Uniwersytet Mikołaja Kopernika w Toruniu
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UNIWERSYTET
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Analiza uwarunkowań czasowej i przestrzennej zmienności zanieczyszczenia światłem w obszarach zurbanizowanych na przykładzie Torunia

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za poświęcony czas, cierpliwość i wszelkie sugestie.

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Spis treści

Lista publikacji wchodzących w skład rozprawy doktorskiej

Lp.	Dane bibliograficzne publikacji	MEiN
[P1]	**Karpińska Dominika**, Kunz Mieczysław, **2021**. Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area: a case study of the Bielany campus at the Nicolaus Copernicus University in Toruń. *Bulletin of Geography. Socio-Economic Series* 54: 137–149. Cite Score – 2,7; SJR – 0,382; SNIP – 0,762; Q1.	100 pkt.
[P2]	Erwinski Krystian, **Karpińska Dominika**, Kunz Mieczysław, Paprocki Marcin, Czokow Jarosław, **2023**. An Autonomous City-Wide Light Pollution Measurement Network System Using LoRa Wireless Communication. *Sensors* 23(11): 5084. **IF – 3,847**; IF_{5lat} – 4,050; Cite Score – 6,4; SJR – 0,76; SNIP – 1.555; Q1.	100 pkt.
[P3]	**Karpińska Dominika**, Kunz Mieczysław, **2022**. Device for automatic measurement of light pollution of the night sky. *Scientific Reports* 12(1): 1–12. **IF – 4,996**; IF_{5lat} – 4,409; Cite Score – 6,9; SJR – 1,005; SNIP – 1,389; Q1.	140 pkt.
[P4]	**Karpińska Dominika**, Kunz Mieczysław, **2023**. Vertical variability of night sky brightness in urbanised areas. *Quaestiones Geographicae* 42(1): 5–14. Cite Score – 2,2; SJR – 0,268; SNIP – 0,570.	100 pkt.
[P5]	**Karpińska Dominika**, Kunz Mieczysław, **2023**. Relationship between the surface brightness of the night sky and meteorological conditions. *Journal of Quantitative Spectroscopy & Radiative Transfer* 306: 1–8. **IF – 2,342**; IF_{5lat} – 3,173; Cite Score – 4,5; SJR – 0,605; SNIP – 0,976.	100 pkt.
[P6]	**Karpińska Dominika**, Kunz Mieczysław, **2023**. Measuring light pollution in the night sky – from technology demonstrator to monitoring system. *Civil and Environmental Engineering Reports* 33(1): 0053–0070.	70 pkt.
[P7]	**Karpińska Dominika**, Kunz Mieczysław, **2023**. Spatial and temporal analysis of artificial light pollution of the city night sky. A case study from Toruń. *Miscellanea Geographica. Regional Studies on Development* 27(3): 1–11. Cite Score – 1,8; SJR – 0,198; SNIP – 0,403.	100 pkt.
	IF = 11,186	**710 pkt.**

Pozostałe publikacje naukowe z punktacją MEiN

1. **Karpińska Dominika**, Kunz Mieczysław, **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 (MEiN – 40 pkt.).
2. **Karpińska Dominika**, Kunz Mieczysław, **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 (MEiN – 70 pkt.).
3. **Dominika Karpińska**, Mieczysław Kunz, **2020**. Zanieczyszczenie nocnego nieba światłem na przykładzie Torunia. [w:] Młynarczyk A. (red.), *Środowisko przyrodnicze jako obszar badań*. Bogucki Wydawnictwo Naukowe, Poznań: 93–112 (MEiN – 20 pkt.).
4. **Dominika Karpińska**, Mieczysław Kunz, **2020**. Wpływ pokrycia terenu na zanieczyszczenie światłem nocnego nieba. [w:] *Badania z zakresu nauk przyrodniczych – nowe trendy.* Lublin: 206–223 (MEiN – 20 pkt.).
5. **Dominika Karpińska**, Mieczysław Kunz, **2020**. Ochrona nocnego nieba – wyzwanie dla Rezerwatu Biosfery Bory Tucholskie. [w:] Kunz M. (red.), *Rola i funkcjonowanie parków krajobrazowych w rezerwatach biosfery.* Wydawnictwo Naukowe UMK, Toruń: 329–346 (MEiN – 20 pkt.).
6. **Dominika Karpińska**, Mieczysław Kunz, **2021**. Rekonstrukcja zasięgu widoczności sieci LoRaWAN na terenie kampusu UMK w Toruniu. [w:] Młynarczyk A. (red.), *Środowisko przyrodnicze jako obszar badań II*. Bogucki Wydawnictwo Naukowe, Poznań: 47–60 (MEiN – 20 pkt.).
7. **Dominika Karpińska**, Mieczysław Kunz, **2021**. Comparison of two measurement methods – photometric and photographic – in studies of the night sky brightness. [in:] Ściężor T. (ed.), *Ecological and astronomical aspects of light pollution*. Wydawnictwo Politechniki Krakowskiej, Kraków: 57–68 (MEiN – 20 pkt.).
8. **Karpińska Dominika**, Kunz Mieczysław, **2022**. Optymalizacja rozmieszczenia sieci pomiarowej do monitoringu zanieczyszczenia światłem nocnego nieba na przykładzie Torunia. [w:] Młynarczyk A. (red.), *Środowisko przyrodnicze jako obszar badań* IV. Bogucki Wydawnictwo Naukowe, Poznań: 9–24 (MEiN – 20 pkt.).
9. Kołomański Sylwester, Kunz Mieczysław, Ścieżor Tomasz, **Karpińska Dominika**, **2022**. Pomiary i monitoring emisji światła pochodzącego ze źródeł elektrycznych. [w:] Szlachetko K. (red.), *Memorandum w sprawie ustanowienia prawnych podstaw zrównoważonej polityki oświetlenia zewnętrznego*. Instytut Metropolitalny, Gdańsk: 35–43 (ISBN 978-83-62198-30-6).
10. Kunz Mieczysław, **Karpińska Dominika**, (in press). Issues related to cartographic visualisation of light pollution measurements. *Cartography and Geographic Information Science*. Taylor & Francis Group.

Wstęp

Intensywnie rozwijająca się cywilizacja znacząco wpłynęła na poprawę komfortu życia przeciętnego mieszkańca naszej planety. Dzisiejsza wysokorozwinięta technologia ułatwia życie człowiekowi w różnych jego działalnościach, aktywnościach i aspektach funkcjonowania. Konsekwencjami tego postępu jest jednak obecność coraz większej liczby źródeł różnych zanieczyszczeń i związków uwalnianych do środowiska, co wpływa znacząco zarówno na ich ilość, jak i różnorodność. Jako ludzie wykazujemy zwiększające się zapotrzebowanie na podstawowe udogodnienia realizowane przy wykorzystaniu ograniczonych zasobów, np. paliw kopalnych, których przetworzenie czy wykorzystanie, negatywnie wpływa na ostatnio szeroko nagłaśnianą w opinii publicznej, obecność w atmosferze pyłów zawieszonych o różnej wielkości, jak również innych równie niebezpiecznych pobocznych zanieczyszczeń środowiska pochodzenia antropogenicznego (Święczkowski i in. 2023; Wang i in. 2004). Rozwój technologiczny, coraz większa ilość urządzeń oraz zwiększający się udział nowoczesnej technologii w życiu codziennym wykazuje rosnące zapotrzebowanie na energię, co przekłada się także na wzrost kosztów życia codziennego, nie tylko statystycznego obywatela, ale także samorządów, firm czy instytucji.

Jednym z efektów rozwoju obszarów zurbanizowanych, oraz realizacji, często teoretycznej, potrzeby poprawy komfortu człowieka jest występowanie w pobliżu aglomeracji miejskich zanieczyszczonego sztucznym światłem nocnego nieba. Powstaje ono na skutek emisji w dolną część troposfery nadmiernej ilości sztucznego światła, rozpraszającego się w atmosferze i tworzącego łunę świetlną (Falchi i Cinzano 2016; Falchi i in. 2023; Jechow i in. 2017; Kołomański 2015; Linares i in. 2020). Przyczyną procesu takiego nieefektywnego wyświetlania w górę światła jest korzystanie z nieodpowiedniej infrastruktury ulicznej, która została zazwyczaj źle zaprojektowana, instalowanie nadmiernych podświetleń architektonicznych czy reklamowych oraz intensywnie świecących banerów i ekranów ledowych. Tak użytkowana zewnętrzna infrastruktura świetlna bezpośrednio wpływa także na nadmierny pobór energii, co jest istotnym elementem powodującym zwiększenie się kosztów jej eksploatacji, np. w budżecie miasta czy innego samorządu lokalnego (Gallaway i in. 2010).

Zjawisko zanieczyszczenia światłem negatywnie oddziałuje na cały ekosystem. Powoduje nie tylko olśnienie przypadkowych osób, oświetlanie miejsc, które nie powinny być tak podświetlone, ale i wpływa na zdrowie i życie człowieka oraz rozwój roślin i zwierząt. Do tej pory zostało opublikowanych wiele prac przyczynkowych i badawczych dotyczących negatywnych konsekwencji zanieczyszczenia światłem wśród organizmów żywych. Nadmierna ilość sztucznego światła w nocy ma wpływ, np. na życie i zachowanie żółwi, nietoperzy, małych ssaków, ptaków, ryb, a nawet owadów (Adams i in. 2019; Connors i in. 2010; Gaston i in. 2013; Lacoeuilhe i in. 2014; Lennox i in. 2016; Rodrigo-Comino i in. 2021). Przyczynia się także do nieodpowiedniego rozwoju roślin, powodując m.in. ich przedwczesne kwitnięcie, czy wydłużenie okresu wegetacji (Bennie i in. 2016; Navara i Nelson 2007). Istotnym faktem jest to, iż istnieją dowody naukowe na negatywny wpływ zjawiska zanieczyszczenia światłem przede wszystkim na zdrowie, funkcjonowanie i życie człowieka. Liczne grupy badawcze uznają, że u ludzi przebywających na terenach z nadmierną ilością sztucznego światła zachwiany zostaje rytm dobowy, zaobserwowano problemy z zasypianiem, osiąganiem odpowiedniego poziomu melatoniny oraz innych hormonów czy utrzymaniem stałej masy ciała. Zwiększyło się także prawdopodobieństwo wystąpienia depresji, a nawet ryzyko zachorowania na choroby nowotworowe (Falchi i in. 2011; Fonken i in. 2010; Fonken i Nelson 2013; Garcia-Saenz i in. 2018; Heim i Portnov 2013; Skwarło-Sońta 2014; Stevens 2009; Zubidat i in. 2017).

Badania dotyczące poznania zasięgu i wielkości degradacji środowiska przyrodniczego pod względem nadmiernej emisji światła pochodzenia antropogenicznego prowadzone były już w XX wieku. Jednak w tym czasie problem ten nie był rozpowszechniony w społeczeństwie, a wiedza o potencjalnych konsekwencjach tego procesu była znikoma. Obecnie, wydaje się, iż świadomość obywateli na temat zanieczyszczenia światłem zwiększa się, powstaje coraz więcej grup badawczych prowadzących punktowe obserwacje, jak i realizujących zaplanowany monitoring tego zjawiska, oraz przeprowadzających ukierunkowane badania dotyczące jego szkodliwości, a także publikujących uzyskane wyniki nie tylko w prasie specjalistycznej.

W realizowanych badaniach wykorzystywane były dotychczas różne metody pomiarowe, stosowane zarówno przez specjalistów, jak i amatorów. Należą do nich m.in. bezpośredni pomiar fotometrem czy radiometrem (Hänel i in. 2017; Karpińska i Kunz 2021c; Kolláth 2010; Mander i in. 2020; Ściężor i in. 2010), ocena jasności nocnego nieba przy użyciu metod obserwacyjnych jak, np. liczenie gwiazd czy określanie jasności komet (Kołomański 2015; Ściężor 2013), analiza zdjęć wykonanych za pomocą aparatu cyfrowego z szerokokątnym obiektywem (Hänel i in. 2017; Jechow i in. 2017; Jechow i in. 2019), jak i zdjęć lotniczych czy satelitarnych (Cinzano i in. 2000; Elvidge i in. 2013; Kotarba 2019; Ściężor 2021; Zhang i in. 2019).

Najbardziej popularną, oraz względnie najszybszą metodą pomiarową jest rejestracja powierzchniowej jasności nocnego nieba za pomocą fotometru SQM (ang. *Sky Quality Meter*) czy TESS (ang. *Telescope Encoder and Sky Sensor*) (Mander i in. 2023; Rodrigo-Comino i in. 2021). Jest to metoda stosunkowo prosta i szeroko wykorzystywana na całym świecie (Bara i in. 2019; Pun i in. 2014; Ściężor i in. 2010). Na rynku dostępnych jest kilka rodzajów fotometrów, np. ręcznych – zasilanych bateryjnie, stacjonarnych z rejestratorem danych zasilanych bateryjnie czy wykonujących odczyty w czasie rzeczywistym podłączanych do jednostki centralnej za pomocą różnych interfejsów komunikacyjnych (Ethernet, RS232 czy USB) (http://www.unihedron.com/index.php; https://tess.stars4all.eu). Umożliwiają one pomiar jasności nieba w praktycznie każdych warunkach, dając możliwość porównania zanieczyszczenia światłem podczas występowania odmiennych warunków meteorologicznych (Kocifaj i Bará 2020; Ribas i in. 2016; Ściężor 2020). Wyniki uzyskiwane są w jednostce mag/arcsec^2, która jest jednostką odwrotną oraz logarytmiczną. W centrach miast możemy spodziewać się odczytów na poziomie 14–17 mag/arcsec^2, natomiast poza miastem na terenach wolnych od źródeł zanieczyszczeń, nawet ponad 22 mag/arcsec^2. Kolejną ważną metodą, coraz częściej wykorzystywaną oraz dopracowywaną jest analiza zdjęć wykonanych aparatem z obiektywem typu *all-sky* (Hänel i in. 2017; Jechow i in. 2019; Kolláth 2010; Mander i in. 2020). Polega ona na wykonaniu cyfrowego zobrazowania nocnego nieboskłonu oraz późniejsze jego przetworzenie za pomocą specjalnego oprogramowania. Metoda ta wymaga specjalistycznej wiedzy, nie tylko podczas samych pomiarów, ale także w procesie przetworzenia i oceny zdjęć. Nieocenionym plusem tej metody jest uwiecznienie warunków pomiarowych na zdjęciu, co umożliwia przeprowadzenie kolejnych analiz. Obie powyżej opisane metody są metodami naziemnymi, a pomiary realizowane są wertykalnie w kierunku nieba. Zupełnie inną metodą pozyskiwania danych na temat zanieczyszczenia światłem jest analiza zdjęć wykonanych przez satelity meteorologiczne oraz astronautów znajdujących się na Międzynarodowej Stacji Kosmicznej (Kotarba 2015; Mander i in. 2023). W tym przypadku zobrazowana jest powierzchnia ziemi, wraz ze wszystkimi punktami świetlnymi. Satelity dostarczające dane umożliwiające dokonanie tego typu pomiarów to np. Suomi NPP zinstrumentem VIIRS, DMSP z instrumentem OLS oraz LuoJia (Elvidge i in. 2017; Falchi i Cinzano 2016; Zhang i in. 2020). Każdy z nich różni się rozdzielczością czasową oraz rozdzielczością przestrzenną i daje możliwości potencjalnego wykorzystania w różnych sytuacjach. Największą rozdzielczością przestrzenną, wynoszącą 130 metrów charakteryzuje się LuoJia, jednak zdjęcia z pokładów tych satelitów dla większości obszarów na świecie były wykonane sporadycznie, a nawet występują miejsca, które nigdy nie zostały zobrazowane. Dlatego też najpowszechniejszymi zobrazowaniami są te wykonane przez instrument VIIRS o rozdzielczości przestrzennej około 500 metrów, które publikowane są codziennie, umożliwiając bieżący i regularny dostęp do aktualnych danych. W celach dalszej analizy, wielkości zarejestrowane na zdjęciach satelitarnych konwertowane są do wartości radiancji ($W/m^2/sr/\mu m$), która jest podstawową wielkością radiometryczną umożliwiającą bezpośrednie przedstawienie ilości emitowanej energii z jednostki powierzchni.

Zanieczyszczenie sztucznym światłem nocnego nieba ma współcześnie charakter globalny. Pomimo wielu dostępnych metod pomiarowych, opublikowania przekrojowych czy szczegółowych studiów przypadku oraz innych prac naukowych wskazujących na wagę problemu, to nieustanowione zostały do tej pory przepisy prawne ograniczające nadmierną emisję sztucznego światła w nocy. Powierzchnia obszarów będących pod wpływem tego zjawiska ciągle wzrasta. Każdego roku niebo staje się o około 10% jaśniejsze, a już prawie połowa mieszkańców globu, nie ma możliwości obserwacji Drogi Mlecznej (Kyba i Coesfeld 2021). W nielicznych krajach na świecie rozpoczęto dyskusje nad wprowadzaniem formalnych regulacji dotyczących oceny poziomu światła zewnętrznego (Ministry of the Environment of the Czech Republic 2022; Szlachetko 2022). Kilka państw, takich jak Niemcy, Francja czy Chorwacja wprowadziło przepisy mające na celu ochronę środowiska przyrodniczego przez skutkami zanieczyszczenia światłem. Stanowią one jednak mniejszość na tle reszty państw Europy czy świata. W Polsce grupa naukowców w 2022 roku przygotowała i opublikowała *Memorandum w sprawie ustanowienia prawnych podstaw zrównoważonej polityki oświetlenia zewnętrznego*, mające na celu zwrócenie uwagi zarówno władz samorządowych i centralnych, jak i społeczności na problem zanieczyszczenia światłem (Szlachetko 2022). Jest to pierwszy z istotnych kroków, jakie trzeba podjąć do formalnego ustanowienia regulacji, ratującej nocne niebo i człowieka przed postępującą degradacją w tym zakresie.

Prawo człowieka do ciemnego nieba jest niepodważalne i jest to jedno z najbardziej naturalnych elementów otaczającego nas świata. Dlatego pomimo braku obowiązującego prawa, powstały liczne organizacje pozarządowe, jednostki naukowe czy podmioty społeczne, które postawiły sobie za cel edukację społeczeństwa w zakresie szkodliwości zanieczyszczenia światłem oraz przeciwdziałaniu jego konsekwencjom (IDA, ang. *International Dark-Sky*

Association; Karpińska i Kunz 2020a). Inną inicjatywą tych organizacji jest także formalna ochrona ciemnego nieba, zakładająca powstawanie różnego rodzaju certyfikowanych miejsc, w których możemy jeszcze obserwować nocne niebo niezanieczyszczone sztucznym światłem. Takie miejsca istnieją także w Polsce, a za ich powołanie odpowiada program „Ciemne Niebo – Polska”, powołany przez Stowarzyszenie Polaris-OPP (POLARIS-OPP 2023).

W celu zapobiegania zwiększania się emisji sztucznego światła, a nawet jego redukcji konieczne jest zbadanie stanu jakości nocnego nieba. Ważne jest przeprowadzanie badań nie tylko w pojedynczych punktach, ale także zakładanie sieci monitoringu zjawiska na większym obszarze. W Toruniu prace dotyczące zanieczyszczenia światłem prowadzone są już od 2017 roku. W niniejszej rozprawie doktorskiej przedstawiono wyniki badań oraz analiz dotyczących zanieczyszczenia sztucznym światłem nocnego nieba na obszarze zurbanizowanym. Przedstawiono także proces projektowania, budowy i eksploatacji systemu monitoringu dotyczącego tego zjawiska na obszarze miasta.

Cel badań

Głównym celem przeprowadzonych badań była analiza zarówno czasowej, jak i przestrzennej zmienności zanieczyszczenia sztucznym światłem nocnego nieba na terenie aglomeracji miejskiej. Celem dodatkowym wynikającym z przyjętych założeń była konstrukcja poprawnie działającego systemu monitoringu zanieczyszczenia światłem na terenie Torunia, uwzględniająca charakterystykę zjawiska oraz możliwości techniczne wybranej technologii.

Biorąc pod uwagę zasięg, znaczenie i potencjalny wpływ na człowieka zanieczyszczenia sztucznym światłem nocnego nieba, uznano, iż niezbędne są pogłębione i ukierunkowane analizy zjawiska oraz możliwości rozwojowe dotyczące wykorzystywanej metody pomiarowej. Uwzględniając doświadczenie zdobyte podczas realizacji wcześniejszych projektów (Karpińska i Kunz 2019, 2020a, 2020b, 2020c) postanowiono, iż najlepszym rozwiązaniem będzie założenie sieci pomiarowej składającej się z automatycznie działających autorskich urządzeń mierzących powierzchniową jasność nocnego nieba. Ważnym elementem działań był wybór odpowiedniej technologii, dzięki której będzie możliwa realizacja wszystkich przewidywanych założeń projektowych. Konieczne było poznanie aktualnych trendów i osiągnięć technicznych, zarówno w zakresie elektroniki dostępnej na rynku, wyboru optymalnego rozwiązania, określenia jego właściwości użytkowych, jak i możliwości oraz ograniczeń stosowania. Istotnym zadaniem było również zbadanie wybranych rozwiązań technologicznych w aspekcie rejestracji zmienności zachodzących zjawisk w dłuższym horyzoncie czasowym.

Przed rozpoczęciem powyższych działań zapoznano się z dostępnymi metodami pomiarowymi oraz ich ograniczeniami. Zauważono, iż dotychczas wykorzystywane fabryczne fotometry do pomiaru powierzchniowej jasności nocnego nieba nie spełniają założeń postawionych na wstępie badań. W realizowanej pracy doktorskiej zasadniczym elementem było przeprowadzenie pomiarów na obszarze miasta, w miejscach o różnej dostępności do infrastruktury energetycznej (zasilającej), co warunkowało wykorzystanie jedynie urządzeń posiadających autonomiczne zasilanie. Wymagane było także zbieranie danych w czasie rzeczywistym, ze stałym łączem z jednostką centralną w celu ich zarchiwizowania. Analiza założeń i dostępnych rozwiązań doprowadziła do wniosku, iż konieczne jest wykonanie własnego urządzenia, autorskiej konstrukcji, które pozwoli na przeprowadzenie rejestracji z wymaganą jakością i częstotliwością akwizycji wartości pomiarowych, działającego w pełni automatycznie, przesyłającego dane w czasie rzeczywistym do serwera i jednocześnie zasilanego bateryjnie o rozszerzonym okresie operacyjnego działania.

Mając na uwadze cel główny pracy oraz cel dodatkowy postawiono następujące tezy:

- zanieczyszczenie sztucznym światłem nocnego nieba można skutecznie zmierzyć i istnieją wielkości fizyczne bezpośrednio przedstawiające jego wartość,
- możliwe jest opracowanie urządzenia własnej konstrukcji realizującego pomiar powierzchniowej jasności nocnego nieba, będący alternatywą do komercyjnych fotometrów SQM, który posiada jednocześnie dodatkowe cechy funkcjonalne,
- autorskie urządzenia pomiarowe mogą funkcjonować na terenie zurbanizowanym w ramach nisko-kosztowej sieci monitoringu, skutecznie realizującej akwizycję danych na większym terenie,
- optymalizacja lokalizacji stanowisk pomiarowych działających w ramach sieci miejskiego monitoringu prowadzi do uzyskania pogłębienia wiedzy na temat emisji sztucznego światła w nocy,
- zjawisko zanieczyszczenie sztucznym światłem nocnego nieba wykazuje zmienność w czasie oraz w przestrzeni, zarówno w kierunku horyzontalnym, jak i wertykalnym.

Opisane powyżej cele szczegółowe były elementami zrealizowanych działań, których poszczególne etapy wraz z otrzymanymi wynikami badań opublikowano w latach 2021–2023 w postaci siedmiu artykułów w recenzowanych czasopismach naukowych.

Omówienie wyników wchodzących w skład rozprawy doktorskiej

W rozprawie doktorskiej przygotowanej jako zbiór siedmiu publikacji, zgromadzone zostały najważniejsze elementy opisujące wszystkie etapy realizacji badań naukowych i rozwojowych służących zaprojektowaniu i realizacji sieci rejestrującej zanieczyszczenie sztucznym światłem nocnego nieba na terenie zurbanizowanym.

Zanieczyszczenie światłem staje się coraz bardziej wnikliwie analizowanym problemem badawczym i wielu naukowców z całego świata prowadzi działania służące lepszemu poznaniu jego przyczyn, uwarunkowań, zmienności i skutków (Falchi i in. 2021; Hänel i in. 2017; Jechow i in. 2019; Mander i in. 2023; Rodrigo-Comino i in. 2021). Analizując dostępną literaturę przedmiotu dotyczącą pomiarów zanieczyszczenia światłem oraz jego zmienności w czasie i przestrzeni uznano, iż dla wnikliwej analizy zjawiska konieczne jest zaprojektowanie i wdrożenie w wybranych obszarach automatycznej sieci monitoringu tego zjawiska, oraz późniejsza wieloaspektowa analiza zebranych danych. Taki monitoring posłużyć może nie tylko zdobyciu wiedzy, ale także dalszemu rozwojowi nauk. Może on stać się też częścią planu środowiskowego dla miast każdej wielkości czy też elementem strategii rozwoju dla samorządów terytorialnych lub ich jednostek, planujących wyznaczenie obszarów mogących zostać w przyszłości objęte ochroną ciemnego nieba i możliwościami związanymi z oferowaniem różnych form astroturystyki.

Jako obszar realizacji szczegółowych badań wybrany został Toruń, który jest średniej wielkości miastem o powierzchni około 116 km^2. Zamieszkuje go dzisiaj niespełna 185 tys. mieszkańców. Administracyjnie miasto podzielone zostało na 24 osiedla mieszkaniowe. W strukturze wybranej jednostki osadniczej wydzielić można charakterystyczne obszary w zasadzie o wszystkich typach zabudowy. Są wśród nich tereny przemysłowe, usługowe, zielone oraz wyróżniające się zabudową wielorodzinną, jednorodzinną i śródmiejską (Karpińska i Kunz 2020b). Każdy z tych obszarów posiada swoje charakterystyczne zewnętrzne warunki oświetleniowe. W Toruniu problem nadmiernej emisji światła w nocy (rycina 1) jest mocno zauważalny, zwłaszcza w strefie śródmiejskiej, jak i na osiedlach mieszkaniowych o zwartej zabudowie rozwijających się od końca lat 70. XX wieku.

Rycina 1. Widok na łunę świetlną występującą nad strefą śródmiejską Torunia (fot. Dominika Karpińska).

Realizację ukierunkowanych pomiarów zanieczyszczenia sztucznym światłem nocnego nieba w Toruniu rozpoczęto od ustalenia głównych założeń projektu. Sieć urządzeń miała być bezprzewodową siecią dalekiego zasięgu, nisko-kosztową, mogącą przesyłać dane z dużej liczby urządzeń pracujących w różnych lokalizacjach. Wybrana technologia przesyłania danych powinna pozwalać na wykorzystanie trybu obniżonego poboru energii oraz umożliwiać urządzeniu przechodzenie samoczynnie w stan uśpienia w celu wydłużenia pracy na jednym pakiecie baterii, oraz na wysyłanie krótkich wiadomości zawierających niezbędne zarejestrowane dane pomiarowe. Zasadniczym elementem urządzenia miał być programowalny czujnik światła o wysokiej rozdzielczości, z czułością spektralną zbliżoną do czułości ludzkiego oka.

Na rynku komercyjnym powszechnie dostępne są różne technologie przesyłania danych, wśród nich znajdziemy te najbardziej rozpowszechnione, jak Wi-Fi, Bluetooth czy GSM (standardy od 2G, przez 3G, 4G aż do 5G) (Bogacz i Krupanek 2013; Chaładyniak 2011). Wymienione rozwiązania posiadają wiele zalet, umożliwiają jednoczesne przesyłanie dużej ilości danych. Jednak technologia Wi-Fi czy Bluetooth posiada tylko kilkudziesięciometrowy zasięg, co jest zasadniczą wadą, gdy chcemy objąć wspomnianą siecią znaczny obszar miejski. Konieczne jest wówczas zaopatrzenie w dużą liczbę punktów dostępowych, zwiększających koszt tworzenia i utrzymania sieci. Większym zasięgiem przesyłania danych charakteryzuje się sieć GSM, jednak konsekwencją tego jest zwiększony pobór energii, co powoduje ograniczenia dla urządzeń zasilanych bateryjnie, mających docelowo działać przez wiele miesięcy. Dla rozległych i energooszczędnych zastosowań, logicznym wyborem będzie wykorzystanie sieci LPWAN (ang. *Low Power Wide Area Network*). Wśród tego rodzaju rozwiązania wyróżnia się trzy najpopularniejsze standardy: Sigfox, LoRaWAN oraz NB-IoT (Mikhaylov i in. 2018). Po analizie potencjalnych możliwości najbardziej optymalną technologią spośród rozwiązań dostępnych na rynku okazała się technologia LoRa (ang. *Long Range*), będąca częścią standardu LoRaWAN.

Standard LoRaWAN jest energooszczędnym radiowym protokołem komunikacyjnym MAC (ang. *Medium Access Control*) dalekiego zasięgu. Jest on szeroko wykorzystywany w obszarze IoT (ang. *Internet of Things*) do komunikacji różnorodnych urządzeń np. wspomagając koncepcję *Smart City* w obszarze *Smart Environment*, będąc przy tym elementem czwartej rewolucji przemysłowej (Przemysł 4.0, ang. *Industry 4.0*) (Ragam i Nimaje 2019; Tomaszewski 2020; Whaiduzzaman i in. 2022). Znajduje zastosowanie, zarówno w nowoczesnych rozwiązaniach inżynierskich, drogowych i logistycznych, jak i zarządzaniu terenami przemysłowymi, osiedlami mieszkaniowymi czy całymi miastami. Technologią komunikacji bezprzewodowej zaprogramowaną dla standardu LoRaWAN jest LoRa (Lorabit 2019a, 2019b; Semtech Corporation 2015; Turčinović i in. 2020). Jest ona dobrym uzupełnieniem niszy między wymienionymi wcześniej technologiami Wi-Fi, Bluetooth czy LTE, przy czym wyróżnia się przy tym przede wszystkim w zakresie energooszczędności, niższych kosztów użytkowania oraz zasięgiem przestrzennym przesyłania danych.

LoRaWAN została zaprojektowana, jako ogólnodostępny standard otwarty, który nie wymaga wnoszenia opłat licencyjnych przez użytkowników. W Europie działa on w paśmie 868 MHz, natomiast w Stanach Zjednoczonych – 915 MHz. Według dotychczasowych badań zasięg przestrzenny transmisji LoRa wynosi nawet kilkaset kilometrów, jednak jest to uwarunkowane licznymi czynnikami, w tym m.in. brakiem przysłon terenowych, długością zastosowanej anteny czy jakością generowanego sygnału.

W celu sprawdzenia w praktyce zasięgu sieci LoRaWAN oraz jej widoczności zostały przeprowadzone badania terenowe na obszarze kampusu Uniwersytetu Mikołaja Kopernika w Toruniu. Działania te zostały opisane w pierwszym załączonym artykule [P1] – ”*Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area: a case study of the Bielany campus at the Nicolaus Copernicus University in Toruń*”.

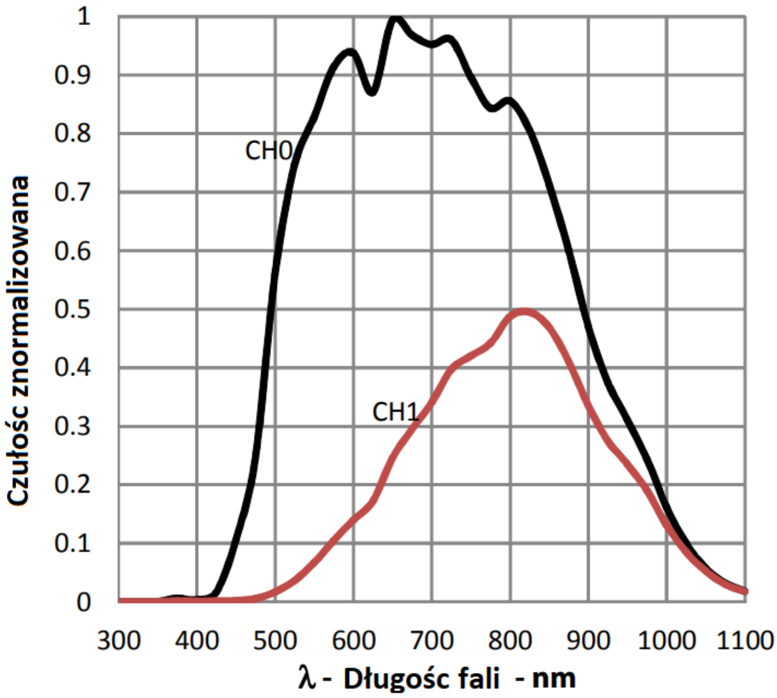
Podczas realizacji tych eksperymentalnych badań uznano, iż kampus uniwersytecki doskonale oddaje realia miejskie, ponieważ znajduje się na nim zarówno zabudowa niska, jak i wysoka, a teren otacza obszar zieleni. Istniała zatem możliwość dokładnego przeanalizowania propagacji i jakości sygnału w tych różnych warunkach zewnętrznych. Określenie widoczności sygnału rozpoczęto od umiejscowienia bramy dostępowej (ang. *gateway*) amerykańskiej firmy Multi-Tech Systems Inc. wraz z anteną zewnętrzną na Tarasie Obserwacyjnym położonym na dachu budynku Wydziału Nauk o Ziemi i Gospodarki Przestrzennej UMK, będącego częścią Obserwatorium Meteorologicznego. Badania jakości i zasięgu propagacji sygnału przeprowadzone zostały za pomocą testera mDOT Box firmy Multi Tech Systems Inc. Podczas pomiarów wykorzystano dwa rodzaje anten, dłuższą o długości 82 cm oraz krótszą 34 cm.

Najważniejszymi uzyskanym wynikiem w ramach tych działań było poznanie rozkładu przestrzennego jakości sygnału sieci na terenie kampusu i jego okolic. Krótsza antena posiadająca wzmocnienie 3 dB umożliwiła przesyłanie danych w najbliższym otoczeniu bramy komunikacyjnej. Mniejsze przeszkody terenowe nie stanowiły istotnej bariery, jednak budynki o większej kubaturze uniemożliwiły efektywne i stabilne połączenie z bramą komunikacyjną. Za występującą przeszkodą (np. wysokie budynki), sygnału sieci LoRaWAN nie odnotowano już w odległości 250 metrów od niej. Na otwartym terenie dobrą jakość sygnału uzyskiwano także w odległości ponad 1 km od bramy komunikacyjnej. Zdecydowanie lepsze wyniki odnotowane zostały przy wykorzystaniu anteny dłuższej, o wzmocnieniu 5,8 dB. Sygnał osiągalny był w odległości ponad 4 km od bramy dostępowej. W odróżnieniu od krótszej anteny przeszkody terenowe nie stanowiły utrudnienia, nawet rosnący w granicach kampusu dojrzały drzewostan nie tworzył bariery dla odbieranej wiadomości, a zakłócały ją jedynie wysokie budowle o znacznej kubaturze.

Badania jakości sygnału sieci LoRaWAN na terenie kampusu UMK określiły rzeczywisty wpływ zabudowy oraz innych przeszkód terenowych na możliwość prawidłowego połączenia urządzenia z bramą komunikacyjną (Karpińska i Kunz 2021a, 2021b). Pozwoliło to nie tylko na dobór odpowiednich elementów sprzętowych i ich odpowiednich ustawień, ale także pokazało rzeczywisty zasięg terenowy, w którym możliwe będzie umiejscowienie urządzeń pomiarowych względem bramy komunikacyjnej.

W przyjętych założeniach, tworzona sieć miejskiego monitoringu zanieczyszczenia światłem powinna składać się z powtarzalnych urządzeń o zasilaniu bateryjnym, bezprzewodowo przesyłających dane pomiarowe w czasie rzeczywistym, wyposażonych w czujnik światła, pozwalający na pomiar światła o niskim natężeniu, oraz posiadających dodatkowe czujniki umożliwiające kontrolę warunków pracy samego urządzenia. Uwzględniając przedstawioną koncepcję, skonstruowane na potrzeby realizacji projektu urządzenie złożone jest z płytki rozwojowej B-L072Z-LRWAN posiadającej moduł komunikacyjny LoRa, płytki z czujnikami środowiskowymi X-NUCLEO-IKS01A2 oraz czujnika światła TSL2591 (Adafruit 2019; STMicroelectronics 2020a, 2020b). Urządzenie zasilane jest trzema bateriami typu AAA (w postaci akumulatorków Ni-MH), co wpływa na jego kompaktowość, operacyjną długość pracy oraz niską wagę.

W procesie budowy własnej konstrukcji urządzenia, jedną z ważniejszych decyzji był nie tylko odpowiedni wybór technologii przesyłania danych, ale i prawidłowy dobór wykorzystywanego czujnika światła. Po analizie dostępnych możliwości, zdecydowano o wyborze czujnika TSL2591, który jest programowalny, fabrycznie kalibrowany oraz łączy się z płytką bazową za pomocą interfejsu I2C. Użytkownik, tworząc kod do obsługi czujnika posiada wiele możliwości ustawienia jego czułości, z jaką dokonywane będą pomiary. Dostępne są zarówno różne wzmocnienia (1, 25, 408, 9876), jak i czasy integracji (od 100 do 600 ms), co umożliwia dostosowanie czujnika do określonych warunków pomiarowych. Posiada on także szeroki zakres pomiarowy wynoszący 0–88 000 lx, co jest jego niewątpliwym atutem (Adafruit 2019). Charakteryzuje się przy tym szerokim zakresem dynamicznym 600M:1. Czujnik światła wyposażony jest w dwie diody: jedną mierzącą światło widzialne i podczerwień (VIS+IR), a drugą wyłącznie podczerwień (IR) (rycina 2). Dzięki temu, po zastosowaniu odpowiedniej formuły matematycznej, możliwe jest uzyskanie przez niego czułości widmowej zbliżonej do czułości ludzkiego oka (Glover 2011).

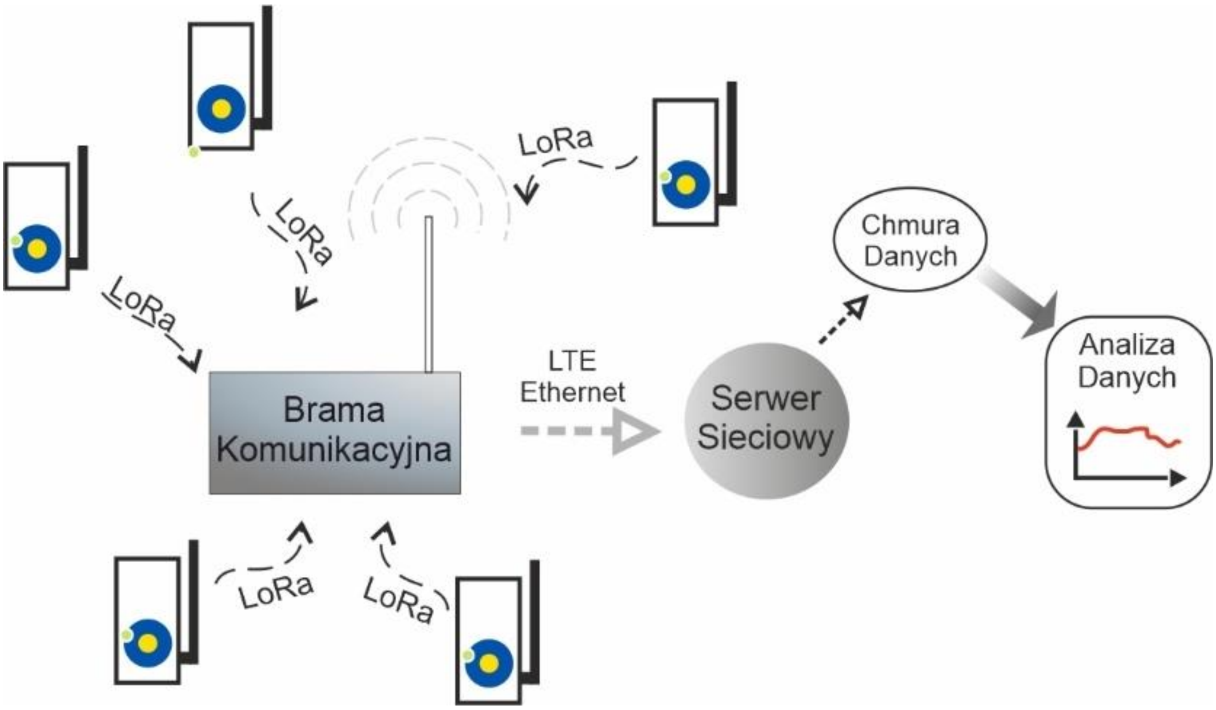


Rycina 2. Charakterystyka spektralna czujnika TSL2591 wykorzystanego w skonstruowanym urządzeniu (Adafruit 2019).

Komponenty wykorzystane do skonstruowania urządzenia do pomiaru zanieczyszczenia światłem został bardzo dokładnie opisany w artykule [P2] – ”*An Autonomous City-Wide Light Pollution Measurement Network System Using LoRa Wireless Communication*”.

Sieć monitoringu zanieczyszczenia światłem zakładana w Toruniu składa się z własnej konstrukcji urządzeń łączących się z bramą komunikacyjną za pomocą technologii LoRa, która przesyła zebrane dane do serwera wykorzystując bezpośrednio Ethernet lub sieć LTE. Rejestrowane dane gromadzone są na serwerze, skąd można je pobierać i dokonywać analiz. Schemat funkcjonalny opisywanej sieci przedstawiony został na rycinie 3.

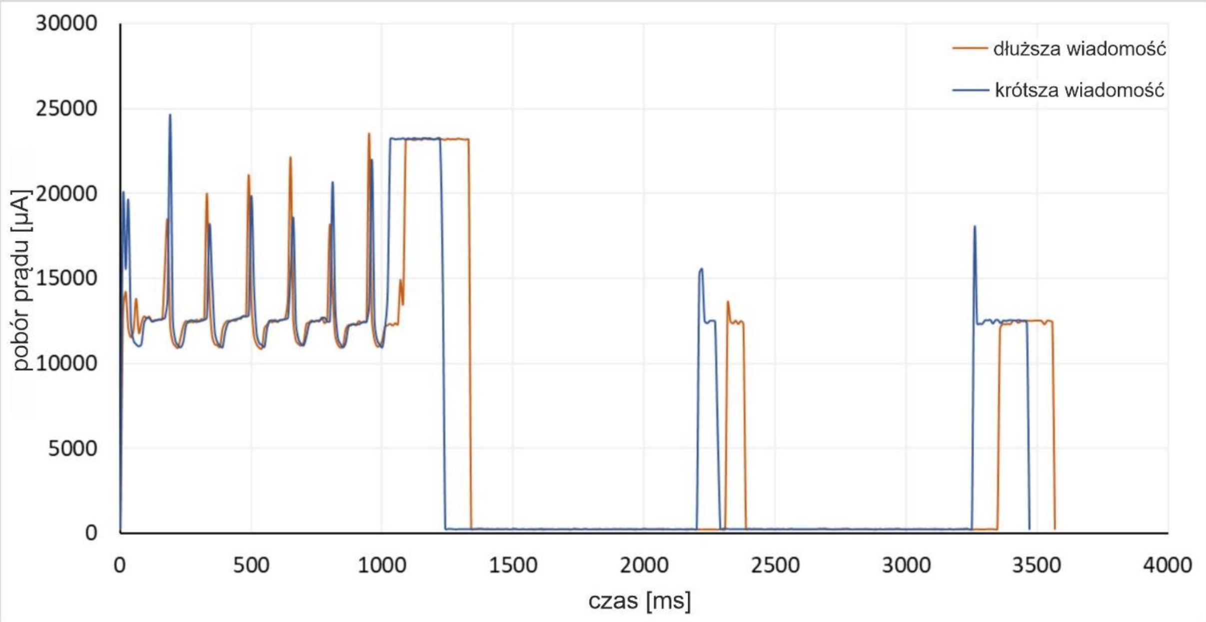
W opublikowanym artykule [P2] opisany został także kolejny etap badań nad możliwościami oraz jakością sieci monitoringu zakładanej w Toruniu. Szczegółowym analizom poddany został pobór prądu urządzenia podczas wysyłania danych pomiarowych w odniesieniu do różnej odległości od bramy komunikacyjnej. Dane te posłużyły także do oszacowania czasu działania urządzeń rejestracyjnych. Badania poboru prądu były możliwe dzięki zastosowaniu płytki X-NUCLEO-LPM01A, podłączonej bezpośrednio do głównej płytki urządzenia. Do odczytania pomiarów konieczne było wykorzystanie specjalistycznego oprogramowania STM32CubeMonitor-Power.



Rycina 3. Schemat funkcjonalny systemu zbierania danych założonego w Toruniu działającego z wykorzystaniem sieci LoRaWAN.

W czasie realizacji zaplanowanych testów, pomiary przeprowadzono na 5 stanowiskach rozlokowanych wzdłuż jednej z głównych ulic Torunia. Ich odległość od bramy komunikacyjnej z zamontowaną dłuższą anteną o wzmocnieniu 5,8 dB wynosiła kolejno: 98, 528, 1108, 1865 oraz 3654 metry. Na każdym stanowisku umiejscowiono urządzenie pomiarowe i w czasie kilkudziesięciominutowego pomiaru przesyłano kilkadziesiąt wiadomości o dwóch różnych długościach (32 oraz 72 bitów). Dłuższa wiadomość (72 bity) zawierała poza odczytem wielkości z czujnika światła, także odczyty z czujników środowiskowych – temperaturę oraz wilgotność. Możliwość przesyłania danych za pomocą technologii LoRa jest uwarunkowana, nie tylko odległością pomiędzy urządzeniem a bramą komunikacyjną, ale i ilością danych, które miałyby zostać wysłane i odebrane. Dlatego też, przed założeniem stałych punktów pomiarowych konieczne było sprawdzenie, jak długość wysyłanej wiadomości wpłynie zarówno na możliwość jej wysłania, jak i na pobór prądu. Przykładowy dane dla pierwszego stanowiska podczas inicjalizacji i wysyłania wiadomości przedstawia rycina 4.

