University of Southern Queensland
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Cloud Detection System for the Mt Kent Observatory

A dissertation submitted by

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Abstract

The extent of cloud cover is crucial for astronomers when making ground based optical astronomical observations. This information is important to astronomers in determining if the sky is suitable for observing and to what extent the cloud cover may affect their data. Normally, estimation of cloud cover is done visually by the astronomer, however in the case of the Mt Kent Observatory this is not possible as the telescope is designed to be operated remotely and there will not be an astronomer on site every night of the year to make these observations.

A review of literature revealed that currently there is only one commercial system on the market capable of detecting clouds, but this system is unable to provide details of the cloud location in the night sky. Several other non-commercial systems have been implemented at other observatories around the world that are capable of determining cloud locations, however they have been very expensive to implement and are not able to be built at the Mt Kent Observatory due to the limited budget. Knowledge of the location and extent of cloud cover in the night sky can prevent valuable telescope time from being wasted when conditions are unsuitable in the area of sky that is of interest and also permit observations to be conducted in other clear areas when only partial cloud cover is present.

This project aimed to provide a solution to this problem by designing a reliable, low maintenance, low cost system to detect the presence and location of clouds at the Mt Kent Observatory (MKO). This was ultimately achieved by utilising an obsolete low-light astronomical camera, the ST-4 Star Tracker Imaging Camera manufactured by Santa Barbra Instrument Group, Inc, which was owned by the University of Southern

Queensland but no longer in use. If it were required to be purchased, a low light security camera would probably have been chosen as the camera of choice.

The design approach finally adopted was to mount the ST-4 camera pointing downwards over a convex mirror. The use of a convex mirror provided an economical solution for obtaining a large field of view image of the sky without having to utilise an expensive fisheye lens.

The ST-4 being an astronomical camera was designed for use with a telescope and no information was available on lens availability or compatibility for the imaging requirements of this project. Much investigation was undertaken to source a suitable lens. Eventually, a C-mount closed circuit television lens was selected as the best option, however the field of view was significantly reduced due to the small size the camera's sensor. Additionally, the ST-4 camera has no hardware controls and is operated entirely by software. As the original control software was unable to be located and the replacement cost was excessive, investigations were also required to be undertaken to source suitable freeware to operate those camera functions required.

Complicating the lens selection was the need to protect the ST-4 camera charged couple device from sunlight during the day. This was eventually solved by utilising an auto-iris lens in conjunction with a photoelectric cell daylight sensor switch to ensure the lens iris was only opened after dark and closed during the day. Other precautions such as weatherproofing, ventilation of the electronics, and bird deterrence measures, were incorporated into the final design.

A simplified prototype was built to prove the concept and successfully demonstrated the capability to accurately image clouds in low light conditions. The images obtained from the experimental trials demonstrated that most cloud types ranging from high cirrus clouds (normally difficult to see with the unaided eye at night) to low stratus clouds could be detected along with their relative positions by the cloud detector. The system also proved sensitive enough to detect the brightest stars with suitable exposure times.

Further work is required to construct and install the final design cloud detector at MKO. Additionally, as the cloud detector is intended to provide up to date images of the night sky on a website for access by remote users, code is required to be written to fully automate the cloud detector operation.

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Limitations of Use

Prof G Baker
Dean
Faculty of Engineering and Surveying

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

A. Gwynne

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Signature

Date

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Chapter 1

Introduction

The days of astronomers working through the night beside their telescopes in isolated locations are all but gone. The use of technology in astronomy has increased significantly over the last century and telescopes are now being developed with the capability of being operated at unattended remote sites using robotic operation. Technology has also introduced new challenges for astronomers such as not knowing the meteorological conditions of the sky before attempting observations, as they are often not observing from the same location as the telescope. This is not only a problem for astronomers leading to wasted telescope time and problems in determining if their observations are accurate, but there is also a very real risk that the telescope could be seriously damaged if the dome were to be opened during bad weather conditions such as rain or hail.

This project aims to find a solution to this problem, by investigating and designing a low cost cloud detecting system for a remotely operated telescope. In order to be effective in assisting astronomers with the planning and conduct of astronomical observations the system must be able to detect the presence of clouds and their location in the sky. Up to date cloud coverage information from the observatory is required to be made available via the Internet, on the observatory website, along with records of cloud coverage information from previous nights. This is important, as many astronomical observations require information of the cloud coverage at the time of the observation. The system is also required to assist in the protection of the telescope from rain damage by reducing the likelihood of the telescope dome being opened during overcast conditions.

This chapter will provide background on the Mt Kent Observatory and detail the types of cloud formations intended to be detected by the cloud detection system. It will further investigate the different techniques of detecting clouds in low light conditions, and critically evaluate the existing alternatives for cloud detection systems for remotely operated telescopes.

1.1 Background

1.1.1 Mt Kent Observatory

The Mt Kent Observatory (MKO) is located 30 km South West of Toowoomba in the Darling Downs. The University of Southern Queensland (USQ) operates MKO as a facility for teaching, research and outreach programs. There are three telescopes on the site, the Webb Telescope, a 16-inch aperture Meade LX200, the O'Mara Robotic Telescope, a 14-inch Celestron on a Software Bisque Paramount ME robotic mount, and the Page (Tamborine) Telescope, a 16-inch Cassegrain telescope.

Later this year the Page Telescope is to be replaced by a completely remotely operated 20-inch telescope. This telescope is being purchased as part of a new Digital Science Partnership with the Northern Kentucky University and the University of Louisville in the United States of America and is intended to assist with the teaching of astronomy at these two universities. The new telescope will be a very important educational tool for students both in the U.S. and at USQ in Australia studying subjects in the field of Astronomy. Not only will classes in the Northern Hemisphere be able to observe the night sky in Southern Hemisphere during their class time but those students studying at USQ by way of distance education will particularly benefit from being able to access images from the telescope from any location around the world via the Internet.

1.1.2 Cloud Detector

The main motivation behind designing and building a cloud detection system is to save time for astronomers and students in determining if the sky is suitable for their intended observations and to assist with the protection of the telescope from damage due to wet weather conditions.

As the telescope is designed to be operated remotely it is not possible for the user to look out the window and directly observe the cloud coverage of the sky and meteorological conditions before attempting to use the telescope. Weather reports, satellite images and meteorological forecasts are of limited value and cannot be relied upon for this purpose due to time delays in their production and the inability to provide the detailed site-specific information required.

1.2 Project Aim

This project aims to provide an economical cloud detection system for a remotely operated telescope, to determine if the sky is suitable for astronomical observing.

1.3 Project Objectives

- Research information of cloud formation in the evening sky and the changes that occur from sunset until dark.
- Investigate different techniques of detecting clouds in low light conditions.
- Critically evaluate existing alternatives for cloud detection systems on remotely operated telescopes.
- Determine the best and most economical technique or combination of techniques for detecting clouds for the location and type of telescope to be used.
- Design a low maintenance cloud detecting system to operate from late afternoon until early morning that can identify sky conditions before starting observing.
- Construct a prototype cloud detection system and evaluate the reliability and accuracy of the system.

In summary, the cloud detection system must be capable of detecting the presence of clouds in the night sky and the location of the detected clouds in the sky. Additionally, the system is required to be low cost, preferably utilising commercial-off-the-shelf hardware and software.

1.4 Overview of the Dissertation

Chapter 2 reviews current literature on current techniques used by astronomers to detect clouds for remotely operated telescopes. It also provides a background on different cloud types along with information regarding closed circuit television (CCTV) lens sizes and the standards for different size sensors.

Chapter 3 critically evaluates the different methods of detecting clouds for remotely operated telescopes and provides a brief outline of the design plan.

Chapter 4 presents a detailed description of the equipment selected for the cloud detection system.

Chapter 5 discusses the methodology used throughout the project and describes the preliminary testing conducted to determine the selection of components for the final design.

Chapter 6 describes the overall design of the prototype cloud detection system and details the results of experimental trials.

Chapter 7 concludes the dissertation and outlines further work considered necessary before an actual system can be placed at Mt Kent Observatory.

Chapter 2

Literature Review

2.1 Clouds

Clouds are generally characterised in two different ways, by appearance and by altitude, including vertical development. There are three categories used to classify clouds by altitude, high clouds, middle clouds and low clouds. High clouds normally have bases above 6000 meters, middle clouds will generally occupy heights between 2000 to 6000 meters, and low clouds form below 2000 meters.

The appearance of clouds can also be broken down into three main categories, cirrus, cumulus and stratus clouds. Cirrus clouds are high clouds and therefore very cold and are made up of ice crystals. They are very thin and white in appearance and are often difficult to see with the naked eye at night. Cumulus clouds consist of globular individual cloud masses. They normally exhibit a flat base and have the appearance of rising domes or towers and may occur as isolated clouds or closely packed and usually fall into the category of middle level clouds. Stratus clouds form in sheets or layers that typically cover extensive areas of the sky and are generally low level clouds. Cirrus and cumulus clouds can also occur in a continuous manner over extensive areas of the sky and in this form they are usually described as cirrostratus and stratocumulus clouds respectively. In addition to these classifications, there are additional less common cloud genera used for specialised purposes such as aviation forecasts.

The term nimbus is also used in combination with cumulus and stratus to describe a severe variation of the cloud formation that produces significant rain. Nimbostratus is rare in Australia as it is typically the product of warm fronts, which are uncommon at Australian latitudes. Cumulonimbus clouds are commonly referred to as thunderstorm clouds. The development of these clouds can be triggered in a number of ways, including trough line convergence, convection, and lifting associated with cold fronts. Cumulonimbus clouds are common to most parts of Australia and can be very destructive. Although they typically form in an isolated manner, they account for almost all of the severe weather phenomena experienced in Australia.

Scattered fair weather cumulus clouds commonly form over land in many regions of Australia during the summer months and are particularly prevalent in sub-tropical regions. The formation of these clouds is a daytime phenomenon and is triggered by convection due to insolation. Fair weather cumulus usually appears in the morning, reaches a maximum development during the afternoon, and clears rapidly when the ground cools in the evening and are therefore unlikely to disrupt astronomical observations made later in the night.

Clouds such as high cirrus clouds, which may not be able to be detected by the naked eye, can reduce the accuracy of data collected by astronomers. For the purposes of astronomy it is therefore very important to be able to detect all types of clouds, as most astronomical observations require information of the cloud coverage at the time of observation. In the case of a remotely operated telescope it is also important to know the location of the clouds in the sky, in order to determine what parts of the sky can be observed. Using the actual telescope to determine cloud location and coverage would waste a significant amount of valuable telescope time as well as risking damage to the telescope from rain or other undesirable weather conditions if they were not previously known.

2.2 Current Techniques of Detecting Clouds

The most common methods used to detect clouds for existing remotely operated telescopes around the world are by use of weather reports and satellite images, infrared (IR) detection using thermocouples, and cameras aimed towards the sky.

2.2.1 Weather Reports and Satellite Images

Accurate and current weather reports and satellite images are often difficult to obtain for some areas and are not always as reliable as one might expect. They can provide general information regarding the weather in the region of the telescope and therefore can be useful in determining if the dome of the telescope should be opened in the case of rain or other potential damaging weather conditions. Weather reports are however quite limited in that they cannot provide the detailed site cloud coverage information necessary for astronomy nor are they updated frequently enough for observation purposes. They do not provide enough information on the type of cloud cover or the exact location of clouds in relation to the telescope.

2.2.2 Detection via Sky Temperature Measurement

A method that is currently used by some astronomers to detect clouds involves measuring and comparing the average sky temperature with ambient ground temperature using thermocouples.

The principle behind this method according to Ashley & Jurcevic (1991) is that the presence of clouds can be detected through the infrared emissions of the clouds. The presence of clouds produces an enhanced signal above that from a clear sky. This property has enabled cloud detectors to be developed according to Clay et al (n.d.) based on infrared sensors which respond to the relatively warm temperatures of cloud compared to clear sky. Thermopile infrared sensors are usually used to measure the temperature difference between the sky and the ambient temperature. A thermopile is a number of thermocouples connected in series. A thermocouple is a junction of dissimilar metals which produce a voltage when one side of the junction has a different temperature to the other (Fuji & Co. 2004). This method can also be achieved using the same principle by using a single thermocouple with one face positioned facing the sky, while the other plate faces the ground (Gillespie 2003). The infrared radiation from the ground warms the side of the thermocouple facing the ground, while the opposite side will measure a warm cloudy sky or a cold clear one. The voltage will vary between the plates depending on the change in temperature between the sky and the ground (See Figure 2.1).

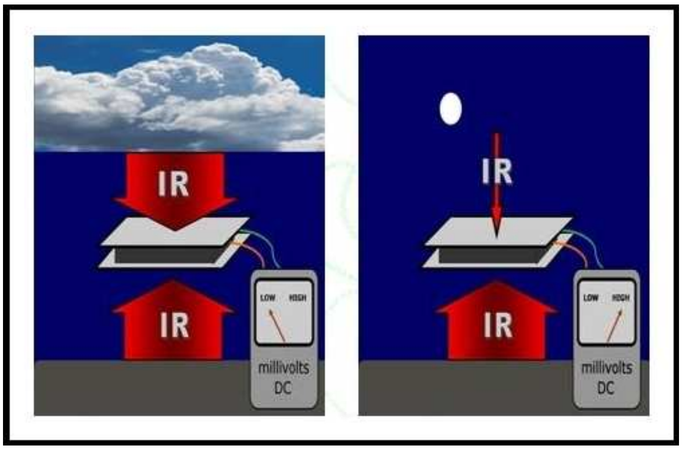

Figure 2.1: Thermopile infrared cloud sensor. The presence of clouds increases the temperature variance due to the clouds emission of infrared radiation detected by the thermopile between the two sides compared to a clear sky (Gillespie 2003).

This is a very effective method of detecting middle and low level, cumulus and stratus clouds, with some systems capable of detecting sub-visual high cirrus clouds (Boltwood 2004). Since it is crucial for astronomers to know the extent of cloud cover when making ground based observations a lot of research and development been conducted on this method of detecting clouds by individual scientists and astronomers and by universities such as the University of New South Wales and the University of Adelaide, as it is inexpensive and reliable solution. A simplified thermocouple IR cloud detector can be built at a relatively low cost with minimal effort. Detailed instructions are easily found on the World Wide Web on how to build such detectors. Papers such as, Droege 2003, Welch 2004 and Gillespie 2003 all give very clear instructions and design details on how to build a cloud detector using a thermocouple. Alternatively, the Boltwood Systems Corporation has designed and manufactured a commercial Cloud Sensor for the specific purpose of detecting clouds for a remotely operated telescope (see Figure 2.2). According to the Boltwood Cloud Sensor User's Manual the system uses a thermocouple to measure the sky temperature by sensing the infrared radiation from the sky in the 8 to 14 micron wavelength range. It then compares this reading to the ambient temperature at the bottom of the Cloud Sensor unit. From the temperature difference the Cloud Sensor is able to determine the average sky conditions. The Cloud Sensor has four output conditions that it will determine *Clear*, *Cloudy*, *Very Cloudy* and *Rain*.

Figure 2.2: Boltwood Cloud Sensor (Boltwood 2004).

Limitations of Sky Temperature Measurement

Whilst this system is very good at detecting clouds in the sky, it cannot determine where the clouds are located in the sky. When the thermocouple or thermopile measures the sky temperature it measures the sky's average temperature. It is possible that a cloud formation occupying only a small part of the sky could give a reading on the cloud detector of a value which could lead an astronomer into thinking the whole sky is unsuitable for observing when it is not. For example, during summer months in subtropical regions it is quite common for large isolated cumulus clouds with low bases to form. These clouds are therefore, relatively warm compared to the rest of sky. Should such a cloud form on the horizon in an otherwise clear sky suitable for observing, a thermocouple device may well erroneously indicate very cloudy or overcast conditions.

Other factors can also affect the accuracy of this type of cloud detector. Problems occur in regions where the ambient air temperature is subject to significant variations, such as is the case at MKO. The problems arise from comparing sky and ground temperatures in an ambient air temperature that varies from summer to the winter months. Another issue is that this method has a limited view of the sky. The Boltwood Cloud Sensor claims to have only an 80^o view of the sky with some sensitivity out to 120^o. This potentially limits the usefulness of the detector, as it may not detect some or all of the clouds in the sky.

2.2.3 Sky Camera

Use of cameras as cloud detectors for remotely operated telescopes is not a technique widely used by astronomers. Sky cameras are generally used for detecting clouds during daylight hours and have various other purposes. There are two main approaches that are generally used when imaging the sky. These are to use a fisheye lens on the camera and point it directly at the sky, or to mount the camera facing downwards over a convex mirror.

Using a fisheye lens is the preferred method of imaging the sky, as it is possible to image the whole sky without obstructions. The drawback of the mirror method is that the camera and its supporting struts will appear in the image. Both of these methods are relatively easy and straight forward for imaging and detecting clouds during the day time, however the difficulty arises when trying to implement either of these methods during the night in very low light conditions.

Cloud camera detectors have been implemented at both the Cerro Tololo Inter-American Observatory (CTIO) and at the Apache Point Observatory (APO). The CTIO cloud camera (CloudCam) uses a IMG1024S charged couple device (CCD) system (cost of U.S.$8254) with a Nikkor 8mm, f/2.8, 180^o fisheye lens (cost of U.S.$2495) mounted on a pillar aimed at the sky (Smith 2001). The total cost of this system was around U.S.$15000 according to Smith (2001). The CTIO CloudCam has proven to be a very effective cloud detector and due to its high resolution (960 pixels) and is capable of detecting diffuse cirrus clouds, which are almost impossible to see with the eye on a moonless night. The CloudCam structure and camera is shown in Figure 2.3.

Figure 2.3: CloudCam structure and camera at Cerro Tololo Inter-American Observatory (Smith 2001).

The APO Infrared Sky Camera (IRSC) pictured in Figure 2.4 uses Raytheon 300A Mid-IR detector, suspended above a hyperbolic solid aluminium mirror, which has been machined and polished (Ketzeback 2001). The camera used in this system (300A) works similarly to a low-resolution surveillance video camera. It produces an RS-170 video signal as an output at 30 Hz (or 30 images per second). This signal is transmitted to their main building where a standard video framegrabber digitizes the video. Software has also been written to analyse the pictures and determine the cloud coverage. Unfortunately there is little documentation reporting on the effectiveness of this system or the total cost. The Raytheon 300A IR camera used at APO is now obsolete however similar models produced by Raytheon range in price from U.S.$4000 to $11000 from America Infrared (www.americaninfrared.com/Raytheon.html).

Figure 2.4: APO Infrared Sky Camera (Ketzeback 2002).

There is another all sky camera project called the Continuous Camera (ConCam) project that is used to monitor the night sky. The goal of the ConCam is not to detect clouds, but to create useful continuous records of the night sky. This project is led by Professor Robert Nemiroff at the Michigan Technological University. There are 10 ConCams around the world including one at Siding Springs in Australia. Images of the night sky are available for all 10 of these locations and are updated every 4 minutes on the Night Sky web page (Available at http://nightskylive.net). Each ConCam consists of a CCD camera with a fisheye lens aimed towards the sky in a weather proof enclosure (See Figure 2.5).

The project is of interest because astronomers who operate telescopes within close proximity of a ConCam utilise the Night Sky web page to check images from their local ConCam for cloud coverage before making the decision to do any observing. Therefore the ConCam project unintentionally doubles as an effective cloud detector for those astronomers fortunate enough to operate telescopes in the same region as a ConCam. Unfortunately a ConCam at a cost of approximately U.S.$10000, are too expensive to form a practical solution for astronomers who require a cloud detecting system.

Figure 2.5: ConCam version 3, located at the Siding Springs Australia (School of Physics - The University of New South Wales, n.d.).

2.3 Lenses

A lens is a material that transmits light, with a special property that an image of a distant object is formed a certain distance behind the lens (Digibird 2002). This distance is the focal length. The focal length is the primary characteristic of a lens. Very simply, in a camera it is the distance from the lens to the imaging element or CCD, when focused on a subject at infinity. In other words, focal length equals image distance for a far subject, see Figure 2.6 below.

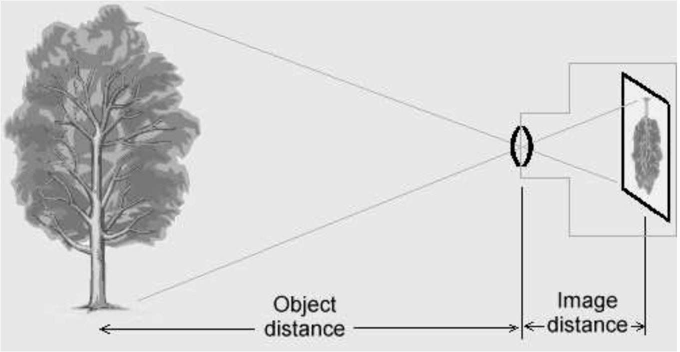

Figure 2.6: Focal length (source: Dahms n.d.)

The focal length for a single lens can be determined with the following formulas (2.1 and 2.2):

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{2.1}$$

Where d_o is the distance to the object, d_i is the distance to the image and f is the focal length.

$$\frac{h_i}{h_o} = \frac{d_i}{d_o} \tag{2.2}$$

Where h_i is the height of the image and h_o is the height of the object being imaged.

2.3.1 Angle of View and Field of View for Video Lenses

The angle of view is the shooting range that can be viewed by the lens given a specified image size and is normally expressed in degrees. The angle of view is measured assuming the lens is focused at infinity. The angle of view can be calculated if the focal length and image size are known using the following equation (Navitar n.d.).

$$\theta = 2\tan^{-1}\left(\frac{H'}{2f}\right) \tag{2.3}$$

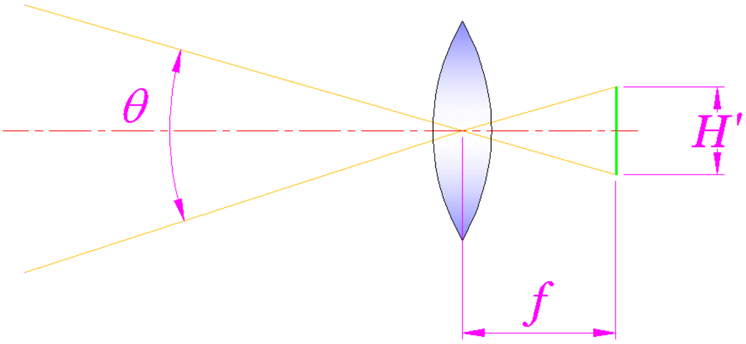

Figure 2.7: Angle of view of a lens.

