Illumination Testing of 4Pi Sun Sensor

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Submitted by

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17/07/2023

CERTIFICATE

This is to certify that the project titled Aerospace Testing and AOCS Technologies at Kepler Aerospace is a record of the bonafide work done by Abhishek Avadhanam (190933018) submitted in partial fulfilment of the requirements for the award of the Degree of Bachelor of Technology (B. Tech) in AERONAUTICAL ENGINEERING of Manipal Institute of Technology, Manipal, Karnataka, during the academic year 2022 -2023.

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ABSTRACT

This report discusses two projects: developing an Illumination Testing Facility for precise solar simulation and; implementing quality checks on a 4Pi Sun Sensor assembly, including creating an Illumination Test Set-Up. The significance of solar simulators is highlighted, as they are crucial for testing and studying the performance of photovoltaic devices being illuminated by sunlight under various environmental conditions. Different types of solar simulators, such as continuous and pulsed, are explained, along with their uses in calibration, efficiency measurement, material testing, component testing, and research of various devices. The 4Pi Sun Sensor's role in Attitude Determination is described, emphasising the need for accurate and reliable testing.

The methodology employed in both projects is presented. The regular maintenance of the Newport 94043A Solar Simulator and the assembly and testing procedures for the 4Pi Sun Sensor are described in detail. The various tests conducted on the sun sensor, such as visual inspection, electrical tests, illumination tests, and operation of the instruments involved, like the Keithley 2401 Sourcemeter and the Murata SCL3300-D01-PCB tilt sensor, are explained.

The results section includes the findings from the solar simulator testing, highlighting the need for replacing the Xe-Arc Lamp and the results from the sun sensor's illumination tests on different axes. The conclusion emphasises the importance of these projects in understanding solar simulation and sun sensor technology, providing hands-on experience in testing and calibration procedures for photovoltaic devices and spacecraft orientation systems.

Overall, these projects contribute to advancement in solar energy and aerospace technology by ensuring accurate testing and calibration of devices used in these fields.

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NOMENCLATURE

M.I.T.: Manipal Institute of Technology

ADCS: Attitude Determination and Control

PCB: Printed Circuit Board

PV: Photo Voltaic

LED: Light Emitting Diode

UV: Ultraviolet

DC: Direct Current

AC: Alternating Current

PC: Personal Computer

I2C: Inter-Integrated Circuit

SPI: Serial Peripheral Interface

KF: Kalman Filter

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CHAPTER 1: INTRODUCTION

The following projects were undertaken as part of the project:

i. Develop an Illumination Testing Facility where the Equipment Under Test can be exposed to light of a specific irradiance and spectra at the required incidence angles.

ii. Implement Quality Checks on all stages of assembly of a Space Grade 4Pi Sun Sensor and create an Illumination Test Set-Up.

1.1 Solar Simulator

Solar simulators are devices used for testing solar cells and photovoltaic modules. They replicate sunlight under controlled and consistent light conditions to study the performance of photovoltaic devices under different environmental and operational situations. Solar simulators are necessary for developing and testing new photovoltaic technologies and quality control in manufacturing [5]. They come in different classes and types with varying precision, spectral match, and uniformity levels. They are subject to several certifications and standards [6]. Regular maintenance and calibration are needed to ensure accuracy [5]. Thus, to perform reliable and accurate testing, it is crucial to comprehend essential concepts such as irradiance, spectral match, air mass filters, and uniformity [5].

1.1.1 Uses of Solar Simulators

Solar simulators serve various purposes in the field of photovoltaics, including:

i. Calibration and testing: Solar simulators allow accurate characterisation of solar cells' electrical and optical properties, enabling performance evaluation and quality control.

ii. Efficiency measurement: Solar simulators are utilised to determine the conversion efficiency of solar cells by exposing them to light with the spectra and irradiance encountered in their operational environments.

iii. Material and component testing: Solar simulators aid in evaluating new materials, coatings, and components for suitability in solar energy applications.

iv. Research and development: They provide a controlled and repeatable light source for studying the behaviour and performance of photovoltaic devices under various environmental conditions.

1.2 Sun Sensor

Sun sensors are used in ADCS (Attitude Determination and Control Systems) to determine the spacecraft's orientation with respect to the sun [3]. This information ensures the spacecraft maintains the correct orientation for payload application, communication systems and mission success [3]. Sun sensors are used with other sensors, such as star trackers and gyroscopes, to provide complete attitude determination [2].

4Pi Sun Sensors typically consist of three or more photodiodes or photocells that are arranged on a “sphere” or “hemisphere”, each pointing in a different direction [2][3]. When the sun shines on the sensors, each photocell detects the intensity of the solar radiation on it[2][3]. The spacecraft’s attitude can be determined based on the current from each photocell [2].

CHAPTER 2: BACKGROUND THEORY

2.1 Solar Simulator

2.1.1 Types and Subtypes of Solar Simulators

Solar simulators are of two main types: continuous and pulsed. [5]

i. Continuous solar simulators produce a constant beam of light with a similar spectral distribution and irradiance to sunlight. They are used to measure the steady-state performance of PV devices. [5]

ii. Pulsed solar simulators produce light in short pulses to check how devices behave to rapid exposure to sunlight. They are used to assess PV devices' response time and transient behaviour. [5]

There are various types and subtypes of solar simulators, each with advantages and disadvantages of their own. Some widely used examples include:

i. Xenon-Arc Lamp-based solar simulators are the most common type of continuous solar simulators. They are accurate and reliable, but the lamp has a finite life and is expensive to replace. [5]

ii. LED solar simulators are the latest type of continuous solar simulators. They are cheaper to operate but are not as accurate or reliable.

iii. Flash solar simulators are the most common type of pulsed solar simulators. They produce short pulses of light. Flash solar simulators are accurate and reliable but are expensive to operate as the lamp must be replaced often.

2.1.2 Irradiance and Spectra

The irradiance is the amount of light energy falling on a surface per unit area. The spectrum of light is the energy distribution across the range of frequencies of electromagnetic waves that are created.

The irradiance and spectrum of a solar simulator should be as close to sunlight as possible.

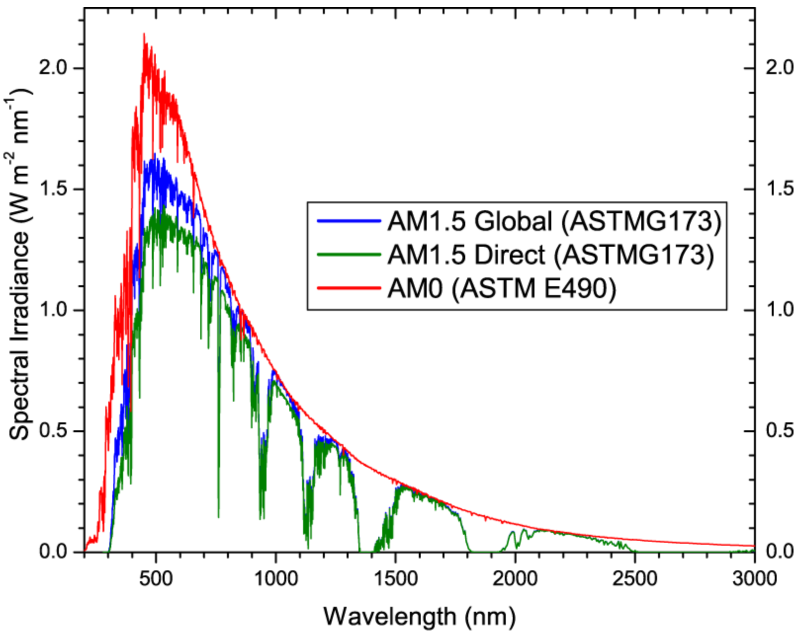


Figure 1. Spectral Irradiance Graph [12]

*2.1.3 **Newport 94043A Solar Simulator***

Figure 2. The Oriel 94043A Solar Simulator

The Newport 94043A Solar Simulator is a Class AAA solar simulator that uses a 450-Watt Xenon arc lamp to produce light with a wide range of wavelengths that closely match the spectrum and irradiance of sunlight. It tests photovoltaic cells, novel materials, and various optical devices.

Table 1. 94043a Specifications [9]

Simulator Class	Class AAA
Lamp Type	Xenon
Lamp Wattage	450 W
Output Beam Size	4 x 4 in.
Beam Uniformity	≤2%
Beam Divergence, Half Angle	≤4% °
Typical Output Power	100mW/cm² (1 Sun) ±20% Adjustable
Spectral Match Classification	A (IEC 60904-9 2007), A (JIS 8904-9 2017), A (ASTM E927-10 2015)
Temporal Instability	≤0.5% STI≤2.0% LTI
Temporal Instability Classification	A (IEC 60904-9 2007), A (JIS 8904-9 2017), A (ASTM E927-10 2015)
Uniformity	≤2%
Uniformity Classification	A (IEC 60904-9 2007) A (JIS 8904-9 2017) A (ASTM E927-10 2015)
Working Distance	6.0 +0.5 in.
Line Regulation	0.01%
Power Requirements	Lamp Housing: 95-264 VAC / 3A (Max) / 47 - 63 Hz Power Supply: 95-264 VAC / 12A(Max) / 47 - 63 Hz

The 94043A has several features that make it ideal for use in a variety of applications, including:

i. A large output beam of 4 inches x 4 inches allows the testing of large devices.

ii. A variable attenuator that adjusts the beam’s irradiance from 0.1 to 1.1 SUN.

iii. The 94043A is a powerful, reliable, easy-to-use solar simulator with various applications.

*2.1.4 **Irradiance and Spectrum Control on the Newport 94043A Solar Simulator***

The Newport 69920 Power Supply Module, Attenuator, and Air Nass Filters can be used in combination to adjust the irradiance and spectrum of the simulator’s output beam.

i. Power module setting: The power module setting includes setting the voltage and current passing through the Xenon Arc Lamp, thus controlling the overall output power of the simulator. The higher the power, the higher the irradiance.

ii. Attenuator: The attenuator is a variable filter that can reduce the irradiance of the simulator. The attenuator has 11 settings, each reducing the irradiance by a factor of 1.1.

iii. Air mass filters: Air mass filters can simulate different amounts of atmospheric filtering of sunlight. For example, the AM 1.5 air mass filter simulates the solar spectrum at a zenith angle of 37 degrees.

*2.1.5 **91150V reference cell***

The 91150V reference cell is a calibrated photocell used to compare the irradiance and spectrum of light incident on it to sunlight at AM1.5. It is a 2 x 2 cm solar cell made of monocrystalline silicon with a fused silica window. The cell is also equipped with a thermocouple that measures the temperature of the cell.