Przeprowadzone badania opisane w tym artykule [P2] wykazały, iż faktycznie w czasie wysyłania dłuższej wiadomości pobór prądu jest większy, niż w czasie wysyłania krótszej wiadomości. Tą zależność zauważono na każdym analizowanym stanowisku. Widoczne jest także zwiększenie poboru prądu wraz ze zwiększeniem odległości oraz ilości występujących przesłon terenowych. Urządzenie znajdujące się najdalej podczas wysyłania wiadomości zużyło o 13,5% więcej prądu, niż urządzenie znajdujące się najbliżej bramy komunikacyjnej. Jednak, w ostatecznym rachunku, obejmującym również pobór prądu w czasie inicjalizacji oraz uśpienia urządzenia podczas dnia oraz pomiędzy nocnymi pomiarami, można zauważyć, iż ani odległość, ani występujące przysłony czy długość wysyłanej wiadomości nie wpływają znacząco na długość pracy urządzenia. Ostatecznie najwięcej prądu urządzenie pobiera w czasie dziennego przejścia w tryb zmniejszonego poboru energii (aż 96% dobowego zużycia energii), co jest spowodowane długością wykonywania tej czynności. Samo wysyłanie wiadomości wraz z inicjalizacją urządzenia zajmuje mniej, niż 0,14% czasu całego cyklu pomiarowego (dziennego i nocnego), dlatego nie przekłada się znacząco na operacyjny czas pracy urządzenia na jednym zestawie bateryjnym o pojemności 3 000 mAh, który w teorii wynosi około 506 dni. Przy planowaniu umiejscowienia punktów pomiarowych oraz ustaleniu harmonogramu wykonywania działań w czasie trwania projektu należy pamiętać, iż wyliczony czas jest czasem teoretycznym, zakładającym takie same stabilne warunki pomiarowe. Podczas kolejnego etapu realizacji projektu – testowania urządzeń oraz ich późniejszej pracy ustalono, iż faktyczny czas nieprzerwanej pracy autorskiego urządzenia wynosi około 9 miesięcy. Wybrane istotne techniczne parametry urządzenia zostały przedstawione w Tabeli 1.



Rycina 4. Pobór prądu zarejestrowany na pierwszym stanowisku przy użyciu płytki X-NUCLEO-LPM01A oraz oprogramowania STM32CubeMonitor-Power dla obu wysyłanych ramek (krótszej i dłuższej).

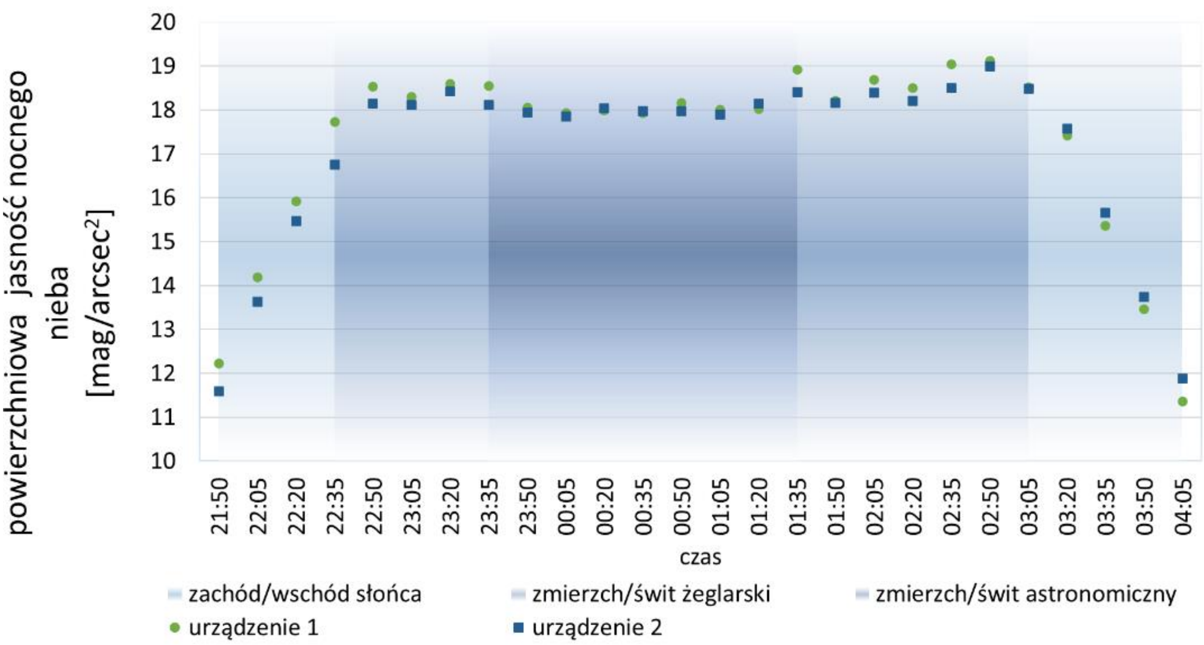
Tabela 1. Wybrane parametry techniczne autorskiego urządzenia mierzącego zanieczyszczenie sztucznym światłem nocnego nieba.

Parametr techniczny	Charakterystyka
wymiary	5,5 x 8,2 x 15,8 cm
waga (z bateriami)	350 g (390 g)
standard transmisji danych	LoRaWAN
czułość spektralna	czułość ludzkiego oka (w przybliżeniu)
zakres pomiarowy	0 lx – 88 000 lx
czułość	188 µlx
czas operacyjny [3 000 mAh]	~ 9 miesięcy
zasięg w terenie zurbanizowanym	3–4 km
częstotliwość nocnych pomiarów	15 min
czas operacyjny	21:00–06:00 CEST
czujniki	natężenie światła, wilgotność, temperatura
kąt zbierania danych	27°
klasa szczelności	IP65

Kolejnym etapem tworzonej sieci monitoringu zanieczyszczenia światłem nocnego nieba na obszarze Torunia były testy kalibracyjne i użytkowe skonstruowanego urządzenia pomiarowego. Zostały one szczegółowo opisane w artykule [P3] – „*Device for automatic measurement of light pollution of the night sky*”.

Pierwszym z przeprowadzonych testów było sprawdzenie w warunkach terenowych poprawności działania (rejestracji) czujnika światła zamontowanego w urządzeniu pomiarowym. W tym celu dwa urządzenia umiejscowiono na tym samym punkcie w bardzo bliskiej od siebie odległości poza obszarem bezpośredniego oddziaływanie światła ulicznego. Równocześnie, w celach porównawczych, dokonywano pomiarów ręcznym, fabrycznym fotometrem SQM–L. Uzyskane wyniki pokazały, iż pomiary są do siebie bardzo zbliżone i posiadają taką samą zmienność w czasie. Dowodzi to, iż wykorzystany czujnik światła, o wysokiej dokładności poprawnie realizuje pomiar w odniesieniu do panujących warunków zewnętrznych. Pokazało to gotowość urządzenia do przeprowadzanie dalszych testów.

Kolejnym z nich było operacyjne sprawdzenie poprawności działania całej sieci pomiarowej, zarówno pracy wszystkich czujników, jak i samego procesu przesyłania danych i ich prawidłowego zapisu na serwerze. Testy te, wykonane w ramach demonstratora technologii, przeprowadzone zostały w siedzibie Toruńskiej Agencji Rozwoju Regionalnego (TARR), gdzie na dachach dwóch sąsiadujących budynków umieszczone na tej samej wysokości dwa bliźniacze urządzenia. Pilotażowe wyniki uzyskane podczas trwania badań prezentuje rycina 5. Zawiera ona średnią wartość powierzchniowej jasności nocnego nieba uzyskaną na każdym ze stanowisk w odniesieniu do czasu rozpoczęcia i zakończenia różnych typów nocy.



Rycina 5. Powierzchniowa jasność nocnego nieba zarejestrowana przez urządzenia 1 i 2 zamontowane na budynkach TARR w Toruniu podczas etapu demonstratora technologii.

W procesie planowania rozkładu w Toruniu punktów monitoringu zanieczyszczenia światłem nocnego nieba, wzięto już pod uwagę, nie tylko testy dotyczące możliwości sieci LoRaWAN, ale także uwarunkowania techniczne montażu samych urządzeń. Założono, że w miarę dostępnych możliwości, pomiarem zostanie objęte całe nocne niebo nad Toruniem. Aby to zrealizować konieczne było określenie docelowej liczby urządzeń, jakie miałyby zostać rozmieszczone na terenie miasta. Biorąc pod uwagę kąt sferyczny zbierania danych przez urządzenie oraz warunki meteorologiczne panujące przeciętnie w Toruniu ustalono, iż najbardziej optymalne będzie założenie około 40 stacji pomiarowych w odległości wzajemnej około 2 500 m (Karpińska i Kunz 2022b). Podczas tych ustaleń warto pamiętać, że obszar zbierania danych przez urządzenie skierowane w górę jest ograniczany przez występujące zachmurzenie. Wyznaczając odległość między stanowiskami należy wziąć pod uwagę, zarówno przeciętną wysokość podstawy chmur (odniesioną do średniej liczby dni pochmurnych), występującą w pobliżu infrastrukturę oświetleniową, zasięg sieci LoRaWAN oraz techniczną możliwość montażu urządzenia.

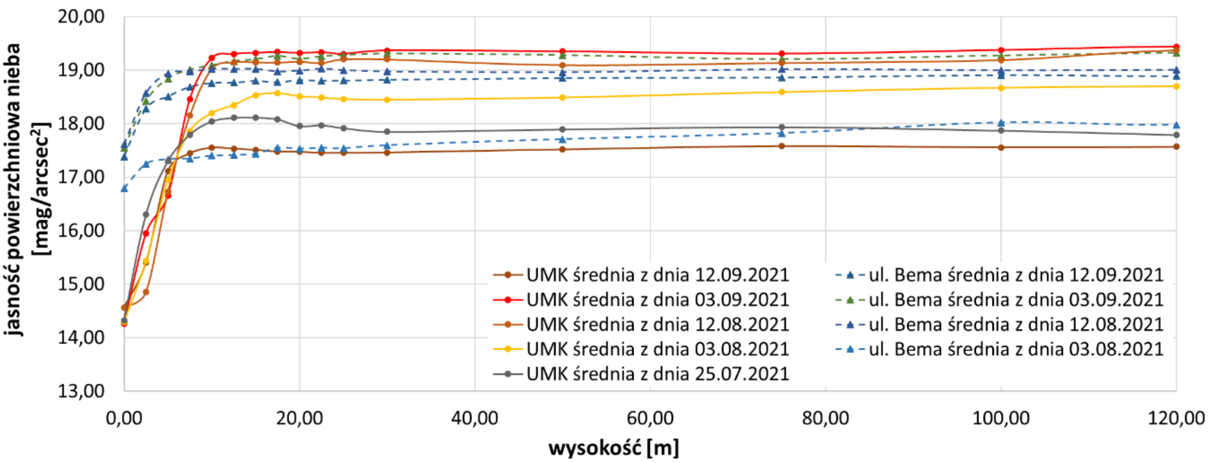
Uwzględniając przytoczone powyżej argumenty oraz możliwości techniczne podjęto decyzję o skonstruowaniu 40 bliźniaczych urządzeń stanowiących infrastrukturę pomiarową sieci monitoringu. Dlatego następnym etapem badań było operacyjne przetestowanie wszystkich urządzeń w tych samych zewnętrznych warunkach pomiarowych. W celu zachowania wiarygodności oraz możliwości późniejszego porównania wyników zaplanowane testy przeprowadzono w tym samym czasie i miejscu, w sąsiedztwie fabrycznego fotometru SQM z wewnętrznym rejestratorem danych. Eksperyment udowodnił, iż pomiary ze wszystkich urządzeń były porównywalne, a uzyskane wartości zgodne z wynikami zarejestrowanymi przez fotometr SQM (Karpińska i Kunz 2022a). Zebrane dane poddano analizie statystycznej, obliczono średnią z pomiarów dla każdego interwału czasowego oraz jego odchylenie standardowe. W czasie nocy bezchmurnej o stałych warunkach pogodowych, wyniki były spójne, a względne odchylenie standardowe (RSD) wyniosło średnio 0,5%. Podczas nocy o zmiennych warunkach pogodowych, gdzie stopień zachmurzenia oraz wysokość podstawy chmur ulegała zmianie, co znacznie wpływa na mierzone wartości, względne odchylenie standardowe było nieznacznie większe i wyniosło 2,15%.

Przeprowadzone analizy i uzyskane wyniki udowodniły gotowość do pracy przygotowanych zestawów pomiarowych. Wszystkie urządzenia mogły zostać kolejno montowane na wybranych stanowiskach pomiarowych. Podczas ustalania tych miejsc zadano sobie jednak pytanie, jak na dokonywany pomiar zanieczyszczenia światłem wpływa wysokość zamontowania urządzenia i czy wyniki pomiarów będą porównywalne zarówno dla rejestratorów umiejscowionych na wysokości parteru, 2, 5 czy 10 piętra.

W tym celu przeprowadzone zostały kolejne badania eksperymentalne, których wyniki zostały opisane w artykule [P4] – ”*Vertical variability of night sky brightness in urbanised areas*”. Polegały one na pionowym (wertykalnym) pomiarze jasności nieba za pomocą skonstruowanego urządzenia przystosowanego do mocowania na górnym pokładzie bezzałogowego statku powietrznego (BSP). W trakcie eksperymentu konieczne było także modyfikacja oprogramowania samego urządzenia, tak, aby pomiary wykonywane były w trybie ciągłym w odstępach kilkunastosekundowych, a nie tak jak dotychczas w interwałach 15 minutowych. W rejestratorze zmieniono także umieszczenie samego czujnika światła, tak aby możliwy był poziomy, stabilny montaż zestawu na BSP. Zmienione zostało także położenie anteny, aby nie kolidowała ona z torem ruchu śmigieł. Wygląd całego zestawu pomiarowego wykorzystanego podczas tych działań przedstawia rycina 6.

Pomiary jasności powierzchniowej nocnego nieba w gradiencie pionowym zostały wykonane na dwóch stanowiskach różniących się intensywnością oświetlenia zewnętrznego, inną odległością od infrastruktury oświetleniowej oraz drogowej. Pierwszym z nich był parking przy budynku Wydziału Nauk o Ziemi i Gospodarki Przestrzennej UMK, natomiast drugi położony był na parkingu przy ulicy Bema w Toruniu. Łącznie przeprowadzono 5 sesji pomiarowych, pomiędzy końcem lipca, a połową września 2021 roku. Podczas tych testów, warunki meteorologiczne były różne, co pomogło sprawdzić czy rozkład wertykalny zjawiska jest zależny od występowanie zachmurzenia. Wyniki wszystkich sesji pomiarowych zaprezentowane zostały na rycinie 7.

Rycina 6. Wykorzystany BSP firmy DJI model Matrice 210 RTK z autorskim urządzeniem pomiarowym służący analizie zmienności jasności powierzchniowej nocnego nieba w gradiencie pionowym (fot. Dominika Karpińska).



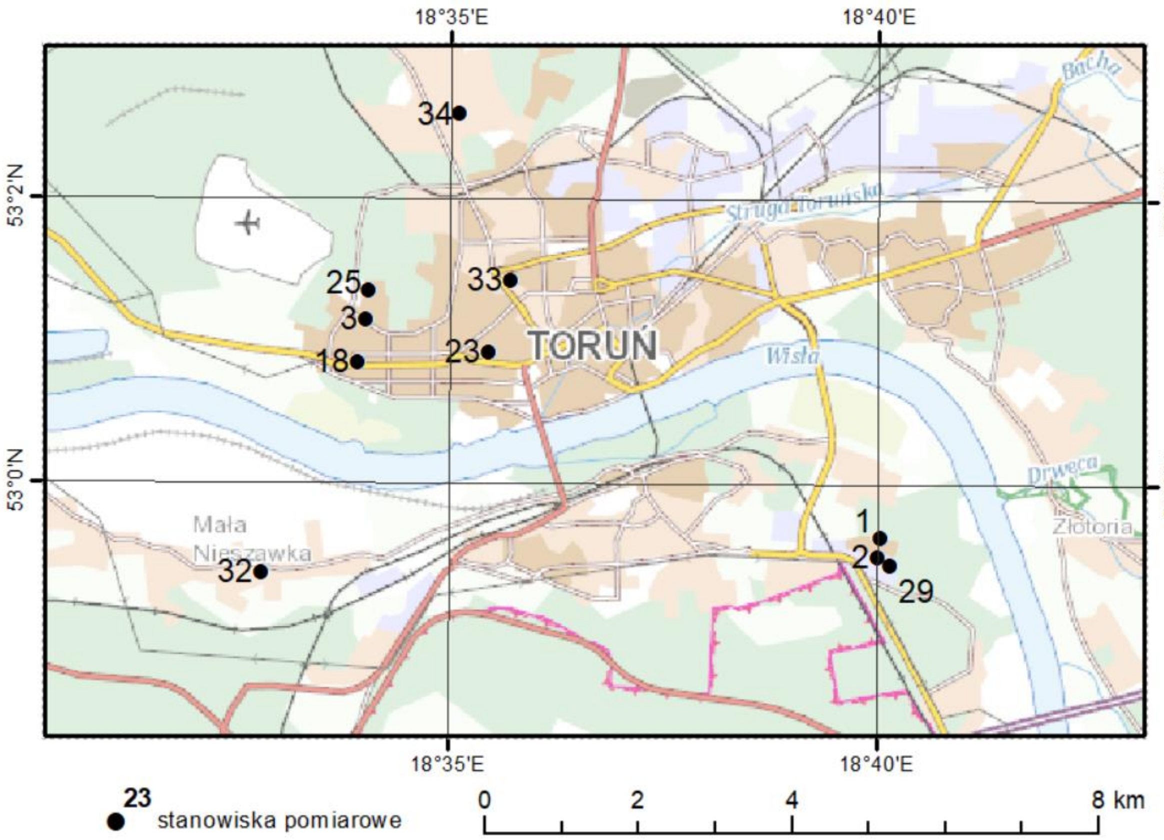
Rycina 7. Uzyskane wyniki jasności powierzchniowej nocnego nieba na dwóch stanowiskach, podczas badań zmienności wertykalnej zjawiska.

Analizując przytoczone wyniki można zauważyć, iż zmienność uzyskanych wartości obserwujemy jedynie do około 10 metrów nad powierzchnią gruntu, a później wyniki stabilizują się. Taką sytuację obserwujemy w każdych warunkach pomiarowych, podczas wszystkich zrealizowanych nocnych sesji. Badania te pozwoliły na stwierdzenie, iż punkt monitoringu zanieczyszczenia światłem powinien znajdować się poza bezpośrednim oddziaływaniem zewnętrznej infrastruktury oświetleniowej. Dla długookresowego monitoringu nie ma już znaczenia, na jakiej wysokości znajdzie się punkt pomiarowy, jeśli będzie on znajdował się powyżej ulicznych lamp. Wniosek z powyższego eksperymentu stwarza dużo większe możliwości rozmieszczenia urządzeń pomiarowych i wykorzystania do tego procesu istniejącej infrastruktury czy elementów budowli.

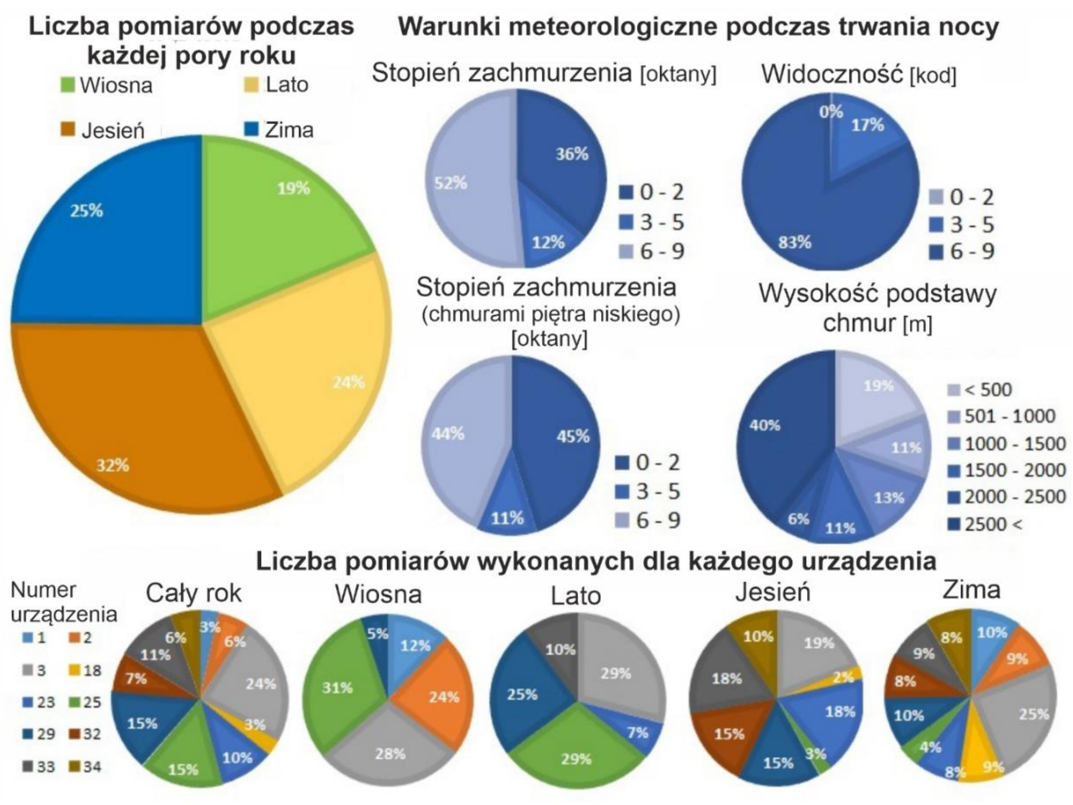
Wykorzystując zdobytą wiedzę, możliwe było rozszerzenie sieci monitoringu, której budowa rozpoczęła się podczas pierwszych pomiarów w siedzibie TARR w Toruniu (etap demonstratora technologii). Stopniowo zwiększała się liczba przyłączanych do sieci monitoringu urządzeń pomiarowych rozmieszczanych na obszarze Torunia i okolic.

Pierwszymi wykonanymi analizami z wykorzystaniem danych zebranych z działającej już sieci monitoringu zanieczyszczenia światłem było sprawdzenie, jaki wpływ ma zachmurzenie na wartości pomiarów jasności powierzchniowej nocnego nieba na terenie zurbanizowanym. Badania o podobnej tematyce są szeroko realizowane przez wybrane grupy badawcze (Cavazzani i in. 2020; Kocifaj i Bará 2020; Ribas i in. 2016; Ściężor 2020). Jest to ważny element poznania zjawiska oraz sprawdzenia jego wpływu na otaczający ekosystem. W zależności od miejsca realizacji pomiarów, występujące zachmurzenie może znacząco podwyższać jasność nocnego nieba lub je obniżać (Cinzano i in. 2001; Kolláth 2010). Na terenach oddalonych od źródeł sztucznego światła obserwujemy ciemniejsze niebo, ponieważ zasłonięte zostaje światło zodiakalne, Księżyc oraz inne obiekty astronomiczne. Podczas przytaczanych badań, skupiono się na zbadaniu jasności nocnego nieba na obszarze zurbanizowanym. Szczegółowy opis wyników zawarty został w artykule [P5] – "*Relationship between the surface brightness of the night sky and meteorological conditions*". Prezentuje on porównanie wyników otrzymanych z rejestracji pierwszych dziesięciu urządzeń działających w sieci monitoringu (urządzenia nr 1 i 2 umiejscowione w siedzibie TARR zostały w późniejszym czasie zastąpione jednym urządzeniem nr 29). Ich lokalizacja oraz numeracja pokazana została na rycinie 8.

Badania przeprowadzone zostały dla danych zarejestrowanych w 2021 roku. W celu poznania zmienności sezonowej przyporządkowano je do każdej z pór roku. Porównanie wyników pomiarów było możliwe dzięki danym meteorologicznym zarejestrownym na stacji pomiarowej IMGW Toruń-Wrzosy. Analizie porównawczej poddano wysokość względną podstawy chmur (podawaną w metrach nad poziomem gruntu), widoczność, stopień zachmurzenia oraz stopień zachmurzenia chmurami piętra niskiego. Oba ostatnie parametry podawane są w skali oktanowej, gdzie 0 oznacza niebo bezchmurne, natomiast 8 – całkowicie zachmurzone. Widoczność definiowana jest kodem od 0 do 9, gdzie 9 oznacza doskonało widoczność, natomiast 0 – złą. Z uwagi na występowanie znacząco krótszych nocy w sezonie letnim, w celu zachowania jednolitych zakresów pomiarowych porównywano tylko dane zarejestrowane między 22:00 a 00:00 UTC. Łącznie analizy porównawcze wykonano na próbie złożonej z 3 650 pomiarów zebranych przez sieć monitoringu. Poszczególne liczebności w porach roku, warunki panujące w analizowanym okresie oraz rozkład pomiarów przedstawia rycina 9.

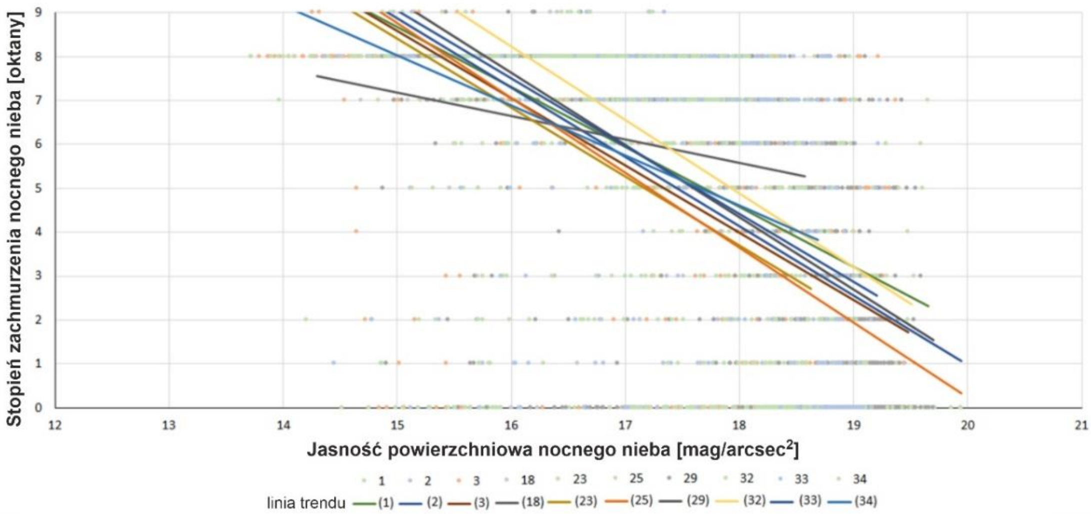


Rycina 8. Lokalizacja stanowisk pomiarowych służących analizie wpływu zachmurzenia na wartość jasności powierzchniowej nocnego nieba na terenie zurbanizowanym. Stan sieci pomiarowej na grudzień 2021 rok.

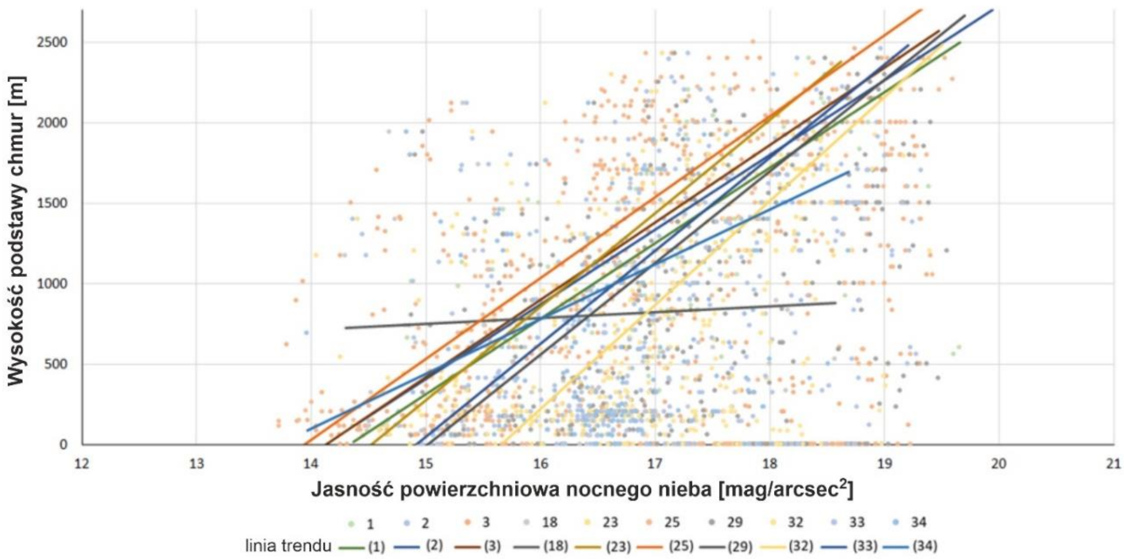


Rycina 9. Wybrana statystyka występowanie każdego z porównywanych parametrów meteorologicznych oraz rozkład pomiarów dla każdego urządzenia.

Dzięki przedstawionej powyżej statystyce pomiarów możemy zauważyć, iż ponad połowa nocy w 2021 roku w Toruniu była w różnym stopniu zachmurzona. Pokazuje to, jak ważne jest określenie stopnia jasności nocnego nieba podczas pochmurnej oraz bezchmurnej nocy na terenie zurbanizowanym, oraz konsekwencje tej sytuacji meteorologicznej. Pierwszym etapem analiz było zestawienie na wykresie wyników powierzchniowej jasności nocnego nieba z występującym w tym czasie stopniem zachmurzenia oraz wysokości podstawy chmur. Zależności te przedstawiają ryciny 10 oraz 11. Na każdej z nich do wszystkich serii danych wygenerowano linię trendu. Analizując wykresy możemy zauważyć, iż linie trendu układają się w zbliżony sposób dla każdego z wykorzystanych urządzeń oraz występują zależności statystyczne między tymi pomiarami. Dowodzi to, iż jasność nocnego nieba zmniejsza się wraz z występowaniem chmur niskich i rośnie wraz ze zwiększeniem ich wysokości zalegania. Zanieczyszczenie światłem zwiększa się wraz ze wzrostem stopnia zachmurzenia i zmniejsza podczas bezchmurnego nieba.



Rycina 10. Zależność powierzchniowej jasności nocnego nieba od stopnia zachmurzenia, analiza dla całego 2021 roku.



Rycina 11. Zależność powierzchniowej jasności nocnego nieba od wysokości występujących chmur, analiza dla całego 2021 roku.

Dane przedstawione na rycinach 10 i 11, dodatkowo rozdzielono na występujące pory roku. Z przeprowadzonych analiz wynika, że bardzo podobna zależność, występuje zarówno wiosną, latem oraz jesienią. Jednak podczas trwania sezonu zimowego dane rozbiegają się i linie trendu nie układają się w podobny sposób. Prawdopodobnie jest to spowodowane obecnością dużej liczby pyłów zawieszonych w atmosferze, które rozpraszają sztuczne światło i zwiększają niezależnie od panujących warunków meteorologicznych zanieczyszczenie świetlne. Zależność ta opisywana jest przez różne grupy badawcze, a przedstawione powyżej wyniki to potwierdzają.

Kolejną wykonaną analizą statystyczną było obliczenie współczynnika korelacji liniowej zebranych danych (Karpińska i Kunz 2023b). Wyniki te przedstawione zostały w Tabeli 2. Pierwszy wiersz przedstawia korelację jasności powierzchniowej nocnego nieba ze stopniem zachmurzenia. Wartości są ujemne, ponieważ jest to zależność odwrotna i możemy jednak zauważyć, iż korelacja między parametrami jest wysoka. Podobna zależność występuje w wierszu 4, gdzie umieszczono korelację ze stopniem zachmurzenia chmurami piętra niskiego. Jeszcze wyższą korelację obserwujemy w zestawieniu pomiarów z wysokością podstawy chmur. Takiego efektu nie widać analizując widzialność i w tym przypadku korelacja jest słaba. Pogrubione wartości wskazują wyniki większe, od 0,4 co wskazuje umiarkowaną, silną lub bardzo silną korelację pomiędzy danymi. Na podstawie tego można wnioskować, iż zgodnie z zebranymi danymi, jasność nocnego jest silnie zależna od występujących warunków pogodowych.

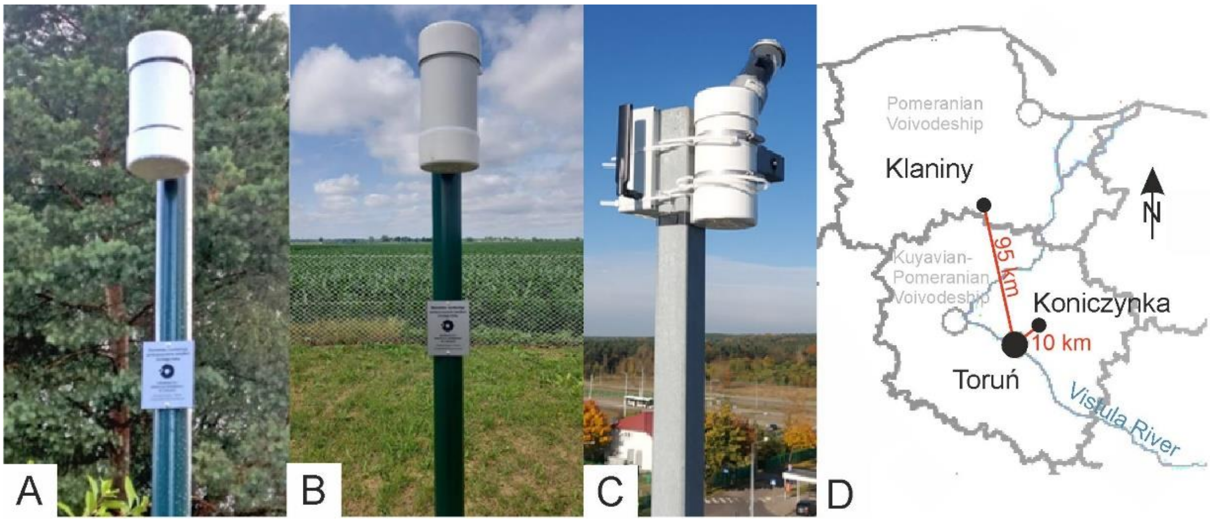
Tabela 2. Zależność statystyczna jasności nocnego nieba nad Toruniem w całym 2021 roku w odniesieniu do wysokości chmur, zachmurzenia ogólnego i widzialności.

Parametr	**Numer urządzenia pomiarowego**								
	1	2	3	23	25	29	32	33	34
stopień zachmurzenia	**-0,60**	**-0,60**	**-0,67**	**-0,58**	**-0,71**	**-0,62**	**-0,49**	**-0,56**	-0,34
wysokość podstawy chmur	**0,73**	**0,65**	**0,69**	**0,67**	**0,71**	**0,66**	**0,57**	**0,65**	0,32
widzialność	0,28	0,36	0,34	0,24	0,23	0,28	0,12	0,23	0,08
stopień zachmurzenia chmurami piętra niskiego	**-0,64**	**-0,61**	**-0,70**	**-0,63**	**-0,73**	**-0,65**	**-0,52**	**-0,61**	-0,37

Grupując dane na sezony otrzymano bardzo podobne zależności, a nawet jeszcze silniejszą korelację dla okresu wiosennego, letniego i jesiennego. Jednak, tak jak podczas analizy lini trendów inną zależnośc obserwujemy zimą. Korelacja dla każdego z parametrów jest słaba i można przypuszczać, iż wpływ ma na to zwiększona ilość pyłów zawieszonych w atmosferze, występująca podczas okresu grzewczego. Szczegółową analizę wszystkich wyników zamieszczono w przytoczonym artykule [P5].

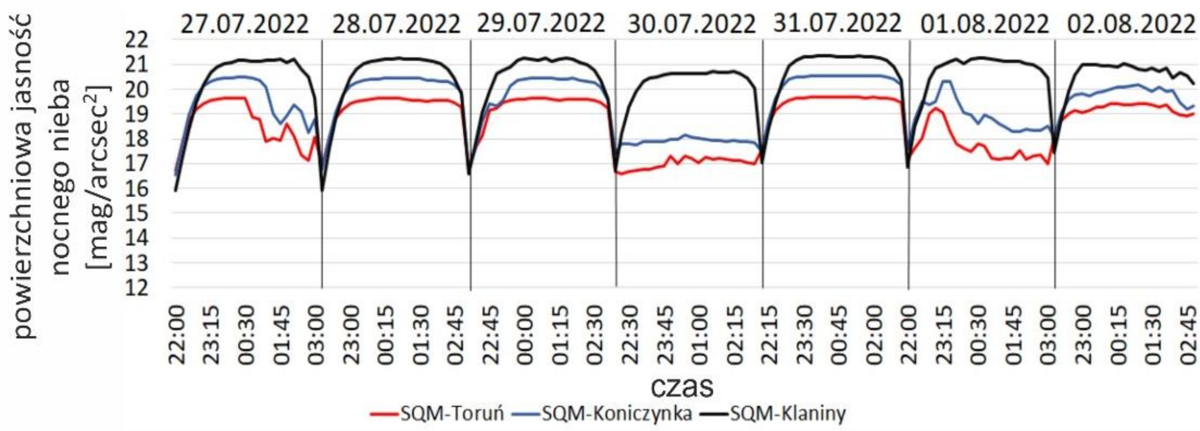
Realizowany projekt doktorski opisywany w niniejszej dysertacji jest bezpośrednio związany z tematyką nowoczesnych technologii na styku metrologii, automatyki czy elektroniki, jak i zapisu oraz transmisji danych pomiarowych w terenie zurbanizowanym. Od początku ukierunkowany był na współpracę interdyscyplinarną oraz międzyinstytucjonalną. Szczegółowe etapy realizacji prac badawczo-rozwojowych służących powstaniu systemu monitoringu, kamienie milowe i zrealizowane okołoprojektowe wątki rozszerzające wiedzę, a także opis kierunków dalszych działań zostały przedstawione w artykule [P6] – ”*Measuring light pollution in the night sky – from technology demonstrator to monitoring system*”.

W artykule tym zaprezentowano także kolejne etapy rozbudowy sieci pomiarowej. Podczas przeprowadzonych analiz zaistniała potrzeba wyznaczenia tła pomiarowego, jako wspomagającego pozyskanie wartości referencyjnych. W tym celu założone zostały 3 stałe stacje pomiarowe, na których zamontowano fotometry SQM serii LU. Wcześniej przeprowadzone badania wykazały, iż wyniki uzyskane z wykorzystaniem tego fotometru są zgodne z pomiarami zrealizowanymi przez własnej konstrukcji urządzenie. Pierwsza stacja, porównawcza, została założona na Tarasie Obserwacyjnym WNoZiGP UMK, w bezpośrednim sąsiedztwie autorskiego urządzenia. Drugą umieszczono na terenie Zintegrowanej Stacji Monitoringu Środowiska Przyrodniczego w Koniczynce, która jest oddalona w linii prostej od granic Torunia o około 10 km. Ostatni fotometr SQM zamontowano w Borach Tucholskich w gminie Osieczna na terenie małej osady śródleśnej Klaniny, oddalonej od Torunia o około 100 km. Lokalizację trzech stacji referencyjnych oraz ich poglądowe zdjęcia pokazano na rycinie 12. Te zamiejscowe stacje działają nieprzerwanie, począwszy od sezonu letniego 2022 roku.



Rycina 12. Stanowiska pomiarowe z fotometrem SQM-LU stanowiące tło pomiarowe dla miasta Torunia: A) Klaniny (Bory Tucholskie), B) Koniczynka, C) Taras Obserwacyjny WNoZiGP UMK w Toruniu oraz D) ich schematyczna lokalizacja (fot: Mieczysław Kunz).

Przyjęta lokalizacja stacji pomiarowych oparta na fabrycznych urządzeniach SQM zakłada malejący udział sztucznego światła w pomiarach zanieczyszczenia nieba. Tezę tą potwierdzono już w pierwszych miesiącach pozyskiwania danych. Przykładowe zestawienie wyników przedstawia rycina 13, prezentująca pomiary z okresu 27.07–02.08.2022 roku.



Rycina 13. Wyniki porównawcze wartości jasności nocnego nieba wykonane urządzeniem SQM na 3 stanowiskach pomiarowych położonych w malejącym gradiencie oddziaływania człowieka.

Analizując powyższy wykres, można zauważyć, iż niezależnie od warunków meteorologicznych (niższa wartość powierzchniowej jasności nocnego nieba wskazuje na zwiększone zachmurzenie), fotometr znajdujący się w Klaninach rejestruje znacząco wyższe wartości, co przekłada się na zdecydowanie mniejsze zanieczyszczenie światłem. Najniższe wartości pomiarowe rejestrowane są na terenie UMK. Wyniki uzyskane przez fotometry SQM-LU potwierdzają słuszność budowania systemu monitoringu zanieczyszczenia światłem na terenach zurbanizowanych oraz wskazują na potrzebę redukcji czynników wpływających na analizowane zjawisko.

W trakcie realizacji projektu sieć monitorująca zanieczyszczenie światem była systematycznie rozbudowywana i gromadzono coraz więcej danych pomiarowych. Stwarza to możliwości wykonywania kolejnych analiz, nie tylko statystycznych, ale i przestrzennych. Nową odsłonę wyników analiz przedstawiono w artykule [P7] – ”*Spatial and temporal analysis of artificial light pollution of the city night sky. A case study from Toruń*”. Miejska sieć mionitoringu w lutym 2023 roku składała się już z 21 w pełni operacyjnych urządzeń oraz 4 bram komunikacyjnych zapewniających dostępność sygnału na terenie prawie całego miasta. Zestawienie dostępnych bram komunikacyjnych, ich lokalizację oraz datę rozpoczęcia pracy przedstawia Tabela 3.

Tabela 3. Zestawienie bram dostępowych podłączonych do sieci LoRaWAN rozmieszczonych w granicach Torunia.

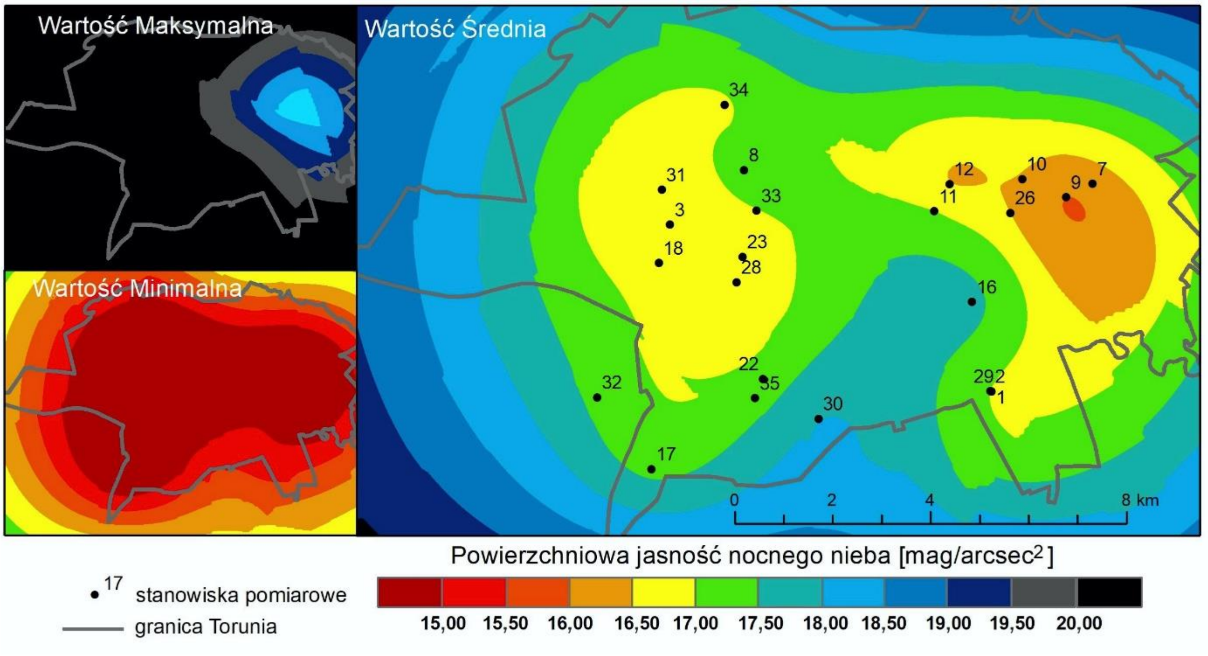
Lp.	Lokalizacja	Typ	Data rozpoczęcia pracy	Miejsce montażu	PUWG 1992	
					X	Y
1	ul. Matejki	zewnętrzny	lipiec 2021	10 piętro	472569	572295
2	ul. Jamontta	zewnętrzny	luty 2022	5 piętro	478088	573608
3	ul. Włocławska	wewnętrzny	kwiecień 2020	4 piętro	477590	569579
4	ul. Lwowska	wewnętrzny	luty 2021	3 piętro	471064	573050

Zebrane dane ze wszystkich pracujących w tym czasie urządzeń rejestrujących, przypisano do sezonu obserwacyjnego. Następnie obliczono średnię z wyników, a także wyznaczono wartości maksymalne i minimalne. Tabela 4 prezentuje otrzymane wartości odniesione do stanowisk pomiarowych.

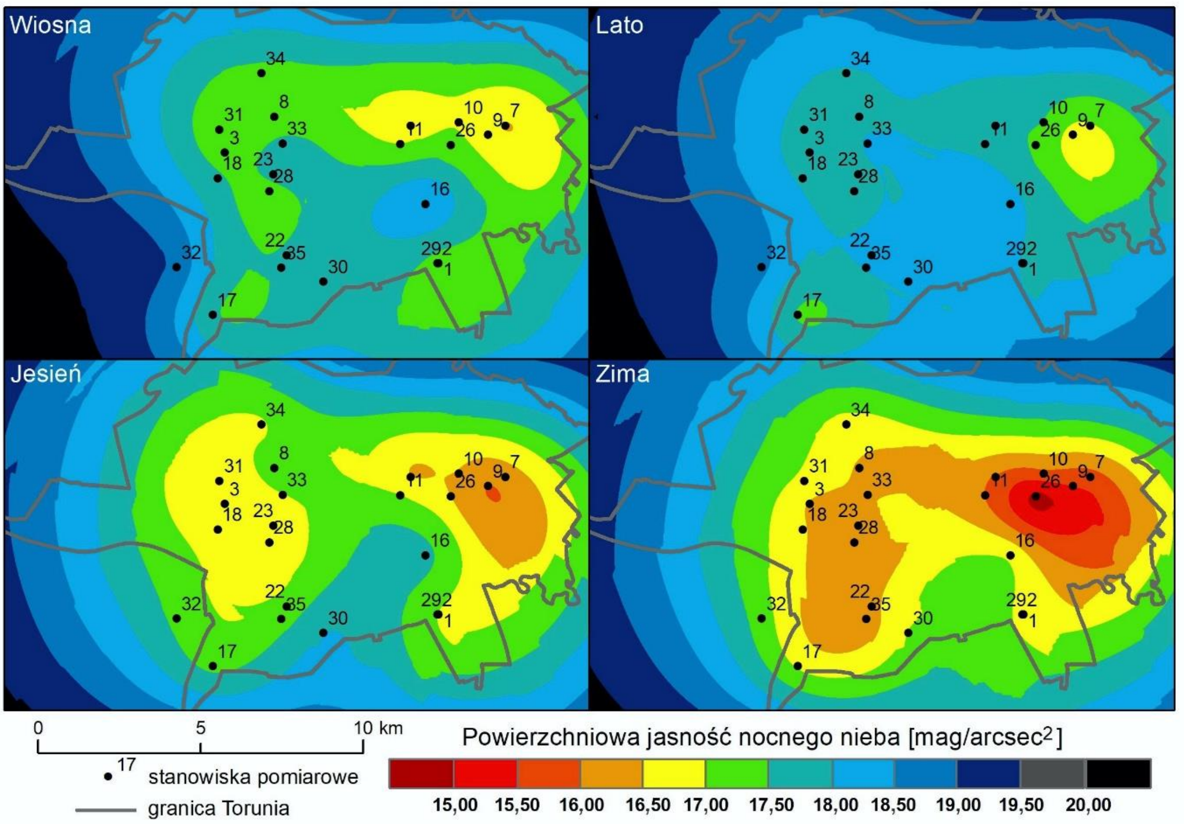
Tabela 4. Zestawienie średnich wartości pomiarów powierzchniowej jasności nocnego nieba zarejestrowanych na stanowiskach monitoringowych w ujęciu całego roku oraz poszczególnych astronomicznych pór roku.

