**EURAMET Comparison**

**Project No. 1226**

**EURAMET.PR-S5**

# Calibration of reference solar cells at standard test conditions

# Final Report

This document was prepared by
Stefan Winter

Physikalisch-Technische Bundesanstalt

2020-12-08

# Contents

# 1 General information on the comparison

1.1 Under the Mutual Recognition Arrangement (MRA)[1] the metrological equivalence of national measurement standards will be determined by a set of key comparisons (KCs) chosen and organised by the Consultative Committees of the CIPM working closely with the Regional Metrology Organisations (RMOs). This set of key comparisons has to be added by supplementary comparisons (SCs) organised by the RMOs.

1.2 The proposal for a comparison was presented during the CCPR meeting in Hawaii Sep. 2011. The EURAMET Photometry and Radiometry contact persons decided to start a supplementary comparison on the calibration of reference solar cells at standard test conditions (EURAMET project 1226) during the Paris meeting in Feb. 2012. The PTB was assigned to act as a pilot laboratory. The comparison was split into three parts. The first part, starting 2012, covers linear WPVS type reference solar cells with standard Si responsivity. Further comparisons will consider filtered solar cells and non-linear solar cells. Although this SC is organized within a EURAMET project, it is a global comparison carried out worldwide.

1.3 The technical protocol has been drawn up by PTB with feedback from NMC A*STAR, VNIIOFI and KRISS.

1.4 The technical protocol was agreed on by all participants and was sent out on April 2$^{nd}$, 2012 to TC-PR of EURAMET for approval. The procedures outlined in the technical protocol cover the technical procedure to be followed during measurement of the reference solar cells. The procedure, which follows the guidelines for RMO PR Supplementary Comparisons[2], is based on current best practise in the use of reference solar cells and takes account of the experience of the participants.

1.5 The organisation of the whole comparison was described in the technical protocol.

1.6 According to the technical protocol (Section 5.4), after receipt of all measurement reports from the participating laboratories, the pilot laboratory has analysed the results and prepared a first pre-draft "A" report on the comparison following the draft guidelines of the Guidelines for CCPR Key Comparison Report Preparation[3]. The results of the participants were sent back to each participant and each participant was asked individually for confirmation of the results and the uncertainty in order to confirm them prior to the publication of Draft A. The pre-draft "A" report included measurement reports of the participants and submitted uncertainty tables, but no results. This was circulated to the participants for comments, additions and corrections. During this phase participants were at liberty to correct their submitted uncertainties, but only in an increased direction and supported by an explanation. Subsequently, the procedure outlined in the BIPM guidelines[3] was followed, which will mean that no results can be changed for whatever reason by any participant except for errors of the pilot lab.

1.7 The comparison was carried out through the calibration of two to three unfiltered reference solar cells with WPVS-design per participant. The reference solar cells were provided by the participants.

1.8 The measurement sequence was participant-pilot-participant. Thus, the comparison had the form of a multiple-star-type comparison (Fig.1). There were three phases:

1) In the first phase every participant calibrated his own reference solar cells and sent the solar cells to the pilot laboratory. The results were sent to the pilot laboratory after the end of the first phase.

[1] MRA, Mutual Recognition Arrangement, BIPM, 1999.
[2] CCPR-G7: Guidelines for RMO PR Supplementary Comparisons, CCPR-G7, 2019, 6 pp
[3] Guidelines for CCPR Comparison Report Preparation, CCPR Working Group on Key Comparisons, CCPR-G2 Rev.4 – approved by WG-KC on January 8, 2019

2) In the second phase the pilot laboratory calibrated all reference solar cells of all participants and sent the reference solar cells back to the participants.
3) In the third phase every participant calibrated his own reference solar cells again to check the drift and provided the results to the pilot laboratory.

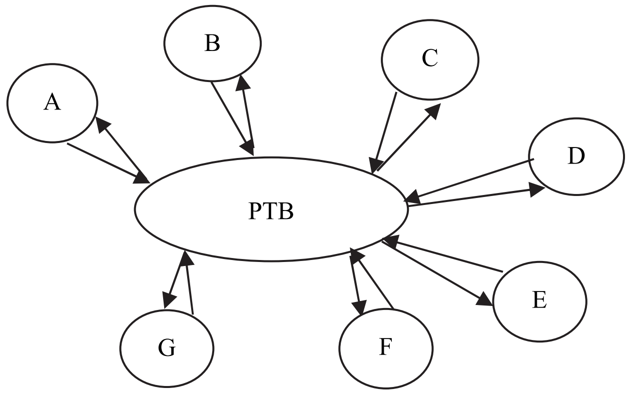



Fig. 1: Diagram of the multiple-star-type comparison

# 2 Laboratory contact persons

| Address | Person(s) in charge | Contact | Phase |
|---|---|---|---|
| Physikalisch-Technische Bundesanstalt<br>Bundesallee 100<br>D-38116 Braunschweig<br>Germany | Stefan Winter,<br>Dirk Friedrich | Tel: +49(531)592-4140<br>Fax: +49(531)592-694140<br>e-mail: Stefan.Winter@ptb.de | 2 (Pilot lab) |
| Physikalisch-Technische Bundesanstalt<br>Bundesallee 100<br>D-38116 Braunschweig<br>Germany | Ingo Kröger | Tel: +49(531)592-4140<br>Fax: +49(531)592-694140<br>e-mail: Ingo.Kroeger@ptb.de | 1,3 |
| FGUP "All-Russian Research Institute For Optical And Physical Measurements" (FGUP "VNIIOFI")<br>46 Ozernaya St.,<br>119361, Moscow, Russia | Morozova Svetlana Petrovna | Tel: +7 (495) 437 37 00<br>Fax: +7 (495) 437 37 00<br>e-mail:<br>morozova-m4@vniiofi.ru | 1,3 |
| Korea Research Institute of Standards and Science (KRISS)<br>267 Gajeong-Ro, Yuseong-Gu<br>305-340 Daejeon<br>Rep. Korea | Dong-Hoon Lee | Tel: +82-42-868-5706<br>Fax: +82-42-868-5022<br>e-mail: dh.lee@kriss.re.kr | 1,3 |
| National Metrology Centre, Agency for Science, Technology and Research (NMC, A*STAR)<br>1 Science Park Drive<br>Singapore 118221 | Xuebo Huang | Tel: +65 6279 1939<br>Fax: +65 6279 1993<br>e-mail: huang_xuebo@nmc.a-star.edu.sg | 1,3 |
| Industrial Technology Research Institute Incorporated (ITRI)<br>321 Sec. 2, Kuang Fu Rd.,<br>Hsinchu 30011, Chinese Taipei | Pin-Hao Wang,<br>Chen-Wei Chen | Tel: +886(3) 5743710<br>Fax: +886(3) 5710180<br>e-mail:<br>Pin-Hao@itri.org.tw | 1,3 |
| National Institute of Metrology, China<br>Room 110, Optical Building,<br>No.18, Beisanhuandong Lu<br>Beijing<br>China | Xiong Limin,<br>Lin Yandong | Tel: 86(10)64524822<br>Fax: 86(10)64524822<br>e-mail: xlmin@nim.ac.cn;<br>Linyd@nim.ac.cn | 1,3 |

Table 1: Data of participants details. PTB participated with two facilities. Their established DSR facility acted as pilot laboratory and their new Laser-DSR facility had the status of a participant.

# 3 Exposure times

The one sun equivalent exposure time during the measurements at the pilot laboratory is about 8 hours, as all cells were measured twice, and two solar cells were mounted during one run.

# 4 Performance of the transfer detectors

The solar cells were measured three times. Before they were sent to PTB by the participants, at PTB and after they were sent back to the participants. The stability of the solar cells was checked by calculation of the deviation of the two measurements by the participants. As all deviations are smaller than the respective expanded measurement uncertainty ($k$ = 2), the solar cells are considered stable.

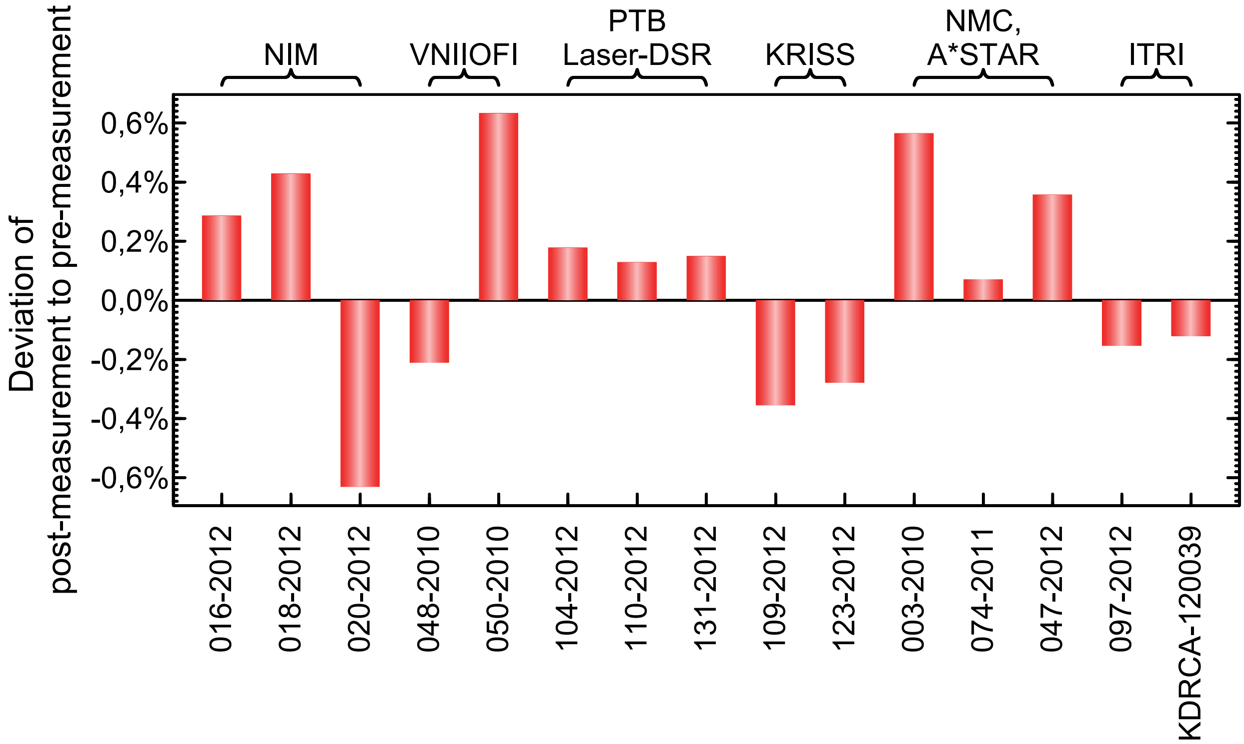



Figure 1: Relative deviation of the $I_{STC}$ measurement after getting back the solar cell from PTB (phase 3) to the measurement before sending the solar cells to PTB (phase 1).

| Institute | Solar Cell | I(STC) before | rel. Std. Unc. | I(STC) after | rel. Std. Unc. | Dev. Stage 3 to Stage 1 |
|---|---|---|---|---|---|---|
| | | in mA | in % | in mA | in % | in % |
| NIM | 016-2012 | 139,70 | 0,61% | 140,1 | 0,46% | 0,29% |
| | 018-2012 | 140,10 | 0,61% | 140,7 | 0,45% | 0,43% |
| | 020-2012 | 142,50 | 0,60% | 141,6 | 0,45% | -0,63% |
| VNIIOFI | 048-2010 | 142,00 | 0,82% | 141,7 | 1,06% | -0,21% |
| | 050-2010 | 142,20 | 0,82% | 143,1 | 1,05% | 0,63% |
| PTB (Laser-DSR) | 104-2012 | 140,53 | 0,20% | 140,78 | 0,20% | 0,18% |
| | 110-2012 | 139,63 | 0,20% | 139,81 | 0,20% | 0,13% |
| | 131-2012 | 113,81 | 0,20% | 113,98 | 0,20% | 0,15% |
| KRISS | 109-2012 | 140,60 | 1,00% | 140,10 | 1,00% | -0,36% |
| | 123-2012 | 143,20 | 1,01% | 142,80 | 1,02% | -0,28% |
| NMC, A*STAR | 003-2010 | 115,03 | 0,45% | 115,68 | 0,32% | 0,57% |
| | 074-2011 | 142,61 | 0,45% | 142,71 | 0,34% | 0,07% |
| | 047-2012 | 111,97 | 0,48% | 112,37 | 0,32% | 0,36% |
| ITRI (only WPVS) | 097-2012 | 142,42 | 0,33% | 142,20 | 0,32% | -0,15% |
| | KDRCA-120039 | 123,89 | 0,32% | 123,74 | 0,32% | -0,12% |

Table 2: Relative deviation of the measurement after getting back the solar cells from PTB (phase 3) to the measurement before sending the solar cells to PTB (phase 1).

# 5 Method for establishing the Reference Value (RV) and the Degrees of Equivalence

It is known that reference values are only evaluated based on Key Comparisons (KCs), these are the Key Comparison Reference Values (KCRVs). However, we believe that it is desirable or at least useful to evaluate a reference value also in the case of this worldwide SC. For simplification, we call this value Reference Value (RV). All calculations were performed according to Appendix B – "An example of a commonly used data analysis for an intercomparison" of the "Guidelines for CCPR Comparison Report Preparation" of 2009.

### Performance of the transfer solar cells

A possible drift of the transfer solar cells was considered by averaging the participant measurements before and after the PTB measurement.

### Determination of the cut-off, the RV and the Degrees of Equivalence

The weighted mean of the short circuit current at standard test conditions of the transfer solar cells represent the RV. Following the Guidelines for CCPR Comparison Report Preparation the weight is calculated with cut-off, which is calculated as the average of the NMIs uncertainties which are less than or equal to the median of the uncertainties of all NMIs. The cut-off uncertainty $u_{\text{cut-off}}$ is then average of the three institutes stating the lowest uncertainties:

$$u_{\text{cut-off}} = \text{average}\{u_{\text{rel}}(I_{\text{STC},i})\} \text{ for } u_{\text{rel}}(I_{\text{STC},i}) \leq \text{median}\{u_{\text{rel}}(I_{\text{STC},i})\}$$

where $u_{\text{rel}}(I_{\text{STC},i})$ is the relative uncertainty stated by the participant $i$ and the median is calculated from the six participants and the pilot (seven values from seven facilities).

