Photovoltaic Calibrations at the National Renewable Energy Laboratory and Uncertainty Analysis Following the ISO 17025 Guidelines

Keith Emery
National Renewable Energy Laboratory

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Technical Report
NREL/TP-5J00-66873
September 2016

Contract No. DE-AC36-08GO28308

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Prepared under Task No. ST6P.1910

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Acknowledgments

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding provided by U.S. DOE Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Program. The contributions of M. Campanelli, T. Moriarty, C. Osterwald, and L. Ottoson are acknowledged.

List of Acronyms

A2LA	American Association for Laboratory Accreditation
AIST	National Institute of Advanced Industrial Science and Technology (Japanese National Metrology Laboratory)
ASTM	American Society for Testing Materials
CIGS	copper indium gallium diselenide
CMP	Photovoltaic Cell and Module Performance Characterization group in the National Center for Photovoltaics at NREL
DC	direct current
I-V	current versus voltage
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LACSS	large-area continuous solar simulator
NIST	National Institute of Standards and Technology (U.S. National Metrology Laboratory)
NREL	National Renewable Energy Laboratory
OSMSS	one-sun multisource solar simulator
PTB	Physikalisch Technische Bundesanstalt (German National Metrology Laboratory)
PV	photovoltaic
RTD	resistance temperature detector
SOMS	standardized outdoor measurement system
WPVS	World Photovoltaic Scale

Executive Summary

The measurement of photovoltaic (PV) performance with respect to reference conditions requires measuring current versus voltage for a given tabular reference spectrum, junction temperature, and total irradiance. This report presents the procedures implemented by the PV Cell and Module Performance Characterization Group at the National Renewable Energy Laboratory (NREL) to achieve the lowest practical uncertainty. A rigorous uncertainty analysis of these procedures is presented, which follows the International Organization for Standardization (ISO) *Guide to the Expression of Uncertainty in Measurement*. This uncertainty analysis is required for the team's laboratory accreditation under ISO standard 17025, "General Requirements for the Competence of Testing and Calibration Laboratories." The report also discusses additional areas where the uncertainty can be reduced.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Sample-Specific Uncertainty of Photovoltaic Cells and Modules

1.1.1 Summary

This LabView-based uncertainty analysis is used by the cell and module software to produce sample-specific uncertainty analysis. This software package is called by all current-voltage (I-V) test beds used by the cell and module performance characterization (CMP) group at the National Renewable Energy Laboratory (NREL), including those outside the scope of the International Organization for Standardization (ISO) 17025 accreditation but that fall under the scope of the group's ISO 9001 accreditation. Different test beds give different inputs into the analysis package, which gives uncertainty estimates for all of the numerical results in the ISO 17025-accredited calibration certificate. The uncertainty analysis is required by the ISO 17025 standard [1] and follows the ISO guide to uncertainty in measurements [2] and standard terminology [3].

The cell uncertainty analysis is for ASTM E948, *Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight* [4]. This procedure meets or exceeds the requirements in the International Electrotechnical Commission (IEC) Standard 60904-1, *Photovoltaic Devices—Measurement of Photovoltaic Current-Voltage Characteristics* [5]. The analysis is for ISO 17025-accredited calibrations and is restricted to single-junction monocrystal or multicrystal Si, GaAs, GaInP, GaInAs, Ge, or InP cells that are packaged with connectors. Unpackaged samples have additional error sources related to contacting, which is quantified separately. Multijunction cells and modules have additional error sources because the uncertainty in the photocurrent of each subcell must be treated separately and is outside the scope of this analysis. For samples that are metastable, an additional metastability factor of 1% relative uncertainty in the voltage, power, and fill factor is included. The I-V characteristics are measured within 2°C of the reference temperature (typically 25°C) and within about 2% of the reference irradiance (typically ASTM E-973 global [6] or, equivalently, IEC 60904-3 [7] spectral irradiance at 1,000 W/m^2).

The module uncertainty analysis is for ASTM E1036, *Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells* [8]. This procedure meets or exceeds the requirements in IEC standard 60904-1 [5]. This uncertainty analysis neglects the meter uncertainty because previous analysis showed the meter uncertainty in determining the current is typically less than 0.02% and below 0.001% for the voltage [9]. The uncertainty of the current sense resistors is included in this analysis.

1.1.2 Procedures

The cell and module simulator-based procedures using a calibrated reference cell or module follow the same procedures described in standards [4, 5, 8]:

1. Measure the area, A, using standard definitions [10, 11, 12]. For modules, this is typically measured with a calibrated tape measure. Cells are typically measured with a microscope that keeps the cross hairs in the same location while the focus and magnification are changed, with a 0.1-micron resolution.

2. Measure the relative spectral responsivity of the photovoltaic (PV) cell to be calibrated using standard test methods [13, 14]. For modules, the responsivity of a representative cell is measured.
3. Choose a reference device with a relative responsivity match to what is being tested. Typically, a stable reference cell of the same material is chosen. For less stable cells, such as a research-level, copper-indium-gallium-diselenide (CIGS) cell, a silicon reference cell is used. To minimize day-to-day variations, the same silicon working standard is used for all silicon cells. For modules, an encapsulated reference cell is used on the continuous simulator, and a small-area reference module is used on the pulsed solar simulator. For outdoor module measurements, an encapsulated reference cell is used.
4. Determine the spectral mismatch parameter, M, using Test Method E973 or IEC 60904-7 [15, 16].

$$M = \frac{\int_{\lambda_1}^{\lambda_2} E_s(\lambda) S_t(\lambda) \mathrm{d}\lambda \int_{\lambda_3}^{\lambda_4} E_{ref}(\lambda) S_r(\lambda) \mathrm{d}\lambda}{\int_{\lambda_3}^{\lambda_4} E_s(\lambda) S_r(\lambda) \mathrm{d}\lambda \int_{\lambda_1}^{\lambda_2} E_{ref}(\lambda) S_t(\lambda) \mathrm{d}\lambda} \tag{1}$$

   where

   $S_t(\lambda)$ = measured spectral responsivity of the test cell (Test Method E1021 or IEC 60904-8 [13,14])

   $S_r(\lambda)$ = measured spectral responsivity of the reference cell (Test Method E1021 [13,14])

   $E_{ref}(\lambda)$ = reference spectral irradiance

   $E_s(\lambda)$ = measured spectral irradiance of the light source

   λ_1, λ_2, λ_3, αvδ λ_4 = the wavelength limits of integration in Eq. 1.

5. Mount the reference cell and verify that its temperature is within ±2°C of the temperature corresponding to the reference cell short-circuit current calibration value, $I_{sc,RD0}$. Any deviation in temperature for the calibration temperature, which is typically 25°C, is treated as an error. For cells, the reference cell is typically placed at the center of the beam. For module simulator measurements, the location of the reference device is calculated by the device placement software. The software follows guidance in the standards to place the reference device at the location of the average light level on the module [5]. For cells larger than 5-by-5 centimeters (cm), a spatial nonuniformity correction procedure is used [17]. Steps 6 and 7 are omitted for outdoor module measurements where the intensity monitor is the reference cell. The reference cell is placed in a fixed location on the side of the outdoor module test bed. The temperature of the reference cell for outdoor measurements is not controlled but the value of the

reference cell's measured current is corrected to the reference temperature and a spectral correction to the measured data is applied after the I-V measurements are performed.

6. Adjust the simulator so that the measured reference cell short-circuit current $I_{sc,RD}$ is within 2% of the spectrally corrected calibration value, or

$$0.98 \le \left(I_{sc,RD0} / M\right) / I_{sc,RD} \le 1.02 \quad (2)$$

7. Many test beds use an intensity monitor to correct the measured current for intensity fluctuations of the light source. Transfer this value to an intensity monitor, giving a calibration value for the intensity monitor.

$$I_{sc,MD0} = \left(I_{sc,MD}\, I_{sc,RD0}\right) / \left(M I_{sc,RD}\right) \quad (3)$$

where

$I_{sc,MD0}$ = calibrated short-circuit current of the intensity monitor located near the edge of the test plane

$I_{sc,MD}$ = measured short-circuit current of the intensity monitor located near the edge of the test plane.

8. Mount the cell to be tested on the temperature-controlled plate in the same position as the reference cell and adjust the plate temperature so the reference cell is within 2°C of the reference temperature. Modules under simulators are mounted according to the guidance in IEC 60904-1 calling for the reference cell to be placed at the average light level on the module [5]. The average light level on the module is determined from a spatial nonuniformity map of 10-by-10 cm pixels.
9. Measure the open-circuit voltage, V_{oc}, with the load disconnected. The software also measures V_{oc} from the curve, and before and after the I-V curve is taken, as metrics of temperature rise and metastability. The Spire unit determines V_{oc} from the I-V curve.
10. Measure the current versus voltage (I_{TM}, V) characteristic of the cell under test by changing the operating point with the variable load so that the curve is swept through 0 volts (V) and 0 amps (A). At each operating point on the (I_{TM}, V) characteristic, measure the cell voltage, V; cell current, I_{TM}; and monitor current, $I_{sc,MD}$. In the uncertainty analysis software, correct the measured current, I_{TM}, for intensity fluctuations, giving the calibrated current of the test cell under the reference spectrum at the reference irradiance and temperature I_{TR}.
11. Call the uncertainty analysis software package to compute the sample-specific uncertainty and V_{oc}, I_{sc}, and P_{max}.
    A. Determine the calibrated I_{sc} by performing a linear regression fit to all I_{TR} *vs*. V points that satisfy the constraint that all currents are within 4% of the current at 0 V and all voltages within 0.20 times the voltage at 0 A.
    B. Determine the maximum power, P_{max}, by performing a polynomial fit of all I_{TR} *vs.* V points that satisfy the constraints that the measured power be within 85% of the

the largest measured power and the voltage is within 80% of voltage at the largest measured power similar to recommendations by E948 [4]. The polynomial that gives the best fit to the data up to a fifth order is used. The voltage at maximum power, V_{max}, is the real root of the derivative of the fit of the power-versus-voltage polynomial set equal to 0. This voltage is then substituted into a power-versus-voltage polynomial to obtain the P_{max}. The current at maximum power, I_{max}, is calculated from the P_{max}/V_{max}.

12. The current versus voltage data points (I_{TR}, V) are saved along with a variety of information, including V_{oc}, I_{sc}, P_{max}, temperature, time, cell ID, cell type, manufacturer, reference cell and its calibration, the record book number and page, and change in V_{oc} before and after the measurement.

1.1.3 Test bed-specific equipment

Photographs of the two cell test beds for single-junction cells are shown in Figure 1 and Figure 2. The spectrally adjustable one-sun multi-source solar simulator (OSMSS) for multijunction cells is shown in Figure 2 [18]. This test bed also allows automated I-V as a function of irradiance and temperature for single-junction cells. A simplified photo of the large-area continuous solar simulator (LACSS) module test bed is provided in Figure 3, whereas Figure 4 shows the Spire 5600 pulsed solar simulator. Figure 5 shows the standardized outdoor measurement system (SOMS). A block diagram of the cell test bed (Figure 1) is provided in Figure 6. Figure 7 shows a block diagram of the LACSS test bed in Figure 3. The reference cell in Figure 1, Figure 2, Figure 3, and Figure 5 is connected to the operational amplifier current-to-voltage converter circuit shown in Figure 8. The circuit senses the voltage, V_{in}, remotely and measures the current I_{in} across R_1, a precision 10-ohm shunt resistor (0.02%) while maintaining the voltage within 1 millivolt (mV) of 0 V. Table 1 summarizes the features, ranges, and limitations of NREL's CMP group's 1-sun test beds where the uncertainty analysis has been applied.

