DESIGN, CONSTRUCTION, CALIBRATION AND PERFORMANCE ANALYSIS OF A LOW COST PYRANOMETER BASED ON THE KIMBALL-HOBBS MODEL

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Abstract. *This paper reports the design, the construction and the calibration of a pyranometer based on the Kimbal-Hobbs model. This instrument determines the solar radiation measuring the temperature difference between two sensitive elements covered by pigments with different reflectance. The choice of the pigmentations was performed by photo-acoustic spectroscopy (PA). This technique allows a choice based on the selective absorption of the visible light spectrum by a given material. The absorbing pigments tested were: black commercial spray painting, carbon black powder, and a mixture of these two materials. The reflective materials tested were: white commercial spray painting, aluminum commercial spray painting, thin aluminum foil, and melted soldering wire (60 /40 lead-tin). The temperature difference is determined by two AD590 mounted in series, this integrated circuit is a solid state temperature transducer. This arrangement produces an output current proportional to the temperature difference between the absorption surfaces. The thermometer used can be powered by a dc voltage between 4V and 30V. This sensor has small size, with 3mm of thickness and 5mm in height and is internally laser trimmed to ensure an optimized operation. Tests based on ISO 9060 and on the World Meteorological Organization (WMO) recommendations has been performed, determining: linearity, sensitivity, external temperature stability and the output signal variation as a function of the distance. In all tests the prototype was classified as a first or second class instrument. A two channels, 12-bits acquisition system has been developed for data taking and electrical signal processing, as well. The calibration and testing of hypotheses were made comparing the results obtained by the developed prototype and a certified Keep&Zonen pyranometer (model CMP03). The calibration procedure and results are also presented on this paper.*

Keywords*: radiometer, pyranometer, solar radiation, solar potential.*

1. INTRODUCTION

The quantification of the solar potential on a given region has fundamental importance on determining the feasibility of any solar energy exploitation array, but also on choosing the type of equipment to be used depending on the levels of global, direct and diffuse solar radiation.

To verify the global radiation on the Earth's surface it was developed a prototype of pyranometer type radiometer by the group of the Laboratório de Propriedades Oticas of the Physics Institute in the Universidade Federal da Bahia – Brazil.

The pyranometer developed has major innovations: the use of temperature sensors (AD590), which can be soldered directly to the sensitive metal backing elements; the use of photoacoustic technique on the choice of absorbing and reflectors pigments; and a system of data acquisition via the parallel port of a personal computer (PC).

Several tests using the Photoacoustic technique were made, to select the absorbing layer (black) and non-absorbing (white), including the characterization of commercial black and white painting, carbon black, aluminum foil, silver paint, melted lead-tin solder, and some mixtures of those materials.

The operation of the pyranometer is based on the temperature difference between the absorber plate and the non-absorbing plate, also called passive mode. The temperature difference is determined by two AD590 mounted in series, this integrated circuit is a solid state temperature transducer. The array produces a current proportional to the temperature difference between the absorbing surfaces.

For the prototype calibration, according to ISO 9847, a reference radiometer was used. In this case, the standard reference was the Kipp&Zonen CMP03 pyranometer, an instrument which produces a minimum off-set deviation (Kratzenberg, 2003). The statistical test of hypotheses was made comparing the results obtained by both instruments.

2. STATE OF THE ART

When a small sensitive area is intercepted by a solar light beam, one is able to measure the intensity of the solar heating radiation, by determining the energy absorbed by this sensitive element. The measuring is made observing changes on the physical properties correlate to the amount of absorbed energy.

If the focused radiation on the sensitive element is coming from all regions of the hemisphere above the plane, excluding the solar disk, it is called diffuse solar radiation. If on the other hand, the radiation reaching the sensitive element comes directly from the solar disk, it is called direct solar radiation. The total or global solar radiation is, therefore, the summation of direct and diffuse solar energies. The equipments designed to measure solar radiation on soil are classified by their ability on measuring those three type of radiation incidence modes.

Radiometers - generic term that defines equipment to measure solar radiation - used to measure only the power per unit of area of the direct solar radiation, incident perpendicular to the plane of the sensitive element, are called pyrheliometer. The radiometers which measure the power per unit of area of the solar radiation are called pyranometer.