2.2 **Sun Sensor**

*2.2.1 **Types of Sun Sensors***

Sun sensors can be classified into two main types: digital sun sensors and analog sun sensors.

i. Digital sun sensors are made of an array of photodiodes or pixels that capture the sunlight through a bore and output an electrical signal. These sensors offer high accuracy and resolution, making them suitable for precise attitude determination applications.

ii. Analog sun sensors operate by measuring the intensity of sunlight incident on a set of photodiodes or photocells by measuring the short-circuit current produced.

*2.2.2 **Analog Sun Sensors***

An analog sun sensor measures the angle between its normal and the sun. It does this by measuring the amount of sunlight incident on it. They are photodiodes or photocells typically made of silicon, producing a short-circuit current proportional to the intensity of light falling on it. \

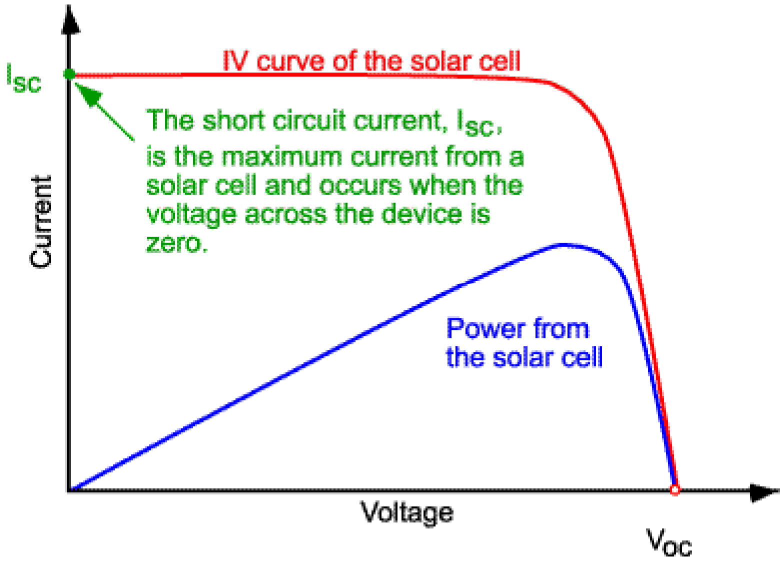


Figure 3. I-V graph of a Solar Cell [18]

2.2.3 ***Calculation of Short Circuit Current***

Equation 1. Short circuit current as an expression on band gap

$$I_{SC} = q\varphi_g A$$

This is the most ideal equation, where q is the charge of the electron, φ_g is the flux of electrons with energy larger than the band-gap energy, W_g, of the semiconductor, and A is the active area of the junction. For a full explanation of how the optical band gap of a material is calculated using ultraviolet-visible light spectroscopy, refer to [16] and [17].

2.2.4 ***Short Circuit Current due to Sunlight***

A full discussion on the various factors like temperature, atmospheric filtering, temperature, material selection, doping etc., on the short circuit current created upon exposure to sunlight is beyond the scope of this paper. An initial understanding can be gained by studying the Shockley-Queisser limit, which is the maximum theoretical efficiency of a single p-n junction-based solar cell where the only loss mechanism is radiative recombination.

The expression for short circuit current in a solar cell can be simplified to:

Equation 2. Short circuit current corrected for recombination

$$I_{SC} = q(t_s\varphi_g A - 2t_c Q_c)$$

Where t_s is the fraction of the photons falling on the photocell that create electron-hole pairs, $t_c Q_c$ is the corrective factor for the photons generated due to recombination of electron-holes pair, this energy is released as a part of the black body radiation Q_c(flux of blackbody radiation above the band gap). The 2 is multiplied assuming the radiation is emitted from both sides of the photocell, which is not always true. For a full discussion on Short Circuit Current Calculation, refer to [19]

The short-circuit current is also proportional to the cosine of the angle between the sun's rays and the photocell.

2.2.5 *Calculation of Sun Vector*

The sun vector is calculated by measuring and comparing the short-circuit currents produced by at least three photocells that are oriented at different angles to each other.

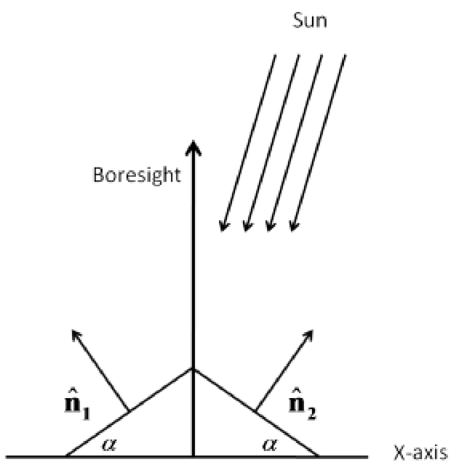


Figure 4. A pair of Analog Sun-Sensors inclined with respect to each other [3]

Equation 3. I_{SC} and angle conversion

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} \mathrm{P_0 k_1} & 0 \\ 0 & \mathrm{P_0 k_2} \end{bmatrix} \begin{bmatrix} -\sin(\alpha) & \cos(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{bmatrix} \begin{bmatrix} \sin(\theta) \\ \cos(\theta) \end{bmatrix}$$

Where I is the short-circuit current, P_0 is the intensity of sunlight, k is the constant of proportionality, and θ is the angle between the sensor's normal and the incident light. Therefore,

Equation 4. I_{SC} and angle conversion

$$\bar{\theta} = \tan^{-1}\left(\frac{1}{\tan(\alpha)}\left(\frac{I_2 k_1 - I_1 k_2}{I_1 k_1 + I_2 k_2}\right)\right)$$

Where θ *is in the range: <-2α, 2α >*

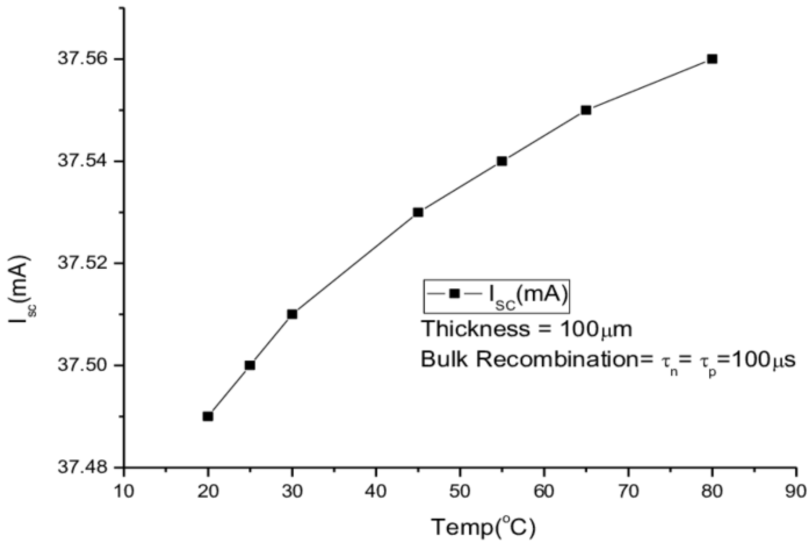


Figure 5. Short-circuit Current Vs. Temp [13]

However, the thermal energy of the electrons in the photocell increases with the temperature, making electron excitation by the light more difficult. Thus, the photocell's short-circuit current decreases as the photocell's temperature increases. This must be considered while designing and using Sun Sensors. Because for example, if a Sun Sensor is used in a high-temperature environment like Low Earth Orbit, the photocell's short-circuit current decreases, reducing its sensitivity.

This effect is typically exponential, depending on the type of photocell and its material. For example, the short-circuit current of a silicon photocell decreases by 7% for every 10° C increase in temperature.

*2.2.6 **Calibration of Sun Sensors***

Calibration is important to ensure the accuracy and reliability of sun sensors. It involves determining the sensor's response to known inputs and characterising errors and deviations. It involves exposing the sun sensor to a controlled light source, such as a solar simulator [4]. By analysing the measured outputs and the known inputs, calibration parameters can be derived to correct errors. [2][3]

2.2.7 *Testing of Sun Sensors*

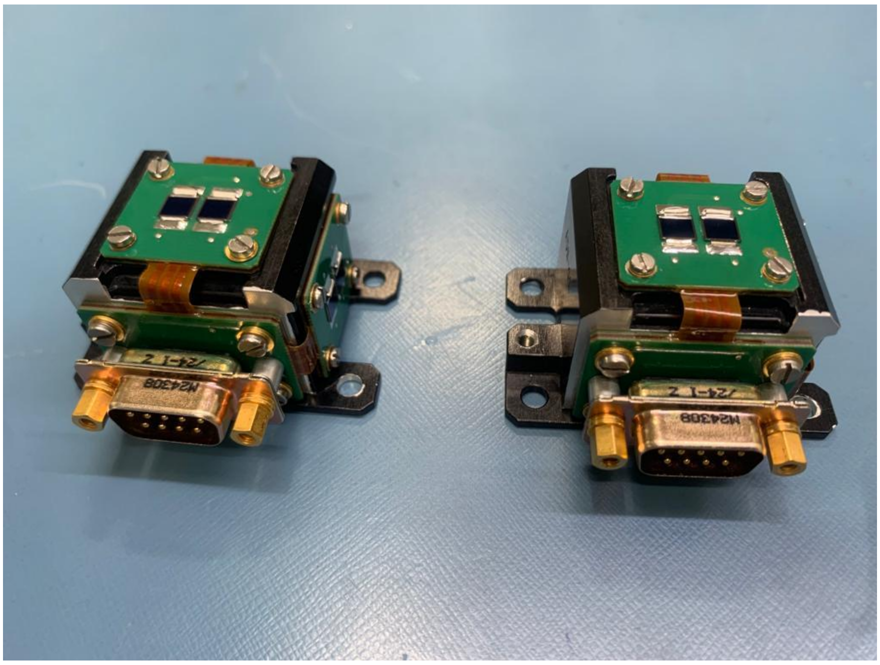


Figure 6. 4Pi Sun Sensor

Sun sensors undergo rigorous testing to verify their accuracy. This includes functional tests to ensure operation and evaluate their response to varying solar illumination conditions. Performance parameters such as angular accuracy, sensitivity, linearity, and repeatability are assessed through various test procedures [10]. Environmental testing, including thermal and vibration tests, is also conducted to assess the sensor's reliability under different operating conditions.

Typical testing of sun sensors includes [4]:

i. Thermal Calibration: Measures the sensor's response to temperature changes.

ii. Radiometric Calibration: Determines the sensor's sensitivity to light.

iii. Misalignment Calibration: Determines any misalignments between the sensor and the spacecraft.