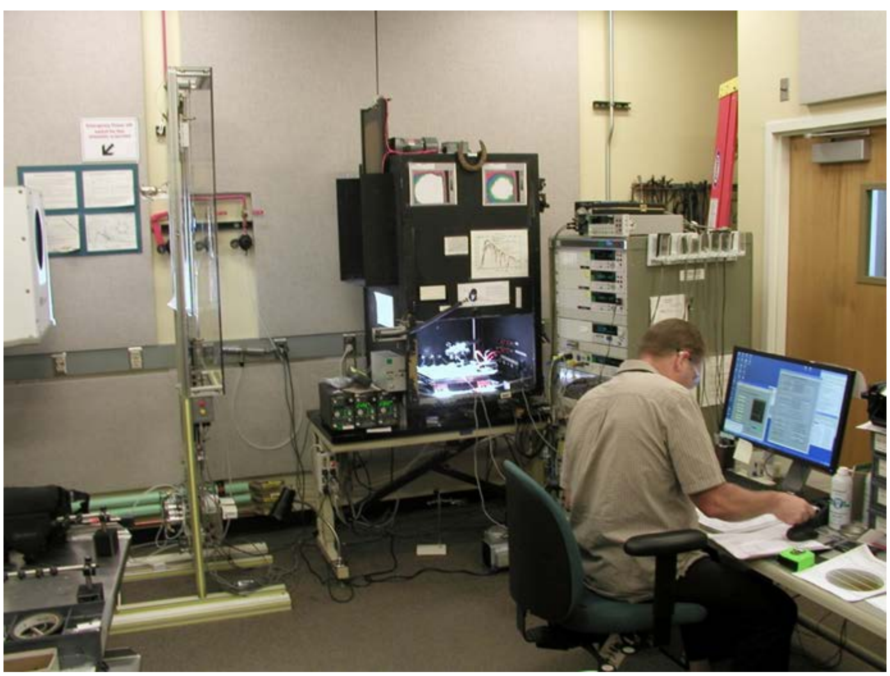


Figure 1. Abet solar simulator and custom cell I-V measurement system

Figure 2. Spectrally adjustable one-sun multi-source solar simulator (OSMSS) [18]. The data acquisition system is a Keithley source measurement unit with a separate meter hardware triggered to correct for intensity fluctuations. The system has a dedicated spectral radiometer for quick and accurate spectral adjustment.

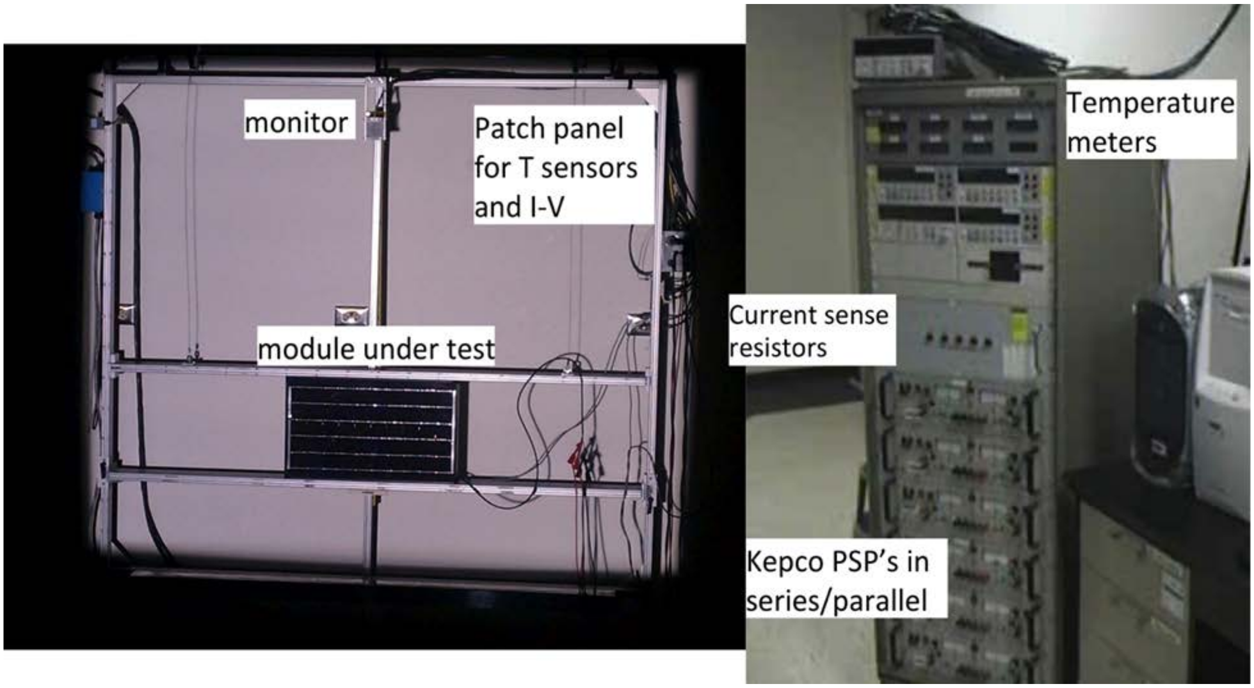


Figure 3. Large-area continuous solar simulator (LACSS) module I-V measurement system

Figure 4. Spire 5600 solar simulator

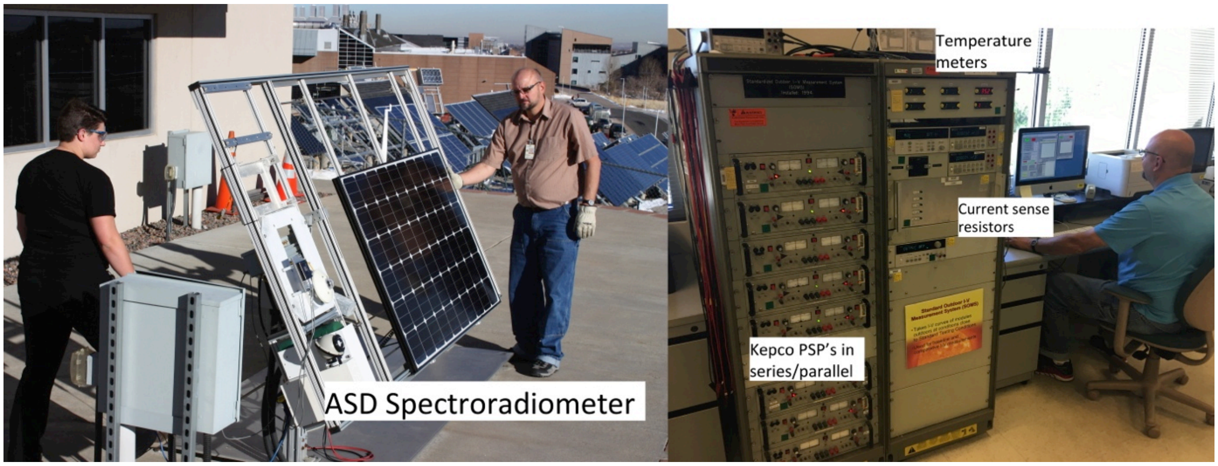


Figure 5. Standardized outdoor measurement system (SOMS) outdoor test bed and custom cell I-V measurement system

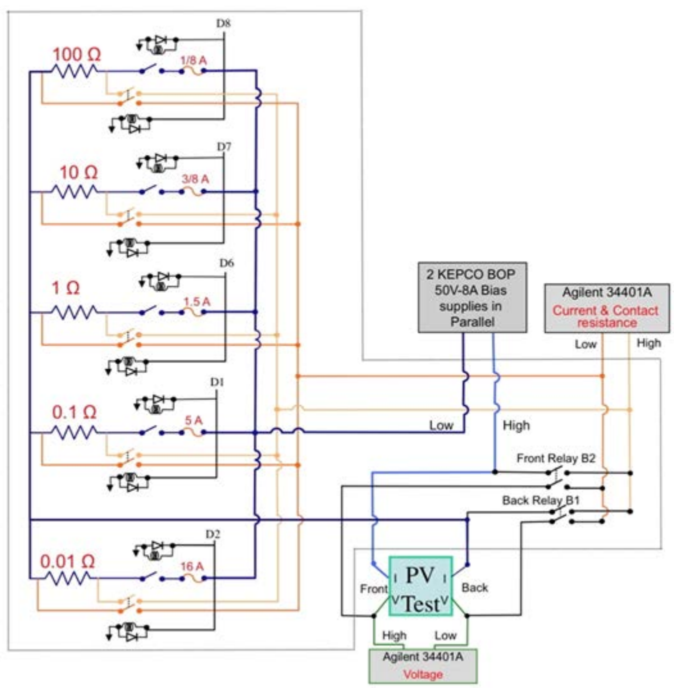


Figure 6. Simplified block diagram of cell current versus voltage test station in Figure 1

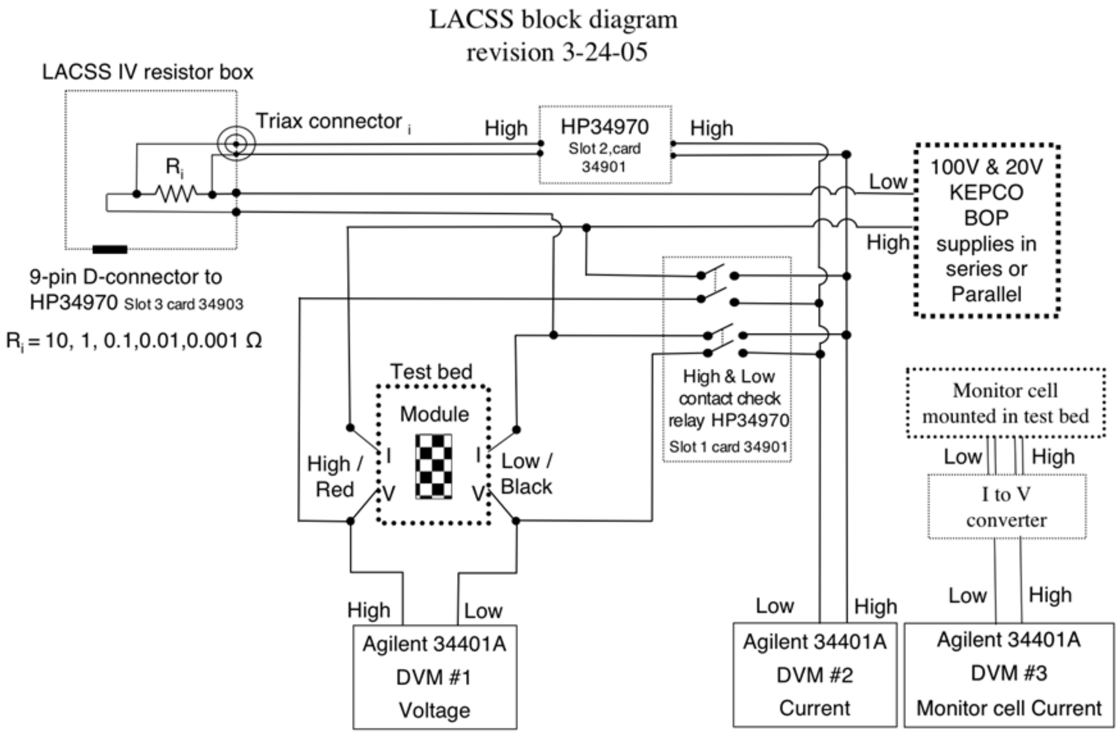


Figure 7. Simplified block diagram of module current versus voltage test station for the continuous solar simulator in Figure 3

