DESIGN OF A LOW-COST SENSOR FOR SOLAR IRRADIANCE

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ABSTRACT: *This paper proposes a novel design for a Low-Cost Sensor (Pyranometer) to measure Solar Irradiance in the North of Chile. The main characteristic of this sensor is the low-cost of all its components. The design of the sensor is based on using the PT202C phototransistor. This device is its better sensitiveness to solar irradiance, allowing an excellent response of the sensor in a range from approximately 300 to 1200 nm. However, the sensor is saturated under the extreme environmental conditions of the North of Chile (high levels of solar radiation). In order to avoid saturation, an attenuation system is also proposed in this paper. An attenuator element of Teflon is tested obtaining excellent results of attenuation, improving the results of the Low-Cost Sensor. Finally, experimental results are compared with data obtained from the CMP11 ISO 9060 Secondary Standard Pyranometer, demonstrating that the solar irradiance obtained with the proposed sensor is reliable (0.9909 of correlation between both results).*

KEY WORDS: Solar irradiance, Pyranometer, Low-Cost Sensor, Phototransistor.

1. INTRODUCTION

The Sun is a nuclear reactor. Its energy is emitted as radiation mainly due the solar surface temperature according the Plack`s Law. The electromagnetic spectrum of the sun light includes wavelengths coming from the infrared to the ultraviolet. This spectral range of electromagnetic is called Solar Radiation [1]. In other words, when we talk about solar energy we are referring to the energy contained in the solar spectrum which reaches the Earth’s surface.

Fig. 1 shows the energy contained in the solar spectrum (area under the curve). It can be seen that the main portion of the energy is contained between 300 and 1300 nm wavelength.

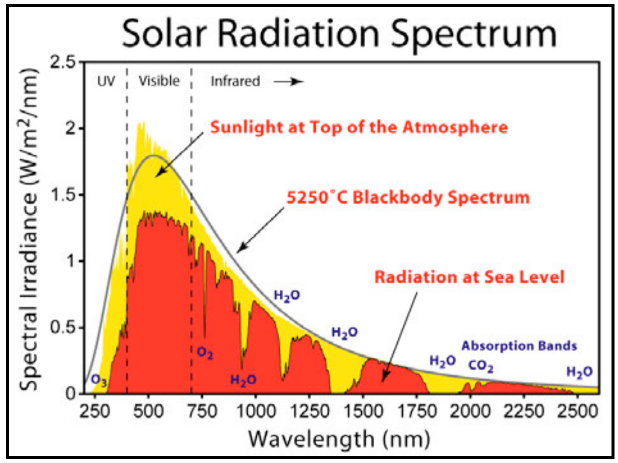

Fig. 1. Solar radiation spectrum diagram [2].

According to above, it is possible to say that Solar Energy does not depend on Sun’s luminous intensity[1]. This is important because the device used to determine the amount of Solar Energy, concentrated in one point, measures radiation (radiometry) rather than luminous flux (photometry).

There are mainly three types of devices to measure solar irradiance over the Earth´s surface [3]: Pyranometers (direct and diffuse solar irradiance), Pyrheliometers (direct solar irradiance) and Albedometers (reflected solar irradiance). These devices measure irradiance in W/m^2 being highly accurate and therefore expensive. In fact, the prize of these devices represents an important cost for the process of collecting solar data, especially for nonprofit institutions, such as schools or universities. This is the reason that leads this project to present the design of a no costly sensor for global irradiance (Pyranometer) with characteristics (performance, accuracy and robustness) similar to those obtained from commonly used devices. Pyranometers use different kind of sensors to measure Solar Irradiance. While commercial instruments use thermopiles [5], there are other kinds of low-cost initiatives that use solar cells or photo diodes [6,8,10]. Nevertheless, unlike designs presented in the literature, this paper proposes the use of a photo transistor as solar sensor. In order to accomplish the goal of designing this sensor, it is necessary to understand how standard

[1] According to [4], luminous intensity refers to the perception of brightness of a source by the human eye.