CHAPTER 3: METHODOLOGY

3.1 Solar Simulator

3.1.1 Regular Maintenance

The calibration and maintenance procedure for the Newport 94043A solar simulator involves several steps, including verifying lamp performance and checking illumination uniformity and alignment using a calibrated reference cell. By following these steps and performing regular maintenance, one can ensure the accurate and reliable performance of their Newport 94043A solar simulator [5][1].

i. Initial Inspection: Before performing any calibration or maintenance, visually inspect the simulator for any signs of damage or wear. Check for any cracked or broken parts, loose connections, or signs of corrosion.

ii. Power on and Warm-up: Connect the simulator to a power source and turn it on. Allow the simulator to warm up for at least 30 minutes to reach a stable temperature. This step ensures that the lamp and other components are at the correct operating temperature for accurate performance.

iii. Verify Lamp Performance: Check the lamp voltage and current readings to ensure they are within the specified range. Refer to the instrument manual for the recommended voltage and current values.

iv. Check Illumination Uniformity: Use a calibrated reference cell to check the illumination uniformity of the simulator. Move the reference cell around the illuminated area systematically to ensure the illumination is uniform across the entire area. This step ensures that the simulator performs accurately across its entire illuminated area.

v. Calibration of the Simulator: Place the reference cell in the centre of the simulator's illuminated area and record the voltage and current readings. Compare these readings to the known values of the reference cell to determine the calibration factor. Adjust the simulator's voltage or current output to match the reference cell's known values. A calibrated reference cell, a digital multimeter, and an ammeter are required to perform this step.

vi. Cleaning: Regular maintenance of the Newport 94043A solar simulator involves cleaning the lamp, reflectors, and optical filters. Use a soft, lint-free cloth and a mild cleaning solution to clean the lamp and reflectors. Avoid touching the lamp with bare hands, as this can cause damage to the lamp. Replace the optical filters and Xenon Arc Lamp as needed.

3.1.2 Checking Irradiance

i. Place the Reference Cell in front of the solar simulator with the detector facing the simulator.

ii. Turn on the Newport 94043A Solar Simulator and wait for the lamp to stabilise for 30 minutes. Please do not open the shutter before it stabilises.

iii. Calculate the Irradiance error by comparing the measured and expected Short-circuit Current on the reference cell.

iv. Make any necessary adjustments to the solar simulator to improve the irradiance, such as changing the lamp or the power setting.

3.1.3 Changing the Xe-Arc Lamp

3.1.3.1 Instructions

i. Please turn off the 94043A solar simulator and unplug it from the power outlet.

ii. Remove the two screws that secure the lamp housing to the simulator.

iii. Carefully remove the lamp housing from the simulator.

iv. Disconnect the power cable from the old lamp.

v. Dispose of the old lamp according to the manufacturer's instructions.

vi. Connect the power cable to the new lamp.

vii. Carefully insert the new lamp into the lamp housing.

viii. Secure the lamp housing to the simulator with the two screws.

3.1.3.2 Alignment Instructions

i. Please turn on the 94043A solar simulator and allow it to warm up for a few minutes.

ii. Attach the alignment tool to the front of the simulator.

iii. Adjust the alignment tool until the beam of light is centred on the target.

iv. Tighten the screws on the alignment tool to secure it in place.

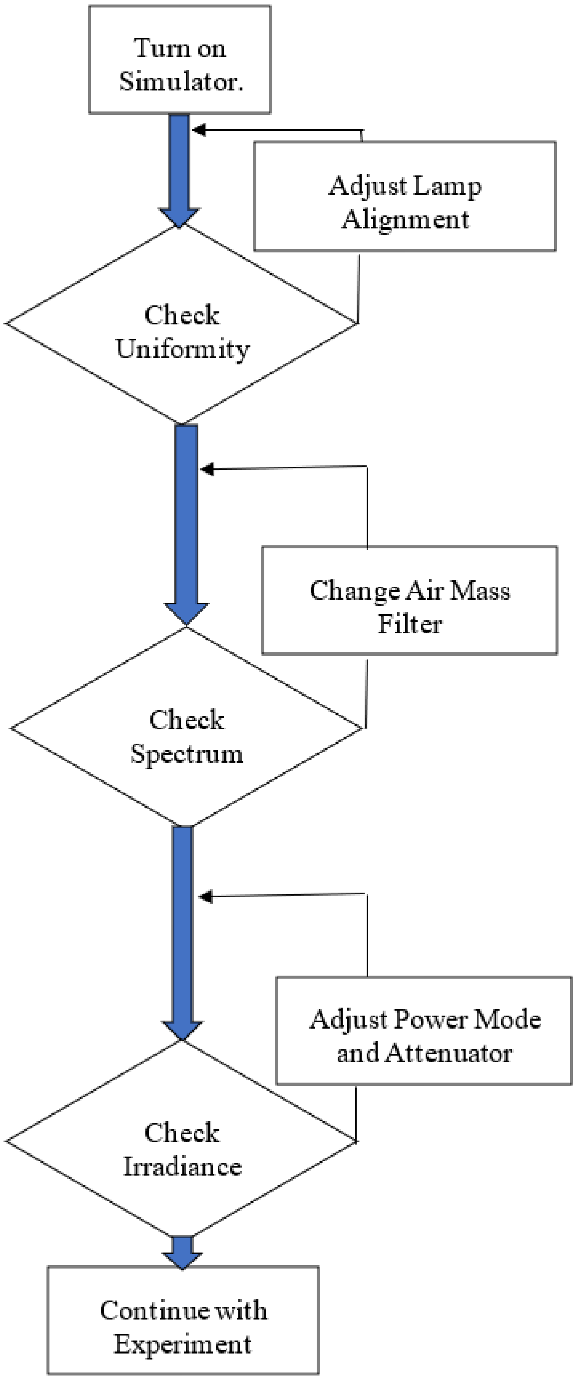
3.1.3.3 Safety Precautions:

i. Always wear gloves and safety glasses when working with the Xe-Arc lamp.

ii. Be careful not to touch the lamp, as it is hot.

iii. Dispose of the old lamp according to the manufacturer’s instructions.

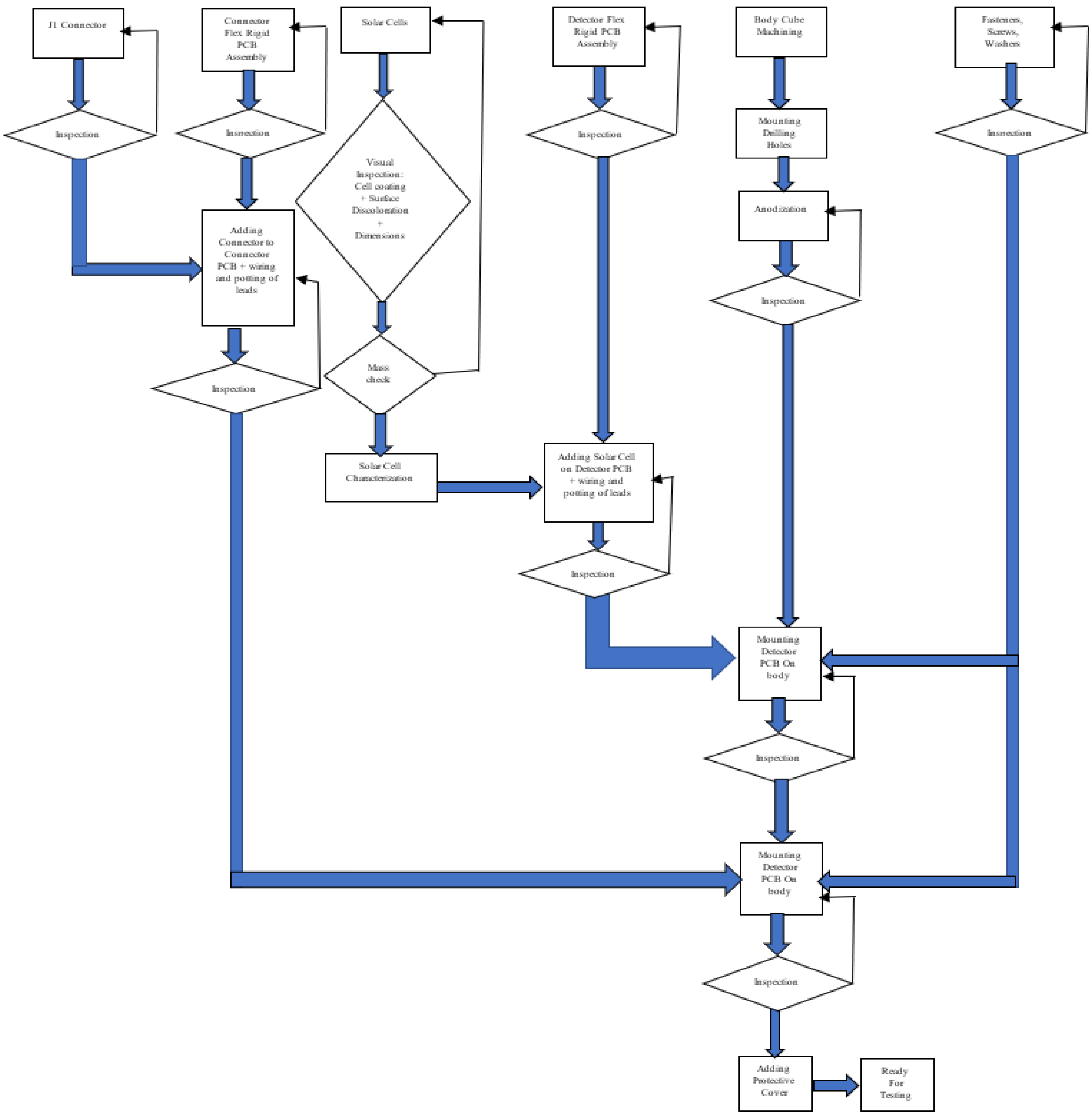
3.1.4 ***General Instructions for operation of Solar Simulator [refer to 3.1.1]***



Flow-Chart 1. Operation of Solar Simulator

3.2 Sun Sensor

3.2.1 Assembly Procedure



Flow-Chart 2. Assembly Procedure of 4Pi Sun Sensor

3.2.2 ***Visual Inspection***

3.2.2.1 Incoming Visual Inspection of Solar Cells

i. Inspect for any body scratches, cracks and dents on the solar cells.

ii. Inspect for any fingerprints, oil and grease on the surface of solar cells.

iii. Inspect for any lead damages on solar cells.

3.2.2.2 Visual Inspection of Head

i. Name Plate

ii. Serial Number

iii. Connector potting

iv. Surface discolouration

v. Fasteners Torquing/Potting

3.2.2.3 Visual Inspection of Solar Cells after Soldering

i. Cell Coating

ii. Pin holes, blow holes, concave shape, shiny, disturbed joints

iii. Damage to the body and cells

iv. Inspect for any body scratches, cracks and dents on the solar cells.

v. Inspect for any fingerprints, oil, and grease on the surface of solar cells.

