Spectral Changes of Solar Simulator Xenon Flash Bulbs over Lifetime and its Effects on Measurement Uncertainty

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Abstract

The effects of lamp age on the spectral output of solar simulator xenon flash lamps and spectral output measurement uncertainty on the spectral mismatch are investigated. It is demonstrated that the spectrum of an older lamp set has a relatively lower blue and larger red content compared to a new set of bulbs. Measurements over the life-time of several sets of bulbs showed large unexpected variations due measurement uncertainty in spectral measurements themselves. The main influencing factors are investigated and a faulty temperature control is found to be the main source of uncertainty. It is shown that this alone can affect the mismatch calculation to a larger degree than the MMF would correct in itself.

1 Introduction

The measurements of a solar simulator ultimately determine the value of a product tested. Low uncertainties are therefore vital for the measurement to be meaningful. The spectral match of a solar simulator is one the most important quality aspects, as it determines how well the spectral output matches to the standard air mass 1.5 global (AM1.5G) sunlight spectrum [1]. Even though most simulators meet the class A spectral match qualification [2] with ease, a spectral mismatch correction (MMF) [3] and a closely matched reference cell are still necessary to correct for differences between the reference and lamp spectra. Not considering the MMF may result in measurement uncertainties beyond 5% for badly matched reference cells [9]. To accurately consider the MMF one requires measurements of the solar simulator lamp output spectrum as well as the quantum efficiency of the device under test. However, the lamp spectrum of xenon flash lamps used typically in these systems dependents on its voltage, intensity and especially on its age [4, 5]. This means that an uncertainty is added if spectral measurements are not conducted frequently or not at the same conditions as during the actual calibration measurement. However, measurement uncertainties in the spectral irradiance measurement itself need to be considered and reduced as much as possible in order not to invalidate the spectral mismatch correction [4, 6, 7].

To gain a better understanding of the factors affecting the MMF measurements of the output spectra of xenon flash lamps are carried out over their lifetime and measurement uncertainty sources of the spectroradiometer are analysed and discussed.

2 Experimental

Spectral output measurements over lamp age and lifetime are carried out on CREST's Pasan 3B solar simulator. This is a class AAA [4] flat hat long pulse simulator with a 10ms flash duration. Each set of bulbs consists of 4 xenon lamps of the same type.

For spectral output measurements two Astra-Net charge-coupled device (CCD) spectroradiometers are used, one with a Si detector (VIS) and one with an InGaAs (NIR) detector. Both detectors are cooled by peltier elements and the total measurement range is 300nm to 1650nm. The spectroradiometers are calibrated in-house using a Newport calibrated quartz tungsten halogen standard lamp. The spectroradiometers share one diffuser detector as input using a dual fibre-optic cable.

Measurements of the pulses from the solar simulator are made with a 3ms integration time. The spectroradiometers do not have hardware triggering option, this means that measurements between the spectroradiometers are not fully synchronised and are not made at a specific or constant point during the pulse duration. Measurements over 10 pulses are averaged to reduce noise in the measurement and, at the same time, reduce influences from unsynchronised measurements.

3 Results and mismatch variations

3.1 First measured set of bulbs

The first set of bulbs was only measured at begin and end of life after ~11k pulses. As illustrated in Figure 1, measurements at end of life conditions revealed relatively smaller blue and larger red content compared to a new set of bulbs. This red shift has also been shown in previous works [4, 5, 8]. Both spectra are within Class A as shown in Table 1.

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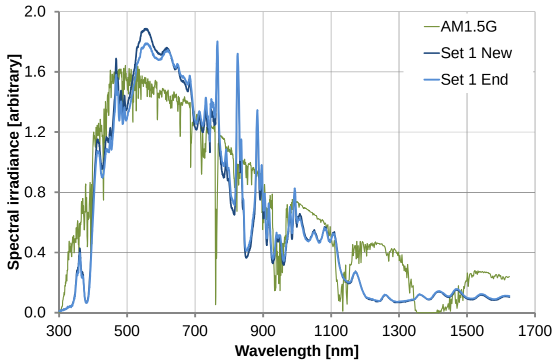

Figure 1: Spectral irradiance of the first set of solar simulator xenon bulbs measured new and at end of life; a significant red-shift is observed

Bin [nm] Ratio/Dev [%]	400-500	500-600	600-700	700-800	800-900	900-1100
Set 1 - New	0.88	1.15	1.14	1.06	0.83	0.87
Set 2 - End	0.83	1.09	1.15	1.11	0.89	0.89
Deviation	-6.07	-4.67	0.95	5.07	7.62	1.87

Table 1: Spectral match classification and deviation between end of life and new bulbs; both spectra meet Class A requirements

The changes in spectral output have an impact on the MMF even when measuring with an appropriately filtered c-Si reference as shown in Table 2. Using a reference cell without a filter for a-Si devices would increase the error in MMF to -4% in the presented case, which highlights the importance of using an appropriate reference. The large change in MMF in case of CdTe is due to the filtered reference not being matched well enough.

