Article

Assessment of light pollution in parking lots using a measuring system with a drone

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Abstract: This article attempts to assess the light pollution of parking lots, using the proprietary measurement method with a drone. The main requirements, reflective features of parking lots and typical light curves of luminaires used in lighting this type of areas were presented. Calculations and simulations for various types of luminaires were performed, and then the obtained results were verified in real conditions. The main factors influencing the increase in light pollution were presented and it was proved that it is possible to use the developed measurement method in order to assess the light pollution degree.

Keywords: light pollution; luminous flux; unmanned aerial vehicles

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1. Introduction

Light pollution, i.e. excessive light beam distribution towards the sky, is mainly the result of incorrectly designed lighting systems. Artificial light that penetrates the upper half-space disturbs not only the functioning of fauna and flora [1, 2, 3, 4], but also disrupts the human biological clock [5, 6, 7] and disrupts our functioning throughout the day. In large, brightly lit cities, blurring the line between day and night is a problem. Too strong night lighting and the lack of visible sky, caused by the glow of light, make us sleep badly, we are tired and irritable.

The open parkings lighting, which have become an integral part of our landscape, has a significant impact on the increase in light pollution. The main problem in lighting outdoor areas, including parking lots, is the need to take into account many competitive aspects, such as energy efficiency, light pollution, comfort of drivers and road users. Often meeting the basic conditions, i.e. achieving the minimum value of the average illuminance and uniformity, precludes the high energy efficiency of the system. The same goes for light pollution. Most designers believe that the use of luminaires with an appropriate light curve and the correct lighting direction is enough to eliminate the effect of contamination. It does not take into account that the luminous flux is reflected from the ground [8] or the surrounding objects, and then it is sent into the upper half-space, thus generating artificial light pollution of the night sky. What's more, the atmospheric conditions, rarely considered in the research, have a significant impact on the light flux distribution. The value of the stream may vary depending on the air temperature, dew point temperature or humidity. The light will disperse differently during rainfall and snowfall, and it will behave differently in heavy fog [9].

Most of the works and publications focus on reducing energy consumption and effective lighting control in parking lots. Attention is paid to more efficient lighting products and good control mechanisms [10, 11, 12, 13]. This is the right direction, but it is worth reaching a bit further and considering the impact of light pollution itself on modern parking lot lighting systems. At the very beginning, it is worth emphasizing once again that light pollution is an undesirable effect, however, it is not physically possible to eliminate this effect completely. The conducted research [14] has shown that light escaping into the upper half-space returns to the ground through reflections from the cloud layer and surrounding objects. This often gives the value of a few additional luxs on the surface of parking lots, which are not taken into account in any calculations. The lighting requirements for parking areas are not high, therefore even a small amount of the luminous flux returning to this area can give noticeable effects while reducing energy consumption for lighting.

The following part of the article presents the basic standards and requirements used in the design of lighting for parking lots. Then, the author's measurement method for the assessment of light pollution degree, with the unmanned aerial vehicles use, was described. Moreover, the results of measurements and simulations for the selected road lighting luminaire are presented, and further research plans are presented.

2. Standards and requirements in the parking lots lighting

Lighting requirements for parking lots, such as for roads, sidewalks and pedestrian crossings, are strictly defined. The most important guidelines presenting the minimum average values of illuminance (E_m), uniformity (U_0) and the required glare factor values (GR_L) or color rendering index (Ra) have been collected in the Polish Standard PN-EN 12464-2:2014-05 [15]. The presented standard is a direct translation of the European Standard EN 12464-2: 2014-05 [16]

Table 1. Lighting requirements for parking lots [15]

Type of area, task or activity	E_m [lx]	U_0	GR_L	R_a
Light traffic e.g. parking areas of shops, terraced and apartment houses, cycle parks	5	0,25	55	20
Medium traffic e.g. parking areas of department stores, office buildings, plants, sports and multipurpose building complex	10	0,25	50	20
Heavy traffic e.g. parking areas of major shopping centres, major sports and multipurpose building complex	20	0,25	50	20

Additionally, the standard defines the notion of disturbing light coming from external luminaires. The definition of obtrusive light is presented in the standard as obtrusive light which, due to inadequate quantitative, directional or spectral characteristics in a given situation, causes irritation, discomfort, distraction or a reduction in the ability to see relevant information. The obtrusive light was described using five parameters: the light on the real estate (E_V), the luminous intensity of the luminaire (I), the light radiated upwards (ULR), the luminance of the facade (L_b) and the luminance of the signs (L_s). The classification was made for four zones from the completely dark (E1), through the low brightness zone (E2), the medium brightness zone (E3), to the high brightness zone (E4).