In Table 3 the relative uncertainty $u_{\text{rel}}(I_{\text{STC},i})$ and the deviation to the pilot of the short circuit current of reference solar cells at standard test conditions for each solar cell and summarized each participant is shown.

| | | | PTB (DSR Pilot laboratory) | | Participant | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Institute** | **Solar Cell** | Type | **PTB-Ref.-Value** (weighted mean) | rel StdUnc - PTB | I(STC) before | Std. Unc. (k=1) | rel. Std. Unc. | I(STC) after | Std. Unc. (k=1) | rel. Std. Unc. | **Dev. Phase 3 to Phase 1** | **Ref.Value of part.** (weighted mean) | rel. Unc. of Part. |
| | | WPVS | in mA | in % | in mA | in mA | in % | in mA | in mA | in % | in % | in mA | in % |
| NIM | 016-2012 | WPVS | **140,18** | 0,25% | 139,70 | 0,85 | 0,61% | 140,1 | 0,64 | 0,46% | 0,29% | **139,90** | 0,53% |
| | 018-2012 | WPVS | **141,42** | 0,25% | 140,10 | 0,85 | 0,61% | 140,7 | 0,64 | 0,45% | 0,43% | **140,40** | 0,53% |
| | 020-2012 | WPVS | **141,94** | 0,24% | 142,50 | 0,85 | 0,60% | 141,6 | 0,64 | 0,45% | -0,63% | **142,05** | 0,52% |
| VNIIOFI | 048-2010 | WPVS | **141,81** | 0,25% | 142,00 | 1,16 | 0,82% | 141,7 | 1,5 | 1,06% | -0,21% | **141,85** | 0,94% |
| | 050-2010 | WPVS | **142,55** | 0,25% | 142,20 | 1,16 | 0,82% | 143,1 | 1,5 | 1,05% | 0,63% | **142,65** | 0,93% |
| PTB (Laser-DSR) | 104-2012 | WPVS | **140,71** | 0,25% | 140,53 | 0,28 | 0,20% | 140,78 | 0,28 | 0,20% | 0,18% | **140,66** | 0,20% |
| | 110-2012 | WPVS | **139,83** | 0,25% | 139,63 | 0,28 | 0,20% | 139,81 | 0,28 | 0,20% | 0,13% | **139,72** | 0,20% |
| | 131-2012 | WPVS | **113,83** | 0,25% | 113,81 | 0,23 | 0,20% | 113,98 | 0,23 | 0,20% | 0,15% | **113,90** | 0,20% |
| KRISS | 109-2012 | WPVS | **139,60** | 0,25% | 140,60 | 1,40 | 1,00% | 140,10 | 1,4 | 1,00% | -0,36% | **140,35** | 1,00% |
| | 123-2012 | WPVS | **141,33** | 0,25% | 143,20 | 1,45 | 1,01% | 142,80 | 1,45 | 1,02% | -0,28% | **143,00** | 1,01% |
| NMC, A*STAR | 003-2010 | WPVS | **115,94** | 0,25% | 115,03 | 0,52 | 0,45% | 115,68 | 0,37 | 0,32% | 0,57% | **115,36** | 0,39% |
| | 074-2011 | WPVS | **142,67** | 0,25% | 142,61 | 0,64 | 0,45% | 142,71 | 0,48 | 0,34% | 0,07% | **142,66** | 0,39% |
| | 047-2012 | WPVS | **112,40** | 0,25% | 111,97 | 0,54 | 0,48% | 112,37 | 0,36 | 0,32% | 0,36% | **112,17** | 0,40% |
| ITRI (only WPVS) | 097-2012 | WPVS | **141,77** | 0,24% | 142,42 | 0,465 | 0,33% | 142,20 | 0,46 | 0,32% | -0,15% | **142,31** | 0,32% |
| | KDRCA-120039 | not WPVS | **126,00** | 0,24% | 123,89 | 0,395 | 0,32% | 123,74 | 0,4 | 0,32% | -0,12% | **123,82** | 0,32% |

Table 3: Measurement results of phase 2 (pilot), phase 1 (participant before sent to pilot) and phase 3 (participant after getting back from pilot) and the deviation of phase 3 to phase 1 measurement results.

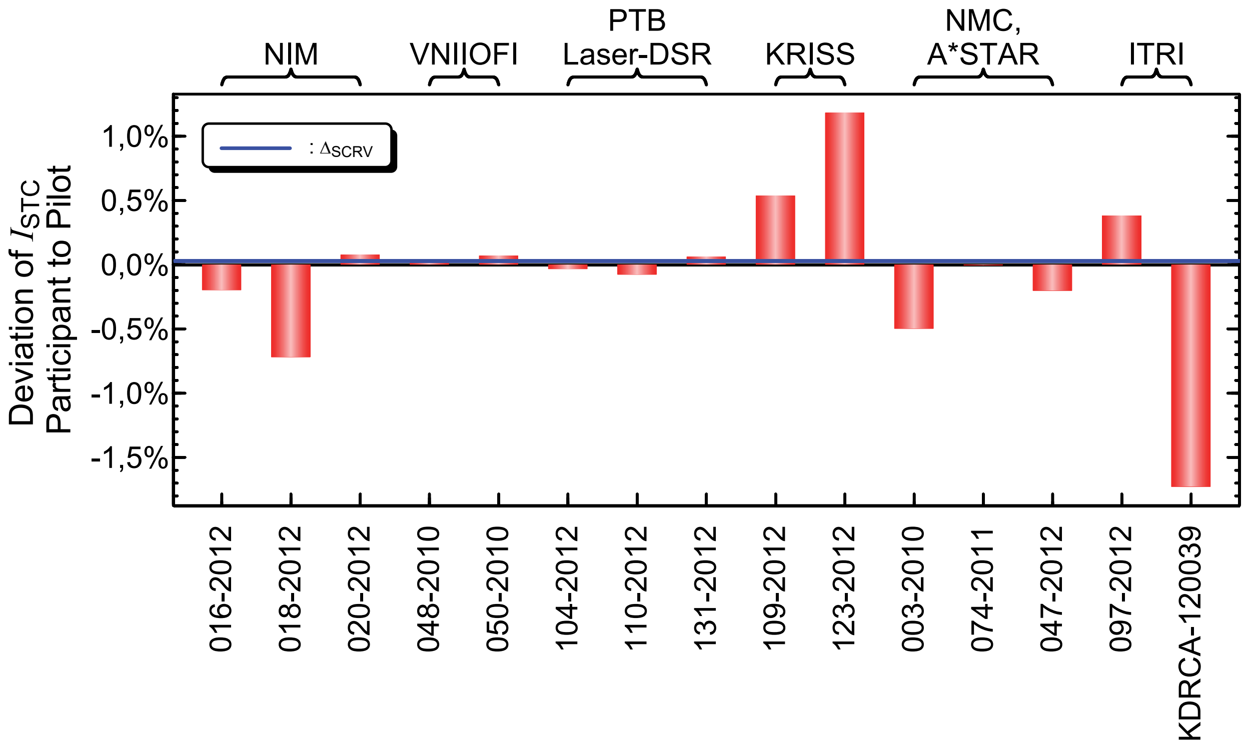



Figure 2. Relative deviation of the participant measurements of the short circuit current of reference solar cells at standard test conditions to the results of the pilot measurements

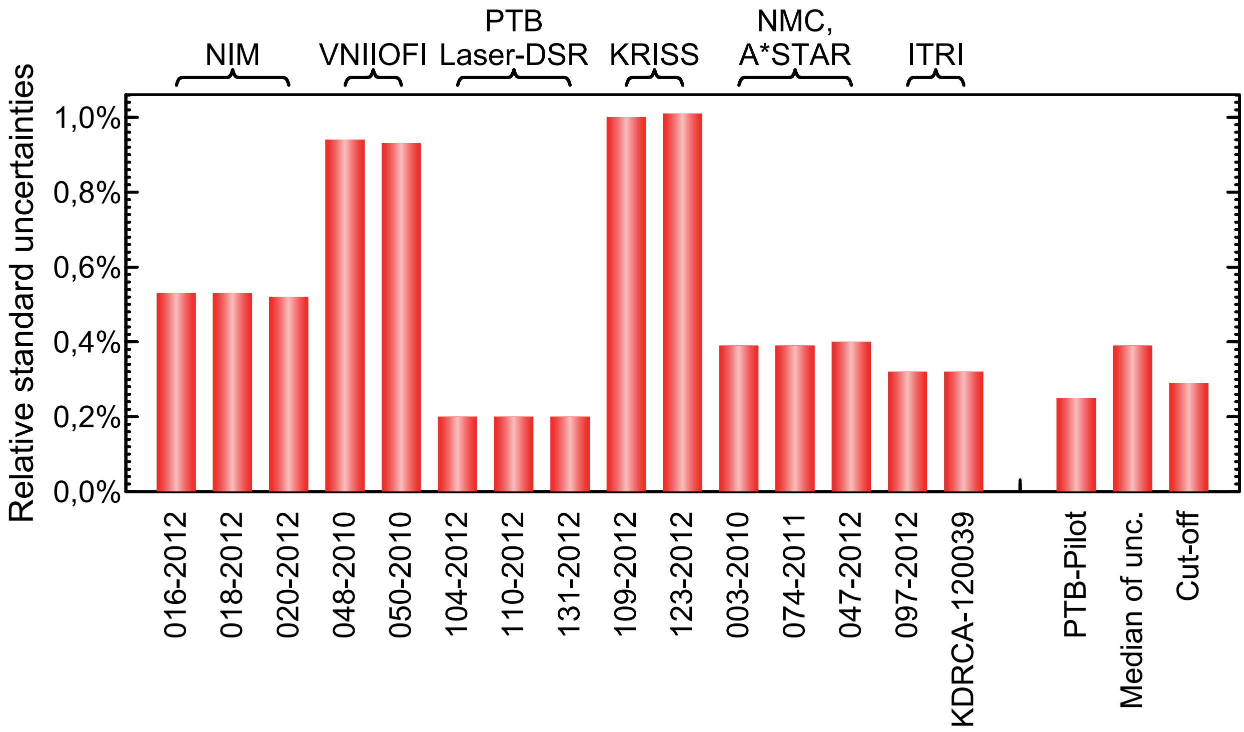



Figure 3. Relative standard uncertainties, median and cut-off. For the calculation of the median the average uncertainty of the respective participant is used.

# 6 Identification of Outliers

The CCPR has not agreed a strict policy on outliers. However, if a reference value is involved, care must be taken that outliers do not skew the reference value. The currently favoured limit is three standard deviations from the reference value produced without the proposed outliers, using their adjusted standard uncertainty value. In this comparison, the following procedure was used: the relative deviation between participant and pilot laboratory, corrected by the Reference Value (RV) $\Delta_{RV}$ of 0,03%, was divided by the standard uncertainty of the respective deviation.

Based on the distributed data, one relative deviation was 4.3 times higher than the standard uncertainty of its deviation (see Figure 4). This value was excluded from the comparison. In addition, it is noted that the corresponding solar cell (KDRCA-120039) was the only solar cell within the comparison that was not of WPVS type. The cut-off value, the weighted mean and the Degrees of Equivalence were calculated without using the values of this solar cell.

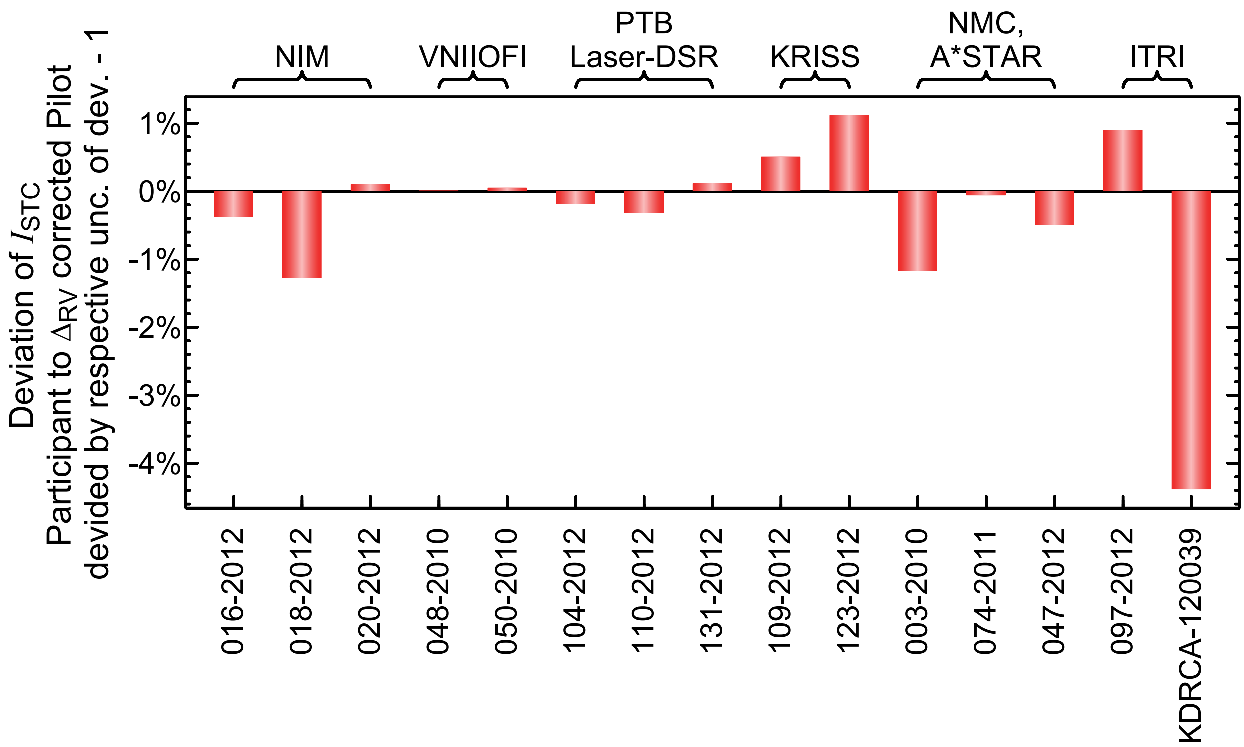



Figure 4. Relative deviation of the participant measurements divided by the respective uncertainty of the deviation minus one.

# 7 Results: RV and DoE for the EURAMET.PR-S5 intercomparison

## 7.1 Summary of participants´ results

Table 4 shows the unilateral degree of equivalence and the $E_n$-value, calculated by $|I_{\mathrm{Part}} - I_{\mathrm{Pilot}}| \,/\, \sqrt{U^2(I_{\mathrm{Part}}) + U^2(I_{\mathrm{Pilot}})}$. All unilateral degrees of equivalence are smaller than their assigned measurement uncertainty. The Reference Value (RV) $\Delta_{RV}$ is 0,03% and its uncertainty is 0,15%. The chi-square test is fully satisfied with $2.09 < \chi^2(5) = 11.07$.

| | | | PTB (DSR Pilot laboratory) | | Participant | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Institute** | **Solar Cell** | Type | **PTB-Ref.-Value** (weighted mean) | rel StdUnc - PTB | **Ref.Value of part.** (weighted mean) | rel. Unc. of Part. | **Dev Part to Pilot∆** | Unc of Dev | **Mean Dev** | **D_i (Unilateral Degree of Equivalence)** | **U_i** | **En (should be < 1)** |
| | | WPVS | in mA | in % | in mA | in % | | | | | | |
| NIM | 016-2012 | WPVS | **140,18** | 0,25% | **139,90** | 0,53% | -0,20% | 0,58% | | | | 0,17 |
| | 018-2012 | WPVS | **141,42** | 0,25% | **140,40** | 0,53% | -0,72% | 0,58% | | | | 0,61 |
| | 020-2012 | WPVS | **141,94** | 0,24% | **142,05** | 0,52% | 0,08% | 0,57% | -0,28% | -0,31% | 1,10% | 0,07 |
| VNIIOFI | 048-2010 | WPVS | **141,81** | 0,25% | **141,85** | 0,94% | 0,03% | 0,97% | | | | 0,01 |
| | 050-2010 | WPVS | **142,55** | 0,25% | **142,65** | 0,93% | 0,07% | 0,96% | 0,05% | 0,02% | 1,89% | 0,04 |
| PTB (Laser-DSR) | 104-2012 | WPVS | **140,71** | 0,25% | **140,66** | 0,20% | -0,04% | 0,30% | | | | 0,06 |
| | 110-2012 | WPVS | **139,83** | 0,25% | **139,72** | 0,20% | -0,08% | 0,31% | | | | 0,12 |
| | 131-2012 | WPVS | **113,83** | 0,25% | **113,90** | 0,20% | 0,06% | 0,31% | -0,02% | -0,05% | 0,56% | 0,09 |
| KRISS | 109-2012 | WPVS | **139,60** | 0,25% | **140,35** | 1,00% | 0,54% | 1,02% | | | | 0,26 |
| | 123-2012 | WPVS | **141,33** | 0,25% | **143,00** | 1,01% | 1,18% | 1,04% | 0,86% | 0,83% | 2,03% | 0,57 |
| NMC, A*STAR | 003-2010 | WPVS | **115,94** | 0,25% | **115,36** | 0,39% | -0,50% | 0,45% | | | | 0,55 |
| | 074-2011 | WPVS | **142,67** | 0,25% | **142,66** | 0,39% | -0,01% | 0,46% | | | | 0,01 |
| | 047-2012 | WPVS | **112,40** | 0,25% | **112,17** | 0,40% | -0,20% | 0,46% | -0,24% | -0,27% | 0,84% | 0,22 |
| ITRI (only WPVS) | 097-2012 | WPVS | **141,77** | 0,24% | **142,31** | 0,32% | 0,38% | 0,40% | 0,38% | 0,35% | 0,71% | 0,47 |
| | KDRCA-120039 | not WPVS | **126,00** | 0,24% | **123,82** | 0,32% | -1,73% | 0,40% | | | | 2,16 |

Table 4: The unilateral degree of equivalence and the $E_n$-value are shown.

