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Correlation between Collimated Flash Test and In-sun Measurements of High Concentration photovoltaic Modules

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ABSTRACT

Due to their limited angular acceptance, and use of spectrally sensitive multi-junction solar cells, high concentration photovoltaic modules represent a challenging measurement task. In collaboration with Instituto de Energia Solar at the Universidad Politecnica de Madrid, SolFocus has designed and manufactured an industrialized solar simulator for characterization of high concentration photovoltaic modules. The simulator measures module peak conversion efficiency and acceptance angle. The simulator uses a Xenon flash source with collimating optics to form a uniform one-sun illumination covering sufficient area to measure two panels of 1 m^2 each, along with reference measurement cells for spectral and power normalization. The on-sun measurement uses a normal incidence pyrheliometer and temperature sensors to provide normalization information.

This paper presents an algorithm for normalization of tests performed under factory conditions to IEC 62108 standard operating conditions (850 W/m^2 direct-normal-irradiance, 20 C ambient temperature). After normalization, tested panels are correlated to actual on-sun performance measurements. We present descriptions of the normalizations applied to both the factory test method and on-sun test method, and compare the results for a population of over 100 modules. As a result of normalization and correlation methods, we conclude that the simulator predicts on-sun performance to better than ±10%, with 99% confidence. The primary source of uncertainty is the normalization of the on-sun data. The repeatability of the flash test is better than ±2%.

Keywords: High concentrator solar photovoltaic module, HCPV, concentrated solar module, concentrator solar photovoltaic, concentrator photovoltaic, CPV, solar flash test, solar simulator.

1. INTRODUCTION

In late 2007, SolFocus Inc, a manufacturer of high concentration photovoltaic (HCPV) modules, commissioned a production line for its first generation HCPV module, the SF1000, in Noida, India. (Figure 1) The SF1000 HCPV module incorporates 16 concentrating systems, each comprised of two reflectors and a non-imaging optical element and a 100 mm^2 multi-junction solar cell (Figure 2), which are referred to as power units. Operating at approximately 500x concentration, the SF1000 module is rated at 205 W at a direct normal irradiation of 850 W/m^2 at ambient temperature of 20 C.

Testing of HCPV modules imposes additional requirements for the collimation and spectral qualities of the test light source. The limited angular acceptance of HCPV modules (approximately ±1 degree) requires that the light be highly collimated with an angular subtense at or near that of the sun. Additionally, because concentrators generally use very high-efficiency III-V multi-junction solar cells[1] whose performance is limited by the lowest performing junction, the test source spectrum must simulate the desired solar spectrum. SolFocus test system was developed under a collaborative effort with the Instituto de Energía Solar, Universidad Politécnica de Madrid (IES-UPM)[2].

Figure 1. SolFocus SF1000 HCPV modules in installed array format.

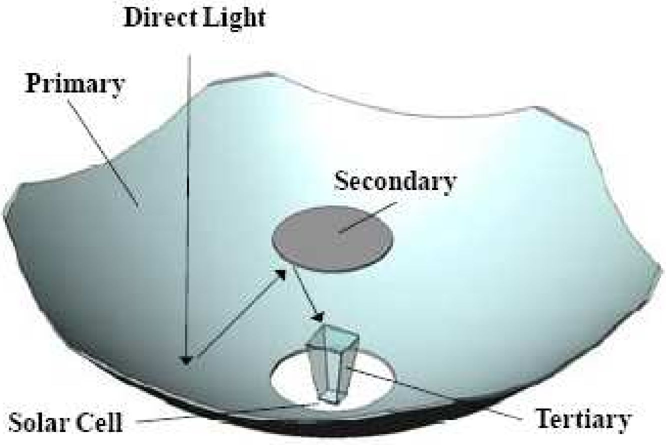

Figure 2. Optical diagram and sample ray-trace of SF1000 power unit.

2. SYSTEM DESCRIPTION

2.1 System Overview

This layout of the simulator (Figure 3) builds off a concept introduced by Dominguez et al. at IES-UPM[3],[4]. A low-cost commercial xenon flash strobe is used as a light source. Only that temporal portion of the flash with appropriate spectral match to desired test conditions is used for module power measurements. This light source is coupled with an array of spherical reflectors to create a beam of collimated light approximately 2.7 m by 2.1 m in size. After focal adjustment, the divergence angle of this beam has been experimentally measured to be approximately 0.7º (full angle, to half-power), which is comparable to the 0.53º angle subtended by the sun. The simulator light intensity is adjustable in the range of 500 to 700 W/m^2. Two HCPV modules are mounted to either side of the light source on a dual axis motion frame, which is also surrounded by reference solar cells for signal normalization.

