Angular-dependent spectral responsivity—Traceable measurements on optical losses in PV devices

F. Plag | I. Kröger | T. Fey | F. Witt | S. Winter

Abstract
Angular-dependent optical losses can have an effect on the spectral responsivity of photovoltaic devices. When these devices with differing angular-dependent spectral responsivity are exposed to incident direct and diffuse solar spectral irradiance they will perform differently compared with direct and perpendicular beam exposure only. However, if the angular and polarization-dependent spectral responsivity is known, optical losses can be determined for any given angular distributed solar spectrum. Here, we show the capabilities of a newly developed laser-based calibration facility for traceable measurements on reference solar cells angular-dependent spectral responsivity for device areas of up to 156 × 156 mm². Our investigation is focused on a comprehensive analysis on all related measurement uncertainties. We present the results of measurements on a variety of reference solar cells as well as an industry type solar cell with and without encapsulation showing that strong differences in their optical properties occur. Additionally, we compare the results obtained with a conventional broadband characterization approach using a halogen lamp as light source. An agreement, better than 1%, was observed for the broadband measurement and the spectral measurements weighted by the spectral responsivity and the lamp spectrum. It is shown why different light sources lead to different angular-dependent responsivities. In conclusion, validation measurements of solar simulator-based or natural sunlight-based angular responsivity facilities at testing and calibrations laboratories can be offered. Furthermore, by means of traceable angular-dependent spectral responsivity measurements and multidimensional models under consideration of diffuse light components, optical losses for photovoltaic performance measurements, energy rating, and related uncertainties can be studied.

KEYWORDS
angle of incidence, calibration, diffuse light, energy rating, optical losses, spectral responsivity

1 | INTRODUCTION

In the field of photovoltaic (PV) energy rating standardization for angular-dependent PV device characterization, procedures to describe optical losses due to angle of incidence (AOI) dependencies are currently under discussion. This paper is targeting at the characterization of AOI effects in PV devices causing optical losses in their performance. These optical losses have a significant effect on the accuracy of PV performance measurements and energy yield predictions. The international standard IEC 61853-21 specifies the use of 2 different characterization methods for the determination of AOI effects on the PV device performance. One method contained in the standard is describing an indoor approach using simulated sunlight.2 The second method, an outdoor approach, is described using a global natural sunlight procedure. However, both methods covered in the standard are using broadband light sources for the characterization of AOI effects. Earlier
research has shown that polarization of the incident light and AOI effects are also apparent for the spectral responsivity.\textsuperscript{3–9}

Angular losses in PV devices can introduce differences in the short circuit current under standard test conditions $I_{STC}$ of up to 3.5% under global normal irradiance conditions with horizontal orientation compared with a device without losses due to angular effects.\textsuperscript{10} In 1987, Shimokawa et al showed within a comparison of indoor and outdoor calibration methods using the same chain of traceability discrepancies ranging from 1% to 4% for short circuit calibration of reference solar cells (SCs).\textsuperscript{11} Typical measurement uncertainties for $I_{STC}$ calibrations using the global normal sunlight method in that time were around 3%, dominated by the contribution of field of view and AOI effects.\textsuperscript{12}

For global measurements or energy rating with fixed PV device orientations, the AOI losses can be considerably larger (up to 15% for specific global irradiance conditions depending on the tilt angle of the device), due to diurnal and annual variations of direct and diffuse sunlight’s AOI.\textsuperscript{13,14}

The IEC standard 61853-2 demands for spectral responsivity measurements in order to consider spectral mismatch for solar spectra differing from the reference solar spectrum $E_{\lambda ,AM1.5G}(\lambda)$ defined in an international standard IEC 60904-3.\textsuperscript{15} However, the AOI measurements demanded by the standard generally do not cover spectral effects, i.e., a spectral angular mismatch correction. To fill this gap, a facility was constructed to investigate and evaluate the significance of spectral effects on AOI measurements and related uncertainties.

The laser-based differential spectral responsivity facility (Laser-DSR) at Germany’s national metrology institute Physikalisch-Technische Bundesanstalt (PTB) already provides high accuracy primary calibration of the absolute spectral responsivity of reference SCs at various irradiance levels and temperatures.\textsuperscript{16} Hence, the short circuit current of the device at any demanded solar spectrum can be derived. This facility has been upgraded to measure the AOI dependency of reference SC spectral responsivity. Consequently, AOI effects can be determined for several different spectral irradiances of light sources. The combination of an angular responsivity facility with a spectral responsivity facility was achieved by using monochromatic radiation at constant broadband bias irradiance level. The angular-dependent spectral responsivity of PV reference devices with an active area of up to $156 \times 156$ mm$^2$ can be calibrated, and the angular responsivity at any given solar spectrum can be derived. Here, we show the characterization of AOI measurements including the determination of the measurement uncertainty budget. The uncertainty budget includes Type A uncertainty, nonlinearity of the current-voltage amplifier, angular-dependent uniformity of the monochromatic light field, uncertainties due to positioning of the device relative to the rotation axis, polarization dependencies, uncertainty of the rotation angle due to an expanded light source, irradiance non-linearity of the PV device, temperature-dependent effects, and wavelength uncertainty. These uncertainty contributions were investigated exemplary for $20 \times 20$ mm$^2$ reference SCs in world photovoltaic scale (WPVS) design and for $156 \times 156$ mm$^2$ sized industrial SCs. Finally, the angular-dependent spectral responsivity $s(\lambda, \theta, \varphi)$ of different types of SCs was determined and compared. This new calibration service will be offered to calibration and testing laboratories for the validation of their own AOI facilities.

