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Original Research Article

MEASURING LIGHT POLLUTION IN THE NIGHT SKY – FROM TECHNOLOGY DEMONSTRATOR TO MONITORING SYSTEM

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A b s t r a c t

Pollution of the night sky by artificial light has now become an important element of the modern city landscape. The decline in the quality of the sky observed at night in urban areas has already been noticed even by residents unaware of its origin. A starry sky is nowadays not easy to observe even in places far from large conurbations or smaller cities. More and more places are losing access to the previously natural privilege of observing the dark sky, and their inhabitants are thus systematically exposed to all the direct and indirect negative effects of this phenomenon. Monitoring the brightness of the night sky is gaining interest from a growing number of interdisciplinary research groups being established around the world, including Poland. In Toruń, the first measurements of the magnitude of this phenomenon, together with the determination of its spatial scale, were started using handheld devices in 2017. In the following years, efforts were made to improve the data acquisition process by creating a prototype – a technology demonstrator and, consequently, a commercial version of an automatic device measuring the surface brightness of the night sky. This paper presents the stages of the project aimed at developing a light pollution monitoring system, which has been consistently implemented in Toruń. The most important component of this system is a measuring device of our own design and construction. The monitoring system designed and operating in Toruń, starting in 2019, is being further developed with new components and monitoring (measurement) sites being systematically added, making the city's observation network increasingly dense. The devices built using the LoRa standard for wireless data exchange implement the concept of the Internet of Things, fitting in with the objectives of a smart city.

Keywords: light pollution, automatic measurement, LoRaWAN, Smart City, Industry 4.0, monitoring system

1. INTRODUCTION

Light pollution is a progressive degradation of the surrounding natural environment, which is defined as the excessive emission of artificial light into the lower atmosphere over an extended period of time (Fig. 1). The glow of light extending over a city can easily be seen from a distance of up to several tens

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of kilometres [2,5,17]. Statistically, over 99% of Europe's population and 80% of the world's population live in areas polluted by artificial light [2]. This phenomenon is therefore global and spreads spatially over time with the progressive development of civilisation and the construction of yet more housing estates and the ill-considered expansion of road, utility and advertising lighting infrastructure.

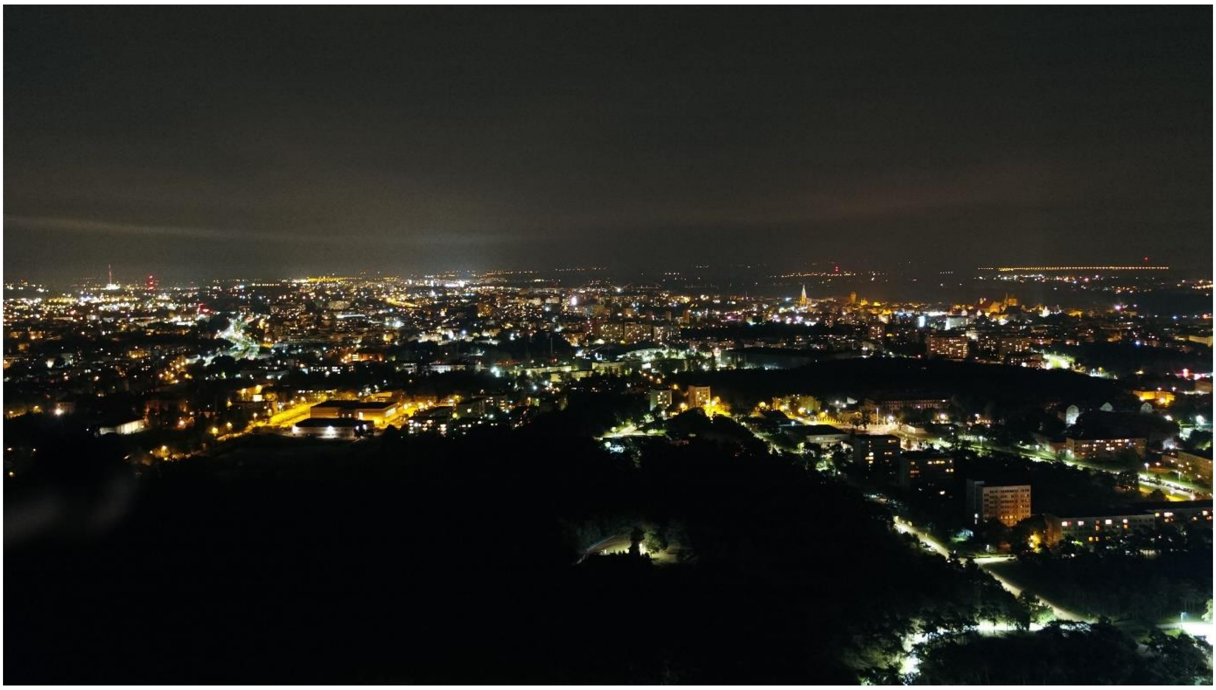

Fig. 1. Night-time image of Toruń taken with a UAV from 120 m above ground level (photo by Mieczysław Kunz)

Light pollution is caused by excessive spot and surface emission of incorrectly designed or installed outdoor lighting, the direction of which has been inadequately adjusted. The phenomenon is aggravated by the presence of illuminated advertising neon signs and excessive backlighting of architectural elements and city illuminations. In addition, research has shown that light pollution is exacerbated by the scattering of artificial light in the atmosphere by dust of anthropogenic origin present in the atmosphere, as well as being amplified by the reflection of light from clouds, especially low- and mid-level clouds [4,6,14,21,22,25,26].