## 7.2 Summary of the unilateral Degrees of Equivalence

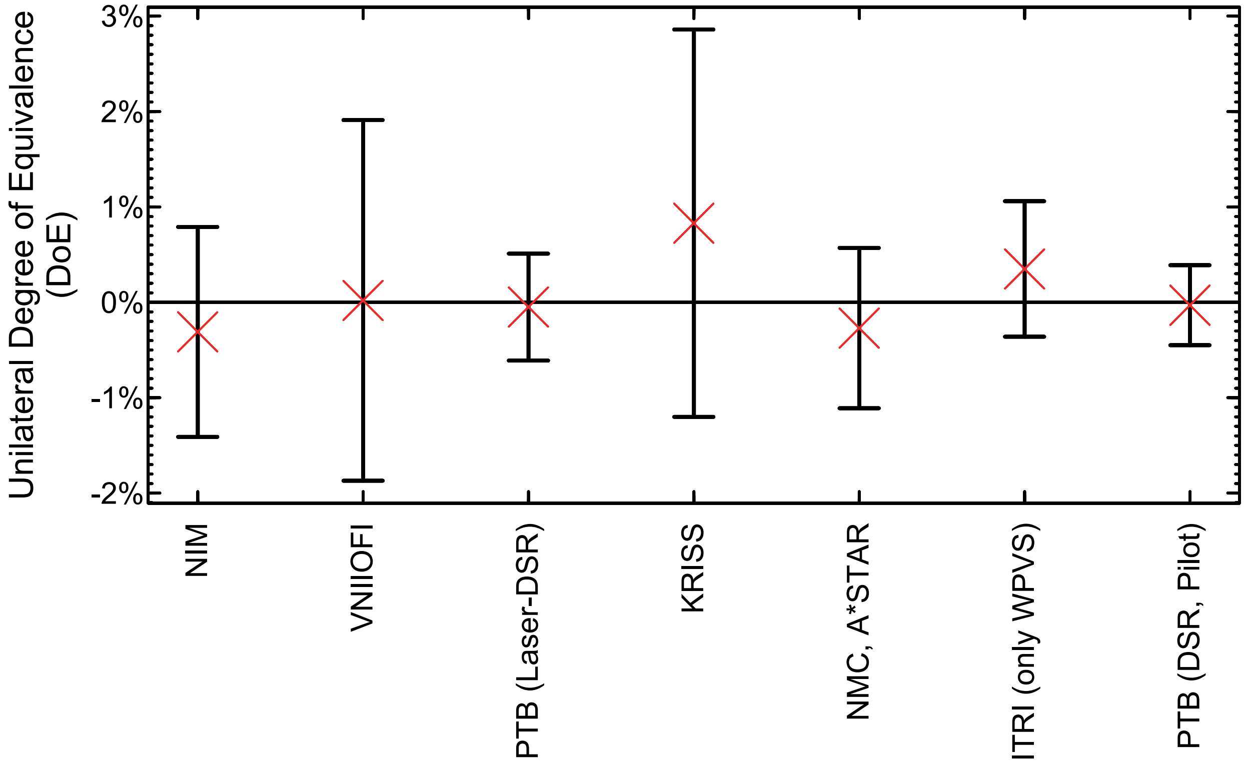



Figure 5: Unilateral Degree of Equivalence (DoE) for each participant and its expanded uncertainty.

## 7.3 Summary of the $E_n$-values

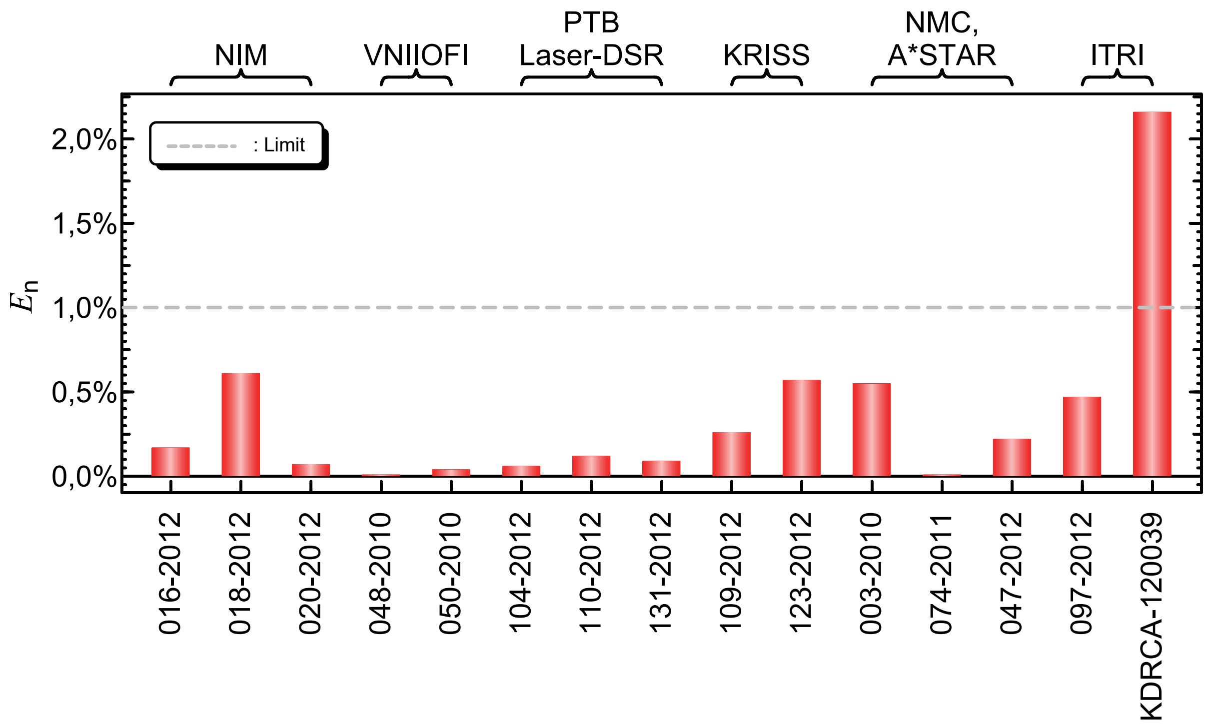



Figure 6: $E_n$-values of the individual solar cell comparisons. The only non-WPVS type solar cell KDRCA-120039 was excluded from the comparison.

# 8 Conclusions

The EURAMET.PR-S5 intercomparison of the short circuit current of reference solar cells at standard test conditions was carried out as star type comparison. In total 6 participants with seven facilities took part, 1 from Europe (PTB/Germany with two facilities: the established DSR facility as pilot lab and the new Laser-DSR facility as participant) and 5 outside Europe (NIM/China, VNIIOFI/Russia, KRISS/South Korea, A-STAR/Singapore, ITRI/Chinese Taipei). Therefore, this comparison can be considered as a worldwide one as all NMIs world-wide that had built up facilities for the primary $I_{STC}$-calibration of reference solar cells when the measurements started, participated. The measurements took place from September 2012 to May 2014. Last changes of the values were sent to the pilot during the value check within the pre-draft A phase in June 2016.

All participants supplied detailed reports of their measurements including full uncertainty statements. All measurement results reported by the participants were used for the intercomparison and no measurement was subject of rejection. The analysis method follows the Guidelines for CCPR Comparison Report Preparation and has been accepted by all participants.

For the calculation of the reference value of the supplementary comparison no participant had to be excluded and the used weighted mean with cut-off has been supported by all participants.

The unilateral Degrees of Equivalence (DoE) calculated for each participant are fully 100 % consistent with their standard uncertainties. The largest $E_n$-value is 0.61 and therefore significant smaller than 1. The chi-square test is fully satisfied with $2.09 < \chi^2(5) = 11.07$. Thus, the DSR method is highly suitable for the calibration of reference solar cells according to the short circuit current at standard test conditions.

# 9 Appendix A: List of Figures

# 10 Appendix B: List of Tables

# 11 Appendix C: Timeline of the comparison

| | |
|---|---|
| Technical Protocol agreed: | 2012-04-02 (sent to TCPR chair) |
| | 2012-04-25 (NIM added and resent to TCPR chair) |
| Start of Measurements: | 2012-09-01 |
| End of Measurements: | 2014-05-07 |
| All reports received: | 2016-06-22 |
| Pre-Draft “A” process 1 published: | 2016-05-23 |
| Pre-Draft “A” process 2 published: | 2016-09-21 |
| Pre-Draft “A” process 3 published: | 2016-09-20 |
| Pre-Draft “A” process 4 published: | 2017-06-14 |
| Pre-Draft “A” agreed: | 2017-07-04 |
| First draft of Draft “A”: | 2019-08-16 |
| Draft “A” approved: | 2019-10-21 |
| Draft “B” submitted to RMO TCC: | 2020-08-27 |
| Final report submitted | 2020-12-08 |