ID	Lokalizacja	Data rozpoczęcia (zakończenia)	Piętro	cały rok [mag/arcsec²]			lato	jesień	zima	wiosna
				średnia	min	max	Średnia [mag/ arcsec²]			
1	ul. Włocławska 167	23.03.2021 (20.04.2021)	3	17,5	15,9	20,1				17,5
2	ul. Włocławska 167	23.03.2021 (20.04.2021)	3	17,6	15,5	19,9				17,3
3	ul. Lwowska 1	16.02.2021	3	16,9	14,1	20,0	17,7	16,4	16,3	17,3
7	ul. Szosa Lubicka 182	30.03.2022	3	16,3	14,1	17,6	17,0	16,3	15,7	16,5
8	Szosa Chełmińska 160	30.03.2022	3	17,2	14,0	19,5	17,9	17,3	16,4	17,0
9	ul. Witosa 7	12.07.2022	3	16,1	13,9	18,5	16,6	15,8	15,6	
10	ul. Niesiołowskiego 26	13.02.2022	1	16,8	14,2	18,9	17,6	16,6	16,1	17,0
11	ul. Kalinowa 17	02.04.2022	parter	16,9	14,19	19,8	17,9	17,1	16,0	17,0
12	ul. Rydygiera 19	30.03.2022	9	16,6	14,5	18,1	17,4	16,3	16,0	16,8
13	ul. Kwiatowa 33	03.01.2023	1	15,8	14,0	19,4			15,8	
14	ul. Dębowa 15	23.05.2022	parter	16,6	14,0	20,0	18,0	16,3	16,8	17,9
16	Działki Rudak	30.05.2022	parter	17,8	15,3	20,6	18,2	17,8	17,1	18,4
17	ul. Szubińska 38	05.06.2022	1	17,2	14,5	20,8	17,3	17,3	16,9	17,6
18	ul. Fałata 82	12.11.2021	2	17,0	14,4	20,8	17,9	16,8	16,6	17,6
22	ul. Drzymały 5	30.03.2022	4	17,2	14,7	20,3	18,2	17,2	16,5	17,6
23	ul. Matejki 55	11.08.2021	10	17,0	14,2	20,2	17,9	16,7	16,5	17,7
25	ul. Lwowska 1	16.02.2021 (12.09.2021)	3	17,1	14,2	20,8	17,2		16,5	16,7
26	ul. Konstytucji 3 Maja 13	13.01.2023	9	14,4	13,7	15,2			14,4	
27	ul. Łączna 40	12.01.2023	3	16,4	14,3	20,9			16,4	
28	ul. Matejki 16	02.04.2022	4	16,9	14,0	20,3	17,8	17,0	16,2	17,3
29	ul. Włocławska 167	18.05.2021	3	17,1	13,3	20,1	18,0	16,9	16,8	17,0
30	ul. Łączna 40	29.03.2022 (12.01.2023)	3	18,1	15,8	20,9	18,1	18,1	17,1	17,9
31	ul. Makuszyńskiego 2	15.01.2022	parter	17,1	13,8	20,0	17,9	16,6	17,0	17,2
32	ul. Dębowa 15	03.09.2021 (23.05.2022)	parter	17,5	14,3	20,8	18,7	17,4	17,3	18,8
33	ul. Końcowa 4	28.07.2021	4	17,1	14,0	20,8	18,1	17,0	16,5	17,7
34	ul. Kwiatowa 33	12.10.2021 (03.01.2023)	1	17,0	14,1	21,0	17,9	16,9	16,7	17,4
35	ul. Okólna 10	30.12.2023	1	16,2	14,1	20,2			16,1	

Przetworzone wartości pomiarowe posłużyły do wykonania map powierzchniowego rozkładu zanieczyszczenia sztucznym światłem na terenie Torunia. Rycina 14 przedstawia średnią, maksymalną oraz minimalną wartość powierzchniowej jasności nocnego nieba, natomiast rycina 15 obrazuje powierzchniowy rozkład obliczonej średniej w podziale na następujące astronomiczne pory roku.



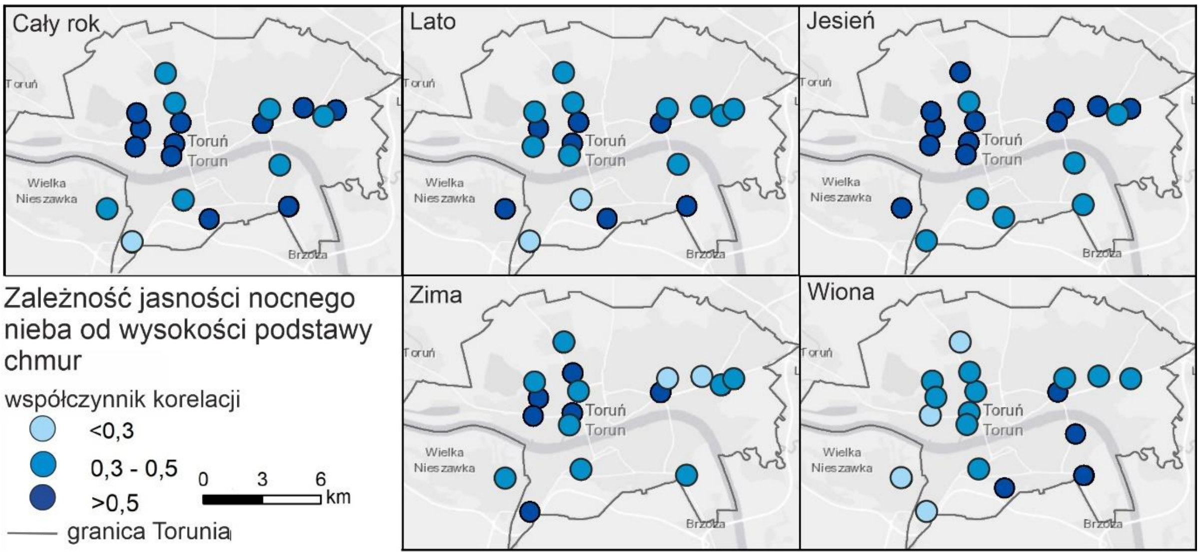
Rycina 14. Rozkład przestrzenny wartości średnich, maksymalnych oraz minimalnych zanieczyszczenia światłem nocnego nieba na obszarze Torunia.



Rycina 15. Rozkład przestrzenny średniej wartości zanieczyszczenia światłem nocnego nieba w odniesieniu do występującej astronomicznej pory roku.

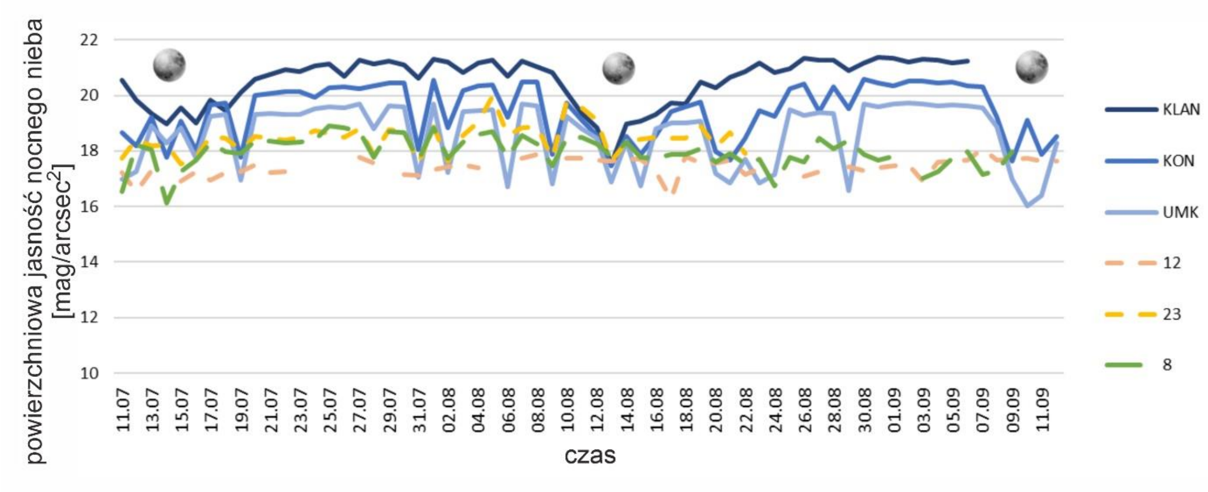
Analizując przedstwione dane można zauważyć, iż najjaśniejsze niebo występuje we wschodniej oraz centralno-zachodniej części miasta. Obszary te pokrywają się z umiejscowieniem największych osiedli mieszkaniowych. Maksymalne zmierzone wartości w większości miasta są większe, niż 19 mag/arcsec^2, co oznacza niebo zanieczyszczone światłem w mniejszym stopniu. Wyjątkiem jest wschodnia część miasta na której dane są nieco niższe. Znając wpływ zachmurzenia na jasność nocnego nieba możemy przypuszczać, iż ta wartość zmierzona została podczas nocy bezchmurnej. Minimalna zmierzona wartość na terenie całego miasta jest mniejsza, niż 15–16 mag/arcsec^2. Możemy przypuszczać, iż została ona zmierzona podczas trwania nocy całkowicie zachmurzonej. Dysproporcja wartości maksymalnej i minimalnej uzyskanej na każdym z punktów jest znacząca, a różnicę tę można przełożyć na kilkukrotnie jaśniejsze niebo w czasie występowania zachmurzenia. Otrzymane średnie wartości oraz ich rozkład przestrzenny są odmienne w czasie trwania różnych pór roku. Latem obserwujemy najwyższą średnią sezonową, a zimą najniższą. Otrzymane wyniki zgadzają się z wcześniejszymi rezultatami i wynikami analiz, mówiącymi, iż zimą jasność nocnego nieba wzrasta z powodu występowania dodatkowego czynnika rozpraszającego światła – pyłów zawieszonych różnej wielkości.

Posiadając wyniki pomiarów do lutego 2023 roku włącznie, ponownie policzono współczynnik korelacji, ale tym razem dla rozszerzonej liczby stanowisk i znacząco większej ilości zarejestrowanych danych. Uzyskując dane ze stacji IMGW Toruń-Wrzosy dla okresu 2022–2023 zauważono jednak, iż od kwietnia 2022 roku brakuje w nich wartości określającej stopień zachmurzenia w godzinach nocnych. Parametr ten określany był do tej pory manualnie, a toruńska Stacja IMGW od tego terminu po godzinie 22:00 pozyskiwała jedynie wartości zapisywane automatycznie. Możliwe pozostało jednak porównanie wyników powierzchniowej jasności nocnego nieba w odniesieniu do wysokości chmur. Tym razem wyliczony współczynnik korelacji przedstawiony został przestrzennie na tle mapy Torunia i przedstawia go rycina 16. Uzyskaną korelację podzielono na 3 grupy: o współczynniku mniejszym niż 0,3, znajdującym się w przedziale od 0,3 do 0,5 oraz większym niż 0,5. W odniesieniu do całorocznych badań najwyższą korelację obserwujemy na obszarach wykazujących się dużą ilością zabudowy oraz licznie występującą infrastrukturą oświetleniową. Niższa korelacja obserwowana jest w miejscach charakteryzujących się większym oddaleniem od ulicznych świateł, natomiast korelacji między danymi praktycznie nie obserwujemy na stanowiskach oddalonych od centrum miasta, na obszarach wykazujących mniejszy stopień zanieczyszczenia światłem. Analizując rozkład przestrzenny podczas trwania kolejnych pór roku, możemy zaobserwować podobną zależność, co w poprzednich przeprowadzonych badaniach [P5]. Jednak rozpatrując korelację przestrzennie, w odniesieniu do warunków zabudowy, możemy zauważyć, iż korelacja zmniejsza się zarówno poprzez występowanie nowego rozpraszającego światło czynnika czyli pyłów pochodzących z instalacji grzewczych, co jest widoczne zimą i wczesną wiosną na obszarach o dużym nagromadzeniu zabudowy, jak i w miejscach oddalonych od centrum miasta, wykazujących się niewielkim stopniem zanieczyszczenia światłem.



Rycina 16. Rozkład przestrzenny korelacji powierzchniowej jasności nocnego nieba i wysokości podstawy chmur, w podziale na występujące sezony obserwacyjne.

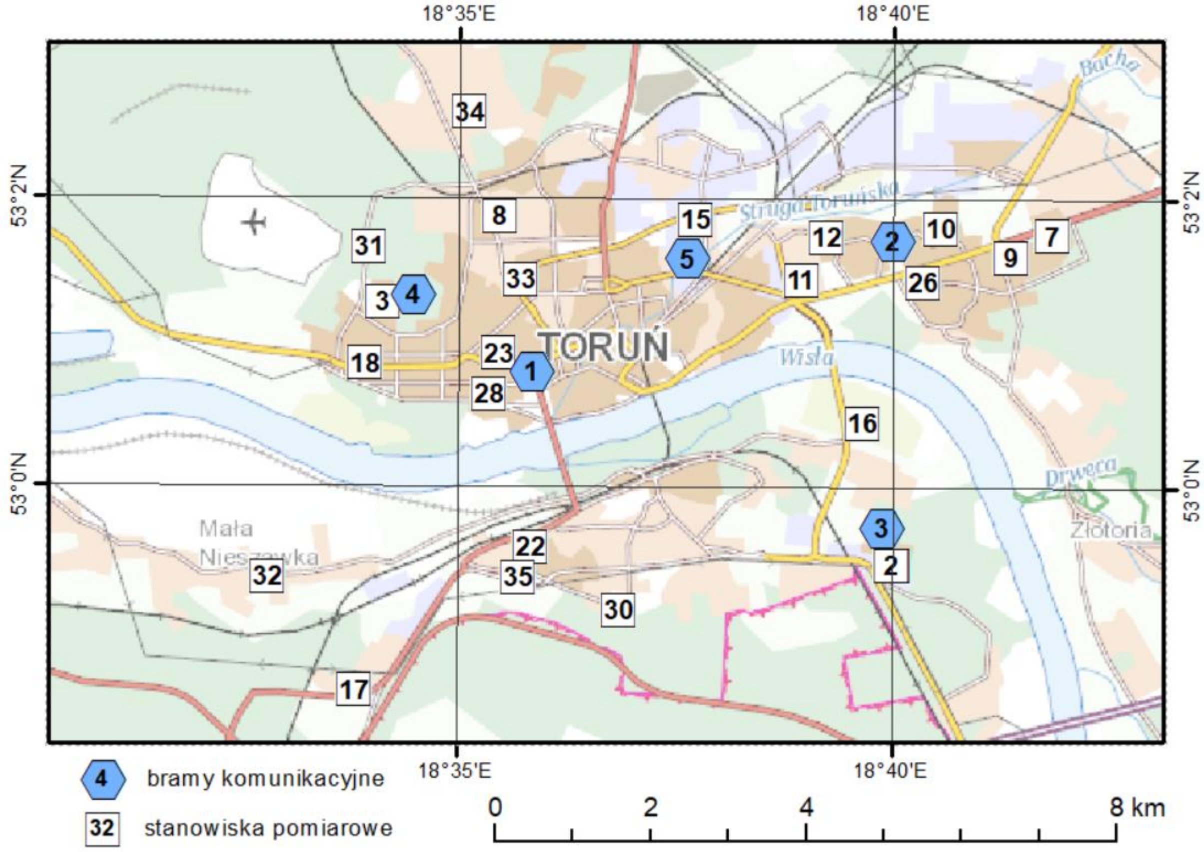
Dodatkowo przeprowadzoną analizą, wykorzystującą dane zebrane zarówno przez autorskie urządzenia pomiarowe, jak i fabryczne fotometry SQM, było zestawienie wyników w odniesieniu występowania różnych faz Księżyca. Badania miały na celu sprawdzenie czy jego obecność istotnie wpływa na pomiary powierzchniowej jasności nocnego nieba na terenach zabudowanych, tak samo, jak na te realizowane poza aglomeracjami miejskimi (Cinzano i in. 2001). W tym celu zestawiono ze sobą wyniki pomiarów zgromadzone na stanowisku w Klaninach, Koniczynce oraz na Tarasie Obserwacyjnym UMK (fotometry SQM) wraz z danymi zebranymi przez autorskie urządzenia znajdujących się na obszarch dużych osiedli mieszkaniowych (stanowiska nr 8, 12 i 23). Otrzymane wyniki przedstawiono na rycinie 17, dodatkowo oznaczając występowanie Księżyca w pełni. Analizując wyniki możemy zauważyć, że, im dalej zlokalizowany od centrum miasta jest punkt pomiarowy, tym większy wpływ na odczyt ma obecność Księżyca. Dane zebrane na stanowisku w Klaninach doskonale pokazują cykl księżycowy, a mniejszą zależność ograniczoną wpływem łuny świetlnej od sąsiadującego miasta obserwujemy niedaleko granic Torunia – w Koniczynce. W pozostałych pomiarach zlokalizowanych na terenach miejskich takiej zależności już nie obserwujemy. Sztuczne światło emitowane w mieście niweluje wpływ Księżyca i nie ma on przez to znaczącego wpływu na powierzchniową jasność nocnego nieba nad miastem.



Rycina 17. Pomiary zanieczyszczenia światłem przeprowadzone na stanowiskach KLAN (Klaniny), KON (Koniczynka) i UMK (Taras Obserwacyjny WNoZiGP UMK) przez fotometry SQM-LU oraz przez urządzenia własnej konstrukcji (8, 12 i 23). Symbol na górze wykresu oznacza Księżyc w pełni.

Założona w Toruniu sieć monitoringu zanieczyszczenia sztucznym światłem nocnego nieba budowana jest począwszy od kwietnia 2020 roku, gdy rozpoczęły się pilotażowe testy w siedzibie TARR dwóch prototypowych wówczas urządzeń podłączonych do pierwszej bramy komunikacyjnej. W 2021 roku swoje operacyjne funkcjonowanie rozpoczęły dwie kolejne bramy komunikacyjne, jedna zlokalizowana na terenie UMK, a druga w centralno-zachodniej części miasta przy ulicy Matejki. Umożliwiło to dołączenie do sieci monitoringu nowych urządzeń pomiarowych zlokalizowanych na stanowiskach w całej zachodniej części miasta. W lutym 2022 roku zamontowano kolejny punkt dostępowy, stwarzając możliwości planowania i montażu stanowisk po wschodniej stronie miasta. Analizując rozkład bram komunikacyjnych oraz ich operacyjny zasięg, uznano, iż konieczne jest uruchomienie jeszcze jednej bramy w centralnej części miasta. Działanie to nastąpiło to w maju 2023 roku na tarasie budynku Centrum Nowoczesności Młyn Wiedzy w Toruniu, otwierając możliwości zapełnienia wytworzonej luki przestrzennej pomiędzy efektywnie pracującymi już urządzeniami.

W chwili obecnej (czerwiec 2023) w bezprzewodowej sieci monitoringu zanieczyszczenia światłem (rycina 18) pracują w pełni operacyjne już 22 urządzenia własnej konstrukcji, 5 bram dostępowych (w tym 3 zewnętrzne oraz 2 wewnętrzne) oraz 3 fabryczne fotometry SQM-LU służące celom porównawczym. Planowana jest dalsza rozbudowa sieci do łącznej liczby około 40 urządzeń pomiarowych.



Rycina 18. Lokalizacja stanowisk pomiarowych oraz bram komunikacyjnych należących do sieci monitoringu zanieczyszczenia światłem budowanego w Toruniu.

Jednocześnie trwają prace nad udoskonaleniem urządzenia pomiarowego rejestrującego zanieczyszczenie sztucznym światłem. Wykorzystując zdobyte w minionych czterech latach doświadczenie zaprojektowany został jego nowy model. Urządzenie jest jeszcze bardziej kompaktowe, zasilane przez zestaw baterii o większej pojemności, co istotnie wpływa na jego długość pracy. Posiada także możliwość rozbudowy układu rejestrującego o nowe czujniki środowiskowe. Wiosną 2023 roku złożony został do Urzędu Patentowego RP wniosek o udzielenie patentu na wynalazek, chroniący prawa autorskie dotyczące skonstruowanego urządzenia w wersji 2.0, które będzie dalej wdrażane, rozwijane, oraz instalowane nie tylko w Toruniu, ale również na innych obszarach zurbanizowanych posiadających infrastrukturę sieci LoRaWAN i gotowość współpracy z zespołem ekspertów.

Podsumowanie i wnioski

Głównym celem przeprowadzonych w ramach pracy doktorskiej badań była analiza zmienności czasowej i przestrzennej zjawiska zanieczyszczenia sztucznym światłem nocnego nieba występującego nad obszarem miejskim. Dodatkowo, jako cel poboczny skonstruowano urządzenie pomiarowe działające w ramach założonej sieci monitoringu. Rozważając przedstawione powyżej wyniki własnych badań, doświadczeń i obserwacji oraz opisane wszystkie istotne etapy realizacji całego procesu badawczo-rozwojowego można dojść do wniosku, iż postawione cele zostały zrealizowane.

Wszystkie przyjęte na wstępie hipotezy zostały potwierdzone. Wykonane badania na terenie zurbanizowanym udowodniły, iż zjawisko zanieczyszczenia światłem jest możliwe do skutecznego i powtarzalnego mierzenia, a różnice między niebem miejskim oraz oddalonym od sztucznych zewnętrznych źródeł światła są dobrze widoczne i możliwe do określenia.

Dowiedziono również praktycznie, iż możliwa jest konstrukcja autorskiego urządzenia mierzącego powierzchniową jasność nocnego nieba, wykazującego podobne właściwości techniczne i operacyjne, jak fabryczne fotometry, jednak posiadającego dodatkowe funkcjonalności ułatwiające skuteczne prowadzenie długookresowych badań. Wykonalne jest także założenie nisko-kosztowej sieci pomiarowej, działającej na terenie zurbanizowanym, do której podłączone są własnej konstrukcji rejestratory, tworzące przemyślaną sieć monitoringu zanieczyszczenia światłem nocnego nieba. Współczesne osiągnięcia techniki dają wiele możliwości realizacji założonych celów projektowych, a konieczny jest jedynie odpowiedni dobór istniejących elementów, rozwiązań oraz technologii.

Zrealizowany proces badawczo-rozwojowy pokazał, iż niezbędne jest wieloaspektowe poznanie badanego zjawiska, a także jego zmienności oraz właściwości, aby docelowo zbudować aktywny system obserwacyjny w postaci sieci monitoringu. Niezbędna jest przy tym optymalizacja kilku zmiennych, począwszy od określenia liczebności stanowisk pomiarowych, ich lokalizacji terenowej, przez wysokość montażu samych rejestratorów czy przyjętych interwałów automatycznego pozyskiwania danych.

Podczas realizacji projektu doktorskiego, w ramach badań cząstkowych założono także, iż zanieczyszczenie światłem posiada zmienność, nie tylko poziomą (horyzontalną), ale także pionową (wertykalną), która wpływa na poprawny pomiar wartości. Hipoteza ta została udowodniona na podstawie zrealizowanych badań. Pozyskana w ten sposób wiedza służy lepszemu poznaniu czynników wpływających na pomiary oraz umożliwia właściwe podjęcie decyzji dotyczących umiejscowienia stanowisk pomiarowych tworzących spójną sieć monitoringu czy system obserwacyjny.

Na podstawie licznie zebranego materiału wejściowego, który został wieloaspektowo przeanalizowany, wykazano, iż zanieczyszczenie światłem nocnego nieba występującego nad miastem, charakteryzuje się zmiennością czasową i przestrzenną. Opublikowane wyniki badań wykazały tę zmienność, a uzyskany materiał dokumentacyjny wspomoże obserwacje innych badaczy z całego świata.

Ukierunkowane badania nad szerokim zakresowo i tematycznie poznaniem zmiennych wpływających na zanieczyszczenie światłem nocnego nieba oraz działania zmierzające do minimalizowania jego skutków są priorytetem osób zajmujących się tym zagadnieniem. Pomimo licznie już opublikowanych w ostatnim okresie prac i raportów z badań, konieczny jest dalszy rozwój i kolejne prace cząstkowe, w tym studia przypadku, dotyczące tej formy zanieczyszczenia antropogenicznego i wszystkich elementów z nim bezpośrednio i pośrednio związanych. Dzięki ograniczeniu zewnętrznych źródeł sztucznego oświetlenia oraz ich właściwej ekspozycji jest duża szansa, iż zjawisko zostanie powoli minimalizowane. Wpłynie to pozytywnie na zdrowie i funkcjonowanie człowieka i rozwój całego ekosystemu, a także przyniesie wymierne korzyści finansowe samorządom, instytucjom i osobom prywatnym wynikające z optymalizacji zewnętrznej infrastruktury oświetleniowej. Niezbędne w tych działaniach są regulacje prawne dotyczące emisji światła zewnętrznego wraz z określeniem metod prowadzenia powtarzalnego pomiaru i monitoringu. Zamieszczone w niniejszej pracy doktorskiej wyniki badań nad zmiennością samego zjawiska wraz z opracowaniem urządzenia pomiarowego są w tym zakresie bardzo pomocne i możliwe do wykorzystania w praktyce.

Literatura

Adafruit, 2019. Adafruit TSL2591 High Dynamic Range Digital Light, Adafruit Learning System.

Adams C.A., Blumenthal A., Fernández-Juricic E. et al., 2019. Effect of anthropogenic light on bird movement, habitat selection, and distribution: A systematic map protocol. *Environmental Evidence* 8(1): 13.

Bara S., Lima R.C., Zamorano J., 2019. Monitoring Long-Term Trends in the Anthropogenic Night Sky Brightness. *Sustainability* 11(11): 3070. https://doi.org/10.3390/su11113070.

Bennie J., Davies T.W., Cruse D., Gaston K.J., 2016. Ecological effects of artificial light at night on wild plants. *Journal of Ecology* 104(3).

Bogacz R., Krupanek B., 2013. Porównanie wybranych metod bezprzewodowego odczytu liczników energii elektrycznej. *PAK* 59(4): 337–440.

Cavazzani S., Ortolani S., Bertolo A., Binotto R., Fiorentin P., Carraro G., Saviane I., Zitelli V., 2020. Sky Quality Meter and satellite correlation for night cloud-cover analysis at astronomical sites. *Monthly Notices of the Royal Astronomical Society* 493(2): 2463–2471.

Chaładyniak D., 2011. Wybrane technologie bezprzewodowej transmisji danych. *Zeszyty Naukowe Warszawskiej Wyższej Szkoły Informatyki* 5: 87–101.

Cinzano P., Falchi F., Elvidge C.D., Baugh KE, 2000. The artificial night sky brightness mapped from DMSP satellite Operational Linescan System measurements. *Monthly Notices of the Royal Astronomical Society* 318: 641–657.

Cinzano P., Falchi P.F., Elvidge C.D., 2001. The first World Atlas of the artificial night sky brightness. *Monthly Notices of the Royal Astronomical Society* 328: 689–707.

Connors B.M., 2010. Effect of artificial light on marine invertebrate and fish abundance in an area of salmon farming. *Marine Ecology Progress Series* 419: 147–156.

Elvidge C.D., Baugh K.E., Zhizhin M., Hsu F.C., 2013. Why VIIRS data are superior to DMSP for mapping nighttime lights. *Proceedings of the Asia-Pacific Advanced Network* 35: 62–69.

Elvidge C.D, Baugh K., Zhizhin M., Hsu F.C., Ghosh T., 2017. VIIRS night-time lights. *Int. J. Remote Sens*. 38: 5860–5879.

Erwiński K., Karpińska D., Kunz M., Paprocki M., Czokow J., 2023. An Autonomous City-Wide Light Pollution Measurement Network System Using LoRa Wireless Communication. *Sensors* 23(11): 5084.

Falchi F., Cinzano P., 2016. The new world atlas of artificial night sky brightness. *Science Advances* 2(6).

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.

Falchi F., Ramos F., Bará S., Sanhueza P., Arancibia M.J., Damke G., Cinzano P., 2023. Light pollution indicators for all the major astronomical observatories. *Monthly Notices of the Royal Astronomical Society* 519(1): 26–33. https://doi.org/10.1093/mnras/stac2929.

Fonken L.K., Nelson R.J., 2013. Dim light at night increases depressive-like responses in male C3H/ HeNHsd mice. *Behavioural Brain Research* 243: 74–78.

Fonken L.K., Workman J.L., Walton J.C. et al. 2010. Light at night increases body mass by shifting the time of food intake. *Proceedings of the National Academy of Sciences* 107(43): 18664–18669.

Gallaway T., Olsen R.N., Mitchell D.M., 2010. The economics of global light pollution. *Ecological Economics* 69(3): 658–665.

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.

Gaston K.J., Bennie J., Davies T.W. et al. 2013. The ecological impacts of nighttime light pollution: A mechanistic appraisal. *Biological Reviews* 88(4): 912–927.

Glover K., 2011. Intelligent opto sensor Designer's Notebook: Using the Lux Equation. Technical Report; AMS OSRAM: Munich, Germany.

Haim A., Portnov B., 2013. *Light Pollution as a New Risk Factor for Human Breast and Prostate Cancers.* Springer: Heidelberg, Germany.

Hänel A., Posch T., Ribas SJ., Aubé M., Duriscoe D., Jechow A., Kollath 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.

International Dark-Sky Association, The International Dark Sky Places conservation program recognizes and promotes excellent stewardship of the night sky. (online: https://www.darksky.org/our-work/conservation/idsp/ (access: 29.12.2022)).

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., Hölker F., Kyba C.C.M., 2019. Using all-sky differential photometry to investigate how nocturnal clouds darken the night sky in rural areas. *Scientific Reports* 9: 1391. https://doi.org/10.1038/s41598-018-37817-8.

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.

Karpińska D., Kunz M., 2020a. Ochrona nocnego nieba - wyzwanie dla Rezerwatu Biosfery Bory Tucholskie. W: Kunz M. (red.), *Rola i funkcjonowanie parków krajobrazowych w rezerwatach biosfery*/ Toruń, Wydawnictwo Naukowe UMK: 329–346, ISBN 978-83-231-4480-9.

Karpińska D., Kunz M., 2020b. Analysis of light pollution of the night sky in Toruń (Poland). *Civil and Environmental Engineering Reports*: 155–172.

Karpińska D., Kunz M., 2020c. Zanieczyszczenie nocnego nieba światłem na przykładzie Torunia. W: Młynarczyk A. (ed.), *Środowisko przyrodnicze jako obszar badań*, Bogucki Wydawnictwo Naukowe, Poznań: 93–112.

Karpińska D., Kunz M., 2020d. Wpływ pokrycia terenu na zanieczyszczenie światłem nocnego nieba. *Badania z zakresu nauk przyrodniczych – nowe trendy*, Lublin: 206–223.

Karpińska D., Kunz M., 2021a. Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area – a case study of the Bielany campus at the Nicolaus Copernicus University in Toruń. *Bulletin of Geography. Socio-Economic Series* 54: 137–149.

Karpińska D., Kunz M., 2021b. Rekonstrukcja zasięgu widoczności sieci LoRaWAN na terenie kampusu UMK w Toruniu. W: Młynarczyk A. (ed.), *Środowisko przyrodnicze jako obszar badań*, Bogucki Wydawnictwo Naukowe, Poznań: 47–60.

Karpińska D., Kunz M., 2021c. Comparison of two measurement methods – photometric and photographic – in studies of the night sky brightness. *Ecological and astronomical aspects of light pollution*, Edited by Tomasz Ściężor, Wydawnictwo Politechniki Krakowskiej, Kraków: 57–68.

Karpińska D., Kunz M., 2022a. Device for automatic measurement of light pollution of the night sky. *Scientific Reports* 12. https://doi.org/10.1038/s41598-022-20624-7.

Karpińska D., Kunz M., 2022b. Optymalizacja rozmieszczenia sieci pomiarowej do monitoringu zanieczyszczenia światłem nocnego nieba na przykładzie Torunia. W: Młynarczyk A. (ed.), *Środowisko przyrodnicze jako obszar badań*, Bogucki Wydawnictwo Naukowe, Poznań: 9–24.

Karpińska D., Kunz M., 2023a. Vertical variability of night sky brightness in urbanised areas. *Quaestiones Geographicae* 42(1): 5–14.

Karpińska D., Kunz M., 2023b. Relationship between the surface brightness of the night sky and meteorological conditions. *Journal of Quantitative Spectroscopy & Radiative Transfer* 306: 1–8.

Karpińska D., Kunz M., 2023c. Measuring light pollution in the night sky – from technology demonstrator to monitoring system. *Civil and Environmental Engineering Reports* 33(1): 0053–0070.

Karpińska D., Kunz M., 2023d. Spatial and temporal analysis of artificial light pollution of the city night sky. A case study from Toruń. *Miscellanea Geographica. Regional Studies on Development* 27(3): 1–11.

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. W: Wiśniewska M.R., Tomasik K. (ed.), *Przejdź na ciemną stronę nocy. Środowiskowe i społeczne skutki zanieczyszczenia światłem*. Wyd. Uniwersytetu Warszawskiego. Warszawa: 29–46.

Kotarba A., 2015. Satelitarne obserwacje nocnych świateł Ziemi. W: Wiśniewska M.R., Tomasik K. (ed.), *Przejdź na ciemną stronę nocy. Środowiskowe i społeczne skutki zanieczyszczenia światłem.* Wyd. Uniwersytetu Warszawskiego. Warszawa: 47–60.

Kotarba A., Chacewicz S., Żmudzka E., 2019. Night sky photometry over Warsaw (Poland) evaluated simultaneously with surface-based and satellite-based cloud observations. *Journal of Quantitative Spectroscopy and Radiative Transfer* 235. DOI: 10.1016/j.jqsrt.2019.06.024.

Kyba C.C.M., Coesfeld J., 2021. Satellite Observations Show Reductions in Light Emissions at International Dark Sky Places During 2012–2020. *International Journal of Sustainable Lighting* 23(2): 51–57.

Lacoeuilhe A., Machon N., Julien J-F. et al. 2014. The influence of low intensities of light pollution on bat communities in a semi-natural context. *PLoS One* 9(10): e103042.

Lennox R.J., Chapman J.M., Souliere C.M. et al. 2016. Conservation physiology of animal migration. Conservation Physiology 4(1). (online: https://academic.oup.com/conphys/article/4/1/cov072/2951315).

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.

Lorabit, 2019a. lorabit.pl, Available online: https://lorabit.pl/co-mozna-zrobic-z-protokolem-lora/(10.08.2021).

Lorabit, 2019b. lorabit.pl, (online: https://lorabit.pl/czestotliwosci-regionalne-lorawan/(12.08.2021)).

Mander S., Alam F., Lovreglio R., Ooi M., 2023. How to measure light pollution—A systematic review of methods and applications. *Sustainable Cities and Society* 92: 104465, https://doi.org/10.1016/j.scs.2023.104465.

Mikhaylov K., Stusek M., Masek P., Petrov V., Petäjäjärvi J., Andreev S., Pokorny J., Hosek J., Pouttu A., Koucheryavy Y., 2018. Multi-RAT LPWAN in Smart Cities: Trial of LoRaWAN and NB-IoT Integration. *IEEE International Conference on Communications* (*ICC*): 1–6. DOI: 10.1109/ICC.2018.8422979.

Ministry of the Environment of the Czech Republic, 2022. *Light pollution reduction measures in Europe.* Working paper for international workshop "Light Pollution 2022", during the Czech Presidency of the Council of the European Union, 60 p.

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.

POLARIS-OPP, 2023. Obszary CN-000 (online: https://www.ciemneniebo.pl/pl/obszary-cn-000).

Pun C.S.J., So C.W., Leung W.Y., Wong C.F., 2014. 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.

Ragam P., Nimaje D.S., 2019. Performance evaluation of LoRa LPWAN technology for IoT-based blast-induced ground vibration system. *Journal of Measurements in Engineering* 7(3): 119–133.

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.

Rodrigo-Comino J., Seeling S., Seeger M.K., Ries J.B., 2021. Light pollution: A review of the scientific literature. *The Anthropocene Review*: 1–26.

Semtech Corporation, 2015. AN1200.22 LoRa™ Modulation Basics, Wireless Sensing and Timing Products. Application Note.

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.

STMicroelectronic, 2020a. STM32L0 Discovery kit LoRa, Sigfox, low-power wireless. https://www.st.com/en/evaluation-tools/b-l072z-lrwan1.html#overview.

STMicroelectronics, 2020b. Motion MEMS and environmental sensor expansion board for STM32 Nucleo. (online: https://www.st.com/en/ecosystems/x-nucleo-iks01a2.html).

Szlachetko K., 2022. red. *Memorandum w sprawie ustanowienia prawnych podstaw zrównoważonej polityki oświetlenia zewnętrznego*. Instytut Metropolitarny, Gdańsk, 48 p.

Ścieżor T., Kubala M., Kaszowski W., Dworak TZ., 2010. *Zanieczyszczenie świetlne nocnego nieba w obszarze aglomeracji krakowskiej. Analiza pomiarów sztucznej poświaty niebieskiej.* Wyd. Politechniki Krakowskiej. Kraków.

Ściężor T., 2013. A new astronomical method for determining the brightness of the night sky and its application to study long-term changes in the level of light pollution. *Monthly Notices of the Royal Astronomical Society* 435(1): 303–310.

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., 2021. Effect of Street Lighting on the Urban and Rural Night-Time Radiance and the Brightness of the Night Sky. *Remote Sens* 13(9). https://doi.org/10.3390/rs13091654.

Święczkowski M., Dobrzycki S., Kuźma Ł., 2023. Multi-City Analysis of the Acute Effect of Polish Smog on Cause-Specific Mortality (EP-PARTICLES Study). *Int. J. Environ. Res. Public Health* 20(8): 5566 DOI: 10.3390/ijerph20085566.

Tomaszewski D., 2020. 11 mitów na temat technologii LoRaWAN. *Elektronik*: 78–81.

Turčinović F., Vuković J., Božo S., Šišul G., 2020. Analysis of LoRa Parameters in Real-World Communication. *2020 International Symposium ELMAR*: 87–90. DOI: 10.1109/ELMAR49956.2020.9219028.

Wang L.K., Pereira N.C., Hung Y.T., 2004. *Air Pollution Control Engineering. Handbook Of Environmental Engineering* 1. Humana Press.

Whaiduzzaman M., Barros A., Chanda M., Barman S., Sultana T., Rahman M.S., Roy S., Fidge C.A., 2022. Review of Emerging Technologies for IoT-Based Smart Cities. *Sensors* 22: 9271

Zhang C., Pei Y., Li J., Qin Q., Yue J., 2019. Application of Luojia 1-01 Nighttime Images for Detecting the Light Changes for the 2019 Spring Festival in Western Cities. *Remote Sensing* 12: 1416.

Zubidat A.E., Haim A., 2017. Artificial light-at-night—A novel lifestyle risk factor for metabolic disorder and cancer morbidity. *J. Basic Clin. Physiol. Pharmacol*. 28: 295–313.

Streszczenie

Otaczające nas środowisko przyrodnicze narażone jest na wpływ wielu różnych form zanieczyszczeń, głównie pochodzenia antropogenicznego. Powszechnym zjawiskiem, obserwowanym nad obszarami zurbanizowanymi i w ich bezpośrednim sąsiedztwie jest zanieczyszczenie sztucznym światłem nocnego nieba. Jest to istotny problem współczesnego nocnego krajobrazu miasta. Spadek jakości wizualnej nocnego nieboskłonu dostrzegają zarówno naukowcy, zajmujący się tą dziedziną, jak i zwykli mieszkańcy. Konsekwencje nadmiernej ilości sztucznego światła w dolnej części troposfery dostrzegalne są w całym ekosystemie i dotyczą zarówno człowieka, jak i zwierząt oraz roślin. Koniecznością staje się poprawa stanu zanieczyszczonego światłem nocnego nieba w większości już dzisiaj miejsc na świecie. W celu poznania skali i rozkładu zjawiska niezbędny jest jego długookresowy monitoring oraz dalsze analizy dotyczące jego charakterystyki, zmienności oraz składowych. Systematyczne i ukierunkowane badania nad problematyką nadmiernej zewnętrznej emisji sztucznego światła prowadzi na świecie tylko kilka interdyscyplinarnych grup badawczych oraz organizacji pozarządowych. Aby lepiej poznać opisywane zjawisko, w Toruniu w 2020 roku założona została bezprzewodowa, automatyczna sieć monitorująca stan miejskiego nocnego nieba i od tej pory jest ona systematycznie rozbudowywana. W ramach rozprawy doktorskiej przedstawiono cały proces budowy sieci monitoringu zanieczyszczenia światłem na obszarze zurbanizowanym, oraz wyniki przeprowadzanych testów i analiz wykonanych na podstawie danych pomiarowych zarejestrowanych przez własnej konstrukcji urządzenia pomiarowe. Zrealizowane badania naukowe pozwoliły nie tylko na poznanie stopnia zanieczyszczenia sztucznym światłem na obszarze Torunia, ale także na poznanie sezonowej oraz przestrzennej (poziomej i pionowej) zmienności opisywanego zjawiska. Dzięki zastosowaniu dodatkowych niezależnych fotometrów uzyskane wyniki badań odniesione zostały także do wyników otrzymanych na obszarach poza skupiskami ludzkimi. Pozwoliło to na określenie zróżnicowania zanieczyszczenia światłem w gradiencie zmieniającego się oddziaływania człowieka.

Słowa kluczowe: zanieczyszczenie światłem, sieć monitoringu, LoRaWAN, nocne niebo, pomiary wertykalne, rozkład przestrzenny, SQM, Toruń

Summary

The natural environment that surrounds us is exposed to the influence of many different pollutants, mainly of anthropogenic origin. A common phenomenon observed over urbanized areas and in their immediate vicinity is artificial light pollution of the night sky. This is a significant problem of the modern night city landscape. The decrease in the visual quality of the night sky is noticed by both scientists dealing with this field and ordinary inhabitants. The consequences of excessive amounts of artificial light in the lower part of the troposphere are noticeable throughout the ecosystem and affect humans, animals and plants. It becomes necessary to improve the condition of the light-polluted night sky in most places in the world today. To understand the scale and distribution of the phenomenon, its long-term monitoring and further analysis of its characteristics, variability and components are necessary. Systematic and focused research on the issue of excessive external emission of artificial light is conducted in the world by only a few interdisciplinary research groups and non-governmental organizations. To better understand the described phenomenon, a wireless, automatic network monitoring the state of the urban night sky was established in Toruń in 2020, and since then it has been systematically expanded. As part of the doctoral dissertation, the entire process of building a light pollution monitoring network in an urbanized area was presented, as well as the results of tests and analyses carried out based on measurement data recorded by self-designed measuring devices. The scientific research carried out allowed us not only to know the degree of artificial light pollution in the area of Toruń, but also to know the seasonal and spatial (horizontal and vertical) variability of the described phenomenon. Thanks to the use of additional independent photometers, the obtained results were also related to the results obtained outside human clusters. This allowed us to determine the differentiation of light pollution in the gradient of decreasing human impact.

Keywords: light pollution, LoRa, monitoring network,LoRaWAN, night sky, vertical measurement, spatial distribution, SQM, Toruń

Załącznik 1: Artykuły naukowe wchodzące w skład zbioru publikacji

Karpińska Dominika, Kunz Mieczysław, **2021**. Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area: a case study of the Bielany campus at the Nicolaus Copernicus University in Toruń. *Bulletin of Geography. Socio-Economic Series* 54: 137–149.
https://doi.org/10.2478/bog-2021-0039

Erwinski Krystian, **Karpinska Dominika**, Kunz Mieczysław, Paprocki Marcin, Czokow Jarosław, **2023**. An Autonomous City-Wide Light Pollution Measurement Network System Using LoRa Wireless Communication. *Sensors* 23(11): 5084.
https://doi.org/10.3390/s23115084

Karpińska Dominika, Kunz Mieczysław, **2022**. Device for automatic measurement of light pollution of the night sky. *Scientific Reports* 12(1): 1–12.
https://doi.org/10.1038/s41598-022-20624-7

Karpińska Dominika, Kunz Mieczysław, **2023**. Vertical variability of night sky brightness in urbanised areas. *Quaestiones Geographicae* 42(1): 5–14.
https://doi.org/10.2478/quageo-2023-0001

Karpińska Dominika, Kunz Mieczysław, **2023**. Relationship between the surface brightness of the night sky and meteorological conditions. *Journal of Quantitative Spectroscopy & Radiative Transfer* 306: 1–8.
https://doi.org/10.1016/j.jqsrt.2023.108621

Karpińska Dominika, Kunz Mieczysław, **2023**. Measuring light pollution in the night sky – from technology demonstrator to monitoring system. *Civil and Environmental Engineering Reports* 33(1): 0053–0070.
https://doi.org/10.59440/ceer-2023-0004

Karpińska Dominika, Kunz Mieczysław, **2023**. Spatial and temporal analysis of artificial light pollution of the city night sky. A case study from Toruń. *Miscellanea Geographica. Regional Studies on Development* 27(3): 1–11.
https://doi.org/10.2478/mgrsd-2023-0015

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Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area – a case study of the Bielany campus at the Nicolaus Copernicus University in Toruń

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Abstract. In order to assess or determine the overall quality of the surrounding geographical environment, it is necessary to measure selected factors that directly or indirectly affect its condition. The aspects to be monitored include i.a. air pollution levels, surface water purity, soil erosion rates, as well as night sky light pollution, a phenomenon increasingly often observed with the unaided eye. To collect data on the night sky brightness on a regular basis, a remote measuring device was designed and constructed using specialised electronic components, wireless communication, programming code, a high-sensitivity digital light data logger and custom-made programme code. LPWAN networks, including LoRa technology, were developed to support a number of mobile devices where long wireless operation is a priority. To determine the potential use of LoRa technology, as well as to plan the target locations of network access gates (gateways) and the deployment of measuring devices for the collection of environmental data, tests of signal coverage and signal visibility, including measurements of its strength, were carried out in a selected, compact part of the city of Toruń. The paper presents the results of research on the visibility of the LoRa network in a built-up area, such as a university campus, using antennas of two different lengths. The obtained results can be used to design distributed measurement networks in areas with varying density of buildings.

