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Solar radiation and the fraction of the visible sun's disk during an eclipse

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Abstract

The change of illumination on the 9th March 2016 solar eclipse has been monitored using a light sensor a simple instrument that is available in most laboratories. This observation was conducted in Yogyakarta (7^0 46'S, 110^0 20'E). The results were normalized to the illumination on the normal day, i.e., on 5th March 2017 and on 8th March 2018, to obtain the fraction of the uncovered sun's disk. The minimum illumination during eclipse corresponded to the 80.5% obscuration. This simple method showed a good agreement with the available data obtained from Stellarium.

Keywords: Eclipse, Solar radiation, Light sensor.

Resumen

El cambio de iluminación del eclipse solar del 9 de marzo de 2016 se ha monitorizado mediante un sensor de luz, un instrumento sencillo que está disponible en la mayoría de los laboratorios. Esta observación se realizó en Yogyakarta (70 46'S, 1100 20'E). Los resultados se normalizaron a la iluminación del día normal, es decir, el 5 de marzo de 2017 y el 8 de marzo de 2018, para obtener la fracción del disco solar descubierto. La iluminación mínima durante el eclipse correspondió al 80,5% de oscurecimiento. Este sencillo método mostró una buena concordancia con los datos disponibles obtenidos de Stellarium.

Palabras clave: Eclipse, Radiación solar, Sensor de luz.

I. INTRODUCTION

Solar radiation has been studied in various fields. These studies are related to the availability of solar energy, the effect of intensity on the season, and temperature distribution. Visible movement of the sun has been modelled. This model can predict daylight duration and be applied for a practical purpose of harvesting the solar energy [1]. The same model is also used to construct global maps with distribution of daily insolation, and to simulate the passage of the seasons on the Earth [2].

Different instruments have been utilized for measuring the solar radiation. Using a homemade pyranometer Zanetti and Zecca showed the light intensity in arbitrary unit for a full day [3]. In the other experiment the pattern of solar radiation has been monitored; thermocouples and an Eppley Precision Spectral Pyranometer were utilized for measuring temperature of the shingles and total solar radiation, respectively. As expected, the temperature follows the pattern of solar radiation [4].

In contrast to the studies above, during the eclipse solar radiation shows a special behaviour. Therefore, the solar eclipse attracts observers from the entire world. Different articles on solar eclipses can be found in the pedagogic journals in physics. Richard and Smart measured a decrease in negative ion concentration in the atmosphere, and recorded solar magnitude as well as studied shadow bands [5]. Production of shadow bands during an eclipse has also been modelled [6]. For the intermediate astronomy courses a solar eclipse has been predicted. It is assumed that the moon's position is along the circular orbit. This simplification and the data from the almanac, can be utilised to predict the longitude and latitude for the observation location. Furthermore, the width of the eclipse's shadow on the earth and the duration of totality can also be calculated [7]. By observing the moon's shadow during the solar eclipse, Sawicki determined the radius of the moon's orbit, i.e. 376 000 km [8]. Resources for observing solar eclipses can be found in a recent article [9].

A decrease of solar radiation has been monitored during an eclipse [10]. The measurement was performed using a photometer operated in three spectral regions, i.e. infrared, red and blue. This article showed the variation of the ratio of the light intensity during an eclipse day and at the previous day without the theoretical background. In a different way a model of solar radiation during an eclipse was developed. The algorithm has been tested in the global solar UV radiation during the partial solar eclipse in Italy [11]. The change of illuminance during a solar eclipse of 2006 has been measured [12]. Calibrated equipment that was oriented perpendicular to the light was utilized for measuring the illuminance. In this case a model was presented based on the assumption that the illuminance is proportional to the unobscured area of the sun's disk. The model is in a good agreement with measured data.

The total solar eclipse of 9 March 2016 over Indonesia was observed from the east to the west regions of the country. This phenomenon could be seen in different parts of Indonesia. In Indonesia the first contact started at 06:19:41 local time. The longest duration of the eclipse was observed in Jayapura, Papua, i.e. 2 hours 55.05 minutes. The maximum duration of totality of the eclipse was 3.325 minutes, which was observed in Maba, North Maluku.

This solar eclipse was also seen partly from Yogyakarta (7^0 46'S, 110^0 20'E) located on Java Island. This location is not in the total eclipse path. This phenomenon lasted for 2 hours and 14.74 minutes. The maximum eclipse obscuration was 80.5%. It was fortunate that during this time the sky was mostly clear and cloudless; the eclipse could be monitored clearly and completely from the beginning to the end.

