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subject: Performance model for Semprius module RDD-MOD-296, PSEL 2941

This memorandum documents a performance model for the Semprius module determined from measurement and characterization of module performance at Sandia National Laboratory's Photovoltaic System Evaluation Laboratory (PSEL). Testing was conducted outdoors on Sandia's two-axis tracker (ATS1) in April and May, 2012. Sandia provided an initial test summary and coefficients for the standard Sandia Array Performance Model (SAPM) [1] on May 30, 2012. Based on feedback from Scott Burroughs, Etienne Menard, and Chris Cameron, Sandia re-examined the fit of the model to the measured performance and arrived at a modified version of SAPM, with accompanying coefficients, that better describes module electrical performance.

Standard SAPM

The standard version of SAPM [1] was developed for flat-plate, crystalline silicon modules but has been found to adequately describe electrical performance of a wide variety of PV technologies ([2]). SAPM comprises the following fundamental equations to describe the electrical performance of a single module:

$$I_{SC} = I_{SC0} E_e \left(1 + \alpha_{Isc}\left(T_C - T_0\right)\right) \tag{1}$$

$$I_{MP} = I_{MP0}\left(C_0 E_e + C_1 E_e^2\right)\left(1 + \alpha_{Imp}\left(T_C - T_0\right)\right) \tag{2}$$

$$V_{OC} = V_{OC0} + N_S \delta\left(T_C\right)\ln\left(E_e\right) + \beta_{Voc}\left(T_C - T_0\right) \tag{3}$$

$$V_{MP} = V_{MP0} + C_2 N_S \delta\left(T_C\right)\ln\left(E_e\right) + C_3 N_S\left(\delta\left(T_C\right)\ln\left(E_e\right)\right)^2 + \beta_{Vmp}\left(T_C - T_0\right) \tag{4}$$

$$E_e \approx f_1\left(AM\right)\left(E_b f_2\left(AOI\right) + f_d E_{diff}\right)/E_0 \tag{5}$$

$$\delta\left(T_C\right) = \frac{nk\left(T_C + 273.15\right)}{q} \tag{6}$$

The coefficients I_{SC0}, I_{MP0}, V_{OC0}, V_{MP0} define short-circuit current, maximum power current, open circuit voltage, and maximum power voltage at standard test conditions (STC); herein we assume that STC is defined at $T_0 = 25°\text{C}$ and $E_0 = 1000\ \text{W/m}^2$ for concentrating PV systems. The coefficients α_{Isc} (1/°C), α_{Imp} (1/°C), β_{Voc} (V/°C), and β_{Vmp} (V/°C) define how current and voltage change with cell temperature T_C; the empirical coefficients C_0, C_1, and C_2, C_3, describe how maximum power current and voltage, respectively, change with effective irradiance E_e. Effective irradiance E_e (suns) is the incident solar power that is converted to electricity, and is normally estimated from incident beam irradiance E_b (W/m^2) and diffuse irradiance E_{diff} (W/m^2). E_e is modified by reflection losses at the module's surface, expressed by the empirical function f_2 (unitless) of angle of incidence AOI (degrees), and by spectrum changes in the of solar irradiance due to atmospheric attenuation, quantified by the empirical function f_1 (unitless) of absolute air mass AM (unitless). The thermal voltage $\delta(T_C)$ (V) is expressed in terms of the diode quality factor n (unitless), Boltzmann's constant $k = 1.38\times10^{-23}$ (J/K) and the elementary charge $q = 1.6\times10^{-19}$ (C).

SAPM for the Semprius module: Piecewise model defined by air mass

The Semprius module uses a triple-junction cell and the module's electrical performance varies with the solar spectrum more than does the performance of modules using single junction cells. We found it necessary to define coefficients for SAPM in a piecewise manner in order to replicate the measured electrical performance. Because solar spectrum is generally parameterized by air mass AM and this quantity is convenient for predictive modeling, we use ranges for AM to define coefficients.

We produced a two-part model (Table 2) and a three-part model (Table 3). The two-part model may be easier to implement in software packages such as NREL's System Advisor Model but the two-part model shows bias in P_{MP} around $AM = 1.8$ that is somewhat reduced when the three-part model is used (Figure 1). In either model, predictions are ± 2 W of measurements.

For the two-part model, coefficients for the low air mass part of the model are estimated using IV curves recorded for $AM \le 1.6$, and coefficients for the high air mass part of the model are estimated using IV curves recorded for $AM \ge 2.0$. For the three-part model, coefficients for the low and high air mass parts of the model are estimated as for the two-part model. In addition, data corresponding to $1.6 < AM < 2.0$ are used to define a mid-air mass part of the model.

Effective irradiance

The general formulation for effective irradiance E_e (Eq. (5)) involves both the beam irradiance E_b and the diffuse irradiance E_{diff}. However, in the case of HCPV, the contribution to electrical energy from diffuse light is typically very small, and so we set the diffuse utilization factor $f_d = 0$.

