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Spectroradiometer comparison under outdoor direct normal irradiance and indoor high-power AM0-like conditions

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ABSTRACT: Intercomparisons of primary instruments are of paramount importance to guarantee reproducibility and equivalence of calibration and are expressly required for laboratories applying the quality scheme outlined in IEC/ISO 17025 standard. The correct and reliable measurement of the spectral content of the used light source(s) is one of the main tasks in the process of a generic photovoltaic (PV) device calibration; this requirement has become more and more important since the technology biodiversity has increased in the PV world. The two afore mentioned issues were among the main driving forces to establish a network of European and International PV laboratories and industries willing to share good practices in spectroradiometric calibration and measurements, and to periodically check their equivalence-of-result in measuring the spectral content of the sun or of solar simulators. This paper will report on the preliminary results from a spectroradiometers intercomparison performed measuring solar direct normal incidence spectral irradiance and global normal incidence spectral irradiance under an indoor high-power AM0-like source.

Keywords: Photovoltaics, Calibration, Spectroradiometers, Solar Radiation

1 INTRODUCTION

Photovoltaic energy is becoming a key factor for the decarbonisation of the power sector in order to comply with the goal of limiting the average global temperature rising to 1.5°C, as acknowledged in the Paris Agreement.

The large worldwide investments in PV need to be supported by reliable and accurate reference measurement and calibration systems. Moreover, the increased presence on the market of PV modules based on diversified technologies represents a new and stringent challenge for the research institutions to deliver accurate and reliable data under changing technological scenarios.

The characterization and calibration of a generic PV device entails the knowledge of the spectral content of the light source, natural or synthetic, used to perform these tasks and is becoming more and more a key factor due to the technological ‘biodiversity’. SI-traceable, reliable, accurate, and equivalent calibration were among the main driving forces to establish a network of European and International PV laboratories and industries willing to share good practices in spectroradiometric calibration and measurements. The participating laboratories, industries periodically check their equivalence-of-result in measuring the spectral content of the sun or of solar simulators daily used in photovoltaics. Moreover, for laboratories with accreditation according to IEC/ISO 17025 standard [1], intercomparisons and round robin exercises are an implementation of the performance-based quality system scheme.

This paper will report on the preliminary results from a spectroradiometers intercomparison performed measuring solar direct normal incidence (DNI) spectral irradiance and global normal incidence (GNI) spectral irradiance using an indoor high-power AM0-like source

2 EXPERIMENTAL SET UP AND APPROACH

2.1 Location, Institutions and instruments involved

The intercomparisons took place at the SPASOLAB laboratory of the Instituto Nacional de Técnica Aerospacial, Torrejon de Ardoz, España, from the 4th to the 8th of June 2018. Eight European Institutions participated with their instruments. The spectroradiometers involved were all but two single grating, CCD-based polychromators; the remaining two were filter-radiometer based. In this last case the output spectra are mathematically inferred from the absolute irradiance measured by six c-Si filter radiometers at different wavelengths plus the measured local pressure and temperature. In this paper preliminary data from seven Institutions will be presented. Some instruments were equipped with removable collimating tubes, allowing the spectroradiometer to measure either GNI or DNI; remaining instruments could only measure GNI or only DNI.

Participating instruments were previously calibrated, either in-house or by an external calibration laboratory, by the owning Institution in order to check with this exercise the entire measurement traceability chain.

Table I summarizes data about institutions involved, instruments type, measurement wavelength range and calibration route.

Table I: Summary of the characteristics of the spectroradiometers involved in the intercomparison. Spectrometer brand and model, measuring wavelength interval and calibration method with calibration reference chain are reported. All but two instruments were CCD-based polychromators; the remaining two instruments were filter radiometer-based.

Institution	Spectroradiometers brand, model	Calibration chain	Measuring wavelength nm
JRC	EKO 701, 710, 712; collimating tube for direct irradiance	In-house, calibrated standard lamp	300-1700
UniRadboud	1 Spectroradiometer MS-711; collimating tube for direct irradiance	Manufacturer	300-1100
INTA	Instrument System 320D GNI only	In-house, calibrated standard lamp	300-1550
ENEA	StellarNet EPP2000Vis, EPP2000NIR; collimating tube for direct irradiance	Manufacturer	280-1700
RSE	SolarSIM-D2 DNI only (filter radiometer based)	Manufacturer	280-4000
DTU	EKO MS711 DNI only	Manufacturer	300-1100
CEA LITEN	Avantes AvaSpec-ULS2048CL-EVO (CMOS) Avantes AvaSpec-NIR256-1.7	In-house, calibrated standard lamp	300-1700
UniCyprus	SolarSIM-D2 DNI only (filter radiometer based)	Manufacturer	300-4000

2.2 Set up and approach

The hosting laboratory gave us the possibility of using a multi lamp custom made AM0-like high intensity solar simulator, denominated EP7, [2] capable to deliver more than 1300 W/m2 irradiance on the 20x20 cm test plane and the use of a large payload tracker for outdoor measurements.

