PROTOTYPE DESIGN FOR CUBESAT CAMERA

TFE4521 - Specialization Project, 7.5 credits

Department of Electronics and Telecommunications
Norwegian University of Science and Technology

Thomas Hanssen Nornes
thomas.nornes@gmail.com

Autumn 2014

Abstract

This report documents the work done during the autumn of 2014 in the course TFE4521 - Specialization project at NTNU.

Over the course of the project, a prototype camera module was made by selecting image sensor, optics and mount and by designing a custom prototyping board in order to interface with the sensor. The camera was manufactured, assembled and confirmed working by successfully importing images from it.

Some problems were discovered and are discussed together with ideas for further work on the camera module.

Acknowledgements

The author would like to thank Amund Gjesvik for his advice and support during the design and assembly of the camera prototype.

Thanks to Roger Birkeland for advice.

Thanks to Andreas Bertheussen for his help during assembly and for general advice.

Contents

Chapter 1

Introduction

This report documents the work done on the specialization project in the course TFE4520 during the autumn semester of 2014 at NTNU. Project supervisors were Amund Gersjvik and Roger Birkeland. The department supervisor was Bjørn B. Larsen.

The aim of this project is to explore the feasability and benefits of designing a custom built camera module compared to the alternative of buying a commercial module, seen in the context of the NUTS project.

1.1 Background

The NTNU Test Satellite project(NUTS) has been going since 2010 with the goal of launching a student made satellite into orbit. The projects follows the CubeSat standard which sets restrictions on available space and weight.

During the duration of the NUTS project, there has been several suggested payloads. The original idea was to use an infra-red camera that would enable scientific measurements. This was abandoned due to the high cost of the technology and workload required. Visual range cameras have been considered as a fall-back option and multiple cameras have been considered.

Most recently, during the autumn 2013, a commercial camera was chosen and tested by Magnus Arnesen [1] as a part of his specialization project. The implementation suffered from instability and the reasons why have not been found. Also, this camera, like many commercial cameras, is not compatible with the satellites internal communication. Custom circuitry needs to be designed in order to interface with the satellites system.

A downside most of the cameras had, was that they did not have high resolution, and it was also not clear if it was possible to manually adjust native camera settings, such as shutter time and sensitivity.

1.2 Scope

The camera should be made by choosing appropriate components, such as lens and image sensor, and by designing custom software. At the end of the project, a working prototype should be completed that should be able to capture images and enable transfer of these to a computer for viewing.

The project consists of two group members, Thomas Hanssen Nornes and Andreas Bertheussen, working on different aspects of the camera prototype and producing two individual reports. This report describes the work done by Thomas Hanssen Nornes.

His responsibility during the project was the selection of camera components and to design, manufacture and test of the camera prototype board.

Andreas Bertheussen was responsible for exploring the required signal processing and designing digital logic for image sensor readout. His work is documented in [2].

Chapter 2

Theory

This chapter will cover some of the theory and concepts employed in the design of the camera prototype.

2.1 Environment

The cameras sensor must be chosen to work in the conditions of Low Earth Orbit(LOE) when looking at the Earth. Some basic theory is needed to understand the properties the camera must have in order to take high quality images in the given environment.

2.1.1 Albedo

The diffuse reflectivity or reflecting power of a surface is called the albedo. It can be thought of as the ”whiteness” of a surface. It is a dimensionless value, being zero for a completely non-reflective surface and one for a completely reflective surface. The reflectivity varies depending on the wavelength of the radiation [3].

The albedo of the earth ranges from almost 0.04 to 0.90 at the most. The former being charcoal and the latter being fresh snow. Large cloud formations, deserts and the poles are the brightest areas on the planet and will constitute the most intense lighting conditions. Dark areas are mostly forests and water.

2.1.2 Illuminance

Illuminance is a measurement of luminous flux over a given area. Luminous flux can be thought of as the amount of visible light present, while illuminance is the intensity of that light.

Light from the sun enters the atmosphere and loses some of its energy before reaching the ground. When sunlight passes trough the atmosphere on its way to the earths surface, it acts as a filter for high frequency light such as ultra-violet light.

The light intensity from the sun outside the atmosphere is close to the solar constant [4]. Having a value of roughly 1.321kW/m^2 [5].

2.2 Exposure

Most image sensors describe their sensitivity in relation to volt per lux seconds($\frac{V}{lux \cdot s}$). Higher sensitivity produces more noise in an image. This is true for both analog and digital films.

$$H = \frac{qLt}{N^2} \tag{2.1}$$

Where L is the luminance, t is exposure time, N is the aperture number and q is given as:

$$q = \frac{\pi}{4} T v(\theta) \cos^4(\theta) \tag{2.2}$$

Where T is transmittance of the lens, $v(\theta)$ is the vignetting factor where θ is the angle relative to the axis of the lens. q is typicaly 0.65 based on $\theta = 10\,\text{deg}$, T = 0.9, v = 0.98.

2.3 Optics

High quality optics is a limiting factor in a camera. You can have the best image sensor in the world, but if your optics are of low quality, the resulting picture will suffer.

2.3.1 Lens diffraction

Lens diffraction puts a limit on the resolving power of the lens. This influences the effective resolution of the camera. This effect is dependent on the wavelength of the light and the f-number(f/#) of the camera. The formula for the diffraction limit is given underneath [6].

$$DL = \frac{1}{(\text{f}/\#) \cdot (\text{wavelength in millimeters})} \tag{2.3}$$

After the diffraction limit is reached, the lens can no longer resolve smaller wavelengths. One of the variables affecting the diffraction limit is the speed of the lens or f/#. This is directly related to the size of the lens aperture and the focal length of the lens as follows:

$$\text{f}/\# = \frac{\text{focal length}}{\text{lens aperture}} \tag{2.4}$$

The airy disk size formula

$$\text{ADD} = (2.44) \cdot (\text{f}/\#) \cdot (\text{wavelength}) \tag{2.5}$$

2.3.2 Depth of field

Depth of field is a term used to describe the distances where objects will appear with sufficient sharpness. When taking a picture there is only one plane that is in ”perfect” focus, everything else will be less sharp the further you move away from that plane. When assessing the lens, one can use the following formula to find the hyper-focal distance. This gives the point where the depth of field goes to infinity.

$$H = \frac{f^2}{Nc} \tag{2.6}$$

Chapter 3

Design

In this chapter covers the considerations and calculations made in the design process of the camera prototype.

3.1 System overview

After some initial research and discussion between the group members, a general design approach was found. An overview of the system is shown in figure 3.1. In order to reduce development time, a Field Programmable Gate Array(FPGA) development board would be used to implement the control logic and to transmit the images to a computer. The image sensor and lens assembly would be placed on a custom prototype board made using the available ”in-house” manufacturing equipment, further reducing development time. It was deemed risky to depend on an external manufacturer in case errors were made in the design process. It would not be possible to wait several weeks for a new board.

3.1.1 Priorities

The image sensor, lens and lens assembly were the components of most interest in this project. If they show positive results, they are likely to be used in the satellite. Therefore they should be chosen with this in mind. Other parts like the FPGA and power system were chosen to ease development of the prototype.

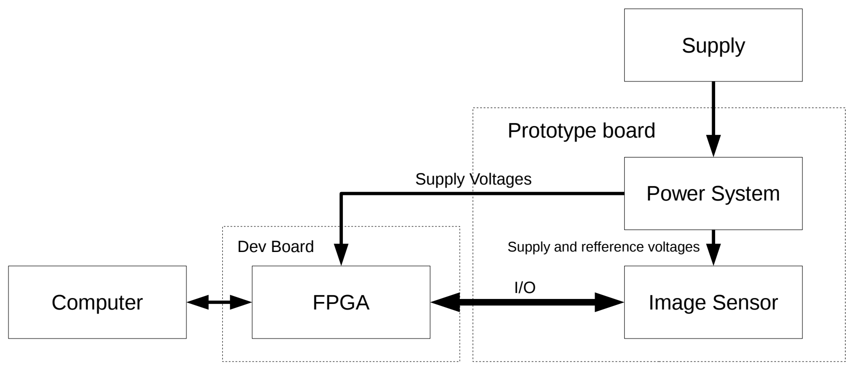


Figure 3.1: High level overview of the system

3.2 Image sensor

Selection of an image sensor had to be made as early as possible due to time constraints. This part explains the work and reasoning behind the choice of image sensor.

3.2.1 Limitations

Our choice of image sensor was limited by the available voltages and power in the satellite. We based our considerations on the satellite specifications as presented at the start of this project. Our design is therefore based on two available voltages, 3.3V and 5V, and a total power consumption that should not exceed 1W. Exceptions could be made for very short durations.

It was also recommended to choose components that satisfy the industrial grade temperature range of -40 to 100 degrees, increasing the likelihood that components will work in a final deployment.

3.2.2 Demands

Since the goal of this project was to find possible benefits of making your own camera compared to buying a commercial module, the prototype needed specifications and functions that were better than previously considered payloads [1]. It also needed to be realistic that the prototype could be finished on time.

One of the most important factors was availability. It was critical that the sensor would arrive early in the project. The project consists of two members that are working on different parts, but some work is not possible without the other work being finished.

Going for a high resolution would make our solution instantly more attractive. Most of the cameras considered in [1] don't go into the mega pixel range. Some calculations where made, factoring in the size of a compressed image and the speed of the downlink, indicating that an image size of up to 5 mega pixels could be transferred in a single pass.