Pyranometers work. References [6-10] describe different parts of Pyranometers and also how they measure solar irradiance. In addition, technical information provided by [11] indicates the properties of Teflon, which is necessary to attenuate the irradiance received by the photo transistor. Finally, in order to prove that the proposed sensor generates reliable data, statistical techniques [12], such as arithmetic mean and correlation have been applied.

The proposed sensor has to be able of measuring global and diffuse irradiance ensuring high precision, as the data obtained will be used to take important decisions for developing projects where solar energy will be used. It also has to be resistant to extreme weather conditions since it will be exposed not only to the Sun's radiation but also to wind gusts and dust. Indeed, the irradiance sensor prototype will be placed in the facilities of the Universidad de Antofagasta (Region of Antofagasta, Chile) to collect data under extreme levels of solar radiation.

The rest of the paper is composed of the following sections: section 2 shows the Pyranometer's state of the art. The design of the sensor is shown in section 3. Testing, calibration and experimental results are presented in section 4. Finally, discussion of results and conclusions along with future improvements for the proposed sensor comprehend sections 5 and 6.

2. STATE OF THE ART

In order to measure global irradiance, it is necessary to understand the fundamentals of a Pyranometer. Fundamentally, a Pyranometer collects solar radiation, around the surface where it is placed, from an angle of 180° [5]. It is composed of a sensor element which is responsible to transform the radiation received into a voltage difference which is proportional to the amount of incident radiation. Figure 2 shows a diagram of a typical Pyranometer.

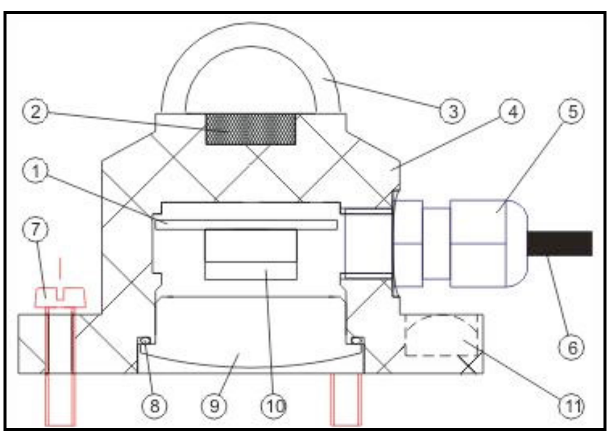

Fig. 2. Pyranometer diagram schematic [6].

Fig. 2 shows the different parts of a Pyranometer; these are: PCB (1), solar sensor (2), protector quartz dome (3), body (4), cable connector (5), electrical cable (6), screw (7), fixings (8), access for cable connection (9), screwed electrical connector (10), level (11).

Another way of measuring solar radiation is using a solar cell. Literature [7] shows the design of a sensor using this technology. However, utilizing photovoltaic cells increases the cost of a radiation sensor.

Both types of radiometers, Pyranometers and Solar cells, follow the same principle; by means of a sensor able to detect solar radiation, they can measure Solar Irradiance. In the first case, the sensor is a thermopile which generates a voltage proportional to the received Solar Irradiance. Then, this voltage is send to a data logger to register the amount of energy received by the sensor. In the second case, the sensor used is principally a photocell made of silica which is able to get the solar spectrum, after absorptions [8] in the atmosphere, and then generates a voltage difference proportional to the radiation on its surface. Generally, sensors are located under a quartz dome which provides protection, a vision angle of 180° and is transparent for a wide range of wavelengths [9]. In addition, there are radiometers that utilize photo diodes. For instance, literature [10] explains the design of a kind of low-cost Pyranometer using a photo diode.