This special occasion makes an interesting study. Here the incoming solar radiation depends on the visible sun's disk. The solar radiation was monitored easily using a light sensor; a simple instrument that is available in most common physics laboratories. Using a simple formula, the fraction of visible sun's disk can be determined from the measured data. The experiment presented in this paper can be conducted by any students using a simple light sensor during an eclipse. The students will also learn a direct effect of the eclipse.

II. THEORY

The direct solar beam radiation intensity on a horizontal sensor surface I_b is a function of the sun-earth distance, the solar zenith angle, solar constant and the transmittance function [13]. The solar zenith angle depends on the latitude, the declination angle, and the angular displacement of the sun due to rotation of the earth on its axis. The declination angle as well as the sun-earth distance varies due to the earth's movement around the sun. These factors give the annual and diurnal variation in the incoming solar radiation. For a particular date the sun-earth distance is relatively constant and therefore the incoming solar radiation on a fixed place only shows the diurnal variation and can be expressed as

$$I_b = I_{\max} \, T \cos\theta_z \ , \tag{1}$$

where I_{max} is the maximum intensity that is determined by the solar constant and the sun-earth distance; θ_z is the solar zenith angle; T is the transmittance function related to the absorption and scattering processes in the atmosphere that depends on the availability of gases in the atmosphere. For the sun's altitude α as seen in Fig. 1, Eq. (1) becomes

$$I_b = I_{\max} \, T \cos(90-\alpha) \, . \tag{2}$$

In this experiment the light sensor was mounted in an inclined holder (Fig. 2). For this tilted sensor the Eq. (2) should be corrected by tilt angle β, and hence [14-15]

$$I_{bt} = I_{\max} \, T \cos(\beta-\alpha) \ . \tag{3}$$

During the eclipse the moon covers part of the sun's disk. The incoming solar radiation is proportional to the area of the visible bright disk [11, 16]. Therefore, the correction should be given, and its intensity during eclipse day I becomes.

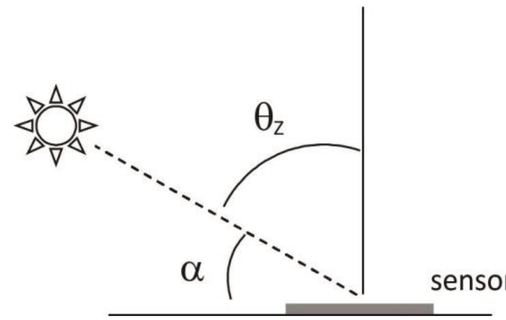

FIGURE 1. The solar radiation on the horizontal sensor.

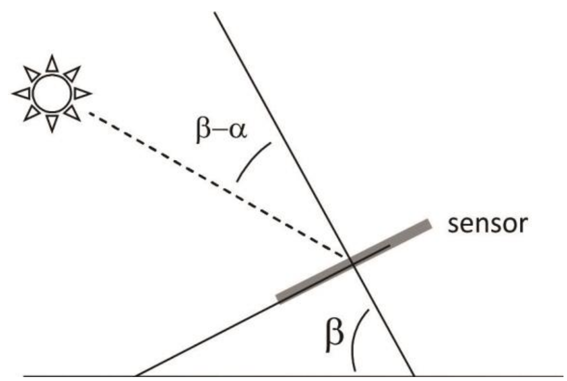

FIGURE 2. The solar radiation on the tilt sensor.

Beside this direct radiation there is also a diffuse radiation I_d. As a result, the total intensity I_T on the tilt sensor follows

$$I_T = I_{bt} + I_d \ , \tag{4}$$

$$I = A_r \, I_T \, , \tag{5}$$

where A_r represents the fraction of the uncovered solar disk. In this case the fraction of the sun's area occulted by the moon is defined as eclipse obscuration E_o and hence

$$A_r = 1 - E_o \, . \tag{6}$$

The fraction of visible sun's disk can be determined from Eq. (5) by measuring the solar radiation during an eclipse day I and in the normal day I_T. These measurements should be in the same experiment's condition, i.e., the date, the time, the position (orientation and tilt angle) of the sensor and the atmosphere. The requirement of the date was approximately fulfilled by measuring I_T on the same week of the eclipse day or at least the same week of the year.

