Department of Precision and Microsystems Engineering

Design and analysis of an optical system to detect changes in the optical payload on a Cubesat

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by

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Abstract

Use of earth observation satellites have grown at a very high rate over the past few decades. On a closer observation of things around, most of them uses satellites, directly or indirectly. Satellites are being used in the day to day life without being aware of its application. Satellites are used for small things like weather report, communication to very large things like internet of things (IOT) and earth observation. Some CubeSats are also used for interplanetary missions. For the purpose of earth observation missions, the satellites are installed with an optical payload which is a camera. The cameras used for space are different from the regular camera and have special specifications in terms of the materials, components and the design which make them suitable for space missions. The optical payload which is to be launched has to be made sure that it can survive the launch and in orbit environment.

This research focuses on the testing of these CubeSats and check if they are suitable for launch. The research starts with reviewing the testing procedure that is followed before the satellite is launched. A brief explanation regarding the importance of testing is given in chapter 2.

The research is focused on a multisprectral camera (Multiscape 100). Chapter 3 includes the specifications and the details of camera construction and working. Various parameters of a camera that can be potentially used for verifying the quality of camera are discussed. After weighing the advantages and disadvantages of various parameters, MTF and cross-correlation is used to compare images.

Chapter 4 depicts the research question formulated based on the requirements. The methodology used for the data analysis experiment is explained in the chapter 5. Chapter 6 explains the preliminary data analysis experiment for the post processing of the images. The results obtained from the data analysis experiment are compiled in the chapter 7. Chapter 8 explains the setup design that is planned for the testing of the camera.

Chapter 9 complies the conclusions drawn from the experimentation. The MTF and correlation method can be used for detecting the changes in the camera. There was a drop in the MTF when there were aberrations induced in the setup and there was a drop in the similarity percentage. Further recommendations have been listed to explore in future.

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For the reader: I hope you enjoy reading this thesis!

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1 Abbreviations

RGB	Red Green Blue
CCD	Charged coupled devices
CMOS	Complemantary metal oxide semiconductor
TDI	Time delay integration
FT	Functional tests
TVAC	Thermal vacuum
AFOV	Angular field of view
F#	F number
λ	Wavelength
MTF	Modulation transfer function
SLR	Single lens reflex
DSLR	Digital single lens reflex
VNIR	Visible and near infrared
ESF	Edge spread function
PSF	Point spread function
SNR	Signal to noise ratio
ADC	Analog to Digital converter
SSIM	Structural similarity index
MSE	Mean square error
PSNR	Peak signal to noise ratio

2
Introduction

The small satellite market has rigorously changed over the last decades: Miniaturization of components and advances in technologies have enabled rapid development of small, low-cost satellites. The market is booming and the demand for high performance missions is increasing. This thesis was conducted at ISISpace - Innovative Solutions in Space BV, which is a leading company in the small satellite market (Cubesats). Founded in 2006, ISIS operates globally and serves customers worldwide in accomplishing their space missions and applications. One of the applications of cubesats is earth observation. ISIS provides satellites which are used for earth observation. The focus of the thesis lies in this area [16].

ISIS deals with the design, analysis and manufacturing of nanosatellites i.e., satellites that weigh in the range of 1-20kg. These are generally called cubesats. Currently, ISIS manufactures 1u, 2u, 3u, 6u satellites and some custom builds.

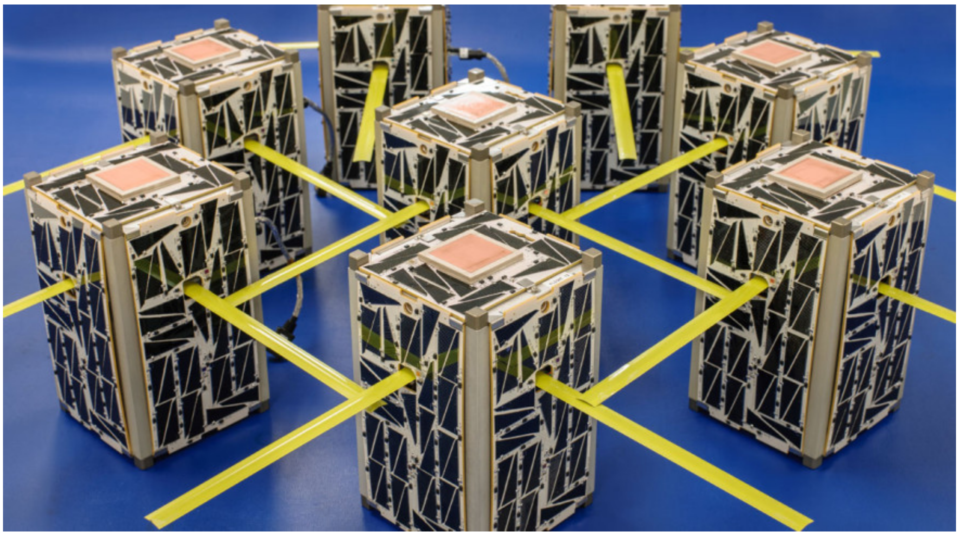


Figure 2.1: CubeSat

2.1. Earth observation

The term Earth observation refers to the accumulation of information about the Earth's physical, chemical, and biological systems through the use of remote sensing technology, which incorporates satellites. In simple terms it means looking at the earth with the help of satellites. Due to the current increase in climate change, the need for global viewing is increasing day by day. This is one of the main reasons for the increase in data required for land awareness. Landscape is used to predict the weather and to predict natural disasters. The basis for earth observation lies in the optical payment load placed on the satellite for this specific purpose. There have been major technological advances in this particular area.

Earlier, the sensing was done with a sensor that used to capture images in grayscale with low signal to noise ratio. This was the first step towards earth observation. As technology advanced, filters were added onto the sensors which gave rise to RGB sensors. This was a big advancement in sensing world. Recently, companies have started using multispectral cameras for sensing. ISIS is planning to use a 7 band multispectral camera which has a CCD in CMOS with TDI sensor. This camera has the ability to capture the image in 7 different bands. [2][9][3][5].

Figure 2.2: Earth observation satellite [18]

2.2. Testing of satellites

It is necessary to check the entire satellite before it enters the orbit. Testing starts from the first production stage for each item. When these components are assembled into larger parts, it undergoes further testing. When the final construction is complete, the whole unit needs a rigorous test [34]. Satellite testing presents different challenges. Unlike testing in the automotive industry or the utility industry, it is not possible to test a particular type before performing a final type. When a satellite is tested, it is usually the last one to enter the orbit. Therefore, while the tests require caution, the test alone cannot damage the satellite in any way.

Testing is a key function in preparing for a satellite launch. A properly executed test will measure the satellites response characteristics and provide its designers the information they need to determine its ability to withstand the rigors of a space launch. Designing for vibration robustness is a key element in any satellite design. On one hand testing of satellites is very important to check whether the satellite survives the launch and in-orbit condition as they are very different from what it undergoes when the satellite is on ground, while on the other hand, it is also possible that these test give rise to some problems in the system which were not present earlier which can make the satellite not suitable for launch [24]. Hence, it is necessary to test the satellite until there are no problems generated due to the process of testing. If all the components of the satellite are intact post testing, the satellite is ready for launch.

Figure 2.3: Satellite being prepared for vibration testing at ISIS [17]

2.3. Testing procedure

There are multiple processes involved during the testing of satellites. They have to be followed according to a sequence. The figure 2.4 gives a flow chart of the the processes that are followed during the testing of a cubesat and their sequence. The abbreviation FT that is used in the flow chart refers to functional test (full check) of the CubeSat that is done after regular intervals to check if it is intact and can be continued for further testing [8].

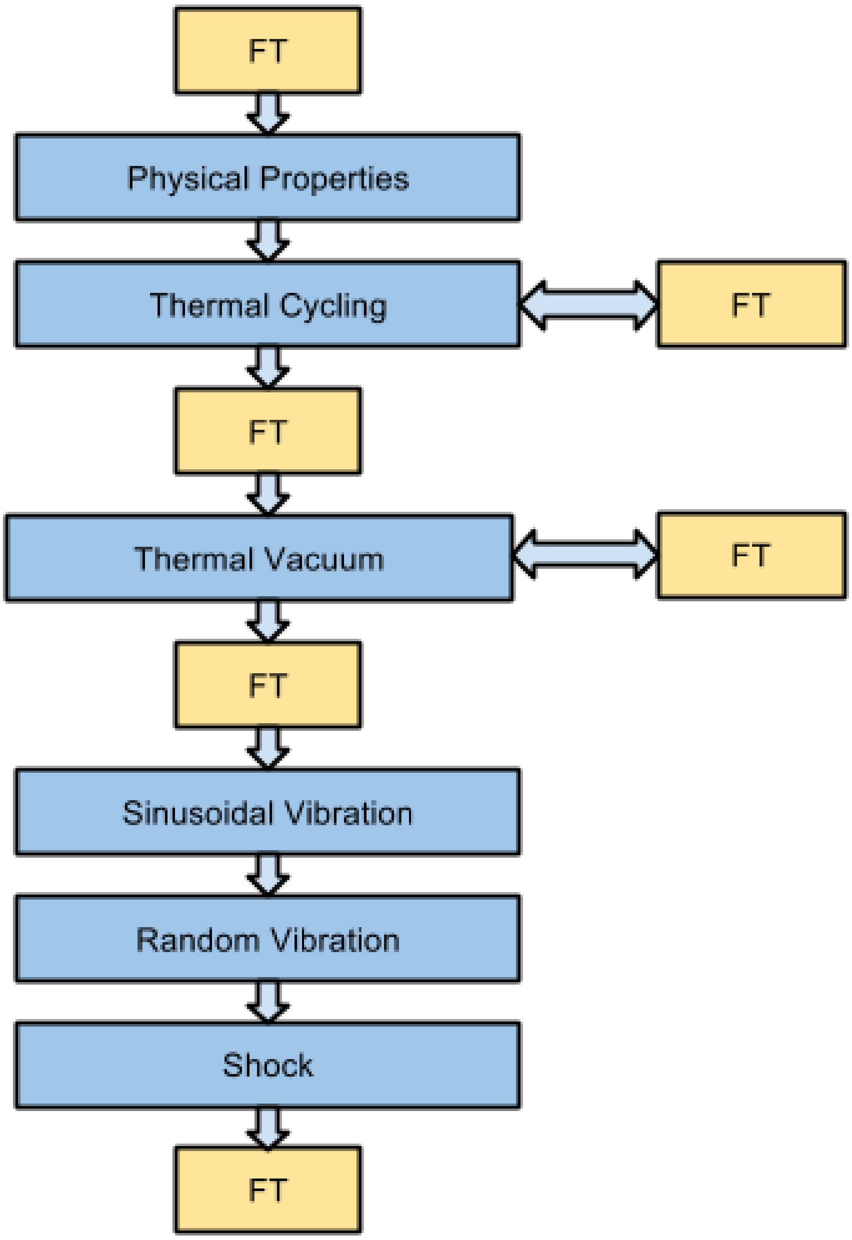


Figure 2.4: Test sequence flow

2.3.1. Physical properties

Once the CubeSat is fully integrated, the first step is to examine the physical properties of the cubesat. These structures include the weight of the cubesat, its center of gravity and its moment of inertia. These were tested to obtain a measured reference again after the completion of the test and between the various steps [8].

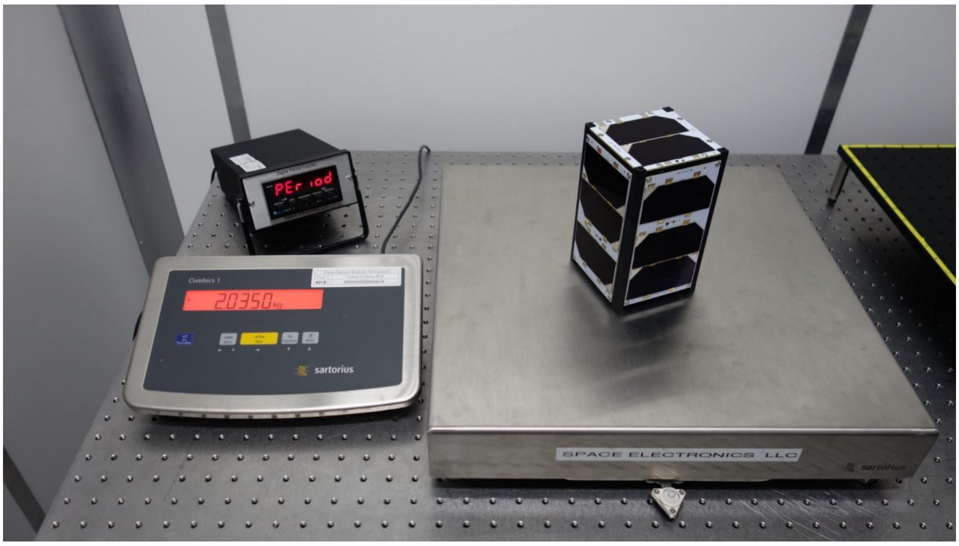


Figure 2.5: Physical properties being evaluated [17]

2.3.2. Thermal cycling

The purpose of thermal cycling is to check if the the CubeSat and the system are able to survive, without loss of integrity or functionality, the thermal loads which are experienced during the space mission. This is done by keeping the CubeSat in a chamber and controlling the temperature in the chamber. Generally, the maximum temperature is 110°C and the minimum temperature is -45°C. The CubeSat is also kept for 1 hour at the extreme temperatures to simulate the space conditions. Figure 2.6 shows a 6U CubeSat being prepared for thermal cycling [8].

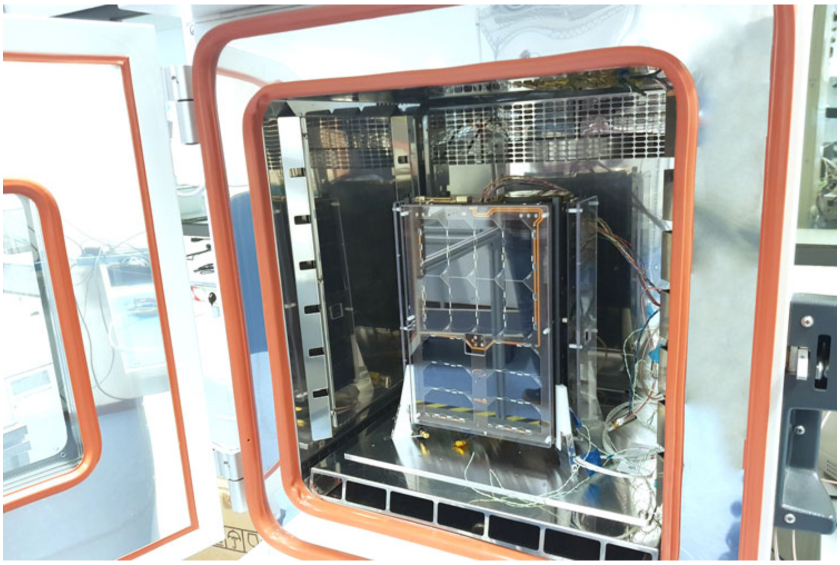


Figure 2.6: Thermal cycling of 6U CubeSat at ISIS

2.3.3. Thermal vacuum (TVAC)

The thermal vacuum chamber testing is different from thermal cycling as the prior one consists of vacuum chamber. The aim of this test is also to demonstrate that the CubeSat is able to survive without the loss of functionality and integrity. As there is vacuum present in space, a deep vacuum environment is created with a pressure of 10-7 bar). To prevent the outgassing during the TVAC, a bakeout of the systems is performed. The CubeSat is kept at these condition for about 2 hours to check the functionality. After the bakeout, the system is the prepared for thermal vacuum test where the pressure is between 10-6 mbar and 10-7 mbar and the temperature is cycled between -30°C to 65°C [8].

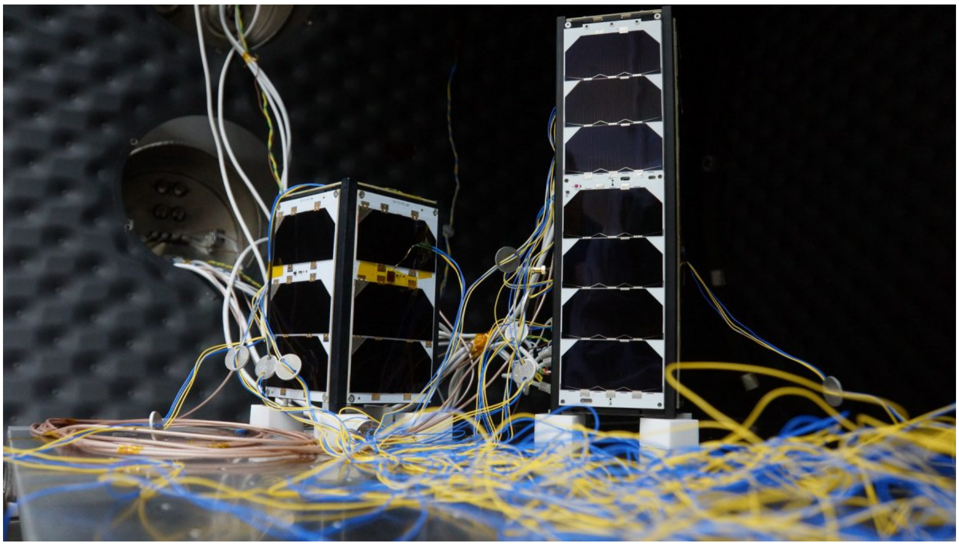


Figure 2.7: Thermal vacuum chamber testing [17]

2.3.4. Mechanical tests

A CubeSat has to sustain an enormous amount of load and vibrations during the deployment. Mechanical tests are performed on the satellite to ensure that the satellite is able to survive the loads and vibrations that a satellite have to face. The mechanical tests consists of different vibration tests and shock tests. The satellite is made to undergo a sinusoidal vibration test followed by random vibration test. Then the satellite undergoes a shock test. A functional test is followed after the mechanical tests. Figure 2.8 shows the mechanical shock testing facility at ISIS [8].

2.4. Motivation

Now-a-days, testing of any component has become a very high priority in the industry. Testing of product is done to verify if all the systems and components in the product or system are in right working conditions. Similarly, a satellite also undergoes various tests before it is being launched into space. During testing of satellites, the launch and in-orbit conditions are simulated while the satellite being on earth. Testing of satellite involves tests like vibration [34], thermal vacuum chamber [7], etc.

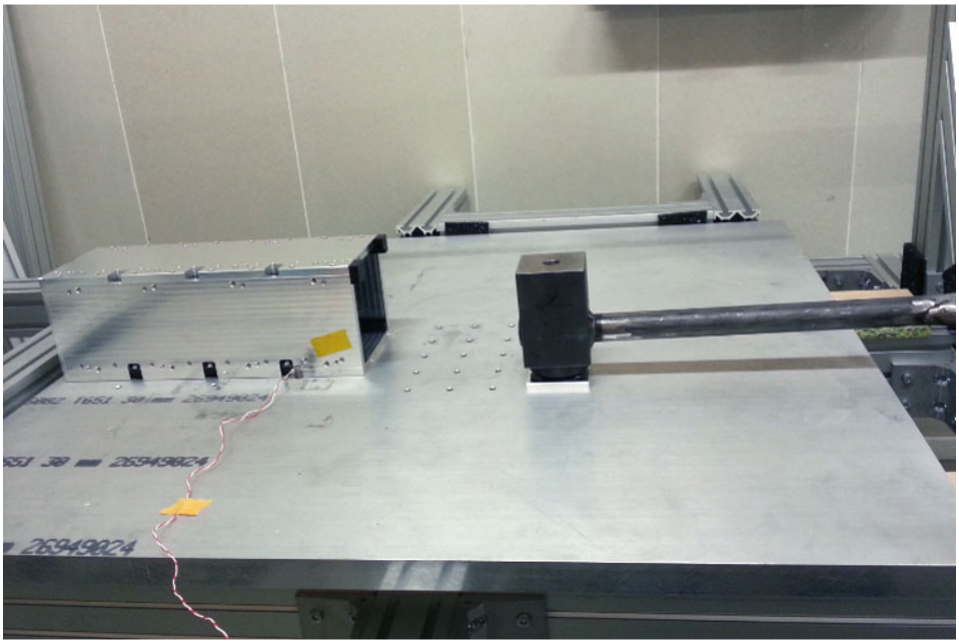


Figure 2.8: Mechanical shock testing facility at ISIS [17]

Since large investments are involved in manufacturing of satellite, it is expected to work like intended. This makes testing a critical process in the manufacturing of satellites.

During the various tests that are done on the satellite after being assembled, there is a chance that the components in the satellite might degrade/change and not function as intended. The focus of this thesis lies in the changes/degradation in the performance that might occur during testing.

The optical payload in the satellite is an important component especially for earth observation missions. Any error in the payload makes the mission a failure because it does not perform its intended function. Hence, it is necessary to check that there is no change in the performance of the camera that is installed on the satellite after testing.

This is the motivation of this thesis. The goal is to check if there is any significant degradation/change in the performance of the camera.

3

Multiscape 100 Camera

Multiscape 100 is a push - broom imager primarily designed for earth observation application as a payload on Cubesats. It is based on CCD in CMOS sensor and a multispectral filter in the visible and near infrared spectral range. The scanning technology used in this camera is continuous line-scan imaging with Time delay integration.

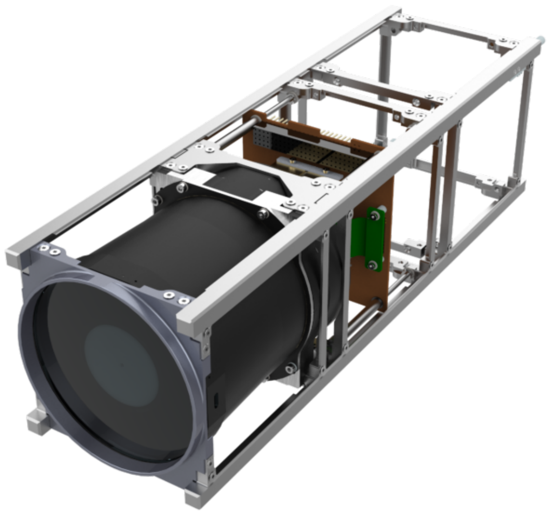


Figure 3.1: Multiscape 100 camera [26]

The specifications and details of the camera and mentioned in the table 3.1.