Filter	none	none	none	KG1	KG5
MMF/Dev [%]	C-Si m	c-Si Cell	CIS	CdTe	a-Si
Set 1 - New	1.02	1.01	1.04	1.04	1.02
Set 1 - End	1.02	1.01	1.05	1.07	1.02
Deviation	0.19	0.16	0.52	2.72	0.22

Table 2: Calculated spectral mismatch factor variations of various device types due to bulb age using a c-Si reference cell with appropriate filter

3.2 Following measured sets of bulbs

With the expectations of repeating the findings when measuring the first set of bulbs, measurements not only at begin and end of live but also in-between where taken to get more information on how fast spectral changes take place. However, when analysing the measurement data of the 2nd and 3rd bulb set (Figure 2) large measurement variations and inconsistencies in the measurement data became apparent.

By examining the classification data in Table 3 one can observe that the earlier seen trend from blue to red rich output spectra is not clearly evident. Furthermore, two measurements of set 3 show a very large difference with a significantly higher irradiance in 1st and 5th wavelength bins and a stronger signal in the 2-4th bins.

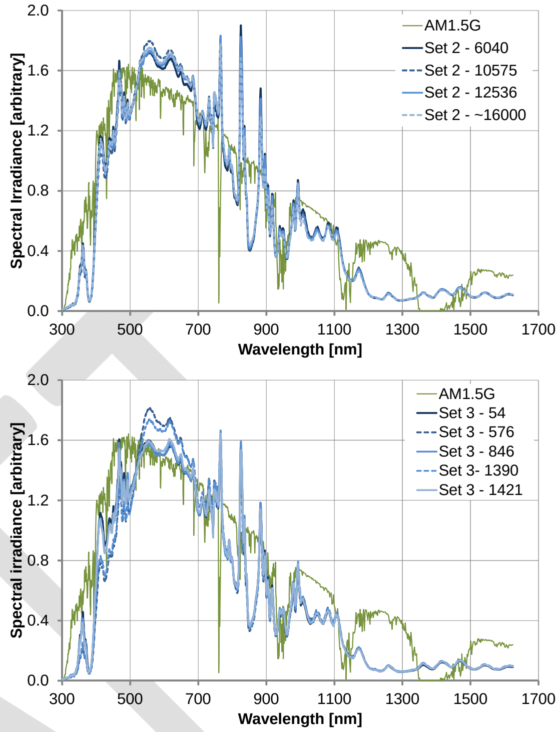

Figure 2: Measurement results of the 2nd (top) and 3rd (bottom) bulb set; the spectroradiometers were not available for the first measurements of set 2; bulb set 3 was at time of writing in use and had not yet reached end of life

Bin [nm] Ratio/Dev [%]	400-500	500-600	600-700	700-800	800-900	900-1100
Set 2 - 6040	0.87	1.07	1.11	1.08	0.92	0.93
Set 2 - 10575	-6.26	2.98	3.35	2.58	-3.41	-2.30
Set 2 - 12536	-3.21	0.16	2.05	2.13	0.09	-1.99
Set 2 - ~16K	-1.86	1.46	2.63	2.90	-2.62	-4.85
Set 3 - 54	0.91	1.10	1.13	1.07	0.88	0.84
Set 3 - 576	-20.15	8.06	8.79	4.74	-9.04	0.24
Set 3 - 846	-2.21	-0.77	0.47	0.72	-0.05	2.48
Set 3 - 1390	-17.62	4.66	8.10	4.71	-6.28	1.45
Set 3 - 1421	-3.78	-0.42	2.05	1.63	-1.17	1.26

Table 3: Spectral match classification of the 2nd and 3rd measured bulb set with the 1st measurement of each set showing actual ratio and the following ones giving the deviation to it; all measured spectra match class A except from the outliers in set 3 at 576 and 1421 pulses.