This phenomenon, like any other environmental deterioration, has its negative consequences for the environment. Excessive light emission at night leads to disruptions in plant and animal development and significantly impairs human health, quality of life and daily functioning [3,19]. Negative effects of this phenomenon include illuminating areas that should not be exposed to artificial light and blinding bystanders, both pedestrians and drivers, which can lead to dangerous situations, incidents and behavior [16]. As the energy crisis progresses from the beginning of 2022, ill-considered, improperly designed outdoor lighting causes excessive electricity consumption, which means additional economic costs for both local authorities at all levels and individuals.

Light pollution of the night sky can be measured using a number of methods that have been developed for use by both amateurs and professionals [2,4,6,15,21,22]. In terms of sophistication, they can be divided into observational and instrumental methods. They include measurements with the unaided eye, measurements with a photometer, taking night-time photographs or analysis of satellite imagery and, increasingly common, night-time aerial photographs.

In typically quantitative studies of this phenomenon, the most commonly used and widespread method is photometric measurement using manual or more advanced photometers and analysis of night sky images taken with cameras equipped with spherical (all-sky) lenses. Such methods are used by scientists from all over the world, including some Polish research groups [4,6,15,21,22].

In order to effectively protect the environment from this yet another type of pollution of anthropogenic origin, some European countries have started to implement regulations on the outdoor emission of artificial light [18]. The human right to enjoy the dark sky and to protect the environment from the effects of light pollution has already been introduced in several countries around the world, including Croatia, Germany and France. However, the vast majority of European countries, including Poland, do not yet have such legal provisions or established standards, and have not even started a public discourse on the subject. In Poland, a group of experts from selected Polish research units has produced an important document over the past year – *Memorandum on Establishing the Legal Basis for a Sustainable Outdoor Lighting Policy* [24], which is intended to serve as a starting point for the preparation of national legal regulations in this area, as well as an audible voice of specialists from various professions drawing attention to the issue described.

2. INTERDISCIPLINARY RESEARCH TEAM AND INSTITUTIONAL COLLABORATION

Measuring, analysing and interpreting the phenomenon of pollution of the night sky by artificial light is a very complex issue that requires multifaceted research and contributory work carried out in collaboration between people representing different scientific disciplines.

The described project, related to the topic of the use of modern technologies for the acquisition and transmission of measurement data in the urban environment, has been from the very beginning oriented at interdisciplinary cooperation and, as its implementation progressed and needs were identified, more specialists were invited to join the team. Initially (2019), the idea of performing this task was suggested as a typical PhD project, but along with its intensive implementation, it was expanded to include a second route – innovation and development, which, as it were, necessitated the expansion of the team. At present (2022), it consists of five specialists in environmental monitoring, geoinformation and geoinformatics, automation and systems of measurement. These professionals represent the Faculty of Earth Sciences and Spatial Management and the Faculty of Physics, Astronomy and Informatics of Toruń University. This approach has resulted in the development of a solution concept, the development of a prototype and its successful testing, the construction of the target measuring device and the handling of user-functional optimisation, as well as the implementation of the monitoring system into operation. In addition, an Innovation Broker from CPATT UMK and a specialist from TARR S.A. have been involved in the work to commercialise the solution for almost a year.

To effectively implement the planned stages of the work, and to successfully and on an going basis solve the technical constraints and technological problems encountered, it was essential to make use of the existing experience of the commercial sector companies and the knowledge bases that had been created. To this end, selected companies were regularly invited to collaborate as advisers at individual highly specialised stages of the project, and this collaboration always had a formal and task-based dimension. In the period from 2018, letters of intent were signed with TARR S.A. IoT North Poland Hub, EXEA Sp. z o.o. Data Processing Centre from Toruń and ACTE Sp. z o.o from Warsaw.

This has made navigating this complex matter at the interface of several disciplines and reducing the technical, logistical and organisational barriers encountered much easier and more efficient.

In July 2022, the first Light Pollution Think Tank (LPTT) was established in Poland, which was possible thanks to a subsidy from the National Freedom Institute – the Centre for Civil Society Development obtained by the POLARIS-OPP Association, while the whole project was a response to the increasing phenomenon of artificial light pollution in Poland and the lack of applicable legislation on outdoor lighting policy. The authors of this paper were part of this *think-tank*, and the results of measurements obtained from the night sky monitoring system being implemented in Toruń will be one of the elements of the report being prepared – an audit on light pollution in Poland.

3. STAGES OF THE PROJECT IMPLEMENTATION

The first study involving measurements of light pollution in the urban area of Toruń began in mid-2017. Measurements were then made with a handheld SQM photometer (see Fig. 5) at selected 24 observation sites located throughout the city [6,7]. More than a year of systematic monitoring allowed analysis and production of the first maps presenting the spatial distribution of the phenomenon in Toruń, both in seasonal and annual terms. The field experience gained and the knowledge acquired regarding the spatial variability and the influence of selected elements on the measured values made it possible to plan the next project, where one of the objectives was to optimise the repeatable measurement and data acquisition process. The most important change was the use of remote data transfer in the measurement process, which reduced the time, organisational and logistical constraints prevalent when using the manual method for such a large area, and also influenced the daily repeatability and comparability of the measurements carried out. This is because the phenomenon of light pollution is characterised by variability depending not only on the phase of the moon, but primarily on the prevailing atmospheric conditions and air quality [22,25]. On cloudless and overcast nights, the measurements obtained do not differ significantly from each other, while on nights with changing cloud cover, the results can differ significantly, as cloud cover considerably affects the night sky brightness measurements. Therefore, measurements in any analysed area should be carried out at approximately the same time to eliminate any possible effect of weather changes.

3.1. Automatic monitoring network construction

While analysing the identified factors that could affect the measurement of the phenomenon described, it was agreed that the measurements would be performed remotely using LoRaWAN technology [20,23]. The results of the nadir-direct recording will be collected in a 15-minute interval, starting at 21:00 h until 06:00 h the following day, with simultaneous transmission of values to the server and saving them in a defined disk cloud. The working time and the intervals of waking up the device from the sleep mode have been set by software. Once the concept was developed, work began on developing an automatic device of our own design, connecting with a communication gateway via LoRaWAN [11]. Table 1 presents basic technical parameters of the designed and constructed measuring device.

