VERTICAL VARIABILITY OF NIGHT SKY BRIGHTNESS IN URBANISED AREAS

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Abstract: Excessive amounts of artificial light emitted into the lower atmosphere at night have already become an everyday feature of modern urban landscapes, and gradually also a phenomenon associated with areas located outside large human settlements. Urban islands of light have been the subject of targeted research conducted for several decades by scientists representing miscellaneous fields of science. In Toruń, regular research on the phenomenon of light smog has been carried out for several years at a number of sites located throughout the city. Recently, research has been started on the variability of the night sky brightness in a vertical gradient. To this end, repeatable measurements were made at specific altitudes at two locations in the city using a drone with an automatic light metre on board. The values of the night sky brightness thus obtained allowed us to determine its variability in the vertical gradient up to an altitude of 120 m, as well as to test the possibility of using drones in targeted studies of the light pollution phenomenon.

Key words: light pollution, smartcity, UAV, urban area, vertical measurement

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Introduction

Humankind, through all its activities, continually transforms the environment in which man lives and functions, including his immediate surroundings and increasingly distant regions. These transformations usually involve variability in the horizontal gradient, with the strongest impact in the immediate vicinity of the operating factor and typically attenuating with distance from the point of application. This impact may also occur in the vertical gradient – upwards or downwards, but this direction is rarely included in the analysis or studied in more detail.

While acting on the surrounding landscape, humans modify selected parameters of its condition over increasingly large areas and spatial scales. The occurrence of various types of pollution and the spatial variability of their concentration is an integral element of progressive urbanisation. These include both surface and groundwater, soil and air pollution with various substances – particulates (dust), heavy metals and radioactive contamination (Wang et al. 2004, Wyszkowski, Wyszkowska 2007, Para, Para 2013, Woźny et al. 2014, Qadri et al. 2020). One of them, previously rarely considered, is the growing pollution of the sky by artificial light (Kyba et al. 2017, Longcore et

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al. 2017, Jechow et al. 2018). This phenomenon is defined as the emission of anthropogenic light released into the lower layer of atmosphere, which causes perceptible and long-term negative effects on both animals and plants, affecting their development, functioning and behaviour, and above all, on human health and quality of life (Jones, Francis 2003, Nelson 2007, Stevens 2009, Connors et al. 2010, Depledge et al. 2010, Falchi et al. 2011, Navara, Skwarło-Sońta 2014, Garcia-Saenz et al. 2018). This phenomenon is widespread in areas of human settlements and their surroundings. Sky glow associated with cities is observed up to several tens of kilometres or even a 100 km outside urban areas (Falchi et al. 2016, Jechow et al. 2017, Linares et al. 2020), and its impact is experienced and visible not only in the horizontal gradient but also in the vertical one.

To understand the negative impact of a given phenomenon on life and functioning of living organisms in the immediate and distant surroundings, it is necessary not only to carry out multithreaded research but also to conduct targeted monitoring, showing the variability of the whole process in a longer time horizon. Measurements of the night sky pollution with artificial light, which belongs to the above-mentioned category of phenomena, have been carried out with different intensities and methods for several decades. Research carried out today is becoming increasingly comprehensive and involves researchers representing miscellaneous scientific fields. As a result, this phenomenon is being more precisely explained and mechanisms involved in this process are more thoroughly understood. In several Polish and foreign research centres, studies are being conducted with the objective of gaining an in-depth understanding of light pollution with respect to its various aspects and conditions of occurrence (Aubé 2007, Kocifaj 2009, Ściężor et al. 2010, Falchi et al. 2016, Jechow et al. 2017, 2018, Kołomański et al. 2019, Aubé et al. 2020, Karpińska, Kunz 2020, Kocifaj, Bará 2020).

Targeted monitoring of light pollution has been carried out in Toruń since 2017. Initially, it was carried out within the framework of 24 measurement sites distributed throughout the city, located in the vicinity of various forms of land cover/land use, where systematic measurements of the night sky brightness were made using the *Sky Quality Meters* (SQM) photometer of the Canadian company Unihedron (Karpińska, Kunz 2019, 2020). Since 2020, measurements have been carried out fully automatically at 19 locations, and this number is systematically growing, reaching 40 locations in mid-2022. This leads to an integrated recording system with remote data transmission. The main element of this system is an original, compact device measuring the brightness of the night sky at specific time intervals (Karpińska, Kunz 2021a, b). After modifying the software code and the installation method, the measuring instrument can be used on mobile devices such as drones (unmanned aerial vehicles).

Vertical measurements of the phenomenon in the lower troposphere, up to 120 m above the ground level, were performed to determine the patterns in the variability of the night sky pollution by artificial light and to provide new data contributing to previous studies (Fiorentin et al. 2019, Bouroussis, Topalis 2020). This was achieved through the use of a drone in the process of data acquisition and a constructed photometer connected to a wireless transmission network, which enabled real-time reading of results at defined altitudes.

The use of drones in scientific research conducted in the geographical environment is becoming a common practice, and this intensively developed technology perfectly bridges the ceiling gap between terrestrial field exploration and aerial and satellite recording (Kunz 2015, Fiorentin et al. 2019).

