TRANSLATION OF DEVICE PERFORMANCE MEASUREMENTS TO REFERENCE CONDITIONS*

C. R. OSTERWALD

SERI, 1617 Cole Boulevard, Golden, CO 80401 (U.S.A.)

1. Introduction

Translation of photovoltaic performance measurements is required when a measurement is made under conditions which are different from those specified in standard measurement procedures. These specifications can be categorized into three areas: the device temperature at the time of measurement; the total incident irradiance level; and the spectral distribution of the incident irradiance. If these three conditions are identical to those specified in the standard measurement procedures, then no translation is required. However, because in practice the standard measurement conditions can be very difficult (and expensive) to achieve, one or more of these three conditions will generally be different and translation is then necessary. In general, the method used for translation is to know how a device responds to different conditions, measure the difference at the time the performance is determined, and correct the performance measurement to the standard conditions.

2. Temperature

Photovoltaic semiconductor devices in general have performance parameters (open-circuit voltage, short-circuit current, and fill factor) which behave linearly with temperature changes. An example of a temperature dependence measurement for a passivated silicon solar cell is shown in Fig. 1. These data have been normalized to 25 °C (the standard measurement temperature) so that all three parameters appear on the same scale. As seen here, the temperature dependence over the normal device operating range 0 - 60 °C is highly linear, and therefore temperature corrections are relatively simple to perform.
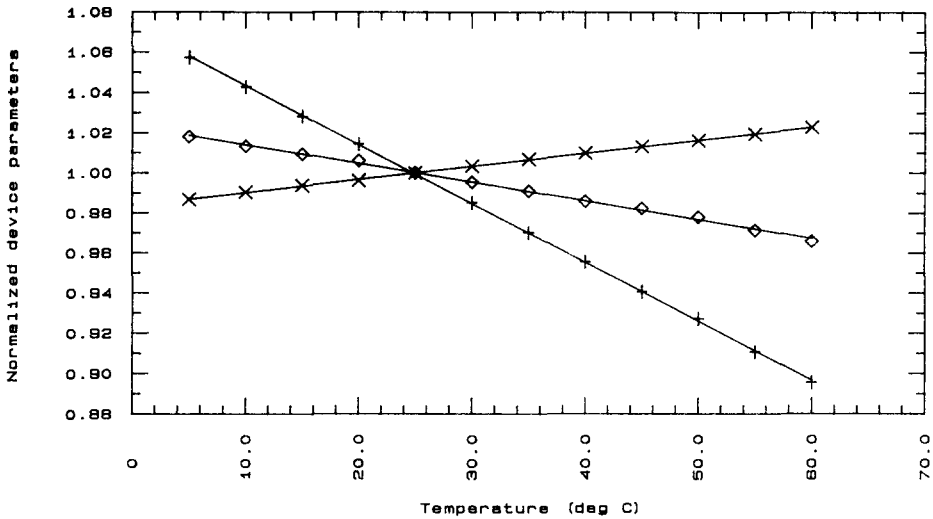

Fig. 1. Normalized (25 °C) V_{oc} (+), I_{sc}(×), and fill factor (◊) *vs.* temperature for a high efficiency passivated silicon solar cell. Solid lines are linear least-squares fits to data.

The temperature correction is normally performed by using a linear least-squares fit to the parameter–temperature data points which yields a slope and intercept. Letting the parameter of interest be termed P, the lines can be represented by

$$P = \frac{dP}{dT} T + P_0 \tag{1}$$

where T is the temperature and P_0 the parameter value at 0 °C. Define the temperatue coefficient for parameter P as

$$TC_p = \frac{dP}{dT} \tag{2}$$

With this information, a parameter can be corrected to 25 °C using

$$P_{25} = P_{T_x} + \frac{dP}{dT}(25 - T_x) \tag{3}$$

where T_x is the temperature (°C) at which the parameter P_{T_x} is measured and P_{25} the value at 25 °C.