Due to the adopted mobility and the location of the monitoring (measurement) sites without access to electricity, it was necessary to choose a technology that would allow efficient use of battery power. To save energy, the device should operate in reduced power consumption mode and wake up only for the duration of the scheduled night measurement sessions (Fig. 2). To ensure accurate measurements of the surface brightness of the night sky, a high-accuracy light sensor TSL2591 was used for the measuring device, which was properly calibrated at the manufacturing stage [1].

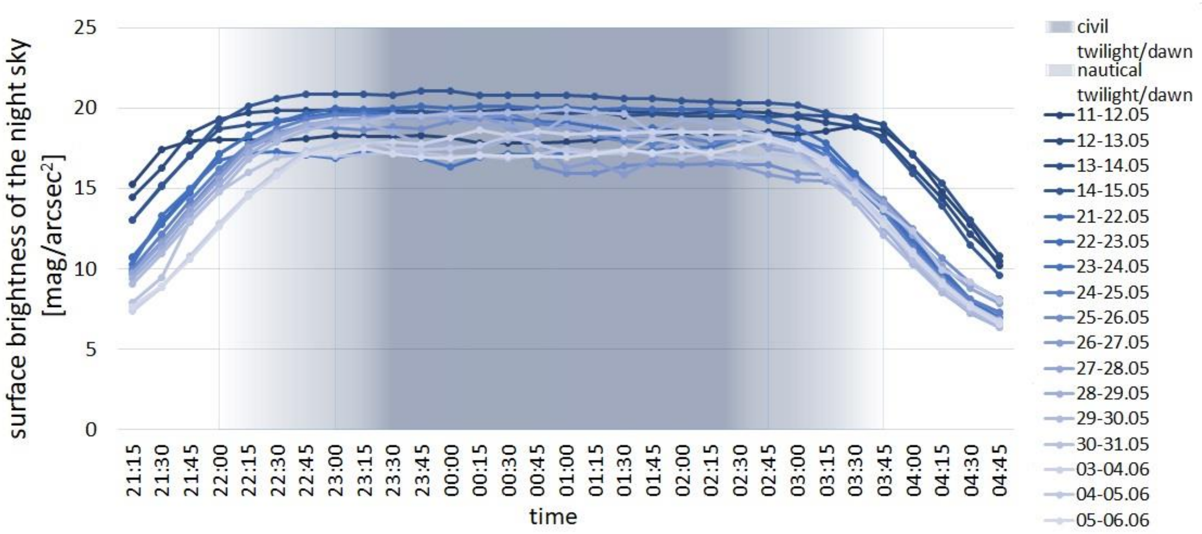

Fig. 2. First results of night sky brightness measurements obtained in the first measurement series between May 11 and June 6, 2020 using one of prototype devices as part of the so-called technology demonstrator stage

Table 1. Selected technical parameters of the constructed measuring device

Parameter	Characteristic
Dimension	5.5 x 8.2 x 15.8 cm
Weight (with batteries)	350 g (390 g)
Standard of data transmission	LoRaWAN
Spectral response	Approximates Human Eye Response
Measurement range	0 lx – 88,000 lx
Sensitivity	188 μlx
Operating time [3 000 mAh]	~ 9 month
Range in built-up areas	3–4 km
Frequency of measurements	15 min
Operational time	21:00 – 06:00 CEST
Measuring sensors	light intensity, temperature, humidity
Half-cone angle of data collection	27o
Tightness class	IP65

After the first tests of the efficiency and correctness of operation of all elements of the system, the twin devices (identical with regard to their design and construction) were connected to form a coherent monitoring network, which had been ultimately planned for the deployment in Toruń and the surrounding area. The assumed network consists of measuring devices that send data to the communication gateway using the LoRa network. Then the message is sent to the server where they are processed and saved to a file. The data collected in the future will be made available to users.

3.2. Technology demonstrator

The first stage of verifying the correct operation of the key devices of the future monitoring network was to carry out tests under operational conditions at the Toruń Technology Park. These tests, known as a technology demonstrator or performance check of the prototype, began on 12 May 2020 and involved two measuring devices being remotely connected to a MultiTech Systems Inc. (USA) communications gateway (operating for other applications) and placed on selected building rooftops. The devices established a correct and stable connection with the network, transmitted data at the designated interval and time range, then went into sleep mode and woke up according to the approved schedule. At this stage, the data recording on the server was working correctly, but in order to make the recording of all collected data transparent, it was necessary to change the size of the data frame sent from the devices. One of the first measurement results is presented in Figure 4. As with the presentation of results from other regions of the world, the *magnitude* measure, which is based on an inverse logarithmic scale, was used to produce the chart. This means that when interpreting the results, it should be borne in mind that the darkest sky will have a brightness of about 22 mag/arcsec^2, while the polluted sky is characterised by values much lower, even in the range of 14–16 mag/arcsec^2 [5,7].

In this figure, the approximate duration of the astronomical night and the civil night were added in the background in blue shades for a better presentation of the results obtained. In this way, the correlation between the night sky brightness values and the intensity of the sunlight is immediately evident. This juxtaposition makes it possible to determine which data show the sky polluted by artificial light of anthropogenic origin.

However, the tests carried out showed the shortcomings of the device consisting in a very short operating time on a single power pack. It turned out that the service life of the first two devices was only 5–7 days and after this period, battery packs had to be replaced to maintain continuity of measurements. This shortcoming of the prototype and its limitation were the subject of in-depth analysis of the components used and additional laboratory work and tests. After interfering with the electronics of the development board by deliberately disconnecting some redundant functions, the target operating time was optimised to approximately nine months of continuous operation.