To further improve the attractiveness of the project solution, the chosen sensor should allow adjustment of most parameters, such as exposure time, sensor sensitivity and others, and output raw image data for external processing.

The sensor needed to have a electronic rolling shutter to control image exposure. It was decided to avoid mechanical shutters, since they are unlikely to pass vibration testing and add complexity with little gain in image quality. Distortion caused by the rolling shutter are not likely to be perceived in the images since the motive moves slowly relative to the camera.

Other considerations where more focused on the development side of the project. Compatibility with the other components logic levels and supply voltages would reduce the number of components needed, such as signal buffers, and decrease the overall complexity. Complete and well written data sheets where valued.

3.2.3 Availability

At the time there were few sensors available from the electronics distributors Farnell and Mouser. The group members and project supervisors have experience with ordering from these suppliers and the delivery time is known to be short. Therefore ordering from these was preferred.

Looking for suppliers proved difficult. With the exception of On Semiconductor and Aptina[1], other manufacturers seem only aimed at mass production. Companies such as Canon and Phillips seem to supply image sensors, but makes information about their sensors difficult to obtain[2]. A common practice is that all data sheets are protected by NDA's and that any price and order must be discussed over phone with a sales representative.

At the time, these extra steps seemed negative and several sensors were not considered as a result, but [7] recommends signing these agreements in order to get data sheets that give further insight into the functionality of the sensor we end up using in our project.

3.2.4 Selecting the sensor

Looking at the preferred suppliers first, the only sensor available, that also had color, was the Aptina MT9P031 at Farnell. It satisfied the initial requirements of high resolution and

[1]Aptina is owned by On Semiconductor.
[2]Aptina also does this, but for sensors with higher performance

Table 3.1: Possible image sensors

Manufacturer	Sensor	Res	Power	Availability
On Semiconductor	KAC-06040	6M	> 0.8W	Contact sales
Aptina	MT9P031	5M	0.350W	Farnell
Aptina	MT9P401	5M	0.350W	Contact sales

low power consumption.

The sensors that were considered are listed in table 3.2.3. The public data sheet available for the Aptina MT9P401 did not show any discernible difference compared to the MT9P031, other than its availability. Because of this the MT9P031 was deemed the best of the two.

The other possible alternative was the KAC-06040, from On Semiconductor, that had slightly higher resolution than the Aptina sensor, but over twice the power consumption. This puts it close to the maximum allowable value. It also didn't help that it had differential output, making it harder to interface with. The data sheet was more cumbersome to read than the one from Aptina.

Due to the time constraints we had to select the first sensor that satisfied our base demands, resolution and power. The Aptina MT9P031 quickly stood out as the best alternative. Further analysis also showed good shutter time and light sensitivity, meeting our criteria for dynamic range based on the considerations done in. This was the image sensor we chose to implement on the prototype board.

3.3 Optics

When selecting the camera optics there were two main considerations, field of view and optical resolution. Both are important for the end result. Field of view will affect the look of the images and set the magnification of the camera. Lens resolution is a measure of the lens quality and is the limiting factor on most camera systems.

3.3.1 Finding the correct aperture

The choice of lens was primarily based on the resolution and size of the Aptina image sensor. Choosing a lens with a resolving power that's lower than the resolution of the image sensor would result in poor utilization of the sensor. Smaller values of f/# gives smaller airy disks which in turn increases the resolution available to the sensor. The f/# is an important factor when considering the quality of the lens. A high f/# means reduced image quality, but will make the camera more forgiving when it comes to focus and field of view.

Using formula 2.5, the table in figure 3.2 is generated. Comparing these values with the size of the individual pixels on a sensor will give you a limit on how small the f/# would have to be in order for you to get the most out of your sensor.

Table 3.2: Calculated Airydisk diameter for different wavelengths and apertures.

Relative aperture	700nm	545nm	390nm
1.0	1.71	1.33	0.95
1.2	2.05	1.60	1.14
1.4	2.39	1.86	1.33
1.8	3.07	2.39	1.71
2.0	3.42	2.66	1.90
2.4	4.10	3.19	2.28
2.8	4.78	3.72	2.66
3.0	5.12	3.99	2.85

3.3.2 Field of view

Choosing the field of view was more about preference than some actual requirement. The only objective is to take pictures of the earth. After a discussion with the project supervisors, getting an impression on what they wanted, the project members found a reference objective. The camera had to have a field of view that would allow it to take a picture of the entire country of Iceland under the assumption of the lowest possible orbit of the satellite.

$$2 \cdot \arctan\left(\frac{0.5 \cdot 678\text{km}}{400\text{km}}\right) = 80.56° \tag{3.1}$$

As can be seen in 3.2, the area to cover has a diameter of roughly 678 km. Calculating using this value, together with the worst case assumption of the closest possible orbit of 400km, gives a reference field of view of 80 degrees.

3.3.3 Estimating lighting conditions

In order to select a lens it was necessary to find some values on how the lighting conditions just outside the earths atmosphere would affect the image sensor. The highest intensity of the light reflected from the surface could saturate the sensor too quickly, producing overexposed images. This puts a limit on how open the aperture can be.

The luminous efficacy of the sun is around 93 lumens per watt. This can be used to convert the suns light intensity just outside the atmosphere into illuminance. A cloud will provide

Figure 3.2: Satellite image of Iceland taken from Google Earth. The yellow diagonal line is a measurement tool available in the software.

the highest albedo and make it possible to calculate the illuminance the image sensor might be exposed to.

$$1321\mathrm{W/m^2} \cdot 0.90 \cdot 93 \quad = \quad 110568\mathrm{lux} \tag{3.2}$$

Finding the resulting voltage on the sampling capacitor after an exposure is done using equation 2.1. The values used are the typical value of q together with the worst case illuminance from equation 3.2 and the minimum shutter time. The minimum shutter time for the Aptina sensor is $36.8\mu s$, assuming it is running at the fastest clock speed of 96MHz. The image sensor has a sensitivity of 1.4V/lux. This forms the basis for table 3.3 which shows how changing the aperture affects the sampled value. The voltage column shows the resulting analog value on the sampling capacitor and the digital column shows the digital integer value assuming a voltage range from 0V to 2.8V. This can be 4095 at the most.

[8] does not describe the architecture of the analog to digital converter(ADC) used in the sensor. This means that the allowable voltage range is unknown. Choosing which aperture value to aim for had to be done with a margin for error.

Table 3.3: Shows how changing aperture affects the sampled values of the image sensor.

Aperture(N)	Lux/s(H)	Voltage	Digital
2.0	0.658	0.921	1397
1.8	0.812	1.140	1725
1.4	1.342	1.880	2851
1.2	1.827	2.556	3881

3.3.4 Selecting a lens

Looking at the spectral characteristics in the Aptina MT9P031 sensor data sheet [8], it is a clear that it will register light outside the visible range. The lens or lens mount has to have an IR-cutoff filter in order to remove unwanted light.

Going for a metal lens and lens mount was a decision made after discussion with the project supervisors. Compared to a plastic lens, the metal one is more suited for a space environment. They are more robust and have less chance of degassing, which can obscure the lens.

The image sensor has pixel size of 2.2x2.2μm. Table 3.2 shows that in order for the airydisk size to be within the pixel size of the sensor, the aperture would have to be 1.2. Going upwards to 2.4 gives disks twice the size.

Looking at table 3.3, the aperture of choice would be 1.2 for an ADC voltage range of 2.8V. This was not known to be the actual range, so a worst case consideration was made. Assuming that the ADC would at least have half the supply voltage to work with puts the available apertures around 1.8. This value gives slightly larger airydisks, but was considered an acceptable compromise.

Finding lenses with an aperture of 1.8 and a field of view close to 80 degrees proved difficult. Lens makers, such as Sunnex supply many lenses with the required aperture number, but these had a field of view of a 100 degrees or more. There weren't many choices, but a lens maker called Lensation supplied the type of lens we wanted. The chosen lens was the Lensagon B5M6018C [9] which comes with a pre mounted IR-cutoff filter. It satisfies the aperture requirement and has a field of view of 75 degrees.

Choosing the Lensagon B5M6018C was a matter of finding the first lens that satisfied the established demands. It has a metal casing, the correct image format, field of view and aperture. It also has an IR-cutoff filter built inn.

3.4 Power supply

Based on the limitations mentioned previously and the choice of components, the power supply had to deliver 2.8V, 1.8V and 5V. The design is based on a single supply voltage of 5V. The only component that needed 5V was the Numato FPGA development board. Other voltages where supplied by linear converters.

The image sensor had an order in which the three power supplies should be enabled. Because of this a power sequencer was added to the design to control the system when it is powered on and off.

3.4.1 Sequencer

Looking for a power sequencer available from Farnell, a sequencer from Texas Instruments was found that was compatible with the available voltages and had no external components. The LM3880 Power Sequencer [10] is available with many different sequence orders and delay times programmed into the chip as a factory setting. It was the simplest sequencer available.

3.4.2 Converters

The MAX883 [11] linear regulator from Maxim was chosen for the system. Three of these regulators are used as supplies to the image sensor. They have on/off pins that enables them to be controlled by the power sequencer. The voltage level is set with a resistor feedback loop and are the only external components, not counting the decoupling capacitors.