Measurement of the night sky brightness

Light pollution can be determined in a number of ways, involving different methodologies and varied complexity of equipment and measurement technologies. Methods include those intended for specialised research groups involving professionals, and those for amateurs, i.e. hobbyists, who are typically interested mainly in the observation of the night sky from the astronomical perspective (Kołomański 2015, Ściężor 2015, 2021). The most common measurement method used by professionals dealing with light pollution is an SQM photometer (Kolláth 2010, Ściężor et al. 2010, Pun et al. 2013, Ribas 2015, Hänel et al.

2017, Jechow et al. 2018, Kołomański et al. 2019). The devices measure the surface brightness of the sky expressed in magnitudes per square arcsecond (mag · $arcsec^{-2}$), a traditional unit used in astronomy. Due to its universal applicability, it is possible to compare the data collected with results obtained in other parts of the globe, but there is a need for intercalibration of photometers and the need to take into account the measurement drift of this kind of photometers with time (Den Outer et al. 2011, 2015, Ribas 2015, Bará et al. 2019, 2021).

In 2019, work began on the creation of a light pollution monitoring system, ultimately covering the entire area of the city of Toruń, operating on the basis of a distributed network of measuring devices. In the established wireless LoRaWAN network (Karpińska, Kunz 2021a, b), an automatic measuring device of our own design was used. One of the most important functional features of the device is the remote measurement of sky brightness along with other selected environmental parameters such as temperature and moisture content. By using the applied transmission technology, data from built-up areas are sent to the access gateway at a distance of up to 4 km, and even further in open areas with no significant altitude differences and no obstacles such as buildings and tall vegetation. The device works in a reduced power consumption mode, which makes the implemented process of monitoring the phenomenon (in this case light pollution) energy-efficient and ensures long-term operation of the recorder on a single power supply set. The device works cyclically, wakes up during the night measurement session, takes readings every 15 min, transmits data, and after the session ends, goes into a sleep mode for a period of time until the next day's waking up (Table 1).

The designed device is additionally programmable, which allows the adaptation of the software code to other tasks, while its compactness and fully remote real-time readout make it possible to use it for vertical measurements using a mobile platform, namely a multi-rotor drone.

When adapting the sensor for measurements with the use of a drone, it was necessary to modify the location of the opening in the casing through which the light sensor takes measurements, so that it was directed towards the zenith side, as well as the transmission antenna, so that it does not interfere with elements of the propulsion unit, namely propellers. It was also necessary to increase the frequency of readings to a 15 s interval, which significantly increased the amount of data transmitted during a single flight.

Table 1. Selected technical parameters of the measuring device.

Parameter	Characteristic
weight	380 g
dimension	5,5 x 8,2 x 15,8 cm
standard of data transmission	LoRaWAN
frequency bands	868 MHz
operating time [3 000 mAh]	~ 12 month
range in built-up areas	3–4 km
number of measurements during the day	36
frequency of measurements	15 min
operational time	21:00–06:00 CEST
measuring sensors	surface brightness of the sky, temperature, humidity
the angle of data collection	20°
tightness class	IP65

Main assumptions for vertical measurements of night sky brightness and description of the study sites

Vertical measurements of the night sky light pollution were aimed at investigating the vertical variability of the phenomenon with the distance of the measuring set from the ground surface and light sources placed on it. In addition, an attempt was made to advance the existing knowledge about the pollution of the night sky by excessive emission of artificial light through measurements carried out at different distances from terrestrial emitters and to try to determine the limit of the phenomenon in three-dimensional space.

Methodology of measurements

A DJI Matrice 210 RTK drone with a measuring device mounted on the upper deck was used to carry out the planned measurements. The whole measuring set (understood hereafter as a drone with its own measuring device) is presented in Figure 1.

Fig. 1. DJI Matrice 210 RTK drone with its proprietary measuring device (photo D.Karpińska).

Vertical measurements of the surface brightness of the night sky were planned at two easily accessible, representative locations, as far away from point light sources as possible, but within the functional range of the LoRaWAN network. The measurement locations are described in the next section.

The first step was a field reconnaissance along with tests to select the most optimal method of work. After the test flights, the results obtained were analysed, showing the distribution and variability of the values in relation to the altitude ranges at which the readings were made. It was observed that the maximum height distribution in the night sky brightness occurs in the zone between the take-off point and an altitude of about 25 m. The experience gained from the test flights enabled us to refine the methodology for conducting vertical measurements using the drone. Taking all the above factors into account, it was assumed that it is necessary to thoroughly understand the characteristics of the phenomenon in the initial phase of the flight by increasing the number of measurements in the range from 0 m to 25 m above the ground. For this reason, measurements in the lower phase of the flight were made every 2.5 m, and subsequently at altitudes of 30 m, 50 m, 75 m, 100 m and 120 m. The upper flight altitude results strictly from *Polish Aviation Law* (Dz.U. of 2020, item 1970, as amended), and not from the technical capacities or limitations of the aircraft used. The concept of drone measurements involved vertical ascending to consecutive selected altitudes and hovering for approximately 1 min (Fig. 2). This was sufficient to acquire four repeatable readings, after which the drone operator would raise the measuring set to the next planned altitude.

