

Accurate performance measurement of silicon solar cells

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Declaration

This PhD thesis contains no material that has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge and belief, no material previously published or written by another person has been included in this thesis, except where due reference is made in the text.

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Abstract

Performance measurement is an important part of the solar cell manufacturing process. Two classes of measurement can be considered: accurate calibration – for the creation of reference cells and the setting of records; and routine measurement – for cell sorting and process improvement. This work describes techniques that address both issues – an accurate calibration technique using natural sunlight, and a routine measurement technique using a xenon flashlamp. Both techniques are low-cost, yet in combination they achieve very good accuracy.

The light source is very important when calibrating solar cells. Commonly used light sources – good quality solar simulators – are expensive and frequently inaccurate. This work shows that testing of solar cells under natural sunlight is simpler, cheaper, more accurate, and more reliable than all but the most careful simulator measurements. Periodic outdoor calibrations under natural sunlight can therefore eliminate the need for an expensive solar simulator and greatly reduce the need for calibration at standards labs.

Solar spectra generated with the model SMARTS2 show that the direct solar spectrum, under clear sky and low air-mass conditions, is an excellent match to the AM1.5G standard spectrum – dramatically better than simulators costing US\$20,000 or more. Millions of simulations of a broad range of silicon cells (efficiencies 6-25%) under the modelled direct spectra show that measurement errors of less than 5% are achievable. This is comparable to the reproducibility of results achieved by national standards laboratories. Climate data shows that the required atmospheric conditions occur commonly in summer for all but polar latitudes. Experimental verification of the modelling is encouraging but not yet conclusive. The outcome of the research is a testing ‘recipe’ that uses low-cost equipment and gives an estimate of measurement uncertainty.

For routine measurement of large numbers of solar cells, an indoor solar simulator is essential. While simulators can introduce large measurement errors, most of these errors can be eliminated by using a reference cell that is well matched to the test cells. The use of a simpler, lower-cost simulator is possible since reference cells can easily be calibrated under natural sunlight. The second half of this work describes the design of a low cost flash-lamp solar simulator.

Most conventional flash testing systems maintain constant light intensity while rapidly sweeping out the I-V curve of the cell. This method has two disadvantages – it requires a flash that is specially engineered to produce constant light output, and the rapid change in cell bias-voltage causes transient errors. The new approach developed in this work essentially does the reverse – it maintains a constant bias voltage on the cell while allowing the light level to vary. This allows the use of a commercial xenon flash, and reduces sensitivity to transient errors. In addition, it extracts a family of I-V curves at different light intensities, whereas the conventional approach only extracts a single I-V curve. The new design has been implemented, using commercial-off-the-shelf equipment costing less than US\$10,000, and it works well. One of these systems is in use at the Centre for Sustainable Energy Systems, ANU, where it has tested tens of thousands of concentrator cells. A second system has been sold to BP Solar, UK.

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Glossary and Symbols

This section defines commonly used terms and symbols (not all terms and symbols used in this work are defined here – those that are only used briefly are defined at the point of use).

Terms

air mass, AM – the relative amount of atmosphere the sunlight must pass through before reaching sea level. If the sun is directly overhead, AM = 1.

ELH lamp – a projector lamp commonly used to build cheap solar simulators

irradiance, E – the flux of radiant energy per unit area of collector (normal to the direction of flow of radiant energy). Typical units, W/m².

light intensity, E – loosely equivalent to irradiance. In this work, usually irradiance measured with a solar cell. Typical units, suns.

pyranometer – an instrument that measures global irradiance, using a thermal detector

pyrheliometer – an instrument that measures direct-beam irradiance, using a thermal detector

quadrature, summing in – n individual error sources, e_n , combine according to

$$e_{total} = \sqrt{e_1^2 + e_2^2 + \dots + e_n^2}$$

radiometer – an instrument that measures irradiance by absorbing light on a blackened surfaced and measuring resulting heat flux

reference detector – a device used to measure light intensity. Can be either a solar cell or a thermal detector

repeatability – the variation within a group of measurements, taken in rapid succession, and using an identical measurement system

reproducibility – the variation within a group of measurements, taken over a long time period and/or using different techniques.

spectral irradiance, $E(\lambda)$ – the flux of radiant energy of a given wavelength per unit area. Integration of spectral irradiance over wavelength gives irradiance. Typical units, W/m²/μm.

thermal detector – see radiometer

uncertainty – a probabilistic estimate of the range of values that the error could take. Subtly different to error

uniformity – the variation of light intensity as a function of position in the illuminated area

Symbols

AM – air mass

AM0 – standard spectrum for solar radiation in space

AM1.5D (ASTM-E891) – standard spectrum for terrestrial direct-beam solar radiation

AM1.5G (ASTM-E892) – standard spectrum for terrestrial global solar radiation

ASTM-E891 – see AM1.5D

ASTM-E892 – see AM1.5G

β – turbidity

E – irradiance or light intensity.

$E(\lambda)$ – spectral irradiance

ϵ_M – the error in a measurement due to spectral mismatch M , ($\epsilon_M = |1-M|$)

λ – wavelength of light

M – spectral mismatch.

RH – relative humidity

S – spectral response

T – temperature, or optical transmittance

w – precipitable water

X – concentration factor. Eg 30X = 30 suns.

Z – zenith angle. Angle between the vertical and the line of sight to the sun. ($Z = 90^\circ$ when sun is approximately on the horizon).

1 Introduction



Figure 1-1: 20kW PV/Trough demonstration system at Rockingham, Western Australia. The array is ~100m long.

1.1 Motivation – PV/Trough concentrator system

Costs must be reduced for the photovoltaic industry to expand. Concentrator systems are one route to achieve this. By collecting light with cheap optics, and focusing it on a small area of high performance solar cells, the overall cost of the system can be reduced. This concept is the basis of the PV/Trough concentrator system, which is one of the major research projects at the Centre for Sustainable Energy Systems, ANU. The project has a strong commercial emphasis, with Solahart Industries as the commercial partner.

The PV/Trough system is a medium concentration system (about 30X geometrical), based on line-focus parabolic mirrors. The largest development of the technology is a 20 kW demonstration system at Rockingham, Western Australia (figure 1-1). Each mirror has an area of approximately 2 m^2 , and produces an average light intensity, at the cells, of about 20 suns. The mirrors track the sun in two axes. The cells are mounted on air-cooled receivers. The receivers are 1.7 m long and contain 31 cells, giving approximately 20V/12A at 20 suns. A receiver is shown in figure 1-2.

A similar system, the EUCLIDES project, is under development in Europe (Luque, Sala et al. 1997).



Figure 1-2: An air-cooled PV/Trough receiver (1.7m long). 31 cells produce approximately 20V/12A at 20X.

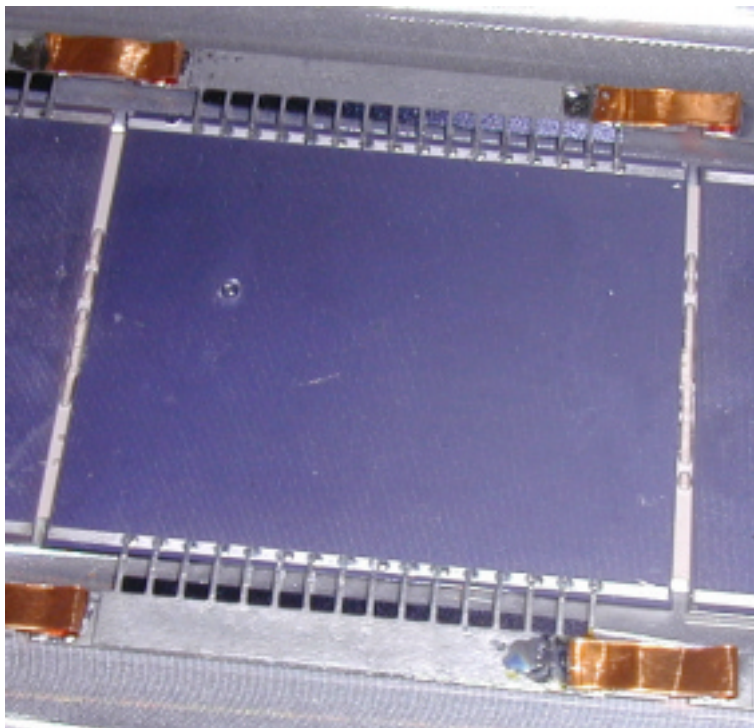


Figure 1-3: An ANU concentrator cell (4 x 5 cm), tabbed and encapsulated.

A water-cooled version of the PV/Trough system, the Combined Heat and Power System (CHAPS), is also in development. It produces both electricity, and hot water suitable for domestic use.

The cells were developed and produced at ANU. They are made by a novel process that use photolithography to achieve high efficiency, but has no aligned steps. Cell efficiencies are above 20% at 20-30 suns. One of the cells is shown in figure 1-3.

The research described in this thesis was motivated by the need to test cells for the PV/Trough system. When operating under continuous concentrated light, the cells produce large amounts of waste heat and have to be mounted on an effective heatsink. For production testing of bare cells, this would be highly inconvenient. Fortunately, the problem can be avoided by using a flash tester, which only illuminates the cell with a brief pulse of light. Commercial flash testers for 1-sun cells are widely available, but for concentrator cells few are available. In addition, the commercial 1-sun systems are quite expensive – a recent review of commercial systems (Schmela 2001) quotes prices of US\$60,000 to US\$270,000.

Consequently, we decided to develop our own flash testing system. The resulting design forms the second half of this work, chapter 3. The flash testing system required some means to calibrate reference cells. To resolve this issue, a calibration method that uses natural sunlight was developed. The natural sunlight calibration procedure forms the first half of this work, chapter 2.

The remainder of this introduction gives a very brief overview of how solar cells work and how to test them. It also summarises the two sections of the research.

1.2 Design and operation of solar cells

A solar cell is a semiconductor device that converts light into electricity. A diagram of a typical high performance silicon solar cell is shown in figure 1-4. The essential features of a solar cell are: an optical design to maximise the absorption of light, a pn junction to convert the absorbed light into electrical current, and metal contacts to extract the current.

The optical features on solar cells consist of anti-reflection coatings and light trapping features. Anti-reflection coatings reduce reflection from the front surface. In the diagram, this function is served by an oxide layer (SiO_2) of carefully chosen thickness. Light trapping is desirable because silicon is an indirect bandgap semiconductor, and so a poor absorber of long wavelength light. In the diagram, light trapping is provided by the inverted pyramids on the front surface, and the reflective internal surface at the rear.

The pn function is formed by introducing impurities (dopants) into the pure silicon. Due to the doping, the Fermi levels are different in the p and n type materials. When a photon is absorbed it excites an electron into the conduction band. This creates an electron and a hole that are both in a high-energy state and free to move. The minority carriers (electrons in the p-type material, and holes in the n-type material) generated this way can drop to a lower energy state by physically moving to the material of opposite polarity. This is the desired operation – the movement of charge will cause an electrical current to flow in an external circuit. Alternatively, the excited carrier can drop back to a low energy state without physically moving, releasing the excess

energy as heat. This process, recombination, is undesirable as the photon energy is wasted.

The amount of recombination depends on the electronic quality of the material and the design of the cell. Recombination in the bulk of the silicon can be minimised by using very pure silicon with very few defects in the crystal structure. Recombination at the surfaces can be minimised by passivating the surface – in the diagram, this function is performed by the oxide layer. Metal contacts to the silicon are particularly bad recombination sites, so the area of contact is kept to a minimum and heavy doping is included directly beneath the metal contacts.

The illumination generates a current uniformly over the area of the cell. To reach the external circuit, this photocurrent has to flow laterally through the silicon, then into, and along, the metal fingers. The resistance of these elements causes losses.

The major difference between concentrator and 1-sun cells is that concentrator cells operate at much higher current densities, and so are designed to have much lower series resistance. They also tend to be higher performance – since the area of cells is greatly reduced compared to a 1-sun system, system economics favour using expensive, high efficiency cells. The higher performance is achieved by using higher quality starting materials and more elaborate processing. In addition, solar cells are inherently more efficient under concentration.

The electrical characteristic of a solar cell is usually described by an I-V curve, an example of which is shown in figure 1-5. The I-V curve gives the important external characteristics of the cell – efficiency, current, voltage, etc. It also gives information about the internal operation of the cell.

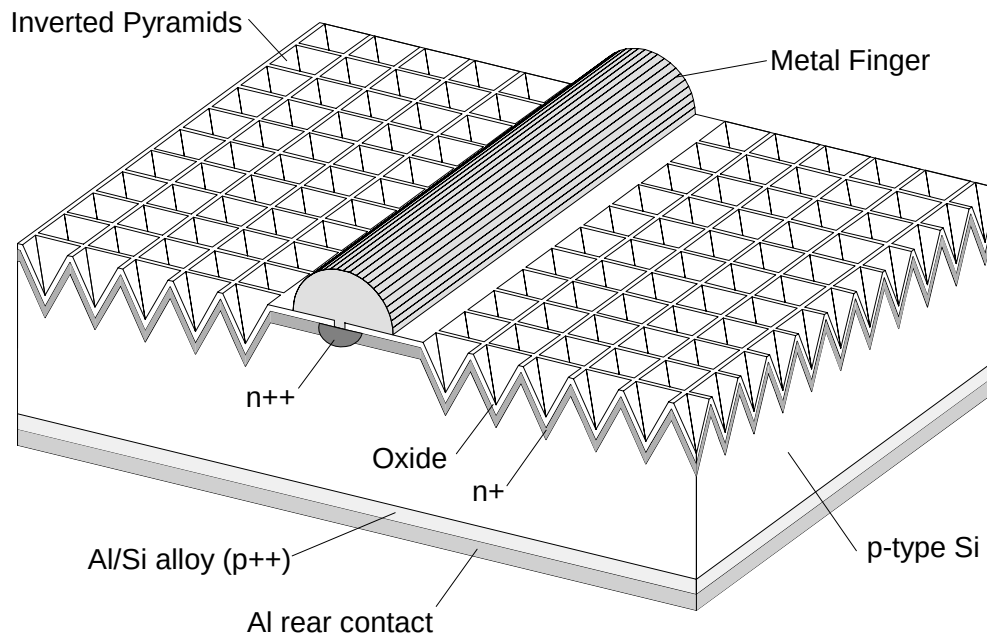


Figure 1-4: Construction of a typical high performance silicon solar cell

The efficiency of a solar cell is defined as electrical power out divided by light power in:

$$\eta = \frac{V_{mp} I_{mp}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}} \quad (1-1)$$

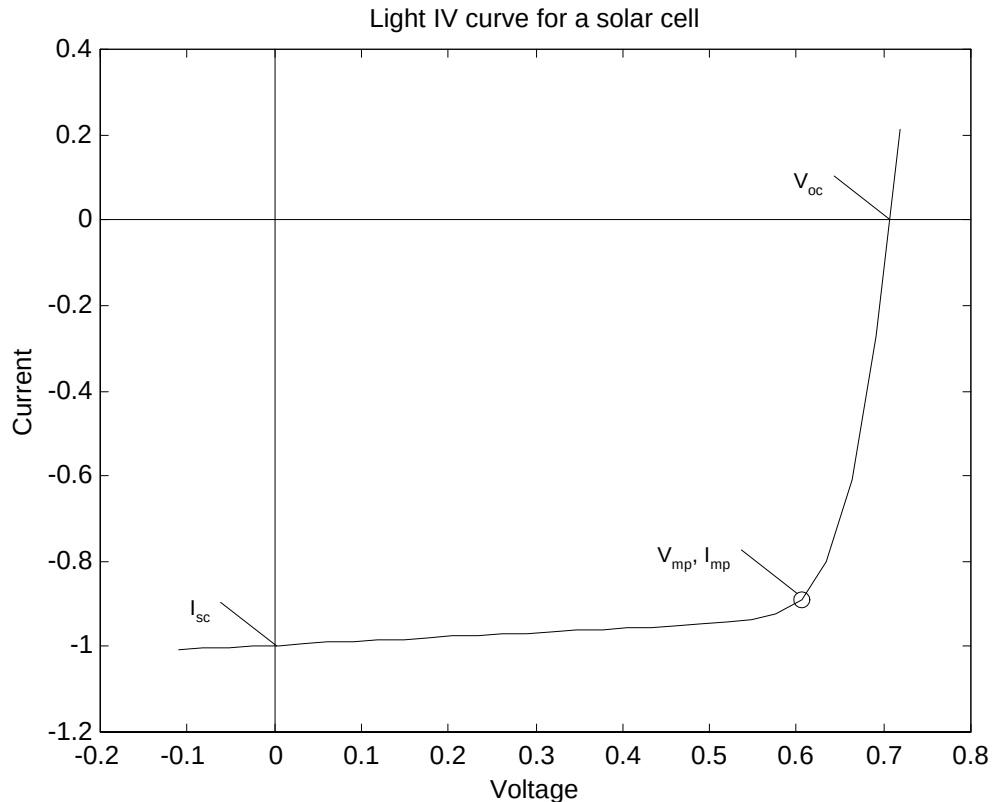


Figure 1-5: I-V curve for a typical solar cell. Open circuit voltage (V_{oc}), short circuit current (I_{sc}), and maximum power voltage and current (V_{mp} , I_{mp}) are shown.

1.3 Measurement of solar cells

A solar cell converts light into electricity. The most important measurement for a cell is therefore its electrical behaviour under illumination. This is the light I-V curve. Many other measurements are possible – for example diagnostic measurements such as spectral response or minority carrier lifetime, or accelerated ageing measurements – but this work deals only with measurement of light I-V curves.

There are many reasons to measure cells, including: for cell sorting in production, to diagnose cell operation for process improvement, to establish record efficiencies to compare to other technologies, and to predict cell performance in the field. The vast majority of measurements are performed for sorting and process improvement. For this purpose, the priorities are speed and convenience and only a relative measurement is required. Reliable relative cell measurement does not require a sophisticated and expensive measurement system. In addition, with an accurately calibrated reference

cell, relative measurement becomes equivalent to absolute measurement. Accurate measurements are required for making reference cells and setting records. These sorts of measurements are not made often, so convenience is less of an issue. The first half of this thesis addresses the latter problem, accurate calibration, and the second half of this thesis addresses the former problem, convenient relative measurement.

Measuring solar cells requires several pieces of equipment, all of which can introduce measurement errors. The most expensive component, and the greatest source of measurement error, is the light source. An ideal light source's output would be perfectly uniform over the testing area, have an exactly known intensity, be a perfect match to the appropriate standard spectrum, and always be available. Of course, no such light source exists. With practical light sources (almost always solar simulators), uniformity, stability, and spectral quality all introduce significant errors. For high measurement accuracy it is necessary to measure the spectrum of the lamp and the spectral responses of the test and reference cells. These measurements are expensive and require elaborate calibration.

A reference detector is frequently used to measure the light intensity. If this reference detector is closely matched to the cell being tested, problems with the light source can be largely eliminated. If the reference detector is the same size as the test cell, errors due to non-uniformity will be greatly reduced. If the reference detector has a similar spectral response to the test cell, errors due to the non-ideal spectrum of the light source will be greatly reduced. Consequently, if a convenient means of calibrating reference cells is available, a lower quality light source can be used.

Solar cell characterisation requires electrical measurements, which can also introduce errors. The arrangement of electrical contacts to the cell must be thought out carefully, or else serious measurement errors can result. A variable load for the cell is needed, to sweep out the I-V curve, and transient errors can arise if this load varies too rapidly. Current and voltage meters are needed to measure the I-V curve (though the accuracy of these meters is rarely a limitation).

The temperature of the cell must be controlled, as the performance of solar cells varies with temperature.

Finally, the cell area must be measured for efficiency measurements. It is sometimes tricky to decide exactly what is the active area of the device.

When measuring solar cells, standards laboratories and solar cell manufacturers have different requirements. Standards laboratories have to measure a very diverse range of cells and are required to achieve high accuracy. In this situation, the use of matched reference cells is very difficult. Solar cell manufacturers (research or production), on the other hand, tend to produce many very similar cells. This makes the use of matched reference cells much easier. Consequently, equipment and procedures that are essential for a standards laboratory may be unnecessarily complex for a cell manufacturer.

1.4 Accurate measurement, at low cost, of silicon solar cells

The measurement of solar cells to the highest accuracy possible requires very expensive equipment, and a great deal of care to maintain calibrations. Few groups, other than standards labs, can afford this level of sophistication. The equipment used by most solar cell groups, in contrast, is simple but frequently inaccurate. This work

addresses the problem of improving the accuracy of solar cell measurement while still using cheap, easily obtained equipment.

The research described in this thesis addresses two problems: how to calibrate cells cheaply and conveniently, and how to make a flash lamp solar simulator at low cost. The two problems are interrelated – if a cheap, convenient calibration method is available, then the design of the simulator can be simplified, thereby reducing its cost.

Some aspects of the research are specific to silicon solar cell technology. However, the results are more generally applicable and could be used for other solar cell technologies. The occasions when results are not generally applicable are highlighted.

1.4.1 Natural sunlight calibration

A review of previous work on accurate cell calibration procedures showed that natural sunlight should be an excellent light source. This led to the questions: how accurate can measurement under natural sunlight be? What are the important atmospheric conditions? Can they be measured without specialised equipment? And how often do suitable conditions occur?

The accuracy of calibration under natural sunlight was investigated by computer modelling. Solar spectra were simulated with the model SMARTS2 for a range of low air mass, clear sky conditions. A group of solar cells, representative of almost any crystalline silicon cell likely to be made (efficiencies 6-25%), were then simulated under the SMARTS2 modelled solar spectra. Over 1 million cell/spectrum combinations were tried. The spectral mismatch error was then calculated for each cell/spectrum combination. The worst-case spectral mismatch error was then plotted as a function of the important atmospheric conditions – air mass, turbidity, and precipitable water.

Simple techniques for measuring the important atmospheric conditions were also identified. These techniques only require measurements of the time, location, relative humidity, air temperature, and direct beam irradiance. No expensive or specialised equipment is needed. Experimental verification of the modelling was also conducted.

The simulations show that the direct solar spectrum under clear sky, low air mass conditions is an excellent match to the standard AM1.5G spectrum - dramatically better than simulators costing US\$20k or more. Solar cell measurement errors of less than 5% should be achievable when using a pyrheliometer to measure irradiance. This is comparable to the reproducibility of results achieved by standards laboratories. Climate data shows that the required atmospheric conditions occur commonly in summer for all but polar latitudes.

This work shows that calibration of solar cells using natural sunlight is convenient and accurate. Consequently, it is easy to make well-matched reference cells for use with an indoor simulator.

1.4.2 Constant voltage flash tester

Convenient measurement of large numbers of concentrator cells requires a flash-lamp solar simulator. A variety of flash testers are available commercially. However, the majority are designed for 1-sun use, and are expensive. Much of the cost is in the custom designed flash unit. In addition, some flash testers also cause transient errors in measurements. The objective of this research was to build a low cost flash tester

that was suitable for testing concentrator cells at approximately 30 suns, and did not suffer from transient errors.

The resulting flash tester design works well. The flash, a low cost commercial xenon strobe, has $\pm 2\%$ uniformity over the cell area at 30 suns. When used to measure any of the ANU concentrator cells, spectral mismatch is below 2.5%. The system produces a family of I-V curves over a decade range of light intensity, rather than the single I-V curve produced by most systems. This allows cell operation to be diagnosed more accurately.

Theoretical analysis of transient errors in flash testing shows that transient errors are largely caused by rapid changes in the cell bias voltage. Existing commercial designs that use constant current loads, or rapidly swept voltage loads, are therefore susceptible to transient errors. The system developed in this work largely eliminates transient errors by using a constant voltage bias circuit for the cell. The circuit used to implement the constant voltage concept, a capacitive load, is cheap and works well for cell currents below a few amps. However, for large currents it is not so effective.

The constant voltage flash tester has been used extensively:

- It has been used to test tens of thousands of concentrator cells produced at ANU for the PV/Trough project.
- One of these systems has been sold to BP Solar, UK. BP Solar uses their system for testing Laser Grooved Buried Grid concentrator cells, and conventional 1-sun cells.

2 Calibration of silicon solar cells under natural sunlight



Figure 2-1: Calibration of solar cells under natural sunlight at Mt Ginini (1762 m), ACT, Australia. This picture was taken during experimental verification of the method, at a high altitude site.

2.1 Introduction

Accurate measurement of solar cells is crucial, both to improve technologies and to predict performance in operation.

The majority of cells are measured for sorting or process improvement. For this purpose, relative measurements are adequate. The main concern is convenience –

absolute accuracy is less of an issue. A much smaller number of cells are measured for use as reference cells and to set efficiency records. In this case, accuracy is the main concern and convenience is less important. This chapter concentrates on the latter case, accurate measurement.

This work is primarily of relevance to groups making solar cells, both in research and in industry. For such groups, accurate cell measurement is not their core business and limited money will be available for measurement procedures. This work describes a method of achieving accurate measurements without spending a large amount of money.

Some details of this work are specific to crystalline silicon solar cells. The concept is certainly applicable to other technologies, but the numerical results may not be.

2.1.1 Overview of this chapter

It is shown in this chapter that natural sunlight is an excellent light source for accurate measurement of solar cells.

In the introduction, a summary of existing cell measurement techniques is given. Particular emphasis is placed on issues related to the light source. Both commonly used, low cost techniques, and the best, high accuracy techniques, are described. The performance of existing techniques is summarised.

Having shown that natural sunlight is an excellent light source for testing solar cells, the rest of the chapter describes the process of determining exactly how good it is for crystalline silicon cells. In summary, a group of cells, representative of any likely crystalline silicon cell, are simulated under a range of typical natural sunlight spectra. Over 1 million cell/spectrum combinations are examined. The spectral mismatch error that results is then plotted as a function of atmospheric conditions. The performance of several commonly used solar simulators is also compared to that of natural sunlight. Finally, to confirm that the modelling results are sensible, the results of experimental verification are described.

In the method section, the modelling is described in detail. A summary of natural sunlight spectrum modelling, and the specific model used in this work, SMARTS2, is given. A reasonable amount of detail is given, as few solar cell researchers (the target audience for this work) are likely to know much about atmospheric modelling. The cell modelling, using the one-dimensional semiconductor-modelling package PC1D, is then described. Finally, the linking of the two models, to determine spectral mismatch error as a function of atmospheric conditions, is described. The testing method developed uses direct beam natural sunlight and so requires a collimating tube to limit the cells field of view. The design of a suitable collimator is described.

In the discussion section, the results are examined. Plots of spectral mismatch error as a function of atmospheric conditions are used to identify the conditions that will give lowest measurement error. These conditions are, roughly speaking, a clear day in summer. Examination of typical weather data for a variety of locations around the world shows that the atmospheric conditions required for accurate measurements occur commonly. Comparison to simulators shows that measurement under natural sunlight is more accurate than measurement under any affordable simulator, and of comparable accuracy to calibration at a standards laboratory.

Finally, appendix B gives a "recipe" for the recommended testing procedure. It includes details of all the equipment required and describes a step-by-step procedure.

2.1.2 Accurate measurement of solar cells

Measuring the efficiency of a solar cell requires a light to illuminate the cell and equipment to measure its electrical characteristics. The light source and related equipment are by far the most expensive parts, and errors associated with them are the most difficult to eliminate. Serious errors can certainly come from other sources, but given knowledge of the sources the errors can be eliminated with relative ease. Consequently, this chapter concentrates on the problem of obtaining a good light source.

For accurate cell measurement, the three main parameters of interest are I_{sc} (short-circuit current), V_{oc} (open-circuit voltage), and FF (fill factor). Efficiency can be calculated from these three and the cell area. V_{oc} and FF are relatively easy to measure accurately. For good cells, both V_{oc} and FF are weak functions of light intensity and spectrum. Hence, problems with the light source introduce relatively little error in V_{oc} and FF. I_{sc} , on the other hand, is a strong function of light intensity and spectrum. Problems with the light source can cause serious errors in measurements of I_{sc} . Hence, this chapter mostly considers the measurement of I_{sc} .

To allow comparison between different types of solar cells, standard testing conditions have been agreed by international bodies. One of the conditions is the spectrum of the light, known as the standard spectrum (sometimes also known as the reference spectrum). There are numerous standard spectrum definitions, but the three most commonly used ones are: AM1.5G (ASTM-E892) for terrestrial global radiation, AM1.5D (ASTM-E891) for terrestrial direct-beam radiation, and AM0 for space. AM is the air mass, which is the relative amount of atmosphere the sunlight must pass through. If the sun is directly overhead, $AM = 1$. These standard spectra are, essentially, average spectra for real world conditions. AM1.5G is used for the majority of cells, which are used in flat plate modules. AM1.5D is used for concentrator cells, since concentrator systems can only capture direct-beam radiation. This work considers measurement of silicon solar cells under both the AM1.5G and AM1.5D standard spectra.

The remainder of this introduction discusses the different measurement techniques possible. First, the ideal solution is described. Secondly, the best solutions available are described and their likely accuracies summarised. Thirdly, some low cost solutions are described. Among the low cost options, natural sunlight is shown to be an excellent light source. Finally, a summary is given of the methodology used, in this work, to determine the accuracy of testing silicon cells under natural sunlight.

2.1.3 Ideal solution

A perfect light source for measuring solar cells would have several ideal characteristics:

- it would exactly match the relevant standard spectrum – i.e., have exactly the right total irradiance and spectral irradiance
- it would have totally uniform light intensity over the entire testing area
- it would be perfectly stable, not changing in intensity or spectrum over time
- it would be convenient – available at any time of the day or night

In the real world, no such light source exists. Practical light sources are limited in all respects. To reduce these limitations, most techniques use a reference detector that measures the light intensity. Measurement errors are a complicated function of the characteristics of both the reference detector and the light. Consequently, it is necessary to consider the characteristics of both. The following two sections discuss the limitations of the best technologies available and the limitations of low cost technologies.

2.1.4 Best real-world solutions

The best light sources available are usually found at standards labs. These institutions are responsible for the most accurate measurements and so can afford the most sophisticated techniques. It is interesting to examine these techniques, as they are a benchmark against which simpler solutions can be compared.

No practical light source has an acceptable match to the standard spectra. To solve this problem, a spectral mismatch correction can be performed. This reduces the error due to the non-standard spectra. Spectral mismatch correction is an expensive and difficult procedure, but all of the best techniques use it. Spectral mismatch correction is described in detail in section 2.1.4.1.

For most light sources, neither the spectrum nor the intensity are known, so measurements are required to determine them (the one exception being the standard lamp method, described in section 2.1.4.2). The spectrum is usually measured with a spectroradiometer and the intensity is usually measured with a reference detector (either a calibrated cell or a thermal detector such as a pyrheliometer).

In principle, the intensity does not need to be measured separately, since it is uniquely defined by the spectrum. However, in practice there are several reasons why it is usually measured as well:

- Spectroradiometers measure spectral irradiance over a limited range of wavelengths, commonly 0.3-1.1 μm . For outdoor measurements, it is possible to fill in the gaps where the spectrum has not been measured by using a computer model of atmospheric transmission and the total irradiance (Osterwald, Emery et al. 1990).
- Spectroradiometers are less accurate than total irradiance sensors. If a total irradiance measurement is available, the spectral irradiance can be considered a relative measurement. It can then be scaled to match the measured total irradiance. However, this is only possible if the spectral irradiance measurement covers the full wavelength range of the total irradiance sensor.
- If the reference detector has a similar spectral response to the cell being measured, the spectral mismatch correction required will be smaller. It has been shown that the uncertainty introduced by the spectral mismatch correction is smaller for smaller corrections (Field and Emery 1993). Hence, use of a reference detector can reduce the effect of inaccuracies in the spectroradiometer (provided it is similar to the test cell).

The measurement instruments need to be regularly calibrated, as do the instruments used for the calibration, and so on. The more links there are in the chain, the greater the potential for errors to creep in.

In the remainder of this section, spectral mismatch is described in detail, the best measurement techniques available are discussed, and the accuracy of the best techniques are summarised.

2.1.4.1 Spectral mismatch

Ideally, the light source used to test solar cells would exactly match the relevant standard spectrum (i.e., have exactly the right irradiance and spectrum). But in the real world, no such light source exists. In practice, cells are tested under a light source having approximately the right spectrum and a reference detector is used to measure the irradiance. The deviation of the source spectrum from the standard spectrum will cause an error, known as the spectral mismatch.

The usual practice is to consider the spectral mismatch for the short circuit current (I_{sc}) only. A different spectral mismatch could be determined for each of the cell characteristics I_{sc} , V_{oc} , and FF, but this is not normally done. V_{oc} and FF mismatches are not considered because V_{oc} and FF are far less sensitive to irradiance and spectrum changes than I_{sc} is.

The spectral mismatch, M , is defined as the ratio of the measured I_{sc} under the non-ideal source spectrum to the 'true' value under the standard spectrum. If the irradiance of the light source is variable, the irradiance can be adjusted to yield the same output from the reference detector as the reference detector shows under the standard spectrum. If the irradiance is not variable, the cell current, I_{test} ($I_{test} \equiv I_{sc}$ for the test cell), can be linearly scaled to correct for the non-standard irradiance. This irradiance correction assumes that I_{test} is linear with irradiance however, so, ideally, the linearity of I_{test} should be checked for each cell.

$$M = \frac{I_{test} \text{ under source spectrum, corrected for non - standard irradiance}}{\text{'true' } I_{test} \text{ under standard spectrum}} \quad (2-1)$$

$$= \frac{I_{test,sor} \frac{O_{det,std}}{O_{det,sor}}}{I_{test,std}}$$

where $O_{det,std}$ is the output of the reference detector (typically voltage if the detector is a radiometer, and current if it is a calibrated PV device) under the standard spectrum, and $O_{det,sor}$ is the output of the reference detector under the source spectrum.

The value of M is usually around 1. The spectral mismatch error, ϵ_M , expresses the error in the cell measurement due to spectral mismatch.

$$\epsilon_M = |1 - M| \quad (2-2)$$

The spectral mismatch can also be expressed in terms of spectral irradiances and device spectral responses:

$$M = \frac{\int_{\lambda_0}^{\lambda_1} E_{sor}(\lambda) \cdot S_{test}(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} E_{std}(\lambda) \cdot S_{test}(\lambda) d\lambda} \cdot \frac{\int_{\lambda_0}^{\lambda_1} E_{std}(\lambda) \cdot S_{det}(\lambda) d\lambda}{\int_{\lambda_0}^{\lambda_1} E_{sor}(\lambda) \cdot S_{det}(\lambda) d\lambda} \quad (2-3)$$

where $E_{sor}(\lambda)$ is the spectral irradiance of the source spectrum, $S_{test}(\lambda)$ is the spectral response of the test cell, $E_{std}(\lambda)$ is the spectral irradiance of the standard spectrum, and $S_{det}(\lambda)$ is the spectral response of the reference detector. The integration limits (λ_0 and λ_1) should encompass the entire range of the standard spectrum (typically 300-4000 nm).

Only relative measurements of spectral response and spectral irradiance are needed (Seaman 1982) – both E terms and both S terms appear on the top and the bottom, so constant terms in any of these will cancel.

What does equation (2-3) mean? It is useful to consider some special cases. If the two devices have identical spectral responses, the integrals all cancel and $M = 1$. In other words, for identical devices the spectra are irrelevant. Alternatively, if the two spectra are identical, the integrals again cancel and $M = 1$. In other words, if the source spectrum exactly matches the standard spectrum the device spectral responses are irrelevant.

The duality discussed above is for the broadband case. To a rough approximation, the same principle applies monochromatically as well. Eg: assume that the source spectrum is significantly different to the standard spectrum at a particular wavelength, λ . If, at wavelength λ , the two devices have the same spectral response, the same amount will be added to the top-left and the bottom-right terms in equation (2-3). If the total quantities in the top-left and bottom-right terms are similar, there will be no change in M . Conversely, if, at wavelength λ , one device responds well and the other does not respond at all, a large amount will be added to one term and none to the other. This will cause a large change in M . In other words, spectrum errors will have the worst impact at wavelengths where the spectral responses of the two devices are most different.

In general, the more similar the cell and the detector are, the more spectral error can be tolerated. Conversely, the closer the source spectrum is to the standard spectrum, the wider the range of cells that can be measured accurately. This is a very useful principle. Given a group of similar cells, only a few of them need to be measured under a good spectrum, and only occasionally. These calibrated cells (known as reference cells) can then be used to measure the rest of the group under a poor spectrum, which may be much cheaper and/or more convenient than the good spectrum.

This reference-cell method is widely used. The procedure for obtaining a reference cell is usually to send a typical cell to a solar-cell testing lab to have it measured. However, this process is expensive (typically about US\$1000) and takes some time. As a result, many labs go years between recalibrations. Recently produced cells can then be quite different to the reference cell, and large spectral mismatch errors result. In addition, reference cells can degrade if not stored very carefully. This can introduce further errors.

Spectral mismatch correction procedure

The best light sources available, even to standards labs, are not an adequate match to the standard solar spectrum. Spectral mismatch errors of many percent often result. It is possible, in principle, to eliminate the spectral mismatch error by determining M and then dividing the measured value of I_{test} by it. This spectral mismatch correction procedure is used by most standards labs. If done with painstaking care, it should be the best way to minimise spectral mismatch error.

The spectral mismatch correction procedure, however, requires measurements of the spectral irradiance of the source and the spectral responses of both the reference and test devices. These are difficult and expensive measurements to make, and there are significant uncertainties associated with them.

Spectral irradiance is usually measured with a spectroradiometer. For a continuous source such as natural sunlight or a continuous solar-simulator, suitable equipment may cost between US\$10,000 and US\$100,000. For a flashlamp simulator the situation is more difficult as the spectrum changes significantly over a period of milliseconds, and may not be repeatable from flash to flash. This necessitates the use of a fast diode-array spectrometer, rather than the commonly used mechanically scanned type. According to (Zaaiman, Ossenbrink et al. 1994), no commercially available systems can do this so it is necessary to custom build an instrument.

In addition, spectrum measurements must be done regularly as the spectrum of a lamp changes as it ages. Emery (Emery, Myers et al. 1988) states that lamp aging in the Spectrolab X25 simulator causes a change in the spectral mismatch of as much as 1.5% over 100 hrs.

Precise spectral response measurement requires a powerful light source, a monochromator, and a lock-in amplifier. This equipment will cost at least US\$10,000. In addition, the spectral response of a solar cell is sensitive to bias conditions. Care must be taken to ensure that the bias conditions are correct.

The cost of the equipment, and the need to constantly re-calibrate it, makes spectral mismatch correction very expensive.

Accuracy of spectral mismatch correction

The accuracy of spectral mismatch correction has been extensively studied, as it is one of the larger uncertainty sources for accurate cell measurements. Numerous authors have estimated the accuracy with which M can be determined, given existing techniques for measuring spectral response and spectral irradiance.

Seaman (Seaman 1982) analysed the effect on M of errors in spectrum and spectral response measurements. He considered two types of error: random error, and bias error. Both were applied to the spectrum and the spectral response measurements. The resulting noisy spectra and spectral responses were then used in Monte Carlo simulations to estimate spectral mismatch. Seaman found that introducing random errors of +5, 0, or -5% (equal probability) at each wavelength gave 0.3% error in the spectral mismatch. Introducing a bias error of 0% @ 360nm to 10% @ 1100nm and vice-versa also gave 0.3% error in the spectral mismatch.

Emery (Emery, Osterwald et al. 1987) performed a similar analysis, but used a normally distributed 5% random error in the spectrum and spectral responses. This resulted in a 0.35% error in spectral mismatch.

A further refinement of this analysis was performed by Field (Field and Emery 1993). He used the specific random and bias uncertainties for a LiCor LI-1800 spectroradiometer. He found that, for a crystalline silicon cell, measured under natural sunlight against a pyrheliometer, and with spectral response uncertainty of 5%, the uncertainty in M was 0.2%.

Possibly contradicting these theoretical analyses, inter-laboratory comparisons of measurement techniques have shown differences between labs of 5% or more (section 2.1.4.3). It is not clear what caused such large differences, but error in spectral mismatch correction is one of the likely culprits. Spectral mismatch correction may not be as accurate, in practice, as theoretically estimated. The correction procedure involves many instruments that require calibration, so there are many places where errors could creep in.

2.1.4.2 Best real-world light sources

A variety of different measurement techniques are used by different standards labs around the world. All of them incorporate some variety of spectral mismatch correction. A few of the more common techniques are described in this section.

For convenient indoor measurements, high quality solar simulators are commonly used. An example is the Spectrolab X-25, used by NREL, and costing around US\$200,000. It contains a continuous xenon arc lamp with elaborate filters to adjust the spectrum to match the desired standard. To minimise spectral mismatch error, these simulators are usually used with a reference cell that is the same technology as the test cell. However, it is still necessary to perform spectral mismatch correction.

The standard-lamp method (King and Hansen 1991), used by Sandia, is an interesting alternative to the use of a solar simulator. The method involves using a standard lamp (an incandescent lamp that produces a known irradiance and spectrum when operated under precisely defined conditions) as the light source rather than a solar simulator. This method simplifies spectral mismatch correction, since it does not require either a reference-detector or a source spectrum measurement. The spectral response of the test cell is the only measurement required. The elimination of these three error sources makes the final cell measurement more accurate. However, the spectrum of a standard lamp is a very poor match to any of the standard spectra and the resulting value of M is large (typically about 1.3). It is concluded in (Field and Emery 1993) that the standard-lamp method is less accurate than calibration using direct-beam natural sunlight.

If the absolute spectral response of a cell is measured, I_{sc} can then be calculated for an arbitrary spectrum. However, for practical cells, the spectral response is not a constant quantity. In particular, it varies between one sun and high concentration. Hence, a measurement of spectral response at 1 sun may not give an accurate prediction of cell current under concentration. However, this method is the preferred technique for some laboratories.

For highly accurate primary calibrations, some labs, for example NREL, use direct-beam natural sunlight (Osterwald, Emery et al. 1990). This procedure is described in (ASTM E1125 1999).

The spectrum of natural sunlight varies with atmospheric conditions and so, to compensate for this variation, a spectral mismatch correction is performed. Since the

spectrum of natural sunlight is a good match to the AM1.5G and AM1.5D standard spectra, the mismatch correction is small – typically only a few percent.

Another benefit of natural sunlight is that it is highly collimated. This eliminates the need to measure exactly where the front of the cell is (which is problematic with encapsulated cells) (Bucher, Stiening et al. 1993).

The reference detector used by NREL is an active cavity radiometer. A radiometer is used instead of a reference cell because radiometers are far more accurate.

The new method proposed in this chapter is similar to the NREL method, but does not include spectral mismatch correction. This makes it a lot cheaper and more accessible.

2.1.4.3 State of the art – present measurement accuracy

The accuracy of current solar-cell measurement methods has been thoroughly investigated, concentrating mainly on 1-sun measurements. This work can be broadly categorised into two approaches: 1) theoretical analyses predicting the total measurement uncertainty, as a sum of all the individual component uncertainties, and 2) inter-laboratory comparisons where cells were circulated amongst different laboratories to determine the reproducibility of real measurements.

Theoretical analyses

Many theoretical analyses of the uncertainty in I_{sc} measurement have been performed. In these analyses, all the component uncertainty sources were identified for each measurement technique, and the total calculated. A few of these analyses are summarised in table 2-1.

Table 2-1: Theoretical estimates of I_{sc} measurement uncertainty for various solar cell measurement techniques.

Light source, with spectral mismatch correction	Reference detector	I_{sc} uncertainty
Natural sunlight, direct beam	Absolute cavity radiometer	0.7% (Emery, Osterwald et al. 1989) 1% (Osterwald, Emery et al. 1990)
X25 Simulator	$\pm 1\%$ reference cell	1.1% (Emery, Osterwald et al. 1989)
Natural sunlight, global radiation, normal to sun	Shaded pyranometer + pyrhelimeter	2.5% (Emery, Osterwald et al. 1989)
	Pyranometer	3.7% (Emery, Osterwald et al. 1989)

Inter-laboratory comparisons

To check the accuracy of the many techniques used by different standards labs around the world, a series of reproducibility tests have been organised.

During 1993-95, a group of cells were measured by 13 national labs in 8 nations (PEP'93) (Osterwald, Anevsky et al. 1996). A wide variety of measurement

techniques were used, both primary and secondary, but all involved spectral mismatch correction. For twenty 2x2 cm silicon cells that were circulated, the 2σ variation in I_{sc} values was 7.3%. After excluding half of the labs, 3 of them because they used a secondary measurement technique and 3 because they returned many results more than 2% from the group mean, the 2σ variation was 2%. A later paper on this inter-comparison, (Osterwald, Anevsky et al. 1999), identifies the remaining 4 ‘good’ labs as: Japan Quality Assurance Organization (JQA) jointly with the Electro-technical Laboratory (ETL), the National Renewable Energy Laboratory (NREL), Physikalisch-Technische Bundesanstalt (PTB), and the Tianjin Institute of Power Sources (TIPS).

For comparison, the 4 labs presently contributing to ‘Solar Cell Efficiency Tables’ (Green, Emery et al. 2001) are: JQA, NREL, Fraunhofer and Sandia National Laboratories.

A very similar inter-comparison, PEP’87, was done in 1987-89 (Metzdorf, Wittchen et al. 1990). For 2x2 cm single-crystal and mono-crystal silicon cells, a 2σ I_{sc} variation of only 1.7% was reported. In spite of using supposedly much less accurate techniques than PEP’93, the reproducibility was much better. Of the 15 measurement technique / group combinations in PEP’87, 3 did not do spectral mismatch correction, 2 were secondary calibrations, and 8 used pyranometers to measure irradiance. In PEP’93, measurements based on secondary methods (and several based on primary methods too) showed a 2σ I_{sc} variation of 7.3%, despite including spectral mismatch correction and avoiding inaccurate pyranometers. It is hard to reconcile the results from PEP’87 and PEP’93.

Another inter-comparison was performed by ASTM during 1992-4. It assessed the standard procedure for calibrating secondary reference cells (ASTM E1362 1999) – (essentially: measurement under a solar simulator or natural sunlight, and including spectral mismatch correction). The U_{95} reproducibility amongst 7 laboratories was found to be 5.7%.

Disagreement between theory and experiments

The theoretical uncertainty analyses and the inter-laboratory comparisons disagree seriously. Primary calibrations against a cavity radiometer are predicted to be accurate to better than 1%, yet show a reproducibility of 2% at best. Secondary measurements under a simulator are predicted to be accurate to 1.1%, yet show a reproducibility of somewhere between 1.7% and 7%. The true uncertainties will be even larger than the reproducibility figures, since the latter show precision only.

The likely causes of these discrepancies are: overly optimistic theoretical analyses, poor calibration of equipment and operator mistakes. Given the elaborate nature of the spectral mismatch correction procedure, calibration problems and operator mistakes are likely. Problems with light uniformity and stability could also be involved.

Similar discrepancies have been found by other sources. Green (Green 1991) reported calibration differences between various labs, during the 1980s, as large as 5%. At the Centre for Sustainable Energy Systems, ANU, we recently received a measurement from an international lab that we strongly suspect (based on modelling and outdoors testing) was out by around 10%.

A major objective of PEP’93 was to calibrate the World PV Scale cell set. Consequently, the laboratories involved would have been aware that they were participating in an important inter-comparison, and would have taken special care in

their measurements. The results of PEP'93 are therefore an optimistic estimate of routine reproducibility.

If the purpose of an inter-comparison is to determine the reproducibility of day-to-day measurements, it should be done double blind. The participants should have no knowledge that they are measuring anything special. I have not seen any references to routine measurement reproducibility tests.

Summary

Inter-laboratory comparisons of measurement accuracy have shown reproducibility far worse than theoretical analyses suggest should be expected. Consequently, it is safer to take the inter-laboratory reproducibility as an indication of present state-of-the-art accuracy. There are 2 situations worth summarising: the best possible measurements, which a national standards lab might have access to, and routine measurements, which most people would have access to.

Under the best possible circumstances (a primary calibration method is used, the lab staff take special care, and it is known which labs are 'unreliable' so they can be avoided), silicon cell calibration uncertainty could be below 2%. However, this level of accuracy is probably not available to most solar cell groups. NREL, for example, will only do primary calibration for national labs (private communication).

Under realistic conditions for an unimportant client getting a routine calibration (a convenient secondary calibration method is used, the lab staff take usual care, and the client doesn't have inside knowledge of which labs to avoid), silicon cell calibration uncertainty is unlikely to be less than 5%.

2.1.5 Affordable real-world solutions

For many groups involved with solar cells, precise measurement is not their core business. Such groups cannot afford to spend large amounts of money on the best light sources and detectors, let alone maintaining them within original specifications. This section reviews some of the lower cost options for light sources.

Few, if any, of the low cost options include spectral mismatch correction. It is too expensive and elaborate. Although some groups do have systems for measuring spectral response, these systems are usually designed for diagnosing cell behaviour. They may not be accurate enough for spectral mismatch correction.

Closely associated with the choice of light source is the choice of reference detector. The two are interrelated. This section also reviews some of the more common choices of reference detector, and gives estimates of their accuracy.

2.1.5.1 Solar simulators

For convenient measurement of a large number of cells, a solar simulator is essential. The solar simulators used by most groups, however, are far from ideal.

Affordable solar simulators have many limitations. They frequently have poor spatial uniformity (at least a few percent variation). This can introduce serious errors if the test and reference cells are different sizes, different thicknesses, or positioned differently. Affordable simulators often emit poorly collimated light, increasing the risk of errors due to multiple reflections. Many simulators also have poor temporal

stability. Since the poor spatial uniformity usually requires swapping the reference and test cells, changes of light intensity over time can introduce errors. Non-uniformity and temporal instability can easily introduce errors of 3% (Emery, Osterwald et al. 1987). Finally, all but the very best solar simulators have a poor match to the standard spectra. For example, it is shown in this work (section 2.4.4) that measurement of one crystalline-silicon cell with reference to another, quite different, crystalline-silicon cell, under an Oriel solar simulator, can cause a 15% spectral mismatch error. Spectral mismatch error can be greatly reduced by spectral mismatch correction, but this is an expensive and difficult procedure. It requires precise measurements of the spectral irradiance of the light source, and the spectral response of both the reference detector and the test cell.

Most of these limitations can be overcome, however, by use of a matched reference cell. If the reference cell is the same size as the test cell, and is placed in the same position under the simulator, most of the error due to non-uniform illumination will be eliminated. If the reference cell has a similar spectral response to the test cell, most of the error due to non-standard spectrum will be eliminated. If a convenient, low cost, calibration method is available then these lower quality simulators are quite acceptable.

By far the cheapest type of solar simulator is an incandescent lamp. Incandescent lamps operate at a much lower temperature than the sun, so have a much redder spectrum. The spectrum can be improved by the use of infrared rejecting filters. Suitably filtered lamps are cheap and widely available, thanks to the large market for projector lamps. The classic example is the ELH lamp. ELH lamps are widely used for cheap solar simulators. Over all wavelengths in the solar spectrum, they have a poor match to any of the standard spectra. However, over the wavelengths of interest for testing silicon solar cells, they provide a reasonable match. They work surprisingly well, given that they are not even remotely optimised for solar cell testing. Indeed, it is shown in this work (section 2.4.4) that, for silicon cells, ELH lamps cause less spectral mismatch error than some special purpose solar simulators. However, the area of uniform illumination they provide is smaller than for most special purpose simulators.

Xenon arc lamps operate at a temperature comparable to the surface of the sun and so produce a similar blackbody spectrum. However, the light still requires filtering to get rid of undesirable spikes in the infrared. Xenon arc sources are moderately expensive, e.g., the Oriel 1kW Solar Simulator is about US\$20,000. Compared to an incandescent lamp, the output from continuous xenon arcs is quite unstable.

Xenon flash lamps are similar to xenon continuous-arc lamps, except that they only operate for a few milliseconds. This is long enough for the cell to reach electrical equilibrium, but causes very little heating. Minimising heating is essential when testing concentrator cells and encapsulated modules that have poor heatsinking. Flash lamps have a very high peak power capability. This allows a large area to be illuminated with excellent uniformity. The spectrum for a xenon flashlamp is better than for continuous arc xenon lamp (Matson, Emery et al. 1984), (Emery 1986).

2.1.5.2 Natural sunlight

Natural sunlight is, in many respects, far superior to a solar simulator for accurate measurement of solar cells. It has superb uniformity for any sized cell or module, which eliminates errors due to spatial non-uniformity. It is extremely well collimated (for direct beam radiation), making it easier to eliminate errors from multiple

reflections. The excellent uniformity allows the test cell and reference detector to be measured simultaneously, side-by-side. This eliminates errors due to changes in light intensity over time. Finally, the spectrum of natural sunlight is, under the right atmospheric conditions, an excellent match to the standard solar spectra (which is not very surprising). This is illustrated in Figure 2-2, which shows a comparison between a typical clear-sky direct spectrum, a solar-simulator, and the AM1.5G standard spectrum. The natural sunlight spectrum is clearly a dramatically better match to the AM1.5G standard than the simulator spectrum. The same conclusion is reached by (Berman and Faiman 1997). Note that the spectral intensities in Figure 2-2 are given in photon flux, rather than the more commonly used spectral irradiance. For PV applications, plots of spectral irradiance (i.e. units of $\text{W/m}^2/\mu\text{m}$) can be misleading. PV devices respond to the number of photons, not the energy in the photons. Hence, plots of spectral irradiance exaggerate the importance of the blue end of the spectrum (high energy photons) and understate the importance of the infra-red end of the spectrum (low energy photons). Plots of photon flux give a more realistic picture. As a further step to allow comparison, the spectra are normalised such that they all integrate to the same value.

The one major shortcoming of natural sunlight is its limited availability. Measurements can only be made when conditions are suitable. However, for organizations making solar cells this is less of a limitation than it might seem. When cells are being produced to a similar recipe, all cells in a group will have similar spectral responses. Only one need be calibrated precisely, and then it can be used to measure the rest under a convenient solar simulator. Accurate measurements under natural sunlight only need to be made occasionally; so waiting for the right weather should not often be a problem.

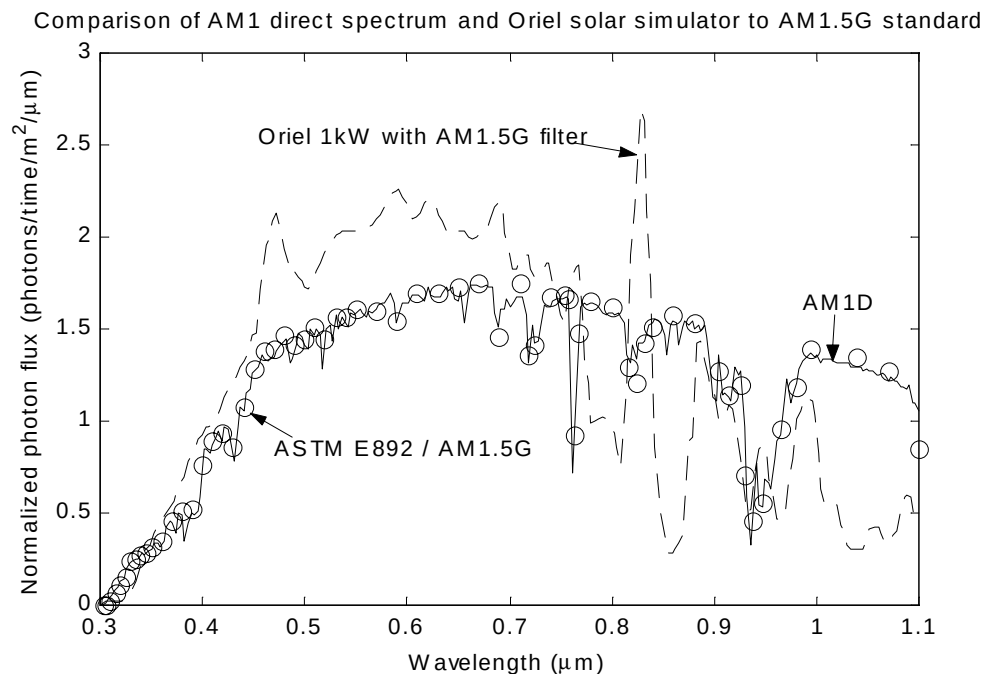


Figure 2-2: Comparison of a typical, clear-sky, low air mass, direct spectrum ($AM = 1.0$, $\beta = 0.04$, $w = 2 \text{ atm-cm}$), and the spectrum from an Oriel solar simulator, to the AM1.5G standard.

Natural sunlight is clearly an excellent light source for accurate solar cell measurement. The only potential problem is the variability of the spectrum. The crucial questions are: what atmospheric conditions produce usefully low spectral mismatch error? How often do these conditions occur? And is it possible to easily tell if conditions are suitable? These questions are answered in this work.

Use direct-beam sunlight or global sunlight?

To measure a cell with reference to the AM1.5 Global standard spectrum, the obvious approach is to measure it outdoors under global radiation. Indeed, this is the method used in ASTM E1039. However, consideration of all the error sources involved shows that measurement under direct radiation is preferable under most conditions.

Global radiation outdoors comes from a wide range of angles, whereas radiation from a simulator is relatively well collimated. Due to the change of cell reflectivity with the angle of incoming radiation, measurements under the two conditions could be noticeably different. This problem has been mentioned by some authors, eg (Matson, Emery et al. 1984), but I have not seen a comprehensive study of it.

The reflectance of good quality solar cells is low – on the order of a few percent – for photons hitting the front surface at a high angle (that is, perpendicular to the front surface). However, the reflectance is high for low angles (approaching grazing incidence). This is particularly so if the cell is encapsulated under glass.

Under the AM1.5 global spectrum outdoors, 23% of the photons in the range 300-1100nm are diffuse radiation, most of them being blue and UV photons. A significant proportion of these diffuse photons will hit the cell at a low angle and be lost due to front surface reflectance. However, these low angle photons will be detected by a pyranometer since it is carefully designed to have an ideal cosine response. In contrast to global radiation outdoors, solar simulators are designed to produce a collimated beam. Very few of the photons from a solar simulator will be affected by low-incidence-angle reflectance. Consequently, cell efficiency measured outdoors against a pyranometer may be significantly lower than efficiency measured indoors under a simulator.

In addition, the effect is spectrally selective – bad cells won't respond to the diffuse, blue photons anyway, so they won't show much difference. High performance cells will respond to the blue photons, so the loss due to reflectance will be a significant error. This will be particularly significant for very high efficiency cell designs on which researchers are struggling for the race winning extra 0.1%. It might even cause incorrect optimisation of a cell design – for example, a texturing design that minimises wide-angle reflectance could be abandoned to reduce surface recombination. Under a well-collimated simulator, the lower recombination cell would perform better, but under real conditions, it would perform worse.

According to this argument, the well-collimated simulator method may be misleading and perhaps it should be modified. However, for most solar-cell groups the objective of cell measurement is not in fact to get the most theoretically correct answer – it is to get the same answer as the standards labs. This is because very accurate measurements are mostly used for comparisons to other technologies. On this basis, the use of direct radiation (which is collimated, like a simulator) is preferable to the use of global radiation.

Reference detector accuracy also favours the use of direct radiation. Different instruments are required to measure direct and global irradiance. Those designed for direct irradiance measurements are significantly more accurate (see section 2.1.5.3). When spectral mismatch error is only a few percent, reference detector accuracy becomes the limiting uncertainty. Consequently, measurement under direct radiation is preferable to measurement under global radiation.

Measurements under global radiation can be upset by light reflected off surrounding objects. Depending on the arrangement of the surroundings, the test cell can be illuminated differently to the reference detector. Even if the reflected light illuminates both cells equally, the spectrum of the reflected light can be quite different to the global illumination. Significant errors can result from this effect. A related effect is that different devices have different fields of view. For example, pyranometers have a full 180° field of view, whereas small cells encapsulated under thick glass will have a restricted field of view. The two devices will therefore see different levels of total irradiance. Both of these effects can be eliminated by constructing an artificial horizon. This ensures that both devices have line-of-sight only to the sky, and to an equal solid angle of sky. However, this will be a large and complex mechanism to cope with the tracking movements of the devices. Under direct radiation, in contrast, a simple collimating tube rejects virtually all reflected light and ensures that both devices see an identical solid angle of sky.

A few percent of the total global irradiance comes via reflections off the ground. Some of this comes via direct reflection; the remainder comes via multiple reflections between ground and sky. The spectral reflectivity of the ground therefore influences the global spectrum. An area of 1-100 km² around the test site is important (Gueymard 1995b). Different surfaces have different spectral reflectivities. Vegetation is usually highly absorbing in the visible and highly reflective in the IR. Snow is the reverse. Mineral surfaces and water have relatively constant reflectivity. Different test sites will therefore have different global spectra according to the local ground cover, and time of year. Characterising the local ground cover is not simple. Assuming a typical characteristic may introduce an error (admittedly, probably quite a small one). In contrast, the direct-beam spectrum is unaffected by the surrounding ground cover. Consequently, the spectral mismatch can be more accurately estimated for direct-beam sunlight.

All of these factors suggest that measurements under direct-beam radiation should be more accurate than measurements under global radiation.

Proposed natural sunlight testing method

Preceding sections have shown that direct-beam natural sunlight is an excellent light source for accurate measurement of solar cells. This section summarises the proposed testing method, using direct-beam natural sunlight.

To simplify the outdoors procedure, it is only necessary to measure I_{sc} under natural sunlight. V_{oc} and FF can be measured indoors, under a convenient simulator. Indeed, as is shown in section 2.4.7.1, it is probably more accurate to measure V_{oc} and FF indoors.

To illuminate both the test cell and the reference detector with direct-beam natural sunlight, both are housed in similar collimating tubes. These are mounted, side-by-

side, on a sun-tracking platform. The current from each can then be measured simultaneously.