Using a linear regulator requires less design time, external components and testing than for example using a switching regulator. The latter is more efficient and is more likely to be used in a final design, but this is outside the scope of the project.

3.5 Layout

The schematic and board layout was made using Altium Designer. This is a software from Altium and was provided by our supervisors. All finished schematics where double checked by Andreas Bertheussen as well as PCB layout. The latter was also checked by supervisor Amund Gjersvik who is familiar with the available manufacturing equipment. He was responsible for the final adjustments of the layout and the actual manufacturing of the prototype card. Layout was done for a two layer board that would be traced by a Computer Numerical Control(CNC) machine.

3.5.1 Routing considerations

An image sensor outputs high frequency signals that could be degraded by a poor board layout. [12] suggest some design approaches that improve high speed performance. An important point is to keep the ground plane as uniform as possible, avoiding gaps that change the path of the return current.

The two layer design presents challenges due to the high number of pins on the image sensor. It is not possible to connect all the sensor signals without creating some considerable loop areas in the ground plane. A ”third” layer was added for the power signal using external wires soldered to the board. This cleaned up the ground plane considerably.

Images are transferred using 12 outputs and syncronization pins on the sensor with paths that run mostly parallel on the prototype board. Since the signals have such a high frequency, the delay caused by varying lengths the signal routing could be an issue. In order to make the signal paths as similar in length as possible they need to be free from obstructions by other components. In the project design, this meant moving the decoupling capacitors to the ground plane layer.

3.5.2 Component library

Altium Designer allows the user to make comprehensive component library entries. This is recommended as makes it easy to generate complete part lists at the end of the design phase. During the project, new components where added consistently using naming conventions and linking them to multiple vendors. Footprints should also be associated with schematic symbols so these do not need to be added later.[3]

[3] A library for the components in the lab was available for use in this project. Unfortunately it does not link schematic components, footprints and vendors, so it was was not used.

Chapter 4

Assembly and testing

This chapter will touch on the different challenges and discoveries made in the assembly and testing of the payload prototype.

4.1 Soldering

The first part to be soldered on the prototype board was the power system. Testing was performed to confirm correct voltages and power on behaviour. Measurements with a oscilloscope confirmed the correct behaviour and are shown in 4.1. The figure shows the power up sequence where two voltages(1.8V and 2.8V) are enabled before another voltage(The analog inputs 2.8V) is enabled after a short delay.

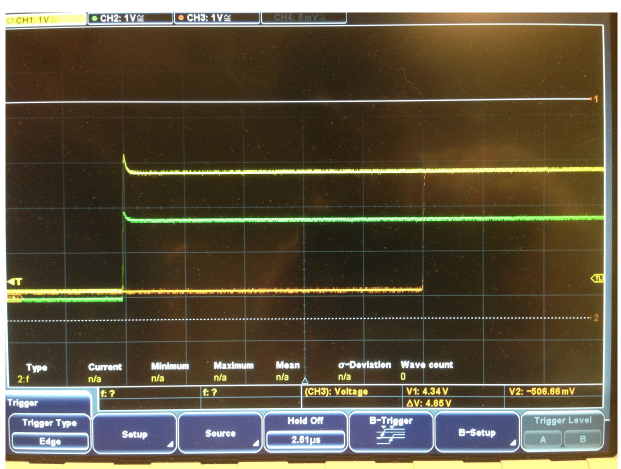


Figure 4.1: Oscilloscope readouts when powering up the prototype board.

4.1.1 Complicated packaging

The Aptina MT9130 image sensor comes in a 48-iLCC package. During the design phase, it was assumed that this package type would have visible connector pads on its side, but this was not the case. With no visual references available and 48 pins that had to be aligned to soldering pads, it was impossible to place it by hand.

To solder the image sensor to the board, special equipment was needed. A high quality soldering iron was use to add soldering flux on all the image sensors pads on the prototype board. The soldering flux was removed and soldering paste applied on all pads. Shown in 4.2 is the APR-500-DZ[1] series ”pick and place” machine available at the lab. This was used to place the image sensor and to solder it using hot air.

Using a scalpel, marks where made on the sides of the package. These were aligned with certain pads and allowed a visual inspection to confirm that the APR-500 had placed it correctly.

Adjacent pins were checked for shorts with a multimeter, but there was no equipment available that could confirm that the soldering was successful.

4.1.2 Powering the system

Remaining components and connectors were soldered on until the complete assembly of the prototype board. After checking that there were no shorts, the board was powered up. Voltages from the regulators where checked again under the new load conditions and where within bounds.

Powering up after connecting the Numato FPGA development board to the prototype board showed a significant design flaw. The FPGA has the ability to set the power state of the sensor via the power sequencers enable pin, but even when the system was supposed to be off, voltages where still measured on the output of the MAX883 DC/DC converters, even higher than in the ”on” state.

The FPGA logic pins seem to supply the image sensor power through its input logic. Luckily the resulting voltages where not high enough to damage the sensor. Switching the system power state is not a necessary function for the prototype, so it was decided that the system would always be on when connected to a power supply. Correct function and power levels was confirmed for the ”on” state of the system.

The outputs of the image sensor were measured using an oscilloscope and expected behaviour was observed. Obscuring the sensor showed a change in output bit values that corresponded to dark and bright conditions.

[1] At the time, the machine did not function correctly and required the use of an external high magnification camera to confirm placement.

After this, the system was handed off to Andreas Bertheussen for further work on the FPGA logic. After a successful readout of images, the system was handed back for further testing.

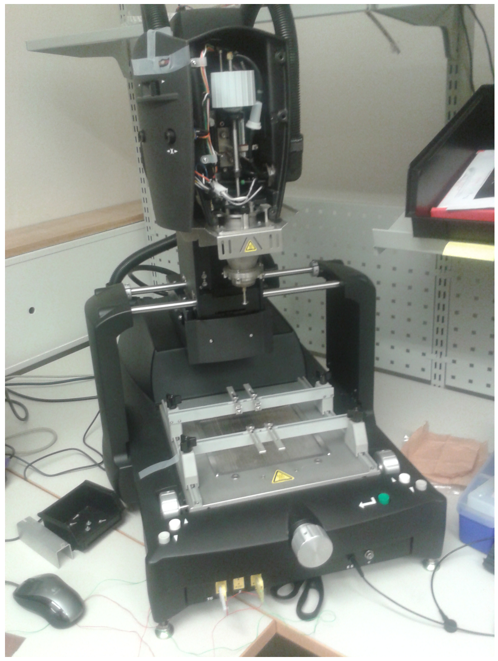


Figure 4.2: The ”Pick and place” machine available at the lab.

4.2 High frequency performance

Some images had noticeable artifacts and alignment errors. Oscilloscope measurements confirmed inconsistent timings on the output signals of the sensor at the input of the development kit connector. Some values where not sampled on the correct clock flank. A reduction of the clock frequency, from 96MHz to 72MHz, was made. Reliable readout was observed.

4.3 Noise removal

After completion of the FPGA logic, strange noise in the high intensity light parts of the images was observed. An example of this noise is showed in figure 4.3.

When the image sensor demands more current, the converter was not able to keep up. Measurements using an oscilloscope showed a 200mV peak to peak fluctuation on the output of the analog linear converter. In order to link this to the observed noise, large decoupling capacitors of up to 47uF where soldered to the output of the regulator and the regulator feedback current was increased by decreasing feedback resistor values.

Final measurements showed a reduction of the fluctuation to under 18mV peak to peak. At this point, the available measuring equipment could not measure any improvements when adding further capacitors.[2] The images showed no perceivable reduction in the high intensity noise. The fluctuations were not the cause of the noise, but would introduce quality degrading noise in the image. [7] recommends a peak to peak voltage of 10mV.

Significant improvements were seen after adjusting the analog amplification factor on the Aptina image sensor internal ADC. At this point no further testing could be done due to lack of time.

Figure 4.3: Strange noise appeared in the bright parts of images.

[2]During measurements, noisy measuring equipment was a problem. Efforts should be made to avoid ground loops and to not use the long ground connectors on the oscilloscope.

Chapter 5

Results and discussion

The end result is the prototype board shown in figure 5.1. It shows how it is connected to the Numato development board and the large decoupling capacitors added in the testing phase. Powering the board does not require a dedicated power supply, but can be done using the usb cable plugged into the development board.

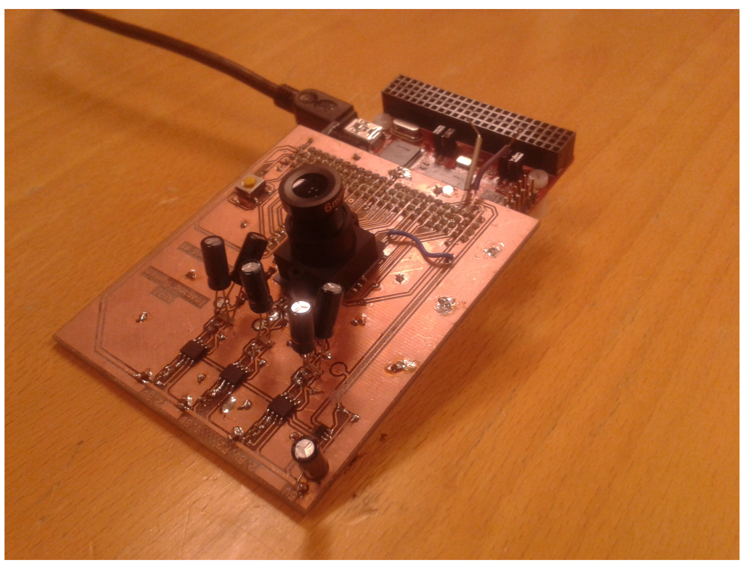


Figure 5.1: The finished prototype board connected to the Numato FPGA development kit.

