J-STAGE Advanced published date: June 17, 2016, doi: 10.2150/jlve.IEIJ150000562

Research Note

Pilot Study on Estimation of Upward Flux by Luminance Distribution of Night Sky Luminance

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Received February 27, 2015, Accepted January 28, 2016

ABSTRACT

The upward flux from the cities may cause sky glow. The purpose of our study is to calculate the upward flux from luminance distribution of night sky viewed from ground level on cloudy days. In this study the clouds' heights and the reflectance of the clouds are used as well as luminance distribution of the night sky to calculate the upward flux. The reflectance of the cloud is presumed from the cloud type which is determined from the cloud model of Liou's study referring to cloud heights and radiant temperature. An experiment is carried out using a scale model to verify the precision of the method. It is confirmed that upward flux can be almost precisely calculated by this method. The Tokyo metropolitan area is divided using grids (2.5 km×2.5 km) and the upward luminous flux of each area is calculated. A set of six measurement points is chosen which can measure the upward luminous flux from all light-emitting areas, and each measurement point must not have any obstacles in the viewing angle of the cloud infrared radiometer. The results show that 5 lm/m^2 of upward luminous flux was emitted from the center of Tokyo. The distribution of the electricity wastage emitted to the sky was also illustrated.

KEYWORDS: light pollution, night sky luminance viewed from ground, reflectance of the cloud, upward flux

1. Introduction

Light pollution, a by-product of artificial lighting at night, is often caused by wasted light emitted into areas where the light is not needed. Upward luminous flux of night-time lighting is one form of wasted light which causes not only light pollution but also energy wastage. The sources of the upward light are numerous, including streetlights, building exterior and interior lighting, advertising, commercial properties and illuminated sporting venues. Also light reflected from the ground or building surfaces is added to upward luminous flux.

Tokyo, a densely populated 24-hour city, is known as a very bright city which uses an excessive amount of light. After the Tohoku Earthquake in 2011, electricity consumption for lighting in Tokyo had to be transitorily decreased. In order to achieve a long-term reduction of wasted light and electricity, a quantitative study is required.

A number of researchers have modelled light pollution in various ways. Cinzano et al. used the Defense Meteorological Satellite Program (DMSP) satellite imaging to compute maps of artificial and total sky brightness in large areas[1]. Chalkias proposed a methodology for modelling light pollution using geographical information systems (GIS) and remote sensing (RS) technology[2]. Recently data from the Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS DNB) is shown to have sufficient resolution to identify major sources of waste light[3]. It has been revealed that applying these technologies is useful for mapping and assessing light pollution. In this study, however, we tried to use not satellite images but celestial images from the ground that can be regularly seen on a day to day basis. Although we expect that the measurements will not be so precise due to the sky conditions, we believe that this method can contribute to raise public awareness about light pollution.

Our previous study proposed a method which could calculate the upward flux from the celestial luminance image[4]. However, that method needs nights with an overcast sky in which the cloud heights can be considered entirely even. In this study, the previous method had been modified by using cloud infrared radiometer, which can determine the cloud height. The method could calculate the upward luminous flux from the reflectance of clouds, the cloud heights, and luminance of the hemisphere. This paper presents the method and an experiment carried out using a scale model to verify the method. It also presents field measurements conducted by using this method to identify the amount

doi: 10.2150/jlve.IEIJ150000562

of electricity wastage emitted to the sky of Tokyo.

2. Outline of calculation method

2.1 Calculation logic

Upward flux is calculated using the configuration factors between the light-emitting areas and light-receiving points which are determined on the image of celestial luminance distribution. The calculation method is shown in Figure 1 and Eq. (1).