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Toruń

Contents:

1. Introduction

Through technological development and successively implemented industrial solutions, man has a significant impact on the surrounding natural environment in all its dimensions. Along with the global development of civilisation, the natural space for the free functioning of organisms and the natural cycle of nature has been limited. Most of the environmental compartments (including the most perceptible ones – air, soil and water) have already been polluted to varying degrees, which can be observed both in the vertical and horizontal gradients, both in urban areas and outside their formal borders and outside human settlements (Lawrence et al., 2004; Qadri et al., 2020; Arsovski et al., 2018).

Each of the diagnosed factors negatively affecting the natural environment should be subject to long-term measurements and targeted monitoring. This helps to understand the specifics of the analysed phenomenon, its impact on the environment, as well as to assess the directions and strength of its spread, and to determine the spatial extent and limits of its occurrence. Such measures help to ultimately create effective mechanisms for limiting and counteracting these negative factors. There are many commonly used methods of measuring phenomena observed in the natural environment. These include measurements made with the use of manual recording devices – detectors, in which the measured value is shown on a display or saved on a memory device (Hänel et al., 2017; Jechow et al., 2019; Ścieżor et al., 2010). There are also more automated measurement methods carried out by means of distributed sensors placed at the target location and remotely transmitting data packets to a server specified in the transmission protocol. In the latter method, measurements are performed with the help of wireless data transmission technology and multidirectional device communication, which is an important element of the Fourth Industrial Revolution (Industry 4.0).

The objective of this work was to analyse and visualise the visibility of the LoRaWAN network in a built-up area using various hardware configurations – antennas of different lengths. The field explorations were aimed at investigating the quality of the LoRaWAN network signal in the Bielany campus, Nicolaus Copernicus University in Toruń, which reflects the typical traditional, dispersed urban development, and therefore can serve as a good testing ground for assessing its applicability for urban areas.

2. Study area

Nicolaus Copernicus University (NCU) in Toruń is the largest university in northern Poland. It is also one of the best universities in the country, which in 2019 was awarded the prestigious status of a research university as part of the "Excellence Initiative – Research University" programme. The NCU centre is distinguished not only in terms of academic potential, the variety of courses offered or the number of students and graduates, but also by the fact that most of its units are located within the university estate in Bielany (Popławski, 1982), which has been designed from scratch, inspired by the American concept of campuses (Fig. 1). This is the location of more than half of the faculties of the Toruń part of the University, the central administration (rector's office), the Main Library,

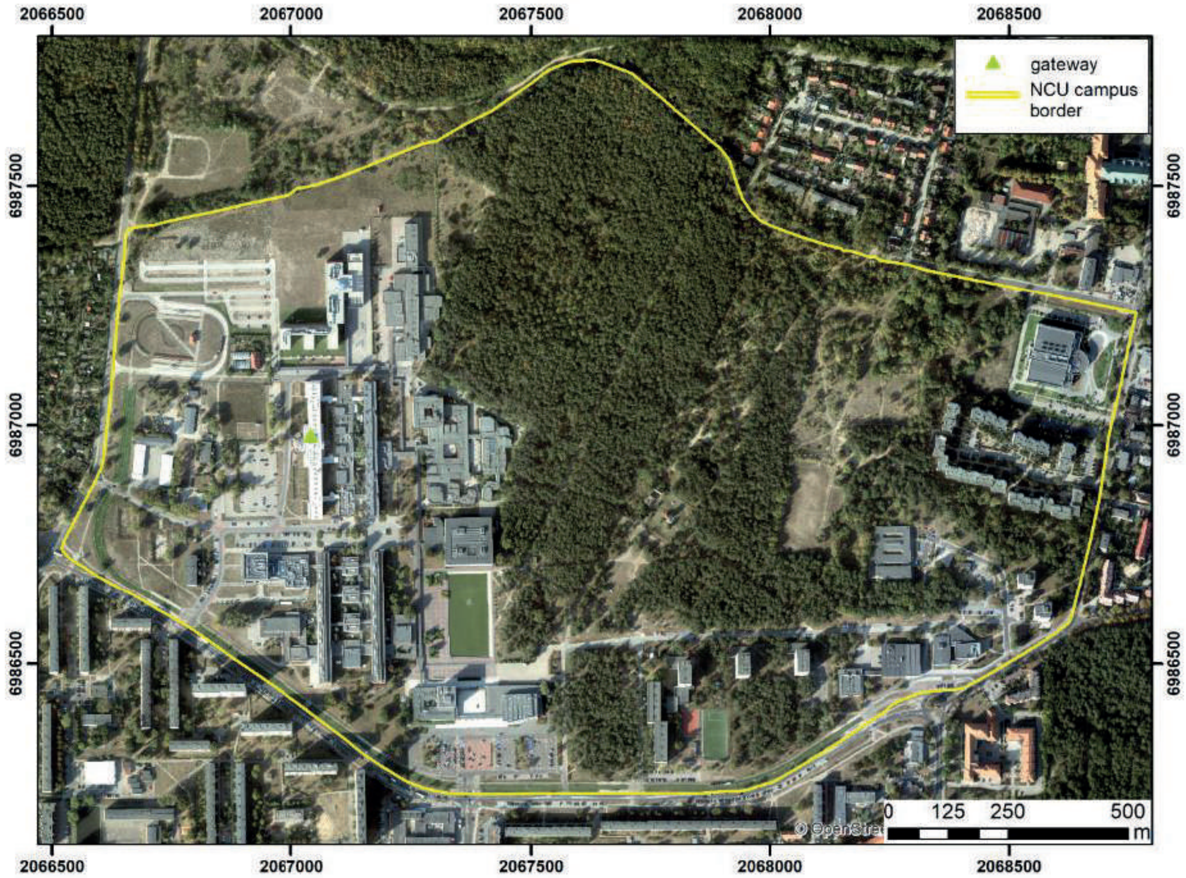

Fig. 1. Orthophotomap of the Nicolaus Copernicus University campus in Toruń with the location of the access gateway and boundaries of the area.
Source: Authors' own elaboration.

educational facilities, research units, university centres, auditoria, student dormitories, and university staff accommodations, and this is also where student life and sport activities are concentrated (Kunz, 2012). The NCU campus was included in the register of monuments by the Kujawy-Pomerania Provincial Heritage Monuments Protection Office in May 2019, which proves its exceptional urban and artistic values.

The height structure of the campus is distinguished by the dominance of 2-storey buildings with a low, fully functional ground floor, but with an atypical, non-standard storey height (about 3.5 m); the Rector's office, consisting of as many as seven levels, is the highest building in the campus.

3. Material and methods

Wireless data transmission technologies are increasingly used during the monitoring of different elements of the natural environment. The use of wireless communication enables measurements of specific parameters in many previously inaccessible locations, including non-urban areas, their viewing and reading at any time, and the inclusion of a given location in the measurement network.

3.1. Wireless data transmission technologies

The available methods of wireless data exchange include well-known technologies such as Wi-Fi, Bluetooth, and GSM (from 2G, through 3G, 4G, to already widely popular 5G). Each of the above mentioned solutions has defined technical and quality parameters, specific technical and infrastructural requirements, as well as limitations in their application (Bogacz & Krupanek, 2013). In terms of remote environmental measurements, the most important characteristics of wireless technologies include the transmission/communication range and power consumption affecting the operating time of a device on a single power supply set. Bluetooth and Wi-Fi technology has a range of several dozen metres and is ideal for sending data over short distances. The commercial GSM network, which has a much longer range, can be used to send data over long distances (Tomaszewski, 2020). Wi-Fi and GSM networks are characterised by the ability to transmit large amounts of data, but the consequence of this process is higher power consumption during data transmission (Chaładyniak, 2011). In terms of accommodating different needs and expectations, which relate to both cost reduction, energy efficiency and long-distance transmission, and supporting cloud logging, LPWAN (Low Power Wide Area Net-work) proved to be the best choice for data transmission, with Sigfox, LoRaWAN and NB-IoT being the most popular standards (Mikhaylov et al., 2018). Each of these standards is characterised by different parameters and specific applications.

Installation of an LPWAN network constitutes part of a larger research project aimed at determining the light pollution of the night sky in Toruń, which is measured using an original, in-house prototype of an autonomous, low-cost measurement set. Forty repeatable devices were constructed, which will form a "distributed measurement cloud" and will ultimately enable monitoring of the entire area of a medium-sized city of approximately 100 km2. Different data transfer technologies were considered for this part of the project, but after analysing their potential possibilities, LoRa technology, which is part of the LoRaWAN standard (Piątek, 2018), was selected.

The LoRaWAN standard is a long-range radio MAC (Medium Access Control) communication protocol that allows devices to connect to the network with low power consumption (Semtech, 2015). LoRaWAN is one of the solutions used for communication of Internet of Things (IoT) devices, which supports the idea of Smart Cities (Lozynskyy et al., 2021) as part of Smart Environment and an element of Industry 4.0 (Turčinovićet al., 2020). It is used in many applications, not only in the field of modern traffic, logistics or environmental solutions, but increasingly also for the management of entire housing estates or large settlement units – towns, cities and agglomerations (Gaël et al., 2019; Lorabit, 2019a: Ragam & Nimaje, 2019). LoRa (Long Range), in turn, is a wireless communication technology programmed for the LoRaWAN standard. In terms of product positioning, LoRa technology fills an existing niche between widely available technologies, such as Wi-Fi, Bluetooth and LTE, and stands out in terms of both reduced operating costs, possible data transmission distances and, above all, energy efficiency due to low requirements for high transmission power (Fig. 2).

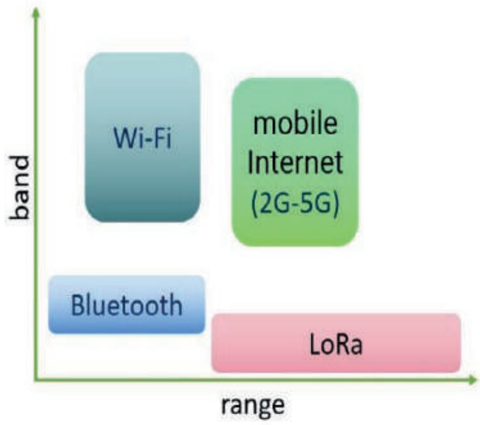

Fig. 2. Schematic comparison of the selected parameters of the wireless technologies.
Source: Authors' own elaboration.

3.2. Methodology of LoRaWAN network signal measurements

The first step in the process of determining the LoRaWAN network signal visibility on the NCU campus in Toruń was to find the potential and optimal, in terms of key parameters, location of the external network access gateway (Karpińska & Kunz, 2021). Ultimately, the most spatially advantageous and accessible location turned out to be the observation deck located on the roof of the two-storey building of the Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University (Fig. 3), which is an integral part of the Meteorological Observatory.

The access gateway of the American company Multi-Tech Systems Inc. together with the external antenna was installed in a permanent way at an

Fig. 3. 360° panorama from the observation deck of the Faculty of Earth Sciences and Spatial Management NCU in Toruń.
Source: Authors' own elaboration.

altitude of 71 m a.s.l. and at the same time 15 m above the ground. Geographic coordinates of the installation site are as follows: 53°1'17.23"N and 18°34'6.45"E. In the horizontal surroundings of the communication gate (see Figure 3), there are university buildings of a similar height, and in the farther perspective – a multi-family housing estate with high buildings (mainly 11-storey tower blocks) in the south, recreational plots and the airport of the Pomeranian Aero Club in the west, a single-family housing estate in the north, and so-called Lasek Bielański (Bielany Forest), i.e. a dune foreland covered with mature coniferous forest stands.

The network signal visibility tests on the NCU campus in Toruń were carried out using two different antennas with a length of 34 and 82 cm (Fig. 4). In the developed assumptions of the designed research, the selection of an appropriate antenna length is an important element in determining the signal coverage, but in densely built-up areas the importance of this parameter is reduced in favour of other variables. The mDOT Box tester from Multi Tech Systems Inc. was used to test the visibility of the LoRaWAN network (Fig. 5). The device is of compact design and has several measurement modes that facilitate data collection and its correct positioning in the geographical space.

To verify the visibility of the signal, the tester uses the single sweep mode, in which the unit availability to the LoRaWAN network is checked for a selected transmission power and a length (size) of the generated message. The device also has a built-in GPS module, which facilitates the spatial location of measurement points. According to the manufacturer (MultiConnect 2020; Multi-Tech Systems 2020), the following information is displayed in one data frame during the reading:

- identifier (ID) of a measurement point,

Fig. 4. External communication gateway of the LoRaWAN network with 34 cm (left) and 82 cm (right) antennas.
Source: Authors' own elaboration.

Fig. 5. Compact LoRaWAN mDOT tester from Multi Tech Systems, Inc. used in the field tests.
Source: Authors' own elaboration.

- location of a measurement point (XY),
- number of a communication gateway, the access to which is being checked,
- factor determining the quality of the signal, so-called margin,
- normalised indicator of received energy, both in terms of signal and noise, so called RSSI (Received Signal Strength Indication),
- Signal to Noise Ratio, so-called SNR.

Of the last three above-mentioned key pieces of information contained in the data frame, the margin factor was selected for further analysis and preparation of LoRaWAN signal visibility maps. It represents the quantified quality of the connection between the tester and the access gateway, with values ranging from 0 to 30 dBm, where higher value indicates better quality of the established communication. In terms of functionality, the best – very good (expected) connection between devices is obtained when the value of the margin factor ranges between 20 and 30 dBm. The value of 12–20 dBm indicates good quality of the signal, and 0 dBm or not value at all translates to an inability to establish a connection with the access gateway (Multi-Tech Systems 2020).

The quality of the LoRaWAN network signal on the NCU campus was determined at points forming an irregular grid covering the entire study area and its immediate surroundings. Measurements were conducted at a height of 1.5 m above the ground. The intervals between the measurement points ranged from a dozen to several dozen metres and covered all places available for pedestrian exploration, i.e. roads, paths and traffic routes, squares, car parks, lawns and urban green space. The points were selected in such a way as to make it possible to determine the availability of the LoRaWAN network at any location, even in so-called building shadow, which is often the case in densely built-up areas or tower blocks. It was assumed that the quality of the transmitted signal is affected by spatial barriers, i.e. buildings of any cubic capacity (Fig. 6), plantings,

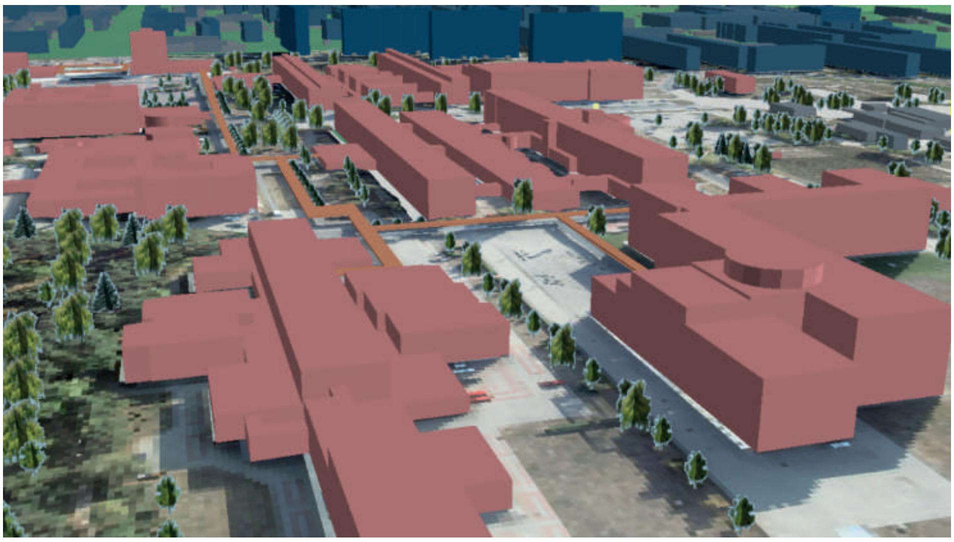

Fig. 6. Three-dimensional visualisation of a part of the NCU campus in Toruń viewed from the south-western side; red colour indicates University buildings, and blue colour indicates all buildings outside the campus.
Source: Authors' own elaboration.

natural visibility obstructions – slopes, cliffs, as well as the increasing Euclidean distance from the access gateway.

4. Results

After collecting the necessary field measurement data, the LoRaWAN signal visibility analysis was performed using ArcGIS (Esri) and the 3D Analyst extension. In the interpolation process, the Spline method was used, with the actual horizontal and vertical extent of the NCU campus building development used for each period of the analysis. The whole analytical process was performed for transmitting antennas of two different lengths – 34 cm and 3 dB gain (Fig. 7) and 82 cm and 5.8 dB gain (Fig. 8).

Figure 7 shows the availability of the LoRaWAN network demonstrated using the shorter of the communication antennas. The strongest network signal was obtained in areas directly visible from the observation deck. There is clearly no signal (red area in this figure) in areas directly behind buildings, in their so-called shadow, i.e. in places where direct, straight-line visibility between two points is not possible. Figure 8 shows the visibility of the LoRaWAN network when the longer antenna is used. In this case, a significantly higher coverage of the NCU campus area was obtained, if not very good, then at least good signal of the tested wireless network, and the recorded minimum exceeds 10 dBm. There are still places, directly behind the buildings, with weaker signal reception, but they are of much smaller sizes than in the first case.

The size comparison of the areas with no LoRaWAN signal is presented in Figure 9. In the case of the shorter antenna, the likely area without the LoRa network coverage is as much as 31% of the entire campus, while for the longer antenna this value drops to only 2% of the campus area.

The spatial range of the LoRaWAN signal when using an antenna with a gain of 3dB gain (shorter)

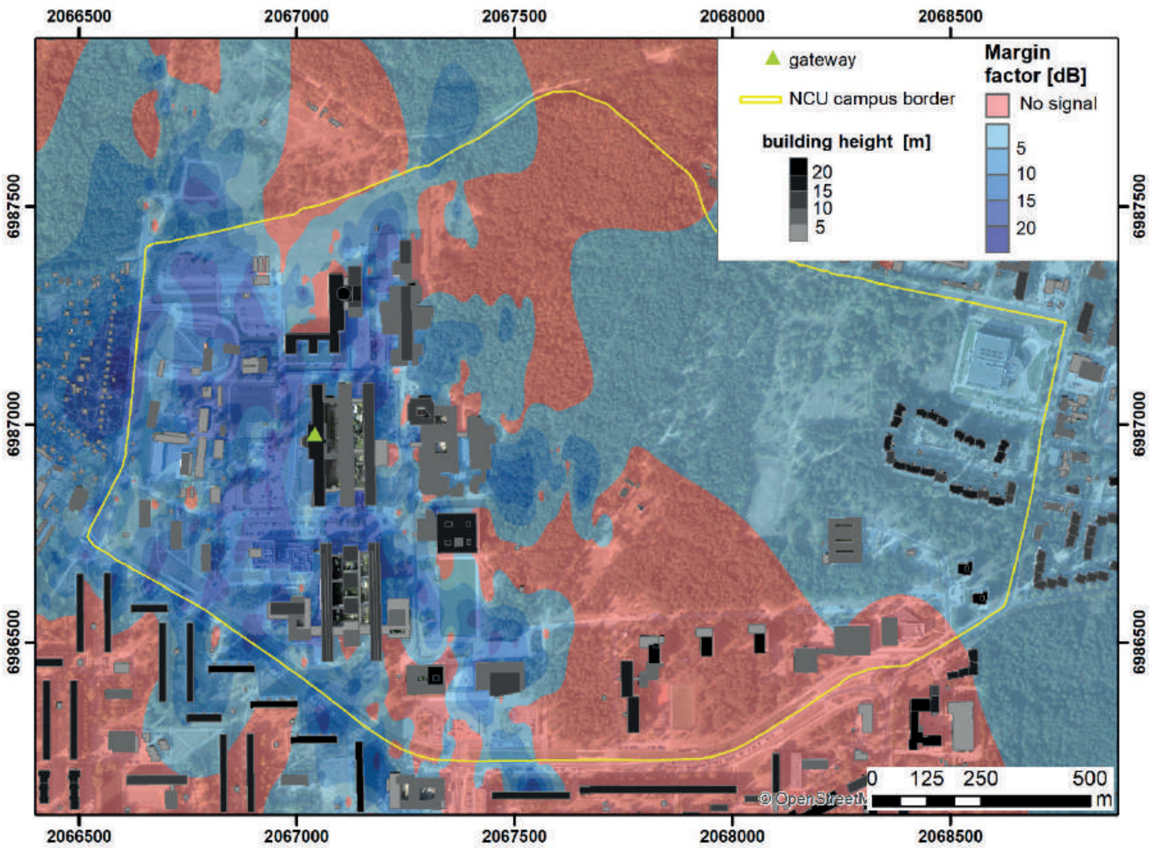

Fig. 7. Visualisation of the LoRaWAN network signal quality on the NCU campus using a 34 cm long antenna.
Source: Authors' own elaboration.

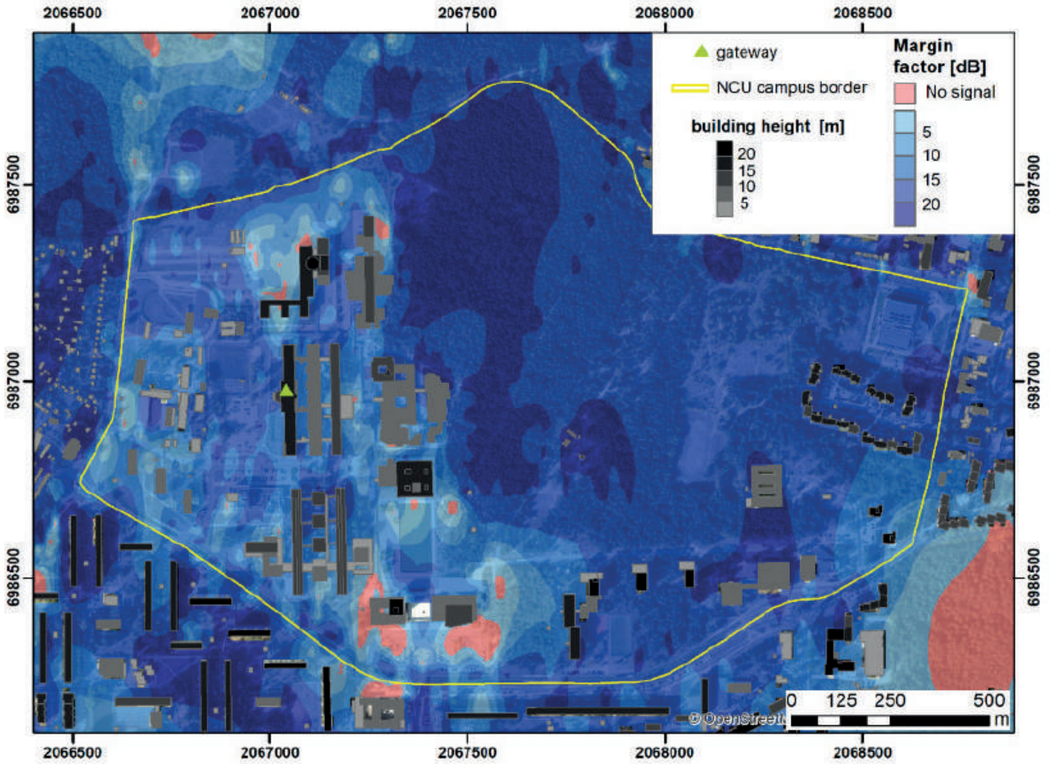

Fig. 8. Visualisation of the LoRaWAN network signal quality on the NCU campus using a 82 cm long antenna.
Source: Authors' own elaboration.

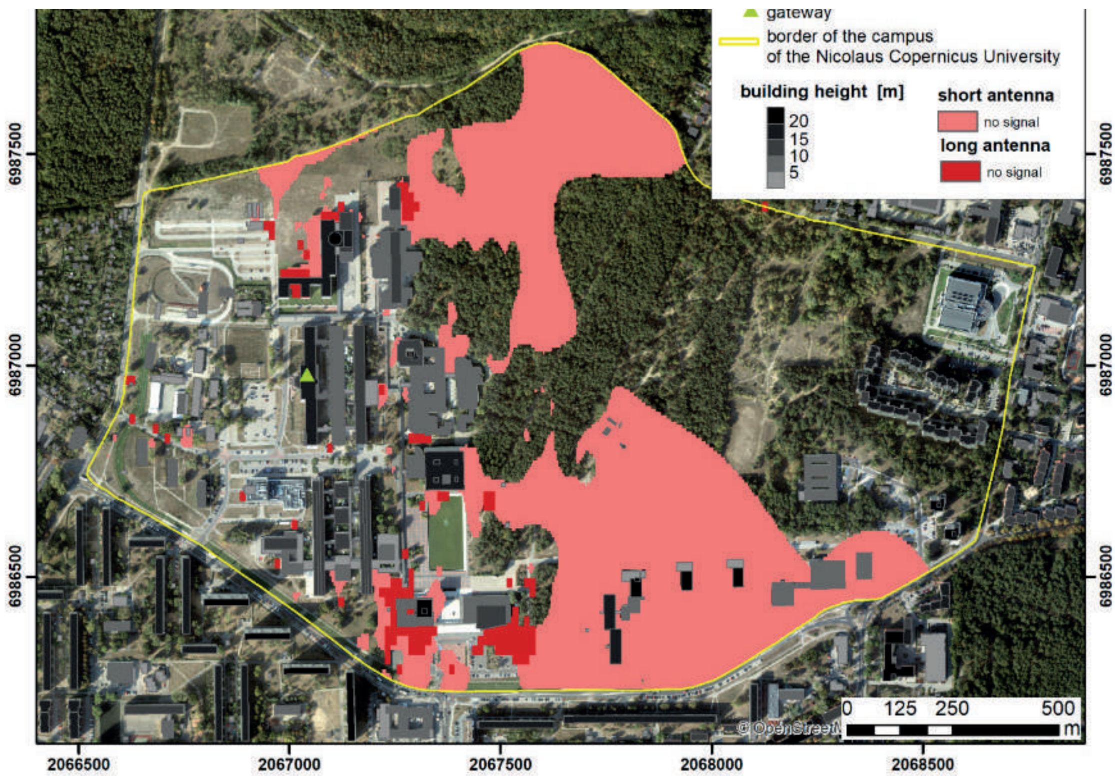

Fig. 9. Campus area with no LoRa signal for the shorter (34 cm) and longer (82 cm) antenna.
Source: Authors' own elaboration.

and 5.8 dB gain (longer) differs significantly. In built-up areas, the achievable range for the shorter antenna is approximately 1 km. On the other hand, the longer antenna enables data transmission from a distance of over 4 km, which significantly increases the possibility of using this infrastructure in built-up areas. Due to the much greater range obtained in the second case, in order to properly visualise the LoRaWAN network visibility, it was necessary to collect measurement data from a much larger area. As in the previous analysis, the data were interpolated using the Spline method, and the results are presented in Figure 10. The study shows that the network signal covers a large area, and a significant limitation are terrain elevation differences, which increase to the north and east from the gateway location, as well as the density and height of buildings. The opposite situation is observed when analysing the visibility of the network to the south and west, where the density and height of buildings is much lower. The process of signal propagation is also enhanced by the presence of areas with low vegetation and the Vistula River, rendering the areas free of taller elements of the urban fabric. This example perfectly illustrates both the advantages and limitations of wireless networks in built-up areas.

The analysis of the effects of the distance from the communication gateway on the signal quality shows that both terrain obstacles and the increasing distance reduce its strength and visibility. For areas close to the transmitter, on the other hand, increasing distance is less important than the size and volume of the object obstructing the signal. As the linear distance increases, the impact of the building height on the signal quality also increases.

In order to verify the results of the above analysis, Fig. 11 presents terrain profiles constructed between the point where the access gate is located and subsequent measurement points. The analysis covered the points where excellent network quality was observed for both the longer and shorter antennas (profiles B and C – blue line), the points where in both cases no LoRaWAN network signal was observed (profiles A and E – red line), and cases where the signal was observed for the longer

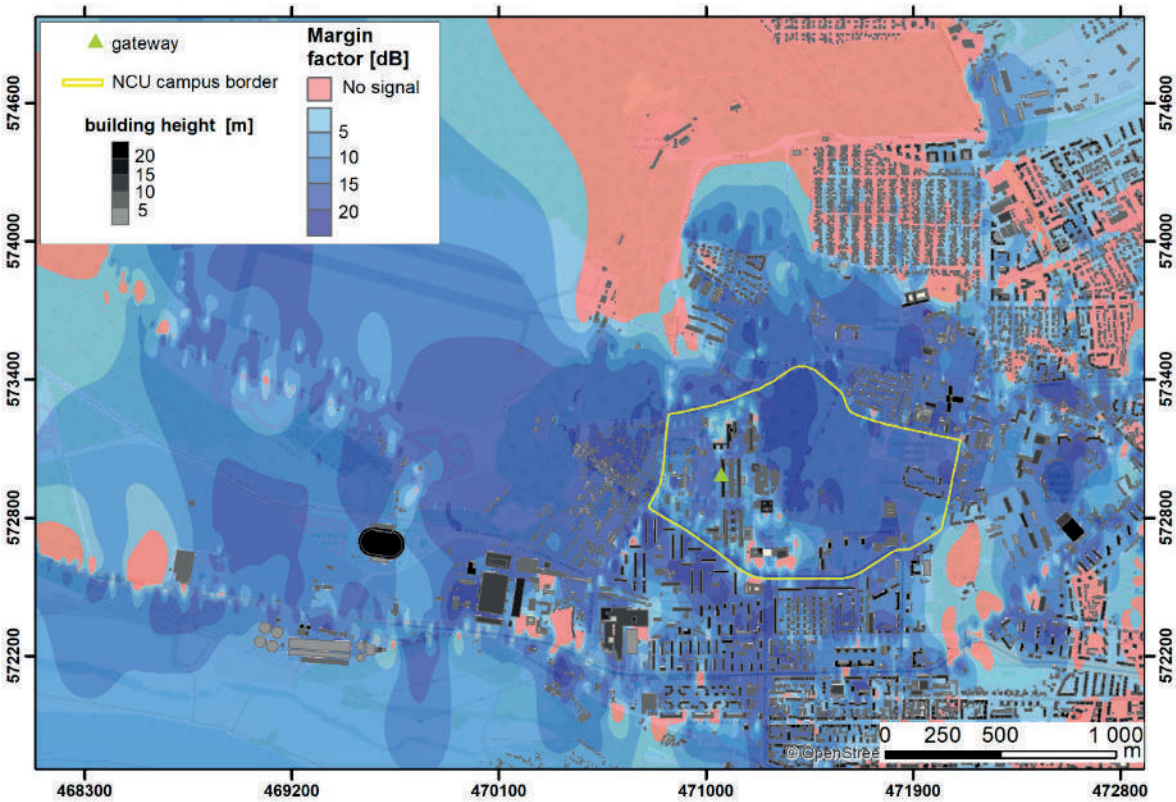

Fig. 10. Interpolation of measurement data for a larger area using a 82 cm long antenna.
Source: Authors' own elaboration.

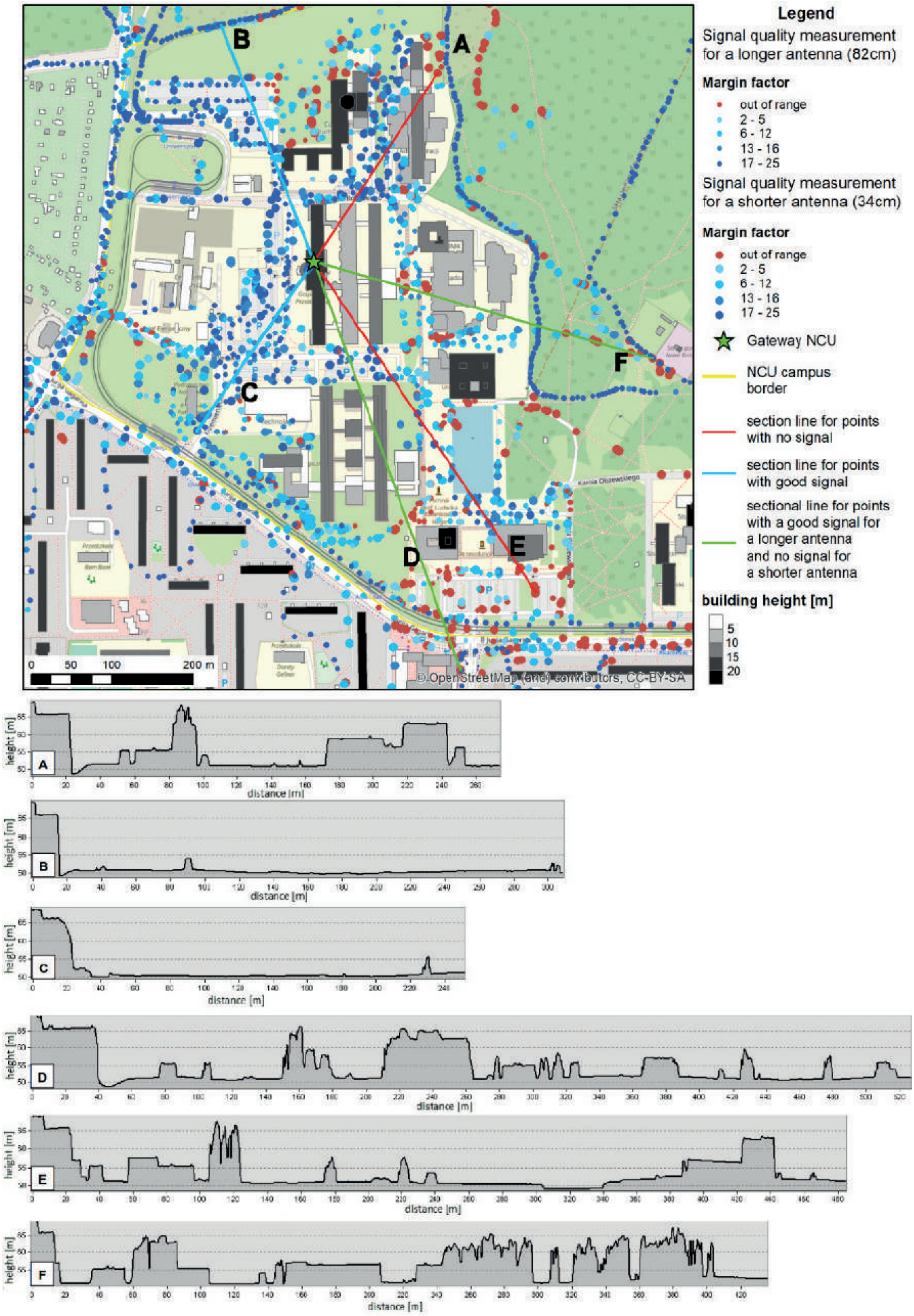

Fig. 11. Location and visualisation of terrain cross-sections showing obstacles in the path of the LoRa signal to the measured measurement points.

Source: Authors' own elaboration.

antenna but not for the shorter one (profiles D and F – green line). The points were selected within the network coverage area with the shorter antenna used.

The analysis of the selected cases shows that for profiles B and C created for points with good signal quality, there are no high terrain obstacles on the way that would prevent signal propagation. In the case of profiles A and E, created for areas with no network coverage, there are numerous terrain obstacles and, what is important, high buildings with considerable cubic capacity are located near the measurement point. Profiles D and F are characterised by a large number of terrain obstacles, however, there are no large-size buildings near the measurement point. The network is not available there if an antenna with a lower gain is used. In addition, the F profile runs through the wooded area, which proved to be disadvantageous for the signal from lower gain antennas. The analysis proves the prior assumptions as the differences between the selected equipment are clear in the presented material. When planning the installation of a network, it is necessary to carefully choose the structural elements of the technology used.

The presented research shows the advantages and limitations of using a wireless network in urban areas. The signal propagation of the selected LoRaWAN wireless network is very limited in areas with high-rise buildings. However, there are areas where even a small infrastructure of this type of technology can successfully provide monitoring of selected environmental parameters. To achieve such an effect in densely built-up areas, it is necessary to increase the density of network infrastructure elements.

With the intensive spatial development of urban areas and the planned construction of further edifices and facilities, the availability of the wireless network signal will also significantly deteriorate. This will result in increased areas of non-surface availability, where it will not be possible to connect any measuring device to a communication gateway of the LoRaWAN network. In such a situation, it will be necessary to install additional access points, which will significantly increase the operating costs of the implemented solution and cause further densification and overlapping of signals of all wireless technologies used in a given area, not to mention their potential negative impact on interference with other electronic devices (Politański et al., 2016; Zmyślony, 2006).

5. Discussion

Nowadays, even when we use only visual rather than instrumental observation methods, we notice the progressive deterioration of the natural environment around us. Distributed monitoring of selected environmental parameters is becoming increasingly common and helpful due to its spatial scope. Targeted measurements are increasingly often carried out using wireless recording systems and technological processes of data transmission over long distances. The Nicolaus Copernicus University campus proved to be a good testing ground for such an experiment, as it is an example of a multifunctional heterogeneous urban area with different characteristics and the presence of all typical components of the urban fabric, from low, through medium to high dispersed and compact building development, as well as numerous trees and characteristic small landscape architecture.

The conducted tests confirm the prior assumptions that the most important barriers for the wireless network are large buildings, which at the same time had a significant relative height in relation to the height at which the access gateway antenna is located. Single trees or larger clusters of trees can also reduce the quality of the received signal, but they do not cause its total disappearance.

An inevitable consequence of the development of urban areas, especially those attractive for housing, is the increasing density of building development, which slowly fills every available space in a modern city. Furthermore, when older buildings are demolished, they tend to be replaced by taller structures and the neighbourhood thus becomes more compact. Studies have proven that the density of building development affects the quality and availability of the wireless network and the range of data transmission. To obtain the same signal availability as before the expansion of selected areas, it will be necessary to launch additional access points, which will significantly affect the costs of the undertaking, and to install a fully operational wireless network supporting a “distributed measurement cloud" of any set of sensors. Unfortunately, this is a negative consequence of the intensification of urban expansion, but on the other hand also a new field for targeted, interdisciplinary research in this field.

The results of the targeted experiment conducted on the NCU campus will be used in designing a LoRaWAN wireless network throughout Toruń. On the basis of these results, potential locations of access points will be selected so as to significantly minimise their number, while increasing the number of connectable devices covering a larger area. In the near future, such a network, consisting of the already prepared forty twin sensors, will be deployed in Toruń under the assumption that all important land cover/land use categories exist in the vicinity of a selected point. These operations will also make use of experience gained during the data acquisition process in the summer season (Karpińska & Kunz, 2019), as well as throughout the year (Karpińska & Kunz, 2020) using standard, hand-held SQM loggers. Measurements conducted on the basis of a synchronised cloud of recording devices will be the basis for the implementation of a project aimed at studying the level of light pollution of the night sky in Toruń over a longer period of time. These results, in turn, can be used by other researchers in determining the relationship between the effects of artificial outdoor light sources in towns and cities on the quality of life and health of their residents.

Both the construction of a wireless network based on the LoRaWAN standard and the measurement of excessive artificial light emitted at night are part of the project involving the smart city concept, being an important element of Industrial Revolution 4.0 (Industry 4.0).

References

Arsovski, S., Kwiatkowski, M., Lewandowska, A., Peshevska, D.J, Sofeska, E., & Dymitrow, M. (2018). Can urban environmental problems be overcome? The case of Skopje—world's most polluted city. *Bulletin of Geography. Socio-economic Series*, 40: 17–39. DOI: https://doi.org/10.2478/bog-2018-0012

Bogacz, R., & Krupanek, B. (2013). Porównanie wybranych metod bezprzewodowego odczytu liczników energii elektrycznej (Comparison of selected methods of wireless reading of electricity meters – in Polish). *PAK*, 59(4): 337–440.

Chaładyniak, D. (2011). Wybrane technologie bezprzewodowej transmisji danych (Selected technologies of wireless data transmission – in Polish). *Zeszyty Naukowe Warszawskiej Wyższej Szkoły Informatyki*, 5: 87–101.

Gaël, L., Takacs, A., Gardner, E., De Luca, A., Udrea F., & Dragomirescu, D. (2019) LoRaWAN Battery-FreeWireless Sensors Network Designed for Structural Health Monitoring in the Construction Domain. *Sensors*, 19(7): 1510.

Hänel A., Posch T, Ribas S.J., Aubé M., Duriscoe D., Jechow A., Kollath 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.

Jechow, A,. Ribas, S.J., Canal-Domingo, R., Hölker, F., Kolláth, Z., & Kyba, C.C.M. (2019). 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.

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: https://doi.org/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: DOI: 10.2478/ceer-2020-0057

Karpińska, D., & Kunz, M. (2021). 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 Polish). In: Młynarczyk, A. (ed.) *Środowisko przyrodnicze jako obszar badań*, Poznań: Bogucki Wydawnictwo Naukowe.

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

Kunz, M. (2012). Rozwój przestrzenny kampusu akademickiego Uniwersytetu Mikołaja Kopernika w Toruniu (Spatial development of the academic campus of the Nicolaus Copernicus University in Toruń – in Polish). *Okólnik TD – Biuletyn Informacyjny KTŚ PTG*, 136: 31

Wang, L.K., Pereira, N.C., & Hung, Y.T. (2004). *Air Pollution Control Engineering, Handbook of Environmental Engineering* Volume 1. New Jersey: Humana Press.

Lorabit, (2019a). Available at: https://lorabit.pl/co-mozna-zrobic-z-protokolem-lora/(10.08.2021).

Lorabit, lorabit.pl, (2019b). Available at: https://lorabit.pl/czestotliwosci-regionalne-lorawan/(12.08.2021).

Lozynskyy, R., Pantyley, V., & Sawicka, A. (2021). Smart city concept in Poland and Ukraine: implementation instruments, problems and successes of cities. *Bulletin of Geography. Socio-economic Series*, 52: 95–109. DOI: https://doi.org/10.2478/bog-2021-0016

Mikhaylov, K., Stusek, M., Masek, P., Petrov, V., Petäjäjärvi, J., Andreev, S., Pokorny, J., Hosek, J., Pouttu, A., & Koucheryavy, Y. (2018). Multi-RAT LPWAN in Smart Cities: Trial of LoRaWAN and NB-IoT Integration. *IEEE International Conference on Communications (ICC)*, 1–6, DOI: 10.1109/ICC.2018.8422979

MultiConnect® mDotTM MTDOT Developer Guide (2020). Multi-Tech Systems, Inc.

Multi-Tech Systems, Inc. (2020). Available at: https://www.multitech.net/developer/software/ (05.06.2021).

Piątek, Z. (2018) Przemysl-40.pl,. Available at: https://przemysl-40.pl/index.php/(15.08.2021).

Politański, P.; Bortkiewicz, A., & Zmyślony, M. (2016). Wpływ pól elektromagnetycznych zakresu radiowego i mikrofalowego, emitowanych przez urządzenia łączności bezprzewodowej, na funkcjonowanie wybranych elementów układu nerwowego (The influence of electromagnetic fields in the radio and microwave range, emitted by wireless communication devices, on the functioning of selected elements of the nervous system – in Polish). *Medycyna Pracy,* 67(3): 411–421.

Popławski, B. (1982). Projektowanie szkół wyższych (Designing universities – in Polish). *Zespoły dydaktyczno-naukowe*, Warszawa.

Qadri, H., Bhat, R.A., Mehmood, M.A., & Dar, G.H. (2020). *Fresh Water Pollution Dynamics and Remediation*. Singapour: Springer.

Ragam, P. and Nimaje, D.S. (2019). Performance evaluation of LoRa LPWAN technology for IoT-based blast-induced ground vibration system. *Journal of Measurements in Engineering*, 7(3): 119–133.

Semtech Corporation (2015), AN1200.22 LoRa™ Modulation Basics, Wireless Sensing and Timing Products, Application Note.

Tomaszewski, D. (2020). 11 mitów na temat technologii LoRaWAN (11 myths about LoRaWAN technology – in Polish). *Elektronik*, 78–81

Turčinović, F., Vuković, J., Božo, S., & Šišul, G. (2020). Analysis of LoRa Parameters in Real-World Communication. *2020 International Symposium ELMAR*, 87–90, DOI: 10.1109/ELMAR49956.2020.9219028

Zmyślony, M. (2006). Biofizyczne mechanizmy działania pól elektromagnetycznych a skutki zdrowotne (Biophysical mechanisms of action of electromagnetic fields and health effects – in Polish). *Medycyna Pracy*, 57(1): 29–39.

sensors

Article

An Autonomous City-Wide Light Pollution Measurement Network System Using LoRa Wireless Communication

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Abstract: Light pollution is an ongoing problem for city populations. Large numbers of light sources at night negatively affect humans' day–night cycle. It is important to measure the amount of light pollution in order to effectively ascertain the amount of light pollution in the city area and effectively reduce it where possible and necessary. In order to perform this task, a prototype wireless sensor network for automated, long-term measurement of light pollution was developed for the Torun (Poland) city area. The sensors use LoRa wireless technology to collect sensor data from an urban area by way of networked gateways. The article investigates the sensor module architecture and design challenges as well as network architecture. Example results of light pollution measurements are presented, which were obtained from the prototype network.

Keywords: light pollution; LoRa; Torun metropolitan area; wireless measurement system

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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. This phenomenon is currently global, and in recent decades, along with the development of industry and the progressing urbanization process, it systematically increases the spatial range of its impact. The glow of light extending over a city can easily be seen from a distance of up to several tens of kilometers [1–3]. According to research, over 99% of Europe's population and 80% of the world's population live in areas polluted by artificial light [1]. The interest in studying this phenomenon is systematically growing, and the group of scientists around the world who are involved in this research is expanding every year [4–7]. The growing interest in the issue is evidenced by the growing number of published scientific articles and conference presentations in recent years [8,9]. The phenomenon of artificial light pollution of the night sky has negative consequences for the environment. Excessive light emission leads to disturbances in the behavior of plants and animals and also significantly impairs human health, quality of life and everyday functioning [10,11]. The negative effect of this phenomenon is the presence of lighting in areas that should not be exposed to it, dazzling random people—both pedestrians and drivers—which can lead to dangerous situations, events and behaviors. In the energy crisis that has been progressing since the beginning of 2022, ill-considered, improperly designed outdoor lighting causes excessive electricity consumption, which leads to additional economic costs for local governments at all levels and individuals. For this reason, the development of measuring devices and the creation of a monitoring network seems very expedient and justified. Industry 4.0 creates new opportunities in this regard. Studies on the above-mentioned phenomenon in urbanized areas also show that light pollution increases further during the occurrence of unfavorable weather conditions, such as fog or cloud cover, and the increased presence of anthropogenic dust in the troposphere [12–14]. This type of comprehensive research is still not very widespread, but the demand of city authorities and agglomeration managers for a multi-threaded understanding and knowledge of the essential components of the formation of light smog is steadily increasing. This counteracts this process and, consequently, prevents its effects. Measuring, analyzing 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 phenomenon of light pollution in the night sky can be measured using various research methods. They can be divided according to specific criteria, e.g., according to the tools used, into instrumental methods and observational methods, or according to the complexity of the measurement process, into methods that can only be used by a qualified operator or a non-professional [2,5,7,15]. However, the most frequently used measurement methods in practice are registrations with the use of photometers and digital cameras, mainly wide-angle lenses or the "fish-eye" type, and their subsequent processing using specialized software [2,6]. Factory-made photometers can be both handheld, portable and stationary. Since 2020, an interdisciplinary team of scientists from the Nicolaus Copernicus University in Toruń has started work on designing, testing and implementing a proprietary automatic measuring device in the city, which is part of the light pollution monitoring system [16]. Measurements made in this way make it possible to compare the intensity of the phenomenon recorded at different locations [5,6]. In some research centres, studies using satellite or UAV imagery or aerial photographs are also used [17]. The most commonly processed images are those taken by the Suomi NPP satellite with the VIIRS instrument, the DMSP satellite with the OLS instrument and the Luojia 1-01 satellites [18,19].