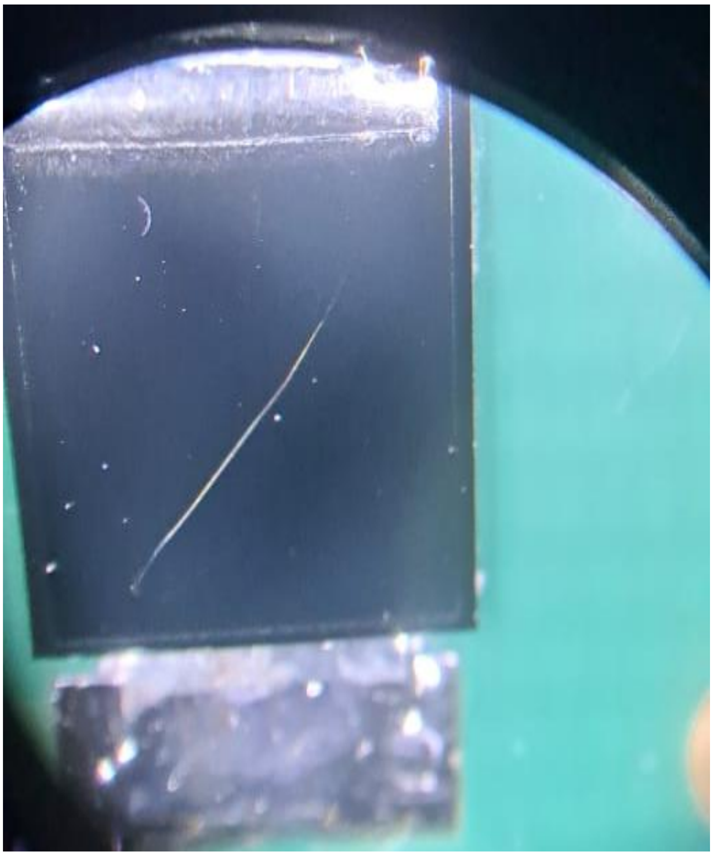


Figure 7. Example of failed visual inspection

3.2.3 *Electrical Tests*

i. PCB Pin Continuity: Before and after photocells are mounted on the PCB, the continuity between each pin (9-pin connector) and Pad in the PCB is checked for all combinations using a digital multimeter & logged for comparison with the expected result before the photocell is placed on the PCB. Refer to Fig 5 to do this test. Enter Results in Annex B, Table 2.

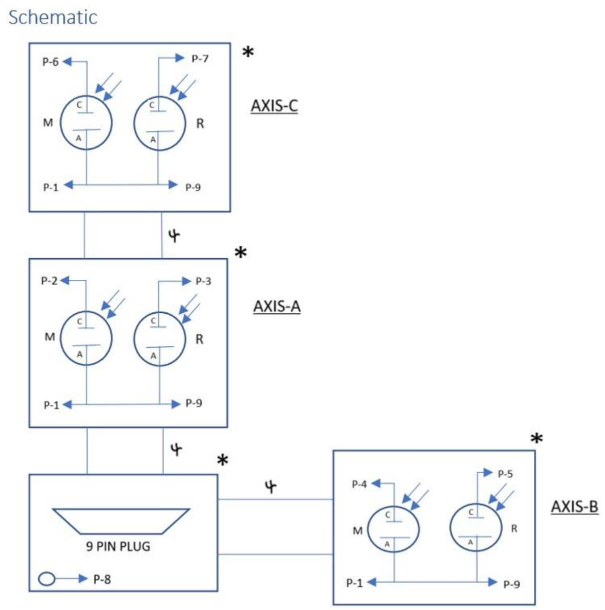


Figure 8. Sun Sensor PCB layout reference

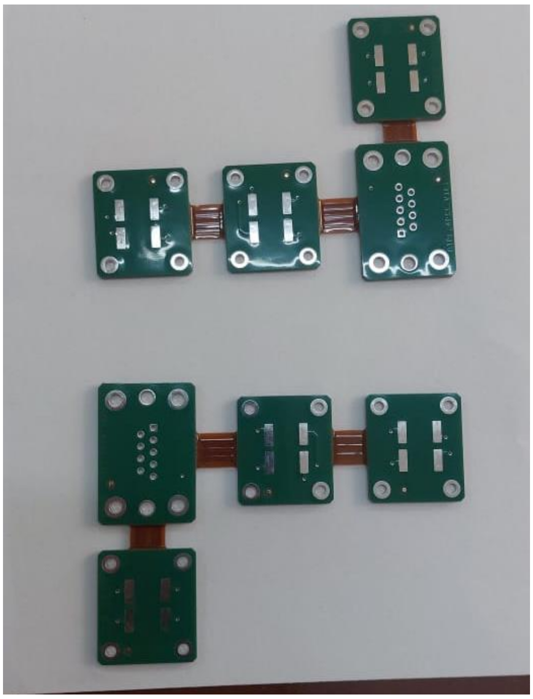


Figure 9. Sun Sensor PCB

ii. Photocell Diode Behaviour Check: Using a multimeter, the forward and reverse resistance of the photocells are checked and compared to the expected values.

iii. Photocell Illumination Check: Check the Short-circuit current of all photocells under 1SUN irradiance at AM0 spectra before installing them on the PCB.

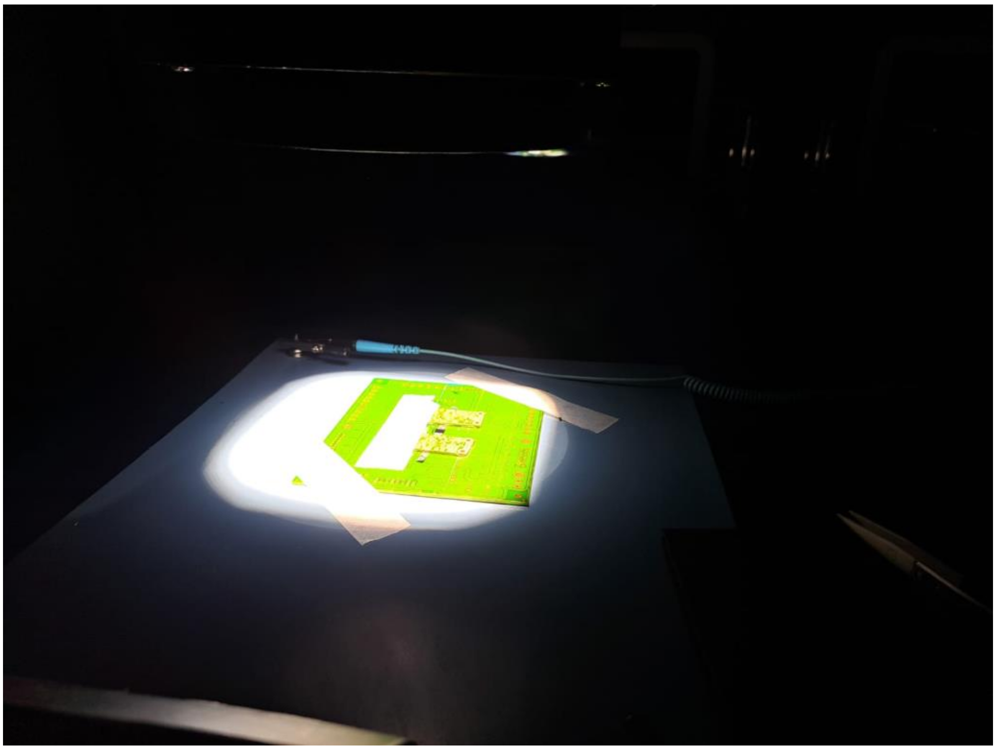


Figure 10. Photocell Illumination Check

*3.2.4 **Illumination Test***

There are two types of Illumination Tests to be done on the 4Pi Sun Sensor

i. Simplified Functional tests: Sampling of Current on the sensor at 5° angle increments at one solar constant.

ii. Full Functional tests: Sampling of Current on the sensor at 0.5° increments at one solar constant.

3.2.5 *Keithley 2401 Sourcemeter*

Figure 11. Keithley 2401 Sourcemeter

The Keithley 2401 sourcemeter is a dual-channel sourcemeter, meaning it can provide both current and voltage sources. This makes it ideal for various applications, including photocell testing. Its features include:

i. A wide range of current and voltage source and measurement values (+/- 10 A and +/- 100 V)

ii. High precision and accuracy (< 0.01%)

iii. A variety of measurement modes (DC, AC, pulse, sweep)

iv. A user-friendly interface.

v. The ability to interface with a computer.

The Keithley 2401 sourcemeter also has limitations for photocell testing. These limitations include:

i. The sourcemeter is not as sensitive as other instruments, such as electrometers.

ii. The sourcemeter can be noisy, which can affect the accuracy of measurements.

3.2.6 *PyMeasure*

PyMeasure is a Python library that provides a high-level interface to various measurement instruments, including the Keithley 2401 sourcemeter.

To use PyMeasure to interface the Keithley 2401 to a PC, the following is needed:

i. A Keithley 2401 sourcemeter

ii. A PC with Python 3 installed

iii. The PyMeasure library

Once the necessary software is available, follow these steps to interface the Keithley 2401 to a PC using PyMeasure:

i. Install the PyMeasure library.

ii. Import the PyMeasure library into a Python script.

iii. Create a Keithley2400 object.

iv. Set the serial port parameters for the Keithley2400 object.

v. Connect to the Keithley2401 sourcemeter.

vi. Control the Keithley2401 sourcemeter from Python.

vii. Collect data from the Keithley2401 source meter.

3.2.7 ***Murata SCL3300-D01-PCB***

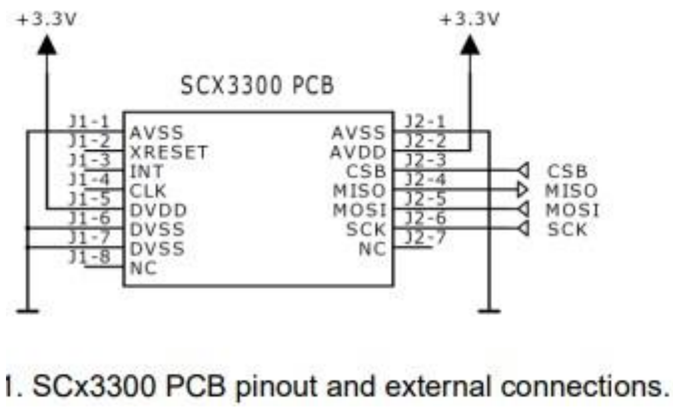


Figure 12. Tiltmeter pinout and connections [15]

The Murata SCL3300-D01-PCB is a capacitive MEMS sensor that precisely measures inclination and tilt angles across various operating conditions.