Table 2. Maximum obtrusive light permitted for exterior lighting installations [15]

Enviromental zone	Light on properties E_V [lx]		Luminaire intensity I [cd]		Upward light ULR [%]
	Pre-curfew*	Post-curfew	Pre-curfew*	Post-curfew	
E1	2	0	2 500	0	0
E2	5	1	7 500	500	5

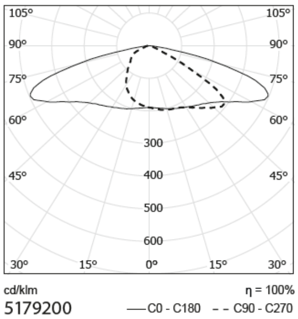
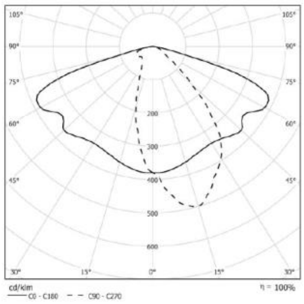
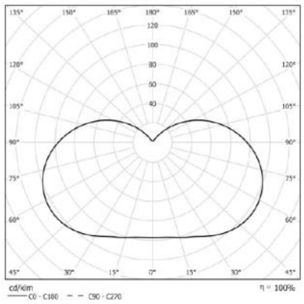
E3	10	2	10 000	1 000	15
E4	25	5	25 000	2 500	25

* In case no curfew regulations are available, the higher values shall not be exceeded and the lower values should be taken as preferable limits.

3. Methodology

The luminaires used in the parking lots lighting are characterized by different light curves. Below are three examples of outdoor luminaires that are or can be used to illuminate these types of areas.

Table 3. ES SYSTEM luminaires and their light curves [17].

<table>
<tr><th>RAPID
30W 3300lm</th><th>RACER MINI VMC
40W 5300lm</th><th>OCP MILEDIA 2 VMC
38W 4000lm</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>
</td><td></td><td></td></tr>
</table>

The luminous curves of individual luminaires determine the luminous flux distribution, and thus may, to a greater or lesser extent, affect light pollution. It is possible to identify luminaires that emit the smallest amounts of light towards the sky on the basis of the parameters LPP (lighting pollution percentage) and LPI (light pollution index) [18]. The lower the value of the indicators, the less the effect of the lamp on light pollution.

The LPP (lighting pollution percentage) factor determines the percentage of light pollution in a single luminaire or a group of luminaires and is calculated on the basis of the formula (1) [18].

$$LPP = (\Phi_A / \Phi_C) \cdot 100\% = ((E_{AV} \cdot S) / \Phi_C) \cdot 100\% \quad (1)$$

Φ_A – luminous flux directed into the upper half-space
Φ_C – total luminous flux
E_{AV} – average illuminance on the computing area
S – calculation area

The determined values for three exemplary outdoor luminaires are summarized in Table 4.

Table 4. Calculation results for selected luminaires

Luminaire	Φ_C [lm]	E_{AV} [lx]	LPP [%]

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RAPID	3300	0,33	4,00
RACER	5300	0,59	4,45
OCP MILEDIA	4000	0,43	5,21

The part of the light emitted directly towards the sky can also be described by the so-called ULOR (upward light output ratio), the formula (2) [19].

$$ULOR = (\Phi_{UP} / \Phi_C) \cdot 100\% = ((E_{śr} \cdot S) / \Phi_C) \cdot 100\% \quad (2)$$

Φ_A – luminous flux emitted into the upper half-space
Φ_C – luminous flux of the light source in the luminaire

For lower light pollution, the ULOR should be as low as possible (preferably 0). Usually, manufacturers provide information on the ULOR value in the luminaire specifications. However, this indicator does not always provide information on the percentage of luminous flux emitted in the upper half of the space [20].

