Solar World Congress 2025

IMPACT OF A PARTIAL SOLAR ECLIPSE ON THE DIRECT NORMAL IRRADIANCE AND FLUX DISTRIBUTION IN A SOLAR TOWER SYSTEM

Summary

A novel study of the effect of a partial solar eclipse on a Solar Tower facility is reported. During the eclipse, a temporary, yet significant reduction in direct normal irradiance (DNI) was observed, with a relative reduction considering the clear-sky case of 23.63%. Ray tracing was performed for the single heliostat used for this experiment, to infer if for a clear-sky scenario, the flux map changes its shape during the eclipse period. It was confirmed by calculating the structural similarity index measure, which value was of 0.98, that the shape throughout the eclipse should be similar. Photographs were then taken at the light spot when pointing the selected heliostat for the experiment, showing that not only the DNI was reduced, but the spot shape also suffered deformation during the eclipse.

Keywords: CSP, Heliostat Field, Flux Map, DNI, Solar Eclipse

1. Introduction

Central receiver systems are pivotal in the deployment of high-efficiency, utility-scale Concentrated Solar Power (CSP) technologies. These systems depend on a field of computer-controlled heliostats that reflect sunlight to a focal point on a tower-mounted receiver. Accurate modelling of solar flux distribution is essential for optimizing energy capture, thermal management and material lifespan. Although, for the authors' best knowledge, the effect of a solar eclipse onto the generated was never studied for any CSP technology. Solar eclipses, while infrequent, can act as controlled, natural experiments that reveal how CSP systems behave under non-standard transients. On March 29, 2025, a partial eclipse was visible across several regions with active CSP installations, such as Spain. This provided a rare opportunity to study the eclipse's impact on real-world flux dynamics.

2. Methodology

Experiments were conducted at the very-high concentration solar tower (VHCST) located in the premises of IMDEA Energy (40°20'24.93"N, 3°52'51.19"W, Móstoles, Madrid, Spain), within an urban area, see Fig. 1. It is an experimental facility containing a highly-compact 250 kW_{th} solar field composed of 169 heliostats of ≈ 3 m^2 each (1.9 m × 1.6 m), able to reach fluxes above 2,500 kW/m^2 for at least 50 kW in an aperture of 16 cm diameter and a peak flux of 3,000 kW/m^2 (Romero et al., 2017).

Fig. 1: Solar field at IMDEA Energy with the field on stand-by and one heliostat pointing to the target at the tower. The camera setup is located on the right side of the photograph near the control room.

This experiment consisted in pointing one heliostat (H07-07, row 7, heliostat number 7 counting from the East) to a target located at the tower, see Fig. 1, while simultaneously taking pictures every 5 minutes to the spot and recording the direct normal irradiance (DNI) every minute. These measurements were performed with a SHP1 pyrheliometer and the photographs were taken with a Prosilica GT 1920, while the solar field was controlled via SCADA.

3. Results and Discussion

The eclipse started at 10:48, with the peak at 11:40 and finished at 12:33. The magnitude of the solar eclipse (how much of the solar diameter is covered by the moon) was of 0.317 while the obscuration (a measure of the Sun's surface area occulted by the Moon) was of 20,64% during the peak. The eclipse progression can be visualized in Fig. 2 in intervals of 10 minutes.

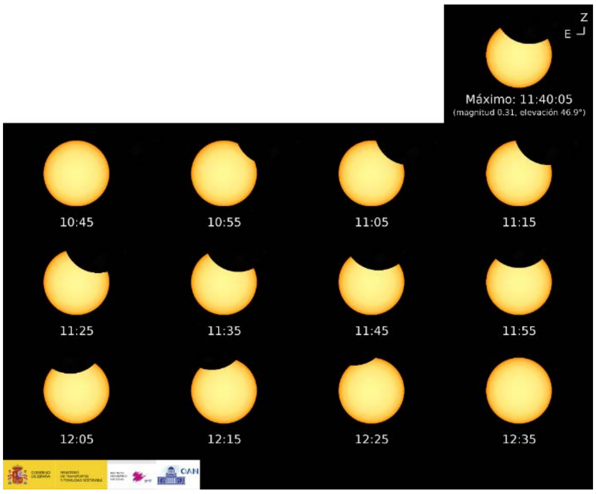

Fig. 2: Solar eclipse stages in 5 minutes intervals during March 29, 2025, observed from Madrid, Spain. Adapted from "https://astronomia.ign.es/web/guest/eclipses-de-sol-y-luna/eclipse-parcial-de-sol-29-marzo-2025".

Regarding the DNI, it was linearly interpolated by removing the values during the eclipse and then the DNI was reconstrued, as if it was clear-sky. In this condition, the DNI during the peak should be around 904 W/m^2, when it was observed a significant reduction to around 731 W/m^2 during the eclipse, see Fig. 3. This accounts for a relative reduction of 23.63%.