Each measurement session at a single location was limited by the maximum flight time on one set of batteries. Technical specification indicates that an unloaded drone should fly for about 32 min. At full load, however, this time is limited to about 24 min, which was sufficient to complete the task safely with spare time for a possible emergency situation.

Depending on weather conditions (wind is the main element contributing to higher energy consumption), the time required to complete all measurements in the planned operation cycle at 16 altitude levels was estimated at about 22 min. The assumptions turned out to be true, and the duration of any of the conducted flights did not exceed 23 min. Live monitoring of the transmitted values was performed during the vertical measurements, which facilitated their control and supervision of the quality of the data acquisition process, with automatic archiving of the collected data on an external server.

Vertical measurements of the vertical variability in the night sky brightness were made at the time when the Sun was at its lowest position below the horizon to minimise its impact on the obtained values.

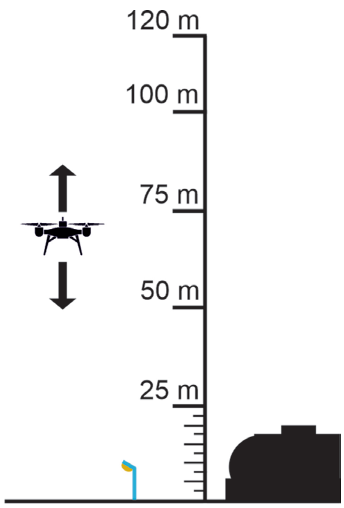

Fig. 2. Schematic representation of the altitudes selected for the acquisition of data on light pollution of the night sky.

Measurement locations

Measurements of the vertical variability of the night sky brightness were carried out at two locations, approximately 1.5 km apart in a straight line. The first one was the car park at the campus of the Nicolaus Copernicus University in Toruń (Fig. 3), located about 3 km from the city centre – the Medieval Town of Toruń. The altitude of the starting point was 48.6 m a.s.l. and its location in the geographical space: 53.021214 N and 18.567517 E. There was no street lighting in the 25 m zone from the starting point of the measuring set, while seven street lamps were located within a 50 m radius, with the nearest one directed towards the measurement site; 21 street lamps were located in the 100 m buffer zone. In the vicinity of the measurement site there are several-storey buildings of the Nicolaus Copernicus University, including the characteristic and well-illuminated façade of the Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University (NCU).

The second location selected for vertical measurements was located in the car park in front of a supermarket at Bema Street in Toruń (Fig. 4), about 1.5 km from the city centre. The altitude of the starting point was 54.6 m a.s.l. and its location in the geographical space: 53.016653 N and 18.588872 E. There was one turned-on street lamp facing the opposite direction, located at a distance of 25 m from the drone's starting point, and two others illuminating the car park of a supermarket, also near the launch site. However, the latter were not turned on at the time of the measurements. There were eight street lamps within a radius of 50 m, while 28 street lamps were located at a distance of up to 100 m. The surroundings of the measurement site included high multi-family buildings, a large shop and a sports hall.

The selected locations varied both in terms of light sources and land cover/land use in their immediate vicinity. To present the differences in this respect at both locations, a visualisation of the measurement locations was prepared in three buffer zones: 25 m, 50 m and 100 m. The red marker in Figure 5 indicates the drone launch site during each measurement session. The upper part of the figure shows a visualisation of the land cover in the buffer zone of 100 m from the take-off location. It shows the surroundings of the location in such a way that their perspective against the neighbouring buildings is revealed. The subsequent smaller buffers, 50 m and 25 m, mainly show the existing lighting infrastructure and its orientation during operation.

Fig. 3. Daytime (bottom) and nighttime (top) 360° panorama around the measurement location at the NCU campus (photo M.Kunz).

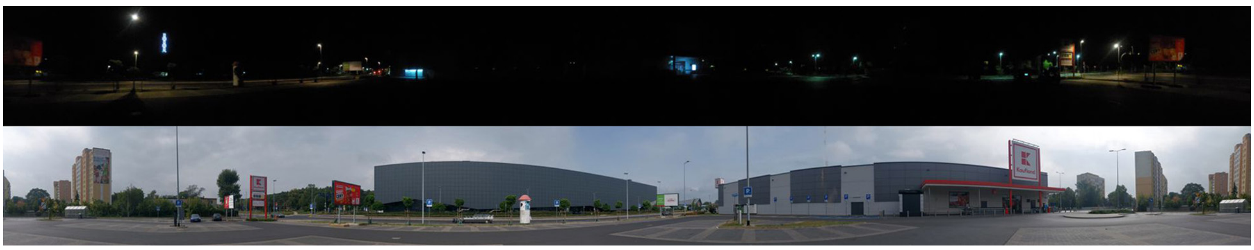

Fig. 4. Daytime (bottom) and nighttime (top) 360° panorama around the measurement location at the car park at Bema Street (photo D.Karpińska).