III. EXPERIMENT

The solar radiation intensity has been measured using a light sensor (BTA Vernier), which is a small photodiode (1mm x 1mm). This sensor was placed inside the glass cylinder and was secured near the tip of the cylinder. This sensor is connected to a laptop via an interface *LabPro* product of Vernier [17]. A laptop provides data acquisition and controls the experiment, and for this purpose it is equipped with software *LoggerPro*. The experimental setup is depicted in Fig. 3. The light sensor is mounted on the holder on an incline of 25°. The sensor position is in front of the holder and perpendicular to this incline. The holder is placed in the balcony oriented to the East, directly toward the sun. All measurements utilize this experimental setup condition.

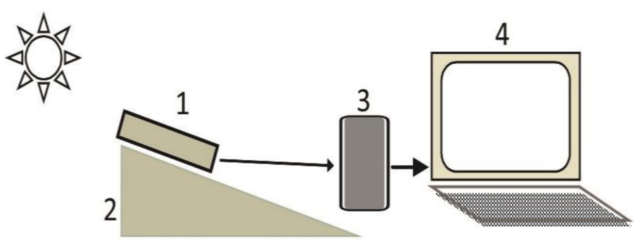

FIGURE 3. The experimental setup. The light sensor (1) is mounted on holder (2). The interface Labpro (3) is used to connect the light sensor to a laptop (4).

The eclipse on 9 March 2016 was predicted to occur from 06:20:32 to 08:35 local time, and it reached a maximum obscuration at 7:23:30 local time. Therefore, on this day the solar radiation was collected continuously from 06:00 local time to 10:00 local time. On the day of the eclipse the sky was mostly clear, although it was in the rainy season. The solar radiation was recorded as illumination in unit lux. Fig. 4 shows the result, the shaded area given highlights the period of the eclipse.

At the beginning, the illumination increased gradually due to the diurnal behaviour. As expected, the effect of eclipse reduced the illumination and in overall showed clearly a dip. If we inspected closely, the decrease in the illumination was not instantaneously following the increase of the covered sun's disk. At first the effect was not dominant, an increase of illumination was still observed. After about 25 minutes from the first contact, the illumination started decreasing, reaching minimum at 07:21 local time and then back to increase. The maximum-recorded illumination was observed at 08:55 local time.

To obtain solar radiation on a normal day, with approximately the same experimental condition as during the eclipse, a series of measurements were also performed from 4th March to 14th March 2016. Unfortunately, the presence of clouds impacted these measurements. The incoming solar radiation showed dips and peaks e.g., as shown in Fig. 5 for the result of 12th March 2016. The heavy clouds in the early morning significantly reduced the solar radiation, subsequently the cloud appeared randomly. Similar or even irregular results were found in this first attempt.

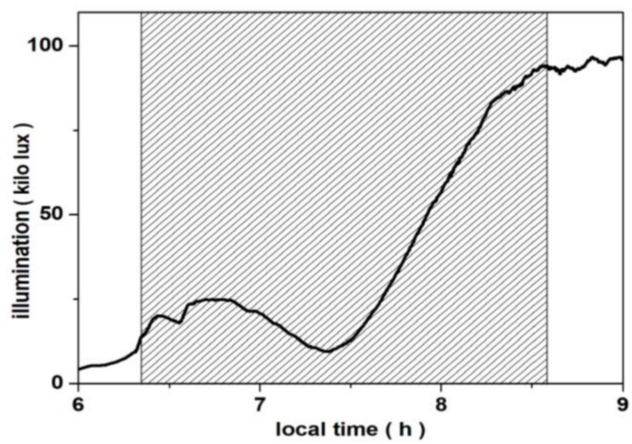

FIGURE 4. The illumination observed during eclipse on 9th March 2016.

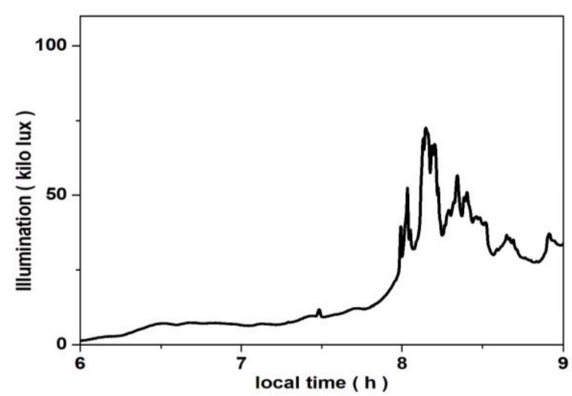

FIGURE 5. The illumination observed on 12th March 2016.

