Celebrating the 2017 Great American Eclipse: Lessons Learned from the Path of Totality
ASP Conference Series, Vol. 516
Sanlyn Buxner, Linda Shore, and Joseph Jensen, eds.

A Simple Model of the Global Horizontal Irradiance During a Total Solar Eclipse

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Abstract. The purpose of this paper is to discuss the measured irradiance during the eclipse and to compare the irradiance with a simple straightforward model that estimates the effect of the eclipse on solar radiation. The intended audience of this paper is for high school and university educators that want to give their students a simple model to predict the effects the eclipse has on the light reaching the earth. The paper is outlined as follows. First a general overview of irradiance on a non-eclipse day and an eclipse day will be discussed. Next, a straightforward model of the eclipse will be used to predict the irradiance during an eclipse from a clear sky model. Lastly, the modeled irradiance will be compared to the measured irradiance and the results will be discussed.

The University of Oregon, Solar Radiation Monitoring Lab (SRML) actively maintains 20 solar monitoring stations throughout the Pacific Northwest to measure and characterize the regional solar energy resource. These monitoring stations measure the irradiance (power per area) of light reaching the surface of the earth. Measurements are made both night and day every day of the year. The monitoring station in Salem, Oregon was in the path of totality during the eclipse event on August 21, 2017. The irradiance measurements from the Salem station were recorded during the entire eclipse at one-minute intervals. The weather conditions during the eclipse at this site were ideal with cloudless skies the entire time.

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Global horizontal irradiance (GHI) is the power per area measured on a horizontal surface coming from all portions of the sky. The units of irradiance are W/m^2. During clear sky periods, roughly 90% of the power is directly from the sun and the remaining 10% is from the rest of the sky. Typical values of GHI on a clear day in midsummer in North America are between 800 and 1000 W/m^2.

Figure 1 shows a plot of GHI vs time for a non-eclipse clear day. The data shown in Figure 1 is from the Salem, Oregon monitoring station on August 16, 2017. This day was chosen as an example because it was a clear day that was close to the date of the eclipse (August 21, 2017). The irradiance reaches a maximum value when the sun is

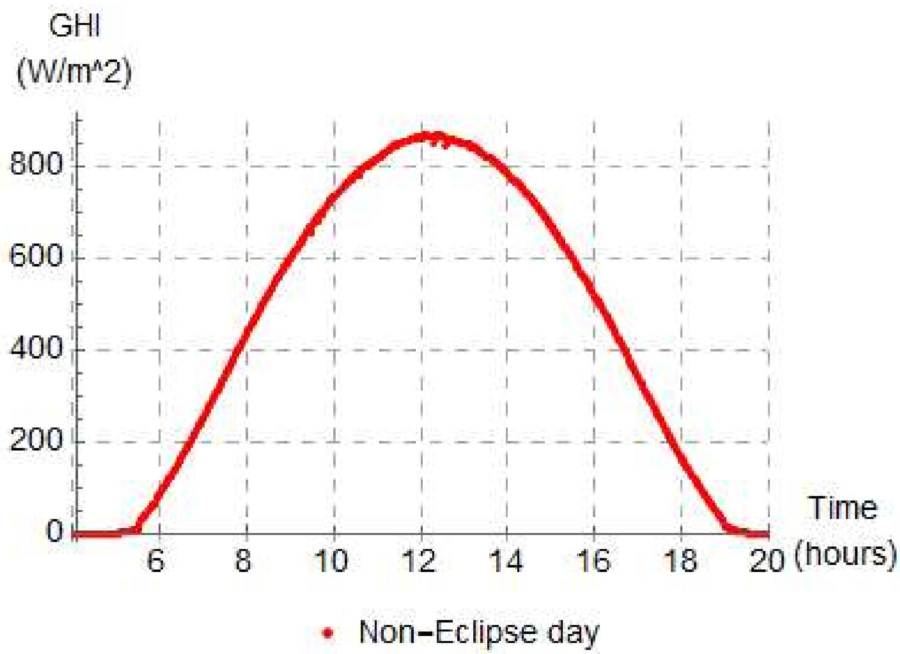

Figure 1. Global Horizontal Irradiance vs time of day for a clear non-eclipse day. The day plotted is August 16, 2017 for the Salem, Oregon solar monitoring station.

highest in the sky at solar noon. Solar noon is defined as the time the sun is highest in the sky. Solar noon is different than clock time noon because clock time is a constant over the whole time zone whereas the sun is highest in the sky at different times inside the time zone. At night the total sky irradiance is essentially zero.