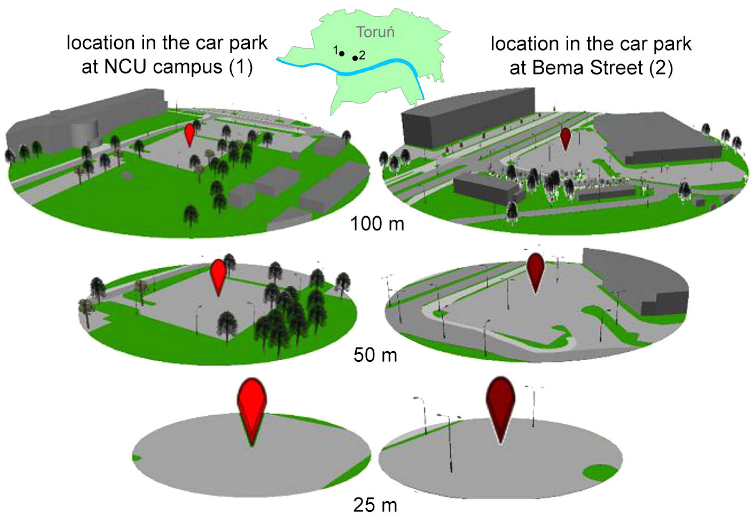

Fig. 5. Visualisation of land cover/land use at measurement locations in three buffer zones (25 m, 50 m and 100 m).

Analysis of vertical gradient measurements

Measurements of the night sky brightness variability in the vertical gradient were conducted several times at each measurement site in the period from July to September 2021. Within the framework of the planned measurement campaign, a total of five sessions were carried out, including four sessions at both selected locations and one – the first one in the series – only at the site located at the car park of the NCU campus in Toruń. The measurement sessions were held on the following dates: 25 July, 3 August, 12 August, 3 September and 12 September 2021. All measurements were carried out during cloudless and partly cloudy nights accompanied with different phases of the moon, but whenever the moon did make an appearance, it was very low above the horizon, since we selected only such times to ensure that the influence of moonlight on the measurements would be minimal to non-existent. The time difference in measurements at the stations did not exceed 30 min, and the distance in a straight line was 1.5 km. The acquired measurement data were processed and are presented in Figures 6 and 7, which compare the sky brightness in relation to the altitude at which the drone measurement was done.

The measured brightness of the night sky was visualised using the magnitudes per square arcsecond unit, and it was thus possible to compare the obtained results with previous measurements and with published studies of other research groups. The logarithmic and inverse scales were adopted on the ordinate axis of the presented graphs, so that high values correspond to a darker sky and low values to a brighter sky. Figure 6a presents the results of all measurements recorded at the site located at the car park of the NCU campus in Toruń. A characteristic feature of all presented results from this location is an initial clear reduction of the night sky brightness observed until a height of approximately 10 m above the ground surface. After crossing this limit, each time the measurements stabilise at a certain level of values. This altitude corresponds to crossing the approximate height line of the street lamp luminaries in the vicinity of the measurement locations. A similar situation is presented in the next graph (Fig. 6b), showing data obtained from the measurement site located at the car park in Bema Street in Toruń, where measured values also stabilised at an altitude of approximately 10 m. A comparison of the two presented graphs (Fig. 6) shows that the measurements taken between the take-off (ground level) and flight at an altitude of about 10 m differ significantly. The sky measured at the NCU car park is much brighter during this part of the flight, which is due to the fact that the nearby street lamps were directly illuminating the area from where the drone took off, which had a significant impact on the measurement, even though the take-off took place at a site relatively distant from the lighting infrastructure. At the Bema Street car park, the lamps were turned away from the drone's launch site and illuminated the surrounding area, including a nearby road. In order to compare the acquired data from both locations, they were collated in one graph (Fig. 7a), which presents the data obtained during the measurement session on the cloudless night of 3 September 2021. The previously discussed difference between the initial measurements taken within the altitude range from 0 m to 10 m is very clearly marked on the graph. Another regularity is the higher value of the night sky brightness at the car park on Bema Street compared to the car

