Sky Camera Network and Data Acquisition System Development for the Purpose of Short-term Photo-Voltaic Power Output Forecasting

By

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Authors Declaration

I declare that the information which is presented in this report, except where indicated, is my own research and has not been submitted to any other tertiary institution.

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Abstract

A sky camera network was installed at Murdoch University capturing high resolution whole sky images every ten seconds for a study, to be completed by the University of Oldenburg, investigating short term solar irradiance forecasting[1]. The study investigates the effectiveness of sky camera imaging and processing techniques used to determine forecasted cloud induced variations on photo-voltaic (PV) power systems based on images and validation data acquired at Murdoch University in Perth, Western Australia. This project demonstrates the effectiveness of two 180-degree fish-eye Vivotek network security cameras recording 1920x1920 pixel RGB images simultaneously at 10 second intervals to provide sufficient information for accurate solar irradiance and PV power output modelling. Results from the collaboration between Murdoch University and the University of Oldenburg were presented at the World Renewable Energy Congress which provide a detailed analysis of solar forecasting accuracy and the associated fuel savings in comparison to other forms of generation and PV management systems. A persistence method of forecasting was determined to properly utilize sky camera forecasting's ability to predict future cloud events and reduce the spinning reserve (SR) that is required in PV and diesel power systems. The results showed that a total of 61% of the time between 10th November and 28th December 2016 the model identified clear sky irradiance. A total of 84 cloud events occurred during this period and 76 of these were correctly identified giving a total miss rate of ~8% [2]. Based on these findings, a further study was conducted by the University of Oldenburg which determined estimated fuel savings achieved with a sky camera based forecasting control method. The findings showed up to 5.5% reduction of fuel consumption in a PV diesel power network with 60% of total capacity being installed PV[3].

The forecasting method used was outlined in a report (West et al 2014) and variations of the image processing methods required were investigated at Murdoch University to explore potential alternatives to more complicated and computationally expensive methods. Various further research is proposed and the effectiveness of alternative methods is presented. The sky camera network and data acquisition system that was developed is discussed in detail and shown to be capable of providing the information required for the forecasting and validation of cloud induced power variations in PV systems.

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Acronyms

CBH	Cloud Base Height
MU	Murdoch University
UoO	University of Oldenburg
EEB	Engineering and Energy Building
REPS	Renewable Energy Power System
RAPS	Remote Area Power Supply
PV	Photo-voltaic
PoE	Power over Ethernet
GHI	Global Horizontal Irradiance
DNI	Direct Normal Irradiance
IT	Information Technology
ROI	Region of Interest
ARENA	Australian Renewable Energy Agency
SR	Spinning Reserve
WREC	World Renewable Energy Congress
RET	Renewable Energy Technology

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Chapter 1 Introduction

1.1 Summary

Murdoch University is undertaking the setup of 2 or more sky cameras calibrated for cloud base height determination at Murdoch University for the purpose of short term solar irradiance forecasting. The University of Oldenburg in Germany is collaborating with Murdoch University on this project and are responsible for the forecasting itself while Murdoch is responsible for the sky camera, data acquisition system set up and cloud base height determination.

Solar Forecasting is an area that has had growing attention in the last decade as PV becomes an increasingly viable and popular option for supplementing various forms of power systems. Global market trends show that PV uptake has been increasing exponentially over the past two decades. While Australia has been a part of this trend, results from the Australian Renewable Energy Agency (ARENA) show that the global market share of solar power has declined[4].

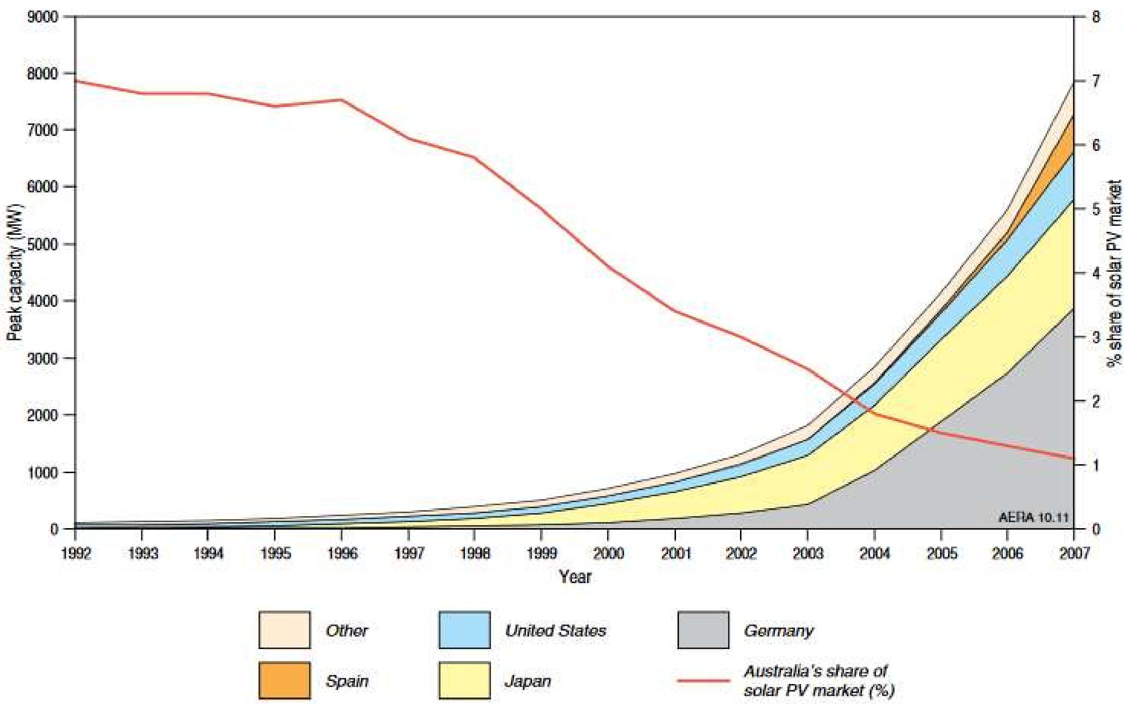

Figure 1 Global PV Uptake in MW and Australian Market Share[4]

This suggests that, as of 2007, Australian had not keeping up with global commitment to PV resulting in a higher dependence on traditional forms of energy that have been linked to adverse effects on the environment. Solar power is particularly suited to the climate of Western Australia which contributed to the interest that Murdoch received from University of Oldenburg.

High levels of PV power generation cause various issues which can adversely affect power systems [5]. Network operators have requirements for consumer power quality regarding frequency and voltage which require generators to operate at low efficiency providing spinning reserve in the case of a significant increase in load power. The effect of a cloud induced variations on solar irradiance effectively causes a variation in load power as seen by the generator. A reliable forecasting method and control system can curtailment PV power output prior to the forecasted decrease in load power allowing generators to operate at lower spinning reserve and may enable a generator to be taken offline[3].

Solar forecasting has been suggested as a solution to some of these issues which are causing network operators to limit the percentage of power generation that is contributed by PV. Various solar forecasting methods have been considered ranging from satellite based forecasting to networked irradiance sensor type predictions [6]. Sky camera forecasting has been made a competitive and desirable option due to the availability of low cost imaging and computing systems. Relatively cheap fish-eye cameras are available as security cameras and have provided a low-cost alternative to the other forms of forecasting. Methods for image processing and data storage are readily available in the form of software packages and cheap processing power.

Sky camera forecasting systems require a fixed camera facing skyward connected via a communication medium to a computational device. Images are processed in real-time to determine cloud motion information which is used to predict when a cloud will cast a shadow on a location or PV array. This collaboration focuses on studying the ability and accuracy of various solar forecasting techniques based on images and environmental information collected by the sky camera and data acquisition system developed at Murdoch University.

1.2 Project Requirements

The requirements of this project were largely dictated by the requirements of University of Oldenburg for effective forecasting and validation. The results of the study of forecasting at Murdoch University were to be presented by Thomas Schmidt at The World Renewable Energy Congress which commenced on the 5th February 2017. The study focused on investigating very short-term forecast times ranging from ten minutes down to one seconds in advance. This required high frequency data collection that was time synchronized with error less than 100ms.

The initial requirements of the project were,

- Store images from two camera locations in the Sky FTP server
- Images required to be stored in daily folders on the sky server in a format YYYYMMDD_HHMMSS.jpg
- Store daily irradiance data as a csv file with data accurate to 0.1 second and in the format YYYYMMDD_EEBGHI.csv
- Communicate with an inverter and store power information on the sky server
- Integrate new software with existing software
- Develop cloud base height determination software and provide data to the University of Oldenburg
- Obtain required data before the end of 2016

Additional requirements were added and are outlined below,

- Provide a status updates in the form of reports to the University of Oldenburg
- Apply for a research licence for LabVIEW
- Install a sensor for irradiance logging at a location 5km from Murdoch campus
- Acquire cloud base height information from Jandakot airport

1.3 Background

This project has been underway since mid-year 2015 and significant progress has been made. Eric Roy made considerable progress with the LabVIEW data acquisition system as well as the installation and calibration of two sky cameras[1]. Many of the tasks that were undertaken during this project have been mentioned by Eric Roy in his thesis as areas that require more work or are necessary changes for continued development of the sky camera network.

Murdoch University has a variety of renewable energy research systems available which have been developed over a history of research in the area of renewable energy sources. The wide range of systems and the geographical distribution are ideal for this make Murdoch campus an ideal location for the implementation of a sky camera system.

The research systems that are of particular use include the Engineering and Energy Building (EEB), as shown in figure 1, and the Renewable Energy Power System (REPS) facility as shown in figure 2. One of the requirements for the software that is used to predict locational PV power output is data for validation purposes. The proposed software uses machine learning to improve the accuracy of forecasting and requires real time data. The EEB and the REPS system combined with the two sky cameras installed by Eric Roy can provide a significant portion of the information required by University of Oldenburg[1].

The EEB has 5 existing PV arrays consisting of polycrystalline, monocrystalline, copper indium gallium selenide (CGIS) and thin film amorphous technologies outputting a total of 8kW[7]. Included in the system is 6 different inverters measuring real time power information which can be logged into a database by a data acquisition system based on the NI LabVIEW programming language[1].

Figure 2 Roof of EEB [7]

The REPS system is a part of Murdoch University's Remote Area Power Supply display (RAPS) which is located at the southern boundary of campus. The facility has a range of renewable power sources including multiple solar arrays and inverters. The REPS now has a sky camera which was recently installed at a nearby location and is connected to the DAQ system with a PoE connection. The REPS data acquisition system was a originally a standalone environmental monitoring system and now has been connected to the Murdoch network for the purposes of forecast validation. During this project a wireless bridge was installed to allow communication between the REPS facility and the Sky Server on the Murdoch University staff network[1].

The REPS is powered by the RAPS and has recently had its battery bank replaced which has resolved some past power stability issues.

Figure 3 REPS Facility [1]

Chapter 2 Application

2.1 Grid Stability & PV

High resolution short-term solar irradiance forecasting is useful information for the management of power systems were a high percentage of power is supplied by PV[2]. High penetration of solar can be detrimental to power quality at the network level of a distribution system[8], cloud shadow events cause a significant decrease in the power that is being supplied by solar which is effectively a sharp increase in load called cloud shear. Power stability is dependent on the balance between load and supply so to handle the normal fluctuation in load the grid operator will run generators with spinning reserve to supply extra power in the event of a small increase in load. The increase in load that can be caused by a cloud shadow on a small solar hybrid network with high PV penetration is significantly larger than normal load fluctuations and requires extra generation to be provided. An extra generator coming online can take up to 2 minutes to start, synchronize with the grid frequency and ramp up power production. During this time, the power difference between load and supply causes poor power quality for the consumer.

Horizon Power is the network manager which is responsible for the distribution of power in remote Western Australian areas which aren't a part of the South West Interconnected System. To maintain power stability Horizon Power requires grid connected solar installation to be approved depending on calculated limits for available managed and unmanaged capacity [9]. As of February 2017, the town of Carnarvon has approximately 1000kW of managed capacity available with no available unmanaged capacity. Capacity management currently requires the installer to provide a management system comprising of a battery and smart controller configuration. Managed systems are expensive with a longer payback period which is a deterrent for the investment into clean energy in Australia's remote towns.

A sky camera network and forecasting system are a cheaper option for managing PV integration in remote networks like Carnarvan's. A cloud shear event can be forecasted and the power provided can curtail the generation produced by each inverter in anticipation of a shortage of solar power, this will provide sufficient time for generation from other sources to ramp up and eliminate the power quality issues of higher PV penetration in an unmanaged network[2].

2.2 Solar Forecasting & Power Stability

Solar Forecasting is an area being investigated for management of power grids with high PV penetration. With advantages in image processing technology solar forecasting has been explored as a solution to cloud shear since early 2000's. It was found in a recent report (Sayeef et a., 2012) that solar forecasting was the most cost-effective way of managing intermittency caused by cloud shear in electrical networks[5]. Since then various studies have been done using sky cameras and satellite imagery to try to predict PV power output over an area of PV systems or at a single PV array location.

A paper published by (West et al., 2014) provides the following list of examples where solar forecasting can provide a benefit and gives details of the benefit types.

Application	Category	Forecasting type	Forecast timing	Benefits of forecasts
Remote area power system with photovoltaics (PV) and fossil fuel backup	Compliance, network information	Local ramp event forecasts Local Global Horizontal Irradiance (GHI)/Direct Normal Irradiance (DNI) forecasts	Minutes	• Reduced fossil fuel consumption • Reduced network step loads
Distributed PV – residential/ commercial rooftop PV	Network information	Wide-area GHI/DNI forecasts	Minutes to hours	• Better informed network operations • Disaggregation of local generation and demand
Large grid-connected PV – PV solar farms	Production, network information	Local ramp event forecasts Medium-area GHI forecasts	Minutes to hours	• Ramp-rate control • Better informed production management via storage and inverter control
Large concentrating solar-thermal – heliostat field solar farms	Production, network information	Local ramp-event forecasts Local DNI forecasts	Seconds to hours	• Over-power protection • Flux management • Reduced plant component fatigue
Small solar-thermal – residential solar hot water	Production	Local GHI/DNI forecasts	Day-ahead	• Minimising booster operation
Energy markets – generator dispatch and maintenance planning	Production, network information	Power forecasts	Minutes to days	• Spot-market revenue management • Increased maintenance schedule efficiency

Figure 4 Applications and benefits of solar forecasting (West et al., 2014)

2.3 Solar Forecasting & Savings

With solar forecasting and an implementation of a solar generation curtailment system generator spinning reserve can be reduced or eliminated entirely[3]. Power generation systems can be comprised of various forms of generation such as coal power stations, diesel generators, gas turbine and renewables sources of power. Diesel generators are often used as spinning reserve because of their fast power ramp up rates and much of the investigation into fuel savings that was carried out using data acquired at Murdoch was based on the diesel generator spinning reserve case. Operating a generator as spinning reserve is effectively running the generator without any mechanical load, this is detrimental to both fuel efficiency and emissions[10] and the effect of solar forecasting on the amount of spinning reserve required can be translated directly into fuel, emissions and maintenance cost savings[3].

Chapter 3 Existing Works

The Sky Camera system had been underway for 2 semesters at Murdoch University prior to the commencement of this project and significant progress had been made in the development of the network and data acquisition aspects. Both SkyCam_1 and SkyCam_2 were installed and standalone DAQ applications were developed. Eric Roy completed his honours project mid-2016 and was instrumental in the design and installation of the sky cameras as well as the software system required to poll the cameras for images. A Python based software which was provided by University of Oldenburg and developed in a Linux environment, wasn't compatible with Murdoch's Windows systems and the software was required to be redeveloped at Murdoch. Eric used LabVIEW for its availability of both licencing and on site expertise at Murdoch. LabVIEW was used for image processing and developing existing data acquisition systems[1]. At the time of the project handover two stand-alone applications were running on the sky server handling image acquisition for SkyCam_1 and SkyCam_2 respectively.

3.1 Existing Hardware

Prior to the commencement of this project both cameras had been installed at different locations on Murdoch University campus. The locations of SkyCam_1 and SkyCam_2 are spatially 680m apart and the lay out is shown below in Figure 5.

Camera 1 (EEB):

32.06613 South 115.83711 East 4m Accuracy

48m above sea level (Google Earth)

Camera 2 (REPS):

32.07048 South 115.84051 East 4m Accuracy

27m above sea level (Google Earth)

Figure 5 Locations of Sky Cameras at MU

The camera mounts were designed and installed by Eric and Murdoch University personnel. The designs allowed for regular cleaning of the camera and provided a fixture that minimised camera movement. SkyCam_1 mounting installation consists of a hinged fixture to provide maximum height and accessibility to the camera.

Figure 6 EEB SkyCam_1

Figure 7 SkyCam_2 at REPS Facility Initial Mounting Design

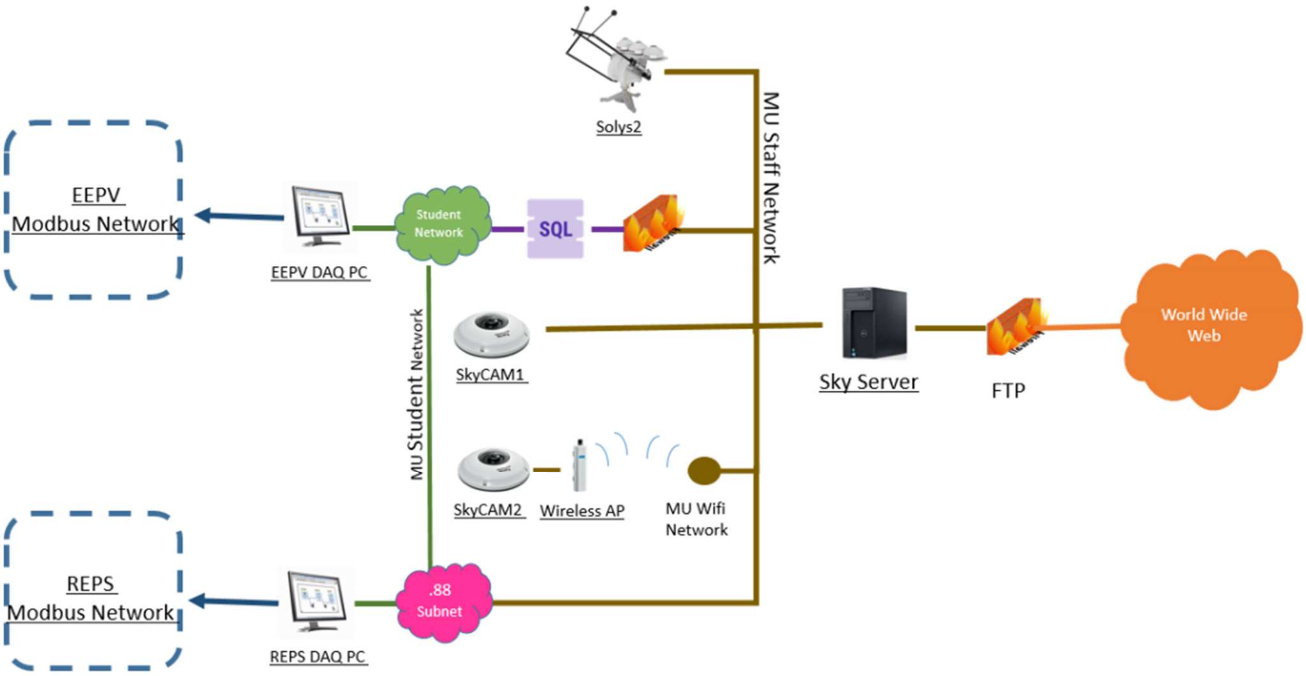

Figure 8 The Sky Camera Network and DAQ System as Depicted by Eric Roy

Error! Reference source not found. shows the sky camera network as it was prior to the project hand over. The Solys2 has since been removed to await approvals.