If the distance of the object is finite, the angle is not used. Instead, the dimension of the range that can actually be shot, or field of view, is used using the following equation (Navitar n.d.).

$$H = H'\frac{l}{f} \tag{2.4}$$

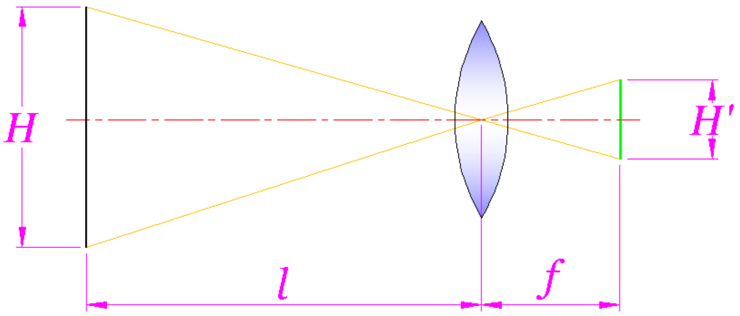

Figure 2.8: Field of view of a lens

The field of view of a lens decreases with increasing focal length. Another important point is that cameras with different image sensors chip sizes (such as 1/4”, 1/3”, 1/2”, 2/3” and 1”), using the same focal length lens, will yield a different field of view.

2.3.2 Aperture of a Lens

The other important parameter of a lens is the diameter, or aperture. The aperture determines the amount of light falling onto the film or sensor. The aperture affects the exposure and depth of field. Because of basic optical principles, the absolute aperture sizes and diameters depend on the focal length. Due to this apertures are normally expressed as fractions of the focal length. These relative apertures are called f-numbers or f-stops and are normally marked on the lens barrel in either fraction or ratio form. Because f-numbers are fractions of the focal length, ”higher” f-numbers represent smaller apertures.

According to Giancoli (2000) the f-stop is formally defined as:

$$f - stop = \frac{f}{D}, \tag{2.5}$$

where f is the focal length of the lens and D is the diameter of the opening.

2.3.3 Video Lenses

A lens produces images in the form of a circle, called the image circle. In a Closed Circuit Television (CCTV) Camera, the imaging element or CCD has a rectangular sensor area (the image size) that detects the image produced within the image circle. The ratio of the horizontal to vertical sides of a video image is called the aspect ratio which is normally 4:3 for a standard CCTV camera (see Figure 2.9 below).

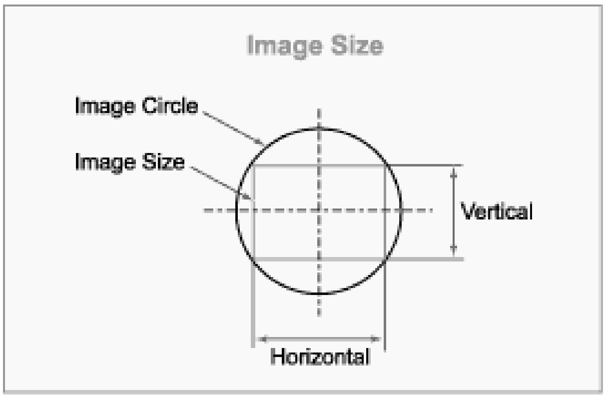

Figure 2.9: Image circle size for corresponding CCD (source: Navitar n.d.).

CCD's generally come in 5 standard sizes for CCTV cameras. Different size CCD's therefore require different size lenses for the image circle produced by the lens to cover the entire sensor (See Table 2.1 below).

Table 2.1: Image Sensor Standard Sizes and Corresponding Image Circle Sizes (Source: Navitar (n.d.)).

Image Sensor	**Image Circle**	**Horizontal**	**Vertical**
1/4"	∅4.0mm	3.2mm	2.4mm
1/3"	∅6.0mm	4.8mm	3.6mm
1/2"	∅8.0mm	6.4mm	4.8mm
2/3"	∅11.0mm	8.8mm	6.6mm
1"	∅16.0mm	12.8mm	9.6mm

From Table 2.1 it can be seen that lenses designed for a larger image sensor device will work on smaller size sensor, but will reduce the field of view of the lens. This is because only the centre portion of the image circle will fall on the image sensor.

The standard lenses used on CCTV cameras are C-mount and CS-mount. The two lenses differ from each other by having different flange distances and back focal lengths. The flange distance is the distance between the mechanical mount surface and the image sensor.

- C-Mount = 17.526mm
- CS-Mount = 12.526mm

The back focal length is the distance between the vertex of the rear element lens and the image sensor. Figure 2.10 gives a graphic representation as what is meant by flange distance and back focal length of a lens.

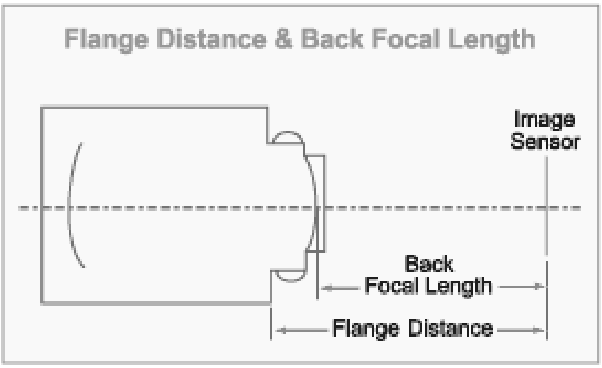

Figure 2.10: Flange and back focal length of CCTV lens (source: Navitar n.d.).

To use a C-mount lens on a CS-mount camera, a C/CS-mount adapter (5mm thick) is required between the lens and the camera (See Figure 2.11 for comparison of C-mount and CS-mount lens).

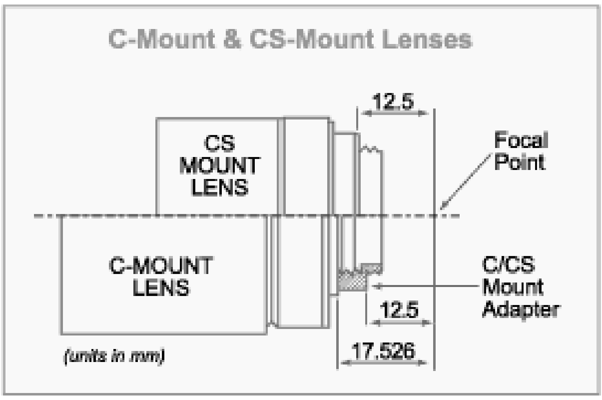

Figure 2.11: C-Mount and CS-Mount comparison of dimensions (source: Navitar n.d.).

2.4 Conclusion

Astronomers use three main techniques when trying to detect clouds for remotely operated telescopes. These include the use of weather reports and satellite images, IR detection using thermocouples, and imaging the sky with a low light camera. It was found that IR detection using thermocouples was the most widely used technique due to its reliability and simplicity. Camera systems were not as widely used due to their high cost and the added complexity of trying to image faint objects in low light conditions. Cameras do however; have an advantage over IR thermocouple systems in that they are able to detect the location and extent of clouds in the night sky.

CCTV C/CS-mount lenses are the most economical and widely available lenses on the market that are suitable for use on a CCD camera. Although CCTV lenses are produced in different sizes for different size CCDs, lenses designed for a small CCD such as a 1/4" CCD, are not widely available. Lenses designed for larger CCDs can be used on smaller CCD chips, but this reduces the field of view of the lens.

Chapter 3

Cloud Detection System Analysis

3.1 Evaluation of Cloud Detection Systems

The cloud detection system objectives state the system must be capable of not only detecting the presence of clouds in the night sky but also the locations of the clouds. Due to these specifications the cloud detecting system to be designed cannot be based on the use of weather reports, satellite images, or the sole use of infrared (IR) thermocouples to measure the sky temperature in order to determine the presence of clouds.

Weather reports and satellite imaging fail to meet the specifications of this project, as they are not site specific and the delays in production and low frequency of updates result in unacceptably low reliability and accuracy. IR detection using thermocouples to measure sky temperature whilst a very effective and economical method of detecting clouds, fails to meet the criteria for determining the location of the clouds it detects in the sky. Consequently, the method proposed to detect clouds for the Mt Kent Observatory (MKO) is to use a camera. This method has already been successfully implemented at Cerro Tololo Inter-American Observatory (CTIO) and the Apache Point Observatory (APO), however both these systems were expensive and a much more affordable system must be designed for MKO. It is anticipated that a low cost camera imaging system would certainly have the capability of detecting not only the presence of clouds, but also their location in the night sky when some moon illumination is present. On dark nights when there is little or no moon illumination to assist with the imaging of clouds, this approach still has the capability to be useful as the presence of clouds will correlate to an absence of stars in the camera image. Should the images taken on dark nights lack sufficient detail, it may also be possible to enhance their usefulness through image processing techniques.

Another significant factor, which contributed to the decision to use a camera to detect the clouds at MKO, is the subtropical climate experienced in this region. During the summer months the predominate cloud formation in subtropical regions tends to be isolated to scattered cumulus clouds, which, unlike high cirrus clouds, can be detected by the unaided eye in low light conditions and should therefore be detectable by camera. Cumulus clouds typically reach their peak formation in the late afternoon and often dissipate in the early evening after sunset and, in the MKO region, rarely cover more than half the observable sky. Under the right conditions of atmospheric instability cumulus clouds can develop significantly in vertical extent and transform into a cumulonimbus or storm clouds capable of producing heavy precipitation. These clouds tend to form in an isolated manner and provided they are sufficiently far away as to pose no danger to the telescope it is possible to still make useful astronomical observations in the rest of the sky.

3.2 Preliminary Design

Due to the high cost and limited availability of fisheye lenses along with the complexity of weather proofing a camera pointing upward at the sky, the design approach adopted for imaging the sky at MKO was to mount a camera facing downward over a convex mirror (similar to the system implemented at APO, see Figure 2.4). Additional investigation was required to determine the most economical components to be used for this cloud detection system. This involved determining:

- the suitability of cheap low light IR black and white charged couple device (CCD) security cameras as a cost effective alternative to purchasing an expensive IR camera;

- the feasibility of using commercially available exterior convex security mirrors as a low cost alternative to purpose built machined convex mirrors;
- the suitability of low cost lenses; and
- a low cost means of protecting the camera CCD from sunlight and high ambient light levels during daylight.

Analysis of camera images for cloud coverage information was conducted following hardware selection.

3.2.1 Analysis of Images from selected Camera

The illumination of the night sky, which can be as low as 0.0001lux on moonless overcast night (CMOS Image Sensors), can cause even the most sensitive low light cameras to have difficulty imaging any detail of the night sky at these levels. In view of this, two approaches for obtaining usable images of the night sky were investigated.

The first method investigated was the effectiveness of using a camera with variable shutter speed. The advantage of this feature is that if the shutter can be held open for a longer duration it will be able to gather more light and therefore produce a superior image. While this feature would normally be useless for motion photography it is suitable for this project as clouds will generally not be moving fast enough to affect the usefulness of the image.

The second method considered was to use signal processing to enhance the images. This was accomplished by writing Matlab code to improve the dynamic range of the images. By creating greater contrast in the pixel intensities a normally unusable image can be enhanced to the point where detail is visible to the eye.

3.2.2 Interfaces

An important factor requiring further investigation is how this project will interface with the weather station located at MKO. This is necessary as the telescope must be protected from wet weather conditions and therefore the dome must have a fail-safe system that prevents it from being opened in these conditions. It is envisaged that such a system would primarily utilise outputs from a Boltwood Cloud Sensor that is to be purchased for MKO. If the Boltwood Sensor output indicates that rain is detected, the dome must not be able to be opened remotely. It is probable that the cloud imaging system would serve as a manual backup to the Boltwood Sensor output by alerting remote users to the potential for rain from the location and extent of cloud coverage in images.

3.2.3 Protection from the Sun

As the camera will be permanently located outdoors facing vertically downwards over a convex mirror that will behave as reflector, it is essential that the CCD be protected from exposure to the Sun during the day. To be considered effective, the method of protection should activate automatically during daylight hours to prevent very high ambient light levels from entering the camera and potentially ruining the internal electronics. The preferred design approach is to utilise a commercially available photoelectric cell (daylight sensor) switch to operate an electrically powered mechanical device. Additionally, in order to preclude the possibility of damage to the camera CCD in the event of an electrical failure, it is a requirement for the protection method to incorporate fail safe, operation.

Chapter 4

Equipment

4.1 Introduction

As the aim of this project was to design an economical cloud detection system, an effort was made to design the system incorporating equipment already owned by the university rather than purchase new products unnecessarily.

4.2 Camera

Senior Physics lecturer and also co-supervisor of this project, Brad Carter from the USQ department Biological and Physical Sciences was able to provide a camera that was no longer being used by the department. The camera is an ST-4 Star Tracker Imaging Camera manufactured by Santa Barbra Instrument Group, Inc (SBIG Astronomical Instruments). Unfortunately, the ST-4 is an old model and no longer in production. As a result, it proved extremely difficult to find the required specifications and other useful information regarding this camera. This situation was further complicated by the fact that the original software, user manual, and camera lens were missing.

Prior to this camera being made available, much research had been conducted into the viability of using low light, black and white security cameras.

4.2.1 Black and White Security Cameras

The primary reason for investigating the suitability of low light, black and white security cameras is that they are relatively cheap compared to all other cameras on the market. Also being black and white, they are more sensitive to near infrared (IR) wavelengths and generally work better in low light conditions.

4.2.2 Measuring Lux

In order to determine the suitability of using a security camera, testing had to be conducted to determine the sky brightness.

The sensitivity of a camera is generally measured in lux, which is the SI unit for illumination. Illuminance is the power per unit area of visible light striking a surface and is measured in the unit lux, which is defined as a lumen per square meter. Lux measurements of the night sky were therefore required in order to determine what sensitivity camera would be required.

Testing equipment (Provided by the Army Aviation Centre, Oakey)

- Minolta Illuminance Meter T-10
- Minolta Chroma Meter CS-100

4.2.3 Testing Procedure

Firstly the illuminance meter (T-10) was aimed towards the sky on a dark night, however no value was able to be recorded as the illuminance meter was not sensitive enough to give a reading.

Since the illuminance meter (T-10) was not sensitive enough to give any measurements the chroma meter (CS-100) was used. The Chroma meter (CS-100) is a more sensitive instrument; however it differs from the illuminance meter as it measures the luminance (brightness) of a surface. The Chroma meter (CS-100) measures luminance in the unit called a foot-lambert. A foot-lambert (ftL) describes the luminance of a surface that emits or reflects one lumen per square foot. One foot-lambert equals 3.426259 candelas per square meter (Cd/m^2), which is an SI unit.

The Chroma Meter (CS-100) has a very narrow field of view and can be aimed at objects with a high degree of accuracy. It was found not to be sensitive enough to take any general readings of the luminance of the night sky unless it was aimed directly at a star that was easily visible to a dark adapted eye. In these cases it recorded the value of 0.01ftL or 0.0343Cd/m^2.

As neither of the tested instruments were sensitive enough to provide useful measurements of the illumination or brightness of the night sky, further literature searches were conducted. Table 4.1 is a summary of the illuminance and luminance of the sky under different conditions with data collected from Hahn (1996) and Micron Technologies (2005).

Table 4.1: Approximation of Illuminance and Luminance of the sky at various times of the day (Source: Hahn (1996) and Micron Technology).

Environment	**Illuminance Level (lux)**	**Luminance Level (Cd/m^2)**
Direct sunlight	100000-130000	
Overcast day	1000	1000
Very dark day	100	100
Twilight	10	10
Deep Twilight	1	1
Night sky - full moon	0.1	0.01
Night sky - no moon	0.001	0.001
Night sky - cloudy without moon	0.0001	0.0001

4.2.4 Investigated Cameras

Finding a suitable low light black and white security camera proved to be more difficult than initially anticipated due to the fact that most low light cameras utilise artificial illumination provided by IR light emitting diodes (LED) incorporated into the camera housing. This design appears to be due to the fact that most security cameras are intended to be used over a relatively short range. By incorporating several IR LEDs, it is possible to covertly illuminate the area of interest in non-visible IR wavelengths and make use of a cheaper camera with less sensitivity. This design feature however is of no use for the purpose of this project.

Several security cameras were investigated that potentially could have been suitable for detecting clouds at night time. The Ness IR-Extend Series Digital Cameras were a prime candidate. The IR-Extend cameras utilises the SONY EXVIEW HAD ultra high sensitivity charged couple device (CCD) sensor, which has an excellent spectrum response ranging from visible light to the near infrared (Ness Security Products). These cameras are highly sensitive in the 780-1100nm spectrum and can produce a useable black and white image with only 0.0002lux illumination. With the night sky having a minimum illumination of 0.0001lux on a cloudy moonless night (Micron Technologies, 2005) the IR-Extend camera should be capable of detecting the presence of clouds in the night sky. The only drawback of the IR-Extend camera is that it generates 25 pictures per second, which may be too fast to gather enough light in extremely low light conditions to produce a detailed image.

The Ness Zoomcam is another camera by Ness Security Products. This camera uses a 1/4” SONY SuperHAD CCD, which is less sensitive than the CCD used in the IR-Extend camera, as it is only sensitive to 0.1lux. This camera differs from the IR-Extend in that it is able to leave its shutter open for longer periods of time (slowing down the rate of pictures per second) in order to gather more light in low light situations. Due to this feature the Ness Zoomcam could also be capable of detecting clouds in the night sky.

Both of these cameras were relatively cheap in comparison to the cost of IR cameras which, as previously mentioned, can exceed the $10000 mark. The IR-Extend camera was quoted at \$335+GST and the Zoomcam at \$440+GST by Peter Burn at Ness Security Products on the 30 May 2005.

Other cameras were investigated; however they were not as sensitive under low light conditions or were considerably more expensive than the two cameras by Ness Security Products. It is difficult to determine exactly how well any of these cameras would perform when it comes to detecting clouds without actually testing them under controlled conditions. This was not possible as none of these cameras were available in Toowoomba. Still, there is good reason to believe that a security camera would be capable of detecting clouds or at least the presence or absence of stars, from the number of amateur astronomers using security cameras to detect meteors. Steve Quirk is an amateur astronomer who claims to be able to detect meteors with a Watec-902H black and white low light surveillance camera. The Watec-902H has a sensitivity of 0.0003lux, and according to Steve Quirk is capable of detecting stars and meteorites without the need to perform any signal processing. The Lowell Observatory is another example of successful night sky imaging utilising a security camera. The Lowell Observatory uses a Watec-903k black and white security camera to monitor clouds at night. This camera has a minimum lux rating of 0.0002lux and is able to provide information about clouds at night even when there is no moon. To achieve enhanced night time sensitivity, this system requires some signal processing which stacks the images. This results in a more detailed image which is capable of detecting clouds.

Investigations of specifications provided by manufacturers of security cameras and the information provided by astronomers with experience in imaging the night sky indicates that a low light black and white security camera with a minimum lux rating of 0.0002lux should be capable of detecting the presence of stars and clouds in the night sky.

4.2.5 ST-4

The SBIG Model ST-4 Star Tracker / Imaging Camera is a multipurpose instrument. It can be used as an automatic star tracker to take long guided exposures of the night sky, or, in conjunction with a personal computer (PC), as a highly sensitive imaging camera.

The ST-4 is a thermoelectrically cooled CCD imaging camera. The ST-4 uses Texas Instruments "TC11 192 × 165 Pixel CCD Image Sensor" chip. The physical size of the CCD is 2.6mm by 2.6mm with a total of 31000 pixels. The camera produces a black and white 8 bit digital image. A full image consists of 31872 bytes which is digitized to 8 bit accuracy. The internal cooling of the CCD reduces the detector thermal noise, therefore increasing the cameras ability of detecting dim stars. The CCD is cooled to a temperature near -30^o using a single stage thermoelectric cooler in the ST-4. The camera operates through a microcontroller (see Figure 4.1) which can communicate with a PC over the RS-232 serial link of the ST-4. A full image can be transmitted at 19.2 baud within 18 seconds and over a distance of 30 meters. Data transfer rates can be as high as 57.6 baud over shorter distances (SBIG 2005).

Figure 4.1: ST-4 CCD camera and microcontroller (SBIG 2005).

The ST-4 is designed to be used in conjunction with a telescope to take images (see Figure 4.2 below). However the SBIG website states that it is possible to use an SLR lens on the ST-4 camera with an adapter. This feature means that it could be possible to use this camera to image the night sky in order to determine the presence of clouds. Another attractive feature of the ST-4 is that the exposure time of the camera can be varied between 0.01 to 600 seconds. This feature is desirable for the purposes of this project as telescopes are located in dark regions away from the light pollution of towns and cities. This means that there is very little stray light at a telescope site and therefore, long exposure times are a practical means of creating a more detailed image of the night sky. Although the ST-4 is capable of exposure times as long as 10 minutes the ST-4 Operators Manual does not recommend exposure times greater then 5 minutes as the CCD array elements can slowly fill up in the dark due to a phenomenon called dark current, and they saturate at about the five minute point. This can be reduced to an extent by creating a dark frame for the same time frame as the desired exposure time prior to capturing an image, which is than subtracted from the image.

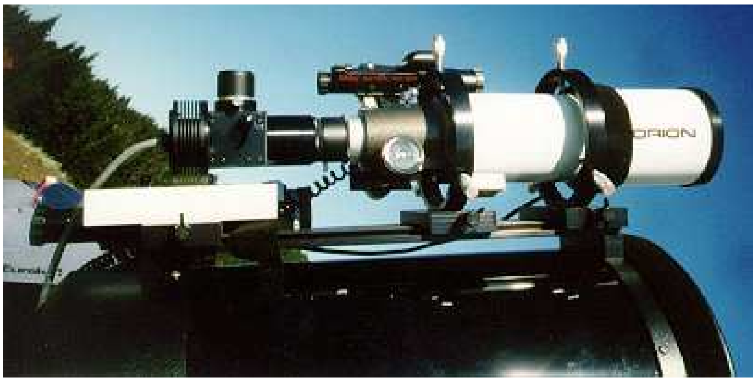

Figure 4.2: ST-4 CCD camera (pictured to the left of the image) attached to a telescope, how it is designed to be used (Haworth 2003).

4.2.6 Selected Camera

The preferred camera and potentially most suitable for use in the cloud detection system was a low light black and white security camera with either a sensitivity of 0.0002lux or the ability to increase the exposure time of each frame during low light conditions. Notwithstanding this preference, since the ST-4 camera was made available by the physics department free of charge, it was decided to utilise this camera for the cloud detection system.

4.3 Software

The ST-4 has no manual controls on the camera and therefore can only be driven by software. The original software package that came with the ST-4 to operate the camera was unable to be located. This software, CCDSoft Version 5 is available from SBIG, but costs U.S.$350 (SBIG 2005), therefore much time and effort was spent finding a software package on the internet that could operate the ST-4 and was also free to download. A program called ImCap (IMage CAPture) was finally chosen as it matched both of these criteria. It can be downloaded from a link on the SBIG website (www.sbig.com).

ImCap image capture software for the ST-4 is freeware written by Howard C. Anderson. This software was written for Windows 95/98 and was designed to control the imaging functions of the ST-4, but not the tracking functions, which was all that was required for the purpose of this project.

ImCap software is a very basic software package which has limited control over the ST-4. Its main function is to capture images and control the exposure time. It produces a square bitmap image 57mm × 57mm.