In Figure 2, the irradiance of a non-eclipse day (August 16, 2017) is compared to the irradiance during the eclipse (August 21, 2017). From Figure 2, it is clear to see how the eclipse alters the irradiance. At this location, the eclipse begins at 8:06 AM and ends at 10:37 AM, with totality from 9:18–9:19 AM. All times listed are in Pacific Standard Time (PST). During totality the irradiance was 0 W/m^2 as one would expect. During this time period, the clear sky irradiance is increasing while simultaneously the sun is being shaded by the moon, producing the interesting curve shown in Figure 2. The shape of the curve is dependent on the time of day the eclipse occurs.

To model the irradiance during the eclipse, the clear sky values of a non-eclipse day will be adjusted in magnitude and then multiplied by a shading factor of the sun. These adjustments will produce a model that is straightforward, simple, and moderately accurate.

In Figure 2, the irradiance of the non-eclipse day is slightly greater than during the eclipse. The elevation of the sun in the sky changes as the seasons change. As summer transitions to fall, the sun is lower in the sky with every passing day. When the sun is lower in the sky, the irradiance of light is less. This is a predominant reason for the difference between the two curves shown in Figure 2. The August 16th data set (non-eclipse day), is one week earlier than the August 21st data set (eclipse day). The average difference between the two days is calculated during non-eclipse times,

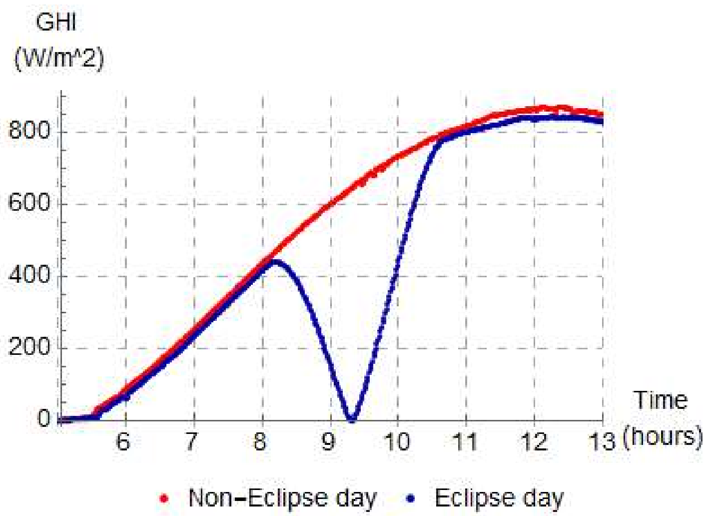

Figure 2. Irradiance vs time for a non-eclipse day and during an eclipse. Note that the before and after the eclipse the irradiance of the non-eclipse day is larger than the eclipse day.

