NATURAL SUNLIGHT CALIBRATION OF SILICON SOLAR CELLS

W. Keogh & A. Blakers
Australian National University
Centre for Sustainable Energy Systems, Engineering Dept, Bldg 32, ANU, Canberra, 0200, Australia.
Tel: +61 2 6125 4914, Fax: +61 2 6125 0506, William.Keogh@anu.edu.au

The light source is very important when calibrating solar cells. Commonly used light sources – solar simulators – are expensive and frequently inaccurate. This work shows that testing solar cells under natural sunlight is simpler, cheaper, and more accurate than all but the most careful simulator measurements. Solar spectra generated with the model SMARTS2 show that the direct-beam solar spectrum, under clear sky and low air mass conditions, is an excellent match to the AM1.5G standard. Millions of simulations of a broad range of silicon cells (efficiencies 6-25%) under the modelled direct-beam spectra show that measurement uncertainty of less than 5% is achievable. 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. Finally, it is shown that the important atmospheric conditions can be measured without expensive equipment.
Keywords: Calibration - 1: Modelling - 2: Reference Cell - 3

1. INTRODUCTION

Of all the pieces of equipment required for measuring solar cells, the light source is both the most expensive and the greatest source of measurement error. Solar simulators, the most commonly used light sources, have serious limitations. The light they produce is an inadequate spectral match to the relevant standard spectra, is spatially non-uniform, and is temporally unstable. To cope with the poor spectrum of solar simulators, highly accurate measurement techniques use spectral mismatch correction. However, this is a complex and expensive procedure, requiring great care to maintain all calibrations. Few organizations other than standards laboratories can afford to use it.

Sunlight is a far superior light source. It has superb spatial uniformity, good stability (and in any case stability is not important since the excellent uniformity allows the reference and test cell to be measured simultaneously), and, under the right conditions, an excellent match to the AM1.5G and AM1.5D standard spectra. However, sunlight is rarely used for calibration of solar cells. The only application that receives much attention in the literature is the primary calibration of reference cells by standards laboratories. This, however, is presented as an obscure and difficult process requiring specialised equipment. It is shown in this work that natural sunlight calibration is far more widely applicable.

The spectrum of sunlight does vary as atmospheric conditions change. Hence, it is important to know how spectral mismatch varies for a typical range of atmospheric conditions and for any likely cell. This question was addressed in this work by simulating a group of 865 silicon solar cells (chosen to be representative of almost any cell likely to be made) under 1350 natural sunlight spectra (chosen to cover all typical atmospheric conditions). Over 1 million cell/spectrum combinations were considered. The worst-case spectral mismatch errors were then extracted, giving an estimate of measurement uncertainty as a function of atmospheric conditions.

Previous work on natural sunlight calibration [1, 2] has generally considered only a few, typically good, cells. This work, in contrast, considers all likely silicon solar cells. Since spectral mismatch error is usually larger for poor quality cells, previous works may have been optimistic in their estimates.

In addition to providing an estimate of measurement uncertainty as a function of atmospheric conditions, it is shown in this work that the important atmospheric conditions can be measured without using specialised, expensive equipment. This makes the technique widely applicable, unlike the primary calibration techniques that do require specialised equipment.

It is interesting to know the accuracy of the best available measurement techniques so that the method described in this work can be compared to them. The accuracy of these techniques can be estimated from numerous inter-laboratory comparisons performed by the standards laboratories. These comparisons have shown a repeatability of 2%, at best, for primary calibrations, and approximately 5% for routine measurements (such as might be available to a typical solar cell group).

Measurement under sunlight is less convenient than measurement indoors under a simulator. However, sunlight measurements are only required to create reference cells. The vast majority of cells can subsequently be measured, relative to the reference cell, under a cheap, convenient solar simulator.

Outdoor measurements can use either global or direct-beam sunlight. For measurements with respect to the AM1.5G standard spectrum, global radiation may seem the natural choice. However, consideration of all the error sources involved shows that measurement under direct beam radiation will be more accurate. Under clear-sky summer conditions, direct and global spectra are sufficiently similar that it is possible to use one to simulate the other. This work considers only the use of direct-beam sunlight.

