# SECOND INTERNATIONAL SPECTRORADIOMETER INTERCOMPARISON: PRELIMINARY RESULTS AND IMPACT ON PV DEVICE CALIBRATION.

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ABSTRACT: This paper describes the preliminary results of an intercomparison of spectroradiometers for global (GNI) and direct normal incidence (DNI) irradiance in the visible (VIS) and near infrared (NIR) spectral regions together with an assessment of the impact these results may have on the calibration of triple-junction photovoltaic devices and on the relevant spectral mismatch calculation. The intercomparison was conducted by six European scientific laboratories and a Japanese industrial partner. Seven institutions and seven spectroradiometer systems, representing different technologies and manufacturers were involved, representing a good cross section of the todays' available instrumentation for solar spectrum measurements.
Keywords: Solar Radiation, Solar Cell, Intercomparison, Spectroradiometer, Calibration

## 1 INTRODUCTION

The large variety of photovoltaic (PV) technologies today available on the market makes the measurement of the spectral content of the incoming sun light a key parameter for the characterization, calibration, and energy yield estimation of these devices. Nowadays spectroradiometers of different types (e.g. single-, double- stage rotating grating monochromator or fixed single grating polychromator with photodiode (PD) array or CCD detectors) are routinely used for solar spectrum measurements. So far, however, in the PV community little attention has been paid to the evaluation of spectroradiometers and relevant measurement procedures to make solar spectrum measurements comparable and directly traceable to SI units [1 to 3]. In the framework of the European project "Apollon" and of an Italian project for the monitoring of the solar direct irradiance throughout the country, a group of European research institutes active in the PV research field, together with an industrial partner, set up the second intercomparison of spectroradiometers for solar spectrum measurements. The aims of the intercomparison were: exchange and compare instrument calibration procedures, measurement capabilities, establish equivalence figures for solar spectra measurement and put in practice lessons learnt from the previous one. This paper describes the intercomparison campaign, reports on the preliminary results and analyzes practical consequences that the differences in measured spectra may have on multi-junction PV device calibration.

## 2 EXPERIMENTAL SET UP AND APPROACH

The intercomparison took place at the 'ENEL Ingegneria e Ricerca' laboratory in Catania (Italy) from $11^{th}$ to $15^{th}$ of June 2012. Seven spectroradiometer systems from different manufacturers and covering two different technologies (single-stage rotating-grating and fast fixed-grating polychromator with single or CCD array detectors) were set to simultaneously measure global normal incidence (GNI) or direct normal incidence (DNI) spectral irradiance from 360 to 1700 nm, depending on their entrance optics configuration. Table 1 summarizes the seven spectroradiometer systems' characteristics together with the relevant calibration chain used by each laboratory.

**Table I:** Summary of the characteristics of the spectroradiometers participating to the intercomparison**.**

| Laboratory | Spectroradiometer | Detectors technology | Wavelength nm | Calibration chain |
|---|---|---|---|---|
| Supsi | EKO MS-710, MS-712 | Si and InGaAs CCD Array | 350-1700 | In-house with calibrated standard lamp |
| JRC | Optronic Lab.OL 750 | Single Si, PbS sandwich | 350-2500 | In-house with calibrated standard lamp |
| ENEA | StellarNet EPR2000NIR, EPP2000UV | 2-CHs Si, InGaAs CCD array | 250-1700 | Accredited cal. Lab. |
| UniRoma | EKO MS-710, MS-712 | Si and InGaAs CCD Array | 350-1700 | Factory calibrated |
| RSE | StellarNet EPR2000NIR, EPP2000UV | 2-CHs Si, InGaAs CCD array | 250-1700 | Accredited cal. Lab. |
| EKO Japan ltd | EKO MS-710, MS-712 | Si and InGaAs CCD Array | 350-1700 | Factory calibrated |
| ENEL | Aventes AvaSpec USB2 | 2-CHs Si+InGaAs CCD array | 250-1700 | Accredited cal. Lab. |