4.4 Mirror

A nominal 30cm diameter security convex mirror with a radius of curvature of 33.16cm made by 'Safe-T-View' was selected for the convex mirror. A small mirror was chosen not only to keep costs down, but also because of the small size of the ST-4 CCD. All of the readily available closed circuit television (CCTV) lenses were designed for a CCD larger than that of the ST-4 and therefore when used with a smaller CCD, the field of view is significantly reduced. This problem can be effectively overcome by using a smaller convex mirror. A larger mirror would require either a specialised and more costly lens with a larger field of view or the CCD to be located at a greater distance from the mirror in order to image the entire mirror.

4.4.1 Mirror Dimensions and Calculations

The actual diameter of the convex mirror was measured to be 280mm and the vertex height was measured to be 31mm from base plane to the upper mirror side. From these two measurements it was possible to determine the radius of curvature of the convex mirror using Pythagoras's Theorem to be approximately 331.63mm. See Appendix B for calculations.

Calculation of the radius of curvature of the convex mirror was necessary to determine the theoretical angle of view of the mirror and evaluate its suitability. In order to accomplish this, the following assumptions had to be made.

- The mirror is a section of a perfect sphere.
- Lens 3 would be the most suitable lens.
- Lens 3 would be placed 27cm in height above mirror (calculations of height of lens 3 were made with equation (2.4), see Appendix B).

From basic geometry, the angle of view for the convex mirror was calculated to be 155^o (See Appendix B for calculations). From these calculations it was decided that the convex mirror would be suitable as it would be capable of seeing the majority of the sky.

4.5 Lens

Three lenses were obtained and tested to determine there suitability for use on the ST-4. All three lenses were standard C-mount lenses, which are usually used for CCTV security cameras. The reason C-mount lenses were chosen was because they are inexpensive, widely available and they are the closest match in size to the mount on the ST-4. The three lenses that were tested are listed in Table 4.2 below. Three lenses were obtained and tested to determine there suitability for use on the ST-4. All three lenses were standard C-mount lenses, which are usually used for CCTV security cameras. The

reason C-mount lenses were chosen was because they are inexpensive, widely available and they are the closest match in size to the mount on the ST-4. The three lenses that were tested are listed in Table 4.2 below.

Table 4.2: Lenses Tested on the ST-4

Characteristics	**Lens1**	**Lens2**	**Lens3**
Focal length (mm)	16.0	8.0	2.5
Image Circle (mm)	16.0	8.0	6.0
Corresponding Sensor Size	1”	1/2”	1/4”
f-stop	1.6	-	1.6
Lens Mount	C	C	CS
Iris type	fixed	fixed	auto (DC)

4.6 CCD Sensor Daylight Protection

Simplicity, reliability, fail safe operation, and minimum image obstruction, were the design criteria for the ST-4 CCD daylight protection system. After evaluation of several options, an automatic iris lens was selected as the best means of protecting the ST-4’s CCD sensor from the sun during the day. Given the overriding budget considerations, this implementation was assessed as being the simplest, most reliable, and least obstructing way of achieving protection for the CCD during the day that could be automatically activated. The auto iris is also fail safe in that it automatically closes if no voltage is applied. Other design approaches considered included a linearly moving cover controlled by a small actuator, and a small electric motor with a gear system that could drive a cover to rotate around the lens. After investigation, both of these options were assessed to be mechanically difficult to ruggardise sufficiently for outdoor use and the implementation was estimated to be unacceptably large and to obstruct too much of the image.

Control of an auto iris can be economically achieved by using a commercially available exterior 240V photoelectric cell daylight switch and small commercial DC power supply. The photoelectric switch will be open during the day and therefore not provide any power to the power supply for operation of the auto iris. When it is dark the photoelectric switch automatically closes, providing power to the power supply which will then open the auto iris.

4.7 Conclusion

The conceptual design (see Figure 4.3), is to place the ST-4 in a locally fabricated waterproof housing at height of approximately 27cm directly over the 28cm diameter convex security mirror. Piping will be used to not only support the camera housing, but also to protect the cables running to the camera and the lens. A single support strut was preferred as it minimized obstruction of the sky image. The camera's 12V power supply and microcontroller along with the power supply for the daylight CCD cover will be situated under the mirror in a locally fabricated waterproof box style container which also serves as the mount for the mirror. It is envisaged that the structure would be mounted on a pole concreted in the ground at a suitable location to be chosen following a site survey. Alternatively, it is possible that it could be mounted on the roof of an existing building with appropriate brackets and cable access however this approach may result in maintenance access difficulties. Spikes on top of the camera support pipe will probably be required to keep birds from perching on the structure and a series of fishing lines extending down from the camera to the mirror edge may also be needed to prevent birds from landing on the mirror. It is hoped that by deterring birds the mirror will stay cleaner and undamaged for longer.

As the system is not required to be powered during the day, the simplest method of controlling the power to the cloud detection system is to route the mains power supply through a 240V photoelectric daylight switch. By doing this the power will only be supplied to the system at night and will be switched off during the day.

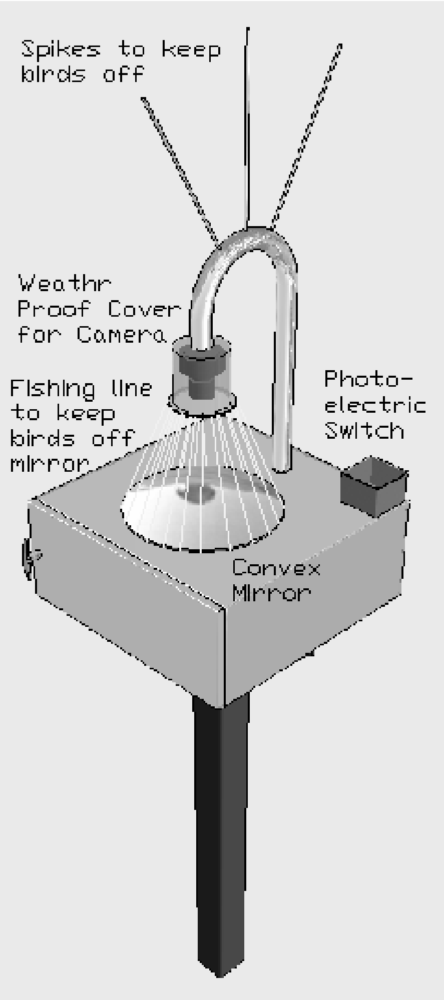

Figure 4.3: Conceptual design of cloud detection system implementing the ST-4.

Chapter 5

Design Approach

This chapter sets out the methodology for designing the cloud detection system and combines both theoretical and experimental techniques.

5.1 Theoretical Component

In order to design an effective cloud detection system a significant of amount of background research was required.

The theoretical component of this project was to research information regarding climate and the types of clouds and their formation. This was followed by investigation of the different techniques currently being used to detect clouds in low light conditions. The next step was to critically evaluate the existing cloud detection systems for remotely operated telescopes in order to decide on the design approach for the cloud detection system for the Mt Kent Observatory (MKO). Further investigation of night ambient light levels under various moon illumination and cloud coverage conditions was also necessary enable minimum camera specifications to be finalised. Lens and mirror optics and signal processing investigations were also required.

5.2 Experimental Component

The experimental component of the project was not able to be conducted until the camera and the convex mirror had been acquired. Prior to this no detailed design could be undertaken as the physical characteristics and interfaces were unknown. Following the procurement of components the design process was largely experimental, as a prototype cloud detector was required to be built and tested and analysed.

5.3 Preliminary Testing of the ST-4, Software and Lenses

Initial testing of the ST-4 was conducted indoors using the ImCap software (see Section 4.3). The ST-4 was designed to be used in low light conditions and therefore all testing had to be done either at night or in a dark room so that the pixels were not over saturated due to excessive light.

The original lens mount that came with the ST-4 was designed to be attached to the end of a telescope. Because of this the length and width of the barrel were too large to fit a standard C-mount lens (see Figure 5.1 for dimensions). This required the construction of a new mount in order for a standard C or CS-mount lens to be fitted.

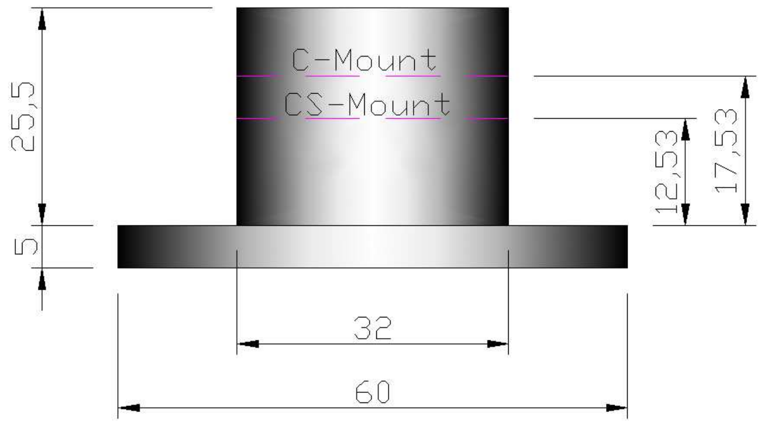

Figure 5.1: Original lens mount dimensions for the ST-4, along with the flange heights for the C and CS-mounts (as stated in Figure 2.11).

The new mount was made to the same dimensions of the original mount, except for the length of the barrel was shortened to a height of 12.0mm above the base height (base height is the same height as the CCD sensor, 0.5mm) to match the flange height of a CS-mount lens. A threaded adapter was also made to screw into the barrel so that a C/CS-mount could be fitted and adjusted to fine tune the focusing.

The testing plan for the cloud detection system required initial trials in order to get the ImCap software to talk to the camera. Once this was accomplished it was possible to commence testing utilising lens 1 (Table 4.2) which had been made available. The primary purpose of these tests was to determine the suitability of the ST-4 with a secondary aim of obtaining data to assist in determining the lens characteristics that would ultimately be required. Once the appropriate lens had been determined and procured, further testing would be required to determine if the ST-4 could effectively detect stars in the night sky. If successful, further design and field testing could be conducted with the convex mirror to confirm the overall system design.

5.3.1 Preliminary Test Procedure

The lenses were tested in extremely low light conditions pointing the camera at a small light source, such as an LED. By this method it was possible to determine firstly if the camera could detect the light source and produce a clear image with varying exposure times, and secondly, to determine by simple geometry the approximate angle of view of the lens. This was achieved by measuring the sizes of the picture and the image of the light source and comparing these to the actual size of the light source. With this information and knowing the distance from the camera to the light source, it was possible to get an approximate measurement of the field of view produced by the lens.

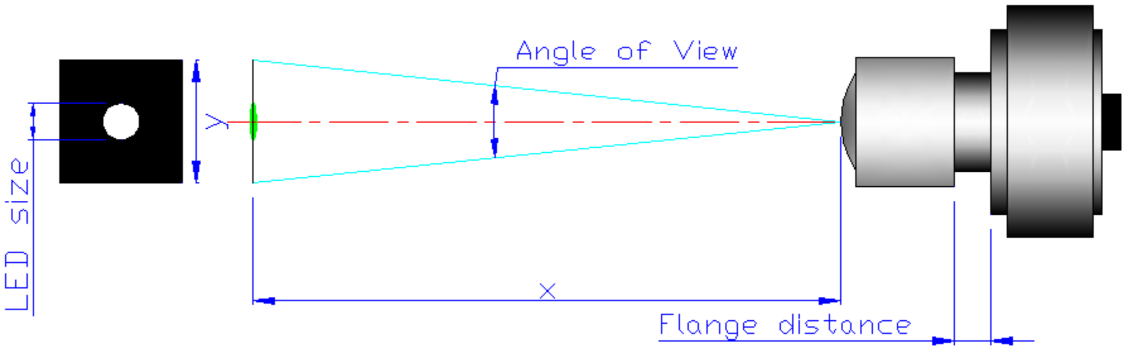

Figure 5.2: Preliminary testing setup of ST-4.

Procedure:

1. Placed yellow 3mm diameter LED in line with ST-4 at a distance of x.
2. Captured image using ImCap software.
3. Checked the clarity of image, if image was sharp skipped to step 5.
4. Adjusted either exposure time or position of lens from the CCD, back to step 2.
5. Measured picture size and the size of the LED in the picture and compared this to the actual size of LED (3mm). From this calculated the field of view of the picture.
6. Calculated the corresponding angle of view of the lens from the formula below:

$$\theta = 2\tan^{-1}\left(\frac{y}{2x}\right) \tag{5.1}$$

5.3.2 Results of Preliminary Testing

The purpose of these tests was mostly to gain an understanding of the ST-4 and the software package. The ST-4 had not been used in many years and it was not known if the camera still worked. Considerable time was expended in setting up the software to communicate with the camera due to complications with hardware interfacing. The

ST-4 requires a serial port, which is no longer common on modern computers and the configuration required for the serial connection was unknown.

Initial testing with lens 1 revealed that the barrel or lens mount on the ST-4 was to long for the focal length of the lens and a new mount had to be constructed before further testing could be undertaken.

Once the new mount was fitted more reliable results were possible as the correct flange distance could be obtained. This provided focused sharp images. The image size produced by ImCap is a 57mm × 57mm square black and white bitmap.

The angle of view of lens 1 was expected to be quite small when used on the ST-4 as it is designed for a 1” CCD sensor and has a focal length of 16mm. The image circle created by this lens has a 16mm diameter, which means most of the image does not fall on the 2.6mm × 2.6mm CCD sensor used on the ST-4. As only a small portion of the image falls on the CCD the angle of view is reduced significantly. If the lens were used on the correct size sensor it would have an angle of view of 33.4^o.

Before Testing an estimation of the angle of view was calculated using equation (2.4) to get an approximation as to what should be expected.

$$\begin{aligned}\theta &= 2\tan^{-1}\left(\frac{H'}{2f}\right)\\ &= 2\tan^{-1}\left(\frac{2.6}{2\times 16}\right)\\ &= 9.3^o\end{aligned}$$

The images obtained from this initial testing can be found in Appendix C. It was estimated from these images that the angle of view in practice was approximately 0.47^o which is about twenty times less than the lens theoretical value of 9.3^o.

Lens 2 was also tested in the same way. Lens 2 was also suspected not be suitable as it had a focal length of 8mm and was designed for 1/2” CCD sensor as its image circle was 8mm in diameter. Its potential angle of view is 33.4^o if used on the correct size sensor.

The angle of view was expected to be approximately 18.5 degrees when used on the ST-4. This was determined from using equation (2.4), however from analysing the images in Appendix C, it was found by the same method that the angle of view was actually about 0.8 degrees or roughly twenty times less than the theoretical value.

5.3.3 Preliminary Testing Discussion

Lenses 1 and 2 were not expected to be suitable for this project application as they were designed for larger CCD sensors than that of the ST-4. In addition to their focal lengths being far too long to have a useful angle of view, this meant that too much of the lens light gathering power would be wasted. Nevertheless they were useful tools, aiding in the understanding of the ST-4 hardware and software operation.

These tests revealed several characteristics of the ST-4 which would affect the design of the system. It was known that the ST-4 is thermoelectrically cooled to lower the noise floor of the CCD. This is a very valuable property, but can affect the ability of the ST-4 to take images if the camera is left switched on for too long or the lens mount is not sealed air tight over the CCD.

During the testing process the lens mount was taken off and on several times to be modified to fit the different lenses as required. This meant the mount was not always properly secured during the tests. It was found that if the camera were switched on for a long period of time or the mount was not properly secured, the CCD sensor would eventually frost over, distorting the images. Although not anticipated, this frosting was simply the result of ambient moisture in the air condensing and eventually freezing on the thermoelectrically cooled CCD. The differences in image quality can be seen below in Figures 5.3:

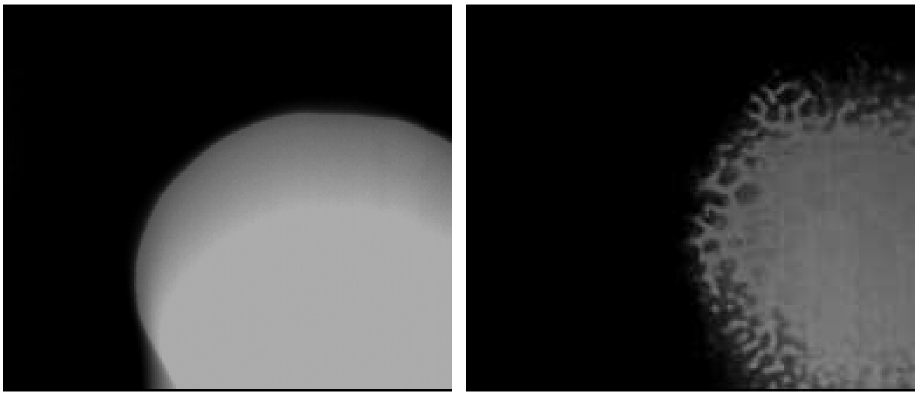

Figure 5.3: Comparison of images taken with the ST-4 of an LED. The image on the left was taken before condensation had formed on the CCD, while the image on the right was taken after condensation had developed on the CCD and crystalised.

The image on the left is of an LED and was taken just after the ST-4 was switched on. The image on the right is of the same LED but was taken an hour later, after a layer of frost had developed on the sensor. It is considered that the frosting effect could be minimised if not eliminated altogether by minimising the cavity between the lens and the CCD and then sealing this cavity under appropriate low humidity conditions so that it is air tight. This action would significantly reduce the amount of moisture available to condense on to the CCD sensor and freeze and should eliminate the problem for all practical purposes.

During testing this issue was kept in mind and the camera was only switched on for small time intervals when the mount was not properly secured.

Another characteristic of the ST-4 that caused problems when imaging bright objects or using long exposure times was the formation of bright lines directly below the object. This can be seen in Figure 5.4below, where an LED was being imaged with an exposure time of 11 seconds. Unwanted lines form downward from the bright object. It isn't exactly known what causes this, but it is most likely due to the charge in the CCD array elements filling up and leaking into the adjacent element. This effect can be minimised by adjusting the brightness and the exposure time in the ImCap software, however it is difficult to avoid when long exposures are needed.

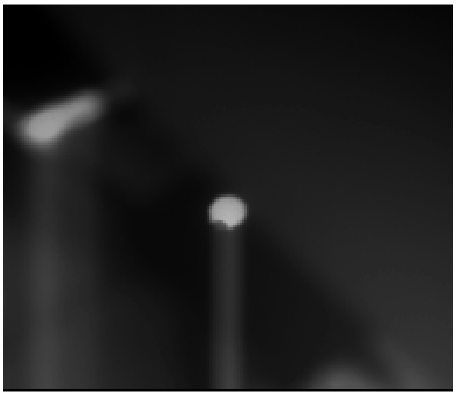

Figure 5.4: Image taken of an LED where the brightness of the LED caused the CCD array elements to saturate and spill over into the next elements causing a white line vertically downward from the LED.

It was also found that the lens mount was affecting the angle of view these two lenses as the field of view measured for both lens 1 and 2 was significantly less than their theoretical values. It was calculated that lens 1 should have an angle of view of approximately 9.3^o and lens 2 should have had a value of approximately double, 18.5^o as its focal length was half as long. The measured value for lens 1 was 0.47^o and lens 2 was approximately double lens 1, with an angle of view of 0.8^o. The fact that the measured values were out by a factor of 20, but still proportional to their theoretical values, indicated that some aspect of the physical setup, either the mount or the CCD location, had to be interfering with the lenses. The cause of this effect on the lenses was eventually isolated and found to be the perspex cover over the CCD in the lens mount.

The original lens mount on the ST-4 had an optical flat to protect the CCD and also to minimise the air gap around the CCD in order to prevent the sensor frosting over. When the workshop built the new mount, they were not able to protect the sensor with an optical flat, but instead used a 3mm thick piece of perspex. The optical properties of the perspex significantly affected the angle of view the lenses and caused unwanted distortions later during the initial testing with lens 3.

5.4 Experimental Trial

It was found from testing lens 1 and 2 that the effect of using a CCTV lens on such a small CCD, such as that used on the ST-4 (2.6 × 2.6mm) reduced the field of view of the lens significantly. This is because the CCD is much smaller than the image circle of the lens and therefore only a small portion of the image falls on the CCD. This effect can be minimised by using CCTV lenses designed for a smaller CCD. The smallest standard CCTV CCD size is 1/4” (3.2mm × 2.4mm), see Table 2.1. 1/4” CCTV lenses have an image circle of 4mm in diameter. This size lens would be ideal for the ST-4 as almost the entire image would fall on the chip, which would mean that the field of view would not be reduced. Unfortunately these lenses are not readily available in Australia.

The smallest size CCTV lens that could be easily obtained is one designed for a 1/3” CCD. These lenses produce an image circle 6mm in diameter. Using this size lens on the ST-4 would mean that over half the image would be wasted and the field of view would be reduced considerably. As a result it was decided that a wide angle lens would be the only way to achieve the desired field of view.

The field of view of a lens is directly related to the focal length. A shorter focal length will result in wider field of view. The smallest focal length of commercially available CCTV lenses is 2.5mm. Before purchasing 1/3” 2.5mm CCTV lens some basic calculations were undertaken to ensure its suitability of being able to image the 280 mm diameter convex mirror.

- Convex mirror diameter, $H = 280$mm
- CCD sensor height, $H' = 2.6$mm
- Focal length of lens, $f = 2.5$mm

Field of View formula (2.4):

$$H = H' \frac{l}{f}$$

From equation (2.4) the theoretical height the camera must be placed above the convex mirror was calculated as follows:

$$\begin{aligned} l &= f\frac{H}{H'} \\ &= 2.5\frac{280}{2.6} \\ &= 270\text{mm} \end{aligned}$$

It was found that using a lens with a 2.5mm focal length in conjunction with a 2.6mm × 2.6 mm CCD would be capable of imaging the entire convex mirror at a reasonable distance of 270mm.

When purchasing the lens another factor that had to be taken into consideration was how to protect the CCD from the sun during the day light hours. By situating the camera pointing downwards over the convex mirror, the CCD is at risk of being damaged by excessive sunlight reflected off of the mirror. The best solution to this problem was determined to be the use of a lens with a DC automatic iris. Most CCTV cameras require an auto iris lens so that the amount of light entering the camera can be adjusted automatically in response to light metering outputs. Auto iris lenses are normally closed and the iris can only be opened when plugged into a CCTV camera, where the camera then is able to control the iris and adjust the aperture depending on the light. By incorporating an auto iris lens into the design of the cloud detection system the CCD in the ST-4 could be protected from the sun during the day. The iris would be controlled by a photoelectric switch, which would open the iris after dark and close it during the day. Another advantage of using an auto iris as a means of protecting the CCD is that it is fail safe. If the power were to be interrupted the iris would automatically close, as it requires voltage to open the iris.

Given that the above calculations indicated that a lens with a 2.5mm focal length would possess a field of view suitable to image the entire convex mirror at reasonable height of approximately 270mm and from the auto iris discussion above, it was decided that a 2.5mm focal length, 1/3", auto iris lens would be purchased for the prototype cloud detection system.