The number of light-receiving points should be set to the same as or more than the number of light-emitting areas. Light-emitting areas are assumed to be a Lambertian surface.

$$X=\left[{}^{t}AA\right]^{-1}\ {}^{t}Ab$$

$$A=\frac{\rho_c}{\pi}\begin{pmatrix}\varphi_{11} & \cdots & \varphi_{1j}\\ \vdots & \ddots & \vdots\\ \varphi_{i1} & \cdots & \varphi_{ij}\end{pmatrix}\quad X=\begin{pmatrix}M_1\\ \vdots\\ M_j\end{pmatrix}\quad b=\begin{pmatrix}L_1\\ \vdots\\ L_i\end{pmatrix} \tag{1}$$

i: Light-receiving point
j: Light-emitting area
M_j: Luminous exitance of light-emitting area [lm/m^2]
φ_{ij}: configuration factor [—]
ρ_c: Reflectance of the clouds
L_i: Luminance of light-receiving point [cd/m^2]

2.2 Cloud height

Cloud height is measured with a cloud infrared radiometer (CIR-4, EKO). The specification of CIR-4 is shown in Table 1.

In CIR-4, the downward thermal emission from the clouds and air between the clouds and sensor are measured by infrared pyrometers. The temperature of the clouds is measured by a combination of Planck's law and Stefan–Boltzmann's law (Eq. (2)).

CIR-4 has four sensors with 30 degrees of the zenith angle in four different orientations shown in Figure 2. The height of the clouds around 30 degrees from the zenith can be measured. When the cloud heights within the measurement area of CIR-4 are even, the upward flux can be computed.

$$Fr=\varepsilon f(T) \tag{2}$$

F_r: The downward IR flux integrated for the band pass of the detector [W/m^2].
ε: The hemispheric emissivity.
$f(T)$: A 4-order relationship between thermodynamic temperature and infrared emission in the spectral range of the detector.

2.3 Cloud type and reflectance

To determine reflectance of clouds, the type of cloud should be determined. From the cloud height and the radiant temperature of the cloud, the type of the cloud is estimated by using Liou's study[5] (Table 2).

For middle and low-level clouds, the reflectance of the clouds is computed by liquid water content and thickness of the cloud by Stephens's method[6]. The method is shown by Eqs. (3) to (5). For high-level clouds, reflectance presented by Reynolds et al[7] is used (Table 3).

$$R(\mu_0)=\frac{\beta(\mu_0)\tau_N/\mu_0}{1+\beta(\mu_0)\tau_N/\mu_0} \tag{3}$$

$$\log_{10}\tau_N=0.2633+1.7095\ln(\log_{10}W) \tag{4}$$

$$W=w\Delta z \tag{5}$$

$R(\mu_0)$: reflectance
$\beta(\mu_0)$: the back scattered fraction of monodirectional incident radiation at the zenith angle μ_0
μ_0: $\cos\theta_0$
θ_0: zenith angle [rad]
τ_N: Optical thickness of the cloud
W: Liquid water path [g/m^2]
Δz: thickness pf cloud [km]
w: liquid water content [g/m^3]

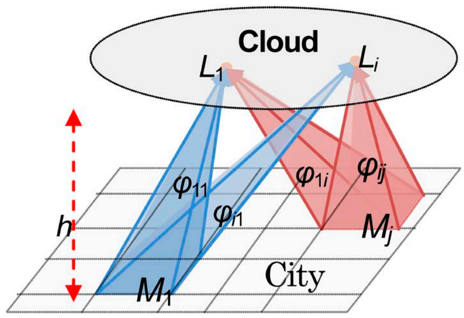

Figure 1 Calculation of upward flux from city.

Table 1 Specification of CIR-4.

	Quantity of clouds	Cloud height
Range	0–100%	300–8000 m
Accuracy	±6%	±6%

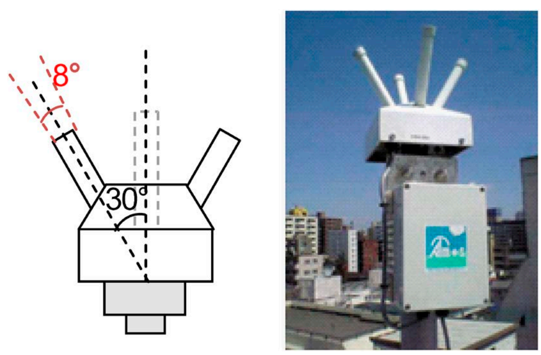

Figure 2 CIR-4.

doi: 10.2150/jlve.IEIJ150000562

Table 2 Cloud parameters (Liou 1976)[5].