From the calculated MMFs in Table 4 it is not possible to observe a clear trend. Furthermore, the two outlying measurements in set 3 show variations of up to 3% in MMF. Since the last two measurements of bulb set 3 have been taken two hours apart from each other without altering the measurement set-up, a large

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measurement uncertainty that clearly overshadows spectral variations of the bulbs is estimated. The following section is looking into the possible causes of the variations in the measurements.

Ref cell filter	none	none	none	KG1	KG5
MMF/Dev [%]	C-Si m	c-Si c	CIS	CdTe	a-Si
Set 2 - 6040	1.02	1.01	1.04	1.06	1.02
Set 2 - 10575	0.36	0.16	0.85	1.03	0.20
Set 2 - 12536	0.21	0.09	0.55	0.92	0.13
Set 2 - ~16K	0.24	0.06	0.68	0.54	0.08
Set 3 - 54	1.02	1.01	1.04	1.04	1.01
Set 3 - 576	0.89	0.52	1.98	2.97	0.55
Set 3 - 846	0.00	0.05	-0.01	0.51	0.06
Set 3 - 1390	0.74	0.46	1.66	3.04	0.52
Set 3 - 1421	0.11	0.10	0.28	0.90	0.12

Table 4: Calculated MMF variations with the 1st measurement of each set showing actual MMF and the following ones giving the deviation to it; for the MMF calculation of CdTe and a-Si filtered reference cell data was used

4 Analysis of uncertainty sources

4.1 Angular response of detector

As reported in [4, 6] care must be taken with the choice of detector input as not all show an optical cosine response similar to flat panel PV modules. To verify that the diffuser input used during this during this work is suitable for the measurements, the angular response has been measured using a standard lamp. The detector was mounted on a turntable with the diffuser surface in the turn point.

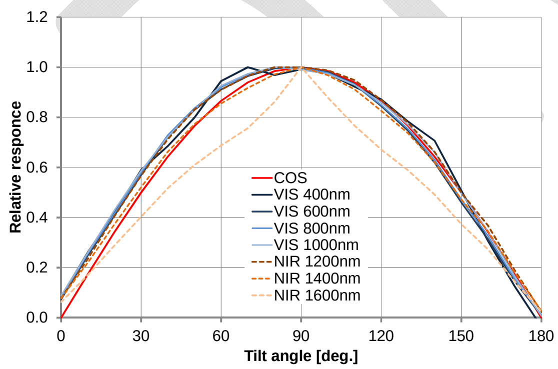

Figure 3: Measured angular response of the diffuser detector

Results show (Figure 3) that the response is slightly asymmetric and better on the side of the fibre input; the response worsens in the infrared at wavelengths above 1400nm. Nevertheless, even though the detector does not show a perfect cosine optical response, the measurement errors from this should be minimal, since the solar simulator uses baffles eliminate reflections from the walls and thus the input angle of the light is limited to the size of the flash simulator lamp. Additionally, the detector was always mounted on the target plane in the same position pointing towards the simulator lamp during bulb measurements, which should have minimised any variations between measurements.

The worsening response above 1400nm is of no significant interest in this work and would only be important when measuring for example triple junction InGaAs devices.

4.2 Detector linearity

One significant source of error in some CCD-spectroradiometers is the nonlinear response to light. This is due to the charge curve of the CCD. The spectroradiometers used in this work did not incorporate linearity correction. However, the linearity curve can be measured using a standard lamp. With the assumption that the integration time control is accurate, one should always get the same measurement result in irradiance (W/m2) per time interval (ms) when measuring at varying integration times if the charge curve of the CCD is linear. Since this was not the case for the spectroradiometers used during this work, a linearity curve was fitted from measurements at varying integration times. Figure 4 shows the linearity curves of the visible and near infrared spectroradiometers.