# 12 Appendix D: Excel sheet used for Table 2, 3 and 4

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $\overline{E}_{i,j}=\frac{1}{2}\sum_{r=1}^{2}E_{i,j,r}$ | $u_{rel}(\overline{E}_{i,j})=\frac{1}{2}\sum_{r=1}^{2}u_{rel}(E_{i,j,r})$ | $\overline{E}_{i,j}=\frac{1}{2}\sum_{r=1}^{2}E_{i,j,r}$ | $u_{rel}(\overline{E}_{i,j})=\frac{1}{2}\sum_{r=1}^{2}u_{rel}(E_{i,j,r})$ | $\Delta_{i,j}=\frac{\overline{E}_{i,j}}{E^{P}_{i,j}}-1$ | $u(\Delta_{i,j})=\sqrt{u_{rel}^{2}(\overline{E}_{i,j})+u_{rel}^{2}(E^{PR}_{i,j})+u_{rel,add}^{2}(E_{i,j})}$ | $\Delta_i=\frac{1}{3}\sum_{j=1}^{3}\Delta_{i,j}$ | $u(\Delta_i)=\frac{1}{3}\sum_{j=1}^{3}u(\Delta_{i,j})$ | $u_{rel}(\overline{E}_i)=\frac{1}{3}\sum_{j=1}^{3}u_{rel}(\overline{E}_{i,j})$ | $u_{rel}(\overline{E}_i)\le\mathrm{median}\{u_{rel}(\overline{E}_i)\}$ | $u_{rel,adj}(\overline{E}_i)=u_{rel}(\overline{E}_i)$ for $u_{rel}(\overline{E}_i)\ge u_{cut-off}$; $u_{rel,adj}(\overline{E}_i)=u_{cut-off}$ for $u_{rel}(\overline{E}_i)<u_{cut-off}$; $i=0$ to N | $u_T(\Delta_i)=\sqrt{u^2(\Delta_i)-u_{rel}^2(\overline{E}_i)}$ | $u_{adj}(\Delta_i)=\sqrt{u_{rel,adj}^2(\overline{E}_i)+u_T^2(\Delta_i)}$ | $u_{adj}^{-2}(\Delta_i)$ | $w_i=u_{adj}^{-2}(\Delta_i)/\sum_{i=0}^{N}u_{adj}^{-2}(\Delta_i)$ | $\Delta_{KCRV}=\sum_{i=0}^{N}w_i\Delta_i$ | $u(\Delta_{KCRV})=\sqrt{\sum_{i=0}^{N}\frac{u^2(\Delta_i)}{u_{adj}^4(\Delta_i)}}\Big/\sum_{i=0}^{N}u_{adj}^{-2}(\Delta_i)$ | $D_i=\Delta_i-\Delta_{KCRV}$ | $U_i=k\sqrt{u^2(\Delta_i)+u^2(\Delta_{KCRV})-2\left(\frac{u^2(\Delta_i)}{u_{adj}^2(\Delta_i)}\Big/\sum_{j=0}^{N}u_{adj}^{-2}(\Delta_j)\right)}$ ; $k=2$ | $\frac{\{\Delta_i-\Delta_{KCRV}\}^2}{u_{adj}^2(\Delta_i)}$ | | |
| | Formula according to appendix B | | | (1) | (2) | (1) | (2) | (3) | (4) | (5) | (6) | (9) | (11) | (12) | (13) | (14) | | (15) | (16) | (17) | (18) | (19) | | | |
| | | | | PTB (DSR Pilot laboratory) | | Participant | | | | | | | | | | | | | | | | | | | |
| Code | Institute | Solar Cell | Type | PTB-Ref.-Value (weighted mean) | rel StdUnc - PTB | Ref.Value of part. (weighted mean) | rel. Unc. of Part. | Dev Part to Pilot Δ | Unc of Dev | Mean Dev | Mean unc. of Dev | Mean unc. of Part. | Used for CutOff | unc, adjusted by cutoff | Transfer unc. Component | u_adjusted of Dev Part to Pilot Δ | Intermediate result for (15) | Weight of NMI | Intermediate result for (16) | Intermediate result for (17) | D_i (Unilateral Degree of Equivalence) | U_i | Intermediate result for Chi-Square (19-2019) | En (should be < 1) | en (should be <2) |
| | | | WPVS | in mA | in % | in mA | in % | | | | | | | | | | | | | | | | | | |
| E | NIM | 016-2012 | WPVS | **140,18** | 0,25% | **139,90** | 0,53% | -0,20% | 0,58% | | | | | | | | | | | | | | | 0,17 | 0,34 |
| | | 018-2012 | WPVS | **141,42** | 0,25% | **140,40** | 0,53% | -0,72% | 0,58% | | | | | | | | | | | | | | | 0,61 | 1,23 |
| | | 020-2012 | WPVS | **141,94** | 0,24% | **142,05** | 0,52% | 0,08% | 0,57% | -0,28% | 0,58% | 0,53% | FALSCH | 0,53% | 0,23% | 0,58% | 29990 | 8,55% | -0,02% | 29990 | -0,31% | 1,10% | 29,21% | 0,07 | 0,13 |
| C | VNIIOFI | 048-2010 | WPVS | **141,81** | 0,25% | **141,85** | 0,94% | 0,03% | 0,97% | | | | | | | | | | | | | | | 0,01 | 0,03 |
| | | 050-2010 | WPVS | **142,55** | 0,25% | **142,65** | 0,93% | 0,07% | 0,96% | 0,05% | 0,96% | 0,93% | FALSCH | 0,93% | 0,23% | 0,96% | 10784 | 3,07% | 0,00% | 10784 | 0,02% | 1,89% | 0,04% | 0,04 | 0,08 |
| D | PTB (Laser-DSR) | 104-2012 | WPVS | **140,71** | 0,25% | **140,66** | 0,20% | -0,04% | 0,30% | | | | | | | | | | | | | | | 0,06 | 0,12 |
| | | 110-2012 | WPVS | **139,83** | 0,25% | **139,72** | 0,20% | -0,08% | 0,31% | | | | | | | | | | | | | | | 0,12 | 0,25 |
| | | 131-2012 | WPVS | **113,83** | 0,25% | **113,90** | 0,20% | 0,06% | 0,31% | -0,02% | 0,31% | 0,20% | WAHR | 0,29% | 0,23% | 0,37% | 72220 | 20,58% | 0,00% | 48801 | -0,05% | 0,56% | 1,98% | 0,09 | 0,18 |
| A | KRISS | 109-2012 | WPVS | **139,60** | 0,25% | **140,35** | 1,00% | 0,54% | 1,02% | | | | | | | | | | | | | | | 0,26 | 0,53 |
| | | 123-2012 | WPVS | **141,33** | 0,25% | **143,00** | 1,01% | 1,18% | 1,04% | 0,86% | 1,03% | 1,01% | FALSCH | 1,01% | 0,23% | 1,03% | 9390 | 2,68% | 0,02% | 9390 | 0,83% | 2,03% | 64,56% | 0,57 | 1,13 |
| B | NMC-A*Star | 003-2010 | WPVS | **115,94** | 0,25% | **115,36** | 0,39% | -0,50% | 0,45% | | | | | | | | | | | | | | | 0,55 | 1,10 |
| | | 074-2011 | WPVS | **142,67** | 0,25% | **142,66** | 0,39% | -0,01% | 0,46% | | | | | | | | | | | | | | | 0,01 | 0,02 |
| | | 047-2012 | WPVS | **112,40** | 0,25% | **112,17** | 0,40% | -0,20% | 0,46% | -0,24% | 0,46% | 0,39% | WAHR | 0,39% | 0,23% | 0,46% | 48065 | 13,70% | -0,03% | 48065 | -0,27% | 0,84% | 35,26% | 0,22 | 0,43 |
| F | ITRI (only WPVS) | 097-2012 | WPVS | **141,77** | 0,24% | **142,31** | 0,32% | 0,38% | 0,40% | 0,38% | 0,40% | 0,32% | WAHR | 0,32% | 0,23% | 0,40% | 62894 | 17,93% | 0,07% | 62894 | 0,35% | 0,71% | 76,52% | 0,47 | 0,94 |
| | | KDRCA-120039 | not WPVS | **126,00** | 0,24% | **123,82** | 0,32% | -1,73% | 0,40% | | | | | | | | | | | | | | | 2,16 | 4,31 |
| | | | | | | | | | | $\Delta_0=0$ | $u_{rel}(\overline{E}^{P})=\frac{1}{3N}\sum_{i=1}^{N}\sum_{j=1}^{3}u_{rel}(E^{P}_{i,j})$ | $u_{rel}(\overline{E}_0)=u_{rel}(\overline{E}^{P})$ | | | | | | | | | | | | | |
| | | | | | | | | | | (7) | (8) | (10) | | | | | | | | | | | | | |
| | PTB (DSR, Pilot) | | | | | | | | | 0,00% | 0,25% | 0,25% | WAHR | 0,29% | 0,00% | 0,29% | 117524 | 33,50% | 0,00% | 84988 | -0,03% | 0,42% | 1,21% | | |
| | | | | | | | | | | | | | | | | | | | | | (16) Δ_KCRV | | | | |
| | u_rel + u_rel,add | 0,23% | | | | | | | | | | | | | | | 350867 | | | | 0,03% | | | | |
| | Median of unc. | 0,39% | | | | | | | | | | | | | | | | | | | | | | | |
| | CutOff-Uncert. (11) | 0,29% | | $u_{cut-off}=\mathrm{average}\{u_{rel}(\overline{E}_i)\}$ for $u_{rel}(\overline{E}_i)\le\mathrm{median}\{u_{rel}(\overline{E}_i)\}$ | | | | | | | | | | | | | | | | | (17) u(Δ_KCRV) | | | | |
| | | | | | | | | | | | | | | | | | | | | | 0,15% | | | | |
| | | | | | | | | | | | | | | | | | | | | $\chi^2_{obs}=\sum_{i=0}^{N}\frac{\{\Delta_i-\Delta_{KCRV}\}^2}{u_{adj}^2(\Delta_i)}$ | (19-2019) Chi-Square Value | | | | |
| | | | | | | | | | | | | | | | | | | | | | 2,09 | | | | |
| | | | | | | | | | | | | | | | | | | | | | < χ^2_0.05(5) = 11.07 | | | | |

# 13 Appendix E: Measurement reports and uncertainty tables of the participants

| Comparison of Meas.Unc. - Contributions | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ITRI | KRISS | NIM | NIM3 | NMC-Astar | PTB (Pilot) | PTB (LaserDS | VNIIOFI | VNIIOFI3 |
| 1 | Calibration of standard detector | 0,089 | 0,9 | 0,2 | 0,3 | 0,3 | 0,1 | 0,1 | 0,2 | 0,79 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0,23 | 0,2 | 0,1 | 0,1 | 0,02 | 0,12 | 0,1 | 0,35 | 0,17 |
| 3 | Spectral mismatch / Wavelength error | 0,16 | 0,3 | 0,1 | 0,1 | 0,015 | 0,1 | 0,06 | 0,06 | 0,06 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0,12 | | 0,4 | 0,05 | 0,068 | 0,05 | 0,05 | 0,04 | 0,04 |
| 5 | Temperature effects | 0,0037 | 0,04 | 0,1 | 0,1 | 0,02 | 0,03 | 0,01 | 0,05 | 0,05 |
| 6 | Reading repeatability of standard detector | 0,05 | 0,05 | 0,1 | 0,1 | 0,047 | 0,05 | 0,05 | 0,21 | 0,08 |
| 7 | Reading repeatability of test reference solar cell | 0,038 | 0,05 | 0,2 | 0,2 | 0,058 | 0,02 | 0,02 | 0,1 | 0,05 |
| 8 | Alignment and xyz-positioning of standard detector | 0,022 | 0,09 | 0,1 | 0,05 | 0,17 | 0,06 | 0,01 | 0,06 | 0,06 |
| 9 | Alignment and xyz-positioning of test detector | 0,022 | | 0,1 | 0,05 | 0,17 | 0,06 | 0,01 | 0,04 | 0,04 |
| 10 | Others (please specify) | | | 0,2 | 0,1 | | | | | |
| | Linearity of spectrometer | | 0,1 | | | | | | | |
| | Lamp drift | | 0,1 | | | | | | | |
| | Non-linearity of pre-amplifier | | | | | 0,062 | | | | |
| | Non-linearity of lock-in amplifier | | | | | 0,036 | | | | |
| | Linear fitting / integration | | | | | 0,2 | | | | |
| | Repeatability of three measurements | | | | | 0,17 | | | | |
| | Multiple reflection, nonlinearity of amplifier, spectral mismatch and non-uniformity of bias, aperture, interpolation for WL and integration for I_STC | | | | | | 0,12 | 0,1 | | |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | Calculated combined relative standard uncertainty (%) | 0,325 | 0,987 | 0,583 | 0,433 | 0,483 | 0,250 | 0,198 | 0,479 | 0,821 |
| | Stated Combined relative standard uncertainty(%) | 0,33 | 0,99 | 0,6 | 0,43 | 0,48 | 0,25 | 0,2 | 0,6 | 0,82 |

## 13.1 PTB (Pilot, DSR-facility), Germany

### 1.1 Description of the measurement facility and traceability

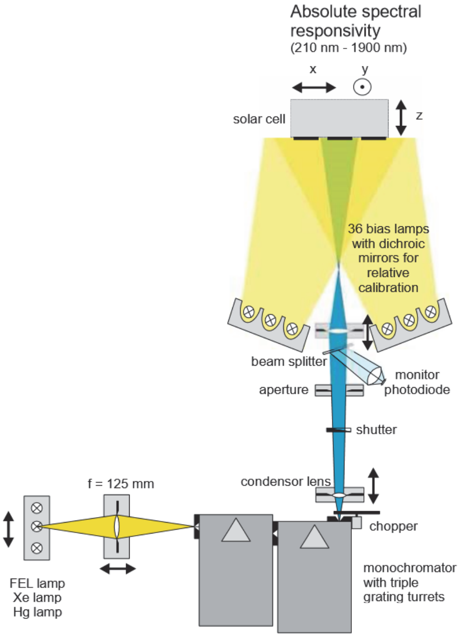
1) Manufacturers and types of the reference photodiode, solar simulator, lock-in amplifier, voltmeter, and any other instruments used:
   Reference PD: Hamamatsu S1337-1010BQ
   Lock-In amplifier: SignalRecovery 7265, SignalRecovery 7265
   Bias Voltage: Keithley 2001
   Temperature: Keithley 2001
   I-U-converter: custom made

2) Laboratory reference standards used:

   Reference PD: PV12
   Last calibrations: 14.10.2009, 22.12.2011 (internal) and 16.04.2012 (used)

   Aperture: PV25 (6.6x6.6 mm²)
   Last calibration: 18.01.2012

3) Description of measuring set-ups:



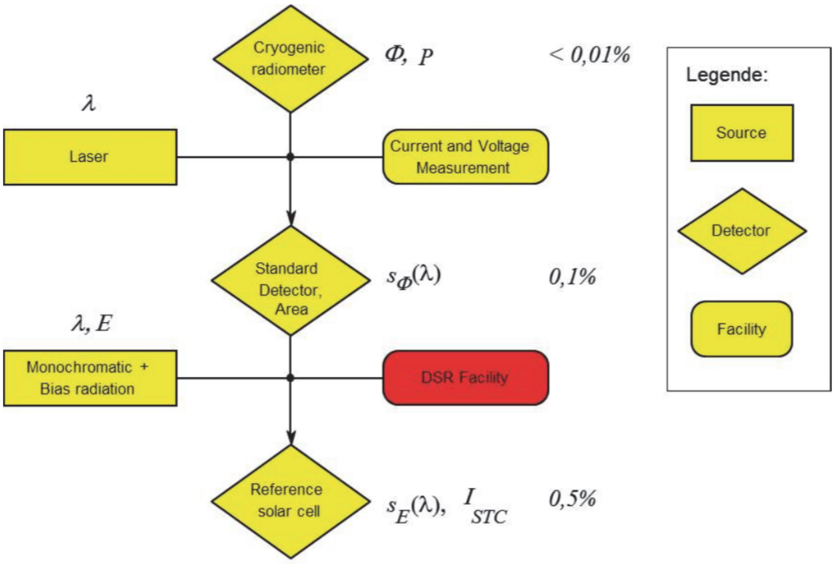

The monochromatic radiation is generated by a xenon lamp (280 nm – 705 nm) and a 1000 W quartz halogen lamp (710 nm – 1220 nm) in combination with a monochromator. The monochromatic radiation is modulated with a chopper that is located behind of the monochromator. The radiation exiting the monochromator is parallelized by a condenser lens, passes a beamsplitter that reflects a fraction of the radiation to the monitor photodiode and is finally

1

expanded by an aperture lens in order to generate a homogeneous radiation field that widely overilluminates the solar cell under test. The solar cells as well as the reference photodiode are mounted on an automatized high precision xyz-table. The photodiode is measured at nine different positions, so that it sees effectively the same part of the monochromatic beam as the solar cell under test. The solar cells are further overilluminated by constant sun-like bias radiation. The photodiodes are hidden by a large aperture when the constant sun-like bias radiation is on.

4) Establishment of traceability route of calibration:

The reference photodiode is traceable via the cryo-radiometer at PTB(Berlin) to the SI. The aperture is traceable via optical measurements of opaque and transmitting chrome-on-quartz glass circles of the PTB-reference mask IMS M0411-45.




5) Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)

The laboratory is air-conditioned to a constant temperature of 25°C +- 0.5°C and a relative humidity of 25%.

6) The following interim results are provided electronically:
- x spectral responsivity at STC
- x spectrally resolved differential non-linearity
- x AM1.5 weighted differential non-linearity

2

- x spectrally resolved temperature coefficient
- x AM1.5 weighted temperature coefficient

Laboratory: DSR, PTB

Officer in charge: Stefan Winter Position: Head of Laboratory

Signature: Stefan Winter……………… Date: 20.09.2016……………

3

## 1.2 Uncertainty of measurement

Uncertainty budget is to be evaluated for the current under standard test conditions

**Table 7.4.1. Uncertainty budget of calibration of travelling reference solar cells**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | <0.1% |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | <0.12% |
| 3 | Spectral mismatch / Wavelength error | <0.1% |
| 4 | Spectral bandwidth of the monochromatic radiation | <0.05% |
| 5 | Temperature effects | <0.03% |
| 6 | Reading repeatability of standard detector | <0.05% |
| 7 | Reading repeatability of test reference solar cell | <0.02% |
| 8 | Alignment and xyz-positioning of standard detector | <0.06% |
| 9 | Alignment and xyz-positioning of test detector | <0.06% |
| 10 | Others (Multiple reflection, nonlinearity of amplifier, spectral mismatch and non-uniformity of bias, aperture, interpolation for WL and integration for I_STC) | <0.12% |
| | **Combined relative standard uncertainty(%)** | **0.25%** |

**The measurement uncertainty, used for the intercomparison, was calculated individually by Monte Carlo Simulation, dependant on the measurement data.**

Laboratory : DSR, PTB

Officer in charge: Stefan Winter

Position: Head of Laboratory

Signature: Stefan Winter

Date: 20.09.2016

## 13.2 NIM, China

### 7.2 Description of the measurement facility and traceability

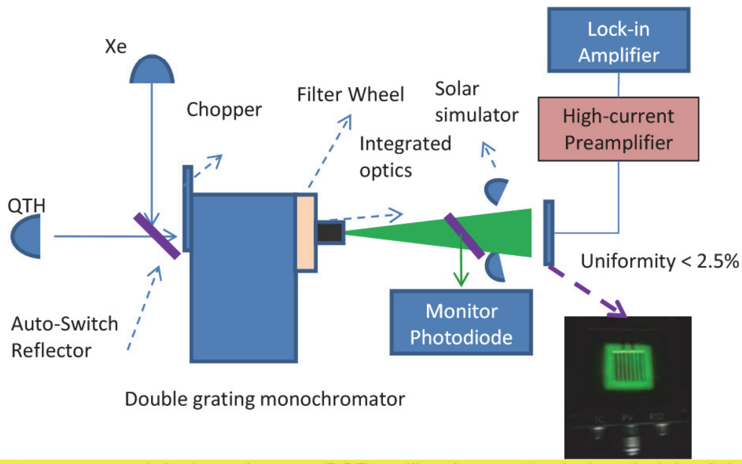
This form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated, please use separate sheets of paper as appropriate.