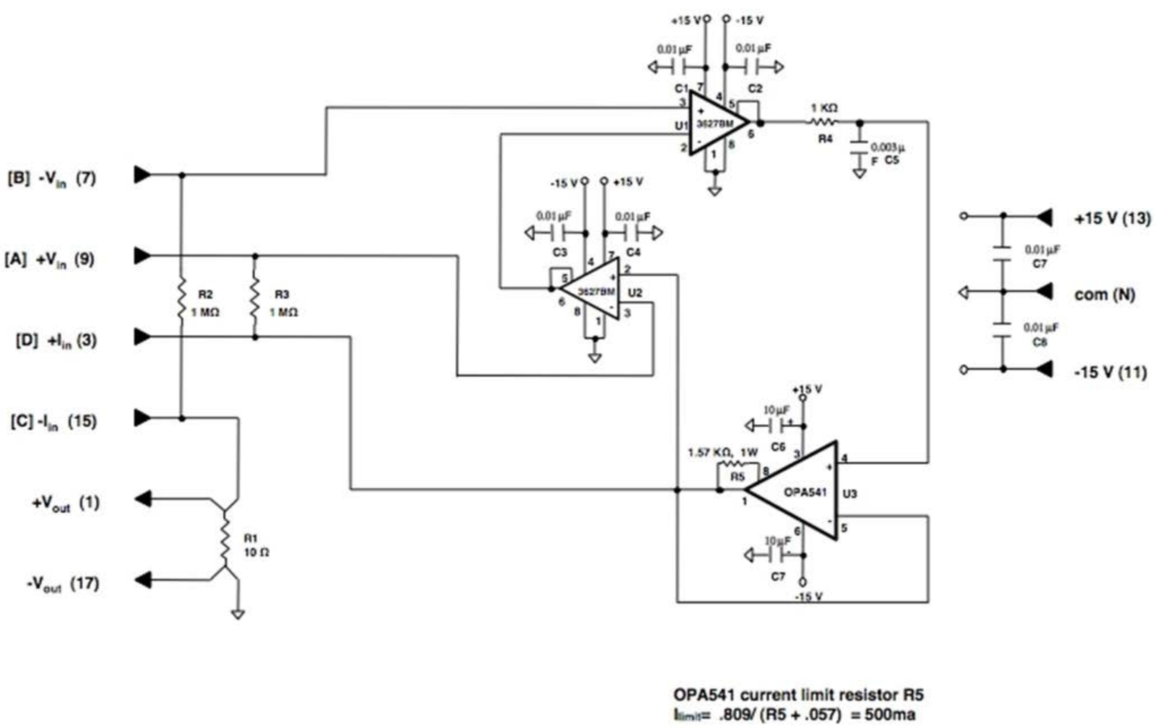


Figure 8. Block diagram of direct current (DC) to MHz current-to-voltage converter.
This converter is used to measure the reference cell's short-circuit current whose uncertainty in the current is determined by the uncertainty in the current sense resistor R1 and not the op-amp's linearity, offset, or gain characteristics.

Table 1. Summary of Test Beds That This Sample-Specific Uncertainty Analysis Covers

I-V Applications	Light Source	Size	Voltage (max/min)	Current (max/min)	Irradiance Range (suns)	Temperature
1-sun cells and modules (Fig. 1)	Abet- filtered 3 kW Xenon (Xe)	30 cm x 30 cm	±0.01 mV / ±50 V	±10 pA / ±16 A	0.1–20	10–50°C
1-sun cells (Fig. 2)	10 channel fiber-optic Xe and tungsten lamps	9 cm x 9 cm	±0.1 mV / ±40 V	±10 nA / ±5 A	0.0–1.1	10–80°C
1-sun modules (Fig. 3)	Spectrolab X200 filtered 25 kW Xe	160 cm x 125 cm	±0.1 mV / ±300 V	±1 μA / ±60 A	0.9–1.1	ambient
1-sun modules (Fig. 4)	Spire 5600 Xe flash, 30 to 100 milliseconds (ms)	200 cm x 137 cm	0.1 mV / 250 V	2 mA / 25 A	0.2–1.2	ambient
1-sun modules (Fig. 2)	Natural sunlight	No limit	±0.1 mV / ±300 V	±1 μA / ±60 A	~1	ambient

1.1.4 Uncertainty analysis

The uncertainty analysis makes several assumptions that have been verified by previous analyses to contribute less than 0.1% to the uncertainty of any reported parameter. The assumptions are [9]:

- The error in the current sense resistor is negligible (0.02%).
- The meter error in measuring the voltage is negligible (Agilent 34410 in 1- or 10-line cycle mode, 5-½ digit mode with measured voltages around 1 V).
- The error in the meter used to measure the voltage across the monitor current sense resistor and test device current sense resistor is negligible (Agilent 34410 in 1- or 10-line cycle mode, 5-½ digit mode with measured voltages around 0.03 V).
- The uncertainty analysis software also neglects the additional error in the voltage for scaling the current in the I-V curve while leaving the voltage the same. This is minimized by not allowing the current to be corrected by more than 5%. The current is normally corrected by less than 2%. The voltage changes logarithmically with changes in the current; restricting the current correction to less than 5% will typically ensure much less than 0.5% additional error in the voltage.

The glossary at the end of this report provides further descriptions of the terms in the following equations. The overset ^ denotes a nominal value, the overset ~ denotes a random variable or variable from Monte-Carlo analysis, the subscript * denotes a parameter corrected to the reference irradiance.

The sequence of events for the software-based uncertainty analysis is where no operator intervention is required:

1. After all measurements have been taken and the data is ready to be saved, the uncertainty is computed by calling "livUA-Main.vi."
2. Load testbed's sample-specific estimated temperature coefficients from template values:

   V_{oc}, I_{sc}, V_{max}, I_{max}, fill factor, and P_{max}

3. Compute input factors with uncertainties and write to XML file.
   A. Measured current (current sense resistor and voltage across resistor), voltage, and light-level intensity
      i. Prior to computing the current from the measured voltage and current sense resistor, correct the test device and reference device current sense resistors $\hat{R}_I$ and $\hat{R}_{Isc,RD0}$ for temperature to the temperature it was calibrated at (23°C) based on the range of possible rack temperatures (23°C–38°C) or measured temperature.
   B. Measured monitor and reference cell values, and temperature, during the transfer of the calibration of the monitor cell using the reference cell.
   C. Area uncertainty for cell based on multiple operator measurements
   D. Module area uncertainty based on tape measure uncertainty (gain and offset)
4. Compute temperature-uncorrected performance parameters with uncertainties.
   A. Correct currents in I-V curve for irradiance using nominal values of all measurement parameters.

$$\hat{I}_* = \hat{S}\frac{\left[1+\hat{\alpha}_{I_{sc,RD_0}}\left(\hat{T}_{RD}-T_{RD_0}\right)\right]\hat{I}_{sc,RD_0}\hat{R}_{I_{sc,RD_0}}\hat{V}_I}{\hat{V}_{I_{sc,MD}}\hat{M}\hat{R}_I}\hat{\mu}_C \tag{4}$$

and no correction to the voltage for intensity fluctuations

$$\hat{V}_* = \hat{V} \tag{5}$$

where the transfer calibration in Step 7 of the procedures in Section 1.1.2 gives the average monitor correction factor

$$\hat{\mu}_C = \frac{1}{K}\sum_{k=1}^{K}\frac{\hat{V}_{I_{sc,MD},k}}{\hat{V}_{I_{sc,RD},k}} \tag{6}$$

with the reference device at T_{RD}°C and assuming negligible changes in the monitor device's temperature and current sense shunt resistor resistance. In

Eq. 4, the term $\hat{S}$ allows for correction for the spatial nonuniformity error on the X25 cell test bed. For module test beds, this term is unity and the spatial nonuniformity error is corrected to a first-order-by-reference device measuring the average light level on the module. The $\left[1+\hat{\alpha}_{I_{sc,RD_0}}\left(\hat{T}_{RD}-T_{RD_0}\right)\right]$ term corrects the reference device with a calibration value of $\hat{I}_{sc,RD_0}$ for temperature. The term $\hat{\mu}_C \hat{R}_{I_{sc,RD_0}} / \hat{V}_{I_{sc,MD}}$ corrects for fluctuations in the intensity. For outdoor measurements where there is no monitor, $\hat{\mu}_C$ is unity and the variable $\hat{V}_{I_{sc,MD}}$ becomes $\hat{V}_{I_{sc,RD}}$.

B. Compute uncertainty in nominal I_{sc} from straight-line regression (t-distribution) denoted $\tilde{I}_{sc,*}$

If the terms in Eq. 4 are expressed as the uncertainty divided by the value, the sensitivity factor calculated from the partial derivative of the parameter with respect to the other parameters is unity and does not need to be computed (e.g., the standard deviation of the spectral correction factor divided by the spectral correction factor $\tilde{M} \setminus \hat{M}$). Using the I-V data window selected in the nominal I_{sc} curve fit, compute the uncertainty in the intercept and slope parameters (a joint, shifted, and scaled t-distribution) using standard Bayesian linear regression with noninformative, improper priors with unknown variance in current-only noise. The t-distribution is applied to the nominal values for $\hat{\alpha}_{I_{sc,RD_0}}$, $\hat{T}_{RD}$, and $\hat{I}_{sc,*}$ for Monte-Carlo analysis giving $\tilde{\alpha}_{I_{sc,RD_0}}$, $\tilde{T}_{RD}$, and $\tilde{\hat{I}}_{sc,*}$. This assumes irradiance-correction noise dominates in current and is negligible in voltage. The voltage varies as the log of the intensity while the current is linear with intensity. The intensity corrections are typically less than 2%. The posterior state-of-knowledge probability density function for the nominally corrected I_{sc} is a shifted and scaled t-distribution (the "fit" uncertainty). Use the variance of this probability density function to get the standard uncertainty $\tilde{I}_{sc,*}$ of the fit to the I-V data to obtain the short-circuit current $\hat{I}_{sc,*}$. If the variance is undefined because there are less than three points, then a typical variance is used.

Treating $\left[1+\tilde{\alpha}_{I_{sc,RD_0}}\left(\tilde{T}_{RD}-T_{RD_0}\right)\right]$ separately allows the uncertainty in Eq. 7 to be written as a simple product and quotient of uncertain quantities relative to their nominal values. This allows one to root-sum-square the relative uncertainties of each quantity assuming the random variables are independent. At present, the uncertainty in $\hat{M}$ is taken from previous Monte-Carlo analyses where it was determined that $\tilde{M}$ varied by 20% of its value for estimated uncertainties in the measured spectral irradiance, test device quantum efficiency, and reference device quantum efficiency [19, 20]. This number is increased to 40% for outdoor measurements because M is not corrected for temperature. The uncertainty $\tilde{S}$ in the spatial uniformity correction factor $\hat{S}$ is estimated from simple variational analysis to be 0.25% of the value for the X25 and OSMSS 1-sun cell test beds [21]. For the LACSS test bed, the value for $\tilde{S}$, assuming the module is placed at the location where the average intensity on the module is the same as the average irradiance of the reference device, is 1.5% for modules with more than 30 cm on a side and 0.5% for smaller modules. There is no correction for spatial nonuniformity in the outdoor data but, because the light is not at normal incidence and the reference device does not have an ideal cosine angular response, this error $\tilde{S}$ is estimated at 0.25%. The uncertainty in the measured monitor calibration factor $\hat{\mu}$ is derived from the standard deviation of k repeated measurements of the monitor value and the reference device's short-circuit current giving $\tilde{\mu}_C$. The uncertainty in the current sense resistors $\tilde{R}_{I_{sc,RD_0}}$ and $\tilde{R}_I$ is taken from the calibration data sheet and is typically a negligible 0.02%. The uncertainty in the reference cell calibration value $\tilde{I}_{sc,RD_0}$ is taken from previous analyses to be 0.91% [9].