As only the slope and not the intercept of the fit is used it is not necessary to have absolute temperature or device parameter measurements in order to determine the temperature coefficients. The most stringent requirement is adequate resolution to ensure a good fit to the data. Also, it may not be necessary to measure the temperature coefficients if data already exists for similar devices. Table 1 presents temperature coefficient

TABLE 1

25 °C Normalized temperature coefficients (ppm °C^{-1})

Device type	V_{oc}	I_{sc}	FF	Efficiency
Si space cells [1]	−3490→	380→	−1000→	−4070→
	−4510	710	−1600	−5350
GaAs [1]	−2040→	520→	−610→	−1950→
	−2160	710	−1000	2650
Passivated Si	−2940	652	−936	−3170
CuInSe$_2$/CdS	−5040	57	−2120	−6880
a-Si:H	−4140	5410	−	−

data for a variety of devices in terms of ppm °C^{-1} (normalized to 25 °C) for comparison purposes.

3. Total irradiance

Theory predicts that, for an ideal p–n junction solar cell with zero series resistance, the short-circuit current I_{sc} *versus* total irradiance (assuming constant spectral distribution) characteristic will be a straight line through the origin, while the open-circuit voltage V_{oc} is given by

$$V_{oc} = n \frac{kT}{q} \ln(I_{sc}/I_0) \tag{4}$$

with I_0 the dark saturation current, n the diode quality factor and kT/q the thermal voltage (about 25 mV at 20 °C). The fill factor is dependent on V_{oc}, I_{sc} and the parasitic series and shunt resistances. V_{oc} therefore varies with total irradiance through I_{sc}, and the fill factor through both I_{sc} and V_{oc}. Because both the V_{oc} and the fill factor can behave in device-dependent, non-linear fashions, a full discussion of procedures to correct the V_{oc} and fill factor is beyond the scope of this paper. Attention will instead be placed upon correcting the short-circuit current.

In most cases, it is reasonable to assume that a device will exhibit a linear I_{sc} *versus* total irradiance characteristic near one sun with a short-circuit current intercept of zero. If this condition is met, then correcting an I_{sc} measurement to 1000 W m^{-2} is merely a matter of using a ratio based upon similar triangles, or

$$I_{sc}^0 = I_{sc}^x \frac{1000 \text{ W m}^{-2}}{E_{tot}^x} \tag{5}$$

where the superscripts 0 and x refer to standard and non-standard conditions, respectively. When a calibrated reference cell is used, the total irradiance is given by

$$E_{tot}^x = \frac{I_{sc}^{RC}}{CN^{RC}} \tag{6}$$

where CN^{RC} is the calibration number of the reference cell (A W^{-1} cm^{-2}), and I_{sc}^{RC} the short-circuit current.

4. Spectral distribution

When a calibrated reference cell is used to measure an unknown device by the so-called reference cell method, an error in the measured short-circuit current results because of the spectral distribution differences between the responses of the two devices, and between the light source and the desired solar reference spectrum. The magnitude of this error can be quantitatively determined using the spectral mismatch parameter, M [2]. To illustrate this point, it is useful to derive the spectral mismatch parameter. Note that in the following derivation, the subscript sc has been dropped from the short-circuit current for simplicity.

To begin, define the fractional error in the measured short-circuit current in an unknown test device to be

$$F = \frac{I_{SIM}^{UN}}{I_{REF}^{UN}} \tag{7}$$

where the subscripts SIM and REF refer to irradiation by the simulator and the reference solar spectral irradiance. In integral form, these short-circuit currents can be written

$$I_{SIM}^{UN} = A^{UN} \int_a^b E_{SIM}(\lambda)\, SR^{UN}(\lambda)\, d\lambda \tag{8}$$

$$I_{REF}^{UN} = A^{UN} \int_a^b E_{REF}(\lambda)\, SR^{UN}(\lambda)\, d\lambda \tag{9}$$