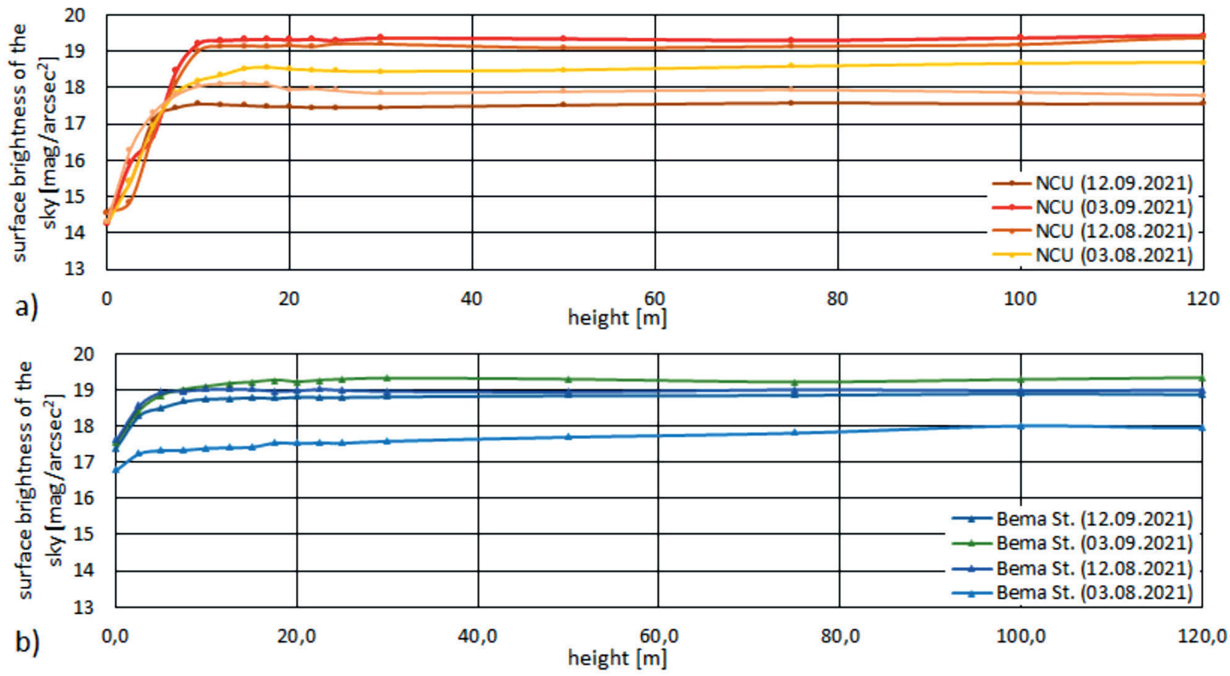

Fig. 6. Summary of the obtained results illustrating the variability of the night sky brightness in the vertical gradient at the measuring site located in Toruń: (a) at the NCU car park, (b) at the car park in Bema Street.

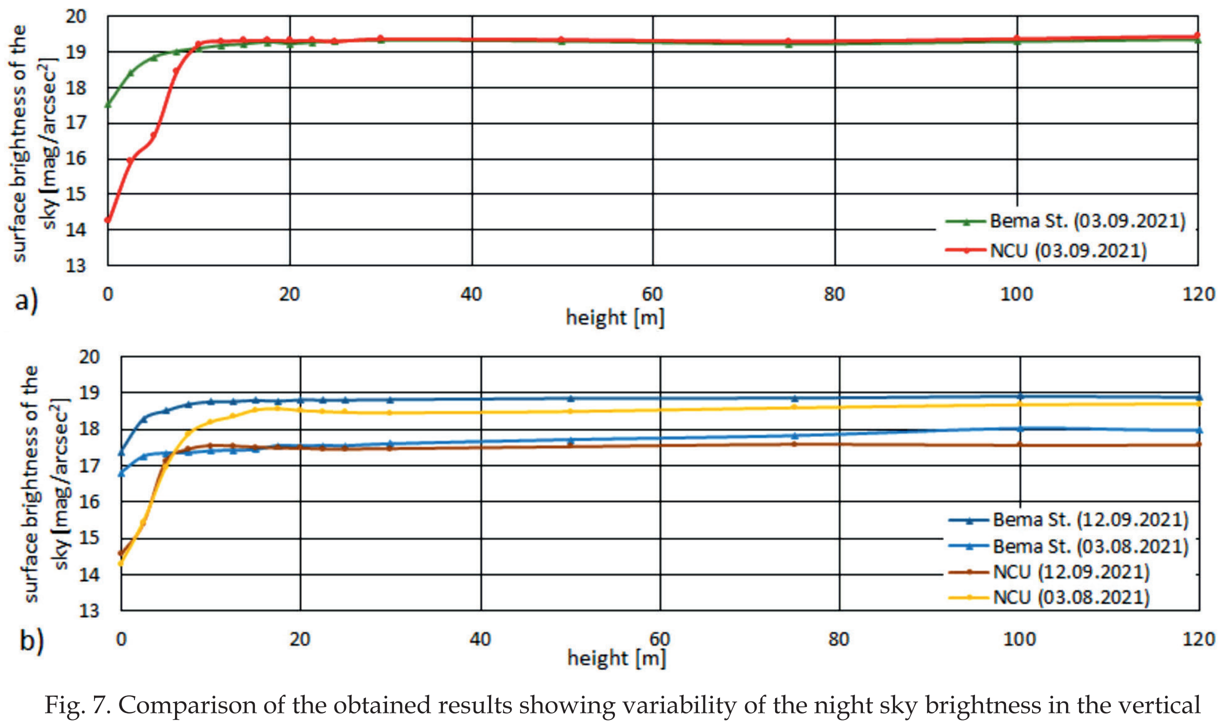

Fig. 7. Comparison of the obtained results showing variability of the night sky brightness in the vertical gradient at both measurement locations during: (a) cloudless night, (b) night with varied cloud cover.

park at the NCU campus measured already after the readings stabilised above 10 m above ground level. The difference between the locations appears to be insignificant, but is consistent with previous studies indicating that the closer the position of the observer to the city centre, which is an urban island of light, the brighter the sky. To be able to fully document the above conclusion, it is necessary to conduct an additional measurement campaign also at other sites located in the vicinity around the Mediaeval Town of Toruń. The last graph (Fig. 7b) shows the comparison of measurements performed during two nights with varying cloud cover. During the entire experiment, it was not possible to make measurements during a night with overcast sky, and thus two representative days were compared, when cloud cover was observed alternately at the first or second location. After analysing the shape of the measurement curves, it can be observed that with increasing cloudiness, the sky brightness increases significantly, which corresponds to the results presented in earlier works and those obtained by other research groups (Kolláth 2010, Ścieżor et al. 2010, Pun et al. 2013, Ribas et al. 2016, Hänel et al. 2017, Karpińska, Kunz 2019, 2020, Ścieżor 2020).