2. Light Sensors

In order to measure and process the illuminance of ambient light, some kind of sensor is required. This sensor converts the value of illuminance in lux to a digital or analogue signal that can be processed by a microcontroller. The application presented in this paper requires the sensor to be low cost, accurate at low light conditions, have low power consumption and operate at voltages provided by batteries such as 3.3 V. The sensors also have to reflect the sensitivity of the human eye, which is modeled by the photopic curve [20] presented on Figure 1.

Electronic ambient light sensors can be based on several types of photosensitive elements such as light-dependent resistors (LDRs), which alter their resistance depending on the intensity of light or photo voltaic cells that generate voltage depending on light intensity. Another type of detector is the photodiode. The photodiode is a reverse-biased P-N junction which generates a small reverse leakage current proportional to the intensity of light. Because the leakage current is very small, the photodiode usually requires an amplifier to achieve useful signal levels. Phototransistors are two P-N junctions that work similarly to photodiodes; however, they also amplify the current so an additional amplifier is not needed. Among the previously mentioned light sensing devices, the photodiode is most widely used as an ambient light sensor. This is due to its fast response, low dependence on temperature and mostly linear illuminance vs. current characteristics. Due to its wide adoption as a light-sensing device, many semiconductor manufacturers offer integrated ambient light sensor chips which contain photodiodes, amplifiers, control electronics and an interface to transfer the measured value to a measurement system (usually a microcontroller). These include analog voltage or current signals, frequency signals or a serial communication interface such as SPI, I2C or UART. The main drawback of semiconductor devices used for ambient light sensing is their high sensitivity to infrared radiation. To alleviate this problem, filters are used which eliminate most of the infrared radiation and enforce spectral characteristics close to the photopic curve.

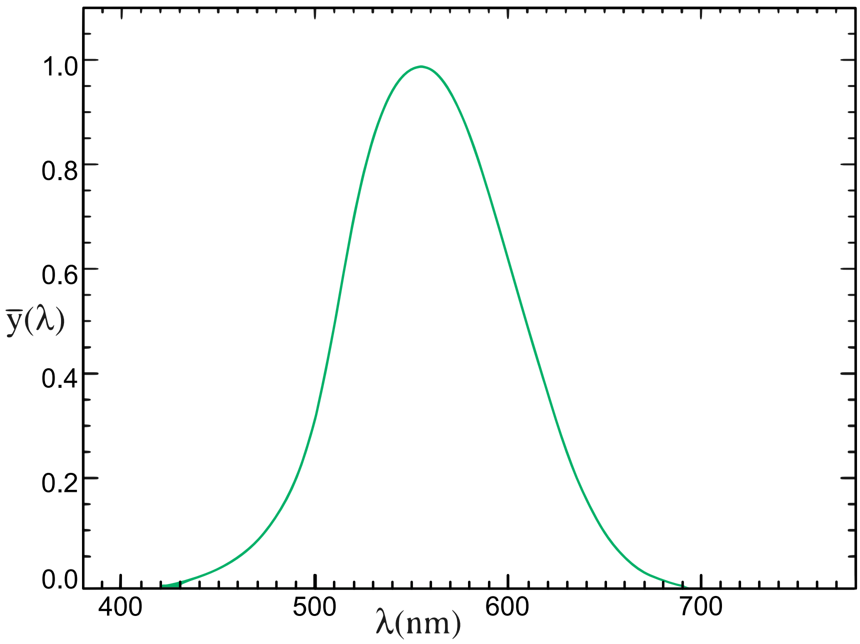

Figure 1. Photopic curve which models the sensitivity of the human eye to different wavelengths of the visible spectrum.

In this work, an alternative solution was chosen in the form of a TSL2591-integrated ambient light sensor manufactured by AMS OSRAM. The sensor chip has two reverse-biased photodiodes. One is sensitive to infrared radiation and the other detects both infrared and visible spectrum. Both currents are measured using integrated amplifiers and converted to a numerical representation (16-bit integer) using integrated analog-to-digital converters (ADCs). The measured values can then be subtracted to eliminate the influence of infrared radiation and achieve the desired spectral characteristics. This allows us to eliminate the filter, which decreases the costs and complexity of the device [21]. The characteristics of the dual diode sensor are shown in Figure 2. The characteristics are inherent to the sensor and cannot be modified. The filter can still be used if the default characteristics are not satisfactory, but in most applications, they do not need to be adjusted. An alternative would be to use spectral sensors which can measure light intensities for several fragments of the visible light spectrum and infrared. The characteristics could then be adjusted to meet specific requirements by applying appropriate gains to each measured spectral intensity.

An exchange of data between the sensor and the microcontroller is achieved via I2C bus. Sending data via digital bus has the advantage of eliminating the influence of noise, which is a problem when using analogue signals. Furthermore, the bidirectional bus can be used to change parameters of the sensor, such as amplifier gain or integration time. The bus can also be used to set low and high limits for measured light, which trigger an interruption when violated. The sensor can also be put into low-power mode in order to conserve energy, which is useful in battery powered devices. A block diagram of the sensor is presented in Figure 3.

The sensor can be purchased as a separate chip or as a small PCB module which contains all the necessary passive elements. A picture of an Adafruit module with the TSL2591 sensor is shown in Figure 4.

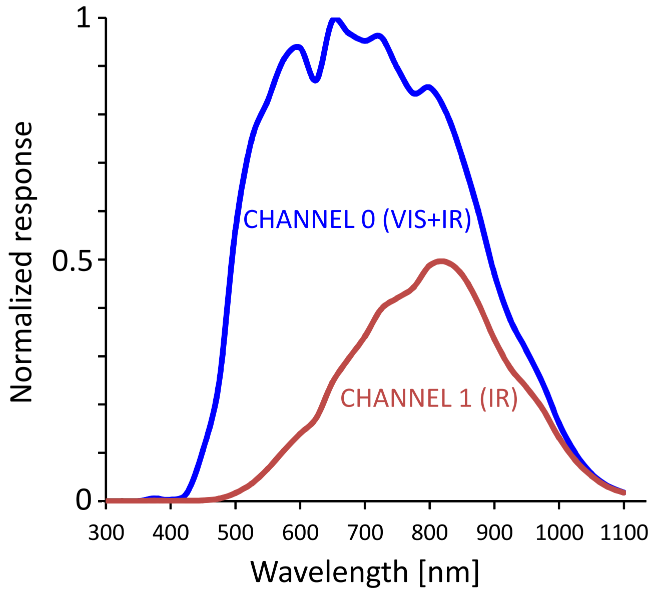

Figure 2. Spectral characteristics of both channels of the TSL2591 sensor.

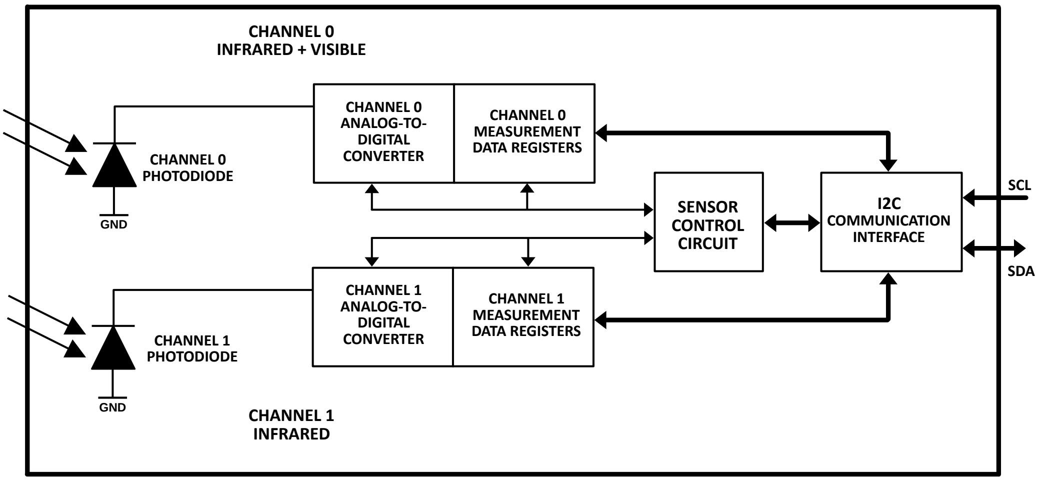

Figure 3. Block diagram of the TSL2591 sensor.

Figure 4. Adafruit module with the TSL2591 lux sensor.

3. Remote Light Measuring Device

The remote light measuring device, developed by the authors, is based on the B-L072Z-LRWAN1 board with the Murata CMWX1ZZABZ-091 processor. This processor integrates a low-power STM32L081 micro-controller and a Semtech SX1276 wireless transceiver compatible with the LoRaWAN standard. An Adafruit 1980 sensor board is used with the TSL2591 Lux sensor (Figure 3, left). The sensor communicates with the processor via I2C serial bus. The board is expanded with an auxiliary sensor board with temperature and humidity sensors to monitor the device during long-term outside operation for abnormal temperatures and leaks. The block schematic of the device is presented in Figure 5.

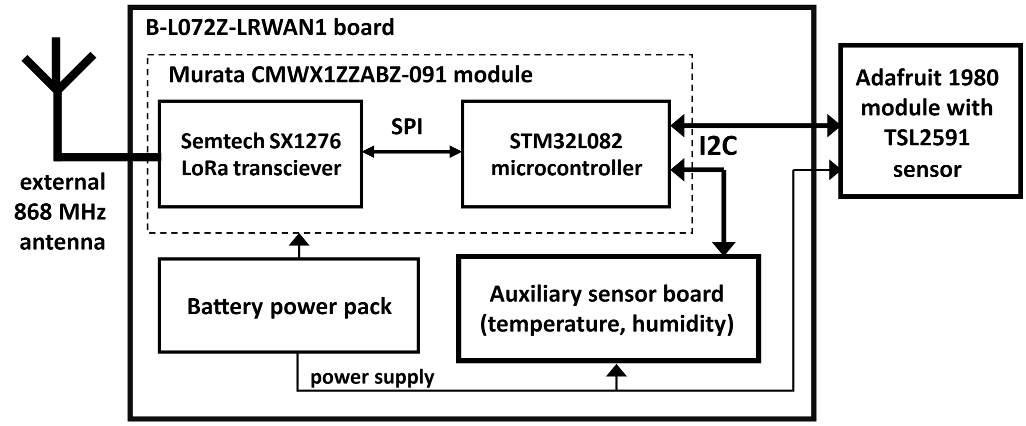

Figure 5. Block schematic of the LoRa light sensor.

The boards are enclosed in a hermetically sealed plastic enclosure. The enclosure also contains a battery pack with three AAA batteries. An external antenna is attached to the enclosure and connected internally to the Murata chip. The sensor monitors the ambient light via a round hole covered by a thin glass window. The window is attached to the enclosure using a resistant marine silicone to protect the device against environmental conditions. The device should be placed on an elevated position so that the sensor window points upwards, toward the night sky. This allows measuring light pollution which is caused by excess light emitted to the atmosphere, where it is scattered and reflected back to the ground. Such placement also limits the influence of small local light sources placed near the device, which might significantly affect the reading while not contributing much to light pollution. Pictures of the developed LoRa light measurement device are shown in Figure 6.

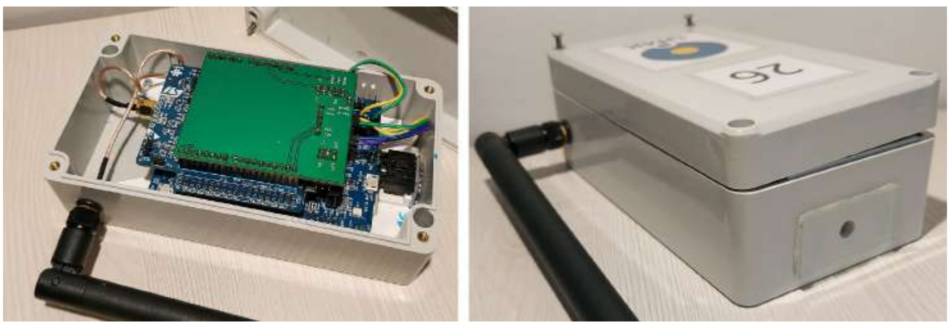

Figure 6. Pictures of the developed LoRa light measurement device (photo by Dominika Karpińska).

The device is designed to operate for an extended period of time (at least one year) on battery power. Therefore, it was necessary to adapt the board hardware and properly configure the software to limit power consumption.

The board hardware was adapted by taking out unnecessary elements. Sensors on the additional sensor boards were soldered out, except for the temperature and humidity sensors. Some of these sensors were powered by power converters which were not necessary after the respective sensors were taken out. Furthermore, unnecessary pullup resistors for the I2C bus were also removed. The ST-Link programming interface which was also used to power the board via USB was also disabled and the board was powered directly from the battery holder

Software modifications mainly included configuration of the microcontroller and LoRa module to revert to sleep mode when not used. The internal real-time clock (RTC) of the microcontroller was configured to wake up the hardware by interrupting at predefined times. The sensors were also configured to sleep when not used and were woken up when the processor initiated transmission. These hardware and software modifications allowed us to significantly reduce the current consumption.

Because the devices' purpose was to measure artificial light pollution, the sky brightness measurements were conducted only at night. In order to properly discern the time of day, a real-time clock embedded in the processor was used. During the daytime, the processor and sensors are put in sleep mode to minimize energy consumption. The processor is woken up at 21:00. It then wakes up the LoRa transceiver and sensors. The measurements are received via I2C, processed and sent to the base station (gateway) using LoRa wireless network. After a successful transmission, the processor and all peripherals go to sleep for 15 min. After that period of time, the measurement and transmission cycle is repeated until 6:00. After that, the device goes into extended sleep until the next night.

At each measurement cycle data registers from both channels are read from the sensor via I2C. Because the registers are 16-bit, each one is read in two steps of one byte during one I2C transmission. After merging the bytes, two integer numbers are obtained with values ranging from 0 to 65,535. These are first converted to floating point numbers and used to compute brightness in Lux using the following formulas:

$$CPL = \frac{IT * GAIN}{U} \tag{1}$$

$$L_1 = \frac{IR_{raw} - B \cdot FULL_{raw}}{CPL} \tag{2}$$

$$L_2 = \frac{(C \cdot IR_{raw}) - (D \cdot FULL_{raw})}{CPL} \tag{3}$$

$$L = \max(L_1, L_2) \tag{4}$$

where: CPL—count per lux, L_1, L_2—lux components from both channels, L—final value in lux with IR influence removed, IT—integration time, $GAIN$—sensor gain, $IR_{raw}, FULL_{raw}$—raw integer values read from IR and FULL range channel registers, U, B, C, D—manufacturer-provided coefficients specific to the TSL2591 sensor, equal to 408, 1.64, 0.59, and 0.86, respectively. The equations and coefficients are based on documents provided by the manufacturer (AMS OSRAM) [22,23].

The user can set four different gains for the sensor (1, 25, 428, and 9876) and different sensor integration times between 100 and 600 ms. A higher integration time makes the sensor more sensitive in low-light conditions. Because this device is used for night sky brightness measurement, the highest gain of 9876 is used by default. The integration time is set to 400 ms by default. These values are adjusted dynamically so that if raw values are larger than 30,000 units, the gain and integration time is decreased. If the raw value is less than 200, the integration time is increased to 600 ms. The final floating point values are multiplied by 1,000,000 and converted back to integer form so that they can easily be sent over the LoRa network.

The data, in the form of integer lux values, are sent to the gateways immediately after being read from the sensors, after which the sensor goes to sleep until the next transmission cycle. Data from measurement devices are collected by their respective gateways. Data from each device are identified based on their unique LoRaWAN identifier and then forwarded to the central server with a timestamp using the internet (WiFi, Ethernet or LTE depending on the gateway location) via MQTT protocol. This is a private cloud server that can be accessed only by authorized personnel. The server hosts a node-red application that collects data from each gateway. The incoming data are stored in the server database and also CSV files for easy access and further analysis. There are also automated mechanisms to notify the user if any of the devices stop working, need a battery replacement (battery voltage measurement), have overheated (internal temperature measurement) or have had their enclosure compromised (internal humidity measurement). Additional data (temperature, humidity, and battery voltage are sent at the beginning and end of the measurement session. Apart from the automated signaling of abnormal states, the data analysis is performed offline by us on our local computers by downloading current data from the cloud. There is ongoing work to implement automated analytics in the cloud and develop a web-based front-end to visualize the collected data in a user-friendly manner. This will include a visualization available to the general public and a more detailed interface for dedicated users.

There are relatively very few examples of a device for autonomous long-term and long-range light pollution measurement in the literature. Compared to a similar device presented in the literature [24], our device has the benefit of being battery powered and optimized for low power consumption, so it does not need an external power supply or power source such as a photovoltaic cell. Furthermore, in the referenced work, an old sensor type was used, which is the same as in the Unihedron SQM photometer (commonly used in light pollution measurement). This sensor type requires a dedicated filter to eliminate the influence of infrared radiation on the light measurement, adding additional cost and complication to the device's construction. Thanks to a more modern sensor and limitation of power consumption, our device is more cost effective than similar devices used for light pollution measurement.

The device developed by us has an additional advantage, because its housing allows for mounting both on poles, roofs or other structural elements of basically any type, as well as on drones. Thus, research was conducted at a vertical gradient. This has been described in [17] and is probably the first such application. In future, it will be a challenge to better understand this aspect of the phenomenon of light pollution.

Further improvements to the device will include development of a custom board, the addition of additional environmental sensors and alternative, more advanced light sensors, including biosensors [25–27].

4. LoRa Network

The current development of Internet of Things (IoT) devices [28] is associated with the 4.0 industrial revolution [29], which has been progressing for over ten years. IoT devices are often referred to as "smart" solutions in the context of their use—most often as sensors for monitoring certain physical quantities, e.g., for buildings, urban infrastructure or healthcare applications, etc. IoT devices should generally be characterized by low energy consumption and, thus, not too much computing power. IoT devices' small size and low production costs are also desirable (mainly due to the mass production of this type of device). Another critical aspect of IoT devices is the type of communication interface involved. The most common type of communication is wireless communication. There are many variations in communication protocols used in IoT devices. The most popular protocols include Bluetooth [30], Zigbee [31] Wi-Fi [32], based on GSM networks (2G, 3G, 4G, 5G) [33], NFC [34] and others. An important aspect of such a communication protocol is the bandwidth-to-range ratio. Figure 7 lists the most popular communication protocols used in IoT devices, taking into account their bandwidth and range.

The Sigfox [35] and LoRaWAN [36] protocols, which are characterized by very long ranges (distance of kilometers) and low energy consumption during use, are particularly noteworthy. Such networks based on these communication protocols are called Low-Power Wide Area Networks (LPWANs). In the devices described in the article, the authors decided to use a network based on LoRaWAN (Long-Range Wide-Area Network), a long-range standard that uses a low data rate with low power consumption needs.

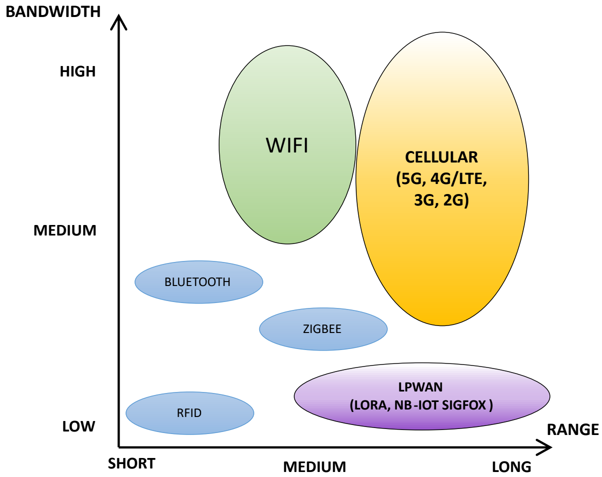

Figure 7. List the most popular communication protocols used in IoT—bandwidth and range comparison.

In LoRa networks (in Europe), the radio frequency used for data transmission is 433 MHz and 868 MHz. In the case of LoRaWAN, a frequency of 868 MHz band is used. LoRa networks use sharing mode—the band is split into several channels that can be used to transmit information. LoRa does not allow devices to transmit data continuously. However, in LoRa networks, devices using it are not immune to communication collisions. To solve this problem, spread spectrum modulation methods are used in LoRa. Chirp Spread Spectrum (CSS) [37] modulation is used.

The authors use the SX1276 chip from Semtech company [38] as a communication module with the LoRa network. The essential characteristics of this chip are summarized in Table 1.

Table 1. Main features of the SX1276 LoRa Transceiver.

Main Features
168 dB maximum link budget
+14 dBm high-efficiency PA
Low RX current of 9.9 mA, 200 nA register retention
Programmable bit rate up to 300 kbps
High sensitivity: down to −148 dBm
Packet engine up to 256 bytes with CRC

The standard LoRaWAN network architecture consists of end devices, gateways, and servers. Data from light sensors (end-device) are sent to gateways via LoRaWAN communication. Data are then processed into a different protocol and sent (e.g., using Wi-Fi, GSM, or other technology) to the data aggregation server. The server also visualizes data from light-intensity sensors. The solution of the light measurement network based on the architecture of the LoRaWAN network is shown in Figure 8.

Due to duty-cycle restrictions in the European Union for the 868 MHz band, each of the end devices (light measurement sensor) should transmit no more than 1% of the time in which it works. In this case, sending a message takes about 3.5 s, which is less than 0.4% of one device work cycle.

To develop the architecture of a LoRa network, preliminary calculations regarding the data transmission time between devices and gateways should be made. This time depends on the Spreading Factor. The higher the Spreading Factor, the longer the transmission time in the LoRa network. Depending on the modulation used, this also affects the bandwidth. The transmission time of each symbol depends on the bandwidth used. This time is inversely proportional to the bandwidth. The higher the Spreading Factor, the lower the bit rate. The higher the bandwidth, the higher the bit rate.

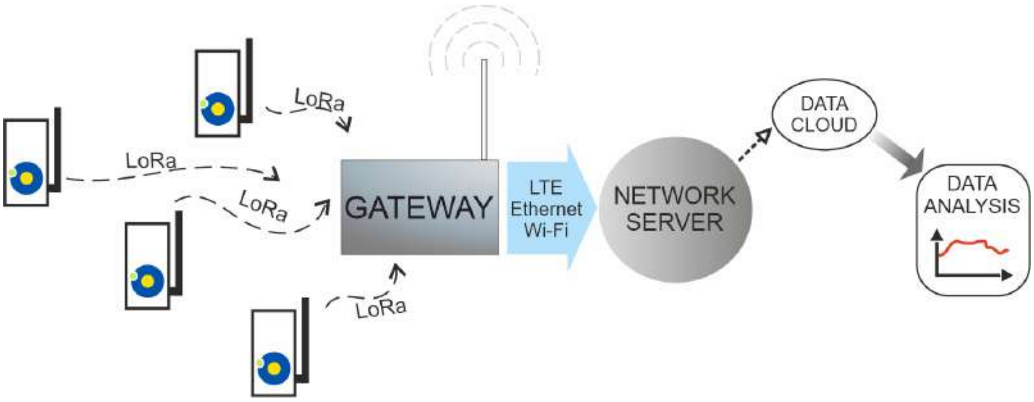

Figure 8. The architecture of the LoRaWAN network with the light intensity sensors.

In the presented application of light pollution measurement, long intervals between measurement are present, so the highest spread factor was used as there is a large amount of time available. This has the benefit of high robustness against interference and increased transmission range. No detailed calculations were necessary. In applications with shorter communication cycles, more attention should be paid to proper adjustment of the spread factor.

The LoRaWAN network is based on the OSI-type network model as standard. Therefore, the encapsulation of data sent in the LoRaWAN frame is also subject to changes (depending on the network layer) [39]. Figure 9 shows the content of the LoRaWAN frame, including individual data processed by subsequent layers of the LoRaWAN network.

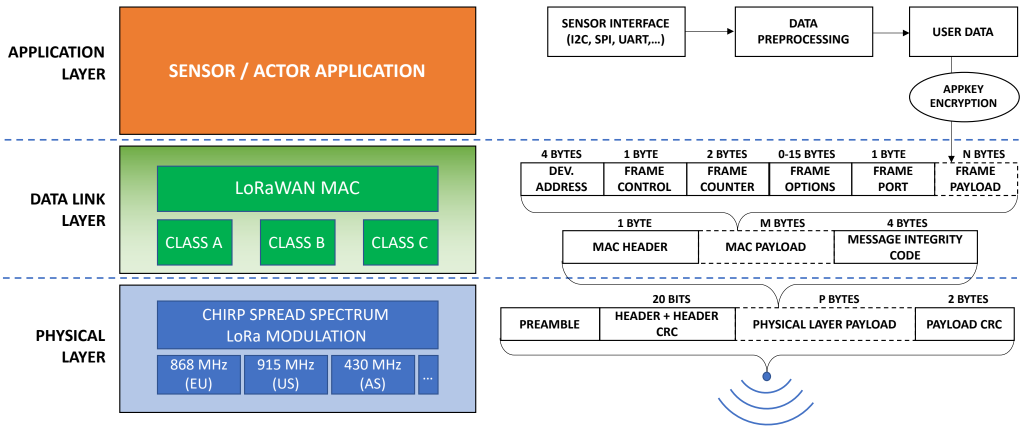

Figure 9. LoRaWAN protocol structure.

5. Experimental Results

Numerous experiments were carried out to verify correct operation of the developed LoRaWAN network and the constructed light measurement devices. One of them was a study determining the current consumption of a constructed device for measuring light intensity at night when sending a data frame at different distances from the communication gateway. The measurements were carried out in a built-up area, which corresponds to the operation of the equipment in the conditions of its intended use. The measurements were carried out by five devices placed in different locations, which were characterized by free access for the duration of the measurements. There were also no obstructions blocking the LoRaWAN signal in their close vicinity. Each of them was surrounded by free space, but it was impossible to avoid the presence of urban buildings to a greater or lesser extent. When analyzing the results, it is worth remembering that the quality of the LoRaWAN network signal is affected not only by the distance from the transmitter, but also by terrain obstacles. The measurement devices were located at a distance of 98, 528, 1108, 1865 and 3664 m from the communication gateway, respectively. A satellite image of Torun and a 3D terrain model with locations of the measuring devices are shown in Figures 10 and 11, respectively.

Figure 10. Locations of measuring devices (red) and LoRa gateway (blue) in Torun with distances.

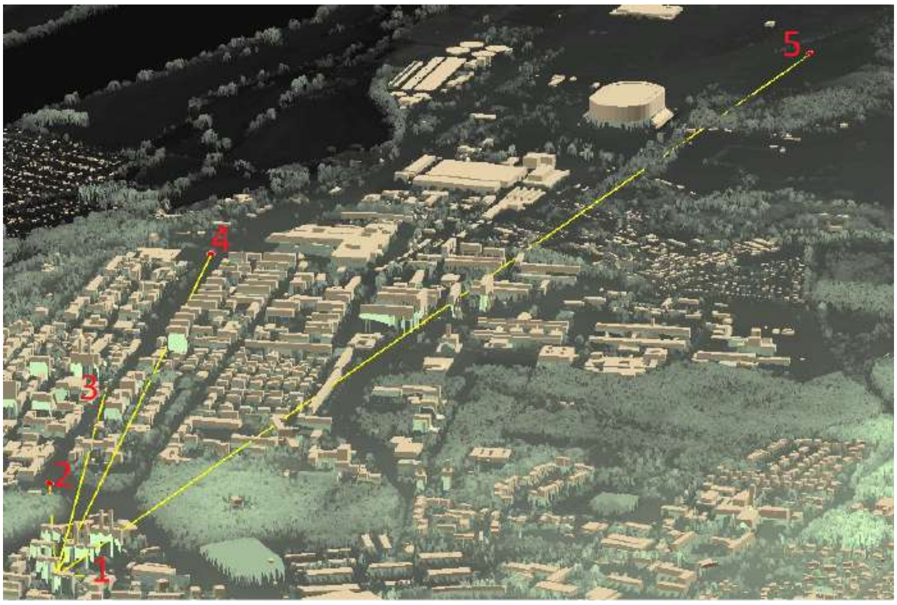

Figure 11. Locations of measuring devices marked on a numerical 3D model of the terrain with buildings.

Pictures of two devices deployed at different locations are shown in Figure 12.

Current consumption measurements were carried out using the X-NUCLEO-LPM01A shield, which is an extension of the STM32 Nucleo boards with power consumption measurement capabilities [40]. In order to read the measurements, it was necessary to use the STM32CubeMonitor-Power software, which enabled both reading parameters in real time and saving the collected data in the STPM file, storing data in the csv format. After collecting data in the same atmospheric conditions from all sites, it was possible to carry out further analysis of the results. From each of the measurements, characteristic waveforms were selected, showing the current consumption while the message was being sent. It is assumed that the constructed device sends two types of messages during one night measurement session, a short one with 32b, in which only the light intensity data are sent, and a long one with a length of 72b, which also sent data concerning the temperature, humidity and battery charge status. During one night, 36 messages are sent, including 2 long ones, monitoring weather conditions and device status. Figure 13 shows an example of power consumption when sending two types of messages.

Figure 12. Pictures of the LoRa light measuring device deployed at outdoor locations (photo by Mieczysław Kunz).

The measurement and transmission interval was set to 15 min which is frequent enough to monitor the slowly changing night sky brightness. Each measurement and transmission cycle results in significantly more current consumption than sleep intervals between cycles. More frequent transmission intervals would result in more energy consumption globally, and therefore a shorter battery life. The interval was determined to achieve the longest possible interval which provides a satisfactory light value sampling rate.

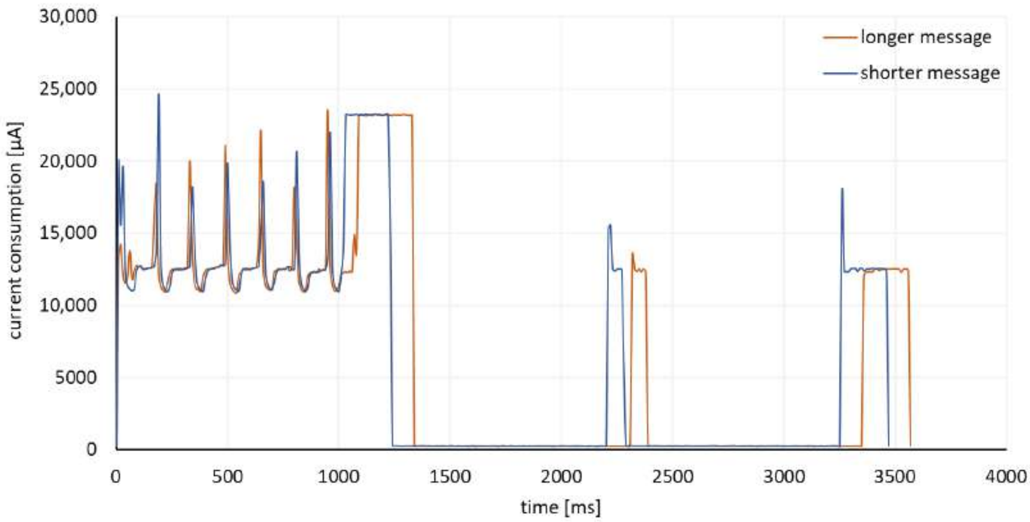

Figure 13. Sensor current consumption acquired using X-NUCLEO-LPM01A shield and STM32CubeMonitor-Power software while sending both long and short data frames.

After extracting several dozen samples showing the energy consumed while sending messages for each device, it was possible to average its value in each case. The obtained results were also averaged for the time when the device was in reduced power mode. For comparison, Table 2 shows the average maximum current consumption during device initialization, which takes place once after turning it on, and the average maximum current consumed while sending a data frame. Data were collected for each of the positions. Analyzing the data, it can be seen that the average during initialization remains similar for each device and does not depend on the distance between the device and the communication gate. However, we can see this dependence with the average power consumption during sending the message. As the distance increases, the average for a given position increases. The only exception is the site located 1108 m from the communication gateway. In its vicinity, there were dense multi-family buildings, which undoubtedly had an impact on the quality of measurements. Unfortunately, in urban conditions, it was not possible to choose a perfect location for the measurement device due to the presence of numerous terrain obstacles.

Table 2. Comparison of average maximum current consumption values during initialization and frame transmission for each measurement device.

Measuring Device	Distance [m]	Average Maximum Current Consumption during Initialization [mA]	Average Maximum Current Consumption during Transmission [mA]
Device 1	98	35.100	19.075
Device 2	528	35.781	19.349
Device 3	1108	34.881	25.871
Device 4	1865	34.698	21.043
Device 5	3664	35.742	35.206

After averaging the data, it was possible to calculate the energy consumption of the device during a single initialization, sending a short and long message, as well as during the transition to a low-power state. With these data, the electricity consumption during one full day was calculated. This allowed us to determine the theoretical working time of the device on batteries with a capacity of 3000 mAh. The calculated data for each of the positions are presented in the Table 3.

Table 3. Comparison of average energy consumption of each device.

Distance [m]	Initialization [MAh]	Sending Long Message [mAh]	Sending Short Message [mAh]	Night Measurement Session [mAh/day]	Daytime Sleep [mAh/day]	3000 mAh Battery Life [Days]
98	0.0233	0.0068	0.0058	0.2122	5.942	507.92
528	0.0233	0.0068	0.0059	0.2137	5.942	507.79
1108	0.0233	0.0070	0.0063	0.2266	5.942	506.69
1865	0.0233	0.0068	0.0060	0.2179	5.942	507.43
3664	0.0233	0.0074	0.0068	0.2454	5.942	505.08

Analyzing the data presented in the Table 3, we can see that the differences in energy consumption during one night measuring session between different devices are noticeable. Power consumption during night measurement session of device 4, which had the highest power consumption, is 13.5% higher than that of device 1, which has the lowest power consumption. The differences are mainly related to current consumption during transmission, which in turn is related to distance and any obstructions between the gateway and each device. However, the power consumption during the long sleep time of the device has the greatest impact on the available operational period. This sleep time is the same for each device. The total time taken to send a small amount of messages is very short compared to the length of the entire standby period, which is the cause of very similar estimated battery life in Table 3 The presented data prove that the distance and terrain obstacles only slightly affect the working time of the device. The highest and lowest results differ by less than 3 days, which is less than 0.6% of the calculated life. The above analysis proves how important it is to use technology that allows the use of reduced power consumption and allows sleep mode to be entered between measurements. This allows them to be placed in a location with limited access and uninterrupted archiving of data for a long time. Measurement devices, designed and built by the authors, that transmit data via LoRa technology have been operating in Toruń since April 2020. Because of this, it was possible to acquire preliminary seasonal results at several locations. Figure 14 presents a comparison of results for devices 1 and 2 in summer and winter, while Figure 15 presents results for device 2 for all seasons. Measurements are shown between 09:00 pm and 01:15 am due to the presence of a shorter astronomical night in the summer.By analyzing the presented data, one can notice the seasonal variability in the brightness of the night sky. Winter nights are definitely the brightest, while summer nights are darkest. The presented results are in agreement with the results obtained by other research teams monitoring the brightness of the night sky [41–43], as well as with the previous instrumental studies conducted in Toruń [4,44].

It is also worth noting that there is a noticeable difference between results obtained from different devices. The sky is brighter at the location of device 1 in winter compared to the location of device 2. In summer, the results for both devices are very similar; however, a slightly larger value for device 2 can still be noticed. This can be attributed to a different location of both devices with different lighting conditions, which also proves the usefulness of the developed system. The difference between seasons can be attributed to differences in the number of cloudy nights and the amount of air pollution, which influences light reflection from the atmosphere.

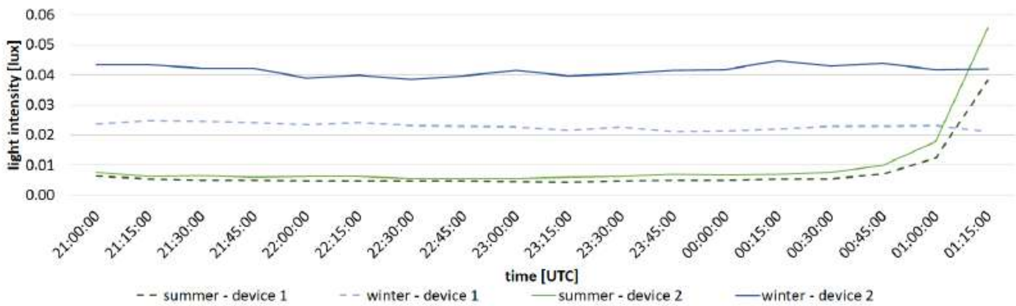

Figure 14. Comparison of measured light intensity for device 1 and 2 in summer and winter (average across all nights).

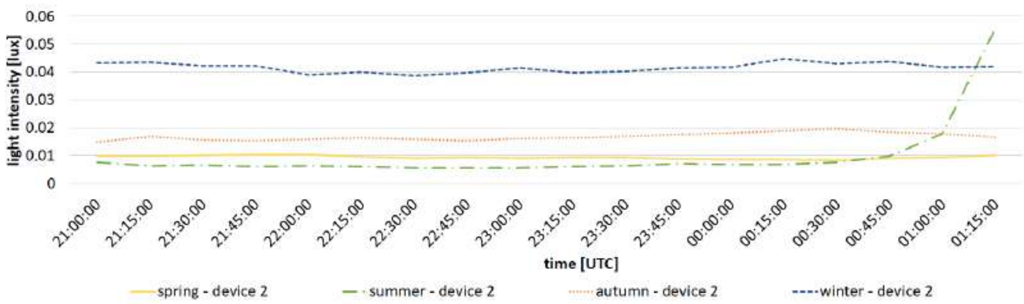

Figure 15. Comparison of measured light intensity for device 2 in all seasons (average across all nights).

The collected data prove the relevance of the selected technologies and components for the construction of devices and the operational readiness of the constructed device in all measurement conditions. Measurements were taken both during the frost of several degrees and during the hottest days of the year. The communication of the device with the communication gateway was also uninterrupted under all conditions. Data archiving proceeded without any major disruptions. The conducted measurement sessions prove the readiness to work of both self-constructed devices and the entire prepared measurement infrastructure.

6. Conclusions

In this paper, an autonomous distributed light measurement system was presented for long-term monitoring of light pollution in an urban environment. The system consists mainly of autonomous measurement devices equipped with LoRa wireless communication, which allows long-range communication in various environments. Compared to similar devices presented in the literature, the device and data acquisition system presented in this paper have the advantage of autonomous long-term operation under battery power with wireless communication to a central network server. The paper presents the developed wireless sensor module and system architecture, as well as design challenges that had to be overcome to make the system operational. Experimental results were presented which prove that the devices are capable of operating in the LoRa network-based system for extended periods of time without maintenance due to low power consumption and an appropriate transmission schedule. Furthermore, long-term measurements of night sky light pollution were presented. These were gathered by several devices in the Torun urban area. The developed system and devices can be used, among other applications, to optimize urban lighting in different seasons in order to lower city-wide energy consumption. The system will be further developed to provide a web-based front-end available for general use and administrative purposes. Currently, 40 devices are being deployed across Torun, which should provide a much more detailed map of urban light pollution in that area. A new version of the device with a dedicated integrated board is currently being developed.

Author Contributions: Conceptualization, M.K. and K.E.; methodology, M.K. and K.E.; software, D.K. and K.E.; hardware, D.K., J.C. and M.P.; validation, M.P. and J.C.; investigation, D.K., J.C and M.P.; resources, M.K. and D.K.; data curation, D.K.; writing—original draft preparation, K.E., D.K., M.K. and M.P.; writing—review and editing, K.E., M.K. and D.K.; visualization, D.K.; supervision, M.K. and K.E.; project administration, M.K.; All authors have read and agreed to the published version of the manuscript.

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References

1. Falchi, F.; Cinzano, P.; Duriscoe, D.; Kyba, C.; Elvidge, C.; Baugh, K.; Portnov, B.; Rybnikova, N.; Furgoni, R. The new world atlas of artificial night sky brightness. *Sci. Adv.* **2016**, *2*, e1600377. [CrossRef] [PubMed]
2. Jechow, A.; Kolláth, Z.; Lerner, A.; Hänel, A.; Shashar, N.; Hölker, F.; Kyba, C. Measuring Light Pollution with Fisheye Lens Imagery from A Moving Boat, A Proof of Concept. *Int. J. Sustain. Light.* **2017**, *36*, 15–25. [CrossRef]
3. Linares Arroyo, H.; Masana, E.; Ribas, S.; Aubé, M.; Simoneau, A.; Bara, S. Night sky brightness simulation over Montsec protected area. *J. Quant. Spectrosc. Radiat. Transf.* **2020**, *249*, 106990. [CrossRef]
4. Karpinska, D.; Kunz, M. Analysis of Light Pollution of the Night Sky in Toruń (Poland). *Civ. Environ. Eng. Rep.* **2020**, *30*, 155–172. [CrossRef]
5. Kyba, C.; Bouroussis, C.; Canal-Domingo, R.; Falchi, F.; Giacomelli, A.; Hänel, A.; Kolláth, Z.; Massetti, L.; Ribas, S.; Spoelstra, H. *Report of the 2015 LoNNe Intercomparison Campaign*; Deutsches GeoForschungsZentrum GFZ: Potsdam, Germany, 2015. Available online: https://gfzpublic.gfz-potsdam.de/rest/items/item_1124000_3/component/file_1124001/content (accessed on 19 May 2023).
6. Kyba, C.; Tong, K.; Bennie, J.; Birriel, I.; Birriel, J.; Cool, A.; Danielsen, A.; Davies, T.; Outer, P.; Edwards, W.; et al. Worldwide variations in artificial skyglow. *Sci. Rep.* **2015**, *5*, 12180. [CrossRef]
7. Pun, C.S.; So, C.w. Night-sky brightness monitoring in Hong Kong—A city-wide light pollution assessment. *Environ. Monit. Assess.* **2011**, *184*, 2537–2557. [CrossRef]
8. Mander, S.; Alam, F.; Lovreglio, R.; Ooi, M. How to measure light pollution—A systematic review of methods and applications. *Sustain. Cities Soc.* **2023**, *92*, 104465. [CrossRef]
9. Levin, N.; Kyba, C.C.; Zhang, Q.; Sánchez de Miguel, A.; Román, M.O.; Li, X.; Portnov, B.A.; Molthan, A.L.; Jechow, A.; Miller, S.D.; et al. Remote sensing of night lights: A review and an outlook for the future. *Remote. Sens. Environ.* **2020**, *237*, 111443. [CrossRef]
10. Garcia-Saenz, A.; Sanchez de Miguel, A.; Espinosa, A.; Crespo, A.; Aragonés, N.; Llorca, J.; Amiano, P.; Martín, V.; Guevara, M.; Capelo, R.; et al. Evaluating the Association between Artificial Light-at-Night Exposure and Breast and Prostate Cancer Risk in Spain (MCC-Spain Study). *Environ. Health Perspect.* **2018**, *126*, 047011. [CrossRef]

11. Longcore, T.; Rich, C. *Artificial Night Lighting and Protected Lands: Ecological Effects and Management Approaches*; Natural Resource Report NPS/NRSS/NSNS/NRR—2016/1213; National Park Service: Washington, DC, USA, 2016.
12. Kocifaj, M.; Bara, S. Night-time monitoring of the aerosol content of the lower atmosphere by differential photometry of the anthropogenic skyglow. *Mon. Not. R. Astron. Soc. Lett.* **2020**, *500*, L47–L51. [CrossRef]
13. Ribas, S.J.; Torra, J.; Figueras, F.; Paricio, S.; Canal-Domingo, R. How Clouds are Amplifying (or not) the Effects of ALAN. *Int. J. Sustain. Light.* **2016**, *35*, 32–39. [CrossRef]
14. Sciezor, T. The impact of clouds on the brightness of the night sky. *J. Quant. Spectrosc. Radiat. Transf.* **2020**, *247*, 106962. [CrossRef]
15. Hänel, A.; Posch, T.; Ribas, S.; Aubé, M.; Duriscoe, D.; Jechow, A.; Kolláth, Z.; Lolkema, D.; Moore, C.; Schmidt, N.; et al. Measuring night sky brightness: Methods and challenges. *J. Quant. Spectrosc. Radiat. Transf.* **2017**, *205*, 278–290. [CrossRef]
16. Karpińska, D.; Kunz, M. Device for automatic measurement of light pollution of the night sky. *Sci. Rep.* **2022**, *12*, 16476. [CrossRef] [PubMed]
17. Karpinska, D.; Kunz, M. Vertical Variability of Night Sky Brightness in Urbanised Areas. *Quaestiones Geographicae* **2023**, *42*, 5–14 . [CrossRef]
18. Elvidge, C.; Baugh, K.; Zhizhin, M.; Hsu, F.C. Why VIIRS data are superior to DMSP for mapping nighttime lights. *Proc. Asia Pac. Adv. Netw.* **2013**, *35*, 62–69. [CrossRef]
19. Wang, C.; Chen, Z.; Yang, C.; Li, Q.; Wu, Q.; Wu, J.; Zhang, G.; Yu, B. Analyzing parcel-level relationships between Luojia 1-01 nighttime light intensity and artificial surface features across Shanghai, China: A comparison with NPP-VIIRS data. *Int. J. Appl. Earth Obs. Geoinf.* **2020**, *85*, 101989. [CrossRef]
20. *ISO/CIE DIS 23539:2021*; Photometry–The CIE System of Physical Photometry. International Organization for Standardization: Geneva, Switzerland, 2022.
21. OSRAM Group. TSL2591 Light-to-Digital Converter, Product Document, 2018. Available online: https://ams.com/documents/20143/9331680/TSL2591_DS000338_7-00.pdf (accessed on 19 May 2023)
22. Glover, K. *Intelligent opto sensor Designer's Notebook: Using the Lux Equation;* Technical Report; AMS OSRAM: Munich, Germany, 2011.
23. Glover, K. *Intelligent opto sensor Designer's Notebook: Developing a Custom Lux Equation*; Technical Report; AMS OSRAM: Munich, Germany, 2011.
24. Alarcon, M.R.; Puig-Subirà, M.; Serra-Ricart, M.; Lemes-Perera, S.; Mallorquín, M.; López, C. SG-WAS: A new wireless autonomous night sky brightness sensor. *Sensors* **2021**, *21*, 5590. [CrossRef] [PubMed]
25. Xu, K. Silicon electro-optic micro-modulator fabricated in standard CMOS technology as components for all silicon monolithic integrated optoelectronic systems. *J. Micromech. Microeng.* **2021**, *31*, 054001. [CrossRef]
26. Zhang, Y.; Wijeratne, L.O.; Talebi, S.; Lary, D.J. Machine learning for light sensor calibration. *Sensors* **2021**, *21*, 6259. [CrossRef]
27. Chen, C.; Wang, J. Optical biosensors: An exhaustive and comprehensive review. *Analyst* **2020**, *145*, 1605–1628. [CrossRef] [PubMed]
28. Whaiduzzaman, M.; Barros, A.; Chanda, M.; Barman, S.; Sultana, T.; Rahman, M.S.; Roy, S.; Fidge, C. A Review of Emerging Technologies for IoT-Based Smart Cities. *Sensors* **2022**, *22*, 9271. [CrossRef] [PubMed]
29. Rosário, A.T.; Dias, J.C. Industry 4.0 and Marketing: Towards an Integrated Future Research Agenda. *J. Sens. Actuator Netw.* **2022**, *11*, 30. [CrossRef]
30. Niebla-Montero, Á.; Froiz-Míguez, I.; Fraga-Lamas, P.; Fernández-Caramés, T.M. Practical Latency Analysis of a Bluetooth 5 Decentralized IoT Opportunistic Edge Computing System for Low-Cost SBCs. *Sensors* **2022**, *22*, 8360. [CrossRef]
31. Dymora, P.; Mazurek, M.; Smalara, K. Modeling and Fault Tolerance Analysis of ZigBee Protocol in IoT Networks. *Energies* **2021**, *14*, 8264. [CrossRef]
32. Bassoli, M.; Bianchi, V.; De Munari, I. A plug and play IoT Wi-Fi smart home system for human monitoring. *Electronics* **2018**, *7*, 200. [CrossRef]
33. Mazhar, T.; Malik, M.A.; Haq, I.; Rozeela, I.; Ullah, I.; Khan, M.A.; Adhikari, D.; Ben Othman, M.T.; Hamam, H. The Role of ML, AI and 5G Technology in Smart Energy and Smart Building Management. *Electronics* **2022**, *11*, 3960. [CrossRef]
34. Raso, E.; Bianco, G.M.; Bracciale, L.; Marrocco, G.; Occhiuzzi, C.; Loreti, P. Privacy-Aware Architectures for NFC and RFID Sensors in Healthcare Applications. *Sensors* **2022**, *22*, 9692. [CrossRef]
35. Kim, B.; Kim, S.; Lee, M.; Chang, H.; Park, E.; Han, T. Application of an Internet of Medical Things (IoMT) to Communications in a Hospital Environment. *Appl. Sci.* **2022**, *12*, 12042. [CrossRef]
36. Finochietto, M.; Santos, R.; Ochoa, S.F.; Meseguer, R. Reducing Operational Expenses of LoRaWAN-Based Internet of Remote Things Applications. *Sensors* **2022**, *22*, 7778. [CrossRef]
37. Noor-A-Rahim, M.; Khyam, M.O.; Mahmud, A.; Li, X.; Pesch, D.; Poor, H.V. Hybrid chirp signal design for improved long-range (LoRa) communications. *Signals* **2022**, *3*, 1–10. [CrossRef]
38. Semtech Corporation. *Data Sheet—SX1276/77/78/79—137 MHz to 1020 MHz Low Power Long Range Transceiver*; Rev. 7; Semtech Corporation: Camarillo, CA, USA, 2020.
39. Montagny, S. *LoRa - LoRaWAN and Internet of Things for Beginners*; Rev. 2; Savoie Mont Blanc University: Chambéry, France, 2022.
40. STMicroelectronics. *STM32 Nucleo Expansion Board for Power Consumption Measurement (UM2243)*; STMicroelectronics: Geneva, Switzerland, 2018.

