Indian Journal of Pure & Applied Physics
Vol. 61, April 2023, pp. 247-253
DOI: 10.56042/ijpap.v61i4.68963

Radiometric Traceability for Pyranometer Calibration Based on High Flux LEDs and Reference Detector

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Received 24 November 2022; accepted 28 March 2023

This article aims to establish a new system for pyranometer calibration traceable to the radiometric chain. Different spectrum high flux LEDs have been used as tunable irradiance sources. The calibration procedure, uncertainty budget, and traceability chain of the solar irradiance measurements are presented. Additionally, the results were evaluated using a reference pyranometer, calibrated traceable to radiometric traceability and World Radiometric Reference (WRR).

The uncertainty values are also estimated to be around 1.19 % (k = 2) for LEDs-based pyranometer-pyranometer calibration (WRR traceability), and about 0.68 % (k = 2) for reference standard radiometer based (Radiometric traceability). The deviation between the reference pyranometer and the pyranometer under test was about 0.8% using LED at 655nm for irradiance of 500 W/m^2.The sensitivity results have been evaluated by reference standard pyranometer traceable to WRR using a xenon lamp as a solar source, with a deviation of about 1 %.

Keywords: Pyranometer; Radiometer; WRR; Radiometric traceability

1 Introduction

Solar radiation can be measured by different methods and different instruments, the irradiance measurements are very important for different sectors, mainly for climate change and renewable energy. Additionally, solar radiation measurements are essential for weather forecasting, heating projects, and agriculture[1–5].

For solar photovoltaic energy, pyranometers are used to measure solar irradiance, monitor the solar panel's performance, and determine the expected output of the photovoltaic installation[6]. The solar spectrum and irradiance levels directly affect the electrical preference and power generated over the solar panel strings to calibrate the pyranometer or any solar radiation radiometer regularly because the pyranometer sensitivity can change or drift, this drift is caused due to day after day solar radiation exposure to the elements.

Solar radiation can be measured with pyranometers, pyrheliometers, pyro-electrics, or photo-detectors. The pyrheliometers are used to measure the Direct Normal Irradiance (DNI) and should be mounted on a solar tracker, while pyranometers are used to measure Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI) on the surface of the earth, or Plane-Of-Array (POA) irradiance. Pyranometer is used to measure solar irradiance which can be global or diffuse radiation from, the direct normal (beam) solar irradiance (DNI) is a part of the global irradiance. The irradiance measurement on the surface of the earth depends on many factors such as sky clouds, aerosol concentration, smog, and location.

The global horizontal irradiance (GHI) can be calculated as the following equation,

$$\text{GHI} = \text{DIF} + \text{DNI} \cos Z \qquad (1)$$

where Z is the sun’s zenith angle, DNI is the direct normal irradiance, and DIF is the diffuse horizontal irradiance.

The preference of the pyranometers depends on various factors and parameters, such as the linearity of the device, spectral response, temperature coefficient, tilt angle, directional response, and the calibration method.

The pyranometers can be classified into three classes according to ISO 9060, secondary standard, first or second class, or high quality, good quality, or moderate quality according to the World Meteorological Organization (WMO) classification. The class of the pyranometers can be defined as a sub-class, so, it can be such a pyranometer of class A with spectrally flat or class A with fast response type, and …*etc*[7].

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Choosing the pyranometer's class according to the measurement mode and application is very essential for accurate measurements, for example, using a spectrally flat pyranometer is very important for horizontally irradiance accurately not just under a clear sky, but also for general GHI or under partial or fully cloudy skies when you measure plane of the array[8].

The pyranometeractive element can be thermal (thermopile pyranometers) or silicon-based (PV) sensors. Thermopile Pyranometer has an almost constant and flat spectral response over the whole solar spectral range and measures the temperature difference between the receiving surface and the body. The thermopile pyranometers derive their signal from atemperature difference in the sensor element. In other words, a thermopile pyranometeris a simple thermometer of two different materials. This thermometer generates a signal in response to a temperature difference between the 'hot' and the'cold' side of the plate, the hot side is attached to the pyranometer body, while the cold side is coated with high-absorbing black paint. This isknown as the 'thermoelectric or See beck effect. While, silicon-based sensors have only responded to wavelengths below 300 nm to 1100 nm, and the spectral response within this interval is not uniform. The photodiode is a photovoltaic receiver below the diffuser that converts the incoming radiation into an electrical signal[8–10].

