Variation of incoming solar radiation flux during a partial eclipse episode: an improved model simulation

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Abstract

Model simulations of solar irradiance reaching the Earth’s surface during a solar eclipse constitute a useful tool for studying the impact of this phenomenon on the radiance propagation through the atmosphere. A simple approach to extend the use of an algorithm already adopted for evaluating the variations in the extraterrestrial solar radiation during a total eclipse is proposed for a partial eclipse case. The application is based on the assessment of the distance between the apparent solar and lunar disk centers on the celestial hemisphere, using the local circumstances and the ratio between the Sun and Moon radii as input parameters. It was found that during the eclipse of March 29, 2006, the present approach led to an estimate of the surface UV solar irradiance trend differing by no more than ±5% from the corresponding trend observed at Bologna (Italy).

1 Introduction

A solar eclipse is a good opportunity for studying the interaction between solar radiation and the Earth’s atmosphere, \cite{1, 2, 3, 4, 5}, and for testing radiative transfer models \cite{6}. Together with ground-based measurements, modeling of the incoming solar irradiance at the surface during an eclipse episode can provide useful information for those investigating such interaction processes \cite{5}.

Möllman and Vollmer \cite{7} proposed an approach aimed to evaluate the broadband solar irradiance during a solar eclipse, in which the limb darkening effect was neglected. An accurate procedure for calculating the spectral variations in the extraterrestrial solar radiation occurring during a total eclipse was developed by Koepke et al. \cite{8}. The approach takes into account the limb darkening and determines the radiance changes in terms of normalized spectral irradiance $I_{\text{norm}, \lambda}$ expressed as the ratio between the radiation coming from the part of the solar disk uncovered by the Moon and the radiation emitted by the entire solar disk. The parameter $I_{\text{norm}, \lambda}$ characterizes the variations in solar irradiance at the top of the atmosphere during an eclipse episode and, therefore, it can be used as a correction factor for evaluating the extra-terrestrial irradiance in the radiative transfer models. The main parameter describing the eclipse geometry in the method is the distance between the apparent solar and lunar disks, which was evaluated in the total eclipse case. The present study aims to extend the approach developed by Koepke et al. \cite{8} to a partial eclipse case, assessing the length of segment defined by the Sun and Moon centers as a function of the ratio between the corresponding radii and local eclipse circumstances.

2 Assessment of the solar-moon apparent distance during a partial solar eclipse

In case of total eclipse, the apparent path of the lunar disk center on the celestial hemisphere, crosses the corresponding center of the solar disk, and pa-
Parameter $I_{\text{norm},\lambda}$ can be determined as a function of the distance $X$ between the Sun and Moon centers, which is assumed to follow a linear time-dependent trend for a constant velocity $v$ of the Moon with respect to the Sun. However, in the case of a partial solar eclipse, the Moon disk center does not cross the corresponding solar center, as is shown in Fig. 1 and, therefore, parameter $X$ does not vary linearly in time. The graph represents the relative movements of the apparent solar and lunar disks of radii $R_S$ and $R_M$, respectively, during an eclipse episode starting at time $t_0$, reaching its maximum at time $t_m$ and finishing at time $t_e$. All the distances shown in Fig. 1 are considered to be normalized to parameter $R_S$, so that the apparent Sun disk radius is considered as unit ($R_S = 1$). In addition, the solar disk has been assumed to have a fixed position. Due to the specific geometry of the problem, the time-interval between $t_0$ and $t_m$ is usually slightly different from the corresponding time-interval between $t_m$ and $t_e$. This is why the eclipse episode is arbitrarily subdivided into two parts, the former of which is taken between times $t_0$ and $t_m$ and labeled with apex ($'$), and the latter between times $t_m$ and $t_e$ with apex ($''$). According to Fig. 1, parameter $X'$ can therefore be expressed as:

$$X' = \sqrt{D^2 + S'^2}. \quad (1)$$

Parameter $D$ is the distance between the centers of apparent Sun and Moon disks at the maximum eclipse time and can be determined in terms of the following equation,

