Extinction and scattering parameters derived from sky brightness measurements

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Abstract. In this study, the moonlit sky brightness model that incorporates extinction and scattering parameters were fitted to the observational data obtained at four locations across Indonesia namely Biak, Garut, Pasuruan and Sumedang. Possible parameters were sampled using Markov Chain Monte Carlo to construct posterior distributions of corresponding parameters. The typical values of extinction parameter are below 0.5 except for Pasuruan whose value almost reaches unity. Atmospheric scattering is represented by Rayleigh scattering factors with values of around 1.0 and Mie scattering factors which are an order magnitude higher than Rayleigh scattering factors. The results indicate that the tropical atmosphere of Indonesia tends to be more turbid than the atmosphere at higher latitudes though more studies are required to confirm this indication.

1. Introduction

Since April 2018, continuous measurements of zenithal night sky brightness have been conducted in several locations across Indonesia [1] as an initial part to mitigate the impacts of artificial light pollution in the country. Clear sky brightness over those locations have been inferred through careful statistical analysis. However, there is a systematic deviation between those in-situ measurements and the values from the world atlas of sky brightness [2] which is accessible through http://www.lightpollutionmap.info. Sky brightness values obtained using Sky Quality Meter (SQM) at locations in Indonesia tend to be larger (or lower in magnitude scale) than the values in the world atlas. The model used for the world atlas assumes aerosol clarity of $K = 1$ while the atmospheric conditions in Indonesia may be better represented by other value. Following earlier works of Cinzano et al. [3] and Garstang [4], the $K$ parameter represents the relative importance of aerosol and molecules for scattering light in the atmosphere, especially in V band. As demonstrated by Falchi et al. [2], SQM data from some locations (e.g. Western United States) fits well to the model with $K = 0.5$.

In order to clarify whether the observed deviation corresponds to the different atmospheric condition, the acquired sky brightness data were examined. Inspired by the work of Yao et al. [5], this study implemented a model of moonlit sky brightness [6] to infer extinction parameter and scattering scaling factors that represent local atmospheric condition in the context of natural and artificial light propagation.
Figure 1. Left: average sky brightness over Garut as a function of Moon phase and lunar zenith distance. Data obtained during cloudy or overcast condition was not filtered. Right: standard deviation of the sky brightness which are less than 0.5 mpsas for most cases.

2. Data and Methods

This study used a one-minute cadence of zenithal sky brightness data acquired using SQM at several locations in Indonesia with different levels of light pollution (Biak, Garut, Pasuruan and Sumber). SQM is a photodiode-based sensor that works effectively at optical window between 400 to 600 nm. The instrument is equipped with a converging lens such that it has limited field of view of about 20° (full-width at half-maximum). Continuous measurements were conducted since April 2018 at those locations and the data from April to December 2018, especially the data obtained during the moonlit condition, were selected for the analysis. The data from months of measurements were mapped into two-dimensional images which show the observed sky brightness as a function of the Moon phase and zenith distance. The ephemeris of the Moon during the time of measurements were computed using Python `pyephem` package by Brandon Rhodes. Figure 1 exhibits the average and standard deviation of sky brightness (in magnitude per square arcsecond, mpsas) measured at Garut.

Moonlit sky brightness model from Krisciunas & Schaefer [6] was fitted to the observed sky brightness. The following are functions used to model the sky brightness (\( B \) is in nanoLamberts and \( \mu \) is in mpsas):

\[
B_0 = 34.08 \exp (20.7233 - 0.92104 \mu_0) \\
I = 10^{-0.4(3.84+0.026\alpha+4\times10^{-9}\alpha^4)} \\
f_R = 10^{5.36(1.06+\cos \rho^2)} \\
f_M = 10^{6.15-0.025p} \\
f = P_A f_R + P_B f_M \\
B = f I \left(10^{-0.4kX_{moon}}\right) \left(1 - 10^{-0.4kX}\right) \\
\mu = \mu_0 - 2.5 \log \frac{B}{B_0}
\]

where \( \alpha = \cos^{-1}(2q - 1) \) is phase angle and \( q \) is the Moon phase. \( \mu_0 \) is moonless sky brightness/background, \( k \) is extinction coefficient, \( X \) is airmass at SQM direction which depends on the zenith distance \( Z = 0^\circ \), \( X_{moon} \) is airmass at the Moon direction (at zenith distance \( Z_{moon} \))
Figure 2. Illustration on how sky brightness brightens due to Moon phase \((q)\), extinction \((k)\), Rayleigh \((P_A)\) and Mie scattering \((P_B)\) scaling factors. The sky brightness was calculated using a simple model prescribed by Krisciunas & Schaefer [6]. In every panel, lighter colors refer to smaller values of the parameter. Except for the leftmost panel, the brightening were calculated for Moon phase \(q = 0.5\) (blues) and \(q = 1.0\) (reds).

and \(\rho\) is the angular distance between the Moon and the SQM direction. \(P_A\) and \(P_B\) respectively are scaling factors of Rayleigh and Mie scattering. In summary, \(\mu_0\), \(k\), \(P_A\) and \(P_B\) were four parameters to be tuned. How sky brightness changes as a function of those parameters can be viewed in Figure 2. The fitting of the model to the observational data was performed on a logarithmic or magnitude scale instead of in the linear luminance scale.