According to the pyranometer standards calibration procedures, the pyranometer can be calibrated based on indoor or outdoor methods, the indoor method hasan advantage over the outdoor[11], the calibration has to carry out at a normal incidence beam, which is the best condition for a directional response, and the ability to control the environmental conditions (condition complies with IEC Standard Test Conditions for solar energy testing (STC)) and weather change independent, thus, sensitivity change is directly traceable to sensor/coating degradation. Additionally, the outdoor calibration depends on the day of the year and the location.

In this research, we present a radiometric method traceable to the SI unit to calibrate the pyranometers, the system, the traceability chain, and the uncertainty budget discussed in detail. Additionally, the results had been compared to different pyranometers which were calibrated traceable to radiometric traceability, and the (WRR), which is located at the World Radiation Centre (WRC) in Davos, Switzerland.

Our new method is based on high flux LEDs with different spectrum bands, the sensitivity of the pyranometers had been measured at an irradiance of 500 W/m^2. The pyranometer sensitivity is temperature dependent, so it can be changed according to the ambient temperature, the traditional calibration method uses a traditional light source as a Halogen lamp which emits significant heat, thus, in our method, we eliminated this factor. Additionally, this research aims to enhance the accuracy and reduce the uncertainty in solar irradiance measurements by calibrating the pyranometer traceable to the SI unit based on different spectral bands and high flux LEDs.

2 System description and treatability chain

Currently, the pyranometer calibration procedure is carried out according to ISO 9847, which is traceable to the (WRR) maintained at the world radiation center in Davos, Switzerland, which represents the " primary standards " for solar irradiance measurements.

The irradiance measurement of the sunlight which is traceable to the WRR is measured with the Cavity Radiometers (CR), this cavity has a very broadband spectral responsivity over the solar spectrum. This cavity is used to calibrate the standard pyranometer or what is called " secondary standards".

However, radiometry laboratories at National Metrology Institute (NMI) around the world take on his shoulder to develop and establish the irradiance and radiance scale traceable to the cryogenic radiometer or blackbodies. Even though, their radiance of the solar radiation measurements was not considered under the scope of activity of the NMI. This had been leads to an evaluation of the primary standards for solar irradiance out from the scope of the International Committee on Weights and Measures(CIPM, Comité International des Poids et Mesures) (CIPM) and, in a certain form, out from the SI, to be under the wings of The International Meteorological Organization (IMO) and WMO[12]. But, according to the International Bureau of Weights and Measures (BIPM, Bureau International des Poids et Mesures) (BIPM), the primary standards scale must be maintained by NMIs, to solve this discrepancy, the Physikalisch-Meteorologisches Observatorium Davos (PMOD) (METAS (NMI in Switzerland)) reveals CMCs for solar irradiance (for pyranometers and pyrheliometers). Thus, PMOD/ World Radiation Center (WRC) is responsible for decimating the solar irradiance scale based on WRR to standard sensors in WMO regional and national radiometric centers.

In this paper, we try to get a new and direct method to calibrate the pyranometers directly to the SI unit as shown in Fig. 1.

The optical power was transferred using three element-based reflection trap detector and filter radiometer, then the absolute responsively (A/W) of the trap detector was linked to the absolute optical power measurements. By knowing the trap's aperture the irradiance can be defined. After that, the traceability of the irradiance measurement can be transferred to another trap detector or photodiode/radiometer. Thus, regarding our new proposed method, a monochromatic high flux LEDs can be used monochromatic high flux LEDs traceable to the cryogenic radiometer and SI system.

The new setup has consist of different spectral band high flux LEDs attached to the temperature controller as shown in Fig. 2, these LEDs have been driven by stabilized current driver. The system has a bunch of optical detectors, these detectors have been calibrated using a trap detector over NIS spectral responsively scale system.