It is also necessary to ensure that the direct-beam natural sunlight spectrum is an adequate match to the standard spectrum (when measuring with respect to AM1.5G the direct-beam spectrum is effectively being used to ‘simulate’ the global spectrum. The two are similar enough for this to work well). Estimating the spectrum requires some simple means to measure the important atmospheric conditions and determine the likely spectral mismatch error. This work shows that the spectral mismatch error can be usefully estimated for any likely silicon solar cell. The only atmospheric conditions that need to be measured are: direct beam irradiance, relative humidity, air temperature, and the position of the sun in the sky. From these measurements, the major factors influencing spectral mismatch – air mass, precipitable water, and turbidity – can be estimated. A diagrammatic summary of the proposed method is shown in Figure 2-3.

Previous work on natural sunlight calibration

Natural sunlight has been used for accurate cell measurements in the past. Indeed, it still is the usual calibration method for primary reference cells for both space and terrestrial applications. Consequently, the problem has been well studied.

Space primary reference cells are usually calibrated under conditions close to AM0 by mounting on a high altitude balloon or aircraft.

Terrestrial primary reference cells are sometimes calibrated under natural sunlight, using either direct or global radiation. ASTM E1125-99 describes a calibration procedure using direct radiation, but requires a spectral mismatch correction. ASTM E1039-99 describes a calibration procedure using global radiation. It is similar to the method proposed in this work, as it does not involve a spectral mismatch correction. However, it is less accessible since it requires use of a sunphotometer (a specialised and expensive piece of equipment), and gives no indication of the likely accuracy of the procedure. The new method proposed here, in contrast, requires no specialised equipment and gives an estimate of worst-case spectral mismatch error.

The NASA Lewis calibration method, developed in the 1970s, used direct-beam natural sunlight (NASA CP-2010 1976; NASA TM 73703 1977; Matson, Emery et al. 1984; Osterwald, Emery et al. 1990). It was similar to the method described in this work in that it used direct beam sunlight and did not involve spectral mismatch correction. However, the method was different in several ways.

The standard spectrum used in the 1970’s was slightly different to AM1.5G, having a higher level of precipitable water. The details of the NASA-Lewis method are therefore no longer directly usable. Due to the high precipitable water requirement, the NASA-Lewis method was only usable at a location with high precipitable water. A location on the Florida coast was chosen. The method proposed in this work, in contrast, is shown to be usable at a wide variety of locations.

The objective of the NASA-Lewis method was the creation of primary reference cells, calibrated to the highest accuracy achievable. This meant that the constraints on suitable testing conditions were strict. The method proposed in this work, in contrast, is more concerned with convenience. Instead of specifying a single hard limit, it shows the variation of measurement accuracy with atmospheric conditions and so allows the user to decide if conditions are good enough for their purpose.

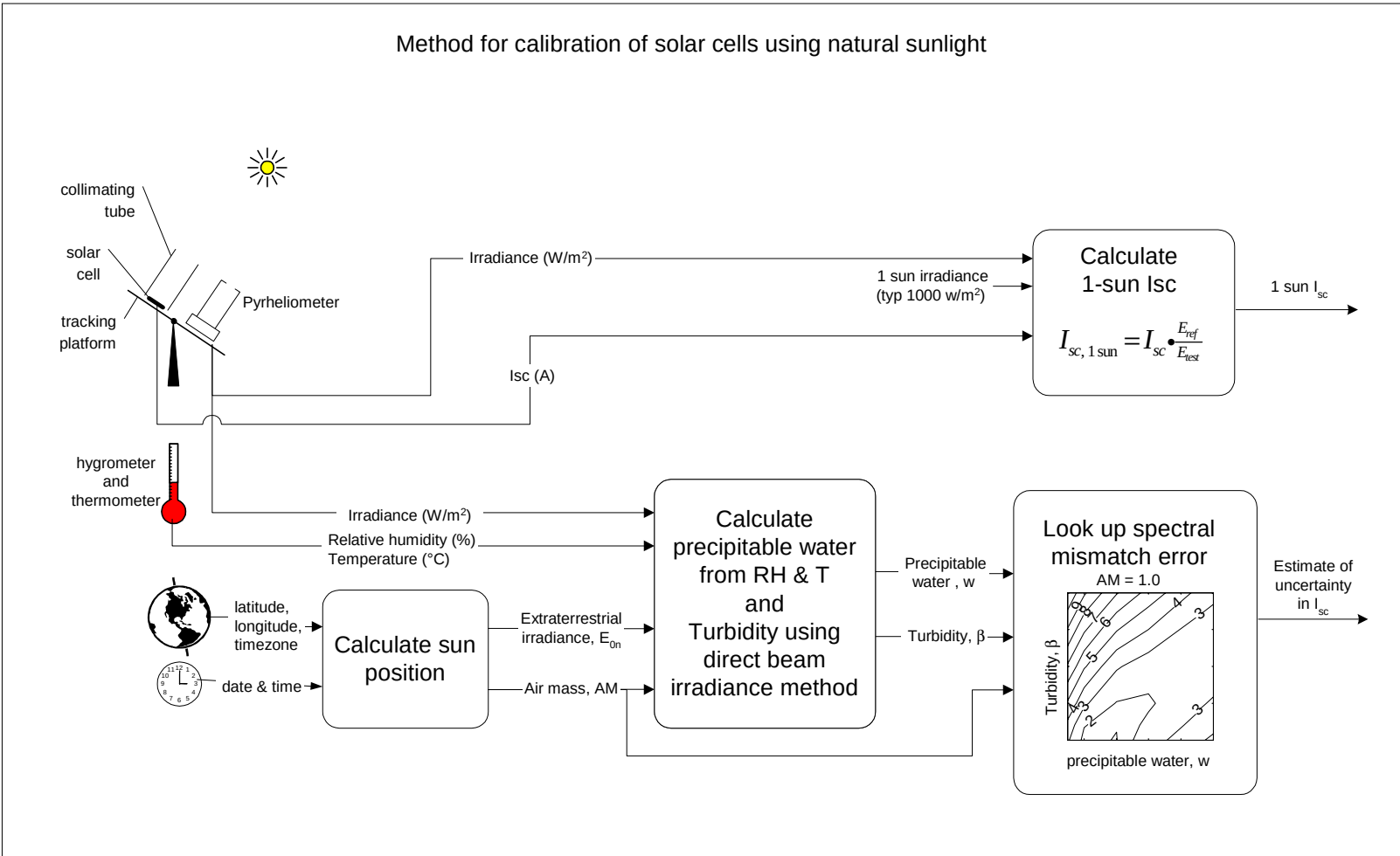


Figure 2-3: A diagrammatic summary of the proposed natural sunlight calibration method.

Finally, the NASA-Lewis method relied on measurements with a sunphotometer, a specialised instrument. The method proposed in this work does not require any specialised instruments. A comparison of the NASA Lewis method to the current best primary calibration method at NREL showed a difference of 3% (Osterwald, Emery et al. 1990). This shows that outdoors measurement without spectral mismatch correction can give excellent results.

In addition to studies specifically about cell calibration methods, many authors have studied the more general question of the variation of cell current under different atmospheric conditions. This is essentially the same process as is used in the present work.

Both (Mueller 1987) and (Osterwald 1985) studied the variation of normalised calibration number, $\overline{CN}$, (which is the same as M if a radiometer is used to measure irradiance) with atmospheric conditions. However, for silicon technology they only used one cell, and a good cell at that. As is shown later in the present work, spectral mismatch error varies according to cell construction and is usually worse for poor cells. Hence, the spectral mismatch error is probably underestimated in Mueller's work and Osterwald's work. In addition, their results, using one cell only, could be interpreted as showing that a particular set of atmospheric conditions will cause a constant mismatch, independent of cell construction. In reality, different cells will have different mismatch errors, sometimes even having opposite trends.

The use of natural sunlight for accurate cell measurement does not have a high profile in the solar cell testing literature. When it is mentioned, it is presented as an obscure and difficult process, requiring specialised equipment, and only possible at special times and in special locations. This work shows that natural sunlight calibration is in fact far more widely applicable. Useful accuracy can be obtained under a commonly occurring range of conditions, in many locations, and using standard equipment.

The present work on natural sunlight calibration is more detailed than previous work on the subject. The improvement in detail was possible because of increases in computer power since the earlier work. Steady improvements in computer speed have allowed the development of sophisticated models of natural sunlight spectra and solar cell behaviour. These models are now accurate enough and fast enough to allow thorough study of spectral mismatch under natural sunlight. In particular, all previous work has examined the spectral mismatch for a few, typically good, cells. The present work, in contrast, examines the spectral mismatch for a large range of cells; a range that is representative of almost any crystalline silicon cell likely to be constructed. The present work simulates the behaviour of 865 cells under 1350 different atmospheric conditions – over 1 million combinations.

2.1.5.3 Reference detectors

A reference detector is commonly used to measure or set the light intensity. There are two main choices of reference detector when measuring silicon cells – a thermal detector or a calibrated silicon cell. For thermal detectors, pyranometers are used to measure global irradiance and pyrhemometers are used to measure direct-beam irradiance. For silicon cells, the same cell can be used for either direct beam or global measurement, but it must be calibrated differently. Table 2-2 shows typical accuracies for several different reference detectors.

Table 2-2: Uncertainties for various reference detectors.

Direct-beam Irradiance measurement	
Active cavity pyrheliometer (Myers, Emery et al. 1989)	$\pm 0.4\%$
Pyrheliometer (sec. std.) (Osterwald, Emery et al. 1990)	$\pm 2\%$
Silicon Primary reference cell – calibrated outdoors under direct radiation (see section 2.1.4.3)	$\pm 2\%$
Silicon reference cell – routine measurement (see section 2.1.4.3)	$\pm 5\%$
Global Irradiance measurement	
Pyranometer (Myers, Emery et al. 1989)	$\pm 5\%$
Silicon Primary reference cell – calibrated outdoors under global radiation (using an elaborate method not relying ultimately on a pyranometer, hence it can be more accurate than a standard pyranometer) (Emery, Osterwald et al. 1989)	$\pm 4\%$

The choice of light source and the choice of reference detector are interrelated. If a cheap simulator is used, a matched reference cell is necessary. Thermal detectors, although they are usually more accurate in their basic calibration than reference cells, cannot be used. Firstly, the spectral mismatch error would be too large. Secondly, the most accurate reference detectors, pyrheliometers, require well-collimated light. They cannot be used with the poorly collimated light from most simulators.

Detail on pyrheliometers

For the method proposed in this work the best choice of reference detector is shown to be a pyrheliometer (see section 2.4.2). The following section discusses pyrheliometers in more detail.

A pyrheliometer consists of a detector housed in a collimating tube (much like that shown in figure 2-14). The tube limits the detector's field of view so that it responds to direct beam radiation only. The two types of pyrheliometers mentioned in this work, standard pyrheliometers and active cavity pyrheliometers, have different detectors.

Standard pyrheliometers use a detector which is a black plate that absorbs sunlight and heats up. The temperature gradient between the detector surface and its heatsink is proportional to the irradiance. A thermopile (a series connected string of thermocouples) measures the temperature drop. The output is typically 10mV at 1 sun. Neither the blackness of the surface nor the response of the thermopile can be accurately predicted. So, each instrument is calibrated against a more accurate reference, such as an active cavity pyrheliometer.

Active cavity pyrheliometers are absolute, or self-calibrating, instruments. In an active cavity pyrheliometer, the detector is a cavity, blackened inside, rather than a flat plate. Cavities typically have reflectivities of $<0.1\%$, compared to several percent for flat detectors. To provide calibration, an electrical heater is used to match the heat generated by the sunlight. Electrical power can be measured very accurately, allowing

the instrument to be highly accurate. For the purposes of this work, active cavity pyrheliometers are too expensive, so the remainder of the discussion will be about standard pyrheliometers.

There are many sources of information about the accuracy of pyrheliometers. For a first-class pyrheliometer (defined in ISO9060 standard), (Osterwald, Emery et al. 1990) refers to an uncertainty of 2%. (Zerlaut 1986) indicates a precision of 1%. The data sheet for a Kipp&Zonen CH1 pyrheliometer (which satisfies ISO9060) specifies: error due to non-standard temperature < 1%, error due to 5°C/hr temperature change < 3W/m² (so about 0.3% at 1 sun), and non-linearity < 0.2%. All of these sources agree, suggesting an uncertainty of about 2%.

To maintain the highest possible level of accuracy, ISO9060 requires annual recalibration for first-class pyrheliometers. Recalibration is usually performed by sending the instrument to an appropriate calibration facility, and will typically cost around US\$500.

Although ISO9060 requires annual recalibration, this may not be necessary for an instrument that is only used intermittently. First-class pyrheliometers are designed for continuous outdoors use. They are simple, robust instruments. For pyranometers, which use a very similar detector, the main degradation process is changing blackness of the detector surface due to sunlight exposure (Zerlaut 1986). If a pyrheliometer is treated well, kept clean, and only used intermittently, its calibration should last longer. As an indication, the standard specifies an instrument stability of better than $\pm 1\%/yr$.

2.1.6 Methodology: How accurate is natural sunlight testing?

It is clear that, under some conditions, natural sunlight is an excellent match to the standard solar spectrum. But how good a match is it under a commonly occurring range of atmospheric conditions, and how big will the spectral mismatch error be for a "worst-case" silicon solar cell? The answers to these questions show the accuracy of measuring solar cells under natural sunlight.

Knowing the variation in the spectrum of sunlight is not sufficient – spectral mismatch is a complicated function of the spectrum and the cell characteristics. In addition, there is no well-defined worst sort of cell – for different spectra, different cells will have the worst mismatch error. To determine the worst mismatch error for a range of clear-sky conditions, natural sunlight spectra were simulated and a group of cells, representative of any crystalline silicon solar cell likely to be made, were then simulated under each of the spectra. The resulting spectral mismatch values were then calculated as a function of atmospheric conditions.

The objective of this work was to determine the worst spectral mismatch error for any likely silicon solar cell when tested under natural sunlight. The first phase in this process was to determine which of the many atmospheric parameters (amount of dust in the air, amount of water in the air, etc.) have a significant influence on spectral mismatch error for silicon solar cells. Secondly, having identified the important atmospheric parameters, the variation of spectral mismatch error with these parameters was simulated in detail.

Both of these phases required the determination of spectral mismatch error as a function of atmospheric parameters. This involved three steps. First, natural sunlight spectra were simulated for a range of atmospheric conditions. The natural sunlight

spectra were simulated with the spectrum model SMARTS2. Second, a group of solar cells was simulated under these natural sunlight spectra, using the cell model PC1D. The group of solar cells was chosen to be representative of any likely silicon solar cell. Third, the spectral mismatch error was calculated for each cell, under each spectrum. For each spectrum, the cell with worst spectral-mismatch error was then selected, giving worst-case spectral mismatch error as a function of the atmospheric parameters.

The detailed mismatch error results were examined to identify the best testing conditions and the likely accuracy that would result under these conditions. Weather data for a variety of locations was then examined to estimate how often suitable conditions would occur. The spectral mismatch error for natural sunlight testing was also compared to the spectral mismatch error for a number of solar simulators. In addition, two groups of solar cells were considered – one representing any likely silicon solar cell, and the other representing good to excellent quality silicon solar cells.

To test that the simulation results were correct, experimental verification was necessary. This was done using a similar method to that used for the simulation. A group of cells, containing a wide range of different technologies and performances, was assembled. The cells were then measured under natural sunlight while measuring the important atmospheric conditions. The variation of cell currents with atmospheric conditions was then compared to the simulation predictions.

2.2 Method

2.2.1 Solar spectrum modelling with SMARTS2

The accuracy of solar cell measurement under natural sunlight is determined mostly by the spectrum of the sunlight. In this work, the spectrum of natural sunlight is modelled using the model SMARTS2. This model accurately predicts the solar spectrum at the surface of the earth, under clear skies, and runs on a desktop computer. A reasonable amount of detail is given in this section, as few solar cell researchers (the target audience for this work) are likely to know much about atmospheric modelling.

Solar spectrum models can be broadly categorised into two groups – sophisticated, rigorous models that are used in fields such as climate modelling and weather forecasting; and simplified, parameterised models. In the sophisticated models, the atmosphere is typically modelled as many separate layers, each having distinct properties. These models require large amounts of computer power and have many parameters. Considerable knowledge of the underlying atmospheric physics is needed to get meaningful results. Examples of sophisticated models are LOWTRAN, MODTRAN, and BRITE.

The parameterised models typically treat the atmosphere as a single homogenous layer in which several independent optical processes occur. The parameterised models are usually a collection of empirical approximations to the results of the rigorous models. The first widely used parameterised model was devised by Leckner, developed further by Brine and Iqbal (Iqbal 1983) and then Justus and Paris. These models were refined to give the widely used SPCTRAL2 code, (Bird 1986; Bird and Riordan 1986). To date, the most accurate parameterised model is SMARTS2 (Gueymard 1995a), (Gueymard 1995b). SMARTS2 was chosen for this work as it appeared to be the best

of the ‘easy to use’ models. It is available for free and can be downloaded from the websites in the preceding reference.

2.2.1.1 Atmospheric modelling and SMARTS2

In SMARTS2, the direct beam spectrum under clear skies is modelled as a series of independent optical processes that attenuate extraterrestrial solar radiation. The direct beam irradiance on a sun-tracking surface at wavelength λ , $E_{bn\lambda}$ is given by:

$$E_{bn\lambda} = E_{0n\lambda} T_{R\lambda} T_{o\lambda} T_{n\lambda} T_{g\lambda} T_{w\lambda} T_{a\lambda} \quad (2-4)$$

where $E_{0n\lambda}$ is the extraterrestrial irradiance at normal incidence and $T_{i\lambda}$ are the atmospheric transmittances due to: Rayleigh scattering, ozone absorption, NO_2 absorption, uniformly mixed gas absorption, water absorption, and aerosol scattering. Note that, throughout this work, if a quantity has λ in the subscript it is a monochromatic quantity at the wavelength λ . Wavelengths are usually specified in μm .

There is some disagreement in the literature about the extraterrestrial spectrum, but for this work the spectrum derived by Gueymard for SMARTS2 is used.

For all of these transmission processes except $T_{w\lambda}$ and $T_{g\lambda}$, the transmittance can be described by the classic Bouguer-Beer law:

$$T_{i\lambda} = e^{-m_i \tau_{i\lambda}} \quad (2-5)$$

where for each process i ($i = R$ gives $T_{R\lambda}$, etc), m_i is the optical mass (air mass) and $\tau_{i\lambda}$ is the spectral optical depth. The transmittance expressions for $T_{w\lambda}$ and $T_{g\lambda}$ (water and uniformly mixed gas absorption) are a little more complex than equation (2-5) but are similar exponential functions of air mass and optical depth.

For each of the processes, $\tau_{i\lambda}$ is a different and complicated function of the wavelength, the ‘amount’ of the variable, (eg atm-cm of precipitable water) and possibly other parameters.

So to calculate the spectrum, $E_{bn\lambda}$, we need the amount of each variable and the air mass. In the following sections, each process is described – what the process is, what model parameters affect it, and the typical range of these parameters. Analysis of spectral mismatch in section 2.2.5 shows that air mass, water, and turbidity are the most important parameters for this work. Consequently, these three processes are discussed in more detail and measurement techniques are described.

2.2.1.2 Air mass

Air mass is a measure of the optical path length through the atmosphere and is determined by the zenith angle Z . The zenith angle is determined by the date, time, latitude, and longitude.

As is shown in section 2.4, low air mass ($\text{AM} \approx 1.0\text{-}1.5$) is necessary for low spectral mismatch error. It is interesting to know how frequently the desired low air mass conditions can be obtained in various locations. The variation of noon air mass with time of year and latitude is shown in Figure 2-4. Most solar cell test sites will be in the temperate latitudes ($30^\circ\text{-}50^\circ$). For those closer to the equator, the desired low air mass

conditions will be available most of the year. For those further from the equator, they will be available for at least a few months around summer.

The zenith angle Z can either be directly measured (perhaps with an inclinometer on the sun tracking platform), or calculated from the latitude, longitude, time and date. There are numerous algorithms available to calculate the zenith angle. SMARTS2 and the most recent version of SPCTRAL2 (Bird 1986), use the algorithm from (Michalsky 1988), which is accurate to $\pm 0.01^\circ$.

For Z greater than 80° , the optical masses for the various processes become significantly different and quite elaborate expressions are required to determine them accurately (Gueymard 1995b, p7). However, for the relatively low air mass values of interest in this work ($AM < 2$ or $Z < 60^\circ$), the following simple expression is adequate:

$$AM = \frac{1}{\cos(Z)} \quad (2-6)$$

Although the path length is shorter at higher altitude (lower atmospheric pressure), the air mass in SMARTS2 is not directly corrected for this. Instead, pressure corrections are applied to each of the optical depths individually. Due to different concentration profiles through the atmosphere, slightly different corrections are needed for each process. Consequently, in this work no use is made of a pressure corrected air mass.

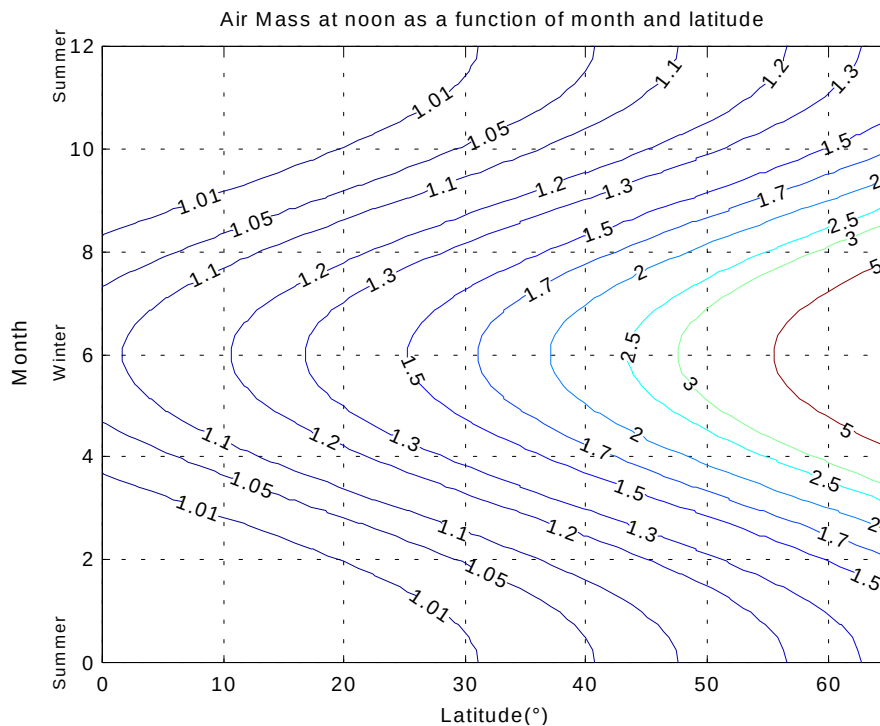


Figure 2-4: Air mass at noon as a function of latitude and month

2.2.1.3 Atmospheric pressure

The atmospheric pressure is determined by the altitude and to some extent by latitude and weather changes. In SMARTS2, the atmospheric pressure influences Rayleigh scattering and mixed gas and water absorption calculations.

The pressure can either be measured directly (being sure to measure true pressure, not sea level equivalent pressure that many barometers are calibrated to) or approximated from the altitude and latitude (Gueymard 1993b).

$$\frac{p}{p_0} = e^{0.00177 - 0.11963h - 0.00136h^2} \left(\frac{0.993 + 2.0783 \cdot 10^{-4}l - 1.1589 \cdot 10^{-6}l^2 + h(8.855 \cdot 10^{-3} - 1.5236 \cdot 10^{-4}l - 0.2907 \cdot 10^{-7}l^2)}{h} \right) \quad (2-7)$$

where p = atmospheric pressure (mbar) at altitude h (km), and l = |latitude| (degrees). Standard atmospheric pressure $p_0 = 1013$ mbar. Equation (2-7) is plotted in Figure 2-5.

It can be seen from Figure 2-5 that, as a rule of thumb, pressure decreases by 10%/1000m. Normal atmospheric pressure changes are less than ± 20 mbar, equivalent to approximately ± 200 m altitude change. Changes of ± 2000 m altitude have only a small affect on spectral mismatch, as shown in section 2.2.5. Consequently, local pressure variations due to weather changes can be safely ignored.

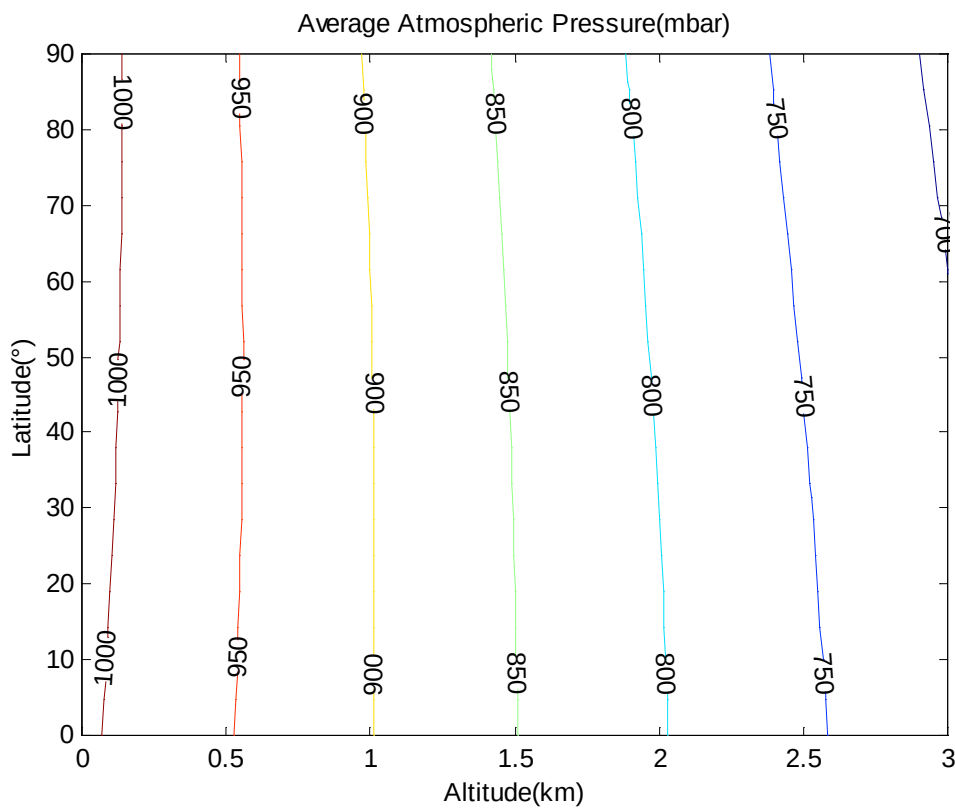


Figure 2-5: Average atmospheric pressure as a function of altitude and latitude

2.2.1.4 Rayleigh scattering and uniformly mixed gas absorption

The gases of the atmosphere affect the spectrum both by Rayleigh scattering and by absorption. Rayleigh scattering by atmospheric gases affects short wavelength photons much more strongly than long wavelength. Scattered photons may be lost into space or continue towards the ground. The effect of Rayleigh scattering is to attenuate blue light, making the spectrum redder. The direct beam spectrum is affected more strongly than the global spectrum. For the global spectrum, a significant proportion of the scattered light ends up as diffuse radiation. Mixed gas absorption attenuates light in narrow bandwidths at many different wavelengths. It affects the global and direct spectra equally.

In SMARTS2 the transmission due to Rayleigh scattering, $T_{R\lambda}$, is a function of air mass, atmospheric pressure and wavelength. The absorption by uniformly mixed gases, $T_{g\lambda}$, is a function of air mass, atmospheric pressure, ambient air temperature, and wavelength.

2.2.1.5 Turbidity

Description of turbidity

Turbidity characterises the scattering and absorption of light by small particles in the atmosphere. The particles are mostly dust, water, ice, or hygroscopic salt particles. The effect is similar to Rayleigh scattering – attenuating blue light and hence making the spectrum redder. Turbidity affects longer wavelengths more than Rayleigh scattering.

Turbidity is a difficult process to quantify as the particles can vary in size, in number, and in other subtle ways. However, it can be adequately described by an empirical relationship developed by Ångström (Ångström 1961):

$$\tau_{a\lambda} = \beta \left(\frac{\lambda}{\lambda_1} \right)^{-\alpha}, \lambda_1 = 1\mu\text{m} \quad (2-8)$$

where β is a measure of the ‘amount’ of turbidity and α characterises the particle size distribution (in other words, the ‘type’ of particles). High β corresponds to high turbidity, and high α corresponds to small particles.

SMARTS2 uses a refined version of the Ångström model where the spectrum is split into two regions, above and below 0.5 μm . Different values of α are applied to each region. The value of β for the short wavelength region is calculated to ensure continuity at 0.5 μm .

The value of α varies relatively little. This allows a simplification of the model by specifying typical α values for different environments – eg Rural, Urban, or Maritime. Turbidity is then reduced to a single parameter, β . Rural aerosols have the smallest particles (largest α) and Maritime aerosols have the largest particles. Urban aerosols are intermediate, but closer to rural.

The smaller the value of α , the less spectrally selective the scattering is. In the extreme case of $\alpha = 0$, the optical depth is a constant, β , independent of wavelength. Turbidity of this type will cause a broadband attenuation of the spectrum but will not alter the shape of the spectrum, and consequently will not affect the spectral mismatch. As the value of α increases, the aerosol scattering becomes more spectrally selective and

hence increasingly changes the shape of the spectrum. Blue light is attenuated more, and red light is attenuated less. This will increase the effect on spectral mismatch. Consequently, the worst kind of turbidity for solar cell calibration is that with the largest value of α . This will most likely be a rural/continental aerosol.

SMARTS2 has 10 different aerosol models: Shettle & Fenn (1979) Rural, Urban, Maritime, and Tropospheric; SRA (Standard Radiation Atmosphere, 1986) Continental, Urban and Maritime; and Braslau and Dave (1973) types C, C1. There is also the option of specifying α_1 & α_2 directly.

The models by Shettle and Fenn are used in this work, as they are the most detailed and so presumably the most accurate. They are the models used in the rigorous code MODTRAN. The Shettle and Fenn models include the influence of humidity – high humidity increases particle size, but the effect is only significant above approximately 70% relative humidity.

A test was done to confirm that, of the Shettle and Fenn models, the rural aerosol causes the worst spectral mismatch. Spectra were generated for 9 cases – 3 values of β (0.02, 0.1, 0.2) and 3 S&F models (Rural, Urban, Maritime). A group of silicon cells were simulated under these spectra, as described in section 2.2.4, and the worst spectral mismatch error selected for each spectrum. The results are shown in Figure 2-6. It can be seen that the rural model causes the worst mismatch error for all typical values of turbidity, that the urban model is similar to the rural model, and that the maritime model causes much less mismatch error.

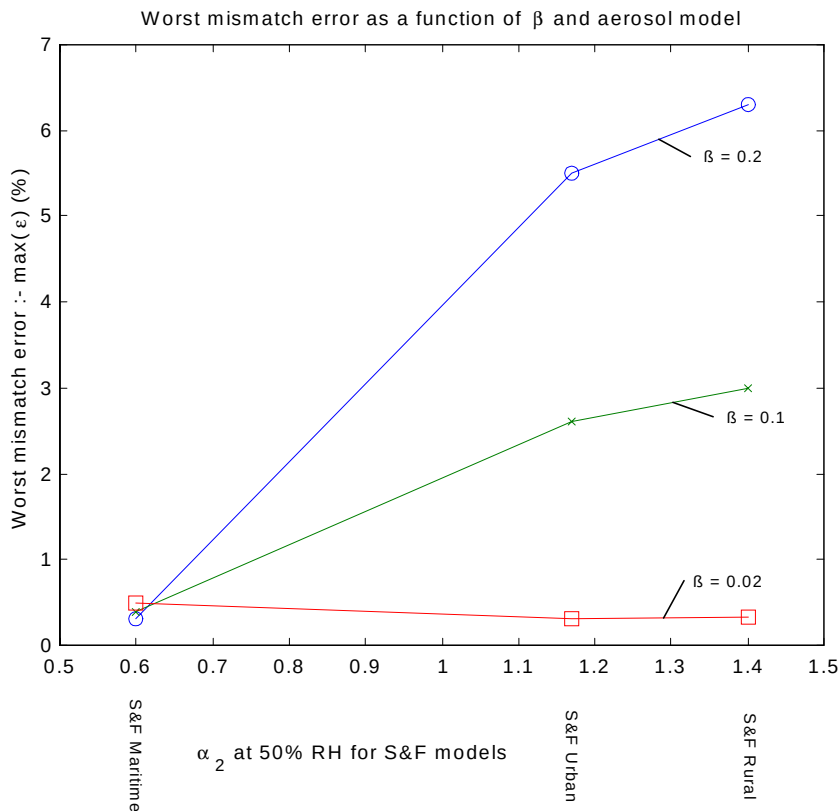


Figure 2-6: Influence of aerosol model on spectral mismatch error

There are numerous different measures of turbidity in use, in addition to β . The other common measure is τ_{500} . Examination of eqn (2-8) shows that β equals the aerosol optical depth, $\tau_{a\lambda}$, at $\lambda = 1\mu\text{m}$. τ_{500} is the aerosol optical depth measured at 500nm, so the two are related by $\beta = 2^{-\alpha}\tau_{500}$. The value of α is typically in the range 1.3 ± 0.5 , so $\beta \cong 0.4\tau_{500}$.

The value of β varies between 0 and approximately 0.4. Several different sources of data on β values are discussed in the following paragraphs.

According to (Ångström 1961), β is highest in the tropics and in early summer. In the tropics, the annual mean value is ≈ 0.12 . The highest measured was 0.25. In temperate zones, the annual mean is ≈ 0.06 .

A subjective description is given by (Iqbal 1983, p118): Clean 0.0, Clear 0.1, Turbid 0.2, Very turbid 0.4.

The Australian Meteorological Bureau stated (private communication with Bruce Forgan) that for Australia the mean turbidity (converted from τ_{500} figures) is ≈ 0.024 , peaking in September/October at ≈ 0.04 and as low as 0.01 in winter.

NREL's NSRDB/TMY dataset (http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2) gives turbidity for many locations in the USA. The turbidity data is specified as the BAOD (broadband aerosol optical depth) or Unsworth-Monteith coefficient. Conversions for this specification can be found in (Gueymard 1998). For many locations around the world, data can be obtained from the NASA/Aeronet dataset (<http://aeronet.gsfc.nasa.gov:8080/>).

For the present work, the values of α_1 and α_2 are determined from the Shettle and Fenn aerosol models so there is no need to know their values. However, for interest (Ångström 1961) reports that for average conditions in a wide range of locations $\alpha = 1.3 \pm 0.2$. He states that it is rarely outside the range 0.5 – 1.6, and is only below 0.5 if polluted by, for example, forest fire or volcanic eruption. (Iqbal 1983, p118) states that α is generally between 0.5 and 2.5 and that in most natural atmospheres $\alpha = 1.3 \pm 0.5$.

In SMARTS2 as it is used for this work, the transmission due to turbidity is a function of air mass, β , spectrum model and relative humidity.

Many different methods can be used to measure turbidity. Accurate measurement requires specialised instruments, but for this work, only a rough estimate of turbidity is required so a simple method is acceptable.

Accurate determination of turbidity requires the measurement of the spectral irradiance as a function of wavelength with a spectroradiometer. Alternatively, the spectral irradiance at a few discrete wavelengths can be measured with a sunphotometer. These methods allow the determination of both α and β . If the value of α is assumed using one of the previously mentioned models then a sun photometer measurement at one carefully chosen wavelength only is necessary. Spectroradiometers and sunphotometers are expensive pieces of equipment and have difficult calibration problems. Fortunately, it is possible to determine turbidity with moderate accuracy using only a broadband irradiance measurement. The only instrument required is a pyrheliometer, which should cost around US\$1500. This method is described in the following section.

Determination of turbidity from broadband irradiance

It is possible to determine turbidity without specialised instrumentation. Irradiance is affected mainly by air mass, turbidity, and water. Since air mass and water can be easily measured, turbidity can be deduced simply from an irradiance measurement. The method is described below, but can be used without a detailed understanding of how it works.

The method is described in (Gueymard 1998). Given a measurement of direct beam irradiance, and estimates of extraterrestrial irradiance and the broadband attenuation due to all processes other than turbidity, the remaining attenuation must be due to turbidity. Broadband transmittance, optical depth, and optical mass quantities can be developed in analogy to the spectral quantities discussed previously, giving the relationship shown in equation (2-9).

$$E_{bn} = E_{0n} T_R T_o T_n T_g T_w T_a \quad (2-9)$$

where $T_i = e^{-m_i \tau_i}$

The irradiance in space, E_{0n} , is attenuated by each of the transmission processes, T_i , to give the terrestrial beam normal irradiance, E_{bn} . The transmission processes, from T_R to T_a are: Rayleigh scattering, ozone absorption, NO₂ absorption, mixed gas absorption, water absorption, and aerosol scattering. For process i , the air mass is m_i and the broadband optical depth is τ_i . Note that these broadband quantities are subtly different to their spectral counterparts.

Equation (2-9) can be solved for the broadband aerosol optical depth, τ_a , which is closely related to the turbidity, β . To simplify the equation, the transmittances due to Rayleigh scattering, ozone, and mixed gases can be lumped together into a hypothetical clean dry atmosphere with optical mass m_R and optical depth τ_c .

$$\tau_a = \frac{1}{m_a} \left(\ln \left(\frac{E_{0n}}{E_{bn}} \right) - m_R \tau_c - m_w \tau_w - m_{nt} \tau_{nt} \right) \quad (2-10)$$

All quantities on the right-hand side can be either measured or estimated, allowing τ_a to be determined:

- The optical masses, m_i , can be calculated from time and location. For the conditions of interest in this work, all the optical masses are very similar and can be set equal to the air mass, AM.
- The extraterrestrial irradiance, E_{0n} , can be calculated from the date (it varies around the mean value 1367 W/m² by $\pm 3.4\%$ over the course of the year). Alternatively, E_{0n} is tabulated in figure 2-7.
- The beam normal irradiance can be measured with a pyrheliometer.
- The three optical depths, τ_c , τ_w , and τ_{nt} , can be calculated from empirical relationships presented in (Gueymard 1998). The functions are: $\tau_c(u_{ns}, u_o, p, m_R)$, $\tau_w(w, p, m_w)$, and $\tau_{nt}(u_{nt}, m_R)$, where u_{ns} and u_{nt} are the stratospheric and total amounts of NO₂ respectively, u_o is the amount of ozone, p is atmospheric pressure, and w is the amount of water. The atmospheric pressure can be calculated from the altitude and latitude and the amount of water can be determined from RH and ambient air temperature. As will be shown shortly, for the conditions of interest in this work the amounts of NO₂ and ozone have relatively little effect on the turbidity and typical values for u_n and u_o can be substituted if measurements are not available.

Having calculated τ_a , β can now be determined. In the case of $\alpha = 0$ (large particles), $\tau_a = \tau_{a\lambda} = \beta$. When $\alpha \neq 0$ the relationship is more complex. In (Gueymard 1998), an empirical relationship is presented that determines $\beta(w, m_a, \tau_a)$ for $\alpha = 1.3$ (the most common value for α). If $\alpha \ll 1.3$, which is possible for a maritime aerosol, then β will be underestimated. Fortunately, however, aerosols with low α have much less effect on spectral mismatch (as shown in Figure 2-6) and so the under-estimation is no concern. For example, for $AM = 2$, if $\alpha = 0.5$ (typical maritime α value), β will be underestimated by about 30%. The reduction in mismatch error going from $\alpha = 1.3$ to $\alpha = 0.5$, shown in figure 2-6, is much larger than this. If anything, the effect of overestimating α should be a reduction in spectral mismatch error.

The presence of light cloud may cause the broadband irradiance method to slightly over-estimate turbidity. However, this will very rarely be a problem when using the turbidity measurement to estimate spectral mismatch error for silicon cells. This issue is discussed in more detail in section 2.2.1.11.

An alternative broadband method for the measurement of turbidity uses the direct/diffuse ratio (Pinazo, Canada et al. 1995; Gueymard and Vignola 1998). The main effect of turbidity is to cause scattering, and the only other process that does this is Rayleigh scattering. Rayleigh scattering can be accurately determined from the air mass, so the remaining scattering must be due to turbidity. This method is insensitive to errors in precipitable water, ozone, and NO_2 , since they cause absorption only and therefore do not affect the direct/diffuse ratio. However, the accuracy with which diffuse irradiance can be measured is a serious limitation. Commonly available pyranometers are barely adequate when measuring low levels of turbidity. The method also requires two instruments – a pyrheliometer for direct beam irradiance, and a shaded pyranometer for diffuse irradiance. In contrast, the direct beam method for the determination of turbidity requires only a pyrheliometer. For these two reasons, the direct beam method was chosen to determine turbidity for this work.

Summarising all the previous steps, turbidity can be determined as a function of calculated values for air mass, atmospheric pressure, and extraterrestrial irradiance, measured values for precipitable water and direct beam irradiance, and assumed values for amounts of ozone and NO_2 . The full equation, $\beta(AM, p, E_{0n}, w, E_{bn}, u_o, u_n)$, is given in Appendix C.

Accuracy of turbidity determination from broadband irradiance

Gueymard tested the accuracy of turbidity determination from broadband irradiance by comparing the model predictions to experimental results. Accurate meteorological measurements (including turbidity) were made under a wide range of conditions at several different locations. The accurate measurements of turbidity were then compared to the method predictions.

- For hazy/humid conditions in summer at Cape Canaveral, Florida, β was predicted to within 0.02 of the true value 0.2-0.3. The level of NO_2 was assumed.
- For average conditions in summer at Albany, New York, β was predicted to within 0.02 of the true value ≈ 0.15 . Precipitable water was determined from surface humidity and the levels of O_3 and NO_2 were assumed.
- For clean dry conditions at Welby, Colorado, β was predicted to within 0.005 of the true value (0.02-0.04). For the dry conditions encountered ($w < 0.4$ atm-cm), the surface humidity method of estimating precipitable water exhibited significant errors. A more accurate sunphotometer method was used instead.

For the present work, measurements of ozone or NO_2 are unlikely to be available and only a surface humidity approximation to precipitable water is available. To test how large an error might result from assumptions of ozone and NO_2 levels and inaccurate measurement of precipitable water and irradiance, a small simulation was done. Spectra were generated using SMARTS2 for a range of atmospheric parameters (AM: 1, 1.5, 2; β : 0.01, 0.05, 0.2; w : 0.5, 2, 5 atm-cm; O_3 : 0.24, 0.34, 0.44 atm-cm; NO_2 : $1\text{e-}4$, $1\text{e-}3$, $5\text{e-}3$ atm-cm, Altitude: 0, 2 km). For each spectrum, the turbidity was estimated using the broadband irradiance method for several cases: first assuming perfect knowledge of the atmospheric parameters (the values used in SMARTS2 to generate the spectrum), and second assuming typical values for ozone (0.34 atm-cm) and NO_2 (0.2 atm-cm) and including errors in water ($\pm 20\%$) and irradiance ($\pm 1\%$). To incorporate the effect of errors in water and irradiance, all 4 possible combinations were tried ($w+20\%$, $E+1\%$; $w+20\%$, $E-1\%$; $w-20\%$, $E+1\%$; $w-20\%$, $E-1\%$). The difference between the ‘true’ turbidity value (the first case) and each of the approximate cases was determined and the case with the largest discrepancy chosen. Then the β errors for all the spectra were compared. For the worst spectrum, the turbidity estimation was in error by 0.03.

Given that some of these simulated error sources were also inherent in Gueymard’s experimental tests (he sometimes assumed levels of O_3 and NO_2 and there were measurement errors in water and irradiance), it can be concluded that the broadband irradiance method can determine turbidity to better than ± 0.04 . As will be seen in section 2.4.1, this is adequate to determine if atmospheric conditions will give low spectral mismatch error.

Plot of β as a function of precipitable water, air mass, and irradiance

The equation to determine β is a function of 7 variables so cannot easily be plotted. However, it can be simplified to a function of 3 variables with only minor loss of accuracy. The simplified function can be plotted, and is shown in figure 2-7. Use of the plot allows β to be estimated without typing in the lengthy code.

The simplifications to the β function are, firstly, the elimination of E_{0n} and, secondly, the assumption of typical values for p , u_o , and u_n .

Firstly, E_{0n} and E_{bn} can be combined into a single term since one is proportional to the other. The irradiance term in the simplified β function is the ratio: $E_{bn} \times 1367/E_{0n}$ (1367 W/m^2 is the mean value of E_{0n}). Values for E_{0n} are tabulated in figure 2-7.

Secondly, the three parameters p , u_o , and u_n have a relatively minor effect on the turbidity estimation. Little error results if typical values are assumed for them. To estimate how large this error is, extreme values for p , u_o , and u_n were tried and the resulting errors in β calculated. Over the entire range plotted in figure 2-7, the worst-case error in β due to the assumption of typical p , u_o , and u_n values is 0.02.

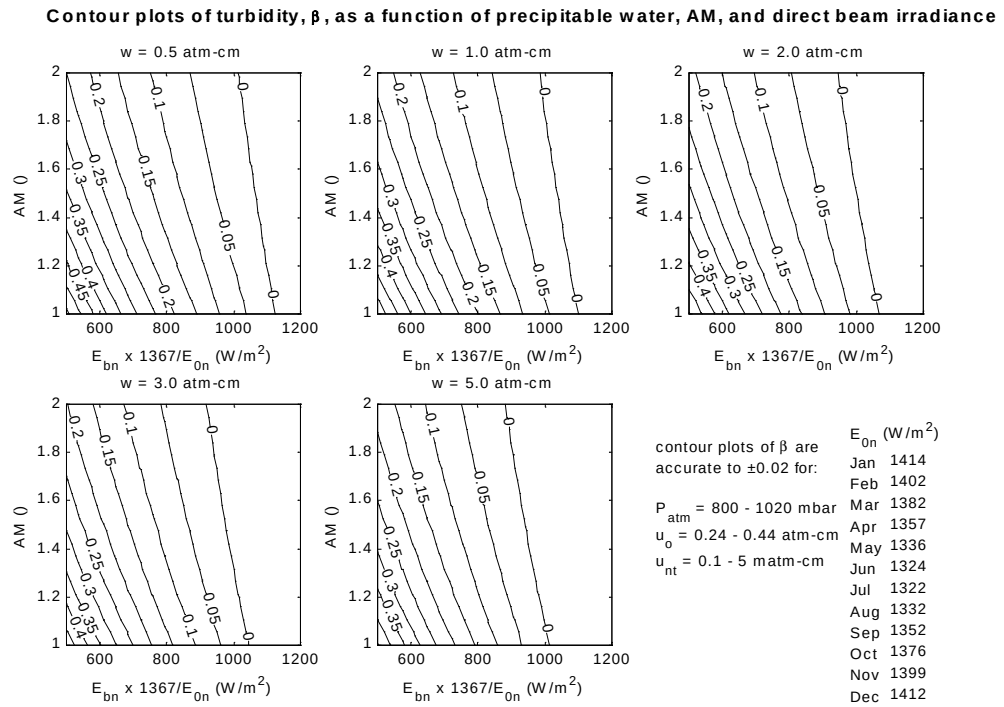


Figure 2-7: Contour plot of turbidity, β , as a function of precipitable water, AM, and direct beam irradiance.

Turbidity determination – summary

In summary, turbidity can easily be determined as a function $\beta(AM, p, E_{0n}, w, E_{bn}, u_o, u_n)$ to an accuracy of ± 0.04 . AM , p , and E_{0n} can be calculated from time and location, w and E_{bn} can be measured, and u_o and u_n can be assumed ($u_o = 0.34 \text{ atm-cm}$, $u_n = 0.2 \text{ matm-cm}$). Code to perform the calculation is given in Appendix C. Although this method requires a large number of calculations, with modern computers this is not a limitation. Alternatively, a simplified approximation to the function is plotted in figure 2-7.

2.2.1.6 Precipitable water

Precipitable water, w , is the total amount of water in a vertical column of the atmosphere. It is usually specified in terms of centimetres of liquid water. Water causes heavy absorption in bands in the IR beyond 900nm.

In temperate locations, w is usually in the range 1-3cm. In tropical locations, w may be as high as 5cm. In deserts or below freezing conditions, w may be as low as 0.5cm.

Highly accurate measurement of precipitable water requires radiosonde balloon soundings. Surprisingly though, it is possible to estimate precipitable water with sufficient accuracy using only ground level relative humidity and temperature. Precipitable water is given by eqn (2-11), derived from (Gueymard 1993a) and (Gueymard 1994). A contour plot of eqn (2-11) is shown in Figure 2-8.

$$\begin{aligned}
 w &= 0.1 H_v \rho_v \\
 H_v &= 0.4976 + 1.5265 \frac{T}{273.15} + e^{\frac{13.6897}{273.15} \frac{T}{273.15} - 14.9188 \left(\frac{T}{273.15} \right)^3} \\
 (H_v &\approx 2.2 \text{ for } T > 0^\circ\text{C}) \\
 \rho_v &= 216.7 \frac{R_H}{100T} e^{\frac{22.330 - 49.140 \frac{100}{T} - 10.922 \left(\frac{100}{T} \right)^2 - 0.39015 \frac{T}{100}}}{100T}
 \end{aligned} \tag{2-11}$$

where T is air temperature (K), and R_H is relative humidity (%). H_v and ρ_v are intermediate terms that are of no importance to this work.

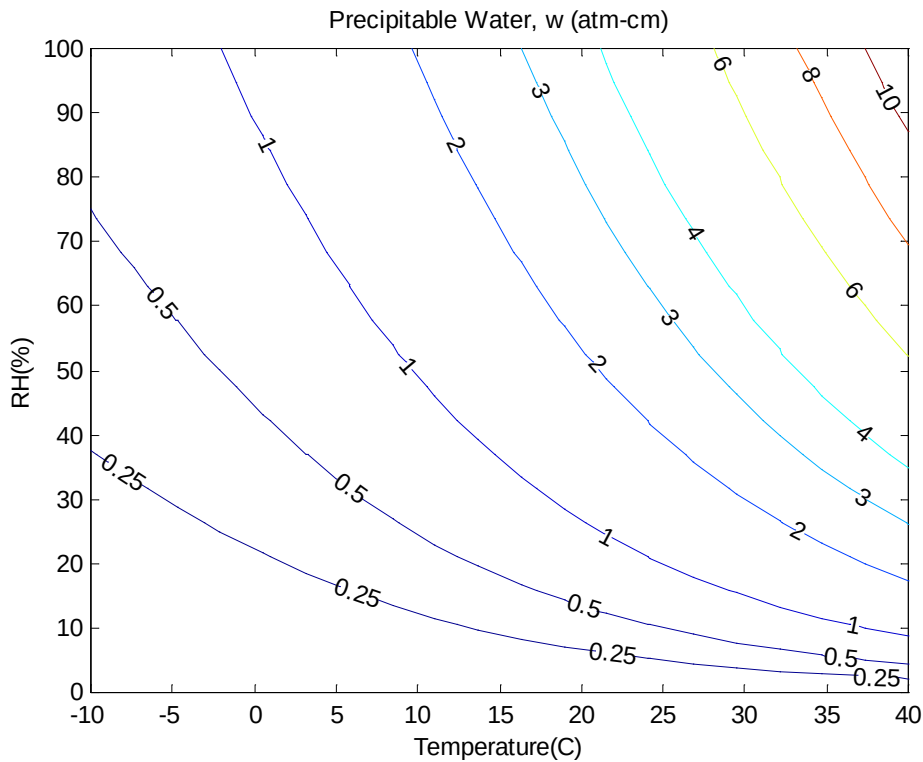


Figure 2-8: Precipitable water as a function of temperature and relative humidity

To determine the accuracy of this method (Gueymard 1993a) compared the predictions of eqn (2-11) to accurate measurements from various sources at Sault Ste. Marie, on the USA/Canada border. Monthly average values of surface temperature, surface humidity, and radiosonde soundings were used. He found that the predictions of eqn (2-11) were within the $\pm 10\%$ scatter of the accurate measurements. For an instantaneous measurement, the prediction may be a little less accurate than for the monthly averages. As a conservative limit, (Gueymard 1998) uses an accuracy of $\pm 20\%$ for the surface humidity method.

When $w < 0.5$ cm, this method becomes less accurate (Gueymard 1998, p428), for two reasons. Low w occurs either when the humidity is low – low humidity is difficult to measure accurately, or when the temperature is low – at low temperatures, inversion layers sometimes form so ground level measurements may be misleading.

2.2.1.7 NO₂

NO₂ occurs naturally in the stratosphere and artificially in the troposphere in urban environments. Stratospheric NO₂ has little effect on the spectrum, but in polluted environments tropospheric NO₂ can have a major effect. NO₂ absorbs in the blue, from 300 nm to 600 nm, making the spectrum redder. SMARTS2 is the first parameterised model to include the effect of NO₂.

As NO₂ has only recently begun to receive attention, there is little data on typical levels in urban environments. According to (Gueymard 1995b, p11), in an industrial city NO₂ measurements varied between 0.04 and 13 matm-cm, with a median value of 1.6 matm-cm. In (Gueymard 1998) a measurement of 2 matm-cm in Welby, Colorado is described as “moderate smog”, and 0.7 matm-cm is described as “clear”. Stratospheric NO₂ levels vary between 0.1 matm-cm in winter and 0.2 matm-cm according to (Gueymard 1995b, p11).

In SMARTS2, the transmission due to NO₂, $T_{n\lambda}$, is a function of air mass, amount of NO₂, u_n , ambient and average daily temperature, season, and altitude.

Measuring NO₂ requires specialised instrumentation. Fortunately, as will be seen in section 2.2.5, NO₂ has a small effect on spectral mismatch. This means that worst-case low and high levels of 0.1 and 5 matm-cm can be assumed. Only in exceptionally clear conditions will it be below 0.1 matm-cm and only in obviously smoggy, polluted conditions will it be over 5 matm-cm.

2.2.1.8 Ozone

Ozone absorbs very strongly in the UV and weakly in the visible. Although some ozone is present in polluted urban environments, it is insignificant compared to the stratospheric amounts.

Worldwide abundance of ozone has been well studied. According to (Iqbal 1983): average value 0.34 atm-cm, at the equator 0.24 ± 0.02 atm-cm, at the poles 0.34 ± 0.1 atm-cm, at 40°S, 0.33 ± 0.05 atm-cm. According to (Gueymard 1995b), ozone is normally in the range 0.2 to 0.5 atm-cm, with an average of 0.3416 atm-cm.

In SMARTS2 the transmission due to ozone, $T_{o\lambda}$, is a function of air mass, amount of ozone, average daily temperature, season, and altitude.

Measuring ozone requires specialised instrumentation. Fortunately, as will be seen in section 2.2.5, ozone has a very small effect on spectral mismatch. A typical value of 0.34 atm-cm can be assumed.

2.2.1.9 Accuracy of SMARTS2

The usefulness of outdoors testing of solar cells method relies on having a prediction of spectral mismatch error. The accuracy of the spectral mismatch error prediction depends on, amongst other things, the accuracy of the spectrum model. In this section, the accuracy of the spectrum model SMARTS2 is considered.

In the SMARTS2 documentation (Gueymard 1995b), the model accuracy was examined in two ways: first by comparing it to more sophisticated models, and second by comparing it to experimental measurements.

In the first case, the output of SMARTS2 was compared to that of BRITE (the model used to generate ASTM E891 and E892). Identical atmospheric conditions were fed into SMARTS2 as were used in BRITE. For the direct beam spectrum (ASTM E891 / AM1.5D), the outputs from the two models are barely distinguishable.

In the second case, the output of SMARTS2 was compared to measured direct beam spectra at Cape Canaveral, Florida, on a summer day (AM = 1.5). The spectra were measured with a LiCor LI-1800 spectroradiometer. Gueymard concluded that the differences between predicted and measured spectra were just within the uncertainty limits of the LiCor LI-1800 (approximately $\pm 5\%$ between 420 nm and 1100 nm).

These comparisons are only for a few isolated sets of atmospheric conditions, so they do not comprehensively prove the accuracy of the model. However, they do still give an indication of its accuracy.

2.2.1.10 Integration of SMARTS2 into spectral mismatch simulation

SMARTS2 is available as Fortran code (Gueymard 1995a) that reads an input file and produces one spectrum. To produce the several thousand spectra used in this work, a shell was written in LabVIEW to call the Fortran executable repeatedly. For each spectrum, three files were generated:

- A description file – listing all the parameter values that defined the spectrum, and some derived quantities such as integrated irradiance.
- A spectral irradiance file – the spectral irradiance as a function of wavelength.
- A PC1D spectrum file – essentially the spectral irradiance, but in the special format that PC1D requires.

The PC1D simulation was run on numerous computers simultaneously over many nights and was subject to frequent problems with computer crashes and missing files. To ensure that this did not introduce any subtle errors, control spectra were included in the process. Every 50th spectrum was a control, generated using identical atmospheric parameters. Since the input at the very beginning of the process was identical for each control, if all steps of the simulation process were running correctly the output files should have been identical. To confirm this, after all PC1D runs had been completed these control files were picked out and compared to ensure that they were all identical.

2.2.1.11 Influence of cloud on the solar spectrum

The spectrum model SMARTS2 only applies to clear sky conditions. In practice, however, slightly hazy or cloudy days might be the only conditions available. For this reason, it is interesting to get a general idea of the effect of cloud on the solar spectrum.

To a first approximation, for visible wavelengths, cloud is a neutral density filter. In the NIR there are absorption bands due to water vapour. Multiple reflections between sky and ground boost the irradiance at all wavelengths, but particularly in the UV (Nann and Riordan 1991). Under totally overcast conditions, causing a tenfold reduction in irradiance, UV was boosted by up to 100% and IR was $\pm 50\%$ for a normalised spectrum (Nann and Riordan 1990). Light cloud or haze, causing only a slight decrease in irradiance, would therefore cause no more than a few percent change at any wavelength. This is less than the uncertainty in SMARTS2 results.

Consequently, light cloud should have little effect on spectral mismatch. This prediction was confirmed during experimental verification of the modelling. The experiment, described in section 2.4.6.2, showed that a clearly visible cirrus cloud passing over the sun had a barely noticeable influence on cell measurements.

Although light cloud has little effect on the spectrum, it can still be problematic due to several other considerations.

Firstly, if a pyrhelimeter is being used to measure light intensity, fast moving clouds can introduce an error. Pyrhelimeters have a much slower response time than silicon cells – seconds vs. milliseconds. If the light intensity is changing on a timescale of seconds, the pyrhelimeter will not be in steady state and so will not give the true light intensity. This problem can easily be avoided by checking that the pyrhelimeter and cell readings are stable to within a percent or so over a few minutes.

Secondly, light cloud scatters light, and so will increase the amount of circumsolar radiation. This could introduce an error if the optical geometry of the pyrhelimeter is different to that of the collimating tube around the cell. However, for a properly designed collimator, this should not be a problem. This issue is discussed in section 2.2.7

Finally, light cloud will slightly upset the broadband turbidity measurement technique described in this work. Both cloud and turbidity scatter and attenuate light. Hence the broadband irradiance technique cannot distinguish cloud from turbidity. In the presence of cloud, turbidity may be over-estimated. However, the experiment described in section 2.4.6.2 showed that the overestimation is not serious. In the experiment, an obvious patch of cirrus only raised β from 0.033 to 0.038. For calibrating silicon solar cells, the over-estimation of turbidity is safe – it will not introduce unexpected errors in cell measurement. As is shown later, under most circumstances spectral mismatch error increases with increasing turbidity. So an over-estimate of turbidity will give an overly cautious estimate of spectral mismatch error. In other words, on a cloudy day the turbidity measurement may indicate that conditions are worse than they really are. The only exception to this rule is in the case of very high precipitable water. In this case, increasing turbidity will slightly decrease spectral mismatch error. However, very high precipitable water only occurs in tropical regions, where turbidity is high anyway. So the troublesome condition is unlikely to ever occur. In addition, the change in mismatch error is no more than 2 percent and so is not a great cause for concern.

In summary, accurate cell calibrations can be performed in the presence of barely visible cloud.

2.2.2 Solar simulator spectra

Typical spectra for several solar simulators were obtained to compare the quality of the simulators to natural sunlight. The spectra were determined by measuring data points off printed graphs. These spectra were then fed into PC1D exactly as the SMARTS2 modelled spectra were.

The solar simulators considered were:

ELH Lamp – a cheap projector lamp (approximately US\$10 each) with a Quartz Tungsten Halogen filament and a dichroic reflector that reflects only the visible. Requiring only the addition of a stable DC supply, these lamps are probably the most

popular way to build a low cost solar simulator. As will be seen later, for testing silicon solar cells the ELH spectrum is just as good, or sometimes even better, than xenon arc simulators costing orders of magnitude more. The spectrum is for the rated voltage of 120V and was obtained from (Emery, Myers et al. 1988).

Oriel 1kW Solar Simulator with AM1.5G filter – Oriel makes a range of continuous xenon arc solar simulators. Different filters are used to match the different standard spectra (AM0, AM1.5D, AM1.5G etc). These simulators cost at least US\$20,000. The spectrum was obtained from the Oriel catalogue (Oriel Corp. 1993, p28).

Spectrolab X-25 – a continuous xenon arc simulator. The main simulator used at NREL, so presumably the best technology available. Cost: about US\$200,000. The spectrum was obtained from (Emery, Myers et al. 1988).