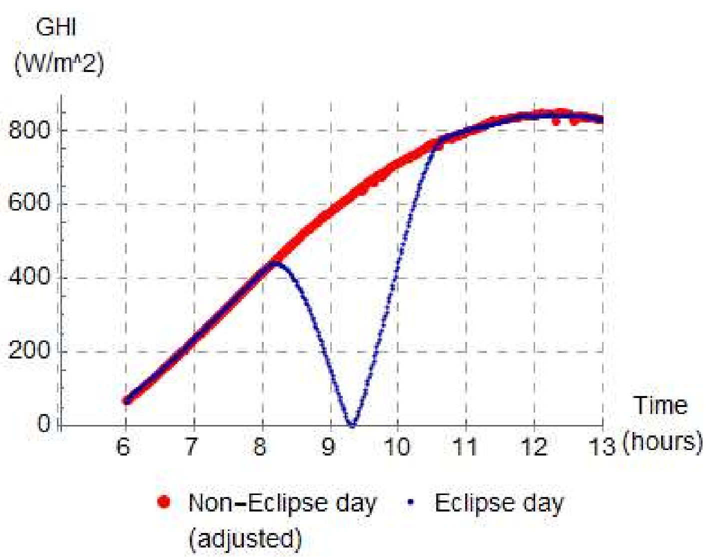

Figure 3. The adjusted non-eclipse data and the eclipse data plotted vs time. The two data sets have been aligned during alltimes when the eclipse is not occurring.

from 6:00–7:30 and from 11:00–13:00. The average difference is 20.6 W/m^2. The non-eclipse data was adjusted according to Equation 1:

$$Non\text{-}Eclipse\ (Adjusted) = Non\text{-}Eclipse - 20.6\mathrm{W/m^2} \quad (1)$$

Figure 3 shows the adjusted non-eclipse data plotted against the eclipse data. The two data sets align nicely during all times when the eclipse was not occurring. The standard deviation between the two data sets is 4 W/m^2.

To minimize variations in the non-eclipse data set caused by minor fluctuations in the atmospheric conditions, the adjusted non-eclipse data is fit to a 5th order polynomial curve. The time period of the fit was from 6:00–13:00. The fit curve is plotted against the adjusted non-eclipse data in Figure 4. The fit curve will provide a basis for how much sun is available during the time of the eclipse. This is the amount of full sun when there is no shading by the moon. The standard deviation of the fit and the adjusted non-eclipse data is 5 W/m^2 at the 95$^{\text{th}}$ level of confidence.

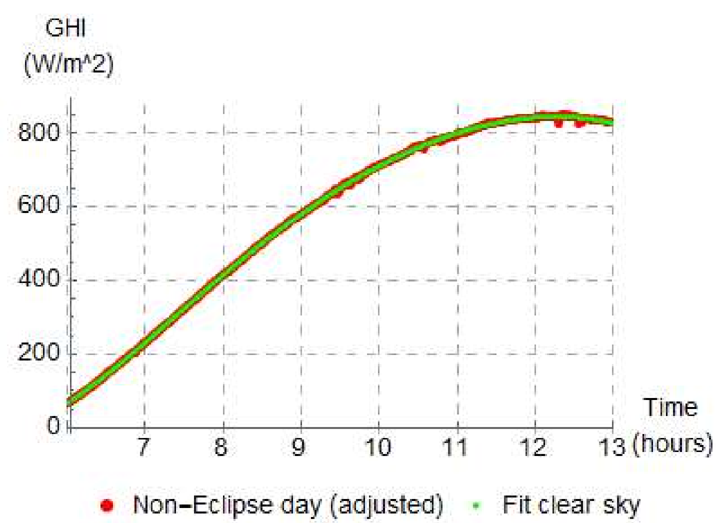

Figure 4. The adjusted non-eclipse data and the fit of the data vs time. Excellent agreement exists between the fit and the data.

Clear sky irradiance calculators can be downloaded from various websites on the internet. These calculators allow the user to compute GHI values at any location on the earth and will produce clear sky data sets similar to the data set shown in Figure 4. The Bird clear sky irradiance model (Bird 1981) is one such example and can be downloaded from the internet.[1]

With an understanding of the clear sky conditions we turn our attention to the eclipse. The MIDC SAMPA calculator (Reda 2010) is a solar/lunar calculator that can downloaded.[2] The calculator can compute the locations and sizes and of both the sun and the moon. The calculator has an uncertainty of $\pm 0.0003°$for the sun position and $\pm 0.003°$for the moon position. The calculator can also compute the percentage of the sun that is not shaded by the moon.