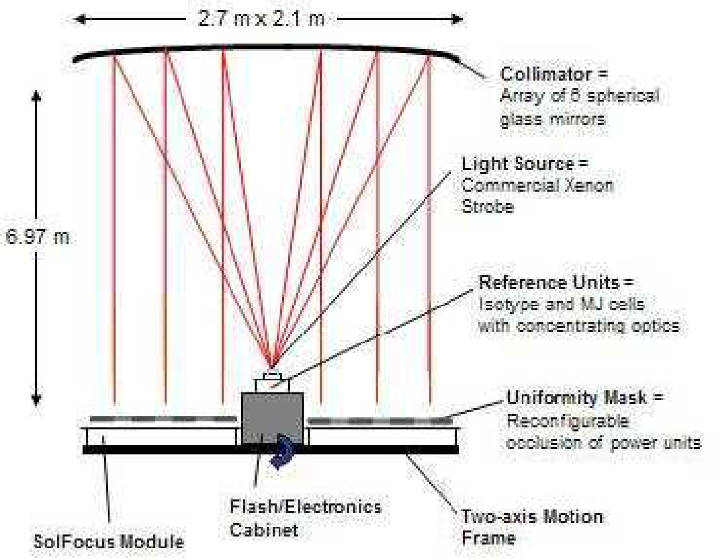

Figure 3. Layout of the SolFocus solar simulator.

2.2 Reference Measurements

Four reference power units employing identical optics to the module are mounted above and below the light source, adjacent to the modules (Figure 4). The solar cells in the four reference power units are each sensitive to a differing spectral band. One reference power unit contains a standard multi-junction solar cell, with the same broad-band sensitivity as that used in the HCPV module. The reference solar cell generates a normalizing monitor photocurrent ($I_{monitor}$) throughout the duration of the flash pulse (used to account for both flash-to-flash and within-flash optical power variation). The remaining reference power units contain iso-type solar cells, of similar materials and fabrication as the standard multi-junction solar cell, but each containing only a single active junction, closely matched to the spectral response of each of the junctions of the cell. The spectral characteristics of the flash pulse are monitored via the ratios of the photocurrents from each iso-type reference power unit.

The use of standardized concentrating optics in the reference power units ensures that spectral and power monitoring measurements are performed at the same spectrum and power level as the device under test. As a calibration step, the four monitor cells are exposed to sun at 850 W/m^2, and the reference current level for each cell is recorded. The reference solar cell value for the full-spectrum cell, $I_{monitor,850}$, will be used to normalize all measured test results. The iso-type solar cell values, I_1, I_2, I_3 for blue-visible, near-infrared and infrared bands respectively are stored as ratios to which the flash source is compared. At system setup, the source is adjusted to match the critical ratio I_1/I_2 to that obtained during on-sun test. The ratio I_1/I_3 is less critical, as long as $I_1/I_3 < 0.8$, indicating that the spectrum is oversaturated with infrared, and therefore the limiting junction during the test is either the visible or near-infrared. Which junction sets the limit depends on the I_1/I_2 ratio. As an operational procedure, I_1, I_2 and I_3 are monitored during each test, and if they fail to be within the expected range of the set target, the test result is invalidated, and the test system requires calibration.

The current and voltage of the module during the selected portion of the flash are measured with a high-speed oscilloscope and filtered. After normalization (described subsequently in Equation 4), a typical module IV curve is shown in Figure 5.