3.2 Existing Software

Software was pre-existing at REPS facility prior to the commencement of this project which logged irradiance and inverter power output at the location of the facility called the Main 24-7 program. Main 24-7 was modified for logging data into the sky server in the required format.

Two standalone applications that were built using LabVIEW were running on the Sky Server and using TCP\IP protocol to poll ten secondly images from each camera. The images were then processed on the server to include a Murdoch University logo and were time stamped

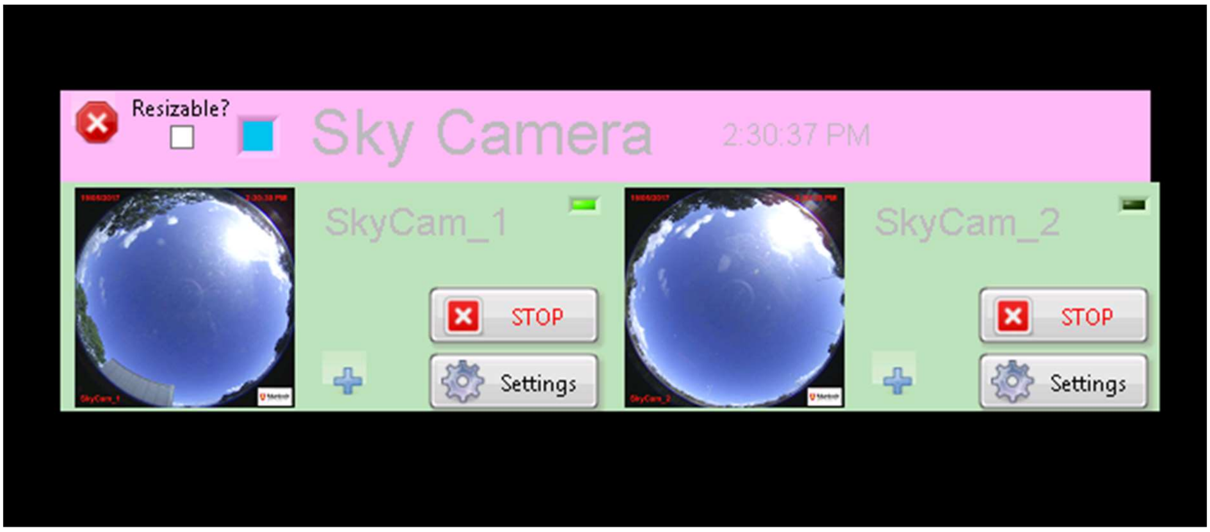

Figure 9 Existing Sky Server Software

Chapter 4 Project Method

4.1 Project Type

The hands-on nature of the Sky Camera network required expertise from various departments adding levels of complexity to the management of this project. The project scope was clear at the commencement of the project as was the dynamic nature of the scope. The dynamic nature of the research at the University of Oldenburg required constant updates and changes to the output of the data acquisition system with frequent monitoring and improvements being required over the two semesters. Some of the scope was dependant on approvals and grants from Murdoch University as well as accessibility to reliable and relevant equipment. During the transition between 2016 and 2017 Murdoch University had scheduled various IT upgrades and maintenance that would require substantial correspondence with the Engineering IT department and a reliance on Murdoch University staff. The management method that was chosen in the early stages of the project needed to be carefully selected such that it was capable of effectively managing the anticipated and unanticipated tasks.

The sky camera network was developed to be continually utilized by the University of Oldenburg and future projects or teachings at Murdoch University. It involved approximately equal parts software and hardware design for the completion of this section of the sky camera network. Murdoch University has onsite expertise which was available for the sky camera network and could be utilized during hardware design and commissioning which allowed the hardware and IT network design to be developed using a collaborative effort.

The continues interaction with various departments and stakeholders meant that the final sky camera network and underlaying software system was to be developed as an interactive system. Stakeholder interaction and expertise from various disciplines at Murdoch and at Oldenburg was important for creating a reliable, dynamic and user-friendly system[11]. Eric Roy's approach to developing an interactive system was effective and his stand-alone application method was continued along with additional consultation with expertise. Continuous personal skill development was required to replace the gap in experience which was left following the departure of Eric from Murdoch University.

4.2 Project Management Approach

The management approach taken to this project had to be a unique method that was suitable for such a multidiscipline task. During the project hand over period a Gantt chart was created to develop a proper understanding of the perceived tasks that would be required to complete the project requirements. The Gantt chart was followed throughout the course of the sky camera network development and was used for the management of task deadlines and time allocation. During the design approach which was applied to each task the management of resources and availability of expertise was considered during the project requirement analysis and the overlap of various tasks was utilized to maximise the productivity of available time. The Gantt chart is shown in Figure 10.

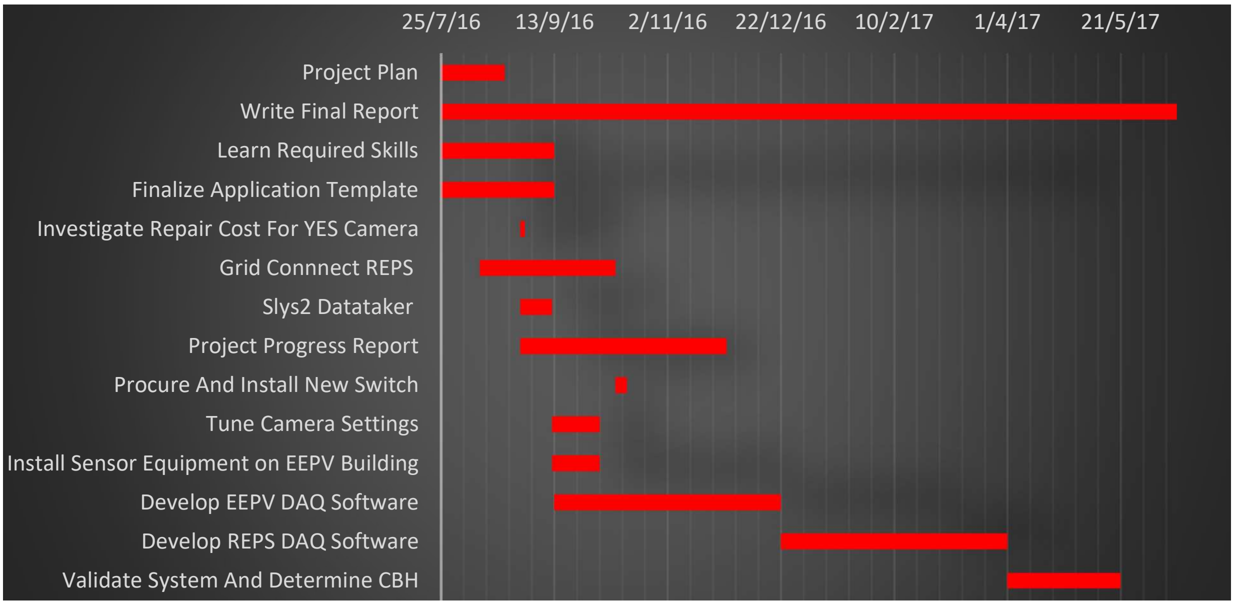

Figure 10 Project Plan Gantt Chart

4.3 Project Design Approach

The tasks associated with the sky camera network were outlined in the development of the Gantt chart during the planning stages of the project and each task was approached as an individual design project. Tasks such as software development and hardware installations were considered and a design approach was chosen which would suit the requirements and available expertise associated with each task. Initially a Waterfall design approach was used [12] and task requirements were investigated. According to The International Journal of IT & Business Management, The Waterfall design approach is best suited to projects with clear requirements[12] and this approach was used for tasks were the objectives were clearly established such as the installation of a solar irradiance sensor on the roof of the EEB. The Waterfall design approach is outlined in Figure 11.

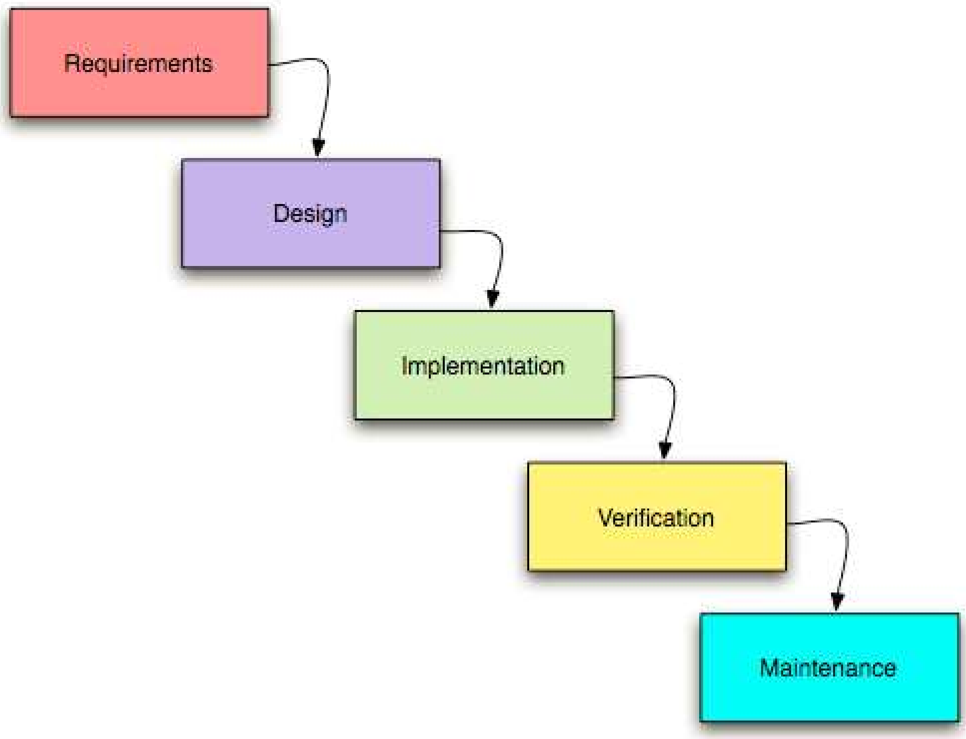

Figure 11 Waterfall Design Approach [12]

The Waterfall approach proved very effective for the tasks with clearly defined requirements and readily available expertise although tasks such as software development had less clearly designed strategies for meeting the broader requirements of the project. Available expertise on LabVIEW software development was greatly reduced with the departure of Eric during mid-2016. The lack of available expertise was the biggest issue facing the design approach to the continued development of the software system and because the implementation of the software was reliant on the necessary skills being developed during the progression of each task, a more versatile design approach was used called the Agile approach [12]. As can be seen in Figure 12, the iterative method this approach uses makes it the kind of versatile approach that was necessary for the development of the required programming skills during the design process.

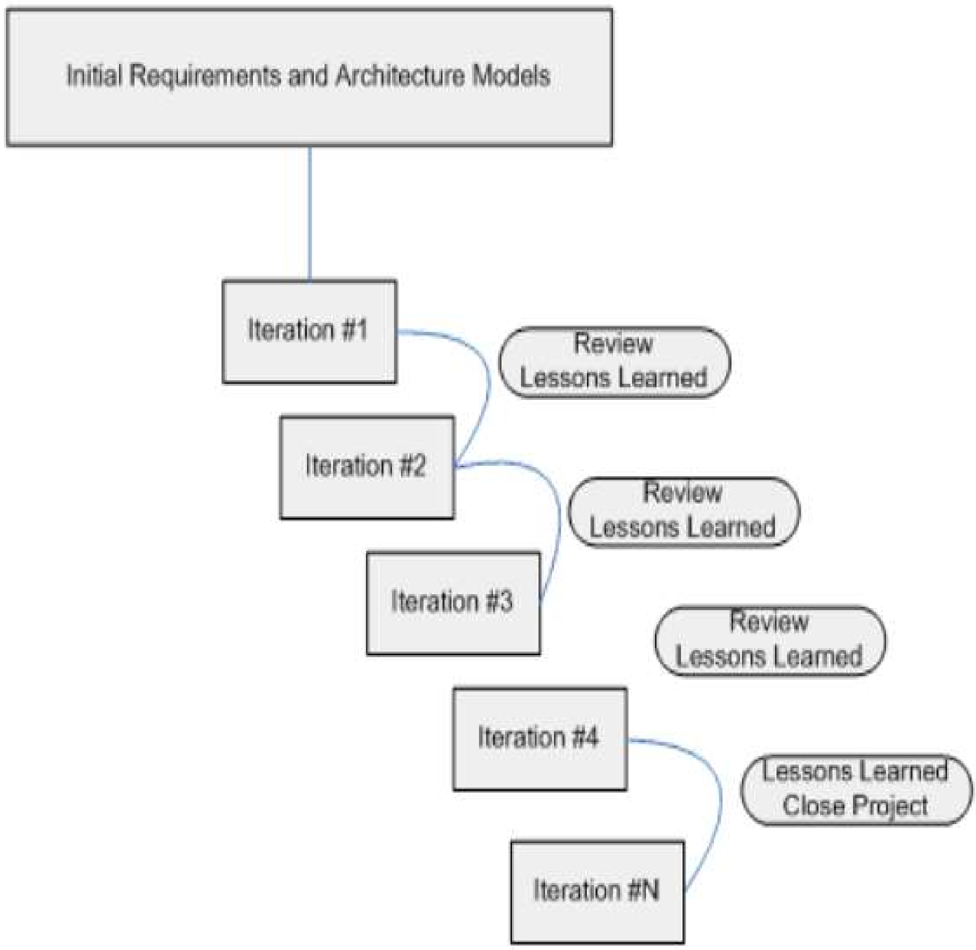

Figure 12 Agile Project Design Method[12]

Chapter 5 Data Acquisition System Development

The objective of the data acquisition system was to provide images and information that would allow University of Oldenburg to forecast irradiance levels and determine the accuracy of their forecasting using real-time validation data. During the early stages of the Sky Camera project, the fish-eye Vivotek security cameras were recommended by University of Oldenburg and Python code was provided to request images from the cameras via TCP/IP HTTP. The code which University of Oldenburg supplied was developed in a Linux environment and was not readily compatible with MU's expertise and windows operating system [1]. Eric Roy made the decision to redevelop the imaging system in the LabVIEW programming language 'G'. Eric's proposed development structure involved a series of standalone applications which would be linked with a master stop button and an interface positioning system which utilized global variables for multi-application communication. Eric Roy developed both applications, in the LabVIEW language, for SkyCam_1 and SkyCam_2. These applications were finished in a master frame design and communicated with the master stop global variable that the master frame stop button controlled. The concept of application mobility and synchronous termination was very user friendly and visually appealing but complications with the global variables which were hosted by LabVIEW resulted in the development design being side-lined after the project take over.

5.1 Software Development

Irradiance Logging

A key requirement for solar forecasting validation was high resolution solar GHI accurate to within a second for validating forecasts in real-time. The proposed installation of the solys2 in conjunction with a CR800 datalogger and a NL201 were to make up the required hardware for the collection of global horizontal irradiance and direct normal irradiance at the EEB near SkyCam_1. The approval process caused the Solys2 to remain uninstalled for the duration of this project and a compromise was reached which would satisfy University of Oldenburg's needs. The LabVIEW language was chosen to build the software which would communicate with the CR800. The application was required to be dynamic enough for the addition of extra sensor to the CR800, LabVIEW was compatible with the likely knowledge of future students working on this project and it had been proven to be effective in executing HTTP commands and requests over the Murdoch University's network.

The NL201 was configured in bridge mode to act as the link between the Murdoch TCP/IP network and the RS232 serial communication method used by the CR800 data-taker. This following an investigation of the NL201 and CR800 duo the CR800's IP capabilities via manual consultation and http command testing using internet explorer. The NL201 was assigned a permanent IP address 134.115.246.47 and all traffic which was sent to or received by this address was converted from TCP to RS232. This provided the required link for a logging system to request data from the CR800 and store it on the sky server.

The CR800 was programmed to log the voltage across the terminals of the SPLITE2 pyronometer at 1 second intervals, convert the data into kW/m^2 of irradiance using the calibration coefficient and store the data in table form on the internal memory of the CR800. Campbell Scientific software called Short Cut was used to develop the CRBasic code which was required by the processor in the data-taker and allowed for the efficient configuration and deployment of the CR800. Configured with the CRBasic program the logger was capable of stand-alone logging and its memory table was set up to discard old data once the memory was full. During the development of the LabVIEW application the CR800 was downloaded via serial communication and manually uploaded to the sky server.

In future extra sensors are to be added to the CR800 once the SOLYS2 is approved and installed at the EEB. Consultation of the CR800 manual provided a list of HTTP commands which could be utilised while the CR800 was paired with the NL201. The below command was found for requesting an XML report from the CR800 which contained the most recent irradiance value/s stored in memory.

http://134.115.246.47/?command=DataQuery&uri=dl:EEB_GHI&format=toa5&mode=most-recent&p1=1

Experimentation with the LabVIEW 'get http' function showed that the NL201 was not capable of processing a request for more than one data point without significant lag which was detrimental to the time stamping process. The most effective way to gather accurate information was to request data every second and a while loop was developed. The XML report contained headers and footers which were of no relevance for logging purposes and the relevant data was parsed out of each report before being appended, along with a time stamp, to a daily CSV file in the sky server.

Fronius Inverter Power Output Logging

Determination of the relationship between cloud induced variations in solar irradiance and the effect of these solar irradiance variations on power output of a PV inverter system was an important link in the forecasting of cloud induced variations on PV power output. To validate this link real-time power output of an inverter was required to be logged at the same location as irradiance logging was taking place. The Fronius inverter in the EEB was chosen for this project due to its proximity to the Murdoch network and the availability of a LabVIEW program which could communicate with it. The Fronius inverter application was developed with Eric Roy's help and utilized the existing algorithm integrated into Eric Roy's user interface design, logging DC and AC power parameters into the sky server at 10 secondly intervals.