5.4.1 Automatic Iris

The specifications of the auto iris were not provided with lens 3 when it was purchased. This lead to delays in testing as nothing could be achieved with the iris closed. With assistance from Brett Richards (Electrical Technical Officer at USQ) it was established that 3V DC was required across pins 3 and 4 (pin 3 is positive and pin 4 is negative) on the auto iris plug (see Figure 5.5 for pin layout) to fully open the iris. The resistance of lens 3 auto iris was measured to be approximately 200Ω. As the auto iris requires 3V to fully open, it should draw roughly 15mA, which is well within the capacity of a cheap small commercial power supply.

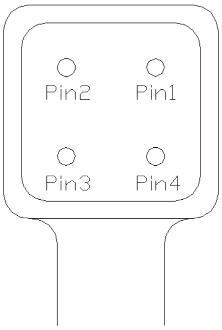

Figure 5.5: Pin layout for auto iris cable plug on lens 3.

5.4.2 Experimental Verification of Design

The design of the system was based on the calculations presented in Appendix B. Two conclusions drawn from appendix B were that the ST-4 camera should be placed facing downwards over the convex mirror at height of 27cm above the base of the mirror in order to image the entire 28cm mirror and that the overall system would have a theoretical field of view of approximately 155^o or, in other words, 12.5^o above the horizon by using the 28cm diameter convex mirror.

Before proceeding to the prototype system it was necessary to confirm the theoretical calculations. This was achieved by placing the camera at a height of 27cm above the base of the mirror and securing it with an apparatus stand. The mirror was placed directly below and centred beneath the ST-4. In order to take accurate measurements and make the fine adjustments necessary to the set up it was decided to perform this testing during the day in a partially darkened room. The ST-4 and the mirror were placed in a 27cm high box to minimise the amount of light entering the ST-4 (see Figure 5.6) as overexposure of the image is a likely outcome under these lighting conditions even when the shortest exposure times are utilised.

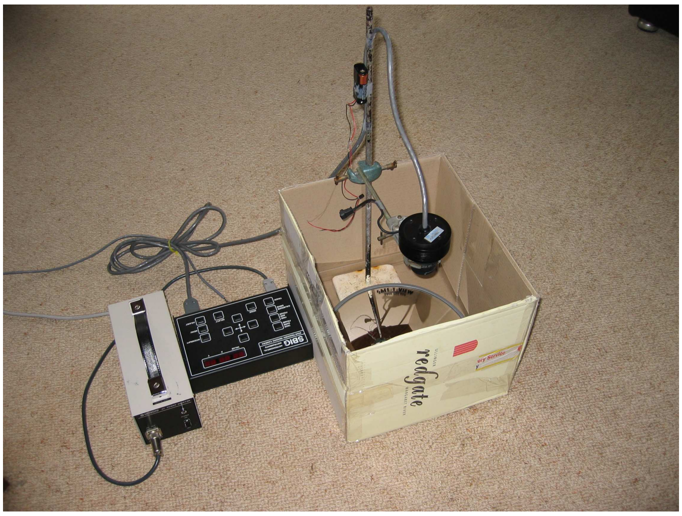

Figure 5.6: The setup of the ST-4 and mirror to determine the appropriate height the camera should be placed above the mirror plane.

It was found that the theoretical height very closely matched that required in practice. The image shown in Figure 5.7 was taken with the ST-4 at a height of 27cm and it can be seen the entire circle of the convex mirror just fits the size of the image confirming the theoretical calculations. Note that the image quality is somewhat degraded due to the protective plastic covering being left on the mirror to prevent accidental damage.

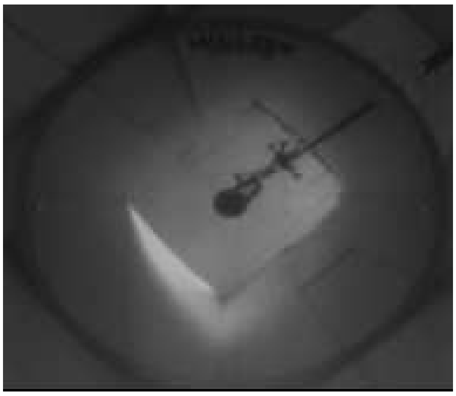

Figure 5.7: Image taken with the ST-4 situated at a height of 27cm above the base of the mirror with an exposure time of 0.19s.

To verify the field of view of the mirror to be approximately 155^o the ST-4 was once again secured vertically over the convex mirror with an apparatus stand at a height of 27cm. To determine the angle of view a laser level was set up on a tripod and the laser beam was angled downward so that the laser beam was focussed at the edge of the mirror and the reflected beam was observed to appear precisely on the centre of the lens. It was critical that during this test that iris on the ST-4 camera was always closed so that the CCD would not be damaged by the high intensity laser beam. Figure 5.8 illustrates the setup of this test. It can be seen that the laser beam strikes the edge of the mirror and is reflected on to the lens which can also be seen the mirror as another reflection.

Figure 5.8: System setup to verify the viewing angle of the sky would be approximately 155^o if the ST-4 is placed 27cm above the base of the mirror. The laser is focused on the edge of the mirror at an angle of 15^o off the horizon, and is reflected directly onto the centre of the lens.

It was found that the laser beam could be reflected onto the centre of the lens if the laser was focused on the edge of the mirror at an angle of 15^o above the horizontal. A closer picture was taken of the mirror to demonstrate that laser beam was reflected precisely onto the lens from an angle of 15^o above the horizontal is shown in Figure 5.9 resulting in a field of view of approximately 150^o. It can be seen that the protective plastic is still on the mirror. This was to prevent the mirror from being damaged before building the prototype and although the image quality is therefore degraded, the laser images are clearly visible.

Even though the angle of view was calculated in theory to be 155^o, it was found in practice from this test that the actual angle of view was approximately 150^o. This value is still very close to what was predicted and within 5% error, proving the mirror to be suitable for the cloud detection system. The most likely explanation for the small but measurable difference between the practical and theoretical field of view is the presence of a raised rubber rim around the edge of the mirror interfering with the light rays arriving at lower angles.

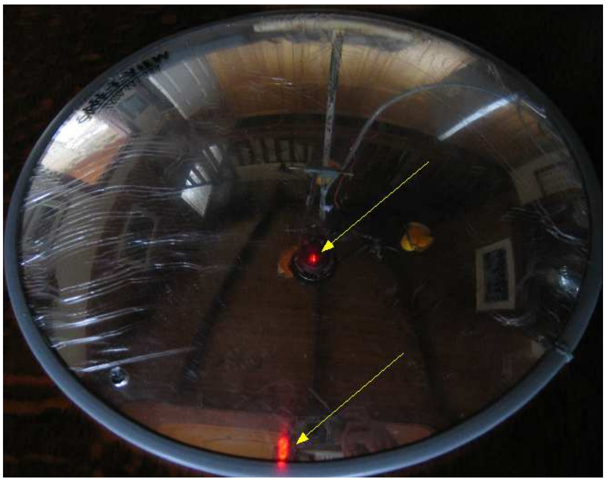

Figure 5.9: Close up photograph of the convex mirror proving the laser beam that is focused on the edge of the mirror at an angle of 15^o is reflected onto the centre of the lens which can be seen in the reflection of the mirror.

5.4.3 Sky Imaging

The first attempts to image the sky with ST-4 were performed by aiming the camera towards the sky (not implementing the mirror) and securing it with an apparatus stand. Unfortunately, when these trials were conducted it was unlikely that the lens was focused on the ST-4 and the 3mm thick piece of perspex which had previously affected field of view measurements with lenses 1 and 2 was present between the lens and the CCD. Focus adjustments were not made as there was no clearly visible object at a distance of optical infinity, such as the moon in the sky, to permit adjusting images to be taken to ensure focus could be achieved.

Despite this, two images were taken of the sky on a dark night, one with a five minute exposure time which can be seen in Figure 5.10 and the other with a ten minute exposure time seen in Figure 5.11 below.

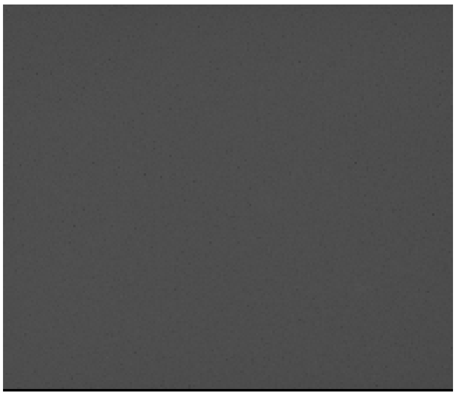

Figure 5.10: Image of the sky taken with the ST-4 (lens 3) on a clear night with an exposure time of 5 minutes (the lens was not able to be precisely focused for this image and the perspex CCD cover was present). The stars are not apparent in this image compared to the image after it has been enhanced, see Figure 5.12.

Figure 5.11: Image of the sky taken with the ST-4 (lens 3) on a clear night with an exposure time of 10 minutes directly after the previous image (the lens was not able to be precisely focused for this image either and the perspex CCD cover was still present). The stars are not apparent in this image compared to the image after it has been enhanced, see Figure 5.13.

From viewing these two images it appears that there is no information in either image and that doubling the exposure time from 5 minutes to 10 minutes had no effect on the quality of the image as both images appear uniformly grey at first glance. When closely examined it can be seen that there is some detail in both these images, however it is practically impossible to discern any features. Due to the extremely poor quality, it was decided that these images would be suitable candidates for the investigation of image processing techniques for use with ST-4 camera images.

To better analyse these images a signal processing method was implemented called image equalisation. This method involves firstly determining the histogram of each of these images. Once the histogram was produced a cumulative histogram could than be plotted adding all the pixel intensities. From the cumulative histogram a new image could be constructed which spread out the pixel values creating an image with a greater contrast in colours. This equalisation technique is somewhat limited in that it cannot improve the image. It can only create a contrast between the pixel values, therefore not eliminating any of the noise present in the images, but rather enhancing it to an extent.

The Matlab code for this image equalisation method can be found in Appendix D. This code also plots the histogram and cumulative histogram of the new image. This code also produces an inverted image of both the original and new image, as sometimes features can appear more prominent on a lighter back ground as opposed to a dark one.

The code was first trialled on the two images taken above in Figures 5.10 and 5.11 to determine if the rectified images created by this code produced features more visible to the eye by creating a greater contrast between the pixel intensities and also to determine if increasing the exposure time from 5 minutes to 10 minutes increased the image quality.

The histograms and rectified images produced by the code can be found in Appendix E. From analysing the histograms of the original images it was found that the pixel values were very close together ranging between values of about 72 to 82. These values were than spread out to create images with a greater dynamic range which can be seen in the histograms of the new images. It must be noted that the number of pixel values used in the image can not be increased, only redistributed by spreading the values out, hence creating a greater contrast in pixel values. From analysing the two rectified images (shown below), not much can be determined apart from three small light patches which are more evident in the 10 minute exposure image (Figure 5.13). These images demonstrate the principle of image equalisation. The new images have a much larger dynamic range than the original images and much more detail can be seen in the images without any loss of data, which is a problem with most other image rectifying methods. The most probable reason that these particular images do not possess much detail is due to the lens not being focused correctly and also the presence of the piece of perspex in front of the CCD.

Although these particular images are extremely poor quality and would normally be discarded as unusable, this signal processing method was able to show that the 10 minute exposure contained more a detailed image than the 5 minute exposure. The 5 minute image appears to be mostly noise and stray back ground light with two faint patches, however the two patches are much clearer in the 10 minute exposure image and a third patch is also discernable. Given the appearance of the original images it is apparent that if this signal processing technique was implemented on a better quality image, significantly more detail could be extracted.

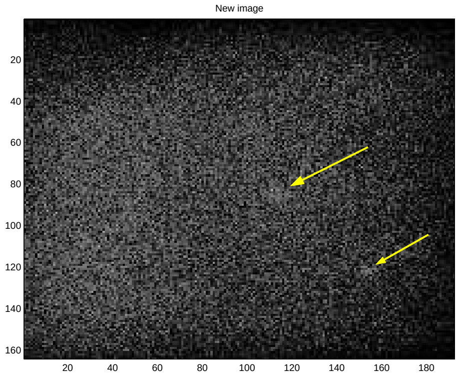

Figure 5.12: Equalised Image of the sky taken with the ST-4 (lens 3) on a clear night with an exposure time of 5 minutes. Also it must be noted the original image possessed significantly greater clarity and contained considerably more star image detail than that which is visible in the exported PDF format.

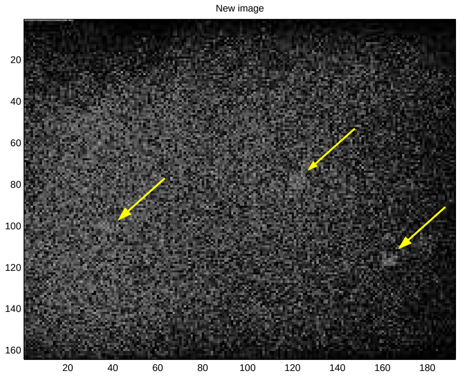

Figure 5.13: Equalised Image of the sky taken with the ST-4 (lens 3) on a clear night with an exposure time of 10 minutes directly after the previous image. Again it must be noted the original image possessed significantly greater clarity and contained considerably more star image detail than that which is visible in the exported PDF format.

5.5 Conclusion

The experiments produced results that confirmed the theoretical system design calculations. It was demonstrated that using a lens designed for a large CCD on smaller CCD will narrow the field of view of the lens.

In order to image the entire mirror, it was determined that the ST-4 needs to be placed at a height of 27cm above the base of the mirror. Given this geometry, the maximum field of view of the system is 150^o or 15^o above the horizon.

The Matlab code written to improve the dynamic range of the dark images demonstrated that signal processing techniques can be successfully used to enhance images and therefore, could be employed in the final system if this proved necessary.

The ST-4 is susceptible to the frosting over of the CCD if it is not properly sealed. This arises as a result of the CCD being thermoelectrically cooled to lower the noise floor of the sensor and ambient moisture in the air condensing and then freezing on the CCD. Additionally, the optical properties of the locally manufactured perspex disc intended to protect the ST-4 CCD caused severe distortion of the images and could not be installed for testing, nor is it suitable for incorporation in the final design.

Chapter 6

Final Design

6.1 Prototype

The prototype was designed and constructed based on the results set out in Chapter 5. The prototype is required to prove the principle that the ST-4 camera and mirror system is capable of detecting clouds at night. Therefore it was not necessary to incorporate features such as weather proofing and the photoelectric switch to ensure the iris is not opened during the day. These features will however be incorporated in the final design, along with other refinements.

The simplest way to achieve accurate results whilst conducting these trial tests was to employ a chemistry apparatus stand to support the ST-4 above the convex mirror. The advantage to this was that it is easily adjustable, as well as being very stable and unlikely to sway or move in the wind. The basic setup of the prototype system was to clamp the ST4 directly over the convex mirror at a height of 27cm above the base of the mirror on a level surface (see Figure 6.1).

To open the iris on the auto iris lens, two AA batteries were connected across pins 3 and 4 (positive to pin 3 and negative to pin 4). This was both convenient for testing and reduced the number of 240V cables and power supplies required. The microcontroller was connected to a laptop via a serial cable. Only the ST-4 power supply and the laptop were required to be connected to mains power.

Figure 6.1: Prototype cloud detection system.

6.1.1 Prototype Trial - Site and Arrangement

The purpose of the prototype trial was to determine if clouds could be detected under a representative variety of night-time viewing conditions with this system alone. If the presence of clouds could not be seen in the images created by the ST-4, then image processing techniques, such as the image equalisation method discussed previously, would be incorporated into the design to extract more information. Additionally, from these trials it was intended to obtain data on exposure times under differing levels of moonlight to assist in determining optimum exposure times.

The test site used to capture images, a suburban garden, was far from ideal. High trees, various garden objects, and a house, were unable to be eliminated from the system field of view and therefore obscured much of the low horizon area. The site was also subject to high stray ambient light levels from other nearby housing, headlights from passing traffic, and some stray lighting from the laptop computer used, and small lights on the equipment itself (although these components would be covered, in the final design).

6.1.2 Prototype Trial - Dusk

The prototype was first trailed on Tuesday 19 October 2005 at a site in the South Eastern part of Toowoomba. The sky conditions for this night were partially cloudy, consisting of high cirrus and cirrostratus clouds in the early evening (around 6:30 to 7:00pm) and low to middle level stratus cloud in the late evening (around 11:00pm). It was a full moon, which rose at 6:51pm and set at 5:24am according to Geoscience Australia (2005).

The first set of images were taken at 6:50pm just as the full moon was predicted to be rising, however it was not visible at all at the test site till a considerable time later due to terrain and vegetation obstructions. Four images were taken in a 5 minute period, varying the exposure time for each image to find the optimum exposure time. By capturing the images in a small timeframe any variations in ambient light levels were minimised. It was observed during the period 6:50 to 6:55pm that there were no clouds directly overhead, but high cirrus and cirrostratus clouds were visible on most of the horizon, particularly the north and south. There were several stars visible to the naked eye, but with one exception they were difficult to discern due to the brightness of the sky.

The four images taken below were taken consecutively, the first image (a) had an exposure time of 30s, the next 45s, followed by 60s and the last had an exposure time of 120s. The apparatus stand that can be seen in the image supporting the camera is situated on the Western side of the mirror, the 'Safe-T-View' sticker that can just be made out on the mirror in the lower right hand corner is pointing approximately towards the North. The 120s exposure time was unsuitable for the light level being overexposed. The 30s exposure provided an acceptable image of the clouds while the 45s and 60s exposures also showed the presence of stars in the clear sky areas and were considered suitable for the light levels. The detail of these images matched the actual observations made by the naked eye at that time of night. The centre part of the image is dark and free of clouds, with a few stars visible while the outer edges of the mirror image are much lighter accurately depicting the visible cirrus cloud.

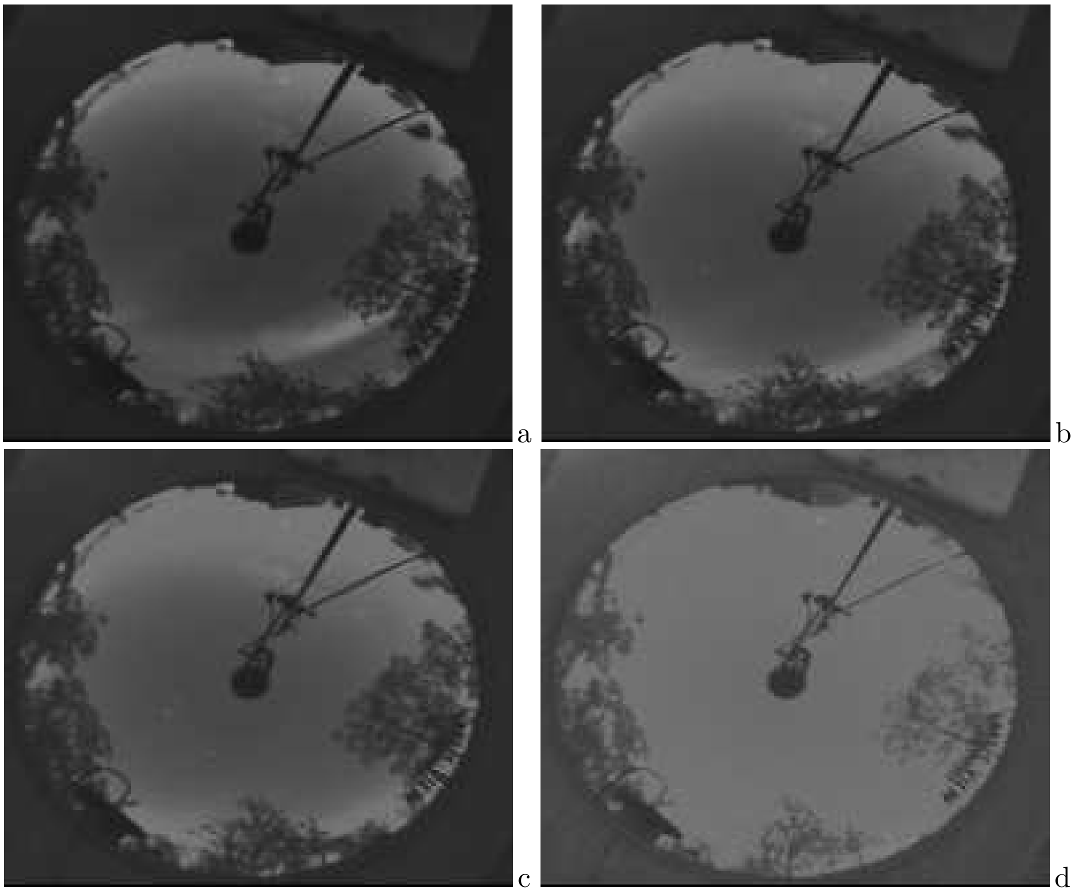

Figure 6.2: Images taken by the prototype cloud detection system consecutively at 6:50pm on 18 October 2005. Image (a) was taken with a 30s exposure time, image (b) was taken with a 45s exposure time, image (c) was taken with a 60s and the final image (d) was taken with a 120s exposure time. The original images possess significantly greater clarity and contain considerably more star image detail than that which is visible in the exported PDF format presented here.

6.1.3 Prototype Trial - Night with a Full Moon

The next part of testing was conducted at 11:00pm that night by which time the full moon could be observed in the North Eastern part of the sky. The sky was mostly covered with thin middle to low level stratus cloud, which was rapidly moving from the East North East, and the full moon could be easily seen shining through the cloud and illuminating the entire sky. Even though a patch of the sky directly overhead was still relatively clear, with the majority of the cloud cover located towards the North and some cirrus observed towards the South, it was difficult to discern any stars in the sky with the naked eye due to the intensity of the moonlight.

The images were once again taken together in a short frame of time to minimise the effects of differing ambient illumination levels. Although the images were captured closely together, they do not necessarily provide the most reliable indication of the optimum exposure time for ambient light levels associated with a full moon at near zenith. This uncertainty arises because the clouds were moving rapidly and their somewhat patchy nature meant that the moon would be intermittently uncovered and partially obstructed during each exposure.

The four images shown below had exposure times of 10s, 20s, 25s and 30s. All of these images show the moon as being extremely luminous. The phenomenon previously encountered during the imaging of bright objects where a white downward trail is produced as the CCD array elements fill up and leak into the next element can clearly be seen with the moon. All four images clearly show the extent and location of the cloud cover compared to the rest of the sky and it can be seen how this changes from image to image as the clouds rapidly moved. The 25 and 30 second exposure images provide good information however due to the speed of the clouds the edges of the cloud image may be more blurred than in the shorter exposure time images.