The detectors are connected to dual channels 2936-R power meter from Newport, this power meter is compatible with a photodiode, thermopile, and

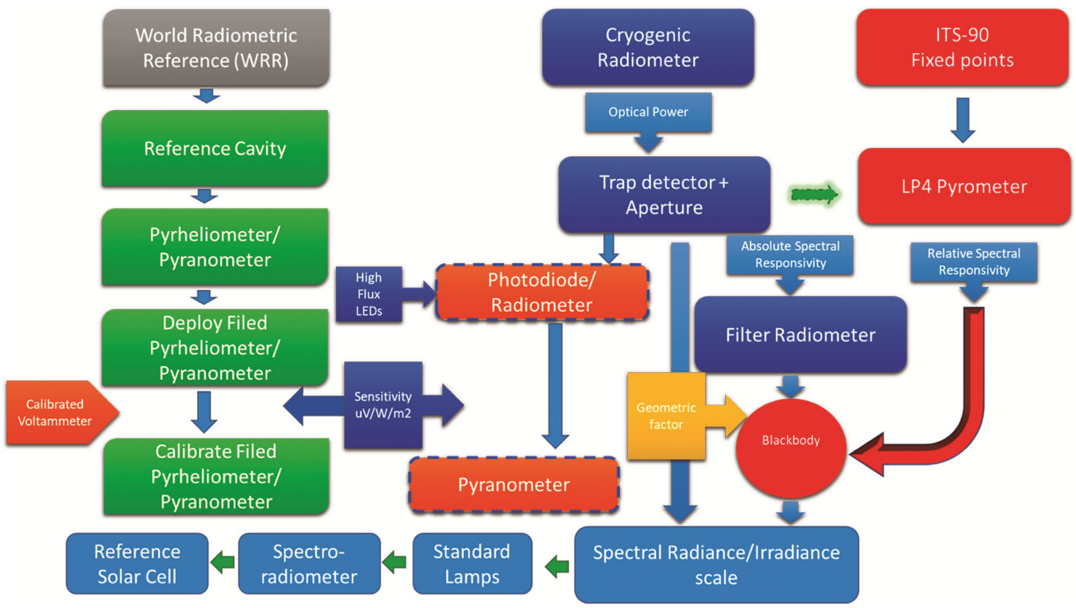

Fig. 1 — Irradiance measurement traceability chains.

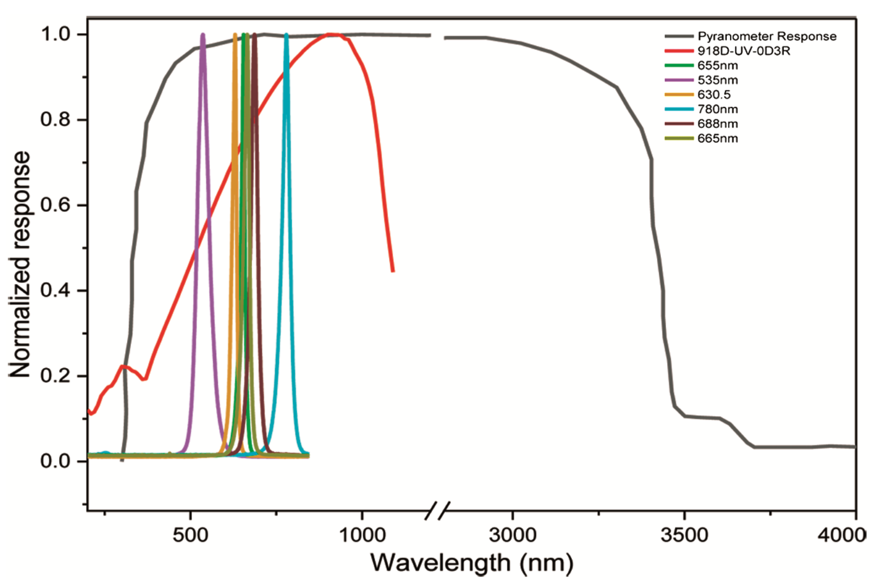

Fig. 2 — Spectral response of the pyranometer, the spectrum of high flux LEDs, and radiometer spectral responsivity.

pyroelectric sensors. (low-power (semiconductor) Family, high-power (thermopile) family, energy (pyroelectric) family, In GaAs cooled. The pyranometers and the reference detectors are mounted on a computerized rotational stage.

All control devices, signal acquisition, and radiometers are connected over customized LabVIEW software. In order to calculate the pyranometer sensitivity in microvolt per watt, we have used calibrated high accuracy Keithley 2010 digital multimeter, which is directly traceable to the National Institute of standards - NIS, the LEDs beam is over-filled on the reference detector getting the reference irradiance value, then the rotational stage has rotated to the pyranometer position getting the signal at 500 W/m^2, and the process was repeated at different irradiance levels.

