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Satellite data-based methods to predict global luminous efficacy

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Abstract

This paper presents constant value and universal models of luminous efficacy for global solar radiation on a horizontal surface. Both are applicable to all sky conditions and are based on satellite derived data available via web servers. Solar radiation data from ten locations in Europe and North Africa was used to obtain two functions for luminous efficacy (K) against solar altitude (α), and sky clearness index (k_t). All were used to estimate illuminance for the ten originating locations; for four locations based on satellite data; and for a further five based on measured data. A statistical assessment showed that the best model is K against α. Comparison between results from the proposed model and those produced using three published models, indicate that the former produce more accurate estimates of luminous efficacy. The satellite based approach makes daylight data available in locations remote from current measurement sites.

Keywords

Daylight, luminous efficacy, global, illuminance, irradiance, satellite.

1. Introduction

Over the last few years the development of 'daylight guidance systems' has made redirection of zenithal daylight into areas remote from the building envelope a practical possibility. Since the systems use daylight as a source, a detailed knowledge of illuminance conditions at potential locations is necessary in order to assess their feasibility [1]. There is a lack of measured illuminance data suitable for this task. As a result, luminous efficacy models can be used to relate direct, global and diffuse radiation components to their photopic equivalents. They enable the calculation of daylight illuminance from the more widely available irradiance data. Luminous efficacy is defined as the ratio between illuminance and irradiance. Thus, if E is the illuminance in lux and I is the irradiance in W/m^2, the luminous efficacy of the solar radiation, K, will be given by:

$$K=E/I \quad (\text{lm/W}) \qquad (1)$$

Work by the authors [2] developed universal models to estimate direct luminous efficacy based on free-access satellite data. This work suggests models to estimate global luminous efficacy using a similar procedure.

2. Review of global luminous efficacy models

Published models of luminous efficacy can be divided into three groups according to the variables used. The first uses solar altitude as the only independent variable [3-7]. The second group uses metrological parameters as independent variables [8-12]. The last group uses constant values without any variables [13].

The majority of models in the first group is specific to sky type and based on polynomial expressions of different degrees functions of solar altitude. They thus could be considered to be one model with different local coefficients. Meanwhile, the models in the second group were developed from either meteorological parameters or experimental data from specific locations, but are intended to represent all sky types. The third group advances constant values for luminous efficacy for each of global, diffuse and direct irradiance.

3. The proposed model of global luminous efficacy

3.1. Aims and advantages

The current work seeks to develop validated universal models for the global horizontal luminous efficacy valid for all skies using satellite-based website data. The independent variables used are available for all points on the earth's surface in free-access web servers. It is not necessary to determine local sky conditions to use the current model and no local coefficients are included.

3.2. Data sources

Data from two sites were used to develop the present models. The European database of daylight and solar radiation website, Satel-light [14], is used in this work to provide irradiance and illuminance data, from which luminous efficacy for the selected locations is directly calculated. Data is available for the three main radiation types: global, direct and diffused incident for any defined surface orientation for the period 1996 to 2000. The second source is NASA Surface meteorology and Solar Energy (SSE) [15], which used to obtain data of independent variables such as hourly solar altitudes.

3.3. Choice of locations

The calculations are based on data for locations which are representative of conditions throughout the area covered by Satel-light. The ten locations include both maritime and continental cities; and latitudes from 55°N to 35°N, as listed in Table 1.

Table 1 Locations frequencies of sky conditions and Luminous Efficacy.

		Location Conditions			Sky Conditions (%)			K_g (lm/W)		
CITY	Country	Lat.	Lon.	Alt.	Sun	Intermed.	Overcast	Max.	Min.	Mean
Copenhage	DK	56	13	0	34	38	28	115	100	111
Moscow	RU	56	38	155	35	40	25	115	100	111
London	UK	51	0	15	31	42	27	116	100	112
Kiev	UA	50	31	169	38	35	27	115	100	111
Bordeaux	FR	45	1	9	47	34	19	115	100	112
Bucharest	RO	44	26	84	49	31	20	114	100	111
Valencia	ES	39	0	11	70	20	10	114	103	111
Athena	GR	38	24	110	68	21	11	113	100	112
Nador	MA	35	03W	155	67	24	9	114	100	111
Khania	GR	36	24	1	69	19	12	113	105	111