Wireless Bridge Configuration

SkyCam_2 is located near to the REPS facility on Murdoch campus and is connected to the Murdoch network via a wireless bridging device. Due to an aging battery system at the REPS, SkyCam_2 was only power during the week and the immittance was causing communication problems which resulted in incomplete image sets. Analysis of the wireless bridge on the LAN side showed that the IP address being assigned by Murdoch's DHCP was differing after each power shut down. The DHCP issues was rectified with the help of IT staff and the port forwarding settings were configured so that HTTP port 8080 was the port used to address SkyCam_2.

5.2 Hardware Development

Installation of the sensors and cameras required for the sky camera network involved significant hardware design and installation. The approach favoured during the design and planning stage was to install all hardware permanently and in such a way that future modifications and addition of instruments was possible. Staff at Murdoch University were instrumental in applying their skills and expertise throughout the design, testing and commissioning stages allowing deadlines to be met and installations to be compliant to a high safety and functionality standard.

Reinstallation of SkyCam_2

SkyCam_2 was housed installed on an adjustable mounting which allowed for easy levelling of the camera. The box which housed the PoE injector and wireless bridge had large rust holes and caused the PoE injector to fail after a rain so a new PoE injector was installed and the holes were sealed to prevent future issues. During the installation, the camera was removed and the adjustable levelling system was shown to be insufficient to keep the camera stable due to deteriorating rubber. The reinstallation of SkyCam_2 involved the permanent fastening of the camera on a levelled steel plate.

Installation of SPLITE2 Pyronometer at EEB

To obtain irradiance measurements at the location of SkyCam_1, an SPLITE2 pyronometer was installed next to the camera on the roof of the EEB. The sensor was installed on a silicon base and communication cable inside cable sheathing was run along the existing cable tray back into level 3 of the EEB. The silicon base allowed the levelling of the pyranometer on the slightly angled roof and the process can be seen in Figure 13.

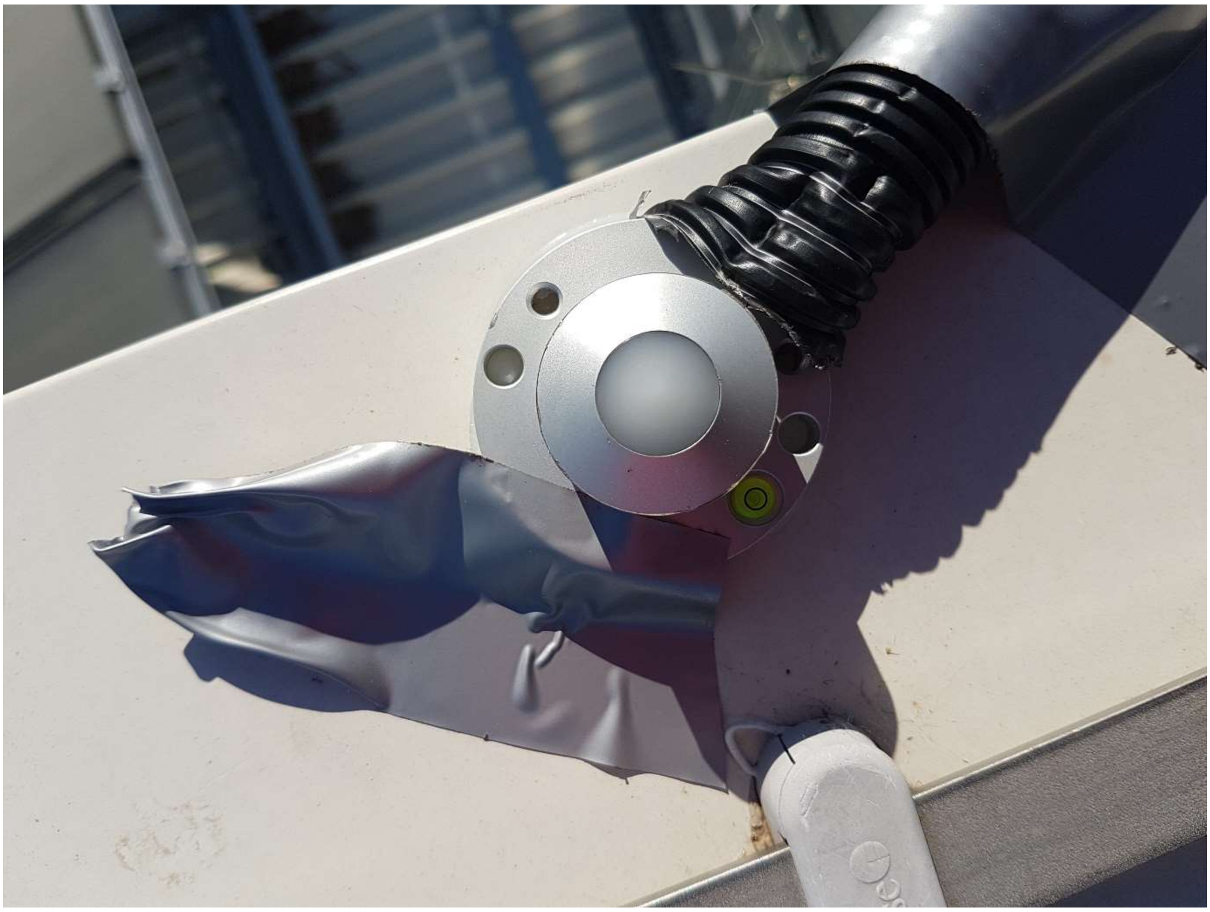

Figure 13 Levelling EEB Irradiance Sensor During Installation

Cable Tray Installation

The existing communication cable for SkyCam_1 at EEB was installed temporarily. With the help of Mark Burt at Murdoch University, a cable tray was installed in level 3 which allowed room for future sensor installation on the roof. The tray also rectified the safety issues associated with a loose cable laying on the floor of a walkway and it ensured data cables were far enough away from AC power cables that the installation complied with Australian standards.

Figure 14 Cable Tray Housing Data Cables in Level 3 EEB

CR800 & NL201 Installation

The CR800 and NL201 were acquired by Murdoch University to be used in conjunction with the SOLYS2 environmental sensors. Careful consideration of the long-term use of the devices and the potential risks associated with leaving them in an unsecure area was undertaken along with consultation of Murdoch University personnel. A collaborative decision was made to design and construct a board in EEB level 3 which would provide a reliable fastening location for the CR800, NL201 and any future expansions. The experience and licences of Mark Burt were valuable in the construction and commissioning of the final design.

Figure 15 CR800 and NL201

Final Sky Camera Network

The final sky camera network as it was at the end of semester 1 2017 is shown in Figure 16.

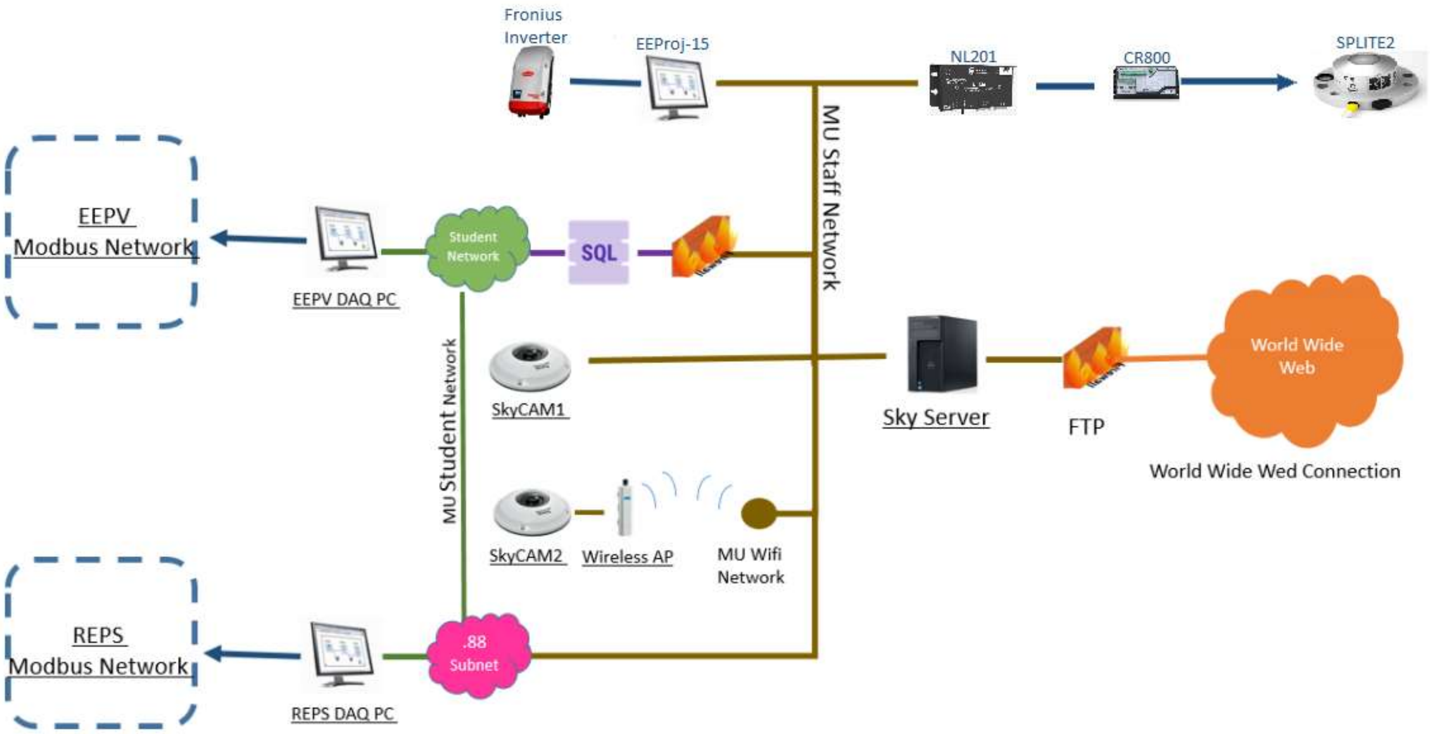

Figure 16 Sky Camera Network Layout

Proposed Walkway to Solys2 Design

The design and construction of a walkway installed on the top of the EEB is currently underway. The walkway will allow safe access to the top most section of the roof where the SOLYS2 is proposed to be installed and has been designed by CDM construction with input from this project and Martina Calais. The preliminary design sketch is shown in Figure 17.

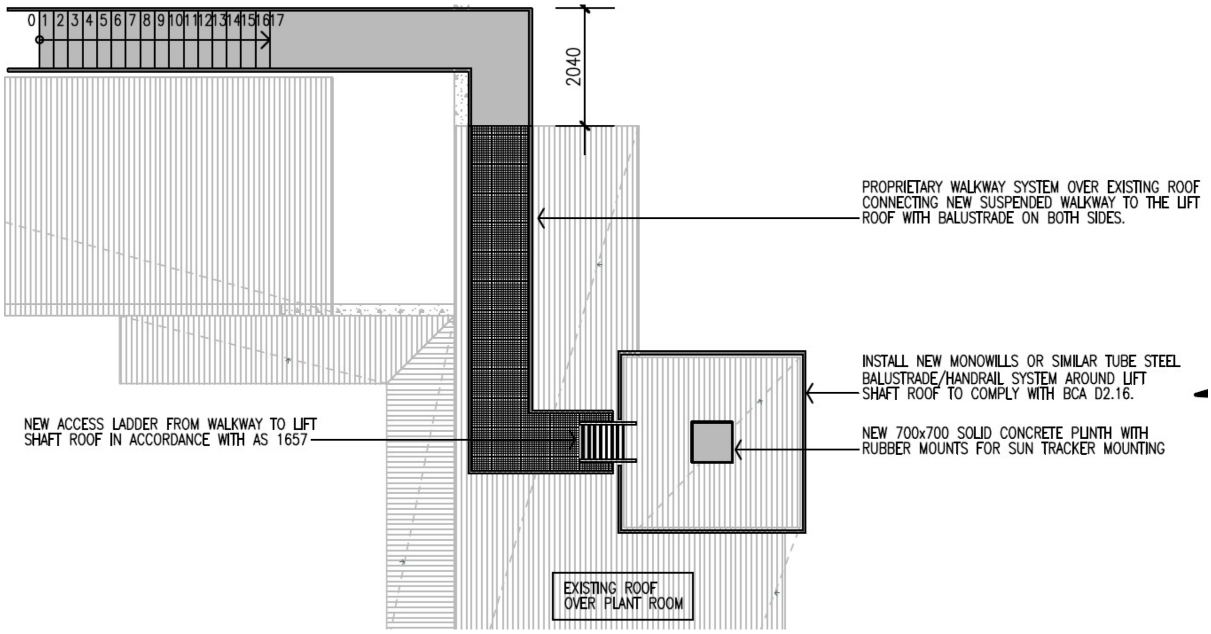

Figure 17 Proposed Walkway to be Installed on EEB

Remote Irradiance Sensor

A sensor was installed on 12 Watts Pl which is approximately 5km from SkyCam_1 and was designed to collect validation data for distance forecasting. A mounting bracket was designed and installed which housed a HoboWare sensor in conjunction with a HoboWare datalogger unit stored in the existing meter box at the household. During the initial trial stage, the datalogger unit failed and the data was lost. A replacement datalogger should be acquired to utilise the existing hardware and reduce the need for additional resources to be used designing and installing a new bracket.

Chapter 6 Research

6.1 Solar Forecasting Literature Review

Research into methods for predicting solar power output has followed closely behind the large uptake of PV over the past decades. Various studies have been done including persistence estimates, satellite & sky camera image forecasting and neural network machine learning approaches [6]. These approaches have had varying degrees of accuracy and feasibility and for comparison, some of the methods outlined are discussed below.

Persistence Estimate

A persistence estimate is the approach used as a comparison for many other forms of solar irradiance forecasting. It involves an extrapolation of real-time irradiance or PV power output measurements to act as an estimate for power output predictions. The persistence method is useful for forecast horizons of 5 mins or less for a distance from the measurement location that is 80m or less[6]. Persistence is found to have a root mean squared error (RMSE) of up to 229 W/m^2[13] depending on cloud conditions and is useful for the prediction of solar irradiance although the persistence method is unable to anticipate cloud events which is the primary purpose of very short-term solar irradiance forecasting.

Artificial Neural Network

Various machine learning approaches have been investigated using different input data and learning models. The methods use statistical data which represents factors that have an effect on solar irradiance levels and apply a form of artificial intelligence to predict future solar irradiance levels. Differing methods have differing forecast horizons depending on input data that is processed[6]. Artificial neural network have obtained forecast root mean squared errors of as low as 84 W/m^2[14] and have been recommended to be used in conjunction with a sky imager to improve the accuracy of cloud shear event prediction[6].

Satellite Image Forecasting

Satellite imaged based forecasting uses images taken from a satellite to identify clouds and cloud motion before geometrically trying to forecast solar irradiance. Satellite forecasting is limited by the availability of satellites and the resolution of the available images, this limits the forecasting window resolution to 30 minutes which is the time taken for a complete image of the earth to be acquired[6]. Satellite image forecasting is found to have a relatively low root mean square error compared to persistence and sky image forecasting approaches [15] although the larger forecast horizon means this approach is not effective for PV power output forecasting for grid stability control purposes.

Sky Camera Image Forecasting

The sky camera technique which was used by Thomas Schmidt from the University of Oldenburg was developed in 2014 by Samuel R. West and published by the CSIRO in a paper called Short-term Irradiance Forecasting using Skycams: Motivation and Development[5]. Thomas developed the forecasting process and modelling that was undertaken on data collected at Murdoch University using the method outline by West[2].

The 2014 paper published by West outlines a general approach as well as presenting various variations on the method to achieve each stage of the process. The technique outlines hardware options and configuration requirements before stepping through the process of determining an irradiance forecast using the camera images. Below is a summary of the forecasting process.

Hardware Development

One or many 180-degree cameras must be installed facing skyward with data connectivity.

Configuration & Masking

Cameras are configured to the appropriate settings depending on the software model used and a binary pixel mask is created to remove objects in the cameras field of view which are not required for forecasting.

Sun Position Tracking

Implementation of software or algorithms which determine the location of the sun as it will appear on the image depending on the time of day and location of the camera.

Cloud Classification

The method of computing pixels which represent clouds in the image. Various methods are outline which use the colour planes of an image to classify it as cloud or sky before building a binary image following the decision.

Motion Vector Extraction

One of many optical flow algorithms is used to determine the motion of each pixel in the images.

Forecast Feature Identification

Cloud features that are significant to the forecast horizon are identified.

Cloud Movement Projection

Motion vectors are filtered to remove the vectors which don't represent a cloud moving and the features which have been identified as relevant to the forecast are projected in the direction of the motion vector average at the same location. A forecast occurs when the features are projected a distance which represents the time of the forecast horizon. The resulting irradiance forecast is determined from the number of cloud pixels which obscure the sun.

Further detail as to how the steps were implemented by Oldenburg and investigated at Murdoch is provided in the follow sections of this chapter.

6.2 Images & Processing

The hardware installation and configuration outlined in section 6.2 was undertaken by Murdoch University as well as some forecasting related image processing to investigate the established forecasting method. Details of the hardware configuration and image processing experimentation are outlined below.

System & Configuration

The Vivotek FE8174V fish-eye cameras captured 1080p PNG images on http request from the SkyCam_ applications. The image is time stamped and a logo is overlaid before it is stored in a directory created daily in the Sky Server. Below is an example of a typical image from SkyCam_1.