The published graphs from which the solar simulator spectra were derived did not cover the full 0.3–4 μm wavelength range. The common range of all 3 was limited to 0.3–1.1 μm . Consequently, the mismatch under the solar simulators could only be determined for a silicon cell reference detector, and not for a thermal detector. In addition, since the solar simulator spectra available were optimised for AM1.5G, their performance at simulating AM1.5D was not tested. In the results section, the solar-simulator mismatch-error results are only shown for AM1.5G and a silicon reference.

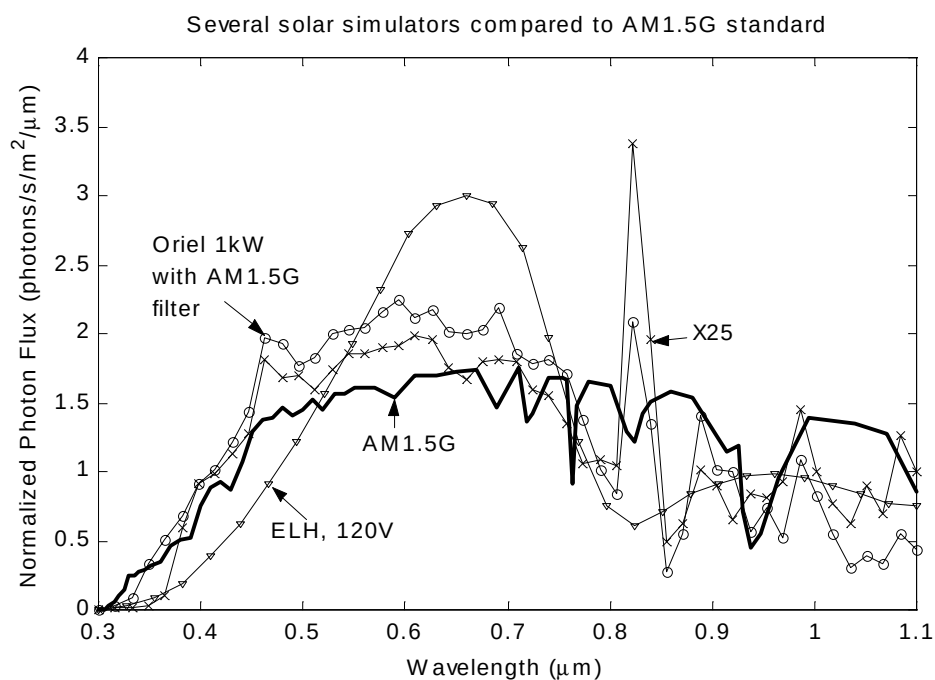


Figure 2-9: Plots of several solar simulator spectra compared to AM1.5G.

2.2.3 Cell modelling with PC1D

The spectral mismatch when testing a cell is dependent on both the source spectrum and the characteristics of the cell. To investigate the effect of cell characteristics, a group of cells was simulated with the one-dimensional semiconductor-modelling package PC1D.

There is no direct way to determine what sort of cell will show the largest mismatch error for a given spectrum and reference detector. To resolve this problem a set of cells was created that was representative of almost any crystalline silicon cell likely to be made. All of these cells were then simulated under each spectrum and the cell with worst mismatch error identified. The mismatch error for this cell was then taken to be the worst mismatch error for the given spectrum. Most cells would have a much smaller mismatch error than this worst cell, so it provides a conservative bound on the spectral mismatch error.

PC1D was used to calculate cell currents, rather than spectral responses. The spectral response formulation of spectral mismatch (eqn (2-3)) was not used because the spectral response of a solar cell is not a well defined quantity. It is difficult to measure and in fact varies depending on the spectrum and intensity of the light illuminating the cell. Consequently, in this work I_{sc} was directly simulated with PC1D, and eqn (2-1) used to calculate spectral mismatch.

2.2.3.1 Test-cell set

The test-cell set was a simulated group of cells, chosen to have characteristics representative of any likely crystalline-silicon solar cell. The cell design parameters described below determine the important generation and recombination processes within solar cells. Other parameters are of secondary importance. The values chosen for each of the parameters bracket the likely values to be found in a silicon solar cell. Thus, conclusions drawn for the cells modelled are likely to hold for almost any silicon solar cell.

Generation in a solar cell is determined by intrinsic properties of the semiconductor and by the following cell design features: front surface anti-reflection coating, encapsulation, texturing, front and rear internal reflectance, and cell thickness.

For encapsulation, texturing, internal reflectance, and cell thickness it is easy to choose representative values. The antireflection coating is not so simple however – it is tricky to consider comprehensively because there are so many possibilities, some of which could result in a very strange spectral response. However, a useful simplification is to exclude unusual coatings. The assumption is: if a cell is coated, the coating will be approximately an optimal design (i.e., it maximises current under AM1.5G). Consequently, three possibilities were modelled: no coating, an optimal single-layer-anti-reflection coating (SLAR), and an optimal double-layer-anti-reflection coating (DLAR). Each of these possibilities were considered textured and un-textured, and encapsulated and un-encapsulated, giving 12 possible front surface treatments. If the cell was encapsulated, the coatings were optimised for the presence of 3mm thick glass. PC1D was used to choose the optimal coating refractive indices and thicknesses by maximising current under AM1.5G. The resulting choices are shown in Table 2-3.

Table 2-3: Details of antireflection coating layers used in the modelling

	Un-encapsulated		Encapsulated	
	Refr. Index	Thick (nm)	Refr. Index	Thick (nm)
SLAR	1.95	80	2.40	62
DLAR Outer Layer	1.50	105	2.00	80
Inner Layer	2.65	53	3.00	44

The only likely exceptions to the optimal coating assumption are coloured cells made for architectural applications. They may have a quite unusual spectral response to get the desired colour. Depending on how unusual, the results of this work may not apply to them. However, compared to the effect of severe recombination losses on spectral response, the front surface coating is a relatively minor influence. The difference between a coloured coating and no coating is probably comparable to that between an optimal antireflection coating and no coating. As the latter case is included in the modelling, the results with coloured cells are unlikely to be dramatically wrong.

Texturing was modelled as 1 μm high pyramids at the crystallographic angle of 54.74° . PC1D's texturing model is limited – it includes the increased surface recombination and the longer optical path length through the silicon, but it does not include the decrease in front surface reflectance. However, the change in front surface reflectance due to texturing has a very weak dependence on wavelength, if any. It will cause a proportional change in reflectivity at all wavelengths, and so have no effect on the spectral mismatch. Hence, this limitation of PC1D can be safely ignored.

The front and rear internal reflectivities were modelled as diffuse at 50% or 100% reflectivity.

The recombination processes in a solar cell have many complex sources but can be summarised by four parameters – bulk minority-carrier lifetime, cell thickness, front-surface recombination velocity, and rear-surface recombination velocity. The following parameter ranges were used:

- Bulk minority-carrier lifetime 0.1, 30, 10 000 μs
- Front-surface recombination $10^3, 10^7$ cm/s
- Rear-surface recombination $10^3, 10^7$ cm/s
- Thickness 30, 100, 500 μm

The range of bulk lifetimes corresponds to diffusion lengths in the range $20\mu\text{m}$ -6mm. This should account for any cell design from thick extremely high quality cells to low quality multi-crystalline cells or very thin single crystal.

Doping levels (bulk and surface diffusions) affect V_{oc} and fill factor but in most cases have minimal influence on current. The only exception is that high doping levels increase recombination, leading in particular to 'dead' front surfaces. This effect is taken into account by the modelled variation in surface and bulk recombination rates, so there is no need to vary either the base resistivity or the n^+ and p^+ diffusions. The range of surface and bulk recombination rates used corresponds to open circuit voltages in the range 527-698 mV. This range includes everything from exotic lab prototypes to the best high performance cells.

Typical values were chosen for doping levels:

- Cell base resistivity: 1 ohm-cm ($n^+/p/p^+$).
- Diffusions: gaussian profile, 0.8 microns deep, maximum doping of $3 \times 10^{19} \text{ cm}^{-3}$ ($100 \Omega/\text{sq}$).

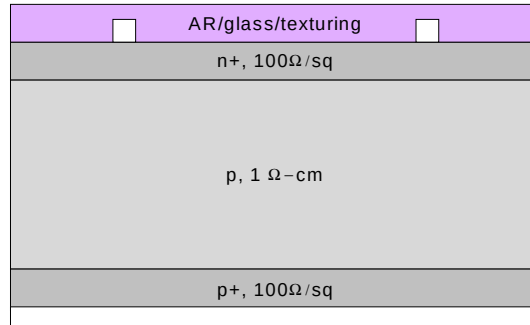


Figure 2-10: A schematic of the general cell design used in the modelling.

Table 2-4: Parameters values for the cells in the cell set. All possible combinations were generated.

Parameter	Values
Bulk Lifetime (n & p)	0.1, 30, 10 000 μs
Front Surface Recombination	$10^3, 10^7 \text{ cm/s}$
Rear Surface Recombination	$10^3, 10^7 \text{ cm/s}$
Thickness	30, 100, 500 μm
Front and Rear internal reflectivity	50, 100%
Texturing	Textured, or not textured
Front surface coating	bare silicon, bare silicon behind glass, optimal SLAR, optimal SLAR behind glass, optimal DLAR, optimal DLAR behind glass
Cell base resistivity	1 ohm-cm ($n^+/p/p^+$)
Diffusions	gaussian profile, 0.8 microns deep, maximum doping of $3 \times 10^{19} \text{ cm}^{-3}$ ($100 \Omega/\text{sq}$)
Material properties	as for single crystal silicon
Temperature	25°C

A summary of the parameter values used to define the cells in the cell set is shown in table 2-4. To give an idea of the range of cell performance that results from the parameter values in table 2-4, histograms of I_{sc} , V_{oc} , and efficiency for the cell set are given in Figure 2-11. The efficiencies given are for ideal cells with zero series resistance and infinite shunt resistance. Real cells with the same cell parameter values but including parasitic resistances would be 5-10% (relative) less efficient.

The spectral responses of all cells are shown in figure 2-12. Although the spectral responses of some of these cells may seem unrealistically good (particularly in the IR), bear in mind that these are meant to represent the very best silicon cells it is possible to make - 10 ms lifetimes, 10^3 cm/s surface recombination, perfect light trapping and double layer antireflection coatings.

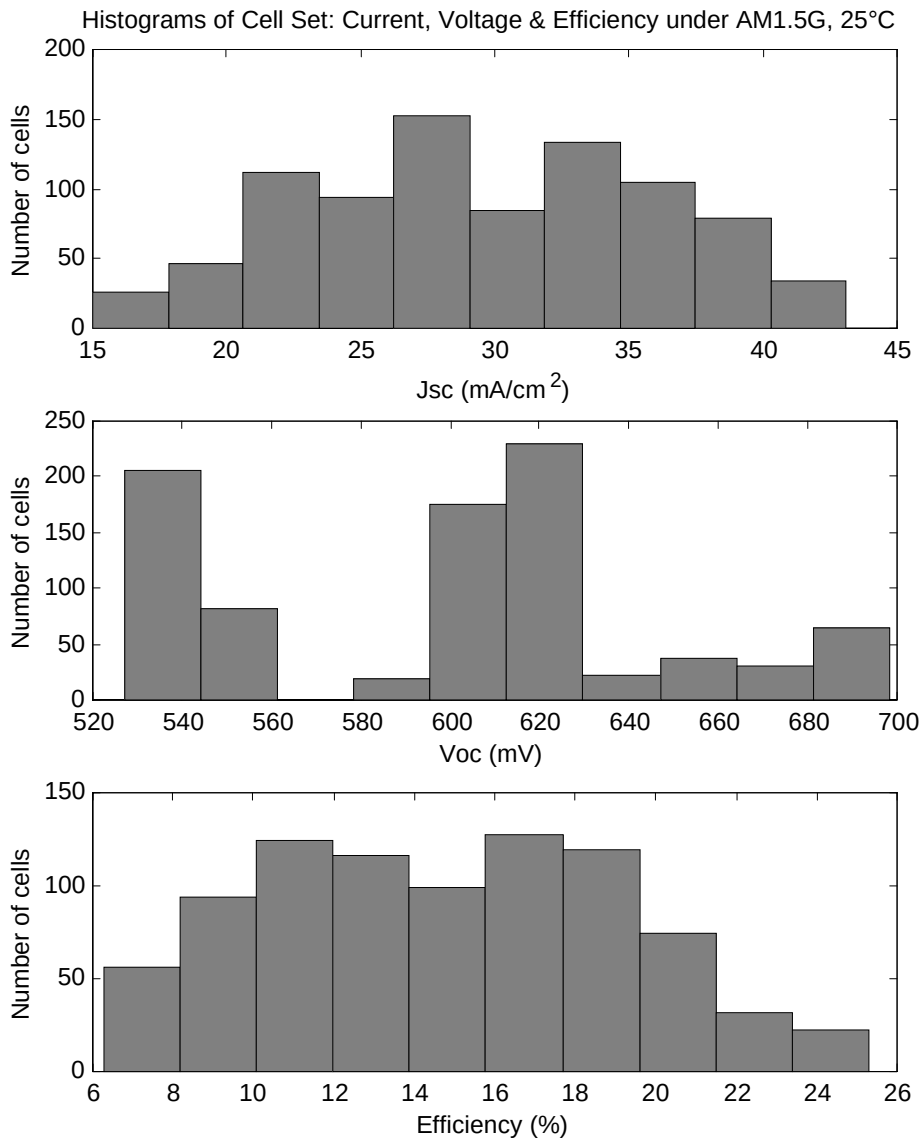


Figure 2-11: Histograms of cell set – current density, open circuit voltage, and ideal efficiency under AM1.5G, 25°C. There are 865 cells in the cell set, and each one was simulated under 1350 different spectra, giving 1.2 million combinations.

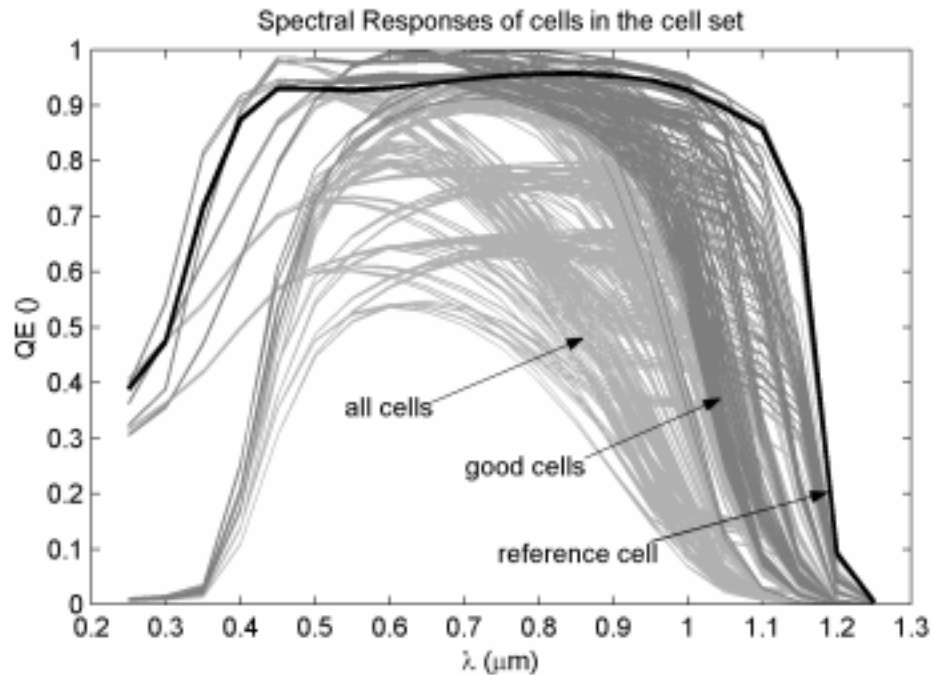


Figure 2-12: Spectral responses of cells in the cell set

The full cell-set includes some very poor cells. Reasonable quality cells will generally have lower mismatch error, so to consider the more common situation of testing reasonable cells, a ‘good’ subset of the full cell-set was also considered.

In practice, determining whether a cell is ‘good’ based on how it is constructed is difficult – many parameters, such as recombination, are hard to measure. In contrast, it is easy to tell whether a cell is ‘good’ from voltage and current density measurements. High voltage is an indication of low recombination, and high current is an indication of low recombination and good optical performance. As a rough guide, good quality commercial cells should have, under AM1.5G, $V_{oc} > 620$ mV and $J_{sc} > 35$ mA/cm² (for FF ≈ 0.75 , $\eta > 16\%$). The set of good cells was created by including only those cells that met the voltage and current density criteria. This subset included 177 of the original 865 cells.

It may seem a circular argument to use the cell current measurement to determine the accuracy of the cell current measurement, but it is possible since the typical range of current values is much larger than the measurement uncertainty. Even if a cell is assumed poor, its current can easily be measured to roughly 10% accuracy, as shown in the discussion section. The full cell set has AM1.5G J_{sc} ’s varying between 15 and 43 mA/cm², so with 10% accuracy cells with current > 35 mA/cm² can easily be identified.

2.2.3.2 Integration of PC1D into spectral mismatch simulation

The cells in the cell-set were simulated under a range of natural sunlight spectra using PC1D. PC1D (Basore and Clugston 1998) is a one-dimensional semiconductor-modelling package. It is commonly used for the design and optimisation of solar cells.

The accuracy of PC1D was less important in this work than the accuracy of SMARTS2. The objective of the cell simulation was not to predict the performance of any particular cell design, but rather to estimate the range of performance of the whole cell-set. Consequently, the accuracy of PC1D was less important than that of SMARTS2. In addition, the calculation of spectral mismatch error used only the relative change in cell current. Many potential error sources would cancel out when looking at relative changes. Given that PC1D is accurate enough to be used for design optimisation, it should easily be accurate enough for this application.

PC1D does not simulate three-dimensional effects. However, they are usually small and not spectrally selective, so this is not a limitation for this work.

PC1D provides a batch mode that allows many simulation parameters to be varied. A batch file was created that included all of the cell set and the reference cell. The batch file output was the short circuit current. The batch parameters used were: bulktaun(1), bulktaup(1), thickness(1), FrSn(1), FrSp(1), RrSn(1), RrSp(1), RrIntRefl1, RrIntRefl2, FrIntRefl1, FrIntRefl2, FrTxAngle, FrOutIndex, FrOutThick, FrMidIndex, FrMidThick, FrInIndex, FrInThick, BaseIsc

In PC1D, the spectrum cannot be varied under batch mode control. To automatically vary the spectrum, a shell was written in LabVIEW to drive PC1D. The shell controlled PC1D by sending keystrokes to it, as if a user had typed them on the keyboard. The operations it performed were: start PC1D, open the cell file, open the correct spectrum, open the batch file, start the simulation, wait for the simulation to complete, copy the simulation results, start a text editor, paste the results into the text editor, save the results, then close both the text editor and PC1D. This process was repeated for each spectrum.

PC1D was run on several computers simultaneously to process more files in the available time. As the process was unstable (it rarely went more than 12 hours without crashing the computer), control files were used to reduce the chance of mistakes. This is described in detail in section 2.2.1.10.

Experimentation with PC1D revealed that the AM1.5G spectrum file supplied with PC1D was a little inaccurate. The supplied spectrum file gave a current approximately 1% different to a spectrum file generated directly from the ASTM E892 AM1.5 global standard. This is probably because the spectrum supplied with PC1D has much less detail in the region 0.3-1.1 μm than that derived from ASTM E892. The more detailed spectrum file derived from ASTM E892 was used in the simulations.

PC1D has several numerical method parameters and it was found that the default values sometimes gave inaccurate results. In particular, the calculated I_{sc} varied by as much as 1% when the value of “element size factor” was decreased from the default 0.5 to 0.1. This problem was most noticeable in thick cells with high recombination ($\tau = 0.1 \mu\text{s}$, $S = 10^7 \text{ cm/s}$, thick = 500 μm). In such a cell, most carrier collection would be from within the front 20 μm . It seems likely that PC1D was using an insufficient number of nodes in the front surface region. The value of element size factor was set to 0.1, at which value I_{sc} was stable.

2.2.4 Calculation of spectral mismatch

Having simulated the current for each of the 865 cells under each of the 1350 spectra, the spectral mismatch was then calculated for the 1.2 million combinations.

For each sunlight spectrum generated with SMARTS2, PC1D simulated the current of every cell in the cell set. PC1D was also run to simulate the current of every cell under the standard spectrum (AM1.5D or G). The spectral mismatch, M , was then calculated using equation (2-1) for every cell under every spectrum. Two possible reference detectors were considered: a thermal detector, and a high quality cell in the cell set. For the thermal detector, the detector output, O_{det} , was the irradiance of the spectrum. For the silicon cell detector, the detector output was the cell current under the given spectrum.

With millions of cell/spectrum combinations, the size of the dataset was a serious limitation. Considerable attention had to be paid to the efficiency of the code – otherwise the computer ran out of memory. Crosschecks were included to reduce the chance of mistakes. First, the output from each PC1D run was compared to ensure that the run started with the same input batchfile (in other words, the same cell set). Secondly, each cell current under each spectrum was checked to see that it was a plausible value (10-52mA). The mismatch calculation and visualisation was done with MATLAB.

2.2.4.1 Reference detector options

For testing silicon solar cells, the most likely reference detectors are a thermal detector or another silicon solar cell. Thermal detectors are interesting because they give the most accurate measurement of irradiance. Silicon detectors are interesting because they will usually give lower spectral mismatch error than a thermal detector (though surprisingly not always, see section 2.4.2).

Thermal detectors are easy to simulate because they all nominally have the same spectral response – constant A/W.

Silicon detectors are harder to simulate. Different silicon cells can have widely different spectral responses. So it is not sufficient to specify simply that the reference detector is a silicon cell; it is also necessary to specify what kind of silicon cell. To test any given cell, the best choice of silicon detector is of course a very similar cell. But the luxury of an identical, calibrated reference cell is rarely available. So, given that a significantly different cell has to be used as the reference, in general what sort of cell is the best choice? The spectral responses of silicon cells can vary between good blue/poor infrared response and poor blue/good infrared response. Two cells at the two extremes will have maximum possible spectral mismatch error. So, a cell with an extreme spectral response is a bad choice. The best general choice is therefore somewhere in the middle. This is a cell with constant external quantum efficiency. The easiest way to get constant external quantum efficiency is to use a high performance cell – the fact that it is a very good cell shows that it must have close to unity external quantum efficiency for all wavelengths. Therefore, for this work, the silicon cell used as the reference detector is an excellent silicon cell.

2.2.4.2 Spectral response check of mismatch calculation method

Prompted by the surprising result that a cheap ELH simulator outperforms an expensive Oriel solar simulator (see section 2.4.4), the mismatch calculation method

based on cell currents was checked by calculating the mismatch from spectral responses instead. The spectral responses for the reference cell and one cell from the cell set were simulated with PC1D, using exactly the same parameters of cell construction as were used in the main method. The spectral responses are shown in Figure 2-13. The spectral mismatch was then calculated, using equation (2-3), for the ELH and Oriel spectra. The calculated mismatch errors, ε_M , for both the spectral response and the current methods agreed to better than 2% (relative). This confirms that the mismatch calculation method used in this work is valid.

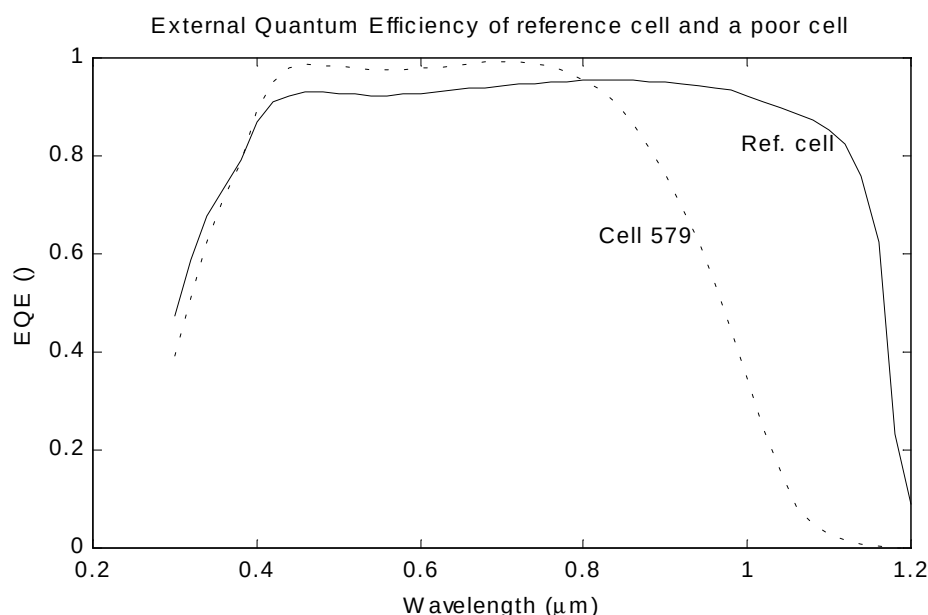


Figure 2-13: Spectral responses for reference cell and cell 579

2.2.4.3 Estimate of uncertainty in modelled mismatch

In this work, the spectral mismatch error is simulated using computer models. It is important to estimate the uncertainty in the simulated spectral mismatch error, as this may limit the usefulness of the method.

The spectral mismatch is predicted using the spectrum model, SMARTS2, and the cell model, PC1D. The accuracy of SMARTS2 is the limiting factor, as discussed in section 2.2.3.2. According to the documentation for SMARTS2, it is accurate to approximately the limits of a LiCor LI-1800 spectroradiometer (see section 2.2.1.9).

The uncertainty in spectral mismatch estimation, given known uncertainties in spectral irradiance and spectral response, has been extensively studied. This is discussed in section 2.1.4.1. The work by Field (Field and Emery 1993) is particularly useful because he considered the same spectroradiometer as Gueymard used to validate SMARTS2. Gueymard found that SMARTS2 was roughly accurate to within the limits of the LiCor LI-1800. Field found that use of a LiCor LI-1800 to measure the spectrum resulted in 0.2% uncertainty in spectral mismatch. Consequently, prediction of spectral mismatch from SMARTS2 should be accurate to $\pm 0.2\%$. However, The uncertainty estimates used by Field were for an unlikely worst case, whereas the

predictions of SMARTS2 were only just within LiCor LI-1800 uncertainty limits. Consequently, the $\pm 0.2\%$ uncertainty estimate is probably a bit optimistic. For this work, a more conservative value of $\pm 0.4\%$ is used.

In practice, the accuracy with which spectral mismatch can be predicted will be limited more by measurements of atmospheric parameters, not the modelling accuracy. For the simple techniques for atmospheric measurement proposed in this work, uncertainty in precipitable water and turbidity will probably be far larger than uncertainty due to the modelling.

2.2.5 Determining importance of atmospheric parameters

The spectral mismatch under natural sunlight is dependent on the sunlight spectrum, which is determined by a range of atmospheric parameters. In SMARTS2, the direct beam spectrum is affected by roughly a dozen parameters. As the first step in the mismatch simulation, a sensitivity analysis was conducted to work out the relative importance of the different parameters. This allowed many of them to be eliminated.

The direct beam spectrum is determined by the following SMARTS2 model parameters (from section 2.2.1.1): air mass, atmospheric pressure, ambient air temperature, average daily temperature, season, altitude, relative humidity, and amounts of NO_2 , ozone, water, and turbidity (u_n , u_o , w , β , α). Several of these can be eliminated immediately: relative humidity can be determined from precipitable water and ambient air temperature; air pressure can be approximated from the altitude and latitude; and α can be determined by choosing an aerosol model (as described in section 2.2.1.5, a worst-case model can be identified). This leaves 10 parameters that influence the spectrum and hence the spectral mismatch. Systematically varying all of these parameters over typical ranges would require a huge number of tests. In addition, it would be very hard to make sense of the resulting 10 dimensional variation. Therefore, as a first step, a sensitivity analysis was conducted to reduce the number of variables.

The objective of the sensitivity analysis was to determine how big an effect each atmospheric parameter had on the spectral mismatch, and hence to categorize the atmospheric parameters into 3 groups:

- 1) Parameters that have minimal influence on the mismatch and can be ignored. In the detailed simulation, these parameters were set to a typical value.
- 2) Parameters that have a small, but still significant effect on the mismatch. In the detailed simulation, these parameters were assigned 2 worst-case values: the highest and the lowest values likely to occur.
- 3) Parameters that have a major influence on the mismatch. In the detailed simulation, these parameters were varied in small increments over their typical range.

The sensitivity analysis was done using the method of 2 level factorial experimental design, as described in (Box, Hunter et al. 1978). Each atmospheric parameter was allowed to take 2 values: the highest, and the lowest, values that would commonly occur (something like 1 standard deviation either side of the mean value). Table 2-5 shows the parameter values used. Then all possible combinations of the parameter values were tested. For n parameters, this required 2^n tests. Each test consisted of generating a spectrum, simulating all cell currents under that spectrum, calculating the mismatch to the standard spectrum for each cell, and then choosing the highest (worst)

mismatch error. So for each test the output was the worst mismatch error under those atmospheric conditions.

Having determined the worst spectral mismatch error for each combination of the atmospheric parameters, the data was analysed to determine the effect of each parameter individually. This was done using the Yates algorithm, as described in (Box, Hunter et al. 1978). The Yates algorithm determines the main effect of each parameter and all the possible interactions.

The main effect of a parameter is the average change in the output due to changing that parameter (the output in this case is the worst-case mismatch error). For each parameter, the 2^n output values can be split into two groups: one where the parameter always takes its low value and the other where the parameter always takes its high value. The difference between the average output values of each group is the main effect of the parameter.

Interactions occur when the effect of a given parameter depends on the value of other parameters. This may occur when some processes magnify or counteract each other. For example, turbidity and precipitable water interact. The two processes somewhat counteract each other in their effect on spectral mismatch. Turbidity attenuates blue light, whereas water attenuates infrared. So the combination is a very rough approximation to broadband attenuation, which causes no spectral mismatch. When turbidity and water are low, (i.e. the spectrum is close to ideal) increasing either will make the mismatch error worse. However, if one of them is high, increasing the other may actually decrease the mismatch. So the effect of one parameter is dependent on the value of the other. Consequently, the main effect of a parameter only has quantitative significance if there are no interactions of significant size involving it.

No attempt was made to interpret the calculated effects quantitatively; they were only used to see which parameters were important.

The spectral mismatch error under the given atmospheric conditions was calculated for two standard spectra – AM1.5G and AM1.5D.

Table 2-5: Atmospheric parameter values used in the sensitivity analysis

Atmospheric Parameter	Low Value	High Value
Air mass (m)	1.1	1.5
Turbidity β (B)	0.02	0.1
Precipitable water (w)	1 atm-cm	4 atm-cm
Ozone (o)	0.3 atm-cm	0.4 atm-cm
NO ₂ (N)	2e-4 atm-cm	2e-3 atm-cm
Season (s)	summer	winter
Latitude (l)	25°	50°
Altitude (a)	0 km	2 km
Daily average air temperature (v)	15°	30°
Ambient air temperature (T)	10°	35°
Aerosol model	S&F Rural	

2.2.5.1 Effects of atmospheric parameters for AM1.5G standard spectrum

Table 2-6: Effects and interactions of atmospheric parameters for AM1.5G standard spectrum

Parameter	Effect (%)	Comments
	3.2	Over all of the spectra, the average worst-case mismatch error is 3.2%.
w	-2.2	Main effect of water: on average, raising water from 1 cm to 4 cm decreases mismatch error by 2.2%. However, see comments for Bw below.
B	1.8	Main effect of turbidity: on average, increasing turbidity from 0.02 to 0.1 increases mismatch error by 1.8%
Bw	-1.7	Interaction of β and water: as described above, turbidity and water counteract each other so there is a significant interaction.
m	1.3	Main effect of air mass: on average, increasing air mass increases mismatch error.
mB	0.6	Interaction of β and air mass: both turbidity and air mass attenuate blue light, and the combination does so even more strongly.
a	-0.4	Main effect of altitude: higher altitude decreases mismatch error.
mw	-0.3	Air mass / water interaction
N	0.2	Main effect of NO ₂ : increasing NO ₂ increases mismatch error.
–	–	all other effects < 0.1%. Includes ozone, season, latitude, ambient temperature, and average temperature.

The sensitivity analysis shows that, for the AM1.5G standard spectrum:

- 1) Ozone, season, latitude, and temperature have minimal influence on spectral mismatch error and can be ignored. It may seem surprising that ozone has so little effect on spectral mismatch, but in terms of the total number of photons (which determines cell current), its effect is in fact relatively small. Ozone is well known only because of the destructive effect of the high-energy photons. Zanesco (Zanesco and Krenzinger 1993) also found that ozone has little effect on cell current.
- 2) NO₂ has a small, but still significant effect on the mismatch.
- 3) Precipitable water, turbidity, air mass and altitude have a major influence on the mismatch.

2.2.5.2 Effects of atmospheric parameters for AM1.5D standard spectrum

Table 2-7: Effects and interactions of atmospheric parameters for AM1.5D standard spectrum

Parameter	Effect (%)	Comments
	3.9	Average worst-case mismatch error
w	3.0	Main effect of water
B	-2.5	Main effect of turbidity
Bw	-1.1	Interaction of β and water
m	-0.8	Main effect of air mass
mBw	-0.6	Interaction of β , water, and air mass
mw	-0.4	Air mass / water interaction
a	0.4	Main effect of altitude
N	-0.2	Main effect of NO ₂
Ba	-0.2	Interaction of β , altitude
mBa	-0.2	Interaction of β , altitude, and air mass
—	—	all other effects < 0.1%. Includes ozone, season, latitude, ambient temperature, and average temperature.

The sensitivity analysis for the AM1.5D standard spectrum shows essentially the same result as for the AM1.5G standard spectrum. The magnitudes of the effects and interactions are different, but the order is still the same. As for AM1.5G, air mass, turbidity, and water are the major influences on mismatch error. This is convenient as it lets one set of simulation results be used for both standard spectra.

2.2.6 Detailed simulation

Having determined which atmospheric parameters were important, a detailed simulation was run. The atmospheric parameter values used are shown in Table 2-8. They define 1350 different spectra. The 865 cells in the cell-set were then simulated under the 1350 different spectra, requiring over 1 million PC1D runs. The results are shown in section 2.3.1.

Table 2-8: Atmospheric parameter values used in detailed simulation

Atmospheric Parameter	Values
air mass	1.0, 1.2, 1.4, 1.6, 1.8, 2.0
Turbidity β	0.00, 0.02, 0.05, 0.1, 0.2
Precipitable water	0.5, 1, 2, 3, 5 atm-cm
Ozone	0.34 atm-cm
NO ₂	0.1, 1, 5 matm-cm
Season	summer
Latitude	40°
Altitude	0, 1, 2 km
Daily average air temperature	20°
Ambient air temperature	25°
Aerosol Model	S&F Rural

2.2.7 Circumsolar radiation and collimator design

Measuring cells under direct-beam radiation requires a collimating tube to restrict the cell's field of view to direct sunlight only. Circumsolar radiation, the diffuse light coming from the region of sky around the sun, can introduce errors if the collimator design is not correct. Circumsolar radiation is mainly due to aerosol scattering, and is strongest for large air mass, high turbidity, large aerosol particle size (i.e. maritime particulates), and high humidity (Gueymard 1998).

2.2.7.1 Errors due to circumsolar radiation

To measure solar cells under direct beam radiation, a collimator is needed to limit the field of view. If the collimator gives a different field of view to that of the pyrheliometer used to measure irradiance, an error in cell measurement will result. For example, if the collimator field of view is too wide, the cell will receive more circumsolar radiation than the pyrheliometer, and the cell current will be overestimated. This leads to the question: how accurately does the collimator geometry need to match that of the pyrheliometer?

The geometry of a typical instrument/collimator is shown in Figure 2-14. The geometry can be scaled to a detector of unit size by dividing all dimensions by r . The three angles are then given by:

$$\begin{aligned}\theta_s &= \arctan\left(\frac{R/r - 1}{L/r}\right) \\ \theta_a &= \arctan\left(\frac{R/r}{L/r}\right) \\ \theta_l &= \arctan\left(\frac{R/r + 1}{L/r}\right)\end{aligned}\quad (2-12)$$

The spectrum model SMARTS2 can generate direct beam spectra including the circumsolar radiation. The parameters required by SMARTS2 are the 3 angles, θ_s , θ_a , and θ_l . These can be determined by the two length parameters: R/r and L/r .

To determine how collimator geometry influences cell measurement error, a variety of different geometries were simulated with SMARTS2 while keeping atmospheric conditions constant. Cell current was estimated by multiplying the simulated spectrum by a typical silicon cell spectral response and then integrating. The nominal ‘true’ current was determined by simulating for geometry identical to a Kipp-Zonen CH1 pyrheliometer (the geometry of many common pyrheliometers are given in (Gueymard 1998)). The cell measurement error for each L,R point was then determined by dividing the estimated current by the ‘true’ current.

The magnitude of the cell measurement error depends on atmospheric conditions. The absolute worst-case conditions would be useless for cell measurement (which requires clear sky, low air-mass conditions), so there is little point estimating circumsolar radiation under these conditions. To determine the worst conditions that are still useful, a variety of conditions likely to give high circumsolar radiation, but still being plausible cell measurement conditions, were tried. Conditions that caused the worst cell measurement error were found to be: AM = 1.5, maritime aerosol, $\beta = 0.2$, $w = 5$ atm-cm.

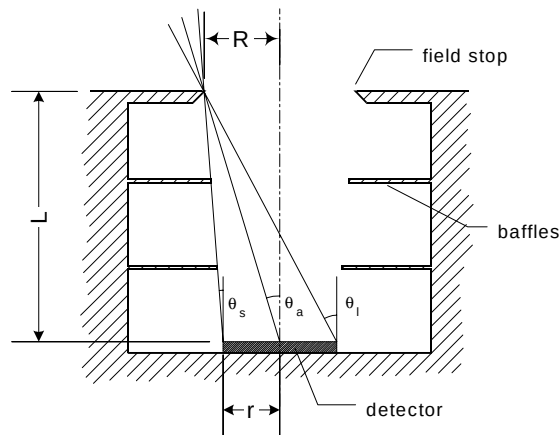


Figure 2-14: Geometry of a cylindrical collimator. The detector is of radius r , the field stop is of radius R , and the tube is of length L . Three angles are defined by this geometry: slope angle, θ_s , aperture angle, θ_a , and limit angle, θ_l .

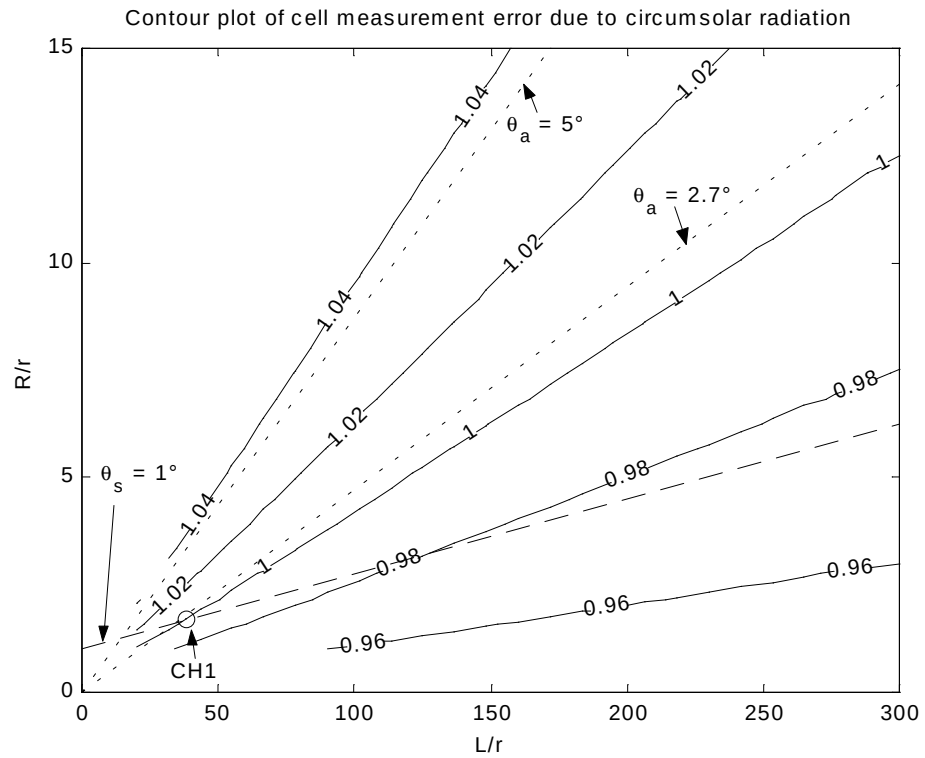


Figure 2-15: Contour plot of cell measurement error due to circumsolar radiation, as a function of collimator geometry. The point “CH1” is the geometry of a Kipp-Zonen CH1 pyrliometer.

The results of this calculation are plotted in figure 2-15. It can be seen that, for a given aperture angle, θ_a , the cell measurement error is nearly constant. For $L/r > \sim 40$ and $R/r > \sim 2$, there is only a minor dependence on the slope angle, θ_s .

This makes sense physically. Consider a collimator of fixed geometry in which the cell gradually increases in size (changing r (cell size) while R and L remain constant is equivalent to moving along a line of constant θ_a). As the cell size, r , increases (θ_s decreasing), the cone of sky seen by the edge of the cell tilts over. It will lose some circumsolar radiation coming from one side of its view and gain some from the other. If θ_s is similar to θ_a (a small cell), the loss and gain will be nearly symmetrical and so there will be very little change in the amount of light received by the edge of the cell. However, as θ_s becomes small (a large cell), the asymmetry of the distribution becomes important. Circumsolar radiation is brightest near the sun and drops off rapidly further from the sun. Hence, as the cone-of-view tilts a large amount, more circumsolar radiation will be lost from the region near the sun than is gained from the region further from the sun. Consequently, the edge of the cell will see less circumsolar radiation as r approaches R (eventually, if θ_s drops below 0.26° , part of the disk of the sun will be cut off and the edge of the cell will see a drastic reduction in radiation). The drop in circumsolar radiation for small values of θ_s can just be seen in the bottom left quarter of figure 2-16, where $L/r < \sim 40$ and $R/r < \sim 2$.

So, there is a dependence of circumsolar error on θ_s if $\theta_s < \sim 1^\circ$. However, provided $\theta_s > \sim 1^\circ$, changing θ_s will change the circumsolar error by less than 1%. In other

words, provided $\theta_a = 2\text{-}3^\circ$ and $\theta_s > \sim 1^\circ$, cell size can be changed without introducing a significant circumsolar measurement error. This is very convenient – it means that a collimator can be built to suit the largest cell likely to be tested, and the same collimator then used with any smaller cells. It also means that the collimator can be a different shape to the cell (eg, a circular collimating tube and a square cell).

Figure 2-16 shows a more detailed view of Figure 2-15, including the recommended design region for a collimator. It can be seen that the two commonly used pyrheliometers, CH1 and NIP, are noticeably different under these worst-case atmospheric conditions. It may be worth designing the collimator to suit the specific pyrheliometer being used.

The slope angle sets a lower limit on the size of the collimator, due to two considerations: the finite angular size of the sun, and practical limits on tracking accuracy. ASTM E1125 suggests a minimum value of 1.26° , derived from the 0.26° half-angle subtended by the sun and pointing and tracking errors of 0.5° . This limit is also above the level where slope angle begins to affect the circumsolar error.

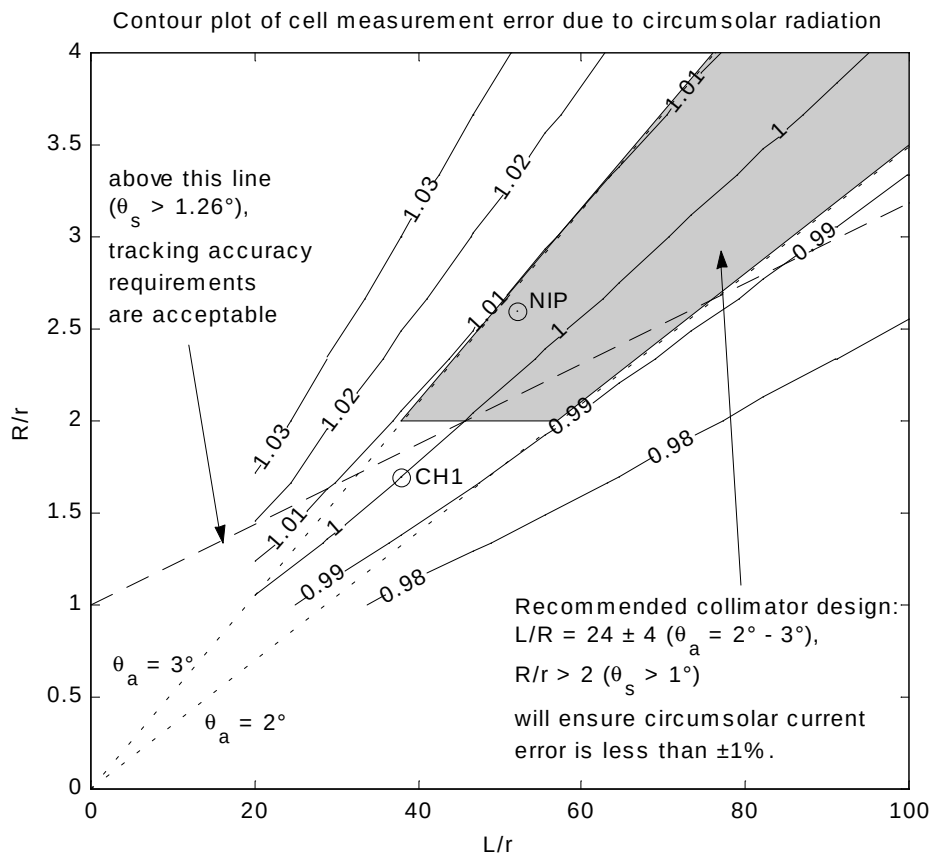


Figure 2-16: Contour plot of cell measurement error due to circumsolar radiation, as a function of collimator geometry. The points “CH1” and “NIP” are the geometry of Kipp-Zonen CH1 and Eppley NIP pyrheliometers.

2.2.7.2 Errors due to multiple reflections

It is possible for the cell to receive more light than expected, due to rays bouncing off internal surfaces in the collimating tube and ending up on the cell. However, this effect can be made insignificant by the use of baffles in the collimating tube, and by painting all internal surfaces black.

There are two main causes of reflection errors: capture of diffuse light from outside the defined aperture angle, and light trapping within the collimating tube.

Diffuse light from outside the defined aperture angle could reach the cell after bouncing off the walls of the collimating tube. For a plain cylindrical tube without baffles, many rays from twice the aperture angle will reach the cell after one bounce. If the aperture angle, θ_a , is increased from 2.5° to 5° , up to 4% additional radiation will be captured (figure 2-15). Most surfaces have higher reflectivity at grazing angle than at normal incidence. So, even if the walls of the collimating tube are painted black, an additional percent or two irradiance could be collected. If the collimating tube has baffles inside, however, it will be impossible for any ray to take a single bounce path to the cell. The only paths possible will involve multiple bounces, some of them at close to normal incidence. For a black painted surface, reflectivity at normal incidence will be less than 10%. After multiple reflections at less than 10% reflectivity, the ray will be reduced to a fraction of a percent of its original intensity. Hence, if the collimating tube contains black painted baffles the capture of additional radiation will be much less than 1%.

Light trapping could occur within the collimating tube due to rays that reflect off the cell, reflect off an internal surface of the collimating tube, and then back onto the cell. However, provided all surfaces are either perpendicular to, or parallel to, the incoming radiation, there will be no single bounce paths from the cell, to the wall, and then back to the cell. The most reflective cell likely is one with no antireflection coating. For such a cell, approximately 30% of the incoming irradiance will be reflected. Even if all these rays end up back on the cell, after several bounces off 10% reflective surfaces they will be reduced to much less than 1% of the incoming irradiance. Hence, if all surfaces inside the collimating tube are perpendicular to or parallel to the incoming radiation, and are painted black, the additional radiation due to light trapping will be much less than 1%. It is also advisable to blacken the surface on which the cell is mounted.

2.2.7.3 Recommended collimator design

A recommended collimator design is the smallest geometry that satisfies $\theta_a \approx 2^\circ - 3^\circ$ and $\theta_s > 1.26^\circ$. For a cell of radius r (for a cell that is not circular, r should be the radius of an enclosing circle – eg for a square, $r = \frac{1}{2}$ the diagonal), this is satisfied by:

$$\begin{aligned} R &> 2r & (\theta_s > 1^\circ) \\ \frac{L}{R} &= 24 \pm 4 & (\theta_a = 2^\circ - 3^\circ) \end{aligned} \quad (2-13)$$

The tolerances given ensure that the current error due to circumsolar radiation is less than 1% under worst-case conditions. These tolerances are easily met – such a collimator does not require precision machining. The same collimator can also be used

for any smaller cell. This design is similar to the recommendations of (ASTM E1125 1999).

The collimating tube should have baffles, and all internal surfaces should be either parallel to, or perpendicular to, the incoming radiation. All internal surfaces should be painted black, including the base where the cell is mounted. A picture of such a collimator, made at ANU, is shown in figure 2-20.

For cells or modules larger than about 10 cm diameter, the required collimator will be impractically large (>2m long). For this situation, it would be best to first calibrate, under direct radiation, a smaller cell or mini-module of identical construction. This reference cell can then be used to measure the full size module under global radiation. Since the spectral-response and angular-reflectance characteristics will be almost identical, very little extra uncertainty will result from the global measurement step. To minimise errors due to light trapping in encapsulated cells, the cell/module calibrated under direct beam radiation should be as large as possible.

2.2.8 Estimation of total measurement uncertainty

The total measurement uncertainty for the technique proposed in this work (measurement of I_{sc} under direct beam natural sunlight) is due to a large number of component uncertainties. The component uncertainty sources, and estimates of their magnitude, are listed in Table 2-9 (over page). The uncertainties given are U_{95} , or 2 standard deviations. Uncertainty calculations are performed in accordance with NIST standard practice (NIST-1297 1994).

It can be seen that, for measurement under direct beam natural sunlight and using a pyrheliometer to measure irradiance, the spectral mismatch error is much larger than any other source of uncertainty. The sum, in quadrature, of all uncertainty sources other than spectral mismatch error is 2.5%. When added, in quadrature, to a spectral mismatch error of at least 3%, the total I_{sc} measurement uncertainty is no more than 1% greater than the spectral mismatch error.

In summary, the relative uncertainty in I_{sc} measurement is given, to a good approximation, by: $\Delta I_{sc}/I_{sc} = \varepsilon_M + 1\%$.

2.2.9 Experimental verification of modelling

With any computer model of a real world phenomenon, it is important to perform physical experiments to confirm that the model is correct. This section describes the experimental verification of the spectral mismatch modelling.

The obvious way to verify the modelling would be to repeat, physically, the same process used in the simulations – take a set of cells, each one having previously been exactly calibrated, measure them outdoors under a range of atmospheric conditions, and compare the simulated and measured values. However, to obtain sufficient accuracy in the initial calibration would be very difficult and expensive. Under some conditions, the modelling predicts a mismatch error of only 1 or 2%, so the cell calibrations would need to be of better accuracy. Even the best calibration techniques available (primary reference cell calibration) do not meet this accuracy requirement. In addition, even if primary calibration were accurate enough, only a standards laboratory would be able to get a large number of cells calibrated this way.

Table 2-9: Uncertainty sources for I_{sc} measurement under direct-beam natural sunlight

Source of uncertainty	Uncertainty in I_{sc} (%)
Reference detector accuracy: secondary standard pyrheliometer; (silicon cell)	2%, Pyrheliometer; (5%, Silicon cell)
Field of view (circumsolar radiation, see section 2.2.7.3): $\pm 1\%$ worst case, $\ll 1\%$ normally.	$< 1\%$
Multiple reflections (see section 2.2.7.2):	$\ll 1\%$
Temperature control: $< 0.1\%$ increase I_{sc} per $^{\circ}\text{C}$, with $\pm 2^{\circ}\text{C}$ temperature control	$< 0.2\%$
I_{sc} linearity with irradiance (Emery, Osterwald et al. 1989)	0.1%
Electrical measurement accuracy: instruments (good hand-held meter)	0.1%
current sense resistor (temp. co. 100ppm, $\pm 10^{\circ}\text{C}$)	0.1%
Alignment: off normal incidence $\pm 1^{\circ}$ causes cosine error	0.01%
x, y, and z position (sunlight is extremely uniform)	$< 0.1\%$
Stray light (can check by blocking aperture)	$< 0.1\%$
Time constants (Emery, Osterwald et al. 1989)	0.1%
Root square sum of all uncertainties other than spectral mismatch	2.5%
<i>Spectral mismatch error</i>	<i>3-20%</i>

In this work, since it was not practical to get absolute calibrations for the cells, relative changes were examined instead. A diverse set of cells was assembled, and this cell set was then measured outdoors under a range of atmospheric conditions. The measured changes in cell currents were then compared to the simulated changes for the same atmospheric conditions.

The cells were measured in several different locations in southeastern Australia, all at latitude approximately 36°S – coastal (Kioloa, 0m), inland urban (Canberra, 600 m), and high altitude (Mt Ginini, 1762 m – shown in figure 2-1). The ranges of atmospheric conditions covered by the measurements were:

- altitude 0-1.8 km
- air mass 1.4-2
- precipitable water 0.5-2 cm
- turbidity 0.02-0.07

The range of atmospheric conditions was limited by what was naturally available within a convenient distance of Canberra. It does not cover the full range used in the modelling, since the modelling includes all conditions likely anywhere in the world. To obtain experimental data under higher levels of precipitable water and turbidity would require experiments to be performed in a more tropical location. Low air mass (around 1) was available in Canberra when measurements were started in midsummer, but problems with the experiment delayed getting useful data until the autumn equinox.

2.2.9.1 Cell set

The cell set used for experimental verification was chosen to contain a diverse range of cell technologies. It included very high performance cells, commercial quality screen-printed cells, low quality lab prototype cells, and cells specially created to be worst-case tests. The individual cells are described in table 2-10. During the experiments one of the cells (the Solarex multi-crystalline cell) failed. Consequently, it is not included in the results. This cell was difficult to solder to, so it is likely that the connection to the cell failed.

Table 2-10: Cells used for experimental verification of the natural sunlight modelling.

Cell name	Description	1 sun J_{sc} (mA/cm ²)
SunPower	SunPower concentrator cell – a high performance back contact concentrator cell	40
C68h, C36b	2 similar ANU concentrator cells – FZ silicon, textured, SiO ₂ antireflection coating, ~20% efficient @ 1X	39
LGBG	BP laser grooved buried grid cell – experimental concentrator cell – single crystal silicon, textured, unknown AR coating (possibly SiN).	35
BPCZ	BP screen printed cell – single crystal silicon (presumably CZ), textured, no antireflection coating	29
SMX	Solarex screen printed cell – multicrystalline silicon, TiO ₂ antireflection coating	-
Epilift	Lab prototype cell, made in a ~50µm thick epitaxial film. Poor quality silicon.	23
Epi	Thin epi-layer cell – cell made in a ~50µm thick epi-layer grown on a multicrystalline substrate. Substrate has very high bulk recombination, so cell is effectively only 50µm thick. Polished front surface and no rear surface reflector, so the cell has exceptionally poor IR response. A worst case test – good blue response, poor IR response	20
C139aa	ANU concentrator cell with a heavy front diffusion (25 Ω/sq), so high front-surface recombination. worst case test – poor blue response, excellent IR response	24

2.2.9.2 Measurement setup

The measurement setup consisted of a temperature-controlled block on which to mount the cells, a collimating tube, and equipment to measure the cell currents, direct beam irradiance, and other atmospheric conditions. The equipment was designed to be portable, so that measurements could be made in a variety of locations.

Temperature controlled block and collimating tube

The cells were mounted on a temperature controlled 20 cm square aluminium block. The block and cells can be seen in figure 2-18. The block was designed so that all points on the front surface would be at the same temperature $\pm 1^\circ\text{C}$. With 1 kW/m^2 absorbed on the front surface, and all of this heat removed by a Peltier cooler in the centre of the back surface, a block thickness of 4 cm was required. The cell temperature was set to 25°C throughout the experiments.

The collimating tube was designed according to the guidelines described in section 2.2.7.3. To illuminate all of the cells simultaneously (effectively considering the cell-block to be a single cell of 30 cm diameter) would have required an impractically large collimating tube – approximately 5 m long. Instead, the collimating tube was designed for the largest single cell, and the cell-block moved around to illuminate one at a time. The entire collimating tube can be seen in figure 2-1, and a view looking into the end is shown in figure 2-20. It is 1.5 m long, and is suitable for cells up to 7 cm diameter (the collimating tube was designed with future routine measurement in mind, not just this experiment). It has 4 baffles (which can be seen in the end-view), and all internal surfaces are covered with black felt.

A smaller collimating tube, of identical geometry to the main tube, was constructed to house a silicon reference cell. This was used to measure the light intensity, analogous to the pyrheliometer. The cell used was a SunPower concentrator cell. The reference tube was mounted on the side of the main tube.

The cell block was mounted in a light proof box. It was on a slide mechanism that allowed each cell in turn to be moved under the collimating tube. The box and slide mechanism can be seen in figure 2-19.

In an unsuccessful earlier experiment, a smaller collimating tube was tried. This tube was designed to illuminate all the cells simultaneously, and so had a smaller than recommended slope angle ($\theta_s = 0.5^\circ$) and a larger than recommended aperture angle ($\theta_a = 5^\circ$). It was thought that, with extra care, the tracking could be made accurate enough, and that circumsolar errors would be small enough not matter. However, this proved not to be the case – the measured variation in cell currents was much larger than the modelled variation. This prompted the construction of the collimating tube with correct geometry.

I_{sc} measurement

The cell currents were measured with a data acquisition card in a computer, allowing the measurements to be logged to disk. Cell currents were converted to voltages with shunt resistors. The shunt resistors were chosen so that cell voltages were approximately 100 mV at 1 sun. The resistors were mounted on the rear of the temperature-controlled block, so that temperature changes would not affect the measurement.

For cells with significant internal shunt resistance, use of an external shunt will not give the true short circuit current. However, since in this application only relative changes in current are of interest, the use of an external shunt resistance is adequate. As can be seen in figure 2-17, the external shunt is in parallel with the internal shunt – although the absolute value of current will not be correct, relative changes will be.

Measurements under natural sunlight will not be at constant light intensity, so nonlinearity in the cells could potentially introduce a small error. However, over the rather small range of light intensities likely to be encountered (0.7-1.1 suns), no cell should exhibit nonlinearity greater than a fraction of a percent. In this work, no attempt was made to measure the linearity of any of the cells.

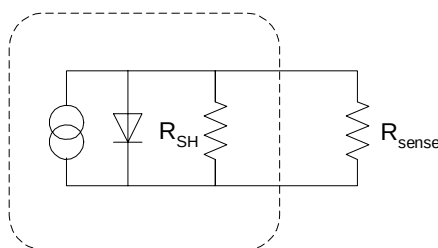


Figure 2-17: Equivalent circuit for a cell with significant internal shunting and an external shunt resistor

The data acquisition card used was a National Instruments MIO16XE50, which has 16-bit resolution. All nine cells could be measured simultaneously. To reduce noise, low pass RC filters were used on all inputs. The filters had corner frequencies of approximately 100 Hz ($R = 100 \Omega$, $C = 10 \mu F$). As a cross check that the data acquisition card remained accurate, individual cells were occasionally measured with a multimeter as well. This confirmed that the data acquisition card was always accurate to $\pm 0.1 \text{ mV}$. The accurate multimeter (a Fluke 85) was calibrated indoors, over the temperature range 25-55°C, using a highly accurate HP 34401 bench meter. To allow the temperature to be varied, the Fluke 85 meter was placed in an insulated box with a heater and fan. On the voltage range used (0-400 mV), the Fluke 85 meter was accurate to $\pm 0.1\% + 0.1 \text{ mV}$ over the full temperature range.

Meteorological instruments

Meteorological instruments were required to measure direct beam irradiance, relative humidity, air temperature, and air mass.

Direct beam irradiance was measured with a Kipp&Zonen CH1 pyrheliometer. Initial measurements used a TMI Mk VI active cavity radiometer (supposedly one of the most accurate instruments available). However, this particular instrument's last noted calibration was in 1982, and when it was compared to a recently calibrated Eppley NIP pyrheliometer it was found to be reading 10% low. After discovering this problem, the CH1 pyrheliometer was used instead. The CH1 was calibrated against the Eppley NIP.