3. DESIGN OF THE SOLAR RADIATION SENSOR

As explained before, the purpose of this paper is to design and built a Solar Radiation Sensor able to collect irradiance data using low cost components. In order to achieve this, the design of the low-cost Pyranometer will be divided into three stages: the selection of the sensor, the design of the electronics and the data logger and the design of housing to enclose the sensor and electronics.

3.1. SELECTION OF THE SENSOR

In the local market, there are three options of photo sensitive devices: photo diodes, light detect resistors (LDR) and photo transistors. The selection will be taken based on technical features of these three devices. Solar cells made of silica will be not considered due to their high cost and temperature restrictions that affects the performance of solar cells. As a consequence, their temperature factor needs to be adjusted increasing the complexity of the design. It is necessary to use temperature detectors and adjustment data (provided by the manufacturer), which are usually difficult to be obtained.

3.1.1. Light detect resistors (LDR)

This device is made of a cadmium sulphide or cadmium selenium cell which varies its resistance according to the incident light on its surface []. The more is the incident light on the LDR's surface, the less resistance is between its terminals. Generally, LDR's resistance varies from 50 to 12600 [Ω] (sunlight) to several MΩ (darkness). LDR´s present a slow response and their spectral peak is near to 550 nm (visible spectrum)[2]. For this reason, they are widely used in photometry and are not suitable for radiometry.

3.1.2. PHOTO DIODES

They are PN juncture semiconductors sensitive to a wide range of wavelengths (from UV to IR). Photo diodes work like common diodes; the difference is that they are inversely biased, conducting current when they are excited by incident light. In this way, photo diodes can generate a current proportional to the amount of incident radiation, which can be used to measure solar irradiance. According to technical data from the SFH 229 photo diode[3], its response to frequency shows a 20% of relative spectral sensitivity at 400 nm and 1100 nm with a peak of 100% at 850 nm approximately. In this way, photo diodes are mainly designed to work near the IR (700 nm – 900 nm). In addition, its response (photo current) to the irradiance is low, from 10^{-1} uA at 10^{1} uW/cm^2 to 10^{1} uA at 10^{2} uW/cm^2. This implies the use of an amplifier stage that could introduce errors to the measurement.

3.1.3. PHOTO TRANSISTORS

Photo transistors are similar to normal transistors. The difference is that the base is sensitive to light. In other words, a light excitation in its base will generate a current between its collector and emitter, which is proportional to the incident radiation. In contrast to photo diodes, photo transistors include (due to their intrinsic characteristics) an amplifier stage. For this reason, they present more sensitivity and a higher response to irradiance than photo diodes. For example, technical data of the PT202C transistor[4] show a 20% of relative spectral sensitivity at 350 nm and 1250 nm with a peak of roughly 100% at 850 nm. However, the difference is that it presents 60% of sensitivity at 450 nm and 1180 nm while a photo diode presents this sensitivity at 600 and 1000 nm approximately. In addition, photo transistor's response to irradiance is between 1 mA at 0.5 mW/cm^2 and 5 mA at 5 mW/cm^2, which is larger than the photo diode one.

Considering the three options analyzed before, the most suitable for the project is the PT202C photo transistor because it presents high levels of relative spectral sensitivity and photo current in a wide range of wavelengths in contrast to the SFH 229 photo diode and the LDR.

3.2. DESIGN OF THE ELECTRONICS

According to the electrical characteristics of the PT202C, a maximum collector current (I_C) of 9 mA and a bias of 5 Vdc will be used. The value of the resistor is calculated according to the ohm's law (R = 550 Ω). This resistance value is made of a resistor of 220 Ω and a potentiometer set to 300 Ω. The configuration of the photo transistor can be seen in Fig. 3.

