Semi-Empirical Modelling of Light Polluted Twilight Sky Brightness

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(Received: 9.2.2018 ; Published: 5.10.2018)

Abstract. The phenomenon of twilight been stipulated as naturally dependent on the variables of solar depression, aerosol concentration and ozone composition. The unique colour spectrum of twilight is attributed to the ozone layer and aerosol, whereas its brightness is heavily relying on the altitude of the sun below the horizon. While all the natural dependent is being researched extensively, the impact of light pollution on the brightness of the twilight is not being explored thoroughly. Most of the model of twilight sky brightness such as Kastner [1] , Schaefer [2] and Belokrylov [3] only consider the factor of solar depression, aerosol concentration and ozone composition, while light pollution variable is not yet considered in the models. The objective of this study is to construct a model of light-polluted twilight sky brightness by understanding the alteration of light pollution towards the natural behaviour of twilight sky brightness. The model is constructed using Kastner expression of twilight sky brightness as a base, with the combination of data from Garstang[4], Berry[5] and 72 data of twilight brightness from various light pollution profile, utilised by Sky Quality Meter (SQM) TableCurve 3D and SigmaPlot. The model is then compared observation on rural light-polluted twilight brightness and found to have range of error around ± 0.5 mag/sec^2. It is the first attempt to express the light-polluted twilight sky brightness in mathematical formulation. The model, however, needs further refinement mainly on the analytical variables of light polluted twilight sky brightness to ensure its applicability on various locations.

Keywords: Twilight Sky Brightness, Light Pollution, Modelling, Astronomical Twilight, Kastner, Sky Quality Meter

I. INTRODUCTION

The phenomenon of twilight sky brightness is attributed to the scattered radiation of the sun[6]. The scattered sunlight, a result from of the sun being located below the horizon, will produce a proportional effect between sun altitude, and the light intensity and colour spectrum of the twilight sky [7]. The depressed sunlight reddens the sky at near sunset altitude, and decrease its brightness, that will reach its minimum and stable intensity at the range of 16-18° of solar depression [8]. This will signify the end of sunlight scattered radiation of twilight and the commencement of the night sky [9].

Modelling of twilight brightness

Rozenberg [6] noted that the brightness of twilight is factored by the depression of solar altitude below the horizon, h, with relation to the relative azimuth of the sun and an observed object, ΔAz and the object zenithal angle, θ.

$$m^{twi} = -\left(7.5 \times 10^{-5}\theta + 5.05 \times 10^{-3}\right)\Delta Az + \left(3.67 \times 10^{-4}\theta - 0.458\right)h \quad (1)$$

Patat [10] then offer additional insight on analytical variables in determining the brightness of twilight with the inclusion of Rayleigh Scattering and atmospheric extinction. Another model of twilight brightness [3], [11–13] essentially follows the same variables with a slight adjustment to ensure the modelling precision. So generally, the relationship of twilight sky brightness can be described as follows;

$$B_{ST} = \frac{C_{ext}(\lambda)}{\theta \Delta Azh} \quad (2)$$

While it has been accepted that the nature of sky brightness during twilight is mainly factored by the sun depression below the horizon, coupled with major variables of ozone composition and aerosol concentration, the research on twilight has never considered the effect of light pollution on its lumination and colour profile. The anthropogenic by-product of the human population, light pollution alters the profile night sky [14] in the form of artificial lighting[14], disrupting the natural limiting contrast of celestial object visibility[15]. This makes the light pollution monitoring is a continuous concern for astronomers throughout years considering its factor on the both optical and radio observation[16], and it has been made mandatory to determine the quality of the observation site[17]. Most the research of light pollution is limited to the study of sky during full night, and never been replicated thoroughly in the study of twilight brightness, even though Garstang[4] & Berry[5] found that the artificial light brightens the suppose night sky in all zenith distance regime of night sky, particular in the horizon where the twilight brightness is monitored. Concerning the essential of this study, a design for semi-empirical modelling of light-polluted twilight sky brightness is constructed.

