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Heat flux solarimeter

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Abstract

The solarimeter presented in this work is easy to assemble. It is calibrated and its performance is validated by means of Hottel's method (Hottel, 1976). Finally, the curves obtained with this solarimeter are compared to the ones obtained with a commercial solarimeter. This device is based on the evaluation of the heat flow in a metal rod. In consequence, measurements are not affected by ambient temperature variations. On the other hand, there is a linear relationship between the temperatures measured at the rod ends and the incident radiation, as can be concluded both from the theory of its operation and the calibration lines obtained. The results obtained from the global irradiance measurements in the area of Los Polvorines (Buenos Aires Province), together with a preliminary evaluation of the solarimeter's response time, are presented in this work.

Keywords: Solar radiation; Solarimeter; Calibration

1. Introduction

The sun comprises the main source of energy involved in most earth processes. It emits large amounts of energy per time unit from its surface. This value is approximately 1367 W/m^2 at top of atmosphere for a plane that is normal to the incident radiation. However, the amount of hourly solar radiation received by a horizontal plane at sea level during a specific time of the year depends mainly on the latitude and the atmospheric conditions related to the gases and particles in suspension (aerosols) that are present (Duffie and Beckman, 1991). Despite the fact that it is possible to estimate global radiation by different calculation methods (Reindl et al., 1990), when dealing with equipment that operates with solar radiation, it is convenient to know its value with accuracy in order to optimize the equipment's performance. For this purpose, it is possible to use a standard solarimeter (Grossi Gallegos and Richijk, 2008), but they are generally quite expensive. According to their working principles, solarimeters available in the market are divided in thermoelectric and photovoltaic. Whereas the former use thermocouples, which allow us to obtain a potential difference that is proportional to the thermal difference, photovoltaic solarimeters use semiconductor materials as detectors. Our model, on the other hand, uses a surface that is exposed to the radiation. This surface is in contact with a metal rod that is thermally insulated along its length. This rod, in turn, is in contact with a metallic piece which is at ambient temperature. This array of elements allows us to obtain a thermal gap determined by the heat flowing through the rod, which, in turn, depends on the incident radiation.

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The most significant advantages of this design are:

- The low cost of its components, which are easy to obtain.
- The low mechanical precision needed to build parts.
- That it is not necessary to evacuate the area below the glass dome to prevent losses by convection because the temperature of the upper disc does not exceed 50 °C.
- The simplicity with which its components may be assembled.
- The reasonable linearity shown by the instrument, which facilitates calibration.

The calibration has been performed comparing the measurements obtained with the instrument, with the values obtained with the Hottel's clear day method. As an alternative calibration, data from our instrument were compared with that obtained ones from a central "Davis Instruments Vantage Pro2", mounted in the vicinity of our university.

2. Details and working principles of the solarimeter

This solarimeter has a blackened copper disk which constitutes the receiving surface (collector). This disk is placed below a glass dome and its lower part is in contact with a laterally insulated metal rod. The bottom of the rod is in contact with a solid aluminum cylinder which is kept from sunlight (see Fig. 1).

Due to the effect of the incident radiation on the receiving disk, its temperature (T_1) is superior to the temperature of the cylinder (T_2).

Thus, its working principle is based on the fact that the heat flowing through the rod is proportional to the incident radiation. In order to calculate the flow, the temperature difference ($T_2 - T_1$) between the ends of the rod is measured by means of electronic temperature sensors (type: DS 1624), which have an accuracy of 0.03 °C for the temperature intervals this device operates with (see Table 1).

Table 1
Solarimeter specifications.

	Height (mm)	Diam. (mm)	Material
Body	50	75	Delrin
Base	20	55	Al
Rod	50	5.35	Iron (SAE 1020)
Top disk	1.5	30	Copper

Both the hardware and the software used for data acquisition were developed by us. The heat flow that goes through the rod ($\dot{Q}_c$) in a stationary state is proportional to the radiation absorbed by the upper sensor disk. The equations that describe the energy balance are as follows:

$$\dot{Q}_{gl} = \dot{Q}_{dir} + \dot{Q}_{dif} \tag{1}$$

$$\dot{Q}_{inc} = \dot{Q}_{gl} - \dot{Q}_{ref} \tag{2}$$

$$\dot{Q}_c = \dot{Q}_{inc} - \dot{Q}'_{ref} - \dot{Q}_p \tag{3}$$

$$\dot{Q}_p = \dot{Q}_{rad} - \dot{Q}_{con} - \dot{Q}_{cond} \tag{4}$$

In these equations, $\dot{Q}$ represents the powers considered and the subscripts have the following meanings:

- *gl*: global radiation,
- *dir*: direct radiation,
- *dif*: diffuse radiation,
- *Inc*: ncident power,
- *ref*: reflected power,
- *c*: conducted by the rod,
- *p*: loss,
- *rad*: loss by radiation,
- *con*: loss by convection,
- *cond*: loss by conduction.