## 2 | Approach

### 2.1 | Description of the angle of incidence facilities

We upgraded the Laser-DSR facility\textsuperscript{16} with a fully automated goniometer that can realize any AOI in the full hemisphere within the SCs field of view ($0^\circ \leq \theta \leq 90^\circ$, $-180^\circ \leq \varphi \leq 180^\circ$). An additional 3 axis translation stage ($x$, $y$, and $z$ direction) allows AOI measurements even if the devices are mounted off-axial relative to the optical axis. It provides a positioning precision of better than $0.1$ mm covering a translation range of several meters. The SC mounting plate provides Pellet-controlled sample holders for sample thermostatization and for investigations of the devices temperature dependencies. Bias lamps, producing a broadband spectrum to set the samples in a steady working point, can be mounted on the rotation stage so that the bias irradiance does not change during rotation. Hence, irradiance non-linearity effects of PV devices under test are considered to be negligible. The SC is then rotated in the uniform monochromatic light field of the Laser-DSR facility to determine the relative angular-dependent spectral responsivity $s(\lambda, \theta, \varphi)$. The spectral range of the Laser-DSR covers $250$ nm $\leq \lambda \leq 1600$ nm. As the AOI dependence of SCs is dependent on the polarization, the angular responsivity is determined subsequently for 2 orthogonal polarization states of the monochromatic light. Afterwards, a complete calibration of the absolute spectral responsivity $s(\lambda)$ at perpendicular AOI with $\theta = 0^\circ$ was performed. Finally, the AM1.5G weighted angular-dependent responsivity $s_{AM1.5G}(\theta, \varphi)$ can be derived by averaging the spectral angular responsivity curves weighted by their corresponding spectral responsivity $s(\lambda)$ and the AM1.5G reference solar spectral irradiance $E_{\lambda ,AM1.5G}(\lambda)$.

In order to validate the AOI-dependent measurements, 2 different setups were used to characterize a series of PV devices. In our first approach, we are using the setup described above and illustrated in Figure 1. In a second step, we are using a tungsten halogen lamp (1000 W FEL) as a broadband light source with a known spectrum $E_{\lambda ,lamp}(\lambda)$.

For angular-dependent measurements, the SC is tilted relative to the light source. The axes of rotation are in the center of the device on the optical axis between SC and light source for $\varphi$-rotation (see Figures 1 and 2).

As reference plane for the tilt-axis $\theta$, we are using the thickness $d_{rear}$ which is not necessarily matching with the geometrical location of the active area relative to the backside of the housing in case if the devices are encapsulated.\textsuperscript{17}

### 2.2 | Derivation of the modeling equation

The light (either monochromatic light or broadband light with a given spectrum) irradiating the SC, which is the PV device under test, generates a photocurrent $I_{SC}$. The photocurrent is measured as a voltage $V_{SC}$ using a transimpedance amplifier (current-to-voltage converter with internal resistance $R_{SC}$) and a multimeter or a lock-in amplifier. The transimpedance amplifier retains the SC operating in a short circuit state. For angular-dependent measurements, the measured current $I_{SC}(\theta, \varphi)$ is normalized to the value at normal incidence $I_{SC}(\theta = 0^\circ, \varphi = 0^\circ)$. Because the irradiance of the light source might drift over an
corresponds to the relative angular responsivity model equation for the device under test AOI dependence, which where modulated quasimonochromatic light is used, the voltages are 

\[ \text{FIGURE 1} \] Schematic of the angular-dependent spectral responsivity measurements using monochromatic light and broadband bias light. To consider polarization effects, 2 polarization filters in a filter wheel were aligned in the monochromatic optical path (not included in this figure) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 2 Schematic of the angular responsivity measurements using a broadband light source. The PV devices were kept attached on the same mounting plate as shown in Figure 1, while the tungsten halogen lamp is located on the same optical table next to the monochromatic source. This setup was used to investigate the disadvantages of using an AIO facility with a given lamp spectrum \( E_{\text{lamp}}(\lambda) \) [Colour figure can be viewed at wileyonlinelibrary.com]

AOI measurement cycle, it is monitored by a fixed photodiode/SC. The photocurrent of the monitor device \( I_{\text{MD}} \) is measured as a voltage \( V_{\text{MD}} \) using an additional transimpedance amplifier. The output voltage of the amplifier \( V_{\text{MD}} \) can be expressed via the amplifiers internal resistance \( R_{\text{MD}} \) for each photocurrent \( I_{\text{MD}} \) monitored during a AOI measurement cycle with different device under test rotation \( \phi \) and tilt \( \theta \). Hence, the modeling equation for the device under test AOI dependence, which corresponds to the relative angular responsivity \( s(\theta, \phi) \), is then:

\[
\begin{align*}
\frac{I_{\text{MD}}(\theta, \phi)}{I_{\text{MD}}(\theta=0^\circ, \phi=0^\circ)} &= \frac{V_{\text{SC}}(\theta, \phi)/R_{\text{SC}}}{V_{\text{MD}}(\theta, \phi)/R_{\text{MD}}} \\
&= \frac{V_{\text{SC}}(\theta, \phi)}{V_{\text{MD}}(\theta, \phi)} \\
&= \frac{Q_{\text{SC}}(\theta, \phi)}{Q_{\text{SC}}(0^\circ, 0^\circ)}
\end{align*}
\]

with \( Q_{\text{SC}} \), the monitor corrected signals.