The early pyranometers made their appearance on the early ‘20. The Kimball-Hobbs model served as a reference for developing the radiometer proposed on this work, this equipment consists of two concentric rings, with different reflectance, made in silver with approximately 0.25 mm thickness, the inner ring is covered with a white magnesium oxide and the outer with a black oxide covering. The temperature difference between the rings was verified with thermocouples and the whole system was mounted inside a transparent hemisphere (Naziazeno, 2009).

Another interesting instrument is the Moll-Gorczynski pyranometer, this equipment is provided with a rectangular thermopile, covered by black ink. This geometry produces a series of problems, as the well known non-cosine output response, when the angle between the incident radiation and the normal to the thermopile plane is higher than 80º (Naziazeno, 2009).

Finally, pyranometer could also be based on photovoltaic solar cells; the out coming of silicon solar cells in 1954 opened such perspectives. Although its high speed response to any variations on the incident radiation, made that photovoltaic pyranometers also have some drawbacks: its sensitivity varies for different components of the solar spectrum; one can observe a highly variation on its calibration over time (Naziazeno, 2009).

Independently of the functioning principle and on the detector choice, the main characteristics of a radiometer according to the Word Meteorological Organization (WMO) are: power resolution, sensitivity, repeatability, temperature stability, linearity digress, response time, cosine function digress or deviation, output impedance (Freire, 2008).

The ISO 9060 standard of 1990, classifies pyranometers on: first class, second class and secondary standard using the following specifications: response time, offsetting of zero point, non-stability, nonlinearity, directional response, spectral selectivity, temperature dependence, response to tilt.

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3. MATERIALS AND METHODS

The pyranometer proposed is based on the classic model of Kimball & Hobbs (1923) which determines the solar radiation intensity from the difference in temperature between two sensitive elements of different reflectance.

The element for the solar energy absorption must be covered with black pigmentation; on the other hand, the element reflecting the radiation may be covered with white coating. There is a large range of white and black pigmentations possibilities. The choice of the pigment was made using Photoacoustic absorption spectroscopy.

For the light-absorbing black pigment, a set of brass discs, with 5.0 mm radius and 0.5 mm thick, were tested, covered with the following pigments: commercial black spray paint, residue of smoke from tow with kerosene burning, and finally a mixture of both.

For reflection the following coatings were tested: food aluminum foil, commercial aluminum spray paint, white spray paint and molten solder.

Figure 1 shows the sensitive elements covered with the chosen pigmentation.

Figure 1. Elements covered with pigmentation chosen.

In sunlight the sensitive elements temperature will change, to measure that change the AD590 high precision thermometer was been chosen as primary sensor. The AD590, from Anolog Devices, is a two-channel temperature transducer integrated circuit, which produces an output current proportional to the sensor absolute temperature. It can be powered in the range between 4.0 and 30.0 Volts and has small size, with 3.0 mm thick and 15.0 mm in height. This thermometer is internally calibrated by laser to ensure the proportional constant of 1μA/K.

Two of those sensors were soldered to the sensitive elements (black and white) and then connected to a four-pin sockets inside the pyranometer. A printed circuit board (PCB) was used to connect and support the electronics parts, the PCB was fixed to a metal base (on copper), used as thermal reference and heat sinker.

To ensure electromagnetic shielding the pyranometer was hosted in a cast aluminum box with dimensions (94x38x27) mm. Two optical windows were cut on the box top lid (25 mm in diameter), a microscopy glass plate (26x76 mm and 1.0 mm thickness) was used for sealing the windows.

The signal and power supply line is a 6 wires plus shielding cable, 10 meters long, providing the necessary shielding to ensure the output signal integrity and the electromagnetic compatibility. Figure 2 shows the developed pyranometer on its final mounting.

Figure 2. Pyranometer mounted.

3.1 Electronics.

The electrical signal from the AD590 is amplified and filtered by two operational amplifiers, one OPA177G (Texas – BurnBrown) and one AD623 (Analog Device).