II. METHODOLOGY AND MODELLING STRATEGY

Observation Site

To find the evidence of the alteration of light pollution on twilight sky brightness, the primary variable, human population density is manipulated and represented as observation profiles. Our observation sites are divided into three profiles, Urban, Rural and Pristine. Urban is the location that has dense population and extreme volume of artificial light propagation towards is the sky, usually has the reading of light pollution in the range of 14 – 18 mag/sec^2. The rural or suburban is the location has a medium level of population and artificial light, usually has the reading of light pollution in the range of 18 – 20 mag/sec^2. While the pristine location is the remote location far from any human activity, a zero light pollution influence site usually has the reading of light pollution in the range of 20– 23 mag/sec^2. Site classification is based on the Bortle Scale [18] and light pollution map by Juraij Stare [19]. The observation sites are listed as follows in Table 1.

Each reading of twilight sky brightness at various observation site is obtained using Sky Quality Meter, SQM, a pocket device that collects the reading of sky brightness in the unit of mag/sec^2 [20, 21]. Due to our limitation of the devices availability, the reading of twilight sky brightness at various observation site is conducted while pointing the SQM towards the horizon, which is around 0-10 degrees of altitude.

TABLE 1. Observation Site

No	Location	Coordinate	Zenith Light Pollution (mag/sec^2)	Site Profile
1.	Putrajaya Malaysia	2°54' N, 101°41' E	17.11 ± 0.6	Urban
2.	Kuala Lumpur, Malaysia	3.12° N, 101.65° E	16.47 ± 1.0	Urban
3.	Shah Alam, Malaysia	3.07° N, 101.50° E	17.01 ± 0.5	Urban
4.	Teluk Kemang Malaysia	2°27' N, 101°51' E	19.50 ± 0.7	Rural
5.	Tanjung Balau Malaysia	1°48' N, 104°24' E	19.78 ± 0.6	Rural
6.	Pantai Masjid Tengku Zaharah	5°24' N, 103°57' E	19.85 ± 0.8	Rural
7.	Pantai Batu Buruk	5°19' N, 103°9' E	19.23 ± 1.0	Rural
8.	Coonabarabran Australia	31°15'S, 149°16' E	21.59 ± 0.2	Pristine
9.	Pantai Mek Mas Malaysia	6°19' N, 102°9' E	21.30 ± 0.4	Pristine
10.	Balai Cerap Unisza Malaysia	5°24' N, 102°35' E	20.08 ± 0.5	Pristine
11.				
12.	Simpang Mengayau Sabah Malaysia	7°12' N, 116°30' E	21.64 ± 0.2	Pristine
13.	Pantai Melawi Bachok	5°24' N, 102°35' E	21.30 ± 0.4	Pristine

Twilight Sky Brightness Data

A total of 72 data of twilight brightness is collected. The data consist of 42 data from the pristine site, 29 data from the rural site and 13 data from the urban site. The error indicates the deviation of the light pollution reading due to cloud composition and present of Milky Way during data acquisition. Data of light pollution on overcast sky and moonlighted night is removed. All of the data is categorised into their respective site location and illustrated into a graph to zoom in on the effect of light pollution on twilight sky brightness. Each site will be presented by one average data and been trendline with R^2 value of more than 0.98 to ensure its reliability and portrayed in FIGURE , FIGURE 1 FIGURE 2. To facilitate data analysis, the average reading on each site profile is measured and expressed in a single graph, as portrayed in FIGURE 3.