GNI spectral irradiance were possible on six systems and DNI measurements were possible on five systems. These last had the possibility to be equipped with collimating tubes on their optical entrance in order to reduce the spectroradiometers' field of view (FOV) to 5° nominal. Due to the differences among various instruments in the measurement timing, bandwidth and spectral resolution, specific procedures for data acquisition and analysis were developed in order to make the spectroradiometers' output data comparable. Prior to the intercomparison each participating laboratory calibrated their own spectroradiometer(s) following their usual procedures, thus allowing the evaluation of the whole instrument performance including the traceability chain and the measurement procedures. Some spectroradiometers were calibrated by an external accredited calibration laboratory, others were in-house calibrated using a calibrated radiometric standard lamp, or at the manufacturer laboratory. All participating instruments were mounted on high-accuracy solar trackers in order to reduce pointing errors, especially when measuring spectral DNI. During the four-day intercomparison clear and cloudy sky conditions were experienced, allowing for the evaluation of limitations in data comparison from such a diversity of instrument technologies. Triple-junction ISO-type cells were also measured during the intercomparison in order to evaluate the impact of using different spectra measured at the same time when calibrating the cells. In parallel to the intercomparison a set of cavity radiometers were also in use as reference instruments for total irradiance data. These last assured the direct link to SI units as these cavity radiometers take part to the world radiometric intercomparison (WRR-IPC) held every 5 year at PMOD-Davos (CH) [4]. For clear-sky conditions the corresponding output data obtained from SMARTS model [5-6] were used for comparison purposes.

## 3 RESULTS OF THE INTERCOMPARISON: PRELIMINARY DATA

In order to compare solar spectra acquired by 'fast' and 'slow' measuring instruments, several sets of average spectra, measured during 4-minute acquisition time series, were analyzed. During the time series, the irradiance must remain stable to 1% peak-to-peak or better to avoid adding errors arising from fast changing weather conditions affecting the output of spectroradiometers in different ways. This constraint limited the useful sky conditions to clear or almost clear, discarding partially cloudy sky and measurements taken close to sunrise and sunset when the solar irradiance is fast changing. Figures 1 (a) shows a typical acquisition data set of spectral DNI by the six partners' instruments equipped with collimating tubes. For comparison purposes also the data obtained running SMARTS code with actual local input parameters (time, temperature, atmospheric pressure, relative humidity and terrain type) is also shown. The graph (b) in the same figure shows the wavelength-by-wavelength per cent deviation of each spectrum with respect to Lab A spectrum and normalized to its peak irradiance.