1) Manufacturers and types of the reference photodiode, solar simulator, lock-in amplifier, voltmeter, and any other instruments used:
Manufacturers and types of the reference photodiode: S1337 of hamamatsu
Lock-in amplifier: SR830 of Stanford
Voltmeter: 6453A of Agilent
Monochromator: SP Inc.

2) Laboratory reference standards used:
The instrument for spectral responsivity of the detector, NIM

3) Description of measuring set-ups (please include a diagram):

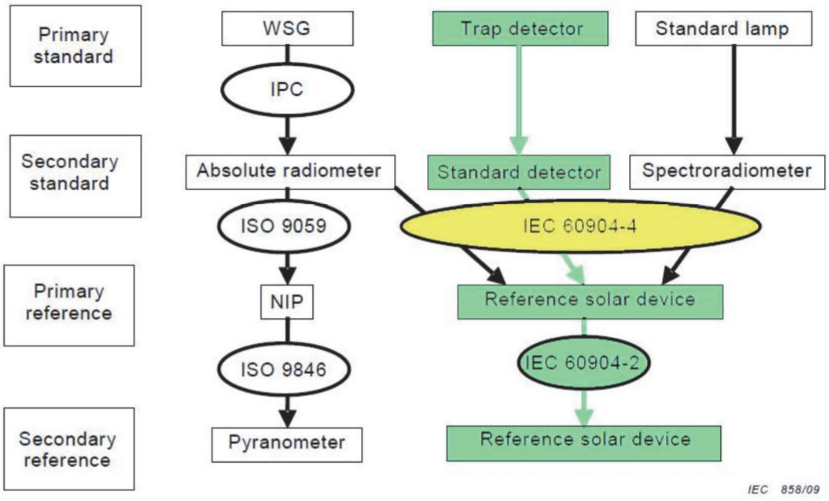
Schematic diagram of SR System (IEC60904-4)




The system we used is based on a DSR calibration method descried in A.3 of IEC60904-4：2009. The spectral responsivity was calibrated in a wavelength range by substituting method between the standard detector and the reference solar cell under test in the condition of bias light used. $I_{STC}$ can be calculated by function when the spectral responsivity of solar cell obtained.

4) Establishment of traceability route of calibration:

21/09/2016 14:06 3




NIM's traceability chain for the calibration of PV devices

The value of solar cell trace from the trap detector which calibrated by cryogenic radiometer

5) Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)

The room's temperature is controlled by air conditioner, and the temperature of the solar cell also controlled with water-cooling platform. The relative humidity can be kept between 30%RH to 70%RH.

6) The following interim results are provided electronically:
- ☐ spectral responsivity at STC
- ☐ spectrally resolved differential non-linearity
- ☐ AM1.5 weighted differential non-linearity
- ☐ spectrally resolved temperature coefficient
- ☐ AM1.5 weighted temperature coefficient

Laboratory: …………National Institute of Metrology…………………..

Officer in charge: Xiong Limin…
Position: ………Director, QE Lab of Solar Cell…………………...

Signature: Xiong Limin…………. Date:……April 24. 2013………………...

21/09/2016 14:06 4

Measurement uncertainty for phase 1 (before sent to PTB)

### 7.3 Uncertainty of measurement

Uncertainty budget is to be evaluated for the current under standard test conditions

**Table 7.4.1. Uncertainty budget of calibration of travelling reference solar cells**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | 0. 2 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0. 1 |
| 3 | Spectral mismatch / Wavelength error | 0. 1 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0. 4 |
| 5 | Temperature effects | 0. 1 |
| 6 | Reading repeatability of standard detector | 0. 1 |
| 7 | Reading repeatability of test reference solar cell | 0. 2 |
| 8 | Alignment and xyz-positioning of standard detector | 0. 1 |
| 9 | Alignment and xyz-positioning of test detector | 0. 1 |
| 10 | Others (please specify) | 0. 2 |
| | **Combined relative standard uncertainty(%)** | 0.6 |

Laboratory: …………National Institute of Metrology……………….…

Officer in charge: Xiong Limin…
Position: ………Director, QE Lab of Solar Cell…………………...

Signature: Xiong Limin…………. Date:……April 24. 2013………………...

21/09/2016 14:06 5

Measurement uncertainty for phase 3 (after received back from PTB)

### 7.1 Uncertainty of measurement

Uncertainty budget is to be evaluated for the current under standard test conditions

**Table 7.4.1. Uncertainty budget of calibration of travelling reference solar cells**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | 0.3 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0.1 |
| 3 | Wavelength error | 0.1 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0.05 |
| 5 | Temperature effects | 0.1 |
| 6 | Reading repeatability of standard detector | 0.1 |
| 7 | Reading repeatability of test reference solar cell | 0.2 |
| 8 | Alignment and xyz-positioning of standard detector | 0.05 |
| 9 | Alignment and xyz-positioning of test detector | 0.05 |
| 10 | Nonlinearity of amplifier | 0.1 |
| | **Combined relative standard uncertainty(%)** | 0.43 |

**Extended relative uncertainty(%)** $U_r$=0.9% (k=2)

Laboratory: …………National Institute of Metrology…………………..…

Officer in charge: Xiong Limin…
Position: ………Director, QE Lab of Solar Cell…………………...

Signature: Xiong Limin…………… Date:……Feb. 17. 2014………………...

1

## 13.3 VNIIOFI, Russia (before sent to PTB)

### 1.3. Description of the measurement facility and traceability

*1) Manufacturers and types of the reference photodiode, solar simulator, lock-in amplifier, voltmeter, and any other instruments used:*

- HAMAMATSU reference photodiode
- The solar cells by Fraunhofer-Institute fur Solare Energysysteme
- The rest of the equipment are presented in the diagram.

*2) Laboratory reference standards used:*
HAMAMATSU reference photodiode.

*3) Description of measuring set-ups (please include a diagram):*

DSR calibration method of PTB for the solar cells calibration was realized in the facility of the VNIIOFI. VNIIOFI facility for the reference solar cell calibration is identical to the PTB facility. Optical scheme of the VNIIOFI facility for the reference solar cell calibration is presented on the Fig. 1.
A dual-beam optical arrangement is used to measure equally normalized relative DSR spectra of reference solar cell at a series of discrete operating points that are set with a steady-state bias radiation at levels between 0.105 $E_{STC}$ and 1.12 $E_{STC}$. The chopped monochromatic radiation behind a double-grating monochromator is measured with a lock-in-amplifier.
Level of the monochromatic radiation in checked up with a help of the monitor photodiode.
The absolute DSR is measured at wavelength 546.1 nm at one of the lowest bias level. Uniformity of the spectral irradiance in the plane where the absolute DSR is measured is not worse than ±0.3% relative to the average value along 20x20mm$^2$ .
Temperature of the reference solar cell is ensured by the liquid thermostat and platinum resistance thermometer. Temperature stability of the reference solar cell is lies within ±20mK.
Temperature of the monitor photodiode and the standard detector also is ensured by the liquid thermostat. Temperature stability of the standard detector and monitor photodiode is lies within ±50mK.
In order to have a possibility to align the optical scheme at different wavelength all the optical elements are installed on the translating stages.
Placing of the monitor, an aperture and lens 3 on the one translating stage allows to focus a monochromatic radiation of different wavelengths on one plane, in which the reference solar cell is fixed.

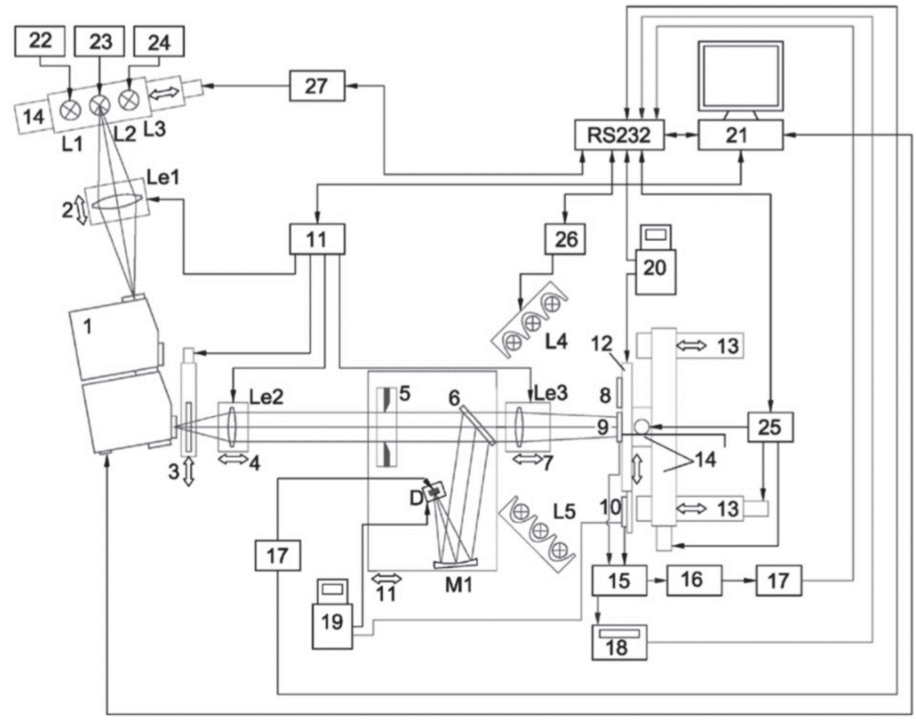



Fig. 1 Diagram of the measuring set-up.

1- Monochromator with triple –grating turrets type DTMc300V GPIB SUB (BENTHAM Instr. Ltd.);
2,4,7- Lens on a Linear Stage LTM80F-150-MSM with Position Controller PS10-32 (OWIS GmbH);
3 - Light Chopper Model 197 (EG&G);
5 - Aperture 20×20 mm;
6 - Beam Splitter;
8,9 - Reference Solar Cells;
10 - Standard Photodiode;
11 - Platform on a Linear Stage LTM80F-150-MSM with Position Controller PS10-32 (OWIS GmbH);
12 - Temperature-stabilized Platform;
13 - Linear Positioner LES 4 (ISEL);
14 - Linear Positioner LES 5 (ISEL);
15 - Commutator ( Made in VNIIOFI);
16 - Preamplifier;
17 - DSP Lock-in Amplifier 7265 ( SIGNAL RECOVERY) ;
18 - Multimeter 34970A with Scan Card (AGILENT);
19 - Liquid Thermostat Polystat R6L ( COLE PARMER);
20 - Liquid Thermostat Polystat R13L ( COLE PARMER);
21 - Computer;
22 - Power Supply SVX 2000 (MULLER ELECTRONIK-OPTIK);
23 - Power Supply PS-120-PU ( Made in VNIIOFI);

24 - Power Supply for Spectral Lamp ( Made in VNIIOFI);
25 - Controller C 142-4 (ISEL);
26 - Two Power Supply PS-200-PU with Lamps Commutator ( Made in VNIIOFI);
L1 - Lamp house COOL 2000 with 2000W Xenon-short arc lamp (MULLER ELECTRONIK-OPTIK);
L2 - Halogen lamp 110 V, 1000W;
L3 - Spectral Lamp ( Made in VNIIOFI);
D - Monitor Photodiode;
M1- Spherical Mirror.

*4) Establishment of traceability route of calibration:*

The used standard detector (photodiode Hamamatsu) is traceable to SI units via broadband cryogenic radiometer.

*5) Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)*

Ambient temperature, ºC ………………………………..23±2
Air humidity, % ………………………………….………..65±15
Atmospheric pressure, kPa………………………………100±4

6) The following interim results are provided electronically:
spectral responsivity at STC for 048-2010 - file 048-2010-25.doc
spectral responsivity at STC for 050-2010 - file 050-2010-25.doc
measurements results for the solar cells 048-2010 and 050-2010 at the temperature of $25^0$ C

Laboratory :……M-4-3………………………………………………………………………..

Officer in charge:…Morozova S.P.………Position…Head of laboratory…………………………

Signature:…………………… ……………..Date:…22.11.2012…………………………….

### 1.4. Uncertainty of measurement

Uncertainty budget is evaluated for the current under standard test conditions

**Table 1.4. 1. Uncertainty budget of calibration of traveling reference solar cell 048-2010**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | 0.2 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0.35 |
| 3 | Spectral mismatch / Wavelength error | 0.02 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0.01 |
| 5 | Temperature effects | 0.05 |
| 6 | Reading repeatability of standard detector | 0.21 |
| 7 | Reading repeatability of test reference solar cell | 0.1 |
| 8 | Alignment and xyz-positioning of standard detector | 0.06 |
| 9 | Alignment and xyz-positioning of test detector | 0.04 |
| 10 | Others (please specify) | |
| | **Combined relative standard uncertainty(%)** | **0.6** |

**Table 1.4. 2. Uncertainty budget of calibration of traveling reference solar cell 050-2010**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | 0.2 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0.35 |
| 3 | Spectral mismatch / Wavelength error | 0.02 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0.01 |
| 5 | Temperature effects | 0.05 |
| 6 | Reading repeatability of standard detector | 0.21 |
| 7 | Reading repeatability of test reference solar cell | 0.1 |
| 8 | Alignment and xyz-positioning of standard detector | 0.06 |
| 9 | Alignment and xyz-positioning of test detector | 0.04 |
| 10 | Others (please specify) | |
| | **Combined relative standard uncertainty(%)** | **0.6** |

Laboratory :……M-4-3…………………………………………………………………………..

Officer in charge:…Morozova S.P.………Position…Head of laboratory…………………………

Signature:………………………………………..Date:…22.11.2012……………………………….

## 13.4 VNIIOFI, Russia (before sent to PTB)

### 1.3. Description of the measurement facility and traceability

*1) Manufacturers and types of the reference photodiode, solar simulator, lock-in amplifier, voltmeter, and any other instruments used:*

- HAMAMATSU reference photodiode
- The solar cells by Fraunhofer-Institute fur Solare Energysysteme
- The rest of the equipment are presented in the diagram.

*2) Laboratory reference standards used:*
HAMAMATSU reference photodiode.

*3) Description of measuring set-ups (please include a diagram):*

DSR calibration method of PTB for the solar cells calibration was realized in the facility of the VNIIOFI. VNIIOFI facility for the reference solar cell calibration is identical to the PTB facility. Optical scheme of the VNIIOFI facility for the reference solar cell calibration is presented on the Fig. 1.
A dual-beam optical arrangement is used to measure equally normalized relative DSR spectra of reference solar cell at a series of discrete operating points that are set with a steady-state bias radiation at levels between 0.105 $E_{STC}$ and 1.12 $E_{STC}$. The chopped monochromatic radiation behind a double-grating monochromator is measured with a lock-in-amplifier.
Level of the monochromatic radiation in checked up with a help of the monitor photodiode.
The absolute DSR is measured at wavelength 546.1 nm at one of the lowest bias level. Uniformity of the spectral irradiance in the plane where the absolute DSR is measured is not worse than ±0.3% relative to the average value along 20x20mm$^2$ .
Temperature of the reference solar cell is ensured by the liquid thermostat and platinum resistance thermometer. Temperature stability of the reference solar cell is lies within ±20mK.
Temperature of the monitor photodiode and the standard detector also is ensured by the liquid thermostat. Temperature stability of the standard detector and monitor photodiode is lies within ±50mK.
In order to have a possibility to align the optical scheme at different wavelength all the optical elements are installed on the translating stages.
Placing of the monitor, an aperture and lens 3 on the one translating stage allows to focus a monochromatic radiation of different wavelengths on one plane, in which the reference solar cell is fixed.