In the figure 3.2, the whole lens is not used for imaging as the aberrations are dominant at the edges and as the distance between the ground and the sensor is large, these aberrations are magnified.

3.1. Parameters of camera

Selection of a camera for photography or for space purpose is done based on some decided parameters. For photography, a camera is selected based on its application and it use case.

Property	Specification
Focal length	580 mm
Front aperture	95 mm
F number (F#)	f6.1
Angular field of view (AFOV)	2.18°
Wavelength spectrum	450nm - 900nm
Resolution	Sensor resolution: 7 bands of 56 x 4096 pixels Resolving limit (Rayleigh): 13.17μm, for 675nm,
On-Axis MTF	18% at Nyquist
Distortion	< 0.165%
Pixel pitch	5.4μm

Table 3.1: Table of specifications

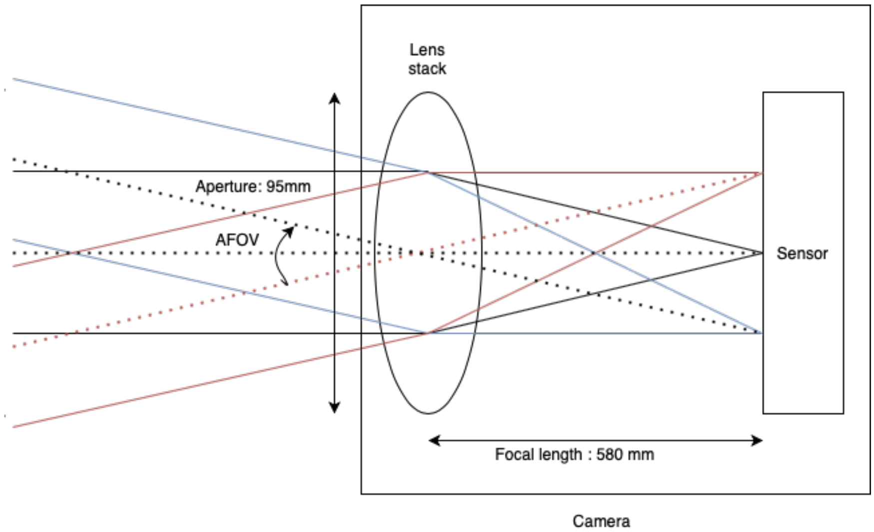


Figure 3.2: Schematic of Multiscape 100 camera

The same thing goes for space cameras. A camera is selected based on the focal length, chip architecture, sensor size, aperture, f-stop, noise and some other parameters.

3.1.1. Focal length

Focal length of the camera is the distance from the optical center of the lens to the sensor of camera in millimeters. In some cameras, the lens is attached to the camera while in some the lens is a separate equipment. In the modern SLRs and DSLRs the lens is always a separate equipment. A camera cannot work without a lens system. The lens system of the camera helps to gather the information from the surrounding and focus it on the sensor. It acts a translating device from the environment to the sensor of the camera. Focal length of the camera is the the parameter which determines the sharpness of the image when the camera and object distance is kept constant. Short focal length lenses have short working distance and long focal length lenses have larger working distance. The focal length of a camera ranges from 5mm to 1500mm. One thing to keep in mind regarding the focal length is that the larger the focal length of a lens, the smaller is the field of view of the lens as the image is zoomed in.

Lenses are also categorised based on if the lens have a variable focal length or a fixed focal length. The fixed focal length lens are called Prime and variable focal length lenses are called Zoom. The camera lens dealt with in this thesis is a prime lens, which has a fixed focal length. This property of the camera lens could be exploited for determining if there is any change in the focal length of the camera.

3.1.2. Aperture

The aperture of a a camera is defined as the opening through which the light enters the camera. It can be opened and closed by which it can can control the light entering the camera. Depth of field of a camera is also affected by changing the aperture of the camera. Large aperture gives a shallow depth of field and small aperture gives a large depth of field.

3.1.3. F number

The F number gives information about how much light is entering the camera. The F number is given by [28]:

$$F\# = \frac{f}{D} \tag{3.1}$$

where
f is the focal length of the lens
D is the diameter of the entrance pupil

The diameter of the entrance pupil can be controlled by expanding or shrinking the aperture size. The aperture is a diaphragm which is situated at the end of the lens before the sensor which can be controlled. Opening and closing of this diaphragm decided the amount of light falling on the sensor. For universal reference, there are some standard f number scales such as f/1.4 f/2.0 f/2.8 f/4.0 f/5.6 f/8.0 f/11.0 f/16.0 f/22.0 f/32.0.

3.1.4. Field of view

Field of view (FOV) in simple terms means the maximum area of a sample that a camera can capture. And the angle subtended between the center point of the lens on the optical axis and the topmost point of the object and the bottom-most point of the object is called the angular field of view (AFOV). This is decided by the focal length of the lens and the sensor size. Assuming the focal length to be constant, a larger sensor has a larger field of view. Figure 3.5 shows a comparison between the field of view and sensor size. Both the blue (4096 x 4096 pixels) and red (2048 x 2048 pixels) square indicate sensors made from 15 x 15 μm pixels, whereas the green square (1024 x 1024 pixels) indicates a sensor made from 13 x 13 μm pixels.

The figure 3.4 shows the influence of how the focal length affects the field of view. Red line indicates light from the bottom of the object, creating the top of the image; blue light is light that is taken from the horizontal; grey lines indicate light that is from the top of the object, creating the bottom of the image. The height of the image is indicated by h.

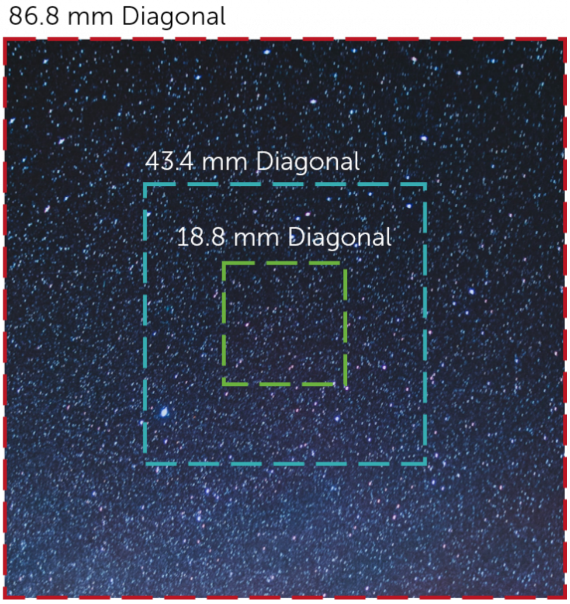


Figure 3.3: Comparison of different sensor sizes, showing how larger sensor sizes contribute to a larger field of view [15]

3.1.5. Wavelength spectrum

The wavelength spectrum of a normal camera is generally the visible spectrum. But there are specialised camera which are capable to capture visible and near infrared light, commonly known as VNIR. Cameras can be modified such that they are able to capture some ultraviolet light, visible light and much of near infrared spectrum, as most of the cameras as capable to capture light from 300 nm to 1000 nm. Full spectrum camera can converted into ultraviolet or infrared camera using filters. Applications include fine art photography, geology, earth observation and ghost hunting.

For this thesis, the camera used is a multispectral camera. This camera has 7 bands with 7 different filters. The wavelength spectrum of the camera is from 350 nm to 900 nm. The central wavelength of every band is given below: Camera specifications:

Band	Central Wavelength (nm)	FWHM Bandwidth (nm)	Band range (nm)
1	490	65	457.5 - 522.5
2	560	35	542.5 - 577.5
3	665	30	650.0 - 680.0
4	705	15	697.5 - 712.5
5	740	15	732.5 - 747.5
6	783	20	773.0 - 793.0
7	842	115	784.5 - 899.5

Table 3.2: Wavelength spectrum

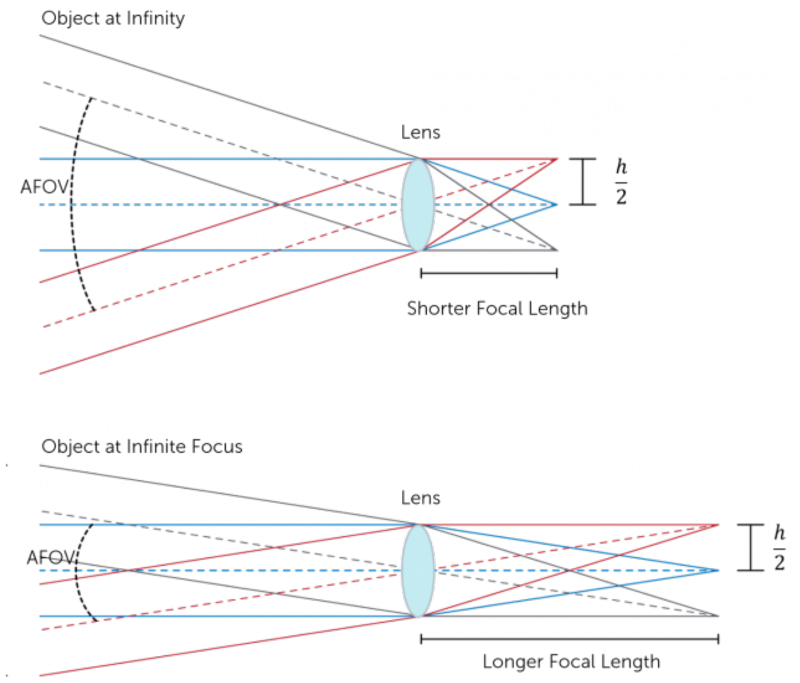


Figure 3.4: Schematic depicting the influence of focal length on FOV [15]

3.1.6. Resolution

Resolution refers to the number of pixels present in the sensor. Higher number of pixels imply higher resolution. The quality of the image is also determined by the optics of the camera.

The construction and selection of lenses for the camera has to be decided taking into consideration the diffraction limit of the lens and the pixel pitch of the sensor. Due to diffraction, there is a physical limit on resolution of the camera. The diffraction limit is given by [10]:

$$p = \frac{1.22 \cdot \lambda \cdot f}{D} = 2.44 \cdot \lambda \cdot f\# \quad (3.2)$$

Where p is the spatial resolution that can receive pixel-level information from the lens. λ is the wavelength of the incident light, D is the diameter of the lens and $f\#$ is the F number. This means that even when the lens made perfect, the system is limited by the diffraction limit of the lens.

3.1.7. MTF

MTF stands for Modulation transfer function. In simple terms, this parameter give information about the frequency response of the system that is under inspection. This is an optical property of an image. The resolution and optical performance of an optical system is calculated by the MTF. MTF is a measure of the transfer of contrast from object plane to image plane. For an ideal system, the MTF is 1 for all spatial frequencies. This property is used in many optical and opto-mechanical applications [14].

The term spatial frequency is defined as the distance between two point sources. Spatial

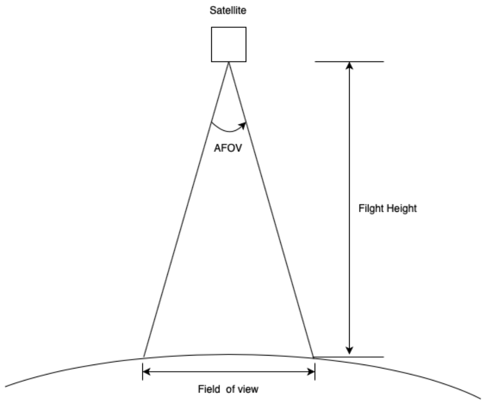


Figure 3.5: Field of view and Angular field of view of a camera

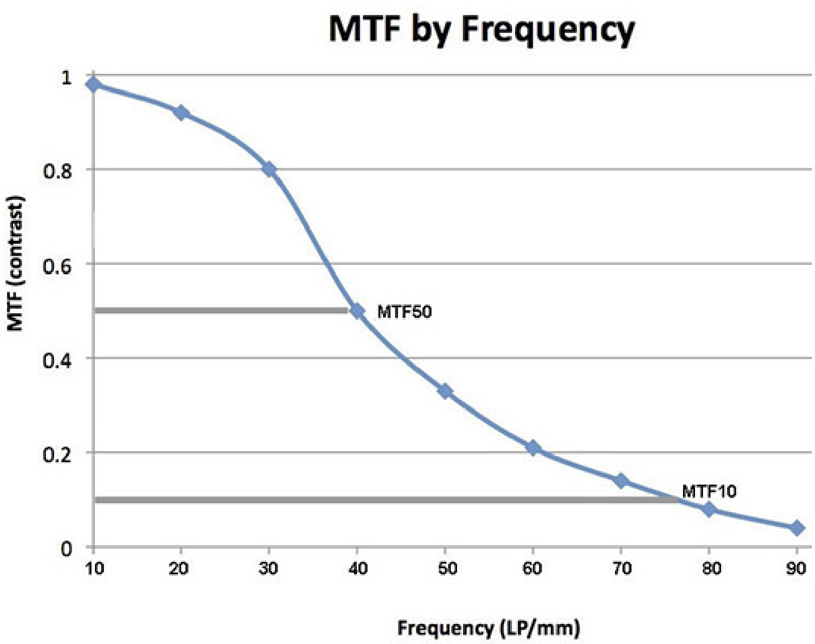


Figure 3.6: Example of an MTF curve

frequency is proportional to the inverse of the distance between the two point sources.

Due to its extensive applications, MTF is also used in electronics and signal processing. MTF gives information regarding the output amplitude relative to input amplitude for every sinusoidal frequency components in an image that is passed through the optical system. If only one frequency is passed through the optical system, the MTF gives information regarding output frequency relative to the input frequency. The figure 3.7 gives an overview of it. In the optics field, MTF refers to an array of sine or bar targets at a given spacing, expressed in line-pairs-per-millimeter (lp/mm) or cylces-per-milliradian (cy/mrad) [21].

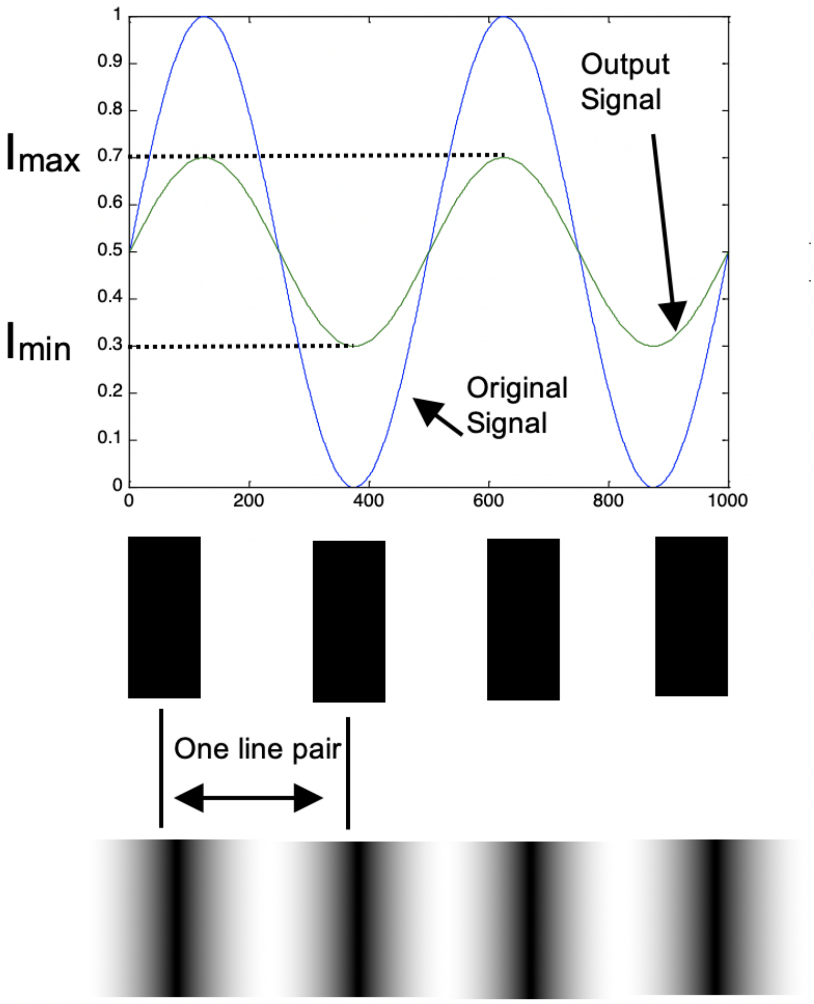


Figure 3.7: Sinusoid chart at one spatial frequency [6]

Along with characterising of traditional optical setups, MTF is also used for characterising of different types of image cameras and intensifiers. Generally, MTF is measured with the help of a bar target method, which is one of the few methods employed for measurement. Different types of measurement methods are discussed further in later chapters. For example if a system has a spatial frequency of 1000 mm, it means that the black lines will repeat for 1000 times in one millimeter [25].

Another important concept in MTF is the Edge spread function (ESF). The ESF of an image gives information of the transition of contrast over range of pixels. For example, the ESF of a pixel with a high contrast is high and that of a pixel with a low contrast is low [32]. These two values fall on the extreme of the ESF function chart. All the intermediate grey values of the transition contrast fall between these. The differentiation of the ESF gives us the Line spread function (LSF). And the fourier transform of the line spread function gives the MTF of the image.

Sharpness of an image gives very vital information about the quality of image as it tell how crisp and detailed the boundaries of an image are. As sharpness of an image deals with the boundaries of the object in image, it directly affects the MTF. For reference consider the figure 3.7, in which it is visible that the top portion of the image is sharp and the bottom portion is blurred. This causes a drastic change in the MTF is the image. The blurrier your image, the lower is your MTF and the lower is the quality of your image as you cannot differentiate between two point after a certain frequency. The Nyquist frequency always corresponds to 0.5 cycles per pixel. All lenses blur the images upto a certain degree, the only difference is that a good lens will blur image less than a bad lens [11].

MTF of an image can be calculated by two methods. MTF of an image is generated by taking two-dimensional Fourier transform of the Point spread function (PSF) or by taking a one-dimensional Fourier transform of the Line spread function (ESF). There are many advantages of using the edge response for calculating the MTF of an image.

First, the measurement is in the same form as the image information is encoded. In fact, the main reason for wanting to know the resolution of a system is to understand how the edges in an image are blurred [27]. The second advantage is that the edge response is simple to measure because edges are easy to generate in images. If needed, the LSF can easily be found by taking the first derivative of the edge response [27].

The third advantage is that all common edges responses have a similar shape, even though they may originate from drastically different PSFs [27]. This is shown in Fig. 3.8a, where the edge responses of the pillbox, Gaussian, and exponential PSFs are displayed. Since the shapes are similar, the 10%-90% distance is an excellent single parameter measure of resolution. The 10%-90% rise distance is the number of pixels between the 10% gray and 90% gray values across othe edge. The fourth advantage is that the MTF can be directly found by taking the one-dimensional FFT of the LSF (unlike the PSF to MTF calculation that must use a two-dimensional Fourier transform) [27]. Figure 3.8b shows the MTFs corresponding to the edge responses of (a). In other words, the curves in (a) are converted into the curves in (b) by taking the first derivative (to find the LSF), and then taking the FFT.

The fifth advantage is that similar edge responses have similar MTF curves, as shown in Figure 3.9 (a) and (b). This allows us to easily convert between the two measurements [27]. In particular, a system that has a 10%-90% edge response of x distance, has a limiting resolution (10% contrast) of about 1 line pair per x distance. The units of the "distance" will depend on the type of system being dealt with. For example, consider three different imaging systems that have 10%-90% edge responses of 0.05 mm, 0.2 milliradian and 3.3 pixels. The 10% contrast level on the corresponding MTF curves will occur at about: 20 lp/mm, 5 lp/milliradian and 0.33 lp/pixel, respectively.

Hence, significant change in the optics of the optical setup will lead to a change in the MTF of the image that is obtained from that setup. This property is being exploited in this thesis.

MTF of an image tells us few very important basics to characterise an optical system:

- The MTF contains some wavefront information, which can provide information about aberrations, including defocus.
- There is a loss of phase information while measuring MTF. This is due to the fact that MTF is calculated by image intensity profile.