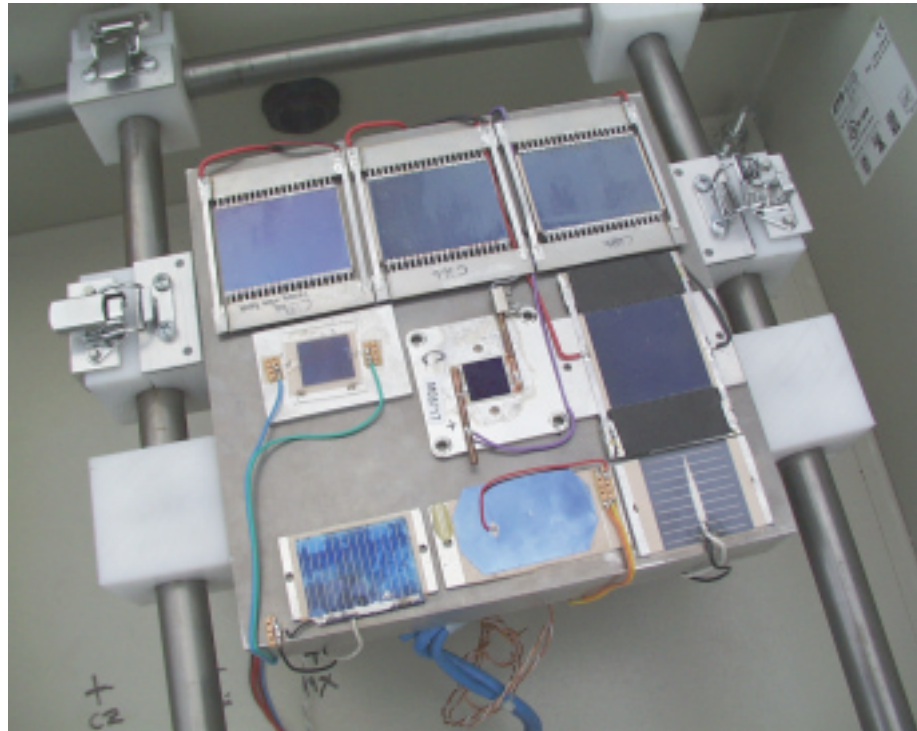


Figure 2-18: Temperature controlled block with the cells mounted on it

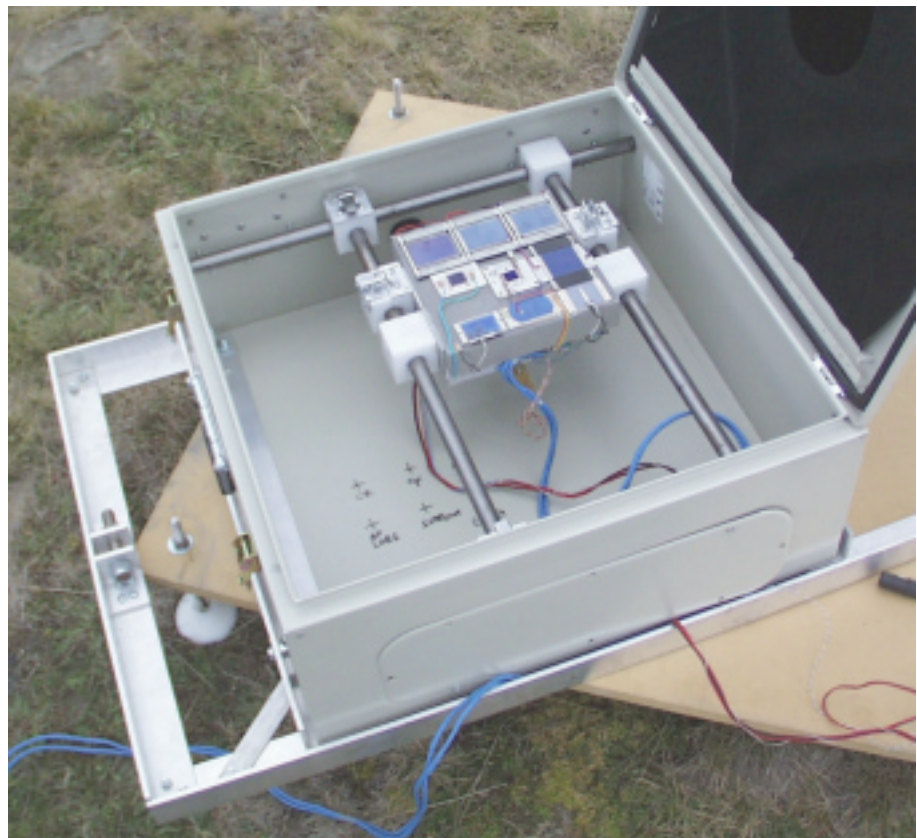


Figure 2-19: Lightproof box to contain the cells and slide mechanism

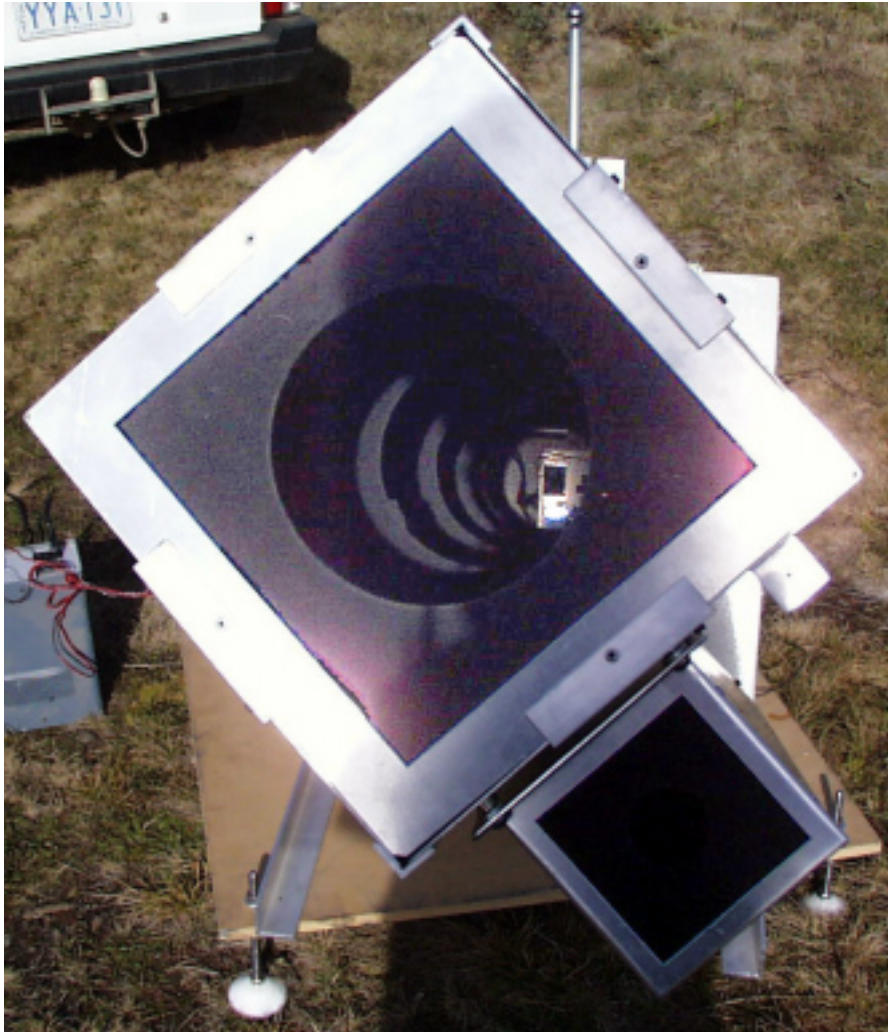


Figure 2-20: End view of the main collimating tube, with the reference tube on the side. A cell can be seen in the centre of the main tube.

Relative humidity and air temperature were measured with a Vaisala HM34 humidity and temperature meter. Temperature measurements were checked against a precision mercury thermometer, and found to be accurate to $\pm 1^\circ\text{C}$. Relative humidity and temperature measurements were also checked against Meteorological Bureau observations that were posted on the Internet the next day. The Meteorological Bureau and the locally measured values of relative humidity were sometimes different by up to 20%, but the calculated value of precipitable water was always within $\pm 5\%$. The Meteorological Bureau observations were for Canberra airport, which is 20km away, so this difference is understandable.

Air mass was calculated from time and location. To obtain accurate time measurements, the computer clock was synchronised to a time reference on the Internet (bernina.ethz.ch).

Data logging software

The measurement procedure was simplified considerably by data-logging software written for the purpose. The cell currents and the direct beam irradiance were measured by the computer. Only relative humidity and temperature had to be entered manually. The program calculated air mass, turbidity, and precipitable water from the time, direct beam irradiance, noted humidity, and temperature. All of this data, along with the measured cell currents, was logged to disk when requested. The program also kept the irradiance measurements for the preceding 2 minutes, allowing irradiance stability to be logged. This was useful for identifying data points that had been corrupted by fast moving clouds or tracking problems.

2.2.9.3 Measurement procedure

Measurement routine

The electrical aspects of the measurement process were largely automated, so taking a measurement required only the pushing of a button. The physical aspects of the measurement procedure – aligning the pyrheliometer and the collimating tube – were done manually.

Measurements were performed, approximately every 15-30 minutes, from when the sun rose past AM2 until it set past AM2 (typically from 9am-3pm). To ensure that everything was in steady state before taking each measurement, the irradiance stability was checked over the preceding two minutes. If the irradiance had varied by more than approximately 1%, measurement was halted until everything had stabilised again.

The routine, for each measurement of the cell set, was:

- read RH and temperature; enter into computer
- note anything interesting about the weather – cloud, wind, etc.

- repeat for all 9 cells (took ~5 minutes in total):
 - align pyrheliometer
 - open cell box, move appropriate cell into position, close box, align collimator
 - check irradiance stability, log data with computer

Measurement of temperature sensitivity of cells

To confirm that small inaccuracies in temperature control were not introducing noticeable measurement errors, the temperature sensitivity of I_{sc} was measured for all the cells. The measurement was performed over 10 minutes, on a clear stable day near solar noon. This ensured that the irradiance and the spectrum were very nearly constant ($E = 960 \text{ W/m}^2 \pm 0.3\%$). The measurement used the ‘old’ collimating tube, which allowed all 9 cells to be illuminated simultaneously. The results are shown in table 2-11.

During normal measurements, the controller maintained the temperature of the cell block to within $\pm 2^\circ\text{C}$. Consequently, I_{sc} measurements would change by no more than $\pm 0.3\%$ due to temperature changes. Compared to the several percent variation in I_{sc} expected due to spectral changes, this is sufficiently small to be ignored.

Table 2-11: Relative change in I_{sc} as a function of temperature, at 1 sun

Cell Name	$(dI_{sc}/dT)/I_{sc}$ (%/°C) at 1 sun	Cell Name	$(dI_{sc}/dT)/I_{sc}$ (%/°C) at 1 sun
SunPower	0.05	SMX	0.07
C68h	0.11	Epilift	0.06
C36b	0.17	Epi	0.17
LGBG	0.08	C139aa	0.12
BPCZ	0.03		

2.2.9.4 Data analysis

The objective of the experimental verification was to compare the changes in measured cell currents to the changes in simulated cell currents for the observed range of atmospheric conditions. If the simulations were accurate, the variation in measured results should have been smaller than the variation in simulated results.

The experimental and the simulation results were in slightly different formats, so some processing was required to allow comparison. The experimental results could be considered as a set of measurement data points, each data point consisting of I_{sc} for the 9 cells, light intensity (measured both with a reference cell and a pyrheliometer), and the atmospheric conditions at that time (AM, β , w , and altitude). The simulation results, in contrast, could be considered as simulated I_{sc} values for many cells (865) and irradiance, as a function of AM, β , w , altitude, and NO_2 .

The first step in the data analysis was to extract the simulated currents, for all 865 cells, at the exact atmospheric conditions observed for each measurement data point. This was done by linear interpolation from the simulation data set.

The atmospheric conditions for each measurement point were not known exactly – w & β were estimated using relatively inaccurate techniques, and NO_2 was not known at all. It would not be fair to compare the simulated variation in I_{sc} , assuming perfect knowledge of atmospheric conditions, to the measured variation in I_{sc} – the measured variation in I_{sc} could be due to error in the estimation of w & β as much as actual variation in w & β . To allow a fair comparison, simulated I_{sc} values were extracted at the estimated limits of w , β , and NO_2 values as well as at the nominal values. So, for each measurement point, simulated I_{sc} values were extracted for 27 different spectra – at $NO_2 = 0.1, 1, 5$ matm-cm, $w = w_{nom}-20\%, w_{nom}, w_{nom}+20\%$, and $\beta = \beta_{nom}-0.04, \beta_{nom}, \beta_{nom}+0.04$.

The cell currents were then divided by the light intensity (the measured currents by the measured light intensity, and the simulated currents by the simulated light intensity). In both the measured and the simulated data 2 choices of reference detector were used – a good silicon cell or a pyrheliometer.

To show the relative change in cell currents, all cell currents were normalised. The normalisation, for each cell, consisted of dividing every I_{sc} value by the mean of all I_{sc} 's for that cell (so, in other words, after normalisation the mean I_{sc} of every cell was 1).

Finally, the scaled, normalised currents were plotted as a function of time. For the measured results, there were only nine cells so they could all be plotted. For the

simulated results, there were a very large number of cells so the range of values was plotted. The results are shown in figure 2-29, and are discussed in section 2.4.6.

2.3 Results

This section gives the results of the simulations and experiments. No analysis of the results is given here; discussion follows in section 2.4.

2.3.1 Simulation results

The results of the simulations are given below. These results are discussed in the following section, 2.4.

In the simulation process, a group of cells was simulated under a range of natural sunlight spectra. For each cell/spectrum combination, the spectral mismatch was then calculated with respect to the two standard spectra, AM1.5G and AM1.5D. The worst-case mismatch error was then chosen for each spectrum. The simulation results are shown in Figures 2-21 to 2-26. These are contour plots of worst-case spectral mismatch error (ϵ_M) as a function of the three most important atmospheric parameters – air mass (AM), precipitable water (w), and turbidity (β). NO_2 and altitude vary in the background. At each point on the graphs, the worst-case ϵ_M was chosen out of all the NO_2 , altitude, and cell possibilities.

The worst-case spectral mismatch error is for the worst cell out of a group of 865 – most cells will have lower spectral mismatch error. To give an idea of the spread of mismatch error values, figures 2-27 and 2-28 show histograms of ϵ_M values (these histograms could be considered as views of the z direction on the worst-case ϵ_M plots).

Plots are shown for two standard spectra, AM1.5G and AM1.5D. For AM1.5G, plots are shown for the four combinations of two reference detectors and two cell sets. The reference detector is either a pyrheliometer or a silicon cell, and the cell set is either the full cell set, discussed in section 2.2.3.1, or the good subset (the good subset is the group of cells with $V_{oc} > 620$ mV and $J_{sc} > 35$ mA/cm²). For the AM1.5D standard spectrum, the good cell set only is shown. This is because the AM1.5D spectrum is only used for concentrator cells, which are usually much higher performance than 1-sun cells.

For AM1.5G and a silicon cell reference detector, the results for several solar simulators are shown as well (NB: they are just a single line of text at the bottom of figures 2-22 and 2-24).

The accuracy with which worst-case spectral mismatch error can be estimated under real testing conditions depends on both the accuracy of the modelling and the accuracy with which atmospheric conditions are measured. As described in section 2.2.4.3, the accuracy of M prediction is $\pm 0.4\%$ relative (eg, $M = 1.06 \pm 0.4\%$). If M is close to 1, the uncertainty in ϵ_M will be approximately $\pm 0.4\%$ absolute (eg $\epsilon_M = (6 \pm 0.4)\%$). Hence, Figures 2-21 to 2-26 are accurate to approximately ± 0.4 . If precipitable water is determined using the RH and T method, it will be accurate to approximately $\pm 20\%$. If turbidity is determined using the direct beam irradiance method, it will be accurate to approximately ± 0.04 . The uncertainty in air mass determination is minimal since it is determined from the very well known quantities of time and location.

2.3.1.1 AM1.5G, all cells

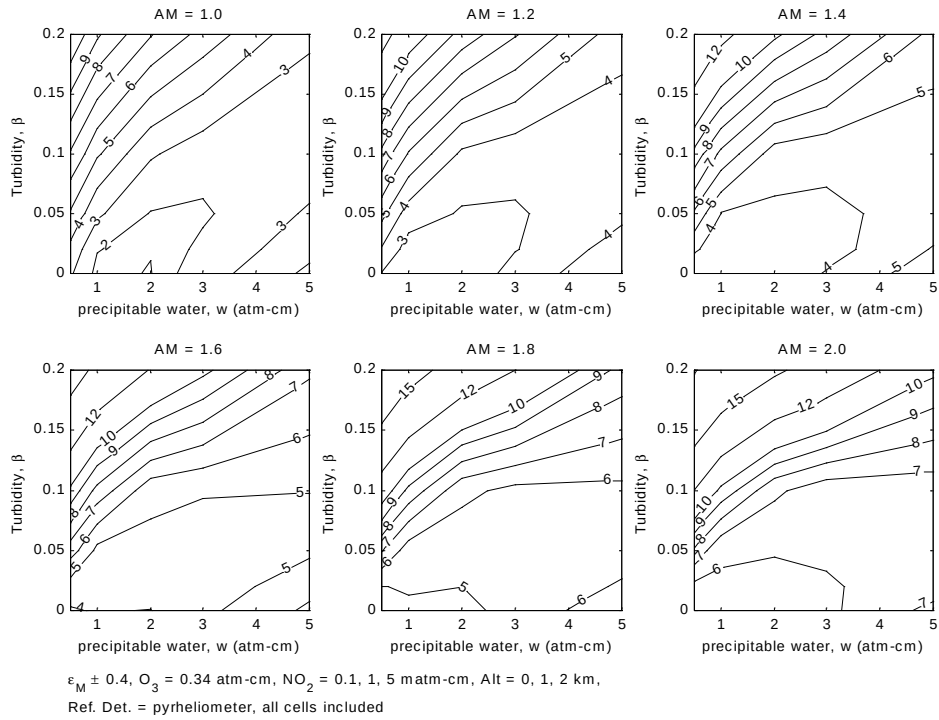
Worst case spectral mismatch error, ϵ_M (%)

Figure 2-21: Worst-case ϵ_M (%). Reference detector: Pyrheliometer, Standard spectrum: AM1.5G, All cells included.

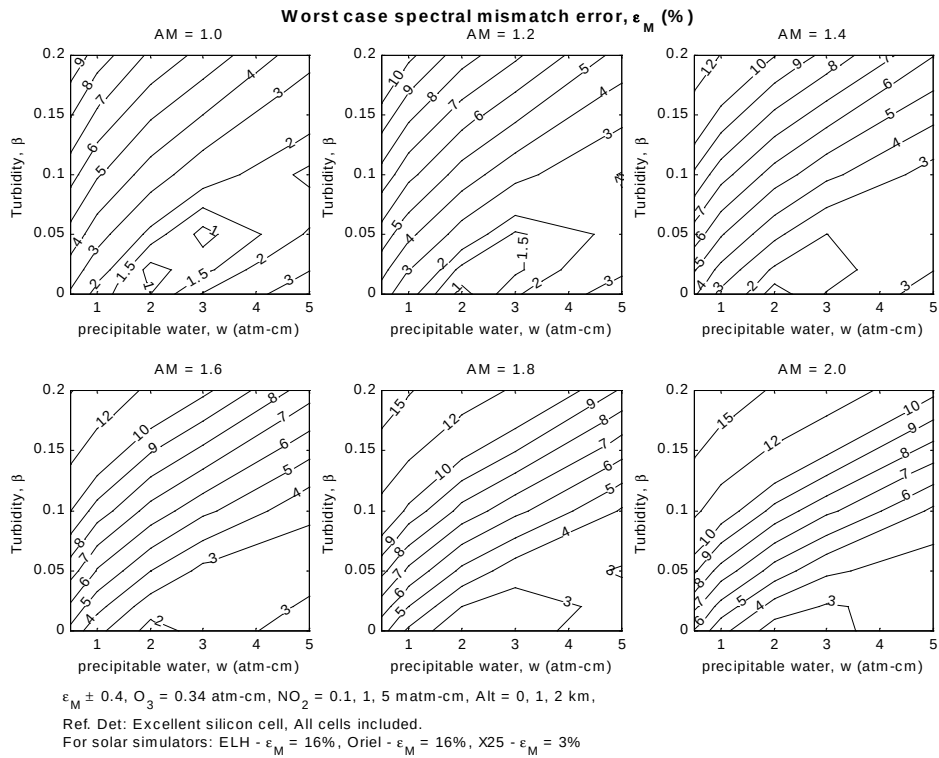


Figure 2-22: Worst-case ϵ_M (%). Ref. det.: Excellent silicon cell, Standard spectrum: AM1.5G, All cells included. Comparative figures for solar simulators at bottom.

2.3.1.2 AM1.5G, good cells

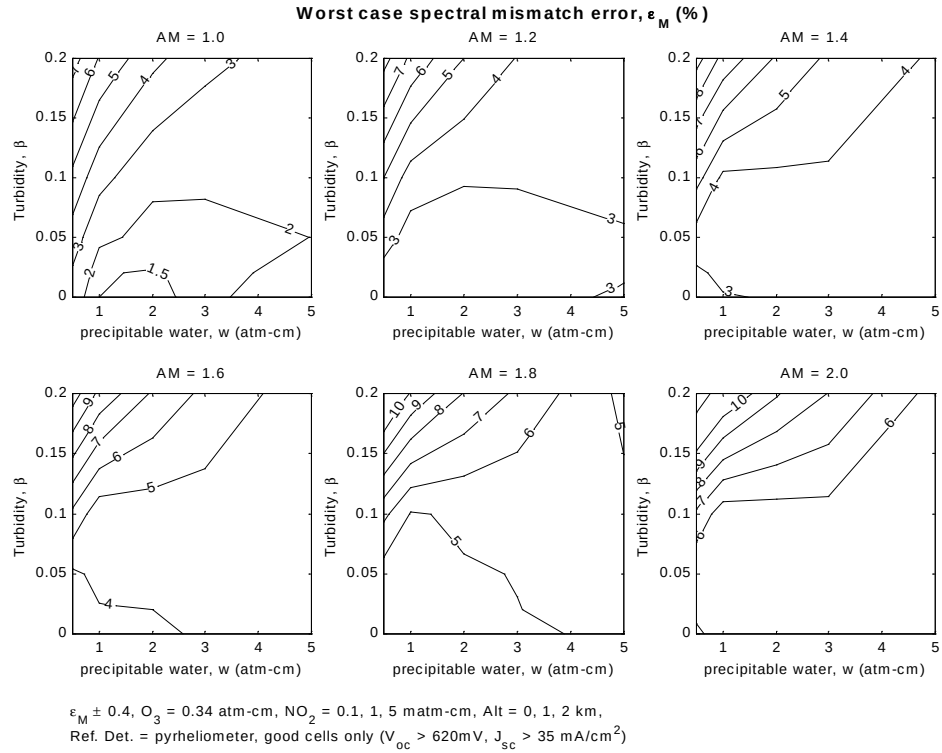


Figure 2-23: Worst-case ϵ_M (%). Reference detector: Pyrheliometer, Standard spectrum: AM1.5G, Only good cells included.

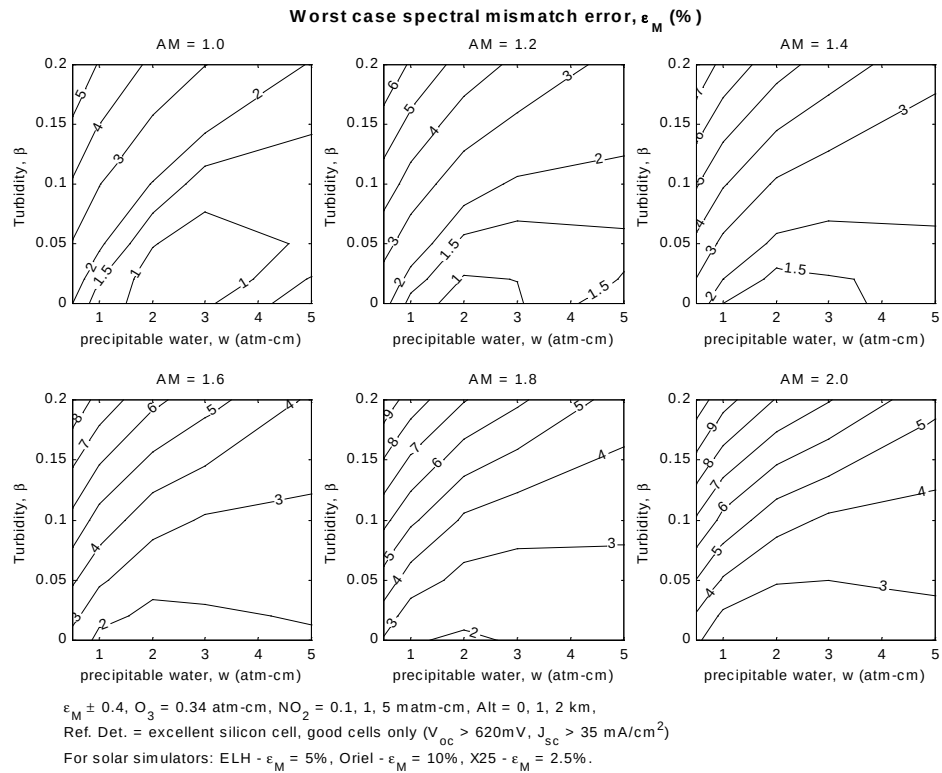


Figure 2-24: Worst-case ϵ_M (%). Ref. det.: Excellent silicon cell, Standard spectrum: AM1.5G, Only good cells included. Comparative figures for solar simulators at bottom.

2.3.1.3 AM1.5D, good cells

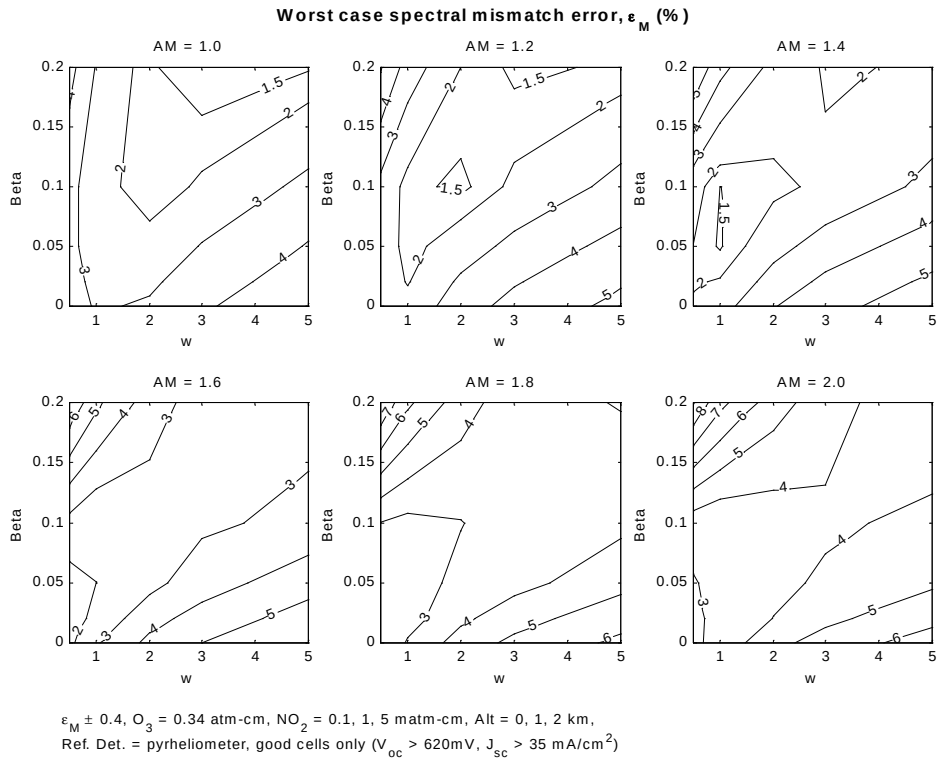


Figure 2-25: Worst-case ϵ_M (%). Reference detector: Pyrheliometer, Standard spectrum: AM1.5D, Only good cells included.

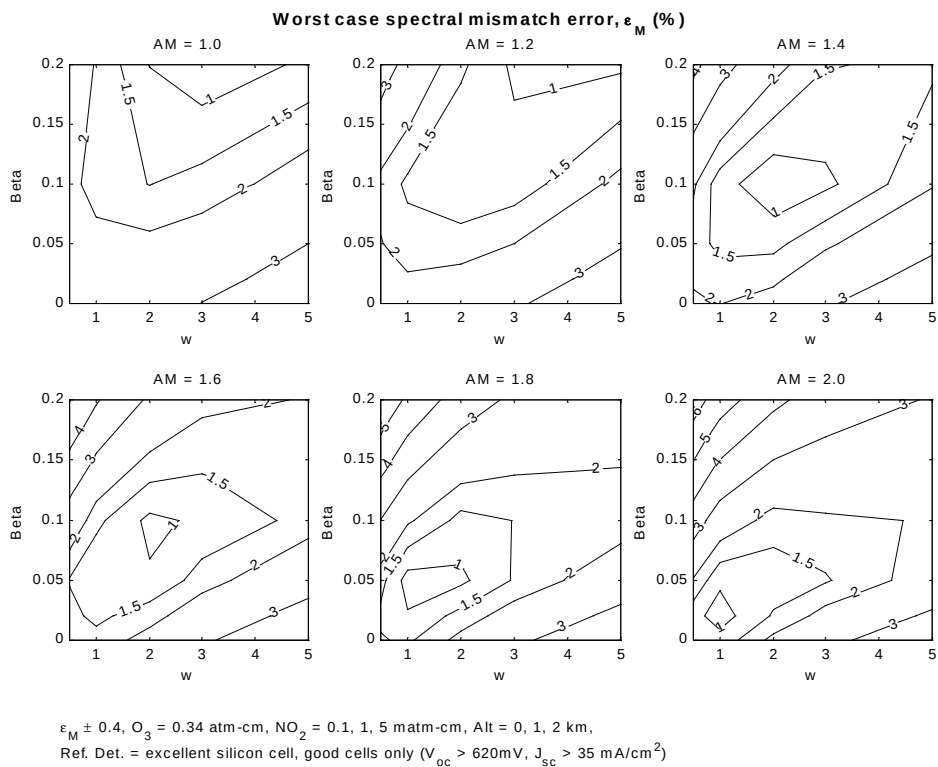


Figure 2-26: Worst-case ϵ_M (%). Reference detector: Excellent silicon cell, Standard spectrum: AM1.5D, Only good cells included.

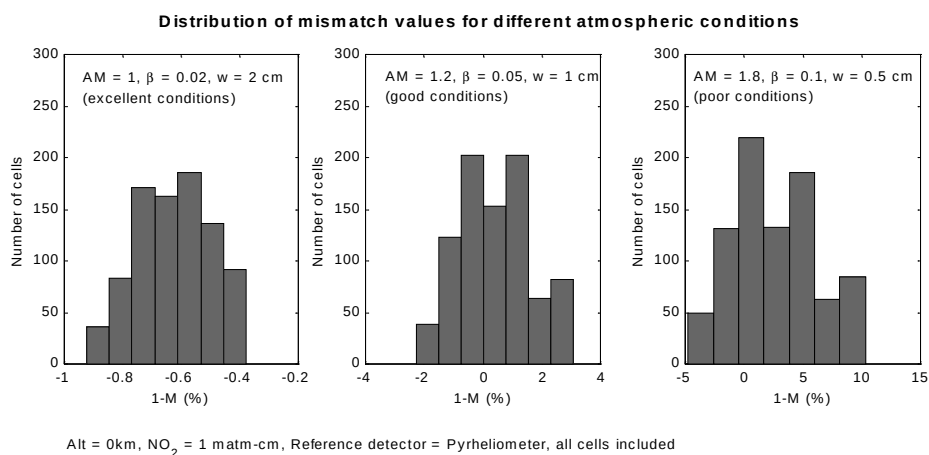


Figure 2-27: Distribution of mismatch values for different atmospheric conditions, reference detector = pyrheliometer, standard spectrum = AM1.5G (3 points in figure 2-21)

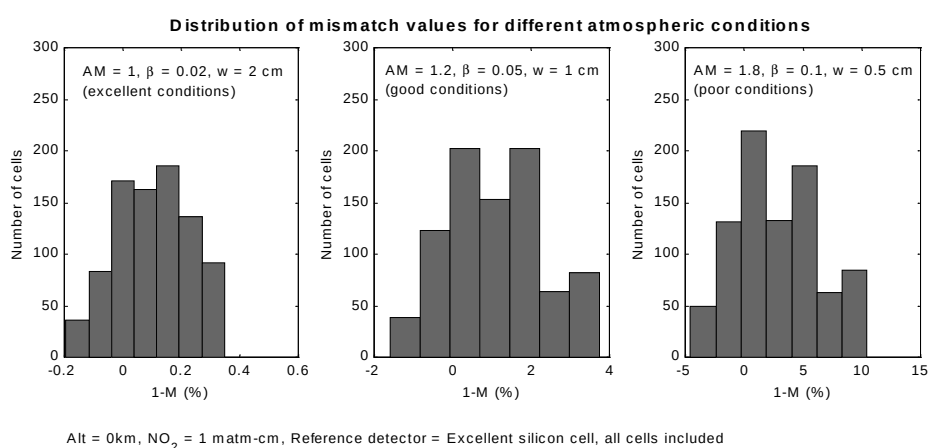


Figure 2-28: Distribution of mismatch values for different atmospheric conditions, reference detector = excellent silicon cell, standard spectrum = AM1.5G (3 points in figure 2-22).

2.3.2 Experimental verification results

The results of experimental variation are given in figure 2-29. The analysis of these results is in section 2.4.6.

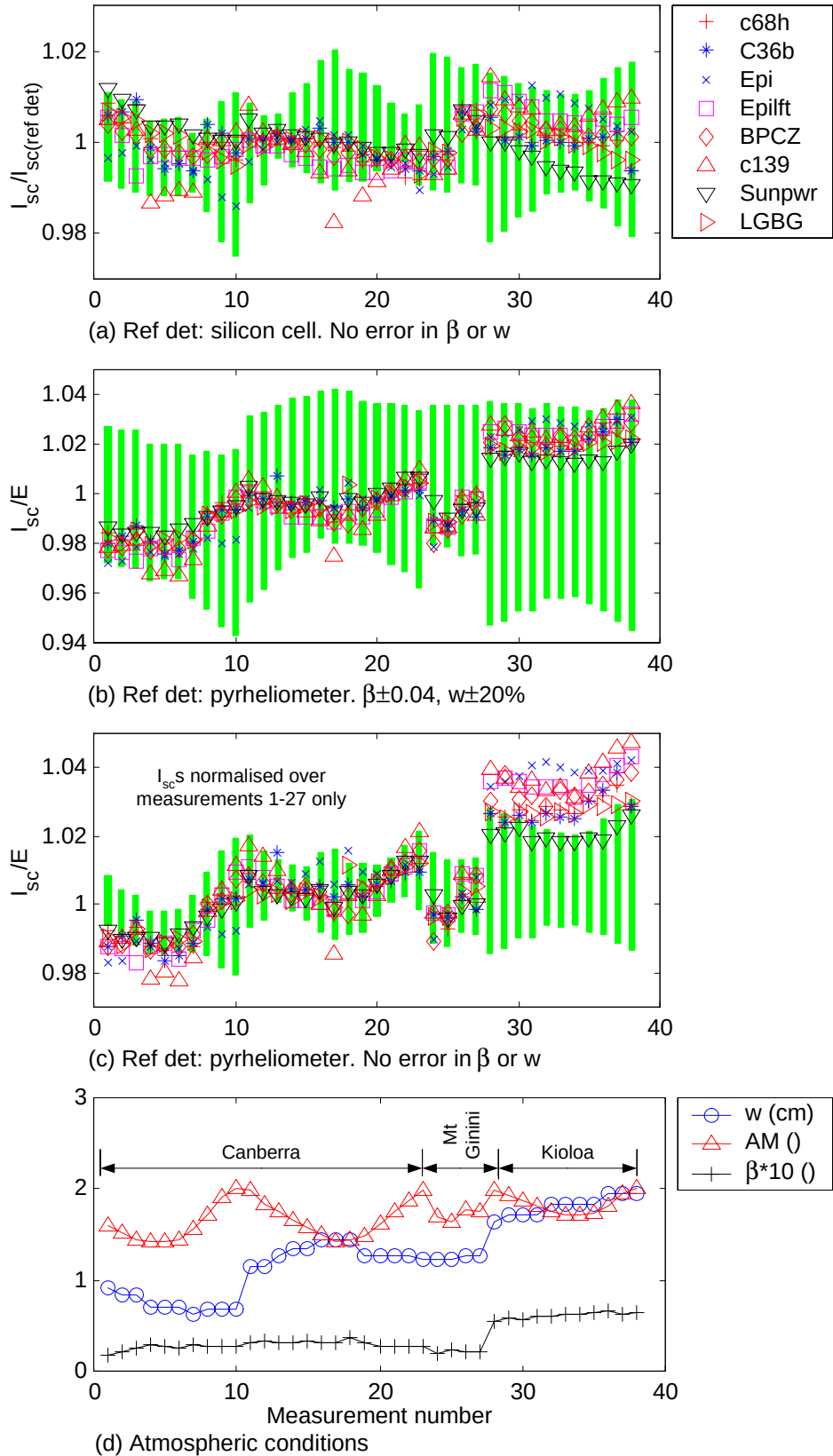


Figure 2-29: Experimental results – comparison of simulated variation to measured variation in cell currents.

2.4 Discussion

Detailed examination of the preceding results allows the best conditions and equipment for testing to be identified.

2.4.1 Lowest spectral mismatch error and best testing conditions

The best conditions for testing will be those that give lowest spectral mismatch error. These conditions can be found by inspecting the simulation results, Figures 2-21 to 2-26. The optimum atmospheric conditions are different for the two different standard spectra (AM1.5G and AM1.5D). For both standard spectra, attention is given mainly to the results for the pyrheliometer reference detector. The silicon cell reference detector will give less accurate measurements under most conditions, as described in section 2.4.2, so is less interesting. In any case, the trends described are similar for both reference detectors.

2.4.1.1 AM1.5G standard spectrum

For measurements with respect to the AM1.5G standard spectrum, direct beam sunlight is effectively being used to simulate the global spectrum. Scattering depletes blue light from the direct spectrum much more than from the global spectrum. Hence it would be expected that under low scattering conditions (low air mass, low turbidity), the direct beam spectrum will be closest to the global spectrum. This is confirmed by Figures 2-21 to 2-24.

The trends for the two cell sets (all cells, and good cells only) are similar. The main difference is that the magnitude of the spectral mismatch error is lower for the good cell set.

AM Optimum: 1 (the lower the better). Lowest air mass will occur in summer.

β Optimum: below 0.05

Higher can be tolerated provided precipitable water is also high.

w Optimum: around 2 atm-cm.

1-3 atm-cm is good (typical conditions in temperate locations).

Up to 5 atm-cm is tolerable provided turbidity is not too low (only semi-tropical or tropical locations will have precipitable water this high, and turbidity will be higher there).

Below 1 atm-cm should be avoided. If air temperature $< 10^{\circ}\text{C}$, precipitable water will probably be below 1 atm-cm. Hence high altitude locations, or winter testing, may give large mismatch error.

The effects of turbidity and precipitable water counteract each other, so if one is high the other should be high as well. Fortunately, nature provides this correlation - both turbidity and precipitable water are higher in summer and in locations closer to the equator.

Under optimum conditions, a spectral mismatch error of 2% or less can be achieved. It may be possible to equal the accuracy of routine secondary calibration at a standards lab. Secondary calibrations currently have a reproducibility of no better than 5%, so

even with all other uncertainty sources included, measurement outdoors should give comparable accuracy.

If precipitable water is too low for accurate testing, the spectrum could perhaps be corrected with a liquid water filter. However, liquid water has a slightly different absorption spectrum to water vapour, so it is not certain that this would work.

In summary: under optimum conditions ($AM \approx 1$, $\beta < 0.05$, and $w \approx 1\text{--}3$ atm-cm – most likely in summer), a spectral mismatch error of 2% or less can be achieved. High altitude sites or winter testing may give poor accuracy, due to low w and/or high AM .

2.4.1.2 AM1.5D standard spectrum

The direct beam natural sunlight spectrum should be an excellent match to the AM1.5D standard spectrum, provided the atmospheric conditions are the same as those used to generate the standard spectrum. The ASTM-E891/AM1.5D standard spectrum was generated by the computer model BRITE, assuming the following atmospheric conditions: $AM = 1.5$, $O_3 = 0.34$ atm-cm, $\tau_{500} = 0.27$ (so $\beta \approx 0.1$), and $w = 1.42$ atm-cm. The simulation results agree with this, showing lowest spectral mismatch error for $AM \approx 1.4$, $\beta \approx 0.1$, and $w \approx 1\text{--}2$ atm-cm (Figure 2-25).

The simulation results also show that conditions different to those used to generate the AM1.5D standard spectrum can also give low mismatch error. The optimum region is quite large, and a mismatch error of $< 2\%$ can be achieved for a wide range of atmospheric conditions.

Similarly to the AM1.5G case, $w < 1$ atm-cm causes more mismatch error. However, provided turbidity is less than 0.1 even winter testing should give a mismatch error of $< 4\%$.

2.4.1.3 Distribution of mismatch errors

The distributions of mismatch values for several different atmospheric conditions are shown in figures 2-27 and 2-28. These could be considered the ‘z-direction’ at a few points in the main contour plots of spectral mismatch error. The plots of mismatch error show only the contours of the ‘top’ maximum surface, whereas the distributions show the range of values for all 865 cells. Distributions are shown for 3 atmospheric conditions – excellent, good, and poor testing conditions, and both reference detectors – pyrheliometer and silicon cell.

The distributions are all similar. They are squarish, and do not have a long tail on either side. This gives confidence in the usefulness of the simulations. It shows that all the cells simulated have reasonably similar mismatch, and there are no disastrously bad cells. If a few cells had vastly worse mismatch than the majority (i.e., a long tail on the distribution) then the characteristics of the central majority would not give much useful information. Most information about the bounds on mismatch would be obtained from the few cells at the limit. A limit obtained this way would be unreliable, as the few cells used might not cover all real-world possibilities. Real-world cells might exist with much worse mismatch error than for any of the modelled cells. The squareness of the distributions gives confidence that the modelling predicts a safe bound for any real-world cell.

The major difference between the distributions for the pyrheliometer and the silicon reference is an offset in the mismatch values. The distributions for the silicon

reference are centred closer to zero. This is to be expected as the silicon reference will be very similar to many cells in the cell set and so give many zero mismatch error values.

An important observation is that, under poor conditions, (high air mass, high turbidity, low precipitable water) the spectral mismatch will tend to *over-estimate* I_{sc} . This is a dangerous tendency. Under these poor conditions, the spectrum is too red (high air mass and turbidity attenuate blue light, and low water does not absorb enough IR). Since a pyrheliometer responds much more strongly to high-energy blue photons than a solar cell, the cell current will be boosted by the reddish spectrum.

2.4.1.4 Irradiance as an indicator of testing conditions

Irradiance is sometimes recommended as an indicator of whether outdoor testing conditions are suitable. Eg, (ASTM E1125 1999) requires that direct beam irradiance be in the range 750-1100 W/m². However, the present work shows that irradiance alone is not a useful indicator of mismatch error.

Using the simulation dataset, worst-case mismatch error (with respect to AM1.5G) is plotted as a function of irradiance in figure 2-30. It can be seen that only for exceptionally high values of irradiance is mismatch error below 5%.

Use of irradiance alone to indicate suitable testing conditions has 2 limitations: firstly, it can't be used to identify conditions with less than roughly 5% mismatch error. In contrast, use of air mass, turbidity, and precipitable water makes it possible to identify conditions with mismatch error of below 2%. Secondly, if irradiance is used to identify suitable conditions, it will be very restrictive. It can be seen in figure 2-30 that, of all the points that satisfy $\epsilon_M < 5\%$, only a small proportion can be identified from high irradiance. In other words, on many days when conditions are in fact quite suitable, irradiance will suggest that they are not.

Irradiance alone clearly is not a good indicator of suitable testing conditions.

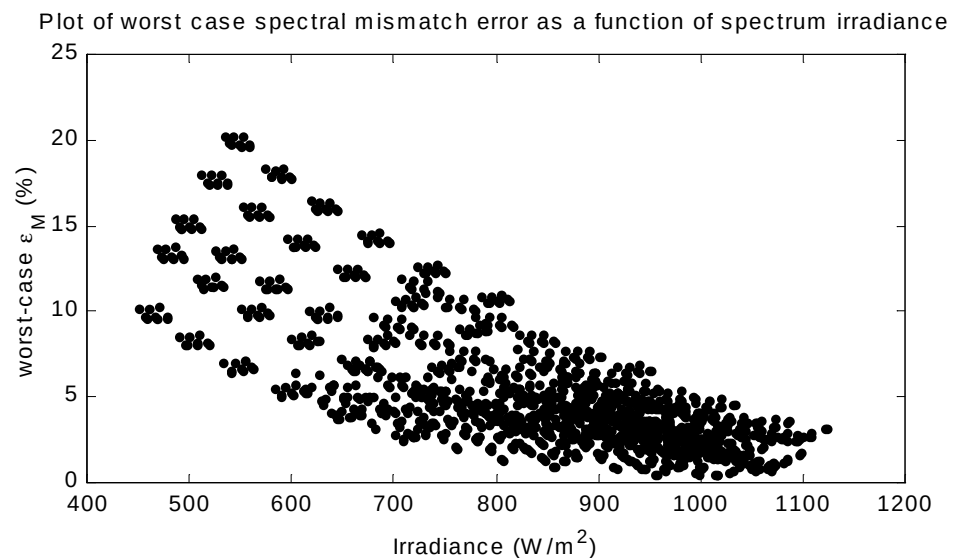


Figure 2-30: Worst-case spectral mismatch error (with respect to AM1.5G) as a function of direct-beam irradiance. Reference detector is a pyrheliometer.

2.4.1.5 Comparison to previous work

The results of the present work can be compared to previous work on natural sunlight calibration of solar cells.

The NASA Lewis method (see section 2.1.5.2) used the direct-beam spectrum without spectral mismatch correction. It set limits on air mass, turbidity, and irradiance to get a spectrum similar to the standard spectrum. It said nothing about cell characteristics or spectral mismatch error. The present work, in contrast, gives bounds on spectral mismatch error as a function of atmospheric conditions.

The atmospheric conditions specified in the NASA Lewis method are: $AM \times \beta < 0.25$ and irradiance in the range 750-900 W/m². These are broadly similar to the ‘good’ testing conditions identified in this work for measurement with respect to the AM1.5G standard spectrum.

Previous work on the variation of cell current as a function of atmospheric conditions can be compared to the results of the present work. The work of (Mueller 1987) and (Osterwald 1985) studied the variation of normalised calibration number, $\overline{CN}$, (which is the same as M if a radiometer is used to measure irradiance) as air mass, turbidity, and precipitable water were varied. Two data points from Osterwald are compared to results from this work in Table 2-12. Osterwald calculated the variation in current for a single cell, and so has a single value for ε_M . The present work calculated ε_M for a large number of cells, and so has a range of values. Osterwald considered only a good cell, whereas the present work considered a wide range of cells. So, as expected, the present work shows a much wider range of ε_M . It includes Osterwald’s values in the middle of the distribution, so the present work is in agreement with Osterwald.

Osterwald’s work might be interpreted as showing a constant trend for any silicon cell (e.g. that for $AM = 1$, $\beta = 0.05$, $w = 1.75$, any silicon cell will read 1% above its true value). This work shows that different cells will behave very differently, even to the extent of some having a positive error while others have a negative error.

The two ASTM methods, (ASTM E1039 1999) and (ASTM E1125 1999), although conceptually similar to the present work, cannot be directly compared. (ASTM E1039 1999) uses the global spectrum outdoors, whereas the present method uses the direct beam spectrum. The recommended atmospheric conditions will therefore be different for the two methods. (ASTM E1125 1999), while it does use the direct beam spectrum, involves spectral mismatch correction. Since deviations from the standard spectrum will be corrected, there is little need for limits on atmospheric conditions.

In summary, the present work is in agreement with all previous work to which it can be directly compared. It is also more comprehensive.

Table 2-12: Comparison of spectral mismatch predictions from (Osterwald 1985) to this work. $\varepsilon_M = |1 - \overline{CN}|$

AM	β	w (atm-cm)	ε_M Osterwald	ε_M This work
1	0.05	1.75	+1%	-1.5% to +2%
2	0.1	1	-2%	-10% to +5%

2.4.2 Choice of reference detector

Two types of reference detector were considered in the modelling – a pyrheliometer, and a silicon cell. This section discusses which reference detector is the better choice.

Naively, it might be expected that a silicon reference detector would be ‘more similar’ to any silicon cell than a thermal detector, and consequently give lower spectral mismatch error under any conditions. However, careful examination of the simulation results shows that this is not always true. In the regions of lowest mismatch error, the silicon detector does indeed give lower mismatch error, but under other conditions, a silicon reference detector can actually give higher mismatch error. This shows that some of the cells are as different from each other as they are from a thermal detector. Given the very large range of cells simulated, this is not entirely surprising.

The best choice of reference detector is considered separately for the 2 standard spectra, AM1.5G and AM1.5D.

Three interesting points from the simulation results for AM1.5G are summarised in Table 2-13. For the full cell set: under excellent conditions, a silicon detector gives lower mismatch error than a pyrheliometer (2% vs. 1%), but under poor conditions, a silicon detector gives higher mismatch error (8% vs. 6%). For good cells only, the silicon detector is always better, but by varying amounts. Obviously, there is no simple best choice of reference detector that minimises spectral mismatch error.

Table 2-13: Effect of reference detector choice and cell set choice on worst mismatch error for 3 selected atmospheric conditions

Reference detector ▼	Poor conditions		Typical conditions		Excellent conditions	
	AM = 2 $\beta = 0.05$ w = 1 cm		AM = 1 $\beta = 0.1$ w = 2 cm		AM = 1 $\beta = 0$ w = 3 cm	
	all cells	good cells	all cells	good cells	all cells	good cells
Pyrheliometer	6%	5.5%	3.1%	2.2%	2%	1.75%
Silicon cell	8%	3.9%	3.5%	2.0%	1%	0.8%

Fortunately, the situation is simplified when the total error due both to mismatch and to reference detector calibration uncertainty is considered. Pyrheliometers can be calibrated much more accurately than silicon cells, so the spectral mismatch advantage of a silicon reference detector is eliminated in almost all cases. Pyrheliometer uncertainty (when properly maintained and calibrated) is 2% or less, as detailed in section 2.1.5.3. Silicon detector uncertainty depends very much on the calibration method used, but for a cell calibrated using a routine secondary-calibration technique the calibration uncertainty is likely to be about 5% (see section 2.1.4.3). The worst-case spectral mismatch error and the reference detector calibration uncertainty are both mostly bias errors. However, they should be largely independent and so the total can be calculated as the quadrature sum of the two components.

The mismatch error and calibration uncertainty for a pyrheliometer is compared to the mismatch error and calibration uncertainty for a silicon detector in figure 2-31.

Examination of this figure shows that measurement with a pyrheliometer will be more accurate under almost all conditions. The few areas where the silicon detector is better have spectral mismatch error of 10-20%, so are not useful testing conditions anyway. For the best testing conditions, the total uncertainty using a pyrheliometer is approximately half that of a silicon detector.

In summary, for the AM1.5G standard spectrum, use of a pyrheliometer as the reference detector will be more accurate.

For the AM1.5D standard spectrum the spectral mismatch error is much smaller than for the AM1.5G spectrum (see section 2.4.1). As discussed in the previous section, pyrheliometers are more accurate but usually cause more spectral mismatch error, whereas silicon detectors are less accurate but usually cause less spectral mismatch error. Since spectral mismatch error is already low for AM1.5D, the smaller calibration uncertainty for the pyrheliometer offsets the slightly larger spectral mismatch error.

For the AM1.5D standard spectrum, use of a pyrheliometer as the reference detector will be more accurate.

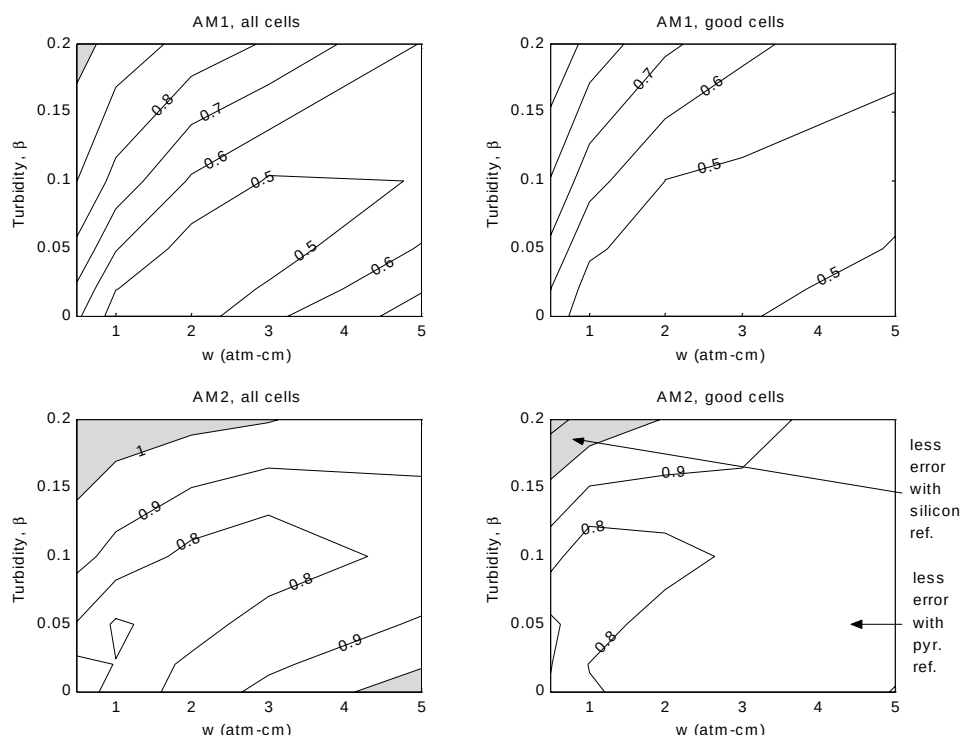


Figure 2-31: Ratio of mismatch error and calibration uncertainty for a pyrheliometer to mismatch error and calibration uncertainty for a silicon cell detector, assuming 2% uncertainty for the pyrheliometer and 5% uncertainty for the silicon detector. Where the ratio is < 1 , the pyrheliometer will give lower total measurement uncertainty, where it is > 1 , the silicon detector will give lower total measurement uncertainty.

2.4.3 Effect of restricting the cell set

Restricting the cell set to include only good cells ($V_{oc} > 620$ mV, $J_{sc} > 35$ mA/cm²) decreases the mismatch error. A plot of the ratio (worst case mismatch error for good cells)/(worst case mismatch error for all cells) is shown in Figure 2-32. The ratio is less than 1 in all cases, showing that the restricted cell set always has less mismatch error.

This result is to be expected, since the cells in the good set are more similar to each other than the cells in the full set are. The cells in the good set are also more similar to a thermal detector (the cells most different to a thermal detector are those with poor blue response and good IR response. These cells will be excluded from the good cell set due both to low voltage and low current). Since spectral mismatch error is smaller for similar cells, it is to be expected that mismatch error will be smaller for the good cell set.

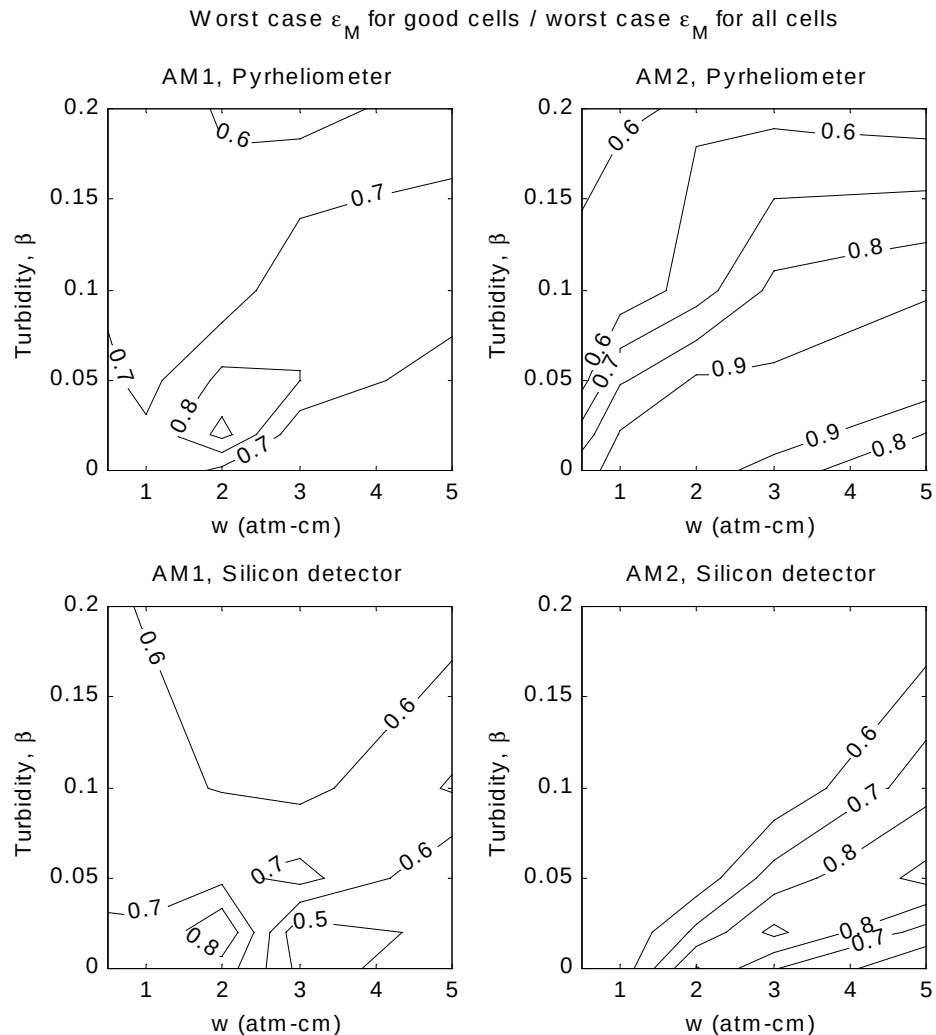


Figure 2-32: Ratio of worst-case ε_M for good cells to worst-case ε_M for all cells, AM1.5G standard spectrum. Good cells have less spectral mismatch error than all cells where ratio < 1 .

It can be seen in Figure 2-32 that restricting the cell set has relatively little effect when spectral mismatch error is smallest. Eg, for $AM = 1$, $w = 2$ cm, $\beta = 0.02$, ε_M is about 1-2% for good cells and the full cell set. If measurements are being performed under ideal testing conditions, considering a restricted cell set has little benefit. Conversely, it can be seen in Figure 2-32 that restricting the cell set has a significant effect when spectral mismatch error is large. Eg, for $AM = 2$, $w = 1$ cm, $\beta = 0.1$, ε_M decreases from almost 10% to about 6%. If measurements are being performed under poor conditions, considering a restricted cell set may give a useful improvement in accuracy.

Restricting the cell set causes a relatively small change in mismatch error. This is consistent with the distributions of mismatch values being squarish (without a long tail), as discussed in section 2.4.1.3. It gives confidence in the robustness of the natural sunlight testing method because it shows that the method is unlikely to be caught out by an unusual cell that is not well represented by the modelling. Restricting the cell set is equivalent to making large changes to cell characteristics. Yet, this results in little change in the mismatch error. Relatively small changes in cell characteristics would be required to go from any particular real world cell to one of the modelled cells. Consequently, the mismatch error for the real world cell will only be marginally different to that predicted by the simulated cells.

In summary, if measurements are being performed under poor testing conditions, considering a restricted cell set may give a useful improvement in accuracy. If measurements are being performed under good testing conditions, there is little benefit from considering a restricted cell set.

2.4.4 Comparison of natural sunlight to solar simulators

The spectral mismatch under natural sunlight can be compared to the spectral mismatch under the three solar simulators. For the solar simulators, the worst-case spectral mismatch errors are shown in the results, figures 2-22 and 2-24. Mismatch errors were only calculated with respect to the AM1.5G spectrum and a silicon cell reference detector. The performance could not be calculated for a pyrhelimeter reference detector because the published spectra for the simulators only covered the wavelength range 0.3-1.1 μm .

The performance of the simulators can be compared to that of natural sunlight by examining the plots. Note that only spectral matching is being compared. Sunlight will always have better uniformity than any simulator. Under sunlight, error due to spatial variation will be eliminated, and error due to temporal variation can be avoided by measuring cells simultaneously. So, even if a simulator has comparable spectral mismatch error, natural sunlight will still be more accurate.

For the full cell set (Figure 2-22), ELH and Oriel are very similar at $\varepsilon_M < 16\%$. Measurement outdoors under any conditions will give a better result than using one of these simulators. The Spectrolab X25 gives $\varepsilon_M < 3\%$. Measurement outdoors should equal or better this under good conditions, but could be significantly worse under bad conditions.

For the good cells (Figure 2-24): ELH $\varepsilon_M < 5\%$, Oriel $\varepsilon_M < 10\%$, X25 $\varepsilon_M < 2.5\%$. Again, measurements under good conditions will equal or better any of the simulators. Measurements under bad conditions will be significantly worse than ELH or X25 simulators, but comparable to Oriel.

Interestingly, the good cell set shows the ELH simulator to be better than the Oriel simulator, in spite of being vastly cheaper. This is a surprising finding. To eliminate the possibility that the particular choice of reference cell favoured the ELH simulator, all 865 cells were tried as the reference. In other words, each cell in the cell set, in turn, was used as the reference against which all other cells were measured. All the mismatch errors were then lumped together and histograms of them are shown in Figure 2-33. This confirms that, for measuring silicon solar cells, the ELH simulator does in fact have a significantly better spectrum than the Oriel simulator. The ELH simulator, for its worst possible combination of cells, gives a 16% mismatch error, whereas the Oriel simulator, for its worst combination, gives a 20% mismatch error. For the restricted cell set, the advantage of the ELH simulator is even greater. However, a single ELH lamp has worse light uniformity than an Oriel simulator. For large-area cells the Oriel simulator would still be better, in spite of the poor spectrum.