In case of angular-dependent spectral responsivity measurements, where modulated quasimonochromatic light is used, the voltages are determined using the lock-in technique by measuring the X-component and Y-component (i.e., the real and imaginary part) of the voltages, both referred to a fixed phase \( \phi_0 \). In order to compensate stray light effects as well as amplifier offsets, a dark signal measurement \( V_{\text{Xdark}} \) and \( V_{\text{Ydark}} \) is subtracted for each AOI measurement and for each detector, respectively. The individual voltages are hence

\[
V = \cos(\phi_0 - \phi) \sqrt{(V_X - V_{\text{Xdark}})^2 + (V_Y - V_{\text{Ydark}})^2}
\]

(2)

For the compensation of polarization dependencies of the SC, the angular-dependent measurement cycle is performed at 2 orthogonal polarisation states of the monochromatic irradiance using broadband polarization filters. Both normalized measurements were averaged to obtain an angular responsivity for unpolarized light. Thus, the modelling equation enhances to

\[
s(\theta, \phi) = \frac{\frac{V_{\text{SC}}(\theta, \phi)}{V_{\text{MD}}(\theta, \phi)}}{\frac{V_{\text{SC}}(0^\circ, 0^\circ)}{V_{\text{MD}}(0^\circ, 0^\circ)}} + \frac{\frac{V_{\text{SC}}(\theta, \phi)}{V_{\text{MD}}(\theta, \phi)}}{\frac{V_{\text{SC}}(0^\circ, 90^\circ)}{V_{\text{MD}}(0^\circ, 90^\circ)}} \int f_i
\]

(3)

with a series of correction factors \( f_i \) with individual uncertainties contributing to the total uncertainty \( u(s(\theta, \phi)) \) of \( s(\theta, \phi) \).

2.3 Characterization of the AOI facility and uncertainty analysis

In this section, we present a thorough characterization of the AOI facilities to determine a measurement uncertainty for measurements of the angular responsivity for the first time. A stepwise discussion of the correction factors \( f_i \) is shown in detail. Contributing influences on the measurement uncertainty are

- Type A uncertainty, due to statistical fluctuation in the corrected signals \( Q_{\text{SC}} \),
- Electrical non-linearities of the current measurement
- Irradiance non-uniformity within the rotation volume,
Positioning of the device under test relative to the rotational axis,
- Thickness of the PV device,
- Polarization,
- Uncertainty of the tilt angle \( \theta \),
- Irradiance non-linearity of the PV device,
- Uncertainty of the temperature measurement and
- Wavelength uncertainty.

#### 2.3.1 Type A uncertainty

To consider type A uncertainties, the voltage measurements at a given AOI are repeated typically \( n = 20 \) to 40 times (see Figure 3).

Type A uncertainties are individually calculated by the variance of the monitor corrected mean signal \( \overline{Q} \):

\[
U(Q_{SC}) = \sqrt{\text{Var}(Q_{SC})}.
\]  

#### 2.3.2 Non-linearity of the current measurement

While the absolute values of the internal resistances of the current-to-voltage converters cancel out in the model equation, the linearity of the amplifiers is of major importance. When tilting the SC, the signal reduces with \( \cos(\theta) \) from 1 (0°) to 0.09 (85°) approximately, roughly 1 order of magnitude. The non-linearity of the transimpedance amplifier was measured to be <0.1% (type B, rectangular). Additionally, typical nonlinearities of similar lock-in amplifiers or digital voltmeter are <0.1% (type B, rectangular).\(^{18}\) Thus, the uncertainty related to electrical components is smaller than 0.15%. So \( f_{el} \) can be estimated to be

\[
f_{el} = 1 \pm 0.0015.
\]  

#### 2.3.3 Irradiance non-uniformity within the rotation volume

For laboratory measurements, a change of the irradiance spatial non-uniformity (nu) inclined on a device surface with a given tilt angle can be expected. The reason is the inverse-square law, which provides a \( 1/z^2 \) dependency for the irradiance in case if a divergent point light source is used. If we combine the spatial distribution of the spectral responsivity of a SC \( s(\lambda_{mono}, x, y) \) at a designated monochromatic wavelength \( \lambda_{mono} \) and the (non-uniform) monochromatic irradiance distribution of the corresponding light field \( E_{mono}(\lambda_{mono}, x, y) \), the generated photocurrent of the SC \( I_{nu} \) can be expressed:

\[
I_{nu} = f(s(\lambda_{mono}, x, y) \cdot E_{mono}(\lambda_{mono}, x, y)) dx dy.
\]  

For a perfect light field with uniform (uni) irradiance distribution, Equation 6 reduces to

\[
I_{uni} = f(s(\lambda_{mono}, x, y) \cdot E_{mono}) dx dy = E_{mono} f(s(\lambda_{mono}, x, y)) dx dy
\]

Hence, a non-uniformity correction factor \( f_{nu} \) for a wavelength \( \lambda_{mono} \) can be derived:

\[
f_{nu} = \frac{I_{uni}}{I_{nu}} = \frac{E_{mono} f(s(\lambda_{mono}, x, y)) dx dy}{f(s(\lambda_{mono}, x, y) \cdot E_{mono}(\lambda_{mono}, x, y)) dx dy}
\]

However, the non-uniformity factor itself is not an uncertainty contribution for angle-dependent measurements. For angular-dependent measurements, only the relative change of the non-uniformity correction factor with respect to normal incidence is of importance. Hence, we approximate the uncertainty of the angular-dependent non-uniformity \( u(nu(\theta)) \) as the relative deviation of the previously determined correction factors \( f_{nu}(\theta) \) to \( f_{nu}(0°) \):

\[
u(nu(\theta)) = \frac{f_{nu}(\theta)}{f_{nu}(0°)} - 1.
\]

Because \( f_{nu}(\theta) \) of a device is strongly related to the non-uniformity of the SC lateral responsivity \( s(\lambda_{mono}, x, y) \), and the lateral non-uniformity of the irradiance distribution at the given angle \( \theta \) within the rotation volume of that device, an extensive characterization would be required to obtain the individual correction parameters. This is not possible within reasonable time and effort for every measurement. Later, we show such an extensive characterization in order to quantify these individual correction parameters for a general case of typical used industrial type c-Si SCs and c-Si reference SCs.