Air mass correction

We use polynomials of degree up to 2 to define the empirical function f_1:

$$f_1\left(AM\right) = a_0 + a_1 AM + a_2 AM^2 \tag{7}$$

We did not find it necessary to use higher order polynomials to achieve a good fit of f_1 to data.

For the two-part model, the empirical function f_1 is modeled by two lines; their intersection at approximately $AM = 1.8$ provides the value of air mass that divides the two model parts in implementation. For the three-part model, the empirical function f_1 is modeled by two lines with a parabolic segment in between. The fit of f_1 to data is illustrated by Figure 2 and Figure 3 for the two and three part models, respectively. For the two-part model the over-prediction of f_1 near $AM = 1.8$ is chiefly responsible for the bias in P_{MP} and results from approximating data that follow a curve with two line segments. Over-prediction of f_1 directly biases predicted E_e (Eq. (5)) and hence I_{SC} and I_{MP}. Consequently in the three-part model the function f_1 uses a quadratic to model data for $1.6 < AM < 2.0$ and the residuals for f_1 are significantly improved (Figure 3b). We note that the piecewise definition of f_1 is not continuous in the three-part model.

Angle of incidence correction

For unity concentration flat-plate PV modules, optical transmission of the glass changes as a function of the angle of incidence (AOI). In the typical formulation of the SAPM, we use a polynomial of degree 5 to define the empirical function f_2 to describe this change in transmission. Because high-concentration PV (HCPV) usually are mounted on a 2-axis solar tracker, for predictive modeling we assume that AOI is approximately 0, i.e., we assume perfect tracking. Consequently we recommend the empirical function $f_2\left(AOI\right) = 1$. At present, the SAPM does not include a term accounting for tracking error. The SAPM could be extended to include this term if it is anticipated that the time series of tracking error would be available as a model input.

Our outdoor testing included measuring I-V curves with the tracker pointed off-normal, to characterize the angle of acceptance for the Semprius module. Sandia obtains these data by sweeping I-V curves while mispointing the module in elevation, from about -2 degrees to +2 degrees. We recorded I_{MP} over a range of values for AOI (Figure 5); at $AOI = 0.7°$, I_{MP} falls to 90% of its value when $AOI = 0°$. We fit a 6th order polynomial to the test results in case a prediction is desired of I_{MP} as a function of AOI. The polynomial does an adequate job of fitting the measured data to an angle of incidences of 1.5 degrees; at angles of incidence greater than 1.5 degrees the module can be assumed to have negligible power production.

Electrical performance

For the Semprius module, we add a cubic term (in red) to the equation for V_{MP} and use Eq. (8) in place of Eq. (4):

$$V_{MP} = V_{MP0} + C_2 N_S \delta(T_C)\ln(E_e) + C_3 N_S \left(\delta(T_C)\ln(E_e)\right)^2 + C_8 N_S \left(\delta(T_C)\ln(E_e)\right)^3 + \beta_{Vmp}(T_C - T_0) \quad (8)$$

The cubic term corrects a bias in predicted V_{MP} at high AM values (Figure 4). However, the overall effect of the bias on P_{MP} is small; consequently, coefficients for the standard SAPM equation (Eq. (4)) are also provided in Table 2 and Table 3.

Cell temperatures used to estimate model coefficients

In the case of HCPV modules, where there is typically a long thermal path length from a cell to the nearest temperature measurement point (e.g. the back side or heat sink), Sandia calculates the cell temperature by a method known as the V_{OC}, I_{SC} method [3]. The method relies on cell coefficients obtained from other testing, namely:

- $I_{SC0,cell}$ the cell I_{SC} (A) at STC conditions;
- $V_{OC0,cell}$ the cell V_{OC} (V) at STC conditions;
- $\beta_{Voc,cell}$ the temperature coefficient (V/°C) for V_{OC} for the cell;
- n_{cell} diode factor representative of a single cell.

The calculated cell temperatures were used in the process of estimating module parameters.

To calculate cell temperature from measured V_{OC} and I_{SC}, first effective irradiance Ee is approximated using the measured module I_{SC} (Eq. (1)):

$$E_e = I_{SC} / \left(N_P I_{SC0,cell}\right) \quad (9)$$

where N_P is the number of strings in parallel in the module and $I_{SC0,cell}$ is the supplied STC value for I_{SC} of a single cell. This approximation of Ee is substituted in Eq. (3) where coefficients are adjusted to represent a cell rather than for the module as a whole:

$$V_{OC} = N_S V_{OC0,cell} + N_S \delta(T_C)\ln\left(I_{SC} / \left(N_P I_{SC0,cell}\right)\right) + N_S \beta_{Voc,cell}(T_C - T_0) \quad (10)$$

and Eq. (10) is solved for T_C in terms of (measured) V_{OC} and I_{SC}. Calculation of the thermal voltage term $\delta(T_C)$ requires a value for the diode factor for a cell, n_{cell}. Cell-level values were provided to Sandia by Semprius as indicated in Table 1.