A reference device is required to measure the intensity of the sunlight. Two possibilities are considered in this work: a pyrheliometer, and an excellent silicon cell.

This paper is a brief summary of work presented in the author's PhD thesis [3]. There is insufficient space here to present many important details. If you are interested in using the method, download the full thesis from the www.

2. SOLAR SPECTRUM MODELLING

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 was modelled using SMARTS2 [4].

The direct beam natural sunlight spectrum in SMARTS2 is a function of 12 atmospheric variables. As the first step in this work, a sensitivity analysis was conducted to determine which were the important variables. It was found that only three parameters have a major influence on spectral mismatch: air mass, turbidity, and precipitable water. In the detailed simulations, these parameters were varied in small increments over their typical range. Two parameters, NO_2 and altitude, have a moderate influence, so these parameters were assigned extreme values. The remaining parameters have minimal influence on spectral mismatch, so were set to a typical value.

Air mass, turbidity, and precipitable water need to be understood, and measured, in order to identify suitable testing conditions. They are discussed in more detail:

Air mass is a measure of the optical path length through the atmosphere. It can be calculated from the date, time, latitude, and longitude.

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 absorption in bands in the IR, making the sunlight spectrum bluer. In temperate locations, w is usually in the range 1-3 cm. In deserts or below freezing conditions, w may be as low as 0.5 cm. Highly accurate measurement of precipitable water requires radiosonde balloon soundings. However, it can be estimated with sufficient accuracy using only ground level relative humidity and air temperature [5].

Turbidity characterises the scattering and absorption of light by small particles in the atmosphere. Turbidity attenuates blue light, making the spectrum redder. 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 two numbers: β, which is a measure of the amount of turbidity, and α, which characterises the particle size. The value of α does not vary much, so it is possible to assume typical values. In addition, small particles are more spectrally selective, and consequently will cause more spectral mismatch. This allows a worst-case value of α to be identified. In this work, $\alpha = 1.4$ is assumed. The value of β varies considerably. In temperate latitudes, β is typically in the range 0-0.1. In highly polluted urban environments, it may be as high as 0.4. Highly accurate measurement of β requires specialised equipment, but it can be usefully estimated from air mass, direct beam irradiance, and precipitable water [6].

SMARTS2 was used to generate 1350 direct-beam natural sunlight spectra. AM, β, w, NO_2, and altitude were all varied. The range of atmospheric parameters used can be found in figure 1.

3. CELL MODELLING

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 diverse set of cells were simulated under each of the natural sunlight spectra. Cell simulation was performed using PC1D. The cell-set was chosen to have characteristics representative of any likely crystalline-silicon solar cell. The design parameters for the cell-set are given in table I. These parameters determine the important generation and recombination processes within a solar cell. Other parameters are of secondary importance. The values chosen for each of the parameters bracket the likely values to be found in any silicon solar cell. Thus, conclusions drawn for the cells modelled are likely to hold for almost any silicon solar cell. All possible combinations of these values were simulated, giving 865 cells. The cells range in performance from very poor to excellent (V_{oc}: 530-700 mV, J_{sc}: 15-43 mA/cm^2, eff: 6-25%). Doping levels were not varied as they have minimal effect on I_{sc} (except for lifetime reduction at very high doping, but this effect is accounted for by the variation in lifetime and surface recombination).

Table I: Parameter values for the cells in the cell set.

Cell Parameter	Values
Bulk lifetime (n & p)	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
Front & Rear internal reflectivity	50%, 100%
Texturing	Textured, not textured
Encapsulation	None, under glass
Front surface coating	None, SLAR, DLAR
Cell base resistivity	1 ohm-cm
Diffusions ($n^+/p/p^+$)	0.8 μm deep, 100Ω/sq

4. SPECTRAL MISMATCH CALCULATION

Having simulated the short-circuit current for the 865 cells under each of the 1350 spectra, the spectral mismatch, M (the ratio of I_{sc} under the non-ideal light source to the 'true' I_{sc} under the relevant standard spectrum) was then calculated for the 1.2 million combinations. From M, the spectral mismatch errors, $\varepsilon_M = |1\text{-}M|$ were then calculated. For each spectrum, the worst-case (largest) spectral mismatch error was then chosen and plotted (figure 1) as a function of the 3 most important atmospheric variables: AM, β, and w. NO_2 and altitude varied in the background – the worst-case ε_M values from all NO_2 and altitude possibilities were selected.