To achieve stable output power, eliminate output power drop due to LED temperature rise, and improve LED performance, the LED has been mounted on a heat sink and attached thermal paste on the Thermoelectric cooling (TEC). The TEC temperature is controlled by Newport temperature Controller Model 350B.

To eliminate the stray light during the calibration, the light is restricted to a small cone around the two radiometers/pyranometer passing through an optical collimator. The collimated beam has to be over-filled for both the pyranometers, as shown in Fig. 3.

The field pyranometers are calibrated over the new setup by comparison of the pyranometer to a reference calibrated radiometer as shown in Fig. 3(b). The results of this comparison have been validated by calibrating the same pyranometers against a high-class standard pyranometer which is traceable to the WRR scheme, as shown in Fig. 3(c).

3 Results and uncertainty budget

3.1 Pyranometer Calibration based on Reference Radiometer

In order to calibrate the pyranometer to the reference radiometer (traceable to SI unit), a batch of different spectrum high flux LEDs has been used as a light

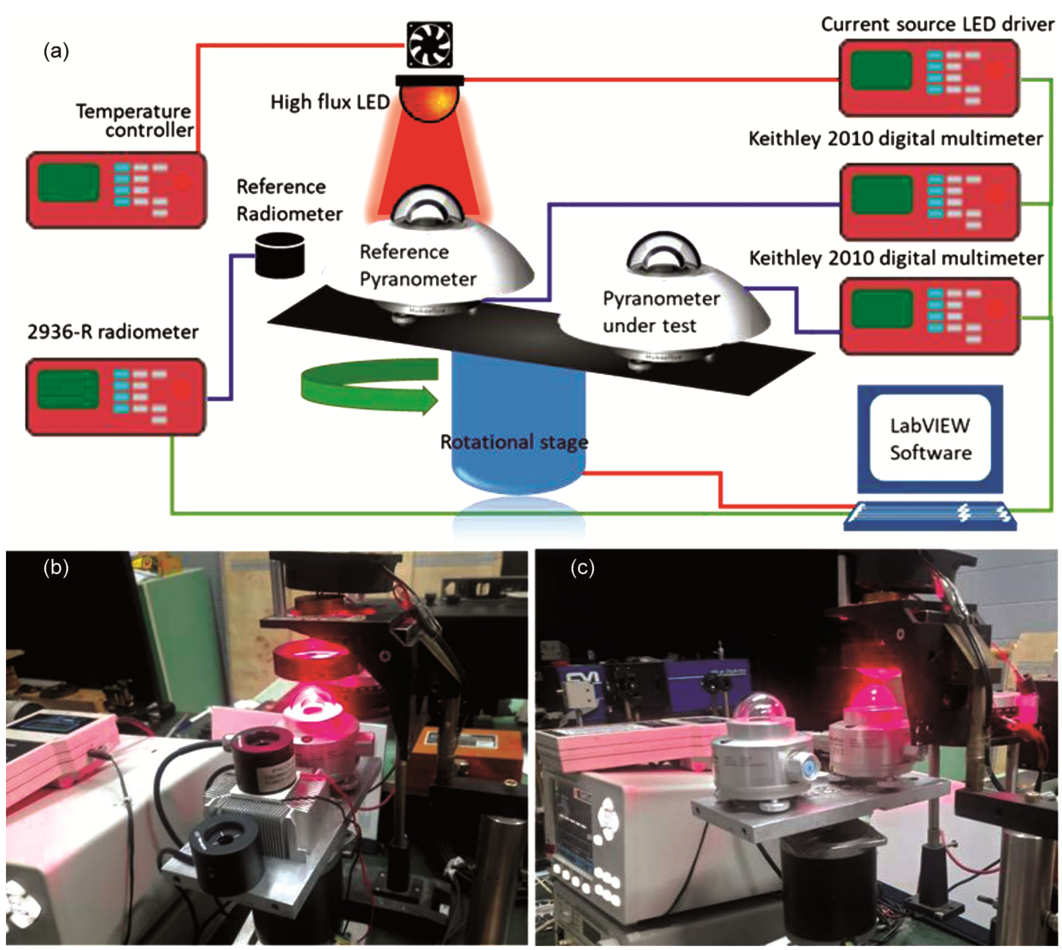

Fig. 3 — (a) The Schematic diagram of high flux LEDs pyranometer calibration set-up (b) Reference detector-based pyranometer calibration traceable to cryogenic radiometer, (c) pyranometer calibration based on reference pyranometer traceable to WRR.

source. Fig. 4, shows the comparison results of the Huksflux pyranometer which is calibrated traceable to WRR, and the reference radiometer (calibrated against trap detector), the results show that the deviation between the WRR and radiometric traceability pyranometer calibration is with the uncertainty budget, where the uncertainty budget related to the radiometer based is around half of WRR pyranometer based as shown in Fig. 5 and Table 1.

