir response gamma-ray burst space observatory concept: The nrg. *Publications of the Astronomical Society of the Pacific Journal*, 126:885–900, September 2014.
- [27] P. R. Wozniak, W. T. Vestrand, et.al. Gamma-ray burst at the extreme: “the naked-eye burst” grb 080319b. Los Alamos National Laboratory, MS-D466, Los Alamos, NM 87545, October 2008.
- [28] M. S. Robbins and B. J. Hadwen. The noise performance of electron multiplying charge-coupled devices. *IEEE Transactions on Electron Devices Journal*, 50:1227–1232, May 2003.
- [29] W. Romanishin. *An Introduction to Astronomical Photometry Using CCDs*. University of Oklahoma, October 2006.
- [30] Rong-Feng Shen and Bing Zhang. Prompt optical emission and synchrotron self-absorption constraints on emission site of grbs. *Monthly Notices of the Royal Astronomical Society Journal*, 398, June 2009.
- [31] Karsten Sperlich and Heinrich Stolz. Quantum efficiency measurements of (em)ccd cameras: high spectral resolution and temperature dependence. *Measurement Science and Technology Journal*, 25:015502–015512, November 2013.
- [32] Andy Taylor. *ASTRONOMICAL STATISTICS*, chapter 2.1.5. The Royal Observatory, Edinburgh, 2004.
- [33] Simon Tulloch. *Technical Note 1: Introduction to EMCCDs*. QUCAM, June 2009.