where A^{UN} is the active area, $SR^{UN}(\lambda)$ the spectral response, $E_{SIM}(\lambda)$ the simulator spectral irradiance, and $E_{REF}(\lambda)$ the reference spectral irradiance. Also, a and b cover a wavelength range which spans the spectral response of the unknown device. For the reference cell, similar short-circuit currents can be defined by exchanging superscripts in eqns. (8) and (9)

$$I_{SIM}^{RC} = A^{RC} \int_a^b E_{SIM}(\lambda)\, SR^{RC}(\lambda)\, d\lambda \tag{10}$$

$$I_{\mathrm{REF}}^{\mathrm{RC}} = A^{\mathrm{RC}} \int_{a}^{b} E_{\mathrm{REF}}(\lambda)\, SR^{\mathrm{RC}}(\lambda)\, \mathrm{d}\lambda \tag{11}$$

Note again that a and b must also span the spectral response range of the reference cell. The normal procedure for simulator measurements is to set the total irradiance of the simulator so that the current produced in the reference cell is equal to the calibrated current. However, in general this is not always true (especially for measurements performed outdoors) and this assumption will not be made here. Now form the ratio of eqns. (10) and (11) and solve for unity

$$1 = \frac{I_{\mathrm{SIM}}^{\mathrm{RC}} \int_{a}^{b} E_{\mathrm{REF}}(\lambda)\, SR^{\mathrm{RC}}(\lambda)\, \mathrm{d}\lambda}{I_{\mathrm{REF}}^{\mathrm{RC}} \int_{a}^{b} E_{\mathrm{SIM}}(\lambda)\, SR^{\mathrm{RC}}(\lambda)\, \mathrm{d}\lambda} \tag{12}$$

Substituting eqns. (8) and (9) into eqn. (7) and multiplying by eqn. (12) gives

$$F = \frac{\int_{a}^{b} E_{\mathrm{SIM}}(\lambda)\, SR^{\mathrm{UN}}(\lambda)\, \mathrm{d}\lambda \int_{a}^{b} E_{\mathrm{REF}}(\lambda)\, SR^{\mathrm{RC}}(\lambda)\, \mathrm{d}\lambda\; I_{\mathrm{SIM}}^{\mathrm{RC}}}{\int_{a}^{b} E_{\mathrm{REF}}(\lambda)\, SR^{\mathrm{UN}}(\lambda)\, \mathrm{d}\lambda \int_{a}^{b} E_{\mathrm{SIM}}(\lambda)\, SR^{\mathrm{RC}}(\lambda)\, \mathrm{d}\lambda\; I_{\mathrm{REF}}^{\mathrm{RC}}} \tag{13}$$

The four integral terms in this expression for the fractional error define the spectral mismatch parameter, or

$$M = \frac{\int_{a}^{b} E_{\mathrm{SIM}}(\lambda)\, SR^{\mathrm{UN}}(\lambda)\, \mathrm{d}\lambda \int_{a}^{b} E_{\mathrm{REF}}(\lambda)\, SR^{\mathrm{RC}}(\lambda)\, \mathrm{d}\lambda}{\int_{a}^{b} E_{\mathrm{REF}}(\lambda)\, SR^{\mathrm{UN}}(\lambda)\, \mathrm{d}\lambda \int_{a}^{b} E_{\mathrm{SIM}}(\lambda)\, SR^{\mathrm{RC}}(\lambda)\, \mathrm{d}\lambda} \tag{14}$$

Equation (14) has some interesting properties. First, notice that the active areas have dropped out which means that this rather difficult measurement is not needed. Second, notice that both spectral responses and both spectral

irradiances appear in both the numerator and the denominator. This important result, which actually was the goal of the derivation, indicates that absolute measurements of these spectral quantities are not needed to calculate the spectral mismatch. This also means that systematic bias errors in these measurements do not affect the spectral mismatch calculation. Finally, if either the spectral responses or the spectral irradiances are identical, then the spectral mismatch is exactly unity and there is no error in the short-circuit current. Therefore, in order to minimize the error, the simulator spectrum should be as close as possible to the desired reference spectrum, and the reference cell spectral response should be close to that of the unknown devices.

