Paper

Sky Glow Caused by the Spill Light from Office Buildings

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ABSTRACT

The sky glow in Tokyo is considered to be caused not only by excessive upward light output from outdoor lighting. The purpose of this study is to determine the influence of the light from windows of office buildings on the sky glow in Tokyo. In order to identify the actual conditions of the spill light from office windows, field measurements were conducted in a park and, based on the results, the upward luminous flux from office windows was compared to that from ou tdoor lighting investigated by Illuminating Engineering Institute of Japan(IEIJ). Our research proves that it is necessary to consider not only the outdoor lighting but also the light spilled from the inside of buildings.

KEYWORDS: sky glow, spill light, office windows, upward luminous flux

1. Introduction

Preserving our nighttime environment is a global issue needing worldwide solutions[1]. The increase of outdoor lighting in urban areas has resulted in levels of sky glow which seriously threaten astronomical observatories. Therefore, the International Astronomical Union (IAU) and the CIE have worked together to prepare the "Guidelines for Minimizing Urban Sky Glow Near Astronomical Observatories"[2]. Moreover, CIE 150[3] shows the guide to help formulate guidelines for assessing the environmental impacts of outdoor lighting and to give recommended limits for relevant lighting parameters to contain the obtrusive effects of outdoor lighting within tolerable levels. The guide refers to the potentially adverse effects on the natural environment, residents, transport users and sightseers, as well as on astronomical observations. Consequently, Crawford et al. have summarized the effects of bad outdoor lighting including waste of energy[4] and Lecocq proposed UFR (Upward flux ratio) which considered the reflection on the ground[5]. Thus for outdoor lighting researches have been done to improve its quality.

However, the sky glow in Tokyo is caused not only by excessive upward light output from outdoor lighting. The spill light from the windows of office buildings is considered to be one of the sources of the sky glow in Tokyo. The purpose of this study is to determine the influence of the light from the office building windows on the sky glow. In order to identify the actual conditions of the spill light from office windows, field measurements were conducted in a park. Based on the results, the upward luminous flux from office windows was compared to the upward light from outdoor lighting investigated by the Illuminating Engineering Institute of Japan(IEIJ).

2. Comparison between field measurements and calculation

2.1 Method of measurements

In order to determine the amount of the spill light from office buildings, night-time illuminances on the ground of a park were measured. These consisted of illuminances from outdoor lighting, the bright part of the sky and the windows of office buildings. The illuminance from the office windows was determined by CCD camera system.

Figure 1 shows two measurement points, o and p. The horizontal illuminances were measured by illuminance meter (MINOLTA) and luminance distribution of the celestial hemisphere was measured by the CCD camera system (Nikon COOL PIX 5000 with a fish-eye lens). The measurements were conducted at 18:30 and 19:15 for Point

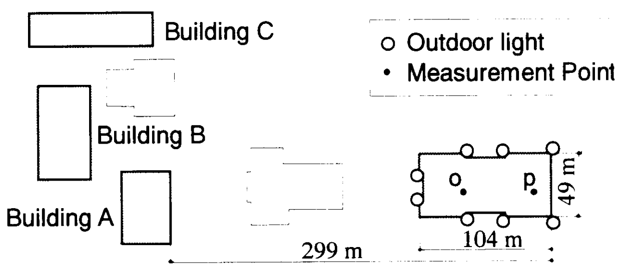

Figure 1 Measurement points

o while at 18:30, 19:15, 20:00 and 20:30 for Point p.

2.2 Methods of calculation

Figure 2, the celestial hemisphere above Point p, shows that light from the three office buildings (Buildings A, B and C) seems to have no small effects on the illuminance of the measurement point. Table 1 shows the outline of the three buildings.

The illuminance from the office windows was calculated. There are two ways, the first one is to assume that upward light equals downward light from the windows and the second one is to assume downward light from the windows consists of only direct light from the ceiling including ceiling lighting.

In the first method, illuminance from the windows of those buildings could be calculated as follows.