In addition to the luminous intensity curve of the luminaire, important factors that affect how much artificial light escapes into the upper half-space are the reflective and structural features of parking lots, as well as the prevailing weather conditions. The most commonly used materials for the construction of the parking surface are asphalt concrete, cement concrete, concrete pavement, stone pavement (often used for historic areas), or plastics. There are also ground, gravel and grass surfaces. Each of the used substrates will have a different reflectance, which is very important if we analyse the lighting of parking lots in terms of light pollution. The higher the reflectance, the more light will hit the half-space above. However, it should be remembered that the reflection properties of individual surfaces will change depending on the prevailing weather conditions. Rain, snow, ice - each of these factors means that the reflectance values can increase or decrease significantly. Table 5 shows the real and theoretical values of selected reflectance factors.

Table 5. Light reflectance values depending on the material used

Material	Reflectance	
	Real	Theoretical
Snow, ice	-	0,46 – 0,87
Concrete (dry trlin)	0,22	0,25
Concrete (wet triline)	0,17	
Concrete (snow-covered triline)	0,42	
Grass	0,15	0,14 – 0,37
Tree	0,11	0,20

The values were verified under real conditions using a Taylor flectometer. In theory, the reflectivity of the concrete should be 0.25. In fact, with a dry surface, it turned out to be a bit lower (0.22), for a layer of melting snow, the value almost doubled (0.42), while with wet slabs it dropped significantly (0.17).

Weather conditions affect not only changes in reflectance, but also the light source itself. The RAPID luminaire was tested in a Heraeus VÖTSCH climatic chamber in the range from –20°C to + 50°C. As a result, it turned out that the luminous flux of the luminaire decreased by about 13% with increasing temperature (table 6).

Table 6. Test results for a lighting fixture in a climatic chamber

LP.	Chamber temperature [°C]	Case temperature [°C]	Illuminance [lx]
1	-20	-2,9	1726

2	-15	-1,6	1718
3	-10	-0,7	1710
4	-5	4,7	1703
5	0	7,7	1686
6	5	11,9	1650
7	10	16,0	1636
8	15	19,5	1631
9	20	23,6	1625
10	25	29,1	1622
11	30	32,9	1605
12	35	37,1	1592
13	40	42,5	1575
14	45	47,1	1560
15	50	52,0	1536
The illuminance value decreased by 190 lux			
16	50	54,7	1530
17	45	54,4	1534
18	40	53,4	1547
19	35	50,1	1569
20	30	46,1	1599
21	25	42,4	1626
22	20	38,5	1651
23	15	35,9	1675
24	10	30,8	1700
25	5	26,2	1718
26	0	19,5	1732
27	-5	14,8	1738
28	-10	9,8	1745
29	-15	5,9	1748
30	-20	1,3	1755
The illuminance value increased by 225 lux			

3.1. Measurements and simulations

In order to estimate the amount of light escaping into the upper half-space, simulations were performed using DIALux simulation software for the three presented road lighting luminaires. Additionally, measurements were carried out in real conditions using the proprietary measurement method for the ES SYSTEM model RAPID luminaire. The area where the selected lamps are located is the existing parking lot, around which there are offices and warehouses. The substrate is made of paving stones, the so-called trilines (Figure 1).

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Figure 1. View from DIALux programme

The tested luminaire was placed on a 6-meter-high pole on a 30 x 40-meter square in Stanislawowo, near Bialystok. A measuring field of 20 x 20 meters on the ground surface and at a height of 10 and 20 meters above the luminaire was adopted in order to determine the degree of light pollution (Figure 2). The highlighted point P8 means a point in the axis with the lighting fixture.