The expression for correcting the measured short-circuit current is obtained substituting eqns. (14) and (13) into eqn. (7) and solving for the unknown cell current under the reference spectrum.

$$I_{REF}^{UN} = \frac{I_{SIM}^{UN}}{M} \frac{I_{REF}^{RC}}{I_{SIM}^{RC}} \tag{15}$$

To illustrate the use of eqn. (15) for correcting short-circuit current data, the following example is offered. An a-Si:H device was measured in a Spectrolab X-25 solar simulator using a calibrated single crystal Si reference cell and a calibrated filtered (pseudo a-Si:H) Si reference cell (see Fig. 2). For both measurements, the simulator total irradiance was set using the calibration of the reference cell so that
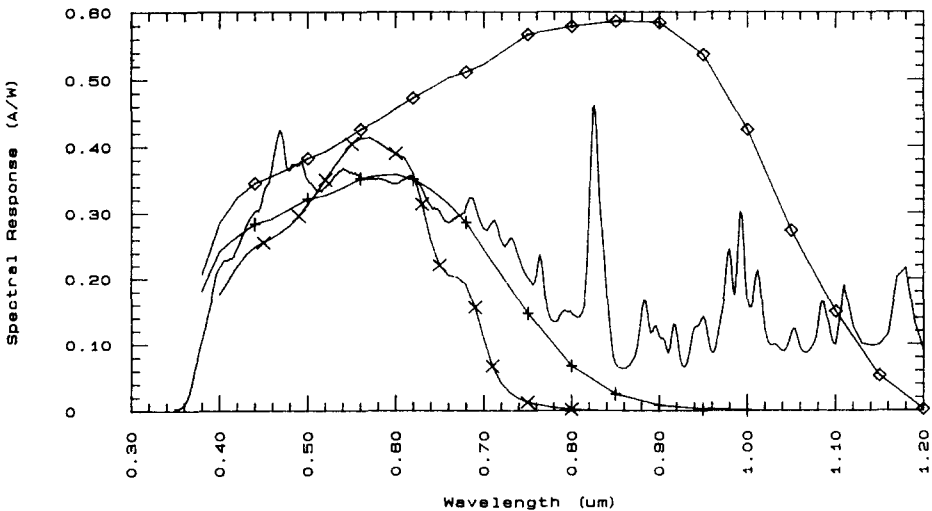

Fig. 2. Spectral response of silicon ($\Diamond$), filtered silicon ($+$), and a-Si:H ($\times$) solar cells, along with relative spectral irradiance of X-25 solar simulator.

TABLE 2

Spectral mismatch correction example

Reference cell	Measured I_{sc} (mA)	M	I_{sc} (mA)
Si	3.706	1.1914	3.11
Filtered Si	3.215	1.0294	3.12

$$\frac{I_{REF}^{RC}}{I_{SIM}^{RC}} = 1$$

and the simulator spectral irradiance was determined using a LICOR LI-1800 spectroradiometer. The spectral responses were measured using a narrow-band interference filter system calibrated with a spectrally flat pyroelectric detector. The results of these measurements are presented in Table 2.

Notice the large discrepancy in the measured currents before correction and that after correction the currents agree to better than 0.5%.

Spectral mismatch is also a problem for reference cell calibrations in a manner that is very similar to the reference cell method discussed above. The difference between the two is primarily that reference cells are calibrated through the calibration number CN, which is defined as short-circuit current divided by total incident irradiance, while device measurements using the reference cell method determine the I_{sc} only. For this reason, the spectral corrections used in the so-called tabular calibration method are formulated in a slightly different manner.

The tabular calibration method involves four different measurements: first, the solar cell's spectral response; second, the short-circuit current; third, the total incident irradiance; and fourth, the incident spectral irradiance. The spectral measurements are used to correct the measured calibration number data, in a manner analogous to the spectral mismatch parameter. To begin, the calibration number of a reference cell under a reference spectral irradiance can be expressed in integral form as

$$CN_{REF} = \frac{A^{RC} \int_0^\infty E_{REF}(\lambda)\, SR^{RC}(\lambda)\, d\lambda}{\int_0^\infty E_{REF}(\lambda)\, d\lambda} \tag{16}$$

Notice that the integration limits have been replaced with all wavelengths, a situation due to the requirement of measuring the total incident irradiance.