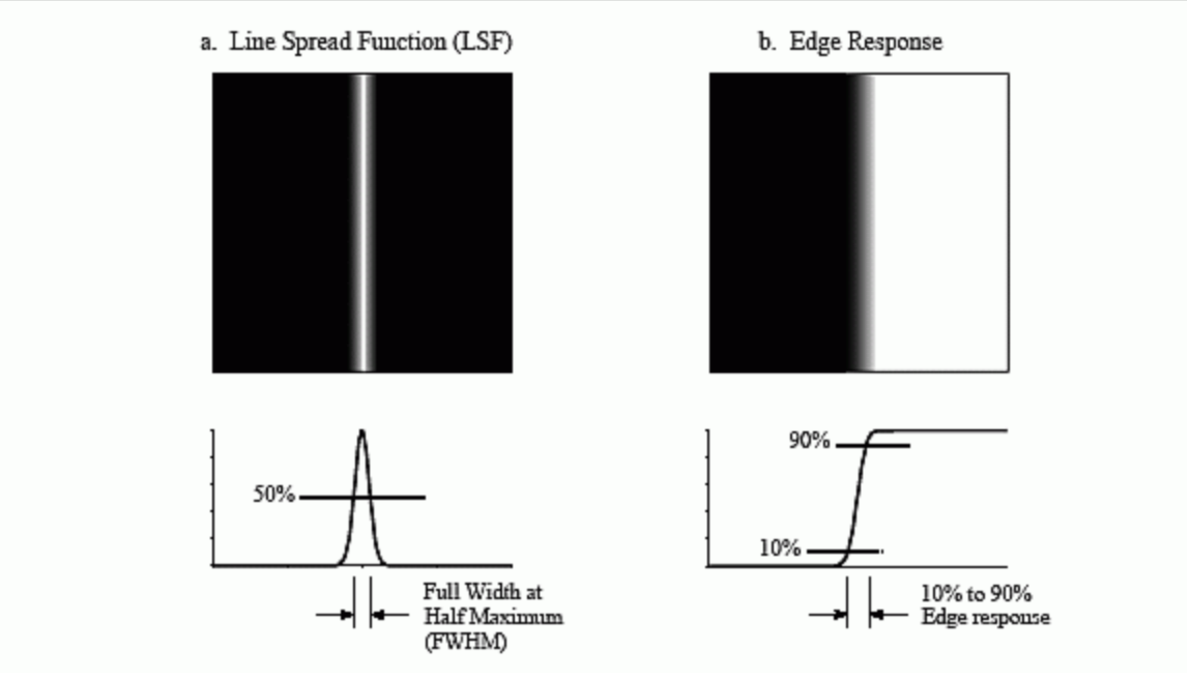


Figure 3.8: Line spread function and edge response. The LSF is the derivative of edge response. The width of the LSF is usually expressed as Full-Width-at-Half-Maximum (FWHM). The width of edge response is expressed by the 10% to 90% distance [27]

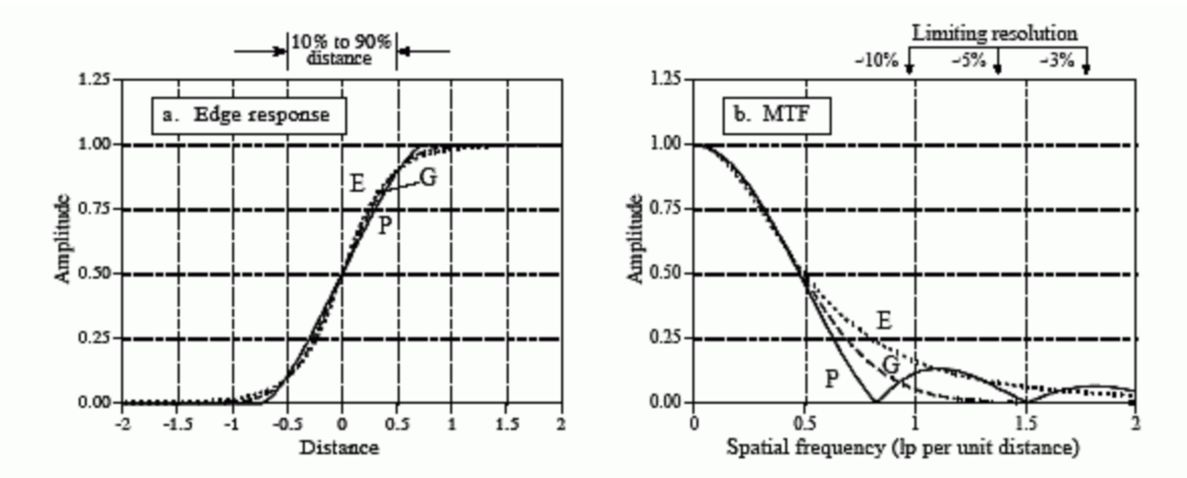


Figure 3.9: Edge response and MTF. Fig (a) shows the edge response of three PSFs: (P)pilllbox, (G) Gaussian, and (E) exponential. Each edge response has a 10% to 90% rise distance of 1 unit. Fig (b) shows the corresponding MTF curves; which are similar above the 10% level. Limiting resolution is a vague term indicating the frequency where the MTF has an amplitude of 3% to 10% [27]

The MTF that is mentioned in the specifications of the camera is the on axis MTF. The MTF of the lens drops as we move away from the optical axis of the lens. This is a factor that has to be considered while using a lens. On axis MTF means the MTF that is on the optical axis of the lens. The maximum MTF of a lens is found at the optical axis of the lens. A reason for the dropoff of the MTF at the edges of the lens is the aberrations are dominant around the edges.

3.1.8. Distortion

Distortion in camera refers to the change in the magnification at points around the field of view with respect to the maximum magnification occurring at the center of field of view. An ideal lens is free from all the distortions but in reality all lenses have some distortion at the edges.

In space cameras, distortion can be defined as the change of ground distance that is mapped on the sensor by the edges of the lens compared to the distance that is mapped at the center of the lens. As the distance between the lens and the ground is large, small distortions have a large effect on the performance of the camera. This large distance magnifies the effect.

As no lens is free form aberrations, it is necessary to choose the correct field of view based on the specifications of distortion that is specified by the camera manufacturer. Based on the image that is produced by a lens, the distortions are classified into following types:

- **Barrel distortion**: In this distortion, the magnification goes on decreasing away as we move away from the optical axis. The image resembles a barrel. This distortion is used and magnified in fish eye lenses. This is also used to map an infinitely large area onto a finite area.

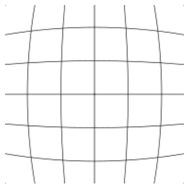


Figure 3.10: Example of barrel distortion [33]

- **Pincushion distortion**: In this distortion, the magnification decreases as we move away from the optical axis of the lens. This gives rise to the effect where the images look shrinking towards the center which gives it the name pincushion.

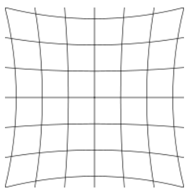


Figure 3.11: Example of pincushion distortion [33]

- **Mustache distortion**: This distortion is a combination of both the types of distortion at the same time. The magnification is such that when horizontal lines are captured through this system, they look like handlebar mustache, hence the name.

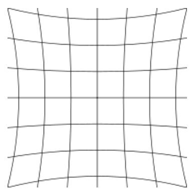


Figure 3.12: Example of mustache distortion [33]

3.1.9. Sensor size

Sensor is analogous to the retina of the camera. For a perfectly focused image, the light coming from the lens is focused on the sensor of the camera. The sensor of the camera is one of the important factor which determines the quality of the image.

The size of the sensor also is an important factor in a camera. It determines the amount light that is being captured by the camera. The large sensor allows more light and more image to be captured and vices versa for the small sensor. When two cameras are compared with identical specification but one having a larger sensor, then every object is projected on more sq.mm on the camera with larger sensor. As more photons are captured on a larger sensor, this gives a cleaner image.

Along with the advantages of the large sensor, there are some disadvantages too. The depth of field associated with a large sensor and a constant f number is shallow. The depth of field of the large sensor camera can be increased by reducing the the aperture of the camera but it then reduces the light falling on the sensor which then removes the advantages over the smaller sensor cameras. Hence it is necessary to choose cameras based on the application. For example nature photographer requires the whole scene to be in focus and hence requires a large depth of field whereas a portrait photographer requires a shallow depth of field for popping the subject in the frame.

In terms of a space camera, the whole scene in the frame needs to be in focus, but also the light entering the camera should be more. hence, an optimal size of sensor should be selected for creating a balance between the two.

3.1.10. Pixel Pitch

The sensor of the camera is made up of a combination of multiple pixels. Pixels are the building blocks of the sensor. The light falling on the sensor creates a charge in the pixel which is then transferred to the analog to digital converter and then to the readout.

Pixel pitch refers to the distance between two consecutive pixels. The resolution of the camera is determined by the number of pixels that are available on the sensor. Resolution of a camera is written in the format of megapixels. It is the multiplication of the number of pixels in the horizontal direction and vertical direction of the sensor.

The pixels on the camera can be small or large. Large pixels allow more light to be captured at any exposure setting which reduces the noise in the captured image (dark current noise). On the other hand, for the same area, if the same sensor is made of smaller pixels, the resolution is higher but the noise increases accordingly. Hence, it is required to maintain a balance between the size of pixels on the sensor. When compared at the same size of the image, between the lager pixels and smaller pixels, the noise effect is almost negligible. For most applications, the image is downsized, so there is mostly resolution advantage and very little downside of having more pixels.

3.1.11. Noise

Noise in a general sense means the unwanted signal which is present in the output. Noise in an image is a property of the camera. Noise is the random variation in the brightness or color information in images. Noise is an undesirable property of a camera. There are two major reasons for the noise in an image: the digital noise caused because of the image sensor and shot noise which is an unavoidable noise as that is caused due to the stray light bouncing of the elements of the lens.

Shot noise or photon noise is randomness due to photons in the scene that is being photographed which is discreet and random. This is due to the fact that the source of light is not uniform all the time. The number of photons that are released from the source keep on changing.

Digital noise or electronic noise is the randomness that is caused due to the camera sensor and the internal electronics which result in an imperfect image. One way to reduce the noise in an image is to increase the exposure time which increases the signal to noise ratio. But the disadvantage of increasing exposure timing is that the frames per second reduces.

3.2. Selection of criteria

From the parameters discussed above, parameters such as aperture, f number, wavelength and sensor size cannot be chosen as a judging criteria as it these parameters will stay the same even after the environmental testing. The parameter focal length cannot be selected because there are not many methods available to test the focal length accurately without taking the camera apart. Noise cannot be considered as a parameter to be considered because of the inconsistency. The noise in an image is a function of temperature but cannot be used as a testing criteria because the system will come back to room temperature when the testing is done. It was chosen to go forward with MTF as a judging criteria because of its appropriate use-case because it can reflect changes in the MTF of the image that can be caused due to environmental testing.

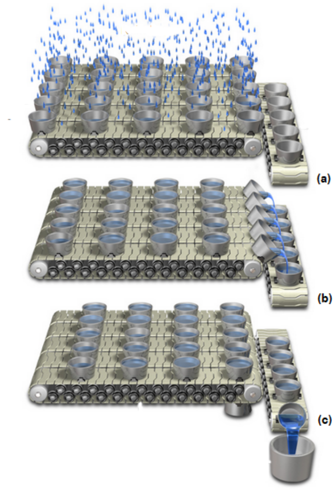
3.3. Sensor technologies

As mentioned above, the camera being discussed has a sensor architecture of CCD in CMOS, which is in-fact a combination of CCD and CMOS architecture. This section will give an explanation of the CCD, CMOS and CCD in CMOS architecture in brief.

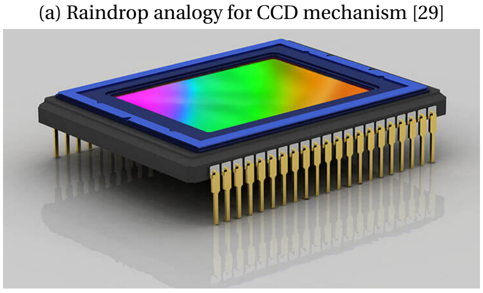
3.3.1. CCD technology

These sensors are also called as line scan sensors. This is because of the functioning of the CCD sensor. These The charges from the CCD pixels are transferred from one pixel to the other and the transferred to the analog to digital converter. As expected from the explanation, this process of transferring charge from pixel to pixel and then to the converter takes a longer time. That is one of the disadvantage of this sensor.

Due to the way of working of a CCD sensor, the image is captured line by line and not a full frame at once. This operation is useful in capturing an image with TDI as the disadvantage of the CCD which is the charge being transferred from pixel to pixel is used for increasing the exposure and increasing the SNR.



(a) Raindrop analogy for CCD mechanism [29]



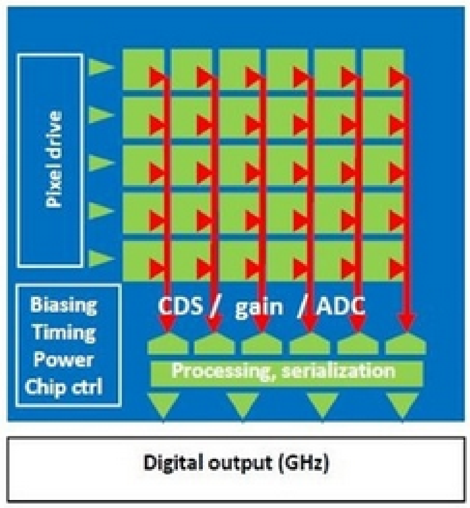
(b) Sensor [22]

Figure 3.13: CCD

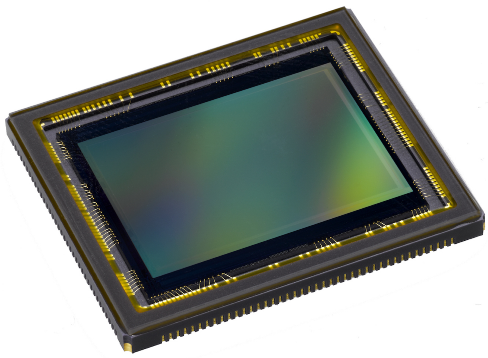
3.3.2. CMOS technology

CMOS stands for Complementary metal oxide semiconductor. These sensors were developed to overcome the malignancy of the CCD sensor. The design of the CMOS sensor is different from that of the CCD as in the COMS sensor a photo-diode and transistor are attached to each pixel that allows for signal magnification at pixel level. These pixels can be accessed with the help of switches that make the charge transfer rate higher than the CCD sensor. Another advantage of having magnified signals is that it reduces the noise applied to the signal when converted from input light. Thanks to this technology of transferring charges directly to the ADC, the image is shot as a whole frame at the same time and not line by line as in the CCD sensor.

Because of these benefits of CMOS over CCD, they are widely used in the industry today. CMOS sensor production is also advantageous as existing production equipment may be intended for the production of these sensors. These sensors have digital circuits that use less energy and therefore reduce semar and blooming problems.



(a) Mechanism [1]



(b) Sensor [30]

Figure 3.14: CMOS

3.3.3. CCD in CMOS Sensor

CCD in CMOS architecture is a quite newly developed one. The first CCD in CMOS sensor was constructed in 2016 in Belgium. This sensor is mostly used in camera which are used for earth observation because this sensor is advantageous while capturing a moving object with TDI.

CCD in CMOS is the combination of best of both worlds of the both sensors. The advantages being the faster readout from the CMOS sensor and line readout from the CCD sensor. The architecture is this type of the sensor is such that the readout is taken out after every row of pixels and not after every column. This means that the readout is faster compared to the regular CCD sensor, where the charge is transferred through the row and the column and then through the ADC. This architecture also enables usage of line scan which can be used for TDI.

TDI stands for time delay integration. In this technology, multiple shots of an object moving along the track of pixels is captured by collecting charges from multiple exposures, without addition of noise. As the charge is required to pass through every pixel along the movement direction, CCD sensors are the appropriate option of choice. The signal to noise ratio is increased with the increased number of CCD stages. By implementing such CCD TDI pixels together with a CMOS readout, the best of both worlds can be realized on a single chip.

As this technology needs a moving target so that multiple exposures can be obtained, this becomes suitable for the application of earth observation cameras, where the satellite is moving along the surface of the earth. In a way, TDI converts the disadvantage of CCD sensor into an advantage and increases the signal to noise ratio (SNR). This is because the object is to be moved with respect to the sensor which is taken care of when the system is installed on a satellite [11].

The sensor that pertained to this thesis is a CCD in CMOS sensor with TDI. This sensor has 7 filters in front of the 7 bands on the sensor. By using the TDI technology, the object is passed through all the filters one by one and the output is obtained for each band. So we have 7 images, ie. one from each band and filter. The final image is the addition of all the 7 images one over the other.

3.4. Time delay integration

Time delay integration is a technique which is generally used in earth observation. This method is similar to registering multiple manifestations of the same moving object and adding them [13]. This method helps to improve the signal and noise level of the image as multiple shots of the same object are taken and added together. [23].

The addition of multiple exposures takes place in the form of charges which are transferred from one pixel line to the other. One thing to take in account during using TDI is the charge transfer speed should be equal to the movement speed of the object being captured. Having a mismatch in the speeds can lead to unusable images [4].

The camera which is used in the thesis is a 7 band multispectral camera. Each of these 7 bands have a sensor size of 4096 X 256 pixels. This means that the camera has a maximum of 256 TDI stages. The image that is captured is passed through all 256 stages before it is added together. This is done for all the 7 bands. The final image is the addition of the images for the 7 bands [11].

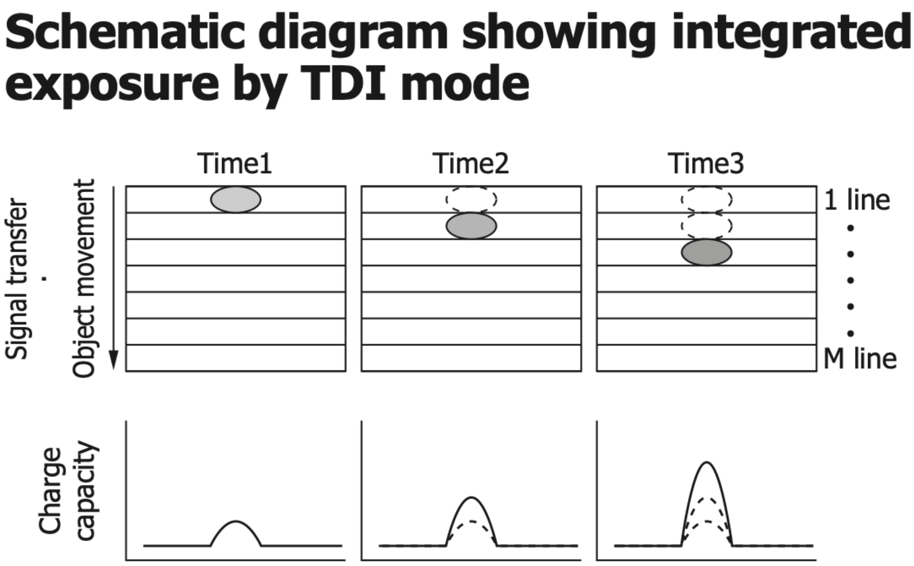


Figure 3.15: Working mechanism of TDI [12]

4

Requirements and research question

4.1. Requirements

The start of an experiment begins with a set of requirements. Requirements are the pointers which help as guidelines for the project. Therefore, it is important to have requirements defined before the start of the project. The requirements also helps to decide between concepts and decide which are viable and which are not.

The requirements for this thesis were set up by ISIS. The table 4.1 gives an overview of these requirements.

Property	**Requirement**	**Requirement driver**
Resolution	For 675nm, r<10.046μm (Rayleigh criteria)	Multicsacpe 100
On axis MTF	30% ± 5% at Nyquist (93 cyc/mm)	Multiscape 100
Wavelength spectrum	450nm to 900nm	Multiscape 100
Field of view	2.18°	Multiscape 100
Aperture	>95mm	Multiscape 100
Sensitivity	No value given	ISISpace
Time required	Assembly : 1 week Experiment : 1 hour	ISISpace ISISpace
Environment	Temperature: 20°C ± 10°C Pressure: 1 bar ± 0.2 bar Size: 5m x 5m x 5m	Multiscape 100 Multiscape 100 ISISpace
Operator	Basic knowledge of optics	Testing setup
Adaptability (optional)	Different camera can be set up with less or no change in setup	ISISpace
Repeatability	No value given	ISISpace

Table 4.1: Table of requirements

In the table 4.1 the r in the requirement column of resolution refers to the minimum distance between resolvable points.

Note: Changes that will occur in the camera after the testing of the satellite will be a result of change in the optics of the camera because the company had cameras from the same supplier and they have verified there is not change in the sensor performance because of the testing.

4.1.1. Remark/Justification

This section comprises some more remarks on the requirements for the experiment.

- **Resolution**: The resolution of the camera lens calculated based on the Rayleigh criteria which is given by [10]:

$$r = \frac{1.22 \cdot \lambda \cdot f}{D} = 2.44 \cdot \lambda \cdot f\# \tag{4.1}$$

  Where: r is the minimum distance between resolvable points, in the same units as λ is specified, λ is the wavelength of light, emission wavelength, in the case of fluorescence, D is the numerical aperture, f is the focal length of the lens. By substituting the values we get the minimum distance between resolving point to be $1.0046 \cdot 10^{-5}$m. This is calculated by considering an average wavelength of 675 nm. Hence, it is necessary for the setup to have a better resolving power than $1.0046 \cdot 10^{-5}$m for 675nm wavelength. If the resolution of the setup is not better than the camera, the results will be dominated by the aberrations of the setup than the camera.

- **On axis MTF**: The requirement of the MTF of the setup was set to be 30% at the nyquist frequency of the camera. The requirement of MTF was set to be 30% because the MTF of the camera is 18% at nyquist frequency which is 93cyc/mm. The MTF of the setup should be better than the camera for the same reason as the resolution. If the MTF of the setup is not better than the camera, the results will be dominated by the characteristics of the setup and to the camera.

- **Wavelength spectrum**: The wavelength spectrum of the camera is 450nm to 900nm. Hence, the requirement of the setup is to be suitable for this wavelength spectrum. his is the minimum requirement for the setup.

- **Field of view**: The field of view of the whole camera needs to be tested. Hence the setup should be withing the field of view. In ideal situation, it should be exact to that of the camera, but if the FOV is less than that of the camera, some adjustments can be made. These adjustments are discussed in the chapter 8.

- **Aperture**: The camera has a diameter of 95 mm diameter, hence it is necessary for the setup to suitable for a large diameter camera.

- **Sensitivity**: This is the parameter that explains how small changes can be detected by the setup. This value was not set before the start of the experiment as the effect of the noise on the decided parameter was not known. In later chapter this is explained in detail.

- **Time required**: The time required for assembly is important due to the timeline that has to be decided before the launch. The experimentation time is the time that is need for one set of experiment, ie the time from the camera is mounted in the setup and then taken out. As the camera is tested multiple number of time before the launch (after every environmental test), the total experimental time will include the time needed for the environmental tests too. The time expressed in the table 4.1 is the time required for 1 set of experiments to be completed.

