Unexplored Indoors method for pyranometers calibration traceable to SI

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Abstract. A method to calibrate pyranometers with direct traceability to the International System of Units (SI) is presented, the method use an electrically calibrated pyroelectric detector (ECPR) as standard and offers numerous advantages over outdoors conventional calibration methods, such as reducing the uncertainty from the reference standard and the final uncertainty of the sensitivity coefficient of the calibrated pyranometer; the measurement uncertainty achieved with this method at normal irradiance is 2.1 % for a coverage factor k = 2 and could be reduce if one reduces the uncertainty level of the reference standard.

1. Introduction
According to various calibration standards reviewed in [1], traditionally the calibration of pyranometers with pyrheliometers as reference [2] and pyranometers with pyranometers as reference [3] have been carried out with instruments traceable to the radiometric scale of the world radiometric reference (WRR) [4], establishing the equivalence of the WRR scale and the SI radiometric scale by comparisons at the primary level [5] through cryogenic radiometer measurements as part of the SI scale and absolute cavity radiometers which are the reference of the WRR. However, direct measurement of pyranometers with conventional radiometric instruments of radiometric laboratory is possible with various inherent benefits from the indoors calibration and decreasing traceability chain to a primary standard and the improvement in the uncertainty of the experiment.

The actual indoor calibration systems of pyranometers, essentially make use of international standards recommendations [3] and the calibration is performed using pyranometers as reference standard and translation systems to ensure same source strength in the measurand and the reference. In these cases it is required a calibrated pyranometer which is referred to a pyrheliometer by outdoors calibration.

The main benefit of the indoors calibration of this kind of instruments is the reduction in time due to constant availability of the light source instead of the natural source and the control of all the related parameters in involve in the measurement.
2. The Pyranometers calibration method

In the definition of the measurand for the calibration of a pyranometer it is relevant to establish that the sensor of the instrument is a set of thermal detectors (thermopiles) arranged in series, the sensitivity to the intensity of the incident light is kept low and is not possible to measure with a laser beam smaller than the size of the area of the sensor due to high spatial dependence of the sensitivity or the uniformity in the response of the detector, therefore the average irradiance on the entire area of the detector is the magnitude to be compare to the standard and is expressed in average irradiance units during a calibration exercise.

The ECPR are radiometric reference standards, like pyranometers are based on thermal detector but pyroelectric principle instead of thermoelectric phenomena of a thermopile, the pyroelectric detector with proper conditioning is able to achieve high sensitivity through reduction systems noise of lock-in filters, and the is electrically calibrated for power measurements using coated sensor with high absorption efficiency of light [6]. The exposed area of an ECPR is defined by a metal mask that can be measured with low uncertainty for example with a non-contact dimensional measurement.

The measurement process using ECPR requires the use of a modulator of the input light to the sensor and the experimental setup use a chopper with 50 % average light exposure. The measurement scheme used is shown in Figure 1.

The proposed method is based on the comparison of measurements of the same irradiance source on both sensors. If a source with flat front of intensity distribution without divergence is consider, one would expect than the irradiance of the source is constant in both sensors regardless of the size of the illuminated sensor area covered by the source. However using a conventional filament source as tungsten-halogen type and MR16 or MR11 diffuser, a radial symmetric intensity distribution is expected at certain distance with a cover size area defined by the normal distance of the source to sensor plane.

Due to the radial intensity distribution of real filament source, it is necessary to correct for the difference in size between the sensitive areas of the pyranometer and ECPR used as a standard and the correction will have no effect when both sensors have the same area or the beam divergence light source were negligible.
For the propose measurement, the plane sensor of the pyranometer sensor must be aligned normal to the source and ideally coplanar to the plane of the reference standard sensor. In practice the alignment is achieved by aligning the reference base of the pyranometer and the plane of the ECPR with a flat mirror simulating sun direct exposure similar to outdoors solar tracker use. In this manner the calibration is carried out considering only direct radiation from the source and the same irradiance magnitude if both sensors have the same distance to the source.

2.1 Definition of the measurand

The pyranometer exposed to outdoor operation will have a response voltage $V$ usually expressed as follows:

$$ V = R(\theta) \left( I_{\text{direct}} \cos(\theta) + I_{\text{diffuse}} \right) $$

With $\theta$ as the solar zenith angle, $I_{\text{direct}}$ the direct irradiance, $I_{\text{diffuse}}$ the diffuse irradiance collected by the dome of the pyranometer in the measured orientation and $R(\theta)$ the sensitivity coefficient as a function of the orientation angle of the tool relative to the sun with units of $[\text{V m}^2 / \text{W}]$. However, in laboratory conditions, diffuse irradiance source is avoided and the plane of the pyranometer and the pattern should be normal to the maximum intensity of the source. So that the voltage response of the pyranometer can be defined according to the following expression:

$$ V = \int_0^b R(\theta_j) I_{\text{direct}} F(r)dr = I_{\text{direct}} \int_0^b R(\theta_j) F(r)dr + \int_0^b F(r)dr $$

With $I_{\text{direct}}$, the maximum irradiance at the center point of the distribution. $F(r)$ is the normalized spatial distribution function of the intensity.