This surprising result can be explained by looking at the spectra for the two simulators (Figure 2-9). Silicon solar cells usually have either poor blue or poor infrared response, or possibly both. Almost all cells have a good response in the middle region ($0.5\text{--}0.8\ \mu\text{m}$). The Oriel simulator has its largest spectrum errors in the blue and the infrared, where cells could have very different spectral responses. Consequently, a large spectral mismatch error could result. The ELH simulator, on the other hand, has its largest spectrum error in the visible. Most cells have similar (good) responses in this region; so much less spectral mismatch error should result.

The ELH spectrum used in the simulation is for the nominal operating voltage of 120 V. It is unlikely that this is the best operating voltage (a simple experiment at ANU suggests that the optimum is around 90 V). Possibly the advantage of the ELH simulator over the Oriel simulator would be even greater when the ELH voltage has been optimised.

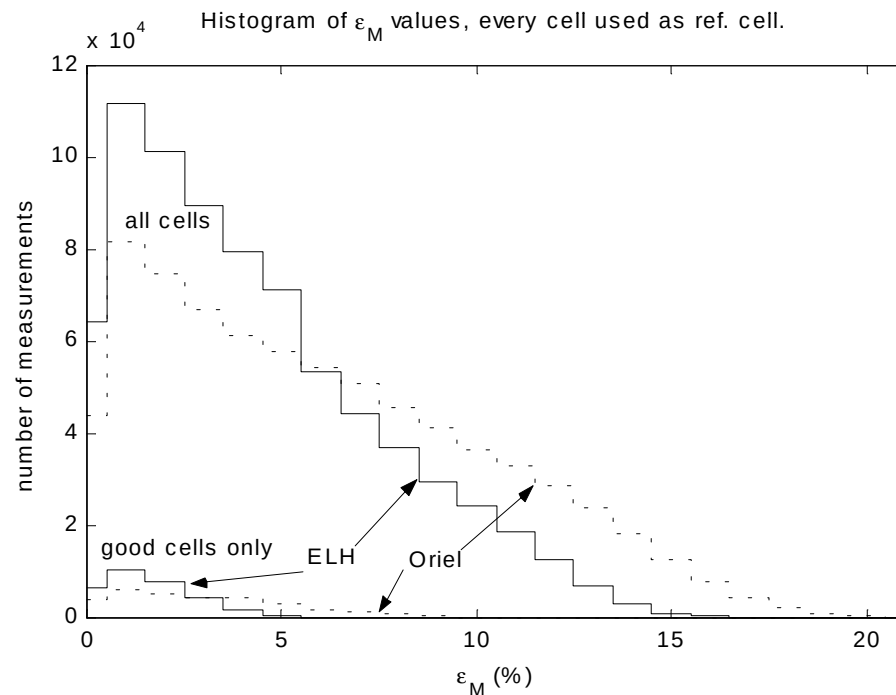


Figure 2-33: Histograms of ϵ_M values for ELH and Oriel simulator spectra. Every cell used, in turn, as the reference cell for testing the rest.

This result may not apply to other cell technologies with different bandgap cut-offs. For example, amorphous silicon has its bandgap cut-off at around $0.7\ \mu\text{m}$, right where the ELH lamp has the biggest spectrum error. So for amorphous silicon, an ELH lamp might give significantly more spectral mismatch error than an Oriel simulator.

In summary, measurement outdoors under good conditions will give accuracy comparable to the best simulator available, and significantly better than any affordable simulator.

2.4.5 How often can outdoor tests be done?

Outdoors testing can only be done when weather conditions are suitable. It is interesting to examine how often suitable conditions are available, in a variety of different locations. Table 2-14 gives typical atmospheric conditions for several different locations. Data is shown for both summer and winter periods. The data given includes: the number of clear days per month, lowest air mass that will always be achievable during the period, turbidity, and water column. For the USA, 4 sites are shown spanning the range of coastal and inland locations, both urbanised and not heavily urbanised.

For measurement with respect to the AM1.5G standard spectrum, the best conditions are: clear sky, $AM \approx 1$, $\beta < 0.05$, and $w \approx 1\text{--}2\ \text{atm-cm}$. In summer, all locations have several days every month that are cloud free, all get close to $AM = 1$, all have suitable levels of precipitable water, and most have suitable levels of turbidity (urbanised locations may have undesirably high turbidity). It should be possible to measure I_{sc} for several months of the year, with an uncertainty of $< 5\%$. In some locations, the I_{sc} uncertainty may be as low as 3% . In winter, all locations still have plenty of clear days, but air mass is usually above 2. Turbidity is excellent, but precipitable water may be too low. In winter, it will be hard to get I_{sc} uncertainty less than 7% .

For measurement with respect to the AM1.5D standard spectrum, the weather constraints are far less severe. The number of clear days, air mass, and turbidity should be suitable for all locations for most of the year. In winter, however, precipitable water may sometimes be too low. It should be possible to measure I_{sc} in most locations, at most times the year, with an uncertainty of $< 5\%$.

In some particularly cloudy parts of the world (eg northern Europe), clear days may be too rare for this technique to be useful. However, the sites discussed here are certainly not deserts. In particular, the Oregon coast is quite wet, yet it still has about 5 clear days per month in summer.

2.4.6 Experimental verification of modelling

2.4.6.1 Comparison of experimental and modelled results

The results of experimental verification are shown in figure 2-29. These are plots of the measured and simulated variation in cell currents over a range of atmospheric conditions. Three graphs are shown: (a) is for the case of a silicon cell reference detector, (b) and (c) are for a pyrliometer reference detector. Graph (d) shows the atmospheric conditions applicable to graphs (a), (b), & (c).

Table 2-14: Typical atmospheric conditions for several locations.

Location →		Valencia, Spain 40° N ⁽³⁾	Canberra, Australia 36°S ^{(1),(2)}	Boulder, CO, USA, inland, urban, 40°N ⁽⁴⁾	San Francisco, CA, USA, coastal, urban, 37°N ⁽⁴⁾	Prescott, AZ, USA, inland, non-urban, 34°N ⁽⁴⁾	North Bend, OR, USA, coastal, non-urban, 43°N ⁽⁴⁾
Summer (3mths)	clr day/mth		8	6	13	14	5
	AM ⁽⁵⁾	1.1	1.05	1.1	1.05	1.05	1.1
	β	0.10-0.25	0.025-0.050	0.045-0.052	0.11-0.13	0.045-0.060	0.070-0.085
	w		1.7-2.4	0.5-3	1.0-2.5	0.5-2.5	1.2-2.2
Winter (3mths)	clr day/mth		8	7	8	14	4
	AM ⁽⁵⁾	2.3	1.9	2.2	2	1.8	2.3
	β	0.02-0.10	0.010-0.025	0.024-0.032	0.07-0.08	0.015-0.025	0.03-0.04
	w		1.1-1.5	0.2-1.0	0.5-2.5	0.5-1.5	1.0-2.0

Notes:

(1) β from private communication with Bruce Forgan, Aust. BOM.

(2) From Aust. BOM webpage climate data. Clear days / month directly available, w derived from RH & T.

(3) β from (Pinazo, Canada et al. 1995)

(4) Data from NREL TMY2 (Typical Meteorological Year).

 β converted from BAOD using $\beta \approx 0.7 * \text{BAOD}$. Rough approximation, accurate to $\pm 50\%$, valid for $Z = 0-60^\circ$ and $\alpha \approx 1.3$, (derived from (Gueymard 1998)).

clear days / mth = number of days with 0 tenths cloud cover.

(5) Highest noon air mass for the period, i.e. an air mass less than this value can always be obtained.

The measurements cover a substantial portion of the simulated range of atmospheric conditions – the full range of altitude, 1/2 the AM range, 1/2 the precipitable water range, and 1/3 of the turbidity range. These measurements therefore give a reasonable indication of the validity of the modelling. Further measurements planned over the next 8 months should cover the full range of altitude and AM, and most of the range of precipitable water and turbidity. This should give more confidence in the validity of the modelling.

Both SMARTS2 and PC1D are reliable models and the calculations used in this work to join them are simple. The modelling predictions should be fairly accurate. Differences between measured and simulated values are more likely to come from other sources such as: the inaccuracy of the techniques used to measure turbidity and precipitable water, the simulated cell set not being representative of real world cells, and miscellaneous measurement errors like electrical noise and tracking problems.

Silicon cell reference detector

For the silicon cell reference detector, graph (a), the experiments are in good agreement with the simulations. For this case – of perfectly accurate β and w – the measured variation in cell currents is almost always smaller than the simulated range. If the simulated range includes the effect of likely error in β and w , the measured variation is much smaller than the simulated variation. This confirms that the modelling is valid for the case of a silicon cell reference detector.

This graph also provides an indication of the measurement repeatability independent of spectral mismatch variation. The SunPower cell (down pointing triangle symbol) is almost identical to the silicon reference detector, which is also a SunPower cell. There should be very little spectral mismatch between them. Yet, when the SunPower cell current is normalised by the silicon reference detector current, there is a $\pm 1\%$ variation. This shows that the measurement repeatability is $\sim 1\%$, since little of this 1% variation could be explained by changing spectral mismatch. The measurement non-repeatability could be due to electrical measurement noise, drifts in the data acquisition card, tracking errors, or pyrheliometer stabilisation errors. As the experiments are trying to verify a simulated variation of only $1\text{--}2\%$, the measurement repeatability is not good enough to accurately discern the variation. Performing experiments over a wider range of atmospheric conditions would improve the situation.

Pyrheliometer reference detector

For the pyrheliometer as the reference detector (graphs (b) and (c)), the simulated and measured results are just in agreement, but the agreement is marginal.

When the simulated variation includes the effect of worst-case errors in β and w (graph b), the measured variation is just within the simulated range. So for this case, the measurements and the simulations are in agreement.

When the simulated variation does not include any error in β and w (graph c), the measured variation is considerably larger than the simulated variation. However, close examination of the results suggests that the discrepancy may be due to measurement problems. It can be seen that, for measurements 1-27, the measured and simulated values fit very nicely. The discrepancy only appears when the measurements from the last day (at the coast) are included. In addition, the scatter of the measurements at the coast is approximately the same as the scatter of the simulated values for the coastal conditions. The major difference between measurements and simulations is an offset of about 2% . This offset does not appear at all when the silicon cell is used as a reference detector (graph a). The effect is clearly something to do with the pyrheliometer measurements.

There are two likely causes of the offset: 1) a change in the spectrum in the far IR, which the pyrliometer sees but the silicon cells do not, or 2) an error in the pyrliometer measurement.

The only major atmospheric process that affects IR exclusively is precipitable water. Experimentation with the simulation data showed that precipitable water would need to have been 4 cm to explain the increase in measured cell currents (not the 2 cm measured). Although the surface level relative humidity method of estimating precipitable water is not highly accurate, it should not have been out by 100%. In addition, climate data shows that $w = 4$ cm is very unlikely on a cool autumn day in a temperate location. This suggests that explanation 1, a change in the spectrum in the far IR, is not very likely.

An error in the pyrliometer measurement could have come either from the pyrliometer itself, or from the data acquisition system. The pyrliometer used, a Kipp & Zonen CH1, is a high-quality instrument that is robustly constructed. Its calibration is unlikely to have drifted 2% over a few weeks. The data acquisition system is the more likely suspect. The pyrliometer produced an output signal of only 10 mV, whereas all the cells (silicon reference detector included) produced an output signal of ~ 100 mV. Consequently, measurements with respect to the pyrliometer would be an order of magnitude more sensitive to errors in the data acquisition system. The crosschecks of the data acquisition system, using a reliable multimeter, only confirmed that it was accurate to a few tenths of a millivolt. These checks would not have detected a few percent error in irradiance. The data acquisition system was a National Instruments MIO16XE50 16-bit data acquisition card. Some odd behaviour had been observed from this card on one occasion in the past. The card will be replaced for future measurements. In addition, the CH1 pyrliometer will be occasionally checked against another pyrliometer kept at ANU.

The measurements planned over the next 8 months should resolve whether the modelling of spectral mismatch against a pyrliometer is valid.

2.4.6.2 Effect of cloud

On an otherwise very clear and stable day, a slow moving patch of cirrus cloud allowed a measurement of the influence of cloud. This measurement confirmed the analysis of section 2.2.1.11, showing that light cloud has little effect on measurement accuracy.

Prior to the cloud, irradiance was 945 W/m^2 , and stable to $\pm 0.3\%$ over 5 minutes. While the cloud passed, taking about $\frac{1}{2}$ hour, irradiance fluctuated between 945 and 925 W/m^2 . A measurement was made on each cell while the cloud was in front of the sun. This is measurement number 18 in figure 2-29. As can be seen in figure 2-29, the measurement taken through the cloud can barely be differentiated from the surrounding measurements taken under clear sky. This confirms the analysis in section 2.2.1.11, which showed that light cloud should have little effect on the spectrum. In addition, the measurement through the cloud confirmed that turbidity measurement by the broad-band irradiance method is not seriously affected by light cloud – during the cloudy period β rose from 0.033 to 0.038, a minor change.

This result does not, however, mean that cloud can be totally ignored – stability problems can still cause serious errors, as discussed in section 2.2.1.11.

2.4.7 Practical considerations

2.4.7.1 Indoors or outdoors measurement of V_{oc} and FF?

The obvious approach when measuring a cell under natural sunlight is to measure all three parameters, I_{sc} , V_{oc} , and FF, outdoors. However, it is shown in this section that it is easier, and probably more accurate, to only measure I_{sc} outdoors. V_{oc} and FF can then be measured indoors, using the previously measured I_{sc} to set the solar-simulator intensity.

Measuring V_{oc} and FF outdoors is less accurate because of the difficulty of correcting for non-standard irradiance, the need for temperature control, and the complexity of contacting arrangements.

Correcting I_{sc} for non-standard irradiance is easy as it is proportional to irradiance. Correcting V_{oc} and FF is more difficult. V_{oc} is proportional to $n \times \ln(I_{sc})$, where n is the ideality factor and I_{sc} is the photocurrent generated by irradiance E . Hence to correct V_{oc} from a non-standard value of E requires knowledge of n . Determining n accurately is tricky. If, on the other hand, a simulator is adjusted to give $I_{sc} = I_{sc(1 \text{ sun})}$, then V_{oc} can be determined without a correction. FF is a weak function of light intensity for good cells. For non-critical measurements, it could be assumed constant. However, for cells with poor series or shunt resistance FF can be a strong function of light intensity. Assumption of constant FF could introduce large errors. It is shown in (van den Berg, Bolingen et al. 1993) that linear scaling from 500 W/m² to 1000 W/m² could introduce FF errors of as much as 50%. Correcting FF for non-standard irradiance is therefore quite difficult.

Measuring V_{oc} and FF indoors ensures that the photocurrent when measuring V_{oc} and FF is equal to the 1 sun condition. However, the generation profile will be slightly different due to the non-ideal spectrum and non-uniformity of the simulator. For example, a redder spectrum will cause a higher proportion of the carriers to be generated in the bulk. This may slightly affect the V_{oc} and FF, but not by much. Similarly, a light that is brighter in the centre of the cell will cause a higher proportion of carriers to be generated in the centre. Solar cells are fairly tolerant of non-uniform illumination. So the few percent non-uniformity in a reasonable quality simulator will introduce minimal error in FF measurement. Finally, stability of the simulator is not a problem in this instance as the cell is effectively its own reference detector.

All cell parameters are sensitive to temperature to some extent. Temperature control is therefore an important issue. V_{oc} is more sensitive to temperature than I_{sc} (about 0.3%/°C for V_{oc} , versus approximately 0.1%/°C for I_{sc}). Since good temperature control is easier indoors, V_{oc} measurement may be more accurate indoors.

The FF of a cell can be quite sensitive to the contacting arrangement, as described in section 3.3.4. It will be easier to get the contacting exactly right indoors. I_{sc} , on the other hand, is insensitive to contacting problems. Hence the jig used to make contact to the cell outdoors can be much simpler if FF is measured indoors.

The suggested sequence of outdoor and indoor measurements is:

- Measure I_{sc} outdoors at the available irradiance, E_{exp} (which is unlikely to match the standard irradiance).

- Calculate the one sun current, $I_{SC(1)} = I_{SC} \frac{E_{std}}{E_{exp}}$, where E_{std} is the irradiance of the relevant standard spectrum (1000 W/m² for standard global conditions).
- Put the cell in the simulator and adjust the simulator so that the cell's short circuit current equals $I_{SC(1)}$.
- Finally, with the cell now operating under 1 sun conditions, measure V_{oc} and FF.

2.4.7.2 Linearity of I_{sc} with irradiance

One potential problem with natural sunlight testing is that the total irradiance will rarely match the standard 1000 W/m². If the test cell's short-circuit current is not directly proportional to irradiance, linear scaling to correct for non-standard irradiance will introduce a small error. It is difficult to measure linearity of cell current to better than 1% accuracy, as is discussed in section 3.1.1.6. So it is not easy to tell whether this effect will be a problem for a particular cell. However, silicon solar cells usually are highly linear around the one sun region. Over the range 1 to hundreds of suns, non-linearities of no more than a few percent appear, and only in some cells. Since the irradiance of natural sunlight under good testing conditions will be in the range of roughly 0.7-1.2 suns, it is safe to assume that linearity errors will be a fraction of a percent. However, for cell measurements at the highest possible accuracy it would be preferable to measure linearity.

2.4.7.3 Temperature control

I_{sc} for silicon solar cells has a weak dependence on temperature, typically increasing by about 0.1%/°C. For accurate outdoor measurements, temperature control is therefore advisable, but not essential.

The temperature of a cell with poor heatsinking can rise by as much as 40°C when exposed to 1 sun irradiation. This could introduce 4% error in the current measurement, so should clearly be avoided. If the cell is mounted to a large thermal mass and only briefly exposed to sunlight, its temperature will remain close to the ambient air temperature. The ambient air temperature should usually be within ±10°C of the standard 25°C, so this method is unlikely to add more than 1% error in I_{sc} . If better accuracy is desired, temperature control of the cell should be considered. A simple temperature-controlled block cooled by a Peltier device can be easily constructed at little cost.

2.4.7.4 Sun tracking platform

An automatic sun-tracking platform would be convenient, but it is certainly not essential to use one. A manually tracked platform is quite acceptable. The sun moves at a fairly slow 0.25°/min, giving several minutes to separately align the cell testing jig and the pyrheliometer and then take the measurement. If a tracking platform is used, it should be accurate to ±0.5°.

2.4.7.5 Electrical instruments

It is recommended to measure only I_{sc} outdoors, as described in section 2.4.7.1. So the only instruments required are an ammeter, or a voltmeter and a shunt resistance. The electrical instruments used for the measurement do not need to be anything fancy.

Given that the spectral mismatch error will be several percent, an uncertainty in the current measurement of less than 1% will be adequate. Hand-held multimeters with 0.1% uncertainty are commonly available.

It is recommended to use a bias circuit to ensure that the cell is exactly at short circuit when measuring I_{sc} . This could simply be a battery and a variable resistor, or for greater convenience an active feedback circuit.

2.4.7.6 Measurement procedure summary

This section gives a summary of the recommended measurement procedure. The full details are given in appendix B.

Check if conditions are suitable

Measurements under natural sunlight are dependent on weather conditions. The first step in the measurement procedure is to determine if conditions are suitable. ‘Suitable’ is a subject term, since the user can decide what level of accuracy is required. To assess whether conditions are suitable:

- Check that the sky is moderately free of cloud.
- Determine air mass, precipitable water, and turbidity, and look up worst-case spectral mismatch error plots to see if measurement accuracy will be acceptable.

Preparation

Before performing a measurement, some preparatory steps are necessary.

- All equipment should be set up and allowed several hours to reach thermal equilibrium.
- Some cells exhibit instabilities when exposed to light – a few hours light soaking may be necessary beforehand.
- For the most accurate measurements, it is advisable to measure the temperature coefficient and linearity of I_{sc} for the test cell.

Measurement

The recommended measurement cycle is as follows:

- Measure relative humidity and air temperature.
- Align the collimating tube and pyrheliometer with the sun.
- Allow the pyrheliometer time to stabilise.
- Check that irradiance is stable to $\pm 0.5\%$ over at least twice the pyrheliometer response time.
- Measure irradiance and cell current simultaneously.

Once the measurements have been performed, the 1-sun I_{sc} and uncertainty in I_{sc} can be calculated:

- Calculate I_{sc} for 1-sun: $I_{sc, 1 \text{ sun}} = I_{sc} \cdot \frac{1000 \text{ W/m}^2}{E_{test}}$
- Calculate air mass, precipitable water, turbidity, and then look-up the worst-case spectral mismatch error plots for an estimate of the spectral mismatch error, ϵ_M .

The measurement cycle should be repeated several times for greater reliability.

2.4.7.7 Accuracy cross-checks

To confirm that the measurement process is achieving the expected accuracy, some cross checks are highly recommended. There are several possibilities:

- Measure any existing reference cells that have been externally calibrated. However, if the cell is more than a few years old its calibration may have drifted. External calibrations are probably accurate to $\pm 5\%$ (see section 2.1.4.3).
- If a cell is to be sent away for external calibration (possibly for a record setting bid), measure it under natural sunlight beforehand.
- Keep a special cell that gets measured every time any other cells are measured. In the short term, this cell may indicate if a mistake has been made during the measurement process. In the long term, it will give reproducibility statistics for the measurement process.

2.4.8 Benefits of outdoors testing

Measurement of cells under natural sunlight has a number of advantages over both affordable simulator measurements and calibrations at standards laboratories. These include:

- Low cost – the only expensive instrument required is a pyrliometer, costing about US\$1500. For comparison, calibration of 1 reference cell at the highly regarded standards lab, Fraunhofer ISE, costs EUR 900 $\approx$ US\$800 (Fraunhofer ISE 2000). If an affordable simulator is being used, new reference cells will periodically need to be calibrated. So the cost of external calibration can add up rapidly. In addition, frequent outdoor calibration of reference cells can allow use of a cheaper, lower performance solar simulator.
- Quick and local – outdoors measurement provides easy access to accurate cell calibration without the need to send cells to distant measurement facilities. This is particularly valuable for delicate prototypes that might not survive the postal system.
- Few possibilities for mistakes. In contrast, simulator measurements including spectral mismatch correction are complex and require careful calibration. Inter-laboratory comparisons have shown a serious discrepancy between the theoretical accuracy of simulator measurement techniques and the actual reproducibility (see section 2.1.4.3). This is testament to the benefit of a simple procedure.
- Spectral mismatch error is lower than for any affordable simulator measurement (without spectral mismatch correction).
- Superb light uniformity over any area. All but the very best solar simulators have several percent variation in light intensity over the test plane. If the test cell and the reference cell are different sizes, different thicknesses, and/or are placed in different positions, large errors can arise. Natural sunlight, in contrast, has almost perfect uniformity.
- Stability over time un-important. Due to the excellent light uniformity of natural sunlight, the test cell and the reference detector can be placed side-by-side and measured simultaneously. In contrast, for most simulator measurements the test cell and reference detector have to be swapped (to minimise spatial uniformity errors). Errors can creep in due to the light intensity changing over time.
- Minimal reflections / stray light. Due to the excellent collimation of direct-beam sunlight, multiple reflections and stray light can be virtually eliminated. This is much harder to do for a simulator.

2.4.9 Application to other PV technologies

The principle of this work – that natural sunlight is a much better light source than any affordable simulator – should apply to other PV technologies. However, the mismatch-error estimates calculated in this work cannot be directly applied to cells made on other materials since some assumptions are specific to crystalline silicon technologies. This work could easily be extended to other technologies. The same methodology could be used, but a different cell set would be required. To create an appropriate cell set would require the involvement of someone with a detailed knowledge of the relevant cell technology.

2.5 Conclusions

The conclusion of this work is that calibration of solar cells under natural sunlight is both convenient and accurate. Its use, presently, seems inappropriately confined to high accuracy calibrations performed only by standards laboratories. This work concludes that the method is far more widely applicable.

Spectral mismatch error under natural sunlight was estimated by modelling a group of solar cells under a range of natural sunlight spectra. The group of cells was chosen to be representative of any likely crystalline silicon solar cell (6-25% efficiency). The natural sunlight spectra were generated using typical atmospheric conditions for a wide range of locations. In total, over one million cell/spectrum combinations were modelled. The modelling showed that:

- The spectrum of natural sunlight, under commonly occurring conditions, is a better match to the AM1.5G and AM1.5D standard spectra than any affordable solar simulator. Under good conditions – $AM \approx 1$, $\beta < 0.05$, and $w \approx 2$ cm – spectral mismatch for any cell should be below 2%.
- Calibration under natural sunlight is accurate – during summer, at most latitudes, a total measurement uncertainty below 5% should be achievable. This is comparable to the accuracy of calibration at a standards laboratory.
- Calibration under natural sunlight is simple – it does not require elaborate procedures to achieve accurate results.
- Little expensive equipment is required for calibration under natural sunlight – the important atmospheric conditions can be estimated using only measurements of relative humidity, air temperature, direct-beam irradiance, time, and location.
- The technique is widely applicable – meteorological data suggests that the required atmospheric conditions should be common at all but polar latitudes.

The practical outcome of the modelling is a recommended calibration procedure. The major novel feature of this procedure is that it provides an estimate of the worst-case spectral mismatch error for any likely crystalline silicon cell.

The modelling has been experimentally verified by measuring the relative changes in short circuit current, for a diverse group of silicon solar cells, under a range of atmospheric conditions. The results are encouraging but not conclusive. When a silicon cell was used as the reference, the measured changes were in agreement with the modelling. When a pyrheliometer was used as the reference, the measured changes were a little larger than the modelling suggested. However, careful examination of the data suggests that the disagreement may have been due to experimental problems rather than errors in the modelling. Further work on this issue is suggested.

Although the modelling was specific to crystalline silicon, similar conclusions should hold for cells made on other materials.

This research still leaves plenty of scope for further work. Most importantly, the experimental verification is not yet convincing. Further measurements are recommended in mid-summer and in a high turbidity location (e.g. a large city). It would also be desirable to verify the method by comparing measurements with a reliable standards laboratory. Finally, it would be useful to extend this method to other solar cell technologies.

Natural sunlight calibration of solar cells is a low cost, convenient, and accurate method. This work presents a procedure that should allow it to be used more widely.

3 Constant voltage flash tester



Figure 3-1: The constant voltage flash testing system.

3.1 Introduction

Testing concentrator cells is difficult because of the high light flux under which they operate. If they are to be tested under continuous illumination, they must be attached to an effective heatsink. For 1 sun testing, cells can be conveniently heatsunk by vacuum hold-down to a temperature-controlled block. But under moderate to high concentration, this method is inadequate. Vacuum hold down typically has a thermal resistance between cell and temperature controlled block of about $1^{\circ}\text{C}/\text{sun}$. This is acceptable at 1 sun, but not at concentrations of tens or hundreds of suns. A permanent glue bond, such as is described in (Mason, Jordan et al. 1991) and (Bruton, Heasman et al. 1993), is commonly needed to achieve sufficiently good heat transfer. This is time consuming and inconvenient. 1-sun modules also have heatsinking problems, due to the glass or plastic encapsulation.

Fortunately, this problem can usually be avoided by testing the cells under brief pulses of light. Silicon cells, and most other solar cell technologies, respond electrically much faster than they respond thermally. Consequently, their electrical characteristics can be measured using a brief pulse of light that does not heat them significantly. This is the basis of a flash tester.

This work was motivated by the need to test concentrator cells produced for the PV/Trough project, at the Centre for Sustainable Energy Systems, ANU. This project is described in more detail in the introduction to the thesis. The cells are designed for a concentration of roughly 30 suns, so a flash tester is clearly essential.

A variety of different flash tester designs are available from commercial manufacturers. Most of these are designed for testing 1-sun modules. At the start of the PV/Trough project, investigation of commercial systems and communication with other groups making concentrator cells led us to the conclusion that no commercially available systems were suitable. Given the high cost of the 1-sun systems, and the potential difficulty of converting them for testing concentrator cells, we decided to develop a concentrator flash tester of our own.

In this work, a new flash tester design is described. It is both low cost and less sensitive to transient errors than other designs. In addition, it extracts a family of I-V curves over a decade range of light intensity with no extra effort.

The constant voltage flash tester described in this work has been used extensively:

- It has been used to test tens of thousands of concentrator cells produced at the Centre for Sustainable Energy Systems, ANU.
- One of these systems has been sold to BP Solar, UK. BP Solar uses their system for testing Laser Grooved Buried Grid concentrator cells, and conventional 1-sun cells.
- SunPower Corp., USA, has recently sold some flash testers (for concentrator cells), which use the capacitive cell bias circuit developed in this work.

In the remainder of this introduction, the technology of flash testing is reviewed. Previous work on flash testing is summarised, and two major problems – cost, and susceptibility to transient errors – are identified. This work describes solutions to these two problems.

The new flash tester design is then described, at a high level, to give an understanding of how the whole system operates. Only a summary of performance is given initially.

In the following sections, the performance of the flash tester is analysed in detail. Each of the components is described in detail, and the problem of transient errors is analysed. Using these analyses, the overall accuracy of the tester is then estimated. To confirm the analysis of performance, experimental verification is described.

Finally, areas for improvement of the flash tester design are described.

3.1.1 Existing flash tester designs and issues

Flash testers have been used for solar cell measurement for at least 30 years. A wide variety of different designs have been tried, both for 1 sun cell and concentrator cell testing. This section reviews existing flash tester designs, and summarises the major design features and issues. First, the individual systems are identified, in roughly chronological order. Then, the major features of all these designs are discussed.

The systems are:

- Varian: a concentrator system developed by Varian for testing the GaAs concentrator cells it produced (Borden, LaRue et al. 1981).
- SNL: a concentrator system, developed by Sandia National Laboratories for their measurement services (Wiczer, Chaffin et al. 1982).
- Spectrosun LAPSS: a 1-sun system, manufactured by Spectrolab and developed/used by JPL (Mueller 1985; Mueller 1993).
- Commercial multi-flash: A commonly used commercial 1-sun system is described by (Ossenbrink, Zaaiman et al. 1993). The manufacturer is not identified.
- Mini-flasher: a portable 1-sun system, primarily for pre-flight checks on space modules (Sturchecher and Larue 1994). Developed by Satellite Services BV, and produced by Phoenicon GmbH.
- Fraunhofer: a 1-sun system used by Fraunhofer ISE for their measurement services (Lipps, Zastrow et al. 1995). It is not clear from the paper whether they developed it in-house or purchased the complete system.
- Pasan: a range of commercial 1-sun systems, produced by Belval SA, Switzerland (Pasan 1997).
- SPI-SUN: a range of commercial 1-sun systems, produced by Spire Corporation (Spire Solar 2001)

The fundamental principle of a flash tester is to measure the electrical characteristics of a cell while it is illuminated by a short pulse of light from a flash lamp. The essential components of a flash tester are therefore:

- a flash,
- circuitry to apply a variable load to the cell,
- equipment to measure the cell current and voltage, and
- software to process and present the data

These components are discussed in the following sections.

3.1.1.1 Flash

The flash sub-system in a flash tester consists of a flash lamp and a power supply to drive it. A xenon discharge tube is the usual choice for the flash lamp. The power supply is usually a large bank of capacitors, and sometimes inductors and other components.

Flash testers can be broadly grouped into single flash and multi-flash. Single flash systems produce a light pulse that has a plateau of constant light intensity lasting a few milliseconds. During this time, the entire I-V curve is traced out. Multi-flash systems, in contrast, use many flashes and only take a single I-V point with each flash. Most of the early systems were multi-flash, but most modern systems are single flash.

Most modern, high performance systems (including LAPSS, Fraunhofer, and Pasan) are single flash. The requirement for a period of constant light greatly complicates the design of the lamp-driving power-supply. It is estimated by (Sturcbecher and Larue 1994) that the constant light requirement increases the size of the power supply by a factor of 50. Pictures of the LAPSS system support this argument – the capacitor bank cabinet occupies at least 1 m³, and according to Sturcbecher the whole LAPSS system weighs 2 tons.

Most of the early systems, and the modern SPI-SUN and mini-flasher systems, are multi-flash. Multi-flash systems, since they only take data at one instant on each flash pulse, impose fewer constraints on flash design. This allows the use of commercial photoflashes (as in the case of the mini-flasher). A multi-flash design was chosen for the mini-flasher as it made the system much lighter and easier to transport. Multi-flash designs are, however, slower than single flash designs. For example, the system described by Ossenbrink takes 20s to measure a full I-V curve. In a fully automated production line, this could be a serious issue. However, in a system where cells are manually loaded and unloaded, the difference between a 20 second test and a 2 second test is not a major issue.

The spectrum of a xenon flash lamp can be made to match the various standard solar spectra very well. Indeed, the spectrum for a carefully designed xenon flash is possibly the best solar simulator available. Both (Matson, Emery et al. 1984) and (Emery 1986) state that it is a better spectral match than any xenon continuous-arc lamp. The main difference is that continuous arc lamps have large emission lines in the near IR, such as can be seen in figure 2-9. Xenon flash lamps operated at appropriate current densities have much smaller emission lines.

In the higher performance systems, (LAPSS, Fraunhofer, SPI-SUN, and optionally Pasan), filters are used to further improve the spectrum. The filters used on the LAPSS system, described in (Mueller 1985), attenuate the UV.

Accurately measuring the spectrum of a flash lamp is difficult and requires specialised equipment. The spectrum changes significantly over milliseconds. Conventional spectroradiometers, which take many seconds to scan the full wavelength range, obviously cannot be used. The need to make this measurement adds significantly to the cost of developing and maintaining a flash lamp simulator.

One of the major benefits of flash testing is that it is easy to get good light uniformity over large areas. The peak power available is very much higher than for continuous systems, so the optics can afford to be inefficient. For example, the Spectrolab LAPSS system has a peak electrical power of about 1 MW per m² of 1 sun illuminated area, whereas Spectrolab's large area continuous illumination system uses only 16 kW/m². The availability of such high power means that the designer can simply use the flash lamp as a point source. This eliminates the need for complicated reflectors and homogenisers, and avoids problems with lamp alignment.

Equivalently, it is also relatively easy to get high concentration with good uniformity. However, a system designed to give good uniformity at 1 sun may not be good at

concentration. For example, (Mueller 1993) states that the illumination area (at $\pm 2\%$ uniformity) of the LAPSS system is reduced from 2.4×2.4 m at 1 sun to only 0.1×0.1 m at 9 suns.

3.1.1.2 Cell bias circuitry

The cell bias circuitry in a flash tester provides a variable load to trace out the I-V curve of the cell. Many different cell bias circuit designs have been used. They can be broadly classified into two groups – active circuits, which use feedback control, and passive circuits, which do not.

A major problem with flash testers is the possibility of transient errors due to the cell not being in steady state. The primary cause of transient error is abrupt changes in the cell bias voltage, as discussed in section 3.3.2. The cell bias circuitry obviously has a major influence on this.

Most modern systems use active cell bias circuitry. For single flash testers, where the entire I-V curve must be swept out in milliseconds, they are almost essential. Most single flash systems linearly ramp bias voltage from one end of the I-V curve to the other. Many do the return direction as well, to detect transient errors. Most active bias circuits can do a full four-quadrant measurement of the cell, allowing the full I-V curve to be traced out. The multi-flash system described by Ossenbrink uses a constant-current active load. This seems like a poor design, since it causes large changes in the bias voltage with each flash, possibly inducing transient errors. In addition, it makes it difficult to measure I_{sc} accurately for cells that have a very flat I-V curve around short circuit.

Active loads are complex pieces of equipment. They have to control large currents (tens of amps at least) with many kHz bandwidth. Due to the feedback loop, they can become unstable. Solar cells are difficult loads to control – they are both highly capacitive and highly non-linear. Avoiding oscillations, for any cell, under any bias condition, is tricky. It is reported by (Mantingh, Zaaiman et al. 1994) that the LAPSS and Pasan cell bias circuits have stability problems with some cells.

A passive cell bias circuit does not attempt any feedback control. The simplest example is a resistor. A slightly more sophisticated version uses a power transistor operated as an electronically variable resistor. The Varian system used such a circuit. A simple transistor load will only allow a one-quadrant measurement however – the curve traced out won't quite reach I_{sc} or V_{oc} . Addition of a battery allows a two-quadrant measurement. This is the basis of the load proposed by (Mantingh, Zaaiman et al. 1994).

Passive loads are very unlikely to oscillate since they do not have any feedback loops. They are also generally much cheaper since they are so much simpler.

This work proposes a new cell bias circuit that is partially passive, partially active. It combines the best features of both. A large capacitor is used essentially as a passive load to maintain a constant voltage on the cell, with minimal risk of oscillation. This capacitor is charged to the desired bias voltage, before the flash, by a low-bandwidth, four-quadrant supply. This bias circuit is discussed in detail in section 3.2.2.4.

3.1.1.3 Current and voltage measurement

One of the complications of flash testing is that everything happens fast. High-speed data acquisition is essential. In early systems this was difficult, but with modern, computerised data-acquisition it no longer is.

The Varian and mini-flasher systems avoided high-speed data acquisition by using analog peak-detector circuits. These do have the shortcoming that they rely on successive flashes being repeatable.

3.1.1.4 Light measurement

Since the light intensity from a flash varies, it is important to measure it. All modern systems have a light detector that measures light intensity simultaneously with cell current and voltage. The measured light intensity is used in several different ways.

In the single flash systems and the mini-flasher, the measured light intensity is used to correct the I-V points for light intensity variations.

The commercial multi-flash system described by Ossenbrink has an odd arrangement for the light detector. It measures light intensity, but only uses it to detect the beginning of the flash. It then takes the I-V point a fixed time after the rising edge of the flash. This does not seem the best design. If successive flashes are not identical, the I-V points may be taken at different light intensities. Also, the rising edge of the light pulse is not very steep (judging by the graphs in the paper, it's a gaussian-like function), so noise on the light intensity signal will perturb the trigger point. Given that the light intensity is being measured, it seems odd that is not used to choose the instant to sample I and V.

Surprisingly, the Varian system did not measure light intensity at all. It simply captured an I-V point using the analog peak detectors, and so relied on flash-to-flash repeatability.

3.1.1.5 Transient errors

For accurate measurements with a flash tester, it is essential for the cell to be in quasi-steady-state. Some silicon solar cells may not be in quasi-steady-state over the timescales typical in flash testers. Measurement errors can occur due to transient effects. Similar problems can also occur with continuous illumination testers, if the I-V curve is swept out too rapidly. Numerous investigators have reported such problems. Transient errors have been identified to be a problem with high resistivity cells, high performance cells, and BSF (back surface field) cells.

Transient errors are caused by rapid changes of the charge distribution in the cell. Minority carrier concentrations are much higher in forward bias than in reverse bias. Consequently, in the moving from one bias condition to another, a large amount of charge has to be moved. Under illumination, there are two current sources to rearrange charge – current from the light source, and current from the external circuit. If the bias voltage is rapidly increased (sweeping from I_{sc} towards V_{oc}), carrier concentrations have to be raised. Excess electrons are added to the p region, and holes to the n region. This charge rearrangement will consume some of the photocurrent, reducing the measured external current. Consequently, FF and V_{oc} will be underestimated. Alternatively, if the bias voltage is rapidly decreased (sweeping from V_{oc} towards I_{sc}) carrier concentrations have to be lowered. This charge rearrangement will add to the

photocurrent, giving an exaggerated FF and V_{oc} . The two effects give the well-known curve splitting phenomenon.

Plots of FF error as a function of bias voltage sweep rate are given in (King, Gee et al. 1988). Cells made on high resistivity substrates ($>200 \Omega\text{cm}$) showed noticeable FF errors ($>1\%$) for bias rates above 20 V/s, and FF could be exaggerated by more than 10% for sweep rates of greater than 100 V/s. For a cell made on a $1 \Omega\text{cm}$ substrate, King found that transient errors began to appear around 100 V/s. A cell made on a $0.2 \Omega\text{cm}$ substrate did not show any transient errors up to 200 V/s, the maximum sweep rate used in the experiment. In a different experiment, using a BSF cell, (Ossenbrink, Drainer et al. 1991) reports a 10% overestimate of FF at $\sim 500 \text{V/s}$.

Given that sweeping the full I-V curve of a typical cell requires a voltage change of about 1 V, it is clear that as much as 50 ms may be required to do so without introducing transient errors. This is much longer than the few millisecond pulse lengths of most single pulse flash testers. This argument is supported by (Wiczer, Chaffin et al. 1982), who found that for silicon with a minority carrier lifetime $>0.5 \text{ ms}$, a 2.5 ms pulse is too short.

Not only high quality silicon cells suffer from transient errors in flash testers. It is reported by (Ossenbrink, Drainer et al. 1991) that most of the common cell technologies suffer from transient errors. An amorphous silicon module was found to be only about a factor of 3 less sensitive than a BSF silicon module.

What can be done about transient errors? For single flash systems, not much. The only possibility is to extend the light pulse to allow slower tracing of the I-V curve. However, there is not much room to do this – some systems are already operating the tube fairly close to its explosion energy (evidenced by the LAPSS system having a recommended tube replacement interval of only 5000 flashes). To allow longer flashes, the tube current must be reduced. However, this will change the spectrum.

For multi-flash systems, the situation is potentially much better. Since the transient errors are due mostly to rapid changes in the bias voltage, it should be possible to greatly reduce them by holding the voltage constant during each flash. With a multi-flash system, it is possible to do this – the bias voltage can be changed slowly between flashes, and then fixed during each flash. However, this possibility has not been examined in detail in the flash testing literature. It is supported though, by (Metzdorf, Meier et al. 1994), who found that when bias voltage was held constant cell current tracked light intensity with no observable distortion. The new method described in this work is a multi-flash system and uses a constant voltage load. Not only does the constant voltage load reduce transient errors, it is also simpler to build. Surprisingly, some multi-flash systems do the exact opposite of maintaining constant voltage. The multi-flash system described in (Ossenbrink, Zaaïman et al. 1993), uses constant *current*. This causes a full sweep from I_{sc} to V_{oc} , in $<1 \text{ ms}$, with every flash. As might be expected, this system suffers from serious transient problems.

For systems where it is impossible to avoid transient errors, methods have been devised to correct for them.

A modelled correction is used in the Fraunhofer system. A 2 exponential model that includes a parallel bias-dependent capacitance is fitted to the measured $I(t), V(t)$ data. The corrected I-V curve is then calculated from the modelled curve with the capacitance set to zero. This method no doubt is effective for well-behaved cells, but it

is debatable how effective it will be for unusual cells that are not well described by a simple bias dependent capacitance.

A dark I-V correction procedure is described by (Metzdorf, Meier et al. 1994). In this procedure, three I-V curves are measured – a slow dark I-V curve, a fast dark I-V curve, and a fast light I-V curve. The differences between the slow and fast dark I-V curves gives an estimate of the transient error current, which is then used to correct the light I-V curve.

3.1.1.6 Linearity of I_{sc} with irradiance

When measuring cells under concentrated light, the light source is usually highly non-uniform and/or highly unstable. This makes it difficult to measure the light intensity that the cell is seeing. To resolve this problem, the test cell is frequently used as its own light detector. The light intensity can then be determined from the short circuit current. However, to do this requires knowledge of the cell's short circuit current as a function of light intensity. The short circuit current of a solar cell is, to a first approximation, proportional to the light intensity. In other words, current is linear with light intensity. However, most silicon cells do exhibit a small degree of nonlinearity. Measuring linearity of short circuit current is surprisingly hard. This section reviews previous work on linearity of short circuit current and describes some of the techniques that can be used to measure it.

Linearity characteristics of silicon solar cells

Most silicon solar cells exhibit some degree of nonlinearity. Cells made on low resistivity substrates tend to be super-linear (current increases faster than light intensity), while cells made on high resistivity substrates tend to be sub-linear (current increases slower than light intensity).

For this work, concentrations of 1-100X are of primary interest. Most attention is given to previous work discussing linearity in this concentration range.

Silicon solar cells made on low resistivity substrates tend to be super-linear. The extent of the super-linearity has been well studied, and several theoretical explanations have been suggested. The most popular explanation is that the large current flow sets up an electric field throughout the base. This electric field will sweep carriers generated near the rear towards the junction, and away from potential recombination at the rear surface (Dondero, Zirkle et al. 1985; Zirkle, Schroder et al. 1989). It has also been suggested that minority carrier lifetime improves at high concentration, and that rear surface recombination velocity decreases (Stryi-Hipp, Schoenecker et al. 1993). All of these explanations suggest that the improvement is in the conversion of long wavelength (IR) light. Spectral response measurements have supported this suggestion, showing increased response to IR at high concentration.

The super-linearity in $n^+/p/p^+$ cells made on 0.15, 0.4, and 1.5 Ωcm substrates, over the concentration range 1-100X, was examined in (Sanderson, Backus et al. 1982). Two methods were used to measure the super-linearity – spectral response with varying bias light (where the bias light went up to 100X intensity), and neutral density filters. A super-linearity of 5-20% at 100X, and 0-3% at 10X was reported. The super-linearity reported here is much larger than anyone else has since measured, and the scatter in the results was frequently larger than the results themselves.

The super-linearity in two 0.3 Ωcm cells, differing only in thickness ($\sim 300\ \mu\text{m}$ vs. $\sim 500\ \mu\text{m}$), was measured by (Dondero, Zirkle et al. 1985). They were found to be 1.3-1.8% super-linear at 100X, and 0.75-1% super-linear at 50X. The thicker cell exhibited greater super-linearity.

The super-linearity in $n^+/p/p^+$ cells, made on 0.15-0.3 Ωcm substrates was measured up to 1500X by (Zirkle, Schroder et al. 1989). A differential linearity method was used. The super-linearity was measured to be 5-7% over 1-500X. Below 500X, the super-linearity characteristic is approximately linear. So, interpolating down, the super-linearity over 1-50X is 0.5-0.7%.

The super-linearity in a silicon concentrator cell (details not specified) was measured by (Stryi-Hipp, Schoenecker et al. 1993), using a spectral response method. The super-linearity was found to be 0.7% at 50X and 2.6% at 200X.

In summary, detailed measurements have shown that super-linearity in low-resistivity silicon concentrator cells is common, and tends to be around 0.5-1% at 50X. However, this is process dependent.

Silicon solar cells made on high resistivity substrates show the opposite trend to low resistivity cells – they tend to be sub-linear. Many explanations have been proposed, but the most commonly cited one is higher recombination at the front of the cell. In a solar cell, most of the sunlight is absorbed close to the front surface. Either the electrons or the holes (or both in the case of back contact cells) generated at the front of the cell must diffuse towards the rear. At high light intensity there must be a large diffusion flux and so a large concentration gradient. This leads to a high concentration of carriers in the front region, which causes increased surface recombination and hence sub-linearity.

The linearity of several cells made on high resistivity substrates was examined by (Gee 1987). It was found that a 150 μm thick Stanford point contact cell made on a 100 Ωcm substrate was $\sim 20\%$ sub-linear at 1000X, and a few percent sub-linear at 100X. The sub-linearity was greater for thicker cells and higher resistivity substrates.

Two cells, approximately 250 μm thick and made on 100 Ωcm substrates were found to be 15% sub-linear at 100X (King, Gee et al. 1988).

The SunPower concentrator cells used as light detectors in the flash tester were measured by SunPower. When masked (to ensure that only the active area is illuminated), they are less than 1% sub-linear. When un-masked, they are 1-2% sub-linear at 100X. However, these measurements are not very reliable as they are quite noisy below 50X (the testing procedure is designed for 100-1000X).

In summary, at 1-100X, cells made on high resistivity substrates can be as much 15% sub-linear. However, well-designed concentrator cells, such as SunPower's, are probably less than 1% sub-linear over this range.

A large series resistance will also cause strong sub-linearity. As series resistance increases, the knee of the curve moves to lower voltages. Initially, series resistance has no effect on short circuit current. But when the knee of the curve comes close to short circuit, a strong sub-linearity will suddenly appear. This effect is easily detected by studying the I-V curve.

Techniques for measuring linearity of I_{sc}

The non-linearity of most silicon solar cells is rather small – on the order of 1% per decade change in light intensity. This makes it difficult to measure linearity accurately.

The effects causing nonlinearity have strong spectral selectivity, so the spectrum of the light is very important when measuring linearity. The spectrum is even more important for linearity measurements than for efficiency measurements. To illustrate by example: for a high-resistivity point-contact cell the sub-linearity is due to reduced collection of blue photons. If the linearity of such a cell were examined using an infrared light source, the nonlinearity would not be found at all. In contrast, if the efficiency of such a device were measured using infrared light, the resulting measurement would at least give a reasonable indication of the cell performance. Clearly, linearity measurements must be done with light of the correct spectrum.

Measurement of short circuit current linearity requires a light source of variable intensity. It also requires knowledge of the light intensity. It is very difficult to vary the intensity of a light source without affecting the spectrum or the uniformity. This complicates measurement of the light intensity. Knowledge of the light intensity can be obtained in two ways: either explicitly by measuring it with some other device, or implicitly by using a differential measurement technique.

Explicit measurement of light intensity requires some sort of light detector. Several characteristics of the light detector can introduce serious errors in the linearity measurement. Firstly, the light detector has to be chosen very carefully to ensure that its linearity is known more accurately than the linearity of the cell being measured. Unfortunately, few light detectors have better linearity than a solar cell. Secondly, if the light detector and the cell are different sizes, changes in the light uniformity as the light intensity is varied can introduce serious errors. Thirdly, if the light detector and the cell have different spectral responses, changes in the light spectrum as the light intensity is varied can also introduce errors. These three factors mean that the light detector must be chosen very carefully to get useful measurements of short circuit current linearity.

Implicit light intensity measurement can avoid problems with the light detector. Effectively, the cell is used as its own light detector. This greatly reduces errors due to uniformity and spectrum changes. The light intensity can be found implicitly by either a two-source superposition method, or a differential method.

A two-source superposition method, such as is described in (Bucher 1997), uses two light sources of similar intensity. First, the two light sources E_A and E_B are applied individually, giving the cell currents I_A and I_B . Then both light sources are applied simultaneously, giving a total light intensity $E_{AB} = E_A + E_B$. If the cell is linear, then $I_{AB} = I_A + I_B$. One of these measurements gives linearity over approximately a factor-of-two range of light intensity. Repeated measurements, with varying E_A and E_B , can then be stitched together to give linearity measurements over a larger range.

A differential linearity measurement, such as is described in (Sanderson, Backus et al. 1982) and (Stryi-Hipp, Schoenecker et al. 1993), uses a continuous bias light and a superimposed chopped probe light. The current from the cell is the superposition of the DC current due to the bias light and the chopped current due to the probe light. As the intensity of the bias light is varied, the magnitude of the chopped current gives the slope of the linearity characteristic (if the cell is linear, the slope will be constant).

This is illustrated in figure 3-2. The resulting measurement of slope as a function of cell current can then be integrated to give cell current as a function of light intensity.

The differential linearity measurement technique is very similar to the method commonly used to measure spectral response. Indeed, (Stryi-Hipp, Schoenecker et al. 1993) describes a measurement of spectral response as a function of bias light intensity for a concentrator cell. This provides detailed information about what is causing the nonlinearity in the cell. For example, the cell described by Stryi-Hipp (a low resistivity concentrator cell) showed a dramatic improvement in its infrared response at high concentration. This confirmed the hypothesis in the paper that the super-linearity was due to improved collection of photons generated near the rear of the cell.

The light intensity can be varied in many ways, but all ways change the spectrum or the uniformity significantly. An implicit measurement of light intensity (differential or two-source linearity measurement) is therefore preferable since it greatly reduces sensitivity to these problems.

With an optical concentrator (lenses or mirrors), part of the collecting area can be masked, or the system can be de-focused. Mirrors are generally better than lenses, as low cost lenses can suffer from severe chromatic aberration. Masking a lens or moving away from its focus can cause significant changes in the spectrum. Masking a mirror should have very little effect on the spectrum, but could have a significant effect on the uniformity.

The light intensity can also be varied using neutral-density filters (the standard ASTM method for measuring linearity – E1143-99 – is based on this concept). However, neutral-density filters are neither perfectly uniform nor perfectly neutral. The non-uniformity over the filter is typically several percent, and the average transmission (over the whole filter, and over all wavelengths) is usually only specified to approximately $\pm 5\%$. The transmission also varies as a function of wavelength – (Sanderson, Backus et al. 1982) reports $\pm 3\%$ deviation from neutrality.

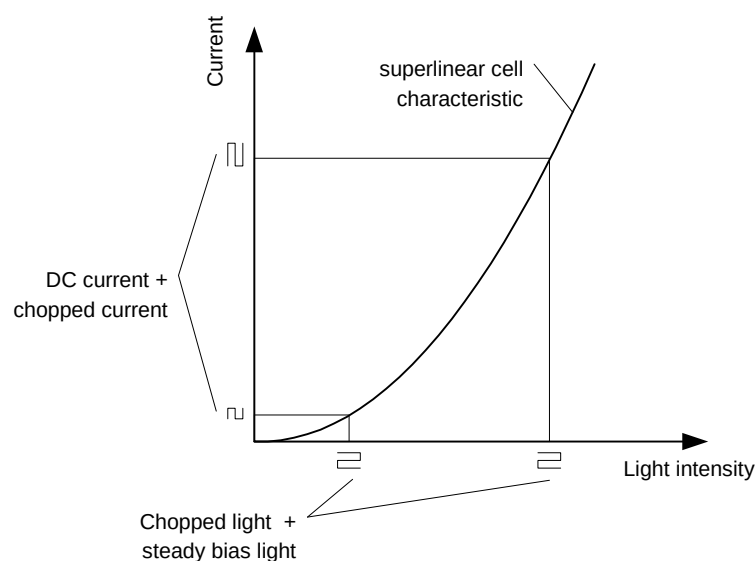


Figure 3-2: Illustration of the differential linearity measurement technique

When using an artificial light source, the light intensity can be varied by changing the distance between the cell and the lamp. However, this can cause large changes in the uniformity of the light. If the light detector and the cell are different sizes, a large error will result. Surprisingly, moving the lamp can also cause changes in the spectrum. For lamps that have spectrally selective reflectors (e.g. ELH lamps), the light reaching the cell comes from two sources – directly from the lamp filament, and via the reflector. These two sources have quite different spectra. Close to the lamp, the spectrum is dominated by light directly from the filament. Further from the lamp, the unfocused light coming direct from the filament is much weaker. The reflected light therefore dominates. Consequently, the spectrum changes as the cell is moved away from the lamp.

3.1.2 Problems with flash testers

Existing flash tester designs are not without problems. Commercial flash testers are expensive – a recent review of commercial systems (Schmela 2001) quotes prices of US\$60,000 to US\$270,000. Designing the flash to produce light of the correct spectrum, and possibly of constant intensity, is difficult and expensive. In addition, most flash tester designs change the bias voltage on the cell rapidly. This can cause transient errors with high performance cells.

3.1.3 Solutions

This work presents a new flash tester design, which provides solutions to both cost and transient error problems.

The cost of a flash tester can be reduced by simplifying the flash. Two simplifications are used in this work. In combination, they allow the use of a low-cost xenon flash (a commercial disco strobe), rather than an expensive custom engineered design. The major simplification is to avoid spectral mismatch problems by using reference cells with a similar spectral response to the test cells. This is made possible by the convenience and simplicity of the natural sunlight calibration procedure described in the preceding chapter. With a well-matched reference cell, the relatively poor spectrum of the disco strobe causes little error (significantly less than the calibration uncertainty for the reference cell). An additional benefit of eliminating the spectral mismatch is that the system can then be used to extract a family of I-V curves over a decade range of light intensity. This allows cell parameters to be estimated more reliably than with a single I-V curve. The second simplification is to use a multi-flash design. This avoids the need for the flash to produce light of constant intensity.

Transient error problems are addressed by using a constant voltage cell bias circuit. This avoids rapid changes in the cell voltage, thereby greatly reducing transient errors.

The constant voltage flash tester design is both cheap (under US\$10,000) and achieves excellent accuracy (limited by the reference cell calibration).

3.2 Implementation of constant voltage flash tester

This section describes how the constant voltage flash-tester works. All of the components are described, and how they fit together. The performance of the components are only summarised in this section – the details are left to the next section, 3.3.

3.2.1 Design concept

The constant voltage flash tester has two major novel features: the use of a simple, commercial flash, and the use of a constant voltage cell bias circuit.

The constant voltage flash tester uses a cheap, simple, commercial flash. The spectrum of this flash is relatively poor, compared to existing flash testers. The uniformity is also a little worse. However, errors due to the spectral mismatch and non-uniformity are greatly reduced by use of a calibrated reference cell that is the same size and has a similar spectral response to the test cell. Calibration under natural sunlight, described in the previous chapter, is an easy and accurate way to calibrate these reference cells. This makes it convenient to create closely matched reference cells, and so the relatively poor spectrum of the flash does not matter.

For groups making solar cells (either research or commercial), the vast majority of cells produced are very similar. Cell production recipes evolve slowly, so new reference cells do not often need to be created. In this situation, the relatively poor spectrum of the flash is no inconvenience.

The flash in most commercial flash testers is designed to maintain a constant light output for several milliseconds, long enough to sweep out the entire I-V curve. Flash tester flashes typically have peak power outputs of at least tens of kilowatts (the JPL LAPSS has a peak power of 7 MW). Designing the flash to produce a constant light output requires circuitry to regulate power flows of this magnitude, which is not easy. It is not essential to have a flash that produces constant light output – if multiple flashes are used, a single I-V point can be taken from each flash. This allows the use of a simple commercial flash without any control of the light intensity.

There is an additional benefit to eliminating problems of non-ideal spectrum by using matched reference cells. If the exact nature of the spectrum is not important, then small changes in the spectrum will not be important either. So, even if the spectrum changes over the course of the flash pulse, this light source of varying intensity can still be used. In a multi-flash system, the gradual decay in the light intensity of each flash can therefore be used to generate a family of I-V curves, each one measured at a different light intensity. To vary the light intensity on a conventional flash tester would require changing the flash-to-cell distance, adding neutral density filters, or masking the flash aperture. This would be tedious to do manually or expensive to automate.

The family of I-V curves can be used to examine how cell behaviour varies with light intensity. This is very useful, both for concentrator cells and for 1-sun cells. For the system described in this work, I-V curves can be obtained over a decade range of light intensity. Compared to a system that measures a single I-V curve, this system provides more information about cell behaviour, allowing more accurate modelling of the cell. For example:

- At high light intensity the influence of series resistance dominates while shunt resistance has little effect. At low light intensity, the reverse is true. Having data at high and low light intensities allows both series and shunt resistance to be estimated accurately.
- To accurately determine the ideality factor, n , requires measurements at different light levels. Having measurements of n over a range of light intensities allows recombination processes to be characterised better.
- In cell design, the thickness of front surface metallisation is a trade-off between shading the cell and maintaining sufficiently low series resistance. By observing the light intensity at which maximum FF occurs it is possible to optimise front surface metallisation.
- Finally, in real-world applications, cells operate under varying light intensity (usually lower than the light intensity under standard testing conditions). Having data for the cell over its full operating range allows performance in the field to be predicted more accurately.

The second major feature of the flash tester design is the use of a constant voltage cell bias circuit. Conventional, single-flash, testers have to rapidly sweep out the full I-V curve of the cell. The rapid change in cell bias voltage can introduce transient errors. The constant voltage flash tester, in contrast, maintains a constant voltage on the cell during each flash. This greatly reduces sensitivity to transient errors. The circuitry used in the constant voltage flash tester consists of a large capacitor, connected directly across the cell, and a low speed amplifier to charge the capacitor to the desired bias voltage. In operation, the constant voltage flash tester allows the light intensity to vary over the course of each flash while maintaining a nearly constant bias voltage. Multiple I-V points are taken during each flash and repeated flashes build up the full family of I-V curves. The process is illustrated in figure 3-3.

A simplified block diagram of the system is shown in figure 3-4. It can be seen that most of the complexity is in the commercial data acquisition card.

In operation, the bias voltage is applied to the cell and capacitor and sufficient time is allowed for the capacitor to charge. The flash is then triggered and the light intensity, cell current, and cell voltage are measured rapidly for the duration of the flash. Then, one I-V point is extracted for each I-V curve that is being generated. This process is repeated for different bias voltages to measure the entire set of I-V curves.

Once a complete set of curves have been measured, various indicators of cell performance (I_{sc} , V_{oc} , FF, efficiency, etc.) are calculated and plotted as a function of light intensity.