$$Eg = \sum_{n}^{i=1} Rwi * \phi wi \qquad (1)$$

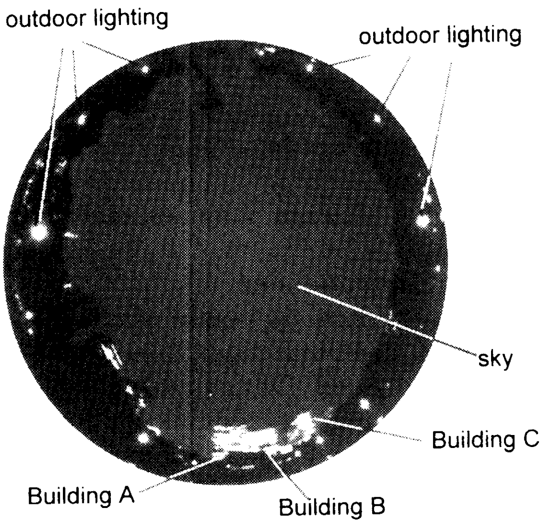

Figure 2 The celestial hemisphere above Point p

Table 1 Outline of the office buildings

	Building A	Building B	Building C
Height of a building [m]	116	128	130
Number of floors	29	31	21
Number of office floors	27	29	10
Floor area / floor [m^2]	1408	2888	1662
Window area /floor [m^2]	164	316	147
Number of windows facing the park	460	308	314
Number of 40W fluorescent lamps*1/ floor	2*288	2*408	4*173

*1 number of lamps * number of fixtures

Eg : the ground illuminance from the windows [lx]
ϕwi : configuration factor of each window from the measurement point
n : number of the windows
Rwi : luminous exittance of each window [rlx]

$$Rwi = (Ewc + Ewf) * \tau \qquad (2)$$

$$Ewc = Fc * \Phi_{CW} / Aw \qquad (3)$$

$$Ewf = Ed * \rho_L * \Phi_{FW} * Af / Aw \qquad (4)$$

Ewc : illuminance of the window by direct light from the ceiling fixtures [lx]
Ewf : illuminance of the window by reflected light from below [lx]
τ : transmittance of the window glass (0.85)
Fc : luminous flux from the ceiling [lm]
Φ_{CW}, Φ_{FW} : form factor of the wall including the window from the ceiling or from the floor
Aw: area of the wall which includes the window [m^2]
Af : floor area [m^2]
Ed: desk illuminance [lx]
ρ_L : working surface reflectance

In the second method, illuminance from the windows of those buildings could be calculated as follows.

$$Eg = \sum_{n}^{i=1} (Rci * \tau * \phi ci) \qquad (5)$$

Rci : luminous exittance of ceiling [rlx]
ϕci : configuration factor of the ceiling which can be seen through the window from the measurement point.

When the distance between a window-side wall and the opposite wall is large or the elevation angle from the measurement point to the window is large, only the ceiling can be seen through the window. In this case the following equation holds good.

$$\phi ci = \phi wi \qquad (6)$$

Eg, τ, n and i are the same values as in the first method.

$$Rci = Fc / Ac \qquad (7)$$

Ac: ceiling area [m^2] (equal to Af)
Fc is the same value in the first method.

Table 2 shows the calculation conditions and luminous exittance of the windows and that of the ceilings.

2.3 Results

It was verified that the illuminance on the ground determined by the CCD camera system, which measured the luminance and the configuration factor of each pixel, equaled that measured by the illuminance meter. The CCD camera system was able to determine the proportion of illuminance on the ground from each light source which

Table 2 Calculated luminous exittance from office windows

		Building		
		A	B	C
The first and the second methods	*Ed* [lx]	700	510	750
	Fc [lm]	774720	1150560	1953170
	$\Phi_{C\text{-}W}$, $\Phi_{F\text{-}W}$	0.094	0.062	0.014
	Aw [m^2]	158	231	87
	Af [m^2]	704	1444	1662
The first method	ρ_L	0.2	0.2	0.2
	Ewc [lx]	460	308	314
	Ewf [lx]	59	40	40
	Rwi [rlx]	441	296	301
The second method	*Rci* [rlx]	1100	800	1180

is shown in Figure 3. Figure 4 shows the change in illuminances from outdoor lighting, the sky and the windows of the buildings. The illuminance from the sky amounts to 50% of the total illuminance in this figure. It depends on the sky condition, e.g. on a clear day no reflected light can be seen. Figure 5 shows the change in the percentage of windows where indoor lights were on. Note that until 8:00 PM almost 50% of indoor lighting was being used for workers.