In this case the Pyroelectric detector area is circular with radius $b$ larger than the ECPR area with detector radius $a$.

The response of the standard is similar and according to the following expression:

$$ I_{\text{standard}} = \int_0^b I_{\text{direct}} F(r)dr $$

The expressions (2) and (3) do not include any correction for spectral response because both sensors have a flat response in the visible and near infrared.

From (2) and (3) the response of the pyranometer irradiance at normal incidence is:

$$ V = \frac{\int_0^b F(r)dr - \int_0^b F(r'_j - r_j)dr}{\int_0^b F(r')dr} = \frac{V}{\int_0^b F(r')dr} $$

The spatial distribution function should be measured during the calibration process and its normalized value has slight variations with the change of the normal distance from the source to the plane of the detectors, such variations are due only to the uncertainty of the alignment process and the weak radial asymmetry of the source.

The determination of the irradiance on the plane of the detectors is based on the premise of having the same normal distance from the source to each of the planes of the detectors, which can be secured by the mechanical alignment of the edges of dome external reference of the pyranometer and known reference pyroelectric plane. The distance from source to detector plane is arbitrary and only limits the maximum possible intensity, which in the case of type 35W MR11 lamps at the evaluated distances reaches a maximum of 800 W/m2.

3. Results

With the method above described, the calibration for different distances from the source to the plane of the sensor of a pyranometer K & Z model CMP6 against ECPR pattern was performed. Both instruments were mounted and aligned in accordance with Figure 1.
The ECPR detector was centered with a laser of 3 mm in diameter and the laser was used to align the plane normal to the source sensor. Additionally the maximum intensity was located and verified that the irradiance distribution with reference to that point was symmetrical. The pyranometer was aligned in a plane normal to the source-detector line, using the reference base and the laser was focused into the same position, displacing the ECPR and centering the laser in the pyranometer using the mobile platform.

The alignment of the planes of the detectors was performed by reference to the outer edge of the pyranometer dome. The normal distance of the edge to the source was adjusted in the ECPR to ensure the same value of the source irradiance.

The measurement results for the different distances from the source are shown in Figure 3.

![Figure 3. Calibrated values as a function of distance from the source. The measurement uncertainty is also shown.](image)

The reproducibility achieved for a fixed length using the proposed method is better than 0.4 % and is the second contribution to the total uncertainty; the first is the calibration of the reference ECPR with an uncertainty less than 0.5 % both at a cover factor of k=1, the uncertainty of the standard includes the no linearity of the spectral response for the spectral emission of the lamp.

The combined uncertainty for the calibration values are shown in Table 1, calculated for a nominal irradiance of 500 W/m2 at the average distances of Figure 3, at lab temperature of 21 C.

The model used for the estimation of uncertainty is defined according to the expression 5 and is employed with the GUM methodology [7] to obtain the final estimate of the uncertainty indicated in expressions 6 and 7.

$$R_i = \frac{V \cdot K_s}{I_{\text{direct}} - I_{\text{direct}} F_s}$$

$$\mu_{R_i}^2 = \sum\left[ \frac{\partial R_i}{\partial x} \right]^2 \mu_x^2 + \mu_{\text{unc}}^2 + \mu_{\text{alt}}^2$$

$$\mu_{R_i}^2 = \left[ \frac{\mu_{I_{\text{direct}} - I_{\text{direct}} F_s}}{I_{\text{direct}} - I_{\text{direct}} F_s} \right]^2 + \left[ \frac{\mu_{V} V}{I_{\text{direct}} - I_{\text{direct}} F_s} \right]^2 + \left[ \frac{\mu_{K_s} V}{I_{\text{direct}} - I_{\text{direct}} F_s} \right]^2$$

$$+ \left[ \frac{\mu_{I_{\text{direct}} - I_{\text{direct}} F_s}}{I_{\text{direct}} - I_{\text{direct}} F_s} \right]^2 + \left[ \frac{\mu_{V} V}{I_{\text{direct}} - I_{\text{direct}} F_s} \right]^2 + \mu_{\text{unc}}^2 + \mu_{\text{alt}}^2$$

Where \( \mu_{R_i} \) is the value of the uncertainty of the different parameters in the expression 5, \( F_s \) is the exposure factor of the optical shopper during calibration, obtained by measuring the ratio of signal to shopper off operation and total openness, \( I_{\text{direct}} \) is the integral value of the radius b of the intensity distribution function of the source also measured during calibration.
The expression 7 is evaluated in Table 1, in it has been considered uncertainty and reproducibility of the method for further alignment sensor uncertainty, which was determined considering a maximum error of 1 mm in the determination of the distance from the source to the plane of the sensors.