3.4. Statistical indicators

Statistical indicators used include mean bias deviations (MBD), and root mean square deviations (RMS). They are defined by the following equations:

MBD= $\sum_{i=1}^{N}[(y_i - x_i)/x_i \, . \, 100]/N$ (2), RMS= $[\sum_{i=1}^{N}[(y_i - x_i)/x_i \, . \, 100]^2/N]^{1/2}$ (3)

Where: y_i is the estimated value, x_i is the given value (selected from Satel-light in the present work) and N is the number of values.

4. Development of the proposed global model

Global horizontal illuminance and irradiance data was obtained from Satel-light for ten ‘originating’ locations. From each the global horizontal ‘reference luminous efficacy’ K_g, was calculated using Equation 1. Table 1 lists the maximum, minimum and mean reference values for each location. It is obvious that the maximum values are very similar with slight decrease in the Southern location. The minimum and mean values are almost identical. The average of the maximum, minimum and mean reference values are 114lm/W, 101lm/W and 111.4lm/W respectively.

Using solar altitude, α, as the only independent variable, polynomial function for K_g against α was obtained by plotting the variation of K_g with α for all ten originating locations. Figure 1 shows the best fit curve, which is as follows:

$$K_{g1} = -0.0032\,\alpha^2 + 0.34\,\alpha + 104.46 \qquad (4)$$

Using clearness index, k_t, as a sole independent variable, the variation of K_g plotted against the k_t for all ten originating locations. Figure 2 shows the best fit polynomial curve, which is as follows:

$$K_{g2} = -44.008\,k_t^{\,2} + 50.826\,k_t + 97.82 \qquad (5)$$

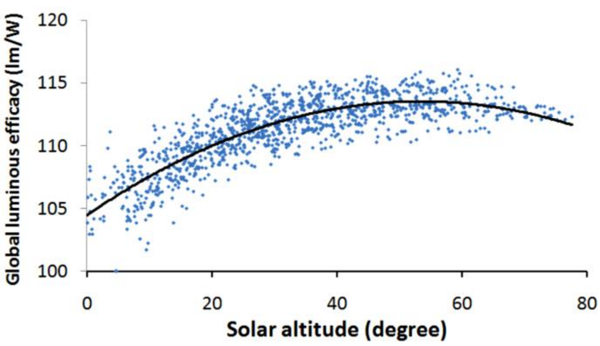

Fig1. G. luminous efficacy against solar altitude

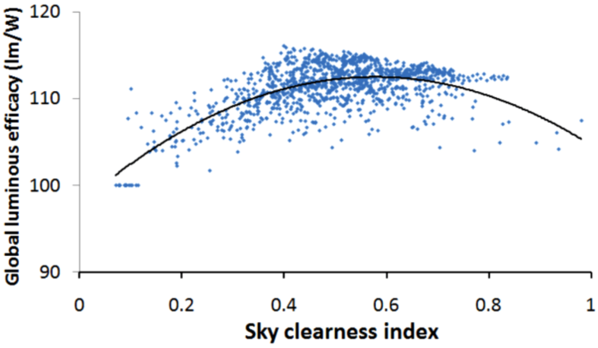

Fig2. G. luminous efficacy against clearness index

5. Statistical performance of the proposed models

The proposed models have been used to generate illuminance values for the ten ‘originating locations’. The generated values were compared with the actual values for the corresponding locations. In addition four more locations were added as ‘validation locations’. These were:

Oslo, NO	(60˚N, 11˚E)	Berlin, DE	(52˚N, 13˚E)
Parma, IT	(45˚N, 10˚E)	Alger, DZ	(37˚N, 3˚E)

Figure 3 shows the statistical performance of the models described by Eqs. (4 & 5); named M-1, and M-2 respectively. The statistical performance of the developed models proved a big agreement between the originating and validation locations. The results show slight superiority of M-1 against M-2 in terms of RMS, and identical results in terms of MBD. M-1, the model based solely on the solar altitude, has the following statistical performance averages: RMS = 1.5% and MBD = 0%, which obtained from the originating locations. And the following averages from the validation locations: RMS = 1.4% and MBD = 0%. Originating and validation location performances showed a great agreement. M-1 highest values for all indicators are remarkably lower than M-2. Moreover, M-1 performance is more stable, which is noted from the variations of the statistical indicators over the fourteen locations. The differences between minimum and maximum values of RMS and MBD are 0.9% and 2.3% respectively, in compare with 1.5%, 1.8% and 2.5% for M-2. It is worth noting that underestimation of luminous efficacy tends to occur in the Northern locations for both models.