- **Environment**: This requirement states the environment that the setup is subjected to. As this is a thesis based on the testing of a camera mounted on satellite, the environment is an important requirement. The size was also a requirement as the size available for the setup was limited.

- **Operator**: The assembly of the setup involves some optical terms such as focal length and F#. Hence, basic knowledge of optics is necessary the setup.

- **Adaptability**: The company ISISpace wants to use the setup for multiple missions, the setup had to be adaptable with multiple cameras.

- **Repeatability**: Repeatability is the ability of the setup to give the same value for the same experimental conditions. Repeatibility should be greater than the sensitivity of the setup because the results will be dominated by the low repeatibility of the setup.

A TDI achitecture in a sensor has a requirement of a relative motion between the sensor and the object being captured. But this is not a requirement for the this experiment because, this camera has a CCD in CMOS architecture, which gives the user to have the ability to capture the whole image at once. This mode of the camera will be used for experimentation as TDI mode makes the setup very complex.

4.2. Research question

How to determine if there is significant change/ degradation in the camera performance without taking the camera apart.

The above mentioned research question can be further divided into two subquestions:

1. What performance criteria should be considered for determining the health of a camera.

2. What are the ways in which the selected criteria can be measured.

The first research question answers the more general question about cameras. This does not answer to specific question as it does not consider a specific camera that is used for space purpose. The second research question focuses more on the approach that is to be implemented for characterising/measurement.
The following task were planned to answer these questions:

- Evaluate various factors that are considered as a measure for the performance of camera.

5
Experiment methodology

This experiment has a parameter which is compared to determine if the performance of a system has improved or degraded after a series of events. Selection of this parameter is an important factor for getting accurate results and draw reasonable conclusions. Improper selection of a parameter can lead to results which are not very accurate and correct conclusions cannot be drawn from them.

Performance criteria in context of this thesis refers to the parameter which will be used to determined whether there is a change in the performance of the camera. The results from this experiment will be used to determine the suitability of the camera to be launched with the satellite.

Different parameters from chapter 3 were considered for this purpose. From the comparison of the parameters explained before, MTF was chosen because of its suitability.

The reason for choosing the MTF lies in the aberrations that are expected after the environmental testing of the satellite. The camera lens consists multiple lenses which are placed at particular distance which help to reduce the aberrations.

During the environmental testing of the satellite, the expected changes in the optics of the camera are due the changes that can occur because of the moving of the lens elements. The movement of these lens elements can give rise to effects such as coma, chromatic aberrations, distortions. These aberrations except distortion have an effect on the MTF of the image that is being captured. This is the important property of the MTF which makes it a suitable choice when the affect of the environmental testing is unknown. The various parameters of a camera that are discussed in the chapter 3 have a limited detectability which does not make it a good option for selecting as the comparing parameter.

This chapter explains the methodology that will followed during the experimentation. Images will be compared before and after the camera undergoes environmental testing. The comparison is done between two images, one of which is a reference image and the other image is a test image. The reference image is considered as the ideal image which is captured before the environmental testing of the camera. The test image is an image which is captured after the environmental testing and then compared.

These images are compared based on the following techniques: cross correlation and

MTF.

5.1. Crosscorrelation

Crosscorrelation refers to a relationship or connection between two or more objects. It is an indicator of the statistical level of similarity between a given time series and the remaining version of two different sequences. It's a measure to association of objects.

Autocorrelation and cross correction are very similar to the variance of the reference sequence. The difference between crosscorrelation and autocorrelation is that in crosscorrelation, interaction occurs when two different sequences are combined and autocorrelation is the correlation between the same sequence; that is, the signal corresponds to itself.

In signal processing, cross correction is where you take two signals and produce a third signal. This method, which is a standard method of direct "normal" direct integration, is a way to differentiate between different time series and allows you to see how the two signals are related and where the best match is taking place. It can be used to create sites that can display hidden sequences.

The basic process involves:

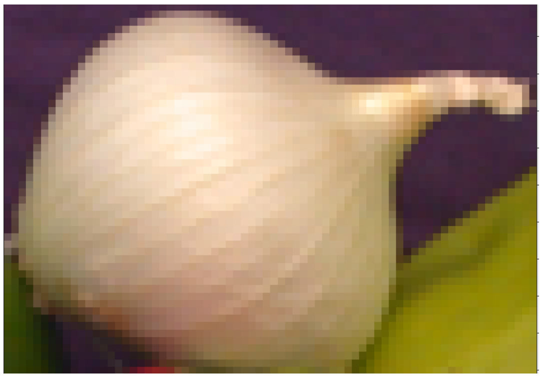
- Calculate a correlation coefficient. The coefficient is a measure of how well one series predicts the other.
- Shift the series, creating a lag. Repeat the calculations for the correlation coefficient.
- Repeat steps 1 and 2. How many times you repeat the process will depend on your data, but as the lag increases the potential matches will decrease.
- Identify the lag with the highest correlation coefficient. The lag with the highest correlation coefficient is where the two series match the best.

When using these steps for finding the best match in the images, the two images are compared with their correlation coefficients. The term lag in the procedure refers to the offset in the images. This property of cross correlation is used in this thesis. The highest correlation coefficient gives the best match between the two signals.

The ideal image and the test image are compared with each other using cross correlation. A portion of the image from the test image is cropped which is then used to find the best spot in the reference image. The highest correlation coefficient give that spot. This is used to overlay the cropped test image on the reference image where the correlation coefficient is maximum.

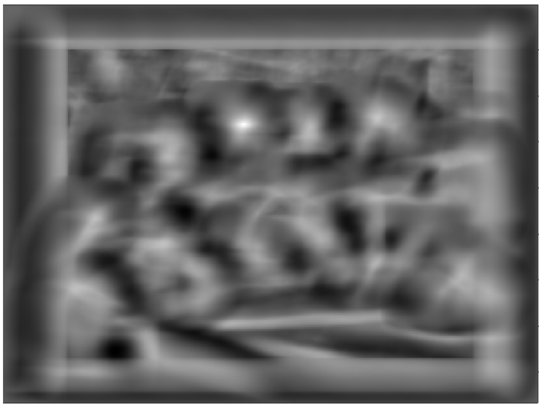
This is shown with the help of an example. In the figure 5.1a the objective is to find the white onion 5.1bin the picture. The image that is to be found is selected from the image. Correlation coefficients are calculated based on the local sums when the image is offsetted over the reference image. The cropped image is the best match in the template image where the correlation coefficient is maximum. This can be seen in the graph 5.2b.

(a) Template image

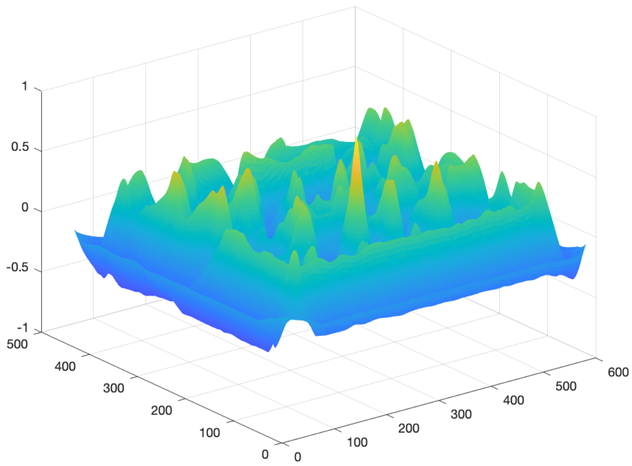


(b) Image to be found

Figure 5.1: Correlation example



(a) Result of cross correlation



(b) 3D graph of correlation coefficients over the entire image

Figure 5.2: Correlation results

Figure 5.3: Location of the cropped image in the template image

The next step is to compare the two images. There are two ways of comparing the two images by indexing.

- Structural Similarity Index (SSIM)
- Mean square error (MSE)

1. Structural similarity index (SSIM) SSIM is used to the similarity between two images. The SSIM is used for prediction of the image quality based on initial uncompressed or distortion free image as a reference. Mathematically it is expressed as [19]:

$$\mathrm{SSIM}(x,y) = \frac{\left(2\mu_x\mu_y + c_1\right)\left(2\sigma_{xy} + c_2\right)}{\left(\mu_x^2 + \mu_y^2 + c_1\right)\left(\sigma_x^2 + \sigma_y^2 + c_2\right)} \tag{5.1}$$

   μ_x the average of x
   μ_y the average of y
   σ_x^2 the variance of x
   σ_y^2 the variance of y
   σ_{xy} the covariance of x and y
   $c_1 = (k_1 L)^2, c_2 = (k_2 L)^2$ two variables to stabilize the division with weak denominator;
   L the dynamic range of the pixel-values (typically this is $2^{\#\text{bits per pizel}} - 1$);
   $k_1 = 0.01$ and $k_2 = 0.03$ by default.

2. Mean square error (MSE) PSNR is most easily defined as the mean square error. It is most commonly used for determining the quality of an image after compression. The signal in this cane is the original image and the noise in the image is the error introduced in the image because of compression.

$$MSE = \frac{1}{mn}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j) - K(i,j)]^2 \tag{5.2}$$

   The PSNR (in dB) is defined as [19]:

$$
\begin{aligned}
PSNR &= 10 \cdot \log_{10}\left(\frac{MAX_I^2}{MSE}\right) \\
&= 20 \cdot \log_{10}\left(\frac{MAX_I}{\sqrt{MSE}}\right) \\
&= 20 \cdot \log_{10}(MAX_I) - 10 \cdot \log_{10}(MSE)
\end{aligned}
\tag{5.3}
$$

5.1.1. Comparison of MSE and SSIM

In an experiment conducted by Peter Ndajah, Hisakazu Kikuchi, Hidenori Watanabe and Shogo Muramatsu in the paper of SSIM quality metric [19] with MSE and SSIM where an image was compared where the original image was compared with the same image with same structural distortions. The added distortions were contrast stretch, negative image, gaussian white noise and blur. When compared using MSE the value was the same but when the same images were compared with the help of SSIM, the value was different. This proved that the MSE is insensitive for the the structural distortions whereas SSIM is sensitive for these changes.

In the experiment with the camera, a blur is expected due to some changes in the camera optics, SSIM seemed to be an appropriate way to go forward. The requirements of the thesis state that change in performance should be detected and not by using a specific means. So the two images can be matched by correlation and compared by indexing methods. This gives a direct similarity percentage between the two images.

Therefore, correlation is chosen as the method to go forward for the post processing of the images to detect changes in the camera performance.

5.2. MTF

Detailed description of MTF was given in the chapter 3. As explained, MTF provides information about the image quality and in-turn the optics of the camera. Because of this property of MTF, it is used for the testing of the camera. Along with correlation, the images captured from the setup will be compared using MTF.

6 Preliminary Data analysis Experiment

Due to the change in timeline and the delay in procurement of the components that was faced as a result of the global pandemic, a data analysis experiment was conducted to verify the image processing ability of MTF and cross correlation.

The data analysis experiment setup was planned to be a preliminary analysis of the setup that will be developed to be the actual setup. The main aim of this prototype setup was to get an estimation on the variation in the results that is being caused due to changes in the camera optics.

The pandemic had a drastic effect on the timeline, methodology and materials required for the project. The data analysis setup was build in a student house because of the pandemic and by making the best use of the materials available at disposal.

Aberrations were introduced in the camera system optics to verify its influence on the deciding parameters.

6.1. Components required

Basic components were used in the construction of the prototype. The components in this setup were provided by the company. The components that were used to build the setup are as follows:

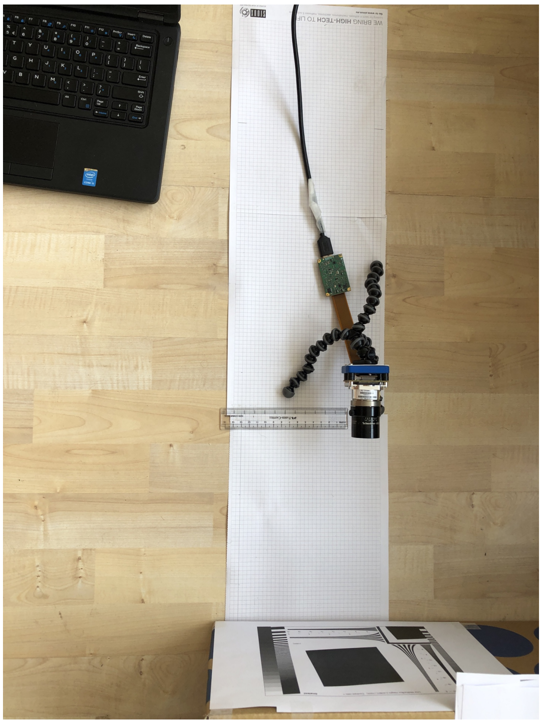
6.1.1. Camera

The camera used in the setup was Pixelink PDL-D726. It has a CMOS sensor architecture, with a pixel pitch of 3.5 μm. It is a monolith camera. It has a resolution of 6.6 MP (2208 X 3000). The camera is mounted with a lens from Schneider. The lens is a variable focus camera having a focal length of the 12mm.

6.1.2. Tripod

It is important to keep the camera stable during the process of experimentation. The camera in the setup was mounted on a tripod to provide the support and maintaining the posi-

(a) Back view of the setup



(b) top view of the setup

Figure 6.1: Preliminary data analysis setup

tion of the frame. During the experimentation with changes in exposure, it is important to keep the camera stable.

6.1.3. Test target

The test target used for testing was a slant edge target with a bar target and some USAF elements. This test target was printed on a paper and used for testing.

6.2. Procedure for prototype testing

The camera was mounted on a tripod for keeping the camera stable. The test target was pasted on a non-movable screen. A graduated paper was pasted in front of the test target for measuring the distance. The working distance of the lens was marked on the paper which was 614mm. Various images were captured by the camera by making some change in the camera optics.

The main problem that was faced while experimenting in student room was controlling the stray light. Some provisions were made to reduce the effect of stray light on the experimentation. Some of them were:

- The experiments were conducted at the same time of the day every time.
- the target was illuminated with the help of a mobile light source so the effect of stray light was further reduced. The mobile light source was kept behind the camera to avoid the illuminating light entering the camera.

Figure 6.2: Camera

6.3. Modifications to camera

The aim of building the experimental setup was to get a proof of concept for the procedure that will be implemented to the actual setup. It was also necessary to check that the experimental setup was sensitive to the changes that will occur in the actual camera (Simera camera) post environmental testing. For this purpose, some aberrations were added into the testing of the experimental setup which could be involved in the camera mechanism. These changes were necessary for examining the change that is observed in the post processing and provide a proof of concept for the actual setup that this technique can be used to detect the changes. The modifications that were done to the camera construction are explained in detail in the further sections.

The software used for capturing the image from the pixelink camera was provided by the OEM. This software had some setting that could be changed such as exposure and gain of the camera. This was further used for testing some additional parameters of the camera and the testing methodology.

6.3.1. Addition of defocus

This was the first aberration that was added to the experimental setup camera. During the environmental testing, as explained in the previous chapters, there are multiple vibrations that the satellite along with the camera expediences These vibrations and shock treatment that the system undergoes, can lead to a change in the focus of the camera.

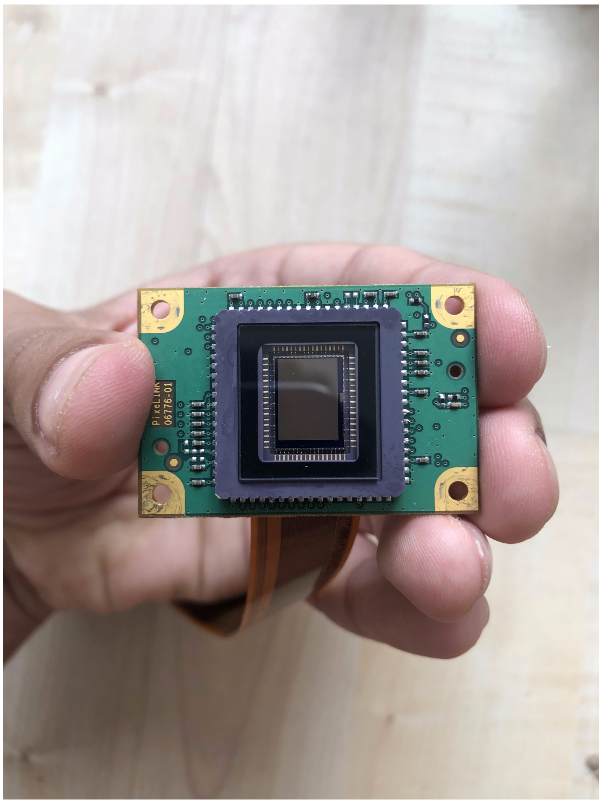


Figure 6.3: Camera sensor

Figure 6.4: Tripod

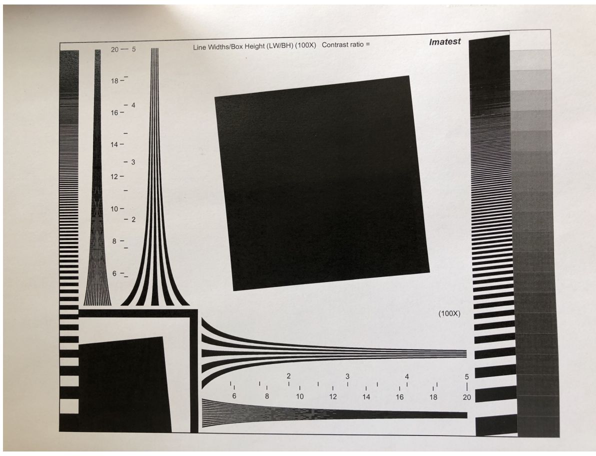


Figure 6.5: Test target

We know that the lens of the camera is not a single lens but a stack of lenses which are placed next to each other very precisely. The reason for using multiple lenses instead of one single lens is to correct for various geometrical and chromatic aberrations.

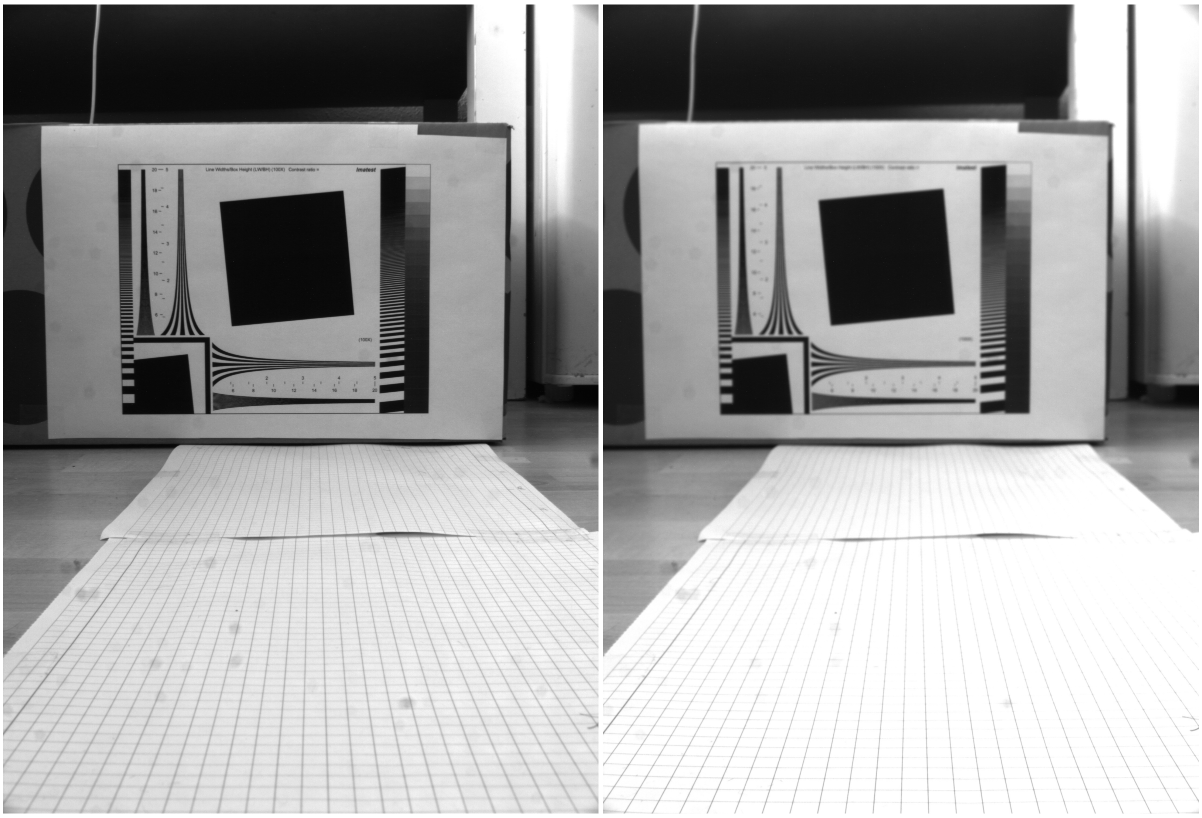
The whole lens system is involved in deciding the focal length of the camera. When the camera undergoes environmental testing, there is a possibility that the whole lens stack or a single lens is dislocated from its original place and moves. If this stack of lens or a single lens moves in an axial direction of the optical axis, there will be a change in the focal length of the camera. It can also be said that the change in the focal length of the camera will be small if a single lens is move compared to when the whole lens stack moves.

For this reason, the defocus was added in the experimentation. The addition of defocus was not a complex job as the camera used for the experimental setup had a variable focus lens.

The methodology that was used for experimentation of addition of defocus was very straightforward. Following are the steps that were followed during the experimentation.