The Fig. 2, schematically outlines the parameters considered in the energy balance.

In according with Fourier's law, the heat flow that goes through the rod equals:

$$\dot{Q}_c = -K(T_1 - T_2) \tag{5}$$

where K is the conductivity of the rod (in W/m^2 °K), T_2 is the temperature of the collector and T_1 is the temperature of the base, which practically coincides with the ambient temperature. Thus, an increase in the incident radiation value will increment temperature T_2, with a subsequent increase in and, naturally, in the temperature difference. Based on this difference, it is possible to calculate using

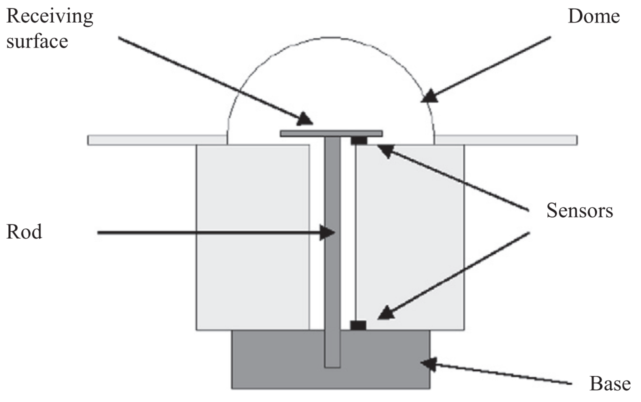

Fig. 1. Diagram of the solarimeter.

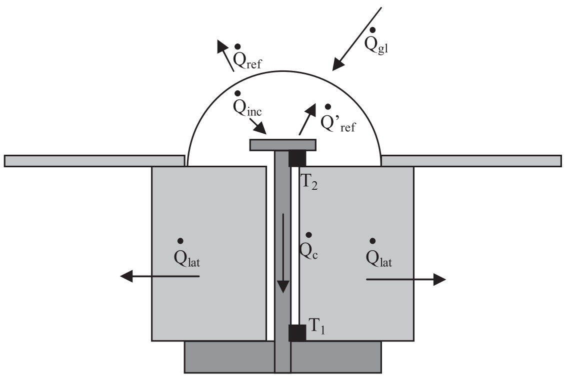

Fig. 2. Energy balance.

expression (5). After obtaining the value of the heat flow through the rod and taking into account the balance between the global radiation that is incident on the solarimeter and the losses of any kind, it is possible to calculate the value of the global radiation.

3. Loss estimation

On the one hand, not all the radiation incident on the solarimeter is absorbed by the blackened surface. Part of it is reflected by the glass dome, and a small portion is reflected by the collecting disk. On the other hand, part of the power entering the instrument is not conducted to its base by the rod due to heat loss produced in different instances. Some of these (for example, radiation loss) are not linear with temperature, which causes non linear effects on the instrument. However, all the significant losses are linear. In relation to the loss by conduction through the rod's lateral insulation ($\dot{Q}_{lat}$), we have considered the least favorable case, which consists in a constant temperature T_2, which remains the same along the rod. For the stationary state, we have considered the transfer towards the lateral surface, given by the thermal resistance of the support material (Delrin), the rod's thermal insulation (expanded polystyrene) and the convection of the surrounding air. Thus, the power dissipated through this body reaches a value of 0.25 W. On the other hand, due to the characteristics of the upper disk's surface, high emissivity (0.95) must be taken into account in order to estimate the loss by radiation in this component. Nevertheless, for its operating temperature (50 °C), there is an emission whose maximum is approximately of 9 μm. For the corresponding curve, the glass that is used in the device's dome is essentially opaque, which significantly reduces loss from the disk. As a consequence, these are negligible compared to the 0.25 W calculated previously. Thus, the global radiation can be written as:

$$\dot{Q}_{gl} = -k(T_1 - T_2) \tag{6}$$

where k is related to K through the loss calculation and the conduction through the rod.