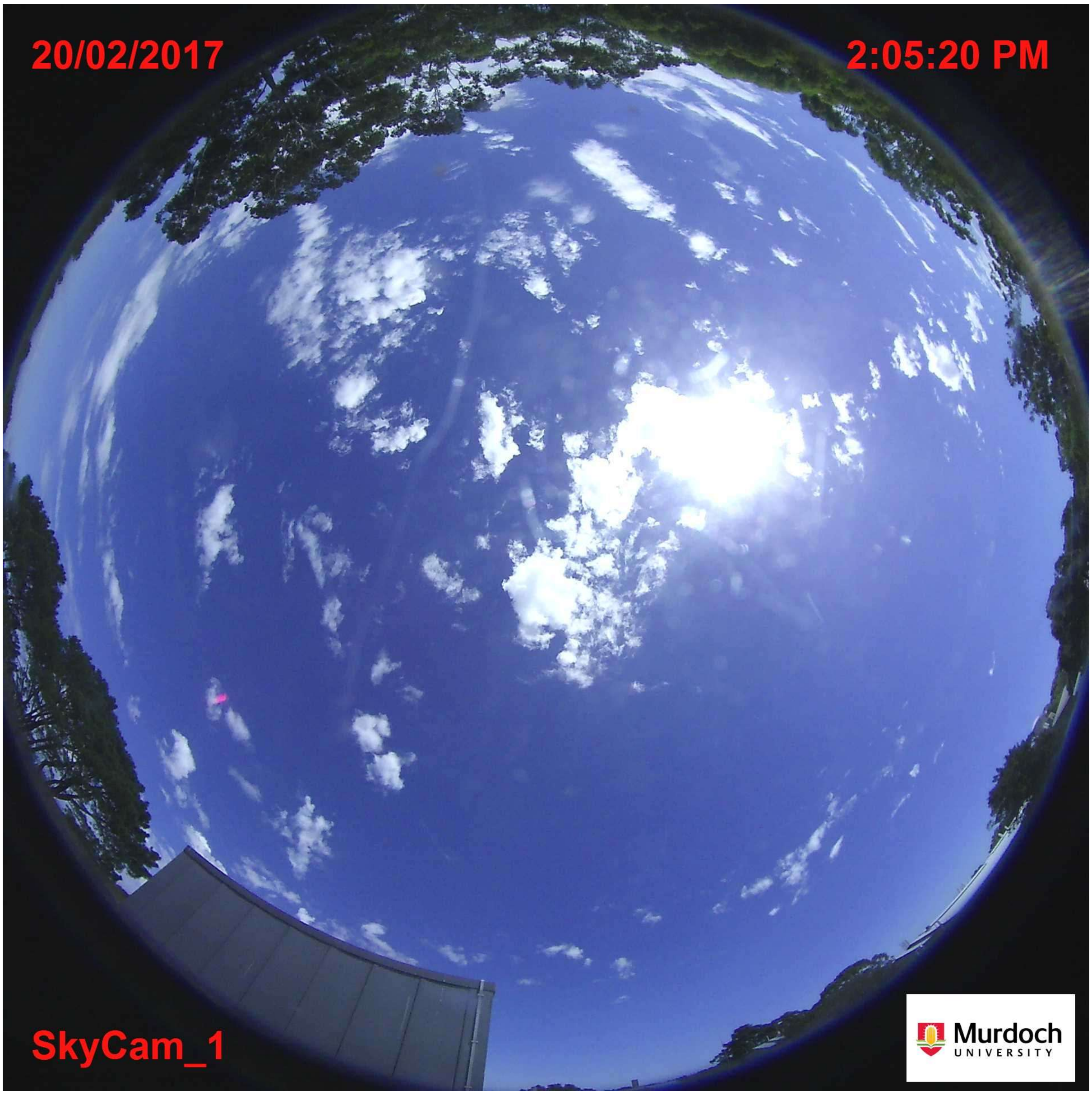

Figure 18 Typical Image from SkyCam_1

The fish-eye nature of the lens and over saturation of the sun spot are very apparent. During a discussion with Thomas during his trip to Murdoch University for the WREC, we investigated using HTTP commands to remotely adjust the exposure settings which would minimize the pixel saturation of the image and therefore reduce information loss.

Figure 20 shown below, compares two images taken from the same location about a minute apart. The sunspot in the left-hand image is significantly smaller and shows more cloud definition in the region surrounding the sun spot.

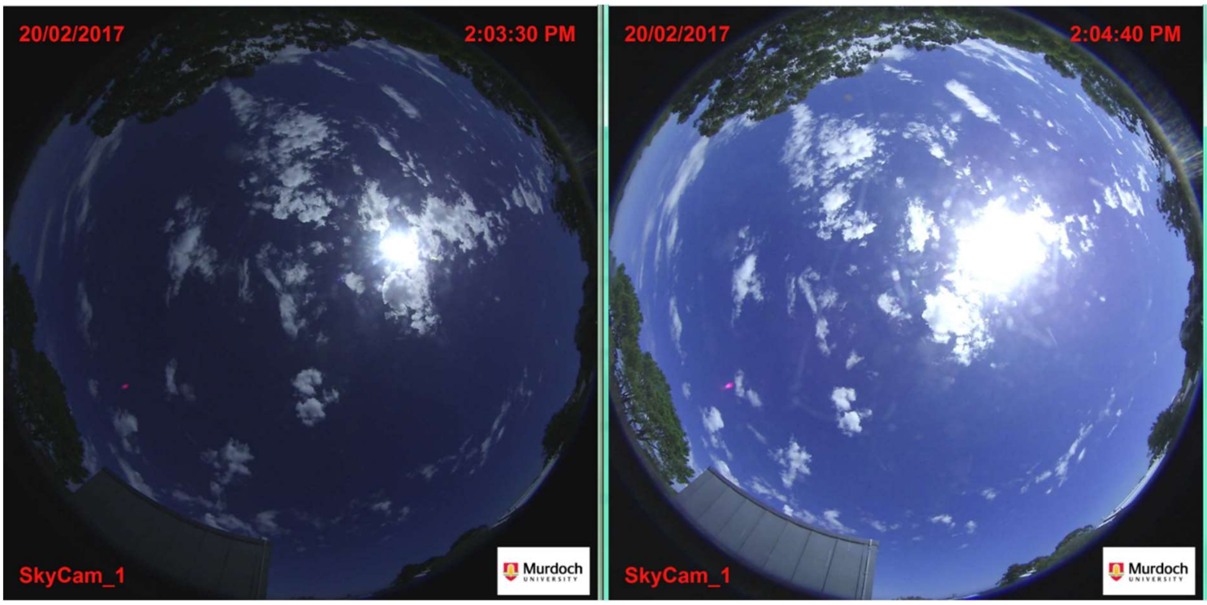

Figure 19 Comparison of Exposure Settings

The solar forecasting model which was built by Thomas at University of Oldenburg was configured for the longer exposure time and required complete sets of images so further investigation was not conducted. The investigation of lower exposure settings is something that is recommended for future image processing at Murdoch University.

Cloud Decision

The image type captured and stored by the sky camera network is RGB which stands for (Red, Green, Blue). Each pixel in the image is represented as 3 values in the range from 0-255 where each value represents a colour plane of red, green or blue. For example, a pixel which represents clear sky on a day a typical day returned a pixel value of (84,104,191), it can be seen that the dominant value in the array is the value representing the blue colour. This is significant because it is possible to split an RGB image into 3 grey scale images each representing a colour plane.

The cloud decision technique chosen by Thomas Schmidt is the red blue ratio method (RBR) [2], first developed by Scripps Institution of Oceanography (Johnson et al., 1989, 1991; Shields et al., 1998). The RBR method was the method that was used in the cloud decision technique at Murdoch University. This method involves each pixel in a grey scale image representing the red plane of the original image being divided by its corresponding pixel in the grey scale image representing the blue plane of the original image and the resulting image containing pixel values that represent the R/B ratio.

The average R/B ratio found for a pixel representing blue sky was 0.9 and the average R/B ratio for a pixel representing cloud was 0.5 so a cloud decision ratio of 0.7 was decided upon (see

Appendix B). LabVIEW has an image processing module where 0.7 was used to filter the R/B image into a binary image where pixels representing cloud were set to 255 or white and pixels representing sky were set to 0 or black. An example of this cloud decision method is shown in Figure 20 below.

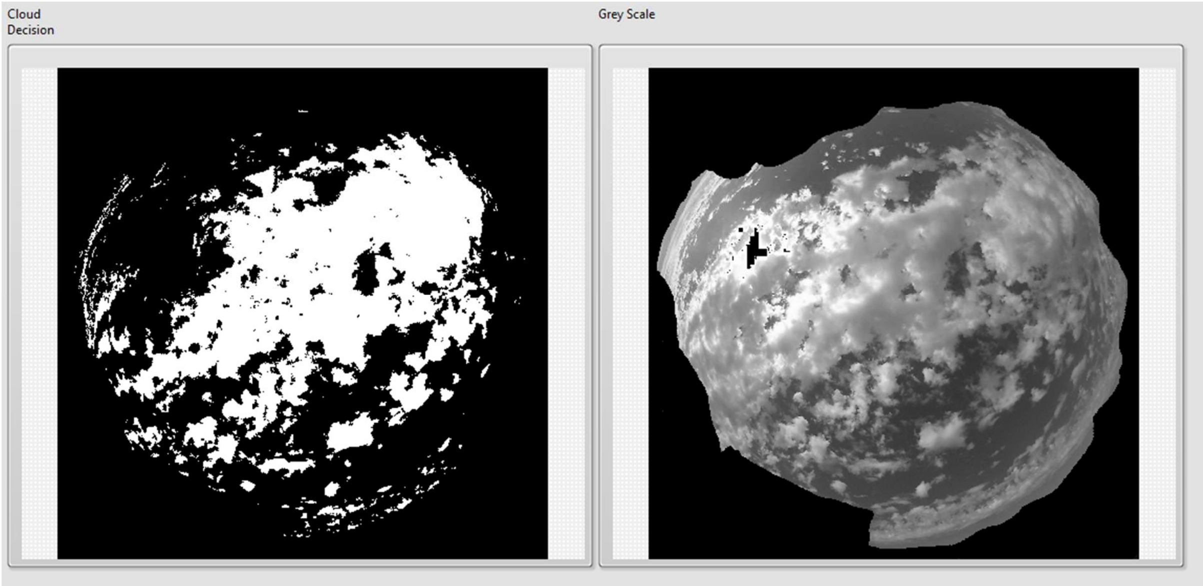

Figure 20 Cloud Decision Example

Clear Sky Image Set

An important aspect of many research projects in the field of solar forecasting is the acquisition of a clear sky data set for the location where the sky images are being taken from. An analysis of clear sky days during the summer months yielded an approximate value of 61% of summer days in Perth were cloud free. This number will reduce significantly in the winter months to >>20%. To collect a full year clear sky image set it is estimated that a sky camera system would have to run for an excess of 20 years before having a full 365-day set. Clear sky images are used to reduce the effect of the sun spot before a cloud decision process is executed on an image[2]. It is suggested that, to reduce the need for a clear sky image set, software should be developed to create an average clear sky image set over the course of a year. Such a method could be used to develop a clear sky image set for any camera location.

A second use for a clear sky image set was investigated at Murdoch University for determining the location of the sun. Using the assumption that the sunspot would be saturated, a filter was applied to a clear sky image and pixels in the grey scale image that were equal to 255 were set to 0. In image processing an area that consists of pixels values of 0 is considered a mask and functions such as the 'Mask to ROI' function in LabVIEW identify areas that are masked and record the pixel coordinates of the edges. Using the ROI determined from a clear sky day, the pixel coordinates were converted into real world coordinates, shifted proportional to the relative cloud speed that was detected and in the opposite direction of the cloud motion before being remapped onto a cloud decision image.

This resulted in an ROI overlaying the clouds which would be covering the sun spot at a time x in the future. By averaging the pixel values inside the ROI, it is possible to predict the affect that the clouds would have on the sun spot and in turn the irradiance levels at time x. Developing a ten secondly sun spot ROI set would eliminate the need for the extra computational power required to determine the location in real-time.

Optical Flow Algorithm

In accordance with the method outlined in (West et al), the Lucas Kanade optical flow algorithm was implemented in the model developed by Thomas Schmidt. The Lucas Kanade algorithm determines motion vectors at a per pixel level using a change in intensity method, according to Dr. Raul Rojas of the University of Germany. The resulting vector images are statistically filtered to determine the average cloud motion information as a part of the forecasting process.

The Lucas Kanade algorithm is available for Python and LabVIEW which made it an intuitive starting point for cloud motion investigation at Murdoch University. The LabVIEW module which contained the Luca Kanade algorithm requires feature points to be provided for the function to execute and was only capable of processing greyscale images. This suggests that the Lucas Kanade function in LabVIEW is implemented differently to the function available as a Python module and a solution was not found after significant trials using the LabVIEW. The failure to find a solution was attributed to the lack of difference in intensity of a greyscale pixels representing cloud compared with pixels representing sky.

Given the requirement to extract feature points from consecutive images for the Lucas Kanade LabVIEW implementation, little modification was required to investigate a simple feature point matching function method. Observation showed that the mode value of pixel translation that was determined from a feature point match was representative of the direction and speed of clouds in the images. It was apparent that a properly implemented filter could be applied to the feature point matches to extract accurate cloud motion information.

The development of an optical flow algorithm using a mode filter was commenced, feature points were identified in consecutive images before feature point descriptors were assigned to each feature point and a feature point matching function was used to match feature points across the two images. The lack of significant features in a greyscale image of a cloudy sky required the tolerable error setting on the feature point matching function to be set low enough that a large number of feature points were matched.

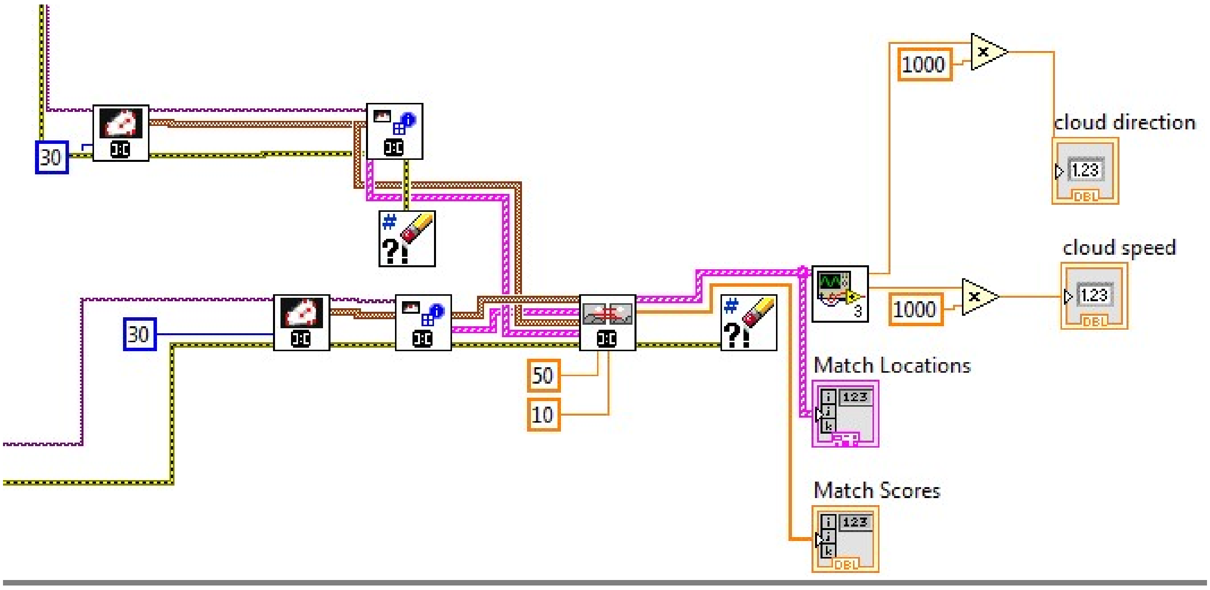

Figure 21 Optical Flow Algorithm Using a Modal Filter

Each feature point match represented a pixel translation which was outputted by the feature matching function, the pixel translation was rectified to represent real world distance and direction relative to the camera. The rectification process is discussed in image rectification below. Separate statistical filters were developed which involved extracting the mode from the real-world motion parameters outputted and only accepting the mode if the data set was within a specified range, standard deviation and above a minimum number of matches. The values for the acceptance parameters was determined by observation and the resulting cloud motion information will be discussed in section 8.3 Results at Murdoch University.

Image Rectification

The process of determining a real-world location from an image pixel coordinate. As outlined in (West et al 2014) a uniform 180-degree camera model was used where a 0 to 1000 pixel translation from the centre of the camera linearly represents a 0 to 180 degree angle from the vertical view of the camera. Basic trigonometric identities were used to convert pixel coordinates to real world distance coordinates relative to the camera using cloud height as 1000m. The image rectification process was necessary to convert pixel translations in the optical flow algorithm to real coordinates for cloud motion information determination. A function for the conversion of a pair of feature points identified in an image was developed in LabVIEW and is shown in Figure 22.

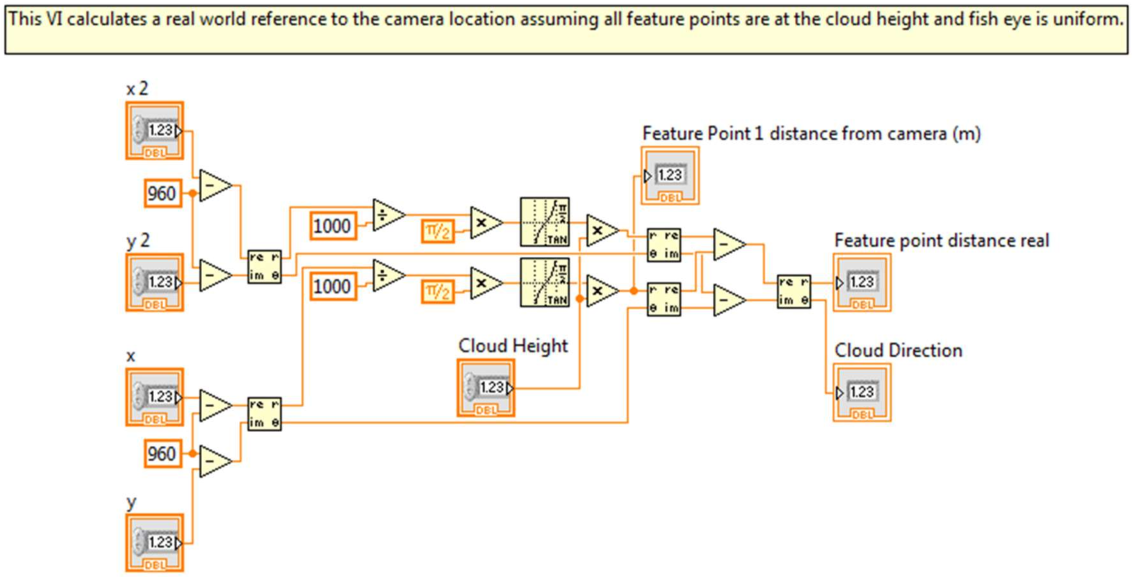

Figure 22 Pixel Coordinate to Real Coordinate Function

ROI Determination

A novel technique for establishing sun position was investigated at Murdoch. Conventional techniques and the technique used by Oldenburg involves a pre-established sun location calculator which uses location, alignment of the camera and time of day to estimate the pixel location of the sun spot. Using a function in LabVIEW which determines an ROI from a mask or area of pixels in an image a technique for determining the location of the sun from a clear sky image was developed which involved masking the most intense pixels in a clear sky image and converting that mask to an ROI or set of pixel coordinates which represent the location of the sun in the image. The implementation of this method using LabVIEW is shown in Figure 23.