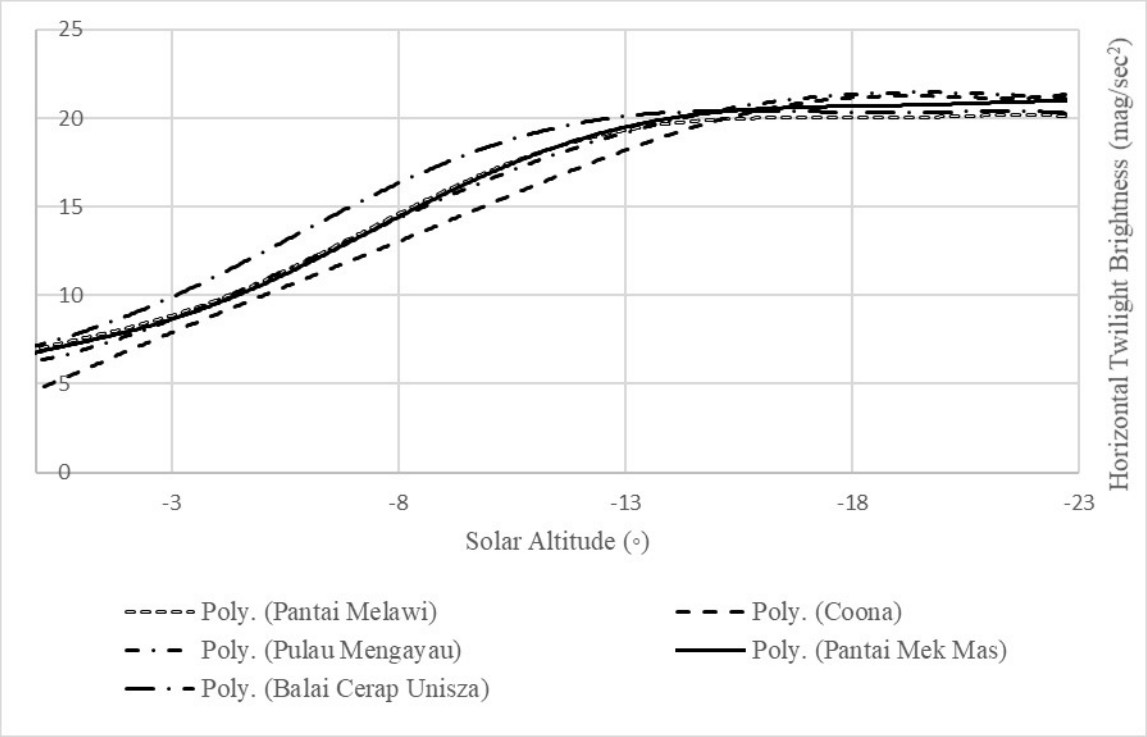

FIGURE 1. Alteration of Light Pollution on Twilight Brightness in Pristine Location.

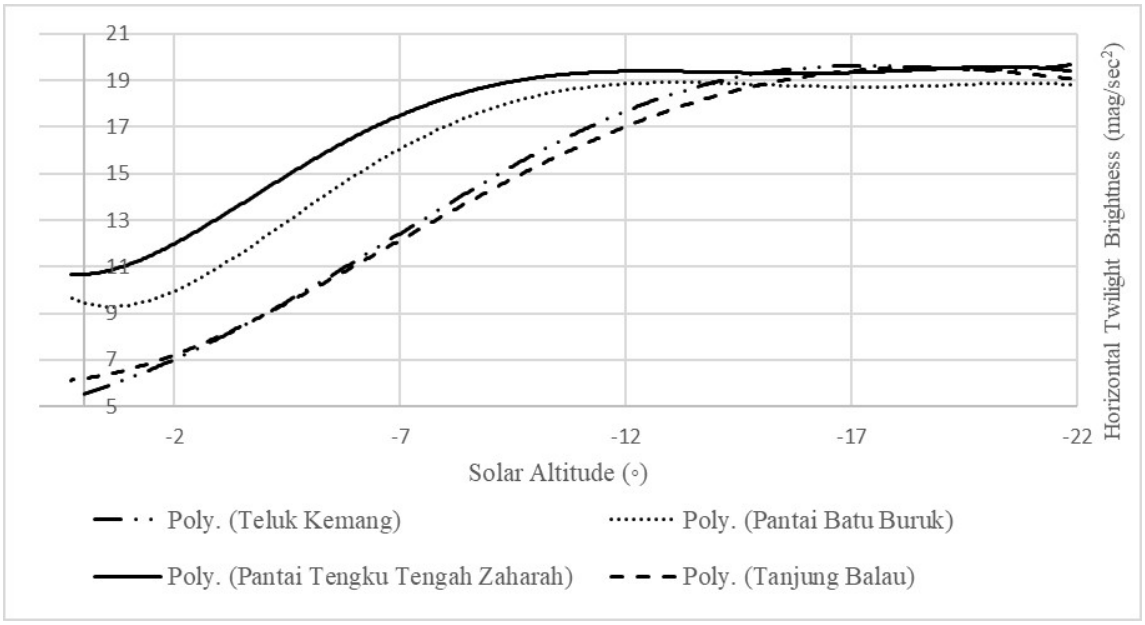

FIGURE 1. Alteration of Light Pollution on Twilight Brightness in Rural Location.

