PV POWER MEASUREMENT UNCERTAINTY IN INDUSTRIAL ENVIRONMENTS

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Abstract. *This work is a practical approach towards the establishment of a common ground among the different stakeholders in the PV field, regarding the PV measurement uncertainty. The main uncertainty sources are identified and the uncertainty components are carefully evaluated to provide a method for the measurement uncertainty estimation. The uncertainties related to the reference modules, the temperature and the optical properties of the solar simulators are the main contributors to the overall value of uncertainty. The importance of the spectral mismatch factor and its related uncertainty are also discussed.*

Key words: *Measurement uncertainty, Characterization, Power Rating, Performance, Qualification and Testing*

1. INTRODUCTION

Power rating of photovoltaic devices is commonly related to their electrical parameters (P_{max}, I_{sc}, V_{oc}, FF) measured under standard test conditions (STC). The reliability of these values and their respective uncertainties are of crucial importance to PV manufacturers and investors. Each PV power performance measurement, carried out either by industry or by accredited laboratories, must contain a careful and traceable calculation of measurement uncertainties in order to provide a closer approximation of the real value of the device. Currently, these calculations are carried out mostly by laboratories, despite it being a real economic impact for the PV manufacturers. Today, there is a lack of easily implementable and appropriate method to estimate the uncertainty in industrial environments.

In the frame of the EC-funded integrated project PERFORMANCE, the various contributions to the overall uncertainty were analyzed (Müllejans et al., 2009). Recommendations were also made for further reduction of uncertainty.

In spite of the fact that the outcome of these analyses is of great interest and usefulness for laboratories and experts and enables them to establish reliable and identical uncertainty budgets, it is still very difficult to adapt them to industrial facilities. Furthermore, providing a customizable uncertainty budget to manufacturers, adaptable to any measurement facility and PV technology, enables them to rely on consistent and impartial level of uncertainty. Moreover, such an uncertainty budget can be used to compare different measurement equipments based on objective criteria.

The purpose of this work is to propose such a tool to the PV industry. It is based on a partnership between providers of PV testing services worldwide and a supplier of photovoltaic measurement equipments.

2. UNCERTAINTY SOURCES

2.1 General approach for the uncertainty determination

The principle of the uncertainty calculation is described by the ISO guide to the expression of uncertainty in measurement (ISO/IEC guide, 2008): all measured variables (measurands) and conditions which contribute to the final measurement result are taken into account. For each variable a measurement uncertainty has to be established and the transfer to the final uncertainty calculated based on the component's contribution to the final measurement result. The standard uncertainty of y, where y is the estimate of the measurand Y and thus the result of the measurement, is obtained by appropriately combining the standard uncertainties of the input estimates *x1, x2, ..., xN*. This combined standard uncertainty of the estimate y is denoted by $u_c(y)$.

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \tag{1}$$

where $\quad Y = f(X_1, X_2, ..., X_N)$

In order to combine the uncertainties associated with different measurement variables they all have to be on the same confidence level and distribution, commonly standard uncertainties with Gaussian distribution. For confidence distributions which differ in shape from a Gaussian distribution, a correction factor is applied. If the variables are independent, the combined standard uncertainty can be calculated as the geometrical mean of all single components (i.e. the square root of the sum of squares). The combined standard uncertainty is then multiplied by the coverage factor (i.e. k=2 for U95%) to obtain the combined expanded uncertainty. In general, components of uncertainty may be categorized according to the method used to evaluate them:

- Type A evaluation: method of evaluation of uncertainty by the statistical analysis of series of observations,
- Type B: uncertainty evaluation method by means other than the statistical analysis of series of observations.
- Type C (introduced in this paper): signifies that the corresponding component is a combined uncertainty.

2.2 Maximum power measurement uncertainty

In the determination of electrical performance of PV modules, a number of measurements are taken and conditions applied, all of which have an influence on the final result and its uncertainty. The main groups are uncertainties related to electrical measurements, temperature and optical effects, the reference device and the connections (cabling). Furthermore there are contributions from any step of data analysis and, last but not least there might be (significant) contributions from the procedures and operators. The latter are beyond the scope of this article but will be addressed by Pasan (please refer to our publication in the frame of EU-PVSEC 2014).