The spatial spectral responsivity \( s(\lambda_{mono}, x, y) \) of a silicon SC (156 × 156 mm\(^2\)) was measured by using a light beam induced current

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**FIGURE 3** (top) Measured voltages for tilting a solar cell from \( \theta = 0° \) to \( \theta = 90° \). Each angular measurement is repeated 20 times; (bottom) monitor corrected and averaged signal \( \overline{Q} \) over angle theta and assigned relative standard uncertainties [Colour figure can be viewed at wileyonlinelibrary.com]
mapping method, scanning across the detector surface with monochromatic light. A defined shaped beam size with a cross section of $5 \times 5 \text{ mm}^2$ allows mappings of $s(x, y)$. This measurement is performed for wavelengths ranging from 350 to 1150 nm in steps of 50 nm. Figure 4 (upper left) shows the measured non-uniformity of the spectral responsivity of a silicon SC ($156 \times 156 \text{ mm}^2$) scanned with a monochromatic beam at a wavelength of $\lambda_{\text{mono}} = 800 \text{ nm}$.

Figure 4 upper right shows the measured irradiance non-uniformity $E_{\text{mono}}(\lambda_{\text{mono}}, x, y, z_0)$ of the monochromatic light field at 800 nm in the measurement plane at a distance $z_0 = 2500 \text{ mm}$ from the light source. The irradiance map was measured using a step width of 5 mm with a photodiode providing an active area of $5 \times 5 \text{ mm}^2$ limited by a precision aperture. The combination of both in 1 map is shown in Figure 4 bottom as a superposition.

The non-uniformity of the irradiance within the rotation volume of the device $E_{\text{mono}}(\lambda_{\text{mono}}, x', y')$ was calculated from the measured $E_{\text{mono}}(\lambda_{\text{mono}}, x, y, z_0)$ using the $E^{-1/z^2}$ law. The irradiances $E_{\text{mono}}(\lambda_{\text{mono}}, x', y')$ for varying AOI corresponding to the surface of the tilted device located at new coordinates $x'$ and $y'$ were obtained by applying an interpolation procedure at the designated intersection points explained in Figure 5.

As an example, the dependence of the irradiance non-uniformity $E_{\text{mono}}(\lambda_{\text{mono}}, x', y')$ during a tilt of a large area device for a light field at $\lambda_{\text{mono}} = 800 \text{ nm}$ and $z_0 = 2500 \text{ mm}$ is shown in Figure 6. In this case, the irradiance non-uniformity in the designated test plane calculated analogous to a procedure defined in the international standard IEC 60904-9 Ed. 2.19 increases from 1.74% at $\theta = 0^\circ$ to 7.07% at $\theta = 80^\circ$ for a $156 \times 156 \text{ mm}^2$ sized field. In the case of a $20 \times 20 \text{ mm}^2$ sized monochromatic field, the non-uniformity increases from 0.25% at $\theta = 0^\circ$ to 0.9% at $\theta = 80^\circ$.

Again, these maps were determined for the wavelengths from 350 to 1150 nm in steps of 50 nm as well as for the broadband light field of a tungsten halogen lamp. Based upon these datasets of $s(\lambda_{\text{mono}}, x, y)$ and $E_{\text{mono}}(\lambda_{\text{mono}}, x', y')$, $uf(\theta)$ for a large area SC ($156 \times 156 \text{ mm}^2$) and different wavelengths was determined. The result is shown in Figure 7 as coloured curves on the top. It can be observed that this uncertainty is strongly dependent on wavelengths which is a direct consequence on the wavelength-dependent non-uniformity of the device and the irradiance distribution. The black dotted line is then taken as a worst-case assumption for a device of $156 \times 156 \text{ mm}^2$. The same analysis was performed for small WPVS reference SCs with the dimensions of $20 \times 20 \text{ mm}^2$ and for both types of devices for the irradiance distribution of the broadband light source. The analogue worst case uncertainties are shown in Figure 7 (bottom). Please note, the uncertainties for the broadband light source are larger, because the non-uniformity of the irradiance distribution is higher.

As already mentioned, such a thorough analysis cannot be made for each calibration within a reasonable time and effort. Therefore, the worst-case assumptions for the uncertainty of $f_{\text{anu}}$, shown in Figure 7 are taken as generally assumed uncertainties for the given combination of device size and light source, so that

$$f_{\text{anu}}(\theta) = 1 \pm uf_{\text{anu}}(\theta).$$

(10)
2.3.4  |  Positioning of the photovoltaic device

The lateral positioning of the sample relative to the \( \phi \)-rotation axis and optical axis (x and y direction) is made individually using an accurate laser-alignment procedure. Hence, the exact position of the device center relative to the rotation axes can be determined with an accuracy of better than \( \pm 0.1 \) mm. This holds both for the monochromator-based and broadband-based setups, because the same goniometer and alignment procedure is used. Hence, positioning uncertainties in x and y direction are negligibly small.

2.3.5  |  Thickness of the solar cell

The thickness \( d_{\text{real}} \), i.e., the exact location of the active surface of the PV device relative to the \( \theta \)-axis in z direction is a more critical parameter compared with the positioning uncertainty in x and y direction. For encapsulated devices, the location of the active area relative to the backside of the housing is usually unknown.\(^\text{17} \) This distance is defined as the thickness with an estimated uncertainty of \( \pm 0.5 \) mm. The exact location of the \( \theta \)-axis relative to the mounting plate of the SCs has an uncertainty of \( d \pm 0.5 \) mm. Hence, the conservatively estimated uncertainty of the real relative position of the active device surface to the tilt axis has a maximum value of \( u(d_{\text{real}}) \pm 1 \) mm. Figure 8 shows the effect of an inaccurate thickness \( d \) on the angular-dependent measurements.

In case of smaller thickness values (b), the device is tilted towards the light source resulting in an overestimation of the values at increasing...
AOI. In case of larger thickness values \( c \), the SC is tilted away from the light source resulting in an underestimation of the values.