Table 1. Cell-level parameters given by Semprius used in calculation of cell temperature

Parameter	Value
$V_{OC0,cell}$	3.430 V/cell
$I_{SC0,cell}$	0.0460 A/cell
$\beta_{Voc,cell}$	-4.3 mV/°C/cell
n_{cell}	4.2 (unitless)

Note: Values provided at SRC, assumed to be DNI=1000 W/m^2, T_C = 25°C, and AMa=1.5.

Predictive model for cell temperature

When modeling HCPV cell temperature using weather input, SAPM uses Eq. (11) and Eq. (12) to estimate cell temperature.

$$T_m = DNI \times \exp\left(a + b \times WS\right) + T_a \tag{11}$$

$$T_c = T_m + \frac{E}{E_0} \times \Delta T \tag{12}$$

First, module temperature T_m (°C) is estimated from ambient temperature T_a (°C), wind speed *WS* (m/s), direct normal irradiance *DNI* (W/m^2) and two empirically derived coefficients, *a*, and *b*. Then cell temperature is calculated from the module temperature, incident POA irradiance *E* (W/m^2) and an empirically determined temperature difference ΔT (°C) between the cell and module back plane.

To calculate *a* and *b*, system and weather data are filtered to include only clear-sky, high sun elevation time periods. The coefficients *a* and *b* are determined by least-squares regression between $\ln\left(\frac{T_m - T_a}{DNI}\right)$ and *WS*; results are illustrated by Figure 6.

Determination of ΔT is based on Eq. (12)

$$\Delta T_i = \frac{E_0}{E_i}\left(T_{c,i} - T_{m,i}\right) \tag{13}$$

where $i = 1, \ldots, N$ indexes the measurements. In this estimation, cell temperature T_c is calculated from Eq. (10), module temperature T_m is the average of measurements by thermocouples attached to the back of the module, and E is plane of array (POA) irradiance. We estimate ΔT as the average of the sample $\{\Delta T_i\}$ as illustrated by Figure 7. We found that using POA irradiance *E* results in a lower standard deviation for $\{\Delta T_i\}$ (0.46 °C) than results when DNI is used in place of *E* (standard deviation of 0.53 °C) but for convenience we provide values for ΔT for both cases (e.g. if DNI is available, but global POA is not). Figure 7 also indicates a slight dependence of ΔT on sun elevation angle (or equivalently on DNI or POA irradiance), but the range of the dependence is relatively small and thus we did not see any significant model improvement to be gained by representing this dependence explicitly in Eq. (12).

Table 2. Coefficients for the two-part SAPM model.

For $AM \leq 1.8$				For $AM > 1.8$			
α_{Isc} (1/°C)	4.83E−4	I_{SC0} (A)	**1.0172**	α_{Isc} (1/°C)	7.77E−4	I_{SC0} (A)	1.0172
α_{Imp} (1/°C)	2.32E−4	I_{MP0} (A)	**0.9947**	α_{Imp} (1/°C)	2.32E−4	I_{MP0} (A)	0.9944
β_{Vmp} (V/°C)	−0.1472	V_{MP0} (V)	**90.916**	β_{Vmp} (V/°C)	−0.1472	V_{MP0} (V)	88.555 (89.273)*
β_{Voc} (V/°C)	−0.1290	V_{OC0} (V)	**103.00**	β_{Voc} (V/°C)	−0.1290	V_{OC0} (V)	103.02
C_0	0.9196	a_0	0.892	C_0	0.9892	a_0	1.14
C_1	0.0804	a_1	0.0725	C_1	0.0108	a_1	−0.067
n	4.383	a_2	0	n	4.299	a_2	0
C_2	1.7636			C_2	−3.7087 (−2.380)*		
C_3	−28.477			C_3	−33.0179 (−13.039)*		
C_8	0			C_8	−85.7881 (0)*		

Note: **Bold** indicates values at standard test conditions (25°C and 1000 W/m^2).
Note: Grey shading indicates values derived from cell measurements rather than from module testing.
Note: * indicates alternate value using standard SAPM equation for V_{MP}.

Table 3. Coefficients for the three-part SAPM model.