Under natural sunlight, the calibration number can be written

$$
CN = \frac{I_{sc}}{E_{INC}} = \frac{A^{RC} \int\limits_{0}^{\infty} E_{INC}(\lambda) \, SR^{RC}(\lambda) \, d\lambda}{\int\limits_{0}^{\infty} E_{INC}(\lambda) \, d\lambda} \tag{17}
$$

where E_{INC} refers to the incident irradiance. The final expression for the calibration is obtained by multiplying eqn. (16) by eqn. (17), or

$$
CN_{REF} = \frac{I_{sc}}{E_{INC}} \frac{\int\limits_{c}^{d} E_{REF}(\lambda) \, SR^{RC}(\lambda) \, d\lambda}{\int\limits_{c}^{d} E_{REF}(\lambda) \, \lambda d} \frac{\int\limits_{c}^{d} E_{INC}(\lambda) \, d\lambda}{\int\limits_{c}^{d} E_{INC}(\lambda) \, SR^{RC}(\lambda) \, d\lambda} \tag{18}
$$

The similarity between the integrals here and in eqn. (14) is evident, with both expressions becoming identical if the spectral response of the reference cell in the spectral mismatch is replaced with the flat response of a blackbody detector. Because over 99.9% of the energy available in the terrestrial solar spectrum lies between 0.3 and 4.0 nm, the integration limits have been changed again in eqn. (18) to avoid having to integrate over all wavelengths. A major advantage of the tabular method is that any spectrum may be used for $E_{REF}(\lambda)$. Also, once a device is calibrated, a calibration number for any other reference spectrum can be obtained by reapplying eqn. (18) to the previous calibration with the original spectrum substituted for $E_{INC}(\lambda)$.

To illustrate how the tabular method is used, two examples of actual measurements are now presented. The spectral responses of the two devices used for this illustration are shown in Fig. 3. The first device is a CuInSe$_2$/CdS cell which has a long wavelength response out to 1.3 μm and no blue/UV response, while the second device is a pseudo a-Si:H cell (single-crystal silicon with a KG5 colored glass filter for IR absorption). In order to obtain the highest absolute accuracy available for the total incident solar irradiance measurement, a self-calibrating TMK MI-VI cavity radiometer was used. The incident spectral irradiance was measured with a LICOR LI-1800 spectroradiometer over the wavelength range 0.35 - 1.1 μm. Both the spectroradiometer and the solar cells were filtered with collimating tubes to match the 5.0° field of view of the cavity radiometer. The short-circuit current and total irradiance were averaged over the 25 s scan time of the spectroradiometer to obtain the uncorrected calibration number. Because
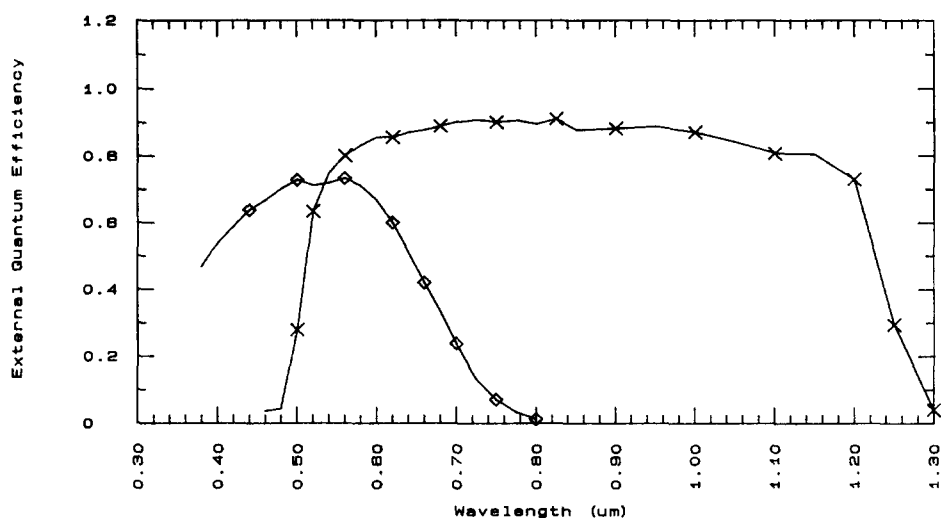
Fig. 3. External quantum efficiency *vs.* wavelength for CuInSe₂/CdS (×) and KG5 colored glass filtered silicon (◇) reference cells.