Figure 6 shows the comparison between illuminance from the spill light measured by the CCD camera systems and illuminance calculated by the two methods. The open circles show the comparison between illuminance measured by the CCD camera systems and illuminance calculated by the first method using equations (1)-(4). Each plot shows illuminance at Point o or p from Building A, B or C, consequently there are 18 plots in total. The regression line showed that a strong correlation was found (R^2=0.95) and that calculated values were lower than measured values ($y = 0.76x - 0.002$). This was caused by the assumption in this calculation that upward light equaled downward light from the windows. Closed circles in Figure 6 show the comparison between illuminance from the spill light measured by the CCD camera system and illuminance calculated by the second method using equations (5)-(7). The regression line showed that a strong correlation was found (R^2=0.96) and that calculated values were higher than measured values ($y = 1.44x + 0.09$). Thus, provisionally, it was determined that the first method is adopted but 0.5 of the ratio of downward luminous flux to total luminous

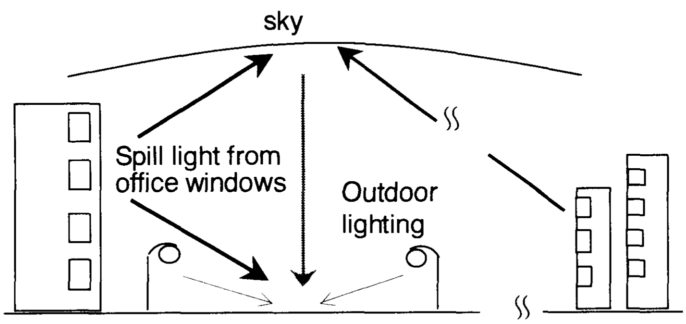

Figure 3 Sources of ground illuminance

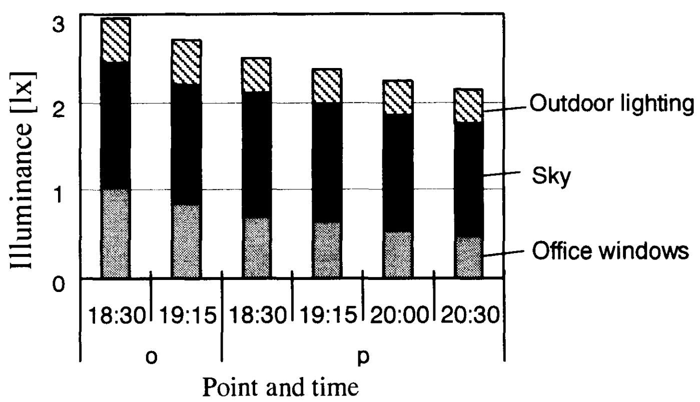

Figure 4 Change in illuminances from outdoor lighting, the sky and the windows of the buildings

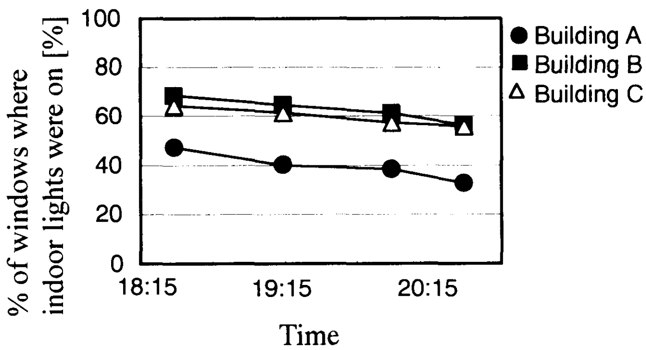

Figure 5 Percentage of windows where indoor lights were on

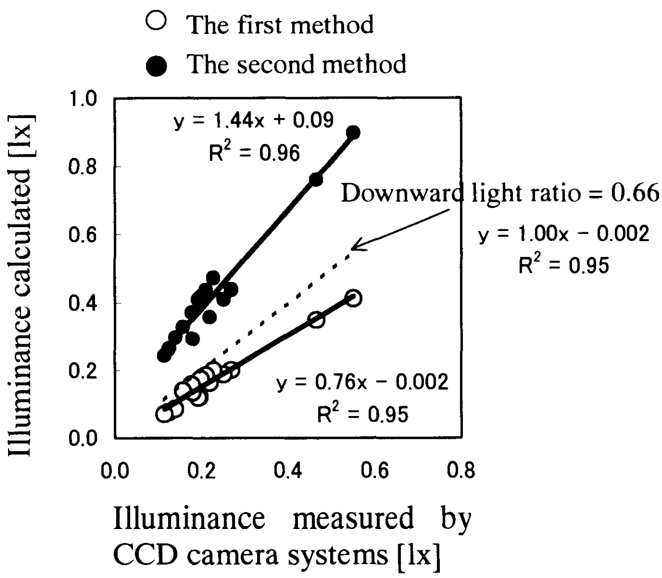

Figure 6 Comparison between illuminance from the spill light measured by the CCD camera system and illuminance calculated by the two methods

flux of a window should be replaced with 0.66 which make the calculated value equal the measured value as shown in the dashed line in Figure 6.