Unfortunately, the bad weather conditions during the exercise limited the outdoor measurements to few hours. Moreover, the instrument limitations, made impossible to check all the instruments under the same light source; in specific two instruments could measure only solar DNI spectral irradiance, three instruments could measure only GNI spectral irradiance under high intensity AM0-like solar simulator, and two instruments could measure both solar DNI spectral irradiance and the simulator GNI spectral irradiance.

The measurement series obtained using the high intensity solar simulator were made positioning each instrument one at a time under the light source allowing a time window of about twenty minutes for alignment and measurements. Careful alignment allowed to maintain the reproducibility of the instruments entrance optics positioning to within ± 0.5 cm in the 3-axes coordinates. The spectra measured in the assigned time window were averaged and, then, the average spectrum compared with those measured by other participants. Compared spectra were the average of three to five measurements, allowing check of spectroradiometer short-term stability. Checks for simulator spectra- and intensity- stability were made by the reference spectroradiometers three to four times during the measurement days. Figure 1 shows the set-up and the positioning of one of the spectroradiometers under the AM0-like high intensity solar simulator.

The outdoor DNI spectral irradiance measurements were made positioning involved spectroradiometers on suitable solar trackers able to maintain a tracking accuracy of ± 0.5 °, synchronizing the measurement timing to within ± 5 s and taking one measurement every minute. Depending on each instrument sensitivity, the acquisition time for one spectrum could vary from 30 ms to 5 s. A post processing check for solar irradiance stability, based on the output of a set of pyrheliometers running in parallel, allowed to select spectra taken when the irradiance stability was within ± 1 %. Spectra satisfying stability requirements were then analyzed and compared.

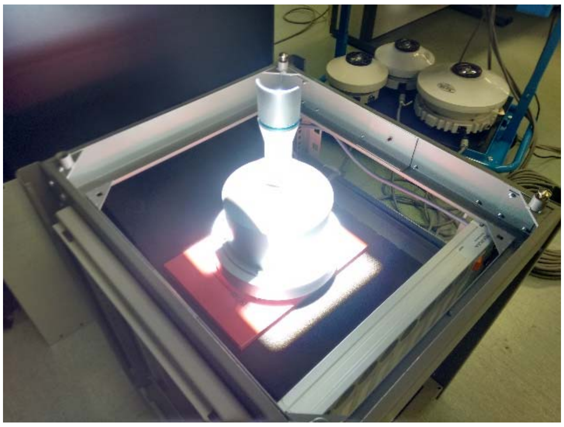

Figure 1: One of the spectroradiometers involved in the intercomparisons mounted for measurements under the high irradiance AM0-like solar simulator.

2.3 Analysis and comparison strategies applied.

Several approaches to data analysis were applied during past intercomparisons [3-5]. This year we were facing two different scenarios deriving from outdoor and indoor measurements, each requiring different approaches.

The outdoor measurements were performed almost at the same time for the four considered instruments, being the time difference contained within ± 5 s. The further irradiance stability check performed with the pyrheliometers minimized effects due to solar irradiance instability. For this case two usual spectra comparison were applied: wavelength-by-wavelength (W-by-W) comparison and wavelength bands subdivision comparison. W-by-W comparison gives information about the differences of the considered spectrum vs the reference one relative to its peak irradiance. It is a figure of merit that considers both spectrum shape and absolute spectral irradiance level effects.

The wavelength bands subdivision comparison is a method derived from the ISO/IEC 60904-9 standard [6]. Each considered spectrum is subdivided in 100 or 200 nm wide wavelength bands; the irradiance level in each band, expressed in percent of the total irradiance, is calculated and compared to the result obtained for the corresponding wavelength band of the reference spectrum. A first analyses covered all instruments measuring outdoor DNI spectral irradiance. The considered wavelength range, 400 to 1100 nm, was subdivided in five 100 nm wide bands (400 to 900 nm), plus one 200 nm wide band (900 to 1100 nm).