C. Compute uncertainty in the temperature, spectral, and intensity-corrected short-circuit current $I_{sc,*}$

Treating $\left[1+\tilde{\alpha}_{I_{sc,RD_0}}\left(\tilde{T}_{RD}-T_{RD_0}\right)\right]$ separately allows the uncertainty in Eq. 4 to be written as a simple product and quotient of uncertain quantities relative to their nominal values. This allows one to root-sum-square the relative uncertainties of each quantity in Eq. 7, assuming the random variables are independent, giving Eq. 8.

$$u\left(I_{sc,*}\right)=\sqrt{u^2\left(S\right)+u^2\left(B_R\right)+u^2\left(B_T\right)+u^2\left(I_{sc,RD_0}\right)+u^2\left(R_{I_{sc,RD_0}}\right)+u^2\left(M\right)+u^2\left(R_I\right)+u^2\left(\mu_C\right)+u^2\left(\hat{I}_{sc,*}\right)} \quad (7)$$

or

$$u\left(I_{sc,*}\right)=\sqrt{u^2\left(\frac{\tilde{S}}{\hat{S}}\right)+u^2\left(\frac{\tilde{B}_R}{\hat{B}_R}\right)+u^2\left(\frac{\tilde{B}_T}{\hat{B}_T}\right)u^2\left(\frac{\tilde{I}_{sc,RD_0}}{\hat{I}_{sc,RD_0}}\right)+u^2\left(\frac{\tilde{R}_{I_{sc,RD_0}}}{\hat{R}_{I_{sc,RD_0}}}\right)+u^2\left(\frac{\tilde{M}}{\hat{M}}\right)+u^2\left(\frac{\tilde{R}_I}{\hat{R}_I}\right)+u^2\left(\frac{\tilde{\mu}_C}{\hat{\mu}_C}\right)+u^2\left(\frac{\tilde{I}_{sc,*}}{\hat{I}_{sc,*}}\right)} \quad (8)$$

where all standard uncertainties are relative and

$$B_R=1+\alpha_{I_{sc,RD_0}}\left(T_{RD}-T_{RD_0}\right) \quad (9)$$

and

$$B_T = 1 + \alpha_{I_{sc,RD_0}}\left(T_{TD} - T_{TD_0}\right) \qquad (10)$$

for k = 2, 95% confidence limit the relative expanded uncertainty is

$$U_{k=2}\left(I_{sc,*}\right) = 2 \cdot u\left(I_{sc,*}\right). \qquad (11)$$

D. Compute uncertainty in the nominal P_{max}, I_{max}, and V_{max}. Using the I-V data window and polynomial degree selected in the nominal P_{max} curve fit, compute the uncertainty in the polynomial coefficients (a joint, shifted, and scaled t-distribution) using standard Bayesian linear regression with noninformative, improper priors with unknown variance in current-only noise. This assumes the irradiance-correction noise dominates in current and is negligible in voltage. Using Monte Carlo simulation, draw samples from the distribution of polynomial functions; for each sample compute I_{max}, V_{max}, and P_{max} with the usual algorithm. Use the Monte Carlo sample variance to get the standard uncertainty of the test device's nominally corrected I_{max}, V_{max}, and P_{max} giving $\tilde{I}_{\max,*}$, $\tilde{V}_{\max,*}$, and $\tilde{P}_{\max,*}$. If there are too few data points in the fit, approximate this variance, which may not exist, using the empirical probability density functions. Uncertainties due to metastability and contacting are treated separately outside of this analysis because it is sample and material specific.

E. Compute I_{max} uncertainty from corrections to Nom I_{max} (root sum of squares). The uncertainty in I_{max} is taken to be the uncertainty in the fit, plus the uncertainty in setting the light level, which includes the spatial nonuniformity S, the deviation of the reference temperature from the reference device calibration temperature B, the reference device calibration uncertainty $R_{I_{sc,RD_0}}$, the spectral error, current sense resistor R_I, and the uncertainty in the transfer of the reference cell calibration to an intensity monitor μ_C. Since I_{max} is a product of terms, the sensitivity coefficients are unity and the uncertainty can be expressed as the square root of the sum of the squares of the elemental error sources.

$$u\left(I_{\max,*}\right) = \sqrt{u^2(S) + u^2(B_R) + u^2(B_T) + u^2\left(I_{sc,RD_0}\right) + u^2\left(R_{I_{sc,RD_0}}\right) + u^2(M) + u^2(R_I) + u^2(\mu_C) + u^2\left(\hat{I}_{\max,*}\right)} \qquad (12)$$

or

$$u\left(I_{\max,*}\right) = \sqrt{u^2\left(\frac{\tilde{S}}{\hat{S}}\right) + u^2\left(\frac{\tilde{B}_R}{\hat{B}_R}\right) + u^2\left(\frac{\tilde{B}_T}{\hat{B}_T}\right) + u^2\left(\frac{\tilde{I}_{sc,RD_0}}{\hat{I}_{sc,RD_0}}\right) + u^2\left(\frac{\tilde{R}_{I_{sc,RD_0}}}{\hat{R}_{I_{sc,RD_0}}}\right) + u^2\left(\frac{\tilde{M}}{\hat{M}}\right) + u^2\left(\frac{\tilde{R}_I}{\hat{R}_I}\right) + u^2\left(\frac{\tilde{\mu}_C}{\hat{\mu}_C}\right) + u^2\left(\frac{\tilde{I}_{\max,*}}{\hat{I}_{\max,*}}\right)}. \qquad (13)$$

where

$$B_T = 1 + \alpha_{V_{\max}} \left(T_{TD} - T_{TD_0} \right)$$

for k = 2, 95% confidence limit the relative expanded uncertainty is

$$U_{k=2}\left(I_{\max,*} \right) = 2 \cdot u\left(I_{\max,*} \right). \tag{14}$$

F. Compute P_{max} uncertainty from corrections to the nominal P_{max} (root sum of squares)

$$u\left(P_{\max,*}\right) = \sqrt{u^2\left(S\right) + u^2\left(B_R\right) + u^2\left(B_T\right) + u^2\left(I_{sc,RD_0}\right) + u^2\left(R_{I_{sc,RD_0}}\right) + u^2\left(M\right) + u^2\left(R_I\right) + u^2\left(\mu_C\right) + u^2\left(\hat{P}_{\max,*}\right)} \tag{15}$$

or

$$u\left(P_{\max,*}\right) = \sqrt{u^2\left(\frac{\tilde{S}}{\hat{S}}\right) + u^2\left(\frac{\tilde{B}_R}{\hat{B}_R}\right) + u^2\left(\frac{\tilde{B}_T}{\hat{B}_T}\right) + u^2\left(\frac{\tilde{I}_{sc,RD_0}}{\hat{I}_{sc,RD_0}}\right) + u^2\left(\frac{\tilde{R}_{I_{sc,RD_0}}}{\hat{R}_{I_{sc,RD_0}}}\right) + u^2\left(\frac{\tilde{M}}{\hat{M}}\right) + u^2\left(\frac{\tilde{R}_I}{\hat{R}_I}\right) + u^2\left(\frac{\tilde{\mu}_C}{\hat{\mu}_C}\right) + u^2\left(\frac{\tilde{P}_{\max,*}}{\hat{P}_{\max,*}}\right)}. \tag{16}$$

where

$$B_T = 1 + \alpha_{P_{\max}} \left(T_{TD} - T_{TD_0} \right) \tag{17}$$

for k = 2, 95% confidence limit the relative expanded uncertainty is

$$U_{k=2}\left(P_{\max,*} \right) = 2 \cdot u\left(P_{\max,*} \right). \tag{18}$$

G. Compute uncertainty in V_{oc} from straight-line regression (Monte Carlo) using the I-V data window selected in the nominal V_{oc} curve fit. Compute the uncertainty in the intercept and slope parameters (a joint, shifted, and scaled t-distribution) using standard Bayesian linear regression with noninformative, improper priors with unknown variance in current-only noise (assumes irradiance-correction noise dominates in current and is negligible in voltage). Using Monte Carlo simulation, draw samples from the distribution of straight-line functions; for each sample compute V_{oc} as the voltage-intercept of the line. Remove outliers in the tails of the distribution that are more than 10 standard deviations from the mean. Use the Monte Carlo sample variance to get the standard uncertainty of the test device's nominally corrected V_{oc}. If there are too few data points in the fit, approximate this variance, which may not exist, using the empirical probability density functions.

$$u\left(V_{oc,*}\right) = \sqrt{u^2\left(B_T\right) + u^2\left(\hat{V}_{oc,*}\right)} \tag{19}$$

or

$$u\left(V_{\max,*}\right)=\sqrt{u^2\left(\frac{\tilde{B}_T}{\hat{B}_T}\right)++u^2\left(\frac{\tilde{V}_{oc,*}}{\hat{V}_{oc,*}}\right)} \tag{20}$$

where

$$B_T = 1+\alpha_{Voc}\left(T_{TD}-T_{TD_0}\right) \tag{21}$$

H. Use the V_{oc} measured with the sample open-circuited, if available. The cell and LACSS module test beds measure V_{oc} with the sample open-circuited, whereas the Spire and OSMSS obtain the V_{oc} from the I-V curve. This value is added to the dataset for the V_{oc} curve fit if there are less than 3 points for the regression that satisfy the filter criteria.

I. Compute J_{sc}, FF, and η

$$J_{sc} = J_{sc}/\mathrm{A} \tag{22}$$

$$FF = 100 * P_{max}/(V_{oc} * I_{sc}) \tag{23}$$

$$\eta = 100 * P_{max}/(A * E_{ref}) \tag{24}$$

J. Using root sum of squares:

i. Compute FF uncertainty

- For FF, the uncertain I_{sc} and I_{max} current-corrections cancel in the quotient; therefore, the uncertain values from the fits are used instead.
- An additional sample-specific component is added to account for errors related to contacting, high currents, and low voltages. This additional component is based on the repeatability in the fill factor studies and is related to variations in the current contact surface area and location—plus the location of the voltage sense.
- Errors due to contacting and metastability are not included in the software based uncertainty analysis but the test bed software can include the estimated uncertainty from these additional components.

ii. Compute J_{sc} uncertainty

iii. Compute η uncertainty

K. The temperature has a residual uncertainty component related to operator judgment that includes sample- and test bed-specific temperature gradients between the sensor and the PV junction.

L. The analysis also allows the user to temperature-correct all performance parameters to a specified temperature (typically 25°C, the normal reference temperature) using a straight-line correction function, including uncertainties in:

    i. uncorrected value

    ii. temperature

    iii. temperature coefficients

   The uncertainty in the quoted temperature is taken to be 0 when these temperature-corrected performance parameters are quoted at a typical reference temperature of 25°C. Errors in the measured temperature are included in the uncertainty in the translation to the reference temperature.

5. The uncertainty analysis is implemented in LabView software with the file name "livUA-Main.vi" and outputs an XML file using the same file-naming convention as the I-V file with an extension of "ua.xml." This file contains all of the elemental error sources and the information used to calculate the uncertainties. The sample-specific uncertainty components from the output of "livUA-Main.vi" are included in the data files used for plotting, summary directory, and customers calibration certificates.

2 Uncertainty Analysis Example

The test beds have been using this software since October 2015.

1. Cell I-V: A sample certificate and corresponding plot following the sample-specific uncertainty analysis are shown in Figure 9 and Figure 10, respectively
2. Module I-V: A sample plot and corresponding certificate following the sample-specific uncertainty analysis are shown in Figure 11 and Figure 12, respectively.