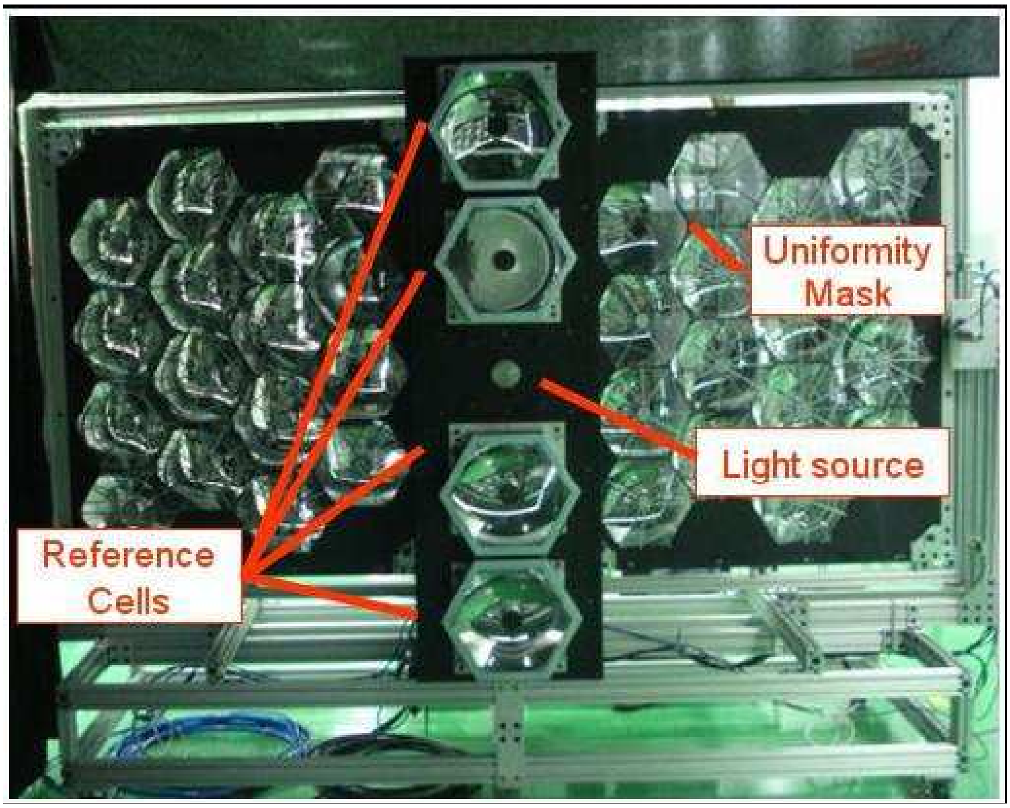

Figure 4. Photographic image of the SolFocus solar simulator as configured for a test.

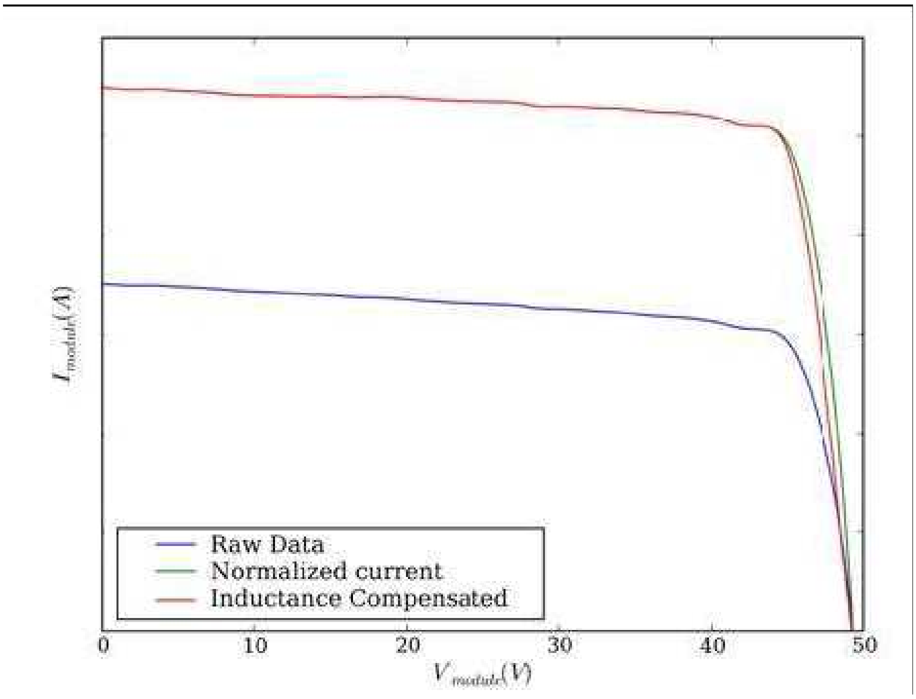

Figure 5. Signal normalization and compensation within the solar simulator detection electronics.