As the maximum power under STC (P_{max_STC}) is defined by

$$P_{\max\_STC} = I_{sc\_STC} \cdot V_{oc\_STC} \cdot FF \tag{2}$$

its combined measurement uncertainty for P_{max_STC} can then be determined as

$$U_{P\max STC} = (U(I_{sc\_STC})^2 + U(V_{oc\_STC})^2 + U(FF)^2)^{1/2} \tag{3}$$

with $U(I_{sc\_STC})$, the combined uncertainty for I_{sc}, $U(V_{oc\_STC})$, the combined uncertainty for V_{oc} and $U(FF)$ the combined uncertainty for Fill Factor.

Table 1 – Uncertainty groups and components

	Uncertainty components	**Type**	**Distribution**	**Divisor**	**Contribution**
Electrical uncertainties	Current measurement channel uncertainty	B	G	1	$U(I_{sc\_STC})$
	Voltage measurement channel uncertainty	B	G	1	$U(V_{oc\_STC})$
	Irradiance measurement channel uncertainty	B	G	1	$U(I_{sc\_STC})$
Temperature-related uncertainties	Temperature-related uncertainty over the current	C	G	1	$U(I_{sc\_STC})$
	Temperature-related uncertainty over the voltage	C	G	1	$U(V_{oc\_STC})$
Optical uncertainties	Spatial non-uniformity of the irradiance	A	G	1	$U(I_{sc\_STC})$
	Spectral mismatch uncertainty	C	G	1	$U(I_{sc\_STC})$
	Uncertainty on current related to the misalignment	B	R	1.73	$U(I_{sc\_STC})$
	Uncertainty on voltage related to the misalignment	B	R	1.73	$U(V_{oc\_STC})$
	Angular response of the DUT	B	U	1.41	$U(I_{sc\_STC})$
Reference-related uncertainties	Primary Reference Device uncertainty over the *Isc*	B	G	1	$U(I_{sc\_STC})$
	Primary Reference Device uncertainty over the *Voc*	B	G	1	$U(V_{oc\_STC})$
	Temperature-related uncertainty over the irradiance	C	G	1	$U(I_{sc\_STC})$
Fill Factor-related uncertainty	Non-repeatability of the *FF* (Within n sets of measurements)	A	G	1	$U(FF)$

The influencing factors for each component ($U(I_{sc\_STC})$, $U(V_{oc\_STC})$ and $U(FF)$), grouped according to their physical class, are listed in Table 1. Each component contributes to one of the combined uncertainties of I_{sc}, V_{oc} or FF using equation (1). The combined measurement uncertainty for $P_{max\text{-}STC}$ is determined using the above mentioned equation. The reported uncertainty is based on this value multiplied by a coverage factor k=2, providing a level of confidence of approximately 95%.

2.3 Temperature-related uncertainties

The temperatures of the device under test (DUT) and the reference cell and their measurement are sources of uncertainty. Their corresponding uncertainty components are listed in Table 2.

Table 2 – Temperature (*T*°)-related uncertainties

Uncertainty components	**Type**	**Distribution**	**Divisor**	**Contribution**
T° measurement channel uncertainty	B	G	1	$U(T_{DUT})$ $U(T_{RC})$
Reference cell T° sensor's uncertainty	B	G	1	$U(T_{RC})$
DUT *T*° sensor's uncertainty	B	G	1	$U(T_{DUT})$
T° non-uniformity on the DUT	A	G	1	$U(T_{DUT})$
Module's *T*° gradient	B	G	1	$U(T_{DUT})$
Emissivity related uncertainty for IR sensors	B	G	1	$U(T_{DUT})$
Uncertainty due to the sensors' contact quality	B	G	1	$U(T_{DUT})$

$U(T_{DUT})$ and $U(T_{RC})$ are the combined uncertainties on DUT’s and reference cell’s temperatures respectively. In order to determine their contribution to $U(I_{sc\text{-}STC})$ and $U(V_{oc\text{-}STC})$, the temperature coefficients for current and voltage α and β and their respective uncertainties need to be known. In order to estimate these uncertainties, the spread of the values reported by six different laboratories for α and β of four modules of different types were taken into account. The deviations can reach 15% for β when a maximum of 50% of deviation was observed for α.