Comparison between the averages of the reference and estimated efficacies values shows the following: the differences between the maximum values are 1.4 and 2.4lm/W for M-1 and M-2 respectively. The average minimum of M-1 is 4lm/W more than the reference, while it is 0.8lm/W for M-2. The differences between the average mean values for all models are negligible. The differences between the models in terms of maximum and mean values are insignificant. In terms of minimum values M-1 got the biggest difference, but since it didn't lower the mean value, this indicates that the number of the minimum values is too low to affect the mean value.

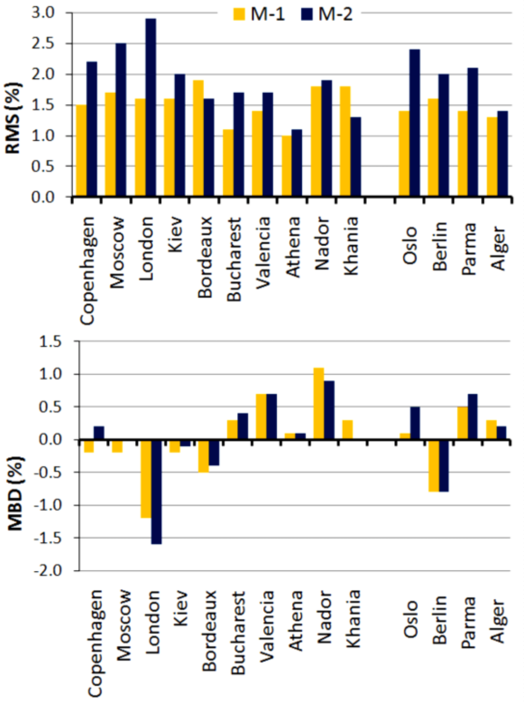

Fig 3. Statistical assessment of global developed models

The differences between the 'estimated efficacies values' suggest that all models could be used for estimation purposes. But the statistical performance tends to favour M-1 model, particularly with its simplicity that satisfy the purpose of this study.

6. Published models

All models mentioned in the review were evaluated using satellite data and those that gave the best results used for comparison with the proposed models. The models considered for estimation of the global luminous efficacy on horizontal surface were:

- Ullah's model [6], which expresses the correlated K_g solely to α for clear skies. The following formula based on a measured data from Singapore:

$$K_{g3} = 107.33+1.14157\alpha-0.0423\alpha^2+0.5395 \times 10^{-3}\alpha^3 - 0.2347 \times 10^{-5}\alpha^4 \qquad (6)$$

- Muneer's model [10], which produced for all skies types, expressed the correlated K_g solely to the k_t. The following formula based on a measured data from five sites in the UK:

$$K_{g4} = 136.6 - 74.541\, k_t + 57.3421\, k_t^{\,2} \qquad (7)$$

- Ruiz's model [11], which produced for all skies types; expressed the correlated K_g to sin α and to k_t. The following formula based on a measured data from Madrid:

$$K_{g5} = 104.83(\sin\alpha)^{0.026}\, k_t^{\,-0.108} \qquad (8)$$

7. Statistical performance of the published models

The published models have been used to generate illuminance values for all the originating and validation locations. Thus the generated values were compared with the actual values for the corresponding locations. Table 2 reports the average statistical performance of the estimated values. In terms of RMS indicator, the average performance of both Ruiz's and

Ullah’s is around 5% against 6.5% for Muneer’s, and the lowest maximum is around 5.8% for the formers in compare with 8.3% for the latest. Also Ruiz’s and Ullah’s showed a similar stability around 1.5% against 3.4% for Muneer’s. Since the MBD indicator has positive and negative values, the average performance and the lowest maximum values may be misleading, thus the stability value is considered to best describe models performance in terms of MBD. Ullah’s comes first with stability of 2.1%, then Ruiz’s with 3.8% and Muneer’s with 4.7%.