	10 m	5 m	0 m	5 m	10 m	
15 m	P21	P22	P23	P24	P25	15 m
10 m	P16	P17	P18	P19	P20	10 m
5 m	P11	P12	P13	P14	P15	5 m
0 m	P6	P7	**P8**	P9	P10	0 m
5 m	P1	P2	P3	P4	P5	5 m
	10 m	5 m	0 m	5 m	10 m	

Figure 2. Measurement grid

The measurement system was created on the basis of the DJI PHANTOM 3 unmanned aerial vehicles (UAV), equipped with a photometric meter – luxmeter, model OPT3001/OPT3001-Q1 Ambient Light Sensor. Four light meter receivers were positioned around the unmanned aerial vehicle camera (Figure 3). The camera stabilization and the measuring device appropriate positioning is ensured by a precise 3-axis gimbal. Measurement data are recorded by the receiver and saved on the MICRO SD card each time the "SAVE" button is pressed [21].

Figure 3. Measuring system

The UVA unmanned aerial vehicle used has a limited operating time. On one battery, in good weather conditions and air temperature above 10 °C, it can work for about 25 minutes. As the temperature drops, and thus also at high altitudes, the operating time is significantly reduced. Keep this in mind and equip yourself with additional batteries. If measurements are made at temperatures below 10 °C, it is necessary to keep spare batteries in a warmer place and activate the device within a few minutes after going outside. [21].

Depending on the method of controlling and moving the drone with a photometric head, it is possible to pilot the aircraft according to the Cartesian coordinate system, in which the movement takes place only vertically in the vertical and horizontal plane (Figure 4, point a), thus limiting positioning errors. However, it is necessary to calculate the photometric distance r in any case. In the spherical system (Figure 4, point b), the photometry distance is kept constant, and the position of the UAV should be calculated for each angle C and γ. In this configuration, the positioning of the drone should be expected, which will affect the measurement errors in the goniometric system [22].

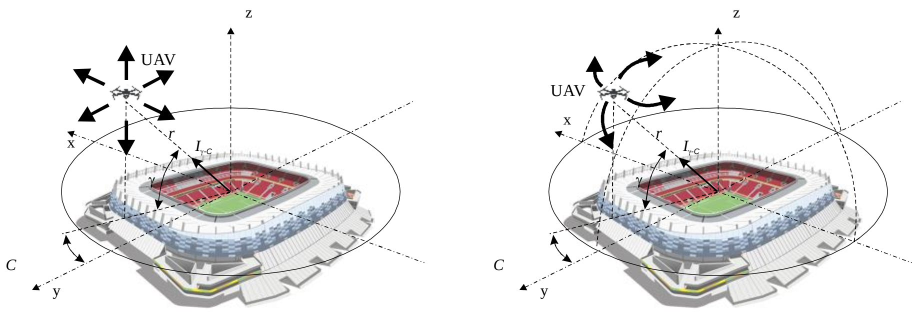

Figure 4. The geometry of the moving UAV to assess the luminous flux emitted by the sports facility: a) straight line, b) spherical [22]

The positioning accuracy of the above method is primarily due to the positioning resolution of the stepper motors that are used to drive the gimbal. Currently available solutions allow for setting the position of the stepper motor shaft with a resolution greater than 1^0, and the repeatability of the setting is carried out with incremental sensors. In photometric measurements such positioning accuracy is acceptable and sufficient when assessing the luminous mass of the light-optical system [23].

In the literature, the presented method is more often used in order to measure the light beam distribution from external lighting fixtures [20, 21, 22, 23, 24, 25]. Most authors introduce their own modifications, however, the method of making measurements and the analysis of the obtained results give grounds to claim that the method is reliable and can be used to measure the night sky pollution with artificial light.

4. Measurements

The table below summarize the values obtained in the DIALux software for all three road lighting luminaires.