2.3 Spatial Uniformity Control

To accurately reproduce on-sun performance, each power unit within the solar module under test should receive the same optical power. Therefore, it is important to ensure that the collimated flash is spatially uniform across the module to be tested. Internally to the SF1000 module, the 16 power units are connected in series, so if one cell receives less light than another, it will generate less photocurrent (or it will generate the same photocurrent at a lower voltage), and it will limit the performance of the module. Under non-uniform illumination test conditions, the peak power of the module being tested will not be a good predictor of performance under the highly uniform light of the sun. Because all of the light falling on the primary optic of any one power unit will be concentrated onto a single cell, it is not necessary to ensure uniformity across the primary optic. It is only necessary to enforce the uniformity of the irradiation level when summed across each mirror.

To establish spatial uniformity, the SolFocus solar simulator is set up with occlusions over each power unit of the solar module under test. The amount of occlusion at each power unit is determined by measuring the integrated flux across the power unit, and then adding occlusions such that the integrated flux will be the same for all power units. A metallic frame is placed in between the mounting plane of the solar modules under test and the collimating reflector, close to the modules. Occlusions are mounted to the metallic frame. Upon confirmation after mounting of occlusions, the difference in irradiation over the area of each power unit is less than 1%.

3. TEST NORMALIZATION

3.1 Concentrator Standard Test Conditions

Concentrator Standard Test Conditions (CSTC) are defined per IEC 62108[5] to include direct normal irradiance level (DNI), spectrum, ambient temperature and wind. At CSTC, DNI is 850 W/m^2, ambient temperature is 20 C, wind speed is 4 m/s, and the spectrum matches to AM 1.5D (air mass 1.5 atmosphere equivalent, direct spectrum only)[6]. The nominal acceptance angle of the SF1000 module is ±1 degree from normal, which further defines the characteristic spectrum to include a small annulus of sky surrounding the solar disc. For purposes of this analysis, wind cooling is considered to be a small effect, which has not been modeled due to uncertainty in thermal transfer from module and ambiguity in the standard regarding wind direction relative to irradiance.

3.2 Normalization of on-sun tests

The relationship between solar cell operating temperature at 850 W/m^2 DNI and directly measured backpan temperature beneath the solar cell was developed experimentally. The underlying assumptions are a solid thermal contact between thermocouple temperature sensor and backpan, and consistent thermal transfer from solar cell to backpan from module to module.

$$T_{\text{cell}} = T_{\text{backpan}} + \gamma \cdot DNI \tag{1}$$

In Equation 1, temperatures are expressed in C and DNI in W/m2. T_{backpan} is the measured temperature at the hottest point on the module. γ is the experimentally derived factor relating the cell temperature at time of test to the observed irradiance. For SF1000 modules, γ is measured to be 0.017 C / W/m^2. Note that γ applies in this case only when tested under no load condition, which increases cell temperature due to lack of a dissipating load. Accordingly, Equation 1 is not accurate for cell temperature predictions under normal operating conditions, but is important for as-tested conditions on sun.

$$P_{\text{sun,CSTC}} = P_{\text{sun,raw}} \cdot \frac{850}{DNI}\left[1 - \alpha\left(T_{\text{cell,CSTC}} - T_{\text{cell,test}}\right)\right] \tag{2}$$

In Equation 2, $T_{\text{cell,CSTC}}$ is the cell temperature at CSTC ($T_{\text{cell,CSTC}}$ = 64 C), α is the experimentally derived temperature derating factor of the module due to solar cell heating, 0.0021 C^{-1}. Normalization of measurements to 850 W/m^2 DNI are performed by direct scaling of the measured power on sun ($P_{\text{sun,raw}}$) by DNI as observed on a Normal Incidence Pyrheliometer (NIP)[7]. The particular NIP in use subtends an angle exceeding 5 degrees, in excess of the acceptance angle of the module's concentrating optics. $T_{\text{cell,CSTC}}$ is developed for the expected operating condition with the module powering a DC-AC inverter and operating at the maximum power transfer point. No normalization is performed for spectral variance of the on-sun test.