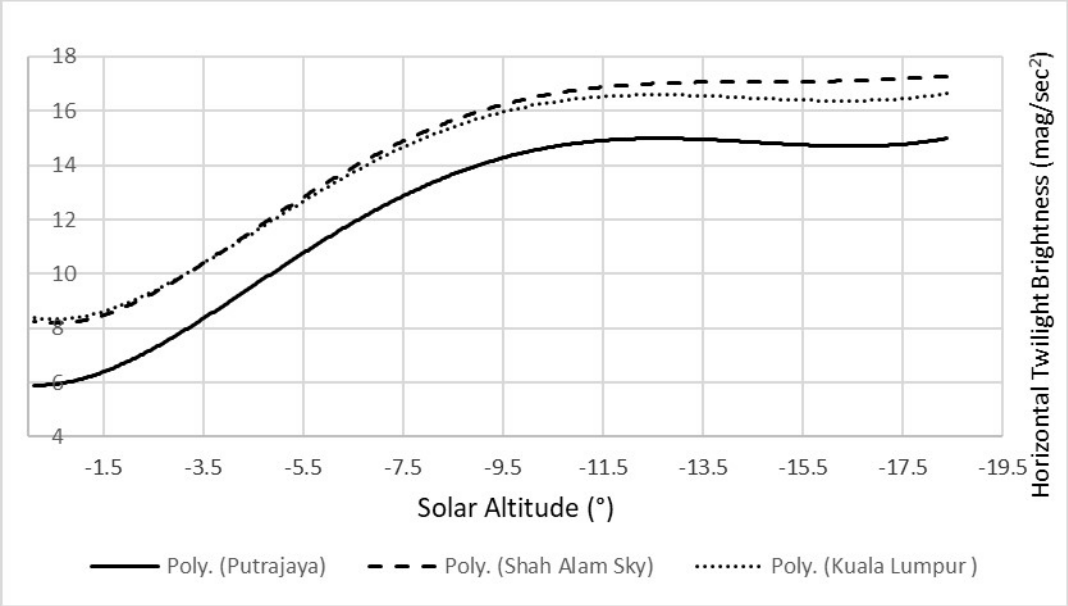

FIGURE 2. Alteration of Light Pollution on Twilight Brightness in Urban Location.

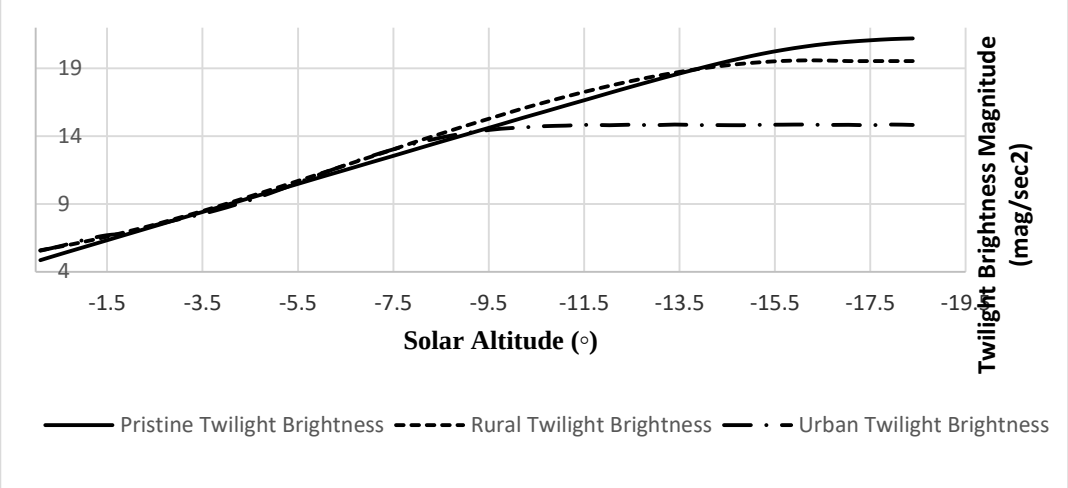

FIGURE 3. Twilight Brightness on Different Light Pollution Profile.