Table 7. Simulation results for selected lighting fixtures

Measure-ment point	EAV [lx] Ground			EAV [lx] 16 meters			EAV [lx] 26 meters		
	RAPID	RACER	OCP	RAPID	RACER	OCP	RAPID	RACER	OCP
P1	2,53	2,23	1,44	0,21	0,37	0,42	0,12	0,22	0,15
P2	5,30	3,41	4,25	0,25	0,51	0,35	0,14	0,25	0,17
P3	7,98	5,93	7,45	0,23	0,51	0,39	0,13	0,23	0,17
P4	5,29	3,39	4,24	0,26	0,52	0,35	0,14	0,25	0,17
P5	2,55	2,25	1,47	0,22	0,38	0,44	0,12	0,22	0,15
P6	3,42	5,80	1,56	0,28	0,50	0,45	0,16	0,28	0,17
P7	8,05	17,00	507	0,36	0,69	0,39	0,18	0,33	0,20
P8	14,00	42,00	9,39	0,38	0,68	0,43	0,18	0,33	0,20
P9	7,96	17,00	5,01	0,36	0,70	0,38	0,19	0,33	0,20
P10	3,41	5,78	1,56	0,30	0,52	0,48	0,17	0,29	0,18
P11	3,75	5,85	1,19	0,28	0,49	0,44	0,16	0,28	0,16
P12	6,27	13,00	3,09	0,36	0,67	0,38	0,19	0,32	0,18
P13	8,53	17,00	5,11	0,39	0,71	0,33	0,18	0,33	0,18
P14	6,32	13,00	3,12	0,36	0,67	0,38	0,19	0,33	0,18
P15	3,76	5,87	1,20	0,30	0,51	0,47	0,17	0,28	0,16
P16	1,68	0,97	0,65	0,24	0,39	0,40	0,15	0,25	0,15
P17	1,84	0,85	1,18	0,29	0,51	0,43	0,17	0,29	0,16
P18	1,93	0,76	1,55	0,31	0,56	0,43	0,17	0,29	0,16
P19	1,84	0,85	1,19	0,30	0,52	0,44	0,17	0,29	0,16
P20	1,68	0,98	0,66	0,26	0,41	0,42	0,15	0,25	0,16
P21	0,11	0,17	0,33	0,17	0,27	0,30	0,13	0,21	0,15
P22	0,10	0,15	0,48	0,20	0,33	0,35	0,14	0,24	0,15
P23	0,11	0,17	0,56	0,22	0,36	0,37	0,14	0,25	0,15
P24	0,10	0,15	0,48	0,21	0,34	0,36	0,14	0,24	0,15
P25	0,11	0,17	0,34	0,18	0,28	0,32	0,13	0,21	0,15
Average	4,49	8,30	2,78	0,33	0,59	0,43	0,18	0,31	0,18

During the analysis of the selected ES SYSTEM lighting fixture, the RAPID model took into account various weather conditions, such as air temperature or humidity. Measurements were made at two different heights. The obtained measurement results are summarized in Table 8.

Table 8. Measurement results

Measurement point	EAV [lx] Ground			EAV [lx] 16 meters			EAV [lx] 26 meters		
	21/03/10 -4°C	21/05/24 9°C	2021/06/10 17°C	21/03/10 -4°C	21/05/24 9°C	2021/06/10 17°C	21/03/10 -4°C	21/05/24 9°C	2021/06/10 17°C
P1	3,10	4,31	4,06	0,24	0,36	0,32	0,18	0,20	0,19
P2	5,14	7,59	6,22	0,28	0,44	0,44	0,19	0,24	0,20
P3	7,70	9,84	7,88	0,35	0,45	0,49	0,23	0,26	0,22
P4	5,55	7,66	5,99	0,33	0,44	0,44	0,22	0,25	0,20
P5	3,86	4,75	4,05	0,28	0,28	0,29	0,20	0,21	0,19
P6	5,56	6,32	3,63	0,41	0,42	0,35	0,24	0,24	0,22