3.3. Field reference measurements using commercially available SQMs

The next stage of testing the constructed device was to simultaneously place it and make repeated measurements over an extended period of time in the vicinity of the factory-made SQM-LU photometer of the Canadian company Unihedron (Fig. 3). A common feature of both devices was a light sensor characterised by similar technical parameters.

These measurements were carried out in November and December 2020. The commercially available SQM-LU photometer was placed near our designed device already operating in the network, so that identical external conditions (both meteorological and lighting) were maintained at the time of measurement. Figure 6 presents the results of the night sky brightness measurements obtained at this stage. The fluctuations in the pattern of all recorded values observed on consecutive days were due to changing weather conditions. Lower results indicate recording during a period of increased cloudiness, while higher results indicate recording during slightly cloudy or cloudless sky.

The values obtained at this stage document the correctness of our designed and constructed device compared to the factory-made SQM photometer. The slight differences in the form of deviation as shown in the graphs are solely due to the similar, but not identical, spectral sensitivity of the light sensors used [1,11].

Fig. 3. Presentation of the measuring devices used: the handheld SQM photometer used in the first stage of the work (left), the LU version of the SQM photometer without its outer casing used as a measurement background (centre) and the night sky surface brightness recorder (right) designed by the authors of this study (photo by Dominika Karpińska)

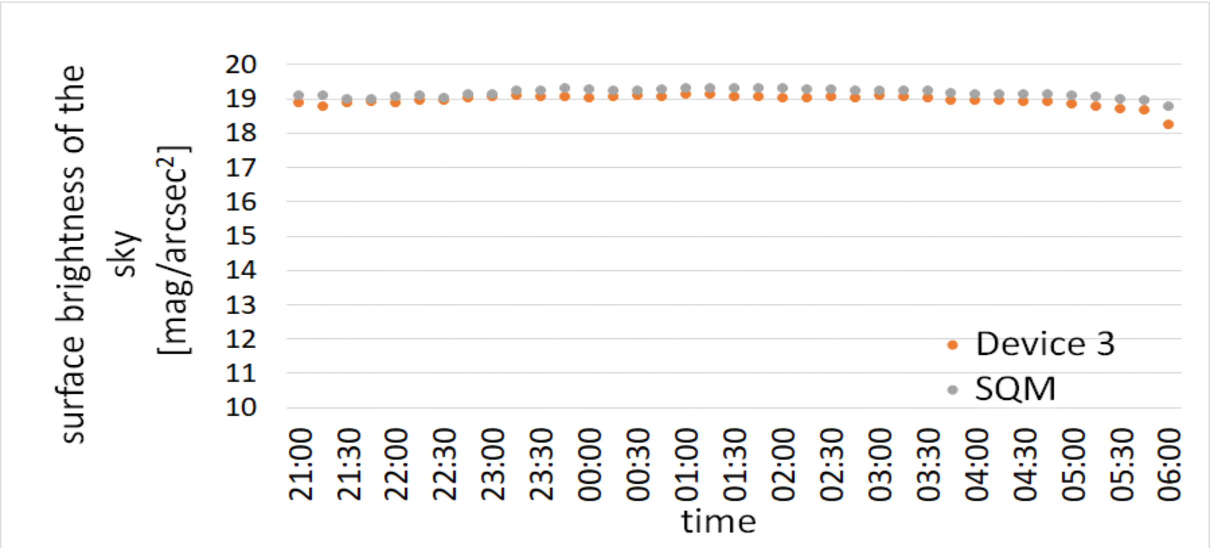

Fig. 4. Sample results of comparisons of night sky brightness values measured simultaneously using the designed SQM and the commercially available off-the-shelf SQM from the night of December 15/16, both mounted on the Observation Platform of the Faculty of Earth Sciences and Spatial Management of NCU

3.4. Testing the recording repeatability of measuring sets forming the future urban “cloud” of devices for observation of light pollution of the night sky

The purpose of this stage was to test the correct performance and measurement accuracy of all 40 measuring devices built. To make this reliable and comparable, the planned tests were carried out at the same time, at one location and under similar external conditions, and additionally near the factory-made data logger.

The experiment showed that the measurements obtained from all the constructed devices were consistent [11]. The obtained night sky brightness values overlapped significantly with the data obtained from the SQM photometer running in parallel. To further statistically analyse the collected data, the mean of all measurements at each point of the intervals and the standard deviation of the results were calculated. During stable weather conditions, these results were consistent and the relative standard deviation (RSD) averaged only 0.5. A slightly higher relative standard deviation was observed during changing weather conditions and was then below 2.15 [11].

3.5. Measurement background as supporting reference values

Measurements of the luminous quality of the night sky, especially in urban areas, require knowledge of as many variables as possible. To correctly interpret the results obtained through a monitoring network, it is necessary to determine the level of light pollution outside built-up areas by potential sources of outdoor illumination. To this end, additional monitoring sites located at some distance from the limits of Toruń were set up as a measurement background (Table 2). At each of them, a factory-made SQM-LU photometer was placed at a level of 2 m above ground level (Fig. 5).

The first one was installed on the premises of the Integrated Environmental Monitoring Station of the Faculty of Earth Sciences and Spatial Management of NCU in Koniczynka, about 10 km from the city limits in a straight line. The station carries out miscellaneous measurements of environmental parameters, including soil, water and air.

The second device was placed in the largest forest complex in Poland – Tuchola Forest in the Osieczna municipality in the small forest hamlet of Klaniny, which is located about 100 km (in a straight line) north of Toruń outside the influence of major cities and industrial areas. An identical measuring device is also located on the Observation Platform of the Faculty of Earth Sciences and Spatial Management NCU in Toruń and therefore the spatial arrangement of these recorders should account for the decreasing gradient of human impact (Fig. 5D).