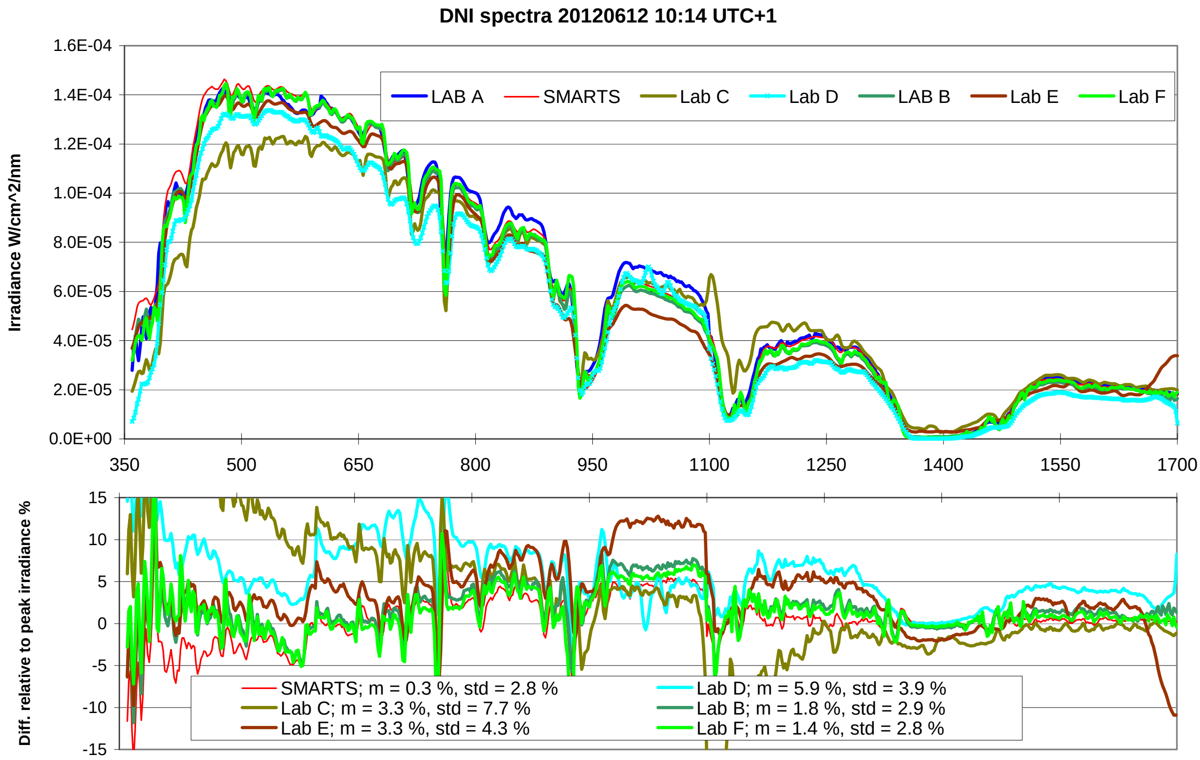


**Figure 1:** Upper, six DNI measured spectra plus spectrum obtained from the same time period by SMARTS code. Lower, wavelength-by-wavelength difference with respect to the Lab A spectrum and normalized to its peak irradiance; average and standard deviation calculated over the interval 360-1700 nm are also reported.

The average difference values for the measured spectra reported in Figure 1 are all positive and lay in a band of ± 2.3% centered at 3.1% with associated standard deviations up to 7.7%. Four systems (Lab B, Lab D, Lab E and Lab F) have most of their wavelength-by-wavelength difference values lying in a band of -5% to + 15%, while Lab C data show larger differences. Figure 2 (a) shows a typical data set relative to a spectral GNI acquisition obtained by the six partners' instruments equipped for global spectral measurements. Also in this case data obtained running SMARTS code is shown. The graph (b) in the same figure shows the wavelength-by-wavelength per cent deviation of each spectrum with respect to Lab A spectrum and normalized to its peak irradiance.