- Camera aperture was set on f11.0
- Camera was set at the minimum working distance for a reference which was 614 mm.
- The focal length adjuster ring of the camera was set to zero turns.
- Images were captured by rotating the ring by a quarter rotation after every image keeping other parameters constant.
- Correlation and MTF analysis was used for post processing of the image.

Following are the images that were captured during the defocus experimentation. It is observed that when the focus ring is turned gradually, the images gets sharper at first and than they start getting blurrier.



(a) Focused image (b) Unfocused image

Figure 6.6: Comparison of focused and unfocused image

6.3.2. Addition of tilt

This was another aberration that was added during the experimental setup. As explained earlier the lens in the camera consists of multiple lenses, the aberrations can be involved if there is any change in the lens stack.

If the lenses in the lens stack or the whole lens stack moves in the direction of optical axis, there is a change in the focal length of the camera. But it is also possible that a single lens or the whole stack of lenses can rotate about the vertical optical axis or about any point on the optical axis.

This was demonstrated in the experimental setup by adding shims between the the sensor and the lens. Here, as the shims were added between the lens and the sensor, the whole lens stack was tilted with respect to the sensor. The methodology that was used for addition of tilt in the system is as follows:

- Camera aperture was set to f11.0
- Camera was set at the minimum working distance for a reference which was 614 mm.
- The focal length of the camera was set such the image is the sharpest.
- An image was captured as a reference image.

(a) Shims added on one side of the camera

(b) Shims added on top side of the camera

Figure 6.7: Setup of shims added in the camera

- Shims were added between the lens and the sensor at multiple positions and images were captured keeping all other parameters constant.
- Correlation and MTF analysis was used for post processing of the image.

Shims on the side

Shims were added on one side of the camera. It can be seen in the figure 6.7a.

Shims on top

Ships were added on top side of the camera. It can be seen in figure 6.7b.

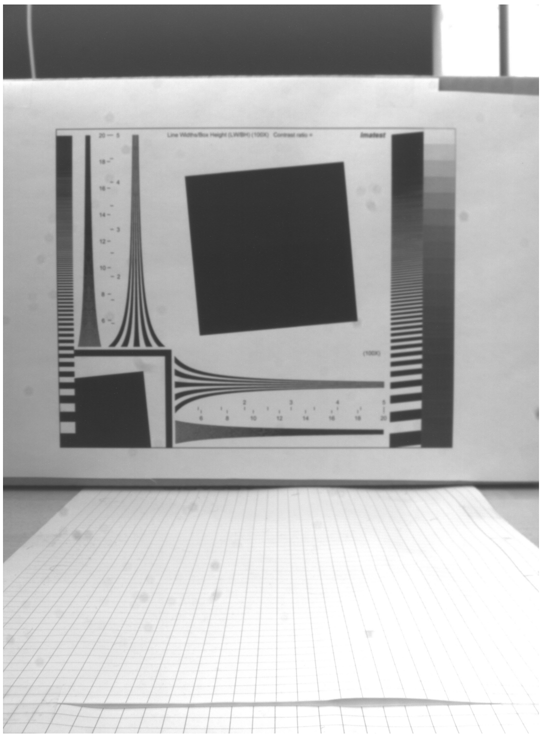
Shims at diagonal

Shims were added at the diagonal of the camera.

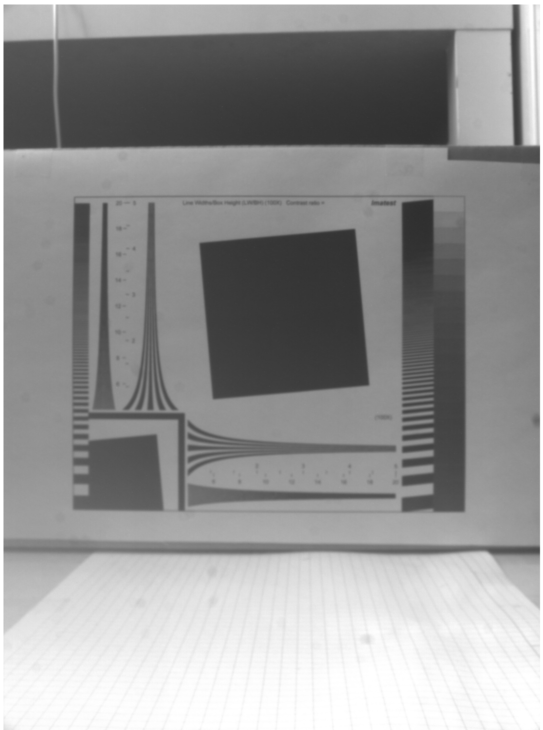
6.3.3. Exposure changes

One of the important condition for an experiment to be good is the robustness of the experimental setup to changes. AN optical experiment is generally sensitive to lighting conditions. Hence it is important to control the lighting conditions during the experimentation. This experimental setup was not an ideal setup because of the pandemic and the resources were not ideal. As this setup was build at home, it was not an ideal setup.

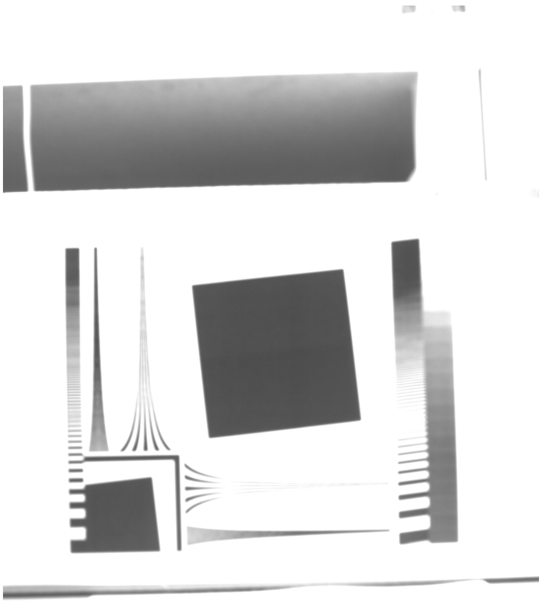
To check the robustness of the setup, the exposure of the camera was changed, keeping all the other parameters constant. By changing exposure, we are changing the amount of



(a) Shims on side

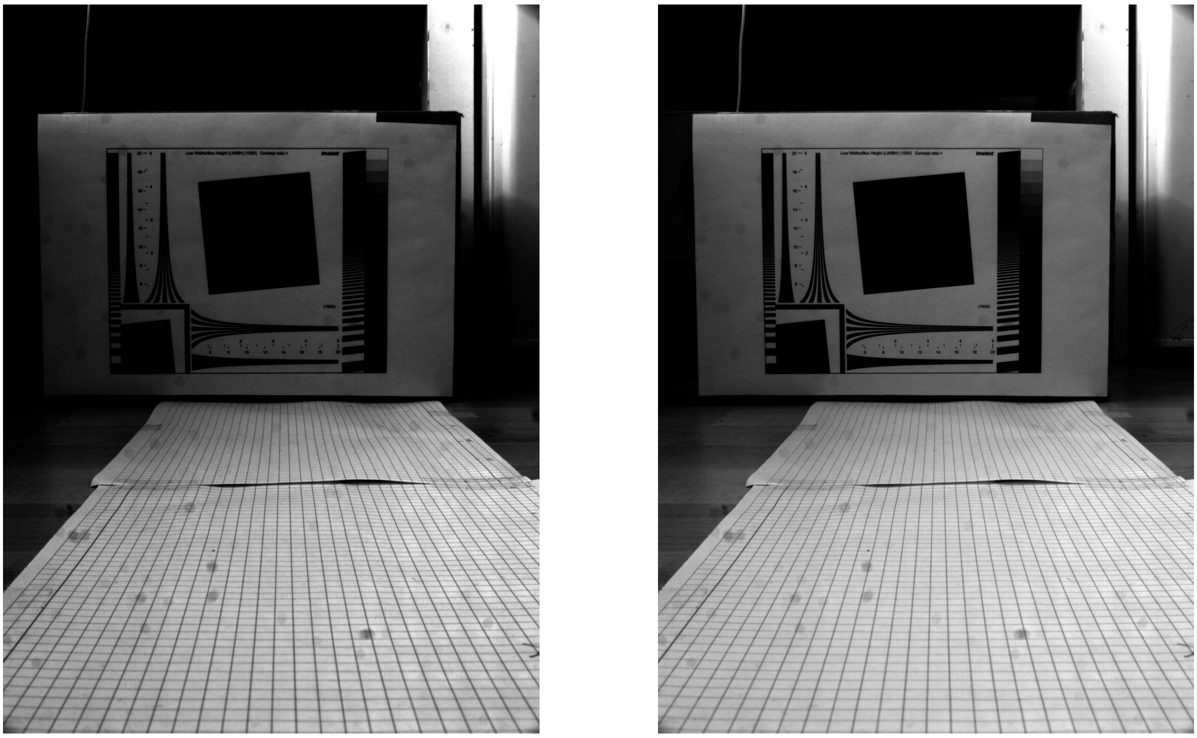


(b) Shims on top



(c) Shims at diagonal

Figure 6.8: Images captured by adding shims at different positions



(a) (b)

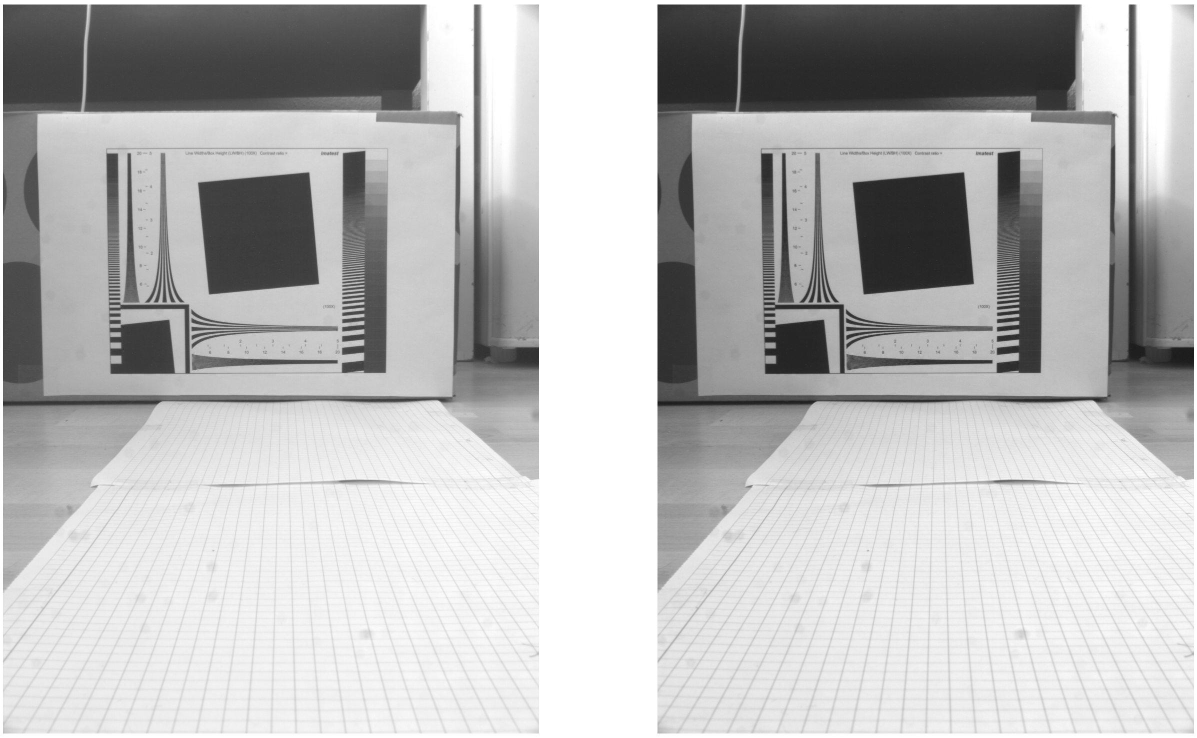
Figure 6.9: (a) Image with 0.0930 sec exposure, (b) Image with 0.8234 sec exposure

light that is falling on the sensor and in a way controlling the light. The objective of this experimentation was to check if there is a drastic difference between the results that are obtained by changing the exposure.

The methodology that was used for checking the robustness was as follows:

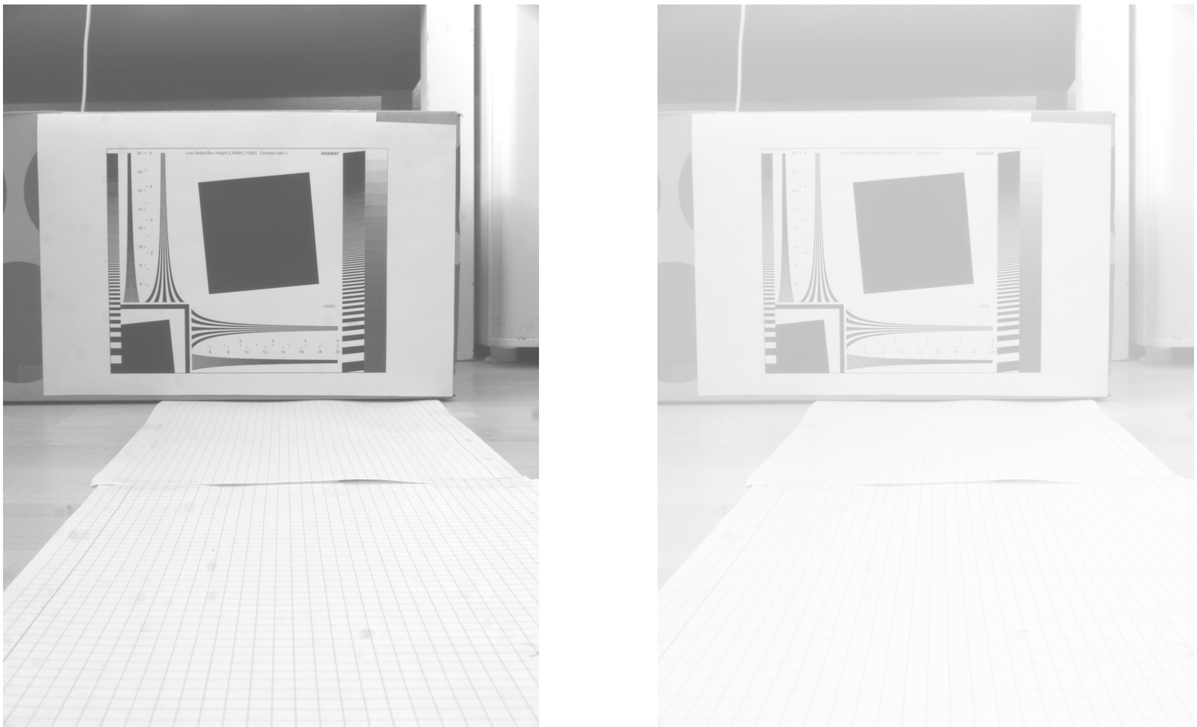
- Camera aperture was set to f11.0
- Camera was set at the minimum working distance for a reference which was 614 mm.
- The focal length of the camera was set such the image is the sharpest.
- The exposure of the camera was changed gradually from 0.0930 sec to 1.945 sec and images were captured.
- Correlation and MTF analysis was used for post processing of the image.

Multiple images were taken by changing the exposure of the camera. The purpose of adding the exposure changes into the prototype testing is to check the robustness of the testing method in different lighting conditions.



(a) (b)

Figure 6.10: (a) Image with 1.0434 sec exposure, (b) Image with 1.614 sec exposure



(a) (b)

Figure 6.11: (a) Image with 1.8324 sec exposure, (b) Image with 1.945 sec exposure

7
Results and Discussion

This chapter comprises the results obtained from the preliminary experiment. Justification is given to explain the results and in later chapter 9, conclusions are drawn from them.

Correlation and MTF analysis were used for the post processing of the images that wee capture during the experimentation phase. The correlation was done using a Matlab script and the MTF of the image was measure using the Imatest software. Following sections gives an overview of the results that were obtained during the testing of the Pixelink camera. As the correlation results give a value between 0 to 1, multiplying it with 100 gives the similarity percentage. This is the value that is referred in further sections.

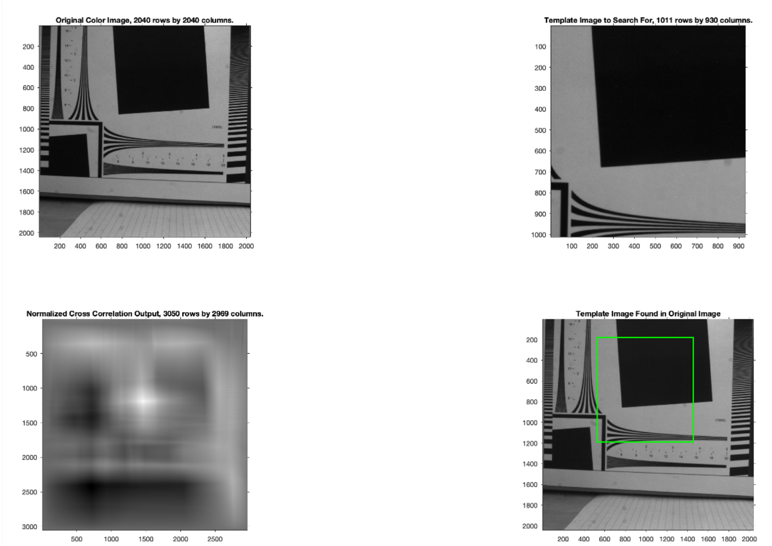
7.1. No induced aberrations

This subsections compiles the results with correlation of the images which were taken back to back without changing any parameters of the camera. This was done to check the sensitivity of the analysing methods to the noise in the image. During the testing the images were capture successively and there was very less time interval between two image.

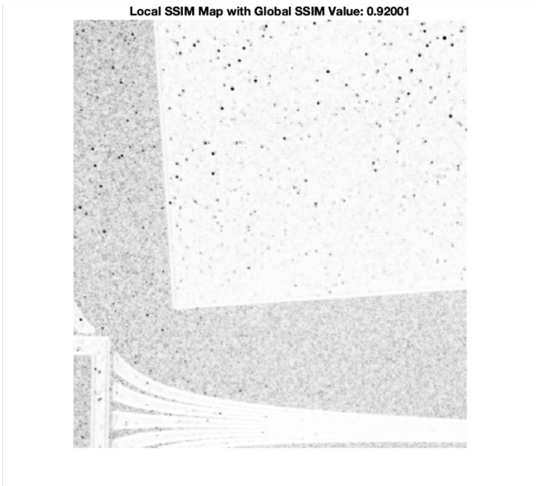
7.1.1. Correlation results

This section complies the results obtained from the Matlab script of correlation. This script consists of comparing an ideal image with the test image. To check the script is running perfectly, same image was taken as image image and test image and the matching percentage was found out to be 100. The matlab script used for this experiment can be found in chapter 10.

After the correlation test on back to back images, it was seen that the similarity percentage of the images lied withing 90 to 99. As all the other parameters are kept constant, the change in the matching percentage is attributed due to the noise in the image. As this was not an ideal setup, there was a lot stray light that was coming onto the setup, some of the loss in the similarity percentage can also be attributed to that. As this experiment was conducted in Netherlands, the weather and hence the lighting conditions can vary a lot.



(a) Finding the similar section



(b) Similarity value

Figure 7.1: Correlation result continuous images

7.1.2. MTF results

As MTF was also found out to be one for the parameter that can be used for comparing the images, they were analysed with the help of MTF.

A general trend was observed in the MTF graphs of the images where it was seen that after a certain frequency the MTF was very noisy. This is attributed to the fact that noise in the image becomes dominant which gives inaccurate results are high frequencies.

When MTF with no induced aberrations was calculated for the images that were captured back to back without any change in the parameters, there was a change in the MTF for about ±2 cyc/mm. This is attributed to the noise in the image which changes the ESF which is used for calculating the MTF.

In order to compare the results with the aberrations induced, an average of MTF calculated from back to back testing was considered which was 37.39 cyc/mm. In further sections this will the value referred to while discussing the performance.

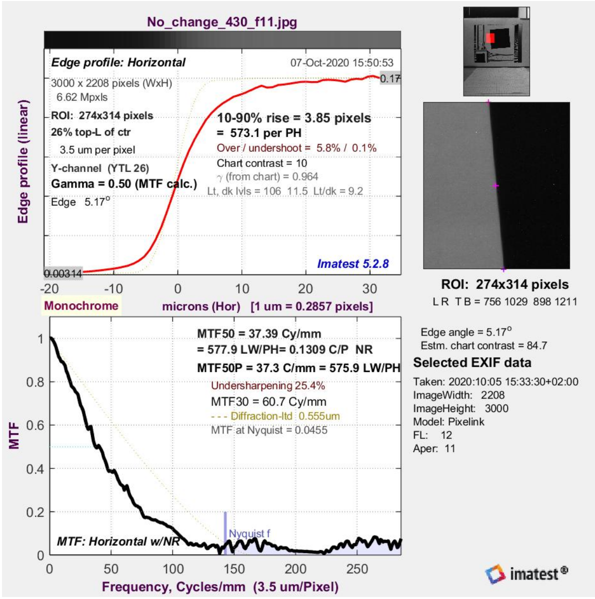


Figure 7.2: MTF with no aberrations induced

7.2. Defocus

For the experiment with defocus, as explained in chapter 6, multiple images were take by changing the focal length of the camera. This section combines the results of correlation and MTF.