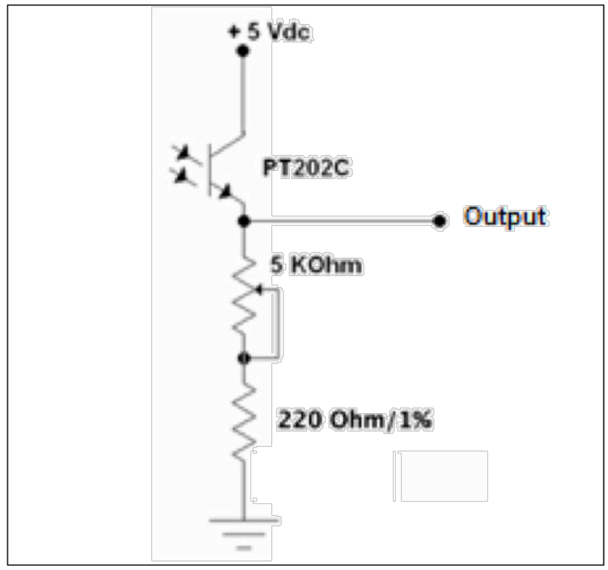

Fig. 3. Common emitter configuration schematic circuit.

The 220 Ω resistor controls the maximum I_C which flows through the photo transistor. The 5 kΩ potentiometer is to set this current.

This configuration works as a current-voltage converter where I_C is proportional to voltage variations between the emitter and ground. Thus, when incident radiation modifies I_C, voltage will vary corresponding to the radiation received by the photo transistor.

The output of the configuration provides an analogue value in the range of 0-5 Vdc which can be send to an analogue-digital conversion stage. This conversion is to generate an irradiance scale in W/m^2.

However, the response of the PT202C photo transistor to irradiance is limited by its intrinsic characteristics; it covers from 0.5 to 5 mW/cm^2. This means that the maximum irradiance level obtained by this photo transistor will be 50 W/m^2 at 5 Vdc. This value is dramatically lower than the maximum level of irradiance measured in the Northern territory of Chile, which is about 1350 W/m^2. In this way, for a maximum irradiance value of 40 W/m^2, on the photo transistor's sensitive surface, it is necessary an attenuation from 1350 W/m^2 to the desired value. This attenuation is calculated according to Eq. (1).

$$x = \frac{40 * 100}{1350} = 2.96 = 97.03\% \qquad (1)$$

Hence, in order to avoid saturation in the photo transistor, it is necessary to place an attenuator element over the sensor.

[2] NORPS-12 LDR Technical information (SILONEX)
[3] SFH 229 Technical curves (Infineon Technologies, OSRAM Opto semiconductors)
[4] PT202C Technical curves (Everlight Electronics Co. Ltd)

The requirements for the attenuator element are the following:

- It has to allow the irradiance bandwidth (300-1200 nm) to pass through it.
- The attenuation has to be proportional to the original value of irradiance.
- Its attenuation features does not have to be affected by the environment.
- It has to be low cost and easily handling.

The attenuator element does not have to present any kind of pigmentation or additives that can absorb or attenuate the irradiance bandwidth. For example, lux meters (Fig. 4) have a plastic attenuator over the photo detector. This plastic is white so it does not filter important wavelengths needed for a right measurement. Another example is the JAZ spectrum-radiometer (Ocean Optics Fig.) which also presents a white material covering the Linear CCD detector (cosine corrector). According to this previous analysis, in order to avoid saturations in the sensor, a kind of white plastic will be suitable as attenuator element.

Fig. 4. Plastic protection and attenuator for Lux meters.

Fig. 5. Ocean optics JAZ sensor.

The most important distributor of plastics for engineering in Chile offers a wide variety of plastics (they can be used outdoor) that presents adequate performance during several years. Table 1 shows main characteristics of five different types of plastics.