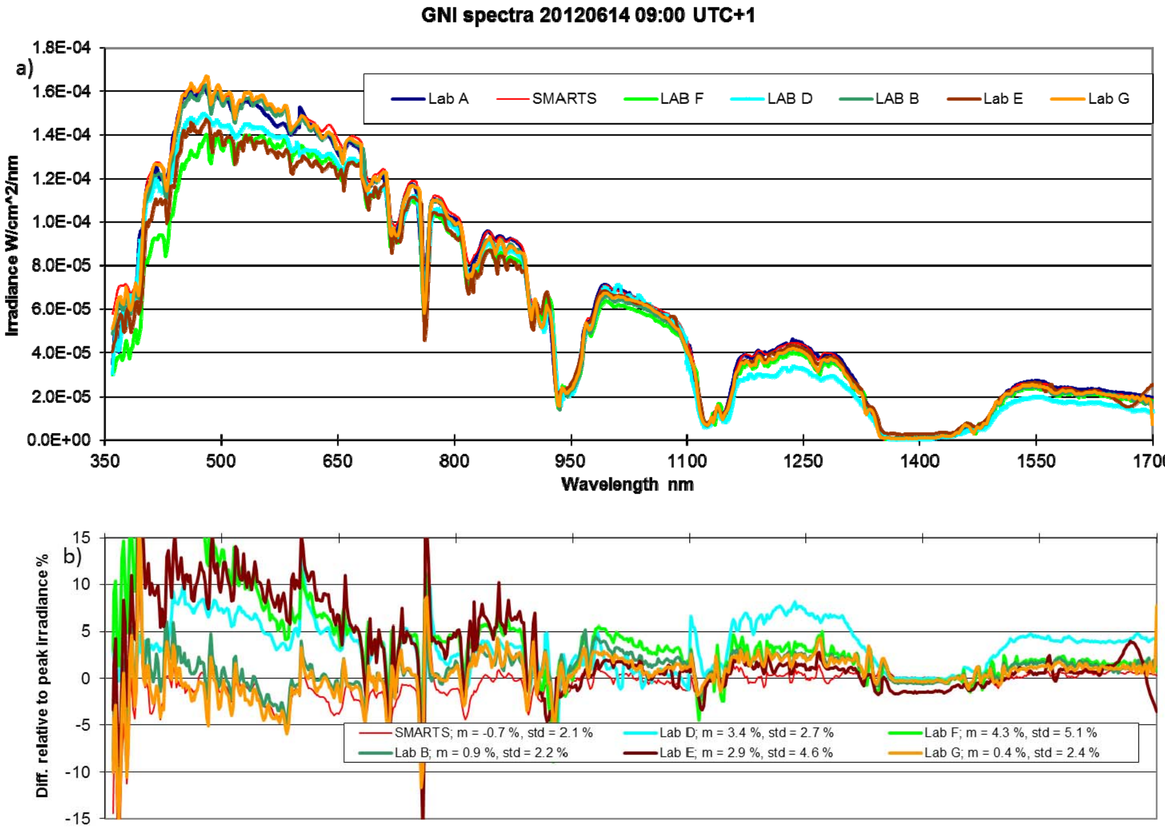


**Figure 2:** (a) Six GNI measured spectra plus spectrum obtained from the same time period by SMARTS code. (b) wavelength-by-wavelength difference with respect to the Lab A spectrum and normalized to its peak irradiance; average and standard deviation calculated over the interval 360-1700 nm are also reported.

The average difference values for the measured spectra reported in Figure 2 are all positive and lay in a band of ± 2% centred at 2.4% with associated standard deviations up to 5.1%. Three systems (Lab B, Lab D and Lab G) have most of their wavelength-by-wavelength difference values lying in a band of - 5% to + 10% while Lab E and Lab F data show larger differences. The larger wavelength-by-wavelength average differences found analyzing spectral DNI data respect to spectral GNI data may be partially explained by the non-uniform field of view among various instruments and by errors in pointing the systems. A further data analysis performed on the acquired solar spectra was to compare the irradiance obtained by integrating the measured spectra with the actual irradiance measured by cavity radiometers and pyranometers. Table 2 reports the average differences between GNI irradiance values, as calculated by integrating spectral irradiance graphs, and the corresponding measured irradiance values obtained by cavity radiometer plus diffused pyranometer data. Measured GNI data were suitably reduced to account for the different measuring bandwidth between spectroradiometers and broadband radiometers. Reported average values refer to 20 GNI spectra acquired during a half day measurement session. Values obtained running SMARTS for the same time at which measurements were made and using actual local input parameters (time, temperature, atmospheric pressure, relative humidity and terrain type) are also shown for consistency check.

**Table 2:** Average difference values, expressed in percent, between calculated and measured GNI irradiance for a group of approximately 20 spectra measured by each partner.

| Laboratory | Average difference % | Standard deviation % |
|---|---|---|
| Lab A | -0. 1 | 0.8 |
| Lab B | -2.7 | 0.3 |
| Lab D | -10.3 | 1.7 |
| Lab E | -6.8 | 0.5 |
| Lab F | -11.2 | 0.7 |
| Lab G | -1.5 | 0.2 |
| SMARTS | 1.4 | 0.5 |

All GNI values obtained integrating spectroradiometers' data are lower than the corresponding values measured by cavity plus shaded pyranometer. Differences range from almost zero to -11.2%; the low standard deviation values suggest systematic and uniform irradiance underestimation. A similar analysis was performed also on a set of spectral DNI acquisition. In this case the integral irradiance data were compared with the simultaneous values measured by the cavity radiometer, duly reduced to account for the different bandwidth. Figure 3 reports the time evolution for integrated vs. cavity-measured percentage difference during a four-hour DNI acquisition. Averages of data shown in Figure 3 are summarized in Table 3.