Table 2. List of points constituting the measurement background

	Location	Start date	Height	Coordinates	
1	Station of Integrated Monitoring of the Natural Environment in Koniczynka	June 2022	2 meters	53.080614	18.684068
2	Tuchola Forest, in the commune of Osieczna, in the mid-forest settlement of Klaniny	July 2022	2 meters	53.828586	18.203112

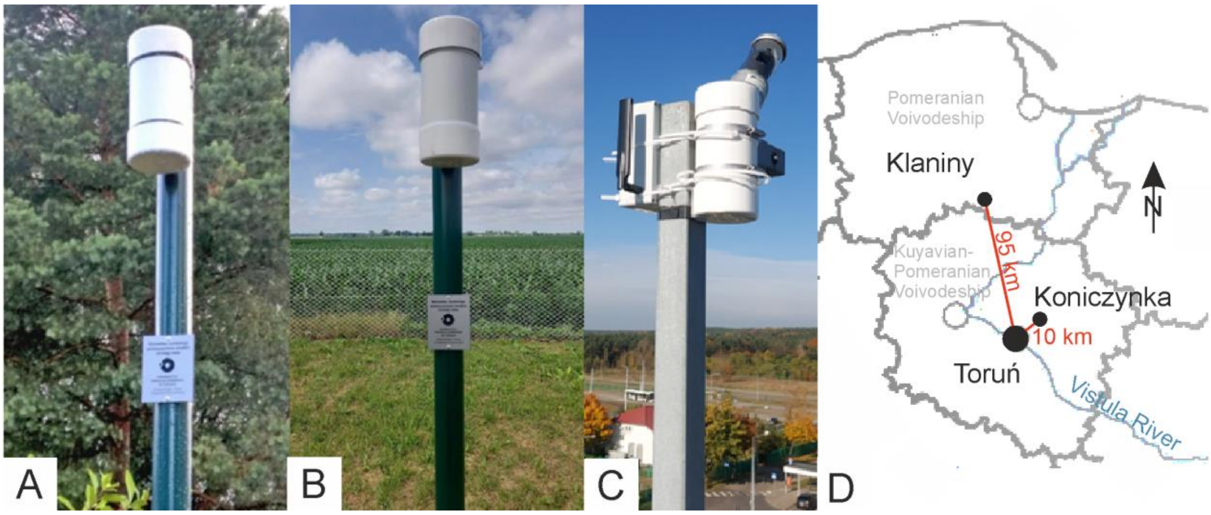

Fig. 5. Monitoring (measurement) sites with the SQM-LU photometer constituting the measurement background for the city of Toruń: A) the village of Klaniny (Tuchola Forest), B) the village of Koniczynka, C) Observation Platform of the Faculty of Earth Sciences and Spatial Management of NCU in Toruń and D) their schematic location (photo by Mieczysław Kunz)

The assumption made in this project was positively verified after analysing the results from the first half of the year, i.e. from July to December 2022, of simultaneous recording at the established reference sites. The shape of the curves presenting the brightness of the night sky is clearly correlated with the linear distance from large human societies and the measured magnitude increases with decreasing gradient of human impact (Fig. 6).

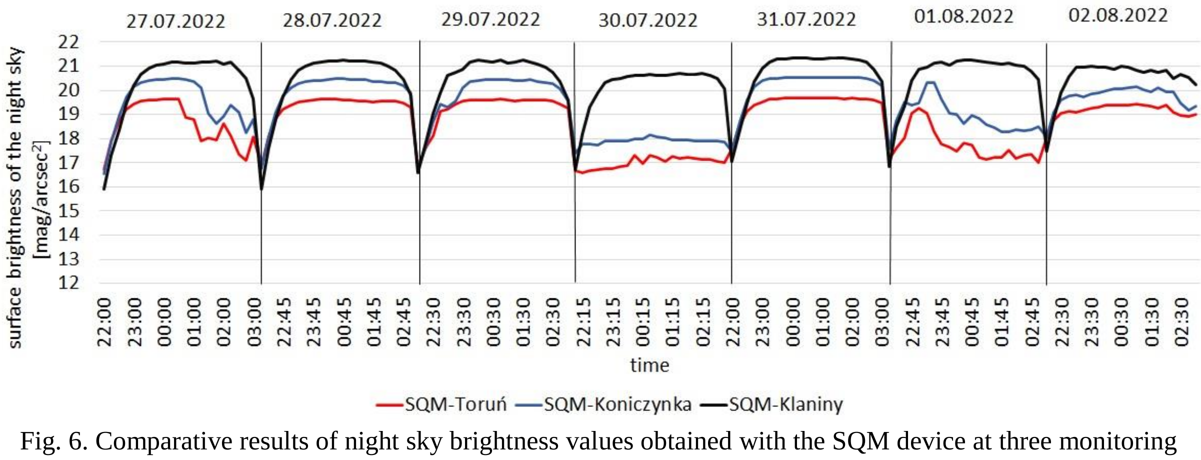

Fig. 6. Comparative results of night sky brightness values obtained with the SQM device at three monitoring sites distributed in the decreasing gradient of human impact

4. AUXILIARY STAGES OF PROJECT IMPLEMENTATION

4.1. Analysis of LoRa network signal coverage in three-dimensional space

A complementary, but from a practical point of view extremely important, activity carried out simultaneously was a field experiment to check the quality and strength of the signal of the previously selected data transmission technology [8,9]. This was necessary for planning and designing the distribution of the devices within the city limits and within the range of the access gateways. To this end, tests were carried out on the campus of Nicolaus Copernicus University in Toruń using an external communication gateway mounted on the Observation Platform of the Faculty of Earth Sciences and Spatial Management at NCU. The coverage and quality of the LoRa network signal was checked using the LoRaWAN mDOT Box network tester from MultiTech Inc. For comparative and exploratory purposes, field tests were carried out using two antennae of different lengths – 34 cm and 82 cm.