Conclusions and summary

A well-thought-out and targeted monitoring of the selected elements of the geographical environment is necessary. Due to the complicated process of variability, relationships and flow of the components, both as regards the identification of causes as well as consequences and effects of the analysed phenomenon, it should be carried out, whenever possible, throughout the three-dimensional space. The hitherto-conducted horizontal measurements of the variability of a given factor should, as far as possible, be supplemented with vertical measurements, which, depending on the type of phenomenon, will be analysed in different directions in relation to the place of interaction and the main impact. This is clearly and specifically visible in the analysis of the phenomenon of artificial light pollution in the night sky. Sky glow surrounding an urban agglomeration and having its main cause in excessive or improperly designed lighting of urbanised areas, including transport routes, extends considerably both in the horizontal and vertical gradients, which is noticeable even from a short distance from human settlements.

The results obtained in the experiment described above show that the most significant variability in the night sky brightness in the vertical gradient occurs immediately after exceeding the height of a typical lighting infrastructure that is a standard element of the urban landscape, i.e. from about 10 m.

Measured values above this limit stabilise at a certain level and vary by <0.3 mag · $arcsec^{-2}$, which shows that measurements of the night sky brightness above this limit can be made at different altitudes without amplification or attenuation of the obtained values. This gives great possibilities in the choice of location for mounting automatic measuring devices (including those developed in-house) for monitoring light pollution of the night sky in various other locations. The acquisition of data on night sky light pollution by drones may be both an alternative and a valuable addition to the monitoring of this phenomenon, harmful for the health and functioning of humans and other living organisms.

The conducted research has also shown that drones offer new possibilities of application and new perspectives for interdisciplinary cooperation. So far, they have been treated as complementary to the ceiling gap in remote and satellite, as well as aerial, measurements of light energy emitted from a given area, and now they can also be used for the measurement of surface brightness and vertical variability of the airglow (nightglow).

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Author's contribution

D. Karpińska: conceptualization, data curation, formal analysis, methodology, investigation, project administration, resources, validation, analysis of results and formulation of conclusions, preparation of figures, text correction, writing – review & editing. M. Kunz: conceptualization, data curation, formal analysis, methodology, investigation, project administration, resources, validation, analysis of results and formulation of conclusions, preparation of figures, text correction, writing – review & editing.

References

Aubé M., 2007. Proceedings of 'starlight, a common heritage' UNESCO conference. In: Marin C., Jafari J. (eds), La Palma: 351.

Aubé M., Marseille C., Farkouh A., Dufour A., Simoneau A., Zamorano J., Roby J., Tapia Ayuga C.E., 2020. Mapping the melatonin suppression, star light and induced photosynthesis indices with the LANcube measurement. Synthetic photometry. *Remote Sensing* 12. DOI 10.3390/rs12233954.

Bará S., Marco E., Ribas S.J., Gil M.G., Miguel A.S., Zamorano J., 2021. Direct assessment of the sensitivity drift of SQM sensors installed outdoors. *International Journal of Sustainable Lighting IJSL* 21(1): 1–6. DOI 10.26607/ijsl.v23i1.109.

Bará S., Tapia C.E., Zamorano J., 2019. Absolute radiometric calibration of TESS-W and SQM night sky brightness sensors. *Sensors* 19(6): 1336. DOI 10.3390/s19061336.

Bouroussis C.A., Topalis F.V., 2020. Assessment of outdoor lighting installations and their impact on light pollution using unmanned aircraft systems – The concept of the drone-gonio-photometer. *Journal of Quantitative Spectroscopy & Radiative Transfer* 259: 107–155. DOI 10.1016/j.jqsrt.2020.107155.

Connors B.M., McConnell A., Routledge R., 2010. Effect of artificial light on marine invertebrate and fish abundance in an area of salmon farming. *Marine Ecology Progress* 419: 147–156. DOI 10.3354/meps08822.

Den Outer P., Lolkema D., Haaima M., Van der Hoff R., Spoelstra H., Schmidt W., 2011. Intercomparisons of nine sky brightness detectors. *Sensors* 11(10): 9603–9612. DOI 10.3390/s111009603.

Den Outer P., Lolkema D., Haaima M., Van der Hoff R., Spoelstra H., Schmidt W., 2015. Stability of the nine sky quality meters in the Dutch night sky brightness monitoring network. *Sensors* 15(4): 9466–9480. DOI 10.3390/s150409466.

Depledge M., Godard-Codding C.A.J., Bowen R.E., 2010. Light pollution in the sea. *Marine Pollution Bulletin* 60(9): 1383–1385. DOI 10.1016/j.marpolbul.2010.08.002.

Falchi F., Cinzano P., Duriscoe D., Kyba C.C.M., Elvidge C.D., Baugh K., Portnov B.A., Rybnikova N.A., Furgoni R., 2016. The new world atlas of artificial night sky brightness. *Science Advances* 2. DOI 10.1126/sciadv.1600377.