In order to roughly check this assumption (0.66 of the ratio of downward luminous flux to total luminous flux) a simple additional measurement was conducted where window luminance was measured from above and from below by the CCD camera system with a standard lens. Pictures of windows on the 20th floor of a building were taken from windows on the 26th floor and on the 14th floor of another building. Figure 7 shows the vertical and horizontal distance between the window and the camera. The average luminance of each window, the solid angle of which was approximately 0.0002sr, was calculated by

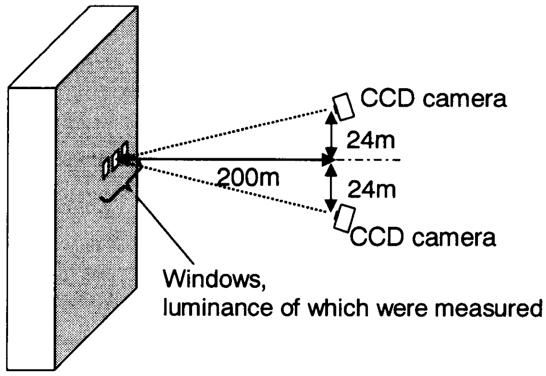

Figure 7 Vertical and horizontal distance between a window and the CCD camera for measuring window luminance from below and above

analyzing the pictures. The results show that the average ratio of downward luminous flux to total luminous flux of a window is 0.7 (ranging from 0.69 to 0.73).

3. Comparison between spill light from office and that from outdoor lighting

3.1 Calculation Methods

The spill light from the buildings in the central area of Tokyo (in three wards) was calculated as shown in Table 3 with notes. The fourth column shows how to calculate the values.

As shown in Note *5, 0.12 of the form factor of the wall including the window from the ceiling or the floor was adopted. The condition for this calculation is shown in Figure 8.

The bottom raw shows values calculated for two different cases. The ratio of upward luminous flux to total luminous flux of a window is assumed 0.34 where 0.66 of the downward luminous flux ratio is assumed from the field measurements. Also 0.30 of the downward ratio derived from the results of the additional measurements is used.

3.2 Results and Discussion

Table 3 shows that huge luminous flux is spilled from the office windows, namely significant amount of electricity is wasted through the windows.

To compare the upward luminous flux from office

Table 3 The spill light from the buildings in the central are of Tokyo (in three wards)

	Value	Unit	Calculation	Note
ATL: Total land area	$42{,}130*10^3$	[m^2]		
ATF: Total floor area of buildings	$25{,}000*10^3$	[m^2]		*1
D: Electric power density used for office lighting	17.7	[W/m^2]		*2
ET: Electricity for office lighting	442.5	[MW]	$=D*ATF$	
N: Number of the luminous fixtures	4,609,375	[-]	$=ET*10^6/96$	*3
FT: Total Luminous flux	$27{,}656*10^6$	[lm]	$=6000*N$	*4
FL: Luminous flux from windows	$1{,}269*10^6$	[lm]	$= FT*0.054*\tau$	*5
EL: Electricity loss from windows	20.3	[MW]	$= ET*0.054*\tau$	*5
ELa: Electricity loss per land area	0.48	[W/m^2]	$= EL/ATL$	
FLa: Luminous flux from windows per land area	30.1	[lm/m^2]	$=FL/ATL$	
UFLa: Upward luminous flux from windows per land area	10.29.0	[lm/m^2]	$=FLa*0.34=FLa*0.30$	*6

Notes

*1 Only buildings with 5,000 square meters or more floor space were considered.

*2 This number is based on the research on office lighting by the Illuminating Engineering Institute of Japan [6)]

*3 Electricity consumption of a lighting fixture utilizing 2 fluorescent lamps (40W each) = 96 [W]

*4 Luminous flux from the fixture = 6000 [lm]

*5 Form factor of the wall including the window from the ceiling, or from the floor $\Phi_{C\text{-}W}, \Phi_{F\text{-}W} = 0.124$ Utilisation factor U=0.5
Working surface reflectance ρ_L=0.2 The ratio of the window area to the area of the wall including window WR =0.4
Therefore, the ratio of the luminous flux through window to the total luminous flux = $(\Phi_{C\text{-}W} + \Phi_{F\text{-}W} * U * \rho_L) * WR = 0.054$ (The details are described in the text.) τ: Transmittance of the window glass (0.85)

*6 The ratio of upward luminous flux to total luminous flux of a window = 1-0.66 = 0.34
The ratio of upward luminous flux to total luminous flux of a window = 1-0.70 = 0.30