3.2Pyranometer calibration based on reference pyranometer

Figure 6, shows the pyranometer under test was calibrated against a calibrated first-class reference standard pyranometer (modelSR20-D2 from Huksflux thermal sensors) at irradiance levels from 500 to 1000 W/m².

The pyranometers are situated vertically and aligned to the optical axis of a normal irradiance of the light source. By changing the position of the standard calibrated reference pyranometer with the Pyranometer under test, the output signals of both pyranometers are recorded over LabVIEW software for 50 measurements, by knowing the reference

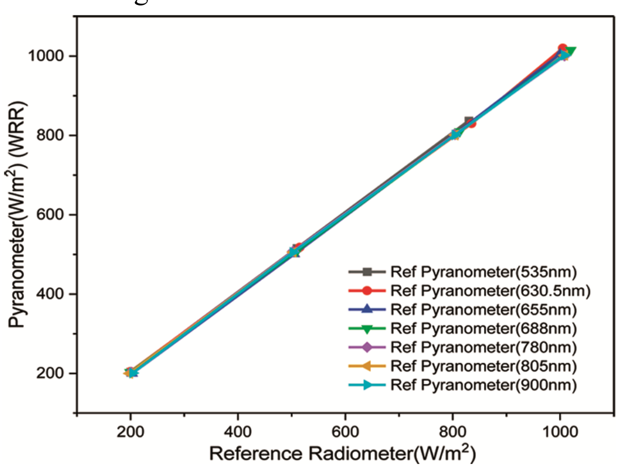

Fig. 4 — LED-based pyranometer calibration using reference radiometer traceable to SI units.

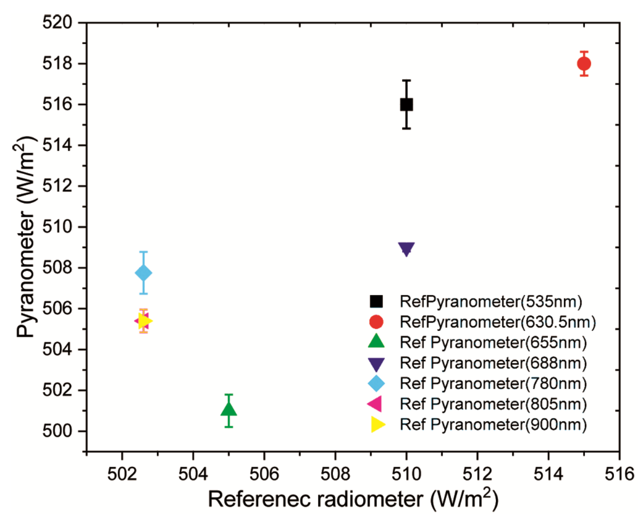

Fig. 5 — Pyranometer-reference radiometer calibration over high flux LEDs, the error bars indicate the irradiance errors.

Table 1 — Shows the uncertainty budget for high-flux LEDs based on pyranometer calibration.

Item	Distribution type	Uncertainty value(%)
Pyranometer-based		
Reference Pyranometer calibration certificate(11.72 μV/(W/m^2)±0.12	B	0.5119
Reference Pyranometer repeatability(Signal μV)	A	0.006
Tested Pyranometer signal repeatability(*,**)	A	0.01
Digital multimeter certificate (*,**) (2.5E-4 mV)	B	0.000125
LED uniformity(*,**)	B	0.02
LED stability(*,**)	A	0.04
Title response(*,**)	B	0.1
Temperature correction(*,**)	B	0.2
Non-linearity(*) (0.5% for the irradiance 100-1000W/m^2)	B	0.2
Cosine correction error(*)	B	0.05
Combined uncertainty		0.597
Expand uncertainty		1.19
Reference radiometer-based Pyranometer calibration(**)		
Reference radiometer calibration (wavelength dependent) (**)	B	0.25
Reference radiometer repeatability(**)	A	0.002
Reference radiometer nonlinearity(**)	B	0.0001
Combined uncertainty		0.338
Expand uncertainty		0.68

(*)The uncertainty item relates to the reference pyranometer.
(**)Uncertainty is related to the reference radiometer.