Due to this situation the second attempt was performed in the following year i.e., 2017. Solar radiation was measured from 4th March to 14th March 2017. A special attention was given to the measurement on 9th March 2017. Similar to the first attempt, the clouds obscured the solar radiation due to the season. The best result was obtained on 5th March 2017. On this day the cloud was relatively absent, the result is shown in Fig. 6.

Fig. 6 shows a pattern of solar radiation on a normal day. Although the pattern is not smooth, due to the atmospheric condition, this gives roughly a complete pattern. The illumination increases and reaches its maximum at around 09:00 local time.

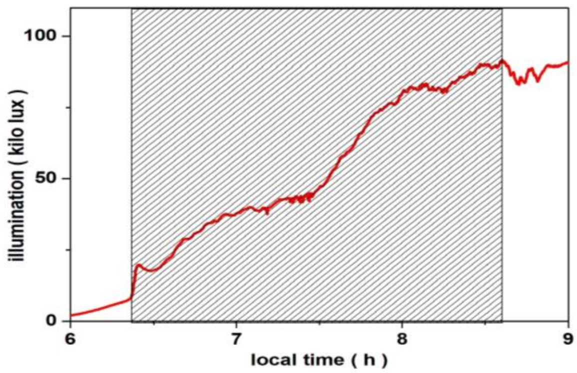

FIGURE 6. The illumination observed on 5th March 2017.

The last attempt was performed on the third year i.e., from 4th March to 14th March 2018. Due to the rainy season the presence of clouds hindered the radiation. In this attempt the best result was measured on 8 March 2018, and it is shown in Fig. 7.

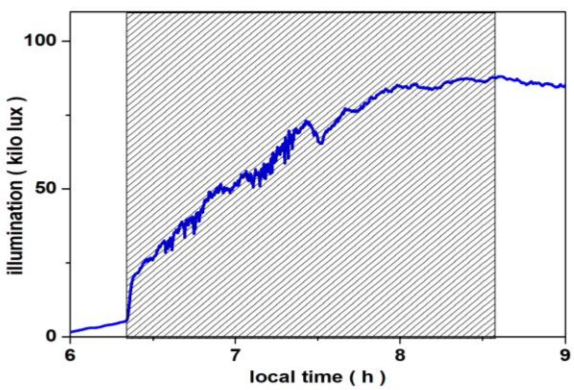

FIGURE 7. The illumination observed on 8th March 2018.

IV. DISCUSSIONS

Following Eq. (5), there are two effects that determined the total incoming solar radiation, the diurnal variation and the percentage of the eclipse. Both of them depend on the time. To show the effects of the eclipse, first we pay close attention to the pattern of solar radiation on a normal day e.g., showed in Fig. 6.

In the beginning the illumination is low, then it increases sharply and reaches its maximum at around 09:00 local time. This pattern is caused by the diurnal variation and the tilt sensor. The low illumination during the first part of the experiment is a diffuse radiation; this is due to the direct solar radiation that was blocked by a building. The following sharp increase of illumination indicates that the sensor was starting to receive the direct solar radiation. An increase of solar altitude will be accompanied by an increase in illumination. Based on Eq. (3), the illumination will increase and reach maximum at $\alpha=\beta$. On 5th March 2017, the sunrise and the sunset occur at 05:43 and 17:53 local time, respectively. From the day length we can calculate the sun's altitude at 09:00 local time is $\alpha=24^0$. The sensor holder is tilted ($\beta=25^0$) causing the sensor surface to be almost perpendicular to the sunrays at 09:00. The rest of the time the oblique sunrays cause less illumination. This similar situation is observed on Fig. 7 for the result of 8th March 2018. A difference of absolute illumination found on those figures is caused by the atmospheric condition.

The information of the sun such as position and other related data can be obtained from a free software e.g., Stellarium [18]. Using this software, we can follow the process of eclipse and collect the appropriate data. The collected eclipse obscuration of the 9th March 2016 eclipse is used to determine the relative visible sun's size using Eq. (4) and is presented in Fig. 8. In a normal condition the relative sun's size is one. During eclipse the visible sun's size decreases, reaching a minimum and then back to a normal size. The maximum eclipse obscuration observed in Yogyakarta was 80.5%, which gave the minimum relative visible sun's size of 0.195.