$$D = R_S + R_M^0 - M = 1 + R_M^0 - M, \quad (2)$$

where $R_M^0$ is the Moon radius at time $t_m$. Segment $M$, which represents the part of solar radius $R_S$ covered by the Moon at the maximum eclipse time $t_m$, can be expressed in terms of the eclipse magnitude $M_g$ for the considered site in the following form:

$$M = 2R_SM_g = 2M_g. \quad (3)$$

At the eclipse start time $t_0$, parameter $X'_0$ is equal to $R_S + R_M^0$ and, hence, during the period $[t_0, t_m]$, the Moon disk center describes the path $S'_0$ shown in Fig. 1 whose length is given by

$$S'_0 = \sqrt{(R_S + R_M^0)^2 - D^2} = \sqrt{(1 + R_M^0)^2 - D^2}. \quad (4)$$

Assuming nearly constant velocity $v'_0$ of the Moon with respect to the Sun during the first phase of the eclipse, it can be stated that

$$v'_0 = \frac{S'_0}{t_m - t_0}. \quad (5)$$

Therefore, parameter $S'$ can be defined at each time $t \in [t_0, t_m]$ in the explicit form,

$$S' = S'_0 - v'_0(t - t_0). \quad (6)$$

Thus, the distance $X'$ can be defined using Eqs (1) – (5). Similarly, the corresponding parameter $S''$ can be expressed as equal to the difference:

$$S'' = S''_0 - v''_0(t_e - t), \quad (7)$$

where $t \in (t_m, t_e]$ and parameters $S''_0$ and $v''_0$ are defined according to the following pair of equations:

$$S''_0 = \sqrt{(1 + R_M^0)^2 - D^2} \quad (8)$$

and

$$v''_0 = \frac{S''_0}{t_e - t_m}. \quad (9)$$
assuming again that velocity $v'_o$ is nearly constant.

Finally, the distance $X''$ between the apparent solar and lunar disk centers during the second phase of the eclipse is defined according to Eq (11), as

$$X'' = \sqrt{D^2 + S''^2}. \quad (10)$$

Equations (11) – (10) provide an algorithm suitable for determining the time-patterns of parameter $X$, denoted as $X'$ during the first half of the event and as $X''$ during the second half, knowing the local circumstance times, eclipse magnitude $M_g$ and behavior of the ratio $R_M/R_S$ during the eclipse. In fact, the present procedure takes into account the ratio $R_M/R_S$ only at the start time $t_o$ of the event, at the maximum eclipse time $t_m$, and at the final time $t_e$, which correspond to parameters $R'_M$, $R'_o$ and $R'_M$, respectively, assuming $R_S = 1$ as established above. Since the variations in ratio $R_M/R_S$ usually do not exceed 1-2%, the error made in estimating parameter $X$ when considering such a ratio at three fixed times only, will be around 1%. In case of total eclipse, parameter $D$ is equal to zero and the above approach gives a linear trend of distance $X$, as assumed by Koepke et al. [8]. It is also worth noting that Koepke et al. [8] normalized the parameter $X$ by $R_M + R_S$ in their procedure, while such a step was avoided in the present procedure for sake of simplicity. The above algorithm is similar to that proposed by Möllman and Vollmer [7] to evaluate the illuminance during a solar eclipse. The main difference is the subdivision of the event into two periods, before the maximum phase and after that, while Möllman and Vollmer [7] assumed a symmetry of the eclipse episode evolutionary features with respect to the maximum. On the other hand they assessed the broad-band irradiance and, hence, the limb darkening was not taken into account. Conversely, the Koepke et al. [8] method considers this effect: based on these concepts, the present algorithm is suitable to estimate the spectral variations of surface solar irradiance during a partial solar eclipse.