High resolution images are taken by the ”trial and error” method and can provide good results, as shown in figure 5.2. There is no post processing of images in the prototype software, so all images have to be gamma and color balance corrected using appropriate software. In the case of figure 5.2, the software used was the freely distributed GNU Image Manipulation Program(GIMP) [13].

Figure 5.2: A clear picture taken from ”Taket” located at NTNU Gløshaugen in Trondheim. The image is post processed with corrected gamma and colors. An unsharp mask was used to sharpen the image.

5.1 Problems

The finished prototype has some significant problems that will need to be addressed in a new design. High frequency performance must be improved in order for the sensor to operate at it highest clock frequency. The circuit design and board layout also needs changes to ensure reliable operation.

5.1.1 High frequency signals

Uncertainty around how much the substrate chosen would degrade the high frequency signals was a risk faced with going for the ”in-house” manufacturing process. Using only two layers meant that there were fewer techniques available to improve high frequency performance.

Due to inconsistent readings, the clock frequency of the system was changed from 96MHz down to 72MHz. Possible causes for the poor signal reliability could be that the lines of the sensor outputs are routed too close together, making capacitive coupling, or that they differ to much in length. Another possible issue is the huge connector between the prototype and development kit, it is likely adding significant impedance continuities to the paths.

5.1.2 Design shortcomings

A problem with the design was that the development kit could power the system through its GPIO pins. This should be eliminated using buffers between the development kits input pins to the image sensor.

Soldering the image sensor was complicated due to the packaging. Since it lacks any visual markings on its side, it's not possible to reliably place it on the board without special equipment. High quality soldering irons and a pick and place machine must be available in order to solder the Aptina MT9031 to a substrate. On its own, this is not enough to confirm correct placement, so an x-ray image should be taken to confirm that the soldering is successful. A new design should should also provide visual guides for package placement.

A different manufacturing process that allows more layers is recommended. Using wires as a way to route power signals is cumbersome and unreliable[1]. It should also be a process that can provide better high frequency performance.

5.2 Choices

As mentioned in the design chapter, the choice of image sensor and optics are the only intended to carry over into future work on the camera module. Unfortunately, proper benchmarking could not be done within the time frame of the project.

5.2.1 Sensor

Choosing the Aptina MT9P031 seems to have been a good choice. It is easy to interface with and has a good resolution. It has a temperature range that is close to the industrial range and a low power consumption.

The noise present in bright parts of images is a result of the architecture and inner workings of the image sensor. Not having access to a more detailed data sheet might have made the

[1] And only valid for dirty prototyping

current design less than optimal. Having a good understanding of the sensors ADC migth have made it possible to predict this kind of behaviour. Further work on this sensor should seek access to the NDA protected data sheets.

Since it is possible to set almost all parameters of the sensor through its communication interface, common camera settings and algorithms can be made available and implemented at a later point in software. Instead of manipulating registers, one can make abstract functions that follow camera conventions, improving the usability.

5.2.2 Optics

At this point in time it's not possible to say how much impact the compromise of going for an aperture of 1.8 had on the overall image quality or to quantify the actual quality and durability of the lens.

5.3 Future work

The current prototype board is a great setup for further work. It provides a testing platform for people that want to work on signal processing or as a reference for a new design and board layout. Reading this and the report from Andreas Bertehussen [2] should give the reader an idea of possible future work.

5.3.1 Improved voltage reference

A new design should focus on the analog voltage reference and ensure that it is able to keep up with the sensor and has minimal change during load conditions. Adding huge capacitors is not a solution, at least the type used in this project, as they can not exist in a vacuum. New components should also have industrial temperature ranges.

5.3.2 New software

Testing the camera is a cumbersome process of taking an image, waiting for the slow transfer, adjusting and repeating. In order for the camera prototype to take good pictures, without it being a huge undertaking, more software is needed. At the end of this project, all parameters are manually set by the operator. Simple light measurements and automatic shutter adjustment algorithms are just some of the possible improvements that would increase usability.

5.3.3 Proper test setup

Proper testing of the camera should be done in order to confirm performance. This requires a test setup with precisely measured distances, some kind of camera tripod and a slew of test patterns. The most interesting performance parameter to measure would be the resolving power of the lens, enabling comparison against other cameras.

The lens needs to be properly mounted at the point of infinite focus before quality assessments can be done. This needs to be measured and confirmed with thorough testing.

5.4 Vacuum and stress testing

At some point, the camera has to be tested in a vacuum. The most likely to fail component is the lens, the exact construction of which is not known. Vibration testing also has to be done in order to know if it the components will survive the trip into space.

Chapter 6

Conclusion

A working prototype has been made that can take high resolution images and transfer these to a computer for viewing. The prototype provides a high level of parameter control that is not common in most commercial camera modules.

Since no proper testing could be done, the quality of the camera could not be quantified, but the system itself forms the basis for new and exciting projects within NUTS.

Bibliography

[1] M. H. Arnesen, “Design & test of camera module nuts,” Norwegian University of Science and Technology, Trondheim, Norway, Tech. Rep., December 2013.

[2] A. Bertheussen, “Digital processing system for a cubesat camera,” Norwegian University of Science and Technology, Tech. Rep., 2014.

[3] Albedo. [Online]. Available: https://en.wikipedia.org/wiki/Albedo

[4] “Solar constant.” [Online]. Available: https://en.wikipedia.org/wiki/Solar_constant

[5] “Sunlight.” [Online]. Available: https://en.wikipedia.org/wiki/Sunlight#Solar_constant

[6] G. Hollows and S. Singer. Matching lenses and sensors. [Online]. Available: "http://www.vision-systems.com/articles/print/volume-14/issue-3/features/matching-lenses-and-sensors.html"

[7] J. Enright, D. Sinclair, and K. C. Fernando, “Cots detectors for nanosatellite star trackers,” Sinclair Interplanetary and Ryerson University, Toronto, Canada, Tech. Rep. SSC11-X-1.

[8] *MT9P031 Data Sheet, 1/2.5-Inch 5Mp CMOS Digital Image Sensor*, Aptina Imaging Corporation, Singapore, Singapore, 2005, rev. G. [Online]. Available: https://www.aptina.com/assets/downloadDocument.do?id=865

[9] *B5M6018 Data Sheet*, Lensation, Karlsruhe, Germany. [Online]. Available: http://www.lensation.de/images/PDF/B5M6018.pdf

[10] *LM3880/LM3880Q-1 Power Sequencer*, 2014th ed., Texas Instruments Incorporated, Texas, United States, 2006-2013. [Online]. Available: http://www.farnell.com/datasheets/1850930.pdf

[11] *MAX883 Data Sheet, 5V/3.3V or Adjustable, Low-Dropout, Low IQ, 200mA Linear Regulators*, 5V/3.3V or Adjustable, Low-Dropout, Low IQ, 200mA Linear Regulators, California, United Stated, 2009, rev 4. [Online]. Available: http://datasheets.maximintegrated.com/en/ds/MAX882-MAX884.pdf