Falchi F., Cinzano P., Elvidge C., Keith D., Haim A., 2011. Limiting the impact of light pollution on human health, environment and stellar visibility. *Journal of Environmental Management* 92: 2714–2722. DOI 10.1016/j.jenvman.2011.06.029.

Fiorentin P., Bettanini C., Bogoni D., 2019. Calibration of an autonomous instrument for monitoring light pollution from drones. *Sensors* 19: 5091. DOI 10.3390/s19235091.

Garcia-Saenz A., Sanchez de Miguel A., Espinosa A., Crespo A., Aragonés N., Llorca J., Amiano P., Martín V., Guevara M., Capelo R., Tardón A., Peiró R., Jiménez-Moleón J., Roca Barcelo A., Perez-Gomez B., Dierssen-Sotos T., Fernández T., Moreno-Iribas C., Moreno V., Kogevinas M., 2018. Evaluating the association between artificial light-at-night exposure and breast and prostate cancer risk in Spain (mcc-spain study). *Environmental Health Perspectives* 126. DOI 10.1289/EHP1837.

Hänel A., Posch T., Ribas S.J., Aubé M., Duriscoe D., Jechow A., Kolláth Z., Lolkema D.E., Moore C., Schmidt N., Spoelstra H., Wuchterl G., Kyba C.C.M., 2017. Measuring night sky brightness: Methods and challenges. *Journal of Quantitative Spectroscopy and Radiative Transfer* 205: 278–290. DOI 10.1016/j.jqsrt.2017.09.008.

Jechow A., Kyba C.C.M., Kolláth Z., Lerner A., Hänel A., Shashar N., Hölker F., 2017. Measuring light pollution with fisheye lens imagery from a moving boat, a proof of concept. *International Journal of Sustainable Lighting* 36(1): 15–255. DOI 10.26607/ijsl.v19i1.62.

Jechow A., Ribas S.J., Canal-Domingo R., Holker F., Kolláth Z., Kyba C.C.M., 2018. Tracking the dynamics of skyglow with differential photometry using a digital camera with fisheye lens. *Journal of Quantitative Spectroscopy and Radiative Transfer* 209: 212–223. DOI 10.1016/j.jqsrt.2018.01.032.

Jones J., Francis C.M., 2003. The effects of light characteristics on avian mortality at lighthouses. *Journal of Avian Biology* 34: 328–333. DOI 10.1111/j.0908-8857.2003.03183.x.

Karpińska D., Kunz M., 2019. Light pollution in the night sky of Toruń in the summer season. *Bulletin of Geography. Physical Geography Series* 17: 91–100. DOI 10.2478/bgeo-2019-0017.

Karpińska D., Kunz M., 2020. Analysis of light pollution of the night sky in Toruń (Poland). *Civil and Environmental Engineering Reports* 30(4): 155–172. DOI 10.2478/ceer-2020-0057.

Karpińska D., Kunz M., 2021a. Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area on the example of the Bielany campus of the Nicolaus Copernicus University in Toruń. In: *Book of Abstracts, Third World Conference of the Society for Urban Ecology*. Fundacja UAM w Poznaniu. Poznań: 143–144. DOI 10.2478/bog-2021-0039.

Karpińska D., Kunz M., 2021b. Rekonstrukcja zasięgu widoczności sieci LoRaWAN na terenie kampusu UMK w Toruniu (Reconstruction of the visibility range of the LoRaWAN network on the campus of the Nicolaus Copernicus University in Toruń). In: Młynarczyk A. (ed.), Środowisko przyrodnicze, jako obszar badań. Bogucki Wydawnictwo Naukowe: Poznań: 47–60.

Kocifaj M., 2009. Light pollution model for cloudy and cloudless night skies with ground-based light sources: Errata. *Applied Optics* 48: 4650–4650. DOI 10.1364/AO.48.004650.

Kocifaj M., Bará S., 2020. Nighttime monitoring of the aerosol content of the lower atmosphere by differential photometry of the anthropogenic skyglow. *Monthly Notices of the Royal Astronomical Society: Letters* 500: 47–51. DOI 10.1093/mnrasl/slaa181.

Kolláth Z., 2010. Measuring and modelling light pollution at the Zselic Starry Sky Park. *Journal of Physics Conference Series* 218,1, 012001. DOI 10.1088/1742-6596/218/1/012001.

Kołomański S., 2015. Zanieczyszczenie światłem i ciemność (Light pollution and darkness). In: Wiśniewska M.R., Tomasik K. (ed.), *Przejdź na ciemną stronę nocy*. Środowiskowe i społeczne skutki zanieczyszczenia światłem. Wyd. Uniwersytetu Warszawskiego. Warszawa: 29–46. DOI 10.31338/uw.9788323514138.pp.29-46.

Kołomański S., Wiernasz A., Borodacz K., Białek R., Mikołajczyk P., 2019. ALPS – stacje obserwacyjne zanieczyszczenia światłem (ALPS – light pollution observation stations). In: Kotarba A. (ed.), *Zanieczyszczenie światłem. Źródła, obserwacje, skutki*. Centrum Badań Kosmicznych PAN. Warszawa: 153–166.