Table 1. Technical information of five potential attenuator elements (Prolipopilene, PVC, PVDF, HMW, FPTE) [11]

Material	Density	Moisture absorption	Temperature (ºC)
Propilene	0.90	0.000	-30 to 120
PVC	1.40	0.400	-20 to 79
PVDF	1.79	0.005	-40 to 150
HMW	0.95	0.000	-150 to 70
FPTE (Teflon)	2.17	0.000	-220 to 260

Any of these five plastics can be used as attenuator element. However, the attenuation depends on the thickness of the element to be used. For this reason, element's thickness has to be easily controlled. According to this criterion, Teflon is the most suitable for this purpose. It is manufactured as thin white ribbons of 10 mm wide and 0.075 mm or 0.1 mm thick. Moreover, it is low-cost and easily found in any hardware store.

Teflon's properties [11] also indicate that it is one of the plastic's most thermally stable with a lineal dilatation coefficient and low thermal conductivity. Against external agents, it is mostly inert, insoluble and resistant to environment agents and radiation. Its physical-mechanical properties show that it is resistant to traction, compression, flexion, friction and mechanical wear. Moreover, Teflon presents high anti adhesiveness so it is hard of being moist. This last attribute is also important to deal with dirtiness caused by dust (especially in the Desert) which could affect irradiance measurements.

3.3. DETERMINING THE THICKNESS OF THE ATTENUATOR

As it was mentioned in section 3.2, the attenuation level depends on the thickness of the attenuator element. Indeed, Teflon was chosen because of it is easy to handle its thickness. This can be achieved placing several layers of 0.075 mm thick until obtaining the desired level of attenuation. The more the layers are placing over the sensor, the more the attenuation level is obtained. Thus, a set of irradiance data is measured to show the Teflon's attenuation characteristic for different values of thickness. In order to register these data, the Jaz spectrum-radiometer of Ocean Optics was used.

The graph data obtained with SpectraSuite software is possible to see the three samples, red line correspond to sample without cut filter green line corresponds to sample with 14 layers (1.05 mm), and blue line corresponds to sample 15 layer (1.125 mm) Teflon. It can be clearly seen that by simply adding a layer or 0.075 [mm] thick at the filter, as it affects the upper end of wavelengths traversing and reach the phototransistor.

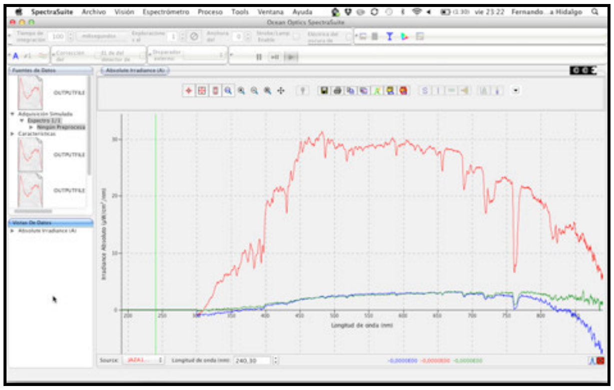

Fig. 6. Graph data from the JAZZ instrument.

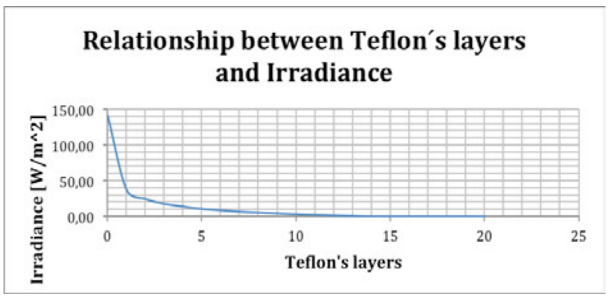

Fig. 7. Relationship between Teflon's layers and Irradiance.

From Fig. 7, it can be seen that the irradiance level measured by the radiometer is strongly attenuated by 1 layer of Teflon. Then, the attenuation steadily increases until 15 layers were used. After this, Irradiance measured by the sensor is close to zero. This information is relevant to determine the number of layers needed to attenuate maximum irradiance (1350 W/m^2) preserving sensitiveness.