For $AM \le 1.6$		For $1.6 < AM < 2.0$		For $AM \ge 2.0$	
α_{Isc} (1/°C)	4.83E–4	α_{Isc} (1/°C)	6.30E–4 #	α_{Isc} (1/°C)	4.83E–4
α_{Imp} (1/°C)	2.32E–4	α_{Imp} (1/°C)	2.32E–4	α_{Imp} (1/°C)	2.32E–4
β_{Vmp} (V/°C)	–0.1472	β_{Vmp} (V/°C)	–0.1472	β_{Vmp} (V/°C)	–0.1472
β_{Voc} (V/°C)	–0.1290	β_{Voc} (V/°C)	–0.1290	β_{Voc} (V/°C)	–0.1290
I_{SC0} (A)	**1.0172**	I_{SC0} (A)	1.0172	I_{SC0} (A)	1.0172
I_{MP0} (A)	**0.9947**	I_{MP0} (A)	0.9820	I_{MP0} (A)	0.9944
V_{MP0} (V)	**90.916**	V_{MP0} (V)	91.473	V_{MP0} (V)	88.555 (89.273)*
V_{OC0} (V)	**103.00**	V_{OC0} (V)	102.97	V_{OC0} (V)	103.022
C_0	0.9196	C_0	1.0277	C_0	09892
C_1	0.0804	C_1	–0.0277	C_1	0.0108
n	4.383	n	3.929	n	4.2987
C_2	1.7636	C_2	6.5068	C_2	–3.7087 (–2.380)*
C_3	–28.477	C_3	226.27	C_3	–33.0179 (–13.039)*
C_8	0	C_8	0	C_8	–85.7881 (0)*
a_0	0.892	a_0	0.4974	a_0	1.1400
a_1	0.0725	a_1	0.5738	a_1	–0.0670
a_2	0	a_2	–0.1601	a_2	0

Note: **Bold** indicates values at standard test conditions (25°C and 1000 W/m^2).
Note: Grey shading indicates values derived from cell measurements rather than from module testing.
Note: * indicates alternate value using standard SAPM equation for V_{MP}.
Note: # calculated as the average of α_{Isc} for low and high AM ranges.

Table 4. Coefficients common to both the two-part and three-part SAPM models.

b_0	1	a	-3.6347
b_1 through b_5	0	b	-0.0830
f_d	0	ΔT	19.1 (for $E = POA$) 20.95 (for $E = DNI$)

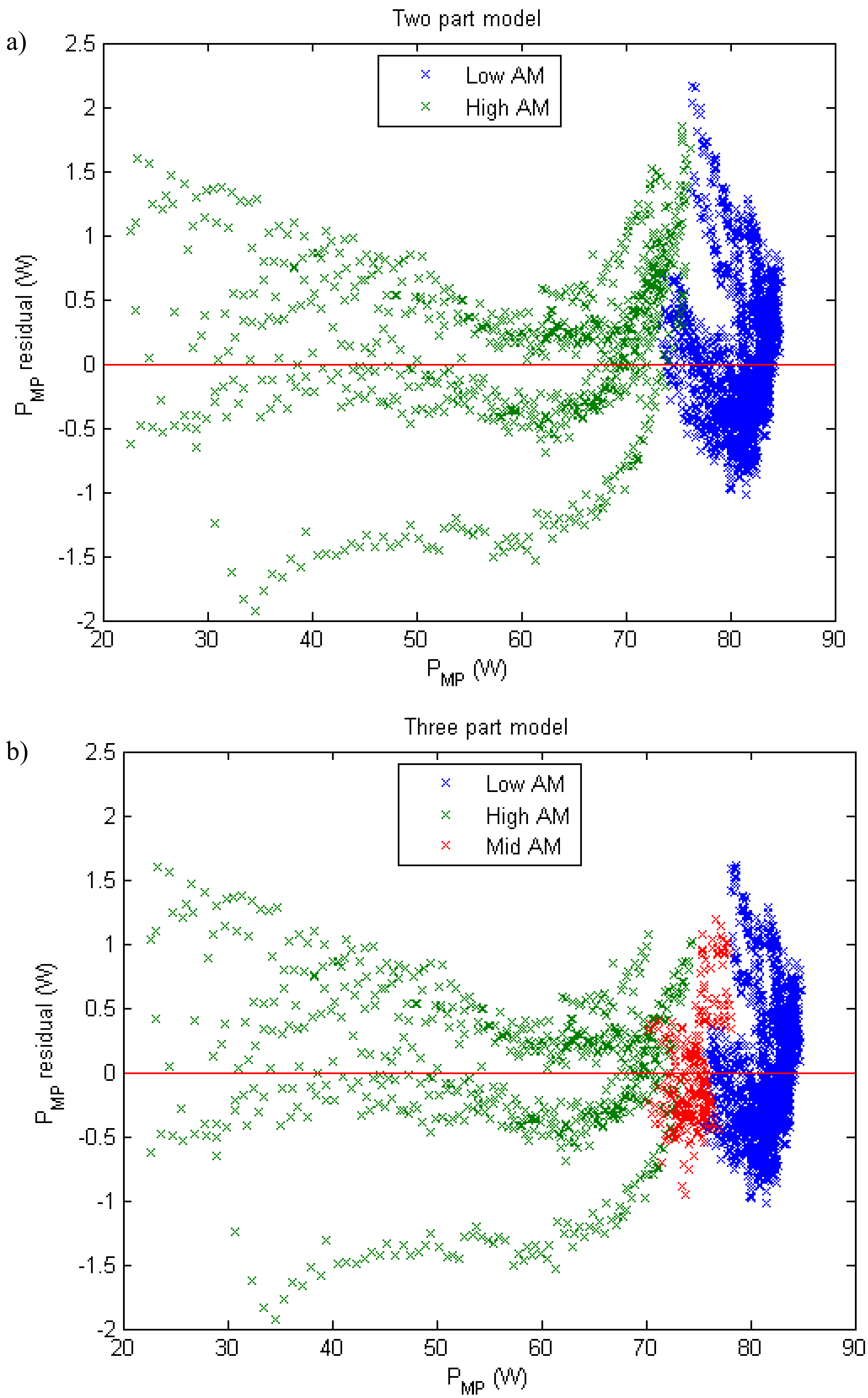

Figure 1. Residuals for P_{MP}: (a) two part model; (b) three part model.