Cloud types	Base height [km]	Thicknesses [km]	Temperature [K]
Low cloud (Cu, Sc)	1.7	0.5	288
Middle cloud (As, Ac)	4.2	0.6	274
High cloud (Ci, Cs, Cc)	4.6	1.7	234
Nimbostratus (Ns)	1.4	1	280
Cumulonimbus (Cb)	17	6	270
Stratus (St)	1.4	0.1	291

Table 3 Reflectance of the clouds.

Cloud types		Reynolds et al. (1975)	Drummond and Hickey (1971)
St, Cu	Reflectance	37–41%	47–56%
	Absorbance	12–36%	—
As, Ac	Reflectance	—	40%
	Absorbance	—	15%
Cb, Ns	Reflectance	66%	—
	Absorbance	31%	—
Ci, Cs	Reflectance	47–59%	20%
	Absorbance	13–15%	—

3. Experiment to verify the method

3.1 Method

3.1.1 Experimental set-up

An experiment is carried out using a scale model to verify the method proposed in this study for calculating the upward flux distribution.

Figure 3 shows the details of the model. The scale of the model is 1/10000.

The model consisted of ground and cloud. The ground has three light sources (Organic light-emitting diode 74 mm×74 mm) imitating light-emitting areas on the land surface. The cloud is a polyurethane foam plate hung above and parallel to the ground.

The model is covered by a blackout curtain and photos of the reflective plate are taken from the center of the ground to measure the luminance of the light-receiving points.

3.1.2 Experimental condition

The cloud condition used in this experiment is shown in Table 4. The positions of the centers of the light-emitting areas are set as shown in Table 5. The upward flux of the light-emitting areas met the five conditions (ItoV) shown in Table 6.

3.1.3 Light-receiving points

The light-receiving points are set every 15 degrees on the concentric circle from 10 to 30 degrees (every 5 degrees) of zenith angle. One hundred twenty light-receiving points are used as shown in Figure 4. The coordinates of light-receiving points on a luminance distribution image are calculated by Eqs. (6) to (8), due to equidistance projection.

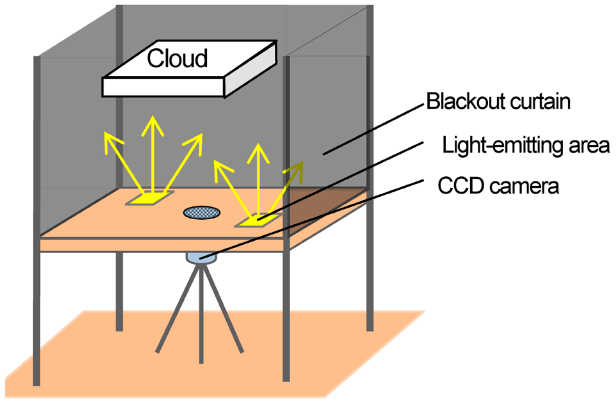

Figure 3 Scale model.

Table 4 Conditions of experiments.

Cloud heights [m]	Reflectance [%]
4550	68

Table 5 Position of light-emitting areas.

Light-emitting areas (center)					
A		B		C	
X_A	Y_A	X_B	Y_B	X_C	Y_C
−2987	−4971	997	2998	4988	−2998

Table 6 Upward flux of experimental conditions.