A sensitivity analysis was performed in order to quantify the impact of this effect for a 20 × 20 mm\(^2\) and a 156 × 156 mm\(^2\) sized PV device. Angular-dependent measurements were performed with different set values for the thickness. Therefore, angular-dependent measurements with both device sizes were performed with varying values for the thickness ranging from −4 mm to +4 mm with an increment of 1 mm. The sensitivity of the angular responsivity \( c_\theta(\theta) \) per mm offset was then determined for each device size to finally obtain a combined uncertainty for the thickness correction factor \( f_d \):

\[
 f_d(\theta) = 1 \pm u_d(\theta) = 1 \pm c_\theta(\theta) \cdot u(d_{\text{real}}),
\]

**2.3.6 | Polarization**

The monochromatic irradiance of the laser-DSR facility is polarized. However, the polarization changes with wavelength because there are different laser sources as well as monochromator gratings. To consider polarization effects on the angular-dependent spectral responsivity measurements, 2 broadband (250–4000 nm) polarization filters were positioned into a filter wheel between the monochromator and the device under test. Hence, 2 polarization states can be realized on the designated test area by placing either the 0° polarizer or the 90° polarizer into the beam. A full angular-dependent measurement cycle is then performed with 0° and with 90° polarizers subsequently, and each cycle is evaluated independently. Normalized angular-dependent responsivities of the 0° and 90° polarized measurements are then averaged to obtain the responsivity for non-polarized light (see Equation 3).

Uncertainties related to the polarization originate from the extinction ratio of the polarizer, the purity of the polarization state, and the alignment uncertainty of the perpendicular orientation of the 2 polarizers which would lead to unequal averaging.

The relative orientation of the mounted polarizers was evaluated by using a third polarizer which was mounted in front of a photodiode in the measurement plane and then rotated by \( \varphi_{\text{pol}} \) around the optical axis. The relative orientation of the 2 polarizers was adjusted leading to a shift between the polarization measurements curves of 90°. The uncertainty of the orientation is estimated to be \( u_{\varphi,\text{pol}} \leq 1° \).

**FIGURE 7** (top) Uncertainty of the angular-dependent non-uniformity of monochromatic irradiance on the measurement of the short circuit current of a for a 156 × 156 mm\(^2\) PV device. The black dotted line shows the worst-case assumption of all measurements. It is then taken as the general assumed uncertainty for such a device. (bottom) The blue curves represent the uncertainties for 20 × 20 mm\(^2\) sized devices, while the red curves stand for 156 × 156 mm\(^2\) industrial sized devices. The continuous lines represent the uncertainties for the broadband integral measurement and the dashed lines for the monochromator-based (spectral), respectively [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 8** Impact of thickness on the angular-dependent measurement. (A) The exact consideration of the device thickness \( d_{\text{real}} \) relative to the position of the tilt axis \( \theta \). (B) the underestimation and (C) overestimation effect under consideration of an inaccurate thickness [Colour figure can be viewed at wileyonlinelibrary.com]
90° polarizer is rotated by the maximum $u_{\text{pol}} = 1°$, overestimation and underestimation of the respective signals for polarization states 0° and 90° are slightly effecting the finally determined averaged angular responsibility for non-polarized light. The extinction ratio of the polarizers used in our work is in the range of 1000:1. Hence, the related polarization uncertainty is < 0.1%.

However, the uncertainty of the polarization is proportional to the individual polarization dependence of the PV device under test. If the devices angular responsivity is independent from polarization-related effects, the polarization uncertainty can be reduced to zero. If the devices angular responsivity shows strong polarization-related effects, the polarization uncertainty increases proportional.

Figure 9 shows our empiric approach for the determination of the worst-case impact of the polarization uncertainty on the output quantity. For an entire measurement cycle of the angular-dependent responsivity, the maximum deviation of the 2 polarization state measurements is taken. This is shown as dotted lines in Figure 9. A conservative estimation of 10% of this deviation is taken as uncertainty (rectangular) $u_{\text{pol}}(\theta)$ for the polarization correction factor $f_{\text{pol}}$:

$$f_{\text{pol}} = 1 \pm u_{\text{pol}}(\theta).$$ (12)

2.3.7 Uncertainty of the tilt angle $\theta$ due to an extended light source

In our setup, the light source for the angular-dependent measurements can be considered as an extended radiant area with an aperture diameter $A$. In our analysis, the aperture area is approximated to represent an equally distributed ensemble of point sources that irradiates the PV device with a diagonal dimension $L$

Under the assumption of a Lambertian source surface, a rectangular distribution of deviating AOIs can be found within an interval of $\Delta \theta$ and $+\Delta \theta$. By applying a simple trigonometric law (see also Figure 10), the maximum deviation can be found in dependence of $\theta$ and the distance $z$:

$$\Delta \theta = \arctan \left( \frac{\frac{A}{2} \cos(\theta) + \frac{L}{2}}{z} \right).$$ (13)

Additionally, a systematic offset $\theta_0$ could be present if the measurement plane is not exactly perpendicular to the z-axis (ie, the optical axis). This offset was experimentally determined to be < 0.1°. The angular-dependent responsivity $s(\theta)$ is an asymmetric function within a given interval $[-\Delta \theta + \theta_0, +\Delta \theta + \theta_0] = \{\theta | -\Delta \theta + \theta_0 \leq \theta \leq +\Delta \theta + \theta_0\}$. The average angular-dependent responsivity $s([-\Delta \theta + \theta_0, +\Delta \theta + \theta_0])$ would lead to a systematic deviation $\Delta s(\theta)$ from $s(\theta)$ at each AOI $\theta_i$:

$$\Delta s(\theta_i) = s([-\Delta \theta + \theta_0, +\Delta \theta + \theta_0]) - s(\theta_i).$$ (14)

The impact of this systematic deviation for an aperture of 10 mm is shown in Figure 11. The error bars in horizontal direction indicate the rectangular $\theta$-interval $[-\Delta \theta + \theta_0, +\Delta \theta + \theta_0]$. The angular-dependent responsivity in this interval $s([-\Delta \theta + \theta_0, +\Delta \theta + \theta_0])$ under the assumption of a constant slope between incremental angular steps is averaged. The systematic deviation $\Delta s(\theta)$ is then the difference of this average and the spectral responsivity at the given angle $\theta_i$. This systematic deviation $\Delta s(\theta)$ is taken as the uncertainty for the AOI $u_{\phi}(\theta)$ (rectangular):

$$f_{\theta} = 1 \pm \frac{\Delta s(\theta)}{s(\theta)} = 1 \pm u_{\phi}(\theta).$$ (15)

These uncertainty contributions are individually calculated for each device visualized as dashed blue curves. Please note that the uncertainty can generally be considered higher for smaller devices, because the effect of the systematic offset outweighs the effect of the angular distribution.