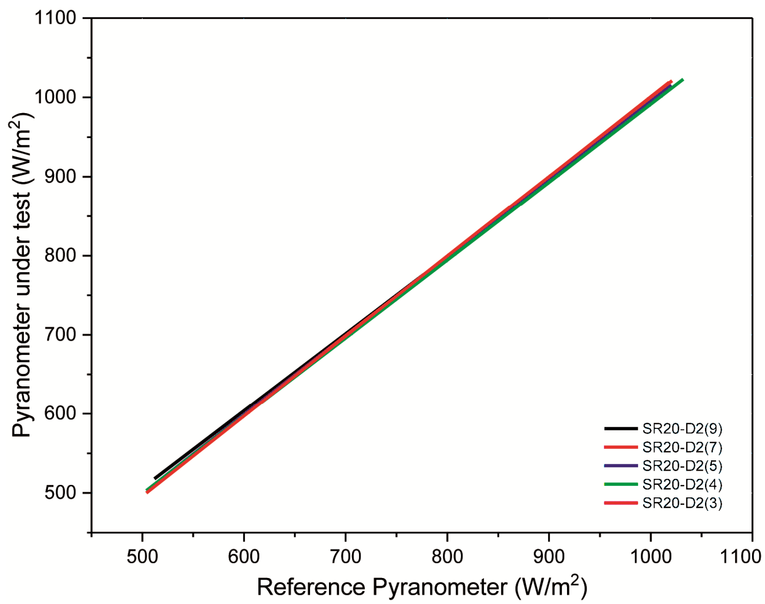

Fig. 6 — Comparison of five pyranometers against reference standard pyranometer traceable to WRR using high flux LED at 655 nm.

irradiance E_{Ref} and the signal of both pyranometers the unknown sensitivity of the pyranometer under test has calculated as the following equation:

$$S_{pyr} = \frac{Signal\ (\mu V)}{E_{ref}(\frac{W}{m^2})} \tag{2}$$

The percentage error between the reference pyranometer and the pyranometer under test was about 0.8%. The expanded uncertainty for the pyranometer sensitivity calculation was estimated to be around 1.2% for coverage factor $k = 2$, the main dominant parameter for this budget arising from the uncertainty of the reference pyranometer.

The uncertainty budget associated with the reference radiometer based is almost half that associated with the standard pyranometer, where the uncertainty was about 1.2 % and 0.68 % at (k = 2) for the reference pyranometer and reference radiometer based respectively.

4 Conclusions

Reference solar radiometers (pyranometers) were calibrated using a new method-based reference radiometer traceable to the radiometric metrology chain linked to the SI unit. This paper described the solar radiation irradiance measurement's traceability schemes, which are traceable to the WRR or based on the radiometric scheme which is directly linked by the SI unit through the Absolute Cryogenic Radiometer (ACR) and trap detector.

The new method is based on high-power LEDs as a monochromatic light source and uses a reference radiometer to transfer the radiometric traceability to measure the irradiance in W/m^2 and calibrate the pyranometers.

The uncertainty values are evaluated to be 1.19 % (k = 2) for LEDs-based pyranometer-pyranometer calibration, and about 0.68 % (k =2) for reference radiometer-pyranometer. The percentage error of deviation between the reference pyranometer and the pyranometer under test was about 0.8% for LED at 655nm.

Further measurements are carried out to confirm and evaluate the results of deviations for the radiometer and pyranometer based on the LEDs method and the result of calibration of a Pyranometer-pyranometerusing an AAA Xenon lamp as a solar simulator (attached with 1.5 air mass filter), the difference between the method was about 1%.

Finally, we can list some advantages and disadvantages and catch up on some limitations of the LEDs pyranometer calibration method. One of the main advantages of this method is that it is traceable to the SI unit, low uncertainty budget, and eliminates the traditional light source heat effect. On the other hand, the disadvantages of the proposed method are presenting some difficulties to find different LEDs covering all the spectrum range and at the same time with high flux intensities.

Acknowledgment

The author would like to acknowledge support from the National Institute of Standards (NIS)- Egypt, and we would like to thank Prof. Dr. Alaa Abd El-Megeed (head of the radiometry Lab.) for his support and guidance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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