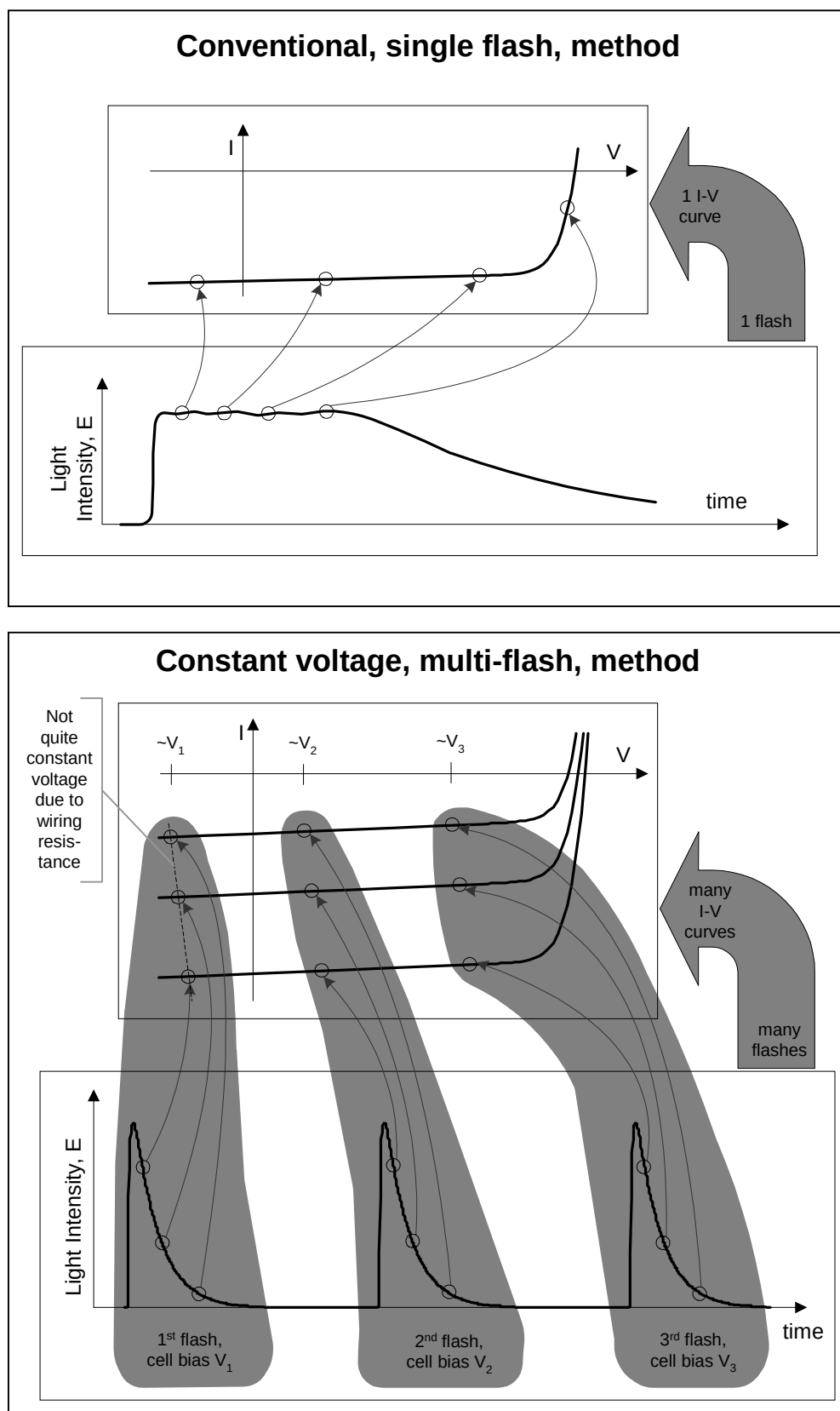


Figure 3-3: Operating principle of a conventional, single flash, design and the new, constant-voltage, multi-flash, design.

3.2.2 System hardware

The flash testing system can be broken into several basic hardware components:

- The flash
- A light detector, to measure the light intensity
- A jig to connect to and temperature control the cell being tested
- Circuitry to apply a bias voltage to the cell
- Instrumentation to measure the cell current and voltage

The hardware required to implement the design is cheap and simple since most of the complexity is in a commercial multi-purpose data acquisition card. A block diagram of the system is shown in figure 3-4.

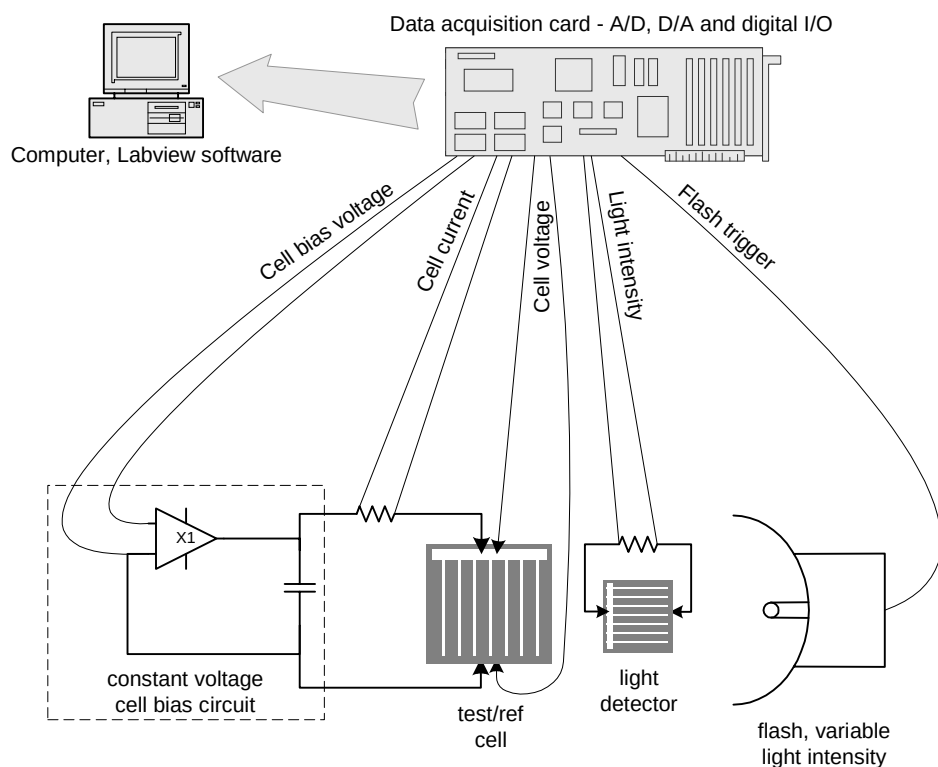


Figure 3-4: Block diagram of the constant voltage flash tester

3.2.2.1 Flash

The flash unit is a commercial disco strobe, a Geni Megastrobe. It is a rectangular unit with a Phillips XOP linear xenon discharge tube. It can be seen in figure 3-5. We originally used a photographic flash lamp, but switched to the disco strobe to get higher flash rates. This section gives a summary of the flash characteristics. Details of its characteristics are given in section 3.3.1.

The flash, as supplied, had poor light uniformity. This was fixed by replacing the polished reflector behind the lamp with a diffuse white surface. The diffuse reflector can be seen in figure 3-5.

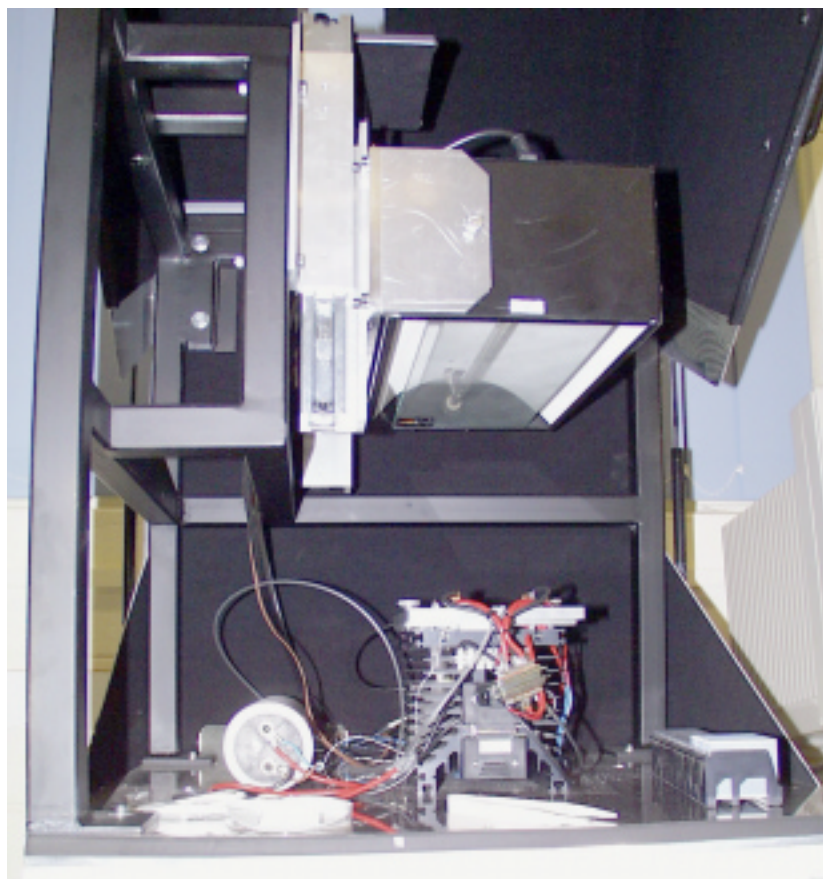


Figure 3-5: The flash unit, with the cell-testing block below it.

A peak light intensity of up to 100 suns can be achieved.

The light uniformity at 30 suns is $\pm 2\%$ (class A) over an area of $\sim 10 \times 10$ cm.

The spectrum of the flash is not known accurately. However, the manufacturers datasheet suggests that it meets ASTM Class C requirements for spectrum. Experimental measurements on a group of ANU concentrator cells showed that spectral mismatch is less than 2.5% for any of these cells.

The gradual decay of light intensity allows a family of I-V curves to be extracted, over approximately a decade range of light intensity. No mechanical movement of the light source is needed. The spectrum of the light does change noticeably as the light intensity drops however, and this will cause errors with poorly matched cells. A mismatch appears most obviously as a measured non-linearity of short circuit current with light intensity. However, with cells that have similar spectral responses, the spectral mismatch will be small.

Due to concerns about transient errors in the measurement, an external capacitor bank was built to power the flash and allow slower flash decay rates. With the external capacitor bank, flash decay times ($1/e$) of between 0.6 ms and 16 ms are possible. Analysis of the transient error problem, in section 3.3.2, shows that the capacitor bank could probably be dispensed with if the cell bias circuit was improved. Providing cell voltage is held constant, the internal flash pulse is slow enough.

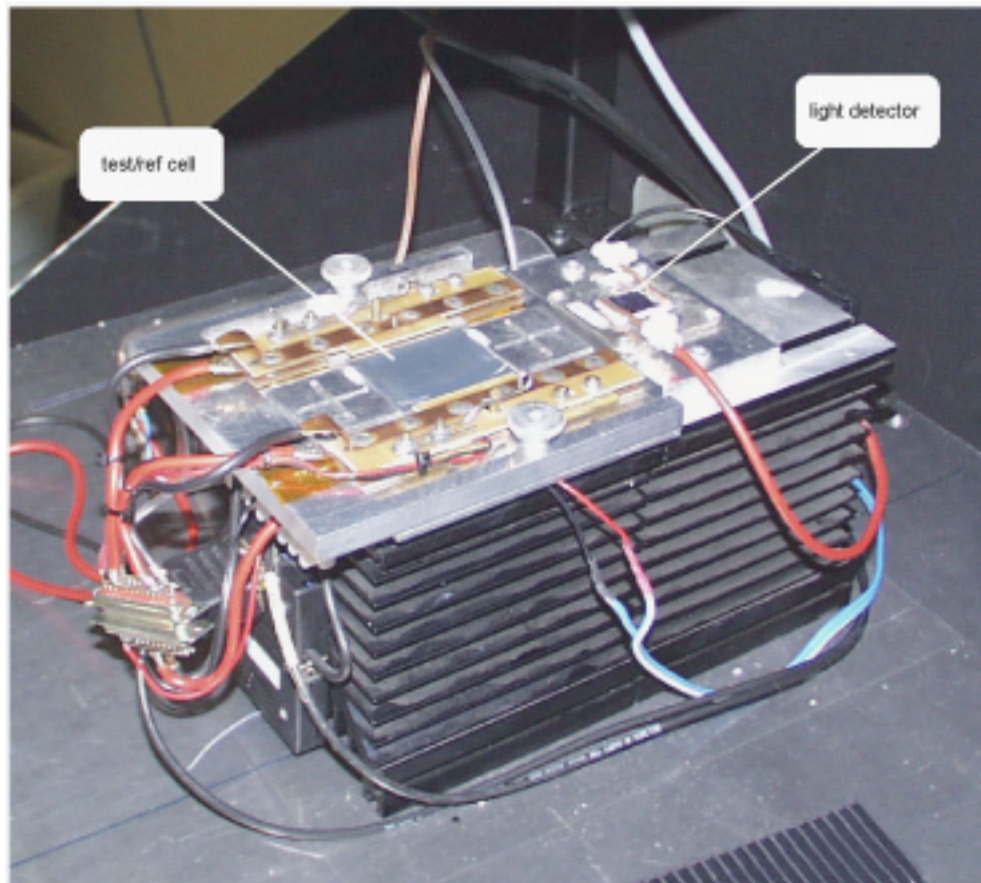


Figure 3-6: Cell-testing block and light detector

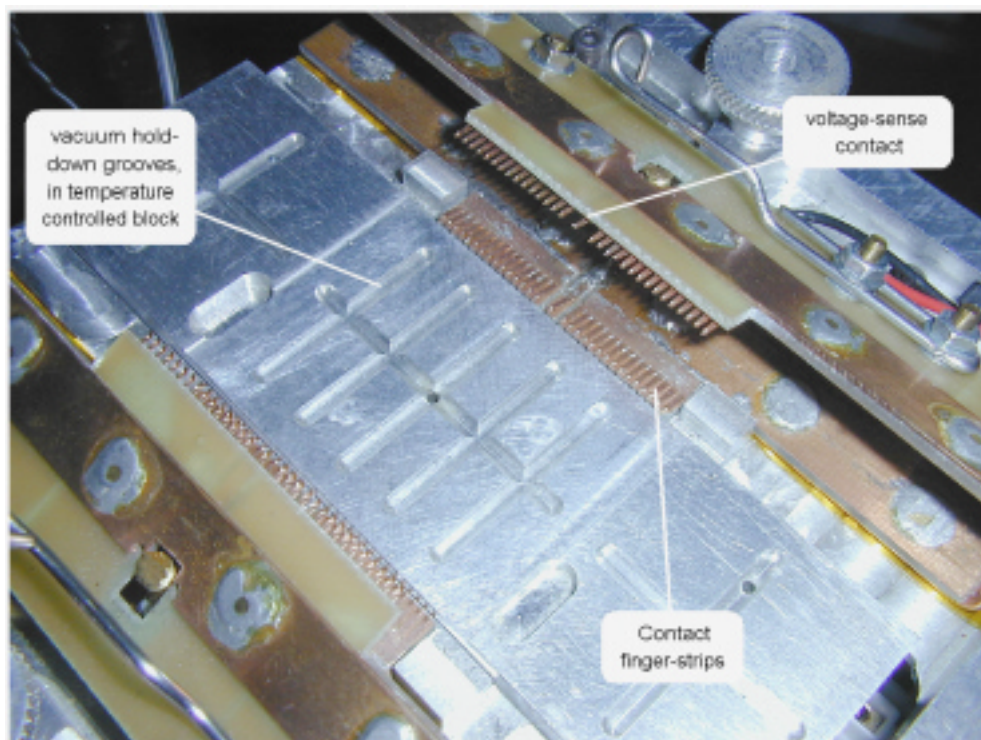


Figure 3-7: Close-up of contact fingers on cell-testing block.

3.2.2.2 Light detector and reference cells

A measurement with this system involves three cells – the light detector, the reference cell, and the test cell. The light detector is positioned next to the cell-testing block, where it continuously measures the light intensity during each flash. The cell-testing block holds either the reference cell or the test cell, and ensures that they are in exactly the same position.

In operation, the reference cell is first used to calibrate the light detector. The reference cell is then swapped for the test cell, and the test cell is measured. Prior calibration with the reference cell cancels both spatial non-uniformity in the light, and spectral mismatch between the light detector and the reference cell.

The nominal spectrum of the flash is different to the standard spectra (AM1.5G etc), and it changes slightly over the course of the flash – it is bluer at the peak of the flash, and redder at the tail. This will cause a varying spectral mismatch between the light detector and the test or reference cell. In the absence of any correction, the varying spectral mismatch will show up most obviously as a nonlinearity of short circuit current.

The obvious way to eliminate the spectral mismatch is to use a light detector that has a very similar spectral response to the test and reference cells. This is inconvenient though, since it requires frequent swapping of light detectors. Fortunately, swapping light detectors is in fact unnecessary. The spectrum of the flash lamp is repeatable, so the spectral mismatch can be calibrated out.

Given that the spectrum is repeatable, and that the flash-to-cell distance is not changed, a given spectrum will always occur at the same light intensity. A conversion function can then be generated that accurately estimates reference cell photocurrent as a function of light detector photocurrent (it will be close to linear, but not quite). This will eliminate the spectral mismatch between the light detector and the reference cell. Since the reference cell and the test cell have similar spectral responses, spectral mismatch between the light detector and the test cell will also be eliminated. The method used to calculate this conversion function is described in section 3.2.3.3.

It is advisable for the light detector to have a roughly similar spectral response to the test and reference cells. This will minimise the size of the correction, and so make it less sensitive to slight non-repeatability in the lamp spectrum.

For the system used at ANU, the light detector is a SunPower concentrator cell. This is a high efficiency cell, with performance similar to the cells produced at ANU.

The reference cells used at ANU are normal production cells that have been calibrated outdoors, using natural sunlight. The convenience of this method allows the frequent creation of new reference cells, which in turn allows the use of a flash lamp with a relatively poor spectrum.

3.2.2.3 Cell-testing block

The cell-testing block performs several functions. It makes electrical contact to the cell, controls the temperature of the cell, and ensures that its physical position is repeatable.

The cell-testing block consists of a temperature controlled aluminium plate. The cell is held onto the plate by vacuum. Mounted along the sides of this plate are electrical contacts to the cell. A picture of the cell-testing block is shown in figure 3-6.

Concentrator cells produce large currents, so contact resistance is an important consideration when testing them. To minimise resistance the contacts to the cell are flexible metal contact finger-strips. These contact the entire busbar area, closely simulating the tabbed contacts. These finger strips can be seen in figure 3-7 (for comparison, a tabbed cell is shown in figure 1-3). In addition, the cell-testing block uses a 4-point contact scheme to minimise voltage-sensing errors.

Concentrator cells have to dissipate far less heat when being tested in a flash testing system than under normal operating conditions. However, temperature control is still important. The aluminium plate that the cell mounts on is temperature controlled. Good thermal contact is maintained between the cell and the plate by vacuum hold-down.

Temperature control of the plate is achieved by use of a thermoelectric cooler (Peltier device) and a digital process controller. The temperature can be quickly set to any value in the range 0°C to 70°C. This system is much smaller, lighter, and cheaper than a water chiller/heater, which is more commonly used. It also allows a much faster change of cell temperature.

3.2.2.4 Cell bias circuitry

The cell bias circuitry provides a variable load for the cell, enabling the I-V curve to be traced out. The objective for this system is to maintain a constant voltage on the cell. This minimises transient errors. Conveniently, a constant voltage load is also relatively easy to implement.

The obvious way to get constant bias voltage is to use an active bias circuit. For example, a four-quadrant power supply operating as a voltage source. However, suitable power supplies are expensive, and can have stability problems.

In this work, an alternative bias circuit is used. It is partially passive and partially active. It consists of a large capacitor (~1 Farad), which is connected directly across the cell, and a low speed four-quadrant power amplifier. During the flash, the capacitor operates as a passive load, maintaining a nearly constant voltage across the cell. The capacitor is sufficiently large that its voltage only changes marginally in response to the current from the cell. Between flashes, the amplifier changes the bias voltage on the cell and capacitor. Since the capacitor handles the high-speed transients, the amplifier can be relatively low speed. This makes the amplifier cheaper, and makes it much easier to guarantee stability. The amplifier consists of an LM12 power op-amp operating as a unity-gain buffer. It produces on its output the same voltage as is supplied by the data acquisition card.

The capacitive load is not quite constant voltage however. Due to unavoidable series resistance, the cell voltage changes in response to changing cell current. The consequences of this problem are examined in detail in section 3.3.2.

3.2.2.5 Data acquisition circuitry

The data acquisition circuitry consists of a data acquisition card and current sensing resistors. The data acquisition card performs several functions:

- It measures the cell current, cell voltage, and light intensity: 12 bit analog inputs
- It generates the bias voltage to be applied to the cell: 12 bit analog output
- It triggers the flash to fire: digital output

The data acquisition card used is a 12 bit 1.25MSa/s, multipurpose card (A-D, D-A, and digital I/O). This card is considerably faster than is necessary. A cheaper, slower, card could be used instead, as discussed in section 3.3.3.1. The flash trigger line includes a level conversion circuit, which converts the 5V TTL trigger signal from the DAQ card to the 12V signal that the flash requires.

To measure the cell current and the output from the light detector, low value resistors are used to convert the current to a voltage. The resistors chosen have a low temperature coefficient and are non-inductive. To allow a range of different cells to be tested the resistors are easily inter-changeable. Each one is mounted in a DB25 connector with 4-point connections to eliminate errors due to contact resistance.

3.2.2.6 Enclosure

The optical parts of the system are enclosed in a large box, which is blackened inside. This minimises errors from stray light and uncontrolled reflections. It also shields the operator from the annoying flashing light. Most of the inside of the enclosure is covered with Edmund Scientific light absorbing blackout material.

3.2.3 System software

The system software controls the measurement hardware and processes the results. The operation of the software can be broken into two major sections. First, the acquisition of a set of I-V curves, and second, processing these I-V curves to extract cell performance parameters. There are also other minor support routines, which deal with things like loading and saving results.

The software is programmed using National Instruments' LabVIEW, which is a high-level instrumentation programming language. It provides excellent support for data acquisition, processing, and display.

3.2.3.1 Measuring I-V curves

When the user starts a test, they are taken first to the set-up screen. At the set-up screen, the user specifies what light intensities to extract I-V curves for, the range of bias voltages to use, etc. This screen also allows the user to check that the connections to the cell are good. Once everything is set correctly, the test is started. It runs automatically, setting the bias voltage, firing the flash, acquiring and processing data, until all flashes have been completed. Once complete, the I-V curves are returned to the main screen, where parameter extraction is done. A flow chart of the software execution is shown in figure 3-8. Each process in the flowchart is explained in more detail below.

Main screen

The main screen is the central part of the software. At this screen cell names, notes, etc. are entered, the test started, and the resulting measurements displayed. A typical screenshot is shown in figure 3-9.

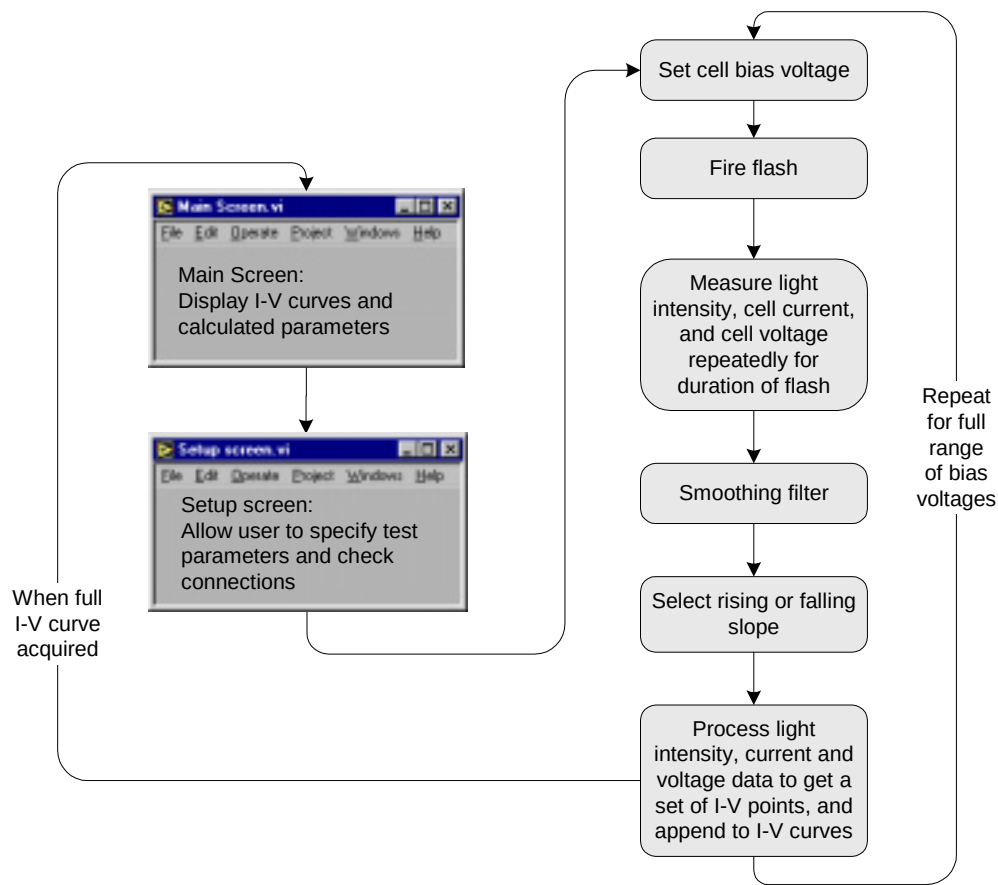


Figure 3-8: Flow-chart of I-V Tester Software Algorithm. A detailed description of each of the boxes is given below

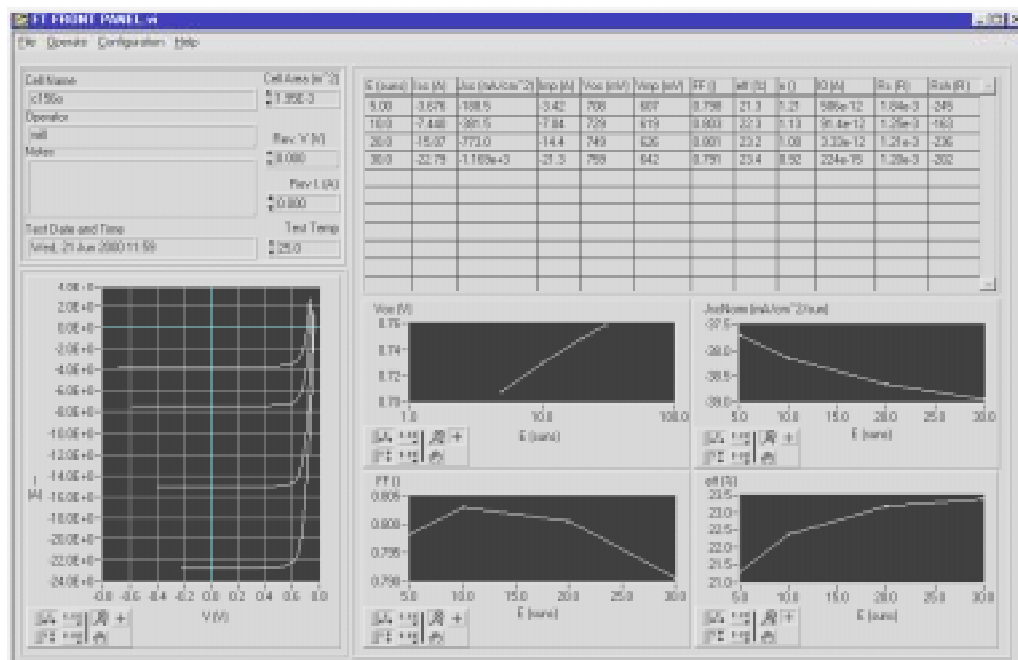


Figure 3-9: Screenshot of flash tester main screen. This is the screen where the finished I-V curves are displayed, along with the extracted cell parameters.

Set-up screen

When a test is started, the set-up screen appears. It allows the user to specify various test parameters and to check that everything is set correctly. The flash can be fired and the resulting light intensity, cell voltage and cell current waveforms examined to ensure that everything is functioning properly. A typical screenshot is shown in figure 3-10. The major functions performed at this screen are:

- The peak light intensity is shown, allowing the user to get the desired decade range of light intensity by changing the distance between the flash and the cell.
- The light intensity, cell voltage and cell current are shown as raw measured voltages, allowing the user to choose appropriate current sensing resistors and check that connections are good. The current sense resistors should be chosen to maximise the size of the signal (hence minimising noise) but without exceeding the largest value measurable by the data acquisition card. If the signal is too large, it will be 'clipped' to the maximum value.
- The initial and final cell bias voltages, as well as the number of different bias voltages (or equivalently, the number of flashes) to test at, can be specified.
- The light intensities for which an I-V curve is desired can be specified.

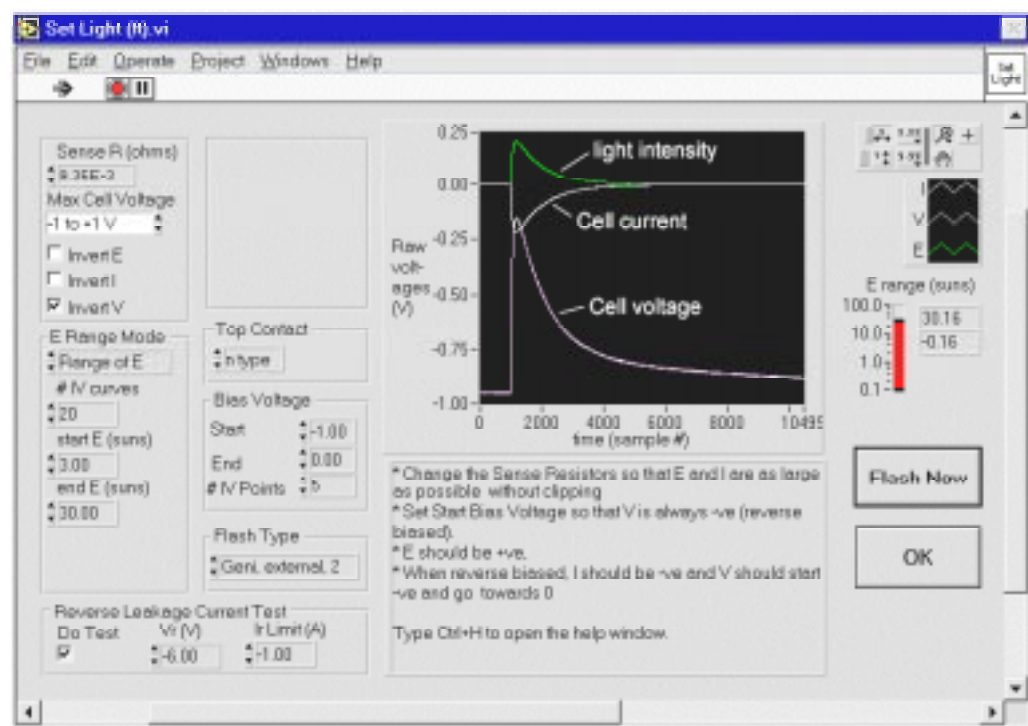


Figure 3-10: Screenshot of setup screen. Test conditions are specified at this screen.

Set bias voltage, fire flash, and measure light intensity, current and voltage

To obtain full I-V curves, the flash has to be fired repeatedly and a different cell bias voltage applied for each flash.

The bias voltage is set to the desired value by writing a value to one of the analog output channels on the data acquisition card.

The flash is fired by toggling one digital line on the data acquisition card.

The 3 input channels on the data acquisition card are set to acquire data continuously, and halt after triggering on the light intensity signal. This allows data to be captured before, during, and after the pulse, as can be seen in figure 3-10.

Light Intensity (E), Cell Current (I), and Cell Voltage (V) are measured as rapidly as possible for the duration of the flash.

Smoothing filter

The light intensity, cell current, and cell voltage are measured as rapidly as the data acquisition card will allow (400 kSample/s). The data acquisition card does not have anti-aliasing low-pass filters on the inputs (aliasing occurs when the presence of high frequency signals generate erroneous data at low frequencies. The sampling process effectively 'wraps' the high frequency signals to lower frequencies). The card's maximum acquisition rate is used to minimise the chance of aliasing. This is possible because the input circuitry on the data acquisition card will inherently provide some degree of low-pass filtering. The amount of data collected at this high rate is excessive, and slows the software down. To reduce the amount of data, it is digitally filtered to eliminate high frequency components and then down-sampled to 100 kSample/s to reduce the number of data points. The data is digitally filtered using a FIR (finite impulse response) low pass filter with a cut-off frequency of 10 kHz. A FIR filter was chosen as it has linear phase and so will introduce minimum distortion in the signal. The cut-off frequency was chosen qualitatively to smooth the signal gently – just enough to reject noise spikes but not enough to change the overall shape of the curve.

Select rising or falling slope

The flash is on for only a small part of the acquired light intensity, cell current, and cell voltage data. Additionally, the light intensity has both a rising and a falling slope. Consequently there are 2 times at which any given light intensity occurs. Most of the data therefore needs to be discarded. This section of the software selects only the portion of the data where the flash is on and with the desired slope.

The software allows either the rising or the falling slope to be selected. Provided there are no transient errors occurring, the choice of slope does not have any significant effect on the measurement. However, if there are transient problems, comparing measurements from the rising and falling slopes can be a useful way to detect them. This issue is discussed in detail in section 3.3.2.

Convert flash data to I-V points

The conversion of flash data to I-V points is the heart of the algorithm. Each flash gives one I-V point on each curve that is being extracted; multiple flashes are required to build up the entire curve (this multi-flash principle is summarised in figure 3-3).

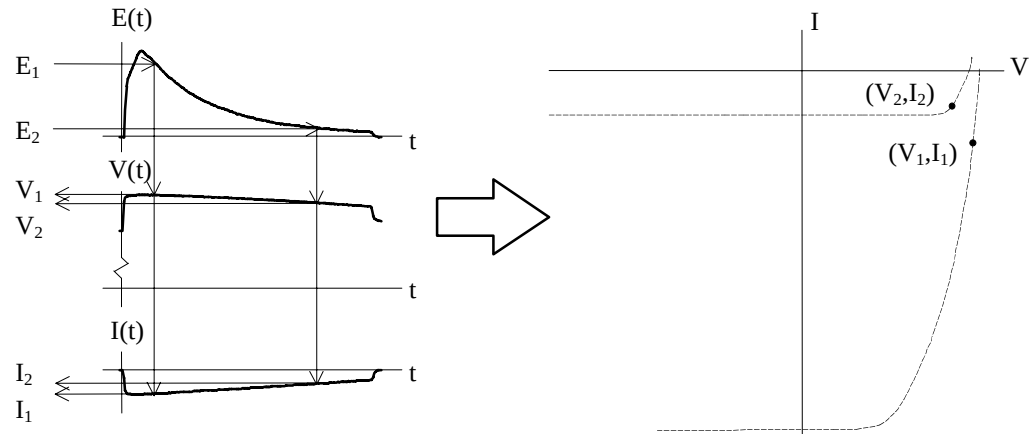


Figure 3-11: Conversion of data from 1 flash to multiple I-V points (multiple flashes are required to obtain entire I-V curves). The figure shows the extraction of two I-V points, at the two light intensities E_1 & E_2 , from light intensity, cell current and cell voltage as functions of time.

The flash data consists of measurements of light intensity, cell voltage and cell current as a function of time. Each I-V point desired is a simultaneous measurement of cell current and voltage when the light is at a particular intensity. To extract an I-V point, an interpolation process is used. This interpolation process is shown in figure 3-11. For the desired light intensity, E_n , the time at which this intensity occurs is determined. The cell current and voltage, (I_n, V_n) , at this time are then taken from the $I(t)$ and $V(t)$ data and the I-V point is added to the existing data for the E_n I-V curve. Linear interpolation between data-points in the time domain signals is used to increase resolution.

3.2.3.2 Parameter extraction

A set of I-V curves on its own gives only a qualitative indication of cell performance. For quantitative information about cell performance, it is necessary to extract various cell parameters from the I-V curves.

Many different techniques have been developed for parameter extraction from I-V curves. No attempt was made in this work to develop better methods – the effort was concentrated on reducing the hardware cost and improving its performance. This system merely implements some of the simpler methods that others have developed. Since the software is written in LabVIEW, which is easy to edit, better parameter extraction algorithms could be added later.

First, the extraction of the ‘external’ cell parameters (V_{oc} , I_{sc} , FF, efficiency, etc.) is described. Then, the extraction of model parameters for the standard single diode model is described. The single diode model with series and shunt resistance is given by equation (3-1) and figure 3-12. This model is a lumped component approximation to a distributed problem, so for some cells, it is a poor model. The parameter extraction process, however, does not indicate whether the model fits the cell well.

$$I = I_0 \left(e^{\frac{V - IR_s}{nkT/q}} - 1 \right) + I_{ph} - \frac{V - IR_s}{R_{sh}} \quad (3-1)$$

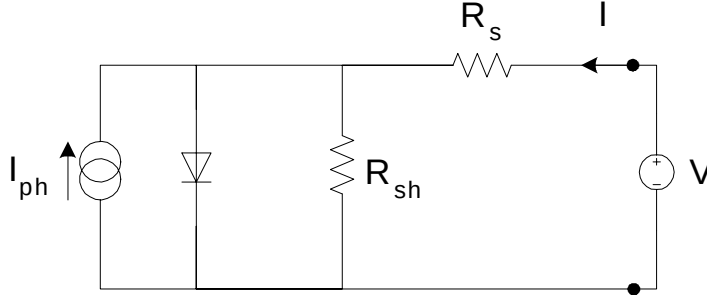


Figure 3-12: Equivalent circuit for a solar cell described by equation (3-1).

Short circuit current, I_{sc}

The short circuit current, I_{sc} , is calculated by performing a least squares linear fit through all the points on the I-V curve within a specified voltage range around short circuit. The voltage range is selectable by the user, but is typically $\pm 100\text{mV}$. Using a range of values reduces sensitivity to noise.

Short circuit current density, J_{sc} ; Normalised short circuit current density, $J_{sc(norm)}$

The short circuit current density, J_{sc} , is calculated by dividing the short-circuit current, I_{sc} , by the cell area.

The normalised short circuit current density, $J_{sc(NORM)}$, is calculated by dividing J_{sc} by the light intensity (in suns). This allows the linearity of the cell current to be examined – if the cell is linear, $J_{sc(NORM)}$ will be constant. The flash tester described in this work cannot accurately measure linearity of J_{sc} , due to spectrum changes in the flash (as described in section 3.3.1.2). Therefore measurements of short circuit current linearity are primarily of use in diagnosing spectral-mismatch problems.

Open circuit voltage, V_{oc}

The open circuit voltage, V_{oc} , is calculated by fitting an exponential curve through a few points around V_{oc} . A straight line fit does not follow the bend of the curve at V_{oc} . If a sufficiently large number of points are used to minimise noise, the straight line fit introduces a significant error. This problem becomes particularly noticeable when V_{oc} is used for the calculation of ideality factor.

The curve fitted to the data is of the form:

$$I = a_1 e^{a_2 V} - I_{sc} \quad (3-2)$$

Where I_{sc} is previously calculated, and a_1 , a_2 are the fitting parameters.

The range of points used in the fit is specified as a proportion of I_{sc} . The range is typically between +25% and -25% of I_{sc} , and it can be adjusted by the user.

Maximum power point and FF

The maximum power point is found simply by choosing the single I-V point at which maximum power occurs. The fill factor is calculated using the standard relationship:

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}} \quad (3-3)$$

Choosing the single point with highest power can underestimate the maximum power point, but not overestimate it – if one of the measured I-V points is, by luck or design, exactly on the maximum power point, then the FF will be correct. If, on the other hand, this I-V point is a little to either side of the maximum power point, then the FF will be underestimated.

Whether the measured I-V points hit the maximum power point or not depends both on the light intensity for the desired I-V curve and on the bias voltage. For a given bias circuit voltage, as the light intensity varies the cell will pass through maximum power at some light intensity. If this happens to be one of the light intensities at which an I-V curve is being extracted, then the FF will be correct. This effect is illustrated in figure 3-13. This figure shows two measurements of the same cell, differing only in the number of flashes (and hence the number of I-V points) used in the measurement. I-V curves were extracted for 100 different light intensities. The ‘200 flashes’ measurement has 200 I-V points on each I-V curve, and so it gives very close to the ‘true’ value of FF. The ‘15 flashes’ measurement has only 15 I-V points on each I-V curve. For some light intensities (eg, 6, 12, 18, ... suns) the particular choice of bias voltages misses the maximum power point quite badly. For other light intensities (eg, 4, 10, 15, ... suns), the choice of bias voltages happens to give I-V points very close to the maximum power point.

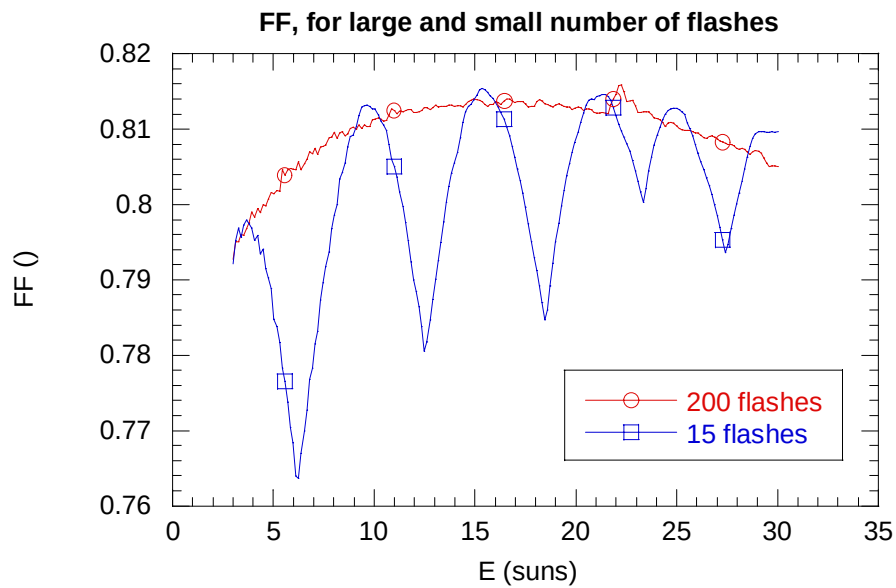


Figure 3-13: Illustration of how using a small number of flashes can underestimate FF

The simple way to avoid this under-estimation problem is simply to get a sufficiently large number of I-V points. This is the procedure used currently. Experiments have shown that 40 I-V points, uniformly distributed by voltage, will under-estimate FF by less than 0.01 (~1%).

With a conventional tester, which measures only one I-V curve, it is possible to iteratively home in on the maximum power point during the measurement. This is not so easy, however, in this system, which extracts many I-V curves simultaneously. Each I-V curve has a different maximum power voltage, so the constant voltage bias circuit would have to find the maximum power point on each curve individually.

Consideration of the process that causes the under-estimation suggests an alternative way to measure maximum power with fewer flashes. For a given bias circuit voltage, as the light intensity varies the cell will pass through maximum power at some light intensity. At this light intensity, the exact (V_{mp} , I_{mp} , E) data point could then be collected. This will be a 'true' maximum power point, and will not be subject to underestimation problems. One point will occur for each bias voltage near to maximum power. These points would be independent of the I-V points – the E values at which maximum power occurred would be unlikely to match the desired I-V curve E values. The $V_{mp}(E)$ and $I_{mp}(E)$ functions could then be interpolated back to the light intensities at which I-V curves had been extracted. This alternative method has not yet been implemented.

As an alternative to the single I-V point method, the maximum power point could be found by fitting an appropriate function to the I-V data. This, in principle, should be more accurate. However, attempts to do this were not successful. Both polynomial and exponential fits were tried, but neither could be made to work with sufficient reliability.

The first attempt used a polynomial fit, as described in (Emery and Osterwald 1990). A polynomial function of order 4 or higher was fitted to a few points around the maximum power point using the least squares method. This was not found to be reliable as the polynomial sometimes had 'wiggles' that departed significantly from the shape of the curve, as illustrated in figure 3-14.

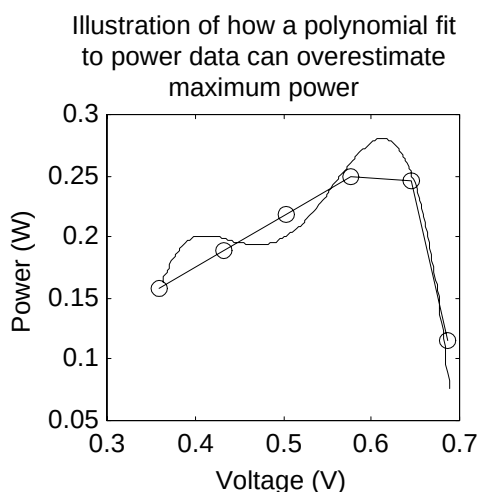


Figure 3-14: An example of the error in FF introduced by a polynomial fit. This was an order 4 fit through 7 data points around the maximum power point. FF is over-estimated by 8%.

Secondly, an exponential fit was tried. Initially, a plain exponential function, as shown in equation (3-2), was fitted to a few points around the maximum power point. However, this did not give the desired result. It was found that in the presence of series resistance the exponential fit over-estimated the maximum power. It is well known that the presence of series resistance reduces the fill factor for an I-V curve, effectively making the I-V curve less 'square' at the maximum power point. A simple exponential function is too square at the knee of the curve and so tends to over-estimate the fill factor.

In an attempt to eliminate the 'squareness' problem, a series resistance component was incorporated into the model, as shown in equation (3-4).

$$I = a_1 e^{a_2(V+a_3I)} - I_{sc} \quad (3-4)$$

where I_{sc} is a previously calculated constant, and a_1 , a_2 , a_3 are the fitting parameters.

However, including the series resistance term (a_3 in equation (3-4)) makes it impossible to get a closed form expression for I in terms of V . This greatly complicates the fitting procedure, requiring a non-linear curve-fitting algorithm. An attempt was made to fit this model, using the Levenberg-Marquardt method, but the fitting routine could not be made to converge reliably enough for routine use.

Fitting a model to the I-V curve is certainly possible – many authors have described successful attempts – but it is clearly not trivial. As it was not central to the main emphasis of this work, curve fitting was not pursued. For future work, a possible alternative solution, as suggested in (King, Hansen et al. 1997), is to use the commercial curve-fitting package FitAll, produced by MTR Software, Canada.

Efficiency, η

The efficiency, η , is calculated using the standard equation:

$$\eta = \frac{V_{MP} I_{MP}}{AE} \quad (3-5)$$

where A is the cell area and E is the light power.

Ideality factor, n

The ideality factor, n , is calculated between adjacent pairs of I-V curves by using V_{oc} , I_{sc} pairs.

$$n = \frac{V_{oc1} - V_{oc2}}{\frac{kT}{q} \ln \left(\frac{I_{sc1}}{I_{sc2}} \right)} \quad (3-6)$$

This is loosely equivalent to finding the slope of a V_{oc}/I_{sc} plot, the difference being that it finds the slope of each section individually.

This method calculates n for some voltage between V_{oc1} and V_{oc2} , and gives one less n value than the number of I-V curves. Since it is desired to have an n value for each curve, a spline interpolation is used to calculate new n values. The value of n is

assumed to be calculated at a V value midway between V_{oc1} and V_{oc2} . A spline curve is fitted through these points and then interpolated back to extract values of n at $V_{oc1,2,3,\dots}$

Saturation current, I_0

The saturation current, I_0 , is calculated using the previously calculated values of I_{sc} , V_{oc} , R_{SH} and n .

$$I_0 = \frac{I_{sc} - \frac{V_{oc}}{R_{SH}}}{e^{\frac{qV_{oc}}{nkT}} - 1} \quad (3-7)$$

Series resistance, R_s

The series resistance, R_s , is calculated from V_{oc} , the slope of the curve at V_{oc} , n , and I_0 .

$$R_s = \frac{dV_{oc}}{dI} - \frac{nkT}{q} e^{\frac{-qV_{oc}}{nkTI_0}} \quad (3-8)$$

where $\frac{dV_{oc}}{dI}$ is the slope of the curve at V_{oc} .

Many other algorithms for extracting series resistance have been published, for example the well-known Wolf-Rauschenbach method. They are more accurate, but more difficult to implement. The slope at V_{oc} method was chosen in this instance simply because it was easy to implement.

Shunt resistance, R_{sh}

The shunt resistance, R_{sh} , is determined from the slope of the I-V curve around I_{sc} . The least squares method is used to fit a line through all the points within a specified voltage range, and the slope of the curve taken to be the slope of the best fit line. The voltage range is selectable by the user, but is typically -400-0 mV. The fit is done over a wider range of voltages than for I_{sc} because the slope of the curve is particularly sensitive to noise in this region, where the curve is very flat.

3.2.3.3 Light detector calibration

Light detector calibration compensates both for spatial non-uniformity in the light, and for spectral mismatch between the light detector and the reference cell. This section describes how the light detector calibration is calculated.

Light detector calibration is an iterative procedure. Starting with an estimate (possibly rough) of the correct calibration, the reference cell is measured. The measured reference cell I_{sc} as a function of light intensity is then compared to the true reference cell I_{sc} as a function of light intensity (which has been determined by some other method). The light detector calibration is then adjusted so that another measurement of the reference cell would give the true characteristic. The new calibration is then saved to disk for later measurements.

The calibration algorithm produces one light detector calibration point for each measured I_{sc} value. The algorithm is illustrated in figure 3-15. At the measured I_{sc}

value (1), the true light intensity (2) is known from the true reference cell calibration, and the approximate light intensity (1) is given by the old light detector calibration. The new light detector calibration point (4) is the true light intensity (2 & 4) at the old light detector voltage (3 & 4).

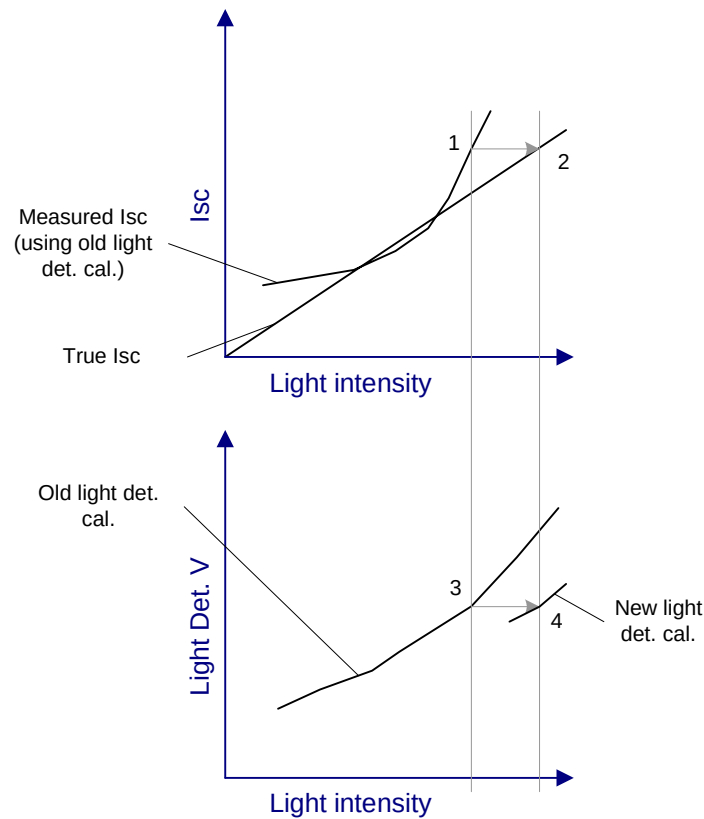


Figure 3-15: Algorithm used to calculate the light detector calibration.

3.2.4 Reference cell calibration procedure

Central to the flash tester design is the concept of using well-matched reference cells to allow a lower quality light source. This requires periodic calibration of new reference cells. Calibration under natural sunlight, which is described in the preceding chapter, is convenient and accurate. The availability of easy reference cell calibration makes the use of a cheap flash possible.

For the concentrator cells produced at ANU, calibration with respect to the AM1.5D standard spectrum is appropriate. According to the natural sunlight modelling work, appropriate weather conditions occur at almost any time of year in Canberra.

Each reference cell is calibrated by first measuring it outdoors to determine its 1-sun I_{sc} . Its 30-sun I_{sc} is then calculated from its 1-sun I_{sc} and an estimate of its linearity characteristic. Neither FF nor V_{oc} are measured during the calibration procedure (for reasons discussed in section 2.4.7.1).

Facilities to accurately measure short-circuit current linearity as a function of light intensity are not presently available at ANU. Attempts to measure the linearity,

described below, were not successful. Lacking measurements of the linearity of the ANU cells, the only option for the calibration procedure is to estimate a value based on previous work on the subject. Fortunately, cells of this type have been found to be highly linear. Little error should result from estimating linearity. The ANU concentrator cells are made on low resistivity wafers, and they operate at a relatively low concentration of 10-30 suns. Previous work on short-circuit current linearity, described in section 3.1.1.6, shows that most low resistivity concentrator cells are between 0 and 1% super-linear under these conditions. Based on this evidence, it is assumed for calibration purposes that the ANU concentrator cells are 1% super-linear over the range 1-30 suns.

In summary, each reference cell is calibrated by first measuring its 1-sun I_{sc} under natural sunlight, and then calculating its 30-sun I_{sc} , assuming 1% super-linearity.

3.2.4.1 Linearity measurement

A measurement of the linearity of one of the ANU concentrator cells was attempted, though unsuccessfully. This attempt used the flash-tester flashlamp as the light source, and varied the light intensity by changing the distance between the lamp and the cell. A SunPower concentrator cell was used as a light detector to measure the light intensity. The measurement was not successful because of the changes in light uniformity as the flash was moved. The ANU concentrator cells are much larger than the SunPower concentrator cells. Consequently, when the cells were close to the flash the SunPower cell saw only the central, uniformly illuminated region of the flash, while the ANU cell extended to the edges of the illuminated area, where the light intensity dropped off. The measurement apparently showed the ANU cell to be 40% sub-linear at 60 suns, which is quite implausible. The non-uniformity problems could have been eliminated by carefully measuring the light distribution as a function of flash-to-cell distance. However, other problems would still have upset the measurement. The most important of these were: firstly, the spectrum of the flash lamp was not a particularly good match to the standard spectra (cell linearity is sensitive to spectrum), and secondly, that the linearity of the SunPower cell was not known precisely.

To resolve the problems with measuring linearity using the flash tester, a parabolic trough concentrator was constructed. However, due to time limitations, measurements have not yet been performed using this trough. The trough will allow cells to be calibrated under concentrated natural sunlight, which is an excellent match to the AM1.5D standard spectrum. A reflective mirror surface was chosen, rather than a lens, because it concentrates the sunlight with minimal alteration to the spectrum. A picture of the trough is shown in figure 3-16. It consists of 40 flat mirror segments mounted on a CNC machined aluminium frame. Each mirror segment illuminates the cell area uniformly with an intensity of ~1 sun. This gives a total illumination of ~35 suns, with uniformity over the cell area of approximately $\pm 10\%$. The remainder of this section describes the proposed method to measure cell linearity using the trough.

The best technique for measuring linearity, given the characteristics of the trough, is the two-source method. The other techniques described in section 3.1.1.6 would be less accurate or less convenient – the use of a separate light detector to measure the light intensity would be inaccurate because of the non-uniformity of the light, and the differential linearity measurement technique would require the addition of a stable, chopped light source.



Figure 3-16: The segmented parabolic trough constructed for measurement of cells under concentrated natural sunlight. It is piggybacked on the tracker for a normal, full-length parabolic trough mirror.

The two-source method can easily be implemented on the trough, requiring only the addition of some adjustable masking on the trough surface and two shutters. The masking allows the intensity of the two light sources to be adjusted, and the two shutters allow the two sources to be turned on and off rapidly. The masking and the shutters should be well blackened so that they do not reflect any light onto the cell.

The recommended procedure is:

- Adjust the masking so that one mirror segment is exposed on each half of the trough (each giving approximately 1 sun illumination, and a total of 2 suns).
- Use one shutter to block one side briefly, giving the cell current due to the other side. Then use the other shutter to block the other side briefly. This will give cell current due to source 1, source 2, and both sources, in rapid succession. If this is done within a second or so, variations in sunlight intensity and imperfect tracking of the concentrator will introduce very little error.
- Repeat for a total illumination of 4 suns, 8 suns, 16 suns, and 32 suns.
- Starting with the 1 sun current measured previously (not using the trough), the current at 2, 4, 8, 16, and 32 suns can then be accurately calculated.

It may be worth measuring the background illumination due to diffuse light. This could introduce a significant error, particularly if surrounding surfaces have a high albedo. The current due to diffuse light can be measured when both shutters are closed.

3.3 Details of components and analysis of performance

In this section, the components of the flash testing system are analysed in detail. Full specifications are given, as opposed to the summary specifications given in the previous section.

The performance of the system is analysed, in general terms, for use testing any silicon solar cell. The following section, 3.4, estimates the measurement uncertainty specifically for the ANU concentrator cells.

3.3.1 Flash

The flash used in this system is a commercial disco strobe, a Geni Megastrobe. These strobes cost about US\$300. Compared to the flash systems in expensive flash testers, the quality of the light (particularly the spectrum) is relatively poor. However, if well-matched reference cells are created periodically by doing outdoor measurements, this problem can be largely eliminated. Use of this simple flash greatly reduces the cost of the system.

This section discusses in detail the light uniformity, spectrum, and pulse duration for the flash.

3.3.1.1 Light uniformity

The light uniformity (in other words, how the light intensity varies with position in the illuminated area) is an important specification for a solar simulator. This section describes the procedure used to measure the light uniformity for the Geni Megastrobe, and presents the results.

Measurements were first performed on the flash as supplied by the manufacturer. These showed that the uniformity was poor, prompting a small modification (described below). After modification, the uniformity was re-measured. The light uniformity was only measured for 30-60 suns, appropriate for the ANU concentrator application. The system can be used for 1-sun measurements too – BP Solar does this with their system. However, the uniformity at 1 sun is not investigated in this work, and BP has not measured it either.

The light uniformity was measured by moving a small cell around the test area while firing the flash repeatedly. Use of a camera to capture an image of the illuminated test area was considered, but the problems of synchronising to the flash and calibrating the image appeared too formidable.

The measurement set-up consisted of a fixed reference cell and a movable test cell. Each time the flash was fired the peak short circuit current (and hence peak light intensity) from both cells was measured. The measurement from the fixed cell was used to correct the measurement from the movable cell for variations of peak intensity between flashes, using equation (3-9).

$$E_{corr(movable)} = E_{meas(movable)} \times \frac{E_{init(fixed)}}{E_{meas(fixed)}} \quad (3-9)$$

where $E_{init(fixed)}$ is the value of E measured by the fixed cell during an initialisation flash.

To test the correction supplied by the fixed cell the flash was fired repeatedly with the movable cell in the same location. This showed the repeatability of the measurement was better than 0.5%.

The test cell used was a 1.5 cm square SunPower concentrator cell. It was scanned in a straight line across the width and along the length of the flash. Both lines passed through the point directly below the centre of the flash.

The results of light uniformity measurements both before and after modifications to the flash are shown in figure 3-17.

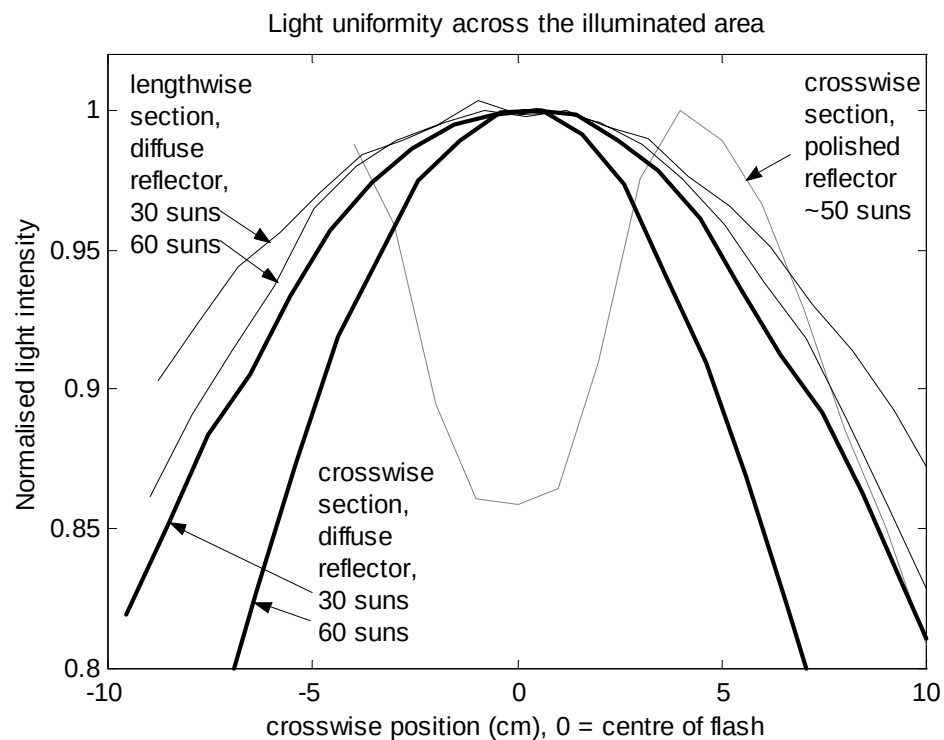


Figure 3-17: Light uniformity of the Geni Megastrobe flash lamp. Curves are shown both for a polished reflector (as-supplied), and for a white diffuse reflector. Flash to cell distance is approximately 240 mm for 30 suns peak.

It can be seen that the light uniformity of the flash with a polished reflector (as supplied by the manufacturer) is poor – there is a dark band in the middle. The system built for BP Solar used a slightly different model of flash unit and its light uniformity was even worse. This prompted modifications to the flash. The first attempt to improve the uniformity involved masking the front of the flash with an inward facing reflector, leaving only a slit open at the centre. The idea was for the reflective front and internal reflector to act as a crude integrating sphere. This method did improve the uniformity but at the expense of greatly decreasing the light output. This method was abandoned. The second attempt to improve the uniformity was to replace the specular internal reflector with a diffuse reflector. The diffuse reflector used was a piece of sheet metal bent to the same curve as the internal reflector and fitted directly over it. The surface was painted with a high temperature matt white paint. The diffuse

reflector resulted in greatly improved uniformity and only slightly reduced light intensity.