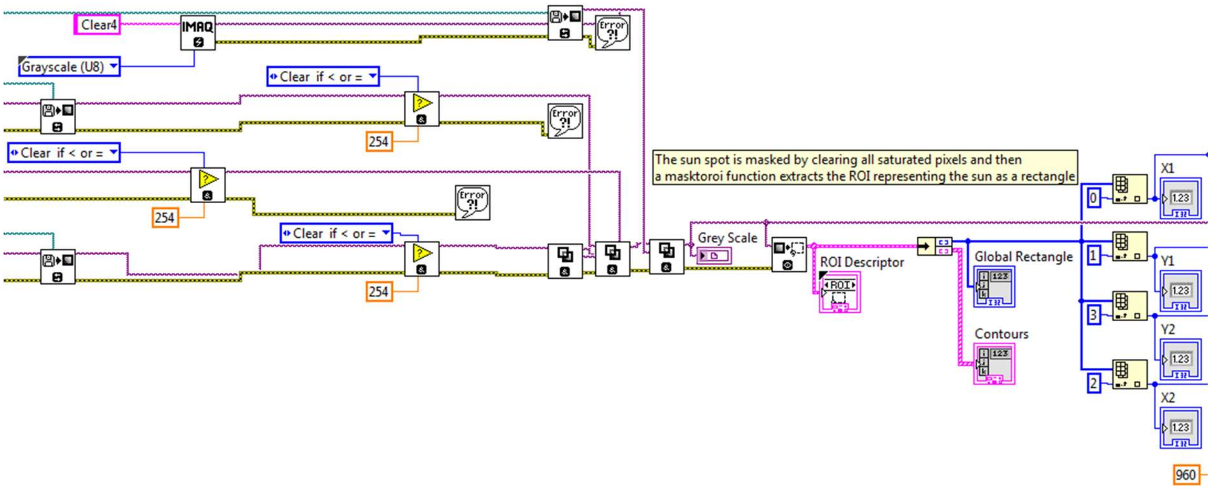

Figure 23 Determining an ROI which Represents the Location of the Sun

Proposed Forecasting Method

The proposed forecast method to be investigated at Murdoch involved determining the ROI which represents the location of the sun spot in a clear sky image before converting the ROI to real world coordinates. The real-world ROI was then shifted according to the cloud motion data and proportional to a pre-determined forecast horizon before being mapped back onto a cloud decision image. The ROI which was mapped onto the cloud decision represents the area of the image which would obscure the sun spot after a time equal to the forecast horizon had passed. A basic cloud to sky ratio could be obtained from the ROI area and used as a method for predicting the portion of clear sky irradiance that was likely to occur at the camera location after the forecast time had occurred. This method could resolve an issue which was faced by Oldenburg where cloud events were missed due to the forecast method using a single vector originating at the middle of the sun location and projecting in the inverse direction of cloud motion. The function for shifting the sun spot ROI proportional to cloud motion and forecast horizon is shown in Figure 24.

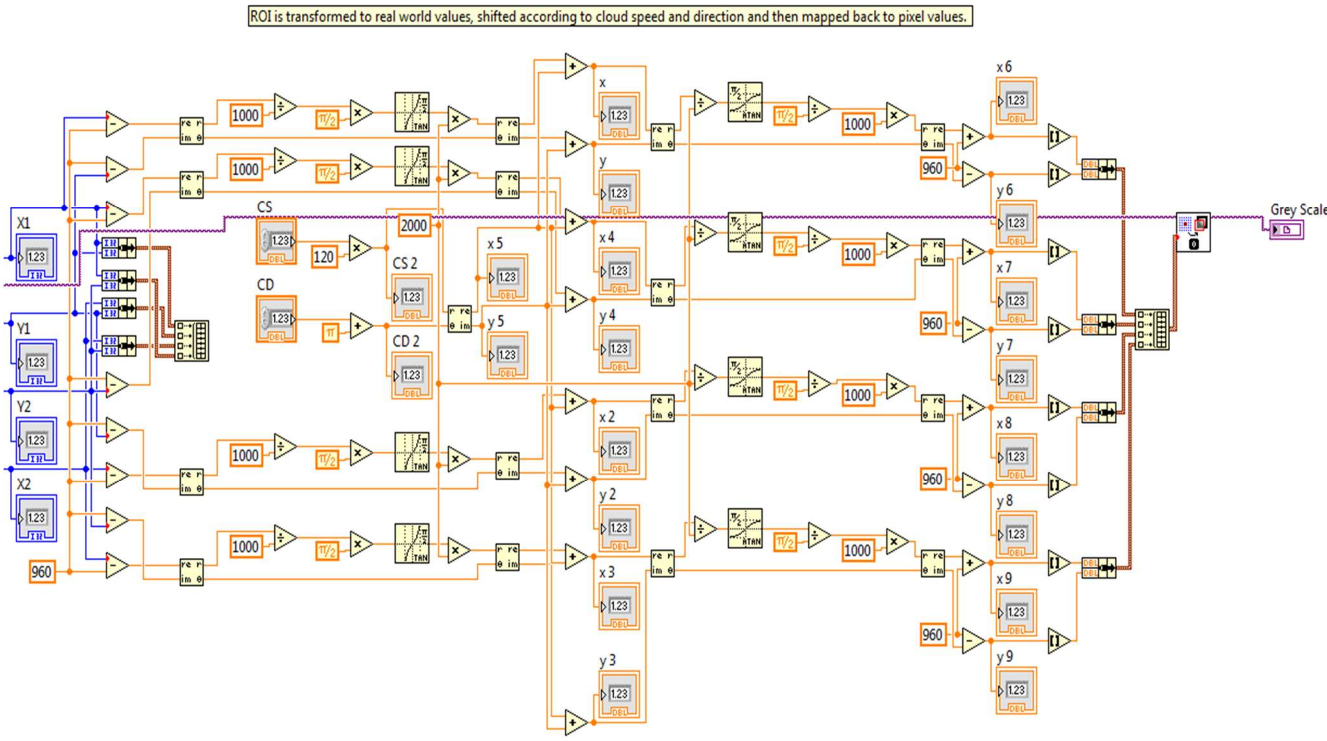

Figure 24 ROI Image Projection

Chapter 7 Cloud Base Height

7.1 Cloud Base Height Applications

Cloud Base Height (CBH) is the height to the base of cloud formations typically expressed in metres above sea level or in Hectopascals of pressure. This height remains relatively uniform spatially due to uniform thermodynamic air mass properties which are the significant contributors to cloud base height[16]; this allows CBH height determined at a single location to be extrapolated over areas larger than the 15km radius visible from the sky imagers.

Cloud base height is important for the visual flight of aircraft and is collected at and made available from airports around the world. Cloud base height is recorded at Jandakot airport using a ceilometer and processed such that it is accurate to within 10 minutes.

As solar forecasting progresses to include investigation into distance forecasting away from the camera location, a high frequency real-time cloud base height measurement is required for cloud shadow projection geometry and cloud speed calculation. Murdoch University was asked to develop a method for determining cloud base height data and making it available for computation at the University of Oldenburg.

7.2 Determination Techniques

Cloud base height is typically estimated using a ceilometer or calculated from temperature and humidity data on the ground. Both methods are relatively costly and require expensive sensors coupled with a software system capable of acquiring the information and processing said information into a reliable cloud base height[17].

Cloud base height was first determined geometrically using two images of cloudy sky in 1968 by (Bradbury & Fujita) where the cloud features were determined by hand and the concept was proven. More recently (Rocks 1987) automatic registration cloud height calculation was demonstrated using an image correlation method for very closely spaced cameras[18]. With advances in machine stereo vision in the late 1900s it has become possible to determine cloud base height from two sky images using pixel correlation and optical flow algorithms to account for the different field of view and image distortion[18] caused by widely space fish-eye cameras. This method has been investigated in literature with errors less than 500m when compared with data from a ceilometer. Variability in cloud structure and type is cause for the largest errors in the stereography method [18]

7.3 Cloud Base Height at Murdoch University

Cloud Base Height Research

SkyCam_1 and SkyCam_2 are 680 metres apart on Murdoch campus and both poll images synchronously every ten seconds. The existing setup provided sufficient data for experimentation with cloud base height determination methods. Consultation with literature showed that the two methods of computing cloud height were cross-correlation of images and feature point matching supported by optical flow data[18].

To determine cloud base height at Murdoch both cloud colour pattern matching and feature point matching methods were investigated. The distortion caused by the 180-degree images and the different fields of view of the cameras was amplified for low lying cloud and cloud colour pattern matching method only identified an accurate image pixel shift in times of high cloud with distinct patterns which was not satisfactory for use in the solar forecasting process.

A similar approach to cloud motion determination was considered where feature points were identified in both images and a feature point matching function attempted to find pixel translations. The feature point matching method was unable to identify similar features in each image due to the camera points of view and other options of obtaining cloud base height data were considered.

The below image shown in Figure 25 visualises the geometry of determining cloud base height using two sky images at a known distance apart. The geometry is fundamental to all methods of cloud stereography.

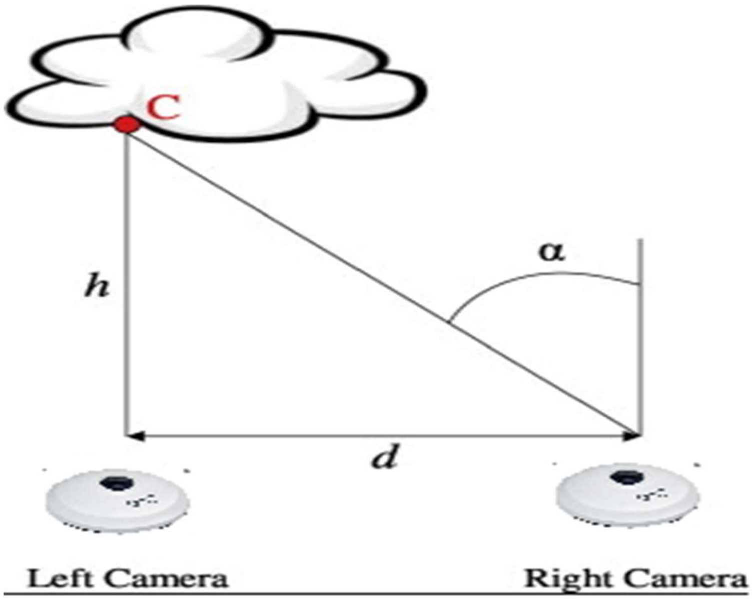

Figure 25 Geometric Determination of Cloud Base Height

Cloud Base Height Method Used

Murdoch University was fortunate to have cloud base height data available from the Bureau of Meteorology for location forecasting, this data was collected at Jandakot airport located approximately 5k from the Sky Camera Network at Murdoch University. Cloud base height was interpolated from the 10-minute data which allowed it to be used for location forecasting with respect to each camera.

The Bureau of Meteorology makes data available in real-time which was autonomously scraped from their website using a Python script and stored for later processing at Oldenburg which mitigated the need for historical data to be purchase prior to a distance forecast modelling simulation. The continued collection of cloud base height data from Jandakot should be maintained during the life of the sky camera network.

Chapter 8 Results

8.1 Data Acquisition Results

The purpose of the DAQ system that was developed at Murdoch University was primarily to provide images from SkyCam_1 and SkyCam_2 and validation data into the desired format in the sky server for FTP access by University of Oldenburg. A full day data set is required for the forecasting model to run continuously and output a complete irradiance prediction. SkyCam_1 was connected directly to the Murdoch University staff network and can provide 10 secondly images with 100% success rate while the SkyCam_1 application was running. SkyCam_2 is connected via a wireless bridging device which had various issues as discussed in Chapter 5. The success of the DAQ is based on its ability to provide sufficient information for University of Oldenburg to determine and validate forecast predictions as well as the continued logging of data at Murdoch University for future teaching.

SkyCam_1 provided sufficient images on days with scattered cloud for Thomas Schmidt to test the forecasting model and present his finding at the WREC. An example of solar irradiance logged at EEB being used do validate a forecast prediction data set is shown in Figure 26.

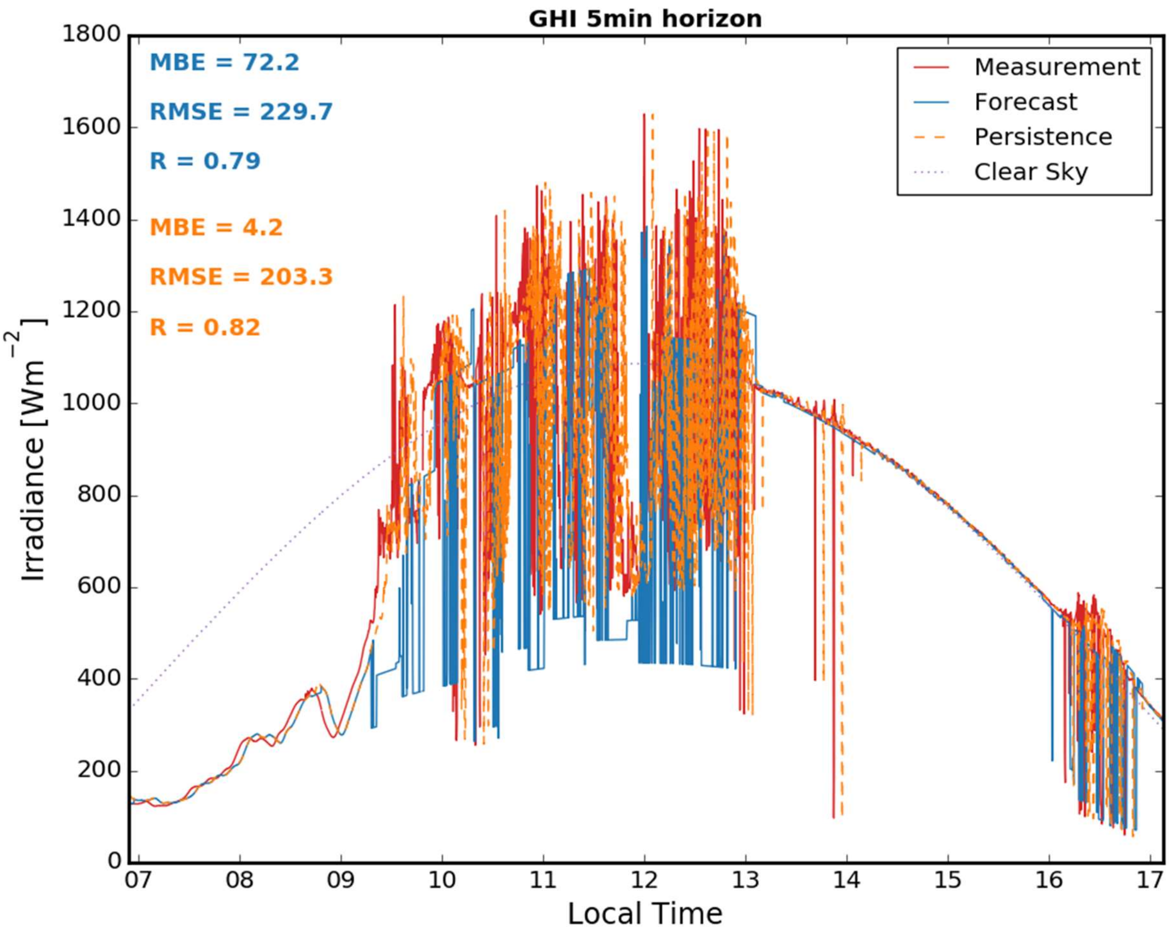

Figure 26 Forecast Model Output Validation Using Solar Irradiance Logged at EEB

The results as found by University of Oldenburg will be discussed in section 8.2.

The logging of irradiance at EEB is continuous over the time since it was commissioned in late 2016. The irradiance outputs graph shown in Figure 27 below shows a typical irradiance from a clear sky day. The effect of a tree to the east of the sensors location can be seen in the slight variation from the nominal looking curve until about 6:00 am. Data during the shadowed period is not required for solar forecasting validation as there are lighting effects that make image processing significantly more complex and there is negligible irradiance to forecast.

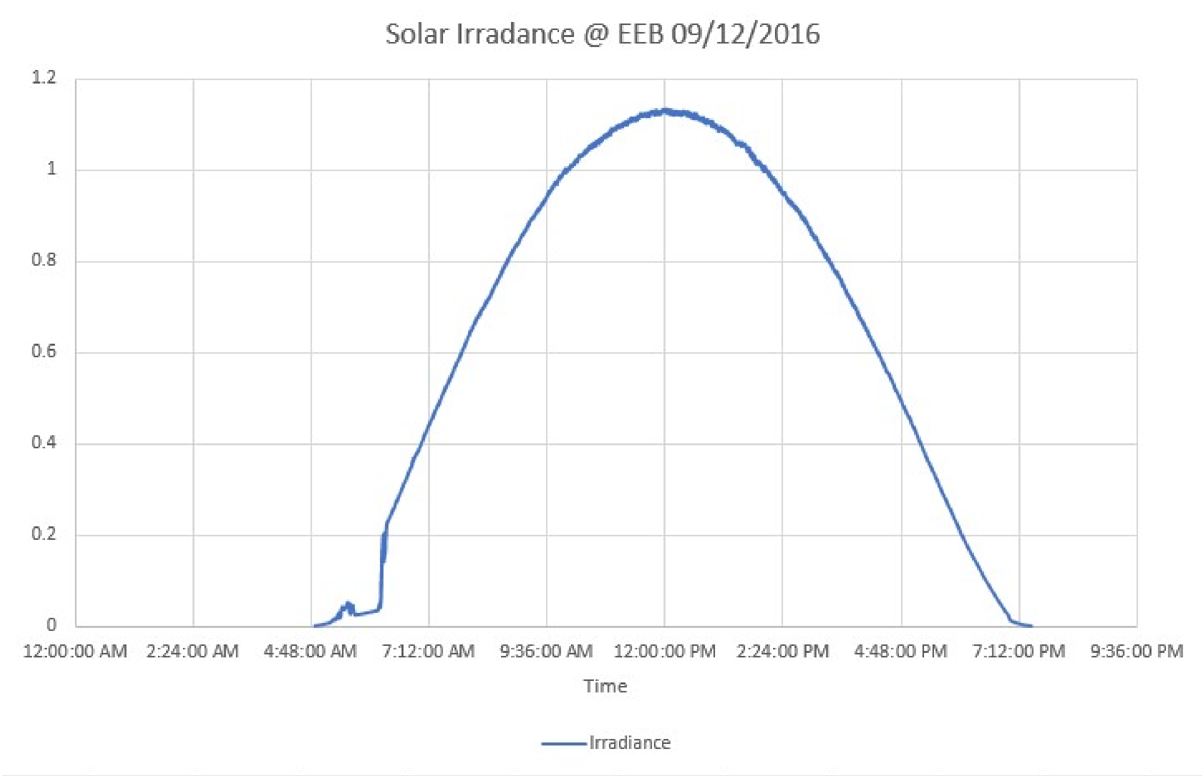

Figure 27 Irradiance at EEB on a Clear Sky Day

Figure 28 below shows the effect of cloud scattered cloud on solar irradiance at EEB building on 9th November 2016. Cloud effect is most prevalent from 9:30 am to 1:00pm and the dips and peaks are caused by scattered cloud crossing the suns path. The peak solar irradiance value of 1.648 kW/m^2 occurred at 11:48:14 am and is caused by an effect on solar radiation called cloud mirroring [19]. The effect occurs when no cloud is covering the region of the sky through which the suns direct radiation passes and a large area of the sky is covered with highly reflective cloud, see Figure 29. Diffuse radiation which is reflected between the reflective surface of Murdoch University roofs and low lying reflective cloud is responsible for the peak in radiation observed. High levels of radiation like this are not generally accounted for in PV inverter sizing but it important to consider this effect while considering the voltage restraints of an inverter. The low durations of these peaks and their proximity to low power events mean that irradiance peaks like these are not beneficial to PV and inverter power output. The Fronius inverter that is used for the analysis of the effect of global horizontal irradiance on inverter power output is rated for 2200 watts and the clipping effect caused by the inverter limit was confirmed by the power output data.