Two possible reference detectors were simulated: a pyrheliometer (thermal detector), and a high quality cell in the cell set. Due to space limitations, the results are only shown for measurement with a pyrheliometer as the reference detector, and with respect to AM1.5G.

The spectra for three solar simulators were also included in the simulations. The simulators considered were: ELH lamp (a projector lamp, commonly used as a solar simulator), Oriel 1 kW xenon arc-lamp solar simulator (a typical 'quality' solar simulator, cost: ~US$20,000), Spectrolab X-25 (top-quality solar simulator, cost: ~US$200,000).

5. DISCUSSION

Best measurement conditions

Examination of figure 1 shows that the atmospheric conditions that will give most accurate measurements are:

- AM: the lower the better, optimally < 1.2
- β: the lower the better, optimally < 0.05
- w: optimally 1-3 atm-cm, <1 atm-cm is bad.

The conditions described above are fairly typical for temperate locations in summer, according to climate data such as NREL TMY2. Accurate measurements should therefore be possible in many locations. In more detail:

- AM: anywhere within 50° of the equator can achieve AM < 1.2 in summer.
- β: achieving low enough β may be problematic in some urbanised areas. However, even in San Francisco, California (not an area renowned for pristine air), in summer $\beta \approx 0.1$

Under good measurement conditions, ε_M < 3% is achievable. Even with all other measurement uncertainties included, total measurement uncertainty should be less than 5%. This is comparable to the accuracy of calibration at a standards laboratory.

Winter measurements are likely to be less accurate as air mass will be high and precipitable water will be low.

Slightly hazy or cloudy days might be the only conditions available. For this reason, it is important to consider the effect of cloud on spectral mismatch. Fortunately, cloud is, to a rough approximation, a neutral density filter. Consequently, light cloud should have little effect on spectral mismatch. This prediction was confirmed experimentally – a clearly visible cirrus cloud passing over the sun had a barely noticeable influence on relative cell measurements.

Choice of reference detector

The full set of results (not shown in this paper) allows the comparison of a pyrheliometer and a silicon cell as the reference detector. Under most conditions, spectral mismatch error is lower for the silicon reference. However, the uncertainty in the calibration of the silicon reference is substantially higher (~5% for a cell calibrated at a standards lab, versus ~2% for a first-class pyrheliometer). Consequently, total measurement uncertainty will be lower with a pyrheliometer under almost all conditions. A pyrheliometer is therefore recommended as the reference device.

Comparison to solar simulators

The simulations allow the comparison of natural sunlight to solar simulators. Comparison was only possible for the case of a silicon reference detector, as the published simulator spectra did not extend beyond 1.1 µm. The result for both the ELH and Oriel simulators was a worst-case ε_M of ~16%. Hence, natural sunlight measurement should be more accurate under almost any conditions, at any time of year. The result for the X-25 simulator was a worst-case ε_M of ~3%. Under good conditions, natural sunlight measurement should equal this.

Interestingly, this comparison shows that the expensive Oriel simulator is not any better than the low cost ELH lamp. Further, considering only the 'good' cells within the cell set (V_{oc} > 620 mV and J_{sc} > 35 mA/cm^2), shows that