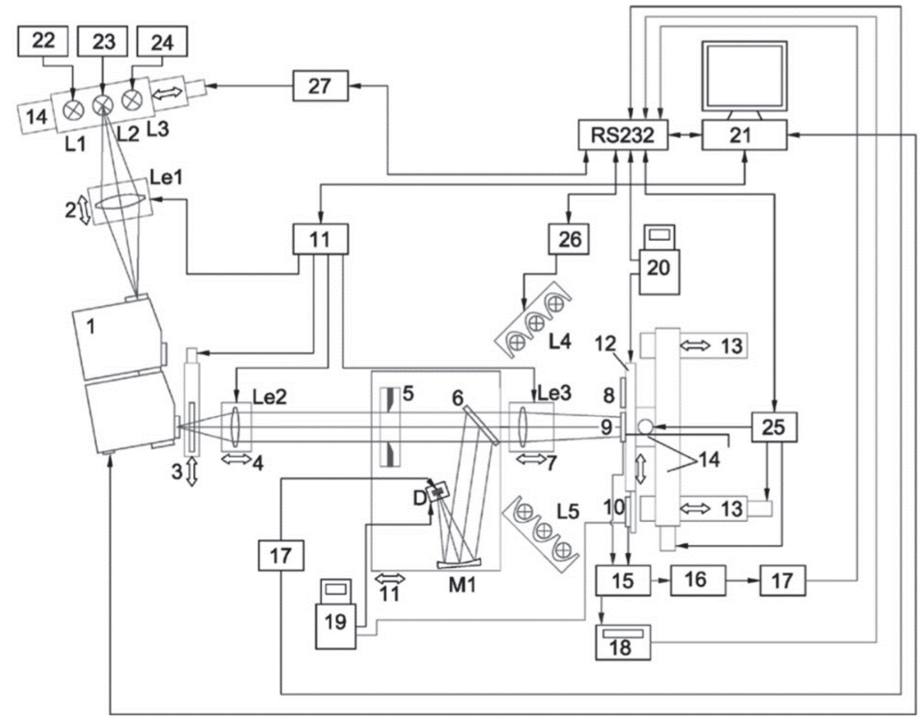



Fig. 1 Diagram of the measuring set-up.

1- Monochromator with triple –grating turrets type DTMc300V GPIB SUB (BENTHAM Instr. Ltd.);
2,4,7- Lens on a Linear Stage LTM80F-150-MSM with Position Controller PS10-32 (OWIS GmbH);
3 - Light Chopper Model 197 (EG&G);
5 - Aperture 20×20 mm;
6 - Beam Splitter;
8,9 - Reference Solar Cells;
10 - Standard Photodiode;
11 - Platform on a Linear Stage LTM80F-150-MSM with Position Controller PS10-32 (OWIS GmbH);
12 - Temperature-stabilized Platform;
13 - Linear Positioner LES 4 (ISEL);
14 - Linear Positioner LES 5 (ISEL);
15 - Commutator ( Made in VNIIOFI);
16 - Preamplifier;
17 - DSP Lock-in Amplifier 7265 ( SIGNAL RECOVERY) ;
18 - Multimeter 34970A with Scan Card (AGILENT);
19 - Liquid Thermostat Polystat R6L ( COLE PARMER);
20 - Liquid Thermostat Polystat R13L ( COLE PARMER);
21 - Computer;
22 - Power Supply SVX 2000 (MULLER ELECTRONIK-OPTIK);
23 - Power Supply PS-120-PU ( Made in VNIIOFI);

24 - Power Supply for Spectral Lamp ( Made in VNIIOFI);
25 - Controller C 142-4 (ISEL);
26 - Two Power Supply PS-200-PU with Lamps Commutator ( Made in VNIIOFI);
L1 - Lamp house COOL 2000 with 2000W Xenon-short arc lamp (MULLER ELECTRONIK-OPTIK);
L2 - Halogen lamp 110 V, 1000W;
L3 - Spectral Lamp ( Made in VNIIOFI);
D - Monitor Photodiode;
M1- Spherical Mirror.

*4) Establishment of traceability route of calibration:*

The used standard detector (photodiode Hamamatsu) is traceable to SI units via broadband cryogenic radiometer.

*5) Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)*

Ambient temperature, ºC ………………………………..23±2
Air humidity, % ……………………………….………..65±15
Atmospheric pressure, kPa………………………………100±4

6) The following interim results are provided electronically:
spectral responsivity at STC for 048-2010 - file 48_last.doc
spectral responsivity at STC for 050-2010 - file 50_last.doc
measurements results for the solar cells 048-2010 and 050-2010 at the temperature of $25^0$ C

Laboratory :……M-4-3……………………………………………………………………..

Officer in charge:…Morozova S.P.………Position…Head of laboratory…………………………

Signature:…………………… ……………..Date:…07.05.2014…………………………….

### 1.4. Uncertainty of measurement

Uncertainty budget is evaluated for the current under standard test conditions

**Table 1.4. 1. Uncertainty budget of calibration of traveling reference solar cell 048-2010**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | 0.8 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0.17 |
| 3 | Spectral mismatch / Wavelength error | 0.02 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0.01 |
| 5 | Temperature effects | 0.05 |
| 6 | Reading repeatability of standard detector | 0.08 |
| 7 | Reading repeatability of test reference solar cell | 0.05 |
| 8 | Alignment and xyz-positioning of standard detector | 0.06 |
| 9 | Alignment and xyz-positioning of test detector | 0.04 |
| 10 | Others (please specify) | |
| | **Combined relative standard uncertainty(%)** | **0.81** |

**Table 1.4. 2. Uncertainty budget of calibration of traveling reference solar cell 050-2010**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | 0.8 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0.17 |
| 3 | Spectral mismatch / Wavelength error | 0.02 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0.01 |
| 5 | Temperature effects | 0.05 |
| 6 | Reading repeatability of standard detector | 0.08 |
| 7 | Reading repeatability of test reference solar cell | 0.05 |
| 8 | Alignment and xyz-positioning of standard detector | 0.06 |
| 9 | Alignment and xyz-positioning of test detector | 0.04 |
| 10 | Others (please specify) | |
| | **Combined relative standard uncertainty(%)** | **0.81** |

Laboratory :……M-4-3………………………………………………………………………..

Officer in charge:…Morozova S.P.………Position…Head of laboratory…………………………

Signature:……………………………………..Date:…07.05.2014……………………………….

### 1.5. Record of reference solar cells radiant exposure

**Table 1.5.1. Record of reference solar cell 048-2010 radiant exposure**

| Date | Activity (test, alignment, measurement) | Exposure spectrum (AMx, or CCT y K) | Exposure time (Second) | Irradiance on detector (W / m²) | Operator initials |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

**Table 1.5.2. Record of reference solar cell 050-2010 radiant exposure**

| Date | Activity (test, alignment, measurement) | Exposure spectrum (AMx, or CCT y K) | Exposure time (Second) | Irradiance on detector (W / m²) | Operator initials |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

Laboratory :……M-4-3…………………………………………………………………………..

Officer in charge:…Morozova S.P………Position…Head of laboratory…………………………

Signature:……………………………..Date:…07.05.2014…………………………….

## 13.5 PTB (Participant, Laser-DSR facility), Germany

### 1.3 Description of the measurement facility and traceability

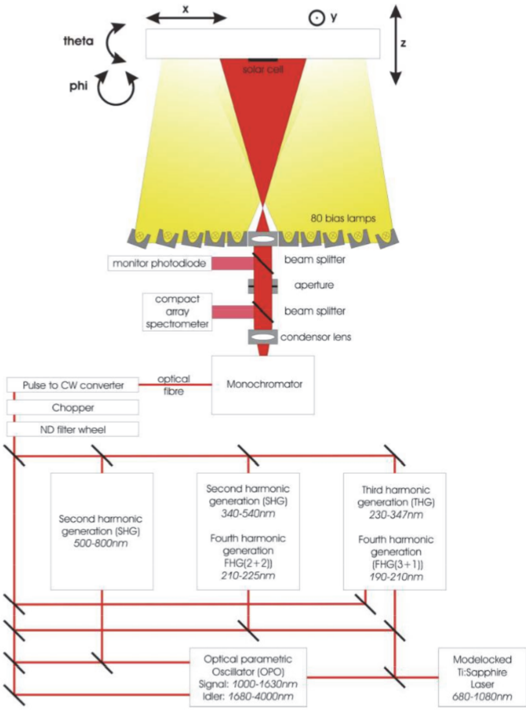
This form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated, please use separate sheets of paper as appropriate.

1) Manufacturers and types of the reference photodiode, solar simulator, lock-in amplifier, voltmeter, and any other instruments used:
   Reference PD: Hamamatsu S6337-01
   Lock-In amplifier: SignalRecovery 7270, SignalRecovery 7265
   Bias Voltage: Keithley 2002
   Temperature: Keithley 2001, Keithley 2002
   I-U-converter: custom made

2) Laboratory reference standards used:

   Reference PD: PV72
   Aperture: PV28

3) Description of measuring set-ups (please include a diagram):




The monochromatic radiation is generated by a tunable laser system in combination with a monochromator, that eliminates sidebands of the laser radiation and further limits the bandwidth of the monochromatic radiation. The monochromatic radiation is modulated with a chopper that is located in front of

3

the monochromator. The radiation exiting the monochromator is parallelized by a lens, passes a beamsplitter that reflects a fraction of the radiation to the monitor photodiode and is finally expanded by a second lens in order to generate a homogeneous radiation field that widely overilluminates the solar cell under test. The solar cells as well as the reference photodiode are mounted on an automatized high precision xyz-table. The detectors are further overilluminated by constant sun-like bias radiation.

4) Establishment of traceability route of calibration:

The reference photodiode is traceable via the cryo-radiometer at PTB(Berlin) to the SI. The aperture is traceable via optical measurements of opaque and transmitting chrome-on-quartz glass circles of the PTB-reference mask IMS M0411-45.

5) Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)

The laboratory is air-conditioned to a constant temperature of 23°C and a relative humidity of 22%.

6) The following interim results are provided electronically:
   - x spectral responsivity at STC
   - x spectrally resolved differential non-linearity
   - x AM1.5 weighted differential non-linearity
   - ☐ spectrally resolved temperature coefficient
   - ☐ AM1.5 weighted temperature coefficient

Laboratory: LaserDSR, PTB

Officer in charge: Ingo Kröger Position: scientist

Signature: Ingo Kröger ……………………… Date: 26.02.2013 ………………………

4

## 1.4 Uncertainty of measurement

Uncertainty budget is to be evaluated for the current under standard test conditions

**Table 7.4.1. Uncertainty budget of calibration of travelling reference solar cells**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | <0.1% |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | <0.1% |
| 3 | Spectral mismatch / Wavelength error | <0.06% |
| 4 | Spectral bandwidth of the monochromatic radiation | <0.05% |
| 5 | Temperature effects | <0.01% |
| 6 | Reading repeatability of standard detector | <0.05% |
| 7 | Reading repeatability of test reference solar cell | <0.02% |
| 8 | Alignment and xyz-positioning of standard detector | <0.01% |
| 9 | Alignment and xyz-positioning of test detector | <0.01% |
| 10 | Others (interreflexions, linearity of amplifiers) | <0.10% |
| | **Combined relative standard uncertainty (%)** | 0.2% |

Laboratory : LaserDSR, PTB

Officer in charge: Ingo Kröger    Position: Scientist

Signature: Ingo Kröger    Date: 26.02.2013

5

## 13.6 KRISS, Rep. Korea

### 7.3 Description of the measurement facility and traceability

This form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated, please use separate sheets of paper as appropriate.

1) Manufacturers and types of the reference photodiode, solar simulator, lock-in amplifier, voltmeter, and any other instruments used:

   Reference solar cells: Fraunhofer ISE WPVS reference solar cell (type: monocrystalline silicon solar cell with HOQ-filter)

   Solar simulator: Oriel class A solar simulator (model: 92251A)
   Power supply: Oriel arc lamp power supply (model: 69907)
   Sourcemeter: Keithley sourcemeter (model: 2400)
   Thermometer: Azonix RTD thermometer (model: A1011)
   Temperature controller: Melcor thermoelectric controller (model: MTCA)
   Spectroradiometer: OTSUKA array spectrometer (model: 2 x MCPD-9800, Si + InGaAs)

2) Laboratory reference standards used:

   Spectral irradiance standard lamp of KRISS (1 kW FEL type, S/N: 20120601-1-FEL)

3) Description of measuring set-ups (please include a diagram):

   The calibration facility of reference solar cells at KRISS mainly consists of a solar simulator, a reference spectroradiometer, a sourcemeter, and a temperature-controlled sample mounts on a translational stage, as shown in Fig. 1-2. The solar simulator is based on a 150 W Xenon lamp with an AM1.5 correction filter. Two reference solar cells can be installed on the two mounts with the TEC modules whose temperatures are separately controlled. Positioning of the reference solar cells are controlled by a 2-axis translation stage. The reference spectroradiometer is calibrated against a KRISS spectral irradiance standard lamp for absolute measurement of spectral irradiance at the sample mount. The measurement range of the spectroradiometer is from 250 nm to 1700 nm, which is covered by combining a Si-based and InGaAs-based spectrometer at an integrating sphere head with an inner-diameter of 50 mm and an input port with a diameter of 6 mm.

   The spectral mismatch correction of the test reference solar cells s performed by using the relative spectral responsivity data, which are measured separately at the KRISS differential spectral responsivity measurement setup shown in Fig. 3-4. The setup is based on a tungsten-lamp white bias source and a modulated tunable monochromatic source. Light beams from the two sources are combined by using an integrating sphere with a diameter of 10 cm. The reference photodiode mounted on the integrating sphere is calibrated traceable to the KRISS spectral irradiance responsivity scale from 300 nm to 1100 nm.