3.3 Normalization of flash test

Module power as measured by flash testing is normalized to CSTC according to Equations 3 and 4.

$$P_{\text{flash,CSTC}} = P_{\text{flash,850}} \cdot \left[1 - \alpha\left(T_{\text{cell,CSTC}} - T_{\text{cell,test}}\right)\right] \tag{3}$$

$$P_{\text{flash,850}} = \max\left(V_{\text{module,i}} \cdot I_{\text{module,i}} \cdot \frac{I_{\text{monitor,850}}}{I_{\text{monitor,i}}}\right) \tag{4}$$

In Equations 3 and 4, $T_{\text{cell,test}}$ is the cell temperature at time of flash test, as measured directly by backpan temperature. There is insufficient energy dissipated in the cell to cause notable temperature rise during the flash test, so backpan and cell temperature are used interchangeably. $P_{\text{flash,850}}$ is the maximum power generated by the module under test, as normalized to 850 W/m^2 DNI. $V_{\text{module},i}$ and $I_{\text{module},i}$ are elements of the array (indexed by i) of measured voltage and current values from the module under test. $I_{\text{monitor},i}$ is the monitored photocurrent from a solar cell co-located with the module under test and $I_{\text{monitor,850}}$ is the known photocurrent from the same monitor solar cell, when tested on sun at 850 W/m^2 DNI. As described in 2.2, the standard spectrum during flash test is controlled by comparison of isolated junction cells for blue and red/near-infrared sensitivity.

4. GAUGE REPEATABILITY

4.1 Overview of sources of test uncertainty

Both on-sun and flash tests have sources of uncertainty. For on-sun measurements, the most important source of variation is weather. CSTC describes a specific weather situation, with regards to DNI, ambient temperature and spectrum. The normalization techniques described in Equation 1 and 2 are attempts to adjust varying weather conditions back to the standard. Inaccuracies in backpan temperature measurements under outdoor test conditions are a further source of variation.

Depending on site, many days simply bear insufficient resemblance to CSTC that no form of normalization will suffice, and no tests can be performed. Within seemingly good conditions, the solar spectrum varies by time of day, or by aerosols or atmospheric water content. Additionally, it can be difficult to accurately measure temperature on the backpan of on-sun modules. The peak temperature is localized directly underneath the central power units, so sensor alignment is important. Close thermal contact must be established between sensor and module under test, which can be difficult under outdoor conditions, due to blocked access, dirt and debris.

Flash test uncertainty stems from long-term drifts of the flash source and measurement electronics. As the Xenon flash source ages, its spectral and spatial properties change. The system is initially calibrated for a lamp, a reference target for I_1/I_2 is established. For practical reasons, a ±2.5% range of variation in I_1/I_2 is allowed before any adjustment or replacement is made to the lamp. Spatial variations are harder to track, because the measurement of spatial uniformity of the 4 m^2 optical beam is time consuming. Aging of the reference optics and monitor cells is unlikely at normal laboratory storage conditions.

4.2 Gauge repeatability for on-sun testing

A series of on-sun tests was performed repeatedly on a set of SF1000 modules. The results are shown graphically in Figure 6. The gauge repeatability was assessed at ±17 W, ±3σ, after normalization for temperature and DNI. No spectral normalization was performed. Due to lack of a strong attachment mechanism, the temperature sensor was not establishing reliable thermal contact with the backpan of the module under test.

4.3 Gauge repeatability for on-sun testing

A series of flash tests was performed repeatedly on a set of SF1000 modules. The results are shown graphically in Figure 7. The gauge repeatability was assessed at ±4 W, ±3σ, after normalization for temperature and reference photocurrent. Expressed as a percentage of the nominal module power, the ±3σ gauge repeatability of the solar simulator is less than ±2%. In order to assess the long-term drift of the calibration, a set of standard modules was established, and measured repeatedly over the course of ten months. The long-term drift is shown as a repeatability measurement in Figure 8 and as a trend in Figure 9. The drift trend appears to be consistently downwards, even after lamp changes and readjustments of the spatial uniformity mask. For that reason, the possibility exists that the downward trend is an actual reduction in power of the standard modules.