Modelling of Light Polluted Twilight Sky Brightness

By analysing the pattern in FIGURE , FIGURE 1, FIGURE 2 and FIGURE 3, it can be conceded the light pollution alters the twilight sky brightness in such way that the twilight sky brightness no longer singular dependent of solar altitude, but conjoined altogether with the level of light pollution. Particularly in figure 4, the level of light pollution dictates the point of solar altitude where the reading of twilight sky brightness become flat. As instance from figure 4, urban light pollution dictates the reading of twilight sky brightness to be flat at the point around -9.5 degrees of solar altitude, rural light pollution dictates the reading of twilight sky brightness to be flat at the point around -13.5 degrees of solar altitude, and pristine light pollution dictates the reading of twilight sky brightness to be flat at the point around -18 degrees of solar altitude. As a pattern on how light pollution alters the twilight sky brightness can be observed, a model of light polluted twilight brightness can be constructed.

We understand that our data is limited around the reading of light polluted twilight sky brightness at horizontal zenith angle. There are numbers of research that focus on the reading of light pollution at multiple zenith angle such as Berry [5] and Garstang [4], but restricted to the study of light pollution, and not light-polluted twilight sky brightness. Since figure 4 illustrated that the reading of twilight sky brightness is dictated by the level of light pollution at observation site, we believe a model of light polluted twilight sky brightness could be designed by combining our data which is light polluted twilight sky brightness and data from Berry[5] and Garstang [4] for the reading of light pollution at multiple zenith distance. The modelling is presented using Tablecurve 3D and is portrayed in FIGURE 4.

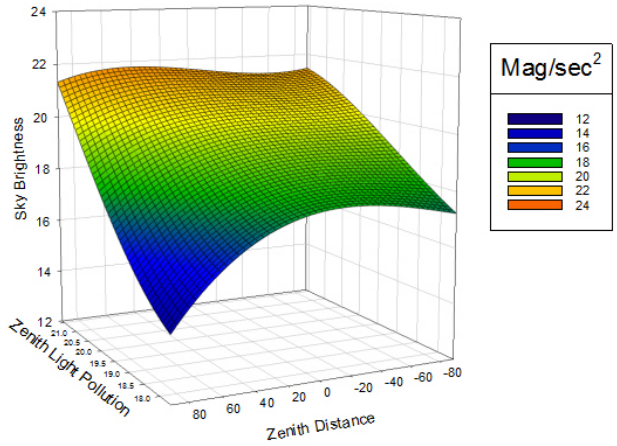

FIGURE 4. Modelling of the Level of Light Pollution at Various Zenith Angle

$$m^{lp} = a + bZ^{LP} + c\theta + dZ^{LP^2} + e\theta^2 + fZ^{LP}\theta + gZ^{LP^2} + h\theta^3 + iZ^{LP}\theta^2 + jZ^{LP^2}\theta \qquad (3)$$

where,
$Z^{LP} = Zenith\ Light\ Pollution,$
$\theta = Observed\ Zenith\ Distance$
$a = 319.186511755673,$
$b = -46.9419919726453,$
$c = 0.434369283318305,$
$d = 2.39138122541257,$
$e = -0.00121311966265414,$
$f = -0.0488735671014705$
$g = -0.0396262989070584,$
$h = -9.28758741258742E-07,$
$i = 0.0000548215089277455,$
$j = 0.00134667559232511$

The value of zenith light pollution, Z^{LP} is either from any theoretical light pollution modelling output or empirical data, and the observed zenith distance, θ is the complement of observed object altitude, with $-\theta$ when the object has the background vicinity to light-polluted city, and

$+\theta$ when the light polluted city background is far from the object location. Kastner modelling is expressed below. ΔAz is the azimuthal sun-moon difference, and h is the solar depression. Please note that this equation only viable for illumination from single-sourced city and magnitude of the sky brightness only accurate at h<18◦.

$$m^{np} = -(7.5 \times 10^{-5}\theta + 5.05 \times 10^{-3})\Delta Az + (3.67 \times 10^{-4}\theta - 0.458)h \quad (4)$$

Finally, the twilight sky brightness in relation to site light pollution is m^{twi}, as expressed in mag/sec^2.

$$\begin{array}{ll} \text{If} & m^{np} < m^{lp}, m^{twi} = m^{np} \\ \text{If} & m^{np} > m^{lp}, m^{twi} = m^{lp} \end{array} \quad (5)$$

where the m^{np} is the twilight sky brightness without the influence of light pollution and m^{lp} is the level of light pollution at various zenith angle.