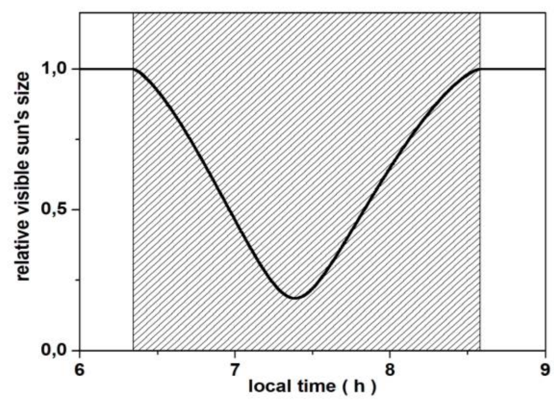

FIGURE 8. The relative visible sun's size obtained from the eclipse obscuration on 9th March 2016 using Stellarium (location: Yogyakarta).

The visible sun's size can be also determined using Eq. (5). The ratios of the solar radiation during the eclipse (Fig. 4) to the solar radiation on the normal day (Fig. 6 and 7) are shown in Fig. 9 and 10. In Fig. 9 the ratio (red line) is obtained from the illumination during the eclipse on 9th March 2016 and on the normal day (5th March 2017). In addition, the calculation using the Stellarium (black line) is presented for the comparison. Due to the atmospheric condition on those days, the ratio is not flawless. During the eclipse period (the shaded area) the ratio decreases, reaches a minimum and returns to the previous value. This ratio represents the fraction of the visible solar disk. Its pattern changes the illumination during the eclipse e.g., a clear dip in Fig. 4.

Fig. 10 shows the ratio (blue line) calculated from the illumination during the eclipse on 9th March 2016 and on the normal day (8th March 2018). It has the same behaviour as Fig. 9. It is clear that the ratio matched to the previous calculation using the eclipse obscuration previously recorded from the Stellarium. The discrepancies in the edge of Fig. 9 and Fig. 10 are caused by the atmospheric conditions and low solar radiation. In this part a small fluctuation in solar radiation will give a large change in the ratio. Overall, the agreement of the experiment and the calculation is quite good.

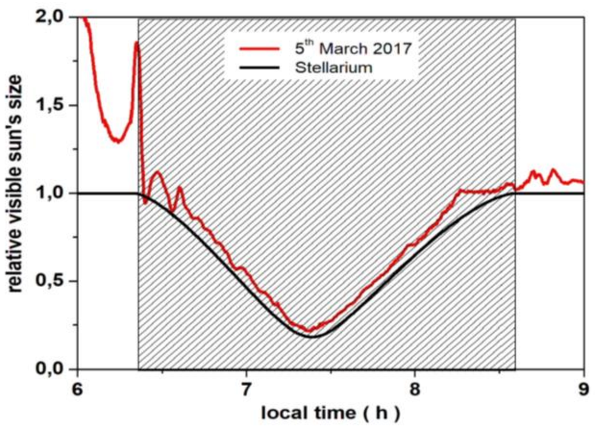

FIGURE 9. The relative visible sun's size obtained from: **(a)** the ratio of solar radiation on 9th March 2016 to solar radiation on 5th March 2017 (red), and **(b)** the calculation using the Stellarium (black).

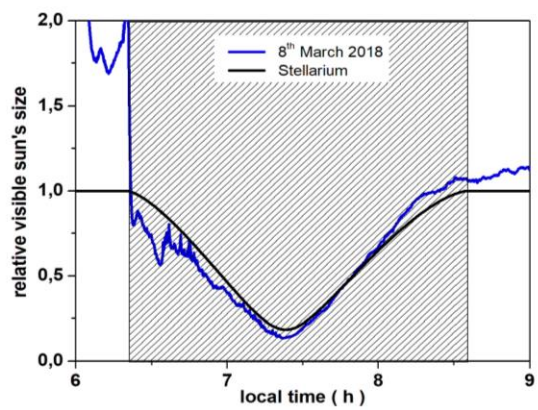

FIGURE 10. The relative visible sun's size obtained from: **(a)** the ratio of solar radiation on 9th March 2016 to solar radiation on 8th March 2018 (blue), and (**b**) the calculation using the Stellarium (black).

The experiment presented here is quite simple, as it directly shows the effect of the obscuration. The observation place can be chosen in a partially eclipse region, it is not necessary in the total eclipse path. The experiment result is a relative number that can be obtained without a calibrated instrument. Therefore, this experiment can be performed using any light sensor such as a solar cell. The overall constraint of this experiment is the weather conditions. The weather conditions during a normal day should be comparable as those of the eclipse.

V. CONCLUSIONS

The solar radiation can be monitored using a simple light sensor that is available in most physics laboratories. Using a simple formula, the visible sun's size can be determined from the solar radiation during an eclipse and a normal day. This experiment can be performed in the partially solar eclipse region.

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