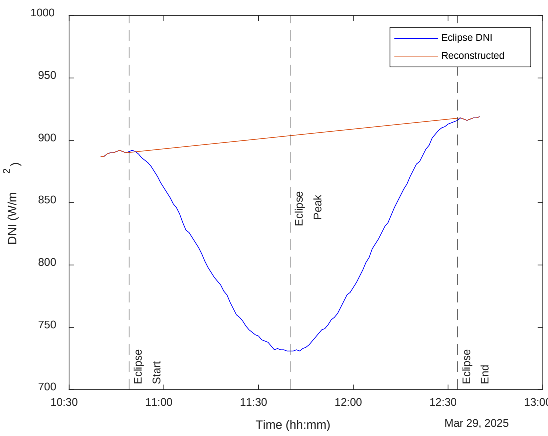

Fig. 3: Direct normal irradiance between 10:40 and 12:35 for March 29, 2025.

It is observed that even during a partial eclipse with low magnitude and obscuration values can create such sharp decrease on the DNI that reduces the light spot's intensity. This can lead to operational problems, if not considered when managing a CSP plant. Ray tracing simulations using slope error matrices obtained by laser-scanning the facet used, were performed and the corresponding DNI was employed. On the superimposition observed in Fig. 4, the data of each flux map was normalized between 0-1 using their corresponding maximum value.

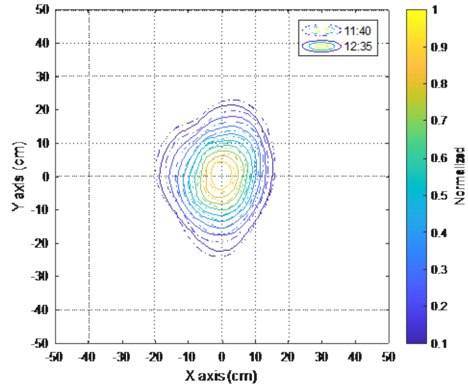

Fig. 4: Normalized flux maps for clear-sky scenario generated through a custom-tailored ray tracing program in Matlab for March 29, 2025, at 11:40 and 12:35.

The shape during both moments is similar, with the one of 12:35 being just slightly smaller (mainly vertically) than the one at 11:40. The area reduction regarding the 11:40 reference was of 7.1%. To confirm the similitude, the structural similarity index measure (SSIM) was calculated between both, showing a value of 0.98. This means the shape should be identical, but only slightly smaller. Photographs of the real spot were taken with the Prosilica CCD camera from 11:00 to 12:35 in intervals of 5 minutes. Images were converted from grayscale to binary, by assuming that everything below 1/15 of the maximum grayscale value was set to zero and then all pixels above 0 were set to 1.

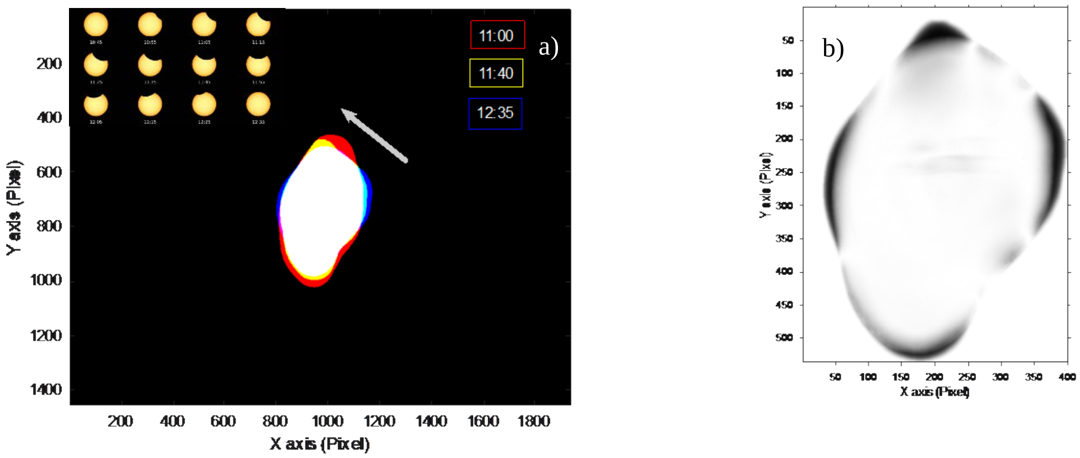

Fig. 5: a) Superimposed photographs from March 29, 2025, at 11:00 (red), 11:40 (yellow) and 12:35 (dark blue) with a gray arrow showing the direction of where the most differences are observed; and b) SSIM map between the 11:40 and 12:35 photographs.

It is observed in Fig. 5, a slight vertical size decrease, has shown in Fig. 4, although the main difference is how the shape of the right and top parts of the spot are modified according to the evolution of the eclipse. Notice that it follows the direction of the eclipse, as in Fig. 2, from right to left. Additionally, the area increased 1.8% at 12:35 compared to 11:40, following an opposite pattern of the ray tracing simulations. The average SSIM between both was of 0.94, also lower than the value obtained from the clear-sky ray tracing case, as expected.

4. Acknowledgements

All the authors acknowledge the PID2020-119693RB-C31 (HECTOR) funded by MCIN/AEI/10.13039/501100011033.

5. References

Romero, M., González-Aguilar, J., Luque, S., 2017. Ultra-modular 500 m^2 heliostat field for high flux/high temperature solar-driven processes. AIP Conf. Proc. 1850. https://doi.org/10.1063/1.4984387