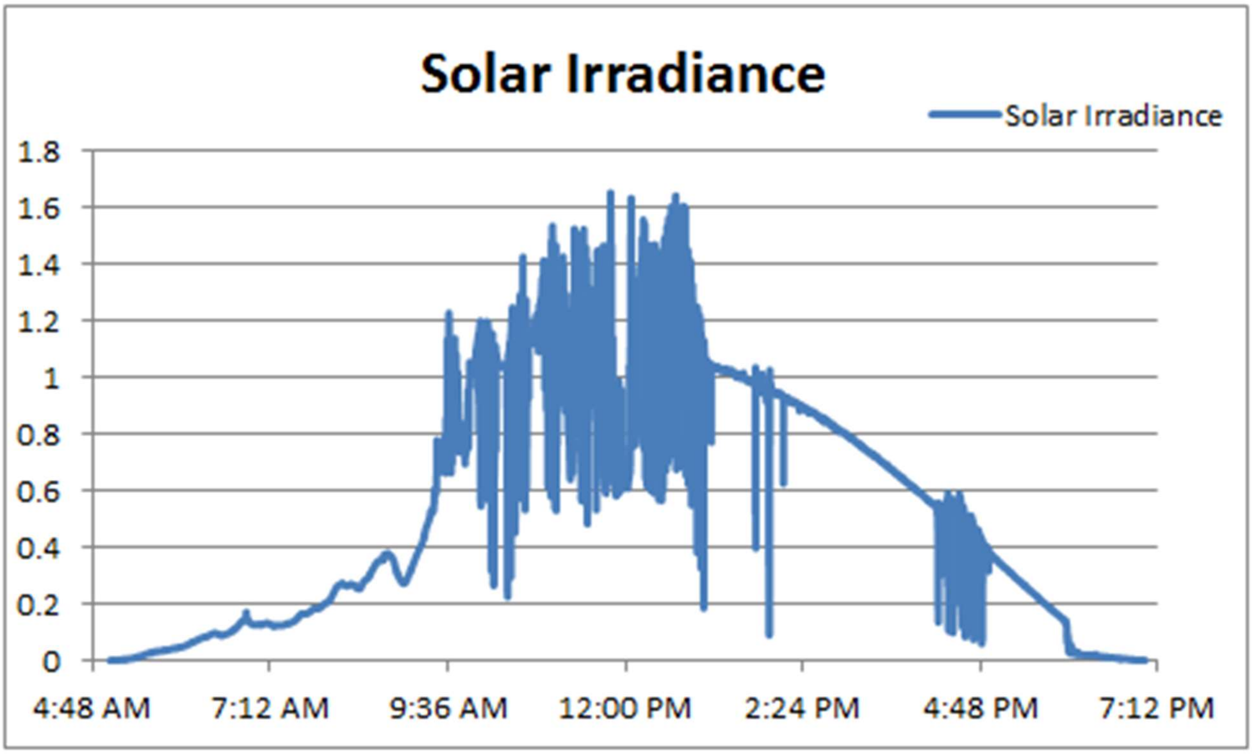

Figure 28 Solar Irradiance at EEB 9th November 2016

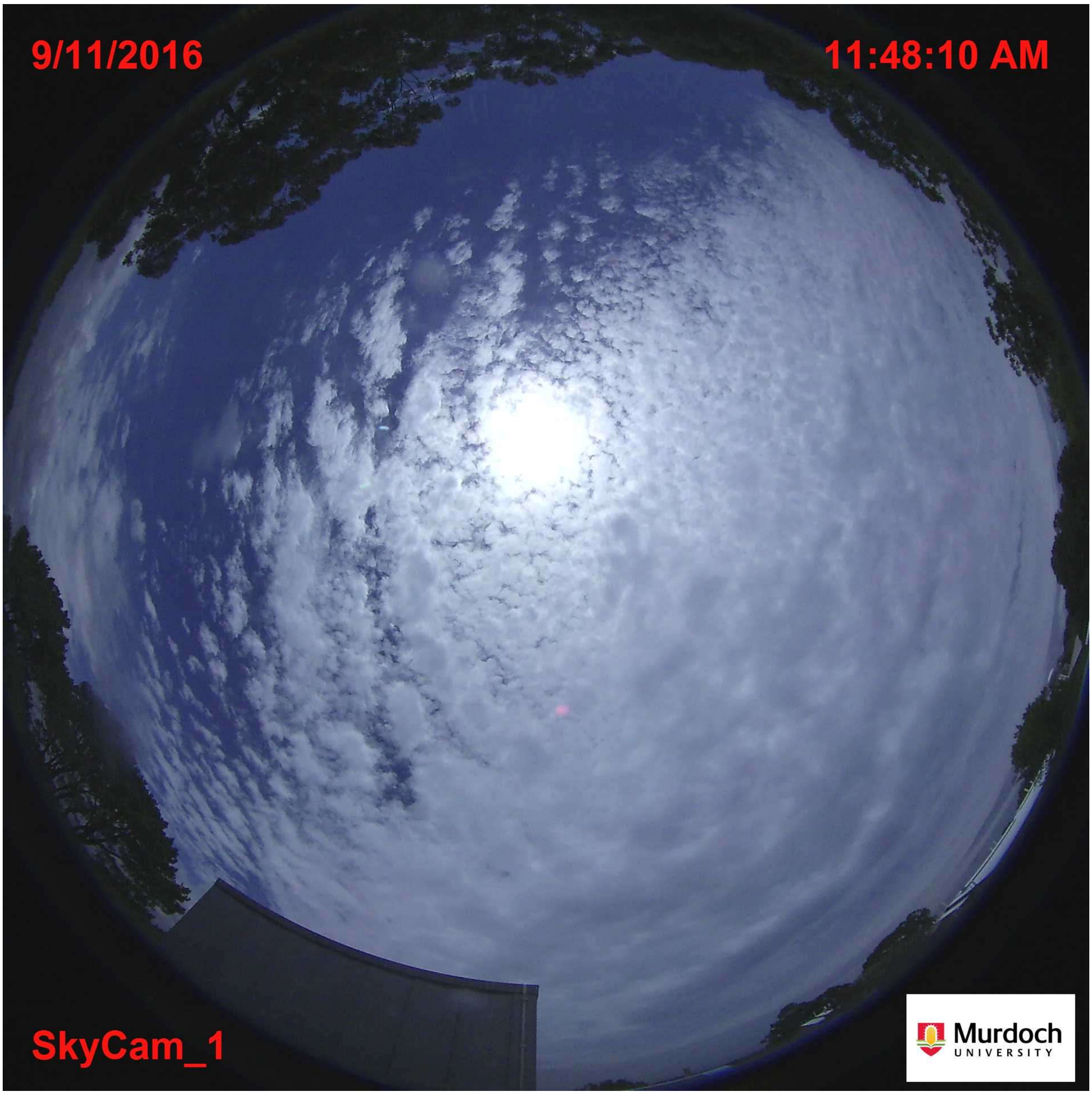

Figure 29 Cloud Conditions near an Irradiance Spike

8.2 Results from University of Oldenburg

Results from a study which was part of the collaboration between Murdoch University and the University of Oldenburg were obtained prior to the 15th of January 2017 the required submission date for presentation at the World Renewable Energy Congress (WREC). A paper called *Short-term solar forecasting based on sky images to enable higher PV generation in remote electricity networks* outlines the findings associated with the sky camera network at Murdoch University by reducing the required amount of spinning reserve in a network with high PV integration.

The solar forecasting data found by (Schmidt et al) was used as a basis for a publication and presentation at the WREC undertaken by Dorethee Peters from Oldenburg[3]. Her publication is called *Solar short-term forecasts for predictive control of battery storage capacities in remote PV diesel networks* and investigates fuel savings associated with solar forecasting control methods in PV and diesel power systems with and without battery storage. The fuel savings found focus on a reduction of spinning reserve required to be maintained for the event of cloud shear effect on PV generation[3].

Solar Forecasting for Higher PV Generation

The ability of the forecast model to predict solar irradiance is shown in the earlier Figure 26. The RMSE value for the forecasted irradiance compared to the measured irradiance is worse for the modelled parameter than it is for a simple persistence assumption method. The advantages of solar forecasting are in its ability to anticipate cloud events in the future and to utilize this, a forecasting method for control of a generator called the clear sky persistence method was developed.

To investigate the possibility of reducing spinning reserve in remote diesel PV power systems a simplified forecasting model was applied which estimates irradiance conditions over the coming ten minutes. If irradiance drops below 600W/m^2 inside a ten-minute window, irradiance conditions are considered non-persistent and if irradiance over the ten-minute forecast window remains above 600W/m^2 conditions are considered persistent. A ten-minute window was chosen for simulation purposes to reduce generator switching and to provide quantifiable time periods where a generator can remain off. The simplified model of a generator control system was developed to investigate the effectiveness of the persistence method.

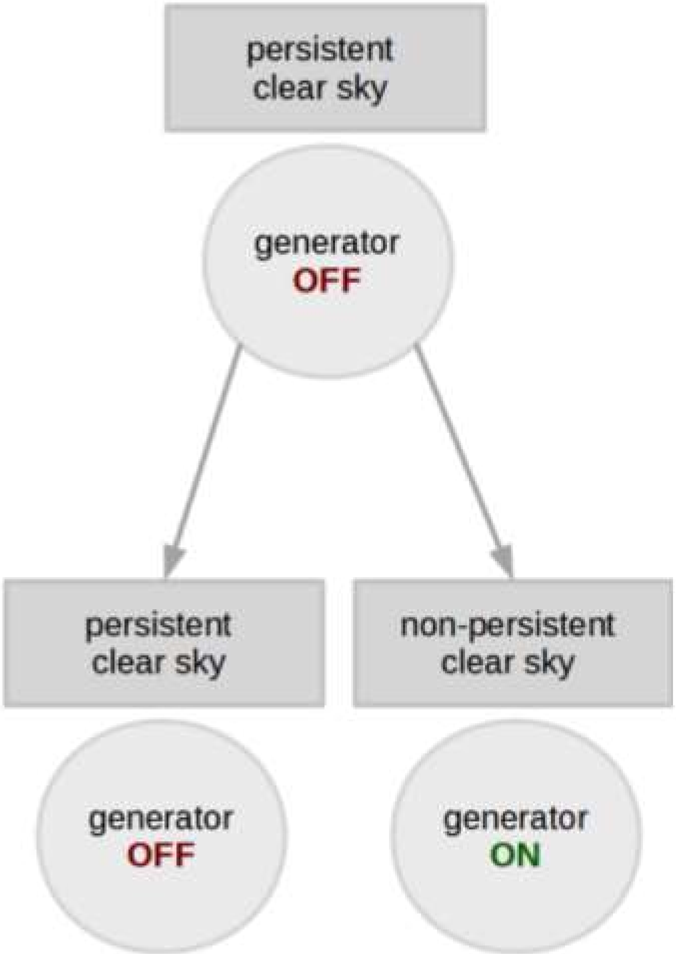

Figure 30 Generator Model for Persistence Forecast Method

Figure 31 shows the implementation of the persistence forecast method and the simplified generator control model. The results show the methods ability and accuracy in switching a generator on and off in anticipation of cloud induced PV power reduction. This method was run as a time series on the complete image set obtained by SkyCam_1 from the 10th of November to the 28th of December 2016.

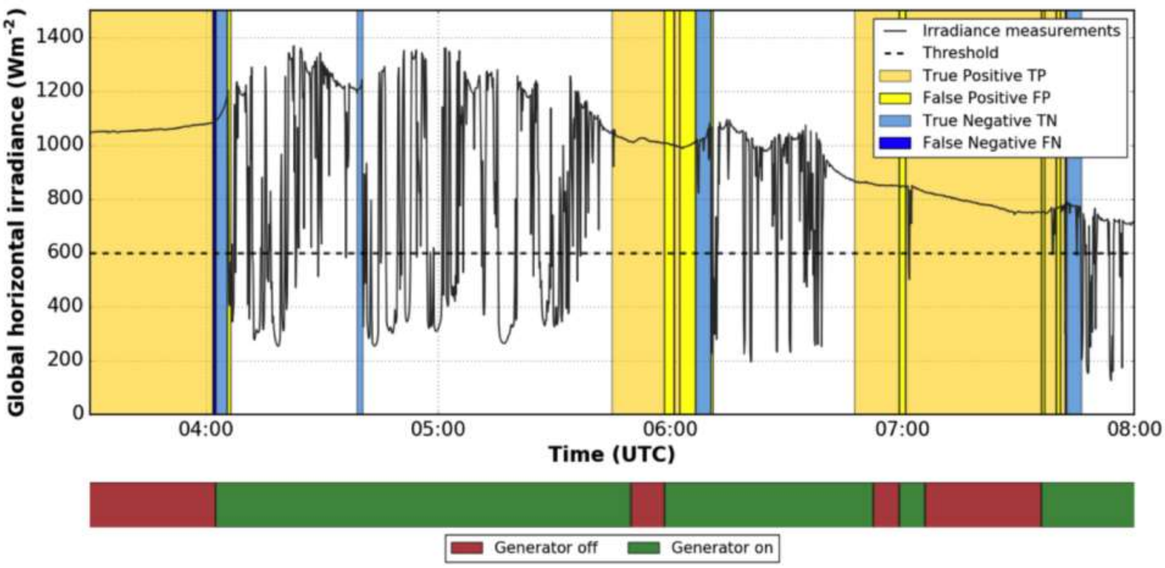

Figure 31 Persistence Forecast Method for Generator Control

Over the examined period, 61% of the time was identified as persistent clear sky and a total of 84 cloud events occurred. The persistence forecast model correctly predicted 76 events giving a cloud event miss rate of ~8%. This is an improvement on previous forecast control methods according to Thomas Schmidt. Data was made available to Dorethee Peters of Oldenburg for an analysis of associated fuel savings and probability of a loss of spinning reserve.

Solar Forecasting and Associated Fuel Savings

A simulation was developed by D. Peters which modelled a remote network with a peak load of 590kW and an average load of 270kW which is covered by 5x140kW diesel generators. Six control strategies were applied to a PV penetration of load at both 40% and 60% to investigate the relative fuels savings and probability of a loss of spinning reserve[3]. The six control cases are outlined by D. Peters below.

#	Case Name	Description of Case
1	No PV	Base case, total fuel consumption is used for comparison with other cases. Diesel generators run with a minimal load of 30 % need 5 minutes for start-up. Gensets meet current load plus 20 % of current load as SR.
2	PV only	Spinning reserve is provided according to current PV power. Tested cases are 0 %, 25 %, 50 %, 75 % and 100 % of current PV power for SR.
3	PV + short-term forecast	Spinning reserve is provided by diesel gensets according to the lowest forecasted PV power in the next 10 minutes.
4	PV + small battery	a) Battery is used to guarantee predefined ramp rates (RR) of PV. Maximum ramp rates are 6 minutes for ramp-up from 0 to 100 % and 12 minutes for ramp-down from 100-0 % (Horizon Power, 2013). Results for this case include 25 % of current PV power as spinning reserve provided by gensets. b) Additionally to control of case 4a, the battery provides spinning reserve when generator higher or lower operation border is reached.
5	PV + small battery + short-term forecast	.1 Method 1: Forecast is used as in case 3a, battery is used for ramp rate control and spinning reserve (case 4a+b). .2 Method 2: PV power is curtailed to the lowest forecasted PV power; when curtailed, higher than maximum allowed ramps are smoothed by the battery as described in case 4a (adaption from Fulcrum, 2016).
6	PV + large battery	The battery is discharged in the peak load hours determined from load time series (20 % of highest values of mean) at fixed power (30 % of inverter capacity). It is only charged with diesel power at low SOC and charged to a higher threshold SOC from PV power. Additionally to RET firming (RF) methods 4a and 4b are used to increase benefits of battery for the integration of PV.

Figure 32 Control Cases used for Determining Relative Fuel Savings[3]

The effectiveness of solar forecasting control method on the PV diesel network was evaluated in terms of fuels savings and lack of spinning reserve which can cause network stability issues. Results regarding fuel savings show that case 3 (PV + short-term forecasting control) achieves 3.1% fuel savings at 40% PV integration and 5.5% savings at 60% PV integration[3]. With the addition of batteries into the control strategies further fuel savings are obtained with the cost of increased expenditure.

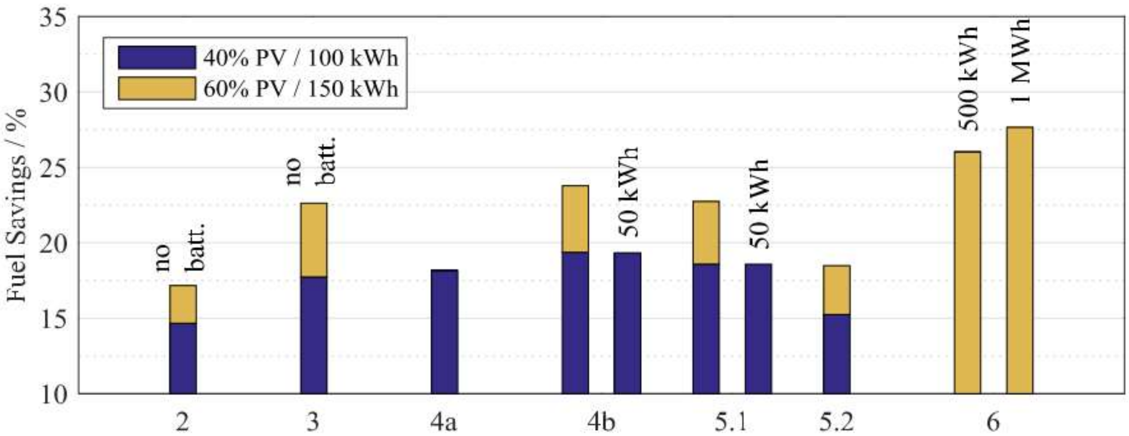

Figure 33 Fuel Savings Compared to Case 1[3]

Case 2 in Figure 34 shows the effect inaccuracy in the forecasting method has on the probability of a lack of spinning reserve, it also highlights in case 5 the benefits of combining solar forcasting with a battery which effectively halves the probability of a lack of spinning reserve compared to the battery only case 4.