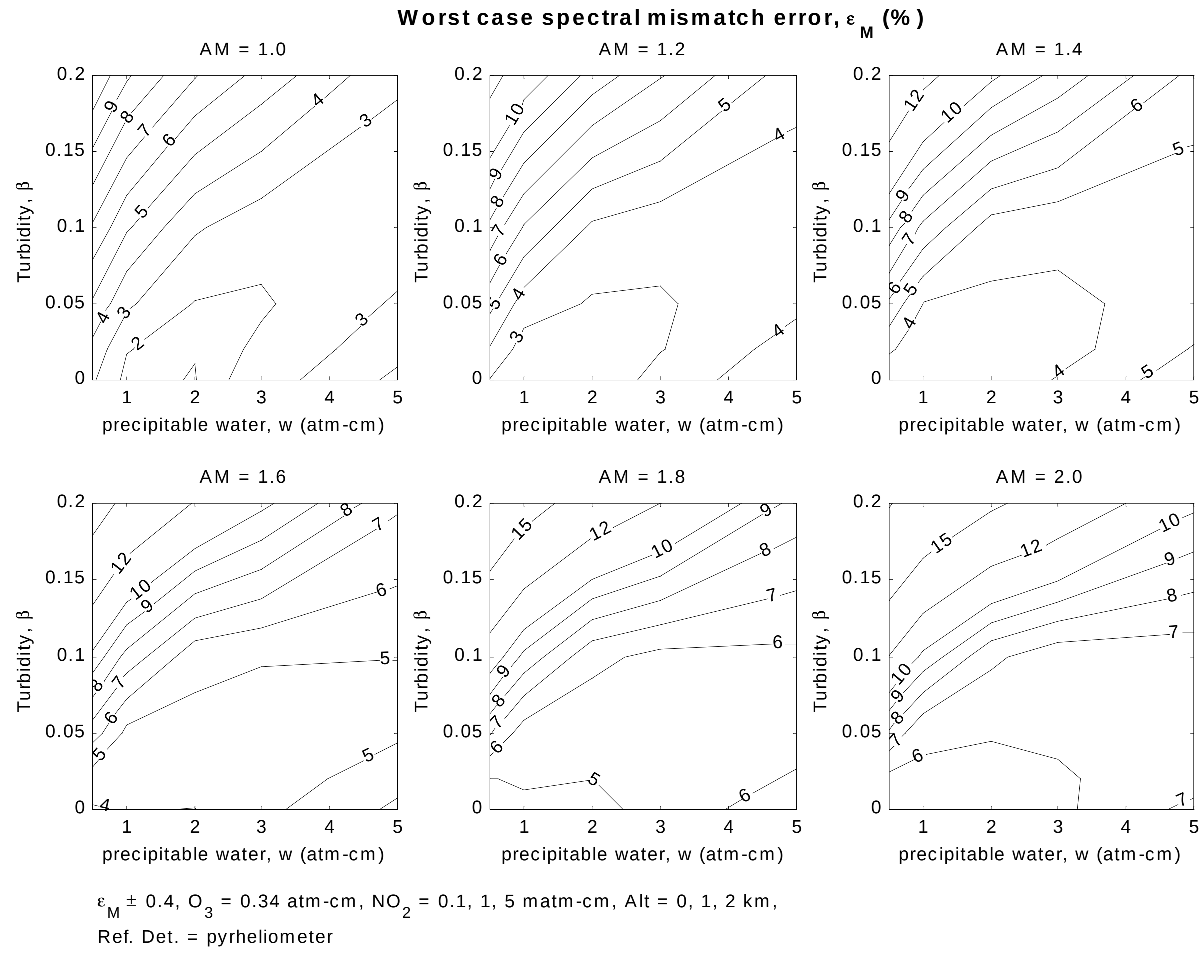

Figure 1: Worst-case spectral mismatch error, ε_M (%), for any cell. Ref. detector: Pyrheliometer, Std. spectrum: AM1.5G

the spectrum of the Oriel simulator is in fact significantly worse than that of the ELH lamp.

Practical considerations

The equipment required for natural sunlight measurement is simple and inexpensive. Measurement of air mass, turbidity, and water requires only a clock, a hygrometer, a thermometer, and a pyrheliometer. The pyrheliometer is the only expensive item, costing ~US$1500. One piece of specialised equipment is required – a collimating tube to ensure that the cell is illuminated by direct-beam sunlight only. This can be constructed in-house; details are given in [3]. A sun-tracking platform is not essential as measurements only take a few minutes and the sun moves slowly enough to allow manual tracking.