41. Jechow, A.; Kolláth, Z.; Ribas, S.; Spoelstra, H.; Hölker, F.; Kyba, C. Imaging and mapping the impact of clouds on skyglow with all-sky photometry. *Sci. Rep.* **2017**, *7*, 6741. [CrossRef] [PubMed]
42. Kyba, C.; Aubé, M.; Bara, S.; Bertolo, A.; Bouroussis, C.; Cavazzani, S.; Espey, B.; Falchi, F.; Gyuk, G.; Jechow, A.; et al. Commentary: Multiple Angle Observations Would Benefit Visible Band Remote Sensing Using Night Lights. *J. Geophys. Res. Atmos.* **2022**, *127*, e2021JD036382. [CrossRef]
43. Kocifaj, M.; Barentine, J. Air pollution mitigation can reduce the brightness of the night sky in and near cities. *Sci. Rep.* **2021**, *11*, 14622. [CrossRef]
44. Karpinska, D.; Kunz, M. Light pollution in the night sky of Toruń in the summer season. *Bull. Geogr. Phys. Geogr. Ser.* **2019**, *17*, 91–100. [CrossRef]

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Device for automatic measurement of light pollution of the night sky

Dominika Karpińska✉ & Mieczysław Kunz

Research on light pollution of the night sky has been carried out in Toruń, Poland since 2017. Initially, the measurements were conducted within a network of 24 points using a handheld sky quality meter with lens (SQM-L) photometer (Unihedron, Canada). Based on these measurements, the first accurate maps of night sky pollution by artificial light in Toruń have been developed, both in seasonal and annual terms. Using the experience gained and elements of modern technology, a decision was made to construct an automatic network of mobile devices measuring light intensity at night, covering the entire city of Toruń. This paper presents the technical characteristics of the constructed automatic measurement devices that make up the distributed monitoring network and the process of testing and using the devices. The implementation of this project has started in 2020. To accommodate the evolving expectations of different user groups and the observed trends in the concept of Smart Cities, especially those related to the communication between devices of the Internet of Things, LoRaWAN was selected for data transmission. The first stage involved the construction of a prototype of an automatic, portable and cost-effective device, which was subjected to months of field testing under operational conditions. The device was built using off-the-shelf electronic components and a housing that met the requirements for outdoor use. The next stage was to calibrate the device by simultaneously comparing the obtained results with measurements taken using professional SQM devices. This was followed by the preparation of 35 identical devices, which are already operating in the measurement network in the city of Toruń. Elements of the network are prepared in a way that allows for further expansion and makes data available in the form of an application for many recipients.

Human actions in the geographical environment transform the last natural ecosystems and further modify previously altered ones. The observed transformations relate to the timing of the factor, its spatial extent and the scale of impact[1,2]. Changes in the environment, their direction and, above all, their intensity, as well as, in some situations, irreversibility of the transformations, have become one of the main reasons for the search for new, effective research methods and for an increased interest in comprehensive monitoring of the key environmental parameters, as well as for strengthening the influence and the role of education and the importance of environmental awareness.

People are becoming increasingly conscious of the impact and consequences of their actions on the state and quality of the environment, especially in the vicinity of their homes and immediate surroundings. They are also increasingly aware of long-term threats and their negative impact on the life, health and functioning of all living organisms. There is growing recognition of the issue of smog and air pollution by particulate matter or concentrations of gases, water and soil by heavy metals and pesticides, radioactive contamination, noise pollution, odour, and increasing light pollution of the night sky[2–11].

The last mentioned phenomenon is caused by excessive emission of artificial light at night, mainly by inappropriately mounted street lamps, illumination of places that should not be lit, and the use of poorly designed light illuminations[9]. About 80% of the world's people and as much as 99% of European and US citizens live in light polluted areas[12]. Excess of this factor can cause hormonal disorders in humans, including melatonin deficiency resulting in problems with metabolism and sleep. The negative consequences are also visible in the development of plants and animals that are used to the circadian rhythm in evolution[13].For many decades, research has been conducted on the impact of these phenomena on human health and the quality of life, resulting in the search for effective ways to reduce or eliminate them. Monitoring of selected environmental parameters is carried out in several different ways and the results are made public in a number of forms. Several so-called instrumental and analytical methods are available, which are widely used to determine the size and extent of the degradation factor. Analysis of various types of pollution is nowadays a thriving part of science involving chemistry, environmental

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sciences, biology and other natural and technical sciences. Monitoring of a global phenomenon has become an interdisciplinary issue, and thanks to the development of technology, it is now highly automated. To determine environmental parameters, methods are used that involve both simple measurements and complex laboratory tests requiring advanced knowledge and equipment[2]. The majority of phenomena negatively affecting the environment are usually subject to spot measurements spread over time. Nevertheless, monitoring networks are becoming increasingly widespread, thanks to which it is possible to determine both the extent and magnitude of a phenomenon and its course and variability in time and space. These efforts enable a more thorough understanding of a harmful process, its course, distribution, impact on the immediate and distant surroundings, as well as on the life and health of living organisms, from plants, through animals to humans. Multi-faceted knowledge of an observed phenomenon allows us to take more effective countermeasures and create an effective mechanism to mitigate its impact. One such example is research on the occurrence of airborne particulate matter. Nowadays, remote measurements and monitoring with real-time assessment of air quality has become standard in most cities[2,14]. Through this type of research, it has been possible to introduce a number of measures to prevent or reduce negative effects, as well as to inform the public about the current level of risk.

This paper describes an automatic device constructed by the authors to measure the pollution of the night sky by artificial light, a phenomenon that is increasingly observed, universally recognised and of interest to a growing group of scientists from many countries[11,15–19]. Various measurement methods have been developed to understand and determine the scale of the phenomenon. In technical terms, they can be divided into instrumental and observational methods, whereas from the functional point of view into those that can be used only by a qualified operator or by an amateur with no professional knowledge[15,17,20,21]. The most commonly used methods of measuring the light pollution are those using photometers and digital cameras[3,15,16,19,20]. Measurements made in this way are standardised, thus it is possible to compare the intensity of the phenomenon at different measurement sites located all over the world[14,20,22]. Research with the use of satellite imagery has also being carried out on an increasingly large scale. For this purpose, images taken by, e.g. the Suomi NPP satellite with the visible/infrared imaging radiometer suite (VIIRS) Day/Night Band instrument, the Defense Meteorological Satellite Program (DMSP) satellite with the operational linescan system (OLS) instrument, and Luojia 1-01 satellites are used[23,24]. Models of night sky brightness have also been developed[12], making it possible to predict brightness values at any location around the globe.

Wireless network

The development of environmental monitoring would not be possible without continuous technological progress, public pressure and targeted environmental education. To meet the expectations of users, measuring instruments must not only be ever more accurate, but also practical and straightforward to use and economical to operate. Environmental analytics has begun to strongly overlap and interpenetrate with broadly defined modern digital technology and informatisation[25,26]. Nowadays, creating new measurement solutions is an interdisciplinary challenge for representatives of both natural and technical sciences, including computer scientists and programmers. In the implementation of largescale measurements of spatially distributed phenomena, fully mobile devices become indispensable, as they transmit the collected data to a server where they are analysed, shared, and often visualised. This will also allow the collected measurement data from ever longer observation sessions to be archived and utilised.

The development of a fully mobile, and thus highly functional recording device anticipated by the target market is accomplished through the use of wireless data transmission technology. Depending on the needs, such technologies can be divided related to the range of data transmission and the transfer size. Each of these technologies is characterised by a specific subset of users, as well as parameters and technical requirements. The most popular long-range data transmission technologies include the widespread GSM network, while Wi-Fi or Bluetooth networks are characterised by a much shorter range of up to several dozen metres[27,28]. In terms of data packet transmission rate, on the other hand, GSM and Wi-Fi networks can transmit significantly more data than Bluetooth. When it comes to environmental measurements implemented by a distributed sensor network, the most important operational parameter, which determines the choice of a given solution, is the power consumption used when sending messages. The raw measurement data will usually contain relatively small-sized information packets, but their deployment in areas with difficult access to power supplies makes it necessary to use a solution based on its own energy source, usually a battery with a long or very long life without the need for frequent replacement or charging. The abovementioned wireless data transmission technologies are too energy-intensive for such tasks, as they consume a significant amount of energy during data transmission, which prevents long-term monitoring of environmental data on a larger spatial scale and in uninhabited areas or areas with limited technical infrastructure. LPWAN (Low Power Wide Area Network) networks have been designed with such applications and peripheral locations in mind[29,30]. Due to its extensive applicability and parameters, LPWAN is one of the most modern technologies increasingly used for the communication between devices[30–33]. As one of the many elements of Industry 4.0, it fits into the idea of internet of things (IoT), supporting Smart City solutions. Of the available types of LPWAN networks, three are most extensively used: Sigfox, NB-IoT and LoRaWAN. Each of these types of solutions has its own parameters and is intended for different applications[30,33].

The LoRaWAN standard was selected for the implementation of this project involving the monitoring of night sky pollution by artificial light. It has the most optimal parameters in relation to the prepared design objectives and applications of the designed device. The LoRaWAN standard is one of the MAC (Medium Access Control) radio communication protocols[28,34,35] and is characterised by a long range allowing network connectivity with low power consumption. LoRa technology is used for communication in the LoRaWAN standard and is, for such applications and with the input limitations indicated, an alternative to other technologies such as LTE, Wi-Fi or Bluetooth (Fig. 1).

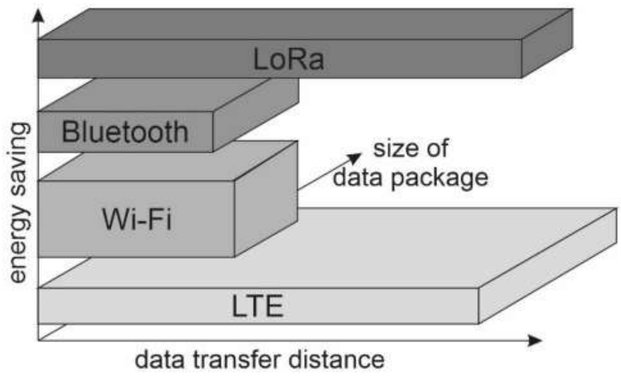

Figure 1. Schematic comparison of selected parameters (data transmission distance vs. energy efficiency) of the most popular wireless technologies on the market.

LoRa is a type of modulation that uses the CSS (Chirp Spread Spectrum) technique, consisting in spreading the spectrum of the transmitted signal[29,33–35]. The CSS modulation makes full use of the allocated transmission bandwidth, which increases the robustness of the communication against interference, and eliminates inaccuracies related to the Doppler effect and route propagation. LoRaWAN is developed as an open standard that uses the ISM (Industrial, Scientific, Medical) radio spectrum and requires no licence fees. In Europe, LoRa operates at the 868 MHz frequency band. The great advantage of the selected technology is its range, which in the field conditions varies, depending on the type of housing development, from several hundred metres to several kilometres[28,33,36]. In the professional literature, one can find examples of measurements and data transmission performed under specific conditions, over a distance of up to 702 km[28]. An additional key function of LoRaWAN is the possibility of bidirectional communication, allowing not only to send but also to receive information. In the process of planning a wireless network, the advantage of LoRaWAN is the use of an unlicensed radio band, thanks to which there are no restrictions and additional requirements, or costs associated with the activation and operation of an already established network. In practice, the LoRaWAN architecture consists of four main components, such as end devices (data loggers), communication gateway(s) and a network and application server.

Due to its universal parameters, LoRaWAN technology is used in many fields of application. Such solutions can be found, among others, in defining the objectives of Smart City, where they form the basis for the transmission of traffic, environmental and logistic information, in the construction industry in monitoring the status of operation and quality of structures, and in modern medicine when monitoring the health of patients staying outside medical facilities[25,32,35,37].

Methodology of work on device for remote measurement of night sky light pollution

For several years, systematic research has been carried out on the pollution of the night sky by artificial light in the city of Toruń[11,36,38]. The main objective is to monitor this phenomenon, including its spatial and temporal variability and the most important factors affecting it. Based on previous experience, an in-house measurement device was constructed to automate the process of data acquisition.

Genesis of the project. The first measurements pertaining to the phenomenon of night sky pollution in Toruń were made in autumn 2017, followed by regular observations using a handheld SQM photometer (Unihedron, Canada) as part of a project implemented in 2017–2018. To this end, a permanent measurement network distributed throughout the city was established, consisting of 24 locations. During a one night measurement session taking place during the astronomical night (there is no such period at the latitude of Toruń in the summer), sky brightness was measured at all sites. The results of spot monitoring were plotted using interpolation methods and visualisation tools available in GIS systems[11,39], which helped to determine the spatial distribution and extent of night sky light pollution. The intensity of this phenomenon at each of the surveyed points was also explored in relation to the distinguished landcover categories and types of urban development.

Repeatable measurements performed regularly over such a long period of time were characterised by significant limitations. One measurement session was very time-consuming, as it lasted about two hours, during which time all measurement locations were visited, covering a distance of almost 50 km each night by car. Despite the observance of all time frames and sticking to the plan of fieldwork, measurements were not carried out simultaneously at all the locations, which affected the results, especially during the night with changing cloud cover. Although the measurements were carried out with great consistency and care, they were performed in a spatial buffer of about 5 m, which could unintentionally slightly affect the obtained results. An additional limitation was also a one-time night measurement at one point, instead of a whole series of measurements at specific time intervals. Inaccuracies in the readings within a single session could have been caused by sudden changes in meteorological parameters. In the adopted procedure, it was not possible to carry out simultaneous measurements in identical time and weather conditions at all the locations, not to mention the involvement of the personnel in each tour of the measurement network points.

Using the experience gained and after an analysis of the identified constraints and the technical capabilities at hand, work began in 2019 on developing a network for automatic remote monitoring of light pollution of the night sky in Toruń, based on designed in-house recording devices.

Design, functional and utility features of the device. To enhance the research on light pollution in urban space, work has begun on the construction of a device that would perform automatic measurements, would be mobile, battery-powered and use long-range wireless communication. All the aforementioned features are in line with the strategy of Industry 4.0 and modern solutions proposed as part of the Smart City concept.

The concept of Industry 4.0 assumes the more and more common use of process automation as well as the processing and exchange of data with the use of new transmission technologies[26]. LoRaWAN is one of the solutions used for communication of Internet of Things (IoT) devices, which supports the development of Smart Cities in the Smart Environment area. As a result, the interactivity, frequency, and scope of measurements carried out in urbanized areas are increased[40,41].

According to the developed project, the device was to serve as a meter of very low intensity light observed in the night sky. In this respect, it was necessary to use a sensor with technical parameters suitable for very accurate measurements of light intensity. To locally verify the weather conditions occurring during the operation of the device, it was decided to carry out additional simultaneous measurements of other environmental parameters—temperature and moisture content. The analysis of the spatial coverage of the study area indicated that 36 measurement devices should be deployed to provide full coverage of Toruń. The concept of creating an urban measurement network assumes the selection of points covering the whole city relatively evenly and representing different types of housing development and elements of land cover. It was assumed that measurements will be made only at night, between 21 p.m. and 6 a.m. on the following day, at 15 min intervals, and in addition, weather conditions will be recorded twice a day.

Construction and technical parameters of the device, and selected characteristics of its components. A prototype device meeting all the predefined functionalities was constructed based on available electronic modules. The B-L072Z-LRWAN Discovery developmental board from STMicroelectronics[42] was selected as the main electronic component providing wireless communication. This board has an integrated LoRa communication module, enabling low-power wireless messaging, and also allows the board to enter a low-power state during hibernation, and thus target long-term battery-powered operation. This module is fully programmable, which enables future expansion of the set with other functionalities. The TSL2591 light sensor from AMS, which has high sensitivity and registration accuracy, was selected as a component implementing the light intensity measurement. Its great advantage is a wide measurement range of 188 μlx to 88 000 lx, sensitivity reaching 0.000377 lx, and a wide dynamic range (WDR) of 600 M:1[43]. The sensor used has two diodes with different spectral properties. One of them registers visible light together with infrared (in the range from 400 to 1 100 nm), while the other is responsible for the registration of infrared light (between 500 and 1 100 nm). Thanks to this solution, we can use the results in various ways. The use of the formula provided by the manufacturer allows us to obtain spectral characteristics similar to the human eye. The presence of a compensating diode makes a difference compared to the sensor used in the SQM device, so the results obtained in the measurements may be slightly different.

To measure additional environmental parameters, the X-NUCLEO-IKS01A2 development board from STMicroelectronics was used, which is connected to the STM32 microcontroller via the I2C interface[44]. This board enables the recording of a number of parameters, however, in the constructed device it is only responsible for reading the temperature and humidity of the environment. This results from the necessity to limit the size of the message packets sent, while at the same time improving the operating range and reducing the power consumption of the device.

Once all the components had been selected, tested and integrated, the process of final connection and programming was carried out. The base of the device, i.e. the B-L072Z-LRWAN development board was connected to the X-NUCLEO-IKS01A2 environmental sensor board, using Arduino connectors. Using standard wires, a TSL2591 light sensor was added by connecting the corresponding I2C (SCL and SDA), power supply (VIN), sensor ground (GND) pins and the X-NUCLEO-IKS01A2 board.

All components used were placed in a standard external casing with dimensions of 8.0 × 5.4 × 15.8 cm. In its lower part an opening was made for an external antenna, while in the upper part a specifically selected opening was cut out, protected with a glass pane, through which measurements are performed by the light sensor (Fig. 2).

Following the above steps, an automatic device was constructed to record light intensity in the lower troposphere, i.e. to measure the pollution of the night sky by artificial light coming from the Earth's surface. Selected technical parameters of the device are presented in Table 1.

Flowchart of the system operation. After constructing the device and writing the control software, the construction of the entire measurement system was started. Each of the measuring instruments is ultimately connected to the communication gateway using LoRa technology. A MultiTech communication gateway with a LoRaWAN module was used as an access device. To successfully connect the gateway to the measuring device, it was necessary to configure the communication gateway software. To this end, the information about the unique device number (Dev EUI) and the application key and its number (App EUI and App Key) was used. Once the unit is configured, it is possible to send data to the communication gateway and read them using NodeRED, a programming tool where data are redirected to a selected server, which stores all measurement results. Figure 3 shows a schematic representation of the constructed measurement system.

Figure 2. Constructed device view (photo by Dominika Karpińska).

Parameter	Characteristic
Weight	380 g
Dimension	5.5 × 8.2 × 15.8 cm
Standard of data transmission	LoRaWAN
Frequency bands	868 MHz
Operating time [3 000 mAh]	~ 9 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	light intensity, temperature, humidity
The half-cone angle of data collection	27°
Tightness class	IP65

Table 1. Selected technical parameters of the device for measuring light pollution of the night sky.

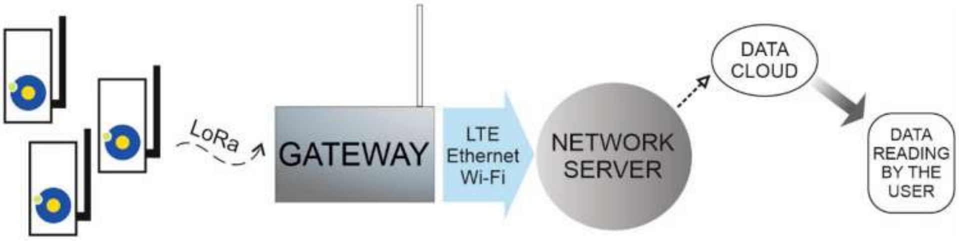

Figure 3. Schematic diagram of the measurement system.

Test results for the measurement devices under operational conditions

Following the construction of the prototype device and the preparation of all elements of the measurement network and their configuration, the necessary tests were carried out. The first of them was to check the correctness of the collected measurement data. For this purpose, two devices (1 and 2) were installed in close proximity to each other in the NCU premises, and the data collected were compared with measurements taken at the same time and place using a handheld SQM photometer version L. Sky brightness values recorded in lux were converted into units used in SQM photometers, by using a spherical angle and a commonly shared formula for converting to mag/arcsec^2 units[18]. The obtained measurement results are presented in Fig. 4.

During the test measurements, the observed sky was cloudless. On the graph between the measurement by 0:01 and 0:16 you can see the change in the brightness of the sky, it is the result of turning off street lamps located on a nearby street. After 3:46 you can also see the rising Sun effect. The differences between the results are due to slightly different lighting conditions at the positions taken and from the possible non-vertical positioning of

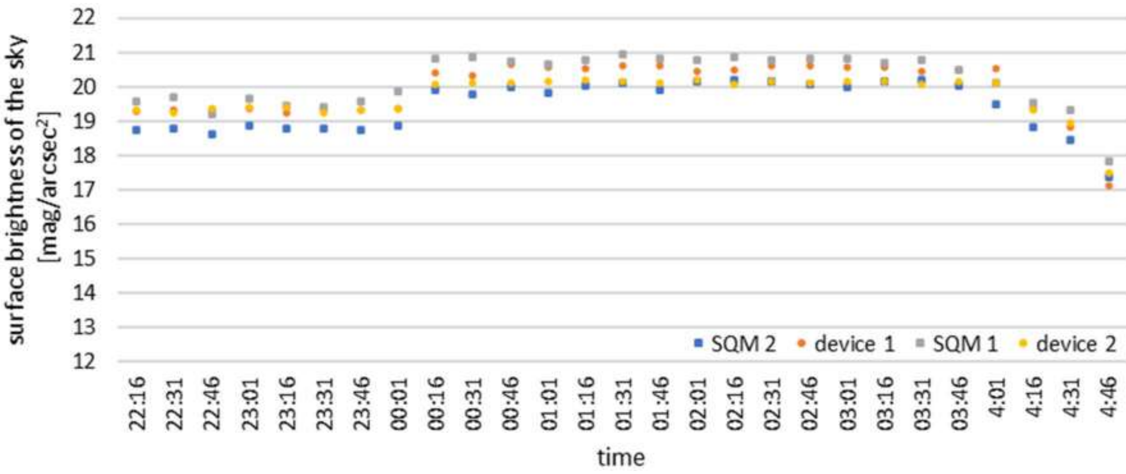

Figure 4. Comparison of the measurement results obtained by a device of its own design with the measurements made by SQM photometer (27–28.03.2020).

Figure 5. Automatic device (1 and 2) measuring the brightness of the sky, placed on one of the buildings in TARR (photo by Mieczysław Kunz).

the manual SQM photometer used for the tests. Analysis of the collected data from the constructed devices and from the SQM photometer shows that they are comparable and overlap throughout the measurement period of 6 h. This proves that the digital light sensor used in the constructed device is of high accuracy and correctly performs the measurements in relation to the prevailing outdoor conditions.

Technology demonstrator stage and comparison with the results from the 2017/2018 season (TARR location). The next stage of the work performed was to check the 24 h operation mode of the devices, connectivity and the correct operation of the server where measurement data were stored. This stage was carried out at the headquarters of the Toruń Regional Development Agency (TARR) in Toruń under a signed trilateral agreement. The devices were deployed in two locations, about 100 m from each other, on the roofs of selected buildings situated within TARR (Fig. 5) and connected to the communication gateway located in the same area. The results of the pilot measurements at the TARR site are presented in Fig. 6. Through a single visualization, it shows the obtained original measurement data recorded simultaneously by the two devices, while the successive stages of the night, from sunset through civil, nautical and astronomical twilight, are shown in the background.

The analysis of the presented data shows a similarity in the curve representing the values of the phenomenon measured at both locations. The differences in their absolute values result from deploying the devices in places with slightly different local light conditions in their immediate vicinity. At the same time, during the analysis of the obtained data, the values measured at the TARR site in the 2020–2021 season using the constructed device were compared with the results obtained with the SQM photometer in the 2017–2018 season. However, weather conditions were not identical during the comparison, but to ensure similar conditions, the presented data were collected at the same time (24:00). The current location of the TARR site corresponds to the nearby RUD site,

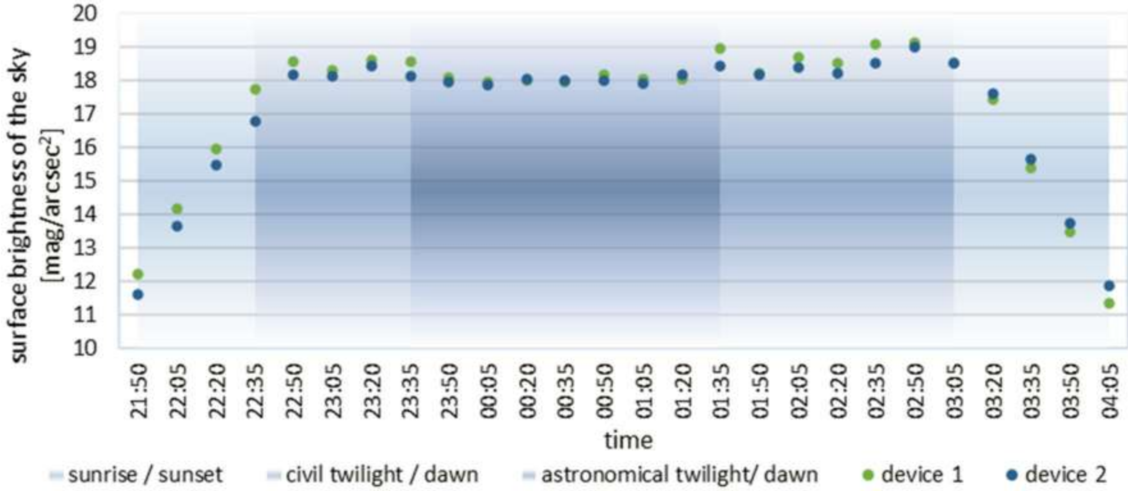

Figure 6. Average of measurement of sky brightness during the tests in TARR during technology demonstrator stage.

Date	2017/2018		2020/2021		
	SQM_RUD (TARR) [mag/arcsec^2]	SQM_OKR (UMK) [mag/arcsec^2]	TARR (device 1) [mag/arcsec^2]	UMK (device 3) [mag/arcsec^2]	SQM_LE (UMK) [mag/arcsec^2]
18 November	19.07	18.66	19.14	19.13	19.12
3 April	19.17	19.02	18.54	19.06	*No data*
26 May	17.58	17.68	17.31	17.54	*No data*

Table 2. Sample measurements from the 2017/2018 project and the new project 2020/21.

while the OKR site, used in the project carried out in the 2017–2018 season, was located near the University (NCU site). The comparison of the results from these two locations is presented in Table 2.

The comparison shows that the results are consistent with each other. The recorded data do not differ significantly from each other, however, an in-depth comparative analysis between the measurement series will only be possible after an automatic measurement network is established throughout the city. Analyzing the data in the table, you can already notice a seasonal change in the value of the brightness of the night sky[45]. This is due to the changing length of the night during the year.

Stage of simultaneous testing of the measuring device with the SQM LE meter. After the measurement results from the first tests and the technology demonstrator stage were completed and found to be correct and reliable, another measurement device (designated as Device 3) was installed at the Nicolaus Copernicus University in Toruń. At the same time, to check again the correctness of the recorded data, a commercial photometer SQM in the LE version was installed in the same place next to that device (Fig. 7). To compare the results from both instruments (Device 3 and SQM) and additional results from one of the TARR devices (Device 1), the recorded values were converted into magnitudes and the results of the measurements taken during six consecutive nights, from 13 to 18 November 2020, were presented graphically (Fig. 8).

The graph shows high similarity between all recorded measurement data. However, it should be remembered that by using two diodes in our device, the infrared band that is present in the SQM device is compensated. Due to this difference, the results can vary statistically by about 0.2 mag/arcsec^2. The lower results correspond to meteorological conditions when the sky was completely or heavily clouded, while fluctuations in the course of the measurement curves are observed during dynamically changing cloud cover. During a cloudless sky, the recorded data reach their maxima and the points from all the devices form a uniform, relatively horizontal, overlapping line on the graph, indistinguishable from each other, both in the course and range of the presented values.

Stage of calibration of the set of measuring devices. After completing all the above steps and stages of testing the first experimental measurement devices, another 35 identical units were produced, which formed the basis for the establishment and operation of a remote network to monitor artificial night light pollution in the urban space of Toruń according to the authors' concept of implementing automatic measurements. To calibrate, i.e. to check the correctness of operation of all devices constituting the future "distributed measurement network", they were set up simultaneously next to each other on the observation terrace of the Meteorological Observatory of the Faculty of Earth Sciences and Spatial Management of the Nicolaus Copernicus University in the direct vicinity of operating device 3 (Fig. 9). This site was selected primarily for its easy accessibility, unob-

Figure 7. Device 3 located on the area of the Nicolaus Copernicus University in Toruń, next to the device is the SQM photometer (photo by Mieczysław Kunz).

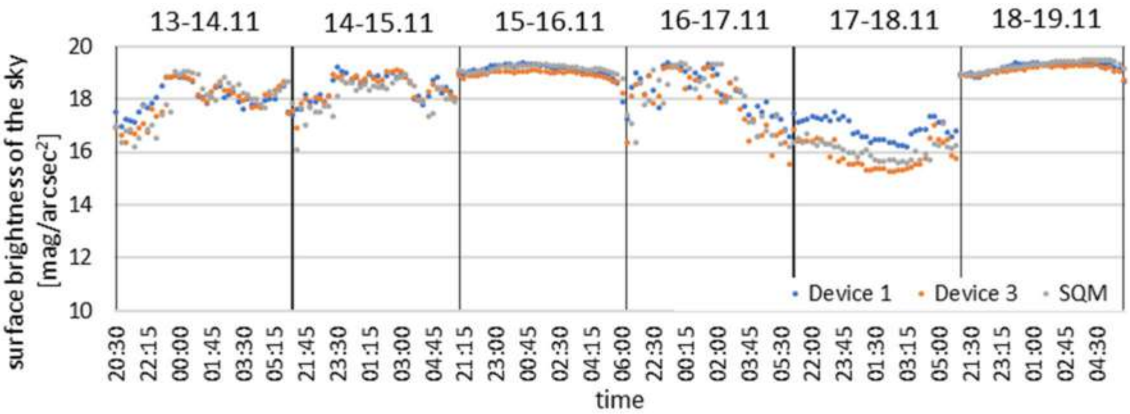

Figure 8. Comparison of measurements from device 1 and 3 with measurements made with the SQM photometer during consecutive nights from November 13 to 18, 2020.

Figure 9. Test the cloud of 35 devices for measuring the sky brightness in winter 2020 on the terrace of the NCU Meteorological Observatory in Toruń (Poland) (photo by Mieczysław Kunz).

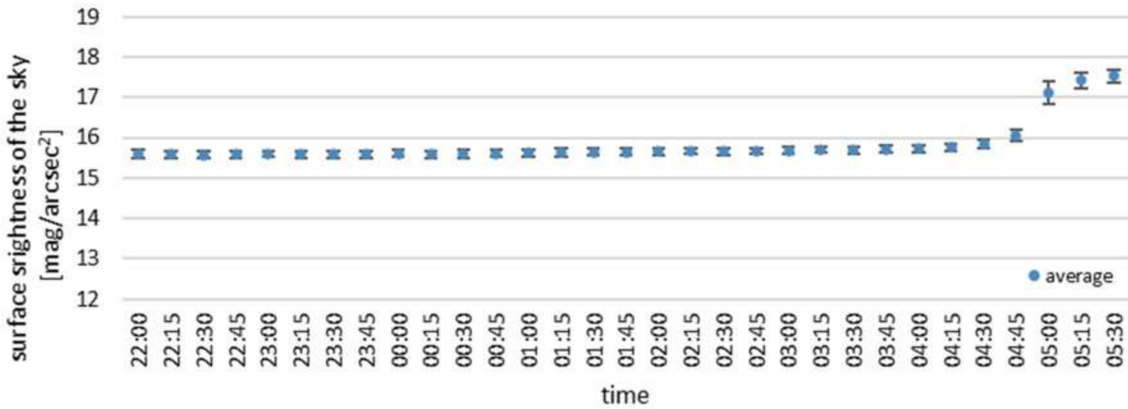

Figure 10. Summary of measurements from all devices during completely cloudy night of November 31 to December 1, 2020.

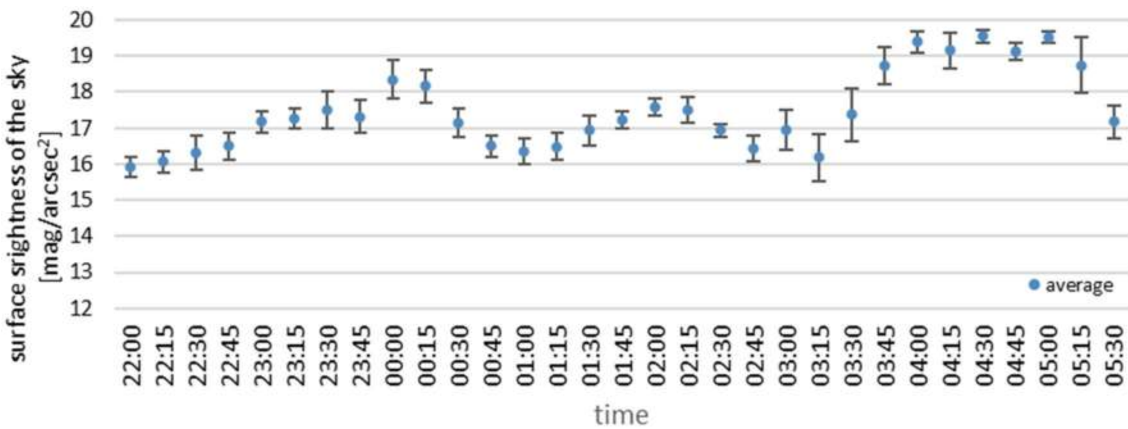

Figure 11. Summary of measurements from all devices during the night with variable cloudiness of December 24 to 25, 2020.

structed vision and the possibility of comparing the obtained results with the reference device (Device 3). At this stage, two test sessions were carried out during the winter season of 2020–2021, lasting continuously for one week each. The light pollution measurements of the night sky recorded by all the tested devices for an average fully cloudy night are shown in Fig. 10, and for a night with varying cloud cover in Fig. 11.

The graphs presented in Figs. 10 and 11 show high similarity of the results, including a similar course of the night measurement curve. Each graph shows the average of all measurements along with the standard deviation. The results shown in Fig. 10 were recorded under constant cloud cover, and the difference in standard deviation at each point is 0.14 mag/arcsec^2 on average. Figure 11 shows the mean of the measurements during changing cloud cover, and here the standard deviation is about 0.3 mag/arcsec^2. Slight differences in the course of the curve result from the fact that the measurements were only made at approximately the same time, as each device was awakened in a different part of the adopted 15 min interval.

To accurately analyse the collected data from all devices, they were averaged and presented together. The summary of the average results with the standard deviation compared to the readings from the SQM photometer at the same location are presented in Fig. 12.

The analysis of the presented graph leads to the already presented conclusions and confirms the correct operational performance, both of the prototype device and of the entire repetitive series of the prepared measuring devices. The results of the recorded measurements are consistent between the devices and correspond to the factory reference device (SQM) value. The slight differences between the readings are only due to the use of a sensor with slightly different parameters, which reduces the recorded infrared band in a different way. The differences for the minimum and maximum values for nights with varying cloud cover are due to the previously mentioned differences in the wakeup of the devices. The mean value coincides with the results from the SQM photometer, therefore the data collected by the devices can be fully comparable with the world datasets.

After all the above steps had been completed, work began on the deployment of measuring devices in Toruń and the surrounding area. At present, there are already 19 devices operating within the monitoring network and more are being deployed to form a complete measurement network evenly covering the whole city.

The studies carried out at the same time show that less than 40 devices are enough to cover a medium-sized city such as Toruń (about 100 km^2)[46]. In these studies, the field of view of the device and the mean, lowest, and

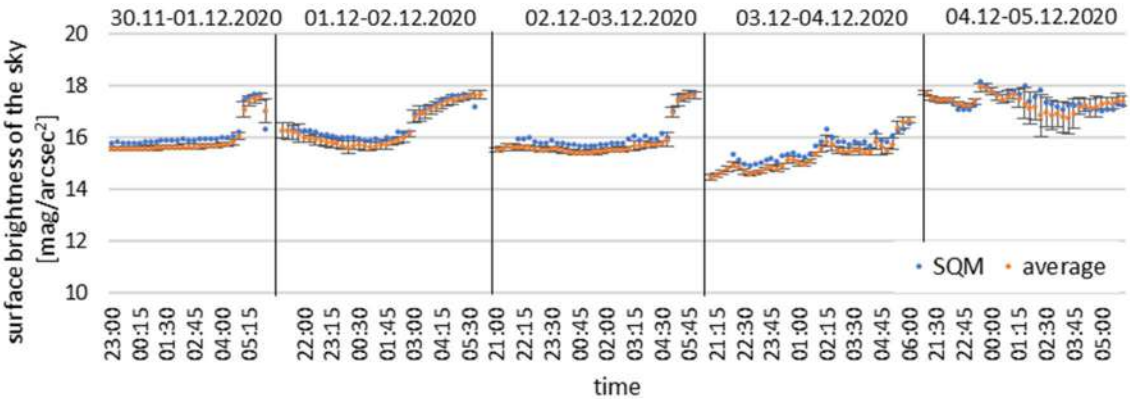

Figure 12. Summary of the average measurement results of all devices with the results measured with the SQM photometer.

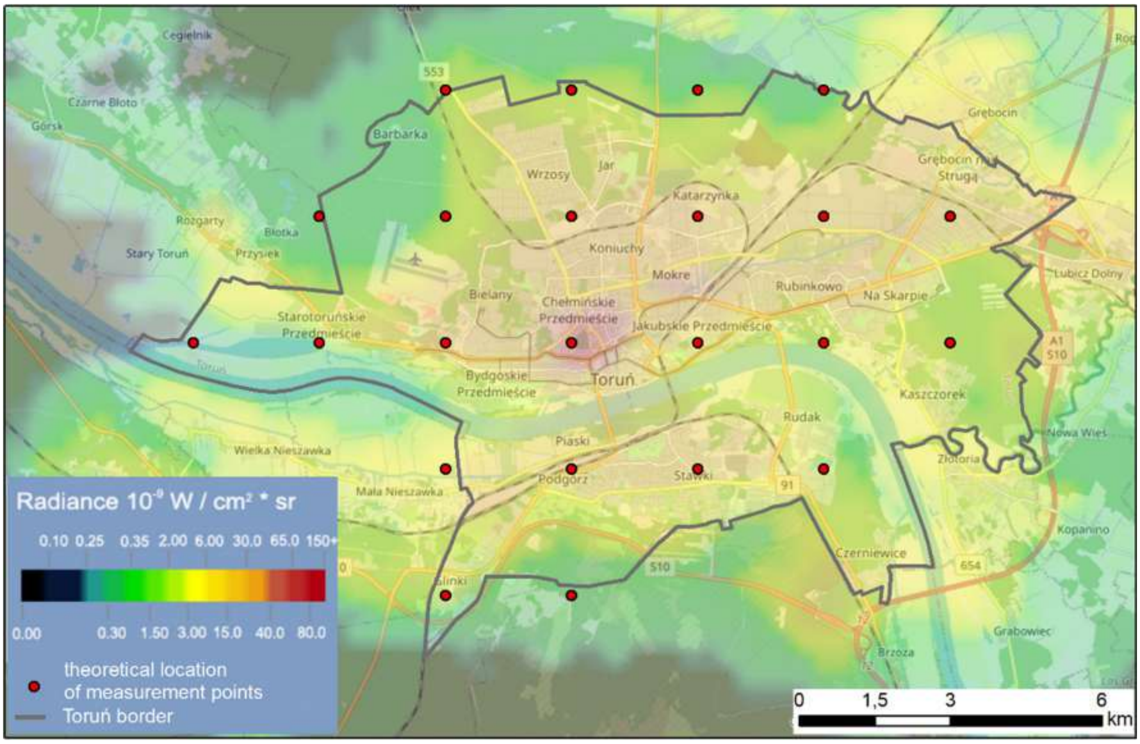

Figure 13. Theoretical location of measurement points. The background is the VIIRS light pollution map from 2021 at https://www.lightpollutionmap.info.

most common cloud base were taken into account. These simulations made it possible to determine the most advantageous distance of approximately 2.5 km. The theoretical layout of these devices is shown in Fig. 13.

Future of the device and its use in further operations

Upon the completion of the night sky light intensity measurement network, it is planned to expand the device so that it will be possible to record also other environmental parameters, including particulate matter and concentrations of selected chemical substances. The established LoRaWAN wireless network is a good start to create multiparameter monitoring of the natural environment in urban space. The establishment of an open-access, low-cost, long-range network in an urbanised area is a value that fits into the functioning of a modern city implementing the objectives of Industrial Revolution 4.0, as well as meeting the solutions of the Smart City concept regarding Smart Environment.

Conclusions

Targeted environmental monitoring is a necessary component of urban planning and a response to the expectations of citizens. Such targeted efforts and investments are necessary to know the extent, magnitude and intensity of all relevant parameters of human induced environmental pollution. The phenomenon of light pollution addressed in this paper is becoming more and more perceptible and a growing number of interdisciplinary studies on this issue is being conducted. They relate both to understanding the causes and extent of this negative phenomenon, as well as to its impact on all living organisms, including primarily human beings. Therefore, it seems necessary to monitor it in a continuous manner. The developed original device for sky brightness measurement, operating in a distributed measurement structure, is a proposal for measuring light smog in urban areas. The network for monitoring the night sky brightness in the area of Toruń, proposed conceptually and implemented, has successfully passed all subsequent efficiency tests, including measurement, operation, communication and data archiving. The measurement data obtained by the constructed remote automatic recording device are accurate and corresponding in value to the data obtained by a commercial photometer available on the market. This gives a full and complementary possibility of comparing the registration by the constructed device with the results obtained during measurements carried out in other parts of the world or in relation to archival values. Further steps are planned to expand and adapt the monitoring network established in Toruń for subsequent projects. The design of the device allows it to be adapted to measure other environmental parameters. There is also great flexibility in configuring the equipment for new tasks and challenges that may arise during operation.

Data availability

All data analysed during this study are included in this article. If anyone wants the datasets they are available from the corresponding author on request.