Comparison between the averages of each of the reference and estimated efficacies values shows the following: the maximum value for Ullah’s model is 2.7lm/W more than the reference, which is much better than the 17.8lm/W and 13.3lm/W achieved by Muneer’s and Ruiz’s models respectively. Meanwhile, Ruiz’s minimum and mean differences are superior with values of 0lm/W and 0.3lm/W respectively; in compare with the 7.1lm/W and 2.8lm/W achieved by Ullah’s, or 11.4lm/W and 3.8lm/W achieved by Muneer’s.

Above performance of the published models suggests that Ruiz’s model is the best in estimating illuminance data from satellite irradiance data.

8. Comparison of models

Statistical performances and differences between reference and estimated luminous efficacies over the fourteen locations were used to compare between developed and published models, in addition to constant luminous efficacy value of 111.4lm/W, which represents the average of the mean efficacies values for all the originating locations. The derived constant value is close to the value of 110lm/W suggested by De Rosa **[13]**.

Table 2 Statistical performance of all models

		RMS	MBD	K_g differences		
Models		(%)	(%)	**Max**	**Min**	**Mean**
M-1	[Eq. 4]	**1.5**	**0.0**	**-1**	4	-0.2
M-2	[Eq. 5]	1.9	0.1	-2	1	**-0.1**
Constant	111.4	2.7	0.3	-	-	-
Ullah	[Eq. 6]	4.8	2.7	3	7	2.8
Muneer	[Eq. 7]	6.5	3.5	18	11	3.8
Ruiz	[Eq. 8]	5.1	0.5	13	**0**	0.4

Table 2 shows that M-1 has the best statistical performance among the developed models; that of Ruiz’s in those published, with the constant value somewhere between the two. The statistical indicators suggest that M-1 performs more than three times better than Ruiz’s model, the best published model, and around twice better than the constant value. Figure 4 illustrates M-1 superiority over the published models and the constant value. The RMS indicator shows that M-1 ranges around 1.5% with stability of 0.9%, whilst the constant value ranges around 2.8% with stability of 1.4%, and Ruiz’s ranges around 5.1% with stability of 1.4%. The MBD indicator tells that the constant value is the most stable one with difference of 1.6% in compare with 2.3% and 2.9% for M-1 and Ruiz’s respectively.

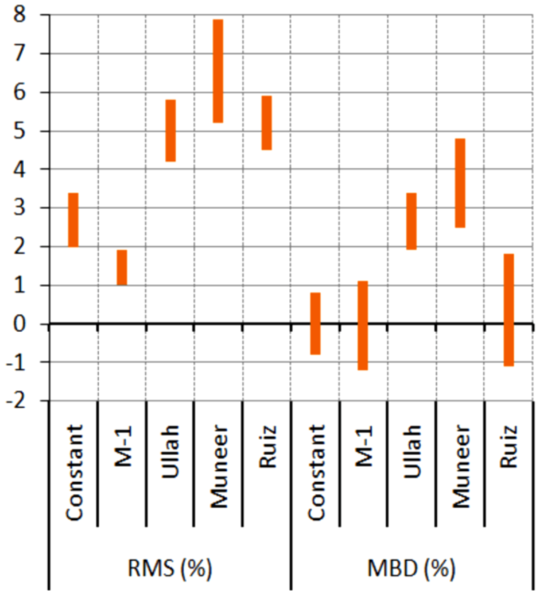

Fig 4. Statistical indicators ranges of the constant value and global developed and published models

9. Application of the proposed and published models

The proposed and published models based on solar altitude were further tested using measured illuminance and irradiance experimental data from the following locations:

Edinburgh, UK	(55.93˚N, 3.30˚W)	Bratislava, SK	(48.17˚N, 17.08˚E)
Arcavacata, IT	(39.36˚N, 16.22˚E)	Fukuoka, JP	(33.52˚N, 130.48˚E)
Hong Kong, CN	(22.40˚N, 114.11˚E)		