7.2.1. MTF results

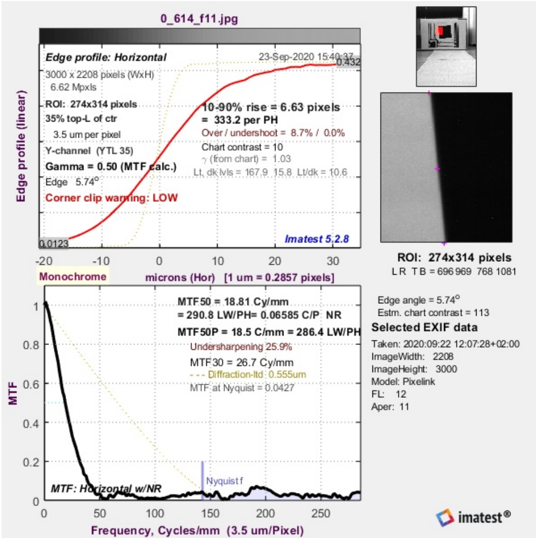
The MTF of the images of captured by changing the focal length of the lens was found to increased at first and then it reduces (figure 7.3). It can be seen in the graph in Fig 7.4. This is attributed to the fact that the focal length of the camera is near the position which gives a sharp image and hence a better MTF.

7.2.2. Correlation results

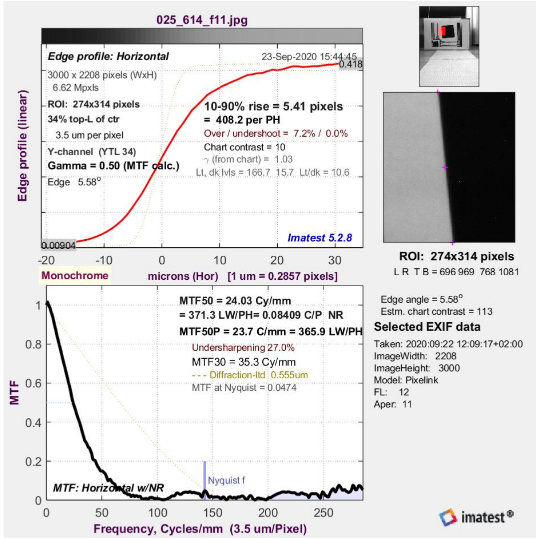
This section complies the results of correlation with the defocus that was induced in the camera.

The image that was selected as the ideal image during this testing was the image which was the sharpest. The sharpest image was selected from the MTF analysis which was done on the set of images. The image with the highest MTF was selected as the ideal image. This sharpest image was compared with all the image.

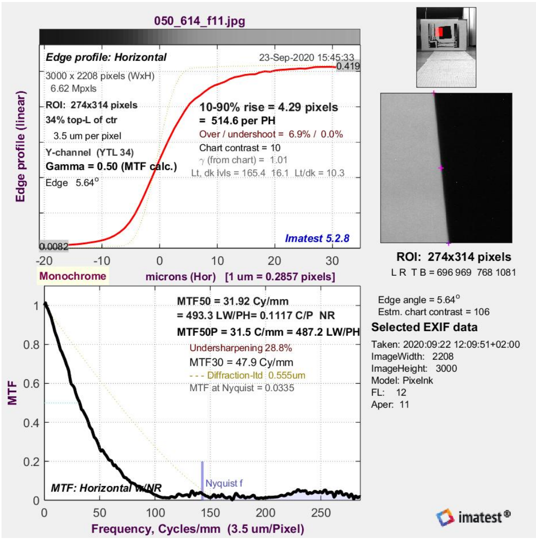
It can be seen in figure 7.6 that the matching percentage of the images first increased and then reduced. From this, it can be said that the focal point of the camera was somewhere between one turn and one and one quarter turn.



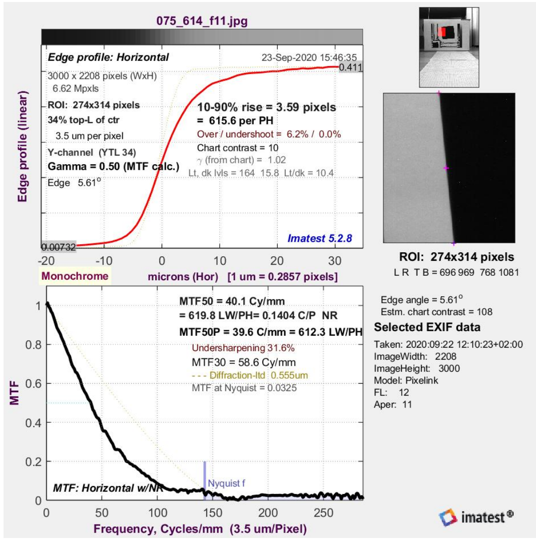
(a) MTF with 0 rotation



(b) MTF with 1/4 rotation



(c) MTF with 1/2 rotation



(d) MTF with 3/4 rotation

Figure 7.3: MTF graphs

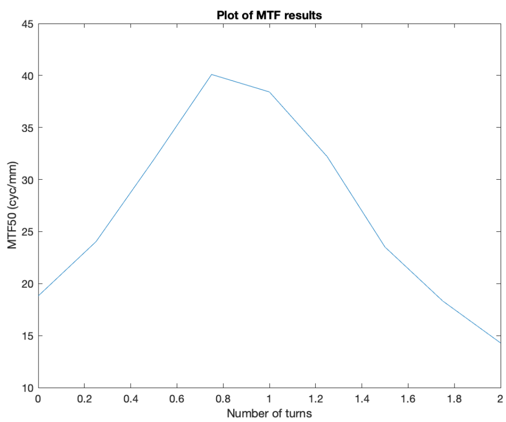
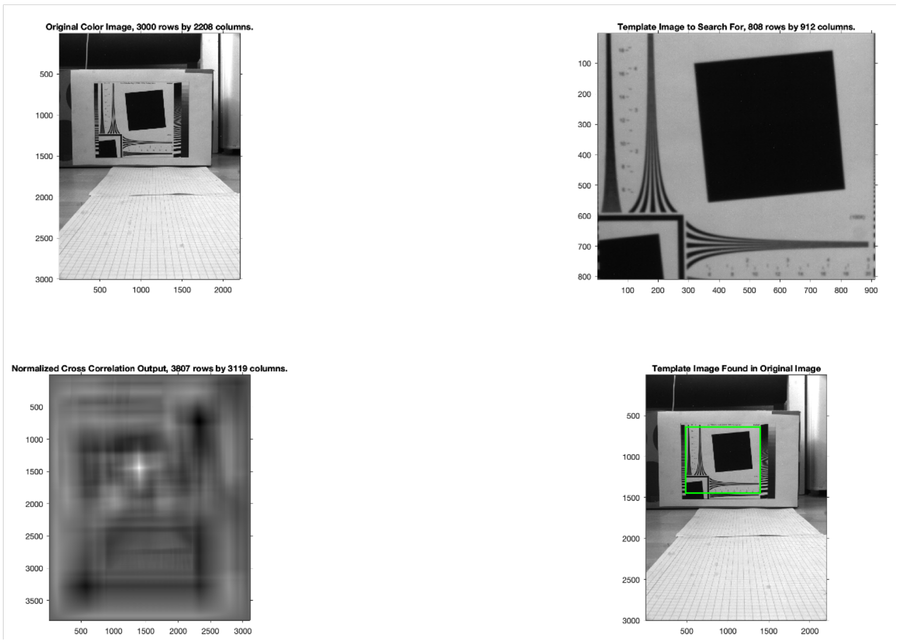


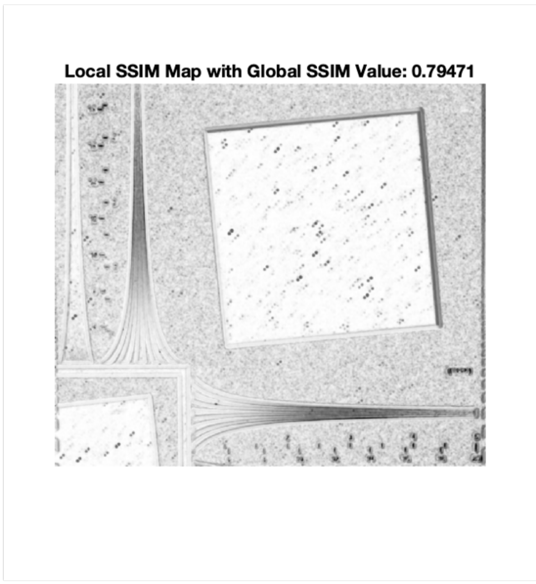
Figure 7.4: Graph of Number of turns vs MTF50

The disadvantage of this technique is that if the camera was defocused at first (focusing infront of the sensor) and that was considered as the ideal image, after environmental testing it can pass the focal point and again be at the same point behind the sensor, it will then show a high similarity percentage. This will give a false positive result. Hence it necessary to select an image which is perfectly focused which reduces the chances of this happening.

From the graph 7.6 the trend can be seen more clearly. The similarity percentage rises and then falls. Ideally the graph should be mirrored about the 0.75 turn mark, as the turning of the lens was done manually, without any marking, the graph is not symmetrical.



(a) Finding the similar section



(b) Similarity value

Figure 7.5: Correlation result with 0 turn and 0.75 turns

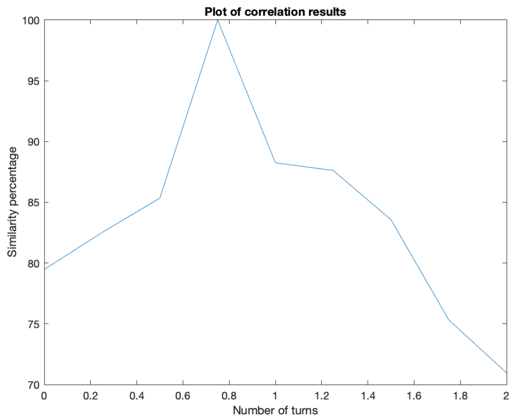


Figure 7.6: Graph of Number of turns vs Similarity percentage

7.3. Tilt changes

When the shims are added into the space between the camera lens and the sensor (top, side or diagonal), the lens of the camera is no more co-planar with the sensor. The lens is rotated around an arbitrary in front of the lens. Due to the movement of the lens, the position of the focal point is also move. As the lens is turned in front, the position of the focal point is also shifted in front of the sensor of the camera. Due to this there is gradient of blur that is added in the image. The side which where the shims are added has the maximum defocus, which gradually reduced when going to the opposites side. It also should be note that the point which has the least blur is also defocused. It has less blur due to the fact that portion of the image is close to the focal plane.

7.3.1. MTF results

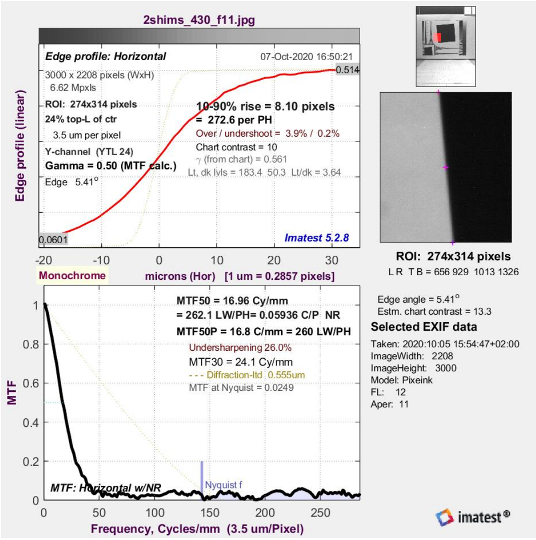
A similar trend is seen in the MTF results as in the correlation results. There was a drop in MTF when the shims were added compared to when no shims were added in the setup. This can be seen in figure 7.7.

Shims position	MTF50 (cyc/mm)
Top	14.29
Side	16.96

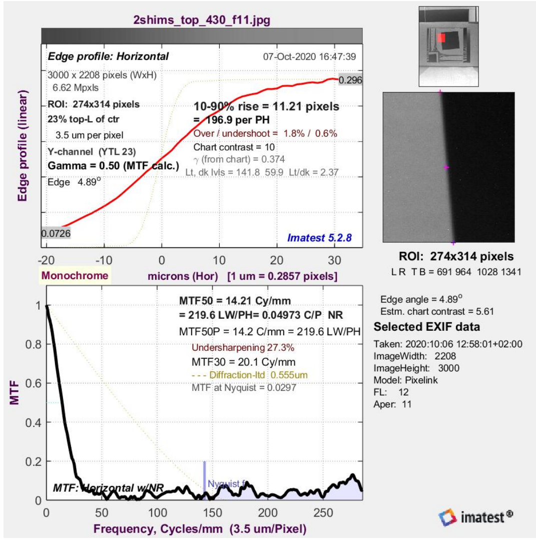
Table 7.1: MTF results of tilt changes

7.3.2. Correlation results

This section compiles the results of correlation with the tilt that was introduced during the experimentation. During the experimentation, it was observed that the similarity percentage was reduced when the shims were added between the sensor and the lens. Refer figure 7.8. The images taken with the shims added in the setup were compared with the image with the image taken with any induced aberration. Additional results are shown in chapter 10.



(a) MTF with shims on side



(b) MTF with shims on top

Figure 7.7: MTF graphs of tilt changes

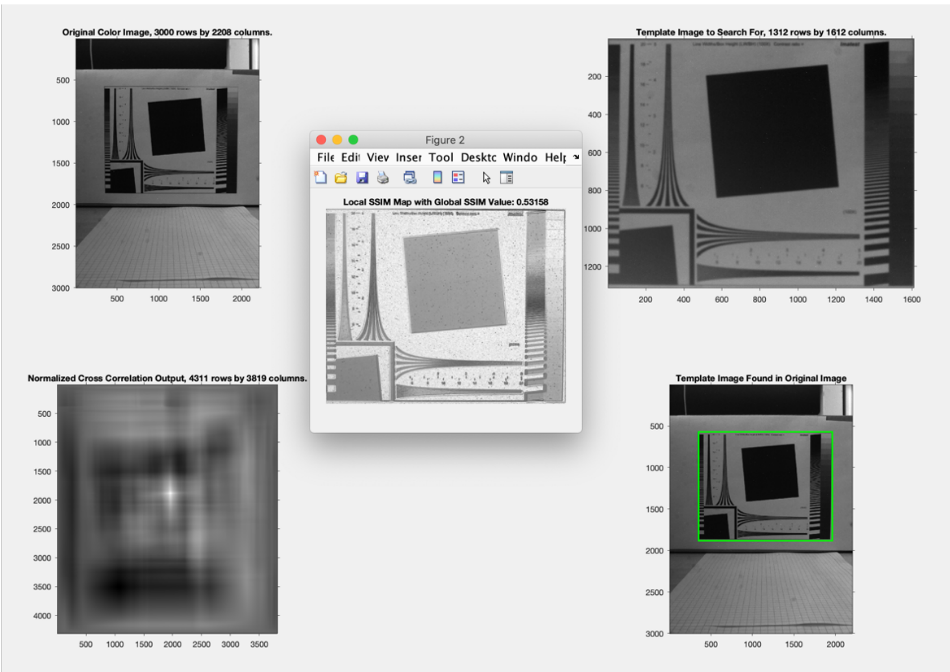


Figure 7.8: Correlation result with no induced aberrations and shims on top

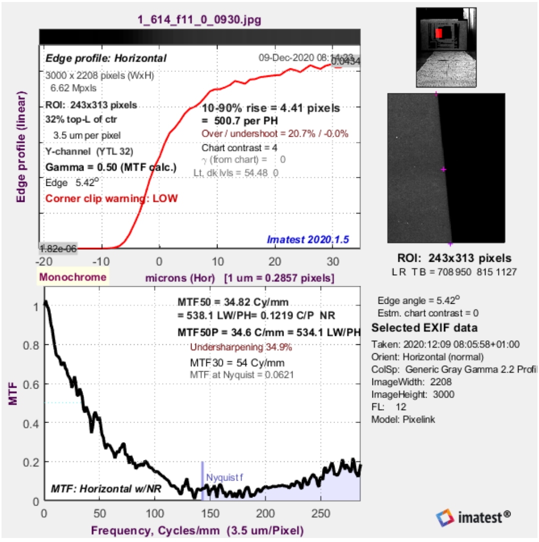
Shims position	Similarity percentage
Top	53.15
Side	47.56

Table 7.2: Correlation results of tilt changes

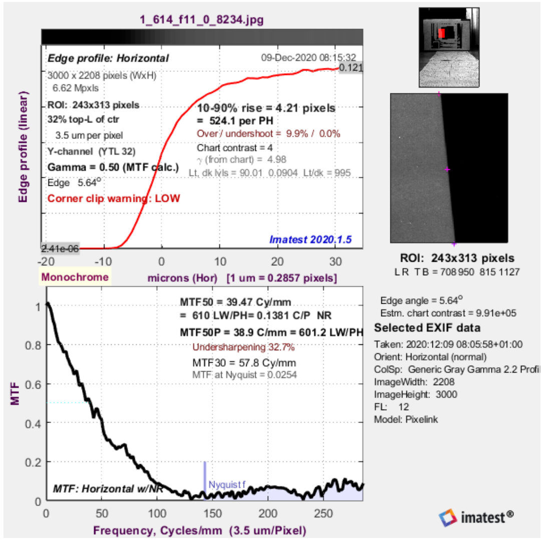
7.4. Exposure changes

The exposure was changed to check the robustness of the experiment methodology. Multiple images were take by changing the exposure and then compared with the correlation script and MTF. The ideal image was selected from the group of image based on the MTF charts.

7.4.1. MTF results

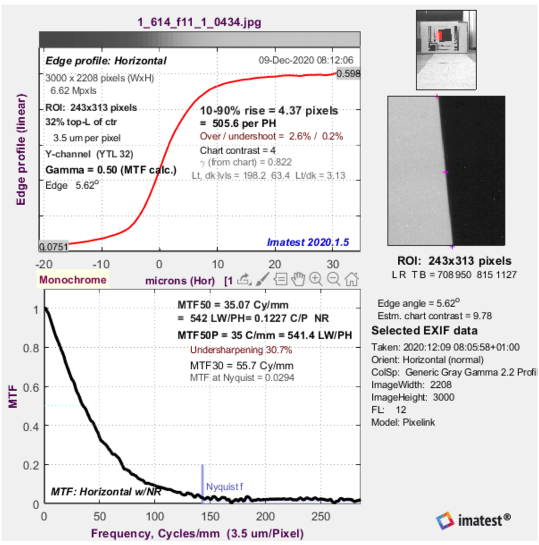


(a) MTF with 0.0930 sec exposure

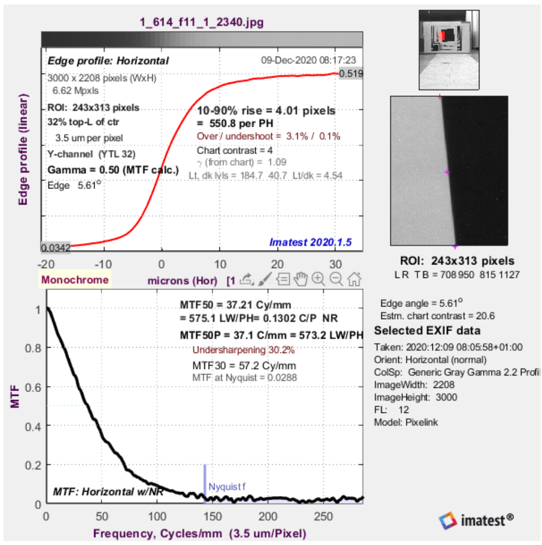


(b) MTF with 0.8234 sec exposure

Figure 7.9: MTF plot of exposure changes



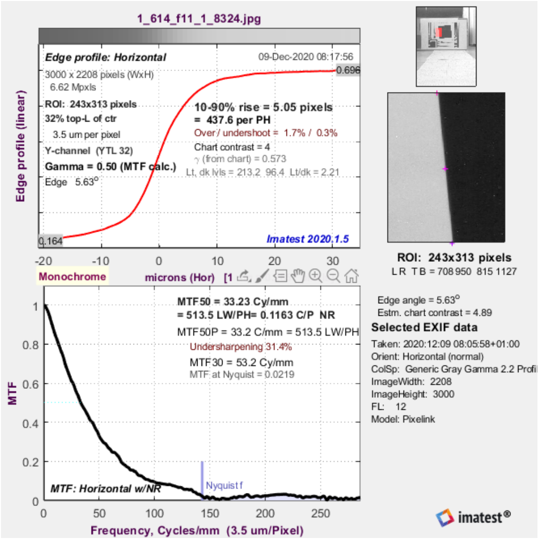
(a) MTF with 1.0434 sec exposure



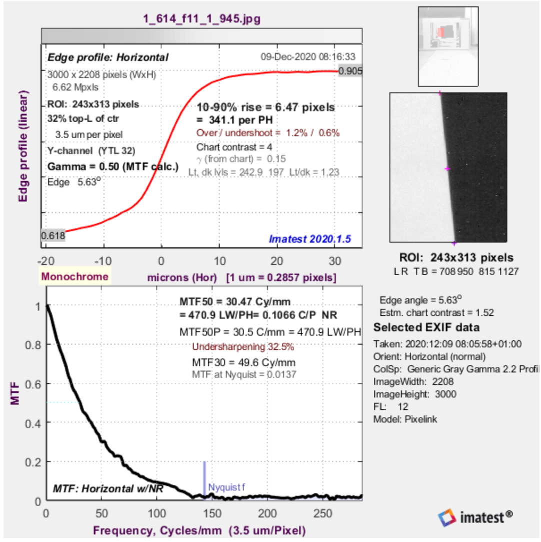
(b) MTF with 1.2340 sec exposure

Figure 7.10: MTF plot of exposure changes

The MTF of the exposure calculation shows that the images at the end of the spectrum are either underexposed or over exposed. The images which are correctly exposed, which



(a) MTF with 1.8234 sec exposure



(b) MTF with 1.9450 sec exposure

Figure 7.11: MTF plot of exposure changes

is found out by the values of black and white from the graph, have MTF which are close to each other.

7.4.2. Correlation results

When the images were captured, two images were selected which were not overexposed or underexposed by check the value of the black and the white region from the MTF graphs from Imatest software. The images wth exposure of 1.0424 sec and 1.2340 sec were selected based on the black and white value as the difference between the When these images were compared with each other, the matching percentage was found out to be 82.72 percent.