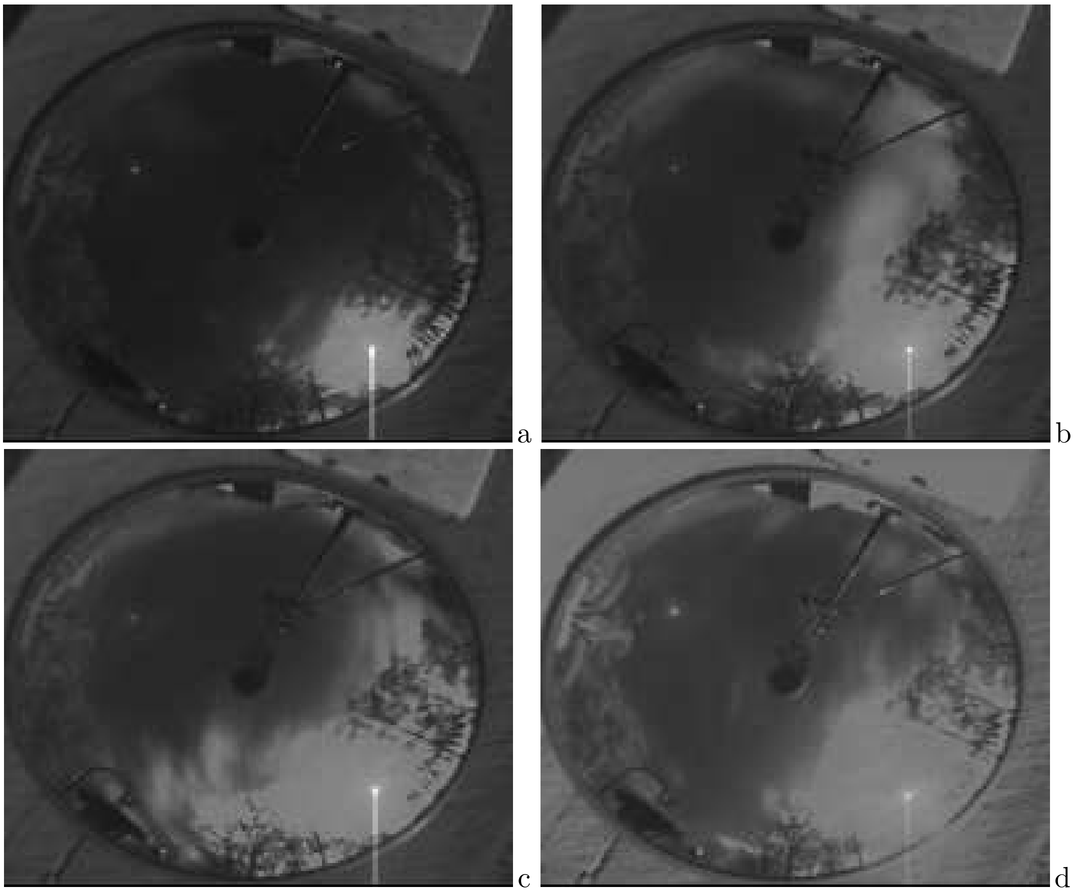

Figure 6.3: Images taken by the prototype cloud detection system consecutively at 11:00pm on 18 October 2005. Image (a) was taken with a 10s exposure time, image (b) was taken with a 20s exposure time, image (c) was taken with a 25s and the final image (d) was taken with a 30s exposure time. The moon is at the bottom right in each image and the vertical line beneath it is an artifact of the sensor (Section 5.3.3). The original images possess significantly greater clarity and contain considerably more star image detail than that which is visible in the exported PDF format.

6.1.4 Prototype Trial - Night without a Moon

A third trial was conducted on a moonless clear night at 7:50pm on the 23 October 2005. The purpose of this trial was to test the system sensitivity in extremely low light conditions without any moonlight. Once again four images were taken (pictured below in Figure 6.4) with varying exposure times over a 15 minute period to determine the ideal exposure time for extreme low light levels. The location was the same as the previous trials with obstructing trees, house, and garden ornaments as well as some stray light from Toowoomba.

The first image taken image (a) was captured with a 150s exposure time, image (b) was with a 120s exposure time, image (c) was with a 90s exposure time and the final image (d) was taken with a 60s exposure. Image (d) was clearly too short an exposure time to gather enough light to show any detail of stars in such dark conditions, however the other three images with longer exposure time clearly picture stars (more evident in images (a) and (b)). The exposure time of 150s was probably too long as the image appears somewhat washed out. Image (b) with an exposure time of 2 minutes (120s) was probably the most satisfactory for the ambient conditions as it shows a clear sky with many visible stars.

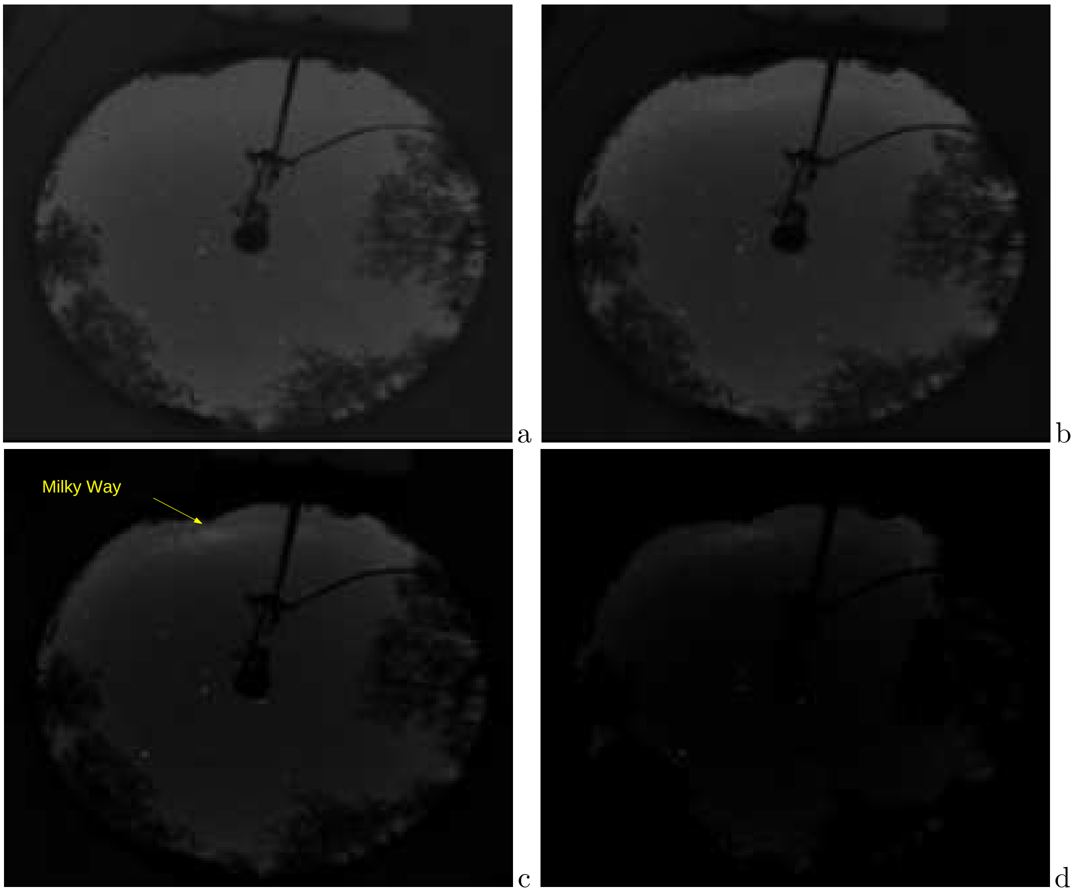

Figure 6.4: Images taken by the prototype cloud detection system consecutively at 7:50pm on 23 October 2005. Image (a) was taken with a 150s exposure time, image (b) was taken with a 120s exposure time, image (c) was taken with a 90s and the final image (d) was taken with a 60s exposure time. The original images possess significantly greater clarity and contain considerably more star image detail than that which is visible in the exported PDF format.

A feature evident in images (b) and (c) is the appearance of the Milky Way. Since these images were taken on a clear dark night the Milky Way had the appearance of a thin fuzzy cloud and can be seen at the top of each image to the left of the support strut. Potential users of the final system will need to be aware of this characteristic so as not to misinterpret the Milky Way for a cloud on a perfectly clear dark night.

If an image taken on a dark night with 120s exposure displayed an absence of stars, it could be assumed that either haze or cloud is obstructing the view of the sky. Given the previously demonstrated camera performance however, it is probable that the presence of any substantive clouds will also be clearly imaged on dark nights.

6.1.5 Trial Summary

From these test results it has been established that it will not be necessary to incorporate any image processing into the final design as the ST-4 performed exceptionally well in both low and high ambient lighting conditions. The camera was able to clearly image both low and high level clouds as well as the brightest stars encountered in the night sky.

The use of a single preset exposure time for the ST-4 is not practical as the ambient light levels vary considerably between dark conditions and bright conditions with a full moon well above the horizon. This requirement to vary the exposure time was not unexpected from consideration of the figures in Table 4.1, where it is stated that a clear night sky with a full moon has an illuminance level of approximately 0.1lux compared to a dark night without a moon which has an illuminance level of 0.001lux.

6.2 Final Design

The cloud detection system was designed to comply with the project aim and objectives stated in Chapter 1. The basic design specifications were determined from the results of both the preliminary testing and prototype trials. The final design envisioned for the cloud detection system in shown below in Figure 6.5.

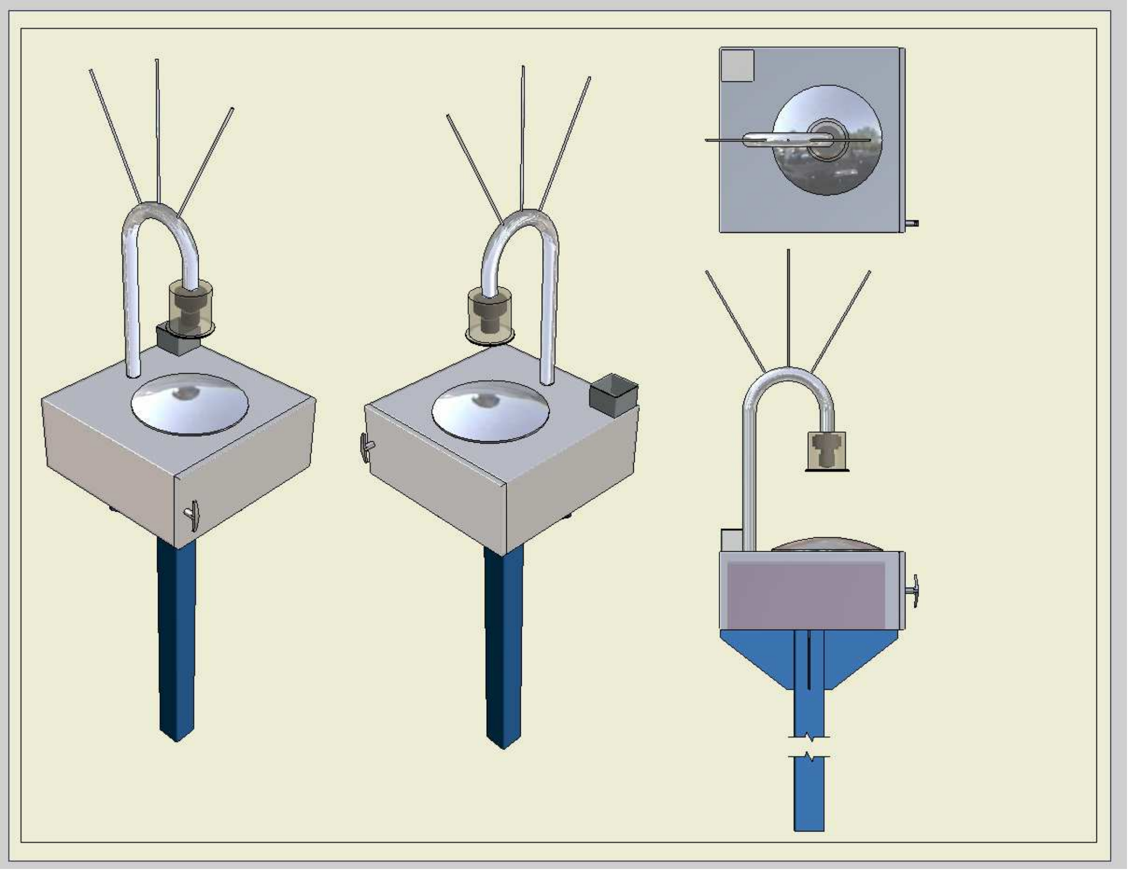

Figure 6.5: Conceptual final design of the Mt Kent Observatory cloud detection system.

6.2.1 System Components

The major components of the proposed system as sketched in Figure 6.5 are:

- The ST-4 was chosen as the imaging camera for the cloud detection system, as it was proven during trials with the prototype that it was capable of accurately detecting clouds and there locations in the sky during low light conditions.
- The 28cm diameter convex mirror was also included as it proved to have a sufficiently large angle of view of the sky (approximately 150^o) and was able to reflect a sharp detailed image.
- Lens 3 (auto iris lens, focal length of 2.5mm and image circle of 6mm diameter) was included as it had a sufficiently large field of view to image the entire con-

vex mirror from a mechanically practical and reasonable height of 27cm above the plane of the mirror and the auto iris feature proved an excellent means of protecting the CCD sensor from the Sun's radiation during the day time.

- Weatherproof photoelectric switch was incorporated into the design to switch the power on at night and off during the day, thus powering the auto iris power supply and the ST-4 power supply only at night.

6.2.2 Camera Housing and Support Strut

The ST-4 is to be situated 27cm above the plane of the mirror in a waterproof housing. The waterproof housing could be locally fabricated from commonly available materials such Polyethylene pipe of approximately 100mm in diameter. To cover and protect the camera lens the base of the housing should have a sheet of glass that is an optical flat so that the optical properties of the glass protector do not interfere with the imaging. A commercial 35mm camera plano filter of appropriate size may also be suitable for this purpose.

The supporting strut should be made of appropriate specification metal pipe that is able to protect the power cables running to the ST-4 and lens internally, and at the same time structurally support the camera. The waterproof housing is required to slide into the pipe support strut to provide a degree of vertical adjustment to compensate for manufacturing tolerances and to enable the camera to be removed for maintenance work and then repositioned accurately to the optimal height. The camera housing slide fit could be secured in place by grub screws, clamps, or similar fixation.

The support strut may also require spikes along the top to keep birds from perching on the cloud detector and potentially dirtying the mirror. It is important that if spikes are positioned on top of the support strut that they are kept inline with the strut so they do not add any additional obstructions to the image.

6.2.3 Convex mirror

The convex mirror is to be placed directly below the ST-4. It is vital that the camera and mirror are aligned accurately; otherwise the mirror will not be imaged accurately and could affect the field of view. It may also be required to attach fishing line down from the camera housing to the outer edge of the mirror to prevent birds from pecking and dirtying the mirror.

A cheap indoor mirror of plastic construction was sourced for the project to minimise potential prototype testing costs. It is recommended that an exterior (outdoor) metal convex mirror be utilised in the final design. This is not only for reasons of durability but also because a plastic mirror, being a dielectric, is more susceptible to attracting dust than metal and therefore would require significantly more frequent cleaning. During prototype testing it was necessary to regularly clean the attracted dust from the mirror.

6.2.4 Lockable Enclosure and Support

A weatherproof box supported on pole will be required to house the ST-4 12V power supply, microcontroller and the 3V power supply for the auto iris lens, as well as to support the convex mirror. The size of the box would have to be approximately 470mm × 470mm × 200mm to allow enough room to store the necessary equipment. Ideally the box should be lockable to prevent people or animals from getting in, and risking damage to cloud detector.

The height of the system can not be determined until a site survey has been conducted to determine the exact location of the system. Once the location is decided it would than be possible to determine the height at which the cloud detection system should be placed above the ground. This decision may have to be a compromise between the desire to minimise obstructions from trees and other structures in order to obtain a maximum field of view and the practical issues of computer cable and electricity access for this device at MKO.

The cloud detection system may also present a physical hazard due to its size, location and working environment. Observatories are located at dark sites as the seeing conditions for astronomy are better in areas less affected by light pollution. Astronomers are continuously eliminating artificial lighting around observatory grounds in order to improve seeing conditions and this may be hazardous to astronomers unfamiliar with structures located in the grounds. Consideration will have to given physical safety when siting the cloud detector at the MKO to minimise the possibility of the structure inflicting injury to personnel.

Ventilation of electrical components must also be addressed in the final design. The lockable box will require weatherproof ventilation to reduce heat produced by the ST-4 and auto iris lens power supplies as well as absorbed heat from the Sun's radiation. Another design feature that could be incorporated into the box design to reduce the heat transference from the Sun is to incorporate a 2mm air flow gap above the lockable box. A platform on which to mount the convex mirror would be placed on top of this air gap. A similar principle could be applied to the camera weatherproof housing. By ensuring there is an air gap between the camera and the weatherproofing housing the camera performance should not be degraded by heat transference.

Some other features, which could be considered in the final implementation of the cloud detector, are the addition of small spikes surrounding the convex mirror and lightning protection. The small spikes on the surface of the cloud detector box would provide further deterrence for birds, preventing them from landing on the surface and damaging the mirror. The spikes would have to be positioned carefully so that they do not obstruct the field of view of the cloud detector. Lightning protection may also be required depending on the height of the installed system however this should probably be addressed as part of broader protective measures for MKO as a whole.

6.2.5 Photoelectric Switch

A photoelectric switch is necessary to ensure the auto iris is closed during the day to protect the ST-4 CCD sensor from being damaged by the sun during the day. This is a simple way of achieving a system that is fail safe and will operate automatically. The auto iris lens requires 3V DC to open the iris, if there is no voltage, the iris cannot be opened. By utilising a commercial weatherproof mains voltage photoelectric switch that is open during the day and closed at night ensures that the iris on the ST-4 will always be closed during the day. Both the ST-4 power supply and the auto iris power supply will be operated by the photoelectric switch for simplicity.

6.2.6 Electrical Design Considerations

According to the ST-4 Operating Manual (1999) a full image can be transmitted at 19.3 baud within 18 seconds over a distance of 30m from the microcontroller to a computer over the ST-4s RS-232 serial link. Data transfer rates as high as 57.6K can be achieved over shorter distances. This constraint will have to be considered when positioning the cloud detection system as to ensure the serial link from the ST-4 to the MKO control room does not exceed 30m.

A commercially available 3V DC power supply will also be required to operate the auto iris lens used on the ST-4. The ST-4 has its own 12V AC/DC 1A transformer. As both power supplies will be located in the lockable box along with the microcontroller, two complying domestic power outlets supplied via the photoelectric switch will need to be provided inside the box.

Electrical hazards should be minimised by ensuring that required electrical standards and procedures are complied with. All wiring should be insulated and weather proofed to the required standards and all practical measures should be taken to reduce early failure or deterioration. Figure 6.6 is an electrical design of the system.

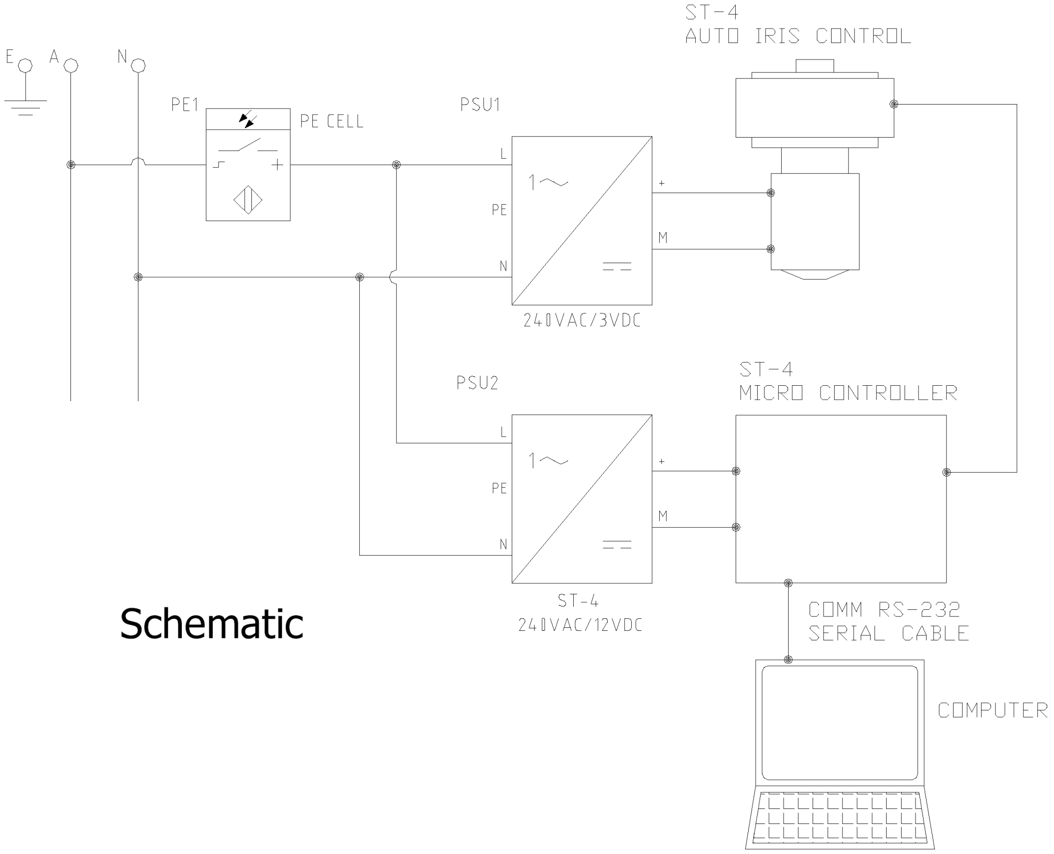

Figure 6.6: Electrical design of final cloud detection system (see Appendix F for more detail).

6.2.7 Cloud Detector Control System

The method used with the prototype system to obtain images of the sky required the use of the software package called ImCap. These images had to be obtained manually, as an operator was required to set the exposure time and individually capture and save each image acquired. This method is not suitable for the final design as the cloud detector is required to function without the direct input of an operator, being primarily intended for use with a remotely operated telescope.

The ImCap software does have the capability to automatically capture and save images to a specific location, which could subsequently be retrieved and viewed over the Internet with some additional software. Another approach for obtaining images and displaying them is to write a program that allows individual users to capture the images directly from the camera and make these available over the Internet for all other users to access.

Four possible options were considered for the final control system. The simplest of these is to utilise just one preset exposure setting for the ST-4 camera. This exposure time would necessarily be a compromise between the optimum exposure time required for a dark night and that required on a maximum bright night, corresponding to an unobstructed full moon well above the horizon. From prototype trials, it is considered that this option would significantly limit the usefulness of the cloud detector, although more extensive trials conducted under a wide variety of conditions would be necessary to quantify this.

The second option is to write code for a user-friendly interface that permits certain users to control the camera exposure setting. For this option to be effective it would be necessary to limit the user to a small picklist of preset exposure times for the ST-4 chosen for their usefulness under various night ambient light conditions. This is important because the camera is very sensitive to changes in light levels and exposure settings. It would not be practical to require users to experiment with a large number of ST-4 exposure settings in order to obtain one useful image. User control of exposure settings would probably require information on the moon phase and elevation for the MKO region to be made available to assist users. Fortunately, such moon information can be easily calculated by aid of an almanac or web based calculators such as the Geoscience Australia moon rise calculator (available: http://www.ga.gov.au/geodesy/astro/moonrise.jsp). An easy implementation would be to place a link to the Geoscience Australia moon rise calculator on the MKO cloud detector website. Once the user has determined the phase and position of the moon, they could then quickly select the most appropriate preset exposure time on the website to efficiently operate the camera and achieve the best image quality.