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References

1. Wang, L. K., Pereira, N. C. & Hung, Y. T. *Air Pollution Control Engineering* (Humana Press, 2004).
2. Stepnowski, P., Synak, E., Szafranek, B. & Kaczyński, Z. *Monitoring i analityka zanieczyszczeń w środowisku* (Wydawnictwo Uniwersytetu Gdańskiego, 2010).
3. Jechow, A. *et al.* Tracking the dynamics of skyglow with differential photometry using a digital camera with fisheye lens. *J. Quant. Spectrosc. Radiat. Transfer* **209**, 212–223 (2019).
4. Para, A. & Para, A. Świadomość skażenia otoczenia człowieka radonem. *Przegląd Naukowy Inżynieria i Kształtowanie Środowiska* **59**, 88–97 (2013).
5. Wyszkowski, M. & Wyszkowska, J. Zanieczyszczenie gleby kadmem a zawartość makropierwiastków w roślinach. *Ochrona Środowiska i Zasobów Naturalnych* **31**, 231–235 (2007).
6. Wani, K. A., Manzoor, J., Dar, A. A., Shuab, R. & Lone, R. *Heavy Metal Intrusion and Accumulation in Aquatic Eco-systems* (Springer Press, 2019).
7. Żurek, Z. H., Jasiński, T., Glinka, T. & Sobota, J. Pole magnetyczne wokół transformatorów energetycznych. *Przegląd Elektrotechniczny* **11**, 54–56 (2017).
8. Woźny, A., Dobosz, M. & Pacana, A. Wpływ hałasu na jakość pracy. *Human. Social Sci.* **21**(2), 251–258 (2014).
9. Longcore, T., Rich, C. & DelBusso, L. Artificial Night Lighting and Protected Lands. Natural Resource Report NPS/NRSS/NSNS/NRR—2017/1493 (2017).
10. Qadri, H., Bhat, R. A., Mehmood, M. A. & Dar, G. H. *Fresh Water Pollution Dynamics and Remediation* (Springer Singapore, 2020).
11. Karpińska, D. & Kunz, M. Light pollution in the night sky of Toruń in the summer season. *Bull. Geogr. Phys. Geogr. Ser.* **17**, 91–100 (2019).
12. Falchi, F. *et al.* The new world atlas of artificial night sky brightness. *Sci. Adv.* **2**(6), e1600377 (2016).
13. Navara, K. J. & Nelson, R. J. The dark side of light at night: physiological, epidemiological, and ecological consequences. *J. Pineal Res.* **43**(3), 215–224 (2007).
14. The World Air Quality Project. Air Pollution in World: Real-time Air Quality Index Visual Map. Retrieved June 26, 2020 from https://aqicn.org/map/world (2021).
15. Pun, C. S. J. & So, C. W. Night sky brightness monitoring in Hong Kong. *Environ. Monit. Assess.* **184**(4), 2537–2557 (2012).
16. Kyba, C. C. *et al.* Worldwide variations in artificial skyglow. *Sci. Rep.* **5**, 8409 (2015).
17. Kyba, C. C. *et al*. Report of the 2015 LoNNe Intercomparison Campaign. Report of the ES, 1204 (2015).
18. Ściężor, T. Effect of street lighting on the urban and rural night-time radiance and the brightness of the night sky. *Remote Sens.* **13**(9), 1–41 (2021).
19. Kołomański, S., Wiernasz, A., Borodacz, K., Białek, R. & Mikołajczyk, P. ALPS – stacje obserwacyjne zanieczyszczenia światłem, [in:] Zanieczyszczenie światłem. Źródła, obserwacje, skutki, (ed.) A. Kotarba, Centrum Badań Kosmicznych PAN, 153–166 (2019).
20. Jechow, A. *et al.* Measuring light pollution with fisheye lens imagery from a moving boat, a proof of concept. *Int. J. Sustain. Light.* **36**, 15–25 (2017).
21. Ściężor, T. Metody pomiaru jasności nocnego nieba. Retrieved December 10, 2021 from http://lightpollution.pk.edu.pl/SOCN/metody.php
22. Pun, C. S. J., So, C. W., Leung, W. Y. & Wong, C. F. Contributions of artificial lighting sources on light pollution in Hong Kong measured through a night sky brightness monitoring network. *J. Quant. Spectrosc. Radiat. Transfer* **139**, 90–108 (2014).
23. Wang, C. *et al.* Analyzing parcel-level relationships between Luojia 1-01 nighttime light intensity and artificial surface features across Shanghai, China: A comparison with NPP-VIIRS data. *Int. J. Appl. Earth Observ. Geoinform.* **85**, 101989 (2020).
24. Elvidge, C. D., Baugh, K. E., Zhizhin, M. & Hsu, F.-C. Why VIIRS data are superior to DMSP for mapping nighttime lights. *Proc. Asia-Pacific Adv. Netw.* **35**, 62–69 (2013).
25. Kwiatkowska, E. M. Rozwój Internetu rzeczy – szanse i zagrożenia. *Internetowy Kwartalnik Antymonopolowy i Regulacyjny* **8**(3), 60–70 (2014).
26. Piątek, Z. Przemysl-40.pl. Retrieved August 15, 2021 from https://przemysl-40.pl/index.php/ (2018).
27. Chaładyniak, D. Wybrane technologie bezprzewodowej transmisji danych. *Zeszyty Naukowe* **5**, 87–101 (2011).
28. Tomaszewski, D. 11 mitów na temat technologii LoRaWAN. *Elektronik*, 78–81. (2020).
29. Liando, J. & Christian, G. A. Known and unknown facts of LoRa: Experiences from a largescale measurement study. *ACM Trans. Sens. Netw.* **15**(2), 1–35 (2019).
30. Mikhaylov, K. *et al.* Multi-RAT LPWAN in Smart Cities: Trial of LoRaWAN and NB-IoT Integration. In: *IEEE International Conference on Communications (ICC)* 1–6 (2018).
31. Perković, T., Rudeš, H., Damjanović, S. & Nakić, A. Low-cost implementation of reactive jammer on LoRaWAN network. *Electronics* **10**, 864 (2021).

32. Loubet, G. *et al.* LoRaWAN battery-freewireless sensors network designed for structural health monitoring in the construction domain. *Sensors* **19**(7), 1510 (2019).
33. Turčinović, F., Vuković, J., Božo, S. & Šišul G. Analysis of LoRa parameters in real-world communication. In: *2020 International Symposium ELMAR* 87–90 (2020).
34. Zhou, W., Tong, Z., Dong, Z.Y. & Wang, Y. LoRa-hybrid: A LoRaWAN based multihop solution for regional microgrid. In: *2019 IEEE 4th International Conference on Computer and Communication Systems (ICCCS)* 650–654 (2019).
35. Semtech Corporation AN1200.22 LoRa™ Modulation Basics, Wireless Sensing and Timing Products, Application Note (2015).
36. Alarcon, M. R. *et al.* SG-WAS: A new wireless autonomous night sky brightness sensor. *Sensors (Basel, Switzerland)* **21**(16), 5590. https://doi.org/10.3390/s21165590 (2021).
37. Karpińska, D. & Kunz, M. Analysis of light pollution of the night sky in Toruń (Poland). Civil and Environmental Engineering Reports, 155–172 (2020).
38. Karpińska, D. & Kunz, M. Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area—A case study of the Bielany campus at the Nicolaus Copernicus University in Toruń. *Bull. Geogr. Socio-Econ. Ser.* **54**, 137–149 (2021).
39. Karpińska, D. & Kunz, M. Wpływ pokrycia terenu na zanieczyszczenie światłem nocnego nieba, Badania z zakresu nauk przyrodniczych – nowe trendy, 206–223 (2020).
40. Semtch. Semiconductor Solutions for Industrial Internet of Things. Retrieved July 21, 2022 from https://www.semtech.com/applications/internet-of-things/smart-industrial-iot
41. Semtch. Semiconductor Solutions for Smart Cities. Retrieved July 21, 2022 from https://www.semtech.com/applications/internet-of-things/smart-cities
42. STMicroelectronic. Retrieved June 18, 2020 from https://www.st.com/en/evaluation-tools/b-l072z-lrwan1.html#overview (2020).
43. Adafruit. Adafruit TSL2591 High Dynamic Range Digital Light, Adafruit Learning System (2019).
44. STMicroelectronics. Retrieved June 26, 2020 from https://www.st.com/en/ecosystems/x-nucleo-iks01a2.html (2020).
45. Karpińska, D. & Kunz, M. Zanieczyszczenie nocnego nieba światłem na przykładzie Torunia. In: Młynarczyk, A. (red.), *Środowisko przyrodnicze jako obszar badań* 93–112 (2020).
46. Karpińska, D. & Kunz, M. Optymalizacja rozmieszczenia sieci pomiarowej do monitoringu zanieczyszczenia światłem nocnego nieba na przykładzie Torunia. in *Środowisko przyrodnicze jako obszar badań*, Vol. III. 9–24 (2022).

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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.

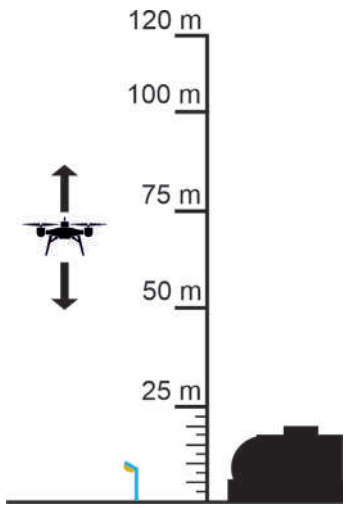

Fig. 2. Schematic representation of the altitudes selected for the acquisition of data on light pollution of the night sky.

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).

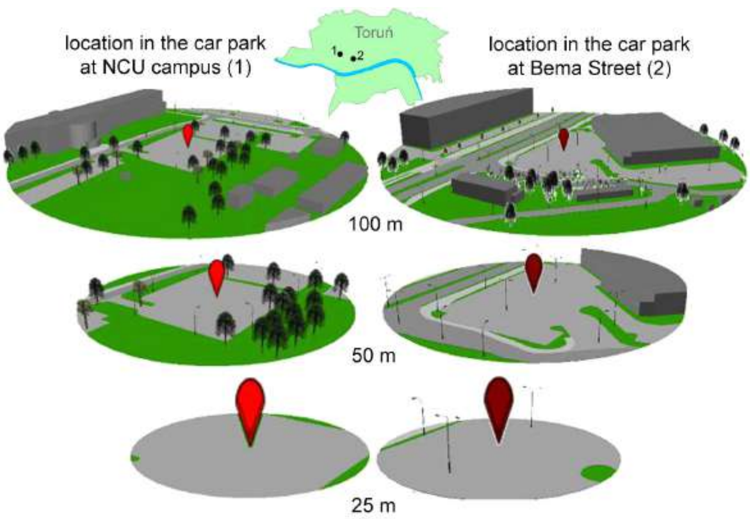

Fig. 5. Visualisation of land cover/land use at measurement locations in three buffer zones (25 m, 50 m and 100 m).

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

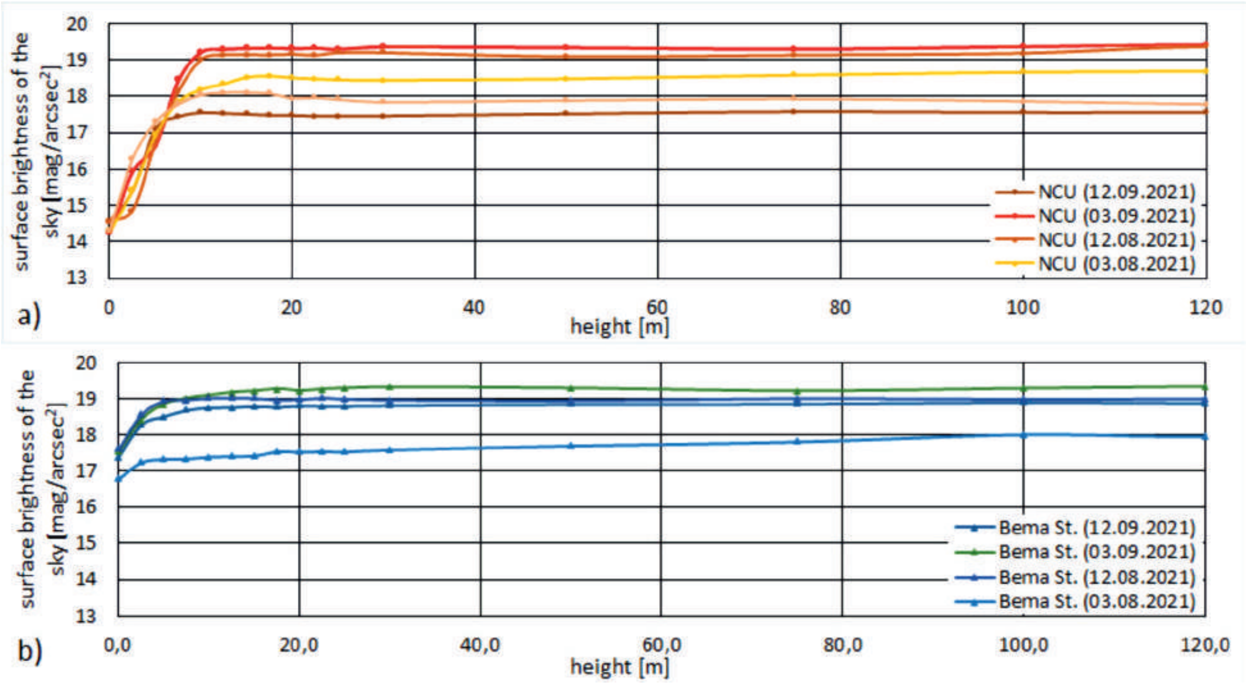

Fig. 6. Summary of the obtained results illustrating the variability of the night sky brightness in the vertical gradient at the measuring site located in Toruń: (a) at the NCU car park, (b) at the car park in Bema Street.

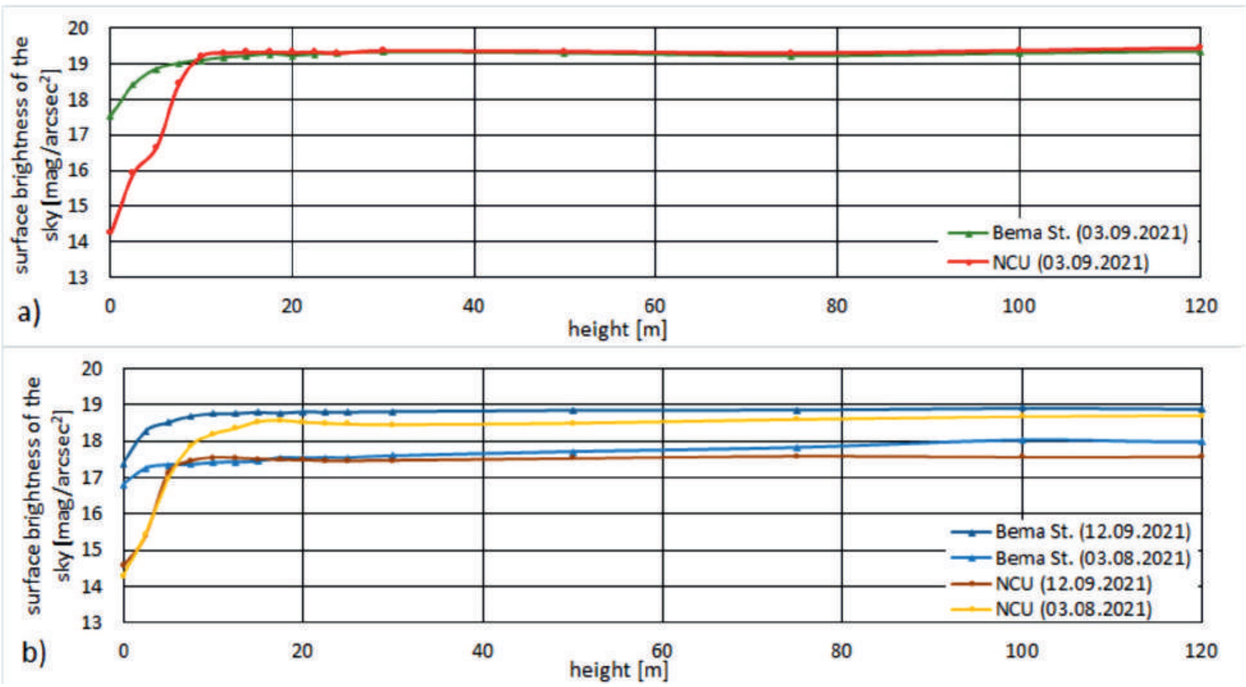

Fig. 7. Comparison of the obtained results showing variability of the night sky brightness in the vertical gradient at both measurement locations during: (a) cloudless night, (b) night with varied cloud cover.

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, Ściężor et al. 2010, Pun et al. 2013, Ribas et al. 2016, Hänel et al. 2017, Karpińska, Kunz 2019, 2020, Ściężor 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.

Ścieżor 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.

Ścieżor 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.

Ścieżor 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.

Ścieżor 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.

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Relationship between the surface brightness of the night sky and meteorological conditions

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ABSTRACT

Measurements of the surface brightness of the night sky have been carried out for many years by interdisciplinary research groups around the world. According to the observations, a significantly higher brightness of the sky, i.e. its light pollution, is observed over the centres of urbanised areas and in their immediate vicinity. Several factors contribute to the high values of the night sky brightness. The parameter that contributes to the exaggeration of the recorded values are meteorological conditions prevailing during the measurement, mainly the altitude and spatial extent of cloud cover. The relationship between the measured value of the surface brightness of the night sky and the occurrence of cloud cover has already been reported in a number of research works. In Toruń, multifaceted measurements of light pollution have been carried out since 2017, and in 2020, an automatic network monitoring the surface brightness of the night sky was established using proprietary low-cost measurement equipment, which is being systematically expanded with new monitoring stations. This paper presents the results of research on the relationship between the observed sky brightness and selected meteorological elements. Data collected at several measurement stations located in different parts of Toruń in a systematic observation series of more than one year were analysed. This allowed us to search for an answer to the question of whether the results of night sky brightness measurements are affected by local meteorological conditions and whether the measured value significantly varies depending on the distance from the city centre.

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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].

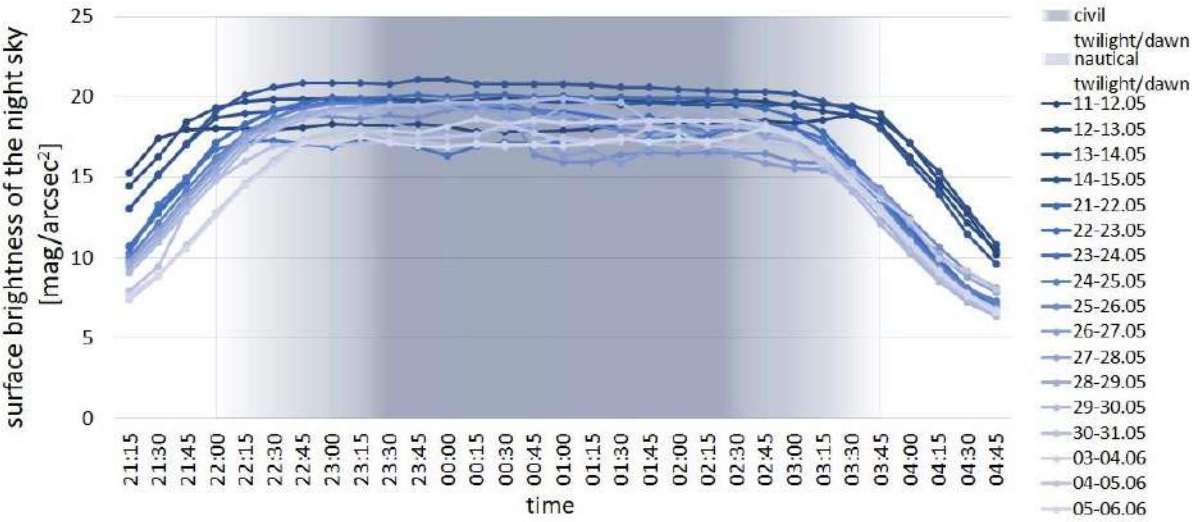

Fig. 2. First results of night sky brightness measurements obtained in the first measurement series between May 11 and June 6, 2020 using one of prototype devices as part of the so-called technology demonstrator stage

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)

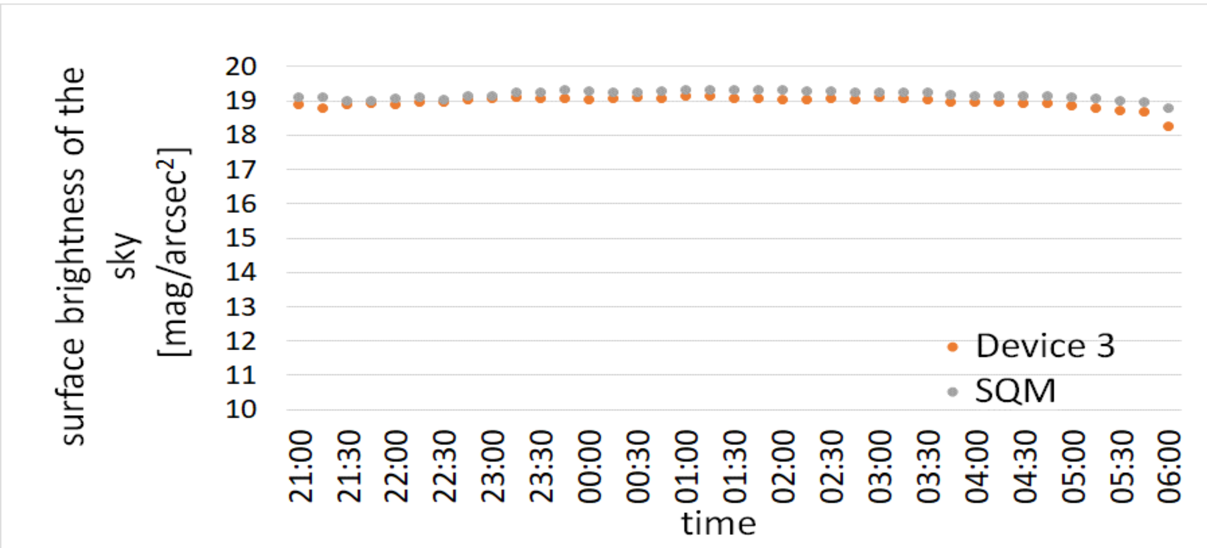

Fig. 4. Sample results of comparisons of night sky brightness values measured simultaneously using the designed SQM and the commercially available off-the-shelf SQM from the night of December 15/16, both mounted on the Observation Platform of the Faculty of Earth Sciences and Spatial Management of NCU

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

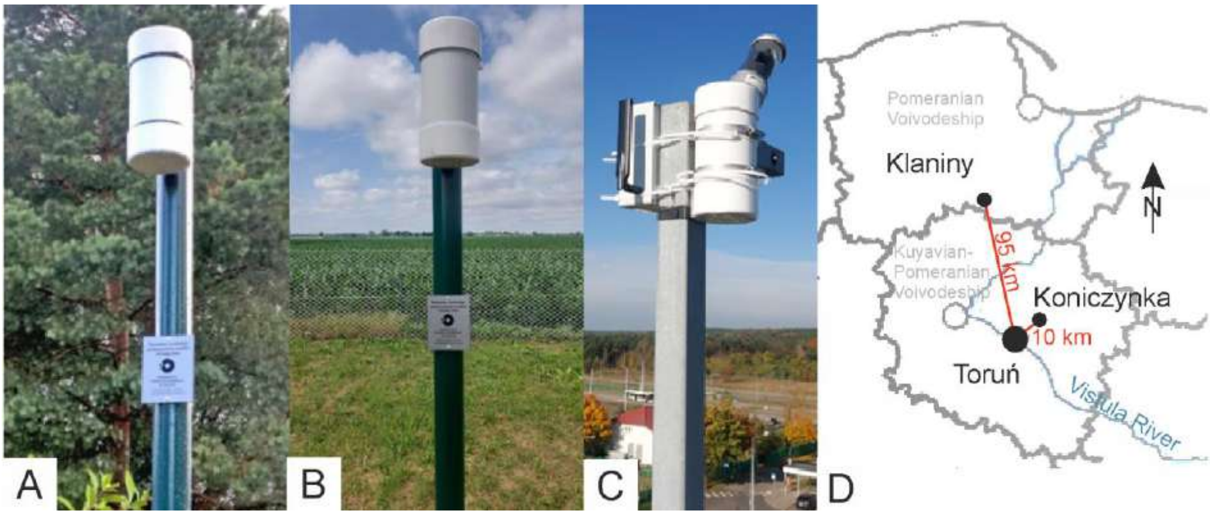

Fig. 5. Monitoring (measurement) sites with the SQM-LU photometer constituting the measurement background for the city of Toruń: A) the village of Klaniny (Tuchola Forest), B) the village of Koniczynka, C) Observation Platform of the Faculty of Earth Sciences and Spatial Management of NCU in Toruń and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

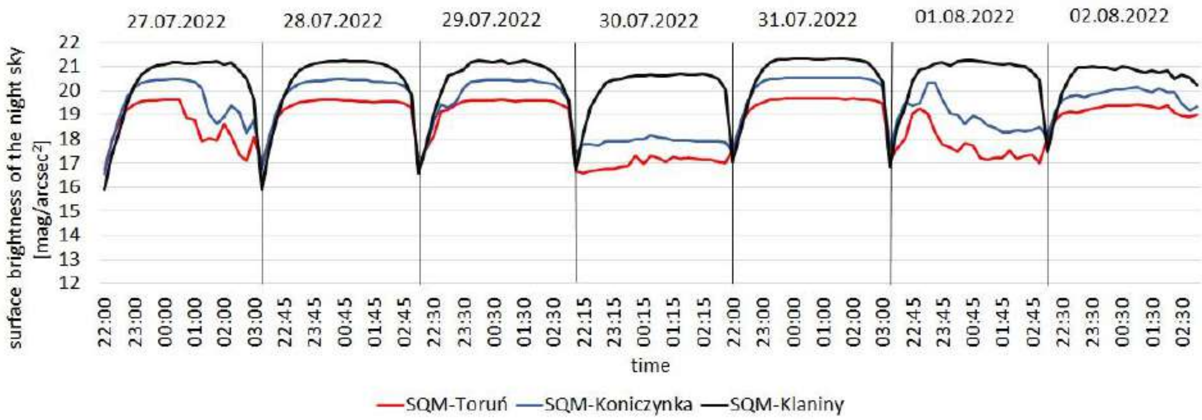

Fig. 6. Comparative results of night sky brightness values obtained with the SQM device at three monitoring sites distributed in the decreasing gradient of human impact

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.

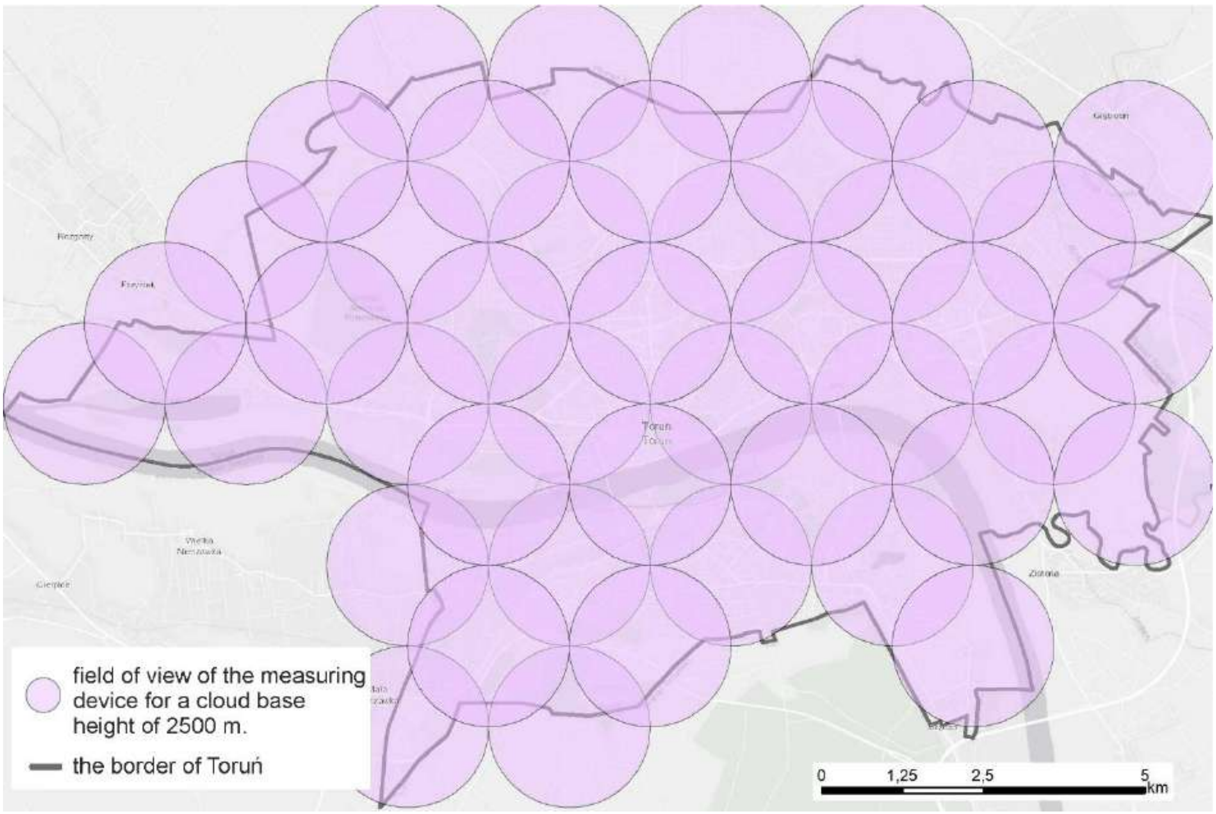

Fig. 7. Theoretical model of spatial distribution of monitoring sites in Toruń

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

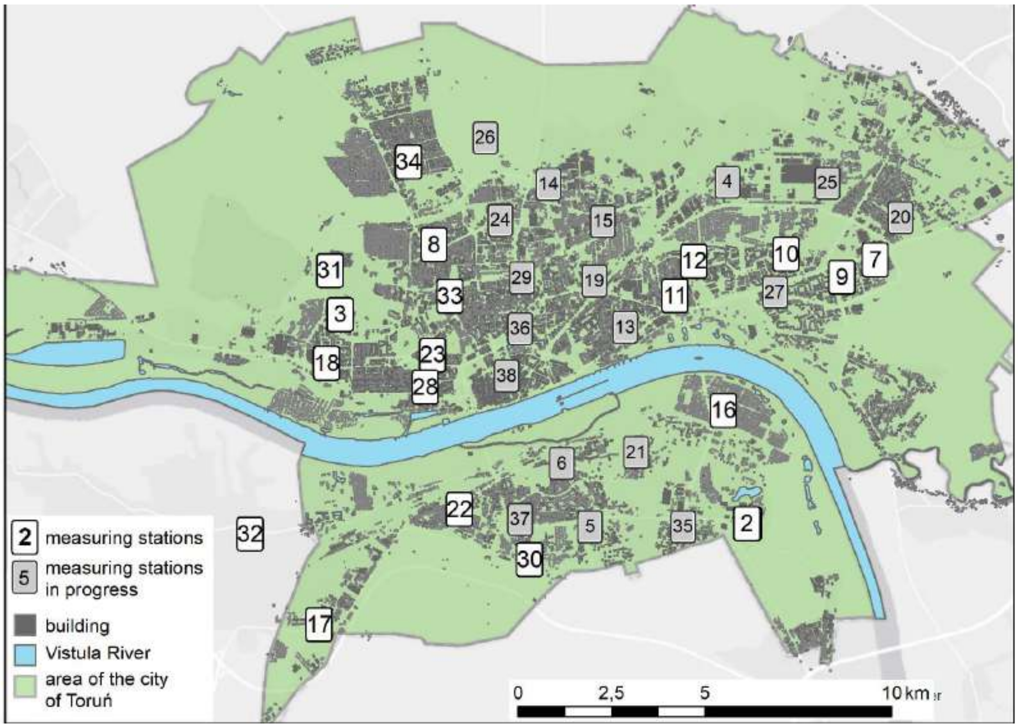

Fig. 8. Location of current and planned monitoring sites in Toruń within the light pollution monitoring network

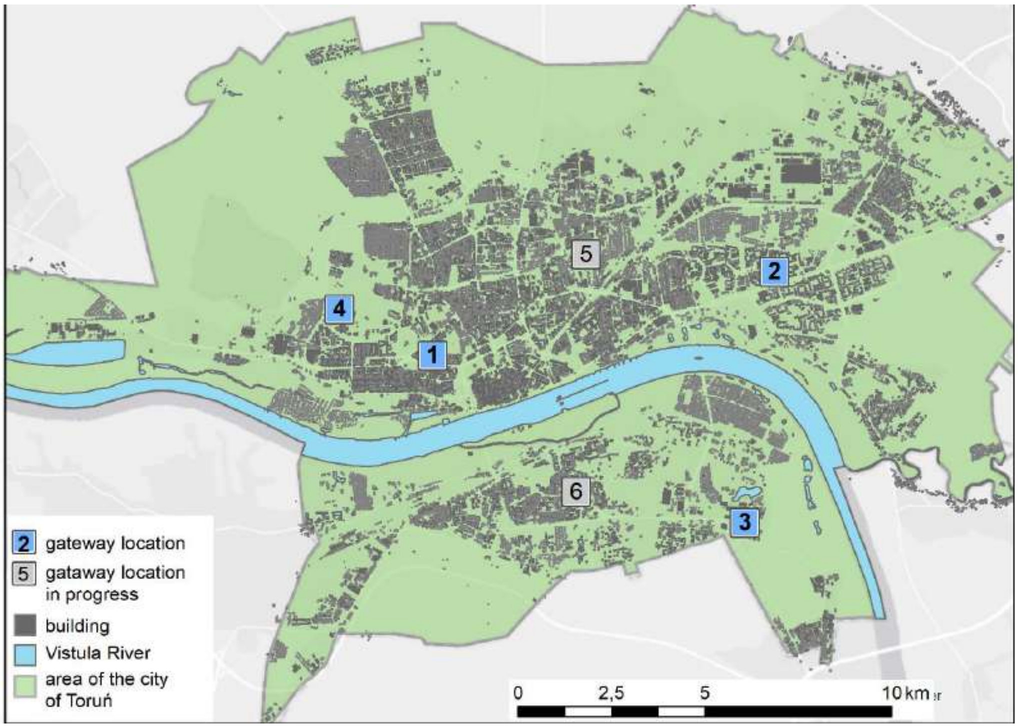

Fig. 9. Location of current and further planned access gateways in Toruń within the light pollution monitoring network

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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REFERENCES

1. Adafruit 2019. Adafruit TSL2591 High Dynamic Range Digital Light, Adafruit Learning System.
2. Falchi, F. et al. 2016. The new world atlas of artificial night sky brightness. *Science advances* **2(6)**, e1600377.
3. 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 and 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.
4. Hänel A, Posch T, Ribas SJ, Aubé M, Duriscoe D, Jechow A, Kollath Z, Lolkema DE, Moore, C, Schmidt, N, Spoelstra, H, Wuchterl, G and Kyba, CCM 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.
5. Jechow, A. et al. 2017. Measuring Light Pollution with Fisheye Lens Imagery from a Moving Boat, A Proof of Concept. *International Journal of Sustainable Lighting* **36**, 15–25.
6. Karpińska, D and 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.
7. Karpińska, D and Kunz, M 2020. Analysis of light pollution of the night sky in Toruń (Poland). *Civil and Environmental Engineering Reports*, 155–172. DOI 10.2478/ceer-2020-0057.

8. Karpińska, D and Kunz, M 2021. Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area – a case study of the Bielany campus at the Nicolaus Copernicus University in Toruń, *Bulletin of Geography. Socio-Economic Series* **54**, 137–149. DOI 10.2478/bog-2021-0039.
9. Karpińska, D and Kunz, M 2021. 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, Vol. II, 47–60.
10. Karpińska, D and Kunz, M 2023. Relationship between the surface brightness of the night sky and meteorological conditions. *Journal of Quantitative Spectroscopy and Radiative Transfer* **306**, 108621. DOI 10.1016/j.jqsrt.2023.108621.
11. Karpińska, D and Kunz, M 2022. Device for automatic measurement of light pollution of the night sky. *Scientific Reports*. DOI: 10.1038/s41598-022-20624-7.
12. Karpińska, D and Kunz, M 2022. Optymalizacja rozmieszczenia sieci pomiarowej do monitoringu zanieczyszczenia światłem nocnego nieba na przykładzie Torunia [Optimization of the distribution of the measurement network for monitoring light pollution in the night sky on the example of Toruń]. [in:] Młynarczyk A. (ed.), *Środowisko przyrodnicze jako obszar badań*, Bogucki Wydawnictwo Naukowe, Poznań, Vol. IV, 9–24.
13. Karpińska, D and Kunz, M 2023. Vertical variability of night sky brightness in urbanised areas. *Quaestiones Geographicae* **42**(1), 5–14. DOI: 10.14746/quageo-2023-0001.
14. Kocifaj, M and 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.
15. 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.
16. Kołomański, S 2015. Zanieczyszczenie światłem i ciemność [Light pollution and darkness]. In: Wiśniewska MR, Tomasik K. (ed.), *Przejdź na ciemną stronę nocy. Środowiskowe i społeczne skutki zanieczyszczenia światłem*. Wyd. Uniwersytetu Warszawskiego. Warszawa, 29–46.
17. Linares, H, Masana, E, Ribas, SJ, Aubé, M, Simoneau, A and 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.
18. Light pollution reduction measures in Europe 2022. *Working paper for international workshop "Light Pollution* 2022", during the Czech Presidency of the Council of the European Union, Ministry of the Environment of the Czech Republic, 60 p.
19. Longcore, T, Rich, C and DelBusso, L 2017. Artificial Night Lighting and Protected Lands. *Natural Resource Report NPS/NRSS/NSNS/NRR*—2017/1493.
20. Mikhaylov, K, Stusek, M, Masek, P, Petrov, V, Petäjäjärvi, J, Andreev, S, Pokorny, J, Hosek, J, Pouttu, A and Koucheryavy, Y 2018. Multi-RAT LPWAN in Smart Cities: Trial of LoRaWAN and NB-IoT Integration. *IEEE International Conference on Communications (ICC*), 1–6. DOI: 10.1109/ICC.2018.8422979.
21. Pun, CSJ, So, CW, Leung, WY and Wong, CF 2014. 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.
22. Ribas, S, Torra, J, Figueras, F, Paricio, S and 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.

23. Semtech Corporation 2015. AN1200.22 LoRa™ Modulation Basics, Wireless Sensing and Timing Products, Application Note.
24. Szlachetko, K 2022. red. Memorandum w sprawie ustanowienia prawnych podstaw zrównoważonej polityki oświetlenia zewnętrznego [Memorandum on establishing the legal basis for a sustainable outdoor lighting policy] Instytut Metropolitarny, Gdańsk, 48 p.
25. Ściężor, T, Kubala, M, Kaszowski, W and Dworak, TZ 2010. *Zanieczyszczenie świetlne nocnego nieba w obszarze aglomeracji krakowskiej. Analiza pomiarów sztucznej poświaty niebieskiej*. [Light pollution of the night sky in the area of the Kraków agglomeration. Analysis of artificial blueglow measurements]. Wyd. Politechniki Krakowskiej. Kraków.
26. 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.

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Spatial and temporal analysis of artificial light pollution of the city night sky. A case study from Toruń

Abstract
Artificial light pollution of the night sky over urban areas and in their immediate vicinity has become a common anthropogenic phenomenon and a major problem of the modern urban landscape. It is no longer only scientists or environmentalists, but increasingly ordinary citizens too, who perceive a decline in the quality of the night sky and suffer the health consequences of this systematically aggravating process. In order to observe the naturally starry sky, it is now necessary to travel to places far away, not only from large conurbations, but also from smaller human settlements. In order for there to be an improvement in the level of night sky pollution, it is necessary to monitor the phenomenon, provide targeted education and take systemic countermeasures to reduce its negative effects in time and space. Several interdisciplinary research groups and non-governmental organisations around the world conduct research on light pollution. In Toruń, the first measurements of this phenomenon were carried out in 2017 using handheld SQM devices, and a wireless automatic network monitoring the state of the city's night sky has been developed since 2020. This paper presents the results of the analysis of measurement data recorded during the two-year operational operation of the monitoring network. The conducted measurements provided data to analyse the seasonal variability of the phenomenon, as well as to perform selected spatial analyses within the city limits. The results obtained were related to the results of measurements made outside human settlements, which made it possible to determine the variation of sky brightness in a gradient of decreasing human impact.

Keywords
Light pollution • night sky • monitoring network • urban landscape • Toruń

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Introduction

Several degrading factors contribute to the deterioration of the modern urban ecosystem, including those that have already been determined and those that are still at the stage of identifying the importance and extent of their impact. Changes in the quality of the natural environment, their assessment and the determination of their direction are the subject of frequent interdisciplinary studies undertaken by teams of experts. In these undertakings, it has become necessary not only to search for new, more efficient recording methods for conducting measurements as such, but also to increase interest in implementing targeted and remote monitoring of factors negatively affecting the environment. As a result, devices and integrated technologies are being developed that allow not only the measurement of a given parameter, but also data processing, visualisation of the results and their effective archiving. The current state of knowledge of environmental degradation, combined with modern Industry 4.0 technology, enables the optimisation of the measurement process in such a way that it is possible to better understand the scale of the phenomenon and more accurately determine its variability and range, as well as contributing factors. This interaction contributes to better targeting of research and automation of the measurement process itself, resulting in new information and ultimately a more complete knowledge of the impact of a given factor on the health and life of plants and animals, as well as the functioning of man himself.

Nowadays, one of the increasingly thoroughly studied phenomenon with a major impact on the human ecosystem is light pollution (Falchi et al. 2016; Jechow et al. 2017; Linares et al. 2020), which is defined as an excessive emission of artificial light at night over an extended period of time (ed. Szlachetko 2022). The phenomenon is caused primarily by incompetently or incorrectly designed or installed outdoor lighting, and is compounded by the presence of glare from LED advertisements and excessive illumination of architectural features. These factors cause excessive light emission at night, resulting not only in higher economic costs, but also in illuminating a space in the upward direction that should not be exposed to this process (Kołomański et al. 2015). Many scientific studies prove that prolonged residence in a light-polluted area causes many detrimental consequences for the health and life of plants, animals and, of course, humans (Adams et al. 2019; Garcia-Saenz et al. 2018; Jechow & Hölker 2019; Lacoeuilhe et al. 2014; Longcore et al. 2017; Macgregor et al. 2017). Research conducted on this phenomenon in urban areas also shows that light pollution further intensifies during adverse weather conditions, such as fog, cloud cover and increased presence of particulates (PM) of anthropogenic origin in the troposphere (Karpińska & Kunz 2023a; Kocifaj & Bará 2020; Ribas et al. 2016; Ściężor et al. 2010; Ściężor 2020).

The pollution of the night sky by artificial light is now a global phenomenon, which, with the development of industry and increasing urbanisation in recent decades, has steadily increased

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the spatial extent of its impact (Falchi et al. 2016). The human right to enjoy the dark sky is unquestionable, so in order to improve its quality and consequently human health and functioning at night, numerous governmental and non-governmental organisations, scientific and social entities have set themselves the goal for the coming years of providing adequate education to people of all age groups (International Dark-Sky Association; Ministry of the Environment of the Czech Republic 2022; ed. Szlachetko 2022). Another initiative involves the establishment of dark sky protection sites, recognising that they are one of the most natural elements of the world around us and therefore worth emphasising and promoting (International Dark-Sky Association; Karpińska & Kunz 2020b). Some European countries have also begun to introduce formal regulations on outdoor artificial light emission (Ministry of the Environment of the Czech Republic, 2022; ed. Szlachetko 2022), while several others, such as Croatia, Germany and France, have enacted laws to protect the environment from the effects of light pollution. These are, however, just few exceptions. The vast majority of countries do not have any legislation governing this issue and little attention is paid to publicising the problem of modern cities and to providing adequate education from an early age.

This paper discusses the results obtained from more than two years of continuous and targeted measurements of light pollution in the night sky over the area of Toruń. The city of Toruń is an example of a medium-sized settlement unit (with an area of about 116 km^2 and a population of up to 200,000), which so far has paid little attention to the operational status of municipal lighting. All processed data were acquired automatically by in-house developed measurement devices operating wirelessly in the monitoring network (Karpińska & Kunz 2022). Testing of the system under natural urban conditions was carried out in 2020, while fully operational operation of the light pollution monitoring network started at the beginning of 2021, and since then the network has been successively expanded with new measuring devices, with duration of the continuous observation series increasing month by month.

Construction of a light pollution monitoring network in Toruń – research methodology

Initially, research into the phenomenon of light pollution was carried out by single researchers, mainly those interested in the deteriorating conditions for observation of the night sky. However, when the increasing impact of excessive light on the natural environment and living organisms was recognised, several research groups from around the world started targeted measurements to understand its variability and specificity, and to try to determine its consequences (Falchi et al. 2016; Hänel et al. 2017; Jechow & Hölker 2019; Kocifaj & Bará 2020; Kolláth 2010; Kołomański et al. 2015; Pun et al. 2014; Ribas et al. 2016; Ściężor et al. 2010; Ściężor, 2020). These teams use several different measurement methods, both highly complex and simple ones, available to amateurs. The most commonly used are measurements with a specialist photometer, which is available in manual (hand-held), portable, and stationary versions (Karpińska & Kunz 2019; Karpińska & Kunz 2022; Mander et al. 2023; Pun et al. 2014; Ściężor 2020). Measurements, e.g. with SQM and TESS devices, are carried out in various places around the world, both through the implementation of single measurements and longer measurement sessions (Bara et al. 2019; Cavazzani et al. 2020; Globe at Night; Pun et al. 2014; Ściężor et al. 2010; Zamorano et al. 2016). Another frequently used method is to take pictures of the night sky using wide-angle or all-sky lenses and then process them using professional software (Jechow et al. 2017; Karpińska & Kunz 2022; Kolláth 2010; Mander et al. 2023). As an alternative to ground-based surveys, remote sensing methods are becoming increasingly widespread, allowing the observation of excess light emissions using satellite imagery and aerial photographs (Ściężor, 2021). This enables a larger area of interest to be surveyed simultaneously and these acquisitions to be prepared periodically (Cinzano et al. 2000; Elvidge et al. 2013; Levin et al. 2020; Zhang et al. 2019).

In the area of Toruń, pioneering measurements of night sky light pollution were carried out in 2017–2018 using hand-held Unihedron SQM-L photometers (Karpińska & Kunz 2019; Karpińska & Kunz 2020a). The result of this work was, among other things, the first insight into the spatial distribution of light pollution in the city and a compilation of mean values obtained over 12 consecutive months. Figure 1 shows the first documented spatial distribution of light pollution collated for Toruń.

The experience gained during these manual logging operations led to the preparation of another research project, which involved the establishment of an automatic monitoring network. Its main objective was long-term systematic recording at permanent monitoring sites carried out without human presence. In this way, it is possible to gain a better understanding of the temporal and spatial variability of light smog and to identify the main factors contributing to the deterioration of the night sky. The studied phenomenon is characterised by variability depending not only on the existing artificial light sources, but also on local atmospheric conditions and the phase of the Moon at the time of recording. The results obtained on cloudless, moonless nights differ significantly from the values obtained on cloudy nights, particularly in urban areas. During nights with changing cloud cover, the results obtained at different monitoring sites, even in relatively close proximity to each other, can vary considerably if taken at different times during one night. It is therefore very important that measurements are taken simultaneously at all sites set up in the area under study.