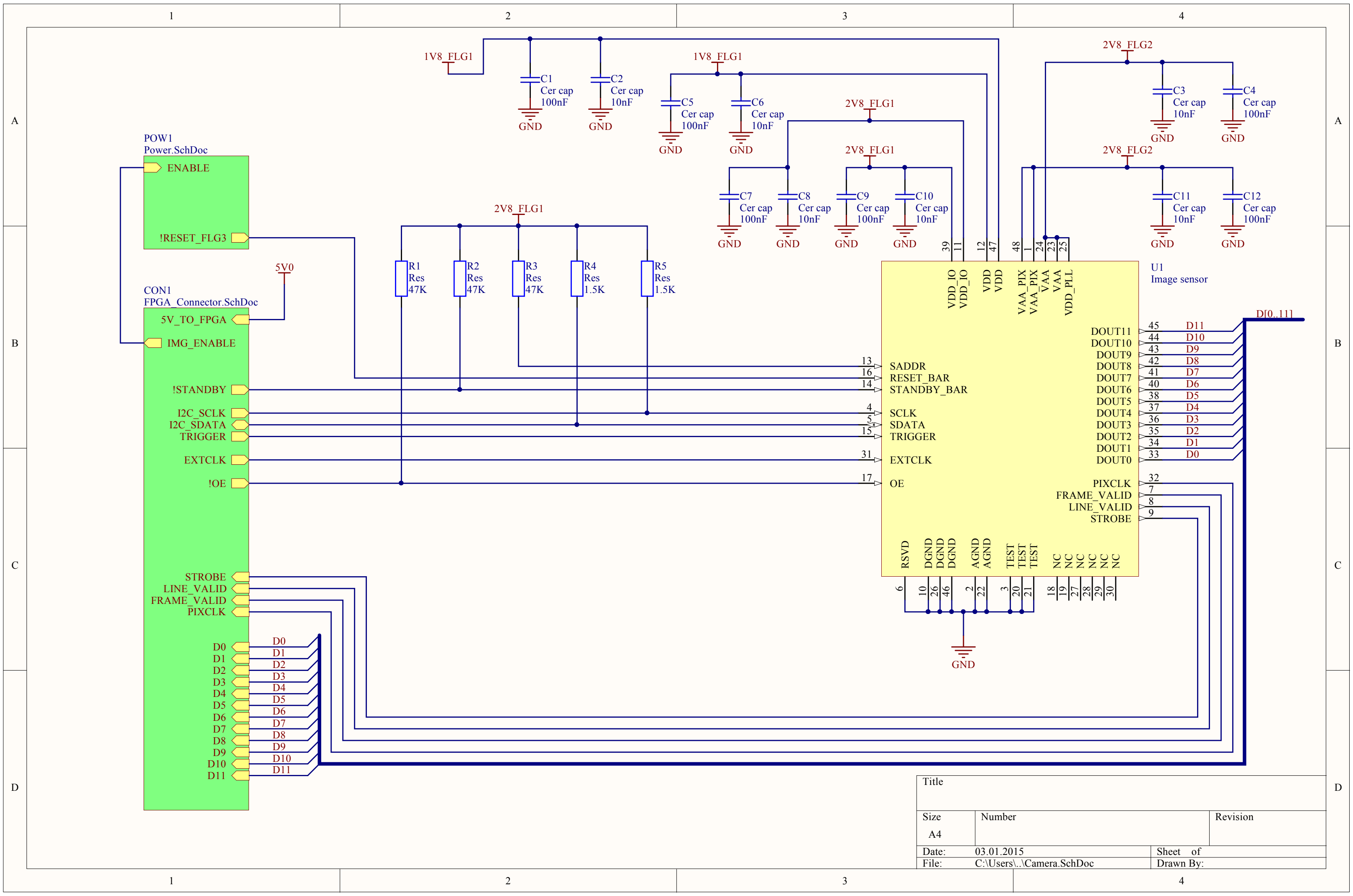
[12] A. Weiler and A. Pakosta, “High-speed layout guidelines,” Texas Instruments, Texas,United States, Tech. Rep., November 2006. [Online]. Available: http://www.ti.com/lit/an/scaa082/scaa082.pdf

[13] GIMP,GNU image manipulation program. Version 2.8. [Online]. Available: http://www.gimp.org

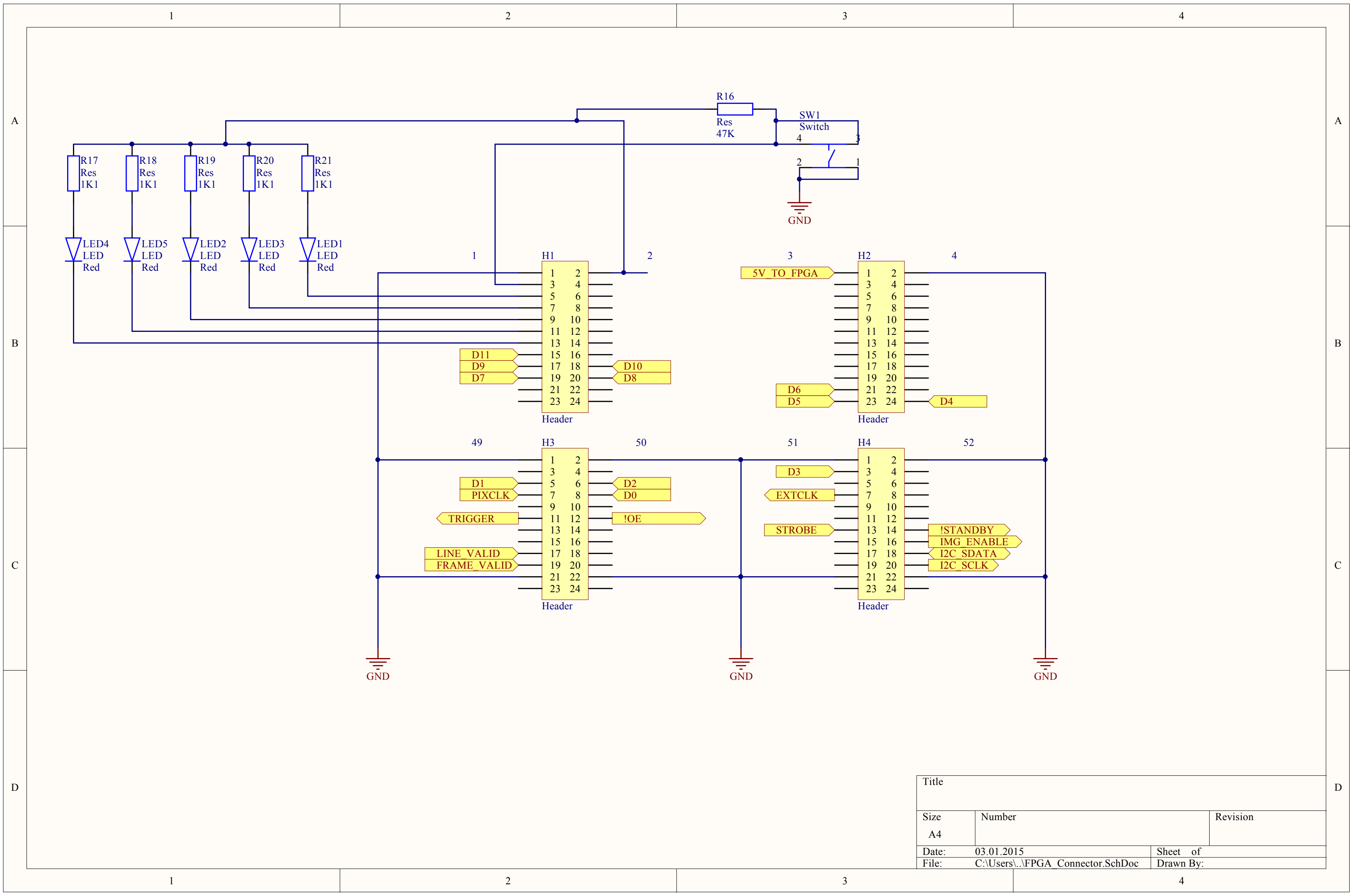
Appendix A

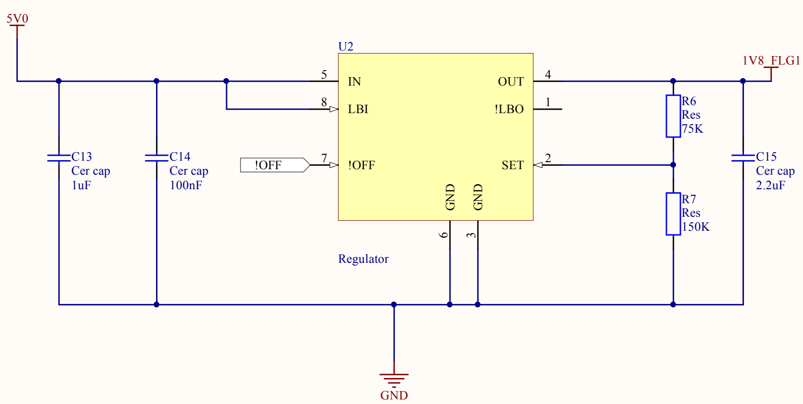
Altium Designer

The following is a print out of the schematic and layout made in Altium Designer. It was exported using the built in SmartPDF function.

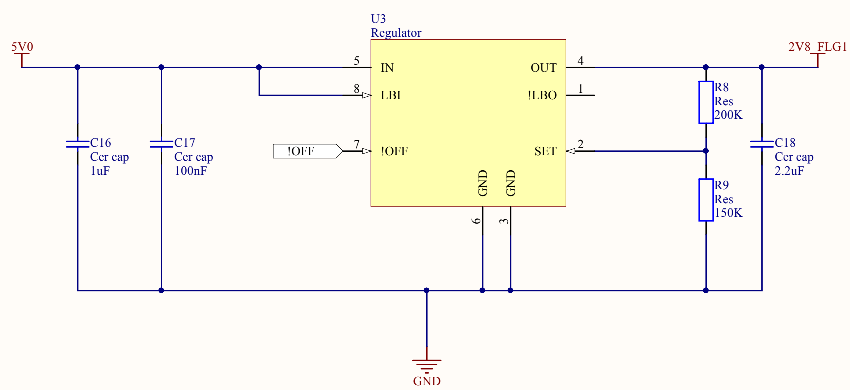


Title		
Size A4	Number	Revision
Date: 03.01.2015		Sheet of
File: C:\Users\..\Camera.SchDoc		Drawn By:

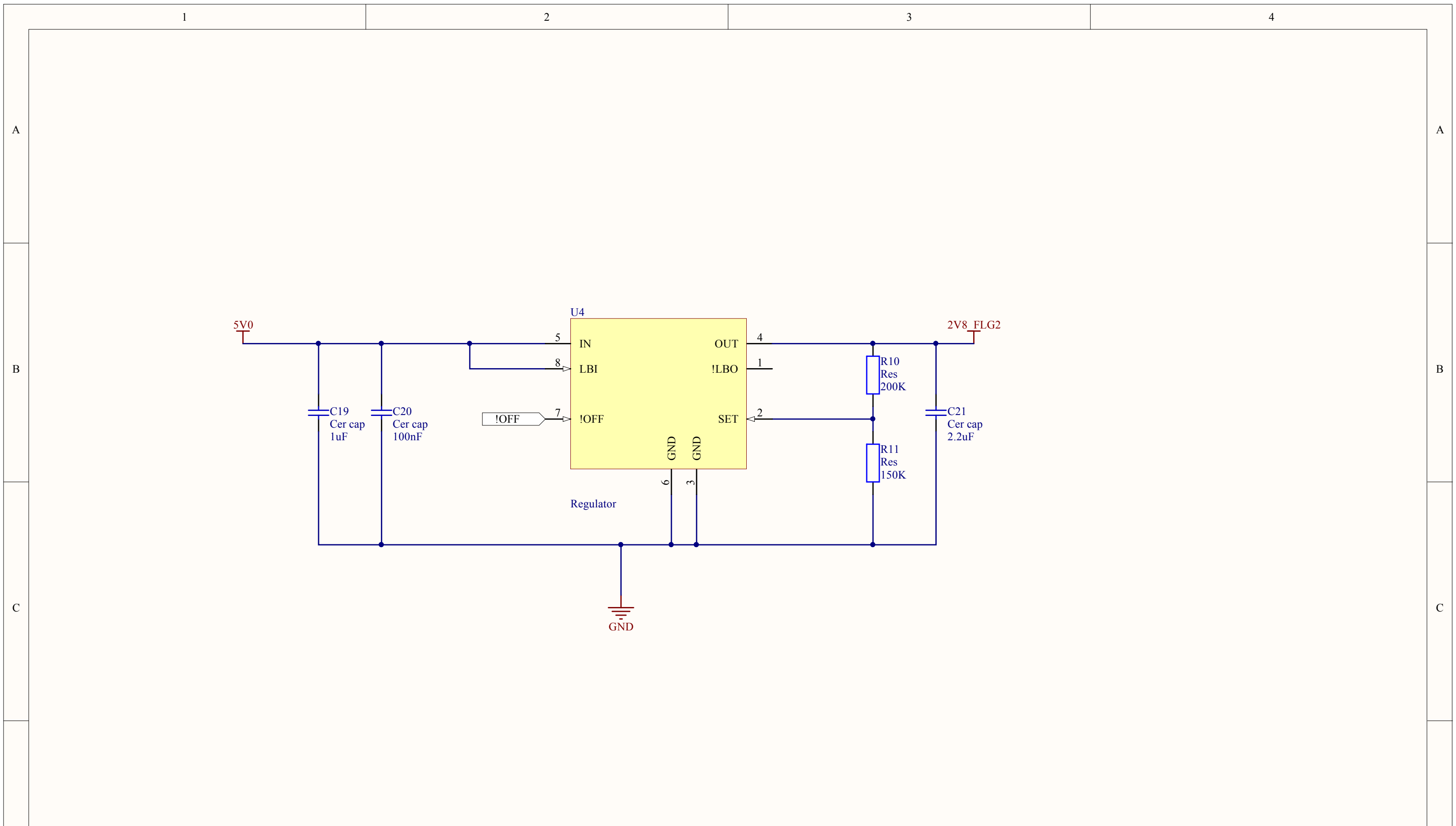

R16
Res
47K
SW1
Switch
GND
R17
Res
1K1
R18
Res
1K1
R19
Res
1K1
R20
Res
1K1
R21
Res
1K1
LED4
LED
Red
LED5
LED
Red
LED2
LED
Red
LED3
LED
Red
LED1
LED
Red
H1
Header
H2
Header
H3
Header
H4
Header
5V_TO_FPGA
D11
D9
D7
D10
D8
D6
D5
D4
D1
PIXCLK
TRIGGER
LINE_VALID
FRAME_VALID
D2
D0
!OE
D3
EXTCLK
STROBE
!STANDBY
IMG_ENABLE
I2C_SDATA
I2C_SCLK
GND
GND
GND
Title
Size
A4
Number
Revision
Date: 03.01.2015
Sheet of
File: C:\Users\..\FPGA_Connector.SchDoc
Drawn By:



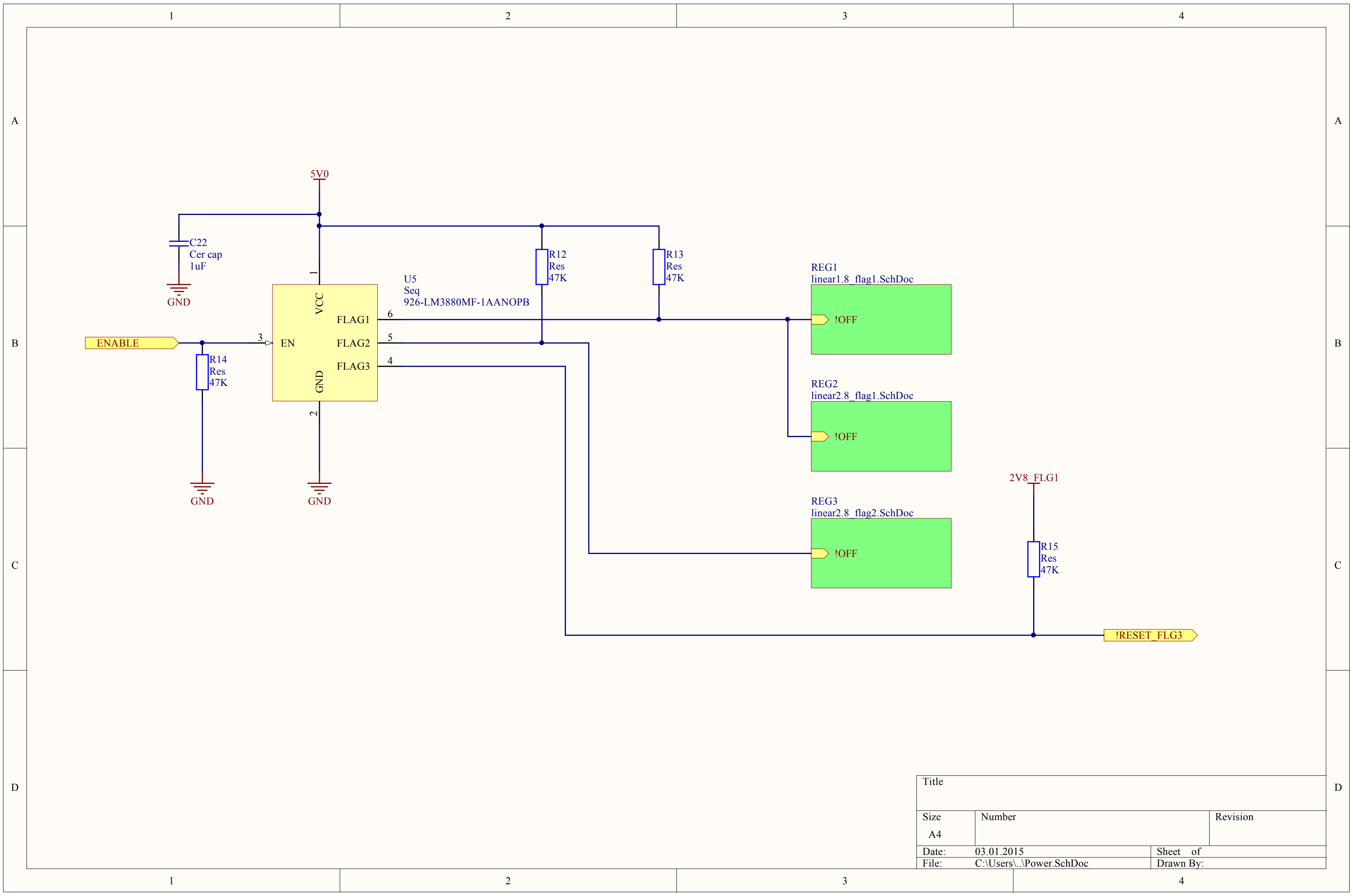
Title			
Size A4	Number		Revision
Date:	03.01.2015	Sheet of	
File:	C:\Users\..\linear1.8_flag1.SchDoc	Drawn By:	