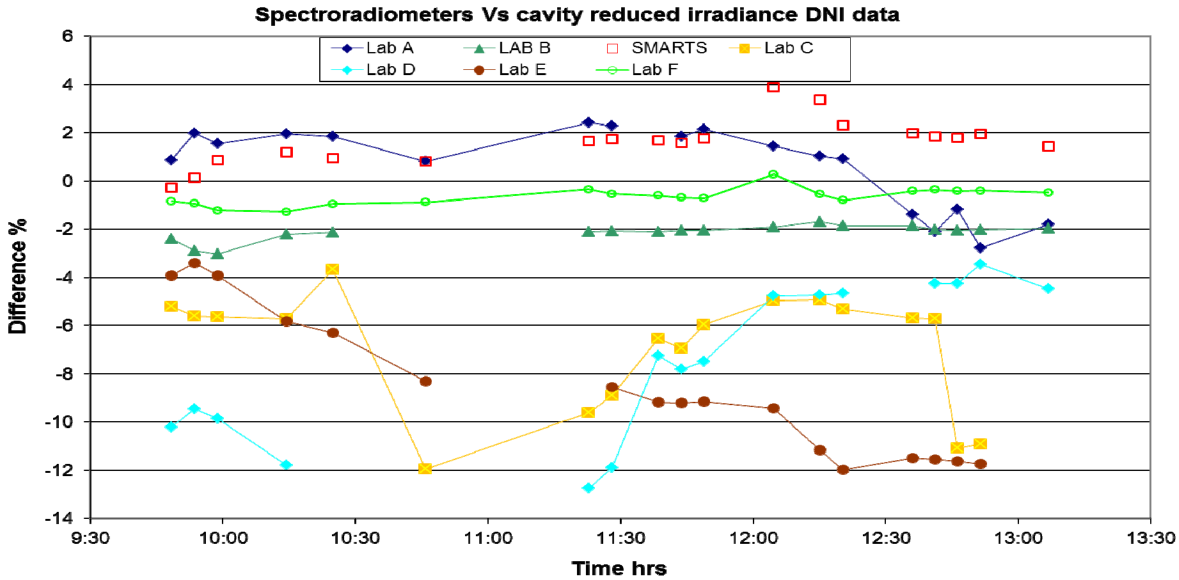


**Figure 3:** Evolution of the integrated vs. cavity measured irradiance data during a spectral DNI measurement session. Discontinuity in the line connecting data points highlights missing measurement points.

All but two laboratories show similar average difference values when measuring both GNI and DNI spectral irradiance. However, Table 3 data show larger standard deviation results as highlighted by the non-uniform trend of some plots in Figure 3.

**Table 3:** Average difference values, expressed in percent, between calculated and measured DNI irradiance.

| Laboratory | Average difference % | Standard deviation % |
|---|---|---|
| Lab A | 0.7 | 1.7 |
| Lab B | -2.1 | 0.3 |
| Lab C | -6.9 | 2.5 |
| Lab D | -7.4 | 3.2 |
| Lab E | -8.6 | 3.0 |
| Lab F | -0.6 | 0.4 |
| SMARTS | 1.6 | 1 |

## 4 IMPACT OF USING SPECTRA MEASURED BY DIFFERENT INSTRUMENTS ON PV DEVICE CALIBRATIONS

The calibration of a generic PV cell at standard test conditions (STC) entails the correction of its measured short circuit current ($I_{sc}$) from the actual irradiance, temperature and spectrum data to 1000 W/m$^2$, 25 °C and AM1.5 standard spectrum, respectively. The correction to AM1.5 standard spectrum is performed by applying to the measured $I_{sc}$, a spectral mismatch correction factor (SMM) described in equation (1).

$$SMM = \frac{\int SR_{dut}(\lambda)E_{AM1.5}(\lambda)d\lambda}{\int SR_{dut}(\lambda)E_{meas}(\lambda)d\lambda} \frac{\int E_{meas}(\lambda)d\lambda}{\int E_{AM1.5}(\lambda)d\lambda} \quad (1)$$

Where: $SR_{dut}(\lambda)$ is the spectral responsivity of the considered device, and $E_{AM1.5}(\lambda)$ and $E_{meas}(\lambda)$ are the spectral irradiances of Air Mass 1.5 standard spectrum and of measured spectrum, respectively. The SMM correction factor accounts for the difference between the actual spectrum under which the calibration was performed and the reference AM1.5 spectrum [7]. During the spectroradiometers comparison a set of Iso-Type cells, whose spectral response is shown in figure 4, were calibrated applying SMM values calculated from the DNI spectra simultaneously measured by each partner. The voltages measured across each cell's shunt were previously converted to Isc and, then, linearly corrected to 1000 W/m$^2$ using irradiance data by a cavity radiometer. The cells calibration values obtained applying different SMM correction factors derived from simultaneously measured spectra can give also a figure of calibration equivalence among laboratories. Table 4 summarizes the average calibration values obtained on each component cell during, approximately, half day of measurements. Calibration values from all partners lay in a band of ±7%, ±1% and ±13.5% for Top, Middle and Bottom cell, respectively. Four out of six laboratories (Labs A, B, E and F) show calibration values in agreement to each other within ±4%, ±1% and ±7% for Top, Middle and Bottom cell, respectively.