Kunz M., 2015. Nowoczesne metody i narzędzia telegeoinformatyczne służące pozyskiwaniu informacji geograficznej (Modern tele-information methods and tools for obtaining geographic information). In: Kunz M., Nienartowicz A. (eds), *Systemy informacji geograficznej w zarządzaniu obszarami chronionymi – od teorii do praktyki*. Wyd. FUH Daniel. Sępólno Kraj.: 85–96.

Kyba C.C.M., Kuester T., Sánchez De Miguel A.K., Jechow A., Hölker F., Bennie J., Elvidge C.D., Gaston K.J., Guanter L., 2017. Artificially lit surface of Earth at night increasing in radiance and extent. *Science Advances* 3(11). DOI 10.1126/sciadv.1701528.

Linares H., Masana E., Ribas S.J., Aubé M., Simoneau A., Bará S., 2020. Night sky brightness simulation over Montsec protected area. *Journal of Quantitative Spectroscopy and Radiative Transfer* 249. DOI 10.1016/j.jqsrt.2020.106990.

Longcore T., Rich C., DelBusso L., 2017. Artificial Night Lighting and Protected Lands; Natural Resource Report NPS/NRSS/NSNS/NRR—2017/1493.

Navara K.J., Nelson R.J., 2007. The dark side of light at night: Physiological, epidemiological, and ecological consequences. *Journal of Pineal Research* 43(3): 215–224. DOI 10.1111/j.1600-079X.2007.00473.x.

Para A.K., Para A., 2013. Świadomość skażenia otoczenia człowieka radonem (Awareness of radon contamination of the human environment). *Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska* 59: 88–97.

Pun C.S.J., So C.W., Leung W.Y., Wong C.F., 2013. Contributions of artificial lighting sources on light pollution in Hong Kong measured through a night sky brightness monitoring network. *Journal of Quantitative Spectroscopy and Radiative Transfer* 139: 90–108. DOI 10.1016/j.jqsrt.2013.12.014.

Qadri H., Bhat R.A., Mehmood M.A., Dar G.H., 2020. *Fresh water pollution dynamics and remediation*. Springer. Singapore. DOI 10.1007/978-981-13-8277-2.

Ribas S., Torra J., Figueras F., Paricio S., Canal-Domingo R., 2016. How clouds are amplifying (or not) the effects of ALAN. *International Journal of Sustainable Lighting* 18. DOI 10.26607/ijsl.v18i0.19.

Ribas S.J., 2015. *Caracteritzacio de la Contaminacio Lumnica en Zones Protegides i Urbanes. PhD thesis*. Universitat de Barcelona, Barcelona.

Ściężor T., 2015. Określenie charakteru zmian jasności nocnego nieba w Polsce w latach 1994–2009 na podstawie amatorskich obserwacji komet (Determining the nature of changes in the brightness of the night sky in Poland in the years 1994–2009 on the basis of amateur comet observations). In: Roge-Wiśniewska M., Tomasik K., (eds), *Przejdź na ciemną stronę nocy. Środowiskowe i społeczne skutki zanieczyszczenia światłem*. Wyd. Uniwersytetu Warszawskiego. Warszawa: 61–80. DOI 10.31338/uw.9788323514138.pp.61-80.

Ściężor T., 2020. The impact of clouds on the brightness of the night sky. *Journal of Quantum Spectroscopy and Radiative Transfer* 247. DOI 10.1016/j.jqsrt.2020.106962.

Ściężor T., Kubala M., Kaszowski W., Dworak T.Z., 2010. Zanieczyszczenie świetlne nocnego nieba w obszarze aglomeracji krakowskiej (Light pollution of the night sky in the area of the Kraków agglomeration). *Analiza pomiarów sztucznej poświaty niebieskiej*. Wyd. Politechniki Krakowskiej. Kraków.

Ściężor T., Metody pomiaru jasności nocnego nieba (Methods of measuring the brightness of the night sky). Online: http://lightpollution.pk.edu.pl/SOCN/metody.php (accessed 10 December 2021).

Skwarło-Sońta K., 2014. Melatonina: hormon snu czy hormon ciemności? Kosmos. *Problemy Nauk Biologicznych* 63(2): 223–231.

Stevens R.G., 2009. Light-at-night, circadian disruption and breast cancer: Assessment of existing evidence. *International Journal of Epidemiology* 38: 1–8. DOI 10.1093/ije/dyp178.

Wang L.K., Pereira N.C., Hung Y.T., 2004. Air pollution control engineering. In:*Handbook of environmental engineering*, Vol. 1. Humana Totowa, NJ. New York..

Woźny A., Dobosz M., Pacana A., 2014. Wpływ hałasu na jakość pracy (The influence of noise on the quality of work). *Humanities and Social Sciences* 21(2): 251–258. DOI 10.7862/rz.2014.hss.31.

Wyszkowski M., Wyszkowska J., 2007. Zanieczyszczenie gleby kadmem a zawartość makropierwiastków w roślinach (Soil contamination with cadmium and the content of macroelements in plants). *Ochrona Środowiska i Zasobów Naturalnych* 3: 231–235.