The difference of the integrated relative irradiance in each band between reference and participant is then analyzed using the performance statistics En number [7] as defined in equation (1).

$$En = \frac{x-X}{\sqrt{{U_{lab}}^2+{U_{ref}}^2}} \qquad (1)$$

X, x are the percent spectral contents in the considered band for participant and reference laboratory, respectively. U_{lab}, U_{ref} are the combined expanded uncertainties for participant and reference laboratory, respectively.

The use of En number entails the establishment of the acceptance limits ± 1: inside these limits the differences are coherent with the declared uncertainty levels.

The analyses of the relative spectral contents in several wavelength bands is focused to highlight spectral shape differences. The spectral content of the light source is a key parameter for calculating the spectral mismatch (MM) factor in PV device calibration [8].

The participants indoor spectra measurements were necessarily performed one after the other and, therefore, is likely a light source drift occurs along the 7 to 8 hours needed to cycle all instruments under the simulator. The solar simulator irradiance time drift was evaluated setting the reference spectroradiometer to measure the simulator spectral irradiance three times during a measurement session: at the beginning, in the middle and at the end of it. Spectra comparison will be performed vs the reference spectrum acquired closest in time.

3 RESULTS AND DISCUSSION

3.1 Outdoor DNI spectral measurements.

Outdoor DNI spectral measurements were performed for a session of seventy minutes approximately only due to bad weather conditions with consequent irradiance instability.

An example of the Wv-by-Wv comparison method is shown in Figure 2 and Figure 3. Because of a non-disclosure agreement, results are reported in an anonymous way. Reported spectra were measured at the beginning and at the end of the measurement session. In Figure 2 and Figure 3 the upper plots show the spectra as they were acquired, while lower plots show the results of the calculation of the Wv-by-Wv differences relative to reference spectrum peak irradiance (Lab A). In both figures the Wv-by-Wv differences are mostly contained in a ± 5% band, some values are laying in the ± 10% band and few others are exceeding these limits. No evidence of drift within the 1-h measurement session is shown.

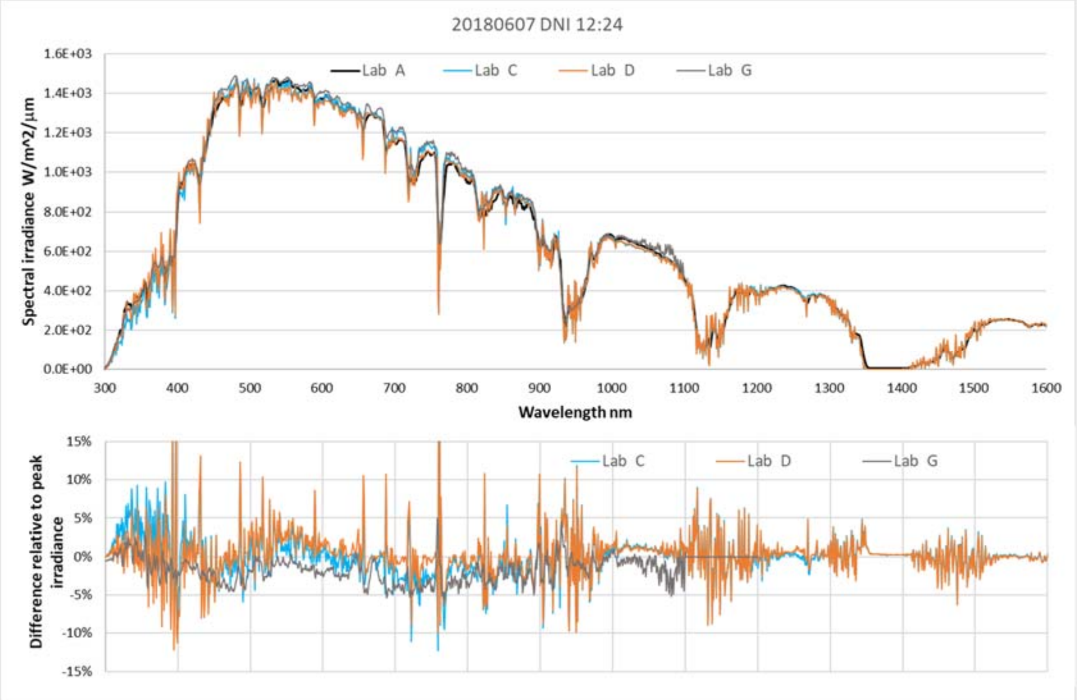

Figure 2: A DNI solar spectrum acquired at the beginning of the measurement session by four spectroradiometers participating to the comparison (upper plot); Wavelength by wavelength difference with reference spectrum (Lab A) and relative to peak irradiance (lower plot). Average difference values and associated standard deviations are also reported for each spectrum.