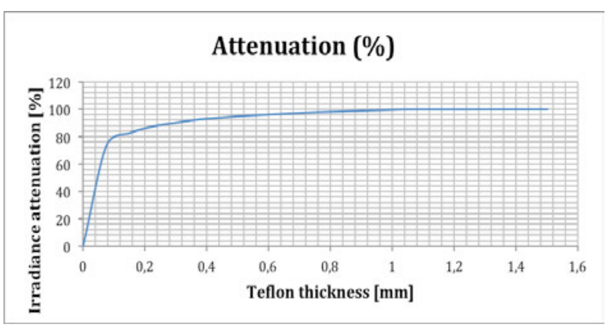

Fig. 8. Relationship between Attenuatión versus Teflon thikness.

3.4. DESIGN OF THE SENSOR HOUSING

The main features that the housing has to satisfy are the following.

- It must allow changes and adjusts in the sensor.
- It must be easy of mounting.
- It must provide access for maintenance.
- It must be resistant to moisture, dust, UV radiation and temperature variations.

The mechanical design is simple; a round case (Fig. 9) with an aperture in one of its faces is enough. In this aperture, a cylinder will be placed which contains the sensor and the attenuator element. In this case, a round outdoor watertight box of 65 mm diameter and 35 mm deep will be used. This box has a protection level of IP44, which is adequate to protect electronic components against the environment (wind, dust, moisture).

Fig. 9. IP44 round case.

This case will enclose the sensor and electronics, providing easy access for maintenance and also for bias and data wires.

In order to contain the photo transistor and the attenuator element, a plastic cylinder will be used. In this case, a blue PVC cylinder of 25 mm diameter and 20 mm long has been chosen. It is suitable for the necessities of the sensor because it provides protection and support for the attenuator. In addition, PVC has excellent characteristic, such as, opacity, robustness and thermal and electrical isolation. The photo transistor is located at 10 mm from the top of the cylinder (Fig. 11). At this distance, the vision angle is 90° which is sufficient to allow enough radiation to reach the sensor.

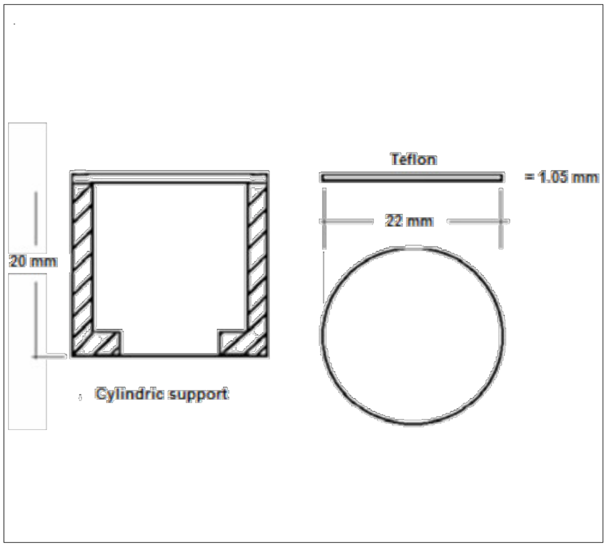

Fig. 10. Design of the PVC cylinder.

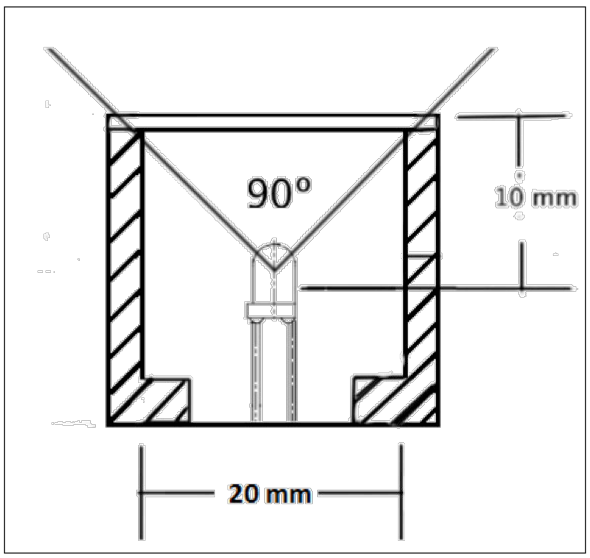

Fig. 11. Disposition of the photo transistor inside the PVC cylinder.