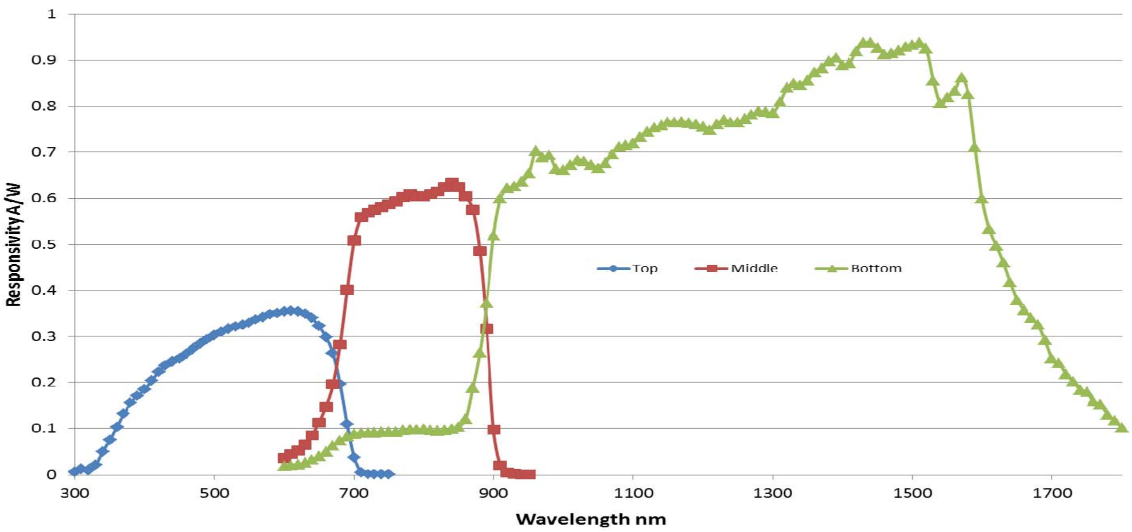


**Figure 4:** Spectral responsivity of the Iso-type cells used in the calibration exercise.

**Table 4:** Average of the calibration values ($I_{sc}$ values corrected at STC) for 3 Iso-type cells applying spectral mismatch correction factors derived from simultaneously measured DNI spectra.

| | ***Cal Value Top mA*** | *Std dev %* | ***Cal Value Middle mA*** | *Std dev %* | ***Cal Value Bottom mA*** | *Std dev %* |
|---|---|---|---|---|---|---|
| **Lab A** | 1.46 | 1.25 | 1.43 | 0.66 | 2.53 | 1.48 |
| **Lab B** | 1.40 | 0.27 | 1.45 | 0.29 | 2.68 | 0.15 |
| **Lab C** | 1.33 | 3.08 | 1.41 | 2.57 | 2.97 | 7.95 |
| **Lab D** | 1.53 | 1.91 | 1.46 | 2.3 | 2.24 | 4.53 |
| **Lab E** | 1.35 | 2.11 | 1.42 | 1.18 | 2.90 | 4.59 |
| **Lab F** | 1.41 | 0.30 | 1.45 | 0.32 | 2.65 | 0.26 |

These results reflect the differences in the shape of the measured spectra within the responsivity band of the considered cell. Looking at Figure 1, one of the measurements used for the calibration exercise, the wavelength interval corresponding to the responsivity of the middle cell (650 - 900 nm) shows lower data spread than in the other two intervals.

## 5 CONCLUSION AND DISCUSSION

An intercomparison of spectroradiometers for global and direct normal incidence irradiance in the visible and near infrared spectral regions, together with the assessment of the impact its results may have on the spectral mismatch calculation of a triple-junction photovoltaic device, were performed. Six European scientific laboratories and a Japanese industrial partner were involved in the intercomparison for a total of seven spectroradiometer systems covering the wavelength range from 360 to 1700 nm. Due to the different technologies of the involved instruments specific timing and measurement procedure, and irradiance stability criteria have been developed in order to make meaningful data comparison. From preliminary analysis of DNI measurements, average wavelength-by-wavelength percentage spectra difference normalized to peak spectral irradiance may be as high as 5.9%. The same analysis on GNI spectra shows a maximum average value of 4.3%. DNI irradiance data, calculated by integrating the spectra curves, and compared to DNI irradiance values measured by cavity radiometer show average differences ranging from + 0.7% to - 8.6%. Cavity measured irradiance values were corrected to account for spectroradiometers' narrower bandwidth. A set of Iso-Type cell were calibrated during the intercomparison and the spectral mismatch factors derived from the measured spectra were used for the Isc correction at STC. The spread of the calibration values for the four laboratories with lower standard uncertainties was found to be within ±4%, ±1% and ±7% for Top, Middle and Bottom cell, respectively. These results are a figure of interlaboratory calibration equivalence and are an experimental confirmation of previously performed simulations analysing the first spectroradiometers comparison campaign results [3].

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