Solar simulators can be classified according to spatial non-uniformity, as specified in ASTM E927-91(1997). Parts of this standard are reproduced in (Emery 1986) (though Emery cites ASTM E928, which presumably has been superseded by E927). The standard states that a class A simulator has non-uniformity $<\pm 2\%$, and class B has non-uniformity $<\pm 5\%$. From figure 3-17, the modified Geni Megastrobe, operating at 30 suns, is class A over approximately 10x10cm, or class B over approximately 15x15cm.

Changing the distance between the flash and the cell will change the light intensity significantly (far more so than sideways movement). Approximate light intensities, at the centre point, as a function of flash-to-cell distance are given in figure 3-18.

The light intensity varies strongly with position. Clearly, the top surface of the reference test cells must be at the same distance from the flash. If both cells are the same thickness, this is easily achieved.

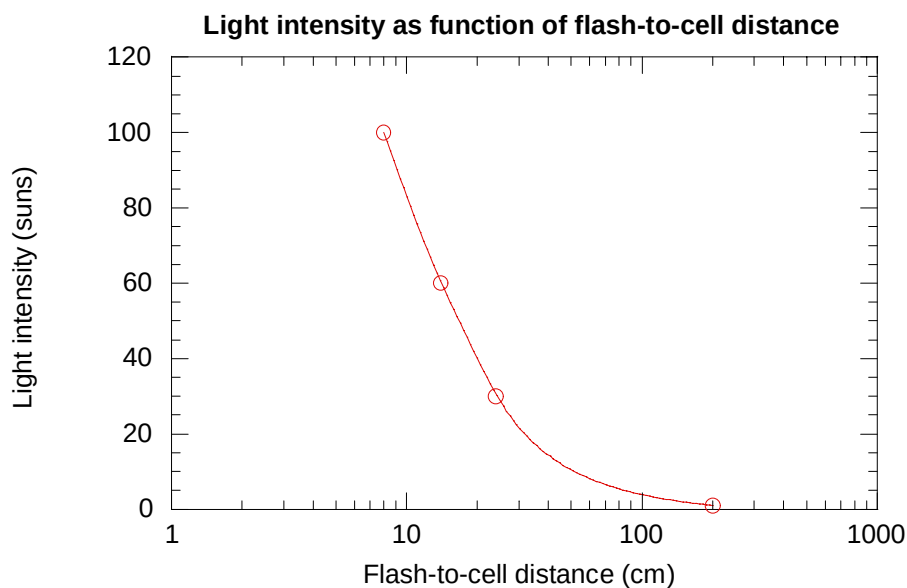


Figure 3-18: Light intensity as a function of flash-to-cell distance

3.3.1.2 Spectrum

For a solar simulator, the spectrum is usually the most important specification. For this system however, it is a less important issue. A central principle of this work is to use outdoor calibration to create matched reference cells. Spectral mismatch is then much less severe, and a much cheaper solar simulator can be used.

Nominal spectrum

The spectrum of the Geni Megastrobe is only known approximately. Measuring the spectrum of a flash lamp requires highly specialised and expensive equipment. Consequently, no attempt was made to measure the spectrum of the Megastrobe. In any case, due to the use of similar reference cells, it is not important to know it precisely.

An estimate of the spectrum is available from the manufacturer of the flash lamp. The lamp is a Phillips XOP xenon discharge tube. The spectrum is shown in figure 3-19, where it is compared to AM1.5G and another commonly used, low-cost solar simulator, the ELH lamp.

According to the ASTM classification of solar simulators (ASTM E927), the XOP spectrum meets Class C requirements. It is also quite similar to the spectrum of the Oriel 150W solar simulator (a low cost, unfiltered, xenon continuous-arc simulator). The XOP spectrum has too many photons in the near IR. The spectrum could possibly be filtered to improve this, but it would be difficult to know if it had worked without measuring the spectrum.

It can be seen that the XOP lamp is not a great solar simulator, but it is not a terrible one either. A moderately good simulator is all that is required for this work, since regular outdoor calibration will greatly reduce spectral mismatch.

Experimental measurements of spectral mismatch were made for a group of the ANU concentrator cells, as described in section 3.5. This showed that, for any of the cells produced during the year 2000 (efficiencies ranging from 15% to 22%), spectral mismatch was less than 2.5%. This confirms that the spectrum is moderately good.

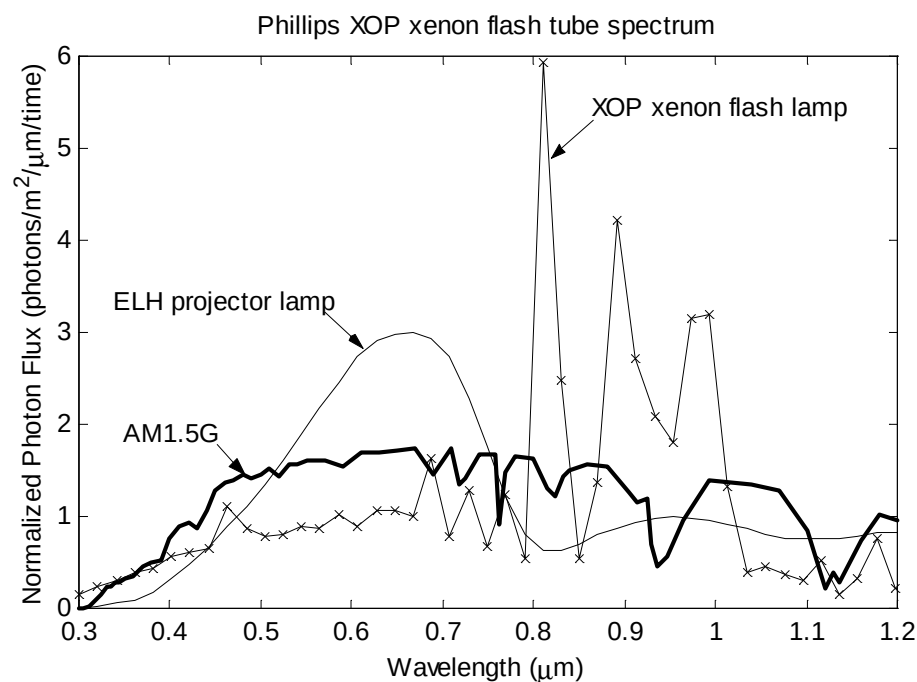


Figure 3-19: Spectrum of the Phillips XOP xenon flash tube compared to AM1.5G and the commonly used ELH projector lamp.

The spectrum of a flash lamp depends on the current flowing through it. According to (EG&G 1997), at current densities of tens of A/cm^2 , a xenon flash has a colour temperature of about 5,000 K (similar to the sun). At these low current densities, there are strong line emissions in the near IR. At current densities of several thousand A/cm^2 , the colour temperature rises to about 10,000 K and the line emissions almost vanish. The XOP lamp in the Megastrobe operates at a current density of $\sim 200 \text{ A}/\text{cm}^2$. It is difficult to make comparisons to existing systems since none of the publications on these systems specify the current densities at which they operate. However, it is stated in (Mueller 1993) that the LAPSS system has a peak power of 7 MW at 2700 V. This gives a peak current of 2600 A, and so a current density that is probably in the range of thousands of A/cm^2 . This is consistent with the absence of near-IR spikes in its spectrum, and the requirement for UV filtering, but not IR filtering, to improve the spectrum. The spectrum of the Megastrobe could probably be improved by building an external power supply to run it at higher current. However, this would be expensive, and it runs counter to the philosophy of using a cheap, commercial, flash.

Change in spectrum as light intensity varies

A major feature of the new flash tester design presented here is its ability to easily extract I-V curves for a range of light intensities. This relies on the gradual decay in light intensity as the flash turns off. However, the spectrum of the lamp becomes redder as it dims. This will complicate the measurement as it introduces a changing spectral mismatch at the same time as a changing light intensity. Fortunately, the light detector calibration process and the use of matched reference cells largely eliminates this problem.

The change in spectrum for a factor-of-2 variation in light intensity has been studied for 1 sun flash testers, and it is relatively small. Spectral mismatch measurements by (van den Berg, Bolingen et al. 1993) found that varying light intensity over the range 0.4-1 sun, by changing flash current, caused no observable mismatch compared to use of neutral density filters. This work involved measuring amorphous silicon cells against a filtered crystalline silicon reference, so the cells are unlikely to have had particularly well matched spectral responses. For the Fraunhofer system (Lipps, Zastrow et al. 1995), a plot is given of the spectrum over the course of the flash. Over the range 0.5-1 sun, the spectral irradiance at most wavelengths barely changes, though the spectral irradiance for the isolated spikes in the near IR does rise by up to 50%. Both of these papers show that there is little change in the spectrum for a factor-of-2 variation in light intensity.

For the new system described in this work, a factor-of-10 variation in light intensity is used. This large range of light intensity allows a family of I-V curves to be measured. Over such a wide range of light intensity, there is noticeable spectral change. This spectral change causes a varying spectral mismatch if the light detector and test/reference cells do not have identical spectral responses. This shows up most obviously in the results as an apparent nonlinearity of short circuit current with light intensity.

Such nonlinearity was observed in the development of the system (prior to introducing the light detector calibration that now eliminates it). When using a SunPower concentrator cell as the light detector and an ANU concentrator cell as the test cell, the ANU cells were measured to have slightly super-linear I_{sc} . Over 3-30 suns the ANU cells showed up to 5% super-linearity, decreasing to about 2% for the best cells. To confirm that this nonlinearity was due to spectral change, a simple experiment was

conducted. First, a cell was tested normally, over the range 3-30 suns. Then, a neutral density filter was placed over both the light detector and test cell and the test cell was measured over the range 0.3-3 suns. The test cell showed the same nonlinearity characteristic, in both shape and magnitude, in both measurements. It is quite implausible that any cell could have such a strange double-humped linearity characteristic. On the other hand, if the apparent nonlinearity was indeed due to spectral change, it should have been unaffected by the neutral density filter. This is what was observed. This experiment confirmed that the apparent nonlinearity was due to spectral change.

The spectral change over the course of the flash is not, however, a significant problem for this system. The use of similar test and reference cells eliminates it. During the light detector calibration process, the changing spectral mismatch between the light detector and the reference cell is calibrated out. Provided the change in the spectrum is the same with each flash (it is, see the next section), the spectral mismatch will remain calibrated out. Measurements of test cells will then not show the changing mismatch.

If, on the other hand, the test and reference cells have different spectral responses, then the spectral mismatch will not be calibrated out and non-linearity will appear. So, in fact, the appearance of nonlinearity is most likely an indication that the test and reference cells are not well matched.

The varying spectrum, unfortunately, does mean that the family of I-V curves cannot be used to determine I_{sc} linearity. It is impossible to distinguish true non-linearity from apparent non-linearity caused by spectral mismatch. However, by using a set of neutral density filters it may be possible to measure I_{sc} linearity with the system.

Spectrum stability as flash heats up

The spectrum of any lamp changes over time, on both long and short time scales. For this system, long-term changes are not a problem since the system is regularly re-calibrated with a reference cell. Short-term changes, however, might be a problem, particularly if the spectrum changes as the flash heats up.

An experiment was conducted to measure how much the spectrum changes as the flash heats up. Spectral variations cause greatest change in I_{sc} , so I_{sc} was measured in this experiment. First, to establish the baseline, a cell was measured with the flash completely cold. The same cell was then measured repeatedly as the flash heated up. To heat the flash, it was fired many times, as fast as it would go, immediately before taking the cell measurement. Up to 500 pre-measurement flashes were tried. After 500 flashes at maximum rate, the flash smelled hot and was uncomfortable to touch. It is unlikely to get this hot in normal operation. The current measured each time was then divided by the baseline current, to show the relative change. The cell was maintained at 25 °C throughout the experiment. The results are shown in figure 3-20. The results show that, even when the flash is very hot, the spectral change will cause no more than 0.2% change in cell current.

A similar experiment was conducted to see if varying the time between flashes (during the test) had any effect on the spectrum. Varying flash-to-flash delay between 0.5 and 20 seconds caused no discernable change in I_{sc} .

These two experiments show that the flash spectrum is in fact quite stable in the short term, even when the flash gets hot. It is safe to measure many cells between re-calibrations with the reference cell.

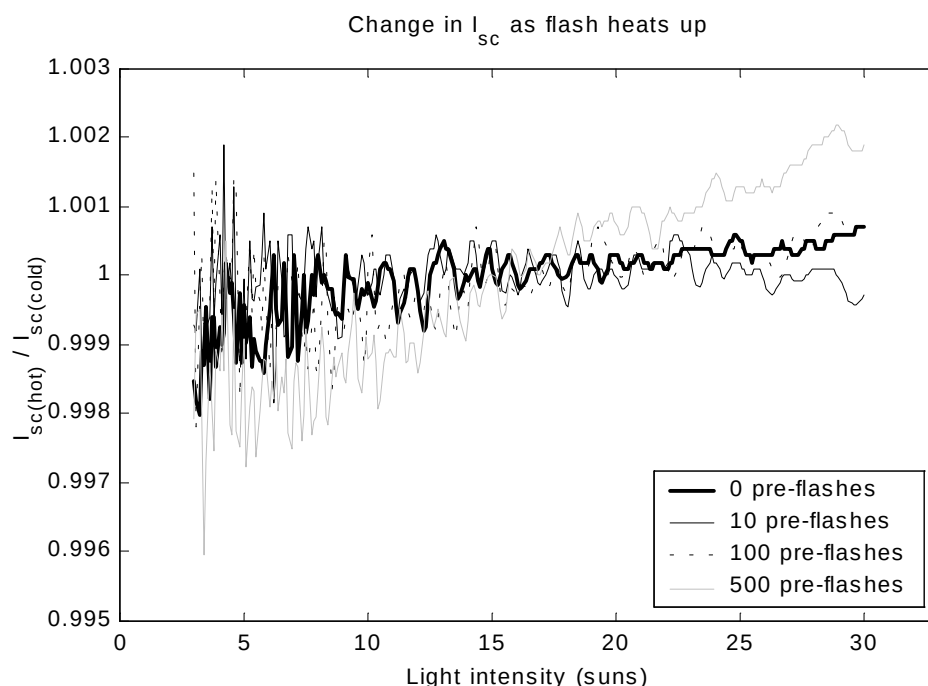


Figure 3-20: Change in flash spectrum due to heating under heavy use.

3.3.1.3 Pulse duration

The flash, as supplied by the manufacturer, can only produce one pulse shape. This is the curve labelled as “internal” in figure 3-21. When operating on the internal supply, the flash tube is connected directly across the 240 V AC mains. Consequently, the flash pulse lasts for half a mains cycle – it can be seen to be roughly a half sine function.

Due to concerns about transient errors, an external capacitor bank was built to power the flash and so allow varying flash durations. The capacitor bank consists of 8 1500 μF 450 V electrolytic capacitors, and circuitry to charge them. Switches allow 1, 2, 4, or 8 capacitors to be connected to the flash. The capacitors are charged with rectified mains voltage, to give approximately the same voltage on the flash tube as with the internal supply. The trigger circuitry in the flash did not need to be changed in any way.

Using the external capacitor bank, flash decay times ($1/e$) between 2 and 16 ms are available. The internal supply has a flash decay time of approximately 0.6 ms.

Transient errors in cell measurements can be due both to the rate of change of light intensity and the rate of change of bias voltage. Provided the bias voltage is sufficiently constant, as discussed in section 3.3.2, the internal flash is quite slow enough. The external capacitor bank would not be necessary in this situation.

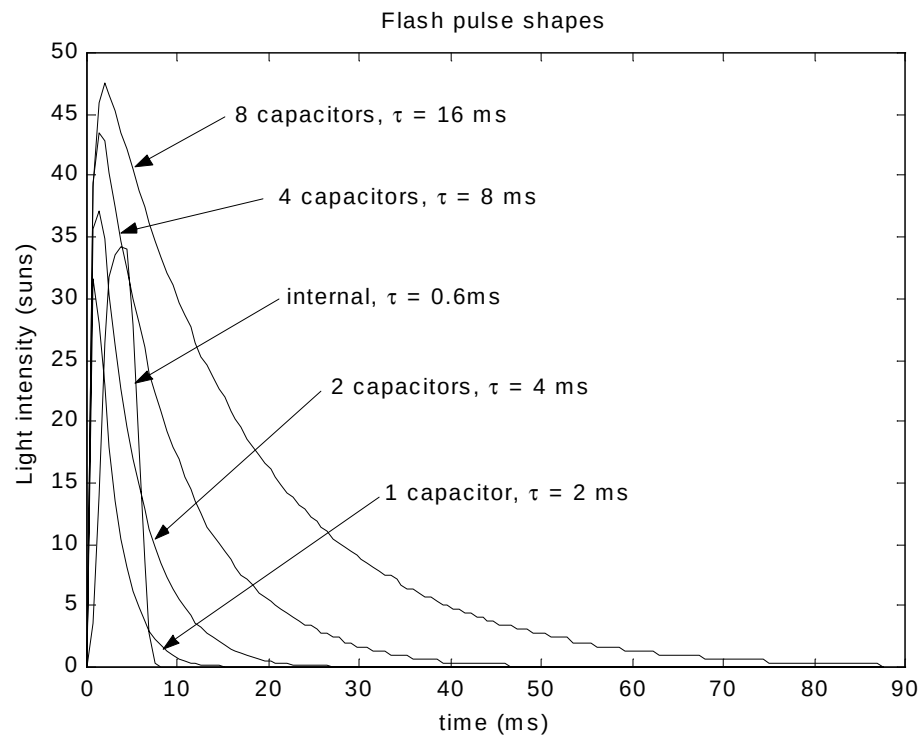


Figure 3-21: Flash pulse shapes. Curves are shown for the internal flash supply and the external supply with 1,2,4 or 8 capacitors.

3.3.2 Transient errors and cell bias circuitry

To minimise transient errors, the cell bias circuit used in the flash tester is a constant voltage design. In this section, transient errors in flash tester measurements are analysed. Particular emphasis is given to the case of constant voltage. The performance of the capacitive cell bias circuit used in this flash tester is then analysed in detail.

3.3.2.1 Analysis of transient errors

Changes in bias voltage and illumination conditions cause changes in the charge distribution within a solar cell. This charge re-distribution requires a current, and if the re-distribution occurs too rapidly, the re-distribution current will become a noticeable transient error. The larger the amount of stored charge, the larger the current that will be required to re-distribute it in a given time.

The following discussion of charge distribution is for the case of a good n^+p cell of unit area. A good cell is discussed since transient errors are mostly a problem with good cells (since they have long effective minority-carrier lifetimes). An n^+p construction is chosen to simplify the discussion – an equivalent analysis applies for p^+n cells.

Understanding transient errors requires knowledge of the charge distribution as a function of bias voltage and illumination conditions. First, the charge distribution as a function of bias voltage is examined.

The electron concentration at the p side edge of a pn-junction, at forward bias voltage, V_F , is given approximately by:

$$n_p = n_{p0} e^{\frac{qV_F}{kT}} \quad (3-10)$$

where n_{p0} is the equilibrium concentration of electrons in the p-type base.

The total amount of excess charge stored in the base is proportional to n_p . It can be seen that the electron concentration, and hence the stored excess charge, increases exponentially with the bias voltage. Going from short circuit to open circuit (0V to approximately 0.7V) causes a factor of 10^{12} change in electron concentration. Transient errors are therefore more serious at higher bias voltages. n_p is proportional to n_{p0} , and n_{p0} is larger for lightly doped material. So the excess charge stored is larger for lightly doped material. The excess charge stored is also larger for longer diffusion lengths, or, in a cell with very long diffusion lengths, cell thickness. All of these factors suggest that transient errors should be worst in lightly doped, long lifetime, thick cells, and at high bias voltage. This agrees with experimental observations of the type of cells that exhibit transient errors.

Redistribution of excess charge is also caused by changes in illumination. If the cell is open circuit, the varying illumination will cause a varying voltage, and so the situation will be similar to an externally applied bias voltage. If, however, the cell is maintained at a constant bias voltage, the change in illumination will not cause much change in the charge distribution. In a good solar cell where the diffusion length is larger than the wafer thickness, the minority carrier concentration in forward bias is roughly constant throughout the base. When the cell is in the dark, electrons are injected from the emitter and diffuse towards the rear. This causes a slightly higher concentration of electrons near the emitter, declining towards the back. When the cell is illuminated, electrons are generated in the base and diffuse towards the emitter. This causes a slightly higher concentration of electrons in the bulk, declining towards the emitter. The difference is illustrated in figure 3-22 for a cell biased at its maximum power voltage. It can be seen that a change in illumination conditions while at constant voltage causes a relatively small change in the excess charge density – about $0.3 \times 10^{14} \text{ cm}^{-3}$, compared to the average level of about $2.6 \times 10^{14} \text{ cm}^{-3}$. In other words, changing illumination from 0 to 1 sun would only require $1/10^{\text{th}}$ as much charge movement as changing voltage from 0 V to V_{mp} . Less charge movement means less current required for the re-distribution, and hence smaller transient errors.

The preceding discussion shows that solar cells should respond more rapidly to changes in illumination while at constant bias voltage than to changes in bias voltage while at constant illumination. In other words, transient errors will be smaller if bias voltage is held constant and light intensity is varied, rather than the conventional approach of holding light intensity constant and varying bias voltage.

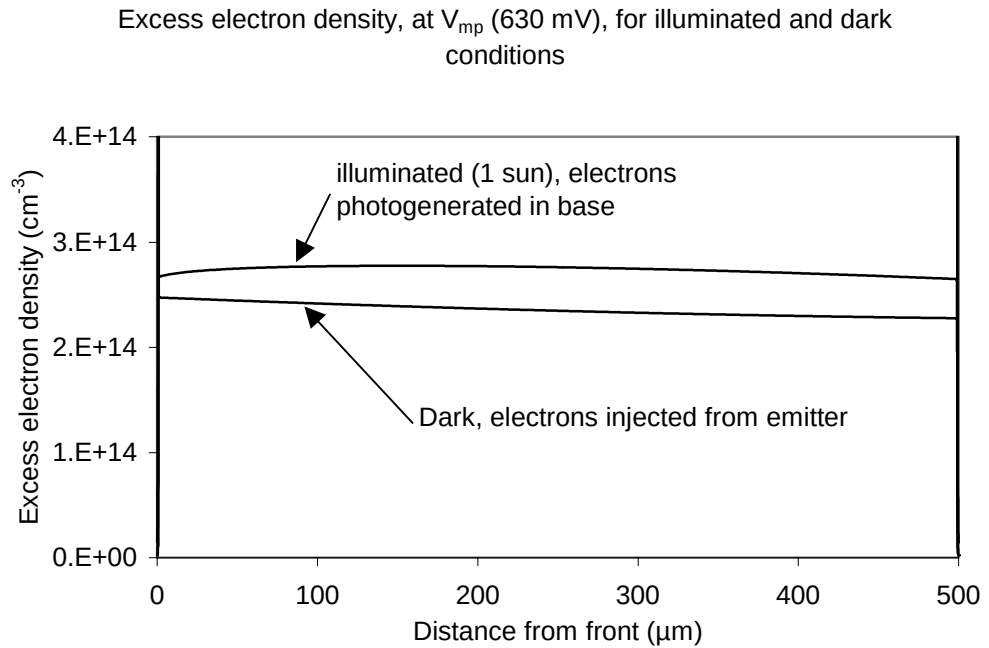


Figure 3-22: Excess electron density in p-type base for illuminated (1 sun) and dark conditions. Simulated with PC1D.

3.3.2.2 Analysis of constant voltage concept

The concept of the constant voltage flash tester relies on cell current responding rapidly to changes in light intensity provided cell voltage is constant. However, as described in the previous section, changes in light intensity do cause some charge redistribution. So, cell current will not respond instantly to changing light intensity, even if cell voltage is held perfectly constant. The important question is: what rate of change of light intensity will cause noticeable errors in the current measurement, assuming perfectly constant cell voltage?

An analytic treatment of this problem is difficult, so, instead, the problem was explored by simulating cells with PC1D. A range of cells were simulated, including typical real world cells and some projected worst-case possibilities. PC1D was used to estimate the time for cell current to reach steady state, in response to an abrupt change in light intensity, while at constant voltage. Two light intensities were used, 1-sun, and 100-sun. Both dark-to-light and light-to-dark transitions were investigated. Cell voltages near short circuit, maximum power, and open circuit were used.

The cell response time was taken to be t_{99} , the time to reach 99% of the steady state value. This was used rather than the more common $1/e$ time because the response characteristic was sometimes not a simple exponential. In many cases, there was a rapid change (in a few μs typically) to about 90%, and then a much slower change to 100%. Use of the $1/e$ time could greatly underestimate the time to reach steady state.

The 99% response time can be directly applied to the constant voltage flash tester design – if the flash rise/fall time is longer than t_{99} , the measurement will be sufficiently accurate.

The previous section showed that the important factors affecting the amount of charge stored in the cell are: cell thickness, minority carrier lifetime in the bulk, background doping levels, and surface recombination rates. The cells simulated include: a typical commercial 1 sun cell with moderately high recombination, a high quality low resistivity cell (like an ANU concentrator cell), a high quality high resistivity cell (like a SunPower concentrator cell), and two projected worst-case cells – very thick, almost no recombination, one high resistivity, and one low resistivity. The cell parameters are summarised in table 3-1, and the results of the simulations for the five cells are shown in table 3-2.

Table 3-1: Construction parameters for the cells used to estimate current response time.

Cell Type	S_R, S_F (cm/s)	τ (ms)	ρ (Ωcm)	Thick (μm)
Typical commercial 1 sun	10^5	0.1	1	500
Excellent low resistivity (eg, ANU concentrator cell)	1000	1	1	500
Excellent high resistivity (eg SunPower cell)	1000	1	200	200
Worst case high resistivity	100	10	2000	1000
Worst case low resistivity	100	10	1	1000

Table 3-2: Time for cell current to reach 99% of steady state, in response to an abrupt change in light intensity, while at constant voltage.

Cell Type	$t_{99\%}$ (μs) at 0 mV		$t_{99\%}$ (μs) at 550 mV		$t_{99\%}$ (μs) at 700mV	
	0 $\rightarrow$ 1X 1 $\rightarrow$ 0X	0 $\rightarrow$ 100X 100 $\rightarrow$ 0X	0 $\rightarrow$ 1X 1 $\rightarrow$ 0X	0 $\rightarrow$ 100X 100 $\rightarrow$ 0X	0 $\rightarrow$ 1X 1 $\rightarrow$ 0X	0 $\rightarrow$ 100X 100 $\rightarrow$ 0X
Commercial	44	18	45	29	84	86
	41	17	43	28	84	84
Excellent low resistivity	100	24	100	54	160	130
	88	21	95	40	160	150
Excellent high resistivity	4	33	39	34	42	35
	4	16	40	32	42	41
Worst case high resistivity	930	550	1000	550	980	550
	370	670	1000	750	1000	870
Worst case low resistivity	350	40	430	370	700	500
	320	30	370	200	710	640

The simulation results show, as expected, that thick, high resistivity cells with low recombination are the slowest to respond to changes in light intensity. However, the results show some complex trends – it is not possible to easily identify the worst-case situation.

The simulation results show that, for realistic cells, the response time is less than a few hundred microseconds. Provided the flash rise/fall time (t_{99}) is greater than a few hundred microseconds, the current measurement will be correct. In addition, the light-to-dark and dark-to-light times are similar. So, measurements on the rising and the falling edges of a flash pulse should be equivalent.

These response times can be compared to the flash characteristics for the Geni Megastrobe used in the constant-voltage flash-testing system. The flash pulse from the internal supply has rise and fall times of a few milliseconds. The flash pulses from the external capacitor bank have rise times of about 500 μs and fall times of 10's of milliseconds. Therefore the light intensity on both slopes of the internal pulse, and the falling slopes of the external pulses, changes far more slowly than the response time of any of the realistic cells. The system can be used for testing any of these cells, without introducing transient errors. The rising slope of the external pulse may even be usable (though it is not used presently). The worst-case cells have slow enough response that the rate of change of light intensity may introduce a small error. However, they are very much hypothetical cases and are unlikely to be made.

The simulation result that realistic cells respond to changes of light intensity in a fraction of a millisecond is supported by experiments performed by (Metzdorf, Meier et al. 1994). They found that when bias voltage was held constant, cell current tracked light intensity with no observable distortion. This experiment used a flash with a rise/fall time of approximately 1 ms.

The preceding discussion assumes perfectly constant voltage. However, this will never be exactly true for a real-world cell – series resistance within the cell will result in different parts of the cell being at different voltages. However, this will only be a problem if the cell is operated at far higher concentrations than it is designed for. A reasonable cell, operating at its design conditions, should have voltage drops due to the series resistance of 10's of mV or less. For typical flash rise/fall times in the range of milliseconds, this will give a rate of change of cell voltage of about 10 V/s. As shown in the following section, this will not cause transient errors.

In conclusion, these simulation results show that for typical flash rise/fall times of several milliseconds, a cell maintained at constant voltage will be in quasi-steady-state. No error will appear in the current measurement. This shows that a constant voltage bias circuit can eliminate transient errors when flash testing.

3.3.2.3 Transient errors with the capacitive bias circuit

The previous section showed that an ideal constant voltage bias circuit should eliminate transient errors. The flash tester design described in this work uses a constant voltage bias circuit, but it is of course not perfect. This section describes how closely the capacitive bias circuit approaches the ideal of constant voltage, and the magnitude of the transient errors that result from its non-ideal behaviour.

During the development of the constant voltage flash tester it was suspected that transient errors were occurring – the FF's being measured were a little too high to be believable. To investigate the problem, an external capacitor bank was built to power

the flash. This allowed a range of different flash pulse durations. Varying the pulse duration confirmed that transient errors were indeed occurring.

Behaviour of capacitive bias circuit

The capacitive bias circuit consists of a large capacitor connected directly across the cell, and a low speed buffer amplifier to charge it to the desired bias voltage. During the flash, the low impedance of the capacitor holds the voltage nearly constant. However, there are several unavoidable series resistances in the circuit. These include: series resistance within the capacitor, the resistance of the short length of wiring connecting the capacitor to the cell, series resistance within the cell, and the sense resistor used to measure the cell current. An equivalent circuit is shown in figure 3-23.

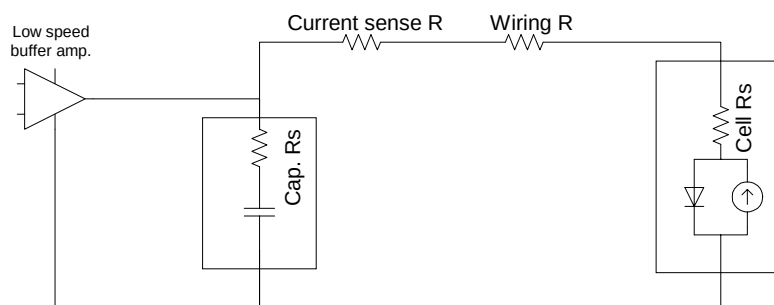


Figure 3-23: Capacitive bias circuit, showing equivalent series resistances.

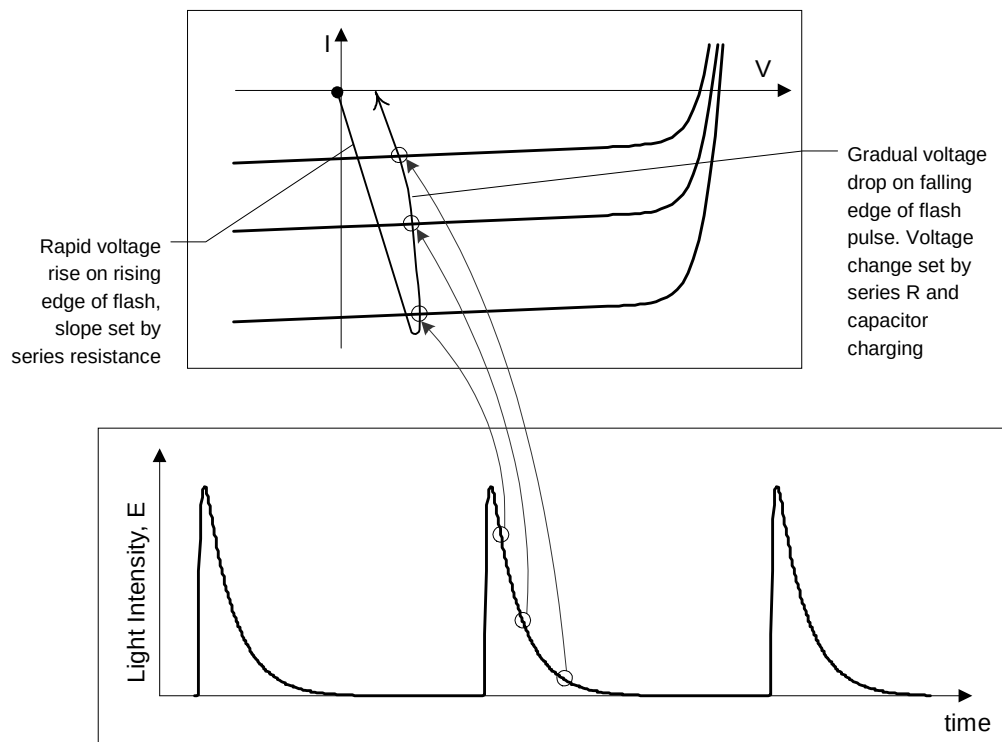


Figure 3-24: I-V points traced out by the capacitive cell-bias circuit over the course of one flash.

Due to these series resistances, the circuit does not maintain a perfectly constant voltage. As the current varies (due to changing light intensity), the cell voltage will change a small amount. The change in cell voltage can cause transient errors, depending on the rate of light intensity variation.

The rate of change of cell voltage, dV/dt , is dependent both on the cell bias circuit and on the flash. dV/dt is higher for faster changing light intensity, and larger series resistance. dV/dt can be positive or negative, depending whether the light intensity is increasing or decreasing.

The behaviour of the capacitive bias circuit over the course of a single flash is shown in figure 3-24. As the light intensity rises, the cell voltage also rises, due to the series resistance. As the light intensity falls, the cell voltage also falls. There is also a small overall increase in voltage due to the capacitor being charged by the cell current. It can be seen that, on the rising edge of the flash pulse, cell voltage is moving from I_{sc} towards V_{oc} . Therefore, if I-V points are taken on the rising slope of the flash pulse, FF and V_{oc} will be underestimated. Conversely, if I-V points are taken on the falling slope of the flash pulse, cell voltage will be moving from V_{oc} towards I_{sc} , and FF and V_{oc} will be overestimated.

Influence of rising vs. falling slope on transient errors

The discussion in the previous section suggests that the FF should be underestimated on the rising edge of the flash pulse, and exaggerated on the falling edge of the flash pulse. This behaviour was confirmed by a simple experiment.

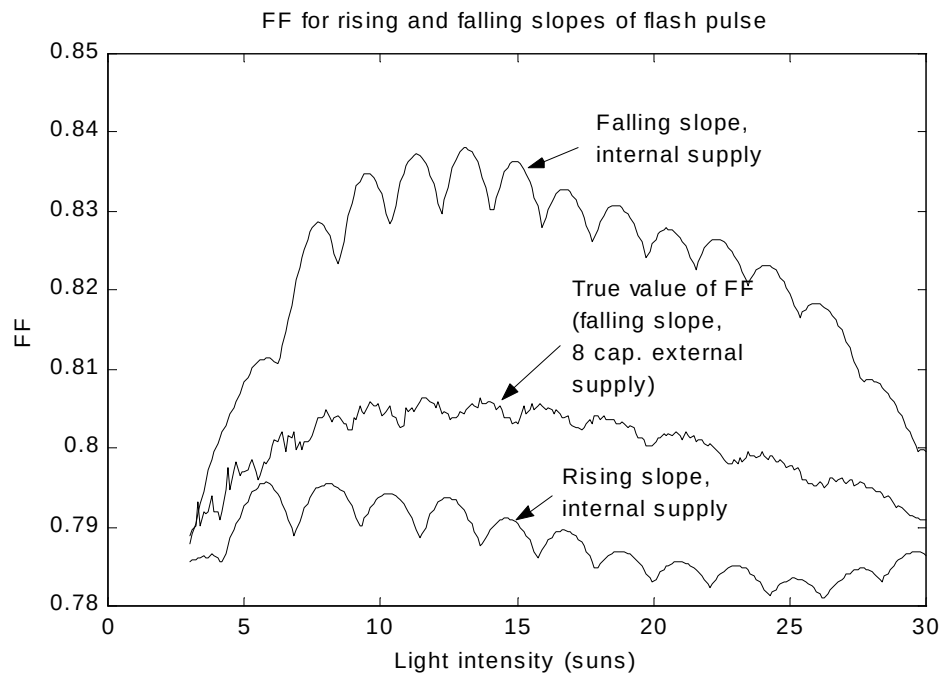


Figure 3-25: Effect of rising and falling slopes of flash pulse on FF measurement.

A high-performance cell, known to exhibit transient errors, was tested using the internal flash pulse. This pulse is roughly symmetrical (unlike the pulses shown in figure 3-24), allowing both the rising and falling edges to be used. The measured FF for this cell is plotted as a function of light intensity in figure 3-25. As expected, FF is underestimated on the rising slope, and exaggerated on the falling slope. In addition, it can be seen that there is less FF error at the lowest and highest light intensities. These points come from the peak and the tail of the flash pulse, where light intensity is changing relatively slowly. Since the light intensity is changing slowly in these regions, it is to be expected that transient errors will be smaller.

Incidentally, the 'humpy' nature of the curves is due to the FF extraction algorithm, and is discussed in section 3.2.3.2.

Confirmation that transient errors are due to dV/dt

The preceding discussion attributed the transient errors to excessive series resistance and so rapid voltage changes. To confirm that rapid voltage change is the true cause (not rapid change of light intensity), a simple experiment was performed.

Ideally, this experiment would have involved reducing dV by reducing series resistance. However, this would have been quite difficult to implement. Instead, the cell current was reduced by masking 90% of its area. This reduced dV by a factor 10, while leaving everything else largely unchanged. If the transient error was in fact due purely to the rate of change of light intensity, dE/dt , masking the cell should have had little effect.

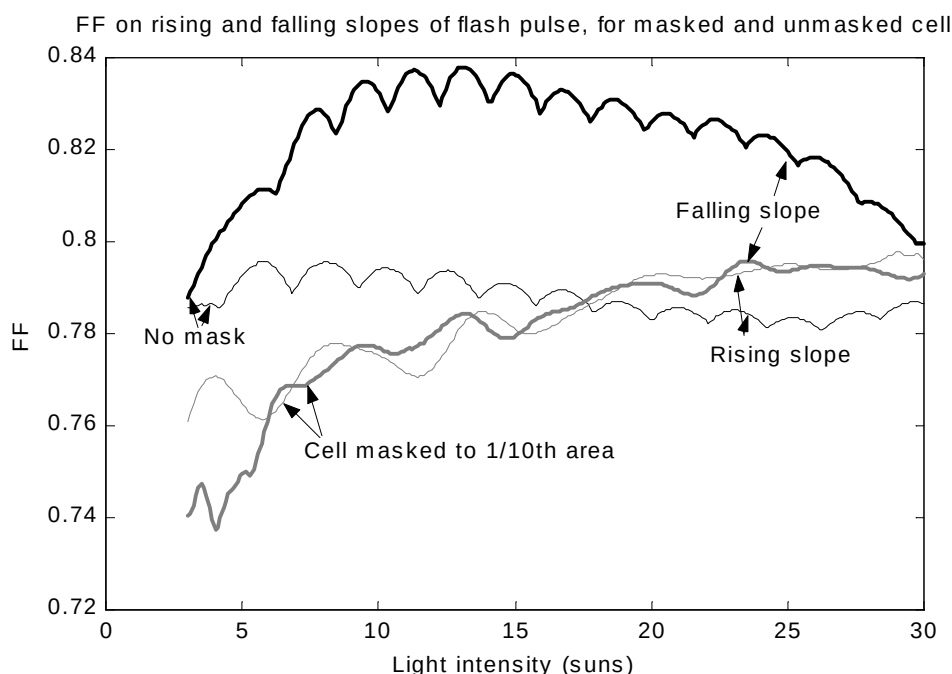


Figure 3-26: Transient errors eliminated by masking the cell. The masking reduces cell current, and hence dV/dt . Since transient errors are caused by high values of dV/dt , at lower dV/dt the transient errors disappear.

The result of this experiment can be seen in figure 3-26. For the unmasked cell, measurements on the rising and falling slope of the flash pulse are substantially different. Transient errors are clearly occurring. For the masked cell, in contrast, measurements on the rising and falling slope are very similar. The transient errors have disappeared at the lower current. This shows that reducing dV/dt by a factor of 10, while leaving dE/dt unchanged, eliminates the transient errors.

Incidentally, the masked FF and the unmasked FF are noticeably different. This is to be expected, as the large area of cell that is in the dark will act as a parasitic shunt on the illuminated section of cell.

Magnitude of transient errors for ANU concentrator cells

It has been shown in previous sections that transient errors with the capacitive bias circuit are due to relatively rapid changes in cell voltage (though far less rapid than if the full I-V curve was swept out during a single flash). This section describes the magnitude of the errors that occur with ANU concentrator cells. This serves two purposes: firstly, the results can be compared to previous work, and secondly, the results provide operating guidelines for the flash tester in its current form.

The measurements shown were made on cell c156o, one of the best ANU concentrator cells produced. It has one of the highest open circuit voltages (so, also the longest lifetime), and so should be the most sensitive to transient errors. The performance of c156o at 1 and 30 suns is:

$$1\text{-sun} \quad V_{oc} = 649 \text{ mV}, J_{sc} = 35 \text{ mA/cm}^2, \eta = 17\%$$

$$30\text{-sun} \quad V_{oc} = 755 \text{ mV}, J_{sc} = 1.06 \text{ A/cm}^2 \text{ (assumed, 1\% super-linearity)}, \eta = 21\%$$

To enable comparison with previous work, the FF was determined as a function of the bias rate, dV/dt . The flash tester measures the cell voltage as a function of time, $V(t)$, so it is simple to calculate dV/dt . dV/dt is a varying function of time, unlike most of the experiments described in previous work where a constant dV/dt was applied to the cell. Consequently, a different dV/dt applies at different points on the I-V curve. It is highest near short circuit, intermediate near maximum power, and lowest near open circuit. When measuring FF as a function of bias rate, dV/dt was taken at the maximum power point. dV/dt was varied by using the full range of flash durations. Flash fall times ($1/e$) of between 1 and 16 ms were used. At the shortest flash duration, dV/dt was increased further by adding an additional 200 m Ω of series resistance. A plot of FF as a function of dV/dt is shown in figure 3-27. FF was extracted at three different light intensities, corresponding to the peak, middle, and tail of the flash pulse. The highest values of dV/dt were from the internal flash pulse. This has its greatest rate of change of light intensity, dE/dt , at middle light intensity (around 10X). Consequently, it is to be expected that the worst FF errors occur for the 10X curve. The results shown in figure 3-27 are consistent with those given in (King, Gee et al. 1988). King found that, for a 1 Ωcm cell, FF errors became significant (> 0.01 absolute) for bias rate above 100 V/s. This is similar to what figure 3-27 shows.

For routine use of the flash tester in its current form (with the external flash supply, and with higher-than-desirable series resistance), it is important to know what the flash settings should be to get acceptably low transient errors. To investigate this question, all possible flash settings were tried while measuring cell c156o. The effects on FF and V_{oc} are shown in figure 3-28 (the curves for I_{sc} are very nearly independent of flash settings since the light detector was re-calibrated each time the flash settings

were changed. I_{sc}/E is therefore constant by definition). It can be seen that FF is affected much more than V_{oc} . The '4 caps', and '8 caps' settings (8 ms decay time, and 16 ms decay time respectively) are barely distinguishable, showing that the '8 caps' setting gives very close to the true value of FF. For routine use, requiring FF accuracy of ± 0.01 ($\sim 1\%$), the '2 caps' setting is adequate. The differences between the V_{oc} curves are only a few millivolts, which is similar to the FF transient effects. Given that the cell temperature can vary by up to 3°C (see section 3.3.5.6), the differences between V_{oc} curves could be due to temperature changes as much as transient effects.

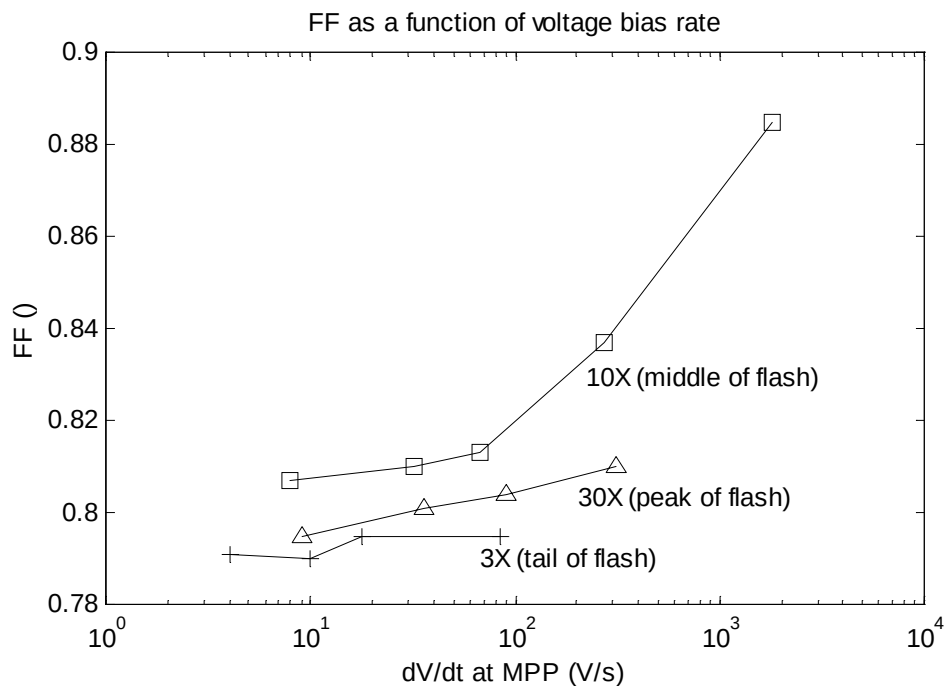


Figure 3-27: FF as a function of dV/dt for cell c156o

How to detect transient errors

It is obviously important to be able to check if transient errors are occurring. There are several possible ways to detect transient errors with this system:

- If the external flash supply is being used, measurements for different flash durations can be compared. If the measurements are different, transient errors are probably occurring.
- If the internal flash supply is being used, measurements on the rising and the falling edges can be compared. If they are different, transient errors are occurring.
- Measurements on the flash tester can be compared to measurements done under steady state (e.g., outdoors). However, this is only useful for 1-sun measurements. It is difficult to do for concentrator measurements, as it requires a high concentration steady state testing system.

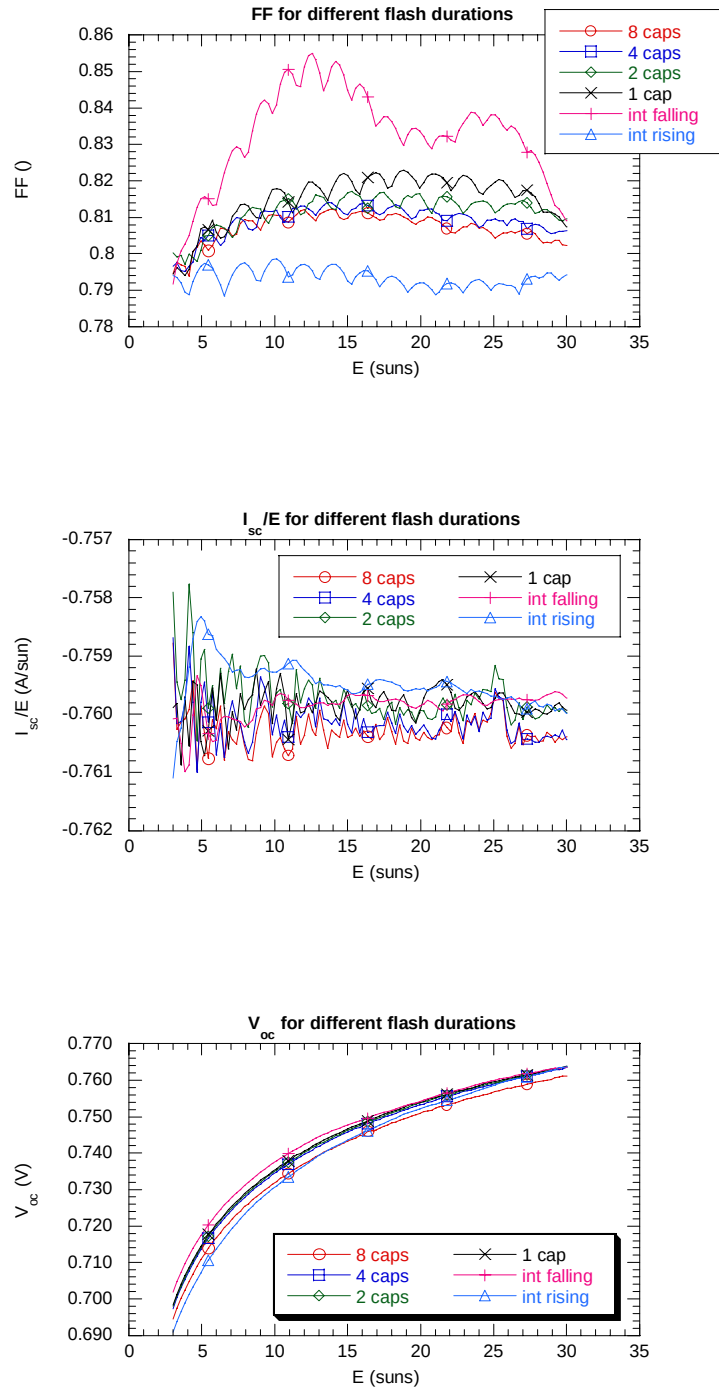


Figure 3-28: Effect of pulse duration on measurements of V_{oc} , FF, I_{sc} , for cell c1560. Pulse durations are specified by the flash supply setting – ‘int’ for internal supply, ‘1 cap’, ‘2 cap’, ... for external capacitor bank with the specified number of capacitors. The flash peak intensity was approximately 30 suns in all cases.

Modifications to the system to avoid transient errors

To eliminate transient errors, it is necessary to reduce dV/dt . This can be done either by maintaining constant voltage better (reducing dV), or by increasing the pulse duration (increasing dt). In the system in its current form, transient errors have been eliminated by building an external flash supply that increases the pulse duration. However, this may not be the best option – in retrospect, the external flash supply is probably more expensive than improving the constant voltage bias circuit, and it slows down the test. Consequently, it is interesting to examine some options to maintain constant voltage better.

According to figure 3-27, $dV/dt < 100 \text{ V/s}$ is necessary to reduce transient errors to a tolerable level with current ANU concentrator cell designs.

The capacitive bias circuit currently used has a total series resistance of $\sim 30 \text{ m}\Omega$, $10 \text{ m}\Omega$ each from the capacitor, the sense resistor, and the wiring. At a peak current of 20 A , $dV = 0.6 \text{ V}$. To maintain $dV/dt < 100 \text{ V/s}$ requires $dt > 6 \text{ ms}$. This is approximately what is supplied by the external flash supply when set to use 4 capacitors.

To use the flash with its internal supply (and so avoid building the external flash supply) requires a smaller dV . The internal flash pulse has a rise/fall time of $\sim 1 \text{ ms}$ for the steep middle section, and so dV must be $< 0.1 \text{ V}$. dV could be reduced either by reducing the series resistance in the capacitive bias circuit, or by going to an active bias circuit that uses feedback to maintain constant voltage.

Reducing the series resistance for the capacitive bias circuit is possible, but not trivial. To achieve $dV < 0.1 \text{ V}$ at 20 A would require total series resistance to be $< 5 \text{ m}\Omega$. Electrolytic capacitors with series resistance of a few $\text{m}\Omega$ are easily available, so several in parallel would have a total series resistance of about $1 \text{ m}\Omega$. The current sense resistor could be reduced to $1 \text{ m}\Omega$ (though inductive errors might then become a major limitation). Wiring resistance could be reduced to about $1 \text{ m}\Omega$ by using short, thick wiring, e.g. welding cable. Finally, the series resistance of the cells is typically about $1 \text{ m}\Omega$. So, it should be possible to achieve a total series resistance of $< 5 \text{ m}\Omega$. However, it would be a bit of a mechanical design challenge to fit everything together, and none too flexible if the cell size were changed.

The alternative to improving the capacitive bias circuit would be to build an active bias circuit that regulates the voltage precisely, by feedback. If feedback is taken directly from the voltage sensing contacts on the cell, voltage drops in all the wiring can be eliminated. However, voltage changes due to series resistance within the cell are unavoidable, so it is impossible to maintain perfectly constant voltage. Building a suitable active bias circuit should not be too difficult. The bandwidth required is only on the order of 10 kHz , and the voltages are low. However, the currents are quite high – many tens of amps. None of the commonly available amplifier/4-quadrant-supplies (e.g., the often used KEPCO BOP) can achieve this. In addition, from personal experience attempting to build such circuits, achieving consistent stability could be difficult.

3.3.3 Data acquisition circuitry

The data acquisition circuitry in the constant-voltage flash tester consists of a data acquisition card that plugs into a PC, current-sensing resistors to convert cell currents into measurable voltages, and wiring to connect the two. Virtually all the complexity of the system is in the data acquisition card – the rest is very simple. This section discusses measurement errors due to the data acquisition circuitry.

3.3.3.1 Data acquisition card

The flash tester system was prototyped with a low cost data acquisition card – a National Instruments LAB-PC+. This was later upgraded to a much higher performance card, a National Instruments MIO16E1, because of concern as to whether the LAB-PC+ was fast enough. The upgrade proved unnecessary – in future systems it should not be necessary to use such a high performance card. A suitable low cost card might be the National Instruments PCI-6024E, a 200kSample/s, 12 bit card (which cost about US\$600 in 2001).

The 12-bit resolution of the data acquisition card is adequate to measure I-V curves over a decade range of light intensity. A 12-bit input has a resolution of 0.05% of full scale. When the signal is reduced to $1/10^{\text{th}}$ of full scale (at the low intensity tail of the flash), the measurement resolution is 0.5%. Both data acquisition card used have 12 bit A/D converters.

The sampling rate of the card is not a significant limitation since the flash pulses are, by modern electronics standards, relatively slow. A minimum sampling rate can be chosen based on the fastest changing part of the flash pulse. This is the rising edge of the pulse when using the external capacitor bank. The falling edge of the pulse from the external capacitor bank, and both slopes of the pulse from the internal supply, are much slower. The rise time of the pulse is 0.5 ms. To get a minimum of 10 samples in this period requires a minimum sampling rate of 20 kSamples/s. The data acquisition card used in fact achieves 400 kSamples/s (though this is later digitally filtered and down-sampled to 100 kSample/s).

Although the sampling rate of the card is fast enough, the fact that the samples are not simultaneous can be a problem. Most low-cost data acquisition cards, including those used in this system, have only one A/D converter, so separate analogue inputs are measured in round robin fashion. In the flash tester, this means that light intensity, cell current, and cell voltage are not measured at exactly the same time. This signal interleaving, if not corrected for, can introduce errors. The first data acquisition card used, the LAB-PC+, had a maximum sampling rate of only 20 kSample/s for 3 channels. The signal interleaving introduced noticeable error, which manifested as a few percent apparent nonlinearity in short circuit current. To eliminate this problem, a software interpolation was used to estimate the truly simultaneous values of the signals. The data acquisition card was upgraded to the 1.25 MSample/s MIO16E1 because of concern about whether this interpolation was working properly. With this much faster card, the delay between measurements is so small that no noticeable error is introduced and interpolation is unnecessary. However, comparison of the results showed that the LAB-PC+ with interpolation worked just as well as the more expensive MIO16E1. On this basis, the cost of future systems could be reduced a little by using a lower performance card.

3.3.3.2 Current sensing resistors

The data acquisition card used in the system only measures voltage, so current-sensing resistors are used to measure current. The resistors chosen are special, non-inductive, low temperature-coefficient current-sensing resistors. The resistors are built into easily swappable DB25 connectors, and use a 4-point connection scheme to eliminate contact resistance errors. This section discusses measurement errors that could be caused by the resistors.

Absolute calibration of the resistor values is not important. Every time the tester is re-calibrated with the reference cell, resistor changes will be cancelled (provided the same resistor is used to measure reference and test cells). So, long-term drift of the resistors is not an issue. Each resistor was calibrated after construction anyway, to $\pm 0.1\%$. This leaves only 2 potential sources of error due to the resistors: change in resistance due to temperature changes and voltages generated by resistor inductance.

The values of the resistors will vary slightly if they change temperature. This could potentially be caused by self-heating or by room temperature changes. Self-heating affects are insignificant, since the peak power dissipated by the resistors for a few milliseconds (less than 1% duty cycle) is approximately equal to their continuous power rating. Room temperature changes may have a small effect. The resistors' temperature coefficient of resistance is specified as 100-600 ppm/ $^{\circ}\text{C}$. Given room temperature variations of $\pm 10^{\circ}\text{C}$ this will result in a current error of $< 0.6\%$. In addition, the error will be eliminated every time the tester is re-calibrated with the reference cell.

The currents in the sense resistors change rapidly. Due to the inductance of the resistors, a small voltage will be generated. This will add to (or subtract from) the resistive voltage drop, and so introduce an error. The 2 currents measured are both converted to a voltage less than 0.25V and measured with a 12-bit converter, so the resolution of the measurement is $100\mu\text{V}$. If the inductive voltage is less than $100\mu\text{V}$ it can safely be ignored. The greatest rate of change of light intensity is about 10 suns in 6 ms (extracted from the curves in figure 3-21). The current produced by a 4x5cm cell is about 20A at 30 suns, so the rate of change of cell current will be about 6A/6ms. The maximum value of inductance that can safely be ignored can be calculated:

$$L = V \frac{dt}{di} = 100\mu\text{V} \times \frac{6\text{ms}}{6\text{A}} = 10\text{nH} \quad (3-11)$$

To estimate the importance of inductive effects, it is necessary to know the inductance of the resistors. The manufacturer of the resistors only specified that they were "virtually non-inductive". Consequently, it was necessary to measure the inductance.

The inductance was measured by placing the resistor in series with a capacitor and a signal generator, as shown in figure 3-29, and then looking for the resonant frequency of the resulting RLC circuit.

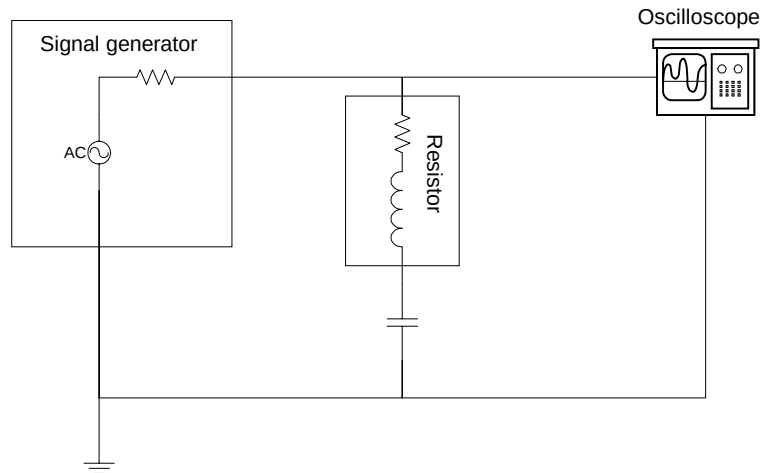


Figure 3-29: Series RLC circuit used to calculate the inductance of the current sensing resistors.

In principle, the resonant frequency could be used to calculate an inductance (using the standard formula $f_{res} = 1/2\pi\sqrt{LC}$), but this inductance would include all the wiring in the circuit as well as the resistor. This problem was eliminated by substituting a variety of known inductances for the resistor. When the same resonant frequency was achieved as with the resistor in circuit, the inductance of the resistor was clearly the same as that of the known inductance. The known inductances were simply single turn loops of wire. The inductance of a single turn, air-cored, loop of radius r is given by (Plonus 1988):

$$L = \mu_0 \frac{\pi r}{2} \quad (3-12)$$

It was found that a wire loop of diameter 10 mm caused the same resonant frequency as the resistor. This was almost the same length of wire as the resistor and its leads. Since the resistor tested was a very low ohm value, it very likely was simply a straight piece of wire inside. So it is not surprising that the resistor had similar inductance to a piece of wire of the same length.

Using equation (3-12), the resistor was calculated to have an inductance of approximately 10 nH. According to equation (3-11), this inductance is just within the safe margin. For the 4x5 cm cells at a peak intensity of 30 suns, the effect of the resistor inductance can therefore be ignored. However, for larger cells, higher light intensity, or faster flash pulses, the effect of resistor inductance could be a problem. Either allowance should be made for the error voltage, or the inductance reduced by using a physically smaller resistor (suitable surface mount resistors are commonly available).

3.3.3.3 Signal grounding and low noise wiring

The wiring between the data acquisition card and the cells, although simple, requires care to keep noise levels sufficiently low.

All signal wiring uses shielded-twisted-pair cable to minimise noise pickup. The inputs on the data acquisition card are differential, to reduce common-mode noise.

However, the data acquisition card has poor common-mode rejection at frequencies above a few hundred hertz. Even when there is no signal between the signal wires, if both wires carry common high-frequency noise, a significant amount of noise appears in the measurements.

Fortunately, the common-mode noise problem can be largely avoided by judicious choice of grounding points. The cell testing block and the light detector can be electrically isolated from each other and from mains earth. This allows both one side of the cell and one side of the light detector to be connected to signal ground at the data acquisition card. Since one side of each of these signals is grounded, there is no common-mode noise. The third connection, cell voltage, cannot be isolated, and so is noisier. This arrangement is the best compromise. Light intensity and cell current vary by an order of magnitude, whereas voltage is roughly constant, so noise on the light intensity and cell current signals is more serious than noise on the cell voltage signal.