In this paper, the average DUT’s temperature was assumed to be 20°C with a temperature non-uniformity of 1°C. The values of 0.039%/°K and -0.360%/°K were considered for α and β respectively. These values need to be carefully determined and adapted to each specific case.

The temperature related uncertainties of I_{sc} and V_{oc} can be determined as

$$
\begin{aligned}
U_T(I_{sc\_STC}) &= U(\alpha)\cdot\frac{\partial I_{sc\_STC}}{\partial\alpha} + U(T_{DUT})\cdot\frac{\partial I_{sc\_STC}}{\partial T_{DUT}} \\
U_T(V_{oc\_STC}) &= U(\beta)\cdot\frac{\partial V_{oc\_STC}}{\partial\beta} + U(T_{DUT})\cdot\frac{\partial V_{oc\_STC}}{\partial T_{DUT}}
\end{aligned}
\qquad (4, 5)
$$

The relative temperature coefficient of the reference device (α_{RC}) and its uncertainty are considered in order to determine the temperature related uncertainty for the irradiance G:

$$
U_T(G) = U(\alpha_{RC})\frac{\partial G}{\partial\alpha_{RC}} + U(T_{RC})\frac{\partial G}{\partial T_{RC}} \qquad (6)
$$

2.4 Spatial non-uniformity of irradiance

The critical level of non-uniformity for performance measurements had been specified by Herrmann and Wiesner (2000). The uncertainty related to the non-uniformity was extrapolated based on the I_{sc} deviations: For an IEC class A solar simulator (IEC 60904-9, 2007) (<2% of non-uniformity), the uncertainty on I_{sc} was 1.6% whereas for an A$^+$ class simulator (<1% non-uniformity), this uncertainty was between 0.3-0.4%.

A more recent sensitivity analysis was conducted by Monokroussos et al. (2013) by varying the non-uniformity of irradiance between 0-5% and identifying the influences on the measurement uncertainty. The influence of uncertainty was quantified based on the results of Monte-Carlo simulation. The results of the calculation are shown in Figure 1 in regards to the uncertainty on P_{MAX} of the test module. It turns out that a substantial error will be inflicted on I_{SC}, I_{MPP} and V_{MPP} of the test module.

The calibration of a non-uniform solar simulator using a large module or the compensation based on the non-uniformity profile, are not enough to reduce or to compensate such uncertainties. The reason is that cells, with different performances, are randomly placed on a module and this non-uniform profile of cells' performances is rarely identical between two large modules.

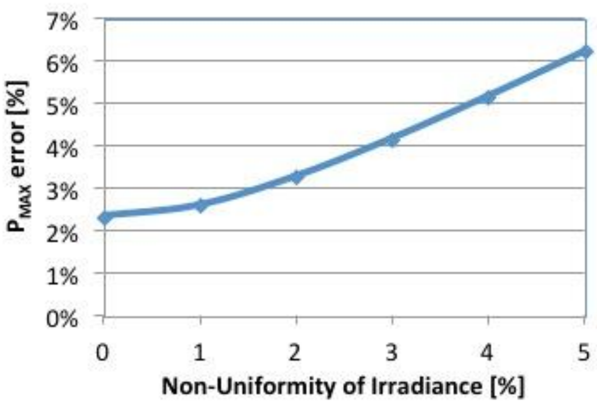

Figure 1 - Effect of non-uniformity of irradiance on the measurement uncertainty of P_{MAX} of a test module, according to Monokroussos et al. (2013).

2.5 Spectral mismatch and its uncertainty

The calculation of the spectral mismatch (*SMM*) depends on the spectral responses (*SR*) of the device under test and of the reference device as well as the simulator's spectrum and the reference AM1.5 spectral distribution (IEC 60904-7, 2008).

$$SMM = \frac{\int E_{ref}(\lambda) SR_{ref}(\lambda) d\lambda \cdot \int E_{meas}(\lambda) SR_{DUT}(\lambda) d\lambda}{\int E_{meas}(\lambda) SR_{ref}(\lambda) d\lambda \cdot \int E_{ref}(\lambda) SR_{DUT}(\lambda) d\lambda} \tag{7}$$

The first three have associated uncertainties which translate into an uncertainty of the spectral mismatch factor (see Table 3).