The field measurements showed that the LoRaWAN network established on the NCU campus in Toruń meets the assumptions of the project. However, a significant difference was observed in the quality of the available signal when using different antenna lengths. When the longer antenna was used, the network's signal visibility covered the entire university area, as well as areas located up to approximately 4 km in a straight line from the communication gateway. Furthermore, this coverage was also obtained in theoretically blind spots, i.e. behind various field obstructions such as tall buildings or topographic depressions. The knowledge gained during the above-described operations was taken into account in the target planning of the spatial distribution of the monitoring sites within the city.

4.2. Measurement of the variability of the night sky surface brightness in a vertical gradient

Another complementary measure to establish a multi-site monitoring network in the city area and to learn about the vertical variability of the measured sky brightness was to investigate how the position of the data recorders above ground level affects the correctness of the measurements made. To this end, vertical measurements of the night sky brightness were carried out using an unmanned aerial vehicle from DJI, model Matrice 210 RTK [13]. Necessary design changes were made to the constructed measuring device described in subsection 3a so that it could be mounted from the top of the drone and target measurements could be taken in the zenithal direction. The position of the light sensor was changed, i.e. relocated to the side of the device housing relative to the prototype, and the reading frequency was increased to 15 seconds intervals. Measurements of the variability of the night sky surface brightness in the vertical gradient in selected intervals, up to a maximum height of 120 m, were carried out at two sites located in Toruń, one on the NCU campus and the other at Bema Street. Each measurement session involved flying the drone vertically upwards and taking measurements at fixed altitudes, up to 30 m every 2.5 m and above this height – every 25 m. The tests carried out showed that measured values of the night sky surface brightness stabilise above the height of street lamps, and above this level, the measured values take on a constant maximum value. The study established that measurements up to a height of 10 m above the ground, and particularly those carried out in the vicinity of intensive street lighting, are subject to additional error due to the presence of directly incident light from surrounding lamps. The practical conclusion of these operations was that measuring devices within the monitoring network can be mounted at different heights above ground level, but should be outside the impact of direct radiation. Otherwise, the results obtained may be slightly overestimated.

5. LIGHT POLLUTION MONITORING NETWORK IN TORUŃ

5.1. Urban monitoring network – theoretical model of spatial distribution of measurement sites

Another important element of the efforts aimed at designing the target model of the network monitoring light pollution of the night sky in Toruń was to determine the optimum number of recording devices required to fully cover the sky within the administrative limits of the city. The area from which measurement data processed by a single light sensor are collected is limited in particular by the angle of its view and the cloud cover above it, especially the height of clouds within the adopted cloud levels. To analyse the last-mentioned factor, meteorological data from the two-year period 2019–2020 recorded by the Institute of Meteorology and Water Management at the Toruń-Wrzosy Monitoring Station were processed in detail [10,12]. The analyses showed that the most frequent cloud height at night was between 50 and 250 m. In those two years, more than 28% of the nights were completely overcast, and almost half of all nights were cloudy to a greater or lesser degree. Throughout the period, 25% of the nights were cloudless. The average height of clouds for this period was 1,013 m above ground level. With the knowledge of the specifically selected solid angle at which the data are collected by the light sensor used in the recording device [1] and the use of statistical characteristics of cloud cover, it was possible to simulate the spatial visibility range of the devices built [12], and to determine their density to cover the entire analysis area.

A theoretical model of the distribution of monitoring sites for Toruń was developed for cloud heights of 200, 1,000 and 2,500 m above ground level. The values adopted are related to the most common height of the cloud base, the average height of clouds and the lower cloud altitude range for the middle layer, i.e. the typical genera of clouds: Altostratus and Altocumulus [12].

The simulation carried out showed that for full, spatially overlapping monitoring of the night sky in Toruń and the three selected cloud heights, it would be necessary to prepare and deploy 5,700, 230 and 44 monitoring sites, respectively. In further considerations, however, it was concluded that the collection of data by 5,700 or 230 monitoring sites on nights with scatted clouds or no cloud cover would be uneconomical and cognitively unjustified and, above all, would generate a very large amount of repetitive data that would not provide additional information on the spatial distribution of the phenomenon.

The simulations carried out showed that the most optimal solution for Toruń, both for cloudless nights and nights with overcast skies (frequency of both situations in a calendar year is similar), is to adopt the number of monitoring sites at a level of 40, assuming their even distribution. Such a theoretical model of the spatial distribution of the sites is presented in Figure 7.

The adoption of the above assumption allowed an attempt to determine the actual linear distance at which the monitoring sites should be located in the field in relation to one another in order to collect data on artificial light pollution of the night sky in the most optimal and effective manner.

In operational practice, however, it turns out that other factors and considerations must be taken into account when planning further monitoring sites, the most important of which are the LoRaWAN signal visibility discussed in subsection 4a and an adequate technical infrastructure that allows permanent and secure mounting of the recording device and subsequent access for maintenance and operation purposes. While it appears that we can try to increase the coverage of the area with the LoRa network by installing additional access gateways (Fig. 9), the choice of sensor mounting locations is already severely limited.

Fig. 7. Theoretical model of spatial distribution of monitoring sites in Toruń

5.2. Urban monitoring network – status of progress

The implementation of the network for monitoring the pollution of the night sky by artificial light in Toruń, based on the previously developed theoretical model and the adopted concept, proved to be a very complex task, difficult to execute. This necessitated additional operations to modify and optimise the project design, as well as the signing of the interinstitutional agreements described in Chapter 2.

To date, 18 monitoring sites have been successfully established and effectively integrated into the urban monitoring system under development, and their number is systematically increasing. Their selected parameters and location in Toruń are presented in Table 3. From the list provided, it follows that six monitoring sites were operational already in 2021, and the remaining 12 sites in 2022. This means that an almost 2-year continuous observation series is already available for some areas, which makes it possible to perform selected analyses, generate statistics and infer the local level, strength and spatial extent of the phenomenon in question. This is probably the first such detailed measurement data, covering such a long and consistent time series, available from the area of Poland.