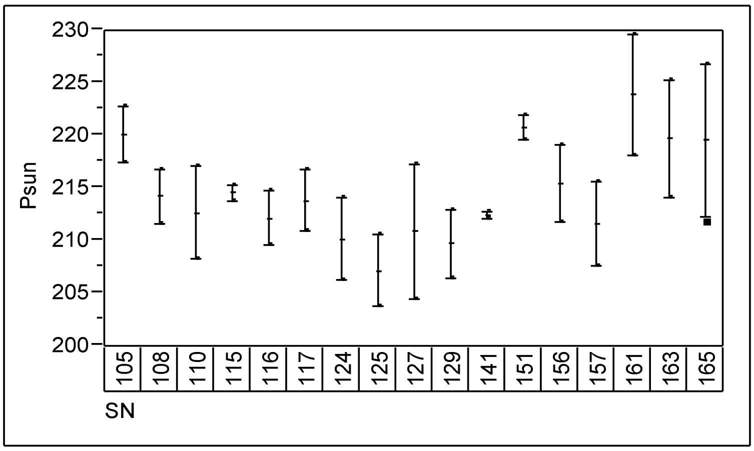

Figure 6. Variability of on-sun tests normalized to 850 W/m2 without temperature or spectral correction. Gauge repeatability at ±3σ is ±17 W.

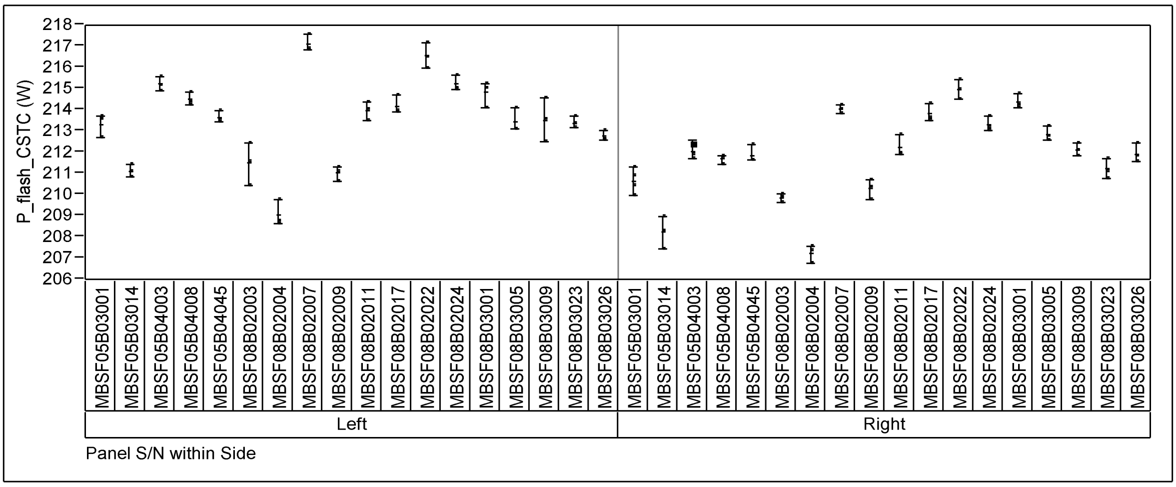

Figure 7. Variability of flash tests normalized to CSTC. Gauge repeatability and reproducibility at ±3σ is ± 4 W.

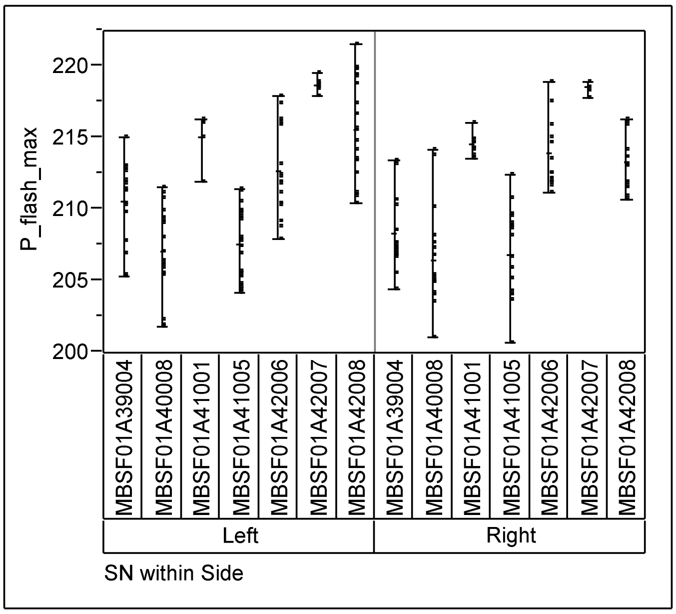

Figure 8. Long-term (10 month) solar simulator gauge repeatability data for a standard set of modules.