Light-emitting areas	Upward flux [lm]				
	I	II	III	IV	V
A	0.732	0.305	0.937	1.56	4.10
B	0.488	0.329	1.08	1.86	0.215
C	0.406	1.69	4.86	1.69	0.892

$$x_i = \gamma \ \cos Av \quad (6)$$

$$y_i = \gamma \ \sin Av \quad (7)$$

$$\gamma = R(\xi/90) \quad (8)$$

xi: Coordinates (x) on the luminance distribution image of the light-receiving points

yi: Coordinates (y) on the luminance distribution image of the light-receiving points

γ: Pixel distance on the luminance distribution image from the center to light-receiving points

ξ: Angle from the zenith of measurement point to light-receiving points

Av: Azimuth of light-receiving points

R: The radius of a luminance distribution image

3.2 Results

Figure 5 shows an example of luminance distribution on the bottom of the cloud. Table 7 shows the upward flux calculated and the ratio of the calculated value to

doi: 10.2150/jlve.IEIJ150000562

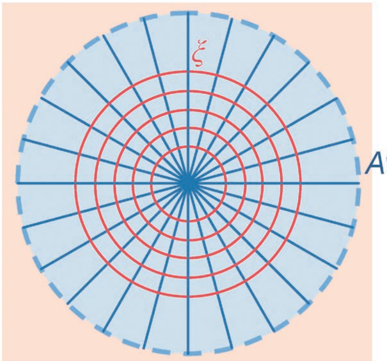

Figure 4 The determination method of light-receiving points.

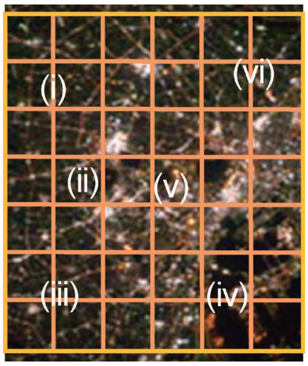

Figure 6 Grid and measurement points with photo of Tokyo[8].

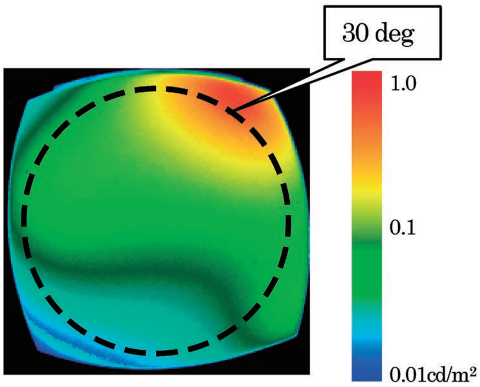

Figure 5 Example of luminance distribution (Condition II).

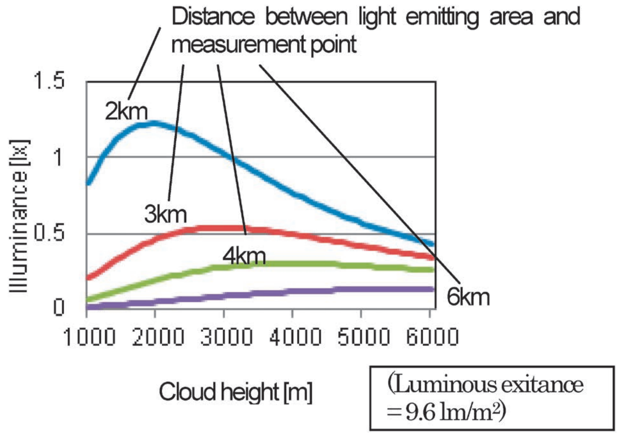

Figure 7 Zenith illuminance from measurement point.

Table 7 The upward flux of light-emitting areas calculated from 120 receiving points by the least square method.