The spatial distribution of the monitoring sites already operating in the urban monitoring system in Toruń, together with the location of further recorders planned for launch in the near future, is shown in Figure 8, while the existing and planned future locations of communication gates of the LoRa network (Table 4) are shown in Figure 9.

Table 3. Characteristics of measurement points within the monitoring network in Toruń

No	Mark	Location	Start date	Height	Coordinates of the 1992 system	
					X	Y
1	3	Lwowska Street	16.02.2021	3rd floor	471081	572962
2	7	Szosa lubicka	30.03.2022	3rd floor	479709	573793
3	8	Szosa Chełmińska	30.03.2022	3rd floor	472596	574073
4	9	Witosa Street	12.07.2022	3rd floor	479172	573518
5	10	Niesiołowskiego Street	13.02.2022	1st floor	478272	573893
6	11	Kalinowa Street	02.04.2022	ground floor	476479	573234
7	12	Rydygiera Street	30.03.2022	9th floor	476787	573790
8	16	Rudak allotment	30.05.2022	ground floor	477252	571388
9	17	Szubińska Street	05.06.2022	1st floor	470709	567977
10	18	Fałata Street	12.11.2021	2nd floor	470857	572180
11	22	Drzymały Street	30.03.2022	4th floor	472981	569815
12	23	Matejki Street	11.08.2021	10th floor	472569	572304
13	28	Matejki Street	02.04.2022	4th floor	472446	571787
14	30	Łączna Street	29.03.2022	3rd floor	474117	569002
15	31	Makuszyńskiego Street	15.01.2022	ground floor	470913	573672
16	32	Dębowa Street	03.09.2021	ground floor	469599	569438
17	33	Końcowa Street	28.07.2021	4th floor	472853	573245
18	34	Kwiatowa Street	12.10.2021	1st floor	472196	575407

To date, four access gateways to the LoRaWAN network have been installed in the city of Toruń. They are fully operational and can also serve other users using devices and technologies of the Internet of Things (IoT). Two of the gateways are typically external and two are internal with modulated antennas to amplify the signal. In addition, two more external access gateways have been purchased and will be added to the system in the near future to increase the LoRaWAN signal in the central and left-bank parts of the city (Fig. 9). This will ensure full and stable signal coverage of the access network and the possibility of installing more monitoring sites in potentially more locations as part of the network densification, according to the scheme shown in Figure 8.

Table 4. Characteristics of activated access gates as part of the city's night sky pollution monitoring network with artificial light

No	Location	Type of use	Start date	Height	Coordinates of the 1992 system	
					X	Y
1	Matejki Street	outdoor	July 2021	10th floor	472569	572295
2	Jamontta Street	outdoor	February 2022	5th floor	478088	573608
3	Włocławska Street	indoor	April 2020	4th floor	477590	569579
4	Lwowska Street	indoor	February 2021	3rd floor	471064	573050

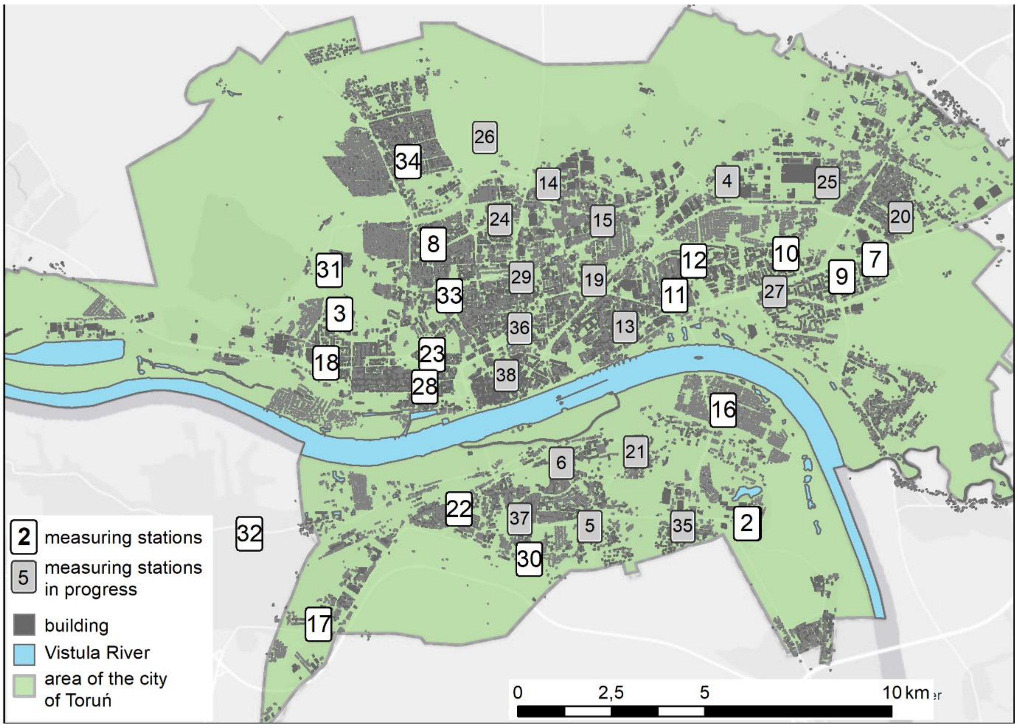

Fig. 8. Location of current and planned monitoring sites in Toruń within the light pollution monitoring network