2.3.8 Irradiance non-linearity of the photovoltaic device

The irradiance non-linearity of the PV device leads to systematic deviations when changing the incident angle and hence the irradiance. This could either be corrected for when the non-linearity is known or otherwise an uncertainty has to be assigned. In the case of the monochromatic AOI facility, the angular-dependent spectral responsivity is measured with constant bias irradiance $E$. This is realized using bias lamps mounted on the rotation stage (see Figure 1). Hence, the non-
which are kept in a fixed position during rotation related to the PV

In case of the monochromatic facility, we use steady

ature constant at 25°C with insignificant fluctuations around ±0.05 K.

The spectral responsivity of the SC is temperature dependent. It is

| 2.3.11 Calculation of a combined uncertainty for the angular-dependent measurements |

All relevant uncertainty contributions described earlier can now be incorporated into the modelling equation 3 leading to the final equation for the angular-dependent spectral responsivity:

\[ s(\theta, \varphi) = \frac{Q_{\text{SC}}(\theta, \varphi)}{Q_{\text{SC}}(0, 0)} \cdot f_{\text{pol}} \cdot f_{\text{polarization}} \cdot f_{\text{unif}} \cdot f_{\text{polari}} \cdot f_{\text{anu}} \cdot f_{\text{e}}. \]

In analogy, the equation for the integral angular-dependent responsivity using a broadband light source can be written as

\[ s(\theta, \varphi) = \frac{Q_{\text{SC}}(\theta, \varphi)}{Q_{\text{SC}}(0, 0)} \cdot f_{\text{pol}} \cdot f_{\text{polarization}} \cdot f_{\text{unif}} \cdot f_{\text{polari}} \cdot f_{\text{anu}} \cdot f_{\text{e}}. \]

The calculation of the uncertainty of the angular-dependent spectral responsivity \( u_s(\theta, \varphi) \) is performed using Monte Carlo methods. The calculation is done for every single measurement because the uncertainty contributions are partly dependent on the measurement result itself (i.e., Type A, \( f_{\text{pol}} \), \( f_{\text{e}} \)). Furthermore, most uncertainty contributions are functions of the AOI. Therefore, the uncertainty budget individually changes dependent on device, device size, wavelength, and AOI. Because the creation of a classical tabulated uncertainty budget cannot cover all these dependencies, we only show a selected example in Figure 12 in order to visualize the magnitude of the

linear of the PV device due to the changing monochromatic irradian-
tance can be neglected.

The situation changes for broadband of the AOI facility used for

device (see Figure 1). The bias irradiance represents the dominant heat

load. Therefore, the heat load on the SC does not change significantly
during rotation. We conclude that uncertainties introduced by temper-

ature effects are assumed to be negligible for the angular-dependent spectral responsivity measurements.

In case of a broadband setup without additional bias irradiance,

the load changes up to 15% across the rotation volume for a

156 x 156 mm² SC at a distance \( z_0 = 2500 \) mm if the 1/z² distance law is assumed. Because the serially connected Peltier elements theo-

retically provide uniform cooling at for a given uniform heat load, a

non-uniform heat load can affect the device temperatures non-uniform-

ity, resulting in differences in the temperature \( \Delta T(x,y) \) for varying AOI. However, we assume that at distances >2 m, the effect of the positive temperature difference in the surface area with a higher heat load is compensated by the effect of the negative temperature differ-

ence in the surface area with lower heat load for tilted devices. Asymmetries in the device temperature non-uniformity \( \Delta T(x,y) \) seem to be negligible for larger distances. Hence, uncertainties due to tem-

perature effects are assumed to be negligible also for the investigated broadband AOI facility.

2.3.10 Wavelength uncertainties

The light source is a laser setup generating the desired wavelength by

using a tunable mode-locked Titan:Sapphire laser and different non-

linear optics. Furthermore, a monochromator reduces the spectral

bandwidth. The wavelength uncertainty is smaller than 0.3 nm and

hence negligible in our study.

2.3.9 Uncertainties due to the device temperature

The spectral responsivity of the SC is temperature dependent. It is

assumed that the temperature coefficient is not influenced by the angular-dependent excitation. Hence, only temperature fluctuations during the measurement remain as a source for uncertainties. The Peltier element-based temperature control keeps the device temper-

ture constant at 25°C with insignificant fluctuations around ±0.05 K.

In case of the monochromatic facility, we use steady-state bias lamps

which are kept in a fixed position during rotation related to the PV


**FIGURE 11** Impact of the variability of the \( \theta \)-distribution due to an extended light source and a systematic \( \theta_0 \) offset on the measured angular-dependent responsivity \( s(\theta) \). On the top, the impact is shown for a 20 x 20 mm² sized solar cell, and on the bottom it is shown for a 156 x 156 mm² sized solar cell [Colour figure can be viewed at wileyonlinelibrary.com]
individual standard uncertainty contributing to the combined standard uncertainty of the angular-dependent spectral responsivity $u_{s}(\theta, \phi)$.