Table 3 – Spectral mismatch uncertainty components

Uncertainty components	**Type**	**Distribution**	**Divisor**	**Contribution**
Spectrum measurement uncertainty	B	G	1	*U(SPC)*
Non-repeatability of the spectrum	A	G	1	*U(SPC)*
Spatial non-uniformity of the spectrum	A	G	1	*U(SPC)*
DUT's spectral response measurement uncertainty	A	G	1	$U(SR_{DUT})$
Non-uniformity of the DUTs' spectral responses	B	G	1	$U(SR_{DUT})$
Primary reference's spectral response measurement uncertainty	A	G	1	$U(SR_{Ref})$

U(SPC), $U(SR_{DUT})$ and $U(SR_{Ref})$ are the combined uncertainties of the simulator's spectrum, the *SR* of the DUT and the one of the reference cell respectively.

In the frame of this work, a class A spectrum (according to IEC 60904-9) was compared with a class A^+ (twice better than class A). Nearly similar *SR*s were selected for the DUT and the reference cell (mono-crystalline Si type devices).

Figure 2 shows the spectra and their measurement uncertainty. Both class A and class A+ spectra were measured using a silicon sensor-based double channel spectrometer. Values within 4%–10% were taken into account for the spectrum measurement uncertainties. The average non-repeatability of the spectrum and its average spatial non-uniformity were measured to be 0.3% and 2% respectively.

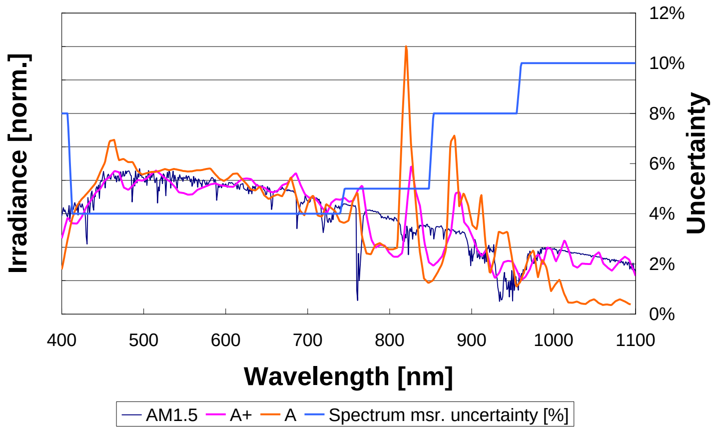

Figure 2 - IEC A and A^+ class spectra and the spectrum measurement uncertainties

In order to determine the dispersions of the DUTs' *SR*s, 6 modules were measured by an accredited laboratory and the SR measurement uncertainty provided by the laboratory was considered (see Figure 3).

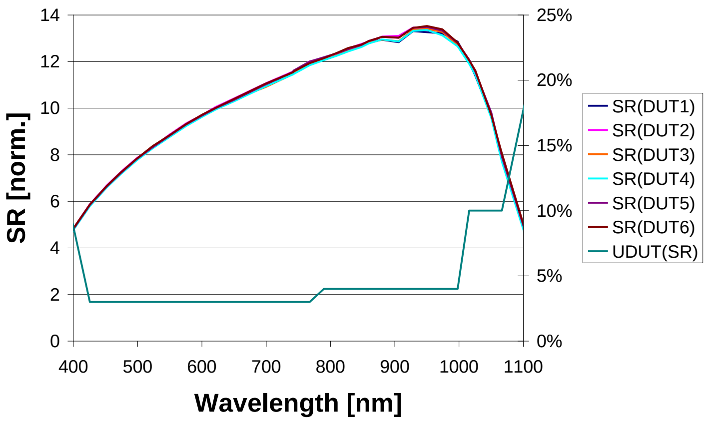

Figure 3 - *SR* measurements of 6 samples with the corresponding measurement uncertainty

The non-uniformity of the DUTs' SRs varies between 0.4% – 2.5% in the 400 – 1100nm wavelength range.

Based on these values, the *SMM* factors and the corresponding uncertainties were calculated for the two spectra. In the case of the A^+ spectrum, the *SMM* is about 7 times lower than in the case of the A class spectrum (0.16% for A^+; 1.21% for A). The results confirm that the *SMM* uncertainty is also reduced in the case of the A^+ spectrum (1.06% vs. 1.09%).