Table 1: Parameters of the solar eclipse of 29 March 2006 estimated by Espenak and Anderson [12] for Bologna, Italy. The values of ratio $R_M/R_S$ are taken from physical ephemeris of the umbral shadow (Table 4 in [12]).

| Contact | Time (UTC) | $R_M/R_S$ ($R_S = 1$) | Magnitude $M_g$ |
|---------|------------|------------------------|-----------------|
| I       | 09:33:01 (t_o) | 1.0500 ($R'_M$) | 0.532 |
| Maximum eclipse | 10:38:03 (t_m) | 1.0509 ($R'_o$) |
| IV      | 11:44:11 (t_e) | 1.0375 ($R'_M$) |

Table II presents the input parameters, as provided by Espenac and Anderson [12]. Figure 2 shows the time-patterns of normalized solar irradiance $I_{norm,325}$ at the 325 nm wavelength, as calculated following the Koepke et al. [8] procedure, together with those of distance $X$ evaluated through Eqs (11) – (10). Parameter $I_{norm,325}$ defines the relative variations of the radiance entering the atmosphere at the 325 nm wavelength, occurring at Bologna during the event. It is suitable for use as a correction factor for extra-terrestrial solar radiation in a radiative transfer model used to evaluate the surface solar irradiance. To perform such an evaluation, the widely used TUV model [13] was applied for the 325 nm spectral component of solar irradiance, keeping constant the daily mean value of columnar ozone amount equal to 390 DU, as determined by UV-RAD on March 29, 2006. Since the eclipse day was characterized by stable clear-sky conditions, cloud effects were not considered in the present assessment. On the basis of ground-level visibility evaluations made on the eclipse day...
an aerosol volume extinction coefficient was assumed at the 550 nm wavelength varying between less than 0.04 and 0.05 km\(^{-1}\). Consequently, assuming a particle scale height close to 1.25 km according to the Penndorf \[14\] evaluations (confirmed by the estimates of 1.0 - 1.5 km made by Tomasi \[15\] in the Po Valley on early spring days), aerosol optical depth (AOD) at visible wavelengths can be evaluated to range between 0.04 and 0.07, for meteorological and atmospheric transparency conditions similar to those of the eclipse day. Thus, an AOD value equal to 0.05 was given as input to the code, together with the Elterman \[16\] vertical distribution of the volume extinction coefficient of aerosol particles. The winter Mid-latitude temperature profile determined by Anderson et al. \[17\] was used in the code calculations for surface albedo equal to 0.08, leading to the best agreement between evaluated and measured irradiances during the part of the day in which perturbations due to the eclipse were not observed.

![Figure 3](image-url)  
**Figure 3:** Upper part: time-patterns of surface UV solar irradiance at the 325 nm wavelength, measured during the partial solar eclipse of 26 March 2006 at Bologna (open circles). The thick grey curve represents the corresponding model evaluations. Lower part: time-patterns of the ratio between UV-RAD measured and model-evaluated irradiances, respectively. The contact times and the maximum eclipse time (see Table \[B\]) are indicated by vertical dotted lines.

In the upper part of Fig. 3 the results of the simulation are presented, showing a comparison between the theoretical and observed variations in solar irradiance. The lower part of Fig. 3 presents the time-patterns of the ratio between measured and calculated irradiance values, providing evidence of the good agreement between the two variables. Except for the times of maximum eclipse and last contact, when discrepancies of about -5% were found, all the other cases exhibit similar differences within ±3%. The comparatively higher deviations between evaluated and measured values at times \(t_m\) and \(t_e\) can be reasonably attributed to the presence of sparse *cumulus congestus* clouds moving around the Sun on 29 March 2006, causing, together with the eclipse event, appreciable changes in the surface solar irradiance that cannot be represented with good precision by using a monodimensional radiative transfer model.

### 4 Conclusions

A simple algorithm has been proposed suitable for extending the method of Koepke et al. \[8\], developed to correct the trend of extra-terrestrial solar radiation during a total solar eclipse to a partial eclipse case. To do this, the evolution of the distance between the apparent Moon and Sun disk centers was evaluated as a function of local eclipse circumstances and the ratio between the lunar and solar radii. The estimation allows the calculation of the variations in the solar irradiance entering the terrestrial atmosphere, where the surface irradiance time-patterns are simulated using a radiative transfer model. It was found that the procedure provides a satisfactory assessment of the evolutionary patterns characterizing the UV solar irradiance during the partial eclipse of March 29, 2006 computed by the TUV model applied to the Bologna (Italy) site.

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