a)

b)

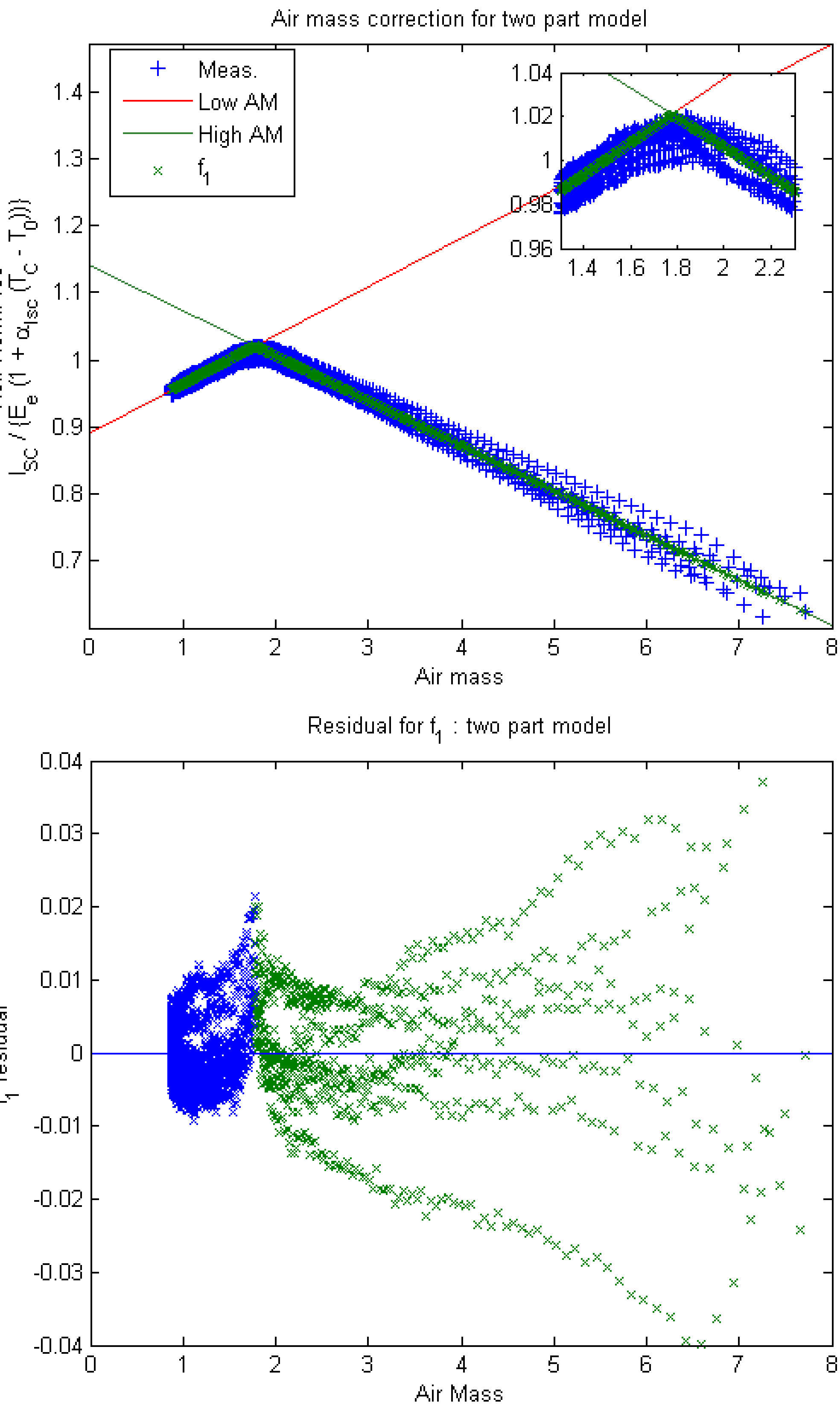

Figure 2. Air mass correction (a) and its residual (b): two part model.