The data acquisition interface is based on a board with two analog channels and eight digital inputs, with 12 bits resolution, controlled by the personal computer (PC) parallel port. The present work was started by the study of the data acquisition system and its BASIC programming. The ADC board acquires input signals between -5.0 V and +5.0 V. A calibration was performed to determine the offset and the amplification factor (real gain) of each channel, as well as the ADC linearity and the channel full-scale limit. The value of each channel amplification was theoretically calculated (G1 = 5 and G2 = 2). On the calibration routine a variable voltage supply and a commercial, bench-top, $5^{1/2}$ digits digital voltmeter has been used. The input voltage of each channel was read by the voltmeter, while the numerical value provided by the ADC was recorded.

3.2 Test method for the response time, linearity, temperature dependence, distance dependence and sensitivity.

For the linearity test, a 300 Watts lamp, used as a punctual light source, was mounted on a metallic support to illuminate the prototype and a Kipp&Zonen (CMP 03) reference pyranometer. The output voltage values of the Kipp&Zone and the prototype were recorded as a function of the distances from the punctual source.
(The sensitivity of Kipp&Zonen, provided by the manufacturer, is 14.86 $\mu V / W. m^{-2}$, what allows the conversion of the output voltage into power per unit of area ($W. m^{-2}$)).

A graphic of the prototype current output as a function of irradiance was then plotted, allowing determine the linearity of this equipment. From this graph view is possible to determine the value of the current as a function of the irradiance, in other words, the developed equipment sensitivity.

The graphic of the variation of the output signal at different distances from the light source was obtained using the same lamp.

To determine the response time and the time constant the instruments were positioned on a laboratory bench. The 300 W halogen lamp was mounted 30 cm away from the pyranometer and a PVC tube (blacked inside) was used as collimator to avoid external radiation. In a dark environment the lamp has been powered initially up and finally off, and the measurements carried out once the instruments were stable. The time constant is equal to the time the instrument takes to reach the value of 63% of the final value for a previously known stimulus (or a standard stimulus) (WMO). The response time is defined in ISO 9060, as the time to the instrument reaches 95% of a given final value (Freire, 2008).

The response times were determined throughout the analysis of the response curves obtained with a digital oscilloscope. The Figure 3 shows the measuring setup.

Figure 3: Response time measuring setup.

For calibration, it was used a reference pyranometer Kipp&Zonen model CMP 03, certified by the World Radiation Center (WRC). The Kipp&Zonen and the prototype were exposed to the sun for nine days. The acquisition system has acquired simultaneously the two illumination curves, each one with 638 points, where 12 hours of sun exposure by day were recorded. During the data analysis, first the Kipp&Zonen voltage curve was converted into irradiance (W/m^2), the next step was subtracted the off-set voltage from prototype curve and then calculate de ratio between the prototype experimental points and the reference pyranometer results. The average of these results is, a very good, first approximation the prototype calibration factor.

Visual adjustments of adhesion were introduced, producing small variations in the calibration factor for each studied day. The average of these factors was finally used on the calibration correction of the prototype. Fig. 4 shows the prototype and the Kipp&Zonen pyranometer exposed to solar radiation.

Figure 4. Kipp&Zonen and prototype under sunlight

4. RESULT AND DISCUSSIONS

4.1 Choice of the pigments

In Photoacoustic spectroscopy (PA) the electric output is proportional to incident light absorbed by the sample surface. For an absorbing pigment the better performance is obtained when its absorption spectrum reaches the reference (black body) curve. Figure 5 shows the behavior of the absorbing pigments tested, when confronted to the reference curve (black line).

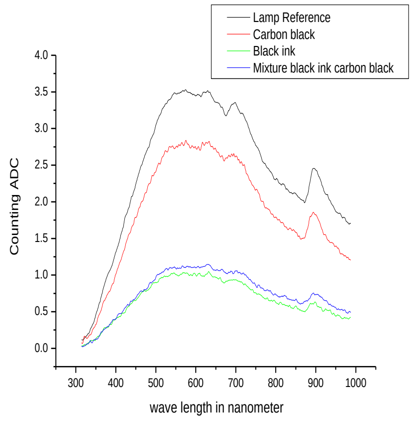

Figure 5. Photoacoustic absorption.