In the upper graph, the relative standard uncertainties of the individual uncertainty contributions are shown for an angular-dependent measurement of the spectral responsivity at 450 nm of an encapsulated reference SC. The black curve donates the combined standard uncertainty. It can be seen that the uncertainty increases with increasing AOI. This is related to the uncertainty contribution from the non-uniformity and the AOI $\theta$. In the lower graph, the contribution of the individual uncertainty components to the combined standard uncertainty is shown as percentage values. This graph visualizes the dominating uncertainty components for the respective AOI in our example.

3 | RESULTS AND DISCUSSION

In the following section, exemplary results of the angular-dependent spectral responsivity of different types of SCs are shown in order to demonstrate the strong differences that can occur. Subsequently, it is shown that the angular responsivity measured by any broadband light source (natural sunlight, solar simulator, etc.) can be mathematically derived from the measured angular-dependent spectral responsivity, the measured spectral responsivity of the device at normal incidence and the spectral irradiance. Subsequently, a validation of the spectral measurements is shown by calculating the angular responsivity for a broadband light source using the spectral data and then comparing it with the actual experimental measurement using this (previously described) broadband light source. Finally, based on these data sets an angular-dependent spectral mismatch referring to

reference conditions is discussed as well as the occurrence of additional measurements uncertainty due to azimuthal asymmetry of a PV device.

3.1 | Measurement results

Figure 13 shows the angular-dependent responsivities at different wavelengths of a non-encapsulated c-Si reference SC (left-hand side), an encapsulated c-Si reference SC (middle), and an encapsulated c-Si reference with an IR-filter as cover glass (right-hand side) that is typically used as a reference for calibration of amorphous Si SCs. In the upper graphs, the angular-dependent responsivity for different wavelengths is shown together with the ideal cosine response (black dotted line). In the lower graphs, the relative deviation from this ideal cosine response is shown.

From these graphs, significant differences in the angular-dependent spectral responsivity can be observed. For the non-encapsulated reference SC, there is a strong deviation from cosine at incidence angles larger than 25° apparent. This deviation is enhanced with decreasing wavelength. The encapsulated devices also show a spectral dependence of the angular-dependent responsivity. However, it is less pronounced. Most interestingly, the encapsulated SC significantly overperforms the ideal cosine response at $\lambda > 900$ nm. This effect most likely originates in interreflections between the cover glass, the SC, and the device housing. The IR-filtered reference SC shows an opposed spectral characteristic of the angular-dependent responsivity. The deviation from cosine increases with increasing wavelength. Please note the differing color scale, due to the filter of the spectral responsivity reduces to zero for $\lambda > 900$ nm. In conclusion, these 3 different types of reference SCs show strongly different angular-dependent spectral responsivities and hence would rate a diffuse light source significantly different. This is of importance when reference devices are used in calibration facilities with a significant contribution of diffuse light, ie, using global natural sunlight or non-collimated solar simulators. Example calculations of such an effect for natural sunlight conditions for exactly these 3 devices can be found in Plag et al.20

Figure 14 shows measurement results for a typical industrial large area SC (top) and for a mini-module made from the same type of SC (bottom). The direct comparison demonstrates similarly to the described WPVS reference SCs the effect of encapsulation on the angular dependence of the spectral responsivity. Similar observations were previously described by Geisemeyer et al.9 For the bare SC, the deviation from cosine is large even at low angles of incidence for short wavelengths below 500 nm. In the VIS-IR region from 500 to 1200 nm, the deviation from cosine is very low even for high angles of incidence up to 60°. After encapsulation of such a SC in a module package, this spectral and angular characteristic significantly changes. The cosine response significantly improves for all wavelengths and even lead to a relative super-cosine response for the infrared region at angles below 65°. Hence, we conclude that the spectral responsivity of typical PV devices can significantly vary for different AOI.

For calibration of PV devices, measurement uncertainties related to angular-dependent spectral responsivity should be considered when light sources with diffuse light components are used and when device under test and reference device can be expected to have different
angle-dependent spectral responsivities. The latter can generally be expected when 1 device is encapsulated and the other is not.

3.2 Validation

For validation of the measurements and the determined measurement uncertainties, the 2 described methods for angular-dependent measurements will be compared. The angular dependence of the previously described IR-filtered device was measured using the broadband 1000 W FEL tungsten halogen lamp and the spectral facility. From the spectral data, an artificial broadband data set was derived by weighting the spectral angular data with the measured spectral responsivity of the device at normal incidence and the spectral irradiance of the 1000 W FEL tungsten halogen lamp. The results are shown in Figure 15.

Please note that the uncertainty contributions of both methods are partly correlated. However, the most significant uncertainty contributions \( f_{\text{anu}}, f_{\text{pol}}, f_{\theta}, \) and \( f_E \) are different for both methods. For validation purposes, the \( E_n \) number according to ISO 17043 is often used. If \( |E_n| \leq 1 \), the measurements can be considered to be consistent within their uncertainties. The \( E_n \) number for this comparison measurement is shown in the upper graph of Figure 15 for each AOI. Hence, we conclude, that both measurements are consistent within the stated expanded uncertainties. Furthermore, it can be concluded that the angular-dependent responsivity for any spectral irradiance can be derived from the spectral data by calculating the weighted average using the spectral responsivity at normal incidence and the spectral irradiance.