4. Calibration

In theory, this type of solarimeter would allow us to absolutely determine the value of solar radiation (that is, determine k). This means to establish the necessary balance between loss and global radiation received by the device in such a way that the value of the global radiation is determined in function of the temperature difference between the receiving surface and the cold source. Nevertheless, we opted for a conventional calibration method. There are different methods for theoretically determining the hourly radiation. All of these methods are based on approximations which are only valid for clear days. In this case, we used Hottel's clear-day method (Hottel, 1976), which allows the estimation of global radiation for clear atmosphere conditions, considering the latitude and the altitude of the location together with the climatic characteristics. Several authors deal with the validation of Hottel's method estimations (for instance, A. Hernandez) (Hernandez, 2003). They show that the correlation between the estimations for global radiation and the data obtained by means of a conventional solarimeter is acceptable. The theoretical curves were calculated using electronic spreadsheets. Fig. 3 shows the global radiation curve estimated for December 29, 2008, in the area of Los Polvorines, in Buenos Aires Province: (35.55° south, 58.7° west, 25 m above sea level). Type of climate: summer, mid latitude.

The calibration values were obtained by recording the values of T_2 and T_1 from the solarimeter and comparing them to the radiation values given by the theoretical curves. In Fig. 4 we can see the hourly radiation values determined by Hottel in function of the temperature difference between the solarimeter plates.

From which the calibration line given by the expression (7) is obtained:

$$I_{UNGS} = (46.1\ \mathrm{W/m^2\,K}) : \Delta T + 23.5\ \mathrm{W/m^2} \tag{7}$$

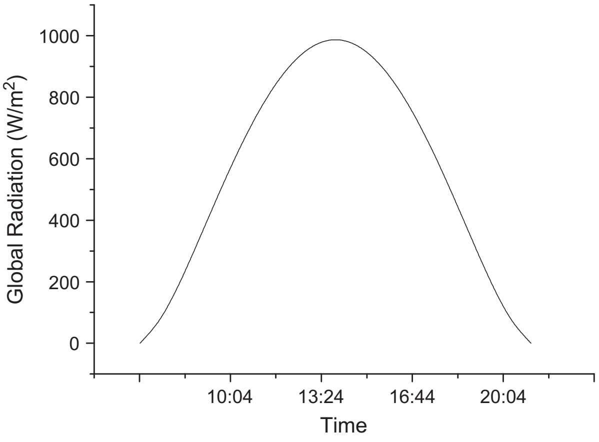

Fig. 3. Hottel's curve December 29, 2008.

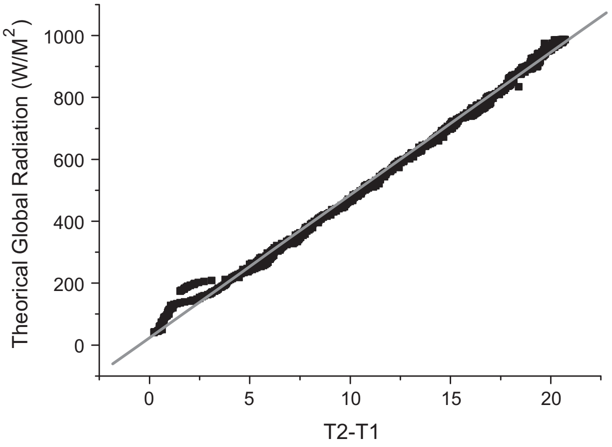

Fig. 4. Determination of the calibration line – December 29, 2008.

where I_{UNGS} represents the radiation determined by the solarimeter and ΔT, the temperature difference between the rod ends. The same method was used to perform the calibrations for December 26 and 30, 2008, and the following lines were obtained respectively (see Figs. 5 and 6):

$$I_{UNGS} = (46.3\ \mathrm{W/m^2\ K}) : \Delta T + 6.3\ \mathrm{W/m^2} \tag{8}$$

$$I_{UNGS} = (46.8\ \mathrm{W/m^2\ K}) : \Delta T + 30.6\ \mathrm{W/m^2} \tag{9}$$

Based on the expressions (7)–(9), it can be assumed that the most suitable calibration line will be determined by the medium value between them:

$$I_{UNGS} = (46.4\ \mathrm{W/m^2\ K}) : \Delta T + 16.8\ \mathrm{W/m^2} \tag{10}$$

After analyzing Figs. 4–6, we can assume that there is a linear relationship between the radiant energy received by the solarimeter and the temperature difference T between the rod ends. However, as can be seen in the graphs, the linear tendency begins to disappear for values below 200 W (also, for zenith angles above 75°). This can be probably explained by the quality of the blackened surface, or by possible shifts in the theoretical values near sunrise and sunset (Salum et al., 2007).

Figs. 7 and 8 show the adjustment of the curves that were obtained with our solarimeter, and the values estimated using Hottel's method.