Using this calculator, the percentage of sun that is not covered at each minute is computed. The light from this portion of the sun reaches the earth. To determine the

[1]`http://rredc.nrel.gov/solar/models/clearsky/`

[2]`http://midcdmz.nrel.gov/solpos/sampa.html`

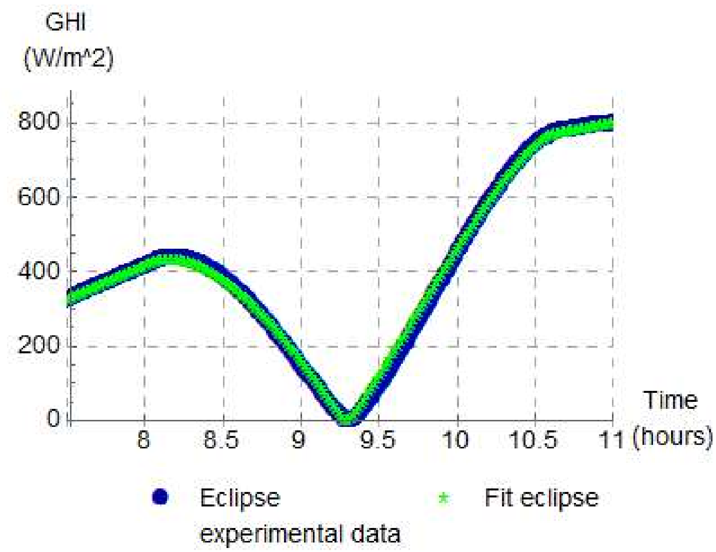

Figure 5. Experimental and modeled eclipse data vs time. The model reproduces all the features of the experimental data.

irradiance during the eclipse, multiply the fit clear sky conditions by the amount of sun visible as shown in Equation 2:

$$eclipse\text{-}fit = clear\text{-}sky\text{-}fit \times percentage\text{-}of\text{-}sun \tag{2}$$

where *eclipse-fit* is the modeled GHI value during the eclipseand *clear-sky-fit* is the clear sky fit values shown in Figure 4. The *percentage-of-sun* is the percentage of the sun visible generated by the MIDC SAMPA calculator.

Figure 5 shows the modeled eclipse and the experimental data acquired during the eclipse. Overall the model does a good job of reproducing the features of the eclipse. The model gets the curvature in the plot from 8:00 until 9:00. Both data sets reach zero irradiance at totality. The model matches the experimental data before and after the eclipse.

The differences between the fit and the experimental data are shown in Figure 6. Before and after the eclipse the differences are less than 5 W/m^2. When the eclipse first begins (8:00–8:30) and when the eclipse is ending (10:00–10:30) the model underestimates the irradiance with differences up to -10 W/m^2. Just before and after totality there is up to a 25 W/m^2 difference in irradiance. This can be seen in Figure 5 with the fit over estimating the experimental data. During totality, the differences between the two curves are zero shown in Figure 6 with the red circled data points. Both data sets produced zero irradiance during totality. The uncertainty (not shown) in the instrument making the irradiance measurements is $\pm$10W/m^2.

The percent difference between the model and the experimental data is shown in Figure 7. When the irradiance is less than 20 W/m^2 the percent difference is not shown. From Figure 4, the fit appeared to adequately describe the eclipse. However, Figure 7 shows that this description produces significant percent errors. Some of these errors can be attributed to the fact that near the time of totality the irradiance is a small value, so that any differences that exist will be enhanced when viewed as the percent difference.