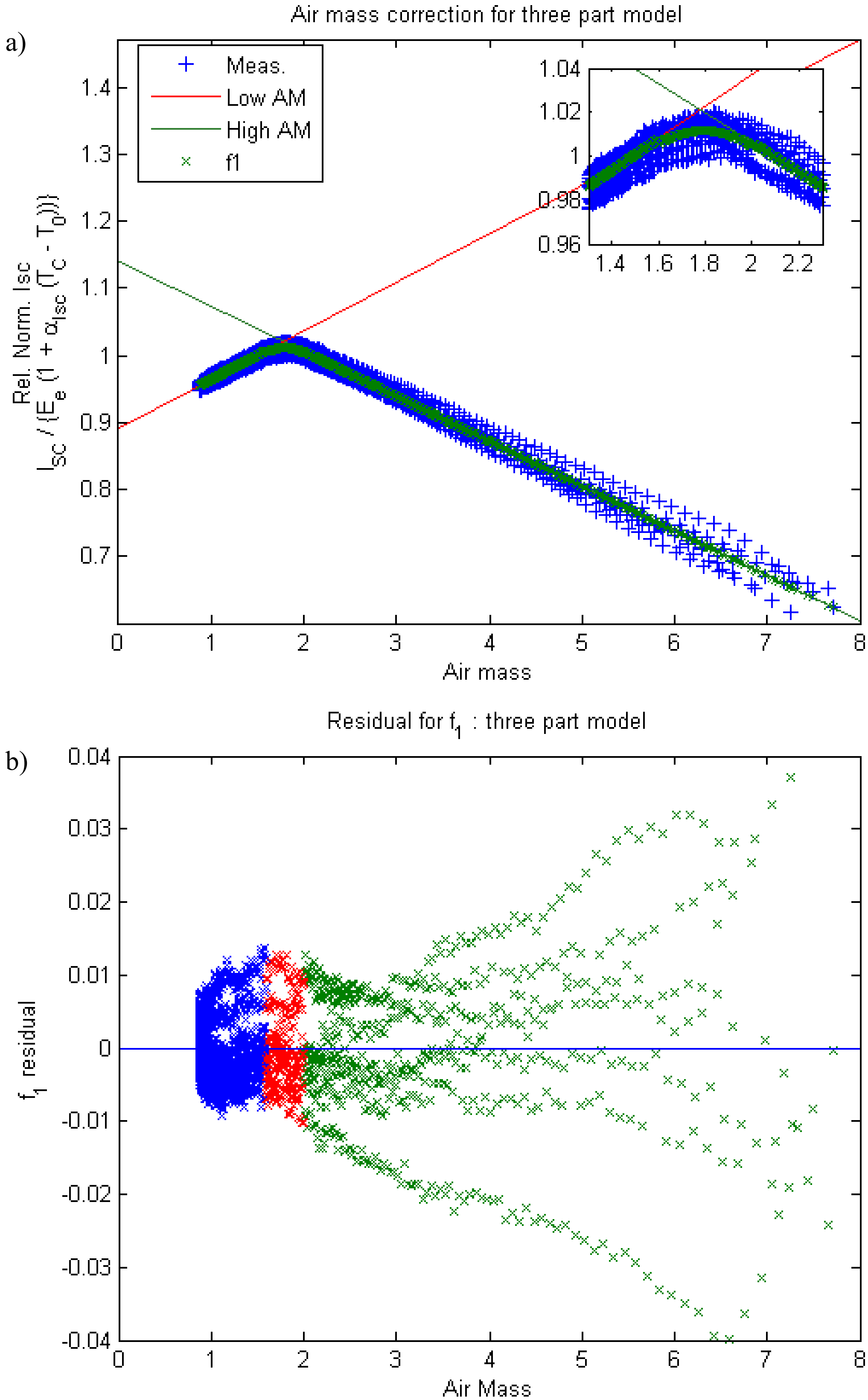

Figure 3. Air mass correction (a) and its residual (b): three part model.