the LICOR did not cover the entire 0.3 - 4.0 μm spectral range needed, a simple solar spectral model [3] was used to extend the measurement range by fitting the model over the 0.35 - 1.1 μm data available. An example of a resultant spectrum is shown in Fig. 4, along with a direct normal reference spectrum. The large difference between the two is evident.
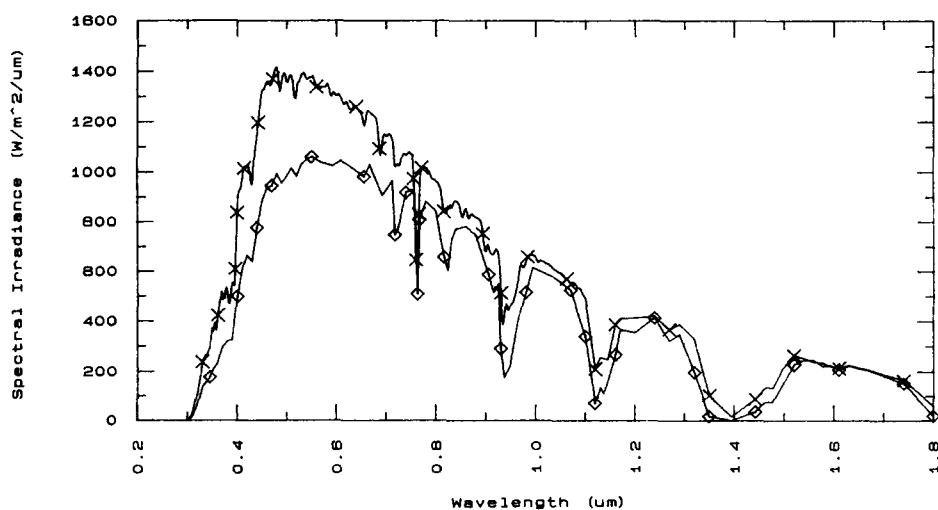

Fig. 4. Direct normal reference spectral irradiance (◇) and typical LICOR measured (×) spectral irradiance with modeled tails (see text).
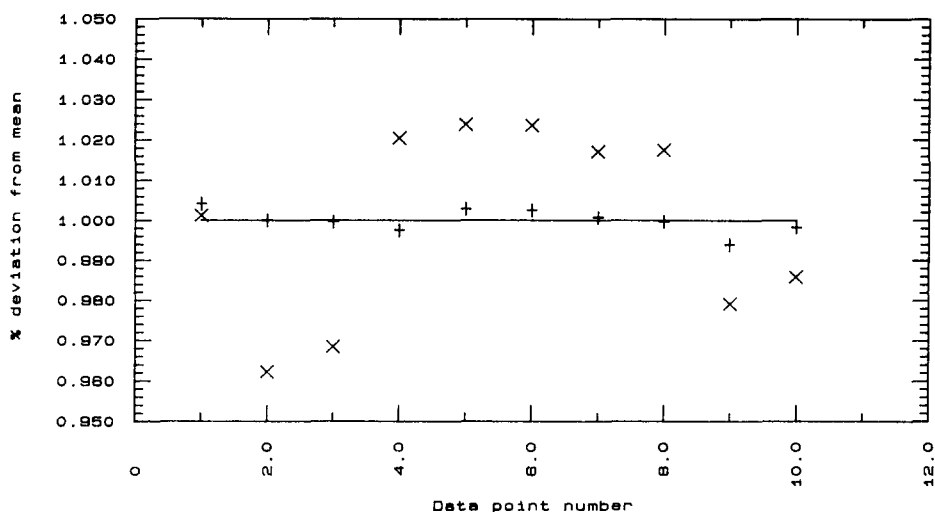
Fig. 5. Uncorrected (×) and corrected (+) calibration number data for filtered silicon reference cell, normalized to mean. Uncorrected mean = 0.479 A W^{-1} cm^{-2}, with standard deviation = 2.3%. Corrected mean = 0.441 A W^{-1} cm^{-2}, with standard deviation = 0.3%.