In an improved flash tester, the common-mode noise could be removed by analogue low pass filtering or isolation amplifiers.

It is important that the two ground points just mentioned are the only grounds. Early in the development of the system, a ground loop was inadvertently created between the cell bias circuitry and the current measurement connection. The voltage drop in the high current cell wiring (during the flash) then appeared between the two grounds, causing a substantial current to flow in the signal ground. This caused an error in the cell current measurement, manifesting as an apparent nonlinearity of short circuit current with light intensity.

3.3.4 Cell contacting

The method used to make electrical contact to the cell can introduce significant errors.

If only two wires are used to connect to the cell, the resistance of the contact and wires will be included in the measurement. This will result in an underestimate of the cell efficiency.

By using a four-point contact, it is possible to greatly reduce the effect of the contact resistance. Two of the contacts carry the main cell current, and the other two contacts measure the cell voltage. Care has to be taken in the placement of the contacts however. If the current and voltage contacts are far apart, the FF can be greatly exaggerated. Series resistance in the cell causes different parts of the cell to be operating at different I-V points. When there is a substantial current flowing, the ohmic voltage drop will cause points further from the current probe to be at a higher voltage. If the current probe is extracting current from a part of the cell that is near I_{sc} while the voltage probe is measuring voltage on a part that is near V_{oc} , the output power will be badly over-estimated. It is reported by (Heidler, Fischer et al. 1989) that a FF over-estimate of 40% is possible, and that a probe separation of only 1 mm on a 10 x 10 cm cell can cause a 0.4% FF error. Similarly, it is reported by (Emery 1992) that getting FF accurate to $\pm 2\%$ requires careful thought as to finger arrangement (for 100 cm² devices).

A good general principle is that the contacts in the testing jig should simulate the connections in the final product as closely as possible. The cells used in the PV/Trough system are tabbed along the length of their bus bars. To simulate this, strips of springy metal fingers are used to contact the bus bars, both on the top and on the bottom of the cell. The voltage sensing contacts are provided by individual fingers,

in the middle of each bus bar, which are electrically isolated from the rest of the fingers. These can be seen in figure 3-7.

Many cell testers use a large copper block to make contact to the entire rear surface of the cell. This could overestimate cell efficiency, since the current could flow directly into the copper block, and avoid flowing laterally through the rear metallisation. In this situation, a cell with poor rear-metallisation would appear unrealistically good.

In this tester, the temperature-controlled block is not used as the rear electrical contact. The rear contact is made by spring-loaded fingers along the underside edge of the cell. However, the metal block still touches the rear of the cell so there is potential for a bypass current flow. Aluminium, rather than copper, was chosen as the block material since the natural oxide will make a worse contact.

A small experiment was performed to ensure that the metal block was not causing a significant bypass path. First, for a cell with poor rear metallisation, the resistance from one side of the metallisation to the other was measured when not on the block. It was found to be 5.0 m Ω . Then the cell was placed on the testing block, the hold down vacuum applied, and the resistance measured again. When in contact with the block the resistance was found to be 4.9 m Ω , a decrease of only 2%. The power loss in the rear metallisation is usually only a few percent of total cell power. Hence, the change in total cell power due to the presence of the rear metal block will be a few percent of a few percent, which is insignificant.

3.3.5 Cell temperature control

Solar cells are sensitive to temperature changes. Consequently testing at a non-standard temperature will cause errors in the measurement. Indeed this is the main rationale for use of a flash tester – that it greatly reduces heating of the cell. However there is still some heating, the effect of which needs to be quantified.

The brief pulse of intense light from the flash will cause the cell to heat up. The degree of heating will be set both by the thermal mass of the cell and the thermal gradients through the cell and across the contact between the cell and the temperature controlled test block. All of these effects need to be quantified in order to estimate the cell temperature during the test.

The concepts described here are applicable to essentially any solar cell technology. However, the numbers used are in most cases correct only for crystalline silicon technologies, and for the thermal mass calculation only thick (~500 μ m) wafers.

3.3.5.1 Temperature gradient through cell during flash

Under illumination, heat is generated in the front of the cell and removed from the back. This will cause a temperature gradient. It will be small, since silicon is an excellent heat conductor, but it is worth estimating anyway. To get a highly accurate estimate of the temperature gradient through the cell it is necessary to do a transient analysis. However, this is difficult to do and in this instance not necessary. The analysis can be simplified by considering a steady state situation. This will be a conservative estimate since the temperature will always be lower in the transient case because of the thermal mass of the silicon.

The temperature gradient across a slab of material with a heat flow through it is given by:

$$P = kA \frac{\Delta T}{x} \quad (3-13)$$

where P is the heat flow, k is the thermal conductivity of the material, A is the slab area, ΔT is the temperature difference through the slab, and x is the slab thickness. For an illuminated cell the heat flow P is given by the light intensity E times the area, A , and so A drops out. Substituting in numbers for a typical 500 μm thick cell exposed to 30 suns with a conductivity of 157 W/mK gives a temperature gradient of 0.1 K. As expected, this is a very small temperature gradient. Compared to the temperature rises described in the following sections, it is insignificant.

$$\Delta T = \frac{x E}{k} = \frac{0.5 \text{ mm} \times 30 \text{ kW} / \text{m}^2}{157 \text{ W} / \text{mK}} = 0.09 \text{ K} \quad (3-14)$$

3.3.5.2 Cell heating limited by thermal mass

Each flash pulse will heat the cell. If the cell were insulated from the environment (a conservative case since it is actually attached to a temperature controlled block), its temperature rise would be determined by its thermal mass and the flash energy over its area:

$$Q = m c_p \Delta T \quad (3-15)$$

Where Q is the flash energy, m is the cell mass, c_p is the specific heat of silicon and ΔT is the temperature rise.

The flash energy is given by:

$$Q = \int_{\text{flash duration}} E(t) A dt \quad (3-16)$$

where $E(t)$ is the light intensity and A is the cell area. Since E is measured at equally spaced time intervals, the integral simplifies to the length of the pulse (T) times the average light intensity ($\hat{E}$) times the cell area.

The cell mass is given by:

$$m = x A \rho_{\text{Si}} \quad (3-17)$$

where x is the cell thickness, A is the cell area and ρ_{Si} is the density of silicon.

The cell area cancels, giving:

$$\Delta T = \frac{\hat{E} T}{x \rho_{\text{Si}} c_p} \quad (3-18)$$

The energy density $\hat{E} T$ varies from 0.15 kJ/m² for the internal supply to 0.87 kJ/m² for the longest pulse from the external capacitor bank. For a cell 500 μm thick, the resulting temperature rise for one flash will be between 0.18K and 1.1K. As was mentioned at the beginning of this section, the cell is mounted on a temperature-controlled block. The thermal resistance between the cell and the block (derived in

section 3.3.5.4) is relatively high, so the thermal mass limit will essentially set the cell heating during each flash. Cell temperature will therefore rise up to 1.1K during each flash.

3.3.5.3 Cell heating due to bias circuit

When measuring the section of the I-V curve near V_{oc} , the cell bias circuit will forward bias the cell when it is in the dark. The cell will dissipate power in this situation. This will cause some heating in the cell, but fortunately not very much. Firstly, the electrical power will be no more than about 20% of the light power. So for 30 suns peak light intensity, the continuous electrical heating would be less than 6 suns equivalent. Secondly, the cell bias circuit only needs to be on briefly during the flash. For the capacitive load used in this system, the cell is forward biased for less than 200 ms. At approximately one flash per second, the average electrical heating is therefore only about one sun equivalent. This is comparable to the heating caused by the flash itself.

3.3.5.4 Temperature gradient between cell and test block

Under illumination, there will be a temperature gradient between the cell and the test block, due to the thermal resistance of the contact between the cell and the block. The back of the cell is pressed against the block by vacuum hold-down. The thermal conductivity of this contact is hard to calculate, so instead it was measured experimentally.

The thermal conductivity was measured by abruptly applying a 1 sun light source and then measuring the decline in V_{oc} as the cell heated up. The light source used was a 250W ELH lamp, driven by a stable DC power supply to ensure that the light intensity did not drift over time. When left running in steady state, V_{oc} was stable to within the measurement limits (0.5 mV) over half an hour. The light intensity was determined by measuring the short circuit current of the cell and dividing by the previously known 1 sun current.

The measurement was performed for 3 cases: 1) cell on the test block with vacuum hold-down, 2) cell on the test block but vacuum turned off, and 3) a piece of filter paper between cell and test block (this last test being a poor thermal contact).

The first step was to calibrate the dV_{oc}/dT characteristic of the cell. The cell used was a good quality concentrator cell, H57ii. The temperature setting of the test block was varied over the range 15-35°C in 5°C steps and the open circuit voltage measured at each setting. A best line fit to this data had a dV_{oc}/dT slope of -2.9 mV/°C.

Having calibrated the cell, the thermal conductivity measurements were started. First, a lightproof shield (a 5mm thick sheet of opaque plastic) was placed over the testing block and cell. The temperature controller was set to 25°C and several minutes allowed for it to stabilise. Then the data acquisition was started – V_{oc} being measured at 100 samples/s. After the acquisition had been running for about a minute the shield was pulled off rapidly. The system was then left to acquire data until everything had re-stabilised under illumination. It was observed that when the shield was removed the block temperature rose about 2°C in the first 10 seconds. Then the temperature controller reacted to the change, and after a few minutes it brought the temperature back down to 25 °C. After the full 10 mins of data acquisition, the data was analysed.

The temperature change was determined from the difference between the peak V_{oc} immediately after the shield was removed and the final stable value of V_{oc} when the controller had brought the block temperature back to 25°C.

The thermal conductivity h_c was calculated from the defining equation:

$$P = \frac{\Delta T}{\frac{1}{h_c A}} \quad (3-19)$$

where P is the power flow through the cell-block contact, ΔT is the temperature drop across the contact, A is the contact (cell) area and h_c is the thermal conductivity of the contact.

Since $P = EA$, the equation simplifies to (independent of cell area, A):

$$h_c = \frac{E}{\Delta T} \quad (3-20)$$

Using the data for ΔT and E during the test, the value of the thermal conductivity, h_c , and the value of ΔT that would result at 1 sun were calculated. The results are shown in table 3-3.

Table 3-3: Calculation of cell to block thermal conductivity, h_c

Condition	ΔT (°C)	E (W/m ²)	h_c (W/m ² K)	ΔT at 1 sun (°C)
On heatsink, vacuum on	1.3±0.3	1190±5%	915±200	1.1±0.3
On heatsink, vacuum off	3.5±0.4	1190±5%	340±40	2.9±0.4
Poor heatsinking (filter paper spacer)	5.9±0.4	1480±5%	247±20	4.0±0.3

Using the results in table 3-3, the temperature drop between the cell and the test block can be estimated for the flash tester. The flash is not a steady state light source. However, when it is flashing repeatedly for a long time the average power can be considered equivalent to a continuous source. Using the flash pulse shape data in figure 3-21 and assuming the maximum possible repetition rate, the average light intensity varies between approximately 0.4 and 0.7 suns for the different pulse lengths.

Using equation (3-20) and the data in table 3-3, the average temperature difference between cell and test block, under a continuous repeating flash, is less than 0.8 °C.

3.3.5.5 Temperature controller uncertainty

The temperature controller manual (CAL controls Ltd 1996) specifies that when using a type T thermocouple it is accurate to ±1.5°C.

Interestingly, during the measurement of temperature gradient between cell and test block, the cell temperature could be seen cycling up and down 0.5°C, in synchrony

with the controller. The controller cycle time was reduced to 1 s to reduce the cycling to 0.1°C.

3.3.5.6 Overall temperature uncertainty

The preceding component temperature uncertainties can be combined to estimate the total temperature uncertainty. The temperature of the cell will be at a mean value determined by the temperature controller uncertainty and heating from the flash and bias circuit. It will oscillate around this value by the 1°C calculated in the thermal mass section. Heating by the flash and the bias circuit will be well correlated, so they must be added linearly. In the worst-case, all three will add to give a temperature rise of 3°C. Adding this in quadrature to the controller uncertainty of 1.5°C gives a total temperature uncertainty of $\pm 3^\circ\text{C}$.

3.3.6 Control of stray light and reflections

Stray light and multiple reflections can cause errors during cell measurement, but for the flash tester these problems are insignificant. The cells and flash are enclosed in a light proof box, which eliminates stray light. This is a minor issue anyway for concentrator cells – compared to 30 suns, room light is barely detectable. To minimise reflections, the inside of the flash-tester enclosure is largely covered with Edmund Scientific light absorbing blackout material. Interestingly, it is reported in (Lipps, Zastrow et al. 1995) that some textiles that appear black to the eye are actually quite reflective for wavelengths longer than 800nm. However, no attempt was made to check the Edmund Scientific material. In any case, provided the reference and test cell are well matched and the same size, reflection errors will cancel out.

3.3.7 Cost estimate

This section estimates the cost of building further copies of the constant voltage flash tester. These cost estimates are based on the costs and time taken to build the system sold to BP Solar (though some prices, particularly computer hardware, have been updated to 2001 prices).

Table 3-4: Cost of the components of the constant voltage flash tester

Item	Cost (US\$)
Computer (a basic computer, eg a Pentium II, is adequate)	1000
Data acquisition card	750
Flash	250
External flash supply OR active cell bias circuit	1000
Temperature control	400
Misc. electronics	1000
Labour for construction (70hr)	2000
LabVIEW software, from National Instruments	1000
Flashtester application software, from ANU	arbitrary
Total	7400

3.4 Estimate of measurement uncertainty

In the previous section, the performance of each of the components of the flash tester was analysed. In this section, the component analyses are brought together to give an estimate of the measurement uncertainty for the whole system.

It is not possible to estimate the measurement uncertainty for any general cell. It is necessary in some cases to make assumptions about the size and characteristics of the cell being tested. Where necessary, the measurement accuracy is estimated for the specific case of the ANU concentrator cells. The ANU concentrator cells are 4x5 cm, and 400 μm thick. Typical characteristics for the best cells at 30 suns are: I_{sc} 20 A, V_{oc} 760 mV, Efficiency 22%. A picture of one of the cells is shown in figure 1-3.

The estimate of measurement uncertainty is based on analyses such as (Emery, Osterwald et al. 1987), (Bucher 1997), and (Emery 1992), each of which show comprehensive lists of potential error sources. This work uses the NIST uncertainty methodology (NIST-1297 1994) (the usual root-sum-square method). It does not separate error sources into bias and random components.

In the following sections, all the component uncertainty sources are discussed separately. Then, in the final section, the component uncertainties are combined to give uncertainty estimates for I_{sc} , V_{oc} , FF, and efficiency.

3.4.1 Light source

In most solar simulators, the light source is one of the major sources of error. In this system however, due to the use of well-matched reference cells, light source errors are much less significant.

Numerous error sources become insignificant when the reference and test cell are of identical size and are tested in an identical position. These include stray light, multiple reflections, collimation, non-normal incidence, and shadowing by probes. Two errors sources – spectrum, and non-uniformity – are however still significant.

The spectrum of the flash lamp is, compared to some solar simulators, relatively poor. However, due to the use of a reference cell with a similar spectral response to the test cell, this is not an important problem. For the cells produced at ANU, periodic outdoor calibrations give a spectral mismatch of < 2.5% for almost any cell (as shown in section 3.5). The error in short circuit current is equal to the spectral mismatch, 2.5%. The errors in V_{oc} and FF resulting from this error in I_{sc} are much smaller. V_{oc} is approximately a factor of 20 less sensitive to light intensity than I_{sc} , so the error in V_{oc} will be around 0.1% and can be neglected. FF, for a cell operating somewhere near its design illumination level, varies by perhaps 10 percent over a decade range of light intensity. Consequently, a few percent error in I_{sc} will cause a fraction of a percent error in FF.

Non-uniformity of the light is, over the area of one ANU concentrator cell, very low. However, it could still cause some small errors. There are 2 main issues:

Firstly, the FF of a cell is weakly dependent on light uniformity. If the majority of the light falls in the centre of the cell then the current collected will have to travel further through the metal fingers and consequently resistive losses will be higher. This will give an underestimate of the FF. Conversely, if the majority of the light falls near the edges the FF will be overestimated. Fortunately, good cells are highly tolerant of light

non-uniformity. Indeed, concentrator cells are designed to be so because the concentrator system usually requires a shadow band along the edges of the cells to cope with tracking errors. Concentrator cells are designed to only degrade slightly under this severe non-uniformity. The few percent non-uniformity of this solar simulator is minute compared to the non-uniformity in the operating system. Hence, this error source can be safely ignored.

Secondly, the accuracy of cell positioning can introduce some error. In principle, use of a reference cell that is the same size as the test cell, and is placed in the same position, will eliminate errors due to non-uniformity. However, in practice the reference and test cells could be placed in slightly different positions. The cell-testing block used for the ANU concentrator cells is machined specifically to fit the cells. Consequently, the reference and test cells will be placed in the same position to within a few mm horizontally, and a fraction of a mm vertically. In the horizontal plane, the light non-uniformity is less than 1% over the area of the ANU concentrator cells. Movement of the cells by a few mm will cause a fraction of a percent change in cell current, which is insignificant. For larger area cells or mini modules though, this could be a more serious error source. In the vertical plane, the light intensity varies from 30 to 60 suns over 100 mm. So, the relative change in light intensity with position is approximately given by:

$$\frac{dE/dx}{E} \approx \frac{30\text{suns}/100\text{mm}}{30\text{suns}} = 1\%/mm \quad (3-21)$$

In other words, a 1mm vertical position error will cause a 1% light intensity error. Given that the thickness and vertical positioning of the reference and test cells will be within a fraction of a mm, non-uniformity in the vertical correction will introduce a fraction of a percent error. For cells of different thickness though, this could be a serious error source.

3.4.2 Transient errors

The constant voltage flash tester is less susceptible to transient errors than most other designs. However, they can still occur, and care must be taken to avoid them.

For the ANU cells, FF is identical to within 1% for the three slowest flash pulses. Given this, it is reasonable to assume that transient errors in V_{oc} and FF are less than 1%. Transient errors have almost no influence on I_{sc} .

3.4.3 Concentrator reference cell calibration

As will be seen at the end of this section, the concentrator reference cell calibration is the dominant source of uncertainty in flash tester measurements.

The concentrator reference cells are calibrated using natural sunlight. First, the 1 sun short circuit current is measured outdoors. The 30 sun current is then calculated by scaling the one sun current, and assuming a 1% super-linearity. This assumption is necessary because the linearity could not be accurately measured, as described in section 3.2.4. The accuracy of the one sun calibration is determined by the quality of the spectrum, the accuracy of the pyrheliometer used to measure the irradiance, and the cell temperature control. According to the natural sunlight calibration modelling, a spectral mismatch of less than 4% (with respect to a pyrheliometer) should be achievable at almost any time of year in Canberra (for the AM1.5D spectrum).

Pyrheliometers are accurate to 2%. The cell temperature, outdoors, is controlled by a very similar system to that used in the flash tester. Consequently, cell temperature is controlled outdoors to $\pm 3^\circ\text{C}$. Given the measured temperature dependence of short circuit current for an ANU concentrator cell of $0.15\%/^\circ\text{C}$, temperature error will cause less than 0.5% current error. The assumption of 1% super-linearity is based on previous work on the subject. It is probably good to about $\pm 1\%$.

Degradation of the reference cell and calibration drift over time are not important issues, since re-calibrations can easily be done outdoors.

The total uncertainty in reference cell I_{sc} calibration is therefore 5%.

3.4.4 Data acquisition accuracy

Uncertainty due to the data acquisition circuitry is very small. Not only is the data acquisition card very accurate, but due to the use of a matched reference cell, many of the measurements are effectively just a relative measurement between the test and reference cells.

The data acquisition card measures voltages with 12-bit resolution. It self-calibrates, when instructed, using a precision internal reference. According to its specifications, it is accurate to 0.05% after self-calibration. At the tail of the flash, light intensity and cell current are reduced by an order of magnitude. Consequently, the measurement will be less accurate there. However, it is reasonable to assume that accurate measurements would be taken at the peak of the flash, where measurement errors will be smaller, and the flash spectrum is a better match to the standard spectra.

Noise on the cell current and light intensity signals is approximately 0.1% pk-pk, and noise on the cell voltage signal is approximately 0.3% pk-pk. Most of this noise is in any case filtered out.

Thermal voltages are insignificant. According to (Horowitz and Hill 1997), they are typically on the order of microvolts/ $^\circ\text{C}$. Compared to the signals, which are several hundred mV, this is trivial.

Errors due to the current sensing resistors are largely cancelled by the use of a matched reference cell (provided the same current sensing resistor is used with both the reference and test cells). The only significant problem is changing ambient temperature, which could cause up to 0.6% error. This error will only effect I_{sc} , since V_{oc} and FF are much less sensitive to light intensity/photo-current.

Uncertainty due to the data acquisition circuitry is therefore 0.1% for V_{oc} , and 0.6% for I_{sc} .

3.4.5 FF algorithm

The FF algorithm on the flash tester is presently less than ideal. If a small number of flashes are used, the FF can be underestimated significantly. However, provided at least 40 flashes are used, FF repeatability is better than 1%.

3.4.6 Light detector

The light detector introduces very little uncertainty in the measurement. Its absolute calibration is irrelevant, since it is calibrated via the reference cell. The only possibility for error is due to short term temperature changes, between calibrations.

The light detector cell has no temperature control. It is a SunPower concentrator cell and is mounted on a large heatsink exposed to room air. Since the cell is designed for high concentration operation and is well mounted to the heatsink it will be close to room temperature at all times. Room temperature variations will be much larger than any transient-heating effects, so the heating effects of the flash can be ignored.

The light intensity is determined from the short circuit current of the light detector. The short circuit current of a SunPower concentrator cell has little sensitivity to temperature – it was measured to be $0.05\%/^{\circ}\text{C}$, as described in section 2.2.9.3. For typical room temperature fluctuations of $\pm 10^{\circ}\text{C}$, the light detector current will therefore change by $<0.5\%$.

If an ANU concentrator cell were used as the light detector, errors due to temperature change in the light detector could become more significant, as the ANU cells are more sensitive to temperature.

3.4.7 Cell temperature control

The cell-testing block keeps the test or reference cell within $\pm 3^{\circ}\text{C}$ of the nominal set point. The measurement errors that result from this temperature error depend on the temperature sensitivity of the cell. The cell parameters have varying temperature dependencies, and different cells behave differently. Table 3-5 gives typical values for the temperature sensitivity of I_{sc} , V_{oc} , FF, and P_{max} . The first two columns show values reported in the literature, while the second two columns are measurements made on ANU cells. The 1X measurement of an ANU concentrator cell was performed outdoors, while the 30X measurements were performed on the flash tester. It can be seen that the ANU cells are fairly typical, with the exception of an unusually high temperature sensitivity of I_{sc} at one sun. The high temperature sensitivity of I_{sc} for the ANU cells is difficult to explain. A commonly cited explanation for temperature sensitivity of I_{sc} is a decrease in the bandgap energy and hence the absorption of more IR photons (Wenham, Green et al. ; Green 1982). However, this gives a temperature coefficient for a silicon cell of only $0.06\%/^{\circ}\text{C}$, whereas the ANU cells have a coefficient of $0.15\%/^{\circ}\text{C}$. Possibly there are some temperature dependent recombination processes adding to the sensitivity.

Table 3-5: Relative change in cell parameters due to temperature ($\%/^{\circ}\text{C}$). The first two columns are from (Emery, Burdick et al. 1996), the second two columns are from experiments at ANU.

	Range of silicon cells	Si Concentrator cell at 250X	ANU concentrator cell at 1X.	ANU concentrator cell at 30X.
I_{sc}	+0.01 to +0.12	+0.02	+0.15	+0.05
V_{oc}	-0.24 to -0.45	-0.17	-	-0.26
FF	-0.1 to -0.2	-0.07	-	-0.14
P_{max}	-0.1 to -0.5	-0.2	-	-0.35

The measurement uncertainty that results from non-ideal temperature control is the product of the temperature uncertainty and the temperature sensitivity.

3.4.8 Cell area measurement

The measurement of cell area, though a simple operation, can be a surprisingly large source of measurement error (Emery 1992). For cells that have not been diced from the wafer, there can be significant carrier collection from areas outside the nominal cell boundary. However, this effect can be eliminated by masking the cell, which only allows light to fall inside the defined cell area.

The cells for the PV/Trough system are diced before measuring. Since they are cut with a computer-controlled dicing saw, the area is highly repeatable. The cells are cut to 40.6 by 50.4 mm, with an accuracy of ± 0.1 mm. This corresponds to an area uncertainty of $<0.3\%$.

3.4.9 Cell instability

Temporal instabilities in cells have been reported by many investigators, eg (Emery 1992, p96), and in a wide range of different solar cell technologies. The early ANU concentrator cells showed instability. After being forward biased (electrically), the current dropped by up to 3%. They recovered after about 1/4 hour of not being forward biased. The effect does not appear in the cells currently being produced. However, it is worth keeping an eye out for such instabilities.

3.4.10 Overall system accuracy

The overall system accuracy can be estimated from the component uncertainty estimates. The various error sources affect I_{sc} , V_{oc} , and FF differently. These effects are tabulated below, in table 3-6. The total uncertainty in I_{sc} , V_{oc} , and FF is calculated as the root sum square of the individual components. It can be seen, as expected, that the reference cell calibration uncertainty dominates the final uncertainty in efficiency.

Table 3-6: Estimates of uncertainty (%) in I_{sc} , V_{oc} , and FF, for measurement of ANU concentrator cells with the constant voltage flash tester

Error source	I_{sc}	V_{oc}	FF
Spectral mismatch	2.5	-	-
Non-uniformity	<1	-	-
Transient errors	-	<1	<1
Ref. cell cal.	5	0.25	-
Data acquisition	0.6	-	-
FF algorithm	-	-	1
Light detector	0.5	-	-
Temperature control	0.15	0.8	0.4
Total (RSS)	5.5	1.3	1.5

Due to the way random errors add, the total error is dominated by the largest component error sources. Small components, less than about 1/10th the largest component, will have almost no effect on the total. In the following table, insignificant errors are indicated by a hyphen (-).

The uncertainty in the efficiency value can be calculated from the uncertainty in I_{sc} , V_{oc} , FF, cell area, and light intensity. The uncertainty in light intensity is already included in the reference cell calibration, so it is 0%.

Table 3-7: estimated uncertainty in efficiency measurement (% , relative)

Error source	Error (%)
I_{sc}	5.5
V_{oc}	1.3
FF	1.5
Area	0.3
Total (RSS)	6

The estimated uncertainty in efficiency is therefore 6%.

3.5 Experimental verification of performance

The accuracy of measurements made with the flash tester is a crucial issue. A theoretical analysis of the measurement accuracy is described in the previous section, but the definitive test is experimental. This section describes experiments performed to verify the accuracy of the flash tester.

A central tenet of the new flash tester design is the use of a well-matched reference cell. Essentially, the tester is designed to perform relative measurements on a group of similar cells. Consequently, it is not meaningful to measure a single cell that has been accurately calibrated. In this work, no attempt was made to measure an externally calibrated cell.

The important question is: given a typical range of cells off the production line, how accurate will measurements be? This question is answered for the specific case of the ANU concentrator cells.

A group of cells was selected from the last year's production, including a few of the best cells, a few typical cells, a few of the worst cells, and some randomly chosen cells. The cells were all measured accurately outdoors, and then measured with the flash tester. Comparison of the two sets of results shows how well the flash tester works. Two aspects of the flash tester performance can be examined using the indoor and outdoor measurements:

Firstly, the spectral mismatch can be estimated for a typical range of cells. Using one of the cells as the reference cell, the spectral mismatch for all the other cells can then be determined. The range of spectral mismatch values indicates how often new reference cell should be created.

Secondly, the accuracy of FF and V_{oc} measurement can be confirmed. Outdoor measurements can be done slowly enough to be certain that there are no transient

errors. This makes it possible to verify that transient errors have been eliminated on the flash tester.

3.5.1 Cell group

The cell group used in the experiment was chosen from the last year's production of ANU concentrator cells. It included cells with efficiency values varying between 15% and 22% (at 30 suns). It clearly is not a very well matched group, so should be a safe estimate of measurement accuracy for normal production. The cells included are described in table 3-8.

Table 3-8: Description of the cells used for experimental verification of flash tester accuracy.

	1 sun	30 suns
a few of the best cells	$V_{oc} \sim 645 \text{ mV}$, $\eta \sim 17\%$	$V_{oc} \sim 755 \text{ mV}$, $\eta \sim 22\%$
a few typical cells (roughly median I_{sc} and V_{oc} values, well matched, all from the same batch)	$V_{oc} \sim 630 \text{ mV}$, $\eta \sim 16\%$	$V_{oc} \sim 720 \text{ mV}$, $\eta \sim 19\%$
a few of the worst cells	$V_{oc} \sim 610 \text{ mV}$, $\eta \sim 13\%$	$V_{oc} \sim 700 \text{ mV}$, $\eta \sim 15\%$
a few cells picked randomly		

3.5.2 Accurate outdoors measurement

All of the cells in the cell group were accurately measured outdoors, under natural sunlight, using the procedure described in chapter 2.

The cells were measured in Canberra, Australia (lat 36°S), on 26 March 2001. This was a clear, stable day and all of the cells were measured within 1 hour, near solar noon. Direct beam irradiance varied by less than 1% over the course of the measurements. This ensured that the cells were all measured under very similar conditions. For the purpose of assessing spectral mismatch, it is only necessary to have relative measurements under the correct spectrum. This meant that pyrheliometer accuracy was not important – the pyrheliometer merely had to be stable (which it certainly would have been).

The measurements were made under the following atmospheric conditions:

AM = 1.3, $w = 1.3 \text{ cm}$, $\beta = 0.02$, irradiance (direct beam) = $995 \pm 5 \text{ W/m}^2$.

For concentrator cells, the appropriate standard spectrum is AM1.5D. Therefore, according to the modelling in chapter 2, the spectral mismatch error in the outdoor calibrations was less than 2.5%.

A full I-V curve was measured for each cell, using a capacitive curve tracer (a large capacitor makes a convenient variable load for a cell. Before the test, it is charged to a small negative voltage. It is then connected across the cell. Initially the cell is reverse biased by the capacitor, then the cell current gradually charges the capacitor, through short-circuit, out to V_{oc} . With $I_{sc} \approx 1 \text{ A}$, a $68,000 \mu\text{F}$ capacitor takes a few hundred milliseconds to trace out the I-V curve). The cells were mounted on the same test block as is used in the flash tester, and were temperature controlled to 25°C.

3.5.3 Spectral mismatch for typical cells

The spectrum of the Geni Megastrobe is not a particularly good match to any of the standard spectra – to achieve low spectral mismatch, the tester relies on having a group of similar cells. The important question is: given a typical range of cells being tested, how big is the range of spectral mismatch? This question was investigated for the group of ANU concentrator cells.

First, all of the cells in the group were measured accurately outdoors at approximately 1 sun. Then, all of the cells were measured with the flash tester, using one of the cells as a reference. The spectral mismatch was then calculated for each cell as the ratio of I_{sc} measured with the flash tester to the ‘true’ value of I_{sc} measured outdoors. The spectral mismatch was measured at 1 sun and at 30 suns.

The flash tester measurement at 1 sun can be directly compared to the outdoor measurement, giving a measure of the quality of the flash lamp spectrum. The flash tester measurement at 30 suns has to be compared to an estimated ‘true’ 30-sun I_{sc} . The estimated 30-sun I_{sc} includes an assumption on cell linearity. So, the 30-sun comparison gives an indication both of the quality of the flash lamp spectrum and of the consistency of the linearity assumption.

For the flash tester measurement at approximately one sun, a neutral density filter was required to reduce the light intensity (the enclosure does not allow the flash to be moved far enough from the cells). No neutral density filter with sufficiently large area was conveniently available. So, a simple neutral density filter was made by laser printing a fine array of black dots on an overhead transparency. Such a filter should be reasonably neutral since laser printer toner is mostly carbon black. The transmission characteristics of the overhead film are unknown. During the 1-sun measurements, it was found that the printed filter did not have good uniformity. Moving the filter around could change the measured I_{sc} by up to 1%. To check the repeatability of the measurement, the reference cell (used to calibrate the light detector) was re-measured several times. The repeatability of the one sun I_{sc} was $\pm 0.5\%$. With the neutral density filter in place, the peak light intensity at the cell was 1.5 suns. All of the cells were measured at 1 sun. The results are shown in table 3-9.

For the flash tester measurement at 30 suns, the ‘true’ 30-sun I_{sc} had to be estimated based on the outdoor measured 1-sun I_{sc} . A 1% super-linearity was assumed, as described in section 3.2.4. However, as these are relative measurements, the average amount of nonlinearity will not be detected. Only differences in nonlinearity will appear in the results.

Due to the absence of the neutral density filter, the repeatability was much better than for 1-sun – approximately 0.1%. The absence of the ND filter also means that the spectral mismatch comparison is more valid. The results are shown in table 3-10.

Both the 1-sun and the 30-sun measurements show that the quality of the Geni Megastrobe spectrum is in fact quite good – a spectral mismatch of less than 2.5% is likely for any of the ANU concentrator cells. Neither the 1-sun nor the 30-sun measurements definitively show the spectral mismatch however. The 1-sun measurements are complicated by the less-than-perfect neutral density filter (which has both poor uniformity and questionable neutrality), and the 30-sun measurements are complicated by having to make assumptions about linearity. However, neither show a worst-case spectral mismatch greater than 2.5%.

In summary, if one of the best ANU concentrator cells is used as the reference, any of the other ANU concentrator cells can be measured with a spectral mismatch of less than 2.5%. This shows that new reference cells do not need to be calibrated very often. Probably once a year is sufficient.

Table 3-9: Comparison of flash-tester measured 1-sun I_{sc} with outdoor measured 1-sun I_{sc}

Cell	1X I_{sc} , outd. (A)	1X I_{sc} , FT (A)	$\Delta I_{sc}/I_{sc}$ (%)
c15600 (FT ref.)	0.684		
c149l	0.634	0.643	1.4
c149ll	0.638	0.643	0.9
c149m	0.636	0.644	1.2
c149mm	0.635	0.643	1.4
c149nn	0.631	0.641	1.6
c154s	0.643	0.646	0.5
c155rr	0.625	0.640	2.3
c156p	0.668	0.682	2.0
c162o	0.652	0.670	2.6
c175o	0.552	0.560	1.4
c194ff	0.614	0.623	1.5
c187e	0.581	0.568	-2.4
2 σ			2.5
mean			1.2

Table 3-10: Comparison of flash-tester measured 30-sun I_{sc} with outdoor-measured/estimated 30-sun I_{sc}

Cell	est. 30X I_{sc} , outd. (A)	30X I_{sc} , FT (A)	$\Delta I_{sc}/I_{sc}$ (%)
c15600 (FT ref.)	20.73		
c149l	19.21	19.08	-0.7
c149ll	19.32	19.12	-1.0
c149m	19.27	19.10	-0.9
c149mm	19.23	19.08	-0.8
c149nn	19.13	19.00	-0.7
c154s	19.49	19.50	0.1
c155rr	18.95	19.28	1.7
c156p	20.25	20.46	1.0
c162o	19.77	20.03	1.3
c175o	16.73	16.50	-1.4
c194ff	18.59	18.55	-0.2
2 σ			2.1
mean			-0.1

3.5.4 FF and V_{oc} accuracy

To check the accuracy of FF and V_{oc} measurements on the flash tester, flash tester and outdoor measurements were compared. The main issue was transient errors. The outdoor measurements could be done slowly enough to be sure that transient errors were not a problem.

FF and V_{oc} could not be measured under concentration, as suitable facilities were not available. Instead, FF and V_{oc} were measured at approximately 1 sun, outdoors, for each cell. The I-V curves were measured with a capacitive curve tracer, which took several hundred milliseconds to trace from short circuit to open circuit. This was slow enough to be certain that there were no transient errors (a bias rate of a few V/s), but at the same time fast enough to ensure that variations in sunlight intensity did not upset the measurement.

For both flash tester and outdoor measurements, the cells were mounted on the flash tester cell-testing block. This ensured that FF would not be affected by different contacting arrangements. The cell-testing block also allowed temperature control, both indoors and outdoors. Temperature control is essential when measuring V_{oc} .

All of the cells were then measured with the flash tester, using the previously mentioned laser-printed neutral-density filter to get approximately 1 sun. To eliminate the complicating influence of spectral mismatch, a large number of I-V curves were measured on the flash tester (at every multiple of 0.01 suns). The outdoor I-V curve could then be compared to a flash tester I-V curve with the same short circuit current.

To ensure that FF measurements were not upset by the simple maximum power point extraction algorithm, 40 flashes were used for each I-V curve.

The flash lamp was run from the external capacitor bank using 2 capacitors (4 ms time constant). This is the usual flash setting for routine measurements. Since the cells were being measured at only 1 sun, the cell currents were quite low, and consequently dV/dt was also relatively low. Typically, dV/dt was about 10 V/s. The analysis of transient errors in section 3.3.2 showed that, for the ANU concentrator cells, errors are a noticeable problem at ~ 100 V/s but apparently non-existent at ~ 10 V/s. The comparison of indoor and outdoor measurements is therefore a good test of whether the measurements truly are transient free at ~ 10 V/s.

The outdoor measured and flash tester measured V_{oc} and FF values are shown in table 3-11.

It can be seen from the results that FF measurements are accurate – $\pm 0.5\%$. Clearly, transient errors are not a problem at ~ 10 V/s. V_{oc} measurements do not agree as well as FF. However, this is not surprising since the temperature control did not work very well outdoors. Restricted airflow to the Peltier cooler meant that it overheated. Cell temperature sometimes rose to 27°C . In addition, different temperature controllers were used indoors and outdoors, so another degree or so temperature difference likely resulted from this. In total, some of the cells may have been as much as 4 degrees hotter outdoors. For a typical -2.5 mV/ $^\circ\text{C}$ temperature coefficient, the outdoors measurements could be expected to be up to 10 mV lower than indoors. This is indeed what the results show. V_{oc} comparisons therefore do not really show much about transient errors. In any case, FF is much more sensitive to transient errors than V_{oc} . So

the excellent accuracy of FF measurements shows that transient errors are not a problem.

Table 3-11: V_{oc} and FF measured outdoors and with the flash tester (both at the same I_{sc}).

Cell	Outdoor irradiance, direct beam (W/m^2)	V_{oc} outd. (mV)	V_{oc} FT (mV)	$\Delta V_{oc}/V_{oc}$ (%)	FF, outd. ()	FF, FT ()	$\Delta FF/FF$ (%)
c156oo	992	646	649	0.5	0.762	0.764	0.3
c149l	993	633	636	0.5	0.790	0.790	0.0
c149ll	991	633	637	0.6	0.784	0.784	0.0
c149m	989	638	637	-0.2	0.790	0.788	-0.3
c149mm	989	635	637	0.3	0.786	0.785	-0.1
c149nn	994	634	637	0.5	0.794	0.796	0.3
c154s	991	549	551	0.4	0.541	0.541	0.0
c155rr	992	613	624	1.8	0.792	0.793	0.1
c156p	993	640	647	1.1	0.760	0.763	0.4
c162o	993	624	635	1.8	0.775	0.777	0.3
c175o	994	597	609	2.0	0.784	0.789	0.6
c194ff	992	623	631	1.3	0.804	0.805	0.1
2σ				1.4			0.5
mean				0.8			0.1

3.6 Potential improvements to the flash tester

The flash tester could be improved in numerous ways. The main improvements are to make it faster, and cheaper. There is little potential to make it more accurate, since measurement accuracy is already limited by the reference cell calibration.

The cell bias circuit, in its present form, does not maintain sufficiently constant voltage. To avoid transient errors, an external flash supply is required. This both increases the cost of construction, and slows down the test. When operating on the external supply, the flash cannot fire faster than approximately once per second. If the cell bias circuit was improved, either by reducing series resistance or by using an active load (as described in section 3.3.2), the flash could be used with its internal supply. When operating on the internal supply, the flash can fire as often as 10 times per second. This would speed up the test. In addition, eliminating the external flash supply would make the tester cheaper.

The present maximum power point extraction algorithm requires a relatively large number of flashes (~ 40). If the algorithm were improved, as described in section 3.2.3.2, fewer flashes would be required. This would reduce the time for the test.

The flash tester presently takes about 30 s to test 1 cell. If the cell bias circuit and the maximum power point extraction algorithm were improved, the test time could be reduced to a few seconds.

3.7 Conclusions

The new constant-voltage flash tester design works successfully. It is both cheap (under US\$10,000) and achieves excellent accuracy (measurement uncertainty estimated to be 6%, although most of this in fact comes from the reference cell calibration).

The low cost is achieved by using a commercial xenon flash instead of an expensive custom engineered design. The use of the low-cost flash is possible because of two simplifications. Firstly, the relatively frequent calibration of reference cells using natural sunlight reduces spectral mismatch, and so allows a flash with a poorer quality spectrum. Secondly, a multi-flash design eliminates the need for constant light intensity.

An important feature of the system is that I-V curves are extracted over a decade range of light intensity. This provides important additional data on cells, allowing extraction of more reliable estimates for cell parameters than from a measurement at a single light intensity. Hence more accurate modelling of cells is possible.

The constant voltage flash tester design is much less sensitive to transient errors than other flash tester designs. Since transient errors are mostly caused by rapid changes in cell voltage, the constant voltage bias concept greatly reduces them. The capacitive bias circuit used to implement the constant voltage concept works well at low currents, below a few amps. However, it is not as effective for higher currents, due to series resistances.

The constant voltage flash tester design has been used extensively. One of these systems is in operation at the Centre for Sustainable Energy Systems, ANU, and has been used to test 10's of thousands of concentrator cells produced there. Another of these systems has been sold to BP Solar, UK, where it is used for testing Laser Grooved Buried Grid concentrator cells and conventional 1 sun cells.

4 Conclusions

The objective of this work was to develop cell-testing procedures for the solar cells used in the PV/Trough concentrator system. This led to two areas of research: the development of a natural sunlight calibration procedure for silicon solar cells, and the development of a low-cost flash tester. The following paragraphs briefly summarise the conclusions of this work – the full conclusions can be found at the ends of chapters 2 and 3.

The investigation of natural sunlight calibration showed that sunlight is a far better light source than any affordable solar simulator. A calibration procedure was developed that should achieve measurement uncertainty of less than 5%, and uses no expensive equipment. Climate data suggests that the weather conditions required to use this technique should occur commonly.

The flash tester developed is a low-cost design, yet still achieves good accuracy. Use of the natural sunlight calibration procedure to create well-matched reference cells allows the use of a low-cost flash. These testers could be built for approximately \$US10,000 each. The flash tester uses a constant voltage cell bias circuit, which reduces sensitivity to transient errors. The tester also produces a family of I-V curves rather than a single I-V curve, allowing better characterisation of cell performance. The tester works well – one is in frequent use at the Centre for Sustainable Energy Systems, ANU, while another has been sold to BP Solar, UK.

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Appendix A Publications

The conference papers listed below have been presented during the course of the work described in this thesis. Several journal papers are also in preparation.

Conference papers:

- “Measurement of Silicon Solar Cells under Natural Sunlight”, Keogh, W., Blakers, A. (2000) Proceedings of Solar 2000 – Annual Conference of the Australian and New Zealand Solar Energy Society, Brisbane, QLD, Australia
- “Simple Flashlamp I-V Testing of Solar Cells”, Keogh, W., Cuevas, A. (1997) Proceedings of 26th IEEE Photovoltaics Specialists Conference, Anaheim, CA, USA
- “Simple Flashlamp I-V Testing of Solar Cells”, Keogh, W., Cuevas, A. (1997) Proceedings of Solar ‘97 – Annual Conference of the Australian and New Zealand Solar Energy Society, Canberra, ACT, Australia
- “The ANU PV/Trough Concentrator System”, Smeltink, J., Matlakowski, G., Carr, A., Cuevas, A., Theden, U., Keogh, W., Stuckings, M.F., Armand, S. and Blakers, A.W., (1996), Proceedings of Solar ‘96 – Annual Conference of the Australian and New Zealand Solar Energy Society, Darwin, NT, Australia
- “Photovoltaic concentrator systems”, Cuevas, A., Keogh, W., Blakers, A., (1995) In proceedings of the workshop on solar power modelling C.A.S.E., Per, WA, Australia
- “PV/Trough Systems”, Keogh, W., Smeltink, J., Blakers, A., Cuevas, A., (1995), Proceedings of Solar ‘95 - Annual Conference of the Australian and New Zealand Solar Energy Society, Hobart, Tasmania, Australia

Papers in preparation and submitted:

- “Natural sunlight calibration of silicon solar cells”, Keogh, W., Blakers, A. Submitted for 17th European Photovoltaic Solar Energy Conference and Exhibition, Oct 2001
- “Constant-voltage I-V flash tester”, to be submitted for First International Conference on Solar Electric Concentrators, Oct 2001
- “Constant-voltage I-V flash tester”, to be submitted to Solar Energy Materials and Solar Cells
- “Calibration of Silicon Solar Cells under Natural Sunlight”, to be submitted to Solar Energy Materials and Solar Cells

Appendix B Recipe for natural sunlight calibration

This document describes a procedure for calibrating silicon solar cells under natural sunlight.

A summary of the method is given, followed by details of the equipment required, and a detailed procedure to be followed.

The procedure uses numerous suggestions from (NASA TM 73703 1977), (ASTM E1039 1999) and (ASTM E1125 1999).

B.1 Summary of test method

This test method describes a procedure for calibrating silicon solar cells under direct-beam natural sunlight. The important atmospheric conditions can be measured with simple equipment, and the method gives an estimate of the measurement accuracy.

The important atmospheric conditions affecting cell measurement are: air mass (the angle of the sun in the sky), turbidity (the amount of dust in the air), and precipitable water (the amount of water vapour in the air). These three parameters can be determined from the time, location, ambient air temperature, relative humidity, and direct beam irradiance.

The sunlight intensity (direct-beam irradiance) is measured with a pyrheliometer, and the cell to be measured is housed in a collimating tube that matches the geometry of the pyrheliometer.

The measurement procedure (summarised in figure 2-3) is:

- Measure irradiance and cell current, then calculate cell current at 1 sun condition.
- Measure air mass, turbidity, and precipitable water, then look up the error estimate for the cell current measurement.

Only I_{sc} should be measured outdoors – it is easier and more accurate to measure V_{oc} and FF indoors.

The measurement error estimate applies for any likely crystalline silicon solar cell with efficiency greater than 6%. Particularly unusual lab prototype cells may exhibit larger measurement errors. In addition, if the cell has a front surface optical coating it should be something close to an optimal antireflection coating. Cells with unusual coloured coatings, as commonly used for architectural purposes, may have slightly larger errors. The error estimates are specific to crystalline silicon technology – measurement errors will probably be different for other solar cell technologies.

B.2 Equipment required

The natural sunlight calibration method does not require any specialised equipment. The only expensive item is a pyrheliometer (around \$1500).

The items of equipment required are:

- Pyrheliometer – to measure direct beam irradiance. Suitable instrument are: Kipp & Zonen CH1 (manufactured by Kipp & Zonen, Netherlands, www.kippzonen.com), or Eppley NIP (manufactured by The Eppley Laboratory, USA, www.eppleylab.com). For long-term accuracy it is advisable to keep the pyrheliometer indoors when not in use.
- Thermometer and Hygrometer – to measure air temperature $\pm 2^\circ\text{C}$, and relative humidity $\pm 5\%$. Many manufacturers produce suitable combined thermometer/hygrometers, one being Vaisala HM34.
- Collimating tube – to restrict the cells field of view to direct beam sunlight only. These are not available commercially and so will need to be made. A suitable design is described in section 2.2.7.3.
- Sun tracking platform – to orient the collimating tube and pyrheliometer towards the sun. If automatic tracking is used, it should be accurate to $\pm 0.5^\circ$. Manual tracking is quite acceptable too.
- Temperature measurement or control for cell – for highly accurate measurements, temperature control of the cell is recommended ($\pm 3^\circ\text{C}$).
- Electrical instruments – to measure cell current. An ammeter, or shunt resistor and voltmeter ($\pm 0.5\%$ accuracy recommended). A circuit is also required to bias the cell to short circuit exactly (either a manual operated battery + variable resistor, or an automatic feedback circuit).

B.3 Procedure

B.3.1 Check if conditions are suitable

Measurements under natural sunlight are dependent on weather conditions. The first step in the measurement procedure is to determine if conditions are suitable. ‘Suitable’ is a relative term, as it depends on the measurement accuracy required. To assess whether conditions are suitable:

- Check that the sky is moderately free of cloud (period when there are no clouds within 15° of the sun).
- Measure relative humidity, air temperature, and irradiance.
- Calculate air mass, precipitable water, and turbidity (see sections 2.2.1.5 and 2.2.1.6 for methods).
- Look up worst-case spectral mismatch error plots (in section 2.3.1) to see if measurement accuracy will be acceptable.

Precipitable water and turbidity vary slowly – if conditions are not suitable when checked, they are unlikely to be better until several days later. Experience will show local trends in turbidity and precipitable water over the day, after rain, after strong winds, etc.

B.3.2 Preparation

Before performing a measurement, some preparatory steps are necessary.

- All equipment should be set up and allowed several hours to reach thermal equilibrium. This is particular important for pyrheliometers, which are sensitive to internal thermal gradients (for the Kipp & Zonen CH1, a 5°C/hr temperature gradient can cause up to 0.3% error). The pyrheliometer window should also be cleaned.

- Some cells exhibit instabilities when exposed to light – a few hours light soaking may be necessary beforehand.
- For the most accurate measurements, it is advisable to measure the temperature coefficient and linearity of I_{sc} for the test cell.

B.3.3 Measurement

The recommended measurement cycle is as follows:

- Measure relative humidity and air temperature.
- Align the collimating tube and pyrheliometer with the sun.
- Allow the pyrheliometer time to stabilise.
- Check that irradiance is stable to $\pm 0.5\%$ over at least twice the pyrheliometer response time.
- Check that there are no obvious cloud formations close to the sun.
- Measure irradiance and cell current simultaneously.

Once the measurements have been performed, the 1-sun I_{sc} and uncertainty in I_{sc} can be calculated:

- Calculate I_{sc} for 1-sun: $I_{sc, 1 \text{ sun}} = I_{sc} \cdot \frac{1000 \text{ W/m}^2}{E_{test}}$
- Calculate air mass, precipitable water, turbidity (see sections 2.2.1.5 and 2.2.1.6 for methods).
- Look-up the worst-case spectral mismatch error plots (in section 2.3.1) for an estimate of the spectral mismatch error, ε_M . Note: if measurements are being performed under high air mass, high turbidity, and low precipitable water conditions, the spectrum will be fairly red and so measurements will tend towards over-estimation rather than under-estimation.
- The total measurement uncertainty is approximately $\varepsilon_M + 1\%$.

The measurement cycle should be repeated several times for greater reliability. For the highest possible accuracy, it is advisable to repeat the measurement on several different days. ASTM-E1039 recommends repeating the measurement at least five times over three different days.

B.4 Report

Once the measurement is complete, report both the raw data and the calculated measurements:

- Irradiance, and I_{sc} at this irradiance.
- Relative humidity, air temperature, time, and calculated air mass, turbidity, precipitable water.
- Calculated I_{sc} at 1000 W/m^2 , and uncertainty in I_{sc} .

Appendix C Source code

The following pseudo-C code calculates turbidity from a direct beam irradiance measurement. It is derived from (Gueymard 1998). Note that Gueymard uses δ_i (deltai) for optical depth, rather than τ_i , which used elsewhere in this document. The following code uses the 'deltai' notation.

```

/* Calculate turbidity, beta, from */
/* p, atmospheric pressure (mbar) */
/* uo, amount of ozone (atm-cm) */
/* mR, air mass () */
/* unt, total column of NO2 (atm-cm) */
/* w, precipitable water column (atm-cm) */
/* Ebn, beam normal irradiance (W/m^2) */
/* E0n, extraterrestrial beam normal irradiance at the actual */
/* earth-sun distance (W/m^2) */
/*
/* from C. Gueymard, 1998, Turbidity Determination From
/* Broadband Irradiance Measurements - A Detailed
/* Multicoefficient Approach, J. Applied Meteorology, p414-435 */
/*
/* Sample values to test if code is free of typos: */
/* p uo mR unt w Ebn E0n deltac deltaw deltan deltaa beta */
/* 1013 0.34 1 2E-4 1 900 1367 0.1195 0.1119 0.0006 0.1860 0.1154 */
/* 950 0.20 2 1e-2 3 500 1300 0.0933 0.1071 0.0283 0.2490 0.1629 */

p0 = 1013.25;
q = 1 - p/p0;

/* calculate Clean Dry Atmosphere Optical Depth */
uns = 2e-4;
a0 = 1 - 0.98173*q;
a1 = 0.18164 - 0.24259*q + 0.050739*q^2;
a2 = 0.18164 - 0.17005*q - 0.0084949*q^2;
b0 = -0.0080617 + 0.028303*uo - 0.014055*uo^2;
b1 = 0.011318 - 0.041018*uo + 0.023471 *uo^2;
b2 = -0.0044577 + 0.016728*uo - 0.01091*uo^2;
c0 = 0.0036916+0.047361*uo +0.0058324*uo^2;
c1= 0.015471+0.061662*uo -0.044022*uo^2;
c2 = 0.039904-0.038633*uo+0.054899*uo^2;
f1 = (a0 + a1*mR)/(1+a2*mR);
f2 = b0 + b1*mR^0.25 + b2*ln(mR);
f3 = (0.19758 + 0.00088585*mR - 0.097557*mR^0.2)/(1+0.0044767*mR);
f4 = (c0 + c1*mR^0.72)/(exp(1+c2*mR));
f5 = uns * (2.8669 - 0.078633*(ln(mR)^2.36));
deltac = f1 * (f2 + f3) + f4 + f5;

/* calculate water Optical Depth */
mw= mR;
y1 = (1.728 - 2.1451*q)/(1-0.96212*q);
y2 = (0.37042 + 0.64537*q)/(1+0.94528*q);
y3 = (3.5145 - 0.12483*q)/(1-0.34018*q);
p1 = (0.63889 - 0.81121*q)/(1 - 0.79988*q);
p2 = (0.06836 + 0.49008*q)/(1+4.7234*q);
p3 = (2.1567 + 1.4546*q)/(1+0.038808*q);
k1 = (-0.1857+0.23871*q)/(1-0.84111*q);
k2 = (-0.022344 - 0.19312*q)/(1+6.2169*q);
k3 = (2.1709 + 1.6423*q)/(1+0.062545*q);
v1 = 3.3704 + 6.8096*q;
v2 = (12.487 - 18.517*q - 0.4089*q^2)/(1 - 1.4104*q);
v3 = (2.5024 - 0.56834*q - 1.4623*q^2)/(1-1.0252*q);
v4 = (-0.030833 - 1.172*q - 0.98878*q^2)/(1+31.546*q);
g1 = (y1*w+y2*w^1.6)/(1+y3*w);
g2 = (p1*w+p2*w^1.6)/(1+p3*w);
g3 = (k1*w+k2*w^1.6)/(1+k3*w);

```

```

g4 = (v1*w+v2*w^0.62)/(1+v3*w+v4*w^2);
M = (1.7135 + 0.10004*mw + 0.00053986*mw^2)
/(1.7149+0.097294*mw+0.002567*mw^2);
deltaw = M*(g1+g2*M*mw+g3*(M*mw)^1.28)/(1+g4*M*mw);

/* calculate NO2 Optical Depth */
deltan = unt * (2.8669 - 0.078633*(ln(mR)^2.36));

/* calculate aerosol Optical Depth */
ma = mR;
mn = mR;
deltaa = (1/ma)*( ln(E0n/Ebn) - mR*deltac - mw*deltaw - mn*deltan);

/* calculate beta from broadband aerosol optical depth */
d0 = (1.6685+4.1257*w+0.018748*w^2)/(1+2.336*w);
d1 = (0.075379+0.066532*w - 0.0042634*w^2)/(1+1.9477*w);
d2 = (0.12867+0.24264*w - 0.0087874*w^2)/(1+3.3566*w);
h0 = (-0.032335 - 0.0060424*w)/(1+0.023563*w);
h1 = (-0.38229 - 0.0009926*w)/(1+0.044137*w^0.594);
h2 = (-0.0059467 + 0.0054054*w)/(1+0.91487*w);
h3 = (0.21989 + 0.041897*w)/(1+0.35717*w);
n = (1.3211+2.2036*w)/(1+1.9367*w);
s1 = (d0 + d1*ma)/(1+d2*ma);
s2 = (h0+h1*ma+h2*ma^2)/(1+h3*ma^n);

beta = (s1/s2)*(-1+(1+4*s2*deltaa/s1^2)^0.5)/2;

```

- p.15: Fast diode-array spectrometers that can measure the spectrum of a flash-lamp are now commercially available.
- p.29: The simulation of spectral mismatch error under natural sunlight relies heavily on the accuracy of the SMARTS2 spectrum model. This model has not been thoroughly validated, as discussed in section 2.2.1.9.
- p.45: The optical model for textured cells in PC1D is limited, so the simulated currents for textured cells will not be quite correct. However, since the modelling only requires a representative scatter of currents, this is not a serious limitation.
- p.46: The choice of doping level and front surface recombination velocities used in the modelling is probably a little too simplistic. It gives two fairly distinct groups of cells, one with very poor UV response, and the other with good UV response. This can be seen in figure 2-12. Solar cells with screen printed emitters, a practically important case, may fall in between. The purpose of the modelling, however, is to look for extreme cases, so the intermediate cases that were not treated are unlikely to invalidate the results.
- p.77, 94: The new natural sunlight calibration method is recommended on the basis of a comparison of the calculated uncertainty for the new method to the measured reproducibility of existing methods. This is not a fair comparison. The new method cannot be strongly recommended until experiments have thoroughly verified it.
- p.90: Use of a non-standard spectrum that is adjusted to give 1-sun I_{sc} may give slight errors in the measurement of V_{oc} and FF. Some cells with a rear dielectric passivation, particularly those with low base resistivity, can have strong sensitivity to changes in excess carrier concentration close to the rear surface.
- p.92, 183: Light soaking should be mandatory, not just recommended. Changes of 1-5% in I_{sc} are commonly observed. Most change occurs in the first few hours, but as much as 24 hours light soaking may be necessary, particularly for Cz cells.
- p.93: Calibration of a reference cell at Fraunhofer costs EURO 600, including a spectral response curve measured with a filter monochromator. The price of EURO 900 quoted on p. 93 is for a calibration including a more precise spectral response curve measured with a grating monochromator.
- p.123: In figure 3-13, the square boxes and circles are only markers to identify the curves. They are not data points.
- p.136: The caption of Fig 3-20 should read: "Change in I_{sc} as flash heats up, reflecting changes in the flash spectrum".
- p.138: The total amount of excess charge stored in the base is proportional to n_p . It can be seen that the electron concentration, and hence the stored excess charge, increases exponentially with the bias voltage. Transient errors are therefore more serious at higher bias voltages. n_p is proportional to n_{p0} , and n_{p0} is larger for lightly doped material. So the excess charge stored is larger for lightly doped material. The excess charge stored is also larger for longer diffusion lengths, or, in a cell with very long diffusion lengths, cell thickness. All of these factors suggest that transient errors should be worst in lightly doped, long lifetime, thick cells, and at high bias voltage. This agrees with experimental observations of the type of cells that exhibit transient errors.

Redistribution of excess charge is also caused by changes in illumination. For the open circuit case, the varying illumination will cause a varying voltage, and the situation will be similar to an externally applied bias voltage. If, however, the cell is maintained at a constant bias voltage, the change in illumination will cause relatively little change in the charge distribution. This is illustrated in figure 3-22 for a cell biased at its maximum power voltage. The cell has a diffusion length larger than the wafer thickness, so the minority carrier concentration in forward bias is roughly constant throughout the base. When the cell is in the dark, electrons are injected from the emitter and diffuse towards the rear. This causes a slightly higher concentration of electrons near the emitter, declining towards the back. When the cell is illuminated, electrons are generated in the

base and diffuse towards the emitter. This causes a slightly higher concentration of electrons in the bulk, declining towards the emitter. It can be seen that a change in illumination conditions while at constant voltage causes a relatively small change in the excess charge density – about $0.3 \times 10^{14} \text{ cm}^{-3}$, compared to the average level of about $2.6 \times 10^{14} \text{ cm}^{-3}$. In other words, changing illumination from 0 to 1 sun would only require $1/10^{\text{th}}$ as much charge movement as changing voltage from 0 V to V_{mp} . Less charge movement means less current required for the re-distribution, and hence smaller transient errors.

The case illustrated is somewhat optimistic. With higher recombination rates the carrier concentrations will vary more between the front and the back of the cell. Changes in illumination will therefore require substantial charge re-distribution. For such cells, maintaining constant bias voltage may not be as beneficial. Cells with high recombination, however, will have much lower average carrier concentrations and so less stored charge. Such cells will be much less sensitive to transient errors, so the point is moot.

The preceding discussion shows that solar cells should respond more rapidly to changes in illumination while at constant bias voltage than to changes in bias voltage while at constant illumination. In other words, transient errors will be smaller if bias voltage is held constant and light intensity is varied, rather than the conventional approach of holding light intensity constant and varying bias voltage.

- p.140: In Table 3-2, the labels ‘Excellent low resistivity’ and ‘excellent high resistivity’ are transposed.
- p.173: Bucher, K is spelled incorrectly. It should be Bücher, K.