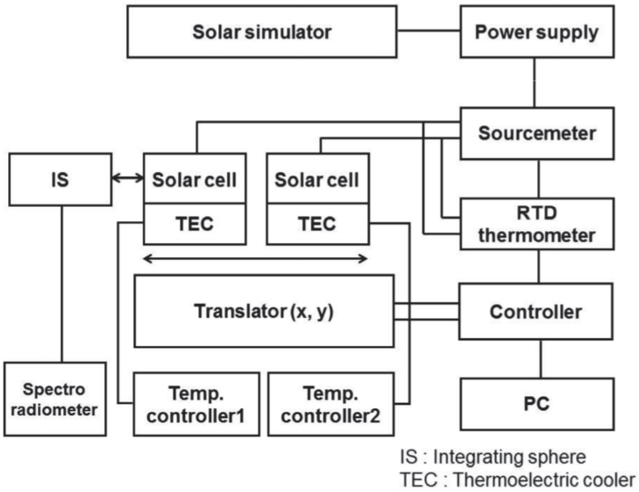



**Fig. 1. Schematic diagram of the KRISS setup for calibration of reference solar cells.**

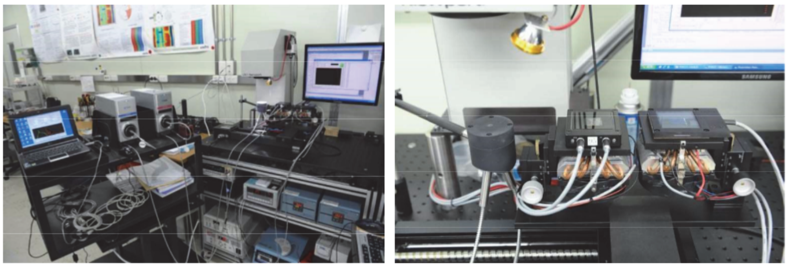


**Fig. 2. Photograph of the KRISS setup for calibration of reference solar cells.**

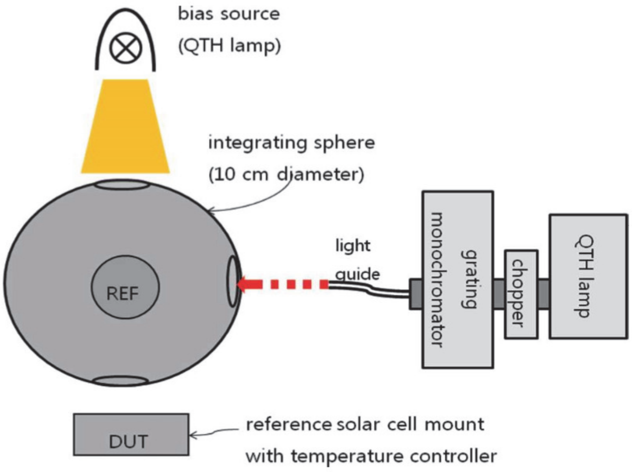
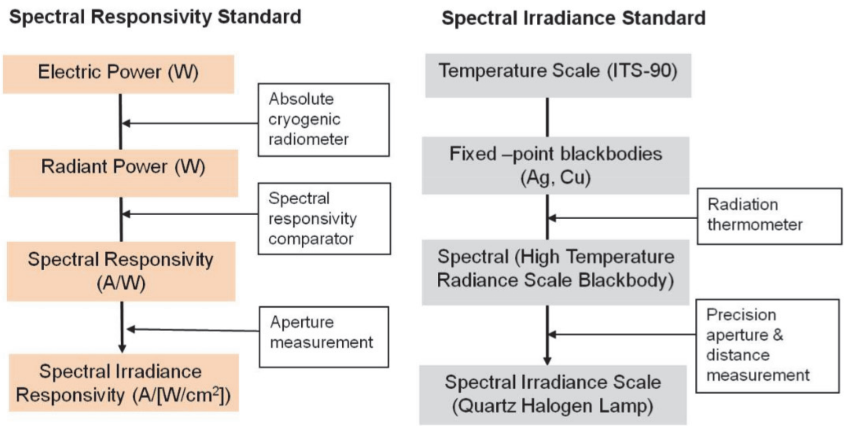



**Fig. 3. Schematic diagram of the KRISS setup for differential spectral responsivity measurement.**

**Fig. 4. Photograph of the KRISS setup for differential spectral responsivity measurement.**

4) Establishment of traceability route of calibration:




5) Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)

Temperature: (23 ± 1) ℃

Relative humidity: (45 ± 15) % R.H.

6) The following interim results are provided electronically:
- ☐ spectral responsivity at STC
- ☐ spectrally resolved differential non-linearity
- ☐ AM1.5 weighted differential non-linearity
- ☐ spectrally resolved temperature coefficient
- ☐ AM1.5 weighted temperature coefficient

Laboratory: KRISS

Officer in charge: Dong-Hoon Lee Position: Principal Research Scientist

Signature: ................................. Date: 2013.03.22

### 7.4 Uncertainty of measurement

Uncertainty budget is to be evaluated for the current under standard test conditions

**Table 7.4.1. Uncertainty budget of calibration of travelling reference solar cells**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector (Spectroradiometer) | 0.9 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0.2 |
| 3 | Spectral mismatch correction | 0.3 |
| 4 | Spectral bandwidth of the monochromatic radiation | N/A |
| 5 | Temperature effects | 0.04 |
| 6 | Reading repeatability of standard detector | 0.05 |
| 7 | Reading repeatability of test reference solar cell | 0.05 |
| 8 | Alignment and xyz-positioning of standard detector | 0.09 |
| 9 | Alignment and xyz-positioning of test detector | N/A |
| 10 | Linearity | 0.1 |
| 11 | Lamp drift | 0.1 |
| | **Combined relative standard uncertainty (%)** | 0.99 |

Laboratory: KRISS

Officer in charge: Dong-Hoon Lee Position: Principal Research Scientist

Signature: ………………. …………….. Date: 2013.03.22

## 13.7 NMC, A*STAR, Singapore

Report on EURAMET PR-S5 PV Cell Comparison

### 2) Description of the measurement facility and traceability

This form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated, please use separate sheets of paper as appropriate.

1) Manufacturers and types of the reference photodiode, solar simulator, lock-in amplifier, voltmeter, and any other instruments used:

(1) DSR system (Industrial Vision Technology, customised)
(2) Silicon photodiode (Hamamatsu, S1337-1010BQ)
(3) InGaAs photodiode (Hamamatsu, G5837)
(4) Pre-amplifier (Vinculum, E775)
(5) I-V tester (i-Itegration, Test and Solutions, customised)
(6) SourceMeter (Keithey, 2651A)
(7) Thermometer (Lutron HT-3003)
(8) Solar simulator (WACOM, WXS-155S-L2, AM1.5GMM)
(9) Lock-in amplifier (Stanford Research Systems, SR830)

2) Laboratory reference standards used:

(1) ISO 15387: 2005 (E), Space systems – single-junction solar cells – measurement and calibration procedures;
(2) IEC 60904-3 (Ed.2.0 2008-04), Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data;
(3) IEC 60904-1, 2nd edition 2006-09, Measurement of Photovoltaic current – voltage characteristics;
(4) IEC 60904-8, 1998-02, Measurement of spectral response of photovoltaic (PV) device

3) Description of measuring set-ups (please include a diagram):

**Method**

As shown in Fig.1, the measurement is based on DSR method developed by PTB, which essentially compares the photocurrent produced by the test solar cell with that produced by a reference photodiode with known (calibrated) spectral responsivity values under the same monochromatic probe beam irradiance with or without a broadband sun-like bias irradiance. The DSIR of the test cell is measured under the irradiation of differential bias while the reference photodiode is measured without any bias light.

The probe beam is modulated by a mechanical chopper so that the

NMC-A*STAR 1st measurement report Page.2 of 11

photocurrents generated by both test solar cell and reference photodiodes are weak AC signals while the photocurrent produced by the bias light is strong DC signal. The ac measurement technique using lock-in amplifiers is used to detect the weak AC probe signal while a source meter is used to direct measure the DC bias signal.

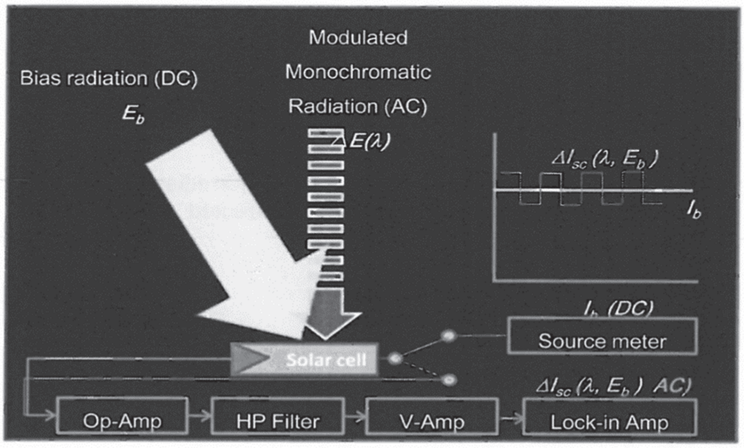



Fig.1 The DSR measurement technique

(1) **Relative Spectral Responsivity [SR] and Spectral Irradiance responsivity (SIR)**

SR is the spectral power responsivity of a solar cell which can be measured by a reference photodiode (ref PD) with known spectral power responsivity both under-filled by the probe beam. If a precision aperture is added in front the ref PD and over-filled by the probe beam which also overfills the DUT, the spectral irradiance responsivity (SIR) of the DUT can be measured just by dividing the spectral power responsivity of the ref PD by the aperture area provided the probe beam is spatially uniform over the DUT receiving area.

Low Resolution Calibration

Low resolution calibration is carried out by two separate wavelength scans. The 1st scan is on the ref PD with the outputs from ref PD and monitor detector (see Fig.2) simultaneously recorded at every wavelength. The 2nd scan is on the test solar cell with the outputs from test cell and monitor detector again recorded simultaneously. Then the SR of the test cell can be calculated by

$$s(\lambda) = s(\lambda)_R \bullet \frac{V(\lambda)^T}{V(\lambda)^{M'}} \bullet \frac{V(\lambda)^M}{V(\lambda)^R} = s(\lambda)_R \bullet \frac{C(\lambda)^T}{C(\lambda)^R} \quad (1)$$

The SIR of the test cell is simply *s (λ)/A.*

Where

- $s(\lambda)_R$ is the known spectral power responsivity of the ref PD;
- $C(\lambda)^R = V(\lambda)^R/V(\lambda)^M$ is the output ratio of ref PD vs. monitor detector during the scan of reference photodiode;
- $C(\lambda)^T = V(\lambda)^T/V(\lambda)^{M'}$ is the output ratio of test solar cell vs. monitor detector during test cell scan;
- *A* is area of the precision aperture of the ref PD.

The effect of any change in the probe beam irradiance due to light source instability on the calibration result is corrected by the use of monitor detector.

High Resolution Calibration

For high resolution calibration, the output of the ref PD and test cell at every wavelength is directly compared by putting them under the probe beam alternatively. Measurement uncertainty due to wavelength non-repeatability of the monochromator during two separate scans can be avoided using mode of calibration. But the speed of calibration is considerably lower than the low resolution calibration.

Note: As the gains in the detection system for ref PDs, monitor detectors and DUT are fixed but not calibrated, the SR and SIR measured are all relative values.

(2) **Differential Spectral Irradiance Responsivity (DSIR) (with bias)**

The DSIR is a function a wavelength ($\lambda$) and bias irradiance ($E_b$) and can be defined as

$$\tilde{s}(\lambda, I_{sc}(E_b)) = \left.\frac{\partial I_{sc}(\lambda, I_{sc}(E_b))}{\partial E(\lambda)}\right|_{E_b} = \tilde{s}(\lambda_0, I_{sc}(E_0)) \bullet \tilde{s}_{rel}(\lambda, I_{sc}(E_b)) \qquad (2)$$

where

- $\tilde{s}(\lambda_0, I_{sc}(E_0))$ is the **absolute** DSIR at a particular wavelength $\lambda_0$ at a bias level $E_0$.
- $\tilde{s}_{rel}(\lambda, I_{sc}(E_b))$ is the **relative** DSIR at any bias level $E_b$, **normalized at wavelength $\lambda_0$**, so that $\tilde{s}_{rel}(\lambda_0, I_{sc}(E_0)) = 1$.

In eq. (2), the SCC ($I_{sc}$) of the DUT, instead of bias irradiance $E_b$, is used as the parameter to indicate the bias irradiance, as the former is a function of (& proportional to) $E_b$ and can be directly measured using a source meter through a shunt resistor. As explained previously, DSIR calibration requires measurement of the response (change of SCC) of the DUT to a small change of the irradiance created by a monochromatic probe beam under a strong bias radiation so that the ac measurement technique must be used.

If all spectral measurements are carried out with the precision aperture (area A) in front the ref PD overfilled and the DUT over-filled by the same probe beam, and the gains of all amplifiers used in the detection system are fixed for each measurement scan, the relative DSIR can be measured by

$$\tilde{s}_{rel}(\lambda, I_{sc}(E_b)) = \frac{s(\lambda)_R}{A} \bullet \frac{V(\lambda)^{T(E_b)}}{V(\lambda)^{M'}} \bullet \frac{V(\lambda)^M}{V(\lambda)^R} = \frac{s(\lambda)_R}{A} \bullet \frac{C(\lambda)^{T(E_b)}}{C(\lambda)^R} \quad (3)$$

Where

- $C(\lambda)^R = V(\lambda)^R / V(\lambda)^M$ is the output ratio of ref PD vs. monitor detector during the scan of ref PD (no bias);
- $C(\lambda)^{T(E_b)} = V(\lambda)^T / V(\lambda)^{M'}$ is the output ratio of test solar cell (with bias $E_b$) vs. monitor detector during test cell scan (under bias, $E_b$).

Notes:

a) Without dividing the aperture area A in the above formula, the result becomes relative DSR;
b) As ref PD can only be measured w/o bias, no high resolution calibration for DSIR calibration.
c) The same $C(\lambda)^R$ will be used for DSR measurements at all different bias levels.
d) The bias level $E_b$ cannot be directly measured and is represented by the SCC ($I_{sc}$) of the test cell measured by a source meter. The corresponding $E_b$ in accordance with STC can be derived from the full DSR measurement data.

(3) **Spectral Irradiance Responsivity [SIR] (absolute)**

Both the SR/SIR and DSR/DSIR measurements described previously are relative values as the gains of the amplifiers for both ref PDs and DUT are not calibrated although they remain constants during measurement.

To obtain the absolute values of DSIR, the absolute DSIR at $\lambda_0$, $\tilde{s}(\lambda_0, I_{sc}(E_0))$ must be determined. By choosing zero bias $E_0$=0,

$$\tilde{s}(\lambda_0, I_{sc}(0)) = SIR(\lambda_0) = s(\lambda_0) / A_{DUT} \quad (4)$$

it can be measured without applying any bias light.

The absolute values of $SIR(\lambda)$ and $DSIR(\lambda)$ at other wavelengths can be obtained by

$$SIR(\lambda) = SIR(\lambda_0) * SIR(\lambda)_{rel} \quad (5)$$

$$DSIR(\lambda) = SIR(\lambda_0) * DISR(\lambda)_{rel} \quad (6)$$

*SIR ($\lambda_0$)* can be measured by using a common current-voltage converter (CVC) for both ref PD and DUT. By aligning ref PD and DUT to the probe beam at $\lambda_0$ alternatively and record the outputs from ref PD-monitor detector and DUT-monitor detector respectively, *SIR($\lambda_0$)* can be calculated:

$$SIR(\lambda_0) = \frac{s(\lambda_0)_R}{A} \bullet \frac{C(\lambda_0)^T}{C(\lambda_0)^R} \bullet C_A \quad (7)$$

Where

- $s(\lambda_0)_R$ is the known (calibrated) spectral responsivity of the ref PD;
- *A* is the known (calibrated) area of precision aperture on the ref PD;
- $C(\lambda_0)^R = V(\lambda_0)^R / V(\lambda_0)^M$ is the ratio of outputs of ref PD vs. monitor;
- $C(\lambda_0)^T = V(\lambda_0)^T / V(\lambda_0)^{M'}$ is the ratio of outputs of DUT vs. Monitor;
- $C_A$ is the correction factor for spatial non-uniformity of the probe beam

As the measurements of $C(\lambda_0)^T$(CR) and $C(\lambda_0)^R$(CT) are not carried out simultaneously, Errors due to change of probe beam irradiance can be corrected by the use of monitor detector as reference.