Although viable, this method introduces additional complications by requiring a system that permits only certain authorised users to have access to the camera exposure control. Additionally, as only one user can be in control of the camera at any one time, other users would be limited to viewing the images produced by the user in control, no matter how exposed or infrequently they may be taken.

A third option is to automate the selection of ST-4 exposure settings, eliminating the need for the user control described above. This could be achieved by writing code that utilises moon almanac data such as that found on the Geoscience Australia moon rise calculator to automatically set the most appropriate exposure time. This implementation would automate the cloud detector and the website could display updated images every few minutes of the current MKO sky conditions, which could be accessible to anyone who logs onto the website.

Finally, a much simpler but, never-the-less very effective implementation could be achieved by writing a program that captures sets of images taken by cycling through a small number of preset exposure times. These preset exposures would correspond to a limited set of representative ambient illumination levels. By displaying each set of images on the website there would be at least one image containing useful up to date information for all users to access at any given time. This option has the added advantage that any variations to predicted ambient illumination levels caused by changing local cloud coverage would be automatically catered for.

This last option is considered the most effective, reliable, and simplest method of automating the cloud detector and is therefore the preferred implementation.

6.2.8 Telescope Protection Interface

A Boltwood cloud sensor (as mentioned in Section 2.2.2) has already been purchased for MKO and it is recommended that this be used as the primary means of preventing the telescope dome being opened in rain or adverse weather. The aim of this project is to generate night sky images for analysis and interpretation by the end user. This form of output is therefore not considered sufficiently reliable for use as a primary means of telescope protection but is ideally suited for use as a backup or confirmatory system. A back up system is considered important as the Boltwood is subject to false readings as a result of measuring the average sky temperature. Since it only deduces one of four possible outputs; *Clear*, *Cloudy*, *Very Cloudy* and *Rain*, the cloud detector image can be used to confirm the conditions and to provide additional information regarding the relative cloud position, which was a requirement of this project.

Both the cloud detector and the Boltwood cloud sensor outputs should be displayed on the website to alert users to conditions and to reduce the likelihood of the telescope dome being remotely opened in rain or adverse weather should the automated system be unreliable or fail.

6.3 Maintenance Considerations

The use of bird spikes and fishing line drawn down from the camera cover to the edge of the mirror as mentioned in Section 6.2.3 to prevent birds from pecking and dirtying the mirror should help considerably to minimise cleaning requirements as well as reducing potential scratching and other permanent physical damage. Despite these measures, regular inspection and cleaning will be necessary due to the design of this system and its outdoor location. The lens protector and convex mirror will need to be kept in a clean and undamaged state in order to maintain the cloud detector performance.

Although the use a fisheye lens with the camera pointed at the sky would eliminate the convex mirror as a potential source of performance degradation; such a system was unable to be implemented due to the unavailability and high cost of small fisheye lenses of a suitable size for the ST-4 camera.

6.4 Resource Analysis

6.4.1 Prototype System

The following components were required to be procured for the prototype system:

- automatic iris CS-mount lens with a 2.5mm focal length at a cost of $89 from Allthings Sales & Services (www.allthings.com.au);

- 30cm diameter indoor convex wall mirror made by 'Safe-T-View' (cost of \$139);
- two AA batteries and a two AA battery holder (cost of \$0.75);
- obsolete ST-4 camera less software, manuals and lens. This was the property of USQ but would have cost approximately U.S.\$990 when new in 1990; and
- ImCap software (freeware).

Additionally, the prototype utilised a chemistry apparatus stand belonging to USQ and a privately owned laptop computer and peripheral items, supplied by the author.

6.4.2 Final Design

The final cloud detection system will require the procurement of the following additional items:

- 30cm diameter exterior metal convex mirror (estimated cost \$200);
- 3V DC power supply for the automatic iris lens (estimated cost of \$15);
- 240V weatherproof photoelectric switch (estimated cost of \$80);
- weatherproof camera housing and lockable box, along with support pole for system and support strut for camera (locally fabricated);
- mains electrical reticulation and power outlets;
- computer cable reticulation; and
- computer workstation and code to control the system.

6.5 Conclusion

Prototype trial results provide a high degree of confidence that the final design will satisfy the requirements for a cloud detector at the Mt Kent Observatory (MKO) site.

The overall design of the prototype cloud detection system proved to be capable of imaging clouds in low light conditions. Experimental trials demonstrated that the major cloud types ranging from high cirrus clouds (normally difficult to see with the unaided eye at night) to low stratus clouds could be detected by the cloud detector with their location and extent depicted accurately on the convex mirror. The system also proved sensitive enough to detect the brightest stars with suitable exposure times.

It is clear from trials that the cloud detection system must be carefully sited well away from obstructions such as buildings and trees and at an appropriate height, to achieve the maximum view of the sky possible. Two options are considered practical in this regard. The cloud detector could be positioned on top of sturdy pole of required height or mounted on top of the roof of an existing building, such as the MKO control room. Considerations such electrical supply, ease of access for maintenance, physical hazards to personnel in the dark, and obstructions to the field of view of the system will need to be considered in determining the final siting selection at MKO.

6.5.1 Constraints and Limitations of the Final Design

Although the system was successful in detecting clouds, several constraints and limitations of the system were observed during experimental trials.

Image Size

The first major limitation observed with the system was that of camera image size (57mm × 57mm in size). The ST-4 Star Tracker / Imaging Camera is now obsolete and was first introduced over 15 years ago (SBIG 2005). Camera technology has both progressed rapidly and become cheaper in recent years and therefore the ST-4 performance is limited in comparison to star tracker/imaging cameras on the market today. Newer cameras produce much larger and more detailed images than is possible with the ST-4. Due to the small size of the images produced by the ST-4, analysis of images can be difficult. Images can be enlarged for viewing; however no further detail can be achieved due to the finite number of pixels.

Exposure Time

The ST-4 has proven to be very sensitive in low light conditions. This means the slightest increase in ambient light can have a large affect on the image produced unless the exposure time is correctly adjusted. The use of a suitable set of preset exposures is therefore necessary to obtain a useful image under varying ambient lighting conditions.

Dark Current

A phenomenon referred to as dark current by the ST-4 manufacturer can potentially degrade the quality of an image. It is caused by the CCD array elements slowly filling up during long exposures and effectively limits the use of very long exposure times on dark nights. Although taking a dark frame of the same exposure time and then subtracting this from the image could reduce the noise produced by dark current, this process is not considered practical for the cloud detector.

ST-4 Obsolete

A potential problem of this design is the choice of camera. The ST-4 Star Tracker/Imaging Camera is no longer in production, which means that if any problems or failures were to occur with the camera it could not be replaced and it may not be possible to repair. The ST-4 retail price when new was U.S.$990 and the last stocks were disposed of in 1997, according the SBIG website. Current camera models which are significantly upgraded by comparison, are not an economical solution for future replacement as they range in price from U.S.$1000 to $3000. Should the ST-4 fail and need to be replaced by a different type of camera, additional redesign and testing would be required before the cloud detector could be recommissioned.

Prototype System Testing

The design of the prototype limited the testing that could be conducted. The prototype system was intended to demonstrate the potential capability of the final cloud detection system and therefore, aspects such as the final control system software, use of an exterior grade mirror, and waterproofing of equipment were not undertaken. As a result, the prototype could not be left outdoors for protracted periods nor could it be tested on nights when there was rain or fog present to assess performance and mirror cleaning requirements.

Chapter 7

Conclusions and Further Work

7.1 Project Objectives

The objectives of this project were as follows:

- Research information of cloud formation in the evening sky and the changes that occur from sunset until dark.
- Investigate different techniques of detecting clouds in low light conditions.
- Critically evaluate existing alternatives for cloud detection systems on remotely operated telescopes.
- Determine the best and most economical technique or combination of techniques for detecting clouds for the location and type of telescope to be used.
- Design a low maintenance cloud detecting system to operate from late afternoon until early morning that can identify sky conditions before starting observing.
- Construct a prototype cloud detection system and evaluate the reliability and accuracy of the system.

All these objectives were completed successfully.

7.2 Achievement of Project Objectives

The following objectives have been addressed:

Research of Clouds The Mt Kent Observatory (MKO) is located in a region that experiences a subtropical climate. During the summer months the predominate cloud formation tends to be isolated to scattered cumulus clouds. Cumulus clouds typically form in the afternoon and often dissipate in the early evening after sunset however under the right conditions of atmospheric instability cumulus clouds can develop significantly in vertical extent and transform into a cumulonimbus or storm clouds capable of producing heavy precipitation. These clouds tend to form in an isolated manner and provided they are sufficiently far away as to pose no danger to the telescope it is possible to still make useful astronomical observations in the rest of the sky.

Investigated cloud detecting methods Three main techniques used by astronomers to detect clouds for remotely operated telescopes were investigated. These included the use of weather reports and satellite images, sky temperature method using thermocouples, and imaging the sky with a low light camera.

Critically evaluated cloud detecting methods It was found that the use of weather reports and satellite images was not practical or reliable. The sky temperature method was extremely good at detecting the presence of clouds and would also be economical, but failed to meet the requirements of this project, as it is unable to determine the location of the clouds in the sky. The use of cameras as cloud detectors for remotely operated telescopes is not a technique widely used by astronomers. This technique can be difficult to implement economically, but does have an advantage over the other methods in that it is capable of detecting not only the presence of clouds in the night sky, but also their location.

Chosen Method The sky imaging technique with a camera was chosen as it was the only method that could detect both the presence and location of clouds in the night sky. It was found that this technique could be potentially be implemented at minimal cost by utilising a low light security camera to image the clouds at the Mt Kent Observatory (MKO). Another significant factor, which contributed to the decision to use a camera to detect the clouds at MKO, is the subtropical climate experienced in this region. During the summer months the predominate cloud formation in subtropical regions tends to be isolated to scattered cumulus clouds, which can be detected by the unaided eye in low light conditions and should therefore be easily detectable by camera.

Cloud Detection Design A low maintenance cloud detecting system was designed which would operate from the late afternoon until early morning. The system uses an ST-4 Star Tracker / Imaging Camera positioned facing downward directly over a convex mirror in order to get an all sky image. The system is relatively low maintenance and is intended to operate automatically with images accessible over the Internet.

Construction of prototype A complete prototype cloud detection system was not able to be fully constructed due to time and cost constraints, however a simplified version was built. Trials with this system were successful in detecting clouds in a variety of low light conditions. From these trials it can be concluded that the final system would be a reliable and accurate method of detecting clouds. This system produced very clear images of the sky including bright stars, from which it was possible to accurately determine the cloud position and coverage relative to systems position. The system proved capable of detecting both low and high clouds.

7.3 Further Work

A site survey must be conducted at MKO to choose the optimum location for installation of the cloud detector, taking into consideration the presence of obstructions impinging on the view of the sky, accessibility for maintenance, electrical and computer cabling reticulation, and the need to avoid structural hazards. Based on the site selection, the height of the system is required to be determined. Following this the cloud detector can be constructed as per the design drawing in Appendix F incorporating any additional site specific details.

Once the system is structurally complete and installed, with reticulated mains electricity and computer cabling, it could be manually operated immediately using the ImCap software (refer to Section 4.3) to control the exposure time of the camera and to capture the images for display on the website. This implementation would serve well as a temporary solution, until further work to set up a link over the Internet for the ImCap software to be operated remotely through the computer system at MKO is completed.

The preferred method of capturing useful images in varying ambient lighting conditions is to write a program that captures images in sets generated by cycling through a small number of preset exposure times. By displaying sets of images on the website, at least one image in each set should provide useful information for users to access no matter what the prevailing ambient lighting conditions may be. From the prototype trials it is considered that four preset exposure times would be adequate. As exposure of 25s for high ambient light conditions such as a full moon well above the horizon; 45s for medium ambient lighting conditions corresponding to a quarter moon well above the horizon, or dusk/dawn periods; 75s for low ambient lighting conditions corresponding to for an overcast night with partial moon, and 120s for dark conditions such as a moonless clear or cloudy dark night. These exposure times could be reviewed and adjusted if necessary, based on feedback from users once the cloud detection system is operational at MKO.

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Appendix A

Project Specification

University of Southern Queensland
Faculty of Engineering and Surveying
ENG 4111/2 Research Project

PROJECT SPECIFICATION

FOR:	**Aeolyn Gwynne**
TOPIC:	Cloud Detection System for the Mt Kent Observatory
SUPERVISOR:	Dr. Nigel Hanckock
ASSOCIATE SUPERVISOR:	Dr. Brad Carter, Faculty of Science
SPONSORSHIP:	Faculty of Engineering and Surveying and Faculty of Science, USQ

PROJECT AIM: This project aims to provide a cloud detection system for a remotely operated telescope, to determine if the sky is suitable for astronomical observing.

PROGRAM: **Issue A, 21 March, 2005**

1. Research information of cloud formation in the evening sky and the changes that occur from sunset until dark.
2. Investigate different techniques of detecting clouds in low light conditions.
3. Critically evaluate existing alternatives for cloud detection systems on remotely operated telescopes.
4. Determine the best and economical technique or combination of techniques for detecting clouds for the location and type of telescope to be used.
5. Design a low maintenance cloud detecting system to operate from late afternoon until early morning that can identify sky conditions before starting observing.
6. Construct a prototype cloud detection system and evaluate the reliability and accuracy of the system.

AGREED:. (student). (supervisor). . . . . (dated)

Appendix B

Convex Mirror Calculations

B.1 Radius of Curvature Calculations for Convex Mirror

The radius of curvature was calculated to determine the angle of view capable for the all sky image. The following measurements were taken of the convex mirror:

- Thickness of mirror: 3mm
- Diameter: 280mm
- Height: 28 + 3 = 31mm (to mirror side)

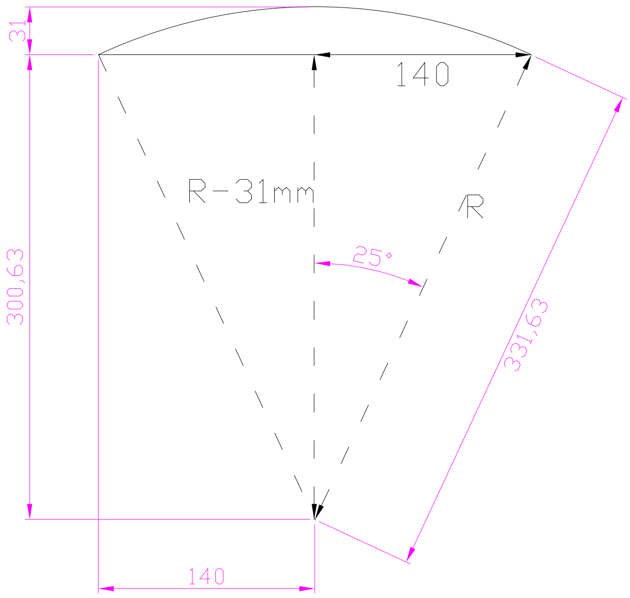

Figure B.1: Dimensions of convex mirror to determine the radius of curvature.

The radius of curvature of the convex mirror was able to be calculated from Pythagoras's Theorem to be 331.63mm (see below for calculations).

$$\begin{aligned} x^2 + y^2 &= R^2 \qquad \text{(B.1)} \\ 140^2 + (R-31)^2 &= R^2 \\ R^2 - 62R + 20561 &= R^2 \\ R &= 331.63\text{mm} \end{aligned}$$

B.2 Determine Angle of View of the Sky

To determine the angle of view of the convex mirror some assumptions had to be made:

- The mirror is a section of a perfect sphere
- Lens 3 would be the most suitable lens
- Lens 3 would be placed 27cm in height above the mirror plane (calculations of height of lens 3 are below).

  Using equation (2.4) the height that lens 3 needed to be placed above the convex mirror plane could be determined as the focal length and object and image size were known.

  - H = 280mm (Diameter of convex mirror)
  - H' = 2.6mm (Width of the CCD)
  - F = 2.5mm (Focal length of Lens 3)

  $$\begin{aligned} H &= H' \frac{l}{f} \\ l &= f \frac{H}{H'} \\ l &= 280 \times \frac{2.5}{2.6} \\ l &= 270\text{mm} \end{aligned}$$

  Lens 3 should theoretically be placed at height of approximately 27cm above the convex mirror plane.

From basic geometry the angle of view could be calculated for the convex mirror based on the above assumptions and calculations. See Figure B.2 below.

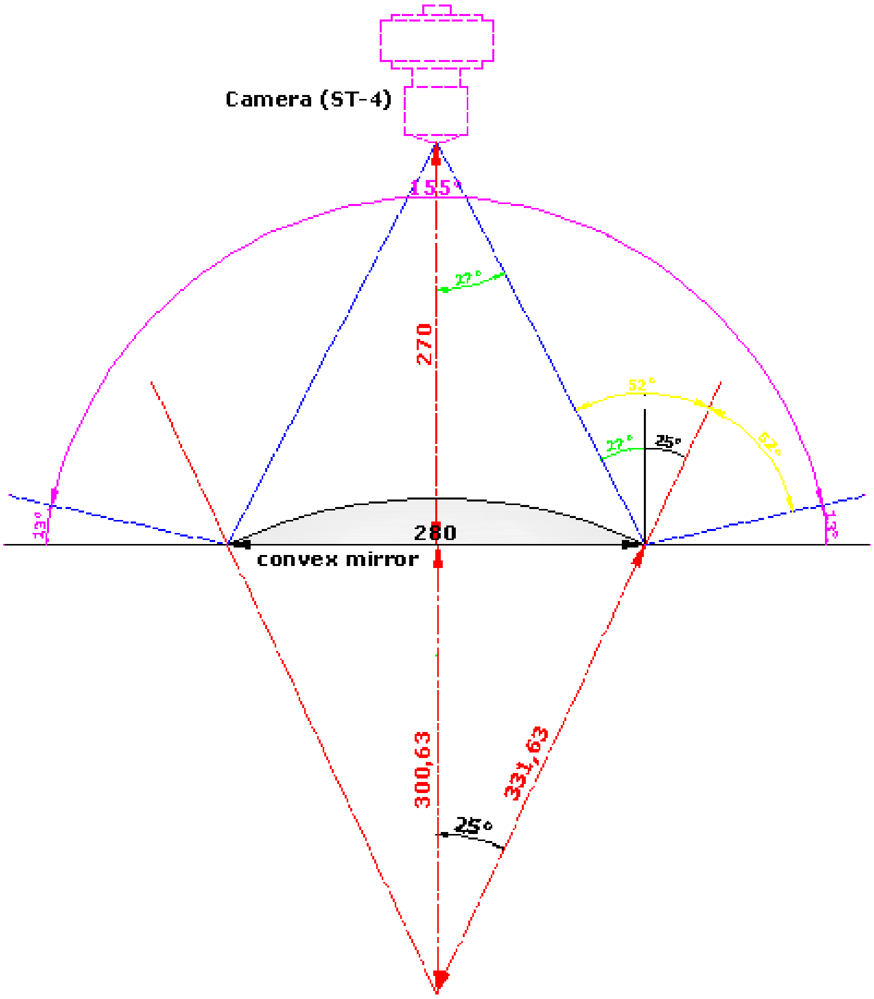

Figure B.2: Dimensions of convex mirror to determine the field of view.

It was found from these calculations that the 280mm diameter convex mirror would have a field of view of 155^o if the lens of the ST-4 were placed at a height of approximately 270mm above the mirror plane.

Appendix C

ST-4 Trial Images and Calculations

All of the following images were taken with the ST-4 of a 3mm yellow LED to determine the angle of view of each of the lenses using equation (5.1).

Figure C.1(a) was taken with lens 1 at a distance of 75cm with the perspex cover over the CCD. The angle of view was calculated to be 0.47^o (see below for calculations).

LED actual size: 3mm
LED image size: 28mm
Photo actual size: y_1
Photo image size: 57mm

$$\begin{aligned} z_1 &= \frac{3 \times 57}{28} \\ &= 6.11\text{mm} \\ \theta &= 2\tan^{-1}\left(\frac{y_1}{2x}\right) \\ &= 2\tan^{-1}\left(\frac{6.1}{2 \times 750}\right) \\ &= 0.47^o \end{aligned}$$

Figure C.1(b) was taken with lens 2 at a distance of 1m with the perspex cover over the CCD. The angle of view was calculated to be 0.8^o (see below for calculations).

LED actual size: 3mm
LED image size: 13mm
Photo actual size: y_2
Photo image size: 57mm

$$\begin{aligned} z_2 &= \frac{3 \times 57}{13} \\ &= 13.15\text{mm} \\ \theta &= 2\tan^{-1}\left(\frac{y_2}{2x}\right) \\ &= 2\tan^{-1}\left(\frac{13.15}{2 \times 1000}\right) \\ &= 0.8^o \end{aligned}$$

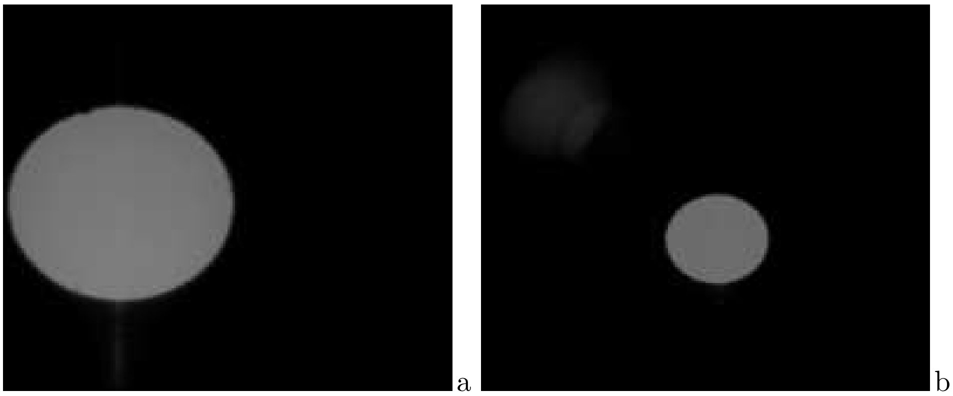

Figure C.1: Image (a) was taken with the ST-4 using lens 1 of a 3mm diameter LED at a distance of 75cm with 3s exposure time. Image (b) was taken with the ST-4 using lens 2 of a 3mm diameter LED at a distance of 1m with 7s exposure time.