It is crucial to consider the *SMM* uncertainty in the combined total uncertainty when the *SMM* itself is used to correct the absolute value of I_{sc}. If the *SMM* correction is not taken into account, a systematic error is added to the power rating.

2.6 Misalignment

Assuming a maximal misalignment of 3° between the DUT and the reference cell, 0.046% of uncertainty was considered for I_{sc} when for V_{oc}, this values is estimated to be 0.002% (Müllejans et al., 2009).

2.7 Angular response of the DUT

The contributions of the maximum light incidence angle and the angular response of the DUT to the overall uncertainty were estimated for simulators with direct light. This uncertainty could be neglected for the simulators with collimated light. In the case of diffused light simulators, the influence of the DUT's angular response need to be investigated.

In order to determine the angular response-related uncertainty, an encapsulated mono-crystalline Si cell was placed in the centre of the illuminated area where the incident light was considered to be perpendicular to the cell. The I_{sc} was measured at this position. The cell was then tilted around its center and the short-circuit currents at different angles were compared with the reference value.

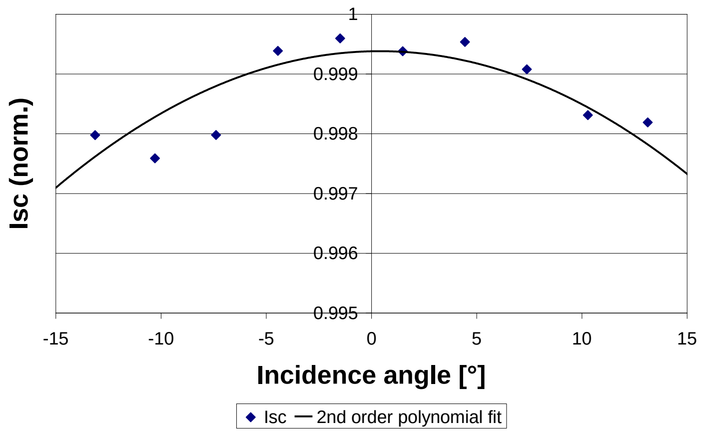

Figure 4 - Angular response of a mono-crystalline Si cell and its second order polynomial fit

For a 1600mm x 1200mm module, two incidence angles of 10° and 20° were assumed and compared. 0.15% and 0.44% of uncertainty over I_{sc} were calculated for the two cases respectively.

2.8 Fill Factor-related uncertainty

To determine the effect of the software, cabling and connections on the fill factor, Müllejans et al. (2009) considered the measured data of a solar simulator. To this end, various module types have been measured repeatedly with disconnecting and reconnecting of the modules, often with several days in between measurements. It is assumed that all sources of variations in the fill factor occur randomly. The standard deviation is then an acceptable metric for the uncertainty of a single measurement.

Table 4 – Experimental determination of variations in fill factor (Müllejans et al., 2009)

Module ID	Nb of measurements	Average *FF*	*STDEV*	
BO01	13	0.7338	0.0016	0.22%
CE01	13	0.6832	0.0028	0.40%
KD01	12	0.7063	0.0014	0.19%
NF01	11	0.6433	0.0049	0.76%
NG01	10	0.6972	0.0045	0.64%
PF01	23	0.6889	0.001	0.15%
SG01	7	0.6967	0.002	0.28%
TC01	9	0.6981	0.0039	0.55%
VE01	18	0.7302	0.0018	0.24%
WB01	7	0.6713	0.0031	0.46%
XG01	14	0.6896	0.0021	0.30%
ZC01	11	0.7178	0.001	0.14%
ZG01	10	0.6925	0.002	0.28%

The average standard deviation value of 0.36% was used for the *FF* uncertainty determination.

3. RESULTS

In order to estimate the overall uncertainty, 1.6% of uncertainty over the I_{sc} and 2% over the V_{oc} of the reference cell were assumed. Three simulators were compared and the main assumptions and the results are summarized in Table 5 and Table 6.