Markov Chain Monte Carlo (MCMC) was used to optimize the model and to obtain the optimal parameters which are background brightness \((\mu_0)\), extinction coefficient \((k)\), Rayleigh scattering \((P_A)\) and Mie scattering factors \((P_B)\). MCMC basically does random sampling to the parameters (e.g. by doing random walks) and evaluate the likelihood of those parameters iteratively in order to obtain posterior distributions. The values of the parameters in the following step are determined by the values in the previous step and also the prior distributions. MCMC becomes an alternative implementation of Bayesian statistics where the prior beliefs are updated using data to construct posterior beliefs. Python EMCEE package, especially the EnsembleSampler was used to do the MCMC with 50 walkers. This code implements Goodman & Weare’s Affine Invariant sampler [7]. Prior distribution of the parameters were set to be uniform within certain boundaries: \(\mu_0 = [15, 25]\), \(k = [0, 2]\), \(P_A = [0, 15]\) and \(P_B = [0, 15]\).

3. Result and Discussion

Figure 3 shows how MCMC samples the parameters in order to achieve a model with the highest likelihood and to produce the posterior probability functions of the parameters. Table 1 summarizes the median values of the parameters extracted from the posterior probabilities and the respective uncertainties. The highest value between the deviation of the 16th and 84th percentile from the median was adopted as the uncertainty. Between those two percentile limits, there is 68% of the sample as in \(\mu \pm \sigma\) limits of Gaussian distribution.

These results can be compared to the works of Yao et al. [5], though there are some substantial differences. In this study, the sky brightness model was matched to the composite or stacked data instead of individual nightly observation as in the work of Yao et al. [5]. By working with individual nightly data, they were able to evaluate the seasonal variabilities of the atmospheric parameters even though the scatters mostly overwhelm the seasonal patterns. The second aspect of difference is that they performed fitting in linear luminance space while this study

\[\begin{align*}
\mu_0 &= [15, 25], \\
k &= [0, 2], \\
P_A &= [0, 15], \\
P_B &= [0, 15].
\end{align*}\]
Figure 3. Corner plot of the parameters imputed to the model during MCMC sampling. The parameters are moonless sky brightness ($\mu_0$ in mpsas), extinction coefficient ($k$), Rayleigh scattering factor ($P_A$) and Mie scattering factor ($P_B$). Darker regions in the two-dimensional density plot correspond to the most probable values. Vertical lines mark $16^{th}$, $50^{th}$ and $84^{th}$ percentile of the sampled parameters. Vertical lines represent the median and the uncertainty of the parameters.

uses logarithmic space. However, the obtained posterior distributions are comparable. For instance, Mie scattering factor ($P_B$) has a broad distribution with pronounced right tail while the distribution for the Rayleigh scattering factor ($P_A$) is more concentrated. High dispersion of $P_B$ can be associated with the notion that the density of Mie scattering particles has a higher chance of variability compared to that of Rayleigh scattering particles [5]. Nevertheless, it is noteworthy that the model behavior (e.g. how sky brightness changes as parameters are tuned,
Table 1. Optimum parameters obtained from the MCMC sampling. The parameters are moonless sky brightness ($\mu_0$ in mpsas), extinction coefficient ($k$), Rayleigh scattering factor ($P_A$) and Mie scattering factor ($P_B$). Values in parentheses are the uncertainties.

| Station      | $\mu_0$   | $k$     | $P_A$   | $P_B$   |
|--------------|-----------|---------|---------|---------|
| Pasuruan (PSR) | 17.01 (0.03) | 0.95 (0.32) | 0.31 (0.23) | 13.77 (0.89) |
| Biak (BIK)   | 19.05 (0.05) | 0.40 (0.06) | 1.19 (0.12) | 7.28 (0.71)   |
| Garut (GRT)  | 20.13 (0.06) | 0.35 (0.06) | 0.85 (0.14) | 11.63 (1.56) |
| Sumedang (SMD) | 20.26 (0.07) | 0.18 (0.07) | 1.02 (0.12) | 12.38 (2.66) |

Figure 2) may contribute to how MCMC infers posterior distributions.

As summarized in Table 1, the values of moonless sky brightness range from 17.01 mpsas at Pasuruan to 20.26 mpsas at Sumedang. There are moderate differences (up to 0.7 mpsas) between the values obtained in this study to the values reported by Admiranto et al. [1]. The optimal values of $\mu_0$ from MCMC sampling tend to be smaller (or brighter) compared to the statistical values reported before. Since this study utilizes an indirect method to determine the background sky brightness, the obtained values may comprise errors from other variables.

Next, the extinction coefficients are below 0.5, except for Pasuruan station where the $k$ almost reaches unity. Even though this location has the highest clear sky fraction compared to the other stations reported in this study or in [1], Pasuruan is located close to a big city (Surabaya), industrial complex, and also mining sites such that extinction and scattering are somewhat high. Mie scattering factor at this location is almost an order of magnitude higher compared to the typical value reported in [5] for Xinglong station. In general, $P_B$ obtained here is much larger while the background (moonless) sky brightness slightly correlates with the extinction coefficient, in agreement with the result from Liu et al. [8].

Regardless of the parameters obtained in this study, further analysis is required to accomplish the main purpose of clarifying whether the model of sky brightness need to be adjusted to match the local condition. The extinction and scattering parameters inferred needs to be confirmed by other means and also need to be articulated in the same way as in the world map of sky brightness [2].

4. Conclusion
In this paper, moonlit sky brightness data acquired in Biak, Garut, Pasuruan and Sumedang using Sky Quality Meter were analyzed in order to obtain the extinction and scattering parameters defined in a particular model [6]. It was found that the atmospheric extinction coefficients at those locations are below 0.5 except for Pasuruan whose extinction coefficient is approximately 0.95. Rayleigh scattering factors are around 1.0 while the Mie scattering factors are about 10.0. These values indicate that aerosols have a higher importance in scattering the moonlight compared to the molecules such that the value of $K$ defined in Garstang [4] deviates from unity. Deeper analyses will be required to confirm this result and the notion that the tropical atmosphere is more turbid compared to subtropical ones.

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