Lower plots in both Figure 1 and Figure 2 report also the average Wv-by-Wv difference and the associated standard deviation as computed in the instrument measuring wavelength range. Although very low average values result for two instruments (Lab C and Lab D), the larger associated standard deviation values denote fluctuating trends. Lab G data in both figures show a slight constant spectral irradiance over estimation from 350 nm onwards; below this limit a slight underestimation is shown. Lab C and Lab D data are more equally distributed around the median line of the lower plots, exhibiting a slight spectral irradiance underestimation up to approximately 400 nm, a weaving trend up to 600 nm, a slight overestimation up to 1000 nm and very good agreement with reference spectrum above. Lab C and Lab D instruments have finer data point interval and narrower spectral resolution, being able to better resolve narrow atmospheric absorption peaks. These characteristics, however, may produce comparison artefacts when instruments with coarse spectral resolution are involved as is the case in this intercomparisons; higher difference peaks shown in both figures may be ascribed to non-homogeneous spectral resolution among instruments (e.g. at 395 nm and at 760 nm).

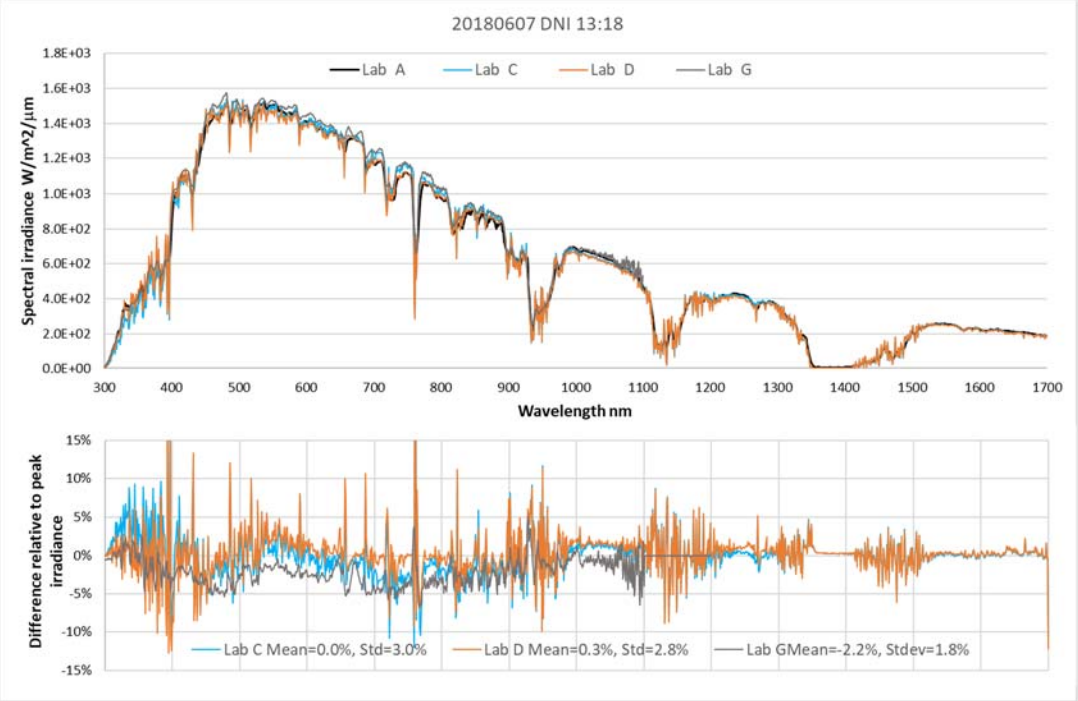

Figure 3: A DNI solar spectrum acquired at the end of the measurement session by four spectroradiometers participating to the comparison (upper plot); Wavelength by wavelength difference with reference spectrum (Lab A) and relative to peak irradiance (lower plot). Average difference values and associated standard deviations are also reported for each spectrum.

The wavelength band subdivision method was applied to the forty-eight spectra acquired during the outdoor DNI spectral measurement session in the 400 to 1100 nm and 300 to 1500 nm regions; in this preliminary paper only results for the 400 to 1100 nm region will be reported.