Figures C.2 (a) and (b) were taken with lens 3 of the same 3mm yellow LED:

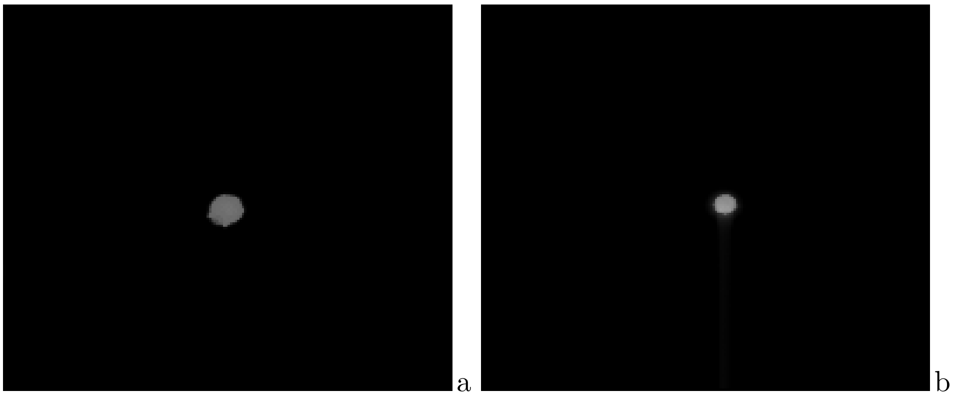

Figure C.2: Image (a) was taken with the ST-4 using lens 3 of a 3mm diameter LED at a distance of 1m with 10s exposure time. It can be seen in this image that LED appears distorted. This was found to be a result of the perspex CCD cover causing unwanted reflections. Image (b) was taken with the ST-4 using lens 3 of a 3mm diameter LED at a distance of 35cm with 0.7s exposure time without the perspex CCD cover. This image is consequently much sharper and has a noticeably larger field of view compared with the previous image (a) which was taken at a distance of 1m.

Appendix D

Image Equalisation Matlab Code

The following Matlab code was written to improve the dynamic range of the ST-4 images. The images created by this code are more visible to the eye, as there is a greater contrast in the pixel intensities. This is evident when comparing the histogram of the new image to that of the original image.

The equalisation technique used in this code is somewhat limited in that it cannot improve the image. It can only create a contrast between the pixel values, therefore not eliminating any of the noise present in the images, but rather enhancing it to an extent.

```
% --------------------------Start of SCRIPT--------------------------
% Script: Image_Extraction
%
% Description: Uses histogram equalisation to extract an image
%
% This program reads in an image taken by the ST-4 and plots a
% histogram of the pixel intensities. From the histogram a cumalitive
% histogram is then ploted. From the orginal image a new equalised
% image is produced by creating more of a contrast between the orginal
% pixel intensities. The orginal image is also plotted for comparison
% purposes. A new histogram and cumulative histogram are then plotted
% for the new image. This program also plots an inverted image of both
% the orginal and new image.
%
% Functions called: makehist -             Inputs: i
%                                          Output: histogram
%                   makecumulativehist -   Inputs: histogram
%                                          Output: cumaltivehist
%                   makeconfhist -         Inputs: newimage
%                                          Output: confhistogram
%                   makeconfcumulativehist -Inputs: confhistogram
%                                          Output: confcumulativehist
%
```

```
% Variables:    i - intensities of each pixel
%               c - color map
%               rows -  number of rows in image
%               cols - number of columns in image
%               x - position in rows
%               y - position in cols
%               histogram - histogram of orginal image
%               cumaltivehist - cumulative histogram of orginal image
%               newimage - reconstructed (equalised) image
%               confhistogram - histogram of new image
%               confcumulativehist - cumulative histogram of new image
%               invert - inverts the colormap (c) for inverted images
%               badimage - orginal image
%
% Author: Aeolyn Gwynne, Q1121988X
% Date:   1 October 2005


% Load the image file from the ST-4
%     i=intensities of each pixel (refers to row in color map)
%     c=color map
[i,c]=imread('10min.bmp');
% Retrieves a colormap from a real 256 colorbitmap
[rubbish,c]=imread('b&wcolourmapsource.bmp'); i=double(i);
% Produces 1 dimension of RGB values because grayscale has RGB values
% all identical.
i=i(:,:,1);

% Get the size of image
%     rows=number of rows in image
%     cols=number of columns in image
[rows cols]=size(i);
% Deletes the blank line from at the bottom of the image which is
```

```
% produced by the ST-4
i=i(1:rows-1,:); rows=rows-1;

% Gives the max and min values for the pixel intensities
max(max(i)) min(min(i))

% Calls function makehist
%     Plots figure 1: pixel intensity histogram of the ST-4 image
histogram=makehist(i);
% Calls function makecumulativehist
%     Plots figure 2: cumulative historgram of the previously
%     calculated pixel histogram
cumulativehist=makecumulativehist(histogram);

% Makes equalized image, figure 3
%     from the cumulative historgram
newimage=zeros(size(i)); for x=1:rows
    for y=1:cols
        newimage(x,y)=floor(cumulativehist(i(x,y))/256);
    end
end

% Compare to original image
figure(3); image(i) title('Original image') colormap(c);

% Plots the new image
figure(4); image(newimage) title('New image'); colormap(c);

% ADDITIONAL CODE: checks the new image
% Plots the new histogram of for the modified image
confhistogram=makeconfhist(newimage);
% Plots the new cumulative histogram of the modified image
confcumulativehist=makeconfcumulativehist(confhistogram);
```

```
% Plots the inverse of the orginal image
figure(7); image(i); invert=c(256:-1:1,:); title('Inverted Orginal
Image'); colormap(invert);

% Inverts the new image
figure(8); image(newimage); title('Inverted New Image');
colormap(invert);
% ---------------------------END of SCRIPT----------------------------

% ---------------------Start of makehist Function---------------------
% Function:     makehist
% Syntax:       [histogram]=makehist(badimage)
% Algorithm:    Plot the pixel intensity histogram of the orginal ST-4
%               image
% Input:        image pixel intensities
% Output:       pixel intensity histogram, plot of the frequency of
%               each intensity level (0-255)
% Author:       Aeolyn Gwynne, Q1121988X
% Date:         1 October 2005

function [histogram]=makehist(badimage)

% Gets size of image
[rows cols]=size(badimage); histogram=zeros(1,256);

% Checks each pixel intensity by looping through each column and
% each row and adding one to the corresponding histogram count
for y=1:rows
    for x=1:cols
        histogram(badimage(y,x)+1)=histogram(badimage(y,x)+1)+1;
    end
end
```

```
% Plots histogram
% Displaying intensity count vs intensity
figure(1) plot(1:256,histogram); axis ([0 255 0 10000]);
title('Histogram of Orginal Image'); xlabel('Pixel Intensity (0 to
255)'); ylabel('Count');
% ----------------------End of makehist Function----------------------

% ----------------Start of makecumulativehist Function----------------
% Function:     makecumulativehist
% Syntax:       [cumulativehist]=makecumulativehist(histogram)
% Algorithm:    Plot the cumulative histogram of the pixel histogram
%               of the orginal ST-4 image
% Input:        histogram - the output of function makehist
% Output:       cumulatvehist - cumulative sum of the histogram
% Author:       Aeolyn Gwynne, Q1121988X
% Date:         1 October 2005

function [cumulativehist]=makecumulativehist(histogram)

% initialises cumulative histogram
cumulativehist=zeros(1,256); cumulativesum=0;

% calculates cumulative sum
for j=1:256
    cumulativesum=cumulativesum+histogram(j);
    cumulativehist(j)=cumulativesum;
end

% Plots cumulative histogram
% Displaying cumulative sum vs pixel intensity
figure(2) plot(1:256,cumulativehist); title('Cumulative Histogram
of Orginal Image'); axis ([0 256 0 40000]); xlabel('Pixel
```

```
Intensity'); ylabel('Cumulative Count');
% -----------------End of makecumulativehist Function-----------------


% -------------------Start of makeconfhist Function-------------------
% Function:     makeconfhist
% Syntax:       [confhistogram]=makehist(newimage)
% Checking
% Algorithm:    Plot the pixel intensity histogram of the new image
% Input:        newimage
% Output:       confhistogram-pixel intensity histogram, plot of the
%                             frequency of each intensity level(0-255)
% Author:       Aeolyn Gwynne, Q1121988X
% Date:         1 October 2005

function [confhistogram]=makeconfhist(newimage)

[rows cols]=size(newimage); confhistogram=zeros(1,256);

for y=1:rows
    for x=1:cols
      confhistogram(newimage(y,x)+1)=confhistogram(newimage(y,x)+1)+1;
    end
end

figure(5) plot(1:256,confhistogram); axis ([0 256 0 10000]);
title('Histogram of Newimage'); xlabel('Pixel Intensity');
ylabel('Count');
% --------------------End of makeconfhist Function--------------------


% -------------Start of makeconfcumulativehist Function--------------
% Function: makeconfcumulativehist
% Syntax:   [confcumulativehist]=makeconfcumulativehist(confhistogram)
% Checking
```

```
% Algorithm:Plot the cumulative histogram of the pixel histogram of
%           new image
% Input:    confhistogram - the output of function makeconfhist
% Output:   confcumulatvehist - cumulative sum of the histogram
% Author:   Aeolyn Gwynne, Q1121988X
% Date:     1 October 2005

function
[confcumulativehist]=makeconfcumulativehist(confhistogram)

confcumulativehist=zeros(1,256); confcumulativesum=0;

for j=1:256
    confcumulativesum=confcumulativesum+confhistogram(j);
    confcumulativehist(j)=confcumulativesum;
end

figure(6) plot(1:256,confcumulativehist); axis ([0 256 0 40000]);
title('Cumulative Historgram of Newimage'); xlabel('Pixel
Intensity'); ylabel('Cumulative Count');
% ---------------End of makeconfcumulativehist Function---------------
```

Appendix E

Image Equalisation Results

The following images were created with the Matlab code in Appendix D.

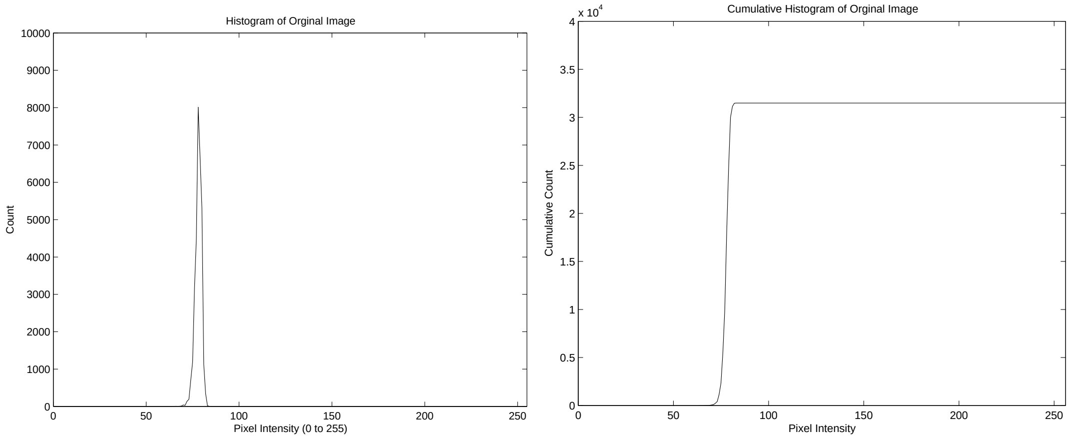

Figure E.1: (a) Histogram of 5 minute exposure image of night sky, (b) Cumulative Histogram of 5 minute exposure image of night sky.

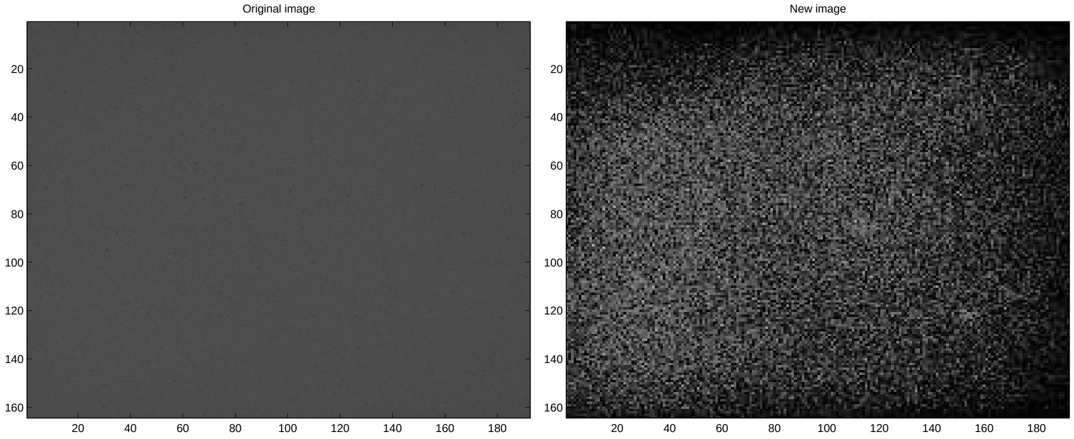

Figure E.2: (a) Original image of the night sky with a 5 minute exposure, (b) New equalised image of the night sky with a 5 minute exposure.

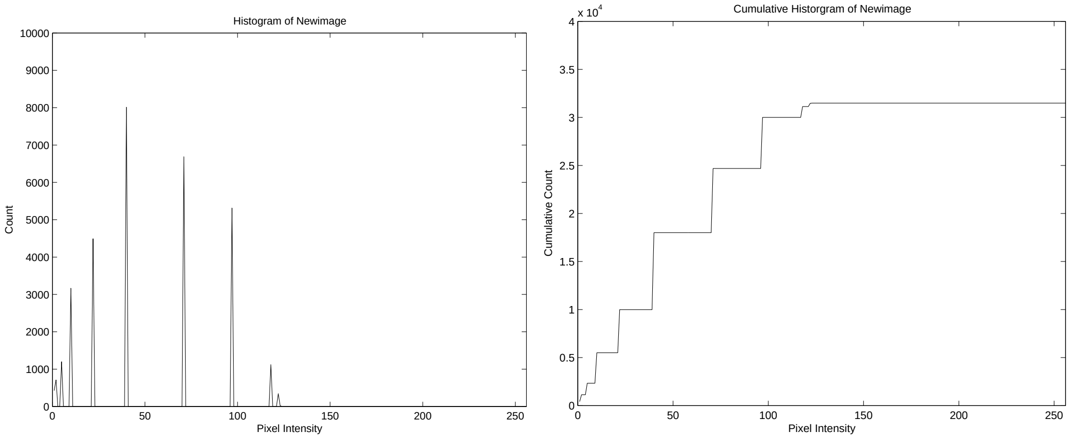

Figure E.3: (a) Histogram of new image with 5 minute exposure of night sky, (b) Cumulative Histogram of new image with 5 minute exposure of night sky.

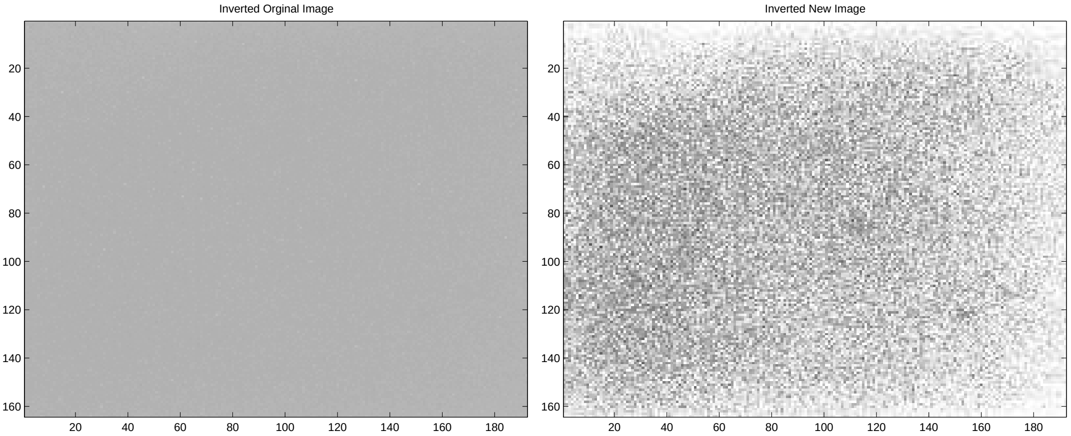

Figure E.4: (a) Inverted original image of the night sky with a 5 minute exposure, (b) Inverted new equalised image of the night sky with a 5 minute exposure.

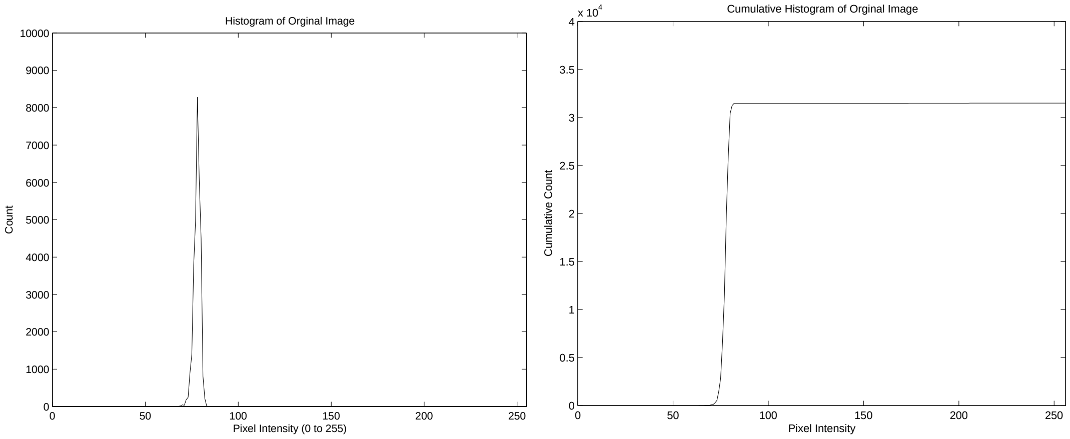

Figure E.5: (a) Histogram of 5 minute exposure image of night sky, (b) Cumulative Histogram of 10 minute exposure image of night sky.

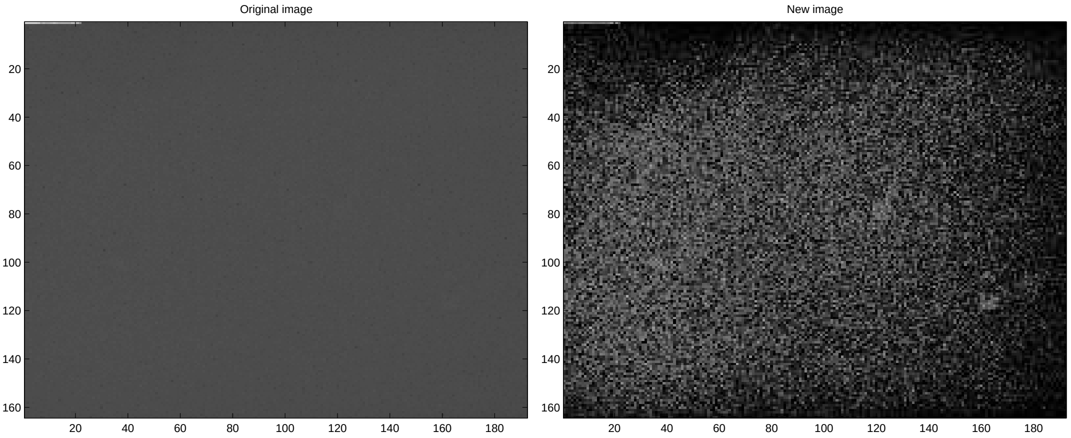

Figure E.6: (a) Original image of the night sky with a 10 minute exposure, (b) New equalised image of the night sky with a 10 minute exposure.

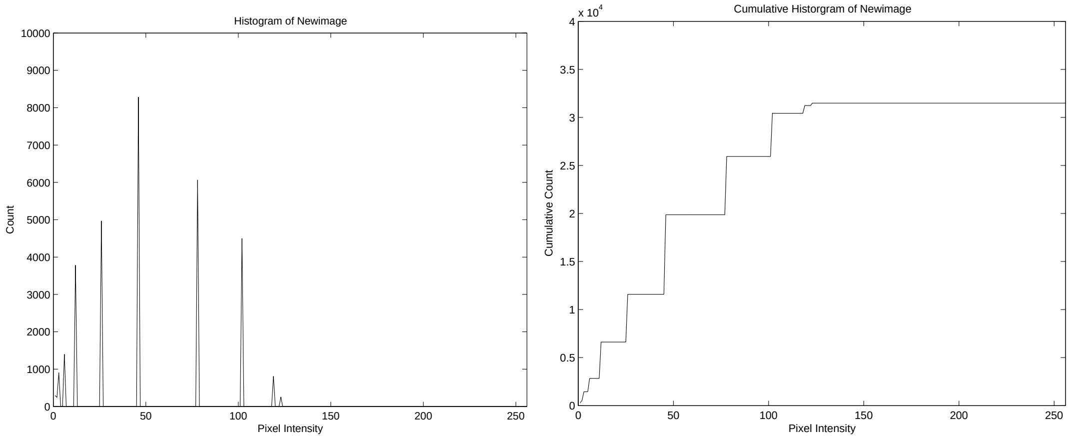

Figure E.7: (a) Histogram of new image with 10 minute exposure of night sky, (b) Cumulative Histogram of new image with 10 minute exposure of night sky.

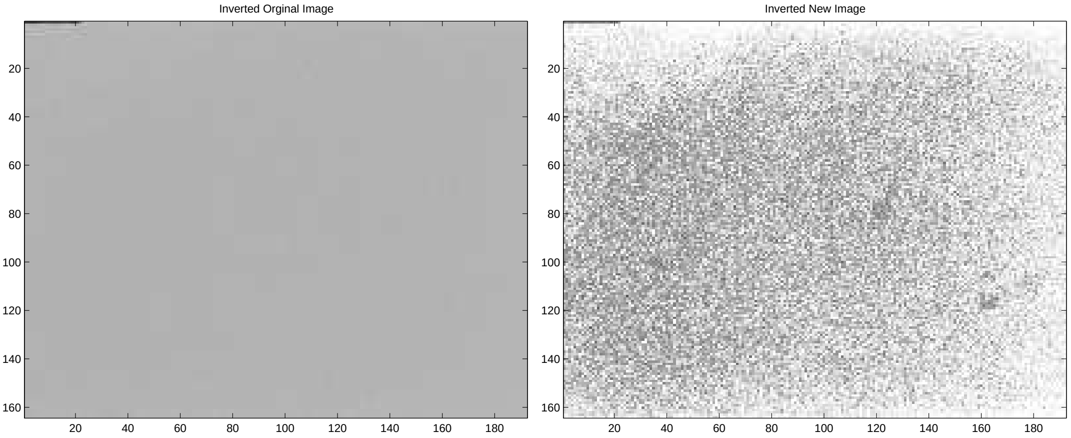

Figure E.8: (a) Inverted original image of the night sky with a 10 minute exposure, (b) Inverted new equalised image of the night sky with a 10 minute exposure.