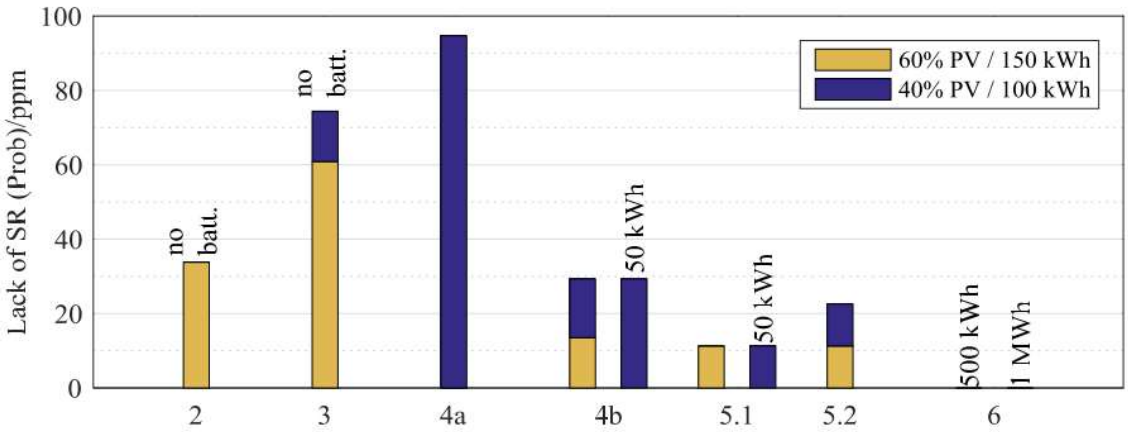

Figure 34 Probability of a Lack of Spinning Reserve[3]

8.3 Results at Murdoch University

Cloud Motion

Application of the cloud motion algorithm developed at Murdoch to a time series of images captured by SkyCam_1 produced cloud direction and cloud speed data over the course of a day. Visual inspection of the image time series confirmed the ability of the algorithm to correctly identify cloud motion information while sufficient cloud features were available. A time value which represents the time since the last cloud motion information was determined as a check value relating to the accuracy of current cloud motion information. The time value is plotted against both forms of cloud motion information to provide a visual understanding of how current each value is. The time since established graph indicates areas where there was insignificant cloud to establish motion parameters. Limitations of the cloud motion algorithm were established by inspection of the times series where a cloud event would occur after a period of clear sky before the algorithm had established motion information that would be used in forecast determination. A more accurate method for cloud motion is needed for continued development of a solar irradiance forecasting program. Cloud direction is recorded in radians where 0 represents west and pi represents east. Cloud speed information is recorded as a unitless number which is relative to cloud height, at cloud height of 1000m, cloud speed is given in millimetres per second.

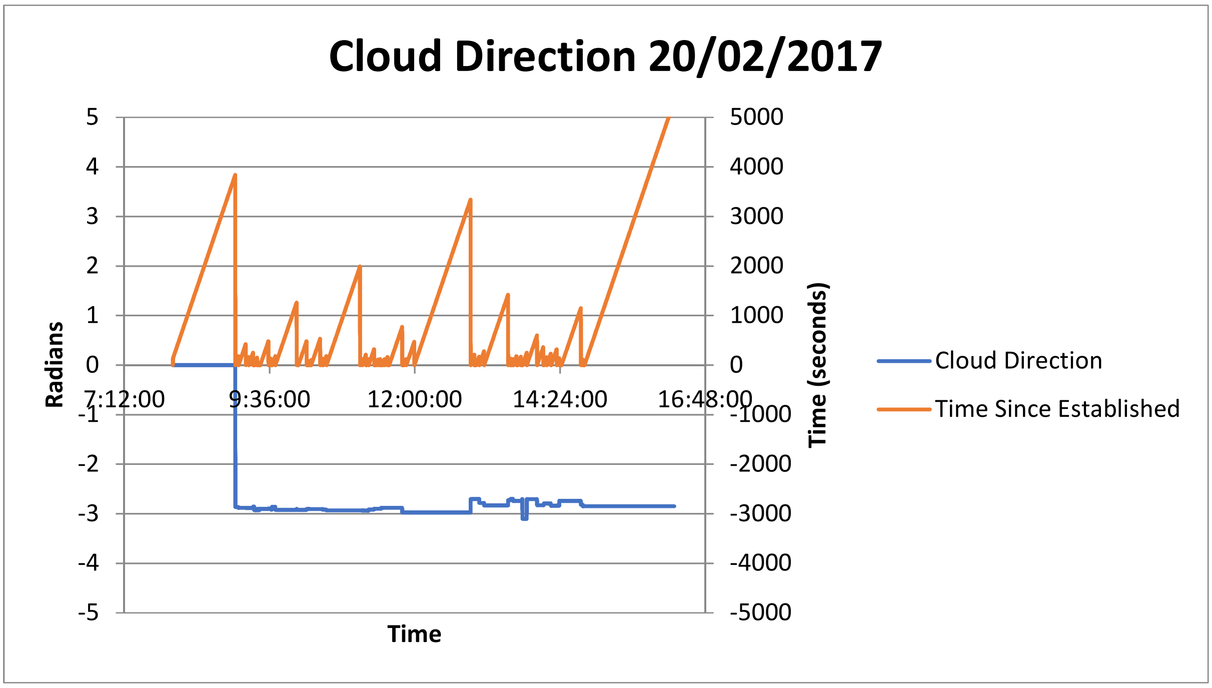

Figure 35 Cloud Direction Determined at Murdoch

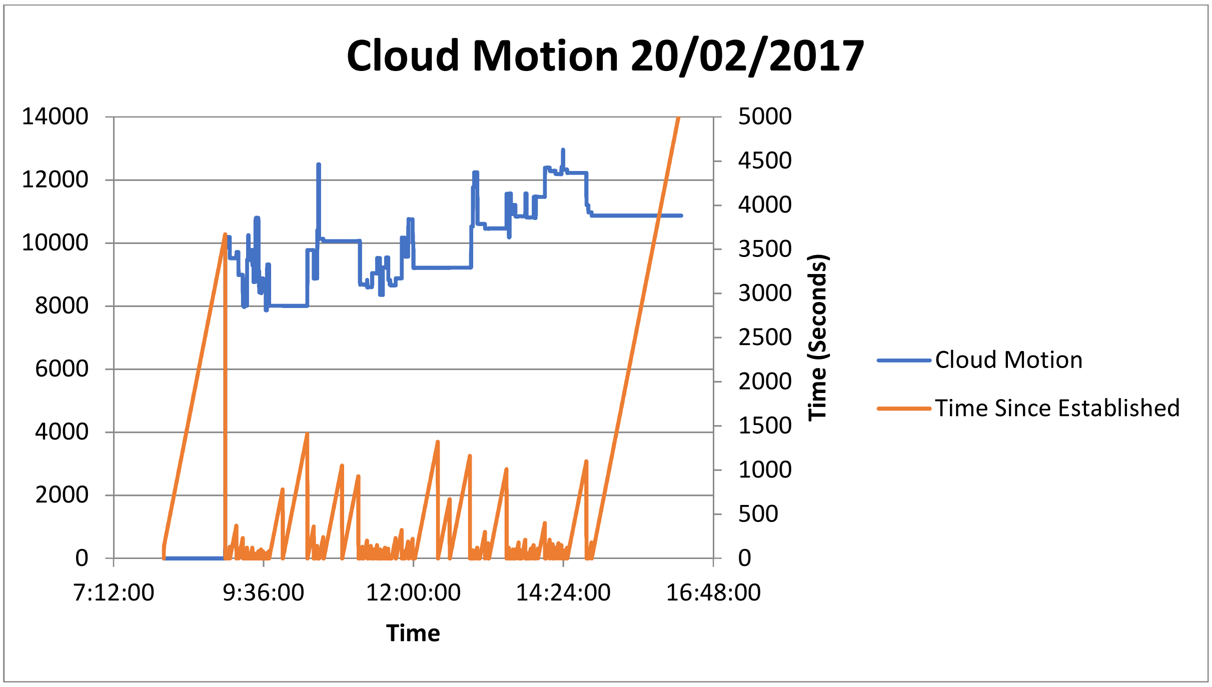

Figure 36 Cloud Speed Determined at Murdoch

Figure 37 shows cloud motion information determined by the Lucas Kanade algorithm in the Oldenburg model. Limitations to the motion information can be seen by outlyers in the graphs and a period where motion information is not available.

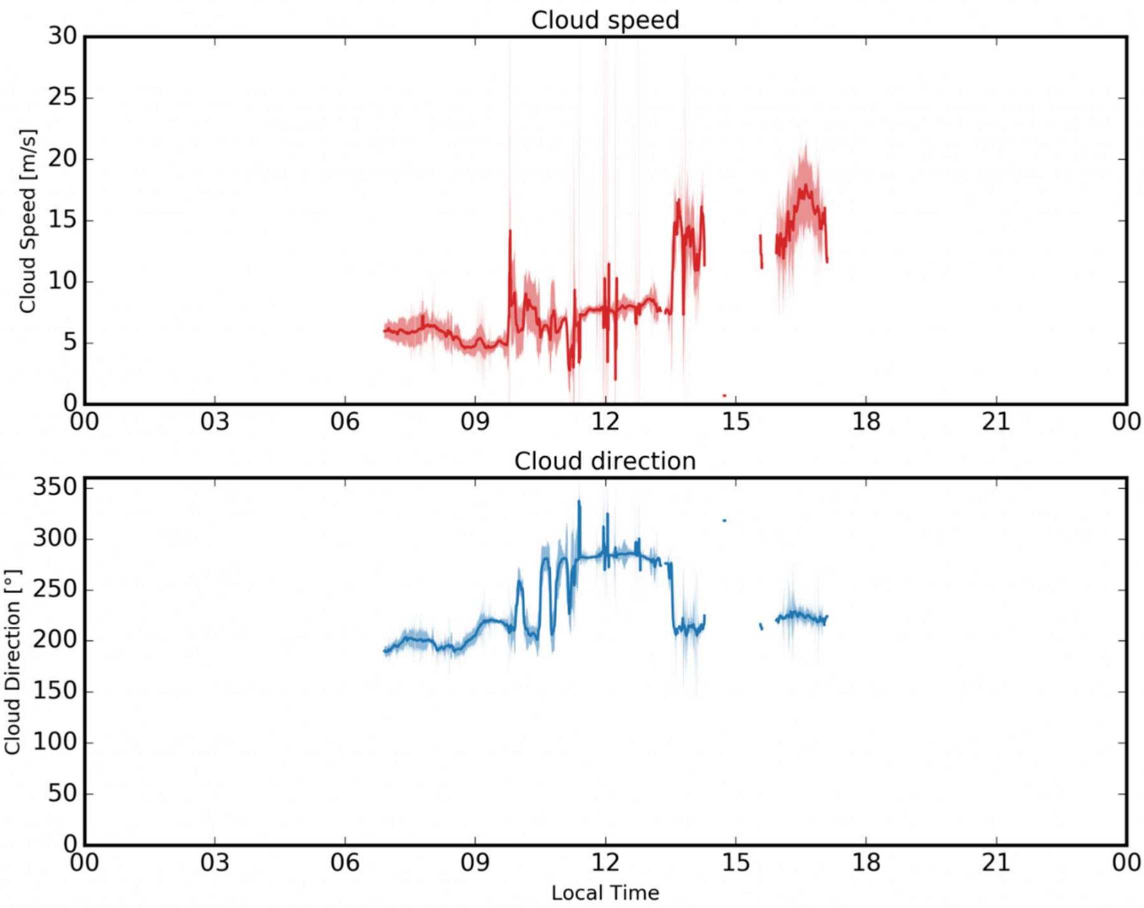

Figure 37 Cloud Motion as Determine by Oldenburg

Cloud to Sky Ratio

Identifying individual cloud events using sky cameras has been the focus of the sky camera network although PV penetration is often widespread over areas larger than the 5km and a forecasting system which identified individual cloud events at individual locations would require existing knowledge of each PV array location, direction and size. Issues such as multiple layers of cloud travelling in different directions would render such a system inaccurate at times and the system would effectively be providing an area forecast estimation. Considering the complexities of the location forecasting approach and the periods during which cloud motion information is hard to establish a simple cloud to sky ratio algorithm was developed. The algorithm worked through the 1920x1920 pixel binary image and each pixel representing cloud was assigned a value dependant on its location with respect to the centre of the image using the uniform fish-eye assumption. The cloud value was then divided by the value which represented all the pixels being cloud. This effectively rectified the image and provided a real-world cloud ratio updated 10 secondly.

The cloud ratio algorithm was initially considered for integration into a solar forecasting system to check that periods of time during which cloud parameters were not being established could be assumed to be cloud free and to serve as a failsafe for an approaching cloud event.

Observation of the cloud ratio changing during a software trial showed that cloud condition changes were always represented in the cloud ratio value. According to the West Australian newspaper, Horizon Power is trialling a sky camera system for Carnarvon which computes average solar irradiance levels for the towns widespread location[20]. Solar irradiance averaging using sky cameras may provide a cheap and reliable alternative to conventional solar forecasting.

Chapter 9 Conclusion

This research presents the effectiveness of using a sky camera network comprising of 180-degree Vivotek IP camera facing skyward to provide images to a model which predicts solar irradiance levels at the location of each camera. The LabVIEW data acquisition system developed was appropriate for validating the accuracy of the model predictions and for identifying the strengths and weaknesses of forecasting using sky camera. The solar forecasting model based on the sky camera system found a cloud event prediction success rate of 92% and up to 5.5% fuel savings associated with forecasting control of a PV diesel power system[3]. These findings were presented at the WREC in early 2017 to make them available to the wider renewable energy community and energy industry.

The developments undertaken over the course of this project will continue to provide useful data for research and teaching at Murdoch University. The methods of data acquisition and software development have addressed the requirements of the project and proven to be the kind of dynamic and capable system which will serve as a basis for future research projects.

Research into image processing and cloud base height determination has identified issues with the sky camera network at Murdoch for providing accurate cloud base height data as well as increasing understanding of the methods which were explored. The simplified method of determining cloud base height was found to be incompatible with widely spaced whole sky images such as the pair currently installed at Murdoch. Cloud ratio and the sun ROI method of forecasting which was investigated shows promise for continued research into sky camera irradiance determination particularly in areas which could incorporate machine learning and battery system control.

Solar forecasting was found to have benefit in reducing fuel consumption and managing the probability of a loss of spinning reserve[3]. Although the benefits were smaller than the benefit of a large battery control system, batteries are still relatively expensive and solar forecasting could become an integral part of managing power systems with various sources of power generation and storage. Further developments in machine vision and software will improve the accuracy of forecasted cloud events and may result in larger fuel savings particularly in standalone PV diesel systems in remote areas.

Chapter 10 Future works

Due to the complex project type and the time required to complete the approval process which is required for the installation of the Solys2 setup, this project hasn't been completed within the time frame of this honours project and will likely be amalgamated into a future project at Murdoch University. Provided below is a list of recommended future works and a summary of how they could be undertaken.

1. Relocate Sky Camera 2 as it is likely that the installation on top of the EEB, which is designed for access to the future Solys2, will impact upon the view of the sky at the current location. It is recommended that a more suitable mounting bracket be designed and that the camera is relocated to nearer the Solys2 such that the camera is higher than the surrounding structure, the camera doesn't impact the solar irradiance seen by the Solys2 and is easily accessible for maintenance.
2. Location assessment and installation of the Solys2. A platform has been designed an is under construction during semester one of 2017. The Solys2 requires maximum exposure to diffuse and horizontal radiation per data collection that will be used by MU for teaching and research purposes.
3. Modify existing data acquisition system that is currently running on the Sky Server as a standalone application built using the LabVIEW programming language. The installation of the Solys2 will require this application to be restructured such that it is capable of parsing multiple variables from the CSV file that is available from the CR800 and logging them to the FTP location on the Sky Server.
4. Reprogram the CR800 datataker from Campbell Scientific using a CRBasic editor or Loggernet software available for download from Campbell Scientific. The outputs of the Solys2 sensors will be logged to the CR800 at the required rate for solar forecasting validation and teaching purposes.
5. Cloud base height determination at Murdoch University. An extensive range of image manipulation functions and algorithms are available through Murdoch's LabVIEW research licence which have been used in this project for investigation into cloud base height determination. Continued research into this area would be beneficial for the research being carried out at University of Oldenburg.

6. Procure and install a standalone irradiance logger at 12 Watts Pl and make data available to the University of Oldenburg

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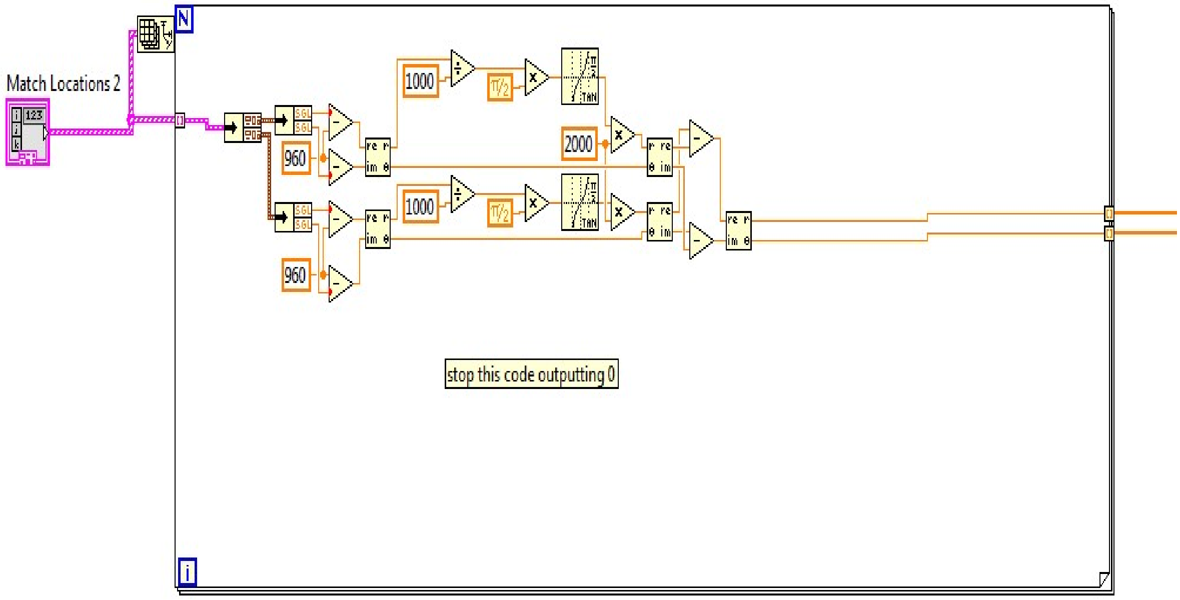
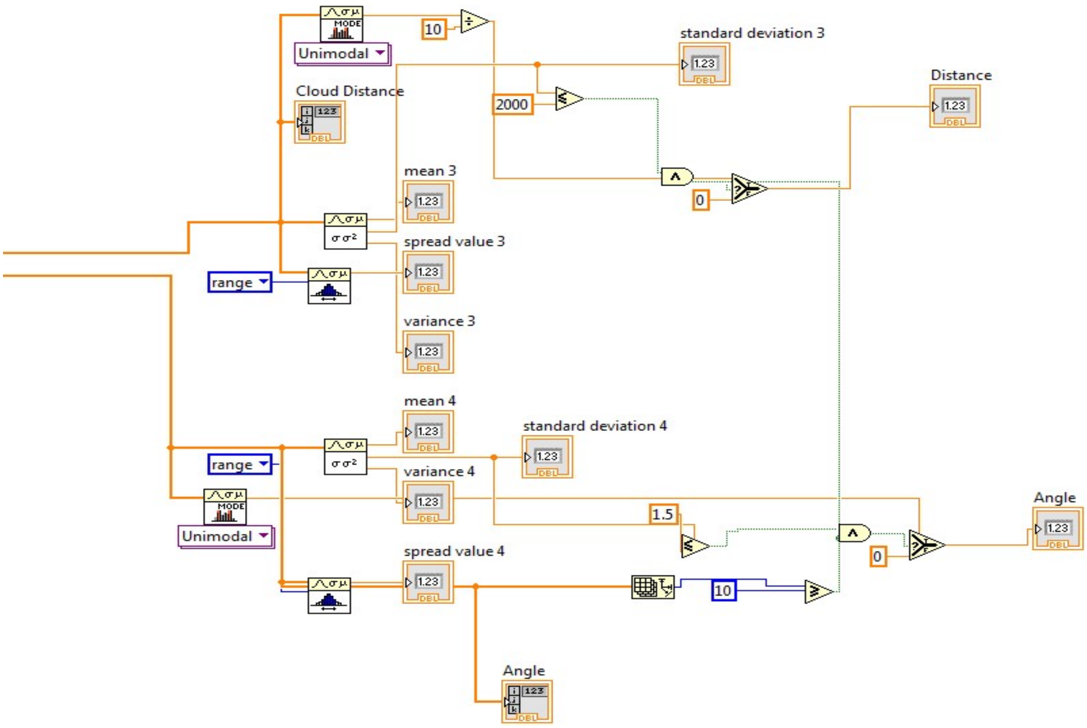
Appendix A

LabVIEW and CR800 application development for data acquisition.