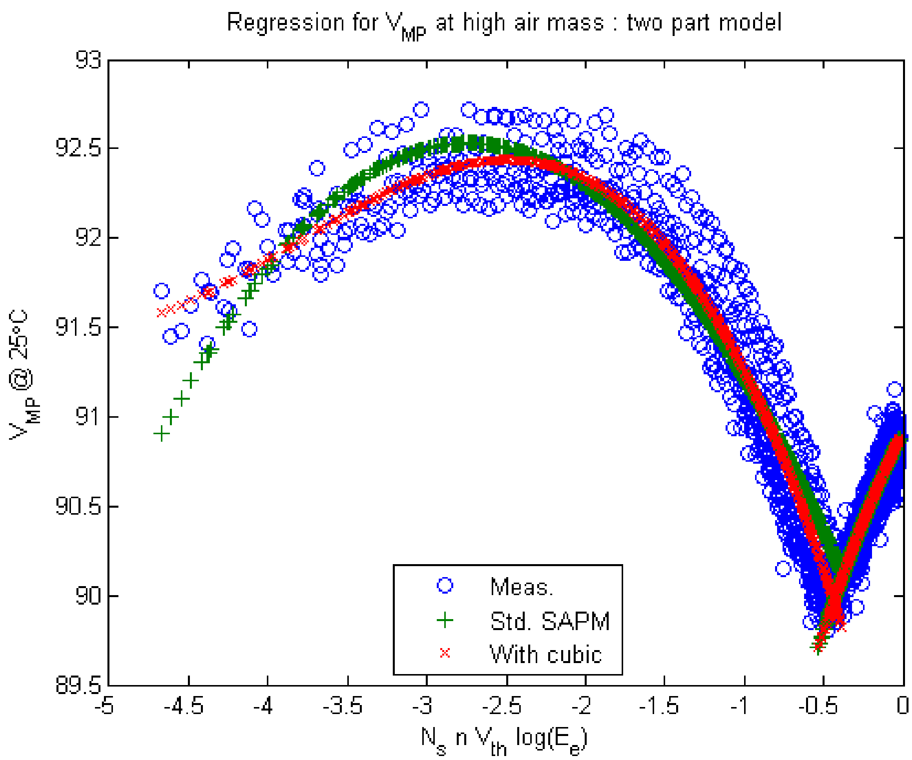

Figure 4. Regression for V_{MP} : two part model (three part model similar).

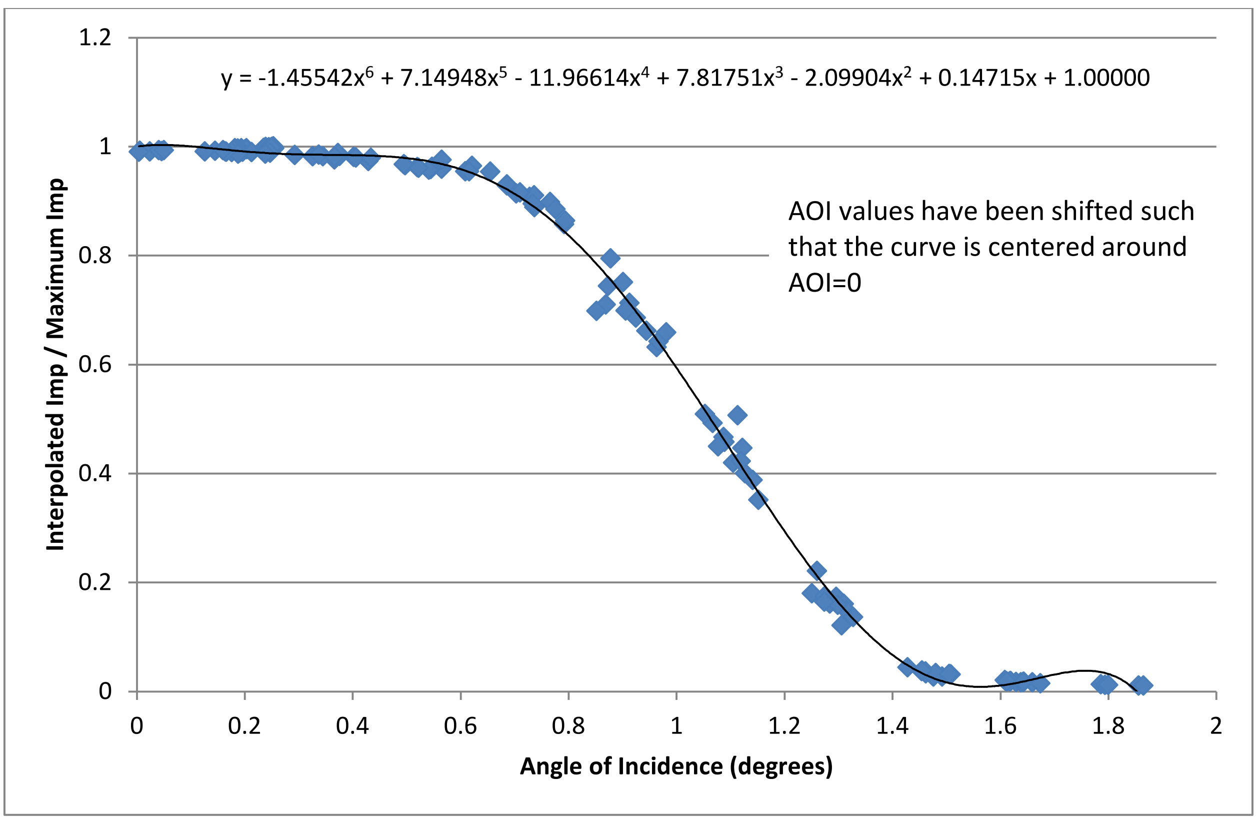

Figure 5. Acceptance angle test results (regression fit for convenience).