3.2.7.1 Features*:*

i. High Accuracy: It has a resolution of 0.01 degrees and a full-scale range of ±90 degrees per axis.

ii. Wide Operating Range: It can operate in a wide temperature range from -40°C to +85°C.

iii. Digital Output: It features a digital I2C and SPI interface, allowing easy integration with microcontrollers.

*3.2.8 **Instructions to install Illumination Test Set-Up:***

Equipment required: Keithley 2401 Sourcemeter, Newport 94043A Solar Simulator, 9-Pin-Connector Test Jig, Murata SCL3300-D01-PCB, Rotary Table, Adjustable Height Table and FPSS sensor mount.

3.2.8.1 Procedure:

i. Procure a rotary table with mt2 type bore and 1 arcsec markings.

ii. Get a rod with mt2 taper and an L shape plate manufactured that are joined to the rotary Table to form the "tilt table."

iii. Include mounting holes on the L shape plate such that when the sensor is mounted to it, the plane of the photocell includes the axis of rotation of the tilt table. If required, procure spacers to achieve this requirement.

iv. Include mounting holes for the SCL3300-DO1-PCB as well.

v. Paint the rotary Table, rod and L shape plate black to minimise reflective surfaces.

vi. Assemble the "Tilt Table", mount the Tiltmeter on it, and create a wiring harness to interface it with the Arduino by referring to the above figure.

vii. Procure 2 sets of multimeter probes and fit them into the front and back ports of the Keithley 2401 Sourcemeter.

viii. Use an RS-232 to USB cable to connect the Sourcemeter to the PC.

ix. Use a micro USB cable to connect the Arduino to the PC.

x. Ground the Arduino, Sourcemeter and the Tiltable.

xi. Attach the probes attached to the source meter to the 9

xii. Now, go to github.com/Abhiavad/sun_sensor and download that file; it includes the codes mentioned in Annex A. Download the necessary Arduino Libraries and Python Packages by following the instructions in the README file.

xiii. Upload the .ino file to the Arduino using the Arduino IDE. Make sure to assign SPI pins as per the Arduino model.

xiv. Open the Python file and run it from the terminal. The tilt table set-up is ready; it automatically takes Short-circuit Current Readings if the remainder of the Tilt table Angle and 0.5 is less than 0.05 or greater than 0.45. These readings are automatically stored in an Excel file.

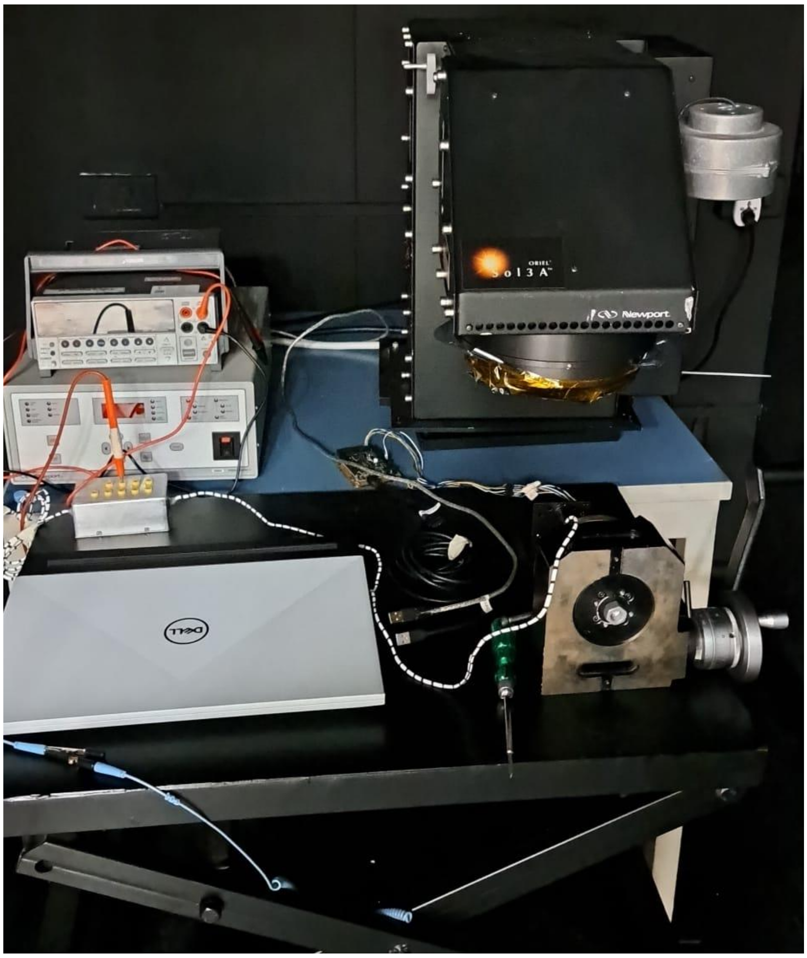
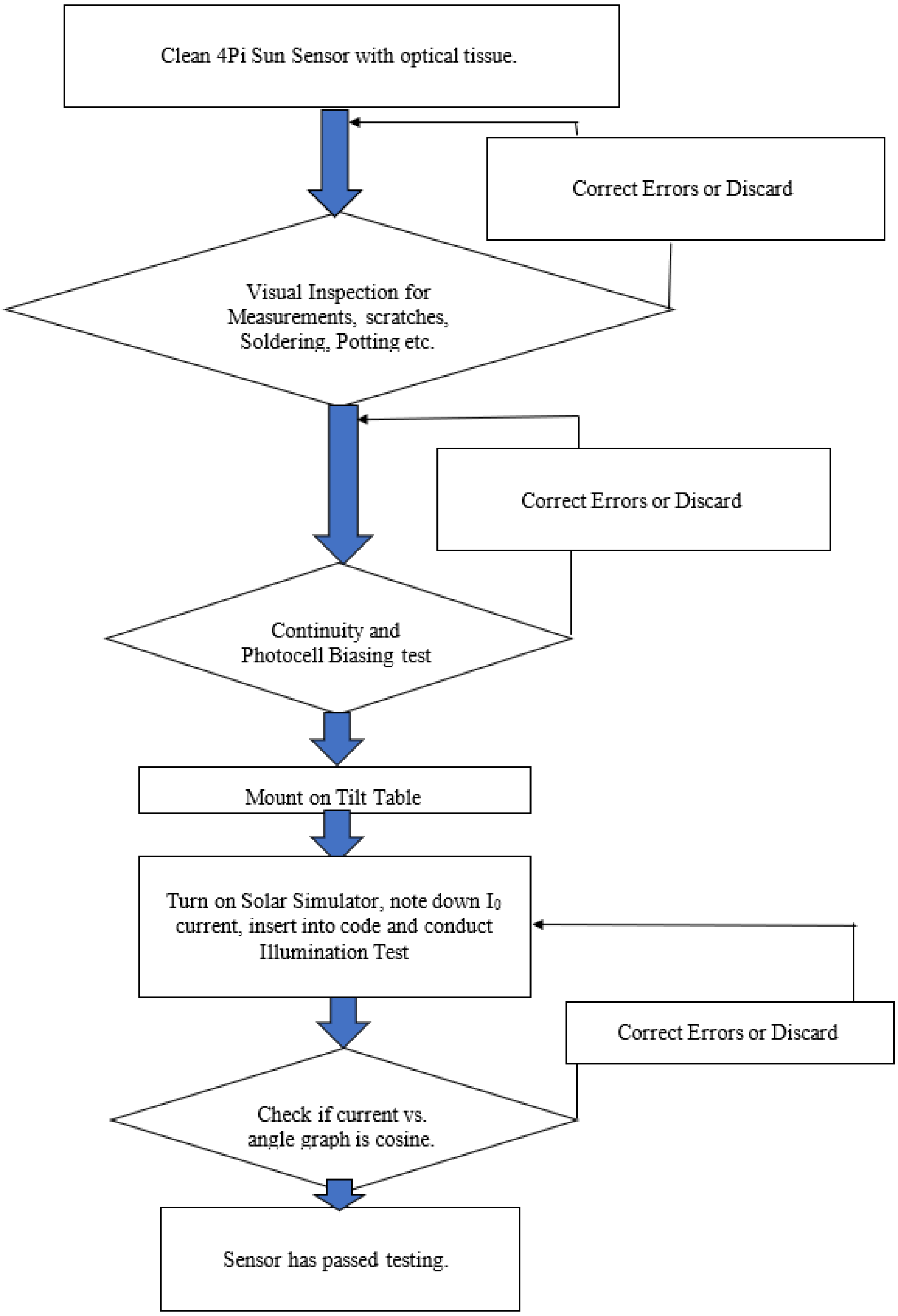


Figure 13. FPSS Illumination Test Set-Up

3.2.9 General Instructions for 4Pi Sun Sensor Testing



Flow-Chart 3. Instructions for 4Pi Sun Sensor Testing

CHAPTER 4: RESULTS

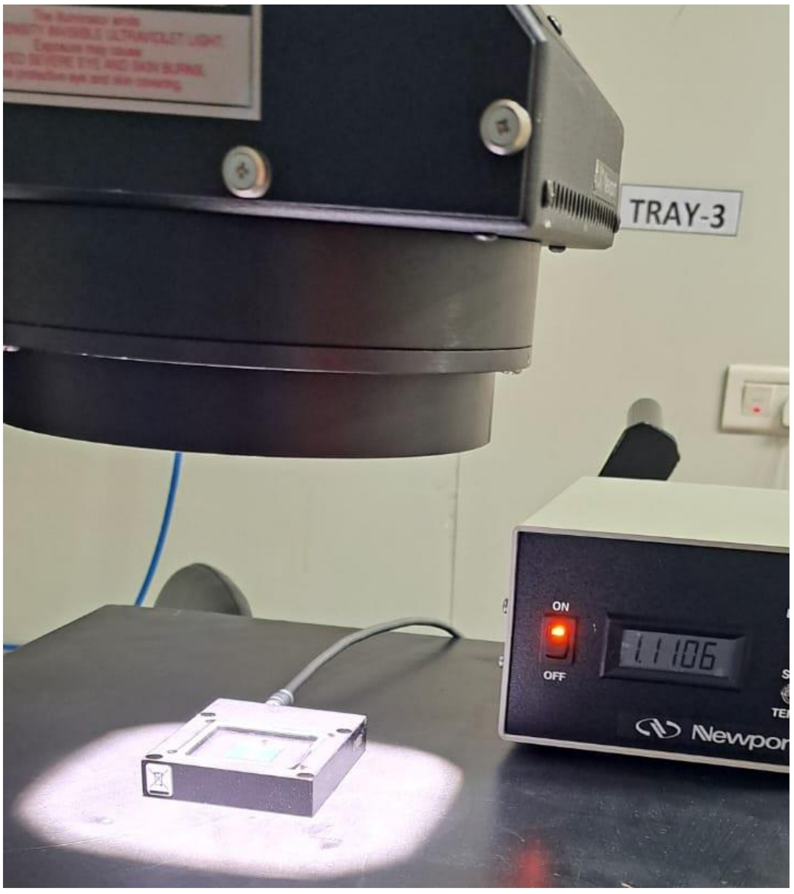
4.1 Solar Simulator

The solar simulator was tested using the Oriel 91150V Reference cell while operated at 495 Watts (the maximum allowed power per the user manual); the following was observed. 1 Sun = 1000 watts/m2 (Reference Cell calibrated for AM1.5G)