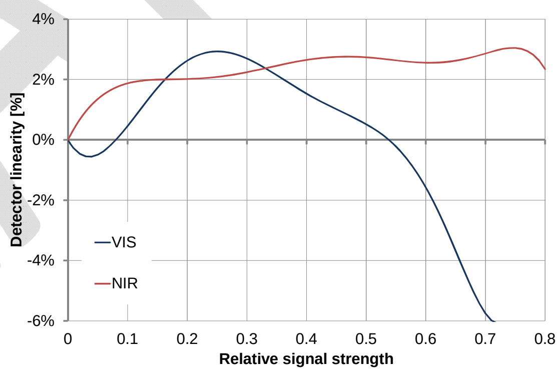

Figure 4: Linearity curve over relative measurement signal strength (charge state of CCD)

The result is a reduction of the error due to non-linearity in the VIS spectroradiometer from ±7.5% down to ±2.5% (NIR from ±3.5% to ±2%). The remaining uncertainty from the linearity correction lies mainly in the fitting residue and on external influences as such as standard lamp fluctuations and temperature influences during the measurement.

With the linearity correction the actual uncertainty due to CCD non-linearity should be minimal as the intensity from the solar simulator was kept as much as possible constant between the tests (~5% on c-Si reference).

4.3 Temperature influences

As mentioned previously, both spectroradiometers have CCD peltier element cooling.

However, when measuring the spectral output of the solar simulator at varying room temperatures (Figure 5) a large temperature influence on the measurement was observed.

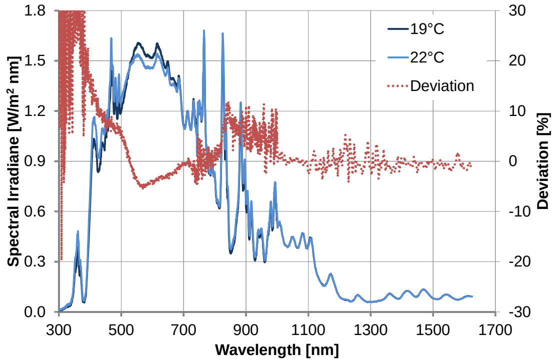

Figure 5: Measurement of the solar simulator output at 19°C and 22°C room temperatures; note that variations are minor on the NIR detector, pointing to an effective temperature control.

Even though the temperature difference was only 3°C, a deviation of -5% at 575nm and over +10% at below 400nm is observed on the VIS spectroradiometer. Since the temperature influence on the solar simulator lamps can be assumed negligible, the observed deviations can be explained by a very ineffective temperature regulation of the VIS detector.

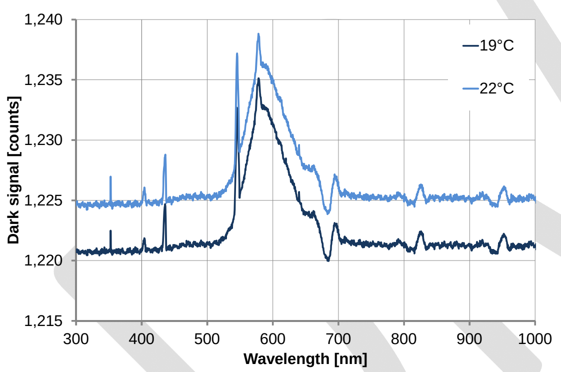

Figure 6: measured dark signal a different temperatures of the detector; the peak at 600nm is the dim florescent light in the room

Detector temperature affects the measured dark response of a CCD spectroradiometer. This was also measured in this case (Figure 6). Furthermore, analysing the dark measurements of the bulb set 3, a separation of ~10 counts in the dark response (twice that in Figure 6) was found between the outlier measurements and the "normal" measurements. However, important to note is that the measured room temperature did not differ by more than 0.3°C. The most feasible explanation is an instable or saturating temperature control i.e. the temperature regulation set point is held over a certain time period and then lost due to insufficient cooling of the Peltier element's "hot side". This results unexpected measurement variations that without further investigations can completely invalidate a PV device calibration due to falsely estimated MMF and spectroradiometer calibration.

5 Conclusions and future work

First measurements of the spectral output of xenon bulbs at begin and end of life have shown a good agreement to reported spectral changes in solar simulator flash lamps.

Further measurements of multiple sets of bulbs have shown a large variability that made a reproducing of the initial results difficult.

This work analysed the main uncertainty sources that could cause such variations and identified a faulty temperature control on the CCD spectroradiometer used for the visible range as the largest source of uncertainty.

Results underline the importance of identifying and quantifying uncertainties in the complete measurement chain.

The next stage of this project will concentrate on improving/repairing the spectroradiometer temperature control. Furthermore, work will look into using the dark signal as an identifier for possible temperature correction. Last but not least, investigations in spectral irradiance changes of xenon bulbs will continue with continued investments into determining and reducing uncertainty sources.

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