PV Measurements
mono-Si Cell

Device ID: PVM 101

Jul 20, 2016 09:29

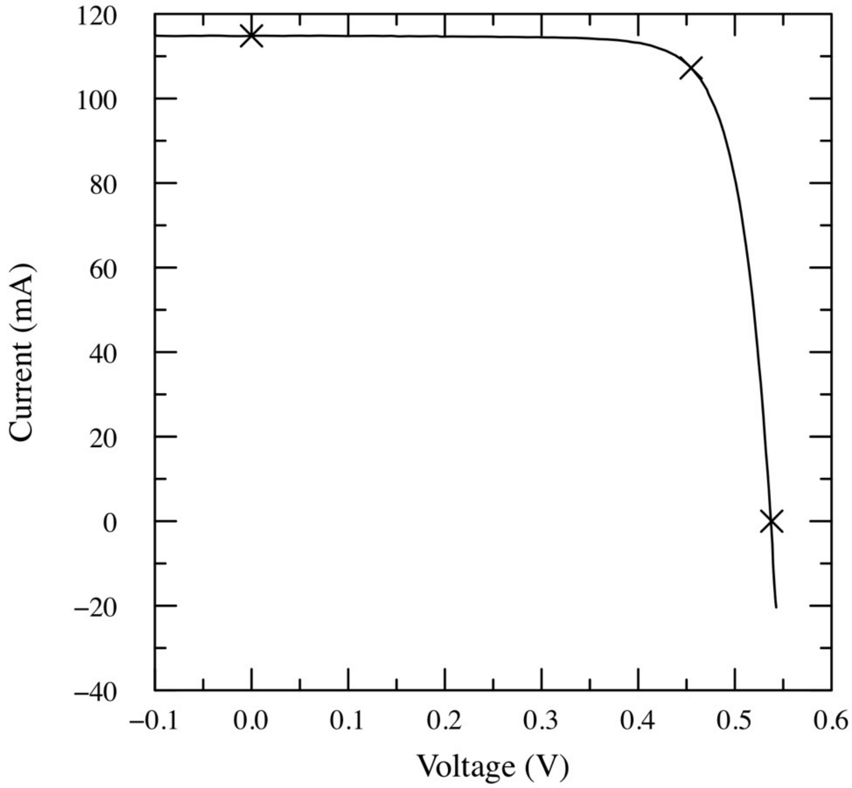
Spectrum: ASTM G173 global

Device Temperature: 24.5 ± 0.6 °C

Device Area: 4.000 cm^2 ± 0.0 %

Irradiance: 1000.0 W/m^2

X25 IV System
PV Cell & Module Characterization Group



V_{oc} = 0.5381 V ± 0.2%

I_{sc} = 0.1148 A ± 1.1%

J_{sc} = 28.704 mA/cm^2 ± 1.1%

Fill Factor = 78.92 % ± 0.5%

I_{max} = 0.1072 A ± 1.1%

V_{max} = 0.4547 V ± 0.1%

P_{max} = 48.761 mW ± 1.2%

Efficiency = 12.19 % ± 1.2%

1660 lamp hours, 62" for PVM 98, 60.6" for N40.

Figure 9. I-V plot of the reference cell in the calibration certificate in Figure 10

PV Testing Group — National Renewable Energy Laboratory
Photovoltaic Reference Cell Calibration Certificate — ISO tracking #: 9999

NATIONAL RENEWABLE ENERGY LABORATORY

Photovoltaic Reference Cell Calibration Certificate

Calibration Conducted For:
Keith Emery
NREL
NREL

Calibration Conducted By:
National Renewable Energy Laboratory
Solar Cell/Module Performance Group
15013 Denver West Parkway
Golden, CO 80401

Performed by:____________________________ Date:_______________
<Tester>

Approved by:____________________________ Date:_______________
<Test Manager>

X25 LIV Cal Certificate v2.3 — Issue date — Page 1 of 2
Printed: 8/10/2016
This certificate shall not be reproduced, except in full, without the written approval of the laboratory.

Figure 10a. Page 1 of cell calibration certificate for the cell in Figure 9

Cell ID: PVM 101
Manufacturer: PV Measurements
Material: mono-Si
Area: 4.000 square centimeters, *U95(Area)* = 0.0%

The current versus voltage of the above device has been evaluated according to the method defined by *Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight* (document: PV-TM948) to meet ISO 17025 specifications by the National Center for Photovoltaics' Device Performance Measurement Team at the National Renewable Energy Laboratory. This certificate is only issued to reference cells that are packaged with four wires allowing separate current and voltage contacts to each side of the cell, good thermal conductivity between the cell and cell package and NREL's test stage, and an attached temperature sensor. All quoted uncertainties, 95% confidence, coverage = 2, are derived in the document *"PV cell and module IV UN"* except where noted. Calibrations are traceable to NIST and the World Radiometric Reference and are valid until Thursday, July 20, 2017.

Reference Conditions:
Spectrum: ASTM G173 global (IEC 60904-3 ed. 2 / ASTM G173)
1000.0 watts per square meter, at 25.0 degrees C.

Primary reference cell:
PVM98 , Calibration value: 115.170 mA ± 0.9% with respect to reference conditions*
Quantum efficiency filename: PVM98 (FQE 061201-1601)
Calibrated according to test method PV-TM1125
reference cell calilbration date: 01/26/15
* See *Uncertainty of Primary Cal* (document "PV-U TM1125") for uncertainty analysis.

Simulator Spectrum:
NREL filename: "X25 spectrum 160627 1309 .txt"
Spectral mismatch correction factor: 1.00033 ± 0.004

Quantum Efficiency for "PVM 101"
NREL filename: "FQE PVM101"
Quantum efficiency measured according to test method PV-TM973.

Results

NREL current vs. voltage filename: X25 LIV 160720-092914

Isc: 0.1148 A, *U95(Isc)* = 1.1%
Voc: 0.5381 V, *U95(Voc)* = 0.2%
Fill Factor: 78.9 %, *U95(FF)* = 0.5%
Efficiency: 12.2 %, *U95(Eff)* = 1.2%

Imax: 0.1072 A, *U95(Imax)* = 1.1%
Vmax: 0.4547 V, *U95(Vmax)* = 0.1%
Pmax: 48.76 mW, *U95(Pmax)* = 1.2%
Device T: 24.5 ± 0.6 degrees C,

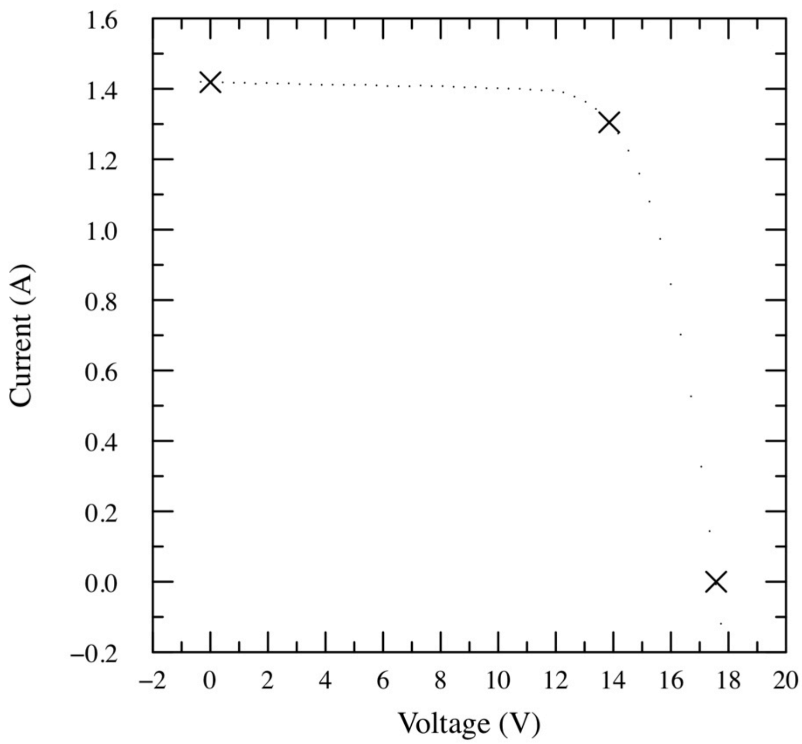
Figure 10b. Page 2 of cell calibration certificate for the cell in Figure 9

ARCO Solar
mono-Si module

Device ID: S1
May 19, 2016 10:27:48 MT
Spectrum: ASTM G173 global

Device Temperature = 24.2 ±2.0 °C
Device Area = 1744.3 cm^2 ±0.7%
Irradiance = 1000.0 W/m^2

NREL — NATIONAL RENEWABLE ENERGY LABORATORY
LACSS IV System
PV Cell & Module Characterization Group



ISO 9001:2008 CERTIFIED

V_{oc} = 17.57 V ±1.2%
I_{sc} = 1.419 A ±3.2%
Fill Factor = 72.5% ±1.3%
Efficiency = 10.4% ±3.4%

V_{max} = 13.86 V ±1.2%
I_{max} = 1.305 A ±3.2%
P_{max} = 18.08 W ±3.3%

Device Dimensions = 55.20 x 31.60 cm
Performance check setup ref @ x89 y47 Jbox towards n with lower bar @ 21cm horizontial
ISO Tracking # Test

Figure 11. I-V plot of the module in the calibration certificate in Figure 12

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

National Renewable Energy Laboratory
Measurement & Characterization Division
15013 Denver West Parkway
Golden, CO 80401-3305

ACCREDITED
certificate number 1239.02
Accredited for photovoltaic secondary cell, secondary module, and primary reference cell calibration

ISO Tracking #: Test

Certificate Of Calibration

Calibration Conducted For:

Keith Emery
NREL-PV Perf
National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401-3305

Device Information:

Manufacturer: ARCO Solar
Device ID: S1
Material: mono-Si
Aperture Area: 1744.3 cm^2 ± 0.6 %
Device Dimensions: 55.20 x 31.60 cm

Calibration Results:

NREL IV Filename: LACSS_LIV 160519-102748

Isc:	1.4188 A ± 3.7 %	**Imax:**	1.3048 A ± 3.5 %	**Fill Factor:**	72.5 % ± 1.2 %
Voc:	17.572 V ± 1.2 %	**Vmax:**	13.856 V ± 1.6 %		
Efficiency:	10.4 % ± 3.9 %	**Pmax:**	18.080 W ± 3.9 %		

Test Conditions:

Reporting Spectrum: ASTM G173 global
Simulator Spectrum: LACSS Spectrum 20160208.txt
Device QE Filename: Arco S1 (3-5-97)
Spectral Mismatch: 1.0014
Device Temperature: 24.2 °C ± 2.0 °C
Reference Irradiance: 1000.0 W/m^2

Reference Cell Information:

Reference Cell ID: 930216-1
Reference Cell Cal Value: 122.47 mA ± 0.9%
Reference Cell Cal Date: 01/26/15
Reference Cell QE Filename: 930216-1 (WPVS 3-1-98)

The current versus voltage of the above device has been evaluated according to the method defined by ASTM standard E1036 "Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells" to meet ISO 17025 specifications by the National Center for Photovoltaics' Device Performance Measurement Team at the National Renewable Energy Laboratory. This procedure meets or exceeds the requirements in IEC standard 60904-1 "Photovoltaic devices - Measurement of photovoltaic current-voltage characteristics". This certificate is only issued to single-junction stable modules or cells in a module package that have four wires allowing separate current and voltage contacts to each polarity of the sample. All quoted uncertainties are derived in IV Module Uncertainty document (PV1036 Module IV UN) except the uncertainty for the primary reference cell calibration located in document (PV1125 Primary Cell UN). The Uncertainties listed are for a coverage of 2 giving 95% confidence. Calibrations are traceable to NIST and the World Radiometric Reference. The recommended calibration interval is one year.

Measurement Performed by: ____________________ Date: __________
<Test Technician>

Measurement Approved by: ____________________ Date: __________
<Test Manager>

LACSS LIV Cal Certificate v2.8	This certificate shall not be reproduced except in full, without the written approval of the National Renewable Energy Laboratory.	Print Date: 05/19/2016	Page 1 of 1

Figure 12. Module IV certificate for the I-V curve in Figure 11

3 Efforts To Further Reduce Uncertainty

The PV community demands lower uncertainties than what the calibration labs are currently reporting. Numerous intercomparisons among the calibration labs have demonstrated that the values are contained within the lab's uncertainty estimates. Efforts to reduce the uncertainty in future NREL calibrations include:

- Specifying the reference conditions more precisely to reduce definitional uncertainties
- Reducing the uncertainty due to spatial nonuniformity of the light source
- Reducing the primary reference cell calibration uncertainty by careful attention to stray light and temperature corrections.