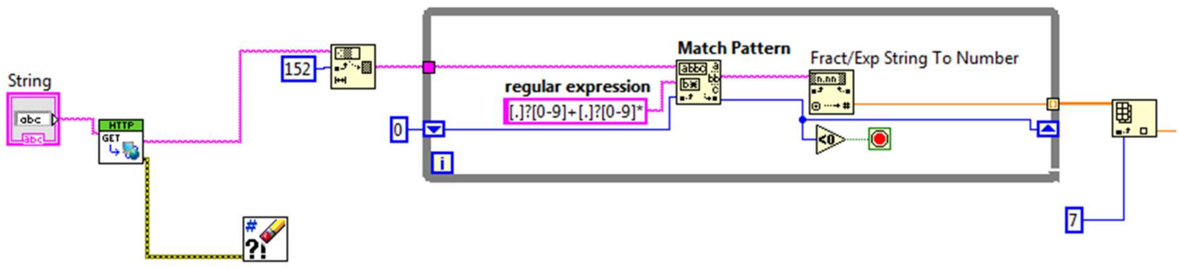
The below image is LabVIEW code for converting pixel coordinates into real coordinates.



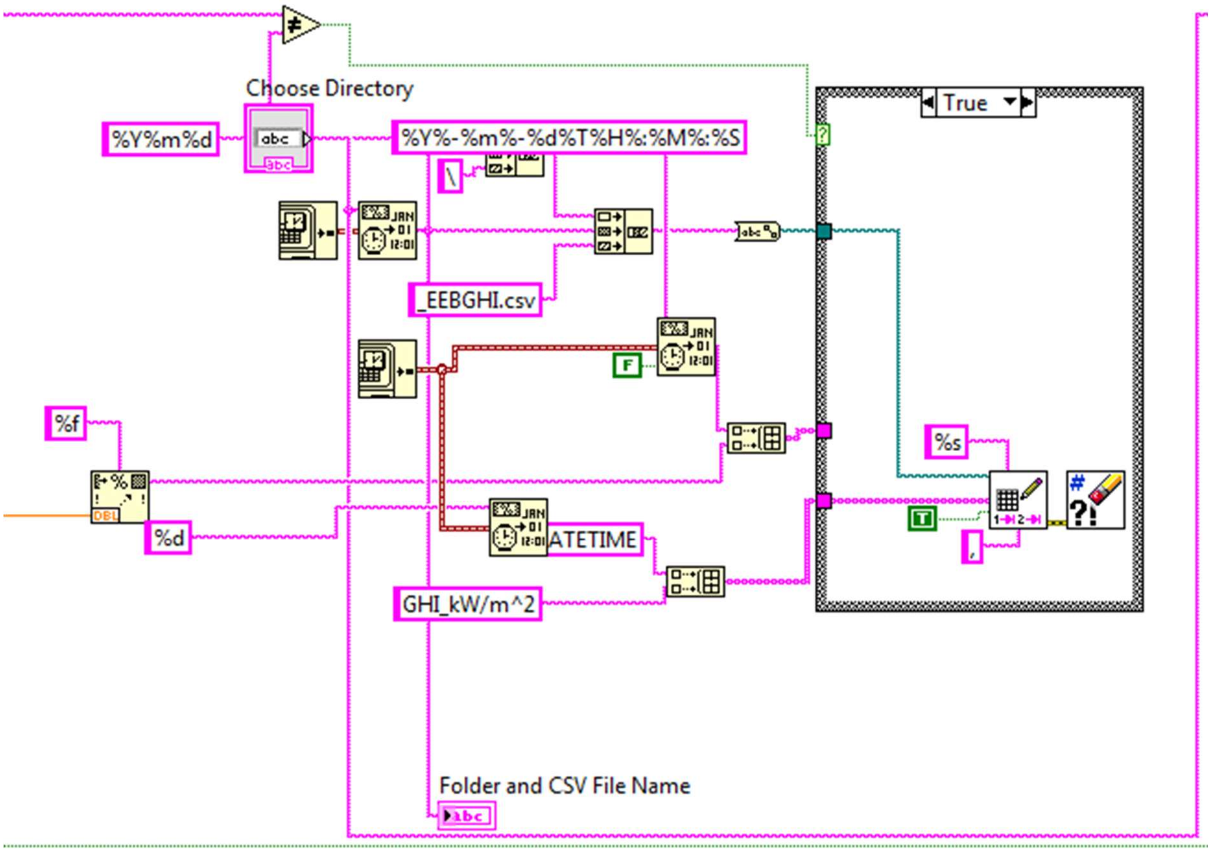
The below image contains LabVIEW which produced statistical information regarding pixel translation to be used by the optical flow algorithm.



The below image contains LabVIEW code which parsed relevant information out of an XML report which was returned by the CR800.



The below image contains LabVIEW code for creating and writing GHI data to a csv file in the Sky Server.



Appendix B

Image processing calculations and verification techniques

A comparison of pixels from an image take at 20170220_140520 with some scattered cloud where forecasting was seen to be most appropriate.

Below is an output from a Python script which was used to determine the threshold of 0.7 between pixels representing cloud and pixels representing sky.

Blue sky RGB value at A,A (75, 96, 179)

R/B PointA: 0.41899441340782123

Blue sky RGB values at B,B (79, 95, 180)

R/B PointB: 0.4388888888888889

Blue sky RGB values at C,C (82, 104, 177)

R/B PointC: 0.4632768361581921

Cloud RGB value at D,D (239, 254, 255)

R/B PointD: 0.9372549019607843

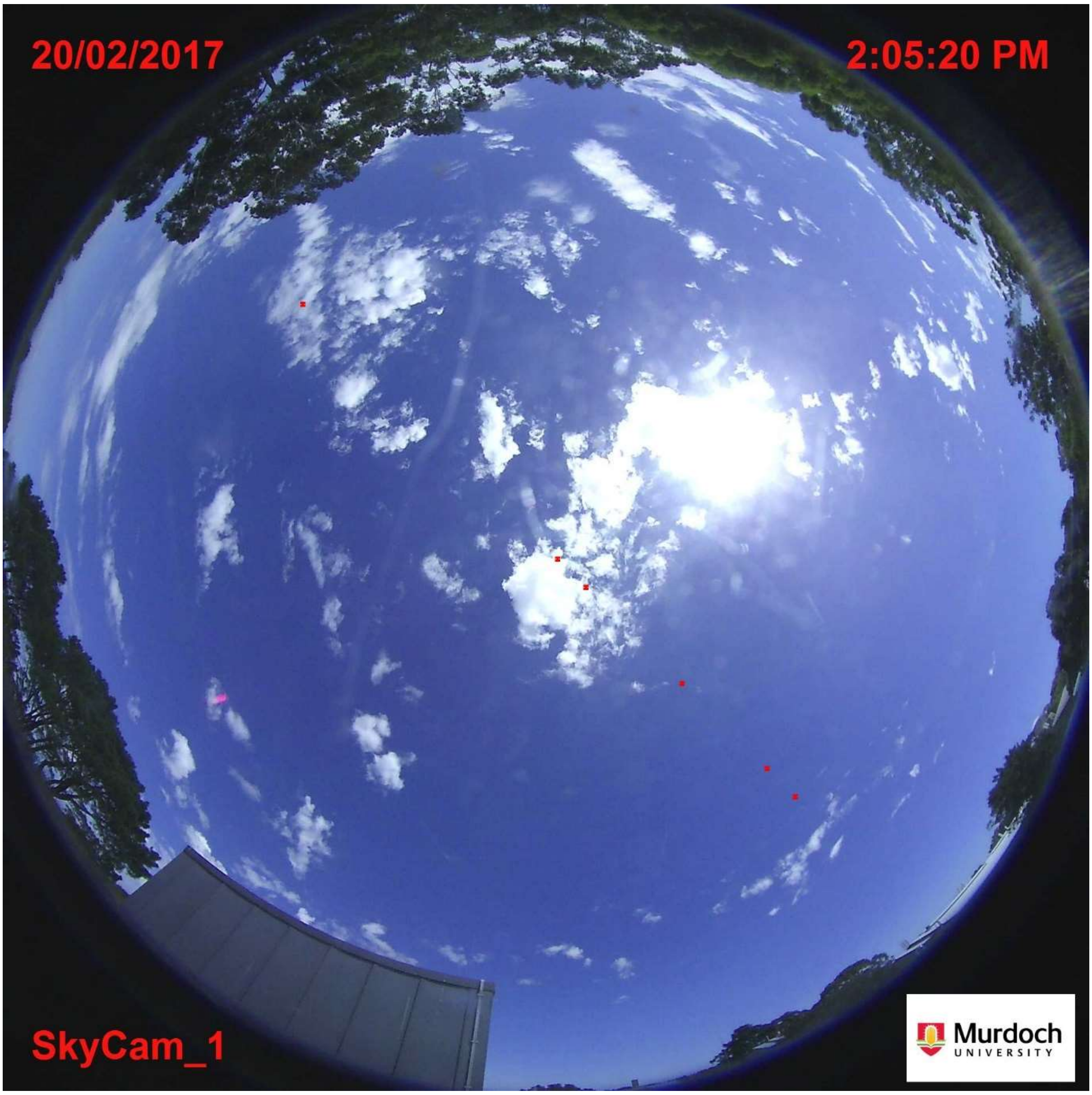
Cloud RGB values at E,E (249, 255, 253)

R/B PointE: 0.9841897233201581

Cloud RGB values at F,F (162, 182, 217)

R/B PointF: 0.7465437788018433

The red squares represent the point where the pixel values were taken from with point A being bottom left in alphabetical order and point F being top left.



Appendix C

Status report For Thomas Schmidt

Below is an update on the status of the project with respect to your email to Martina,

Currently the camera located on the Engineering and Energy building (SkyCam_1) is active and recording images into the FTP server. Unfortunately, the camera located on the southern edge of campus (SkyCam_2) has been having networking troubles due to a faulty PoE injector. We expect to have this replaced and the camera reinstalled by 20th October. The camera will be pointed north, levelled and secured such that it shouldn't move again.

Eric Roy has made a program which can be used to create a mask or I can make it on paint depending on which gives you the best result.

If you have any suggestions for image settings such as contrast etc. please let me know, otherwise I will set them similar (with less blue) to the settings you have provided.

Cloud Base Height

Cloud height information is recorded by the Bureau of Meteorology(BOM) on a half hourly basis at Jandakot Airport which is approximately 5 km away from Murdoch University.

Station Details	**ID:** 009172	**Name:** JANDAKOT AERO	**Lat:** -32.10	**Lon:** 115.88	**Height:** 30.0 m

This data can be found at the BOM website in the form of METAR/SPECIs and is also provided in a format compatible with importation into excel at http://www.aviador.es/Weather/Metar_Taf/ypjt .

I can extract the data into excel and I'm happy to set up the software required to write it into the Sky FTP Server after the 14th of October if you require.

Cloud height is given in layers in the format,

'YPJT 2705:34 Z AUTO 240°26G36KT 9999 -SHRA SCT019 BKN031 BKN047 12/11 Q1010='

'YPJT 2705:34' - Jandakot on the 27th of the month at 5:34am UTC

'SCT019 BKN031 BKN047' – Cloud Base Height at 1900 feet with a 2nd and 3rd layer at 3100 feet and 4700 feet respectively.

The rules that govern how the cloud heights and densities get represented are outlined in the image below.

SS	Sandstorm
VA	Volcanic ash
UP	Unidentified precipitation

Cloud

Cloud information is reported from the lowest to the highest layers in accordance with the following rules:

- 1st group: the lowest layer regardless of amount.
- 2nd group: the next layer covering more than 2 oktas of the sky.

Code	Cloud Amount
FEW	Few (1 to 2 oktas)
SCT	Scattered (3 to 4 oktas)
BKN	Broken (5 to 7 oktas)
OVC	Overcast (8 oktas)
NSC	Nil significant cloud
NCD*	Nil cloud detected

* NCD is only reported in fully automated reports when a cloud sensor detects nil cloud.

- 3rd group: the next higher layer covering more than 4 oktas of the sky.
- Extra groups: for cumulonimbus and/or towering cumulus clouds, whenever observed and not reported in any of the above.

Cloud amount is described using the codes in the table on the left.

Cloud height is given as a three-figure group in hundreds of feet above the aerodrome elevation, e.g. cloud at 700 feet is shown as 007.

Cloud type is identified only for cumulonimbus and towering cumulus, e.g. FEW030CB, SCT045TCU.

When an individual layer is composed of cumulonimbus and towering cumulus with a common base, the cloud is reported as CB only.

CAVOK

The abbreviation CAVOK (Cloud And Visibility OK) is used when the following conditions are observed simultaneously:

- Visibility is 10 kilometres or more;
- No cloud below 5000 feet or below the highest 25NM minimum sector altitude, which-ever is the higher, and no cumulonimbus and no towering cumulus; and
- No weather of significance to aviation, i.e. none of the weather phenomena listed in the weather table.

I was quoted $99 from the BOM for past cloud height data. It's unclear whether this includes future real-time data as was requested. Either way the data is still in half hourly intervals and would only provide a benefit if you are interested in past information.

GHI

As Martina mentioned in her email, the Solys2 is being held up by factors out of our control but Simon Glenister may be able to install individual pyranometers at both locations to provide GHI and possible some other weather data. Please liaise with Martina about this.

Engineering and Energy (EEB) Array

Solar power output can successfully be recorded from the 2kW Fronius IG 20 inverter located in the EEB. The Fronius inverter is supplied by 9 x 238W SunPower SPR-238E-WHT-D panels.

Array Location: 32.06603 South 115.83717 East 4m Accuracy

From Google Earth the SunPower array on the Engineering and Energy Building has an elevation at its midpoint of 47m.

Array Tilt: 29.5 degrees facing North

Reps Array

This array contains 16 Solarex MSX-77 modules, has a peak power of 1.2kW and is connected with the SMA Sunny Boy 1100. Currently a group of students are working on the data acquisition system at this location but it is hard to say when the power output from this array will be available on the FTP server.

I don't know if this system is designed to optimize solar and will therefore produce the maximum power that is available from the panels or whether the inverter will ramp down due to low loading.

Array Location:

32.070404 South 115.84097 East 4m Accuracy

From Google Earth the Solarex array at REPS has a midpoint elevation of 24m.

Tilt: 27.6 degrees and facing north.

Camera 1 (EEB):

32.06613 South 115.83711 East 4m Accuracy

48m above sea level (Google Earth)

Camera 2 (REPS):

32.07048 South 115.84051 East 4m Accuracy

27m above sea level (Google Earth)

Appendix D

The Use of LabVIEW in the Development of a Sky Camera Network and Data Acquisition System at Murdoch University for the Purpose of Short-term Photovoltaic Power Output Forecasting and Cloud Base Height Determination

LabVIEW has been the development platform of choice for the data acquisition system at Murdoch University. The software has been instrumental in overcoming a variety of obstacles which have arisen while using a range of different devices on the data acquisition network which was developed to acquire, store and process 180degree sky images from two locations on Murdoch University Campus. The images are used for the continued development of a University of Oldenburg model which forecasts solar irradiance both at the image location and at other locations within a 5km radius. Environmental data that is acquired by the LabVIEW data acquisition systems is used for forecast validations, for research into the relationship between solar irradiance and photovoltaic output power and for the investigation of the solar resource at Murdoch University.

Sky Images

Two built LabVIEW programs have been linked using global variables to simultaneously pull images from two cameras using a ‘get http’ function. The programs run on a server which is a part of Murdoch University’s AD domain, this allows accurate time stamping and coordinated acquisition to within the tolerance which would allow accurate forecasting and cloud base height determination.

Solar Irradiance Logging

Again a ‘get http’ and ‘get time’ function have been used to accurately record solar irradiance data every second. A LabVIEW application overcomes the need for data to be manually downloaded from a datalogger and for the clock to be updated daily to keep within tolerances.

Environmental Data and PV Power Logging

A range of LabVIEW functions and techniques have been used to communicate with Modbus devices, inverters, sensors, field points and computers allowing the correct data to be stored real-time in an FTP server available to Oldenburg.

Cloud Base Height Determination

An area where LabVIEW is playing a key role in this project is during the determination of cloud height. Cloud height is important for Oldenburg to determine solar irradiance point forecasting due to the geometry of shadow casting. LabVIEW’s image processing functions and in particular the IMAQ vision module are being used to investigate different cloud matching techniques which allow for the real-time calculation of cloud height.

Appendix E

Investigating CR800 and NL201 response times

The response time from the CR800 while configured with the NL201 is very delayed compared to the typical response time of <1ms.