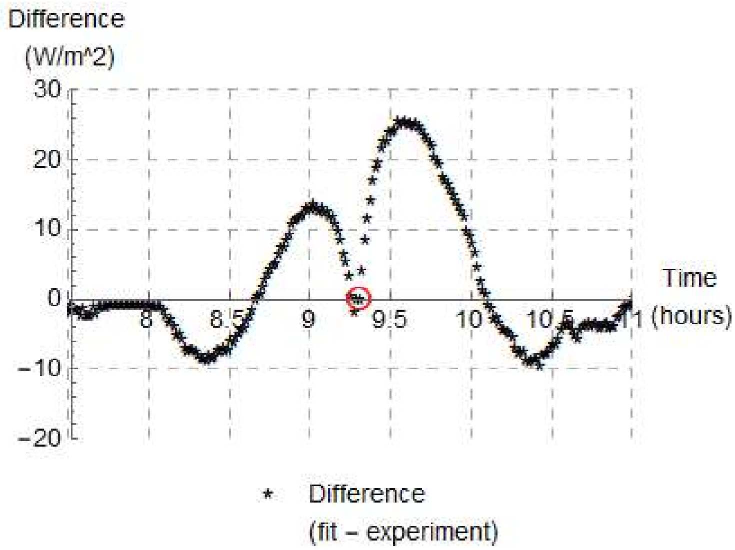

Figure 6. The difference between the fit and the experiment vs time. The data points that exist during totality are circled in red and have a difference of zero.

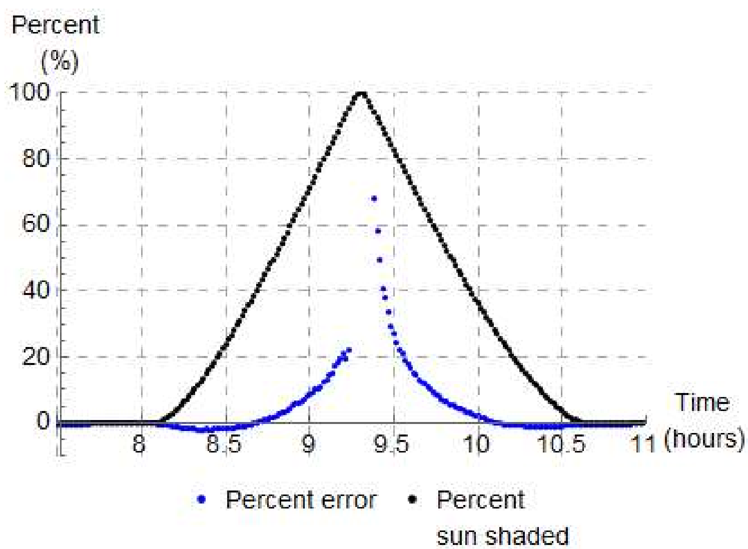

Figure 7. The percent difference between the fit and the experimental data vs time. For comparison purposes, the percent of sun that is shaded is also shown in the figure.

Light reaching a horizontal sensor, is incident from two sources; light directly from the sun and light from the rest of the sky. One reason for the differences seen in Figure 6 is that the model treats these two sources identically. An improvement to the model can be made if these two components are treated separately and added together using Equation 3.

$$GHI = DrHI + DfHI \tag{3}$$

Where DrHI is the irradiance of light directly from the sun (Direct Horizontal Irradiance) and DfHI is the light from all other portions of the sky (Diffuse Horizontal Irradiance). During the eclipse, the decreased irradiance in the DrHI would be performed exactly using a modified version of Equation 2.

The diffuse irradiance calculation can become significantly more challenging depending on how detailed one gets. The original origin of the diffuse light is the sun, however this light has been scattered by particles in the atmosphere. Moreover, the location of the scattering may be a significant distance away from the observation point. During an eclipse, the amount of sunlight incident on the different locations of the sky will vary and in turn the diffuse light from the various locations will be different. During totality, there is no direct light to create diffuse light. Before and after totality, some direct light scatters creating diffuse light that gets added to the GHI. The errors that exist in Figure 6 are probably due to an inaccurate understanding of the diffuse component of the light.

In conclusion, the irradiance of an eclipse can be modeled using a simple straightforward algorithm that includes the irradiance during clear sky periods of non-eclipse time periods and a percentage of the unshaded sun during the eclipse. Both sets of data are available on various online solar and eclipse calculators. The model produces errors in irradiance of up to 25 W/m^2. Improvements to this model are possible however, these improvements will complicate the discussion. If the goal is to educate young people, then keeping the model simple has obvious benefits.

Acknowledgments. The authors would like to acknowledge the U.S. Department of Energy (DOE)/NREL/ALLIANCE for supplying the Bird Model and the SAMPA calculator.

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