3.1 Definitional uncertainty

There is a definitional uncertainty in the photocurrent and hence power rating and efficiency because the angular distribution of the diffuse component of the terrestrial reference spectrum is not specified [22]. This definitional uncertainty ranges from 0.25% for an isotropic diffuse component to 1.5% for a diffuse component that falls off as the cosine of the zenith angle. This magnitude is larger than the 0.5%–1.0% primary reference cell uncertainty quoted by the recognized terrestrial primary reference calibrations labs. This error has not been identified in field data because primary calibration methods that are accurate to better than 1% all use normal incidence light only, and methods that do measure the diffuse light have a 2%–3% uncertainty, which is too large of an error to identify this uncertainty. The method to handle this uncertainty has been well established in the measurement theory and can be accommodated by the existing direct normal calibration methods [23]. The only additional information required to remove this definitional uncertainty in the primary calibration values is the angular resolved quantum efficiency and the angular resolved reference spectrum. If the angular resolved reference spectrum is well specified, then outdoor methods under global sunlight would be required to measure the angular resolved solar spectral irradiance, which is beyond the state-of-the-art to accomplish in less than a few minutes. The direct indoor and outdoor under natural sunlight methods followed by Physikalisch Technische Bundesanstalt (PTB), National Institute of Advanced Industrial Science and Technology (AIST), and NREL do not need to know the angular distribution of the source spectrum because it is under collimated normal incidence light sources.

Another definitional related uncertainty is the lack of reference conditions for rating bifacial PV technologies. The current recommended practice is to report the power rating based on the total irradiance incident on the front and back surfaces. The temperature and reference spectra have not been specified, but by convention, to be compatible with 1-sun measurements, the bifacial module should be rated at a total irradiance of 1,000 W/m^2 under the global reference spectrum and at 25°C. The uncertainty exists because the reference spectrum has 90% direct on the front surface, leaving up to 10% additional light to reach the back surface—but this value is not specified and the user can choose the conditions that give the optimum power rating.

The lack of specification of the angular distribution of the diffuse component also causes problems for rating PV at concentrations less than 10 times because the field of view is much larger than a concentrator where direct beam light is used and less than the full sky where global light is used. This means low-concentrating PV must be evaluated outside with a site-specific rating that depends on the relative contribution of the diffuse component.

3.2 Primary reference cell calibration uncertainty

A dominant source of uncertainty in secondary cell and module calibrations is the primary reference cell uncertainty. The group currently quotes a 95% confidence limit coverage factor of 2 uncertainty of 0.91% of the calibration value. The NREL CMP group discovered that incomplete illumination of the package—even by a few millimeters in the corner of encapsulated packages—impacts the calibration value even when the cell is completely illuminated. Figure 13 shows the impact of partial versus full illumination for a World Photovoltaic Scale (WPVS) reference cell designed to minimize artifacts from incomplete package illumination or internal reflections [24]. The new tube was also designed to eliminate more reflected light with baffles and ultralow broadband reflectance paint and is shown in Figure 14. The NREL CMP group also paid considerable attention to minimizing all sources of light that could reach the reference cell that did not go through the collimating tube. As a result, the day-to-day variation in the calibration value was much less than ever before. Figure 15 shows a typical improvement as manifested by a reduction in the standard deviation over all days and within a day.

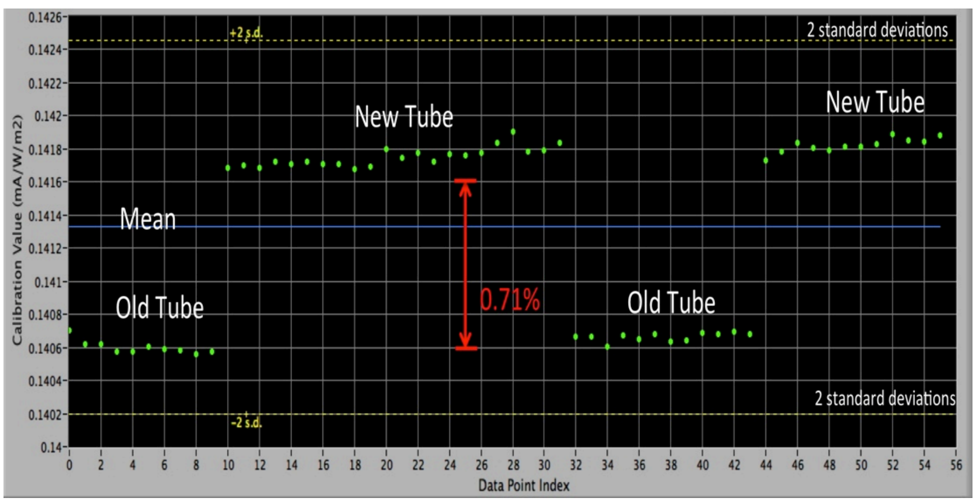
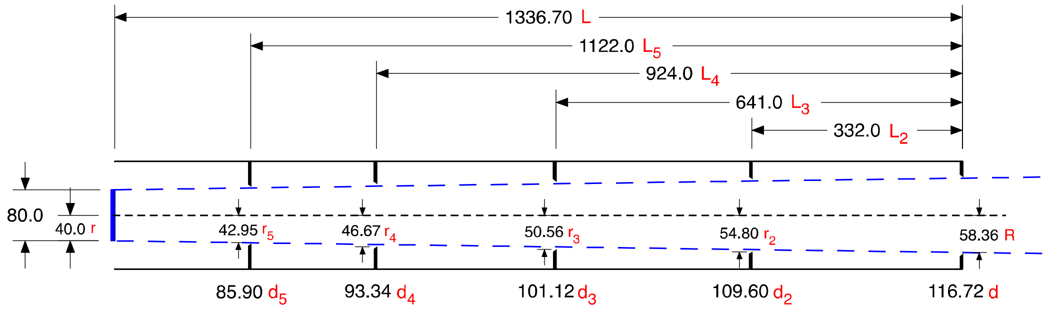


Figure 13. Impact of complete package illumination with larger diameter 5.00° field of view collimating tube on WPVS cell 027-2005

Collimating Tube Aperture Placements



1.0 mm added to radius r_2, r_3, and r_4 so as not to intercept the light between the Entrance and Receiving Apertures.		
FOV	Field of View (°)	5.0
θs	Slope Angle (°)	0.7870
r	Test Plane Radius (mm)	40.0
θo	Opening Angle (°)	2.50
Cr	Collimation Ratio	11.45
R	Entrance Aperture Radius (mm)	58.36
L	Entrance Aperture to Test Plane Distance (mm)	1336.70
L_2	Entrance to Baffle #1 Distance (mm)	332.00
L_3	Entrance to Baffle #2 Distance (mm)	641.00
L_4	Entrance to Baffle #3 Distance (mm)	924.00
L_5	Entrance to Receiving Aperture Distance (mm)	1122.00
r_2	Baffle #1 Radius (mm)	54.80
r_3	Baffle #2 Radius (mm)	50.56
r_4	Baffle #3 Radius (mm)	46.67
r_5	Receiving Aperture Radius (mm)	42.95

Figure 14. Drawing for improved 5.00° field of view collimating tube for reference cell package windows that can fit in an 8.5-cm-diameter circle

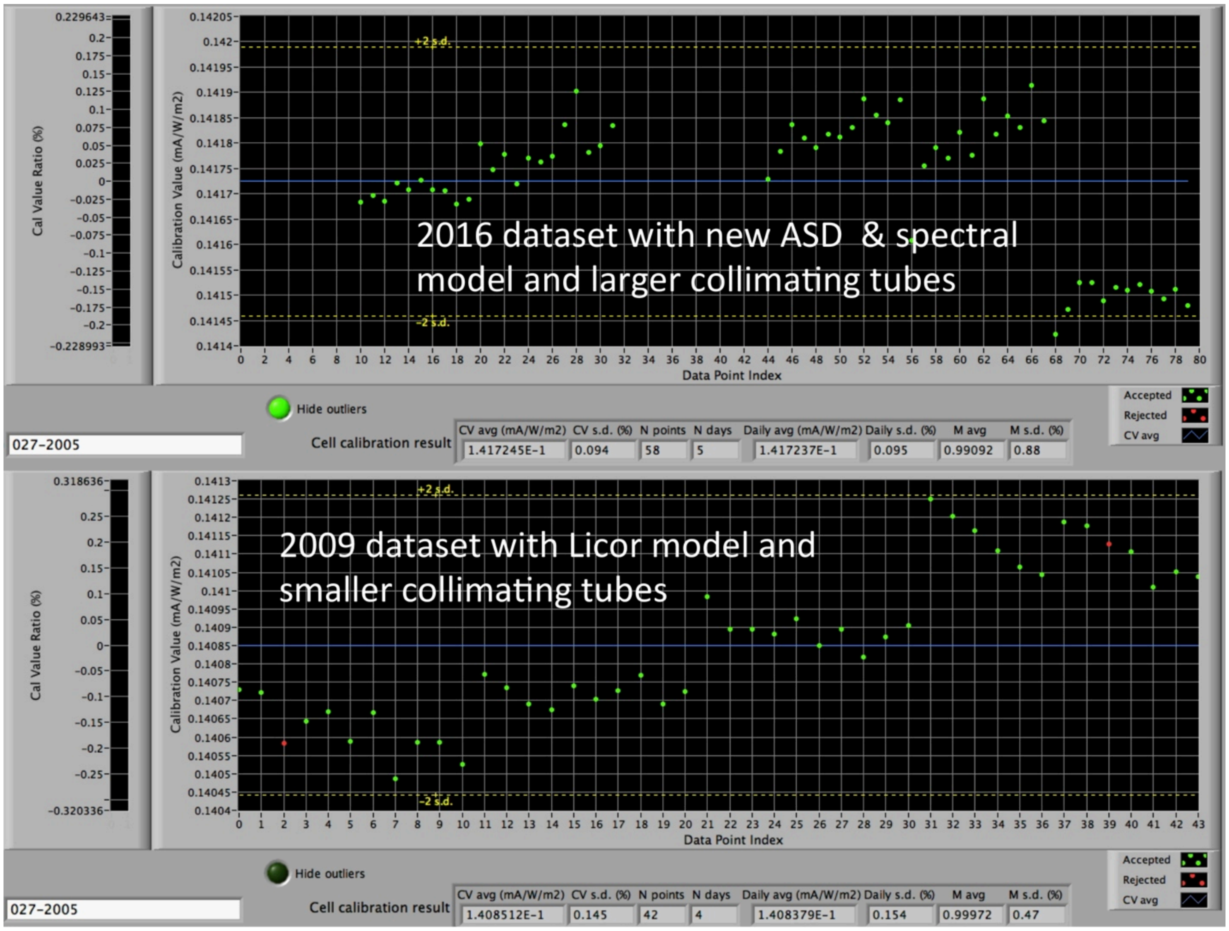


Figure 15. 2009 dataset compared against 2016 data set for the cell in Figure 13

3.3 Contacting large area cells

A lack of specificity of how to make probe contacts to cells beyond 4-wire Kelvin contacts results in a contacting-related variability in the fill factor and power that can be larger than 50% for large-area commercial silicon cells. To reduce the variability, the world uses multipoint probes to simulate ribbons. These probes have spring-loaded, waffle-shaped, pogo-pin current contacts that are on approximate 1-cm intervals with multiple voltage sense probes. The exact configuration of these multipoint probes and the use of balance resistors cause 0%–3% differences in the fill factor among calibration labs.