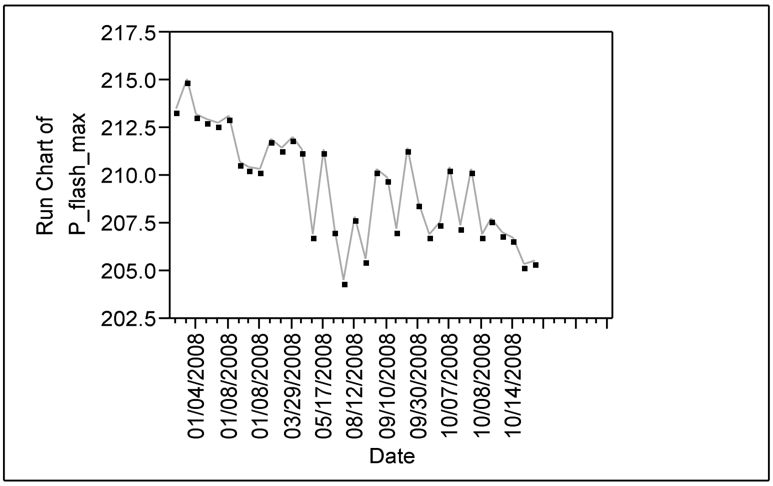

Figure 9. Long-term solar simulator measurements of individual CPV module. Approximate decrease in power standard of 5 to 10 W over a 10 month period.

5. CORRELATION RESULTS

Using the normalization procedures above, a data set of 350 tests was used to test correlation between on-sun performance and test results from the solar simulator. The complete data set is shown in the correlation plot of Figure 10. The test results were obtained in three sets. All modules were first tested in the solar simulator at the factory of origin. After transit, the panels were re-measured on sun in Puertollano, Spain. The on-sun test system was established at a receiving warehouse, and modules were tested after arrival, prior to installation into systems at ISFOC site in Puertollano[8].

As part of the third data set, the correlation range was expanded by artificially reducing module power during test. Power was reduced by obscuring one or two power units within a given module under test. Care was taken to obscure a common set of power units during on-sun and flash testing to guard against individual power unit variation within a module. Figure 11 shows the correlation result for this reduced data set.

Figure 12 shows the spread of differences between on-sun and flash tested results for the 350 tests, plotted as residuals of the best-fit prediction curve derived in Figure 10. The ±3σ spread is ±24 W. Based on the gauge repeatability of on-sun and flash testing, we would predict a spread of ±17.5 W. The excess spread is most likely due to exceedingly poor weather conditions encountered during test set number three. Figure 11 shows the residuals of the fit if data set 3 is excluded, with a ±3σ spread of ±15 W.

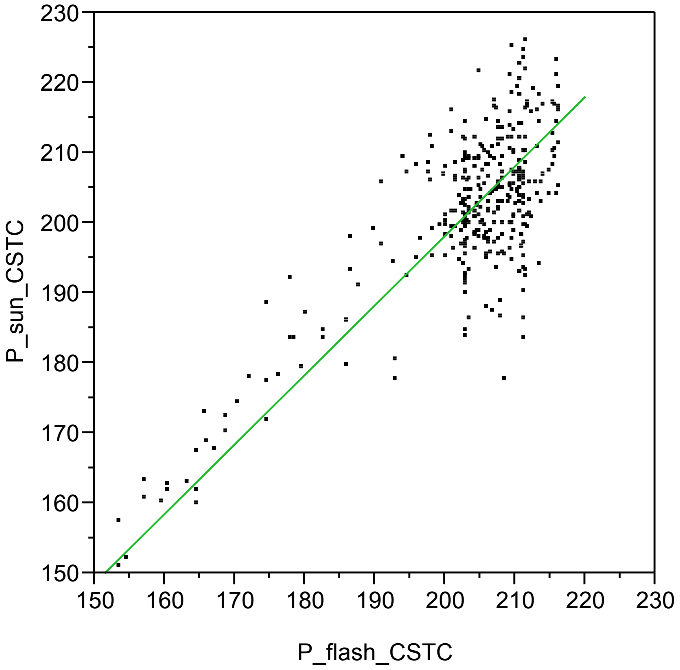

Figure 10. Correlation plot showing on-sun test result compared to flash test result. The linear fit is performed with a forced zero intercept, and has best-fit slope of 0.99 with a standard error of 0.002.