Teflon have to be carefully placed over the top face of the cylinder (Fig. 12), which has to be rotated after putting each layer on. Rotating the cylinder is necessary because of Teflon's layers are not completely uniform. Using this technique improves the uniformity of the final attenuator surface.

Fig. 12. Teflon's layers over the PVC cylinder.

Finally, the schematic of the Low-Cost Solar Sensor is presented in Fig. 13.

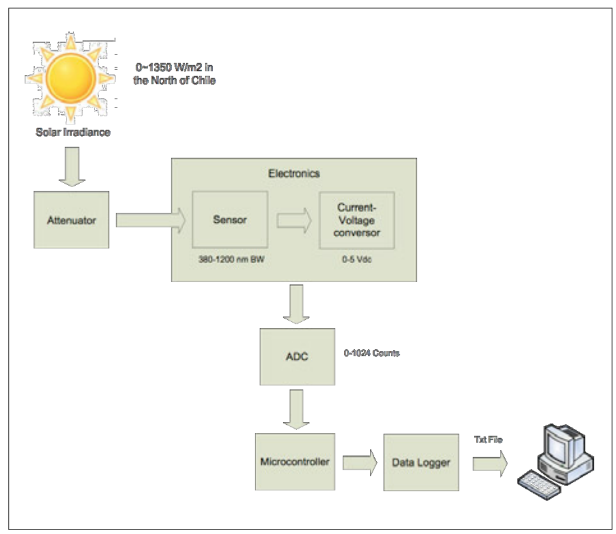

Fig. 13. Block diagram of the Low-cost Solar Sensor designed.

The Data Logger is implemented using a PIC Microcontroller.

4. TESTING, CALIBRATION AND EXPERIMENTAL RESULTS

The data obtained from the designed sensor are compared with those generated by the CMP11 ISO 9060 Secondary Standard Pyranometer of Kipp&Zonen [5]. The proposed sensor's data correspond to 0-5 [Vdc] variations, which are represented by 0-1024 counts. Fig. 14 shows the comparison between the data obtained.

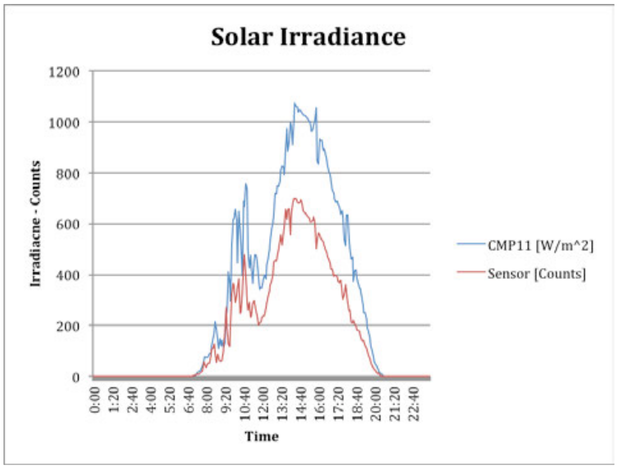

Fig. 14. Comparison between the results of the CMP11 and the proposed sensor (12-26-2011).

The results obtained from each sensor are computed using the arithmetic mean for ungroup data method [12]. Each 5 minutes, one datum of the set is generated according to the following acquisition process:

- A sample is taken from the microcontroller ADC port each 10 seconds.
- The numerical value of the conversion is stored in a variable.
- Then, the system computes an accumulative sum of the samples taken.
- When the system computes the sum of the 30th value, the arithmetic mean is calculated.
- Finally, the mean value is stored in a device able to be read and plotted by a computer.