3.4 Elemental error analysis

The uncertainty analysis software saves the elemental errors for each uncertainty component. Figure 16 shows the elemental errors for the cell data in Figures 9 and 10. Figure 16 shows that the reference cell uncertainty is a dominant error source in I_{sc} for this cell along with smaller components because of spatial nonuniformity and the spectral correction uncertainty. The uncertainty in Voc is dominated by temperature. Figure 17 shows the elemental error sources for a typical silicon module described in Figure 11 and Figure 12. The uncertainty analysis indicates that the spatial nonuniformity error is a dominant error in the module I_{sc} with the reference device calibration uncertainty a lesser component. These same errors translate into dominant errors for the maximum power along with temperature to a lesser extent.

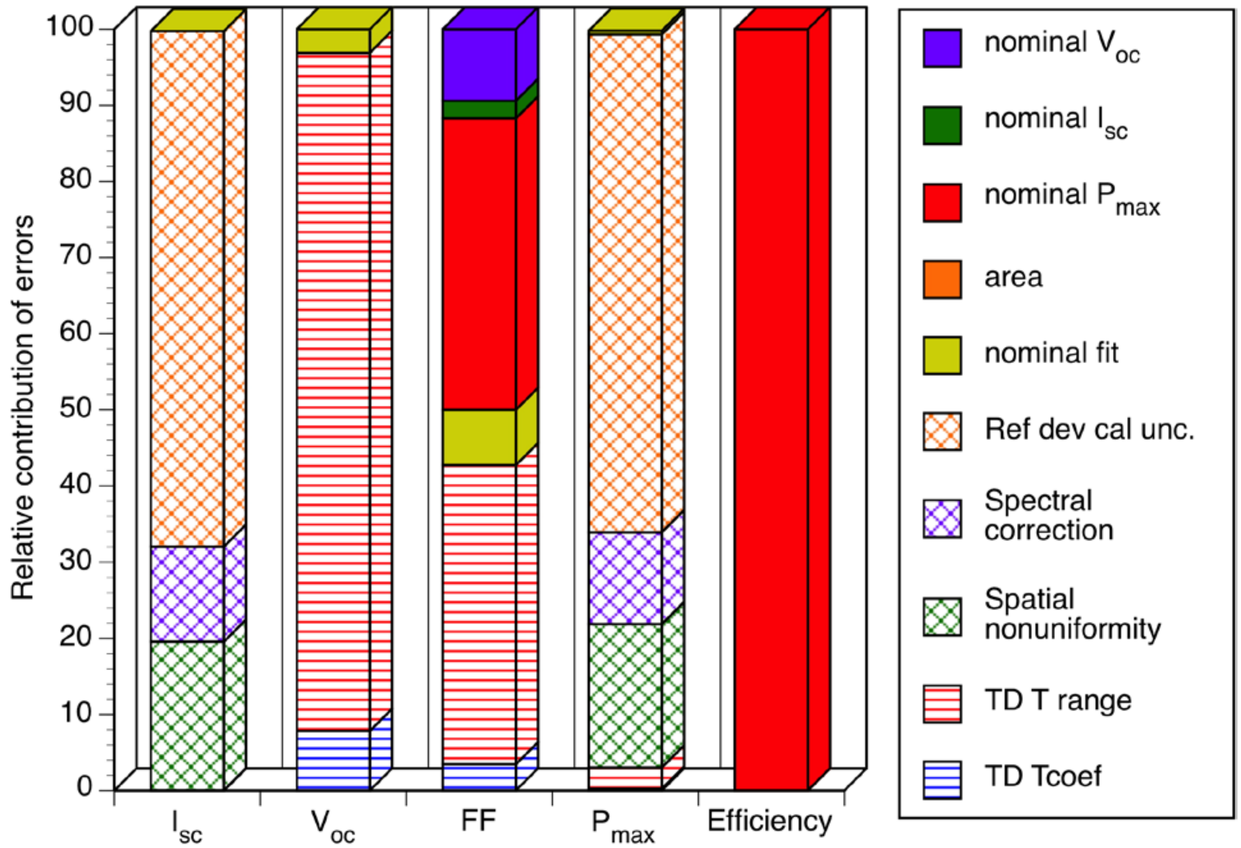


Figure 16. Elemental errors for the cell data in Figures 9 and 10

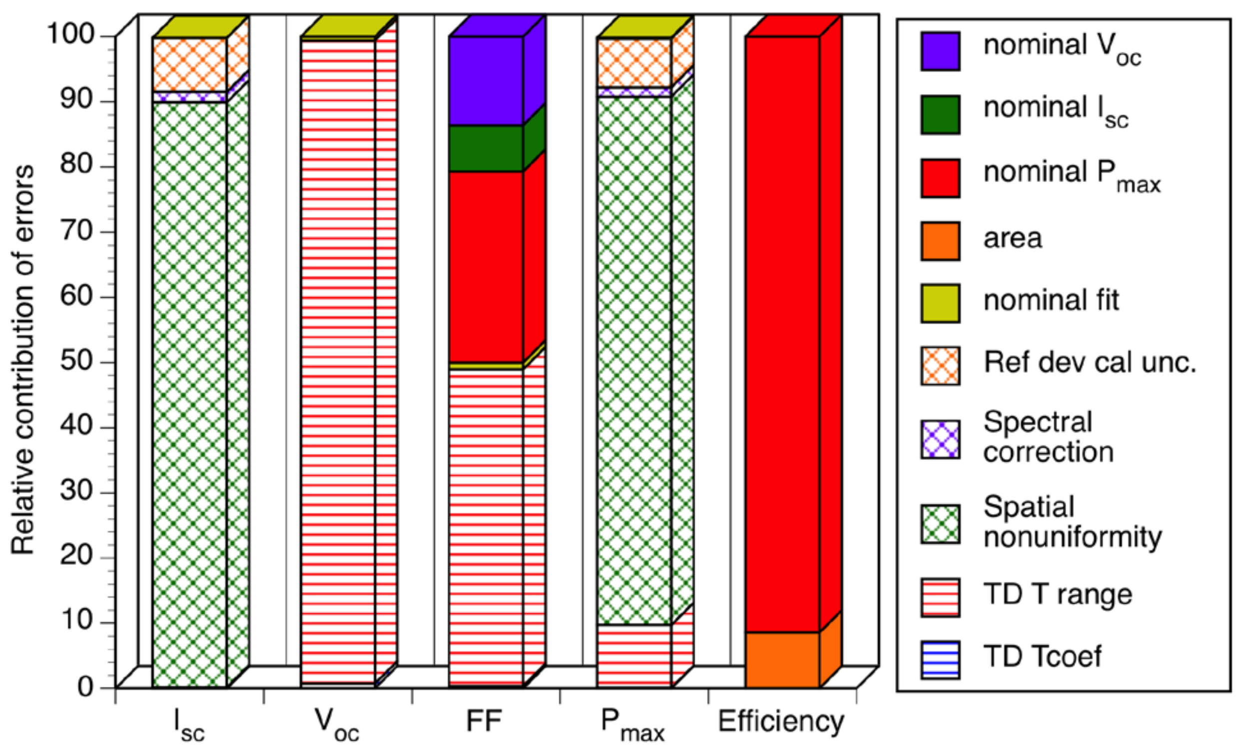


Figure 17. Elemental errors for the module data in Figures 11 and 12

4 Scope of ISO 9001 and ISO 17025 accreditation

The NREL CMP group is ISO 9001 accredited for all numerical results in reports to customers. The ISO 9001 accreditation follows the ISO 17025 quality system, except that a formal calibration certificate is not issued, a formal uncertainty analysis is not required, and a formal checklist is not used. Cells or modules that fall outside the constraints of the ISO 17025 scope are tested under the ISO 9001 scope of accreditation. The scope of our ISO 17025 accreditation is restricted to cells that are suitable for use as a reference cell and for stable, single-junction modules. Our requirements for an ISO 17025-certified calibration of a single-junction secondary reference cell or module are:

- Permanent sample identification must be marked on the sample
- Cell package constraints
    - There should be no known metastability in the short-circuit current (I_{sc}). This constraint eliminates amorphous silicon and many thin-film devices. There should be no inherent instabilities or metastable behavior such as in amorphous silicon
    - An attached temperature sensor is required for cell calibrations of type J, K, T thermocouple; a thermistor; or resistance temperature detector (RTD). The sensor type must be specified or obvious by the type of thermocouple connector
    - Two voltage and two current wires are connected to the sample
    - The cell must be mounted in a metal package for temperature control for cell calibration
    - The cell package should be mechanically sound and protected from damage during shipment and handling. An air gap between the sensor and any window is allowed
    - The maximum V_{oc} for cells is 40 V; the minimum V_{oc} is 0.1 V
    - The maximum I_{sc} for cells is 15 amperes (A); the minimum I_{sc} is 1 milliampere (mA)
    - The area must be between 0.5 cm by 0.5 cm and 20 cm by 20 cm for cells
    - Any required mating connector should be supplied with the wires identified (+, -, current, and voltage).
- Module package constraints
    - There should be no known metastability in the short-circuit current (I_{sc}). This constraint eliminates amorphous silicon and many thin-film devices. There should be no inherent instabilities or metastable behavior such as in amorphous silicon
    - The spectral responsivity of the module must be determined via a cell that is representative of the module or wires connected to a single cell in the module being calibrated
    - The maximum V_{oc} for modules is 290 V; the minimum V_{oc} is 0.5 V
    - The maximum I_{sc} for modules is 50 A; the minimum I_{sc} is 1 mA

- The area must be between 1 cm by 1 cm and 160 cm by 125 cm for modules
- Any required mating connector should be supplied with the wires identified (+, -, current, and voltage).

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GLOSSARY

^	A nominal value
~	A random variable
*	A parameter corrected to the reference irradiance
0	The 0 after the subscript D refers to reference conditions for the reference or test device
$\alpha_{I_{sc,RD_0}}$	Reference device I_{sc} temperature coefficient under the simulator spectrum [1/°C]
η	Efficiency with respect to reference conditions
λ	Wavelength
μ_C	Monitor calibration factor ($I_{sc,MD}$ / $I_{sc,RD}$)
A	Test device area
$E_{ref}(\lambda)$	Reference spectral irradiance
E_{ref}	Reference total irradiance
$E_s(\lambda)$	Measured spectral irradiance of the light source
FF	Fill factor
I_*	Irradiance corrected test device current (A)
I_{max}	Current at P_{max}
I_{TM}	Measured test device current
I_{TR}	Calibrated current of the test device under the reference conditions
I-V	Current versus voltage
I_{sc,MD_0}	Monitor cell calibrated current under the reference spectrum at the reference irradiance (A)
$I_{sc,MD}$	Monitor cell measured short-circuit current
I_{sc,RD_0}	Reference device calibrated current at the reference temperature, spectrum, and irradiance (A)
$I_{sc,RD}$	Reference device measured short-circuit current
K	Number of transfer calibration samples
M	Spectral mismatch parameter (unit less)
P_{max}	Test maximum power under reference conditions
R_I	Current sense resistor used to measure test device current (Ω)
$R_{I_{sc,RD_0}}$	Current sense resistor used to measure the reference device current (Ω)
S	Spatial nonuniformity of light source correction factor (unit less)
$S_t(\lambda)$	Measured spectral responsivity of the test device
$S_r(\lambda)$	Measured spectral responsivity of the reference cell
T_{RD}	Reference device temperature during the transfer calibration (°C)
T_{RD_0}	Temperature reference device calibrated at (°C)
T_{TD}	Device under test temperature (°C)
T_{TD_0}	Reference conditions temperature (°C)
$U(I_{sc,*})$	Combined uncertainty in the short-circuit current of the test device with respect to reference conditions
$U(\eta)$	Uncertainty in efficiency
$U(A)$	Uncertainty in area
$U(FF)$	Uncertainty in the fill factor
$U(M)$	Uncertainty in M
$U(P_{max})$	Uncertainty in the fit of the restricted current versus voltage data
$U(S)$	Uncertainty in current related to spatial nonuniformity
$U(V_{oc})$	Uncertainty in V_{oc}
V	Measured test device voltage (V)
V_I	Test device current as measured by the voltage across a current sense resistor (V)
V_*	Irradiance corrected test device voltage (V)

$V_{I_{sc,MD}}$ Monitor cell current as measured by the voltage across a current sense resistor (V)

$V_{I_{sc,MD,k}}$ k^{th} Monitor device current transfer calibration voltage sample as measured by the voltage across a current sense resistor (V)

$V_{I_{sc,RD,k}}$ k^{th} Reference device current transfer calibration voltage sample as measured by the voltage across a current sense resistor (V)

V_{max} Voltage at P_{max} (V)

V_{oc} Open-circuit voltage (V)

APPENDIX

The photovoltaic (PV) cell and module performance laboratory is certified by the American Association for Laboratory Accreditation (A2LA) to perform International Organization for Standardization (ISO) 17025-accredited calibrations. The scope of the group's ISO 17025 accreditation and certificate of accreditation are shown below along with the certificate of ISO 9001 accreditation. The group's ISO 9001 accreditation applies to all numerical results in reports to customers. The ISO 9001 quality system follows the ISO 17025 quality system except in the requirement of an approved calibration certificate and formal uncertainty analysis.