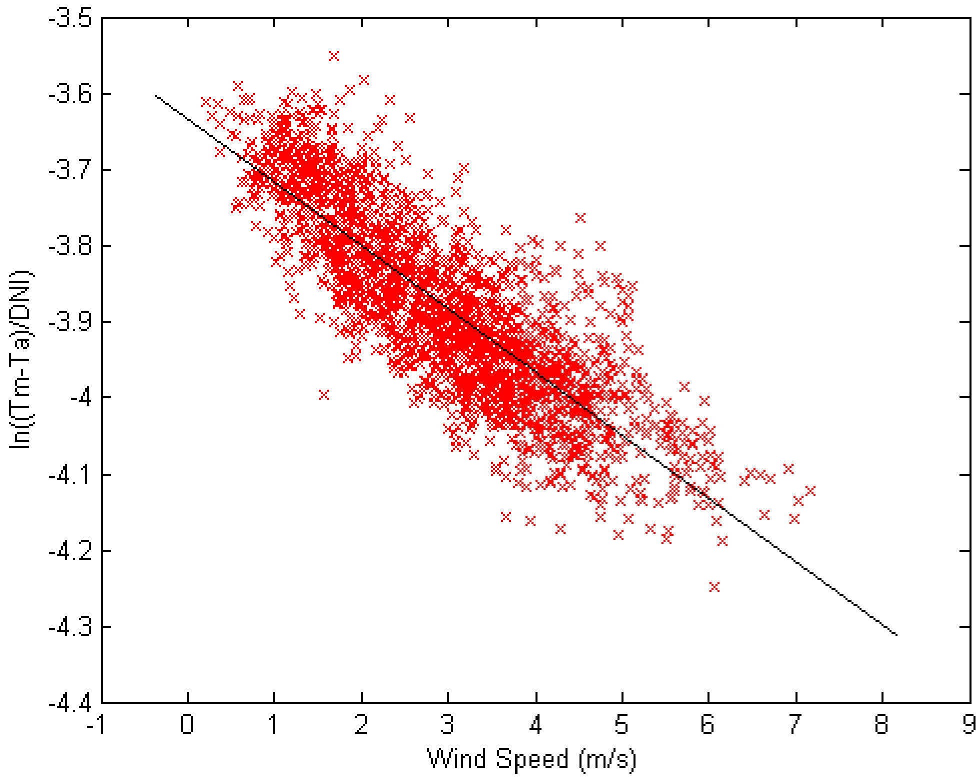

Figure 6. Determination of a and b coefficients for predictive model for cell temperature.

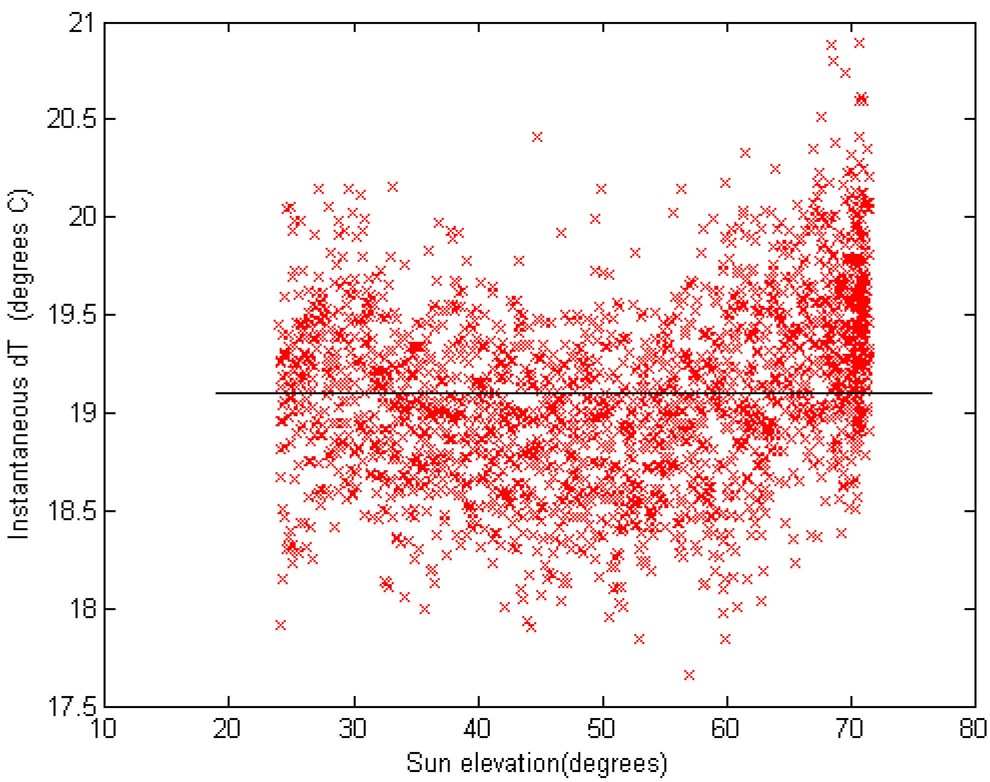

Figure 7. Estimation of ΔT value using global POA irradiance.

References

References

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[2] J.S. Stein, Sutterlueti, J., Ransome, S., Hansen, C. W., King, B. H., Outdoor PV Performance Evaluation of Three Different Models: Single-Diode, SAPM and Loss Factor Model, in: 28th European PV Solar Energy Conference, Paris, France, 2013.
[3] D.L. King, Calculating Cell Temperature from Isc and Voc Measurements, unpublished test notes, October 2009.