Although the results of the proposed sensor follow a pattern similar to that from the CMP11, there is a clear difference between the magnitude values of each sensor. In order to cope with this problem, a calibration algorithm will be applied. Even though it is clear that there is a relationship between both set of data, it is necessary to calculate the correlation (R^2) between them [13]. It was calculated using radiation measurements obtained in a period of seven days. In this way, an empirical algorithm to correct the magnitude error was determined in Eq. (2) with which the correlation linear is Eq.(3).

$$y = 1.5933 * x + 5.8753 \qquad (2)$$

$$R^2 = 0.99099 \qquad (3)$$

Therefore, using this calibration algorithm ensures that the results of our low-cost Pyranometer will be close enough to the results generated by the ISO 9060 Secondary Standard Pyranometer CMP11.

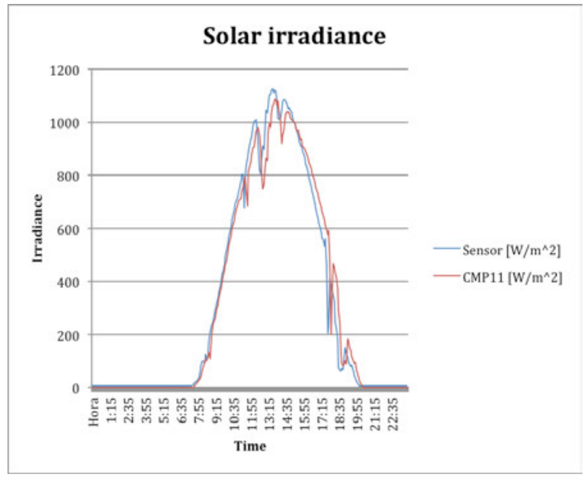

Fig. 15. Irradiance measurements using the calibration algorithm (02-17-2012).

5. DISCUSSION

From Fig. 15, it can be seen that done measurements with the proposed Low-cost Pyranometer were improved when the calibration algorithm was applied. According to these results, its performance is considerably similar to that shown by the CMP11 ISO 9060 Secondary Standard Pyranometer.

It is important to remember that the main difference between the proposed sensor and the CMP11 is the vision angle (respectively 90° and 180°). This difference means a limitation for the low-cost Pyranometer because the photo transistor received less irradiance than the CMP11. However, despite this constraint, the proposed sensor was able to measure irradiance closely similar to that measured by the CMP11.

6. CONCLUSIONS

After analyzing the results generated by the proposed low-cost Pyranometer, it is possible to state that the goal of this project was achieved. Using low-cost components easily found in the local market, it was possible to design and built a reliable Pyranometer to measure Solar Irradiance in the North of Chile (the world's First highest Solar Irradiance place).

The performance of the photo transistor (PT202C) as sensor was reasonably good although it was necessary an attenuation element to avoid saturation. The attenuator (Teflon) also showed good performance under the extreme climate conditions it had to face. It is important to state that even though the sensor was tested during the summer (Dec-Feb), particular climate conditions in the Chilean Northern territory generate rains, cloudy days and dramatic temperature variations (from day to night) during this season.

Regarding the vision angle of the Pyranometer, it was sufficient to allow enough Irradiance to reach the photo transistor even though it corresponds to just 90°.

In this case, the sensitiveness of the sensor (photo transistor) plays an important role in the accuracy of the measurements.

Future work for this low-cost Pyranometer comprehends a new design of the attenuator element to allow more irradiance to reach the sensor. The idea is to emulate the quartz dome of commercial Pyranometers to obtain a vision angle of 180°. In addition, it is necessary to keep the Pyranometer collecting solar data for about one year in order to define a better calibration algorithm. Thus, Irradiance measurements will be more representative during any period of the year.

ACKNOWLEDGEMENTS

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