All equipment in the laboratory that produces a numerical result must be calibrated by a national metrology laboratory such as the National Institute of Standards and Technology (NIST) or by an ISO 176025 accredited calibration lab. NIST-traceable calibrations are not adequate for the group's quality system. NREL performs many of its calibrations in-house using NIST-calibrated lamps, NIST-calibrated detectors, (PTB)-calibrated reference cells, and ISO 17025-calibrated labs for length, temperature, voltage, and current standards. The calibration traceability path is provided for all of the group's PV cell and module calibrations.


ilac-MRA A2LA

Accredited Laboratory

A2LA has accredited

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)

Golden, CO

for technical competence in the field of

Calibration

This laboratory is accredited in accordance with the recognized International Standard ISO/IEC 17025:2005 *General requirements for the competence of testing and calibration laboratories*. This laboratory also meets any additional program requirements in the field of calibration. This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (*refer to joint ISO-ILAC-IAF Communiqué dated 8 January 2009*).

AMERICAN ASSOCIATION FOR LABORATORY ACCREDITATION CORPORATE SEAL 1978 DISTRICT OF COLUMBIA A2LA

Presented this 29th day of September, 2014.

Senior Director of Quality and Communications
For the Accreditation Council
Certificate Number 1239.02
Valid to November 30, 2016
Revised February 24, 2016

For the calibrations to which this accreditation applies, please refer to the laboratory's Calibration Scope of Accreditation.

SCOPE OF ACCREDITATION TO ISO/IEC 17025:2005

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)
PV Cell and Module Group, Broadband Outdoor Radiometer Calibration (BORCAL) Group & Spectral Irradiance Group (SIG)
15013 Denver West Parkway, MS: RSF040
Golden, CO 80401-3305
John Morris Phone: 303 275 4618

CALIBRATION

Valid To: November 30, 2016 Certificate Number: 1239.02

In recognition of the successful completion of the A2LA evaluation process, accreditation is granted to this laboratory to perform the following calibrations[1]:

I. Optical Quantities

Parameter/Equipment	Range	CMC[2, 3] (±)	Comments
Primary Photovoltaic Reference Cells –			ASTM E1125 with:
DC Current	(0.1 to 200) mA	0.91 %	Agilent 34401, precision resistor
Photovoltaic Reference Cells –			ASTM E948, IEC 60904-1 (Sec. 4) with:
DC Voltage	(0.1 to 40) V	0.2 %	Agilent 34410
DC Current	1 mA to 15 A	1.1 %	Agilent 34410 precision resistor
Power	1 mW to 600 W	1.2 %	Agilent 34410
Area	(0.5 × 0.5) cm to (20 × 20) cm	0.1 %	Nikon-NEXIV

Parameter/Equipment	Range[4]	CMC[2, 3, 5] (±)	Comments
Photovoltaic Reference Modules –			ASTM E1036, IEC 60904-1 (Sec. 4) with:
DC Voltage	(0.4 to 290) V	1.2 %	Agilent 34401
DC Current	(0.1 to 50) A		Agilent 34401, precision resistor
	A ≤ (30 × 30) cm A > (30 × 30) cm	1.6 % 3.2 %	
Power	50 mW to 1200 W		Agilent 34401
	A ≤ (30 × 30) cm A > (30 × 30) cm	1.9 % 3.3 %	
Area	(1 × 1) cm to (160 × 125) cm	0.7 %	Tape measure
Broadband Outdoor Radiometer Calibration –			
Pyranometers –			
Irradiance Level: Direct Beam ≥ 700 W/m^2 ± 0.35 %	Minimum Zenith Angle Range: Up to 30º (30 to 60)°	 0.6 % 1.2 %	Traceability: SI, through World Radiometric Reference (WRR)
Diffuse: 10 W/m^2 to 150 W/m^2 ± (2.6 % + 1 W/m^2)	Maximum Zenith Angle Range: (16.5 to 80)°		Reference irradiance: the outdoor direct beam irradiance from the sun disk and the diffuse irradiance
Pyrheliometers –			
Irradiance Level: Direct Beam ≥ 700 W/m^2 ± 0.35 %	Minimum Zenith Angle Range: (30 to 60)° Maximum Zenith Angle Range: (16.5 to 80)°	0.78 %	

Parameter/Equipment	Range	CMC[2, 3] (±)	Comments
Spectral Irradiance – Spectroradiometer (250 to 2400) nm	250 nm 350 nm 450 nm 555 nm 655 nm 900 nm 1600 nm 2000 nm 2300 nm 2400 nm	2.1 % 1.7 % 1.4 % 1.4 % 1.3 % 1.3 % 1.2 % 1.2 % 1.2 % 1.6 %	ASTM G138 w/: NIST spectral irradiance standard 1000 W FEL lamp

[1] This laboratory is conditionally available for commercial service.

[2] Calibration and Measurement Capability Uncertainty (CMC) is the smallest uncertainty of measurement that a laboratory can achieve within its scope of accreditation when performing more or less routine calibrations of nearly ideal measurement standards or nearly ideal measuring equipment. CMCs represent expanded uncertainties expressed at approximately the 95 % level of confidence, usually using a coverage factor of $k = 2$. The actual measurement uncertainty of a specific calibration performed by the laboratory may be greater than the CMC due to the behavior of the customer's device and to influences from the circumstances of the specific calibration.

[3] In the statement of CMC, percentages are percentage of reading, unless otherwise indicated.

[4] Zenith angle range of calibration of the NREL location will vary with the day of year and sky conditions during the calibration event, and are limited to the zenith angle ranges listed on the scope of accreditation. In addition, the maximum zenith angle range might change during the calibration event due to the irradiance level limitation.

[5] The uncertainty resulting from the UUT's performance outdoor will be added (RSS) to the uncertainty of the nominal values; therefore the combined uncertainty will vary based on the instrument model, serial number, and the reported environmental conditions during the calibration event.

Orion Registrar, Inc.

Thorough and Fair Auditing

Certificate of Certification

Orion Registrar, Inc. - USA

This is to certify the Quality Management System of:

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
USA

Has been assessed by Orion Registrar and found to be in compliance with the following Quality Standard:

ISO 9001:2008

The Quality Management System is applicable to:

The Management of Metrology Laboratory, Construction Quality Assurance, Records Management, Environment, Safety, Occupational Health, Physical Security, Emergency Preparedness, Sustainability, Prime Contract Management Activities, Contract and Business Services, and Calibration and Efficiency Measurements of Photovoltaic Cells and Modules.

The Certification period is from

August 24, 2014 to August 23, 2017

This certification is subject to the company maintaining its system to the required standard, and applicable exceptions, which will be monitored by Orion.

Client ID 01954-00001. Certificate ID A0003253-2
IAF / NAICS / SIC Code(s): 35 / 92711 / 9661

ANAB ACCREDITED

Paul M. Burck, President — 7/2/2014 (Date)

IAF — Member of Multilateral Recognition Arrangement

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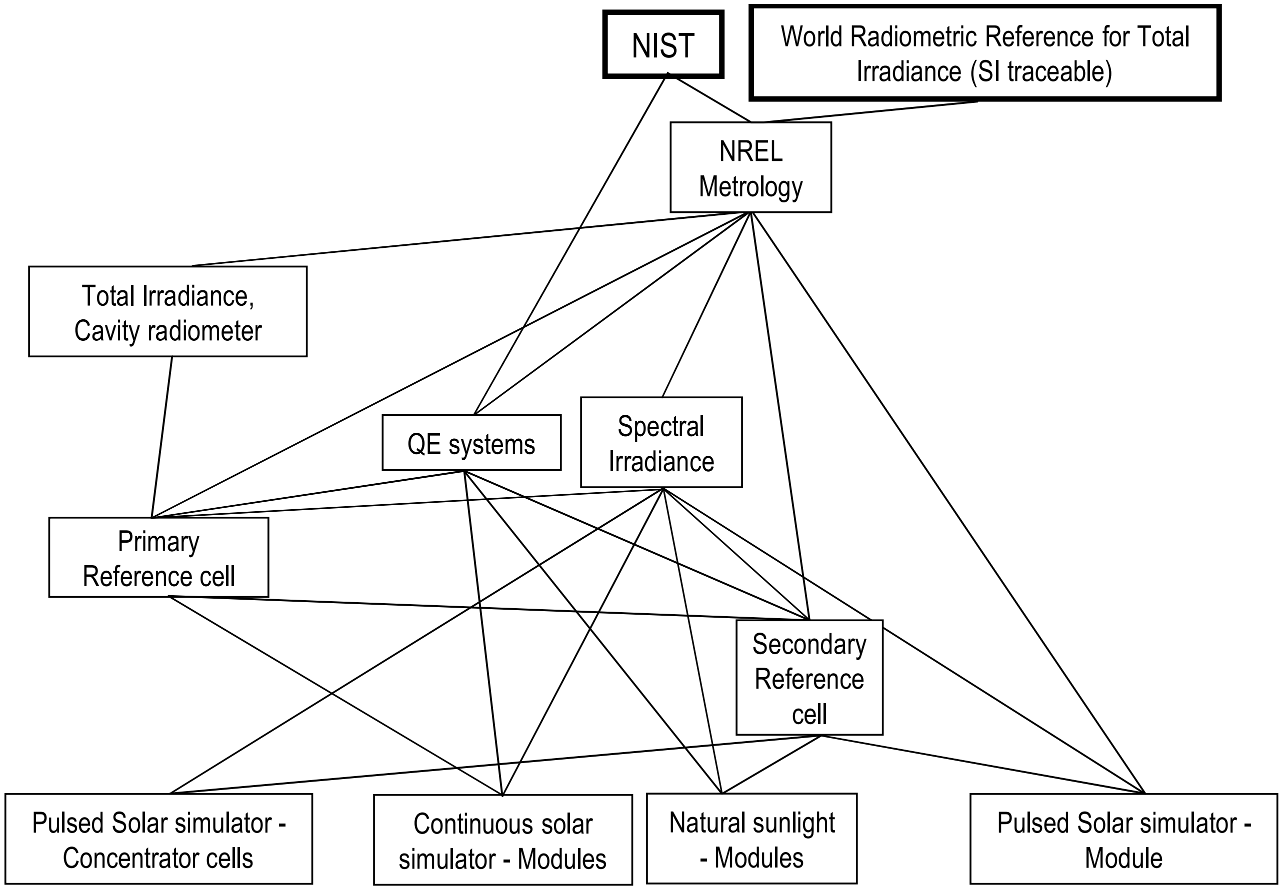
NIST
World Radiometric Reference for Total Irradiance (SI traceable)
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Natural sunlight - Modules
Pulsed Solar simulator - Module