Appendix F

Final Design

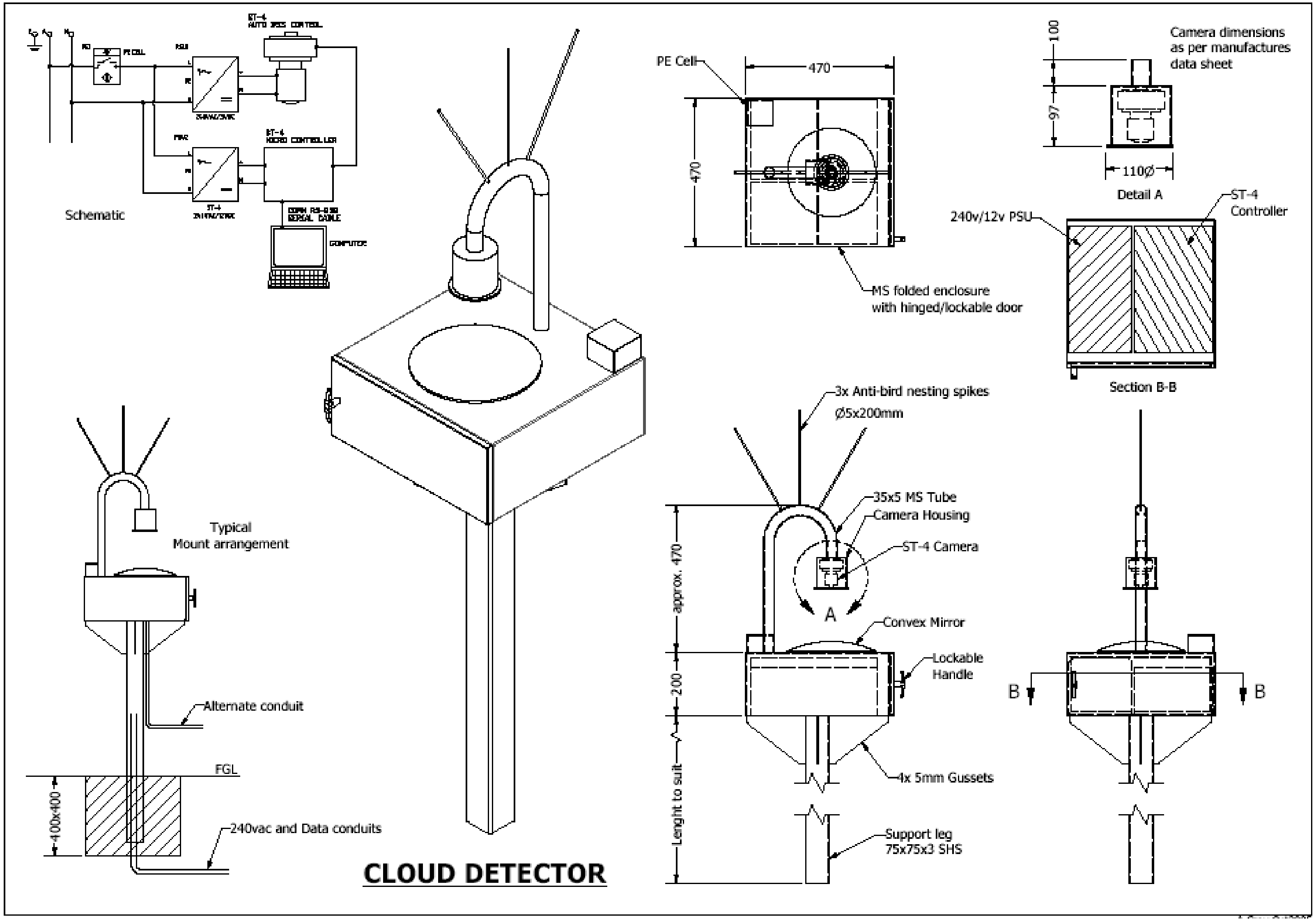

Figure F.1: Final Design of cloud detection system.

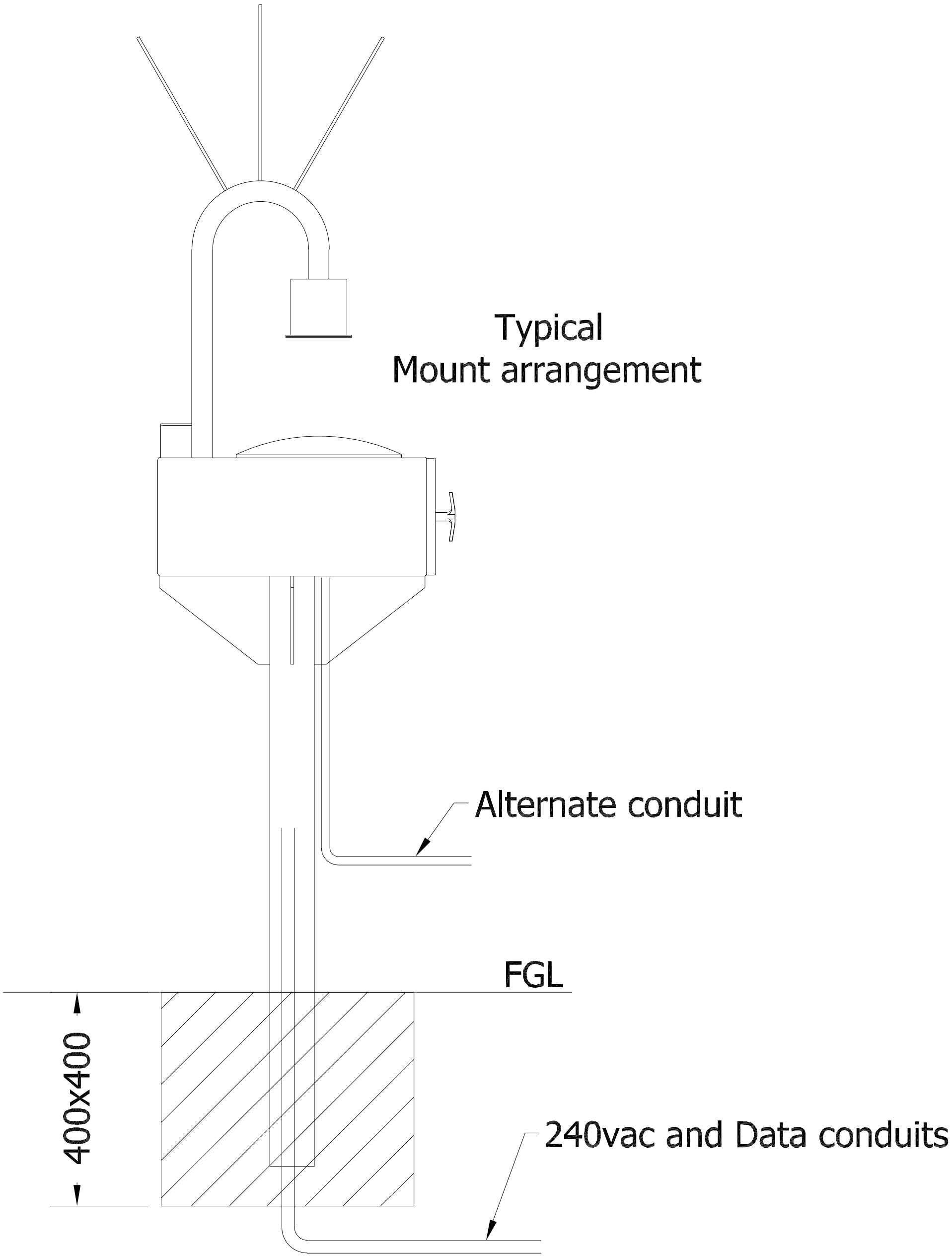

Figure F.2: Mount arrangement from Figure F.1.

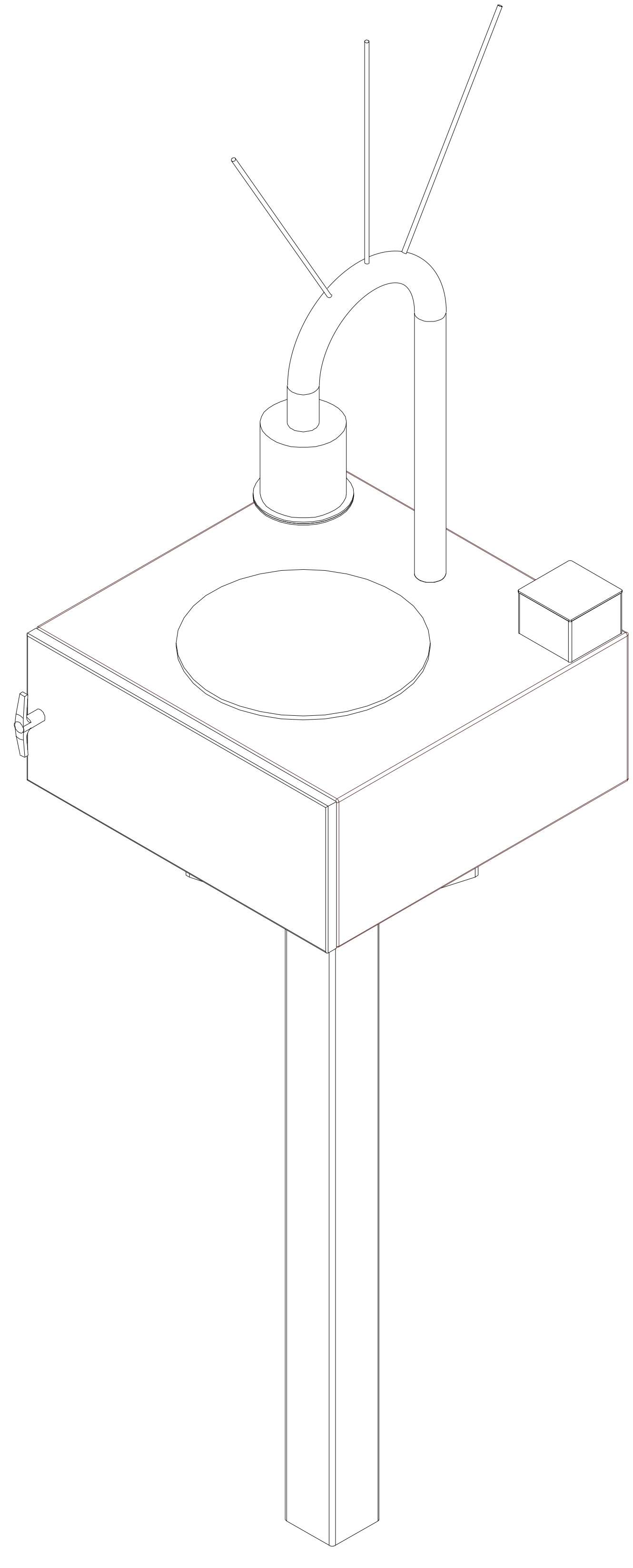

Figure F.3: Cloud detection system overall view from Figure F.1.

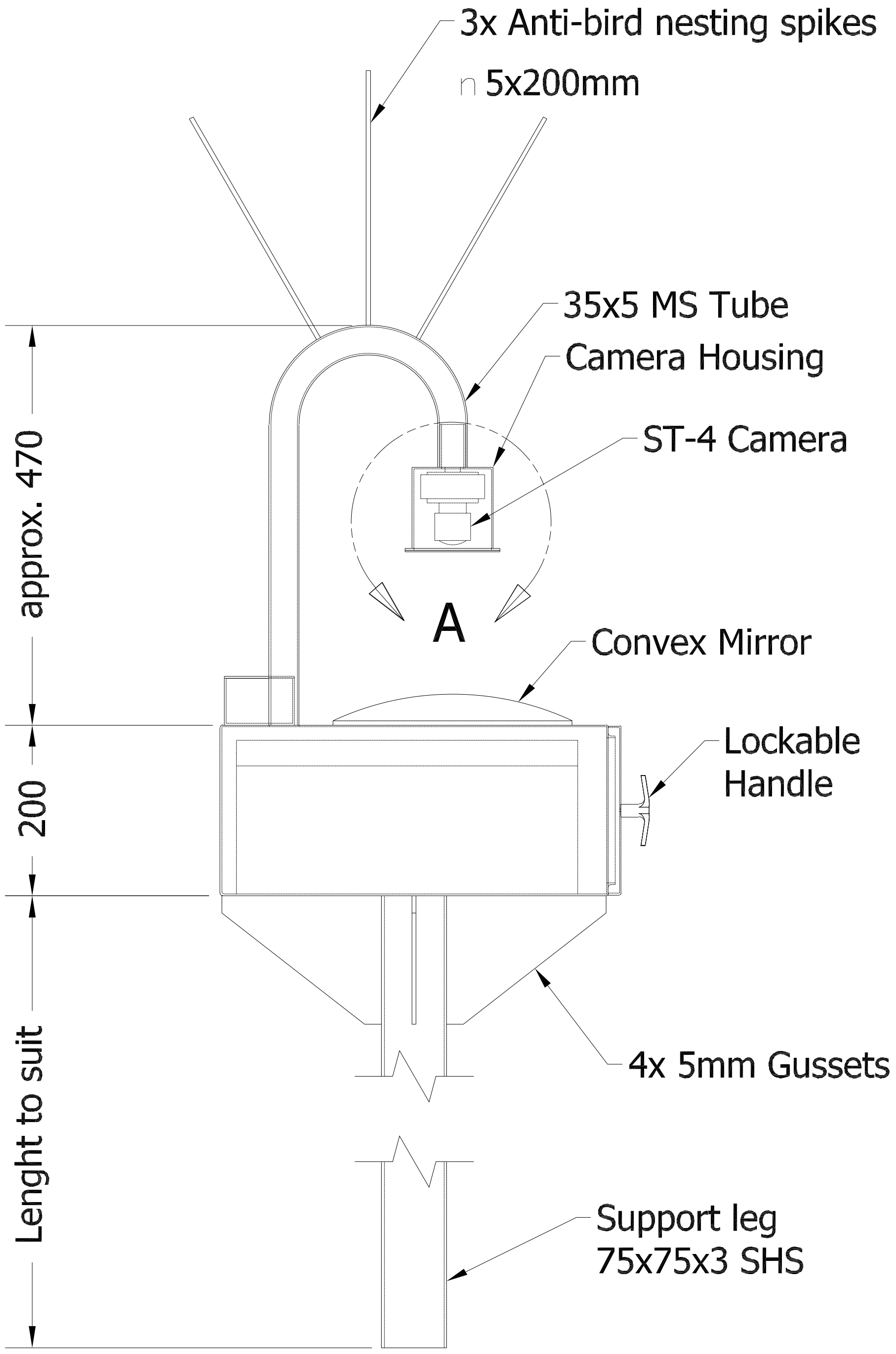

Figure F.4: Side view of system from Figure F.1.

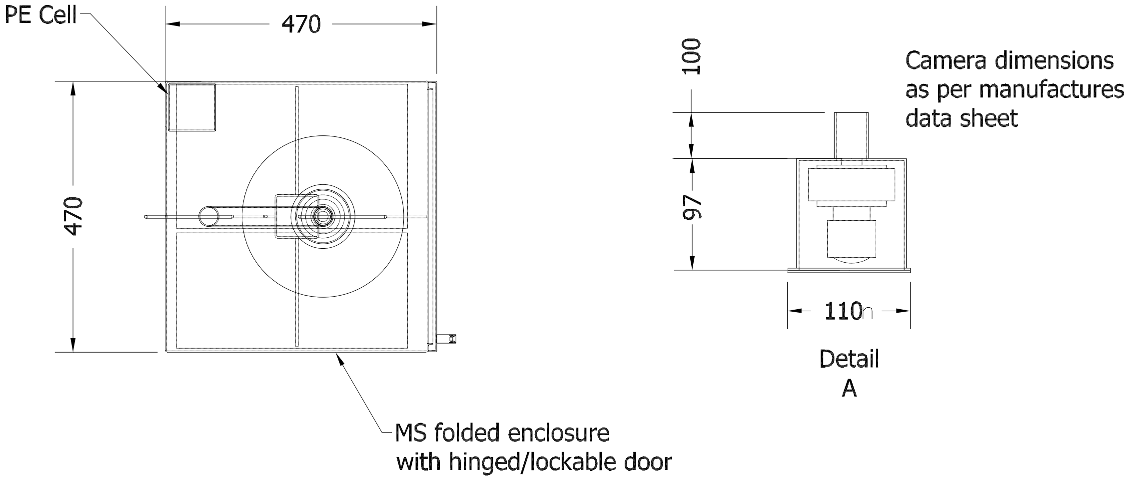

Figure F.5: Top view and approximate dimensions of ST-4 camera weatherproof housing from Figure F.1.

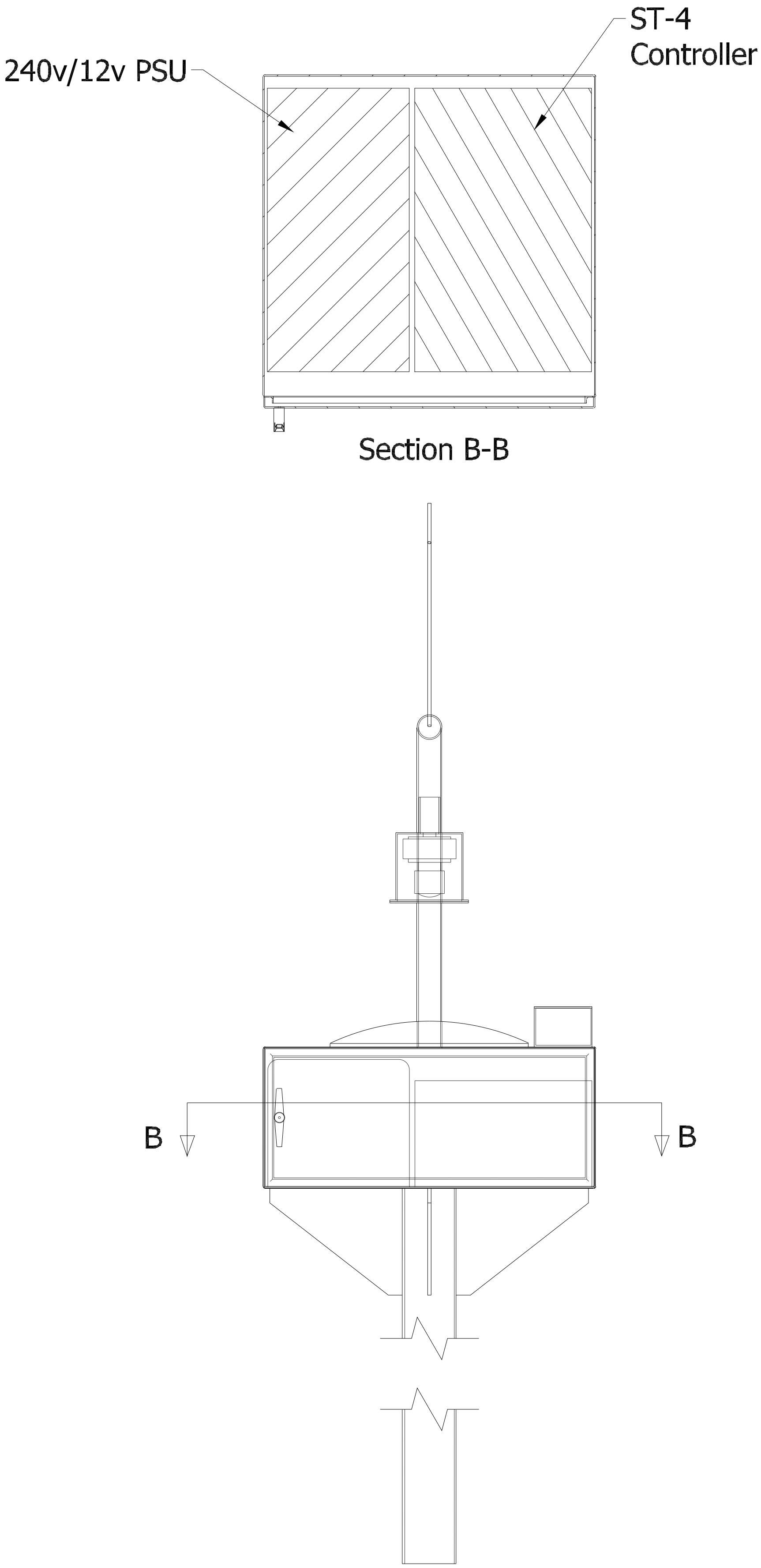

Figure F.6: Front view and top view of system from Figure F.1.

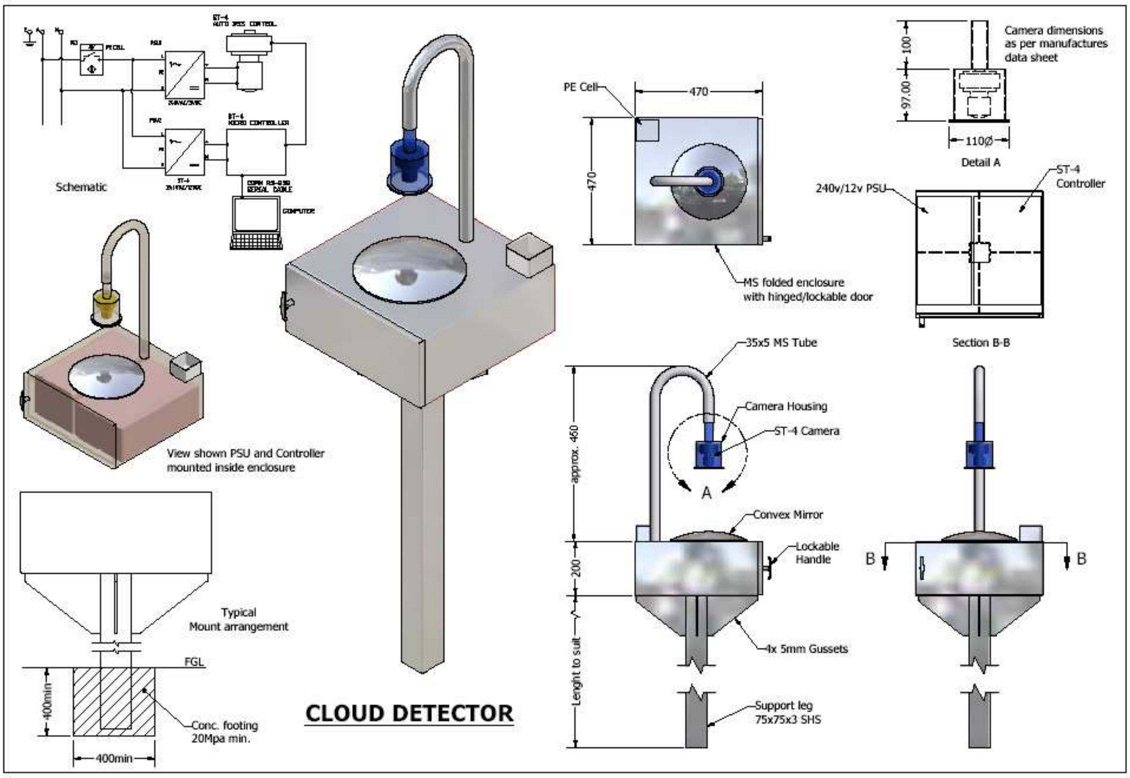

Figure F.7: Rendered final design drawing of Figure F.1.