P7	10,57	10,70	10,39	0,53	0,51	0,44	0,28	0,27	0,26
P8	14,21	17,97	17,04	0,54	0,55	0,55	0,30	0,28	0,25
P9	10,03	9,97	8,77	0,46	0,50	0,49	0,25	0,25	0,25
P10	5,19	6,39	3,34	0,32	0,49	0,32	0,21	0,22	0,21
P11	5,98	4,72	3,17	0,41	0,43	036	0,23	0,26	0,23
P12	7,38	7,35	5,73	0,48	0,48	0,43	0,28	0,29	0,27
P13	8,23	10,09	8,44	0,49	0,55	0,50	0,30	0,30	0,26
P14	7,85	7,29	5,48	0,34	0,50	0,35	0,24	0,27	0,24
P15	5,09	4,46	2,80	0,33	0,32	0,31	0,22	0,25	0,21
P16	1,88	2,79	1,34	0,31	0,35	0,34	0,21	0,24	0,20
P17	2,53	3,34	1,72	0,33	0,43	0,36	0,22	0,25	0,24
P18	3,10	4,07	1,73	0,34	0,44	0,42	0,23	0,26	0,23
P19	2,32	3,44	1,61	0,23	0,37	0,30	0,18	0,25	0,18
P20	1,80	2,71	1,58	0,22	0,30	0,25	0,18	0,23	0,20
P21	0,17	0,96	0,10	0,17	0,26	0,20	0,16	0,22	0,17
P22	0,19	1,01	0,15	0,18	0,27	0,23	0,17	0,23	0,20
P23	0,21	1,27	0,16	0,20	0,28	0,27	0,18	0,25	0,20
P24	0,18	0,97	0,12	0,17	0,27	0,22	0,16	0,21	0,16
P25	0,14	0,85	0,11	0,16	0,26	0,17	0,15	0,18	0,15
Average	4,72	5,63	4,22	0,32	0,40	0,35	0,21	0,24	0,21

5. Discussion

The highest illuminance values, both on the ground surface and on the surfaces above the luminaire, were obtained in the case of the RACER luminaire. Almost two times lower values were achieved for the RAPID luminaire. In the case of the OCP MILEDIA lamp, the lowest illuminance values on the ground surface were obtained, but it does not translate into limiting light pollution. The luminaire generates a much larger amount of light directly into the upper half-space due to its spherical structure.

The errors that occur between the simulations in DIALux and the measurements in real conditions are usually around 20%. However, it can be noticed that in the case of measurements from March (-4 °C) and June (17 °C), the obtained values are very similar to those obtained in the simulation.

Table 9. Summary of the measurements results and calculations as well as the included atmospheric conditions

Date		2021/03/10 -4°C, dry	2021/05/24 9°C, dry	2021/06/10 17°C, dry
Hour		20:00	22:00	23:00
Conditions		Dry	Dry	Dry
Temperature	[°C]	-4	9	17
Dew point temperature	[°C]	-5	7	15
Relative humidity	[%]	80	70	85
Pressure	[hPa]	1022	995	1015
Air density	[kg/m³]	1,286	1,209	1,188
Fog	[fraction]	0	0	0
Wind	[m/s]	1	1	2
Cloudy	[octanes]	Cloudless	Cloudless	Cloudless
Average illumination on the ground	[lx]	4,72	5,63	4,22
Relative error	[%]	23%	43%	16%
Average illuminance at 16 m	[lx]	0,32	0,40	0,35
Relative error	[%]	19%	29%	20%

Average illuminance at 26 m	[lx]	0,21	0,24	0,21
Relative error	[%]	25%	36%	26%
The amount of light escaping into the upper half-space (16m)	[%]	7%	7%	8%
The amount of light escaping into the upper half-space (26m)	[%]	4%	4%	5%
Average luminous intensity on the ground	[cd]	853,34	1146,34	684,14
Average luminous intensity per 16 m	[cd]	136,88	173,28	151,08
Average luminous intensity at 26 m	[cd]	182,14	209,71	181,75

Measurements carried out for the RAPID luminaire show that the distribution of the luminous flux of the luminaire changes depending on environmental conditions, air temperature or humidity. The conducted research did not allow to clearly define the extent to which particular parameters affect the luminous flux of a given luminaire. Therefore, the next test will be carried out in laboratory conditions, so that it is possible to carry out an analysis for individual humidity states, and to perform measurements in the case of fogging and various precipitation.

Work on improving the presented measurement method is still ongoing. However, already at this stage it can be concluded that it is possible to estimate the degree of light pollution using unmanned aerial vehicles and publicly available photometric meters [24].

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