According to the assumptions made, the monitoring network was to be wireless, unmanned and cost-effective to set up and maintain. A battery-powered device of our own design was connected to the non-commercial wireless transmission network. Another assumption was to perform measurements of very low light intensity at night with spectral characteristics similar to commercially available SQM photometers. During the analysis of available optoelectronic components, it was decided to choose a light sensor with high accuracy, whose calibration was performed at the factory production stage (Adafruit 2019). The spectral response of the selected light sensor is similar to the human eye. Thanks to the use of two diodes (VIS+IR and IR) and their compensation, there is no need to use additional filters to eliminate part of the spectrum. It was assumed that the measurement session would be performed daily at 15-minute intervals, starting at 21:00 and ending at 06:00 CEST the following day. Data from the measuring devices will be transmitted via LoRaWAN technology (Mikhaylov et al. 2018; Semtech Corporation 2015) to a server and stored in the cloud disk. The selected technology enables efficient use of battery power, which improves the mobility of the devices. The aforementioned features of the system under development are in line with the strategy of Industry 4.0 and the spectrum of solutions used in the development and implementation of the Smart City concept.

The first stage of testing the monitoring system was to check its correct operation based on the case of two devices mounted on the roofs of the buildings of the Toruń Regional Development Agency located in the left-bank part of Toruń (Karpińska & Kunz 2022). The measurement of the night sky brightness and the communication between the devices and the network proved to be correct, whereby only the length of the message, the so-called frame size, was changed after analysis of the data sent to the server. The identified problem of the constructed recorders was the operating time of only a few days, which was extended to more than nine months after important hardware and software improvements were made. Following these measures, the

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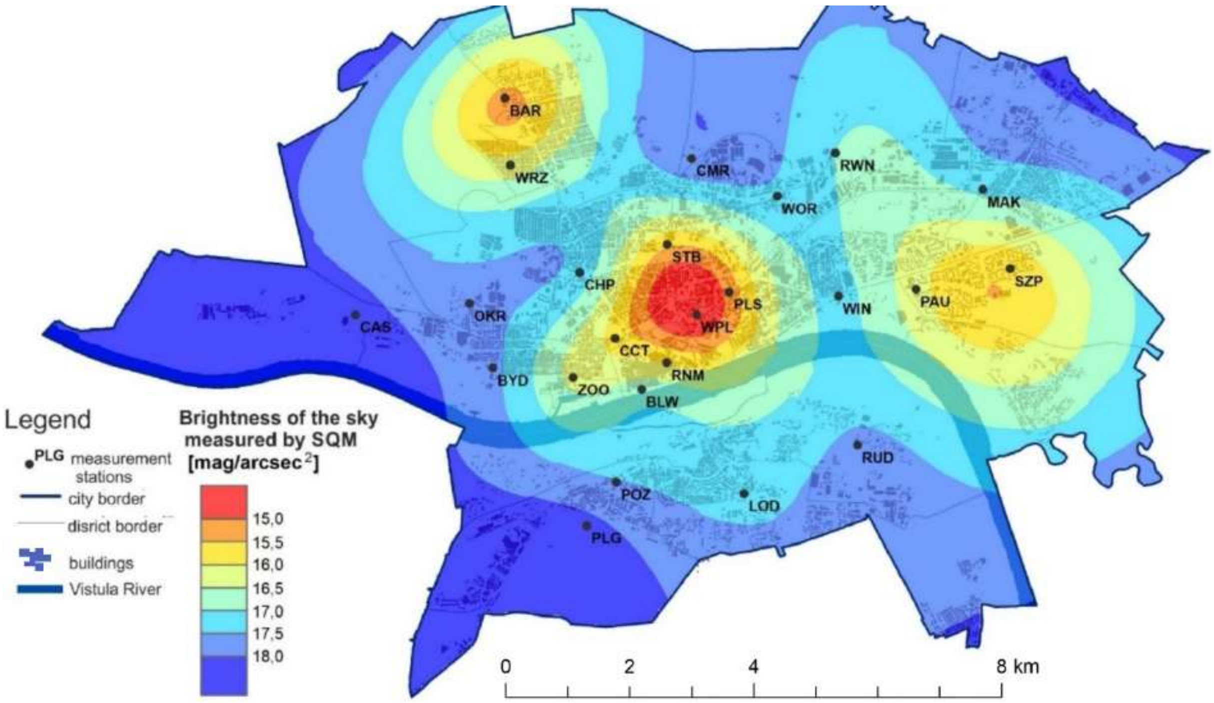

Figure 1. Distribution of the surface brightness of the night sky in Toruń in the period 2017–2018 measured using an SQM-L hand-held photometer, with the locations of repeated measurements marked
Source: own elaboration

operation of the entire monitoring network of 40 loggers was tested. For this purpose, all devices were placed on the roof of the Observation Platform of the Faculty of Earth Sciences and Spatial Management (Nicolaus Copernicus University) in the vicinity of the operating factory-made SQM device and the results obtained in weekly measurement sessions were compared. In addition, measurements of the LoRaWAN network signal quality were carried out on the campus of Nicolaus Copernicus University (NCU) in Toruń and its vicinity to verify the capabilities of the LoRa network. This field experiment confirmed the spatial range of the selected data transmission technology of up to 4 km in a built-up area, i.e. in a typically urban landscape consisting of buildings of different sizes and heights, further diversified by tall vegetation (Karpińska & Kunz 2021). Measurements of the vertical variability of the night sky surface brightness were also carried out using UAVs, the purpose of which was to determine the limit heights above ground level for the placement of devices at the monitoring sites. These tests showed that above street infrastructure, the measured brightness of the night sky does not change, which makes it possible to place devices at any height above street lighting away from point light sources (Karpińska & Kunz 2023).

After the tests, field experiments as well as additional and complementary studies, the construction of a monitoring network based on measuring devices developed in-house was launched. The location of the measuring devices and access gateways of the LoRa network based on the status at the end of February 2023 is presented in Figure 1.

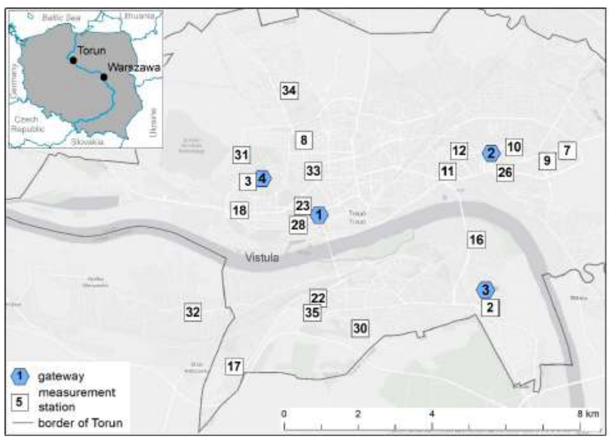

Figure 2. Location of the monitoring sites and communication gateways in Toruń, launched by the end of February 2023 as part of the night sky pollution monitoring system
Source: own elaboration

Analysis of measurement data on light pollution for Toruń

Measurement data recorded between the beginning of 2021 and the end of December 2022 were analysed in detail. During this period, the monitoring network was systematically expanded with new measuring devices. In 2023, further expansion is planned in the area of Toruń, especially in the central part of the city, both with new measuring devices (up to about 40 field stations) and access gateways (up to six devices in total). As a result, the city will be covered by a complete monitoring network, with a density of data loggers unmatched by any other settlement unit in the world.

The data collected over the two years of operation of the monitoring network has already allowed several elements to be identified, including the seasonal variability of the results, the relationship between the brightness of the night sky and meteorological conditions, the representation of the spatial

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Table 1. Mean values of night sky surface brightness measurements recorded at the monitoring sites for the entire year and for individual astronomical seasons

Device ID	LOCATION	START DATE (END DATE)	HEIGHT (floor)	ALL YEAR [mag/arcsec^2]			SUMMER	AUTUMN	WINTER	SPRING
				MEAN	MIN	MAX	MEAN [mag/ arcsec^2]			
1	Włocławska 167 Street	23.03.2021 (20.04.2021)	3rd	17.5	15.9	20.1				17.5
2	Włocławska 167 Street	23.03.2021 (20.04.2021)	3rd	17.6	15.5	19.9				17.3
3	Lwowska 1 Street	16.02.2021	3rd	16.9	14.1	20.0	17.7	16.4	16.3	17.3
7	Szosa Lubicka 182	30.03.2022	3rd	16.3	14.1	17.6	17.0	16.3	15.7	16.5
8	Szosa Chełmińska 160	30.03.2022	3rd	17.2	14.0	19.5	17.9	17.3	16.4	17.0
9	Witosa 7 Street	12.07.2022	3rd	16.1	13.9	18.5	16.6	15.8	15.6	
10	Niesiołowskiego 26 Street	13.02.2022	1st	16.8	14.2	18.9	17.6	16.6	16.1	17.0
11	Kalinowa 17 Street	02.04.2022	ground	16.9	14.19	19.8	17.9	17.1	16.0	17.0
12	Rydygiera 19 Street	30.03.2022	9th	16.6	14.5	18.1	17.4	16.3	16.0	16.8
13	Kwiatowa 33 Street	03.01.2023	1st	15.8	14.0	19.4			15.8	
14	Dębowa 15 Street	23.05.2022	ground	16.6	14.0	20.0	18.0	16.3	16.8	17.9
16	Rudak allotment	30.05.2022	ground	17.8	15.3	20.6	18.2	17.8	17.1	18.4
17	Szubińska 38 Street	05.06.2022	1st	17.2	14.5	20.8	17.3	17.3	16.9	17.6
18	Fałata 82 Street	12.11.2021	2nd	17.0	14.4	20.8	17.9	16.8	16.6	17.6
22	Drzymały 5 Street	30.03.2022	4th	17.2	14.7	20.3	18.2	17.2	16.5	17.6
23	Matejki 55 Street	11.08.2021	10th	17.0	14.2	20.2	17.9	16.7	16.5	17.7
25	Lwowska 1 Street	16.02.2021 (12.09.2021)	3rd	17.1	14.2	20.8	17.2		16.5	16.7
26	Konstytucji 3 Maja 13 Street	13.01.2023	9th	14.4	13.7	15.2			14.4	
27	Łączna 40 Street	12.01.2023	3rd	16.4	14.3	20.9			16.4	
28	Matejki 16 Street	02.04.2022	4th	16.9	14.0	20.3	17.8	17.0	16.2	17.3
29	Włocławska 167 Street	18.05.2021	3rd	17.1	13.3	20.1	18.0	16.9	16.8	17.0
30	Łączna 40 Street	29.03.2022 (12.01.2023)	3rd	18.1	15.8	20.9	18.1	18.1	17.1	17.9
31	Makuszyńskiego 2 Street	15.01.2022	ground	17.1	13.8	20.0	17.9	16.6	17.0	17.2
32	Dębowa 15 Street	03.09.2021 (23.05.2022)	ground	17.5	14.3	20.8	18.7	17.4	17.3	18.8
33	Końcowa 4 Street	28.07.2021	4th	17.1	14.0	20.8	18.1	17.0	16.5	17.7
34	Kwiatowa 33 Street	12.10.2021 (03.01.2023)	1st	17.0	14.1	21.0	17.9	16.9	16.7	17.4
35	Okólna 10 Street	30.12.2023	1st	16.2	14.1	20.2			16.1	

Explanation:
- *in the 'Device ID' column, the numbers of the sites are consistent with the internal, technical numbering of the devices; the location of the sites on the map of Toruń is shown in Figure 2;*
- *no value in selected rows means that a given device was not working in a given time window;*
- *the date in brackets in the 'Start date' column indicates the end date of the device's operation (due to its replacement or malfunction).*

Source: own elaboration

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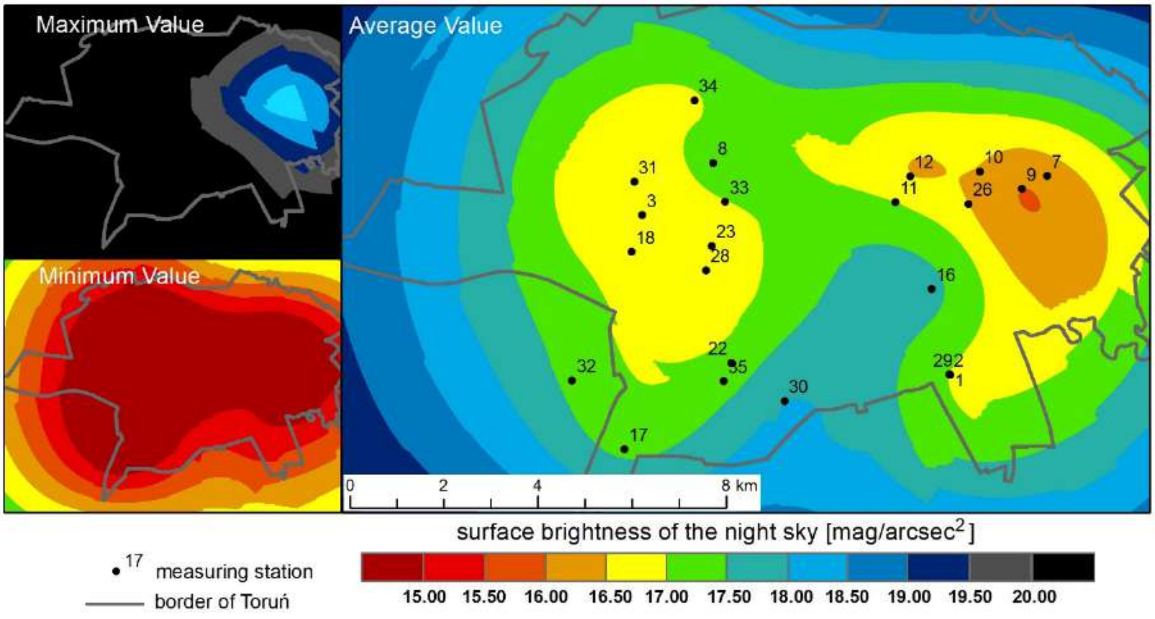

Figure 3. Spatial distribution of the mean annual value of surface brightness of the night sky in Toruń and the minimum and maximum values
Source: own elaboration

distribution of the light smog phenomenon, and the comparison of the data collected with the results obtained at locations far from the influence of the urban agglomeration.

The measurement results are presented in mag/arcsec^2 units and are based on the astronomical unit: magnitude. When analyzing the results, it is worth remembering that it is a logarithmic and inverse unit. Results above 20 mag/arcsec^2 will represent dark skies, while results between 14 and 17 mag/arcsec^2 or less will represent bright, urban skies.

Seasonal variability of light pollution in the night sky

To check for the differences between measurements of the night sky surface brightness in relation to the astronomical seasons, all collected data were divided with respect to the observation season. The arithmetic mean of the registration results, the maximum value and the minimum value were calculated for each of them. The results thus obtained are presented in Table 1. The mean values over the analysis period were calculated on the basis of more than 46,000 recorded data, with an mean of 1,700 measurements per location. In the summer season, the mean value for all locations was obtained on the basis of more than 9,900 collected data, in the autumn season – 12,000, in the winter season – 12,200 and in the spring season – 15,500. The difference in these figures results from different dates on which individual measuring devices, systematically added to the monitoring network, started operating.

The obtained mean, maximum and minimum values of the surface brightness of the night sky for Toruń were also presented graphically, as documented in Fig. 3. The analysis was prepared using ArcGIS (Esri) software and geostatistical interpolation using the Empirical Bayesian Kriging method. The latter method is also used for small sets of input data. Spatial distributions of mean values in Toruń by astronomical seasons are also presented using the same tool (Fig. 4).

The results of the interpolation analyses presented in Figs 3 and 4 indicate that the highest mean values of surface brightness of the night sky coincide with the largest housing estates in Toruń. The eastern part of the city is characterised by dense multi-family housing, interspersed with a network of streets equipped with abundant municipal lighting. High light pollution is also found in the western part of Toruń, where older housing estates are located, characterised by compact and low-rise buildings. The presentation of the mean value of the data by astronomical seasons clearly shows that the highest light pollution is observed in winter, while the lowest in summer. According to previous studies, the brightness of the night sky is greater when various scatterers are present in the troposphere, such as particulate matter or fog. A significant increase in the recorded measurement values occurs mainly in the autumn and winter seasons. In addition, light pollution is further exacerbated when cloud cover is present, which in Poland is more common in winter. The impact of this element on sky brightness measurements is documented by the analyses described in the next section.

Comparing the two interpolations shown in Figures 1 and 3, which come from different measurement periods (2017–2018 and 2021–2022) and were obtained using different data acquisition methods (commercial, factory-made SQMs vs. devices of our own design and construction), we can see a strong similarity in the spatial distribution of the phenomenon across the city – there is an overlap between areas with the brightest sky, i.e. the most polluted ones, and those with relatively better night sky quality. The difference can only be seen in the north-eastern part of the city, where a wrong site was selected during the first measurements, as it was located too close to an intensive source of outdoor lighting. Consequently, this element significantly overstated the measurement in its vicinity. The results obtained in the last two years with our measuring devices operating in the monitoring network are more accurate, mutually comparable and obtained simultaneously at identical time intervals, and thus not burdened with errors of non-simultaneity of measurements. The identified flaws and imperfections of the manual data acquisition process carried out in 2017–2018 during the first pioneering light pollution studies in Toruń were thus improved and automated.

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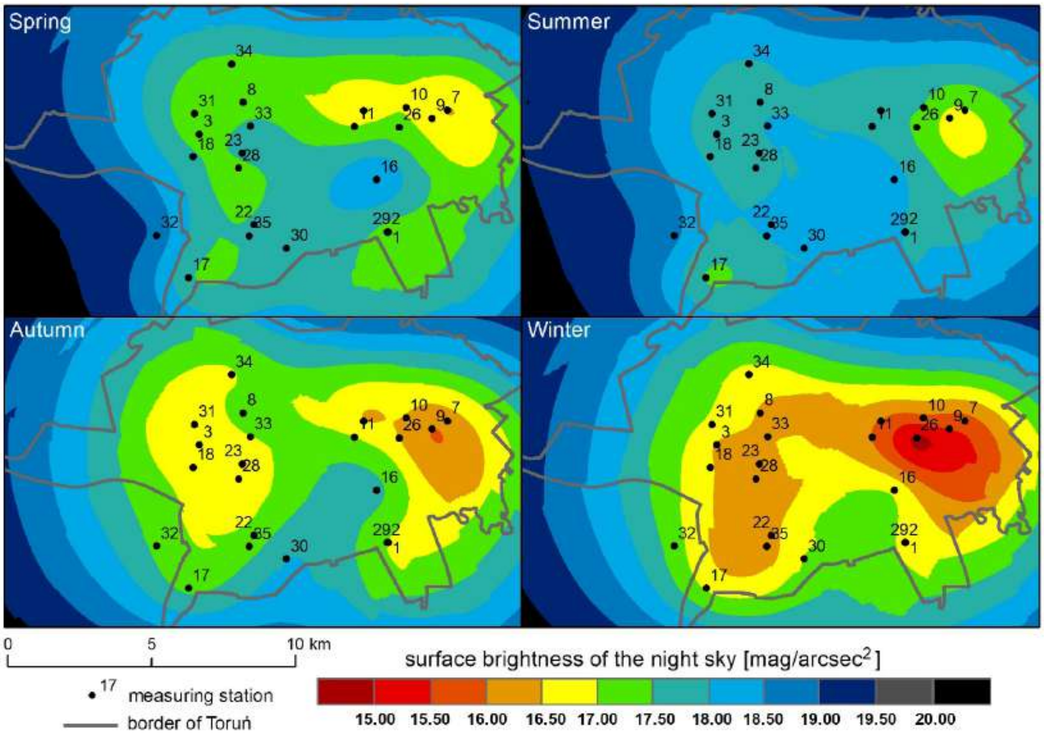

Figure 4. Spatial distribution of the mean value of surface brightness of the night sky in Toruń by astronomical seasons
Source: own elaboration

Correlation between the surface brightness of the night sky and meteorological conditions

Meteorological conditions prevailing at the time of logging affect the level of values recorded by photometers. With a long and continuous observation series, one can try to determine the relationship between these variables. Therefore, the relationship between the measured value of the surface brightness of the night sky and the atmospheric factors was analysed. The following were used to determine the linear correlation: cloud base height expressed in metres above the ground, cloud cover in oktas, where 0 means clear sky, while 8 means a completely cloudy sky (completely overcast) and 9 is used when it is impossible to determine the degree of cloud cover (sky obstructed from view) due to e.g. fog, and visibility expressed on a scale from 0 to 9, where 0 indicates the worst visibility and 9 indicates perfect visibility.

The meteorological data used as a basis for the analysis were recorded at the Meteorological Station of the Institute of Meteorology and Water Management (IMGW) Toruń-Wrzosy in the period 2021–2022. Until the end of March 2022, data were collected 24h a day on an hourly basis, but from April 2022 only automatic measurements were recorded at night. Total cloud cover is determined manually, so no night-time measurements of this element are available from April 2022. Furthermore, the summer season is characterised by the absence of an astronomical night, so only measurements taken at a full hour between 22:00 and 01:00 CEST were included in the data comparison, and during the summer solstice this time window was further narrowed to the hours between 23:00 and 00:00 CEST due to the noticeable influence of sunlight.

Due to the large number of cloudy days in Toruń, it is necessary to take meteorological conditions into account in the analysis of night sky brightness measurements. According to the data from the IMGW Toruń-Wrzosy Meteorological Station (Table 2) for the period 2019–2022, as many as 30% of nights were completely cloudy (overcast skies), 45% – partly cloudy to varying degrees, and about 25% – cloudless (clear skies).

The linear correlation between the selected factors and the surface brightness of the night sky is presented in Table 3. The

Table 2. Prevalence (%) of each degree of cloud cover by astronomical season in the period from January 2019 to April 2022

OKTANS	ALL YEAR	SPRING	SUMMER	AUTUMN	WINTER
0	22%	28%	24%	15%	22%
1	6%	10%	8%	3%	2%
2	6%	7%	9%	4%	4%
3	4%	5%	6%	4%	3%
4	3%	4%	4%	2%	2%
5	5%	6%	7%	4%	4%
6	5%	7%	6%	4%	4%
7	18%	17%	19%	17%	18%
8	30%	16%	17%	44%	40%
9	1%	0%	0%	3%	1%

Source: own elaboration

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Table 3. Total correlation and correlation calculated for each astronomical season between surface brightness of the night sky and selected meteorological conditions related to the monitoring sites, with absolute values above 0.5 in bold

	ENTIRE YEAR			SUMMER			AUTUMN			WINTER			SPRING		
Device ID	The height of the cloud base	Overall cloudiness	Visibility	The height of the cloud base	Overall cloudiness	Visibility	The height of the cloud base	Overall cloudiness	Visibility	The height of the cloud base	Overall cloudiness	Visibility	The height of the cloud base	Overall cloudiness	Visibility
1	**0.6**	**-0.5**	0.2										**0.6**	**-0.5**	0.2
2	**0.5**	**-0.5**	0.2										**0.5**	**-0.5**	0.2
3	**0.6**	**-0.6**	0.4	**0.6**	**-0.6**	0.2	**0.7**	**-0.6**	0.2	**0.6**	**-0.6**	0.3	**0.5**	**-0.7**	0.2
7	**0.5**		0.2	0.4		0.1	**0.5**		0.0	0.4		**0.6**	0.4		0.0
8	0.4	0.0	0.2	0.4		0.3	0.4		-0.2	**0.5**		-0.2	0.3	0.0	0.2
9	**0.5**		0.1	0.4		0.1	0.4		0.0	0.4		0.3			
10	**0.5**	-0.3	0.1	0.4		0.1	**0.7**		0.0	0.2	-0.3	0.1	0.4		0.0
11	**0.6**		0.0	**0.7**		-0.1	**0.6**		-0.1	**1.0**		-0.1	**0.6**		0.1
12	**0.5**		0.2	0.4		0.2	**0.5**		-0.1	0.2		0.3	0.4		0.0
14	**0.7**		0.3	**0.5**		0.4	**0.7**		0.0	**0.6**		**0.7**	0.4		0.2
16	0.4		-0.1	0.4		0.0	0.4		-0.3				**0.7**		-0.2
17	0.2		-0.2	0.2		0.0	0.4		-0.2	**0.7**		0.4	0.4		0.0
18	**0.6**	**-0.5**	0.2	0.4		0.2	**0.6**	-0.4	0.0	**0.5**	**-0.5**	0.4	0.2	-0.4	0.1
22	**0.5**	0.0	0.3	0.2		**0.5**	**0.5**		-0.1	0.4		**0.5**	0.4	0.0	0.2
23	**0.6**	**-0.6**	0.3	**0.5**	**-0.6**	0.2	**0.6**	**-0.6**	0.0	**0.5**	**-0.6**	0.2	0.4	-0.4	0.0
25	**0.5**	**-0.6**	0.2	**0.6**	**-0.6**	0.0				0.4	-0.4	0.2	**0.6**	**-0.7**	0.2
28	**0.6**		0.4	0.3		0.2	**0.6**		-0.1	**0.5**		**0.7**	0.4		0.1
29	**0.5**	**-0.5**	0.3	**0.6**	**-0.5**	0.1	**0.5**	**-0.5**	0.1	0.3	-0.3	0.3	0.4	**-0.5**	0.1
30	**0.5**		0.0	**0.6**		0.0	0.4		-0.1				**0.6**		0.1
31	**0.5**	**-0.5**	0.3	0.3		0.3	**0.7**		-0.2	0.4	**-0.5**	0.1	0.3	**-0.6**	0.2
32	**0.5**	-0.4	0.1	**0.6**	**-0.7**	0.1	**0.6**	**-0.5**	0.1	0.4	-0.4	0.0	-0.2	**-0.6**	-0.3
33	**0.6**	**-0.5**	0.3	**0.5**	**-0.6**	0.2	**0.6**	**-0.6**	0.0	0.4	**-0.5**	0.2	0.4	-0.4	0.1
34	**0.5**	**-0.5**	0.2	0.4		0.1	**0.6**	**-0.5**	0.0	**0.5**	**-0.5**	0.3	0.3	-0.1	0.0

Source: own elaboration

table shows the correlation results from each device related to both the entire period of analysis and the individual astronomical seasons.

The reduced number of comparisons for the total cloud cover parameter results from the aforementioned unavailability of these data, starting from April 2022 onwards. However, even with this number of analyses, a high correlation between this parameter and the measurements made is evident. The correlation value for almost all locations in each distinguished season and on an annual basis is above 0.5. The correlation results are negative due to the selected mag/arcsec^2 unit for the presentation of the phenomenon. It is the opposite, so the more clouds, the lower the result.

The results of the correlation analysis between the height of the cloud base and the values of the night sky brightness recorded by measuring devices, carried out both for the whole year and individual seasons, are also presented graphically in spatial terms. Figure 5, prepared using the point cartogram method, shows the value of correlation relative to the location of a monitoring site on the map of Toruń.

The results presented in Figure 5 indicate the highest correlation for locations with considerable light pollution resulting

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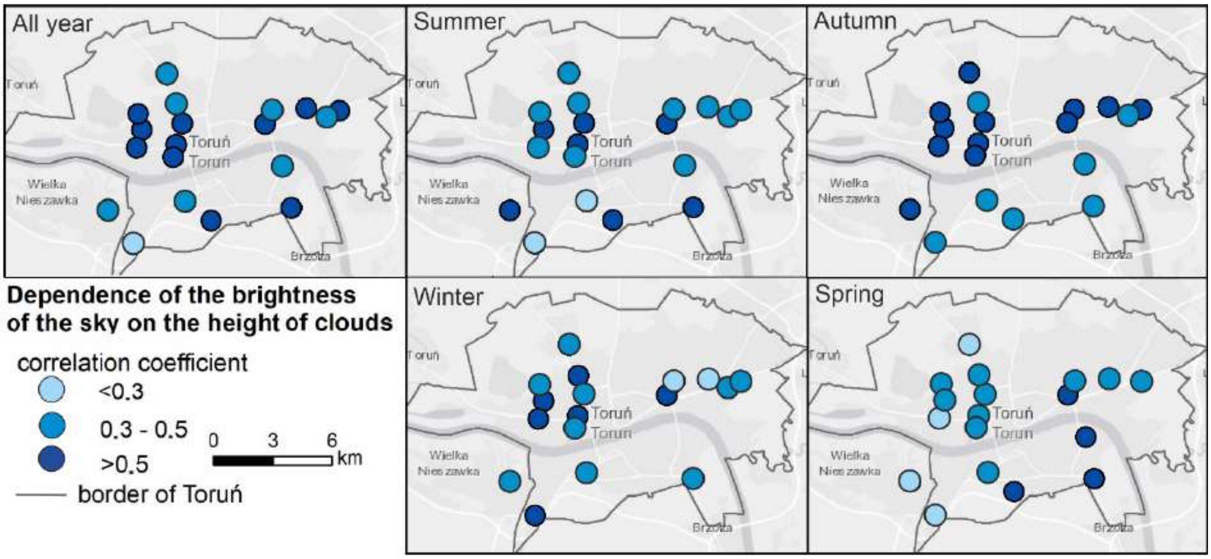

Figure 5. Spatial distribution of the correlation between the cloud base height and the measured surface brightness of the night sky in Toruń
Source: own elaboration

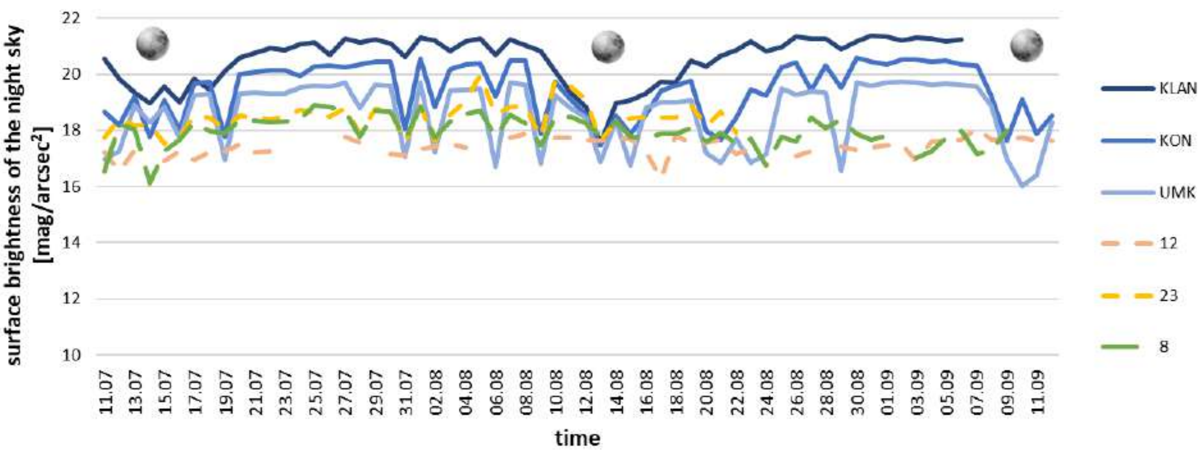

Figure 6. Measurements of night sky light pollution carried out at the sites located outside the built-up area (KLAN and KON) and those located in Toruń in different parts of the city (NCU and measurement sites No. 12, 23 and 8). The symbol of the Moon indicates a full moon
Source: own elaboration

from the presence of a large number of street lamps whose light is reflected by clouds and derivatively increases the values of the recorded parameters. The correlation between these variables varies throughout the year. Most of the monitoring locations in each season showed a high correlation between the measurements and the cloud base height and total cloud cover. However, such a correlation is not observed for the visibility. Most values above a correlation of 0.5 were obtained in autumn, followed by summer and winter, while the weakest correlation was determined in spring. The underestimated correlation for this period may be caused by additional factors, such as numerous light scatterers in the form of particulate matter or water particles in the atmosphere, but also by the decreasing duration of the night. Even though only the hours between 23:00 and 00:00 were selected for data logging during the summer solstice, this may have affected the results and the smaller number of comparisons for correlation.

Relating the results of light pollution measurements from an urban area to reference measurements

The analysis was further extended by comparing the night sky pollution values recorded in the urban area of Toruń with locations away from larger human settlements. To this end, it was necessary to use factory-made SQM photometers, as the LoRaWAN network signal could not be used outside the city limits of Toruń. A total of three such devices further enriched the observations, and they were deployed in a decreasing gradient of human impact. One of the devices was deployed at the Integrated Environmental Monitoring Station in Koniczynka, located 10 km in a straight line north-east of Toruń's boundaries, while the second was installed in the forest hamlet of Klaniny in Tuchola Forest (about 100 km in a straight line north of Toruń), away from any influence of light sources. The third SQM photometer is located on the Observation Platform of the Faculty of Earth Sciences and

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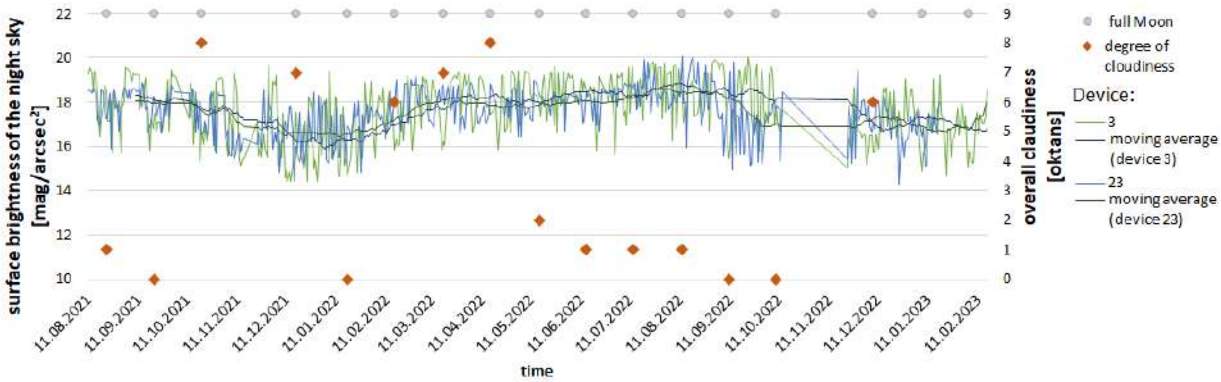

Figure 7. Measurements of night sky light pollution carried out at selected monitoring sites in Toruń (No. 3 and 23) in relation to the phase of the Moon and the degree of cloud cover; additionally, the moving mean calculated for 30 periods for measurements from each device is presented
Source: own elaboration

Spatial Management NCU and has already been used for testing all of the proprietary devices at the technology demonstrator stage. The results from the three locations were collated and compared with each other in the context of increasing distance from a large city and a decreasing gradient of impact exerted by the urban fabric. In addition, the results obtained by the three devices operating in the urban monitoring network located in areas with identified significant light pollution were added to the comparison (Fig. 6).

Analysis of Figure 6 shows a significant difference between the measurements obtained at these selected locations. The data recorded in Tuchola Forest (KLAN) show the highest values, which translates into the lowest light pollution in this area, while the measurements made at the station in Koniczynka (KON) show the influence of the urban light island of Toruń. This graph also shows the previously proven effect of cloudy nights on the level of measured values. When comparing these measurements made over several months, one can also see the effect of the full moon on the recorded value. This is very apparent from the data obtained in the village of Klaniny. This effect, however, is not observed when juxtaposing the phases of the Moon with measurements made in urban areas. This means that the presence of street infrastructure has a significantly greater impact on the measured values in urban areas than the natural light of the Moon in inhabited areas.

A similar relationship is presented in Figure 7, which shows the results of measurements carried out over several months at two selected stations (device No. 3 located on the premises of Nicolaus Copernicus University and No. 23 located closer to the city centre). A moving mean has been superimposed on the graph, making the seasonal variation in the measurements mentioned earlier more pronounced. In addition, the time of the full moon (in this case marked with grey dots at the top of the graph) and the cloud cover occurring at that time, presented on the okta scale, were added to the graph. The presented data show an increase in the measured brightness of the night sky at the time of the full moon. This, however, is not an absolute rule, but a certain regularity. A greater effect of variation in the surface brightness of the night sky is observed when the sky is completely overcast. A stronger correlation of the obtained results is demonstrated by device no. 3, located further from the city centre, which confirms the previous results of the analysis shown in Figure 6. The data cited prove that it is necessary to further investigate the influence of various meteorological factors on the increase in recorded values of the surface brightness of the night sky, so that in future it will be possible to gain an even better understanding of this phenomenon and to develop a more accurate model of light pollution taking into account different atmospheric conditions.

Summary and Conclusions

Pollution of the night sky by artificial light is becoming an increasingly understood and observed (not only by specialists) phenomenon that degrades our environment in which we function and live. To better understand it, interdisciplinary research is being conducted to determine both its extent, scale and severity, as well as its nature and impact on individual living organisms. The growing interest in the subject is evidenced by the increasing number of scientific articles and conference presentations published in recent years (Levin et al. 2020; Mander et al. 2023). This study presents the occurrence of this phenomenon in the Toruń area, its spatial distribution and magnitude, as well as its seasonal variability and correlation with selected atmospheric conditions. The presented results show the complexity of the measurement process and describe a comprehensive analysis of light pollution carried out in an urban area. In the process, the role and impact of external factors on the recording of measurement values, resulting in the increased emission of artificial light at night, were also estimated. The winter period shows the highest light pollution further aggravated by the presence of numerous scatterers of anthropogenic origin in the troposphere, while in summer the effect is considerably smaller. Presentation of the annual data correlation with typical meteorological elements indicates their effect on the increase in surface brightness of the night sky in urban areas. During the continuous two-year research in Toruń, no significant effect of the full moon on the brightness of the night sky was observed. This effect is dominated by the presence of mainly street lights, LED advertisements and the illumination of architectural objects. This is the opposite relationship to that observed in areas far from city lights, where the full moon significantly affects measurements of the night sky brightness. The automatic network for monitoring night sky pollution, designed and operated in Toruń for the purposes of the project, proved to be fully effective and indispensable for continuous data acquisition aimed mainly at better understanding of the phenomenon and its accurate spatial mapping. The correctness of the operation of the low-cost measuring devices designed from scratch and the selection of the locations of the loggers to cover full and comprehensive acquisition in an urban area of this surface size

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and type of development was also operationally verified. The developed method of data acquisition in an urban area, which uses Industry 4.0 technologies and smart transmission grids, appears to be a good complement to the methods already in use for monitoring not only the pollution of the night sky by artificial light, but also other environmental parameters in the near future. The obtained results provide an excellent basis for planning further analysis and research into light pollution in urban areas. Toruń is one of the few cities in the world for which targeted studies of light pollution in the night sky have been carried out in such a dense scattered measurement network and which has such a long series of simultaneous and comparable ground-based observations.

The next stage of the work should be a complex analysis of the relationship between the brightness of the night sky and all elements that can affect its value, such as the presence of atmospheric particulate matter of various sizes, fog, cloud cover, snow cover or technological solutions used for outdoor lighting in terms of light colour, temperature and operating time.

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References

Adafruit 2019, *Adafruit TSL2591 High Dynamic Range Digital Light*, Adafruit Learning System.

Adams, CA, Blumenthal, A, Fernández-Juricic, E, Bayne, E & St. Clair, CC 2019, 'Effect of anthropogenic light on bird movement, habitat selection, and distribution: A systematic map protocol', *Environmental Evidence,* vol. 8, no. 13.

Bara, S, Lima, RC & Zamorano, J 2019, 'Monitoring long-term trends in the Anthropogenic Night Sky Brightness', *Sustainability*, vol. 11.

Cavazzani, S, Cavazzani, S, Ortolani, S, Bertolo, A, Binotto, R, Fiorentin, P, Carraro, G, Saviane, I & Zitelli, V 2020, 'Sky quality meter and satellite correlation for night cloud-cover analysis at astronomical sites', *Monthly Notices of the Royal Astronomical Society*, vol. 493(2), pp. 2463–2471.

Cinzano, P, Falchi, F, Elvidge, CD & Baugh, KE 2000, 'The artificial night sky brightness mapped from DMSP satellite Operational Linescan System measurements', *Monthly Notices of the Royal Astronomical Society,* vol. 318, pp. 641–657.

Elvidge, CD, Baugh, KE, Zhizhin, M & Hsu, FC 2013, 'Why VIIRS data are superior to DMSP for mapping nighttime lights', *Proceedings of the Asia-Pacific Advanced Network,* vol. 35.

Falchi, F, Cinzano, P, Duriscoe, D, Kyba, C.C.M, Elvidge, CD, Baugh, K, Portnov, BA, Rybnikova, NA Furgoni, R 2016, 'The new world atlas of artificial night sky brightness', *Science advances,* vol. 2, no. 6, e1600377.

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,* vol. 126.

Globe at Night. Available from: <https://app.globeatnight.org/map>. [18 May 2023].

Hänel A, Posch, T, Ribas, S.J, Aubé, M, Duriscoe, D, Jechow, A, Kollath, Z, Lolkema, DE, Moore, C, Schmidt, N, Spoelstra, H, Wuchterl, G & Kyba, CCM 2017, 'Measuring night sky brightness: Methods and challenges', *Journal of Quantitative Spectroscopy and Radiative Transfer* vol. 205, pp. 278–290.

International Dark-Sky Association, *The International Dark Sky Places conservation program recognizes and promotes excellent stewardship of the night sky*. Available from: <https://www.darksky.org/our-work/conservation/idsp/> [29 December 2022].

Jechow, A & Hölker, F 2019, 'How dark is a river? Artificial light at night in aquatic systems and the need for comprehensive night-time light measurements', *WIREs Water,* vol. 6(6), e1388.

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*, vol. 36, pp. 15–25.

Karpińska, D & Kunz, M 2019, 'Light pollution in the night sky of Toruń in the summer season', *Bulletin of Geography. Physical Geography Series,* vol. 17, pp. 91–100.

Karpińska, D & Kunz, M 2020a, 'Analysis of light pollution of the night sky in Toruń (Poland)', *Civil and Environmental Engineering Reports*, pp. 155–172.

Karpińska D & Kunz M. 2020b, 'Ochrona nocnego nieba - wyzwanie dla Rezerwatu Biosfery Bory Tucholskie' ['Protection of the night sky – a challenge for the Tuchola Forest Biosphere Reserve'] in '*Rola i funkcjonowanie parków krajobrazowych w rezerwatach biosfery*' [The role and functioning of landscape parks in biosphere reserves'], ed. Kunz Mieczysław, pp. 329–346, Toruń, Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika.

Karpińska, D & Kunz, M 2021, 'Analysis of the visibility and signal strength of the LoRaWAN network in an urbanized area – a case study of the Bielany campus at the Nicolaus Copernicus University in Toruń'*, Bulletin of Geography. Socio-Economic Series*, vol. 54*,* pp. 137–149.

Karpińska, D & Kunz, M 2022, 'Device for automatic measurement of light pollution of the night sky', *Scientific Reports,* vol. 12. https://doi.org/10.1038/s41598-022-20624-7.

Karpińska, D & Kunz, M 2023a, 'Relationship between the surface brightness of the night sky and meteorological conditions', *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 306.

Karpińska, D & Kunz, M 2023b, 'Vertical variability of night sky brightness in urbanised areas', *Quaestiones Geographicae,* vol. 42(1), pp. 5–14.

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,* vol. 500, 47–51.

Kolláth, Z 2010, 'Measuring and modelling light pollution at the Zselic Starry Sky Park', *Journal of Physics Conference Series,* vol. 218(1).

Kołomański, S 2015, 'Zanieczyszczenie światłem i ciemność' ['Light pollution and darkness'] in *Przejdź na ciemną stronę nocy. Środowiskowe i społeczne skutki zanieczyszczenia* światłem [Go to the dark side of the night. Environmental and social effects of light pollution], ed. MR Wiśniewska K Tomasik, pp. 29–46, Wyd. UW. Warszawa.

Lacoeuilhe, A, Machon, N, Julien, JF, Le Bocq, A, & Kerbiriou, C 2014, 'The influence of low intensities of light pollution on bat communities in a semi-natural context', *PLoS One* vol. 9(10), e103042.

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Levin, N, Kyba, CCM, Zhang, Q, Sánchez de Miguel, A, Román, MO, Li, X, Portnov, BA, Molthan, AL, Jechow, A, Miller, SD, Wang, Z, Shrestha, RM & Elvidge, CD,2020, 'Remote sensing of night lights: A review and an outlook for the future', *Remote Sensing of Environment,* vol. 237.

Linares, H, Masana, E, Ribas, SJ, Aubé, M, Simoneau, A & Bará, S 2020, 'Night sky brightness simulation over Montsec protected area', *Journal of Quantitative Spectroscopy and Radiative Transfer,* vol 249.

Longcore, T, Rich, C & DelBusso, L 2017, 'Artificial Night Lighting and Protected Lands', *Natural Resource Report* NPS/NRSS/NSNS/NRR–2017/1493.

Macgregor, CJ, Evans, DM, Fox, R & Pocock, MJO 2017, 'The dark side of street lighting: Impacts on moths and evidence for the disruption of nocturnal pollen transport', *Global Change Biology*, vol. 23(2), pp. 697–707.

Mander, S, Alam, F, Lovreglio, R & Ooi, M 2023, 'How to measure light pollution – A systematic review of methods and applications', *Sustainable Cities and Society,* vol. 92.

Mikhaylov, K, Stusek, M, Masek, P, Petrov, V, Petäjäjärvi, J, Andreev, S, Pokorny, J, Hosek, J, Pouttu, A & Koucheryavy, Y 2018, 'Multi-RAT LPWAN in Smart Cities: Trial of LoRaWAN and NB-IoT Integration', *IEEE International Conference on Communications (ICC)*, pp. 1–6.

Ministry of the Environment of the Czech Republic, 2022, 'Light pollution reduction measures in Europe', *Working paper for international workshop "Light Pollution 2022", during the Czech Presidency of the Council of the European Union*.

Pun, CSJ, So, CW, Leung, WY & Wong, CF 2014, '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,* vol. 139, pp. 90–108.

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,* vol. 18.

Semtech Corporation, 2015, AN1200.22 LoRa™ Modulation Basics, Wireless Sensing and Timing Products, Application Note.

Szlachetko, K (ed.) 2022, *Memorandum w sprawie ustanowienia prawnych podstaw zrównoważonej polityki oświetlenia zewnętrznego*. [*Memorandum on establishing the legal basis for a sustainable outdoor lighting policy*] Instytut Metropolitarny, Gdańsk.

Ściężor, T 2020, 'The impact of clouds on the brightness of the night sky', *Journal of Quantum Spectroscopy and Radiative Transfer*, vol. 247.

Ściężor, T 2021, 'Effect of street lighting on the urban and rural night-time radiance and the brightness of the night sky', *Remote Sensetion*, vol. 13(9).

Ściężor, T, Kubala, M, Kaszowski, W & Dworak, TZ,2010, *Zanieczyszczenie świetlne nocnego nieba w obszarze aglomeracji krakowskiej. Analiza pomiarów sztucznej poświaty niebieskiej.* [*Light pollution of the night sky in the area of the Kraków agglomeration. Analysis of artificial blueglow measurements*]. Wyd. Politechniki Krakowskiej. Kraków.

Zamorano, J, García, C, Tapia, C, de Miguel, AS, Pascual, S, Gallego, J 2016, 'Stars4all night sky brightness photometer', *International Journal of Sustainable Lighting,* vol. 18, pp. 49–54.

Zhang, C, Pei, Y, Li, J, Qin, Q & Yue, J 2019, 'Application of Luojia 1-01 Nighttime Images for Detecting the Light Changes for the 2019 Spring Festival in Western Cities', *Remote Sensing* vol. 12, pp. 14–16.