It was also observed that when the ideal image was compared with an overexposed or an underexposed image, there was a drop in the similarity percentage. Refer figure 7.12

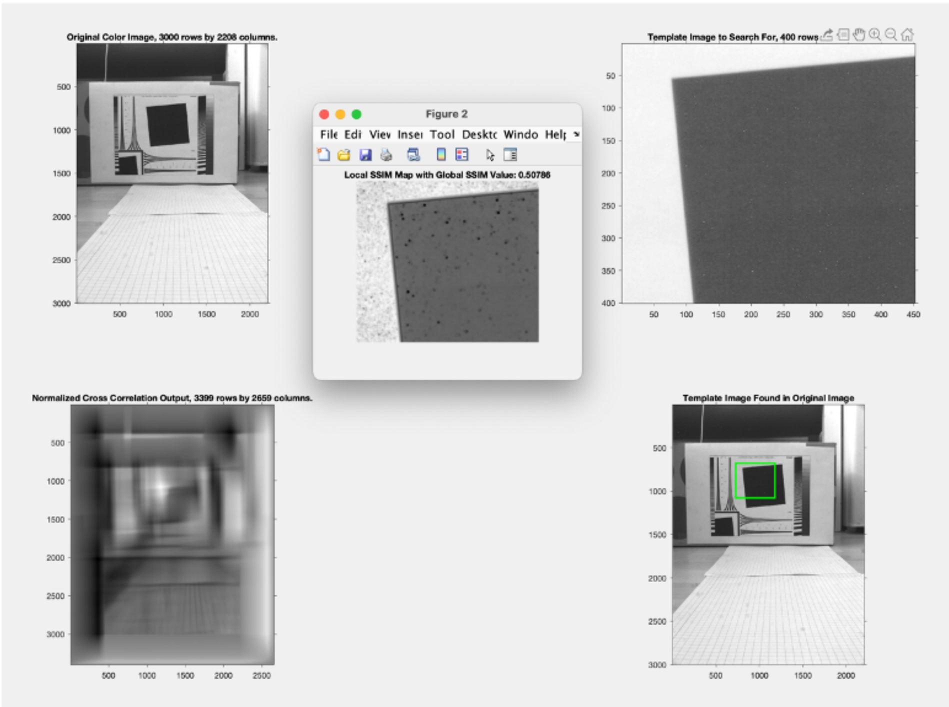


Figure 7.12: Correlation result with with exposure changes

8

Experimental Setup

The test arrangement is produced for the Simera camera which is a camera that is focused at infinity. Infinity focus is something contrary to limit depth of field. It is like having wide depth of field. At the point when the focal point is focused at infinity then everything in the casing will be in focus independent of the separation from the focal point. However there are few caveats to this. Above all else, infinity focus isn't exactly infinite. Certainly, everything somewhere far off will be in focus, however the point of convergence really begins a good ways off before the focal point. The region between your focal point and where everything comes into focus is known as the hyperfocal distance. The hyperfocal distance varies based on your aperture, the crop factor of your camera and the length of your lens, but in short, to take an effective photo at infinity focus, you'll need to make sure that no objects falling within the hyperfocal distance make it into your image. For this the testing of this camera has to be done with the objects kept at infinity.

Hence, to get a clear image of the object that is at infinity, the sensor of the camera should be at the focal length of the camera. The construction of a camera is such that the sensor is placed at the focal length of the lens. By using the basic principles of optics, the rays coming from infinity, when passed through a convex lens, are converged at the focal point of the lens ie. the sensor in the case of a camera. This property is going to be exploited in for the building of the experimental setup. The problem with an infinity focused camera is that the object should be kept at infinity to get parallel rays. Following are the ways to create parallel ray that can be used as an object kept at infinity.

8.1. Physical infinity

Physical infinity is actually creating infinity. As inifinty is not an actual number, when the distance between the detector and the object becomes large, it is termed as infinity. A good approximation for physical infinity are the stars. Star are objects which more than a $40 \cdot 10^{12} km$ away. For practical purposes this distance can be considered as infinity.

8.1.1. Star method

Ideally, a point should be chosen at infinity for this purpose. Generally, a star is chosen as the source point. For practical purposes, stars are considered to be at infinity as the distance between the sensor and the object is large.

The experimentation of this method starts with capturing the image of the object which is at infinity, which is a star in this case. This captured image is then analysed for the performance criteria decided with the help of post-processing techniques.

The advantage of this method is that this setup do not require a lot of components. The assembly is very simple and quick. A disadvantage of this method is that a controlled environment is needed. There is atmosphere which occupies the the space between the star and the lens which causes turbulence due change of refractive index which may give false results. Due to this this method is not suitable for experimentation . Another disadvantage of this method is that the experimentation has to be done during clear skies which rarely happens in the Netherlands. This adds a lot of uncertainty during experimentation.

Another way of conducting this experiment is by creating a virtual star with the help of a collimated light source and keeping at a distance within diffraction limit which will create a virtual infinity.

Again the disadvantage of this method is that the environmental conditions cannot be controlled which can create an uncertainty in the results.

8.2. Creating virtual infinity

This is another option for setting an object at infinity. But using different optics it is possible to create a virtual infinity. The basic principle of creating a virtual infinity is to manipulate the rays entering the camera lens to make them parallel. This can be done by using a collimator. A collimator is a lens in which light enters the lens diverging and comes out as parallel rays. A list of methods were devised which make use of this principle which are summaries below:

8.2.1. Telescope method

This method is a way where the rays are virtually made to look like they come from infinity. A telescope is used to create a virtual infinity.

To create virtual infinity, a refractive telescope is used. The basic construction of a refractive telescope consists of two lens, one primary lens, which is the front aperture and one eyepiece. The primary lens decides the focal length of the telescope and the eyepiece influences the magnification of the object that is being observed. For this setup, the eyepiece of the telescope is removed and the primary lens along with the casing is used. As the eyepiece is used for changing the magnification, the focal length is not affected.

The criteria for choosing a telescope is that the diameter of the telescope should be larger than the aperture of the camera. This is due to the fact that the collimated beam size

Wavelength (nm)	Diffraction limit (μm)
490	7.299
560	8.332
665	9.895
705	10.490
740	11.011
783	11.651
842	12.528

Table 8.1: Table of diffraction limit of the camera for central wavelength of the bands

should be greater than the opening aperture of the camera to prevent the loss of information. The second criteria is that the diffraction limit of the telescope should be grater than that of the camera.

When the eyepiece of the telescope is removed, the telescope is converted into a collimator with a casing. This casing also plays an important role in the setup. It becomes easier to align the lens of the telescope parallel to the object. It also becomes easier for mounting of the lens.

The second factor while choosing a telescope is the diffraction limit. Diffraction limit of an optical setup is the minimum distance that the system can identify different features. The diffraction limit for a camera is given by the Rayleigh criteria which is given by:

$$\frac{d}{2} = 1.22 \cdot \lambda \cdot N \tag{8.1}$$

where λ is the wavelength of the light N is the F-number of the imaging optics

F number is given by:

$$Fnumber = \frac{f}{D} \tag{8.2}$$

f is the focal length of the camera D is the diameter of the lens

According to the datasheet of the Simera multiscape 100, the bands are at the wavelength of 490nm, 560nm, 665nm, 705 nm, 740nm, 783 nm and 842 nm. As the diffraction limit of the camera is given by the formula above, The diffraction limit for every wavelength is given in the table 8.1.

From the above table, it is seen that the lowest diameter is for the wavelength of 490 nm. Hence the telescope that is selected for the experimentation purpose should have a diffraction limit lower than 7.299 μm. This criteria has to be satisfied because if the diffraction limit of the telescope is larger than that of the camera, then the image will be dominated by the aberrations of the telescope optics rather than that of the camera optics.

The diffraction limit for the telescope is given by:

$$R = \frac{\lambda}{D} \tag{8.3}$$

where R is the angular resolution of the telescope in radians λ is the wavelength of the light. D is the diameter of the telescope's objective.

While calculating the diffraction limit of the camera, the diffraction limit is calculated at the average wavelength at each of the seven bands. The criteria that has to be satisfied by the telescope to be selected is that the diffraction limit of the telescope should be lower than that of the camera.

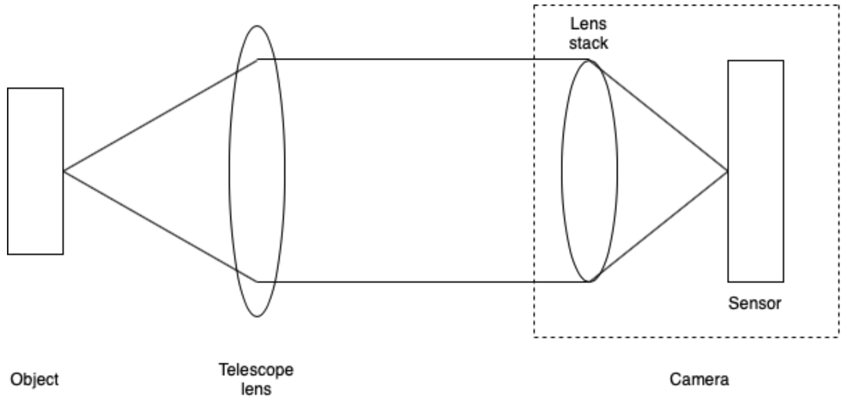


Figure 8.1: Telescope method

8.2.2. Caliberated collimator

Caliberated collimator is a method which is similar to the telescope method which is a type in virtual infinity method. The difference between the telescope method and caliberated collimator method is that a caliberated collimator is used instead of the telescope. This method is generally used for the testing of cameras these setups reduce the size of total setups.

There are two types of caliberated collimator available in the market. An off the shelf collimator and the other is custom caliberated collimator. The criteria for selecting a collimator is that the aperture of the collimator should be larger than the telescope. The second criteria is that the diffraction limit of the telescope should be larger than that of the camera. The third criteria is that the MTF of the collimator should be better than that of the camera at nyquist frequency.

One of the disadvantage of the caliberated collimator is that it has a small field of view on axis compared to the telescope. Hence, when capturing an image with a caliberated collimator, only a small portion of the image will be in focus. As the MTF depends on the sharpness of the image, it is vital that the portion in test should be in focus.

This can be done in two ways.

- The first method is a simpler one. The MTF vs Field of view graphs of the selected caliberated collimator should be produced. From the graph it can be seen if the MTF of the collimator drops more that the MTF of the camera lens with the selected field of view. The field of view is selected based on the portion of the image that is needed for the calculation of the MTF. This process ensures that the MTF of the final image is not overshadowed by the MTF of the collimator.
- The second option is more complex. This involves using a caliberated collimator with a small field of view. Some changes are done in the design of the setup such that the

whole field of view of the camera lens is used. The camera is mounted on a rotatory mount which has a pivot point on the optical center of the lens stack. The pivot point is selected on the optical center of the lens because if the point is selected in front or behind this point there will be loss of information as the light entering the lens will reduce. The figure 8.2 shows the setup.

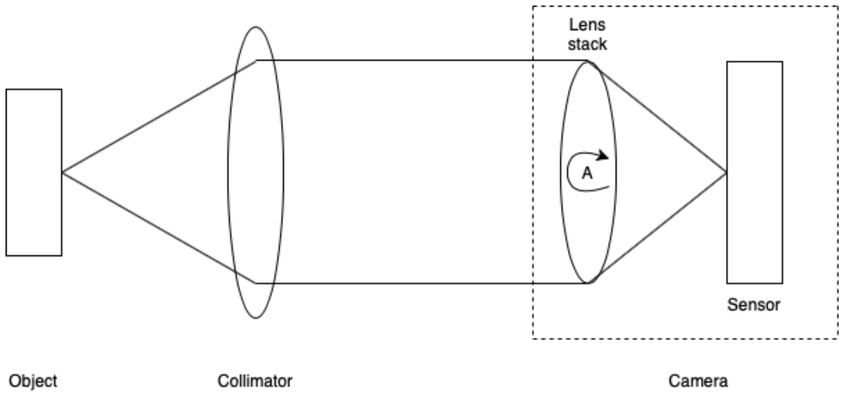


Figure 8.2: Caliberated collimator

8.2.3. Same lens as camera

Having the same lens as the camera gives an advantage that there will be no magnification, positive or negative of the image as they will have the same focal length. It is not possible to get an off the shelf lens with the same focal length as it is not a standard number. Hence, to get the same lens as he camera, a new camera has to be bought and the disassemble the lens.

This method is not viable as the camera is expensive. Hence, procuring the same camera twice is not possible because of the cost. Another way of procuring the same lens as camera is manufacturing a custom lens. This way is also not possible because of the high cost attached to manufacturing a custom lens.

8.3. Shack Hartmann Method

This method has been named Shack Hartmann method because it is inspired from the Shack Hartmann sensor. Shack Hartmann sensor is a device which is generally used for characterising imaging systems. It consists of a array of small lenses with same focal lengths. A CCD or a CMOS sensor is placed at the focal plane of the array and is uniformly illuminated. The gradient that is formed due the illumination is proportional to the displacement of the centroid. Any aberration in the wavefront will have an effect of the displacement in the focused point from the array. These local tilts can be used to reconstruct the whole wavefront.

The Shack Hartmann sensor inspired setup has similar components. The figure below shows the construction of the setup. In this setup, a laser or a point source is used as a light source. The light source has to be mounted on a high precision XY translating platform.

The high precision platform is necessary. This light source is moved in a pattern like one from the Shack Hartmann sensor on the lens of the camera. Every point on the pattern will cast an image on the sensor of the camera. The coordinates of this image is noted from every point in the pattern. This experiment is conducted before the environmental testing and after the testing. The whole process is repeated after the testing and the coordinates are noted.

If there is any difference between the coordinates of the image before and after testing, it means that there is a change in the camera optics. The advantages of this method is that it can detect very small deviations in the optics. This is a very sophisticated method to detect any changes in the given system. The disadvantages of this method is that it requires very high precision equipment for maintaining the position of the light source throughout the experiment and able to reproduce the same deflection again. A high precision positioning system is necessary for this which increases the cost of the setup.

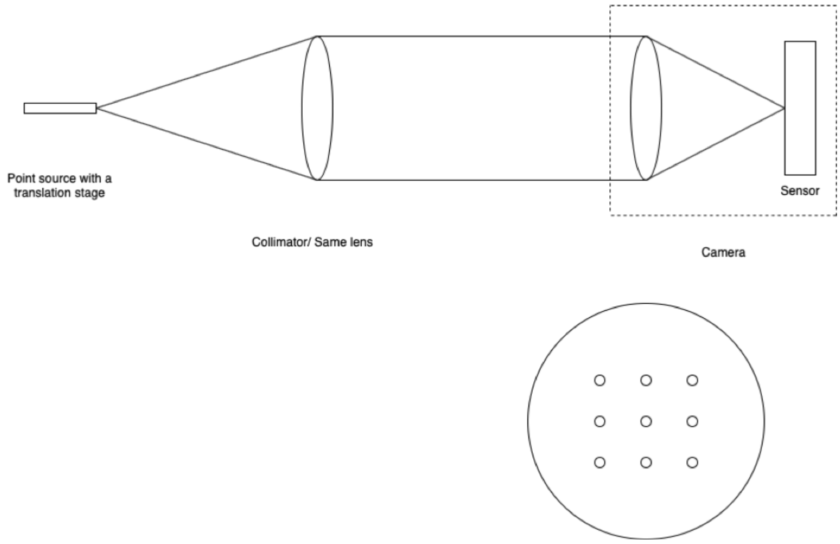


Figure 8.3: Shack hartmann method

8.4. Comparison of all methods

The table 8.2 shows the comparison for the methods which are discussed earlier. The factors considered for comparison are :

- Cost: Cost plays an important role in deciding the setup and its feasibility. The table consists of ’+’ and ’-’. ’+’ refers to setup which costs more than 3000 euros and a ’-’ refers to cost less than 2000 euros.
- Ease of setting up: This parameter refers to the complication of building the setup.
- Aberrations: The parameter aberrations refer to the environmental aberrations. These are predominant in natural star method.
- Moving components: This is included as a decided parameter as the moving components involved there is a higher chance of error added into the system. ’+’ is at-

Setup type	Parameters					
	Cost	Ease of setting up	Aberrations	Moving components	Precision	Field of view
Star method (Natural)	+	+	-	+	-	+
Star method (Artificial)	+	+	+	+	+	+
Telescope	-	+	+	+	+	+
Caliberated collimator (off the shelf)	+	+	+	+	+	-
Same lens	-	+	+	+	+	-
Shack Hartmann	-	-	+	-	+	-

Table 8.2: Trade-off table

tributed to the system having less than one moving component. '-' refers to a system having one or more moving components.

- Precision: Precision refers to the ability to produce same results with same conditions multiple number of times. No results will be same because there is always random noise present. Weighing is done neglecting the effect of noise on the system.
- Field of view: This parameter refers to the field of view of the system.

8.5. Actual setup

After considering the advantages and disadvantages of all the discussed methods, the caliberated collimator method is selected because of its low cost.

8.5.1. Components of the setup

The components required for the setup are mostly the optical components that are used in different experiments.

Light source

The light source is necessary for illuminating the test target. The light source can be categorised as single wavelength light source or a broad spectrum wavelength light source.

The single wavelength light source can be selected as a laser which also gives an advantage that the light source is already collimated. As a collimating lens is used to collimate the light, using a laser defies the necessity for it. The problem of using a single wavelength is that the camera is a multi spectral camera which means that it has 7 band for 7 different wavelengths. By using just one laser, it will active only a small portion of the sensor which will not check the overall sensing capabilities of the camera. To check the functioning of every band, it will require it activate all the band, which in turn mean using 7 different leasers as the light source, which will increase the cost of the setup substantially.

The second option is using a broad spectrum. The requirement for the broad spectrum light is that the light should cover the 7 band spectrum. The halogen lamp was a good candidate. It covers the whole range of spectrum of the camera which is visible below. The advantage of using a brad spectrum lamp is that all the 7 bands of the camera is activated at the same time. Hence, halogen lamp is selected as a light source because of the low cost attached to it.

Collimator

Lens is selected by considering the MTF of the camera and MTF of lens. The collimator lens which is selected has to qualify certain requirements to be able to be used in the setup. The requirements are as follows

- The diameter of the lens should be equal to or larger than the opening aperture of the lens. By ensuring the diameter of the collimating lens is larger than the camera lens, the characteristics of the entire lens can be determined. If the diameter of the collimating lens is smaller, it will illuminate entire camera lens.
- The MTF of the collimator lens should be better than that of the camera lens. By ensuring this, the MTF of the object that is being captured will not be degraded because of the collimating lens.
- The focal length of the collimator lens should be larger than that of the camera lens. This is due to the fact that the combination of the lens will then have a negative magnification and then the nyquist frequency of the camera can be reached at a frequency which is actually less than the nyquist frequency.

  The magnification of the new system of lenses will be given by:

  $$Magnification = \frac{f1}{f2} \tag{8.4}$$

  where f1 is the focal length of the camera lens and f2 is the focal length of the collimator lens.

This change in the focal length leads to a change in the spatial frequency that is passed through the series of lens. The so the actual spatial frequency that is printed on the test target is not the one that is captured on the camera. This has to be considered while choosing the collimator lens. As the MTF around the Nyqiust frequency of the camera was a requirement, the lens should have a better MTF at a frequency which is captured by the camera. Choosing an achromatic lens will be better for the the setup as it will reduce the chromatic aberrations which will influence the results.

Figure 8.4 shows the schematic of an achromatic lens. Two lenses are used for compensation of the chromatic aberrations that are more predominant in singlets. Here, the diagram is of an airspaced achromat. This space can be replaced by vacuum or no space, depending on the application.

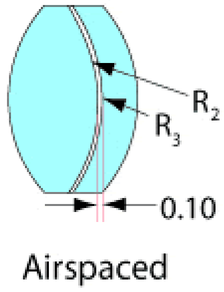


Figure 8.4: Schematic of an achromatic lens [20]

Test target

A test target is necessary for calculating the MTF of the imaging system. This can be done in multiple ways. For this experiment, MTF is calculated with the help of slant edge test target [35]. This test target allows the user to determine the frequency response of the system with the help of Slant edge and Ronchi pattern. The edge is slanted a 5°. For calculating the MTF by slant edge method, generally an edge slanted at 1° to 5° is used. The edge should be as distinct an edge as possible. The selected test target has an edge which is produced by photo-lithography.

The test target also has Ronchi pattern which can be used to calculate the MTF using the bar target method. It can be seen at the edges of the target which have the grated bar pattern in the figure8.5.

Figure 8.5: Test target [31]

MTF is calculated with bar target method and slant edge. Test target with slant edge and bar target is selected.

Diffuser

The use of a diffuser is to create a uniform distribution of light and to illuminate the test target uniformly. This is due to the fact that the test target is made of glass with a substrate which is printed on it. This test target has to be illuminated to create a contrast for measuring the MTF.

To have accurate results, the illumination has to be uniform throughout the test target. As a light source is not collimated, the light source needs to be diffused.

The diffuser that is chosen for this purpose is the white diffusing glass. This diffuser uses a material which is collidal in nature which creates tyndall effect which scatters the light that is being projected. Tyndall effect requires the particles contributing to scatter be roughly the same size as that of the wavelength of the incident light. As the wavelength of the incident light increases, the amount of light scattered decreases and the transmitted light increases. Therefore, these diffusers have a working range. This range should be equal to the working range of the camera to check for all wavelengths. Multiple diffusers can be used for this purpose of fulfilling the entire spectrum of the camera.

Geometric scattering occurs when the feature scattering light is much larger than the wavelength of light. Put simply, if light hits a surface whose surface normal changes randomly, then light will refract at random angles along the surface. This is the mechanism at work for ground glass diffusers. When you add a sandblasted surface to colloidal material, you get a diffuser that is effective across a wide wavelength range.