Light-emitting area	Upward flux calculated [lm] (ratio to the measured value shown in Table 6)				
	I	II	III	IV	V
A	0.521 (0.712)	0.274 (0.897)	1.01 (1.08)	1.80 (1.15)	3.74 (0.913)
B	0.364 (0.746)	0.406 (1.23)	1.13 (1.04)	1.92 (1.03)	0.214 (1.00)
C	0.395 (0.974)	1.79 (1.06)	5.27 (1.09)	2.46 (1.45)	0.948 (1.06)

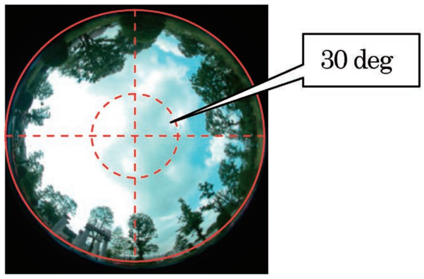

Figure 8 Celestial hemisphere of measurement point (v).

experimental condition shown in Table 6.

The results show that our method can generally determine upward flux, if the reduction of luminance by the air between the light-emitting area and the light-receiving point is negligible.

4. Applying the program to metropolitan area

4.1 Method

4.1.1 Determination of measurement points

The metropolitan area of Tokyo (622[km^2]) is divided using grids (2.5 km×2.5 km) as shown in Figure 6, and each division is considered to be a light-emitting area.

In order to determine the area which a measurement point can cover, a simulation is carried out. Figure 7 shows the effect of the cloud height and the distance between the light emitting area and measurement point on zenith illuminance at the measurement point. The measurable area for one measurement point varies according to the cloud height.

A set of six measurement points is chosen which can measure the upward luminous flux from all light-emitting areas (Figure 5), and each measurement point must not have any obstacles in the viewing angle of the cloud infrared radiometer which has four sensors with 30 degrees of the zenith angle in four different orientations (Figure 8).

4.1.2 Procedure

The measurement was carried out at 18:00, 19:00 and 20:00 on December 21, 2012 when a suitable cloud con-

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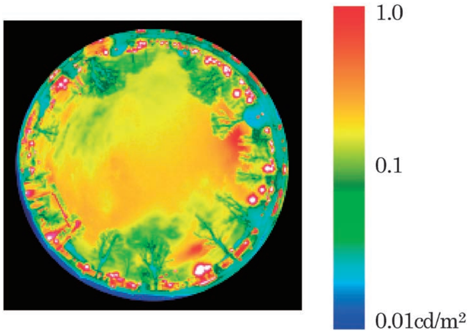

Figure 9 Luminance of celestial hemisphere at measurement point (v).

Table 8 Radiant temperature and height of cloud.

Time	Radiant temperature [K]				Cloud cover [%]	Cloud height [m]
	North	East	South	West		
19:00	265	286	269	286	60	6500
					38	5400
20:00	267	286	267	286	9	6900
					90	4600

dition could be obtained. Luminance distribution of the celestial hemisphere is measured by the CCD camera system (Nikon with an equidistance fish-eye lens). The cloud cover and the cloud height are measured by the cloud infrared radiometer. From the cloud height and radiant temperature, as well as visual inspection, the type and the reflectance of cloud are estimated.

4.2 Results

4.2.1 Upward flux

Table 8 shows the radiant temperature, the cloud cover and the cloud height. Since the 4600 m-high cloud occupied 90% of measured sky area at 20:00, the upward flux at 20:00 was calculated. It was estimated that the cloud type was Altostratus and the reflectance was 0.4. Figure 9 shows luminance distribution of the celestial hemisphere. Figure 10 and Table 9 show symbols of areas and the upward luminous flux from each area calculated.

The upward luminous exitance around the center of Tokyo was 5 lm/m^2 on average on December 21, 2012, which was around Christmas time, so the results were influenced by Christmas illuminations. Compared to 5 lx of the night-time illuminance required for a street in residential areas, it is not a negligible quantity.

4.2.2 Electricity wastage

The electricity wasted through upward flux can be calculated by Eq. (9). To determine the average luminous efficacy, the kinds of lamps used in these areas were estimated from GIS. Figure 11 shows the distribution of wasted electricity.