### (4) Temperature Coefficient of Spectral Responsivity

The temperature coefficient of spectral responsivity of the spectral responsivity or spectral irradiance responsivity can be measured at 25 °C can be derived from the average gradient of SR/SIR vs. temperature based on results of SR/SIR measurements at 20 °C, 25 °C and 30 °C.

$$T_c(\lambda) = [s(\lambda)_{30°C} - s(\lambda)_{20°C}]/10 \quad (8)$$

or

$$T_c(\lambda) = [SIR(\lambda)_{30°C} - SIR(\lambda)_{20°C}]/10 \qquad A \cdot W^{-1} \cdot °C^{-1} \quad (9)$$

### (5) Differential irradiance responsivity (DIR) in accordance to AM1.5 reference spectrum as a function of SCC/bias level

The broadband differential irradiance responsivity assessed in accordance with AM1.5 reference solar spectrum as a function of the SCC ($I_{sc}$) of the DUT can be obtained by

$$\tilde{s}_{AM1.5}(I_{sc}(E_b)) = \tilde{s}(\lambda_0, I_{sc}(E_0)) \cdot \frac{\int_0^\infty \tilde{s}_{rel}(\lambda, I_{sc}(E_b)) E_{\lambda,AM1.5}(\lambda) d\lambda}{\int_0^\infty E_{\lambda,AM1.5}(\lambda) d\lambda} \quad (10)$$

### (6) Short-Circuit Current under STC

The value of the SCC of DUT under standard STC conditions $I_{STC} = I_{sc}(E_{STC})$ can be derived by finding the upper integration limit in the following equation:

$$1{,}000 W/m^2 = E_{STC} = \int_0^{I_{STC}} \frac{dI_{sc}}{\tilde{s}_{AM1.5}(I_{sc})} \qquad (11)$$

To find the upper limit, the reciprocal of 1/ $\tilde{s}_{AM1.5}(I_{sc})$ as a function of the measured SCC ($I_{sc}$) should be plotted and modeled using curve fitting such as Add Trend line function in Excel.

Note: If the values of $\tilde{s}_{AM1.5}(I_{sc})$ at different bias levels are very close (the relative STDEV of these values < 0.5%), indicating the cell is linear, the simple arithmetic average of all $\tilde{s}_{AM1.5}(I_{sc})$ values can be taken as the value of $I_{STC}$.

The (broadband) irradiance responsivity of the DUT under STC can be now calculated:

$$S_{STC} = \frac{I_{STC}}{E_{STC}} \qquad (12)$$

### (7) Absolute spectral irradiance responsivity (SIR) under STC

Can be calculated by

$$S_{STC}(\lambda) = \frac{I_{STC}}{\int_0^{I_{STC}} \frac{dI_{sc}}{\tilde{s}(\lambda, I_{sc})}} \qquad (13)$$

The result can be verified by

$$I_{STC} = \int_0^{\infty} s_{STC}(\lambda) \cdot E_{AM1.5}(\lambda) d\lambda \qquad (14)$$

The result should be the same as $I_{STC}$ obtained using equation (11).

### (8) Temperature Coefficient of Short-circuit Current under STC

If the DSR measurements is done in the full spectral range (280 nm – 1200 nm) at different bias levels at the above 3 temperatures, the temperature coefficient of SCC around 25 °C can also be derived from the measured SCC.

Report on EURAMET PR-S5 PV Cell Comparison

(9) **Measurement Set-up (The DSRF)**

Fig.2 shows the optical layout of the DSR facility (DSRF) and Fig.3 shows the functionality of the system software.

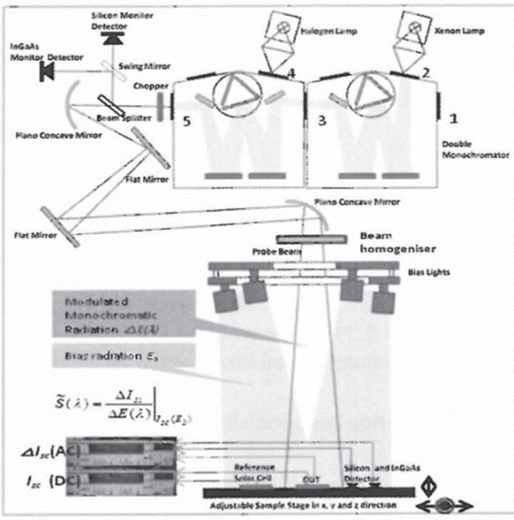



Fig.2 The Optical Layout of the DSRF at NMC

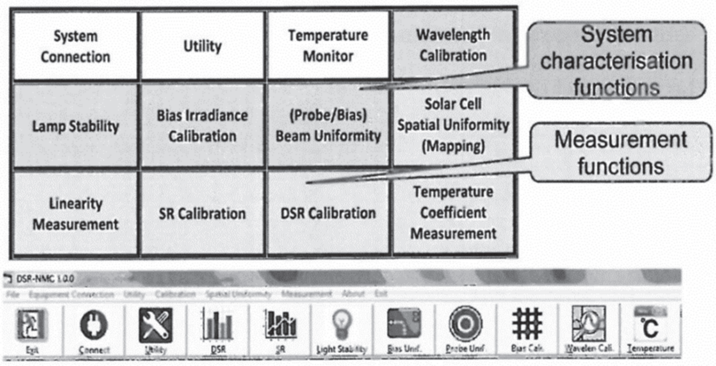
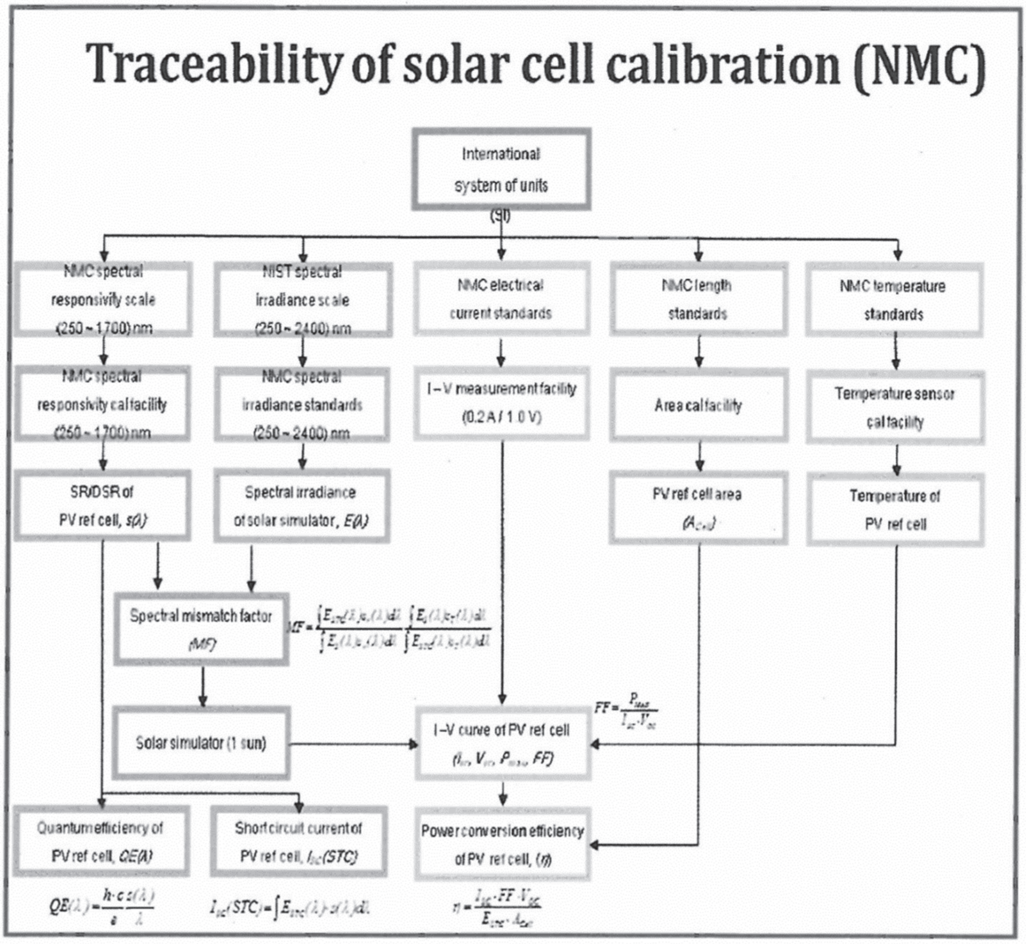



Fig.3 Functionality of the system software of DSRF

NMC-A*STAR 1st measurement report Page.8 of 11

Report on EURAMET PR-S5 PV Cell Comparison

4) Establishment of traceability route of calibration:



Report on EURAMET PR-S5 PV Cell Comparison

5) Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)

Temperature : (25 ± 2) °C

Relative Humidity: (50 ± 10) % relative humidity

6) The following interim results are provided electronically (see attachment):
- ☐ spectral responsivity at STC
- ☐ spectrally resolved differential non-linearity
- ☐ AM1.5 weighted differential non-linearity
- ☐ spectrally resolved temperature coefficient
- ☐ AM1.5 weighted temperature coefficient

Laboratory: ...**NMC-A*STAR**...............................

Officer in charge: **Huang Xuebo**....... Position: ...**Principal Metrologist**.........

Signature: ......[signature]...... Date: ...24 Dec 2012...

NMC-A*STAR 1st measurement report Page.10 of 11

Report on EURAMET PR-S5 PV Cell Comparison

## 7) Uncertainty of measurement

Uncertainty budget is to be evaluated for the current under standard test conditions

**Table 1. Uncertainty budget of calibration of travelling reference solar cells**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | 0.30 |
| 2 | Residue uncertainty after spatial non-uniformity correction | 0.020 |
| 3 | Spectral mismatch / Wavelength error | 0.015 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0.068 |
| 5 | Temperature effects | 0.020 |
| 6 | Reading repeatability of standard detector | 0.047 |
| 7 | Reading repeatability of test reference solar cell | 0.058 |
| 8 | Alignment and xyz-positioning of standard detector | 0.17 |
| 9 | Alignment and xyz-positioning of test solar cell | 0.16 |
| 10 | Non-linearity of pre-amplifier | 0.062 |
| 11 | Non-linearity of lock-in amplifier | 0.036 |
| 12 | Linear fitting | 0.20 |
| 13 | Repeatability of three measurements | 0.17 |
| | **Combined relative standard uncertainty(%)** | 0.48 |

Laboratory :………**NMC – A*STAR**………………………………………………………

Officer in charge:…**Huang Xuebo**……Position: **Principal Metrologist**……………

Signature:……[signature]…………………Date:…24 Dec 2012……………

NMC-A*STAR 1st measurement report Page.11 of 11

## 13.8 ITRI, Chinese Taipei

### 7.3 Description of the measurement facility and traceability

This form should be used as a guide. It is anticipated that many of the questions will require more information than the space allocated, please use separate sheets of paper as appropriate.

1) Manufacturers and types of the reference photodiode, solar simulator, lock-in amplifier, voltmeter, and any other instruments used:

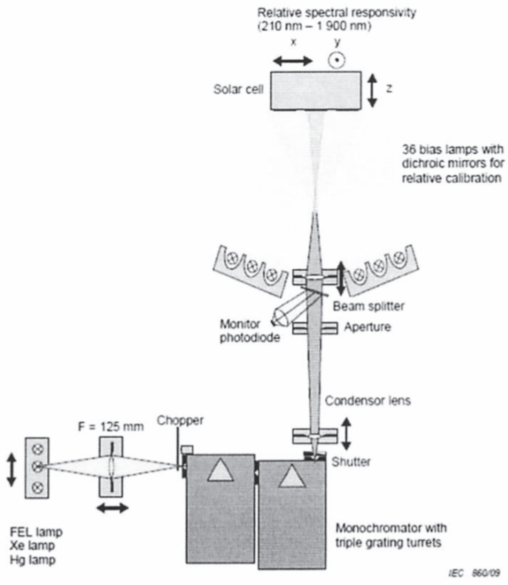
| | |
|---|---|
| Reference photodiode | HAMAMATSU/S1337-1010BQ |
| Light source | 1. Xenon: OSRAM/1000 W<br>2. Halogen: OSRAM/1000 W |
| Lock-in amplifer | Signal Recovery/ SR-7265 |
| Meter | Keithley/2700 |
| monochromator | Princeton Instruments/ SP-2300 |

2) Laboratory reference standards used:

Si-detector ; type: S1337－1010BQ / Hamamatsu Photonics ; Ref. No. : 73323 12 PTB.
Ge-detector ; type: PD82 / Teledyne Judson Technologies ; Ref. No. : 73322 12 PTB.

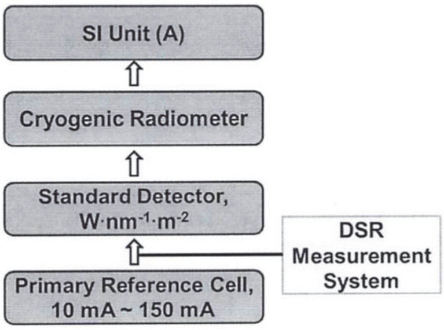
3) Description of measuring set-ups (please include a diagram):

Traceability is based on a calibration of spectral responsivity based on standard detectors directly traceable to SI units. The calibration value is computed from the measured absolute spectral responsivity of the reference cell and the reference solar spectral irradiance distribution.




16/12/2013 15:42 3

4) Establishment of traceability route of calibration:




5) Description of calibration laboratory conditions: (eg. Temperature, relative humidity etc.)

Ambient temperature: ( 23 ± **5** ) °C

Relative humidity: ( 50 ± **20** ) %

6) The following interim results are provided electronically:
- spectral responsivity at STC
- spectrally resolved differential non-linearity
- AM1.5 weighted differential non-linearity
- spectrally resolved temperature coefficient
- AM1.5 weighted temperature coefficient

**As the attached file "ITRI-CMS-PTB-097(Phase III).xlsx"**

Laboratory: Center for Measurement Standards/ITRI

Officer in charge: Gwo-Sheng Peng.... Position: Division Director

Signature: Gwo-Sheng Peng...... Date: 2013.12.16...............................

16/12/2013 15:42 4

### 7.4 Uncertainty of measurement

Uncertainty budget is to be evaluated for the current under standard test conditions

**Table 7.4.1. Uncertainty budget of calibration of travelling reference solar cells**

| | Source of uncertainty | Value of standard uncertainty (%) |
|---|---|---|
| 1 | Calibration of standard detector | 0.089 |
| 2 | Uncertainty due to uniformity of the radiation in the measuring plane | 0.23 |
| 3 | Spectral mismatch / Wavelength error | 0.16 |
| 4 | Spectral bandwidth of the monochromatic radiation | 0.12 |
| 5 | Temperature effects | 0.0037 |
| 6 | Reading repeatability of standard detector | 0.050 |
| 7 | Reading repeatability of test reference solar cell | 0.038 |
| 8 | Alignment and xyz-positioning of standard detector | 0.0022 |
| 9 | Alignment and xyz-positioning of test detector | 0.0022 |
| 10 | Others (please specify) | |
| | **Combined relative standard uncertainty(%)** | 0.33 |

Laboratory: Center for Measurement Standards/ITRI

Officer in charge: Gwo-Sheng Peng.... Position: Division Director

Signature: Gwosheng Peng Date: 2013.12.16

16/12/2013 15:42 5