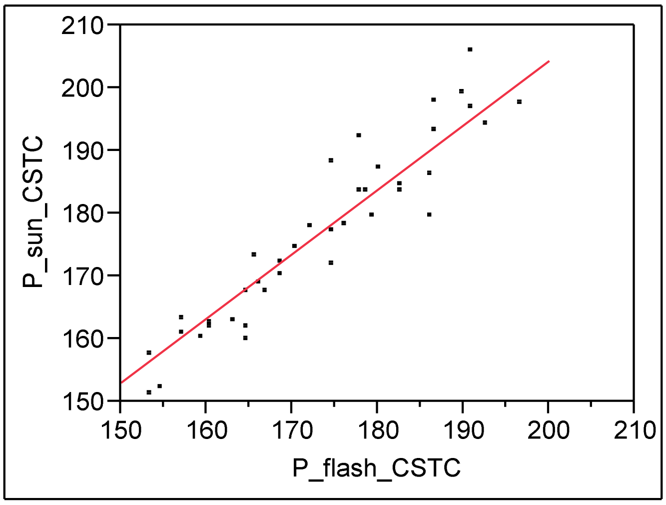

Figure 11. Correlation results for modules tested by obscuring of power units, 39 individual tests with ±15 W fit error (±3σ).

A correlation spread of less than that predicted by gauge repeatability is indicative either of the improvements made in on-sun testing through improved caution in temperature measurement, or simply indicates the uncertainty expected from relatively small sample sizes used during on-sun gauge repeatability study.

The slope calculation based on the aggregate data set is indicates a strong predictive capability in the flash tester. Using a constrained linear best fit to the two independently derived measurement values (note that flash and on-sun test results are normalized to CSTC independently, with no fit parameters), the calculated slope of the best fit line is 0.99, with a standard error of 0.002. If we take this as an estimate of the predictive capability of the flash test, there is an offset of 1% ±0.6% at ±3σ. Taking a worst-case view, we can conclude that the flash test measurement predicts the mean of on-sun performance of the population of modules to ±1.6%, or ±3.3 W for the nominal 205 W modules in the test population, although any individual module’s performance may vary more widely, in particular because of the uncertainty in establishing its true on-sun performance at CSTC.

Looking for the weaknesses in the correlation, the residuals of the fit Figure 12 shows a tendency to underestimate on-sun performance for the lower power modules. This tendency is most likely due to longer term drifts in the solar simulator power measurement. The data set used for low power measurements was obtained almost three months after the data set which forms the bulk of the correlation. Referring back to Figure 9, it is likely that the solar simulator output power drifted downwards during the time of this study.

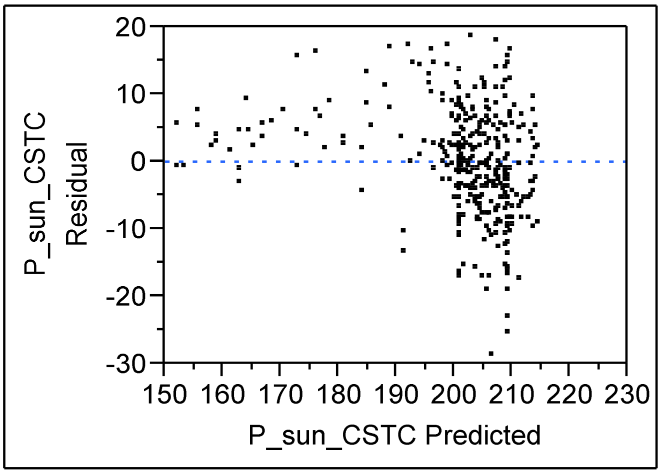

Figure 12. Residuals of the best fit line $P_{sun,CSTC} = 0.99\ P_{flash,CSTC}$.

6. CONCLUSIONS

We have demonstrated a flash solar simulator with accurate predictive capability for on-sun performance for HCPV modules. The overall population mean of a set of modules tested with flash test will differ by less than 2% from the measured on-sun performance. Power normalization methods used in developing the solar simulator were independently derived for both on-sun and flash tests. No fit parameters were used to develop the correlation. Each test result is normalized according to a simple set of principles. Development of a tighter predictive capability than ±15 W (±7%) for individual module tests will require improved spectral normalization for on-sun measurements, and lamp aging compensation for flash measurements.

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