i. Power: 495 Watts, Distance from Lens: 15 cm, Air Mass Filter: Am0

   Result: 1.1 Sun

   Expected Result: 1.38 Sun (at least)



ii. Power: 495 Watts, Distance from Lens: 15cm, Air Mass Filter: AM1.5G

   Result: 0.89 Sun

   Expected Result: 1 Sun (at least)

iii. Power: 450 Watts, Distance from Lens: 15 cm, Air Mass Filter: 1.5G

Result: 0.79 Sun

Expected Result: 1 Sun

Result: Thus, it was concluded that the Xe-Arc Lamp was operating in a degraded state and needed to be replaced.

4.2 **Sun Sensor**

4.2.1 ***Photocell***

As the irradiance of the Solar Simulator was lower than 1 SUN, the Short-circuit observed was proportionately lower than the values observed by LEOS. After accounting for this error, the variation in current was within the expected 1% due to fluctuations in the solar simulator.

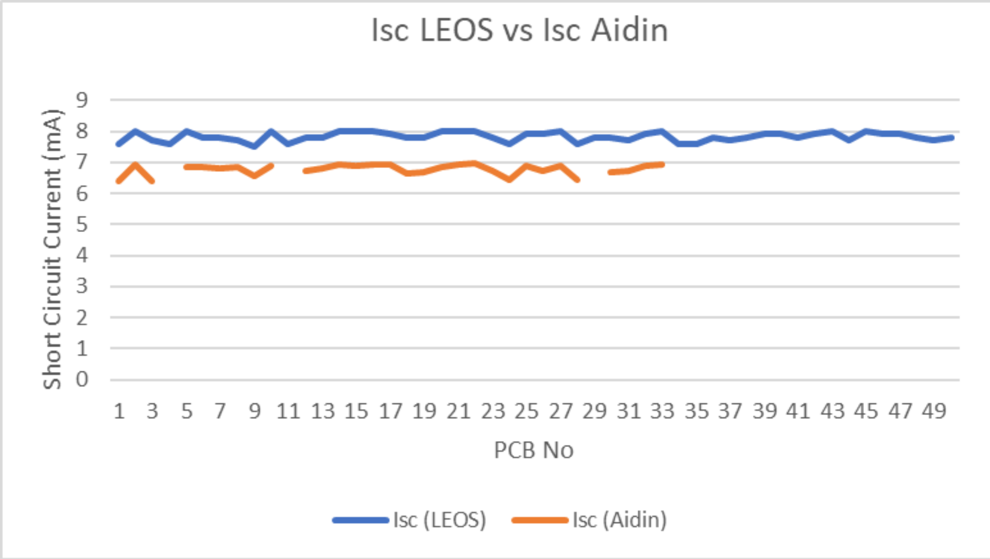


Figure 14. ISc LEOS vs Isc Aidin

4.2.2 ***Sun Sensor***

The following results were obtained upon Testing the Sun sensor's Faces A, B and C.

4.2.2.1 4Pi Sun Sensor Axis A Illumination Test Results

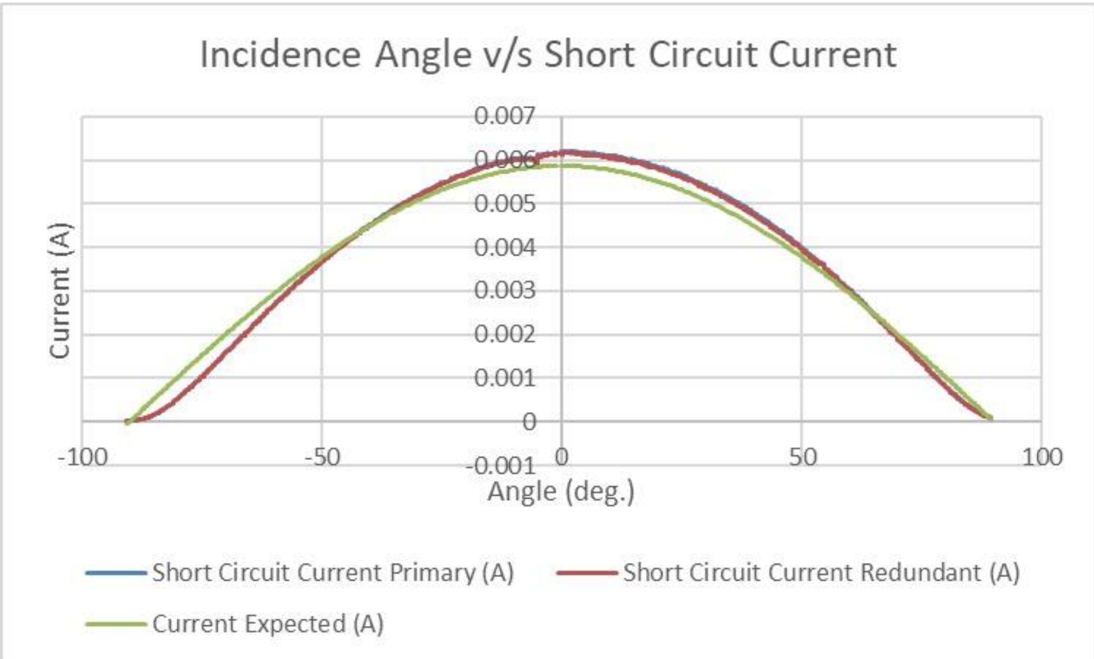


Figure 15 Axis A, Full Illumination Test Results

4.2.2.2 4Pi Sun Sensor Axis B Illumination Test Results

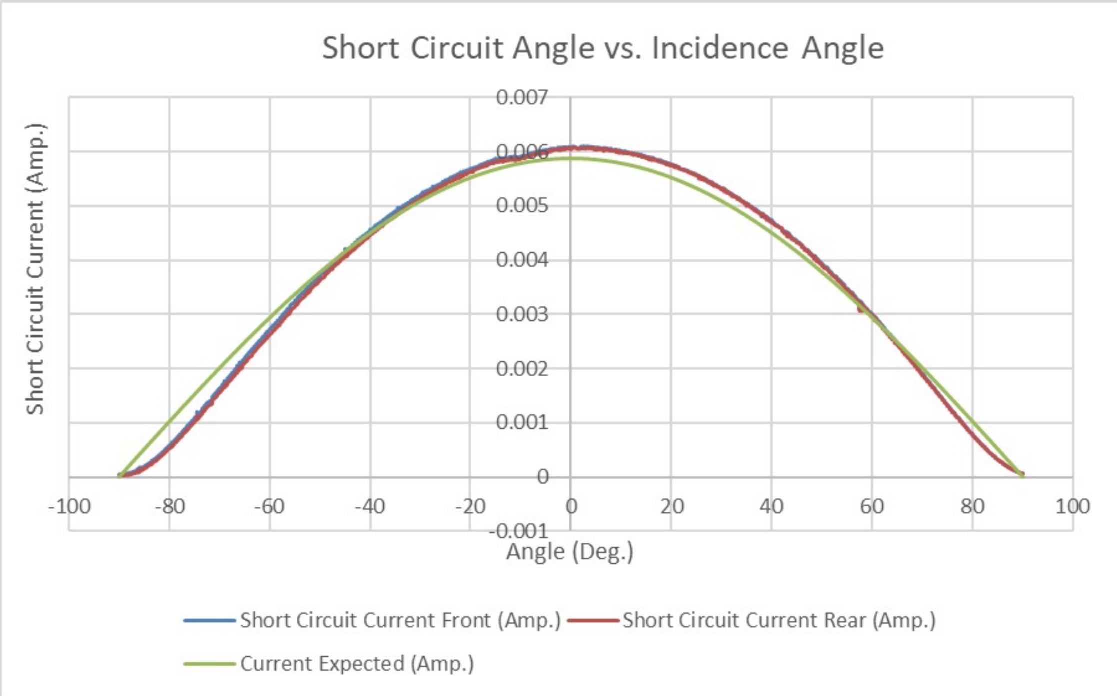


Figure 16 Axis B, Full Illumination Test Results

4.2.2.3 4Pi Sun Sensor Axis C Illumination Test Results

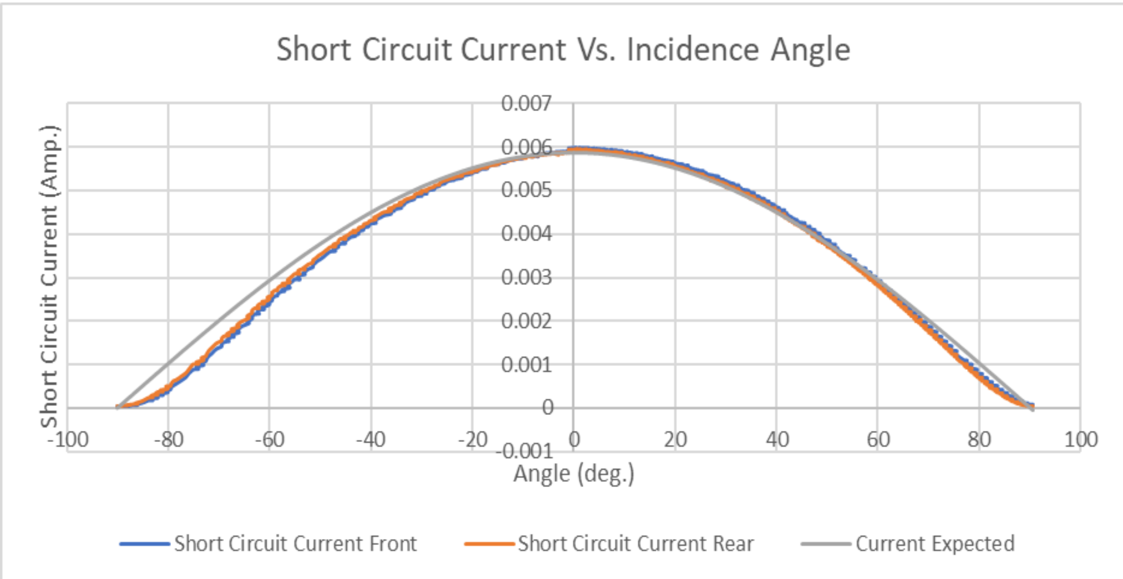


Figure 17. Axis C, Full Illumination Test Results

The "Short-circuit Current Front" refers to the readings from the primary cell, and the "Short-circuit Current Rear" refers to the readings from the redundant cell on the same face. The expected readings were calculated using the formula:

Equation 5. I_{SC} vs Angle relation

$$I_\theta = I_0 * \cos(\theta)$$

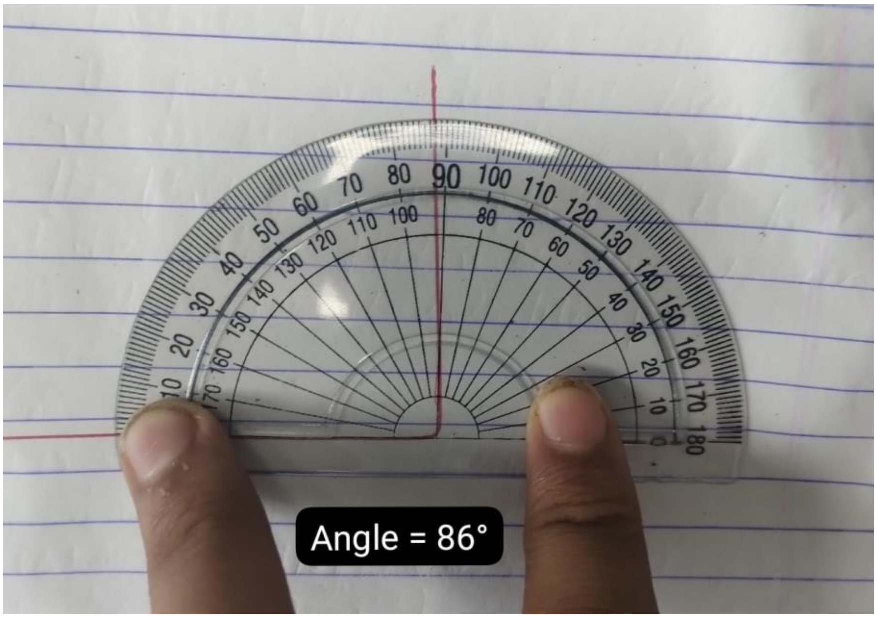


Figure 18. Tracing of the Tilt Table being measured

Where θ is the angle of incidence of light on the photocell, the deviations can be attributed to the slowly increasing temperature of the photocell and the unprecise bending of the L shape metal plate.

Thus, we can conclude that the sensor has passed the Illumination Test.

CHAPTER 5: CONCLUSION AND SCOPE FOR FUTURE WORK

5.1 CONCLUSION

This report presents two projects contributing to solar energy and aerospace technology by developing procedures for precisely testing and calibrating devices in these fields.

The first project, the development of an Illumination Testing Facility for precise solar simulation, provides insights into the practical implementation of solar simulation test facilities. The regular maintenance and calibration of the solar simulator are emphasised to ensure accurate simulation of the solar spectrum. This ensures reliable testing and characterisation of the performance of photovoltaic devices under various types of natural illumination.

The second project is implementing quality checks on a 4Pi Sun Sensor assembly essential for determining the orientation of a spacecraft with respect to the sun. It offers insight into testing and calibration procedures for space-grade ADCS hardware used in spacecrafts. Despite deviations from expected values, the sun sensor's illumination test validates its functionality and accuracy. These findings demonstrate how vital accurate and reliable testing is for such sensors.

Overall, these projects demonstrate innovation in aerospace engineering, particularly in ensuring the reliability and accuracy of the devices used.

5.2 Scope of Future Work

While this project provides insight into solar simulators and sun sensors, several areas offer further improvements and research opportunities. Some examples include:

i. Performance Optimisation of Sun Sensors: Optimisation of the performance of sun sensors by improving their sensitivity, accuracy, and reliability. This involves the development of new sensor designs and signal-processing algorithms.

ii. Environmental Testing: This report briefly mentioned environmental testing for sun sensors, including thermal and vibration tests. Future research can delve deeper into this area to study the impact of environmental factors on the performance and reliability of sun sensors. This can involve temperature cycling, thermal vacuum testing, and mechanical vibration testing.

iii. Integration with Attitude Control Systems: Integration of sun sensors with other sensors, such as star trackers and gyroscopes, to improve the accuracy and reliability of attitude determination through sensor fusion algorithms.

iv. Improved Calibration Techniques: Exploration of calibration methods for sun sensors to reduce measurement uncertainties, including investigation of in-situ calibration techniques.

v. Sensitivity Analysis: Analysis of digital sun sensors to determine the factors that affect their accuracy, such as temperature variations, external vibrations, and stray light on sensor measurements.

vi. Characterisation of Novel Materials: Investigate the efficiency, stability, and reliability of photovoltaic devices incorporating new materials, such as perovskite solar cells or organic photovoltaics. Assess their potential for commercialisation and identify optimisation strategies.

REFERENCES

6.1 **Journal / Conference Papers**

[1] "A Method for the Measurement of the Spectral Distribution of Solar Simulators Used for Photovoltaic Cell Calibration" by J.H. Lehman and R.C. Osborn: https://nvlpubs.nist.gov/nistpubs/jres/094/j94leh.pdf

[2] O'Keefe, S. (2012). A Digital Sun Sensor for Low-Cost CubeSat Attitude Determination. Retrieved from https://hanspeterschaub.info/Papers/grads/SteveOKeefe.pdf

[3] Kamata, S., & Hyodo, M. (1970). Onboard Sun Sensor for Three-axis Stabilized Satellites. Retrieved from https://ntrs.nasa.gov/api/citations/19710008281/downloads/19710008281.pdf

[4] O'Keefe, S. (2012). A Digital Sun Sensor for Low-Cost CubeSat Attitude Determination. Retrieved from https://hanspeterschaub.info/Papers/grads/SteveOKeefe.pdf

[5] "Fundamentals of Solar Simulators for Photovoltaic Testing" by Daryl Myers and Sarah Kurtz: https://www.nrel.gov/docs/fy10osti/47240.pdf

6.2 **Web**

[6] "Solar Simulator Selection Guide" by Newport Corporation: https://www.newport.com/medias/sys_master/images/images/hb4/h50/8790964396062/Solar-Simulator-Selection-Guide.pdf\

[7] Newport Corporation. (2021). SOL3A Solar Simulator. Retrieved from https://www.newport.com/p/94043A

[8] Newport Corporation. (2015, July 28). SOL3A Solar Simulator | Product Overview. [Video]. YouTube. https://www.youtube.com/watch?v=3LmFDg-7LOY&ab_channel=NewportCorpbyMKS

[9] Newport Corporation. (2019). SOL3A™ Solar Simulators User Manual. Retrieved from https://www.newport.com/medias/sys_master/software/software/h5a/h26/9342467440670/m940x3A.pdf

[10] NASA Small Satellite Technologies: Guidance, Navigation and Control. Retrieved from https://www.nasa.gov/smallsat-institute/sst-soa/guidance-navigation-and-control#_Toc120697547

[11] Newport Corporation. (n.d.). 91150V Reference Cell. Retrieved from https://www.newport.com/p/91150V

[12] National Renewable Energy Laboratory. (n.d.). Solar Spectra & Components Data: AM1.5. Retrieved from https://www.nrel.gov/grid/solar-resource/spectra-am1.5.html

[13] Babu, M. R., & Senthil, R. A. (2015). The Effect of Temperatures on the Silicon Solar Cell. Retrieved from https://www.researchgate.net/publication/283644148_The_Effect_of_Temperatures_on_the_Silicon_Solar_Cell

[14] Tektronix. (2011). Model 2400S SourceMeter User Manual. Retrieved from https://download.tek.com/manual/2400S-900-01_K-Sep2011_User.pdf

[15] Murata Manufacturing Co., Ltd. (n.d.). SCL3300-D01-PCB Datasheet. Retrieved from https://www.murata.com/~/media/webrenewal/products/sensor/pdf/datasheet/datasheet_scl3300-d01.ashx?la=en-us

[16] https://rdcu.be/dhbsa

[17] https://mmrc.caltech.edu/Cary%20UV-Vis%20Int.Sphere/Literature/Spectroscopy%20Jaramillo.pdf

[18] https://www.pveducation.org/pvcdrom/solar-cell-operation/short-circuit-current

[19] https://www.ee.uconn.edu/course-materials/crsdata/250ln14.pdf

ANNEXURE A (Sun Sensor)

7.1 Code for Arduino for the inclinometer:

```
#include <SPI.h>
#include <SCL3300.h>
#include <math.h>
#include <SimpleKalmanFilter.h>

SCL3300 inclinometer;
SimpleKalmanFilter kf(0.02, 0.02, 0.01);

double RawXAng, RawYAng, RawZAng, Tilt, Tilt_prev, Tilt_delta, filteredTilt = 0.00;
double dt=0.05;
int flag=0;

// Serial output refresh time
const long SERIAL_REFRESH_TIME = 100;
long refresh_time;

// Need the following define for SAMD processors
#if defined(ARDUINO_SAMD_ZERO) && defined(SERIAL_PORT_USBVIRTUAL)
#define Serial SERIAL_PORT_USBVIRTUAL
#endif

void setup() {
  Serial.begin(9600);
  delay(2000); //SAMD boards may need a long time to init SerialUSB
  Serial.println("Reading Raw register values from SCL3300 Inclinometer");
  if (inclinometer.begin() == false) {
    Serial.println("Murata SCL3300 inclinometer not connected.");
    while(1); //Freeze
  }
  inclinometer.setMode(4);

}

void loop() {
  if (inclinometer.available()) {
    //Get Tilt readings
    RawXAng=((inclinometer.sclData.AngX)/ 16384.00)*90.00;
    RawYAng=((inclinometer.sclData.AngY)/ 16384.00)*90.00;
    RawZAng=((inclinometer.sclData.AngZ)/ 16384.00)*90.00;
```

```
    // //Get acceleration readings
    double RawYAcc=(inclinometer.sclData.AccY)/12000.00;
    double RawZAcc=(inclinometer.sclData.AccZ)/12000.00;
    double Tilt=(180.00-
(acos(RawZAcc/(pow((pow(RawYAcc,2.00)+pow(RawZAcc,2.00)),0.5))))*(180.00/M_PI
));
    if (RawYAcc>=0)
      Tilt=360.00-Tilt;

    Tilt_delta=Tilt_prev-Tilt;

    if(Tilt_delta>300 || Tilt==0 || filteredTilt==0)
      flag=0;
     // calculate Tilt

    // Calculate Tilt
    if (flag==1)
      filteredTilt = kf.updateEstimate(Tilt);
    else if (flag==0){
      filteredTilt=kf.resetKalman(Tilt, 0.02, 0.02, 0.01);
      flag=1;
    }

    // Print stuff
    Tilt_prev=Tilt;
    Serial.print(filteredTilt);
    Serial.print(",");
    Serial.print(RawXAng);
    Serial.print(",");
    Serial.print(RawYAng);
    Serial.print(",");
    Serial.print(RawZAng);
    Serial.println("");

    delay(100);

  } else {
    inclinometer.reset();
  }
}
```