The graphic on Figure 5 shows the absorbing performance of the carbon black, the mixture between the carbon black and black paint, and finally black paint. Facing a certain difficulties on handling pure carbon black coating surfaces, extremely delicate and fragile, one chose to use the mixture of painting and carbon as absorber element. Figure 6 shows the behavior of the absorption power (percentage) as a function of the light wavelength (nm) for both pigments when compared to the reference curve.

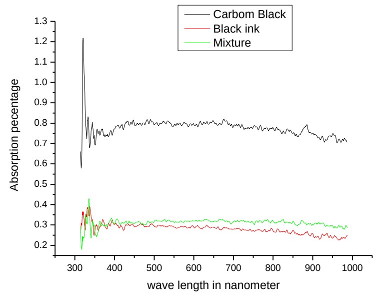

Figure 6. Absorption percentage.

For reflecting pigment, the best candidate curve is the one as far as possible from the reference curve. Figure 7 shows the graph views of the pigmentations tested by PA spectroscopy.

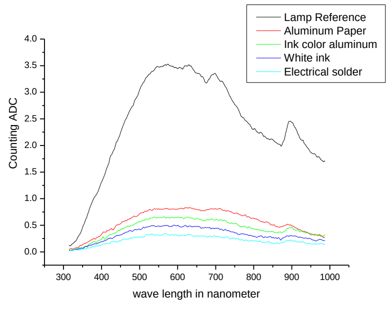

Figure 7. Reflecting pigments Photoacoustic absorption spectra

The best result respect to the reflection of the sunlight was obtained by the melted solder sample, followed by the commercial white painting. The aluminum paint and aluminum foil had the worst results.

Long term sun exposure is typical for equipments such as pyranometer, changes on the chemical characteristics of melted (60/40) soldering; due to the oxygen reactions; could cause the coating degradation. On that case, is observed a variation on the lead original metallic shining, which changes to green. This possible change on the coating color makes impossible the use of such kind of covering film, despite its optical advantages. On the other hand, the white commercial painting choose has long term UV-light stability, warranted by the manufacturer, thus was chosen as the outside layer for the sensitive element.

4.2 Test Classification

Linearity is a desired characteristic of most measuring equipments, in the case of pyranometer this is the expected relation between the equipment output signal and incident solar power (Abelardo, 2008). To verify this relation, a light source of constant power (300 Watt) was used to illuminate the prototype and a Kipp&Zonen reference pyranometer, simultaneously and at different distances. The graphic of Figure 8 shows the results.

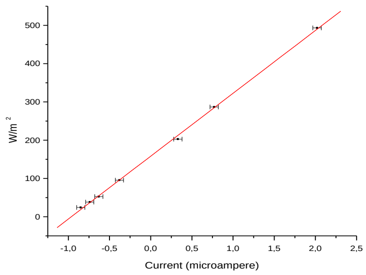

Figure 8. Linearity of prototype.

The non-linearity amount for the developed prototype computes 2.4% around 500 W.m^{-2}, norm ISO 9060 ranks pyranometer with non-linearity within ± 3% as a second class instrument. Thus, the developed prototype belongs to that category and its sensibility is 6.1 x 10^{-3} µA/Wm^{-2}.

The change in the prototype electrical signal depending on the distance to the punctual light source is presented on Figure 9.

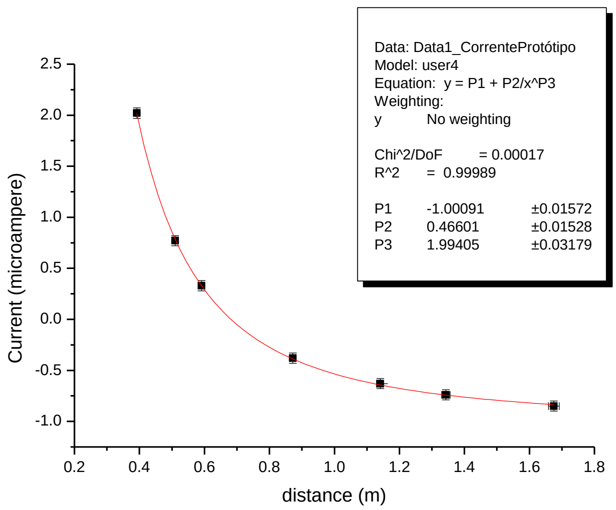

Figure 9. Variation of prototype electric signal as a function of the distance

The experimental points could be adjusted by the following function:

$$y = P_1 + \frac{P_2}{x^{P_3}} \tag{1}$$

The terms P_1 and P_2 were introduced due to the need of more free parameters during the numerical fitting; nevertheless, just free parameter P_3 has a physical meaning. The intensity of an electromagnetic wave, generated by a constant power light source, is inversely proportional to the square of the distance between the source and the measuring point. In the experimental curve fitting the value (P_3 = 1,994 +/- 0,032) shows high compatibility between the equipment response and the theoretical expectation.

The instrument time response indicates how fast its output signal stabilizes after a light exposure. In fact, WMO preconizes it as the time necessary to the output signal reaches approximately 63% of the final stabilized value for a given excitation. On the other hand, the ISO 9060 defines time response as 95% of the stabilization time. The graphic on Figure 10 shows the timing behavior when the prototype is illuminated by a 300 watts lamp at a constant distance of 11 cm.

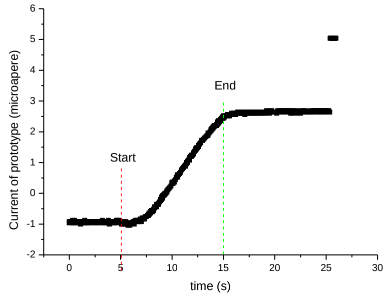

Figure 10: Time behavior of the prototype to be illuminated.

The stabilization time during the heating process (lamp turned on) is of about 10s, calculating the time constant as 63% of the stabilization time, one can find 6s. Using norm ISO 9060 this parameter is 9.5 s.

Figure 11 shows the prototype time behavior when the lamp is turned off.

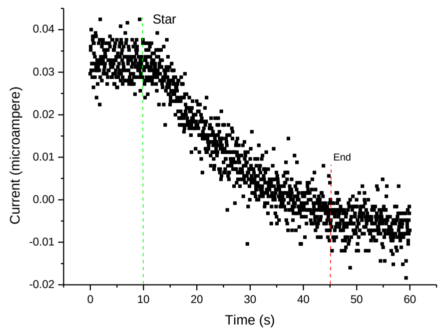

Figure 11. Temporal behavior of the prototype to have the lamp off

The stabilization time on the cooling process is about 35s, so the time constant is approximately 22 s or 33 s. The WMO and ISO 9060 classification time tables are shown respectively in Tables 1 and 2.

Table 1. WMO Classification

Pyranometer	Maximum time constant of (s)
1ª Class	25
2 ª Class	60
3 ª Class	240

Table 2. ISO 9060 Classification

Standard pyranometer	Response time (s)
Secondary	< 15s
1ª Class	< 30s
2 ª Class	< 60s

Note that according to the WMO classification the tested prototype is a first class instrument, with a time response of 14 s. Observing the ISO 9060 classification the prototype tested is ranked first class as well (time response equal to 21.3 s).

4.3 Calibration and Statistics

Figure 12 shows both prototype and the Kipp&Zonen curves after calibration.

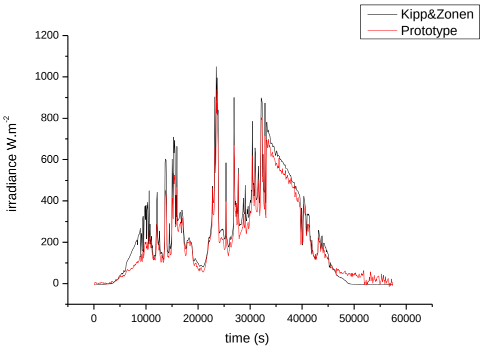

Figure 12. One day prototype and Kipp&Zonen sunlight measuring

The prototype and the reference pyranometer were exposed to sunlight for nine days. The integral of each daily curve gives the amount of energy arriving on the soil, Table 3 shows the results.