The statistical performance of M-1, all published models, and the constant value (see Table 3**)** shows that no single model performs best over all locations. The constant value is best for Bratislava and Hong Kong, closely followed by M-1 (less than 0.5%). Muneer’s model is best for Edinburgh and Fukuoka and Ruiz’s for Arcavacata. Although Ullah’s model didn’t perform best in any location, its average performance over the five locations compare well with the constant value. They both have the following averages: RMS= 13.8%, MBD= -1.1% for the constant value and 1% for Ullah’s. M-1 came next with very close performance; not more than 0.3% difference for each of the statistical indicators. Then emerge Muneer’s with 14.4% and 5.2% for the RMS and MBD respectively. Finally came out Ruiz’s with 1.5-2.5% difference between its averages and the best performance over all the statistical indicators.

Though the differences between the statistical performance of M-1, the constant value and Ullah’s model are insignificant, M-1 and the constant value have shown more stability than Ullah’s; with values of 11% for the RMS in compare with 13.3% for Ullah’s, and similar stability for all of them in terms of MBD around 21.7%. Muneer’s and Ruiz’s stabilities are 2-6.5% more than M-1 for all indicators.

The previous comparison shows that constant value of 111.4lm/W gives the best performance along with the developed model M-1; the second degree polynomial formula of solar altitude solely. Next, with only slight difference, comes out Ullah’s model. Muneer’s and Ruiz’s to some extend overestimates luminous efficacies values, their deviation is to far extend close to M-1, and they are remarkably less stable than M-1. They both can be considered more complicated than the previous alternatives.

Table 3 Average statistical performance of proposed and published models

Models	**Edinburgh**		**Bratislava**		**Arcavacata**		**Fukuoka**		**Hong Kong**	
	RMS (%)	MBD (%)	RMS (%)	MBD (%)	RMS (%)	MBD (%)	RMS (%)	MBD (%)	RMS (%)	MBD (%)
M-1	9.0	-5.1	12.4	**0.4**	15.0	-2.6	13.9	-10.5	19.8	11.5
Constant	8.4	-4.8	**12.1**	0.7	14.8	-2.1	13.6	-10.6	**19.5**	**11.1**
Ullah	7.8	-2.5	13.0	3.3	15.1	0.6	12.0	-8.8	21.1	12.7
Muneer	**6.1**	**0.6**	17.7	11.0	15.0	3.0	**9.8**	**-6.2**	23.6	17.6
Ruiz	6.9	-2.6	22.3	12.6	**14.3**	**-0.5**	11.5	-8.6	22.0	15.6

10. Conclusion

This work suggests new methods of estimation of horizontal global luminous efficacy based on satellite data which is widely available, free of charge, on web servers. The resulting methods are a constant value or a universal model with a minimum requirement for additional variables or coefficients. It makes the availability of realistic design illuminance data independent of the availability of local measured daylight data. For these reasons the satellite based approach to generation of illuminance data is likely to become increasingly important for design purposes.

The new approach was developed using satellite irradiance and illuminance data for ten locations in Europe and North Africa. The proposed models were developed from the relation between the luminous efficacy and any of solar altitude or sky clearness index. Among the proposed models, the model based on solar altitude, M-1, emerged as the simplest and best statistically performing model over the fourteen locations throughout Europe and North Africa. In compare with the published models, the statistical performance of M-1 is up to three times more accurate than the best performing published models, Ruiz's model. The constant value showed better statistical performance than the published models, but M-1 still two times better as illustrated in table 2.

In the final part of the work, the constant value, the published and proposed models were used to estimate illuminance data for five locations for which actual global irradiance, global illuminance and solar altitude data was available. The statistical indicators showed that M-1 and the constant value slightly produce more accurate estimates of luminous efficacy than the published models, but without the use of extensive local data (see table 3).

This work has its origins in study of daylight guidance systems but could equally be applied to other lighting technologies. It suggests that the methods can be applied to a wide range of geographical locations. Satellite irradiance data is available for all points on earth's surface so, in principle, luminous efficacy can be estimated for all locations.

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