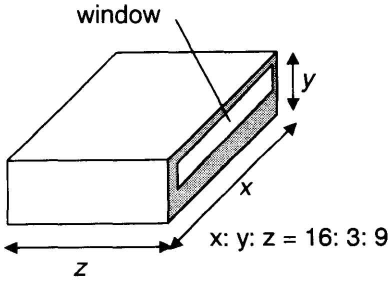

Figure 8 Width, height, depth of typical condition where 0.12 of the configuration factor of the wall including the window from the ceiling or the floor was determined

Table 4 Area surveyed

Zoning	Surrounding	Area surveyed	Symbol	Area (m^2)
E1	Natural	National park (Kyushu)	Q	780,000
E2	Rural	Rural area (Saitama)	R	176,000
E3	Suburban	Suburban area	S	142,000
		Urban residential area	T	106,000
E4	Urban	Urban area in a big city	U	58,000
		Business area in a big city	V	79,000
		Commercial area in a big city	W	150,000

windows and that from outdoor lighting, the data of outdoor lighting from the results of the survey of IEIJ in 1996[7),8)] was used. The IEIJ's outdoor lighting research was conducted on highway lighting, security lighting, pole lighting, approach lighting, HID flood lighting, floodlight lamps and bracket fixture lighting. A number of sites were selected so as to represent most of the typical lighting situations in zones classified in the CIE guide. The zones surveyed are summarized in Table 4. The outlines of the surveyed areas are as follows.

Q: National park in Kyushu: To protect the natural environment, hotels and residential buildings may only be built in a limited area.

R: Outskirts of a town in Saitama: Simple and relatively poor lighting is provided on the streets.

S: Suburbs of a town in Saitama: Relatively simple street lighting is installed.

T: A residential area in Tokyo: Relatively sufficient lighting is installed.

U: A commercial area in Tokyo: The adjacent to a railway station with heavy rail traffic, surrounded by the residential areas in the Tokyo district.

V: A business center of Nagoya: It is the governmental district of a big city and a well lit area with a variety of lighting, including landscape lighting and flood lighting for municipal buildings.

W: A shopping center of Nagoya: Streets and buildings in this area are brightly lit. There are lots of bright advertising signs including self-illuminating signs (signs equipped with inside luminaires).

Figure 9 shows the comparison between the upward luminous flux from office windows and that from outdoor lighting. Since the self-illuminating signs in commercial areas were major causes of the upward luminous flux, they were separated. The number in the figure shows the total upward luminous flux for each area. It was found that office windows had so much upward luminous flux as the self-illuminating signs in the commercial area.

In this study 0.3 of the ratio of upward luminous flux to total luminous flux of a window is used provisionally and several values, e.g. transmittance of windows, are assumed. Therefore there is possibility the luminous flux from the office windows was overestimated in this study. However, on the other hand, light reflected by the ground or the surface of the buildings is not included in this study. On balance, it is considered that our calculation is not so far from the actual situation.

4. Conclusions

This research shows that a considerable amount of light pollution can be directly traced to light spilled from building windows. The Ministry of the Environment produced a set of light pollution guidelines in 1998 to prevent inappropriate outdoor lighting affecting astronomical observations. Our research proves that it is necessary to consider not only the outdoor lighting but also the light spilled from the inside of buildings.

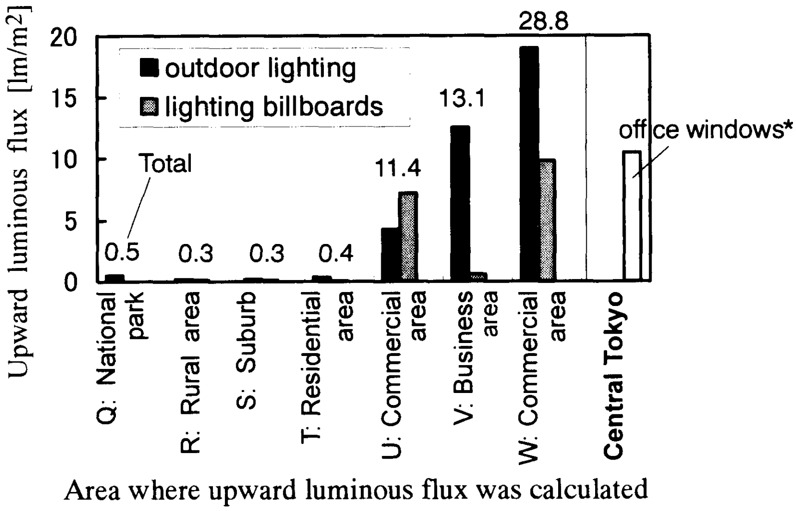

Figure 9 Comparison between the upward luminous flux from office windows and that from outdoor lighting

*The ratio of upward luminous flux to total luminous flux of a window = 0.34

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