Camera

The specifications of the camera are explained in detail in Chapter 3. Some mechanical characteristics of the camera are mentioned in the table 8.3:

Property	Specification
Mass	1.2 kg
Dimensions	98 x 98 x 176 mm

Table 8.3: Mechanical characteristics of the camera

Other components

Some other components are also used for the construction of this setup. Other optical components such as breadboard, lens holder, optical post, test target holder, etc. Ideally a vibration isolation table is also used, but it is not a necessary component.

- Rotatory platform: This is a platform on which the camera will be mounted. This is needed as the camera has to be moved to test the entire field. The platform should have degrees marked on it which can be used to reproduce the same rotation every time the camera is being tested. The rotatory platform should be able to sustain a weight load of 15-20 kgs because the cubesat at the end of testing will be full assembled which will increase its weight.

- Optical breadboard: This is a platform which is used for constructing the setup. All the supporting components are assembled on this platform. The breadboard is the backbone of the setup. This helps in providing the stability that is required during the experimentation.
- Lens holder: This component is used to hold lens. As collimating lens should be lager than the camera opening aperture, the lens will have a diameter of 95cm and above which is a comparatively large lens.
- Optical posts: These components are used to attach the lens holder and test target holder on the optical breadboard.
- Test target holder: The test target is mounted on the test target holder and then mounted on the optical breadboard.

8.5.2. Setup design

This section gives an overview of the schematics of the setup. The figure 8.6 gives a basic schematics of the setup along with the sequence of components. The components are are mounted on holders which are then mounted on the optical breadboard.

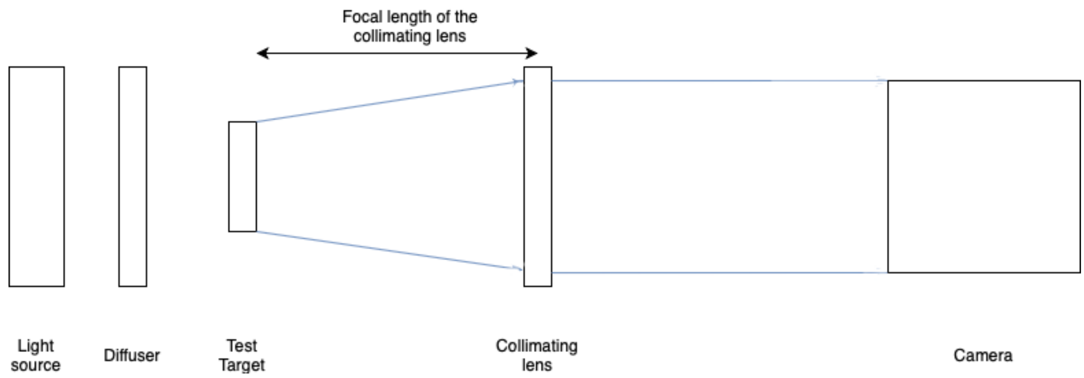


Figure 8.6: Schematic the setup

9
Conclusion

This chapter compiles the discussion and the conclusions drawn from the preliminary data analysis experiment. Some limitations of the setup and recommendations for future research are also explained in brief.

9.1. Conclusion

The research objective of the thesis which was mentioned at the start was to detect changes in the performance of the camera. This objective has been well achieved by suggesting a setup for the testing along with the preliminary data analysis experiment. This experimentation shows that correlation and MTF analysis of the images can used for detecting the in the camera before and after testing.

The plan of action to comply with the above intentions was to study the camera, its sensing techniques and the underlying principle of testing of a camera. Hence, a detailed literature study was conducted on testing of satellites, working principle of TDI camera, concept generation for the testing setup concepts along with their advantages and disadvantages. Different concepts were mentioned with different ways of creating virtual infinity with real targets. A caliberated collimator concept was chosen to benefit from its ease of access and availability along with other advantages. As there was a requirement that the camera could not be taken apart for testing, it reduced the number of options.

The second part of experimentation was the data processing of the image. For this, various parameters of the camera were explored such as focal length, MTF, noise, aperture, and some more. From the detailed analysis in chapter 3, it was decided to use MTF as a comparing parameter along with cross correlation. A matlab script was created for the cross correlation which can be found out in chapter 10. Structural similarity indexing method (SSIM) was used for comparing the images because of its advantages. MTF was calculated by using the Imatest software, which used slant edge method for calculating the MTF. Edge spread function (ESF) was selected over Point spread function (PSF) used to calculate the MTF after weighing the advantages and disadvantages of both the methods which are mentioned in chapter 3.

Correlation can be used for detection of changes in the performance of the camera. MTF also provides information regarding change/ degradation in the camera. The lighting conditions have an effect on the testing of the camera. It can provide false results. From the results of the preliminary experimentation with the basic setup, it was evident that there was a change in the MTF and similarity percentage when there was a change in the camera optics. It was also seen that noise in the camera has an effect on the MTF and similarity percentage. Noise attribute to a change of 4% in the MTF and 10% in the similarity percentage.

The research question 1 posed in chapter 4 is answered by selecting MTF and correlation as the performance criteria. The research question 2 is answered by suggesting a collimator setup for the experimentation and measuring the selected performance criteria.

9.1.1. Limitations

There were some limitation that were faced due the camera that was used for experimentation.

- Because of the crisis all around the world there are restrictions in place which made the timeline of the thesis to be altered and building the actual setup was not possible.
- Due to unavailability of an actual testing facility, some unknown aberrations might have been involved in the experimentation major one of them being stray light. Experimentation can be done by controlling stray light.

9.1.2. Recommendations

The future recommendations are:

- It would be interesting to explore other parameters that can be used for comparing the images, as the camera cannot be taken apart.
- As mentioned earlier, the MTF was calculated using the edge spread function, it would interesting to see the effect due to the point spread function.
- Other experiment methodologies can be adopted such as Shack Hartmann to check the performance.

10 Appendix

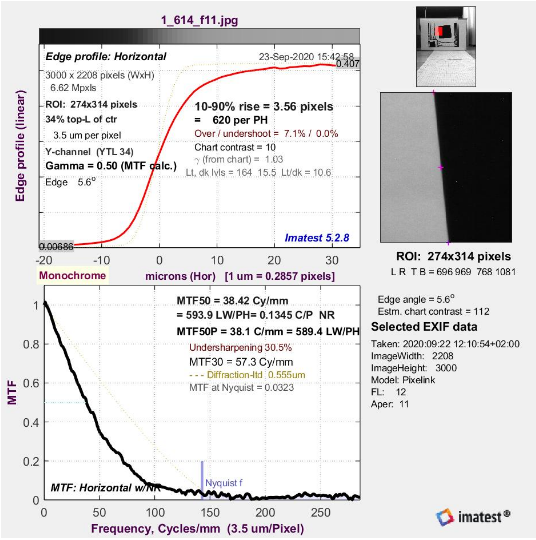
10.1. MATLAB code for correlation

```
clc;    % Clear the command window.
close all;  % Close all figures (except those of imtool.)
imtool close all;  % Close all imtool figures.
clear;  % Erase all existing variables.
workspace;  % Make sure the workspace panel is showing.
format long g;
format compact;
fontSize = 11;

Button_Image_Import = questdlg('What type of image would you like ...
    to import ?',...
    'Image type?',...
    'Dicom','Tiff or Jpeg','Matlab file','Tiff or Jpeg');

switch Button_Image_Import,
    case 'Dicom',
    [image_file, path_name] = uigetfile('*.dcm','Please select the ...
        dicom image you wish to import');
    idealimage = double(dicomread([path_name image_file]));
    case 'Tiff or Jpeg'
    [image_file, path_name] = uigetfile({'*.tif; *.tiff; *.jpg; ...
        *.jpeg'},'Please select the jpeg or tiff image you wish to ...
        import');
    idealimage = imread([path_name image_file])
    case 'Matlab file'
    [image_file, path_name] = uigetfile('*.mat','Please select the ...
        Matlab file containing an image named "image"in you wish to ...
        load');
    matstruct = load([path_name image_file])
    idealimage = double(matstruct.image);
end

switch Button_Image_Import,
    case 'Dicom',
    [image_file, path_name] = uigetfile('*.dcm','Please select the ...
        dicom image you wish to import');
```

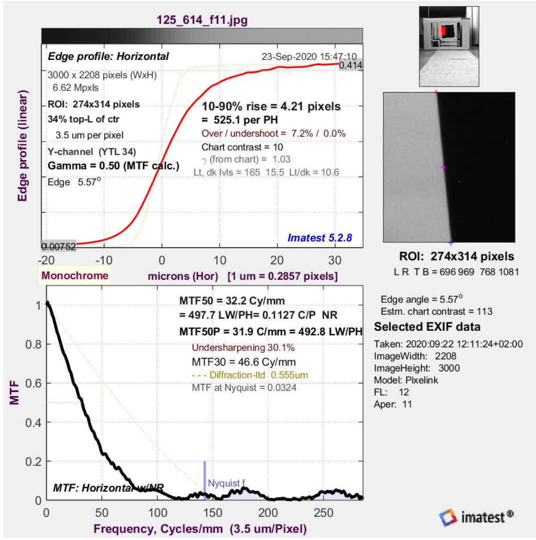
```
    pretestimage = double(dicomread([path_name image_file]));
    case 'Tiff or Jpeg'
    [image_file, path_name] = uigetfile({'*.tif; *.tiff; *.jpg; ...
        *.jpeg'},'Please select the jpeg or tiff image you wish to ...
        import');
    pretestimage = imread([path_name image_file])
    case 'Matlab file'
    [image_file, path_name] = uigetfile('*.mat','Please select the ...
        Matlab file containing an image named "image"in you wish to ...
        load');
    matstruct = load([path_name image_file])
    pretestimage = double(matstruct.image);
end

[testimage,rect] = imcrop(pretestimage); % Selecting region of interest

[rows, columns] = size(idealimage);
% Display the original color image.
subplot(2, 2, 1);
imshow(idealimage, []);
axis on;
caption = sprintf('Original Color Image, %d rows by %d columns.', ...
    rows, columns);
title(caption, 'FontSize', fontSize);
% Enlarge figure to full screen.
set(gcf, 'units','normalized','outerposition',[0, 0, 1, 1]);

[rows1, columns1] = size(testimage); % dimensions of the test image
subplot(2, 2, 2);
imshow(testimage, []);
axis on;
caption = sprintf('Template Image to Search For, %d rows by %d ...
    columns.', rows1, columns1);
title(caption, 'FontSize', fontSize);

correlationOutput = normxcorr2(testimage, idealimage);
subplot(2, 2, 3);
imshow(correlationOutput, []);
axis on;
% Get the dimensions of the image.
[rows, columns] = size(correlationOutput);
caption = sprintf('Normalized Cross Correlation Output, %d rows by ...
    %d columns.', rows, columns);
title(caption, 'FontSize', fontSize);

% Find out where the normalized cross correlation image is brightest.
[maxCorrValue, maxIndex] = max(abs(correlationOutput(:)));
[yPeak, xPeak] = ind2sub(size(correlationOutput),maxIndex(1))
% Because cross correlation increases the size of the image,
% we need to shift back to find out where it would be in the ...
    original image.
corr_offset = [(xPeak-size(testimage,2)) (yPeak-size(testimage,1))]

% Plot it over the original image.
subplot(2, 2, 4); % Re-display image in lower right.
imshow(idealimage);
```

```
axis on; % Show tick marks giving pixels
hold on; % Don't allow rectangle to blow away image.
% Calculate the rectangle for the template box.  Rect = [xLeft, ...
    yTop, widthInColumns, heightInRows]
boxRect = [corr_offset(1) corr_offset(2) columns1, rows1]
% Plot the box over the image.
rectangle('position', boxRect, 'edgecolor', 'g', 'linewidth',2);
% Give a caption above the image.
title('Template Image Found in Original Image', 'FontSize', fontSize);


idealimagecrop = imcrop(idealimage, [boxRect(1) boxRect(2) ...
    boxRect(3) boxRect(4)]);
idealimageresize = imresize(idealimagecrop, size(testimage));
%idealimagecrop1 = imread(idealimagecrop);
[ssimval,ssimmap] =  ssim(idealimageresize,testimage);
%ssimval = ssim (idealimageresize, testimage);
figure, imshow(ssimmap,[]);
title(['Local SSIM Map with Global SSIM Value: ', num2str(ssimval)])
```

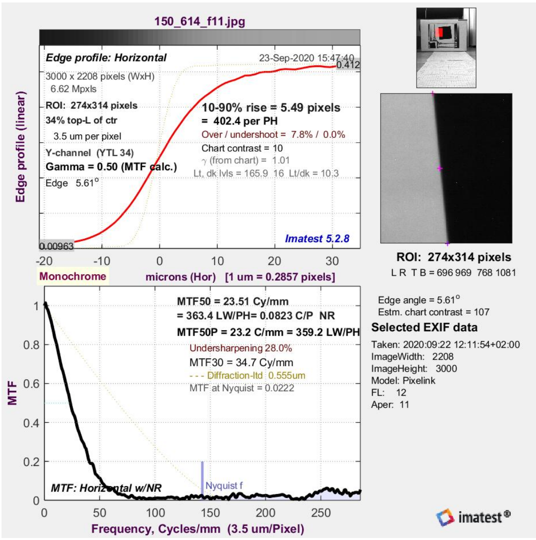
10.2. MTF results for focal length changes



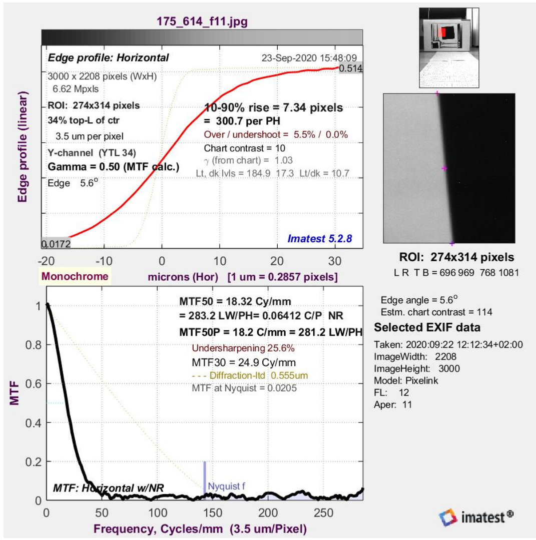
(a) MTF with 1 rotation



(b) MTF with 1 1/4 rotation



(c) MTF with 1 1/2 rotation



(d) MTF with 1 3/4 rotation

Figure 10.1: MTF plots with focal length changes

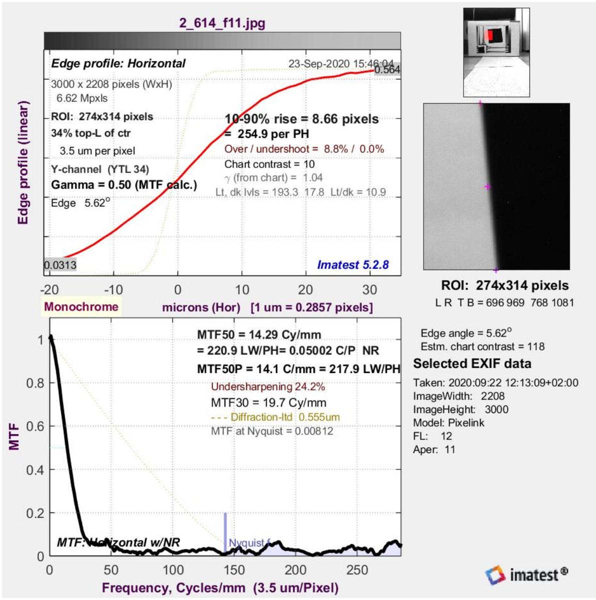
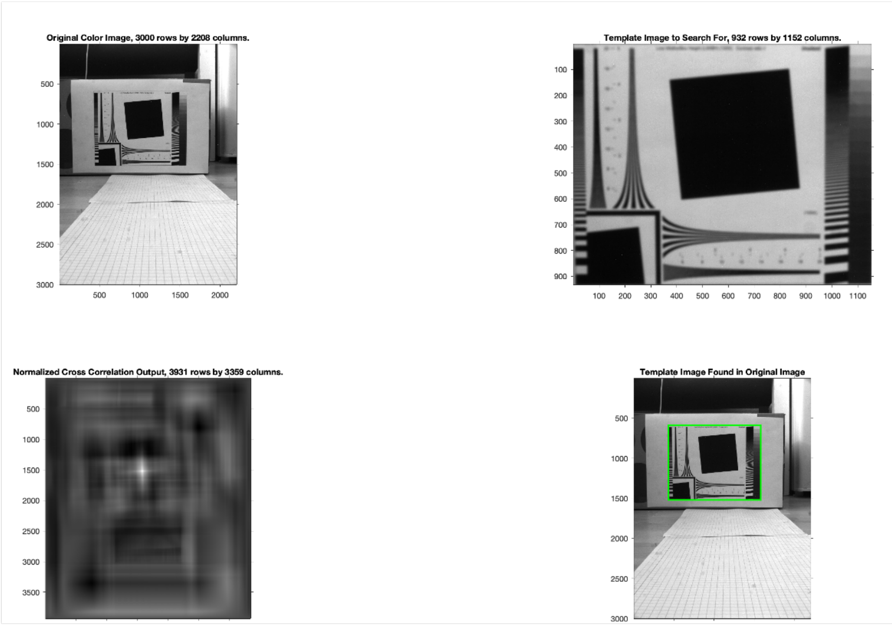
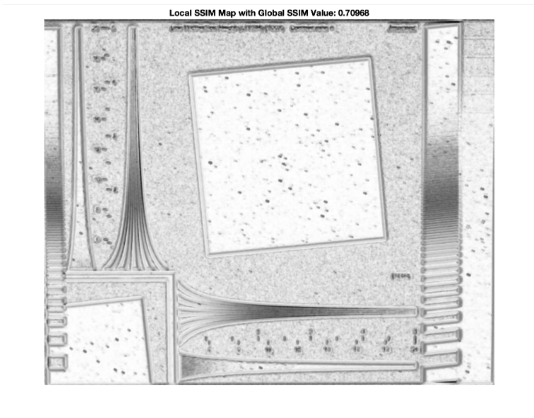


Figure 10.2: MTF with 2 rotation

10.3. Correlation results for focal length changes



(a) Finding the similar section



(b) Similarity value

Figure 10.3: Correlation result with 0.75 turn and 2 turns

10.4. Correlation results for tilt changes

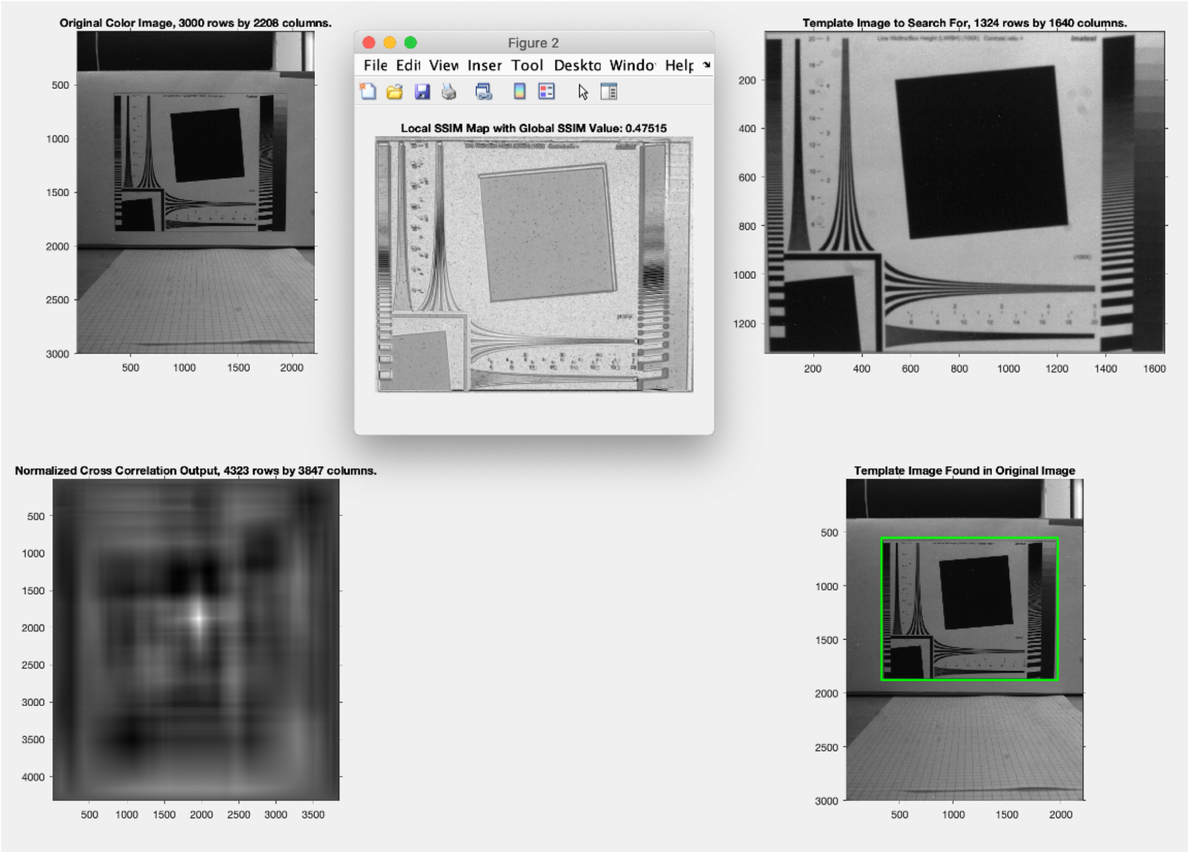


Figure 10.4: Correlation result with no induced aberrations and shims on side

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