Table 3. Global energy measure

Day	Global Energy. Kipp&Zonen ($M.J.day^{-1}.m^{-2}$)	Global Energy. Prototype ($M.J.day^{-1}.m^{-2}$)
1	21	19
2	15	14
3	16	14
4	13	12
5	22	18
6	20	16
7	19	15
8	22	20
9	24	22
Average	$19{,}1 \pm 3{,}7$	$16{,}2 \pm 3{,}3$

From these results it is possible to test the hypothesis that both equipments produce equal population averages. The estimator parameter can be calculated combining variances:

$$S_p^2 = \frac{(n_1 - 1).S_1^2 + (n_2 - 1).S_2^2}{n_1 + n_2 - 2} \tag{2}$$

Where:
n_1 and n_2 represent the size of the samples;
S_1 and S_2 are the standard deviations.
In such situation, one can write:

$$S_p = \left(\frac{(9-1).(3{,}7)^2 + (9-1)(3{,}3)^2}{9+9-2} \right)^{1/2} = 3{,}5057 \tag{3}$$

The appropriate statistical hypothesis testing is type *t*, defined by (MONTGOMERY, 2001):

$$T_0 = \frac{\overline{X}_1 - \overline{X}_2 - (\mu_1 - \mu_2)}{S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{4}$$

Where:
$\overline{X}_1$ e $\overline{X}_2$ are the samples meaning values;
μ_1 e μ_2 are the population averages
Rewriting expression 4:

$$T_0 = \frac{19{,}1 - 16{,}2 - 0}{3{,}5057 \sqrt{\frac{1}{9} + \frac{1}{9}}} = 1{,}755 \tag{5}$$

The hypothesis test was done, in a bi-lateral mode, within 95% confidence level, what gives the following limits for a hypothesis rejection:

- If $T_0 > t_{0,025;9} = 2{,}262$ or $T_0 < t_{0,025;9} = -2{,}262$.

So, as in the present study T_0 is 1.755, belonging to the interval -2.262 < T_0 < 2.262, one can not reject the hypothesis that both equipments are able to measures with equal averages at 95% confidence level.

Further statistical and repeatability studies support that the developed instrument has an intrinsic relative deviation of 3.2% on sunlight irradiance measurement.

5. CONCLUSIONS AND SUGGESTIONS

5.1. Conclusions

1. The pigment used as coating for the sensitive elements provide the difference in absorbance of sunlight and therefore the difference in temperature between the sensitive elements and PA spectroscopy showed be a very interesting and precise tooling on the pigment choice process;
2. The desired linear relationship between the sensor electrical signal and incident light power was fully achieved by the developed instrument. On that particular characteristic the prototype is classified as second-class in accordance to ISO 9060;
3. Respect to the time constant, according to World Society for Meteorology (WMO) and ISO 9060, the built pyranometer is classified as a first class instrument. In other words, independently on the adopted standard the prototype is ranked as first class;
4. The prototype building cost is of U$ 150.00, very low cost compared to the commercial similar (U$ 1,500.00), and this achievement represents an important new option on the Brazilian solar instrument market. The data acquisition system cost is about U $ 1500.00, half of the commercial one.
5. The prototype could be easily constructed and assembled, having very low maintenance needs and cost;
6. The prototype may be read out by simple ammeter, allowing instant readings of the solar irradiance;
7. The statistical analysis, developed for the hypothesis testing, found no difference in the solar radiation measuring performance for the prototype compared to the commercial radiometer (Kipp&Zonen) ;
8. In general it appears that the prototype can contribute to the dissemination of the solar measuring routines, contributing on research and technical works, allowing obtain daily or instantaneous solar irradiation samplings.

5.2. Suggestions

1. Enhance and develop the prototype testing routine, looking forward to the dependence of the output signal as a function of the prototype to sun light tilt angle, as well as, testing the output signal degradation as a function of the cable length and cable impedance.
2. Developing of visual exploitation software and a data acquisition systems by USB port;
3. In future prototypes one could use the present discarded absorption and reflective pigmentations trying to optimize and solve some technological problems faced during this work.

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