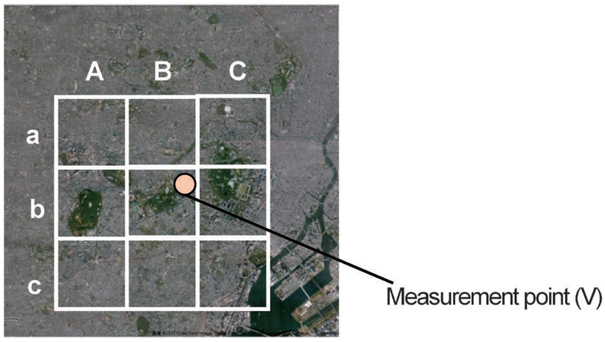

Figure 10 Light emitting area.

Table 9 Upward flux from each area.

	A	B	C
a	4.6×10^7[lm]	7.0×10^6[lm]	2.9×10^7[lm]
b	3.7×10^7[lm]	4.0×10^7[lm]	4.4×10^7[lm]
c	2.7×10^7[lm]	1.4×10^7[lm]	4.0×10^7[lm]

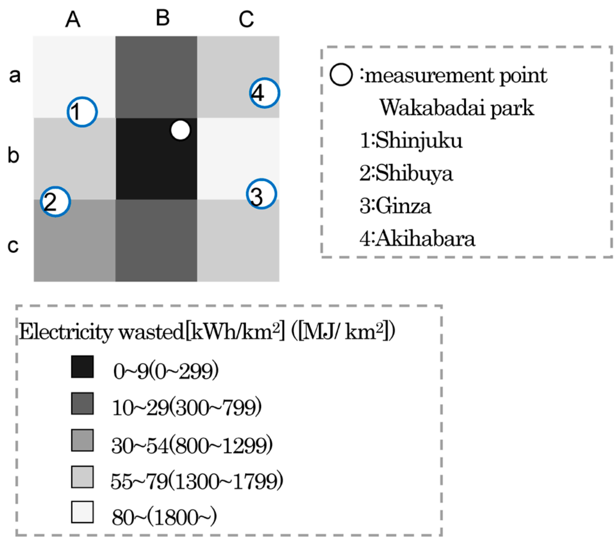

Figure 11 Example of distribution of electricity wastage through upward flux.

$$Le = \frac{tM}{\eta_{\mathrm{ave}}} \quad (9)$$

Le: Electricity wasted [Wh/km^2],
t: hour(=1),
M: Upward luminous exitance [lm/m^2]
η_{ave}: Average luminous efficacy [lm/W]=$\Sigma P_k \eta_k$
P_k: Percentage of flux from each kind of lamp
η_k: Luminous efficacy of each kind of lamp [lm/W]

5. Conclusions

The method which can calculate the upward flux from the reflectance of clouds, the cloud heights, and luminance of the hemisphere is proposed. To verify the method, a preliminary experiment using a scale is carried out. The result shows that the method can generally determine upward flux, if the reduction of

doi: 10.2150/jlve.IEIJ150000562

luminance by the air between the light-emitting area and the light-receiving point is negligible.

In order to identify the amount of light and electricity wastage emitted to the night sky, field measurements are carried out. The metropolitan area of Tokyo is divided using grids and the upward luminous flux of each area is calculated using the method which can calculate the upward flux from the reflectance of clouds, the cloud heights, and luminance of the hemisphere. The results show that $5 lm/m^2$ of upward flux was emitted from the center of Tokyo, which is equivalent to nighttime illuminance required for a street in residential areas. The distribution of the electricity wastage emitted to the sky was also illustrated.

On the other hand, problems of this method are identified. It is not easy to catch a night with a new moon under a stable cloud condition. This method will help to change the public perception, especially of people living in Tokyo, that a bright night sky is normal.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 23656351 (Grant-in-Aid for Challenging Exploratory Research).

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Parts of this work were presented at 7th Lux Pacifica Conference (March, 2013, Bangkok, Thailand), at 46th annual conference of IEIJ (September 2013, Nagoya, Japan) and at Energy for Sustainability 2013 (September 2013, Coimbra, Portugal).