The spectral distribution of the tungsten halogen source does not affect the measuring method and can be replaced by any other lamp that provides an intensity distribution with radial symmetry and the low possible divergence. A Si CCD spectrometer was used to measure the smooth curve of spectral distribution of several tungsten-halogen sources, the source used correspond to the more efficient commercial available source in the visible without dichroic filter.

Table 1. Budget of the uncertainties for the measurement results.

| Uncertainty source                                      | Standard uncertainty | Unit | Sens. Coef | Coef. unit | Contribution | Degrees of freedom | Weight |
|--------------------------------------------------------|----------------------|------|------------|------------|--------------|--------------------|--------|
| Measurement of the Pyranometer voltage, V              | 7.00E-09             | V    | 4.02E-03   | m2/W       | 2.81E-11     | 200                | 0%     |
| Exposition coefficient, Ks                             | 1.00E-05             | 1.00E-05 | Vm2/W     | 1.00E-08   | 100          | 1%                 |        |
| Irradiance calibration of the standard, Istandand     | 2.500                | W/m2 | 4.03E-08   | Vm2/W/y'2  | 1.01E-07     | 50                 | 89%    |
| Normal irradiance measure, (Iirecta)                  | 1.000                | W/m2 | 3.35E-10   | Vm2/W/y'2  | 3.35E-10     | 10                 | 0%     |
| Areas correction factor, (FA)                         | 1.35E-08             | 1.01E-05 | Vm2/W     | 1.37E-13    | 200          | 0%                 |        |
| Reproductibility of the measurements                   | 3.42E-08             | Vm2/W| 1.00E+00   | 3.42E-08   | 200          | 10%                |        |
|                                                         |                      |      |            |            |              |                    |        |
| u_v                                                    | 0.107                | µVm2/W |          |            |              |                    |        |
| k                                                      | 2.02                 |      |            |            |              |                    |        |
| U                                                      | 0.22                 | µVm2/W |          |            |              |                    |        |
| U                                                      | 2.1%                 |      |            |            |              |                    |        |

3.1 Correction for difference in sensor areas

The area of the pyranometer sensor is determined by a laser beam of 3 mm in diameter aligned at normal incidence with respect to the base of the instrument using a flat mirror for such alignment; and by means of a sweep across the diameter of the detector, and the intensity distribution chart with respect to the displacement of the sensor.

According to the optical geometrical analysis from Figure 4, the calculation of the maximum beam refraction caused by the passage through both domes of the pyranometer will result a \( \Delta y_i \) variation in height of less than 0.03 % ( 0.06 % taking into account both ends) , this contribution to the uncertainty is negligible according to the values shown in the table 1 where the calculation of the uncertainty area correction factor, have included the uncertainty in estimating the diameter.

Figure 4. Diagram for the refraction analysis of laser beam through CMP6 pyranometer domes, for the analysis the beam enters horizontally (normal to the detector) with height \( y_i \), considering a refractive index of glass \( n = 1.5 \). The beam leaves to the sensor at height \( y_o \) which is only function of the income height.

The average coefficient of sensitivity obtained for different distances shown in Figure 3, is of 10.24 uVm2 / W with expanded uncertainty of ± 2.1 % (k = 2 ). A systematic error was identified related
with the divergence of the illumination in the cases where the divergence of the source is greater than natural source, some test with the corrected divergence using lens, show than the error could be negligible but could be corrected due to the great reproducibility of the method.

3. Conclusions
The presented method for calibrating pyranometers using a pyroelectric radiometer traceable to cryogenic radiometer is novel and it could be contained in the recommendations of international standards, the results for the reproducibility of the method and traceability to the international system of units ensuring the reliability for the indoor calibration of pyranometers. Additionally, there are several advantages; the calibration do not required spectral correction or an ad hoc spectral distribution of the source, the method is significantly fast and simple compared to outdoors methods and provides the ability to obtain the response factor at normal irradiance for any instrument based on thermopile. The angular response of the instrument should be studied further with the appropriate rotational mount.

Systematic errors such as the position of the detectors plane respect to the plane of the reference ECPR occurs in all methods of laboratory, however its influence is negligible according to the estimated uncertainty if is taken the necessary attention during the measurement and the divergence of the sources is low. The error by the intensity distribution and the difference in area of the detector is appropriately adjusted when the diameter of the detector is known or measured using a laser beam. The uncertainty value obtained by the present method is lower than that obtained for some instruments at factory and is mainly limited by the calibration uncertainty of the standard used.

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