Table II reports, for the analyzed Wv bands, the average of the percent spectral content for the reference (A) and the participant laboratories (C, D and G). Percent spectral content values for the ASTM G173-03 AM1.5 direct spectrum are also reported for reference [9].

Table II: Average percent spectral content values of the measured DNI spectra and tabulated AM1.5D spectra in the wavelength regions from 400 to 1100 nm

Wv band nm	LabA %	LabC %	LabD %	LabG %	Am 1.5 D
400-500	17.9	18.0	18.2	18.0	20.7
500-600	20.6	20.3	20.3	20.3	20.3
600-700	18.6	18.6	18.5	18.6	17.5
700-800	14.7	15.0	14.8	14.9	14.0
800-900	12.1	12.4	12.3	12.2	11.1
900-1100	16.2	15.8	15.8	16.0	16.3

The En number proficiency test was then applied to the spectral content percent differences between spectra measured by reference and participants. Values for expanded uncertainties referred in equation (1) as U_{lab}, U_{ref} were set to 5% and 3%, respectively.

Figure (4) summarizes results of the proficiency test.

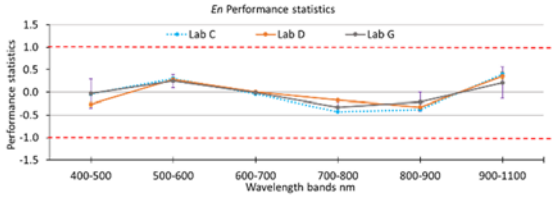

Figure 4: *En* performance statistics results as applied to the average differences in percent spectral content in selected Wv bands between spectra measured by reference and other participants spectroradiometers. Error bars represent the standard deviation of the average *En* values calculated on forty-eight measured spectra. Dashed red lines define the limits within which the differences are coherent with the declared uncertainties.

All points reported in Figure 4 lay well within the ± 1 acceptance limits; this means all differences among considered instruments are coherent with the declared measurement uncertainties. Error bars in Figure 4 represent the standard deviation associated to the average *En* numbers calculated on forty-eight measured spectra for each instrument. This good results may be different when extending the analysis to a wider Wv range (e.g. 300 to 1500 nm) due to, for instance, an increased sensitivity to internal stray light below 400 nm.

3.2 Indoor GNI measurements

For indoor comparison a high intensity solar simulator, specifically designed for space cell characterization and calibration, was used. Simulator irradiance, as integrated in the measurement wavelength range, was measured to be between 1315 and 1380 W/m^2. All shown spectra were acquired by fixed-grating CCD-based instruments with diffuser cosine correctors as entrance optics. The upper graph in Figure 5, shows spectra measured during a 1-day measurement session; it is evident an almost 5 % mid-day drift (Lab A 3rd spectrum) in the simulator intensity for the 400 to 750 nm wavelength band. Therefore, the Wv-by-Wv difference values reported in the lower plot, were computed vs the reference spectrum measured at the closest possible time. Saturation is also evident for Lab B at measuring the high irradiance level of the simulator Xe lamp. However, Lab B instrument gave coherent data elsewhere.