By analyzing the data obtained from the measurements and the theoretical curve, it can be deduced that the average error is of 9.3%. However, this value is significantly reduced if the values below 200 $\mathrm{W/m^2}$ are not taken into account. In that case, the average error is of 3.2%. Thus, the correlation between the experimental data and the values obtained by Hottel's method is satisfactory when the radiation values are higher than 200 $\mathrm{W/m^2}$. As can be observed in the graphs corresponding to December 26 and 29, this phenomenon was present in most of the measurements that were performed. Even though it is desirable that the experimental data correlates with the hourly radiation values throughout the day, for many applications this misadjustment below 200 $\mathrm{W/m^2}$ is not relevant. It is important to highlight the temporal displacement between both curves. As can be seen in the graph shown in Fig. 9, the maximum of radiation for the experimental data is produced 12 min later than the corresponding theoretical value.

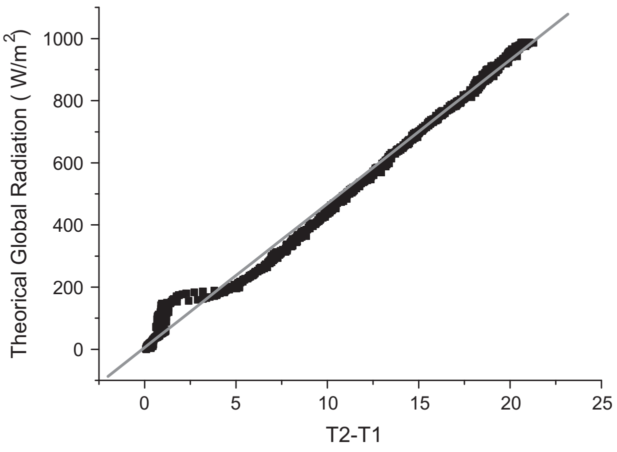

Fig. 5. Determination of the calibration line – December 26, 2008.

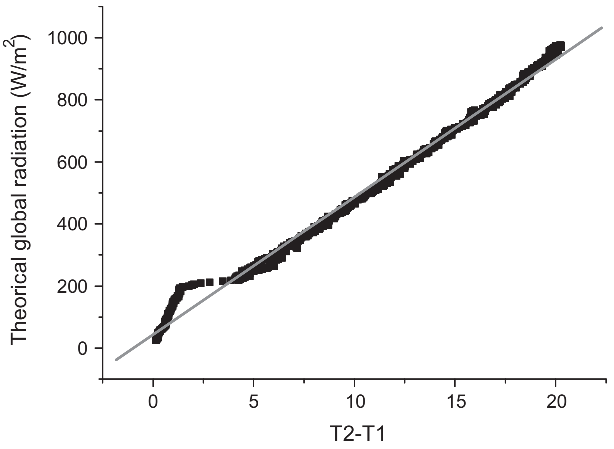

Fig. 6. Determination of the calibration line – December 30, 2008.

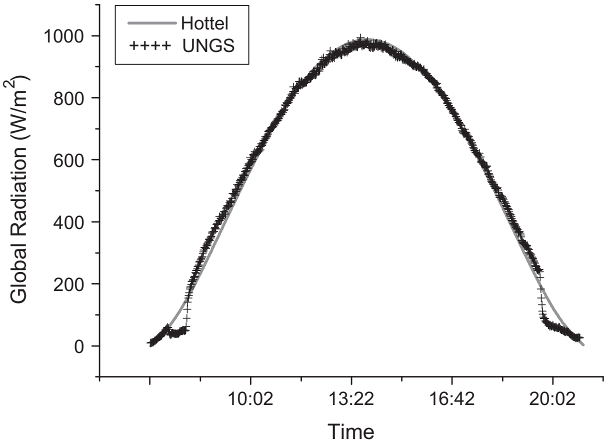

Fig. 7. Comparison of curves December 26, 2008.

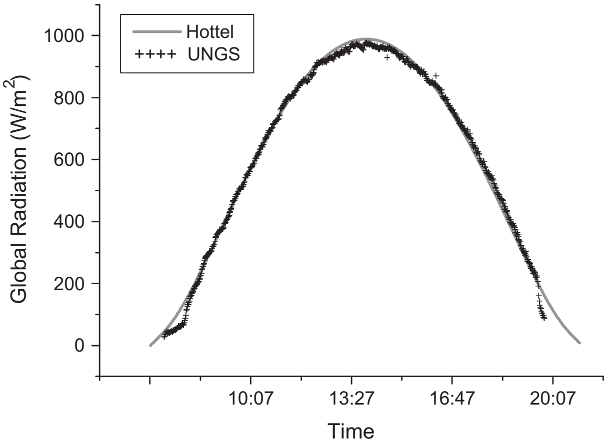

Fig. 8. Comparison of curves December 29, 2008.