Only I_{sc} need be measured outdoors. Indeed, it is probably more accurate to measure V_{oc} and FF under a solar simulator as it is difficult to correct them for irradiances other than 1-sun. Measuring only I_{sc} outdoors simplifies the testing set-up, as neither contacting arrangements nor temperature control are critical for I_{sc}.

Benefits of outdoors testing

Measurement of cells under natural sunlight has a number of advantages over both affordable simulator measurement and calibration at a standards laboratory. These include:

- Low cost – the only expensive instrument required is a pyrheliometer, costing about US$1500. For comparison, external calibration of a cell costs around US$1000.
- Quick and local – no 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 precise calibration.
- Spectral mismatch error is lower than for any affordable simulator measurement (without spectral mismatch correction).
- Superb light uniformity over any area.
- Stability over time un-important.
- Minimal reflections / stray light. Due to the excellent collimation of direct-beam sunlight, multiple reflections and stray light can be virtually eliminated.

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. The mismatch-error estimates calculated in this work, however, cannot be directly applied to cells made on other materials since some assumptions are specific to crystalline silicon technologies.

6. EXPERIMENTAL VERIFICATION

To test the validity of the modelling, a diverse group of cells was measured outdoors under a range of atmospheric conditions. Ideally, these cells would previously have been calibrated by some other means. However, this would have been too expensive. So, instead, the experiment compared the relative changes in measured currents to the relative changes in simulated currents under the same atmospheric conditions. If the modelling was correct, the measured changes should have been smaller than the simulated changes.

The 9 cells in the cell-group were chosen to be representative of a wide range of silicon technologies. The cell-group included high-performance cells, commercial screen-printed cells, lab prototypes, and some specially made worst-case-test cells. The cells were mounted on a temperature-controlled block, which was placed behind a collimating tube. The cells were measured in coastal, inland urban, and high-altitude locations. The range of atmospheric conditions during measurements was: AM: 1.4-2, w: 0.5-2 cm, β: 0.02-0.07. Light intensity was measured with a pyrheliometer and with a silicon reference cell.

Some data processing was necessary in order to compare the measured and simulated results. First, the simulated results were interpolated to the exact measured atmospheric conditions. To accommodate possible error in estimation of β and w, simulated short circuit currents were also extracted for extreme values of β and w ($\beta \pm 0.04$, w±20%). The currents for all cells were then normalised to a mean value of 1 to allow comparison of relative changes.

The results of the experiments are encouraging. For measurements with respect to the silicon reference, the measured currents varied by less than ±2% over the full range of atmospheric conditions. This was within the simulated range, even assuming perfect knowledge of β & w. The results for measurements with respect to the pyrheliometer were not quite so convincing. The measured range of I_{sc}'s was ±4%. When worst case errors in β and w estimation were included, this was just within the simulated range. However, when perfect knowledge of β and w was assumed, the measured range was significantly larger than the simulated range. In addition, there was an obvious offset for all measurements on the last day. A problem with the data acquisition system is suspected.

In summary, the results of experimental verification are encouraging, although not yet convincing proof of the method.

7. CONCLUSION

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.

REFERENCES

[1] NASA TM 73703, Terrestrial Photovoltaic Measurement Procedures, TM 73702. NASA. (1977).

[2] R.L. Mueller. in Nineteenth IEEE Photovoltaic Specialists Conference. (1987). p. 166-70.

[3] W. Keogh, PhD. (2001), Australian National University, Canberra, Australia, http://solar.anu.edu.au/publications2001.html.

[4] C. Gueymard, SMARTS2, a Simple Model of the Atmospheric Radiative Transfer of Sunshine, FSEC-PF-270-95. Florida Solar Energy Centre. (1995). ftp://alpha.fsec.ucf.edu/public/smarts2/ or http://homepage.mac.com/cgueymard.

[5] C. Gueymard, Solar Energy, **53** (1994): p. 57-71.

[6] C.A. Gueymard, J. App. Met., **37** (1998): p. 414-435.