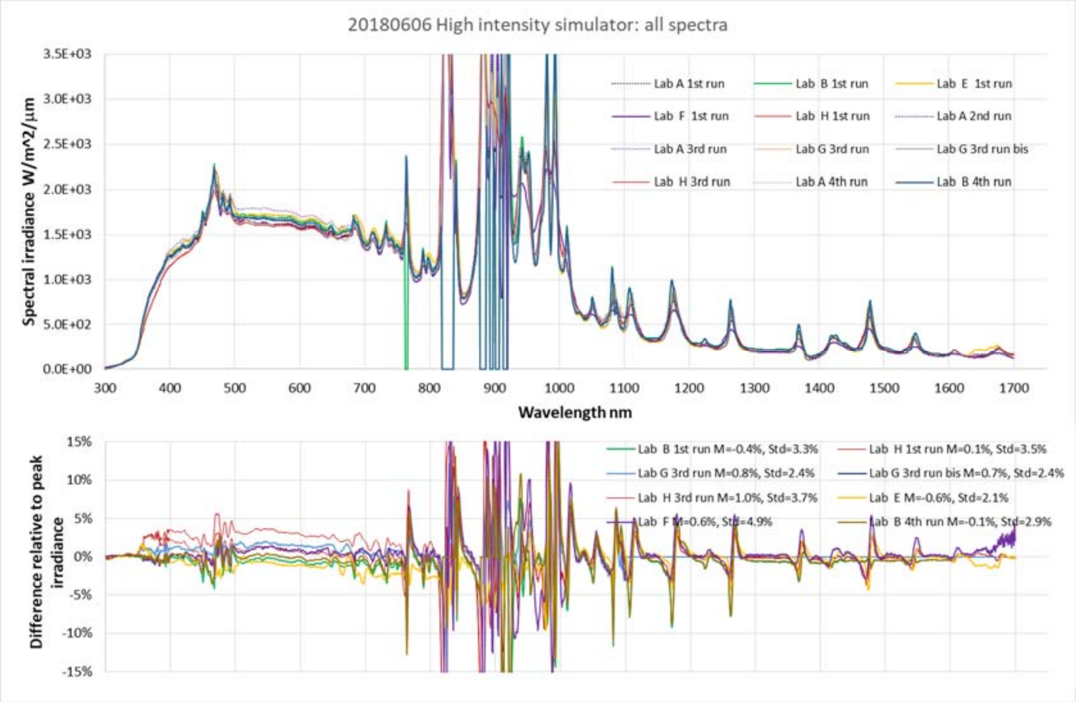

Figure 5: Upper graph shows spectra sequentially acquired by six participating spectroradiometers. Lower graph shows wavelength-by-wavelength difference to reference lab spectrum and relative to its peak irradiance. Mean difference values computed over the reported wavelengths range together with associated standard deviation are also reported.

In the Wv range from 300 to 800 nm and from 1000 to 1650 nm most of the spectra differences relative to peak irradiance are contained in a 5% peak-to-peak band. Some outlier difference values are contained in a ± 5% region and are concentrated in the Xe lamp emission peaks at 450-500 nm and 765 nm.

In the wavelength region from 800 to 1000 nm it is difficult to extract useful information due to very high intensity Xe lamp emission lines; in this portion of the spectrum a slight wavelength misalignment, a different spectral bandwidth resolution or a non-linearity effect may result in very high difference values.

Average Wv-by-Wv difference values as integrated in the instrument Wv measuring range lay in the -0.6% to +1% band with associated standard deviation ranging from 2.1% to 4.9%. Standard deviation values larger than respective mean values highlight uneven differences.

In general, the GNI spectral irradiance measurements performed in the laboratory controlled environment showed a somewhat better agreement than the DNI spectral irradiance measurements acquired in outdoor condition.

4 CONCLUSIONS

A spectroradiometers intercomparisons using the sun and a high-intensity AM0-like solar simulator as common measurement sources was organized at Instituto Nacional de Técnica Aerospacial, Torrejon de Ardoz, España, from the 4th to the 8th of June 2018.

Eight systems from European Institutions participated and preliminary results from seven systems were here presented. The two light sources available allowed to check instruments in different measurement and irradiance conditions; irradiance levels were 870 W/m^2 and 1340 W/m^2 approximately for outdoor and indoor measurements, respectively.

The four instruments measuring outdoor spectral DNI irradiance showed differences mostly contained in a ± 5% band with few values exceeding the ± 10% band. No evidence of measurement drift was found during the seventy minutes measurement session.

The relative irradiance contents of each spectra in selected wavelength bands were, then, calculated and compared vs the reference spectrum data; the results were analyzed using the *En* number proficiency test, all resulting coherent with the declared measurement uncertainties.

Indoor spectral GNI measurements were performed by six spectroradiometric systems, each installed one at a time under the light source and paying special care to 3-D axes positioning reproducibility.

In the Wv range from 300 to 800 nm and from 1000 to 1650 nm most of the spectra differences relative to peak irradiance are contained in a 5% peak-to-peak band, while the region from 800 to 1000 nm was affected by artefacts.

The Wv-by-Wv averaged difference values ranged from -0.6% to +1% with associated standard deviation ranging from 2.1% to 4.9%.

One system showed systematic saturation in the Wv region where the simulator Xe light emits higher intensity peaks. However, the CCD seemed not to be influenced by the saturation in the remaining part of the spectrum, delivering coherent results.

To this regard, is worth noticing the intercomparisons can be a useful exercise to build up knowledge on limitations and results quality confidence when instruments are exposed to extreme conditions, and how to tackle unusual contexts.

Spectra measured in the controlled laboratory environment showed a slight better agreement than in outdoor environment.

Further analysis on a larger data set are under way extending the wavelength band subdivision approach to DNI measurement downward to 300 nm and upward to 1500 nm. In this extended wavelength interval uncertainties effects deriving, for instance, from internal stray light and lower spectral irradiance levels play a major role.

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