3.3 Discussion of spectral mismatch effect

From the previous section, we can conclude that the measurement of the angular-dependent spectral responsivity allows the analysis of spectral and angular effects under any given spectrum including diffuse irradiance components. While spectral mismatch errors can be neglected for monochromator-based AOI measurements, they have to be considered for measurements taken with broadband setups providing a fixed spectrum. The angular-dependent spectral mismatch factor \( \text{SMM}(\theta) \) due to the spectral irradiance of the broadband light source \( E_{\text{lamp}}(\lambda) \) and due to the angular-dependent spectral responsivity \( s(\lambda, \theta) \) of the individual PV device can be expressed as analog to the definition in\(^22:\)

\[
\text{SMM}(\theta) = \frac{\int \lambda E(\lambda) s(\lambda, \theta = 0^\circ) \, d\lambda}{\int \lambda E_{\text{lamp}}(\lambda) s(\lambda, \theta) \, d\lambda} = \frac{\int \lambda E_{\text{lamp}}(\lambda) s(\lambda, \theta) \, d\lambda}{\int \lambda E_{\text{lamp}}(\lambda) s(\lambda, \theta = 0^\circ) \, d\lambda}. \tag{19}
\]

As a reference spectral responsivity, we used for this computation the devices spectral responsivity under normal incidence \((\theta = 0^\circ)\). \( E(\lambda) \)
is the spectral irradiance of the condition where the spectral mismatch refers to. Please note, that under global outdoor conditions, a variety of different spectra \( E_r(\lambda) \) can be apparent. When the AOI dependence of a PV devices short circuit current is used, which was measured with a broadband source \( E_{\text{lamp}}(\lambda) \), spectral mismatch effects have impact on the determination of an angular responsivity under a given spectrum \( E(\lambda) \).

We calculated the spectral mismatch factors in dependence of the AOI \( \theta \) for 3 different PV devices (see Figure 16). In our example, we refer to the global solar reference spectrum under air mass 1.5 defined in the IEC standard\(^{23} \) by using it in Equation 19 for \( E_r(\lambda) \) and the spectral irradiance of a 1000 W tungsten halogen lamp \( E_{\text{lamp}}(\lambda) \) used in the previously described broadband AOI-facility.

In analogy to the conventional need for spectral mismatch correction when either the spectral irradiance of the solar simulator differs significantly from the AM1.5G spectrum or the spectral responsivity of reference and DUT differ significantly also a need for spectral mismatch correction can be observed for AOI-dependent measurements. In this case, the spectral irradiance of the halogen lamp differs significantly and can be considered to be a poor performing solar simulator. Hence, this scenario can be considered as a worst-case scenario. For the encapsulated device, the angular-dependent change of spectral responsivity (shown in Figure 13 middle) is less pronounced. Hence, spectral mismatch correction of less than 0.5% is needed, even at larger AOI. For the non-encapsulated device, angle-dependent change of spectral responsivity (shown in Figure 13 left) is more pronounced, especially in the UV-VIS region above 30°. This leads to a needed spectral mismatch correction up to 1.2%. The most pronounced angular-dependent change of spectral responsivity was observed for the IR-filtered reference device (shown in Figure 13 right-hand side). The resulting spectral mismatch correction is up to 6%.

Hence, we conclude that an angular-dependent spectral mismatch can be considered to be of major importance and should be included in any uncertainty budget for a broadband light source AOI facility. If the angular-dependent spectral responsivity is not known, a larger uncertainty should be estimated.

### 3.4 Azimuthal asymmetry of a photovoltaic device

Angle of incident-dependent measurements using a broadband light source or even monochromatic light can be considered as a very time-consuming measurement. Furthermore, the parameter space that should be covered \((\theta, \varphi, \lambda)\) is very large; hence, often a full characterization is not possible. The energy rating standard IEC 61853-2\(^{21} \) demands measurements to be taken along 2 orthogonal azimuthal directions with respect to the module normal. Rotational symmetry should be verified at \( \theta = -90^\circ \) and \( \theta = 90^\circ \) AOI. We tested the azimuthal symmetry for several devices in order to evaluate the measurement uncertainty if only measurements along 2 orthogonal azimuthal directions are performed compared with measurements in the full half space using the previously described broadband light source facility.

Figure 17 shows the result for the non-encapsulated reference SC (see also Figure 13 left-hand side). This example was found to have the...
largest azimuthal asymmetry within the investigated sample set. Therefore, it represents a worst case scenario in order to underline the possible magnitude of this effect. The blue and red dotted lines correspond to the measurements along the 2 orthogonal angular directions at \( \varphi = 0^\circ \) and \( \varphi = 90^\circ \). The grey area shows the maximum deviation observed for all other azimuthal orientations. For this example, the asymmetry at 80° along the \( \varphi = 0^\circ \) and \( \varphi = 90^\circ \) direction is 3.5% and 5.6%, respectively. Hence, this non-encapsulated WPVS reference SC must be considered to be non-symmetrical according to the standard. However, the maximum azimuthal deviation shown as the grey area in Figure 17 is 12%. Therefore, we conclude that the azimuthal symmetry in the studied reference PV device is not apparent. If such dependence is found, the procedure defined in the energy rating standard cannot be applied properly. Please note that a measurement error related to a systematic offset of the AOI \( \theta \) can lead to asymmetric measurements. A systematic offset of only 1° leads to a measured asymmetry of 22% at 80° AOI.

4 | SUMMARY

We have improved PTB's primary calibration facility for reference SCs with the capability to measure optical losses in dependence of the spectrum and AOI of PV devices, such as reference SCs and mini-modules with active areas of up to 156 × 156 mm². By means of a comprehensive characterization of the setup and measurement method, we were able to derive a detailed measurement uncertainty budget for the angular-dependent spectral responsivity measurement. We show measurement results of angular-dependent spectral responsivities for a diversity of different PV devices. Dependent on the device, we observed strong differences in the responsivities particularly in the UV and IR wavelength regions for varying AOI. We validated the measurement results obtained with our primary setup with a comparison against a broadband facility, providing a fixed lamp spectrum. The impact of an angular-dependent spectral mismatch problem was outlined. Finally, we have shown the significance of PV devices azimuthal symmetry for angular-dependent PV device characterization. As a result of this study, PTB offers the calibration of the angular-dependent spectral responsivity of reference SCs and will transfer these findings to standardization bodies. Furthermore, based on this characterization method, a variety of investigations regarding the impact of diffuse light components on high accuracy PV device performance measurements and energy rating is now feasible.20,24

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ORCID

F. Plag http://orcid.org/0000-0001-8728-6504

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