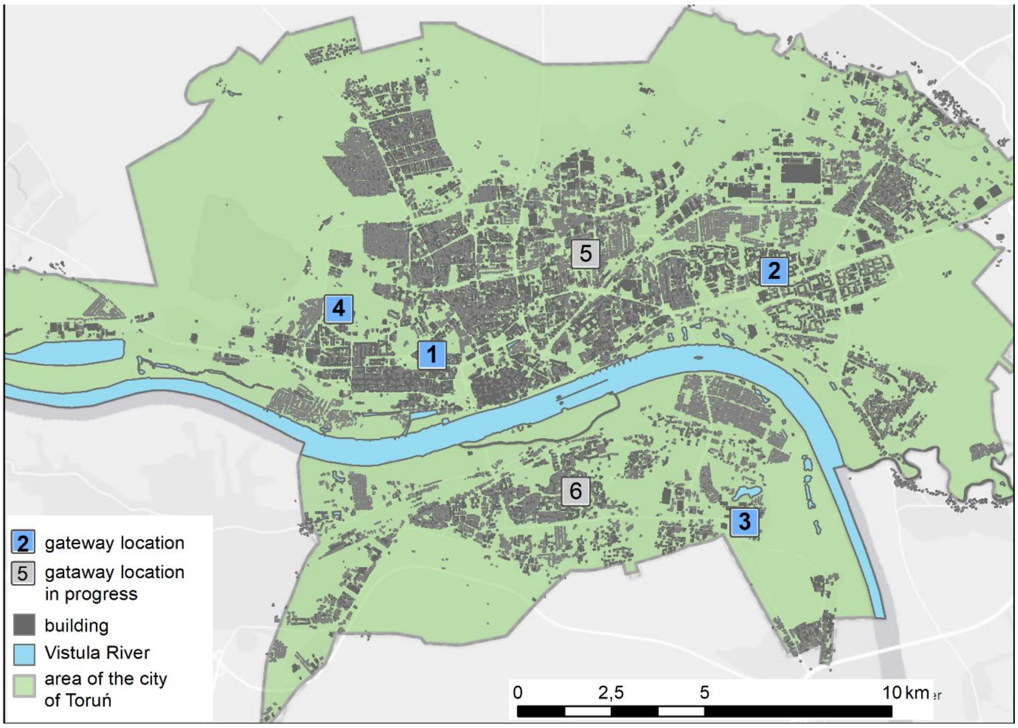

Fig. 9. Location of current and further planned access gateways in Toruń within the light pollution monitoring network

5.3. Urban monitoring network – near future of the project

The network for monitoring artificial light pollution of the night sky, established and operating in the city of Toruń, is now fully operational and will be expanded with further measuring devices in accordance with the presented schedule and spatial scope. In parallel, during the course of this project, the constructed measuring device is being technically and functionally upgraded to a more compact version that can be expanded with additional spectral ranges for recording the brightness of the night sky, as well as with other environmental sensors. All these operations are aimed at designing a new and improved measuring device that will be able to comprehensively monitor the condition of the natural environment through the expansion of the sensor array. Such a device will, however, have to go through all the steps and operations described in this paper.

Notwithstanding the foregoing, work on the application for the visualisation of spatial data collected as part of the city's expanding night sky pollution monitoring network and their effective archiving is being finalised. In this way, every concerned resident of the city will be able to see the current and archived spatial and statistical distribution of the light smog phenomenon in the adopted time levels, both point-wise and area-wise, based on the interpolation of all values.

6. DISCUSSION AND CONCLUSION

In a technologically evolving world and with conscious human actions aimed at protecting the environment, any monitoring of its condition and parameters is important and provides reliable data as well as convincing arguments for its maintenance and further expansion. Sources of environmental pollution of anthropogenic origin, adversely affecting our health and functioning, are increasing in quantity and intensity. One of these is the pollution of the night sky by artificial light, a phenomenon not previously considered. This phenomenon, due to its intensification and the lack of previous extensive research into its variability, nature and impact on living organisms, now requires constant monitoring and targeted interdisciplinary research efforts.

The pollution of the night sky by artificial light, like other observed phenomena caused by human activity, has a significant impact on the health, quality of life, functioning and well-being of the inhabitants of urban areas. The design, construction and subsequent maintenance of a distributed monitoring network over a larger area, providing multidimensional information on selected environmental parameters, is a very important measure to better understand the phenomenon and its variability and to determine its impact on selected elements of flora and fauna, as well as man himself.

The automatic monitoring network system described in this study, which collects distributed data on the surface brightness of the night sky in Toruń, is now fully operational and monitoring data are systematically acquired and archived. The system will be expanded in subsequent periods with new functionalities, capabilities and monitoring (measurement) sites. Based on experience to date, it can be concluded that the implemented project is a complex operation, involving background studies of miscellaneous topics, in the course of which the necessary parameters required for reliable monitoring of the night sky surface brightness using the LoRaWAN network were determined. To properly understand the phenomenon of artificial light pollution, it is also necessary to perform multifaceted processing and analysis of all collected data. The results obtained and the conclusions drawn from them can be helpful to citizens, research groups and especially local authorities at all levels with regard to rational electricity management options, including the implementation of a well-thought-out process of modifying outdoor street lighting, which will certainly contribute to significant savings in the current situation of rising electricity prices.

The developed monitoring system, together with the wireless communication infrastructure and the application for visualisation and sharing of measurement data, enables the measurement and monitoring of the outdoor lighting intensity in the urban environment over a long period of time. Using the LoRaWAN wireless data exchange technology, the devices implement the concept of the Internet of Things (IoT) and fit in with the idea of Smart Cities in the Smart Environment.

Further pilot monitoring (measurement) sites, based on the designed recording devices, can be placed in any location where LoRaWAN network infrastructure is available. In the Kujawy-Pomerania Province, such possibilities have emerged in Bydgoszcz and Grudziądz, and these two cities are likely to be included in the programme for monitoring the phenomenon of light pollution (i.e. excess artificial light in the night sky), which will increase the spatial scale of observations, and the added value will certainly be the educational aspect among the inhabitants of these cities interested in the results of the monitoring.

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