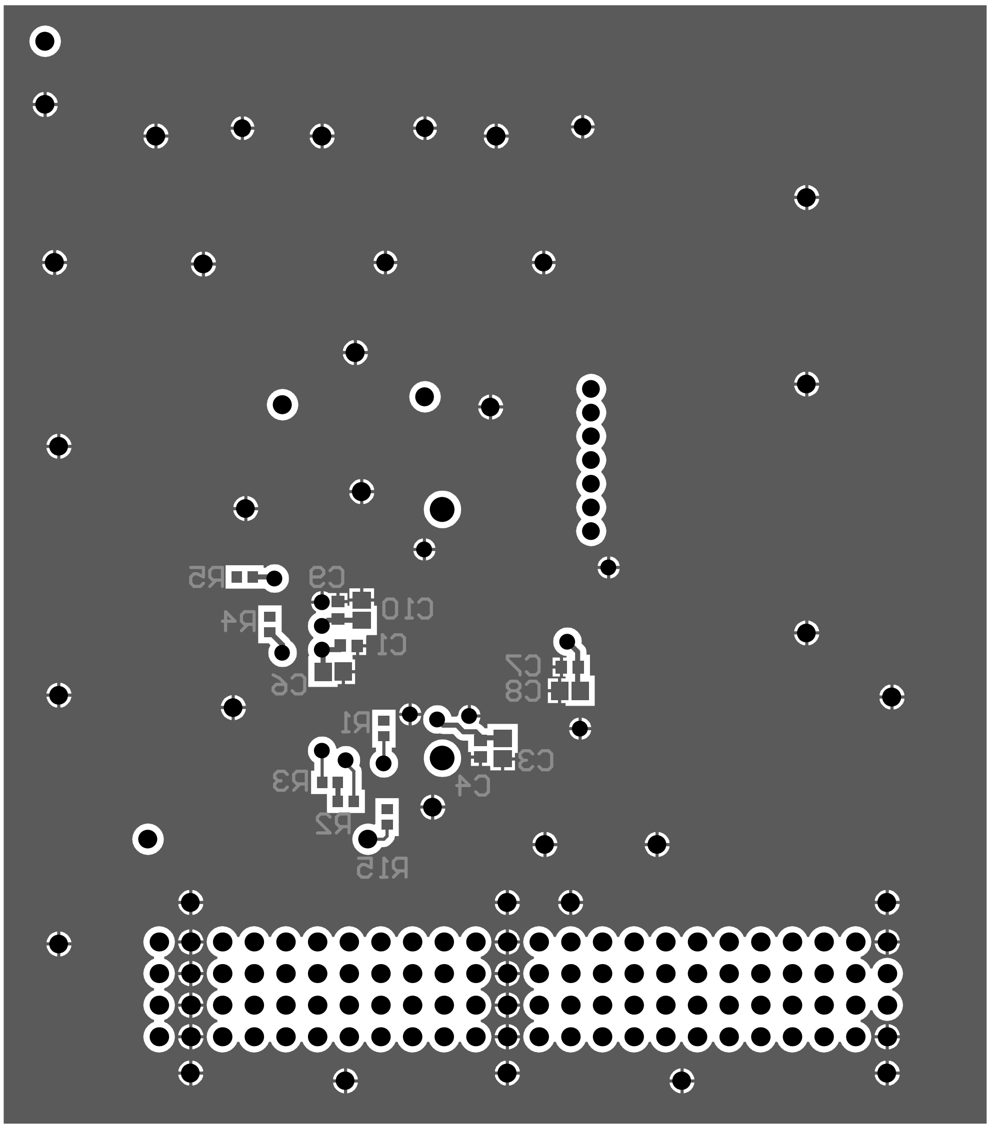
Title		
Size A4	Number	Revision
Date: 03.01.2015		Sheet of
File: C:\Users\..\linear2.8_flag1.SchDoc		Drawn By:

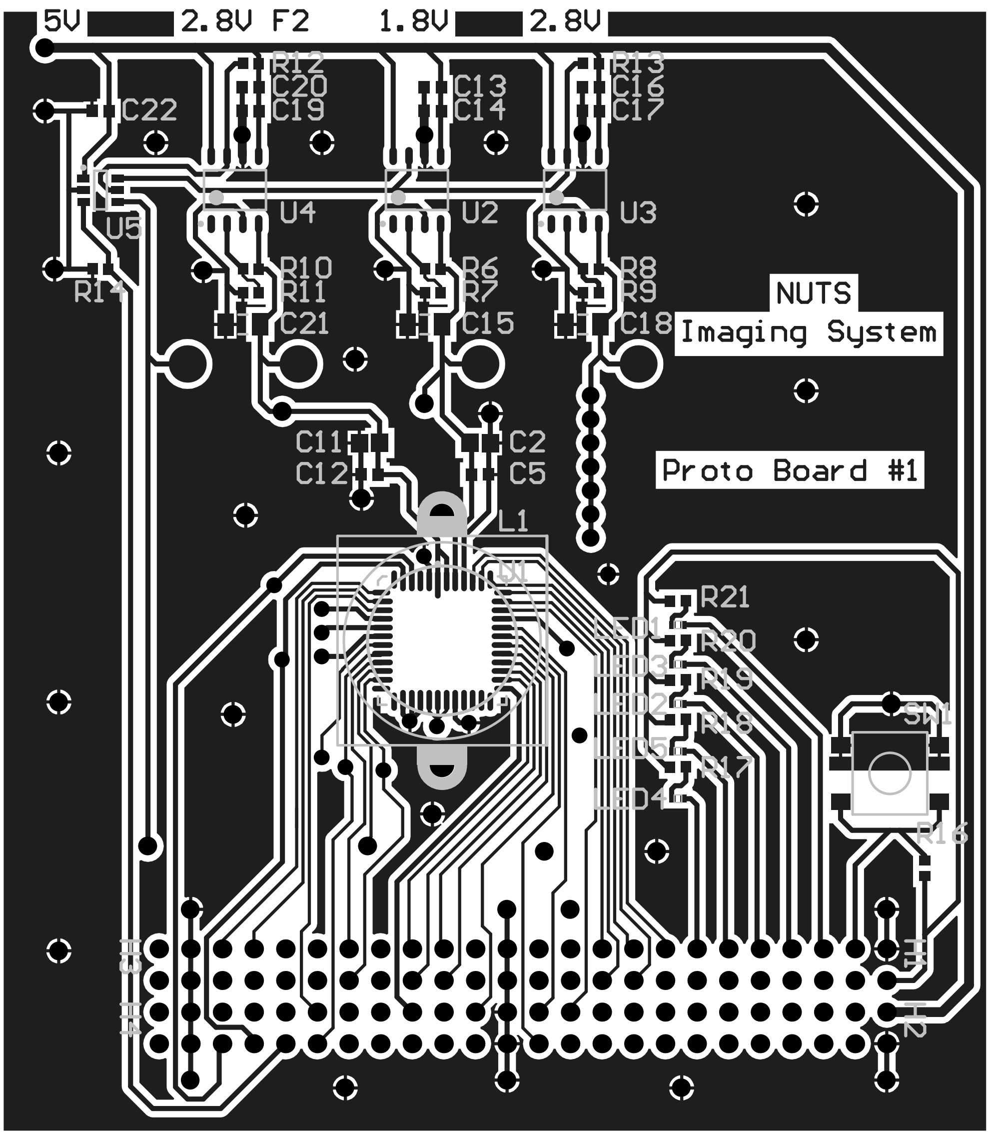


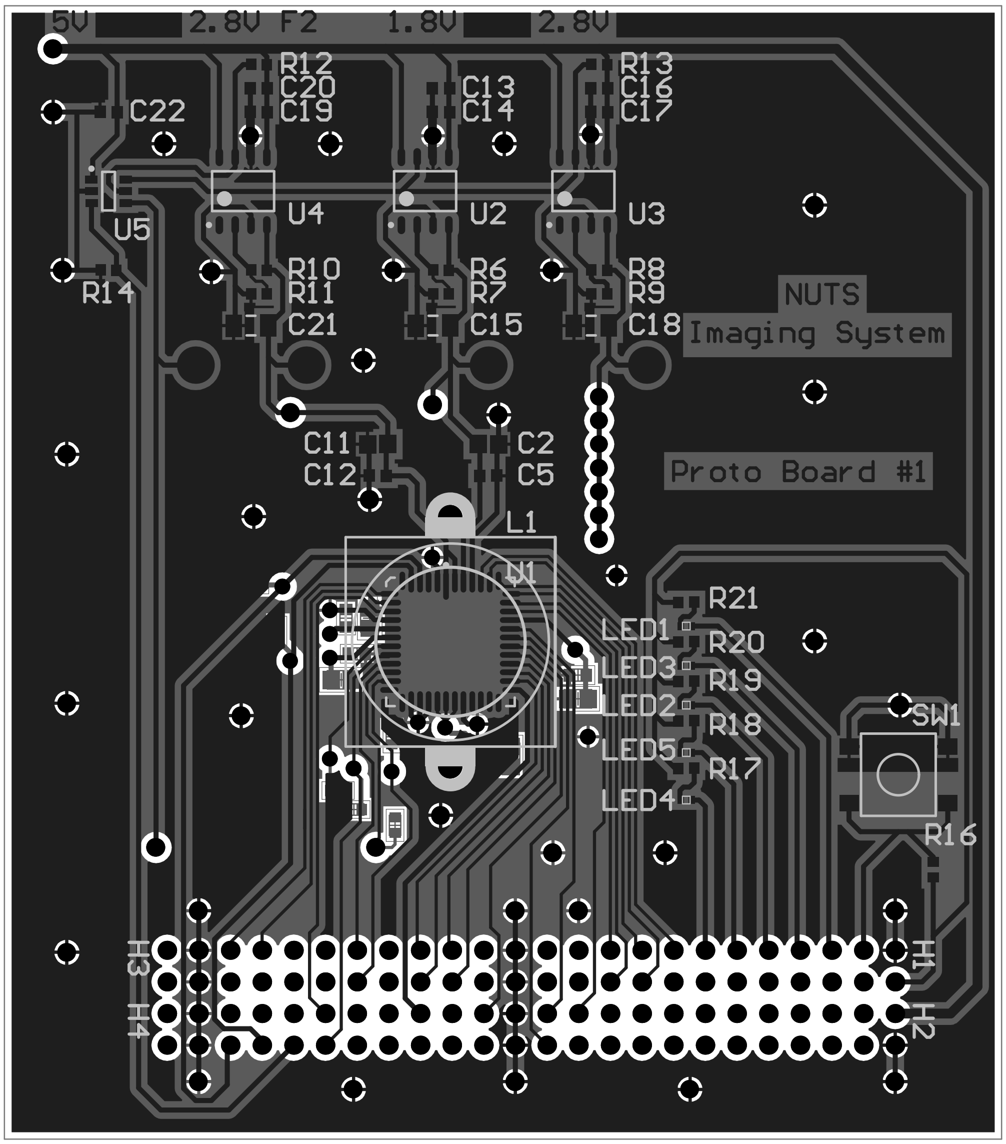
Title		
Size A4	Number	Revision
Date: 03.01.2015		Sheet of
File: C:\Users\..\linear2.8_flag2.SchDoc		Drawn By:



5V0
C22
Cer cap
1uF
GND
U5
Seq
926-LM3880MF-1AANOPB
VCC
FLAG1
FLAG2
FLAG3
EN
GND
R12
Res
47K
R13
Res
47K
ENABLE
R14
Res
47K
GND
GND
REG1
linear1.8_flag1.SchDoc
!OFF
REG2
linear2.8_flag1.SchDoc
!OFF
REG3
linear2.8_flag2.SchDoc
!OFF
2V8_FLG1
R15
Res
47K
!RESET_FLG3
Title
Size
A4
Number
Revision
Date: 03.01.2015
Sheet of
File: C:\Users\..\Power.SchDoc
Drawn By:


R5
C9
R4
C10
C1
C6
C7
C8
R1
C3
R3
C4
R2
R15


5V
2.8V F2
1.8V
2.8V
NUTS
Imaging System
Proto Board #1
R12
C20
C19
C13
C14
R13
C16
C17
C22
U4
U2
U3
U5
R10
R11
R6
R7
R8
R9
R14
C21
C15
C18
C11
C12
C2
C5
L1
R21
R20
R19
R18
R17
R16
LED1
LED3
LED2
LED5
LED4
SW1


5V
2.8V F2
1.8V
2.8V
R12
C20
C19
C22
C13
C14
R13
C16
C17
U5
U4
U2
U3
R14
R10
R11
C21
R6
R7
C15
R8
R9
C18
NUTS
Imaging System
C11
C12
C2
C5
Proto Board #1
L1
U1
R21
LED1
R20
LED3
R19
LED2
R18
LED5
R17
LED4
SW1
R16
H3
H4
H1
H2

Appendix B

Night conditions

Some calculations where made to check if the sensor would be able to take images during low light conditions and still produce a sharp image.

B.1 Reducing image blur

When taking a photograph it is neccessary that the motive is somewhat stationary in relation to the camera in order to get a sharp image. Even though the satellite will be a large distance from the earth it will at the same time travel with incredible relative speed. To set a maximum shutter time, we used image blur as a limit.

B.1.1 Acceptable pixel shift

The most important factor to consider regarding blur is the amount of detail that the motive will have. When taking a picture of a person or household object, blur plays a less important part since the pixel patterns do not vary too much or you only need certain parts of the image to be sharp. When viewing such an image most people would have a higher treshold for noticing blur. The earth on the other hand, has lots of details. A single pixel could be a buidling or something even larger, resulting in suddent changes in pixel gradient.

When taking pictures of the earth you really want all the details, a super crisp image to conway the awsomeness. Therefore we set our aim at having a small as possible pixel shift during exposure.

B.1.2 The longest exposure time

We base our calculations on a simplified premise. We do not take into account the curvature of the earth. This simplification will result in harder limits compared to a more realistic calculation. The main reason for this simplification is that calculations considering curvature and other factors requires would require a more complex algorithm. We simply don't have the time to get bogged down in such details. The values will be worst case, and such it will not have a negative impact on the sensor specifications. In fact, the opposite will be true.

With this in mind, finding a formula for the pixelshift given the shutter time only requires a little triogonometry. First we find the relation between the shuttertime and how far the satellite will travel during that time.

$$\Delta(\text{Distance}) = \frac{1000 \cdot V_{\text{SAT}}}{3600} \cdot \frac{1}{T_{\text{SHUTTER}}}$$

Then you can calculate the change in angle given that the startposition is in angle zero.

$$\Delta(\text{Angle}) = \arctan\left(\frac{\Delta(\text{Distance})}{(\text{Orbit})}\right)$$

Then you can cacluate the percentage of the FOV that the point has moved and multiply it with the resolution of the sensor.

$$\Delta(\text{Pixels}) = \frac{\Delta(\text{Angle})}{(\text{FOV})} \cdot (\text{Resolution})$$

As can be seen from figure B.1, the worst case is if the satellite goes into orbit close to 400 km. The camera should not take a picture with the exposure time longer than $\frac{1}{30}$. Keeping within this time period will ensure that the image doesn't get blurred.

Listing B.1: speedtest.py

```
#!/usr/bin/python
from pylab import *
import sys
import math
import numpy as py

hSensorRes = 3000 #Pixels

distances = [400,500,600] #km
speed = 7.8 #km/s
hFOV = 120 #Degrees

# Antall piksler punktet kan bevege seg i lopet av tiden det
# tar aa ta et bilde.

# Hvor langt beveger objektet seg i forhold til flyet i lopet av lukkertiden
#figure()

```

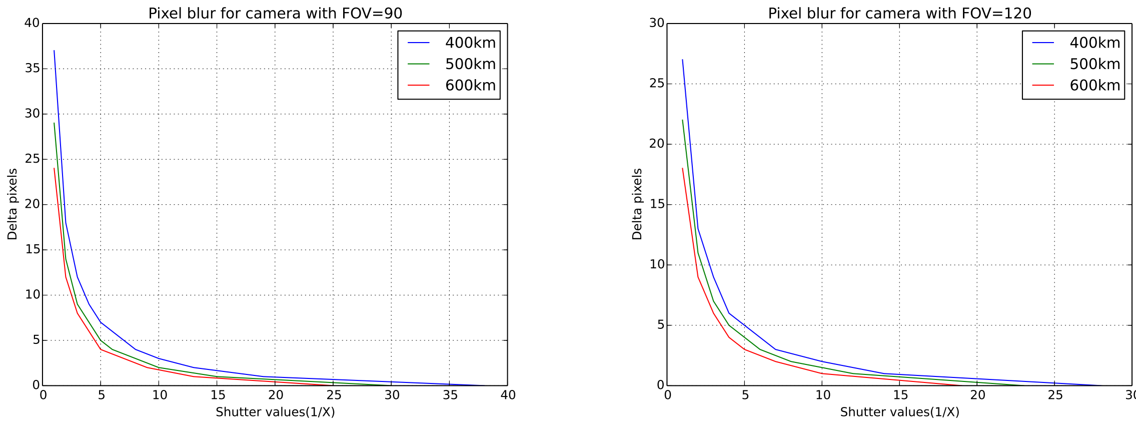


Figure B.1: Calculations of pixel shift at different shutter speeds and heights.

```
figure()
for earth2sat in distances:
    print ""
    print 'Shutter\tAngle\tDistance\tPixels\tOrbit'
    deltaPixels = 1223123123
    shutter = 1.0
    lastPixel = 319283192
    xplot = []
    yplot = []

    while deltaPixels > 0:
        deltaDist = speed * (1.0/shutter)

        # Hva tilsvarer dette i grader (Worst case)
        deltaAngle = math.degrees(math.atan(deltaDist/earth2sat) )

        #Hvor mange piksler tilsvarer dette?
        deltaPixels = int ( ( deltaAngle / hFOV ) * hSensorRes )

        if deltaPixels != lastPixel:
            print("%d\t%4.3f\t%4.3f\t\t%d\t%d"%(shutter,deltaAngle,deltaDist,deltaPixels,earth2sat))
            xplot.append(shutter)
            yplot.append(deltaPixels)
            lastPixel = deltaPixels

        shutter = shutter+1

    plot(xplot,yplot,label='%dkm'%earth2sat)
    legend()

title('Pixel blur for camera with FOV=%d'%hFOV)
ylabel('Delta pixels')
xlabel('Shutter values(1/X)')
grid()
show()
```

Appendix C

Automating steps

The code written by Andreas Bertheussen was a collection of several low level functions that could be used to take a picture and transfer it over a virtual serial port. He had also made a couple of programs to handle the transfer and image interpolation.

Manually entering every single command was time consuming and prone to errors, thankfully the functions made by Andreas could be adapted into the high level script shown below. This script eliminates the need for manually changing between serial terminal instances and provides a single command that takes a picture and starts the transfer.

Listing C.1: pterminal.py

```
import serial
import io
import sys
import os

io.DEFAULT_BUFFER_SIZE=1024
ser = serial.Serial(timeout=1)
ser.baudrate = 921600
ser.port=4
ser.open()

sio=io.TextIOWrapper(io.BufferedRWPair(ser,ser))

if ser.isOpen():
  print "open"

  while ser.isOpen():
    input = raw_input("Send:")
    if input == "exit":
      exit()
    sio.write(unicode(input+'\n'))
    sio.flush()
    if "shoot" in input:
      size = input.split(' ',1)
      size = size[1]
      print size
      #sio.encode="binary"
      ser.close()
      f = open('dothis','w')
```

```
      f.write("vdma\ndump "+size+"\n")
      f.close()
      #orig_stdout = sys.stdout
      #sys.stdout = f
      os.system("serialdump com5 921600 dothis dump.txt")
      os.system("Python extract.py dump.txt")
      ser.open()
      #sys.stdout = orig_stdout
      #f.close()
    else:
      print sio.read()

else:
  print "fuck"
```