Figure 5 shows nine uncorrected and corrected calibration numbers from four different days for the filtered silicon cell with each data point normalized to the average value of the set. It is seen that while a large scatter exists for the uncorrected data (standard deviation of 2.3% of mean),
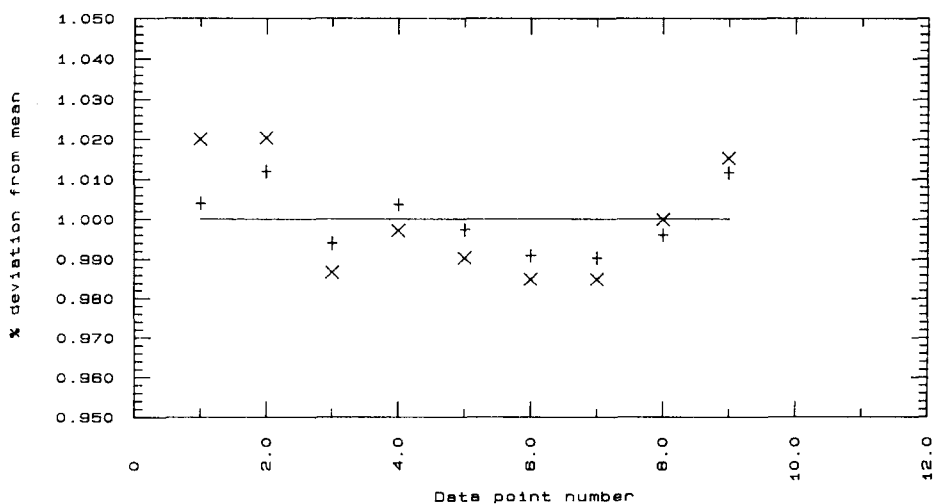

Fig. 6. Uncorrected (×) and corrected (+) calibration number data for CuInSe$_2$/CdS reference cell. Uncorrected mean = 0.336 A W^{-1} cm^{-2}, with standard deviation = 1.4%. Corrected mean = 0.351 A W^{-1} cm^{-2}, with standard deviation = 0.8%.

the scatter is greatly reduced for the corrected data. The large deviation for the uncorrected calibration number is indicative of the variability of outdoor spectral conditions. Also, a large change occurs in the calibration number mean between the uncorrected and corrected data. This reduction, about 9%, is due to (referring to Fig. 4) the large amount of energy in the short wavelength end of the incident spectrum compared to the reference spectrum. Figure 6 is a similar plot during the same period for the $CuInSe_2/CdS$ device. Again, the corrected data show a reduction in the standard deviation for the uncorrected data, but the reduction is not as great. This trend could be due to the high responsivity of the $CuInSe_2/CdS$ device beyond 1.1 μm where spectral irradiance data were not available and modeled data were substituted. Also, notice that the calibration increased by about 5% over the uncorrected case. This effect is opposite to that of the filtered silicon cell and is due to the long wavelength responsivity.

References

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3 R. Bird and C. Riordan, Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the earth's surface for cloudless atmospheres, *SERI/TR-215-2436*, December 1984, (available from NTIS).