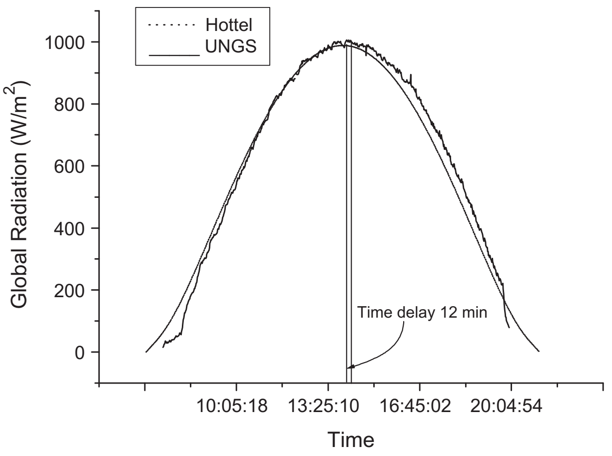

Fig. 9. Graph that shows the temporal displacement of the solar midday for December 29.

The response time of the solarimeter is currently under analysis. The first results obtained seem to indicate that this shift is correlated with approximately three times our instrument's relaxation time. However, this may be due to other phenomena, such as the presence of aerosols in the atmosphere (Salum et al., 2007).

In addition, the qualitative behavior against the wind seems to be acceptable, although we must carried out a quantitative analysis using controlled gusts of wind in laboratory.

5. Alternative calibration

An alternative way of calibrating our instrument was using the data obtained from an automatic station located in the lands belonging to the Servicio Meteorológico Nacional (National Weather Service), located in the area of Villa Ortúzar, Ciudad Autónoma de Buenos Aires (http://www.smn.gov.ar). Since our device is located in the campus belonging to Universidad Nacional de General Sarmiento (in Los Polvorines) and the weather station is approximately 20 km away, we were confined to perform comparative measurements only on clear-sky days. This is because the variation of radiation due to clouds or specific atmospheric conditions might affect each device differently. On the other hand, the solar hourly difference (resulting from the different geographical locations) was not significant enough since it is only of 1 min approximately (0.25° longitude) and in addition the latitude is almost the same. The line corresponding to this calibration (naturally, the same days were considered) is as follows:

$$I_{UNGS} = (48.3\ \mathrm{W/m^2\,K}) : \Delta T - 0.3\ \mathrm{W/m^2} \tag{11}$$

This shows that there is satisfactory concordance between both calibration methods. Fig. 10 shows the adjustment of the data obtained from the Servicio Meteorológico Nacional and the values measured with our solarimeter, which were determined with the calibration line (5).

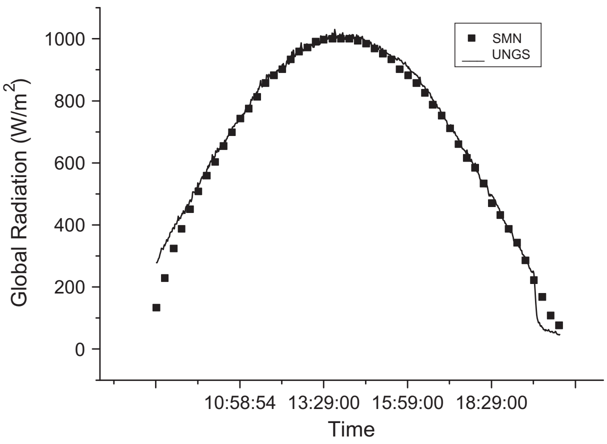

Fig. 10. Comparison of the curves of the SMN and the UNGS for December 29, 2008.

6. Conclusions

The device designed presents a satisfactory response for the measurement of global radiation. As can be seen, the straight lines obtained by calibration using Hottel's method and the data from the Servicio Meteorológico Nacional are similar. This indicates a stable behavior when compared to the curves obtained with both types of data (theoretical and experimental). On the other hand, we can identify some misadjustment in the correlation of the values both from the first hour after sunrise and the hour previous to sunset. Even though this is not desirable, it does not take place significantly in the interval during which the radiation power is above 200 W/m^2. Finally, the typical response time of the solarimeter is of about 12 min. Since it would be convenient to shorten it, some aspects are currently under reevaluation in order to verify whether it can be improved. Among other things, an evaluation to determine the level that sets the response characteristic of temperature sensors will be performed.

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