Table 5 – Main assumptions

Characteristics & assumptions	**Simulator 1 : $A^+A^+A^+$**	**Simulators 2/3 : AAA / BBB**
Spectral Match	< ± 12.5%	± 25% / ± 50%
Non-uniformity	< 1%	2% / 5%
Instability	< 1%	2% / 5%
DUT type	Mono-crystalline Si	Mono-crystalline Si
Reference Device	Mono-Si, same type as DUT	Mono-Si, same type as DUT
Reference Device uncertainty over *Isc* and *Voc*	1.6%, 1.2%	1.6%, 1.2%
Maximum incidence angle	15°	20°
SMM	Considered	Considered

Table 6 – Combined uncertainties

Uncertainty on *Pmax* (coverage factor *k*=2)	**$A^+A^+A^+$**	**AAA**	**BBB**
Overall uncertainty	5.89%	6.72%	9.31%
Without the reference contribution	2.91%	4.35%	7.78%

The comparison of the uncertainty group contributions demonstrates the importance of the reference cell, the temperature and the optical specifications of the simulators.

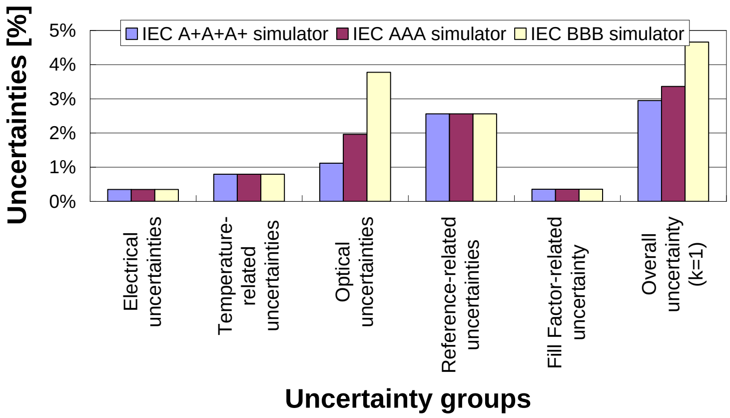

Figure 5 - Contributions of the uncertainty sources

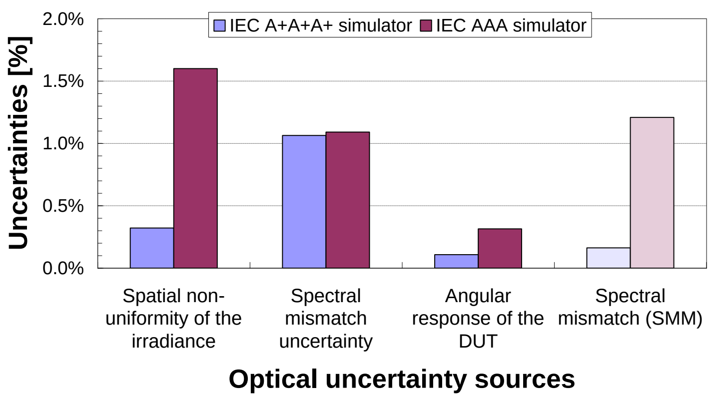

Figure 6 - Optical uncertainties

A detailed analysis of the optical uncertainties highlights the added value of an accurate solar simulator. In fact, with an A+ spectrum and a slight reduction of the incidence angle (15° instead of 20°), a gain of close to 1% on the overall uncertainty can be reached. The uncertainty differences can reach 3.5% when comparing simulators with higher incidence angles (60°).

When the reference related uncertainties are not taken into account, a class B simulator has an uncertainty of 7.78%. This is higher than the uncertainties with A and A+ simulators, even when the reference-related uncertainties are considered. This means that the use of simulators with low accuracy in the production lines combined with one accurate simulator cannot be a good approach to reduce the uncertainty of the production power rating. In such a case, the 7.78% of class B uncertainty must be combined with the total uncertainty of the accurate simulator when reporting the power rating uncertainty (e.g. 9.76% of uncertainty when a class B simulator is used in combination with an A+ simulator).

4. CONCLUSION

A method was provided to the PV industry to evaluate the measurement uncertainty. The main sources of uncertainty were listed and the uncertainty components were estimated in details. The results prove the significant added value of an accurate A+ simulator. The optical-, temperature- and reference-related uncertainties are the major contributors to the overall value of uncertainty. The spectral mismatch factor is a systematic error if it is not taken into account to report the P_{max}. The spectral mismatch uncertainty is reduced when the spectral match with AM1.5 is increased. The use of less accurate simulators, even with high-accuracy references, results in higher uncertainties.

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