III. RESULTS

To ensure the modelling accuracy in real light polluted twilight sky brightness, the modelling is tested on rural location. The rural location selected is Teluk Kemang, which is located 4 km from the city centre that has around 150 000 people in its city. Using Garstang equation, it indicates that Teluk Kemang has a level of light pollution around 19.5 – 18.5 mag/sec^2 . The test is illustrated in FIGURE 5. Using nls package from R library [22], it is found that the model has an error of $\pm$0.5 mag/sec^2 for rural location. This indicates that the modelling can accurately present the real light polluted twilight sky brightness on rural location. An extensive examination on the model needs to carry out to ensure the reliability of the model, particularly on urban dan pristine location.

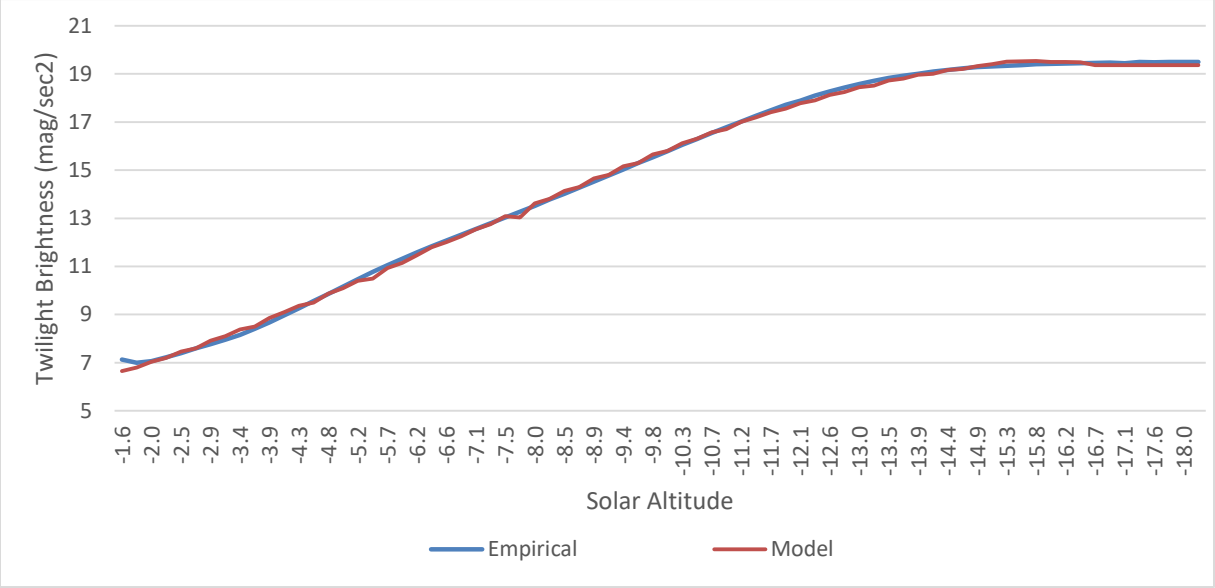

FIGURE 5. Modelling testing of Rural Location.

IV. CONCLUSION

It is found that the light pollution crops a brightening mark that alters of the nature of twilight brightness. The association between twilight sky brightness and light pollution is never linked in the literature thus far making the discovery essential. A semi-empirical modelling is constructed to represent how the relationship between the light pollution and twilight sky brightness intertwined. The model found to have an error of $\pm$ 0.5 mag/sec^2 for rural location signifying its reliability to predict the light polluted twilight sky brightness on rural location. However, a comprehensive examination of the model accuracy particularly on urban and pristine location to investigate its accuracy on real observation.

ACKNOWLEDGMENTS

This work was supported by BESTARI GRANT 600-IRMI/DANA 5/3/BESTARI (067/2017), BK056-2015 UM and Kementerian Pengajian Tinggi Malaysia. Special thanks to the Juraij Stare of www.lightpollutionmap.info providing thematic map of night time irradiance.

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