7.2 Python code to integrate Sourcemeter, Inclinometer and PC:

```
# Import necessary packages
from pymeasure.instruments.keithley import Keithley2400
import numpy as np
import pandas as pd
import time
import serial
# import matplotlib.pyplot as plt

# Define the data structure
data = []
i=0 #number of readings taken
j=0 #number of readings at current angle
no_tot_readings=10000
no_ang_readings=5

I_o=5.93 #Io value in mA (short-circuit current at 0 degrees, check and set it before testing)

# Configure the serial ports
#Arduino
ser = serial.Serial('COM3', 9600, timeout=1) #Check this at device manager and set it accordingly
response = ser.readline()
print('\n',response)
time.sleep(1)

def getLatestAngles():
    while ser.inWaiting() > 0:
        Angles = ser.readline()
    else:
        Angles = ser.readline()
    return Angles



#Connect and configure the Keithley
sourcemeter = Keithley2400("ASRL4::INSTR") #Check this at device manager and set it accordingly
print('\n',sourcemeter.id)
sourcemeter.reset()
sourcemeter.apply_voltage(voltage_range=0,compliance_current=0.01)
sourcemeter.measure_current(nplc=1,current=0.01,auto_range=True)
```

```
time.sleep(1) # wait here to give the instrument time to react
sourcemeter.beep(frequency=100000,duration=1)

# Loop
while True:
   # Read the sensor data from the Arduino
   Angles = getLatestAngles().decode("utf-8").strip()
   Tilt, x, y, z = Angles.split(',')
   Tilt=float(Tilt)
   x = float(x)
   y = float(y)
   z = float(z)

   if (Tilt%(0.5)>=0.45 or Tilt%(0.5)<=0.05) and i<no_tot_readings and j<no_ang_readings:
      #rn this is set at 0.05 degrees above or below 0.5 degrees increments
      i=i+1
      j=j+1

      #Timestamp
      timestamp = time.strftime('%Y-%m-%d %H:%M:%S')

      #Make Keithley Measurements
      #use front terminals for primary cell
      sourcemeter.use_front_terminals()
      sourcemeter.enable_source()
      sourcemeter.beep(frequency=1000,duration=0.01)
      time.sleep(0.5)
      current_measured_front=float(sourcemeter.current)*1000
      sourcemeter.disable_source()

      #use rear terminals for redundant cell
      sourcemeter.use_rear_terminals()
      sourcemeter.enable_source()
      sourcemeter.beep(frequency=1000,duration=0.01)
      time.sleep(0.5)
      current_measured_rear=float(sourcemeter.current)*1000
      sourcemeter.disable_source()

      #calculate expected current using Io value
      current_expected = I_o*np.cos(Tilt*np.pi/180.00)
```

```
    #Print for refernce
    print(‘\nTilt:’,Tilt,’,    x:’,x,’,    y:’,y,’,    z:’,z,’,    i:’,i,’,    j:’,j,’,    time:’,timestamp,’,
cur_frnt:’,current_measured_front,’,                    cur_bck:’,current_measured_rear,’,
cur_exp:’,current_expected)
    #store the data with a timestamp

data.append([Tilt,x,y,z,timestamp,current_measured_front,current_measured_rear,current_
expected])
    df = pd.DataFrame(data, columns=[‘Tilt (deg.)’,’ x (deg.)’,’ y (deg.)’,’ z (deg.)’,
‘Timestamp’, ‘Short-circuit Current Primary (mA)’, ‘Short-circuit Current Redundant
(mA)’,’ Current Expected (mA)’])

    #RESET THIS AFTER EVERY SET OF READINGS TO NOT OVERWRITE
PREVIOUS READINGS
    df.to_excel(".\Results\july07_2023_ADN05_AxisB_2.xlsx", index=False)
    df.to_csv(".\Results\july07_2023_ADN05_AxisB_2.csv")

    # df.plot(x='Y’,y=[‘Short-circuit Current Front’, ‘Short-circuit Current Rear’,’ Current
Expected’],title= “Current(A) vs Angle(deg)”, xlabel= “Angle(deg)”, ylabel= “Current
(A)”, legend=([‘Short-circuit Current Front’, ‘Short-circuit Current Rear’,’ Current
Expected’]))

  elif i>=no_tot_readings:
    ser.close()
    sourcemeter.shutdown()
    exit()
  elif j>=no_ang_readings:
    sourcemeter.beep(frequency=2000,duration=1)
    time.sleep(2)
    j=0
  else:
    print('\nTilt', Tilt,', x:',x,', y:',y,', z:',z,', i:',', i:',i,', j:',j)
    time.sleep(0.1)
    j=0
```

ANNEXURE B (Testing)

Table 2. PCB Continuity Check

PCB No.:					
From		**To**		**Results**	
PCB	**Pad No.**	**PCB**	**Pad No.**	**Expected**	**Observed**
9 Pin PCB	Connector Pad 1	9 Pin PCB	Connector Pad 9	Yes	
9 Pin PCB	Connector Pad 8	9 Pin PCB	Mounting Hole Pad 3	Yes	
9 Pin PCB	Connector Pad 8	9 Pin PCB	Mounting Hole Pad 5	Yes	
9 Pin PCB	Connector Pad 8	9 Pin PCB	Mounting Hole Pad 6	Yes	
Axis-A PCB	Mounting Hole Pad 3	9 Pin PCB	Connector Pad 8	Yes	
Axis-A PCB	Main Anode Pad	Axis-A PCB	Redundant Anode	Yes	
Axis-A PCB	Main Anode Pad	9 Pin PCB	Connector Pad 1	Yes	
Axis-A PCB	Main Cathode Pad	9 Pin PCB	Connector Pad 2	Yes	
Axis-A PCB	Redundant Cathode Pad	9 Pin PCB	Connector Pad 3	Yes	
Axis-B PCB	Mounting Hole Pad 1	9 Pin PCB	Connector Pad 8	Yes	
Axis-B PCB	Main Anode Pad	Axis-B PCB	Redundant Anode	Yes	
Axis-B PCB	Main Anode Pad	9 Pin PCB	Connector Pad 1	Yes	
Axis-B PCB	Main Cathode Pad	9 Pin PCB	Connector Pad 4	Yes	
Axis-B PCB	Redundant Cathode Pad	9 Pin PCB	Connector Pad 5	Yes	
Axis-C PCB	Mounting Hole Pad 3	9 Pin PCB	Connector Pad 8	Yes	
Axis-C PCB	Main Anode Pad	Axis-C PCB	Redundant Anode	Yes	
Axis-C PCB	Main Anode Pad	9 Pin PCB	Connector Pad 1	Yes	
Axis-C PCB	Main Cathode Pad	9 Pin PCB	Connector Pad 6	Yes	

Axis-C PCB	Redundant Cathode Pad	9 Pin PCB	Connector Pad 7	Yes	
9 Pin PCB	Connector Pad 1	9 Pin PCB	Connector Pad 2	No	
9 Pin PCB	Connector Pad 1	9 Pin PCB	Connector Pad 3	No	
9 Pin PCB	Connector Pad 1	9 Pin PCB	Connector Pad 4	No	
9 Pin PCB	Connector Pad 1	9 Pin PCB	Connector Pad 5	No	
9 Pin PCB	Connector Pad 1	9 Pin PCB	Connector Pad 6	No	
9 Pin PCB	Connector Pad 1	9 Pin PCB	Connector Pad 7	No	
9 Pin PCB	Connector Pad 1	9 Pin PCB	Connector Pad 8	No	
9 Pin PCB	Connector Pad 2	9 Pin PCB	Connector Pad 3	No	
9 Pin PCB	Connector Pad 2	9 Pin PCB	Connector Pad 4	No	
9 Pin PCB	Connector Pad 2	9 Pin PCB	Connector Pad 5	No	
9 Pin PCB	Connector Pad 2	9 Pin PCB	Connector Pad 6	No	
9 Pin PCB	Connector Pad 2	9 Pin PCB	Connector Pad 7	No	
9 Pin PCB	Connector Pad 2	9 Pin PCB	Connector Pad 8	No	
9 Pin PCB	Connector Pad 3	9 Pin PCB	Connector Pad 4	No	
9 Pin PCB	Connector Pad 3	9 Pin PCB	Connector Pad 5	No	
9 Pin PCB	Connector Pad 3	9 Pin PCB	Connector Pad 6	No	
9 Pin PCB	Connector Pad 3	9 Pin PCB	Connector Pad 7	No	
9 Pin PCB	Connector Pad 3	9 Pin PCB	Connector Pad 8	No	
9 Pin PCB	Connector Pad 4	9 Pin PCB	Connector Pad 5	No	
9 Pin PCB	Connector Pad 4	9 Pin PCB	Connector Pad 6	No	
9 Pin PCB	Connector Pad 4	9 Pin PCB	Connector Pad 7	No	
9 Pin PCB	Connector Pad 4	9 Pin PCB	Connector Pad 8	No	
9 Pin PCB	Connector Pad 5	9 Pin PCB	Connector Pad 6	No	
9 Pin PCB	Connector Pad 5	9 Pin PCB	Connector Pad 7	No	
9 Pin PCB	Connector Pad 5	9 Pin PCB	Connector Pad 8	No	
9 Pin PCB	Connector Pad 6	9 Pin PCB	Connector Pad 7	No	
9 Pin PCB	Connector Pad 6	9 Pin PCB	Connector Pad 8	No	
9 Pin PCB	Connector Pad 7	9 Pin PCB	Connector Pad 8	No	

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41	S. Irwan Sulaiman. "Analysis of fitted Suns-V/sub oc/ curves using two-diode model", 2004 IEEE International Conference on Semiconductor Electronics SMELEC-04, 2004 Publication	<1%

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